

Searches for CP violation in $D^+ \rightarrow K^- K^+ \pi^+$ decays at the LHCb experiment

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Abstract

This thesis documents searches for direct CP violation in the Cabibbo-suppressed $D^+ \rightarrow K^- K^+ \pi^+$ decay at the LHCb experiment. Two complementary analyses are described. Direct CP -violating asymmetries are predicted to exist in singly Cabibbo-suppressed charm decays with magnitudes of up to $\mathcal{O}(10^{-3})$ in the Standard Model, and can be enhanced to the percent level by contributions from new physics. No such asymmetry has yet been observed.

The LHCb detector is a forward spectrometer with a precise vertex detector and powerful particle identification capabilities, designed to collect large, pure samples of charm and B decays. Data collected at LHCb in 2010 corresponding to an integrated luminosity of 35 pb^{-1} are used to perform a model-independent search for direct CP violation in the $D^+ \rightarrow K^- K^+ \pi^+$ decay. The Dalitz plot is divided into bins and a χ^2 test of the compatibility of the dataset with no CP violation is performed. No evidence of CP violation is found.

A second search for CP violation in the region of the $D^+ \rightarrow K^- K^+ \pi^+$ Dalitz plot around the ϕ resonance is described. The charge asymmetry in this decay is calculated and compared to that in the control channel $D^+ \rightarrow K_s^0(\pi^- \pi^+) \pi^+$. The 1.0 fb^{-1} of data collected at LHCb in 2011 are used. The CP -violating asymmetry is found to be $(-0.04 \pm 0.14 \pm 0.14)\%$ where the uncertainties are statistical and systematic, respectively. A new observable sensitive to CP violation that varies across the ϕ resonance is defined and measured, and is consistent with no CP violation at the current level of sensitivity. In addition, the CP -violating asymmetry in the decay $D_s^+ \rightarrow K_s^0 \pi^+$ is determined to be $(0.61 \pm 0.83 \pm 0.14)\%$. There is no evidence for CP violation in either channel. The prospects for new results using data collected in 2012 are very promising and a significant improvement in our understanding of these decays is anticipated.

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Introduction

The LHCb experiment at the Large Hadron Collider is designed to study CP violation and rare decays in the beauty and charm systems. In many decays of B and D mesons, currently undiscovered heavy virtual particles could contribute to penguin loop diagrams with observable effects on branching ratios and CP asymmetries. The LHCb experiment aims to test the Standard Model of particle physics by determining these quantities with unprecedented levels of precision. Measurements of the Standard Model parameters themselves, such as the elements of the CKM matrix, also form a crucial part of the LHCb physics programme. The first significant data taking period of the experiment, from 2010 to 2012 inclusive, is now over, and major progress in many areas of flavour physics has been made. Results of note include the first evidence for the $B_s^0 \rightarrow \mu^+ \mu^-$ decay [1], some hints of CP violation in charm decays [2, 3, 4], the first 5σ observation of charm mixing in a single measurement [5], and new more accurate measurements of the CKM angle γ [6]. The prospects for further exciting physics measurements from the data taken in 2012 are excellent. An upgrade to the detector is envisaged for 2018 to augment the rate and improve the efficiency of data taking.

While the initial studies of the physics potential of the experiment focused on B decays [7], the characteristics of the detector which make it suitable for B physics are also invaluable for charm. The most important of these are precise vertexing and excellent particle identification capabilities. Early measurements established key characteristics of

charm production in proton-proton collisions, which have since proved useful to studies of quantum chromodynamics. Evidence for a charge asymmetry in the production of $D^\pm$ mesons in the forward region was published by the author in late 2011 [8], but is not described in detail in this thesis. Likewise, the author also collaborated on a measurement of the cross sections for production of the charm mesons in pp collisions at a centre of mass energy $\sqrt{s}$ of 7 TeV. This is now published in Nuclear Physics B [9].

This thesis describes two searches for CP violation in the decay of a charged D meson to two kaons and one pion. In both analyses, techniques that exploit the Dalitz plot to gain sensitivity to plausible types of CP violation and to remove systematic effects are developed. Chapter 1 introduces the Standard Model of particle physics, CP violation, and the kinematics of multi-body particle decays. Chapter 2 describes the LHCb detector, with particular emphasis on the components most crucial to isolating a pure unbiased sample of the D decay in question. Chapter 3 presents a model-independent search for CP violation in the Dalitz plot of the $D^+ \rightarrow K^- K^+ \pi^+$ decay published in Physical Review D [10]. This study used the 35 pb^{-1} of data collected during 2010 at $\sqrt{s} = 7 \text{ TeV}$. Chapter 4 describes a subsequent search for CP violation in the part of the $D^+ \rightarrow K^- K^+ \pi^+$ Dalitz plot around the ϕ resonance, performed with the 1 fb^{-1} of data collected in 2011, also at $\sqrt{s} = 7 \text{ TeV}$. This is published in the Journal of High Energy Physics [11]. While restricted to a small part of the Dalitz plot, the increased size of the dataset means the sensitivity of this analysis is substantially greater than that described in Chapter 3. No evidence for CP violation is found in either study. A conclusion and outlook details the prospects for similar measurements with data collected more recently.

Chapter 1

Theoretical background

1.1 Introduction to the Standard Model

The Standard Model (SM) of particle physics describes a set of fundamental building blocks, or elementary particles, and their interactions. In the theory, these particles interact via the strong, electromagnetic and weak forces.

Within the mathematical framework of the SM, particles and forces are the observable manifestations of scalar, vector or spinor fields which interact with each other according to a well-defined set of rules. The quanta of the scalar and vector fields are bosons, which are defined by their integer spin quantum number and which ‘carry’ forces from one place to another. The bosons include the scalar Higgs particle, the gluon, which is a vector, and the electroweak vectors W , Z , and γ . The quanta of the spinor fields are fermions, which have half-integer spins and are categorised as quarks or leptons. The leptons can be observed directly, and comprise the electron, muon, tau, and their neutrinos. The quarks do not exist in isolation¹, but make up all other observable massive particles, which are called hadrons and include the proton and neutron. Quarks come in six flavours:

¹The exception to this rule is that decays of a single top quark can be reconstructed.

up, down, strange, charm, bottom, and top. Quarks and leptons (except neutrinos) are charged, and each particle has a partner of opposite charge, which is referred to as its antiparticle. Most fundamental particles acquire their masses via the Higgs mechanism. The exceptions are the photon and gluon, which are massless, and perhaps the neutrinos. Most of the mass of the more common composite hadrons such as the proton and neutron results from the strong forces binding their constituent quarks together, rather than from the quarks themselves.

Mathematically, the SM is a quantum field theory whose properties emanate from the symmetries of the $SU(3) \times SU(2) \times U(1)$ gauge groups. It is probably the simplest quantum field theory that can describe the particles we see reasonably well while satisfying the common-sense requirements of unitarity and causality. There is a natural division of the theory into quantum chromodynamics, associated with the $SU(3)$ symmetry and the strong force, and the electroweak theory, $SU(2) \times U(1)$, which is associated with the weak and electromagnetic interactions.

The various symmetries permit only certain types of particle interactions. For example, unstable hadronic particles are only likely to decay to a small number of well-defined final states. The SM provides a framework for calculating the probability of these interactions. This is generally written in terms of the square of a complex amplitude defined as

$$\langle f|H|i\rangle \tag{1.1}$$

where H is the effective Hamiltonian for the process $i \rightarrow f$. The squared amplitude is related to the probability by variables that depend on the kinematic characteristics of the process. The Feynman rules provide a useful toolkit which gives recipes for assembling amplitudes of this form from the constituents of a Feynman diagram. Usually, however, the amplitude is not calculable analytically, and one must resort to perturbative

approaches or lattice calculations. The perturbative approach involves expansions of the amplitudes in ‘small’ parameters. However, parameters which are small at one energy scale may be large at others. It is often possible to find simplified field theories valid only at an energy scale of particular interest, and these are referred to as *effective* field theories [12].

The squared amplitudes representing the relative probabilities of given processes are usually expressed as cross sections. These can be compared with experiment to test the theory, and sometimes they can be used to constrain possible extensions to the framework of the SM.

The next sections outline the Standard Model in more detail, discussing the two constituent theories, electroweak physics and quantum chromodynamics (QCD). With a basic theoretical framework established, the following sections introduce charm physics, mixing and CP violation within and beyond the Standard Model. The chapter closes with a brief exploration of the complexities introduced by the kinematics of multi-body decays.

1.2 Quantum chromodynamics

The quark model was proposed in the early 1960s. Each hadron is either a quark-antiquark pair, known as a meson, or a set of three quarks or antiquarks called a baryon. In units of the electron charge $-e$, the up, charm and top quarks possess a charge of $\frac{2}{3}$ while the down, strange and bottom quarks have charge $-\frac{1}{3}$. The quarks are abbreviated by their initial letters. The requirement that hadrons have integer charge constrains their quark composition. All quarks have a spin of $\pm\frac{1}{2}$. Evidence from spectroscopy proves that baryons are fermionic. Mesons, on the other hand, are bosons. Therefore, it was asserted that quarks must also have a property like spin known as colour, which allows the overall wavefunction of a baryon to be antisymmetric even if it is spin-symmetric and

flavour-symmetric. This is the case, for example, for the Δ^{++} or Δ^- particles, which have compositions uuu and ddd respectively. The colour property corresponds to the $SU(3)$ symmetry of the Standard Model, so there are three possible colours, and the quanta of the $SU(3)$ gauge field $A_{\nu a}$ are the eight possible gluons. If three quarks with different colours are combined, the resulting baryon will have zero net colour. Antiquarks have ‘anti-colour’ and so a meson can be formed from a quark-antiquark pair if the anti-colour of the antiquark matches the colour of the quark.

The field strength tensor for the strong interaction is

$$F_{\mu\nu a} = \partial_\mu A_{\nu a} - \partial_\nu A_{\mu a} + gf_{abc}A_{\mu b}A_{\nu c}. \quad (1.2)$$

where f_{abc} are the totally antisymmetric structure constants of $SU(3)$ and g is the unrenormalised coupling constant. The properties of the theory are largely determined by the requirement of local gauge invariance, which enables the unitarity principle to be satisfied [13, 14]. Since a Lagrangian needs a ‘kinetic’ term which includes first derivatives of the field in question, the first derivative of the quark field $q(x)$ must transform in the same way as the field itself under a local gauge transformation,

$$q(x) \rightarrow q(x)' = e^{i\frac{1}{2}\lambda_a\xi_a(x)}q(x) \quad (1.3)$$

where λ_a are the 3×3 generalisations of the Pauli matrices and $\xi_a(x)$ represents position-dependent phases. For this requirement to be satisfied, it is necessary to replace the simple first derivative $\partial_\mu q$ with a covariant derivative that reflects the $SU(3)$ symmetry,

$$D_\mu q = \left(\partial_\mu - igA_{\mu a}\frac{1}{2}\lambda_a \right) q. \quad (1.4)$$

The Lagrangian formed from the difference of kinetic and potential energy terms can be

cast in terms of correlation functions, which give rise to the amplitudes for a process in terms of ‘propagators’, which describe how particles are transferred in free space, and ‘vertices’, which describe how they interact. This is the origin of the Feynman rules introduced in Sect. 1.1.

The gluons that mediate the strong interaction have colour charge themselves, so the screening of a quark by a gluon augments the strong force (unlike in the electromagnetic case, where the uncharged photons weaken the electromagnetic force by screening). The screened, or ‘renormalised’ QCD coupling constant is generally labelled α_S . In QCD, perturbative expansions in α_S are only valid when α_S is small: in practise, this means at energies well above 200 MeV. The theory is asymptotically free: the strong force becomes weaker at higher energy scales.

Along with asymptotic freedom, QCD exhibits a property known as ‘confinement’: it appears that only colour singlet states can exist in isolation. The obvious evidence for this is that free quarks have never been observed [15]. Therefore, when heavy mesons like D^+ decay, the light quarks that result from the weak decay must interact strongly to hadronise. Often a short-lived intermediate resonance will be formed before the final state particles are produced. These ‘final state interactions’ are not well understood, but have important implications for the kinematics of the final state particles, discussed in Sect. 1.10.

1.3 The GWS theory of electroweak interactions

The first evidence for weak interactions came in the form of nuclear beta decay. Weak interactions are important, since they are the only mechanism by which quarks can change their flavour. The focus of this thesis is the study of D meson decays, all of which involve a weak interaction. As well as describing these interactions, the electroweak theory provides

a means for fundamental particles to acquire mass, known as the Higgs mechanism, which forms the starting point of this discussion. The fields that correspond to the particles couple to a scalar Higgs field ϕ , which exists at up to order four in the Lagrangian. As in QCD, the first derivative of this field must transform in the same way as the field itself under a local gauge transformation, leading to a covariant derivative which reflects the $SU(2) \times U(1)$ symmetry,

$$D_\mu \phi = \left(\partial_\mu - ig W_\mu^a \frac{\sigma^a}{2} - i \frac{1}{2} g' B_\mu \right) \phi \quad (1.5)$$

where σ^a are the Pauli matrices and g, g' are the $SU(2)$ and $U(1)$ coupling constants respectively. There are four vector fields corresponding to this symmetry, W_μ^a and B_μ . The electromagnetic and weak coupling constants and fields will be related to g and g' , and W_μ^a and B_μ respectively by linear combinations. The Higgs field is subject to a mechanism known as spontaneous symmetry breaking in which three of its four degrees of freedom are lost, becoming longitudinal degrees of freedom in three of the four vector fields. This implies that the vector bosons acquire masses, since massless particles can have only transverse polarisation degrees of freedom. The charged vector fields $W^\pm$ come from linear combinations of the $SU(2)$ bosons W_μ^a ,

$$W_\mu^\pm = \frac{1}{\sqrt{2}} (W_\mu^1 \pm W_\mu^2) \quad (1.6)$$

while the neutral boson fields Z and A (which corresponds to the photon) are formed from a linear combination of the third $SU(2)$ boson W_3^0 and the $U(1)$ boson B^0 ,

$$\begin{aligned} Z^0 &= \cos \theta_W W_3^0 - \sin \theta_W B^0 \\ A^0 &= \sin \theta_W W_3^0 + \cos \theta_W B^0 \end{aligned} \quad (1.7)$$

where θ_W is the weak mixing angle. This is defined by $m_W = m_Z \cos \theta_W$, where m_W is the mass of the $W^\pm$ boson, and m_Z is the mass of the Z . The photon stays massless, and the bare electron charge is

$$e = \frac{gg'}{\sqrt{g^2 + g'^2}}. \quad (1.8)$$

The mass term of the Higgs field is quadratic in ϕ , and has a sign opposite to the quartic term, resulting in a ‘Mexican hat’ potential. Spontaneous symmetry breaking can be thought of as the field choosing a minimum in this potential. The minimum is referred to as the Higgs ‘vacuum expectation value’, and is $246 \text{ GeV}/c^2$ [16], while the mass of the Higgs boson is around $125 \text{ GeV}/c^2$ [17, 18].

Experimentally, quarks and leptons each come in three ‘generations’, each of which contains a pair of quarks and a pair of leptons (and their antiparticles). Furthermore, fermion fields can be decomposed into left- and right-handed ‘chiral’ components with the Dirac matrices:

$$\psi_L = \frac{1}{2}(1 - \gamma_5)\psi, \quad \psi_R = \frac{1}{2}(1 + \gamma_5)\psi \quad (1.9)$$

and this decomposition has physical significance. The parity operator P reverses the spatial component of a four-vector while leaving the time component unchanged. The momentum of a particle is reversed under the parity operation while its spin is not changed. A parity transform converts a left-handed particle to a right-handed particle. The parity of a particle or combination of particles is conserved in strong and electromagnetic interactions, but violated in weak interactions. This parity violation was observed experimentally in 1957 via the spatial asymmetry of the decay products of ^{60}Co [19]. The left-handed quarks and leptons (and right-handed antiquarks and antileptons) can couple within and between generations via the exchange of a W boson, while their opposite-handed partners

cannot. Therefore the left-handed fields are written as doublets

$$Q_L^i = \begin{pmatrix} u^i \\ d^i \end{pmatrix}_L = \left(\begin{pmatrix} u \\ d \end{pmatrix}_L, \begin{pmatrix} c \\ s \end{pmatrix}_L, \begin{pmatrix} t \\ b \end{pmatrix}_L \right) \quad (1.10)$$

and the right-handed quarks and leptons as singlets

$$u_R^i = (u_R, c_R, t_R), \quad d_R^i = (d_R, s_R, b_R). \quad (1.11)$$

In addition to parity, there are other related symmetries. The charge operator C converts a left-handed particle to a left-handed antiparticle. A particle and its antiparticle will always have opposite parities. Chiral gauge theories naturally violate C and P separately, but CP is usually conserved, and the combination with time-reversal symmetry T , referred to as CPT , represents a symmetry that is unlikely to be broken (if it were, the quantum field theory would not be Lorentz-invariant [20]).

The mass of the quarks and leptons is acquired via the coupling of the fermion fields to the Higgs field with fermion-specific constant λ_f , which contributes $\Delta\mathcal{L}_f$ to the overall Lagrangian:

$$\Delta\mathcal{L}_f = -\lambda_f F_L \phi f_R + \text{h.c.} \quad (1.12)$$

where F_L stands for the left-handed fermion doublet and f_L for the right-handed singlet. The particles propagate through space as mass eigenstates but the weak interactions use a different set of eigenstates. The matrix that relates these bases is known as the CKM matrix [21, 22]:

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}. \quad (1.13)$$

This 3×3 unitary matrix has four physical degrees of freedom, given that the overall

phase associated with each row can be incorporated into the quark field. There are three mixing angles θ_{ij} and one phase δ_{13} , often referred to as γ . If cosines and sines of θ_{ij} are represented by c_{ij} and s_{ij} respectively, the CKM matrix can be rewritten as

$$\begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta_{13}} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta_{13}} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta_{13}} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta_{13}} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta_{13}} & c_{23}c_{13} \end{pmatrix}. \quad (1.14)$$

The four parameters that determine the CKM matrix elements, the three coupling constants, a parameter which gives the (as yet undiscovered or nonexistent) CP violation in strong interactions, the Higgs vacuum expectation value and the parameters determining the masses of the quarks, leptons and Higgs boson comprise the 19 free parameters of the Standard Model which cannot be derived from the theory.

The complex phase in the CKM matrix has a value of $\delta_{13} = \gamma = (72.2 \pm 9.2)^\circ$ [23]. It allows for CP violation in weak decays, which is discussed in Sect. 1.4. Weak decays whose amplitudes contain only diagonal CKM elements are referred to as Cabibbo favoured, while those with one factor of V_{us} , V_{cb} , V_{cd} or V_{ts} are singly Cabibbo suppressed. Decays containing two of these factors, or one of V_{ub} or V_{td} , are doubly Cabibbo suppressed.

1.4 Introduction to CP violation

It is thought that in the very early Universe particles and antiparticles were produced in equal numbers. It is not known how an excess of matter over antimatter came to exist, but there are three conditions, due to Sakharov [24], which must be satisfied before the observed excess can be formed. The first of these is violation of the CP symmetry. In practise, CP violation (CPV) causes differences between the decay rate of a particle to a given final state and the decay rate of its antiparticle to the CP -conjugate final state. It

arises when there are two possible decay amplitudes to the same set of daughter particles, for example a tree diagram and a penguin diagram (see Sect. 1.8), and these amplitudes interfere with different strong and weak phases. If the particle can mix into its antiparticle and then decay to a CP eigenstate, CPV is also possible, as explained below.

For CP violation to help explain baryogenesis, the second and third Sakharov conditions, the requirements of baryon number violation and of departure from thermal equilibrium, must be satisfied. Baryon number violation has not yet been observed: the global limit on proton decay is 2.1×10^{29} years (at 90% C.L.), and the 90% confidence limits on proton decay to many plausible final states such as $e^+ \pi^0$ are as high as $\mathcal{O}(10^{34})$ years [16]. Furthermore, the CPT symmetry constrains the flavour eigenstates of a particle and its antiparticle to decay at the same overall rate [25], so CP violation does not automatically produce an excess of matter over antimatter. Therefore finding CPV is necessary, but not sufficient, to explain the observed particle-antiparticle asymmetry. The fact that it might be related to this imbalance has helped to motivate large experiments to study it.

CP violation is categorised as direct CPV, in which a particle is more likely to decay to a given final state in a given time interval than its antiparticle, or vice versa, indirect CPV, in which the rate of mixing of a particle to its antiparticle is faster than the converse process, and indirect CPV in the interference between mixing and decay. Indirect CPV was discovered first, by Cronin and Fitch in the neutral kaon system in 1964 [26]. The first evidence for direct CPV was also found in the neutral kaon system by the NA31 experiment in 1988 [27], but it is a somewhat smaller effect than the indirect case. CPV in mixing is expected to be independent of the final state for a given parent particle [28]. Searches for direct CPV in the charm system form the main topic of this thesis, but the indirect CPV in the neutral kaon system is important in Chapter 4 so is also explained in Sect. 1.6.

A direct CP violating asymmetry is usually defined in terms of the decay rates of a

particle and its antiparticle to a given final state. These are labelled Γ_+ and Γ_- respectively, and then the CP asymmetry takes the form (ignoring experimental corrections) of

$$A_{CP} = \frac{\Gamma_+ - \Gamma_-}{\Gamma_+ + \Gamma_-}. \quad (1.15)$$

Direct CP asymmetries can often be determined from experimental observations of time-independent decay rates or yields of a given final state. For direct CPV to be observable (i.e. for the measured A_{CP} to differ from zero) two competing amplitudes to the same final state with moduli A and B , and different relative strong and weak phases δ and γ between these amplitudes, are required. The theoretical value of A_{CP} is then given by

$$A_{CP} = \frac{2AB \sin \delta \sin \gamma}{A^2 + B^2 + 2AB \cos \delta \cos \gamma}. \quad (1.16)$$

Depending on the nature of any observed direct CPV, it may be possible to determine the relevant amplitudes and phases via an amplitude analysis if the decay in question has more than two daughter particles, following methods outlined in Sect. 1.10. Indirect CPV depends on the lifetime and mixing properties of the particle in question, and requires a different approach.

1.5 Neutral meson mixing

Neutral mesons, for example the K^0 , exist as mass eigenstates K_L^0 and K_S^0 , which can be expressed as superpositions of the flavour eigenstates, K^0 and $\bar{K}^0$ ($\bar{s}d$ and $s\bar{d}$ respectively), or of the CP eigenstates, which I will refer to as K_1 and K_2 . This mixing of K^0 and $\bar{K}^0$ states can be thought of as the interference of their respective amplitudes, and can be represented by the box diagram in Fig. 1.1.

To describe the mixing, an effective Hamiltonian $\mathbf{H}$ is defined, following Ref. [16].

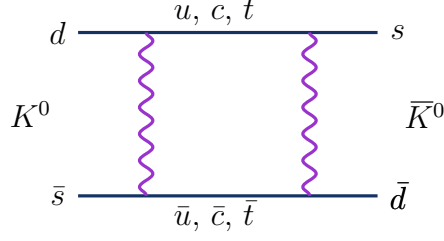


Figure 1.1: Representation of mixing in the neutral kaon system. A K^0 meson transforms to its antiparticle via two exchanges of W bosons.

This is a 2×2 matrix that describes the time evolution of an initial state $|\psi(0)\rangle$. A meson is produced as a flavour eigenstate $|\psi(0)\rangle = |K^0\rangle$ or $|\bar{K}^0\rangle$, but propagates as a mass eigenstate, so its wavefunction evolves as

$$|\psi(t)\rangle = \mathbf{H}(\mathbf{t})|\psi(0)\rangle = \mathbf{H} \left(a(0)|K_s^0\rangle + b(0)|K_L^0\rangle \right). \quad (1.17)$$

Here the flavour eigenstates are related to the mass eigenstates by complex coefficients a and b . The inverse relation conventionally uses constants q and p , so

$$|K_s^0\rangle = p|K^0\rangle + q|\bar{K}^0\rangle \quad (1.18)$$

and

$$|K_L^0\rangle = p|K^0\rangle - q|\bar{K}^0\rangle \quad (1.19)$$

where $|q|^2 + |p|^2 = 1$. The action of the operators P and C on the flavour eigenstates is to change the sign and the flavour respectively, for example $CP|K^0\rangle = -|\bar{K}^0\rangle$, so the CP eigenstates can be related to the flavour eigenstates by

$$|K_1\rangle = \frac{1}{\sqrt{2}} (|K^0\rangle - |\bar{K}^0\rangle) \quad (1.20)$$

and

$$|K_2\rangle = \frac{1}{\sqrt{2}} (|K^0\rangle + |\bar{K}^0\rangle) \quad (1.21)$$

The mass eigenstates are very nearly the same as the CP eigenstates, as the CPV in the neutral kaon system is small. The Hamiltonian can be written as the sum of two Hermitian matrices $\mathbf{M}$ and $\mathbf{\Gamma}$,

$$\mathbf{H} = \mathbf{M} - \frac{i}{2}\mathbf{\Gamma} \quad (1.22)$$

and their off-diagonal components give the extent of the mixing,

$$\left(\frac{q}{p}\right)^2 = \frac{M_{12}^* - (i/2)\Gamma_{12}^*}{M_{12} - (i/2)\Gamma_{12}}. \quad (1.23)$$

The experimental observable that relates to this ratio is the semileptonic asymmetry a_{sl} , defined as

$$a_{sl} = \frac{(1 - |q/p|^4)}{(1 + |q/p|^4)} \quad (1.24)$$

and measured using semileptonic decays such as $K^0 \rightarrow \pi^- e^+ \nu_e$. Hermiticity implies that $M_{12}^* = M_{21}$ and $\Gamma_{12}^* = \Gamma_{21}$. The CPT symmetry implies that $M_{11} = M_{22} \equiv M$ and $\Gamma_{11} = \Gamma_{22} \equiv \Gamma$. When the matrix is diagonalised, the mass eigenstates emerge, with masses m_L and m_S , and widths Γ_L and Γ_S ,

$$m_{L,S} = M \pm \mathcal{R}e \left(\sqrt{(M_{12}^* - \frac{i}{2}\Gamma_{12}^*)(M_{12} - \frac{i}{2}\Gamma_{12}^*)} \right) \quad (1.25)$$

and

$$\Gamma_{L,S} = \Gamma \mp 2\mathcal{I}m \left(\sqrt{(M_{12}^* - \frac{i}{2}\Gamma_{12}^*)(M_{12} - \frac{i}{2}\Gamma_{12}^*)} \right) \quad (1.26)$$

The long-lived eigenstate, K_L^0 , turns out to be heavier than the short-lived K_S^0 by $\Delta m = m_S - m_L = 3.5 \times 10^{-6} \text{ eV}$ [16]. The width difference is $\Delta\Gamma = \Gamma_S - \Gamma_L$, and it is often conventional in studies of both kaon and charm mixing to define parameters $x = \Delta m/\Gamma$

and $y = \Delta\Gamma/(2\Gamma)$. The mixing, parameterised by p and q or x and y , thus depends on the lifetimes and masses of the eigenstates in which the particles propagate through space.

1.6 CP violation in the $K^0 \rightarrow \pi^-\pi^+$ decay

If CP were conserved, the mass eigenstates of the neutral kaon system would be the same as the CP eigenstates and the $K_L^0 \rightarrow \pi^-\pi^+$ and $K_L^0 \rightarrow \pi^0\pi^0$ decays, for example, would not occur. In fact both of these CP -violating decays have been observed, and the amplitude ratio

$$\eta_{+-} = \frac{\langle \pi^-\pi^+ | \mathcal{H} | K_L^0 \rangle}{\langle \pi^-\pi^+ | \mathcal{H} | K_S^0 \rangle} \quad (1.27)$$

takes the value $(2.232 \pm 0.011) \times 10^{-3}$. The corresponding ratio for the $\pi^0\pi^0$ final state is $\eta_{00} = (2.221 \pm 0.011) \times 10^{-3}$ [16]. In this thesis, CP violation in the neutral kaon system is considered in the context of the $D^+ \rightarrow K_S^0(\pi^-\pi^+)\pi^+$ decay. The D^+ meson decays to a $\bar{K}^0$ and a π^+ , while the D^- meson decays to a K^0 and a π^- . However, the K^0 and $\bar{K}^0$ decays are not detected directly: the $\bar{K}^0$ and K^0 amplitudes interfere, and, as discussed in the previous section, the neutral kaons propagate as K_S^0 and K_L^0 mesons. To a very good approximation, only the K_S^0 mesons are detected, as the K_L^0 meson flies out of the detector before decaying. Due to the CPV, the relative amount of K_S^0 and K_L^0 mesons can differ depending on whether the initial state was a K^0 or $\bar{K}^0$ meson, and on the time at which the neutral kaon decays. Therefore a correction for the CPV is needed in order to determine the asymmetry in the decay of the parent $D^\pm$.

The mixing and CP violation parameters ϵ and ϵ' are defined in terms of η_{+-} by

$$\epsilon = \frac{\eta_{00} + 2\eta_{+-}}{3} \quad (1.28)$$

and

$$\epsilon' = \frac{\eta_{+-} - \eta_{00}}{3} \quad (1.29)$$

The real part of ϵ' parameterises direct CPV, $\mathcal{R}e(\epsilon)$ parameterises CPV in mixing, and the imaginary parts parameterise CPV in the interference between the two. Since ϵ' is much smaller than ϵ , in practice it can often be neglected ($\mathcal{R}e(\epsilon'/\epsilon) = (1.65 \pm 0.26) \times 10^{-3}$). Then, following Ref. [29] and also ignoring terms of order $|\epsilon|^2$,

$$\frac{|p|^2 - |q|^2}{|p|^2 + |q|^2} \equiv 2\mathcal{R}e(\epsilon) \quad (1.30)$$

and the amplitude for a K_S^0 to decay into the $\pi^+\pi^-$ final state with effective Hamiltonian $\mathcal{H}$ can be defined as

$$A_S = \langle \pi^+\pi^- | \mathcal{H} | K_S^0 \rangle. \quad (1.31)$$

The corresponding amplitude for the K_L^0 decay to two pions A_L satisfies $A_L/A_S \sim \epsilon$. The time-dependent decay rates of the K^0 and the $\bar{K}^0$ into two pions are then given in terms of the K_S^0 and K_L^0 decay times $\Gamma_{S,L}$, their average Γ , and the mass difference Δm , by

$$\Gamma_{\pi\pi}(t) \equiv \Gamma(K^0(t) \rightarrow \pi^-\pi^+) \quad (1.32)$$

$$= \frac{|A_S|^2}{4|p|^2} (e^{-\Gamma_S t} + |\epsilon|^2 e^{-\Gamma_L t} + 2\mathcal{R}e(e^{i\Delta m t - \Gamma t} \epsilon^*))$$

$$\bar{\Gamma}_{\pi\pi}(t) \equiv \Gamma(\bar{K}^0(t) \rightarrow \pi^-\pi^+) \quad (1.33)$$

$$= \frac{|A_S|^2}{4|q|^2} (e^{-\Gamma_S t} + |\epsilon|^2 e^{-\Gamma_L t} - 2\mathcal{R}e(e^{i\Delta m t - \Gamma t} \epsilon^*))$$

where kinematic factors have been ignored. For the numerator and denominator of a CP asymmetry with the form of Eq. 1.15, we are interested in the difference and sum of these

rates respectively. They are

$$\begin{aligned}\frac{D_{\pi\pi}(t)}{N} &\equiv \frac{\Gamma_{\pi\pi}(t) - \bar{\Gamma}_{\pi\pi}(t)}{N} \\ &= -2\mathcal{R}e(\epsilon) (e^{-\Gamma_S t} + |\epsilon|^2 e^{-\Gamma_L t}) \\ &\quad + 2e^{-\Gamma t} (\mathcal{R}e(\epsilon) \cos(\Delta m t) + \mathcal{I}m(\epsilon) \sin(\Delta m t)),\end{aligned}\tag{1.34}$$

$$\begin{aligned}\frac{S_{\pi\pi}(t)}{N} &\equiv \frac{\Gamma_{\pi\pi}(t) + \bar{\Gamma}_{\pi\pi}(t)}{N} \\ &= e^{-\Gamma_S t} + |\epsilon|^2 e^{-\Gamma_L t} - 4\mathcal{R}e(\epsilon) e^{-\Gamma t} \\ &\quad \times (\mathcal{R}e(\epsilon) \cos(\Delta m t) + \mathcal{I}m(\epsilon) \sin(\Delta m t)),\end{aligned}\tag{1.35}$$

where

$$N = |A_S|^2 \frac{|p|^2 + |q|^2}{4|p|^2|q|^2}.\tag{1.36}$$

The measured CP asymmetry in the $K_S^0 \rightarrow \pi^- \pi^+$ decay, A_ϵ , then depends on the decay time of the kaon via

$$A_\epsilon = \frac{\int_0^\infty F(t) D_{\pi\pi}(t) dt}{\int_0^\infty F(t) S_{\pi\pi}(t) dt}\tag{1.37}$$

where $F(t)$ encapsulates the decay time dependence of the efficiency with which the K_S^0 is detected. This CP asymmetry directly influences any measured asymmetry between D^+ and D^- parent particles, and the formalism is used in Chapter 4.

1.7 Charm and CP violation

The charm quark was predicted in the late 1960s to complete the GIM mechanism [30]. The first experimental evidence for it was the discovery in 1974 of the J/ψ , a $c\bar{c}$ resonance, while the first open charm mesons (D^0 , D^+) were found at the Mark I experiment

System	x	y	a_{sl}
K^0	~ 500	~ 1	$(0.332 \pm 0.006)\%$
D^0	$(0.63 \pm 0.19)\%$	$(0.75 \pm 0.12)\%$	$(52^{+19}_{-24})\%$
B^0	$(77.0 \pm 0.8)\%$	$(0.8 \pm 0.9)\%$	$(-0.03 \pm 0.21)\%$
B_s^0	26.49 ± 0.29	$(7.5 \pm 1.0)\%$	$(-1.09 \pm 0.40)\%$

Table 1.1: Measured values of neutral meson mixing parameters, from Refs. [33, 16, 34].

in 1976 [12]. At leading order, the effective weak Lagrangian responsible for Cabibbo-favoured hadronic charm decays, from the Feynman rules, is

$$\mathcal{L} = 4G_F\sqrt{2}V_{cs}V_{ud}^*(\bar{s}_L\gamma_\nu c_L)(\bar{u}_L\gamma^\nu d_L) + h.c. \quad (1.38)$$

where the Dirac spinor fields for the up, down, charm and strange quarks are denoted by the appropriate letter and G_F is the Fermi constant $g^2\sqrt{2}/8m_W^2$. However, the unfortunate mass of the charm quark m_c of around $1\text{ GeV}/c^2$ makes perturbative expansions difficult as neither m_c nor $1/m_c$ are small, and the many final state interaction and rescattering possibilities make it challenging to match theoretical predictions to experimental data.

In 2007, the first evidence for the mixing of neutral charm mesons was found at the B -factory experiments BaBar and Belle [31, 32]. This is now well-established, and the most recent study at LHCb [5] measures $x'^2 = (-0.9 \pm 1.3) \times 10^{-4}$ and $y' = (7.2 \pm 2.4) \times 10^{-3}$, where the parameters x' and y' are related to x and y by a rotation by the (poorly known) strong phase difference δ between Cabibbo-favoured and doubly Cabibbo-suppressed amplitudes. The mixing is compared to that in the K and B systems in Table 1.1. The x and y parameters are significantly smaller for charm than for either the K or B systems, and their small size means that most neutral D mesons will decay before appreciable mixing can take place.

As discussed in Sect. 1.4, direct CPV in charm decays requires the interference of two amplitudes to the same final state with different strong and weak phases. The two

amplitudes must have similar size in order to create appreciable interference. In the charm system, such amplitudes can be found in singly Cabibbo-suppressed decays, where tree and loop diagrams with comparable matrix elements are possible. Examples of possible Feynman graphs for these amplitudes are given in the next section, Fig. 1.3.

There are some hints of CP violation in the singly Cabibbo-suppressed charm decays $D^0 \rightarrow K^- K^+$ and/or $D^0 \rightarrow \pi^- \pi^+$ from the LHCb and CDF collaborations, although the latest results do not confirm the initial evidence for CPV that was reported in 2012 [2, 3, 4, 35]. The difference in CP asymmetries between these two final states, referred to as Δa_{CP} , is calculated. At the time of writing the result was slightly less than three Gaussian standard deviations from zero. Since the measurements are time-integrated, but the detection efficiency for the two final states differs as a function of D^0 decay time, additional information is required to determine whether any CPV is direct or indirect. In terms of the direct and indirect CP asymmetries, a_{CP}^{dir} and a_{CP}^{ind} respectively, and the D^0 lifetime τ [2],

$$\Delta a_{CP} = a_{CP}^{dir}(K^- K^+) - a_{CP}^{dir}(\pi^- \pi^+) + \frac{\Delta \langle t \rangle}{\tau} a_{CP}^{ind} \quad (1.39)$$

where $\langle t \rangle$ denotes the difference in average decay time between the reconstructed samples of the two final states. The prefactor $\frac{\Delta \langle t \rangle}{\tau}$ is an approximation designed to account for the different effects of the signal selection criteria on the $D^0 \rightarrow K^- K^+$ and $D^0 \rightarrow \pi^- \pi^+$ decay time acceptances. Any indirect CPV in D^0 - $\bar{D}^0$ mixing could contribute to the time-integrated asymmetry in Eq. 1.39 due to the different decay time distributions of the two final states. The value of the prefactor is of order 0.1 at LHCb, meaning that a_{CP}^{ind} would have to be ten times larger than a_{CP}^{dir} to generate the same signal. Since indirect CPV is constrained to be small by other observables that depend on the D^0 and $\bar{D}^0$ lifetimes Γ

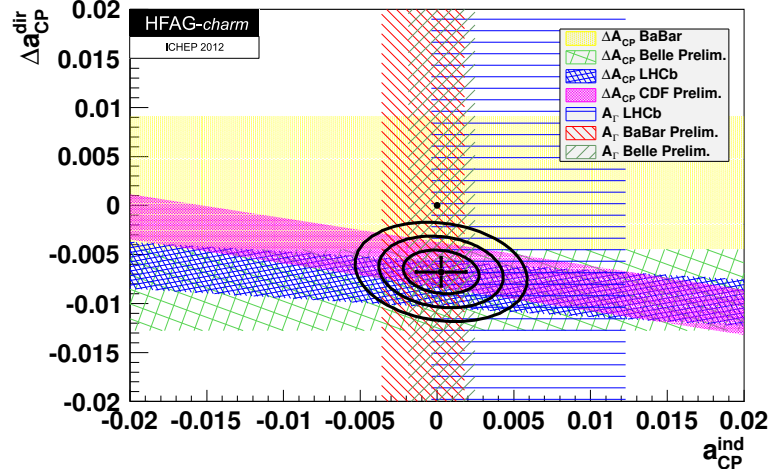


Figure 1.2: Constraints on direct (Δa_{CP}^{dir}) and indirect (a_{ind}^{CP}) CP violation in D^0 decays from the observables Δa_{CP} and A_Γ as of 26 September 2012, from the BaBar, Belle, LHCb and CDF experiments [34]. The world average value, indicated by the cross, is more significantly displaced from zero in the vertical direction than the horizontal direction, suggesting that any CPV is likely to be direct.

and $\bar{\Gamma}$ respectively, such as

$$A_\Gamma = \frac{\Gamma - \bar{\Gamma}}{\Gamma + \bar{\Gamma}}, \quad (1.40)$$

any CPV is likely to be direct [34]. The naive world average, assuming no indirect CPV, was $\Delta a_{CP} = (-0.33 \pm 0.12)\%$ in March 2013 [36]. The more sophisticated calculations from the Heavy Flavour Averaging Group reproduced in Fig. 1.2 suggest a larger value, but are not updated with the latest results from the LHCb collaboration [3, 4].

1.8 Feynman diagrams and predicted CP violation in charged D decays

This thesis is concerned primarily with charged D decays, specifically the singly Cabibbo-suppressed channel $D^+ \rightarrow K^- K^+ \pi^+$. There are several possible Feynman graphs for the tree-level D^+ decay which contribute to the overall matrix element. The diagrams shown

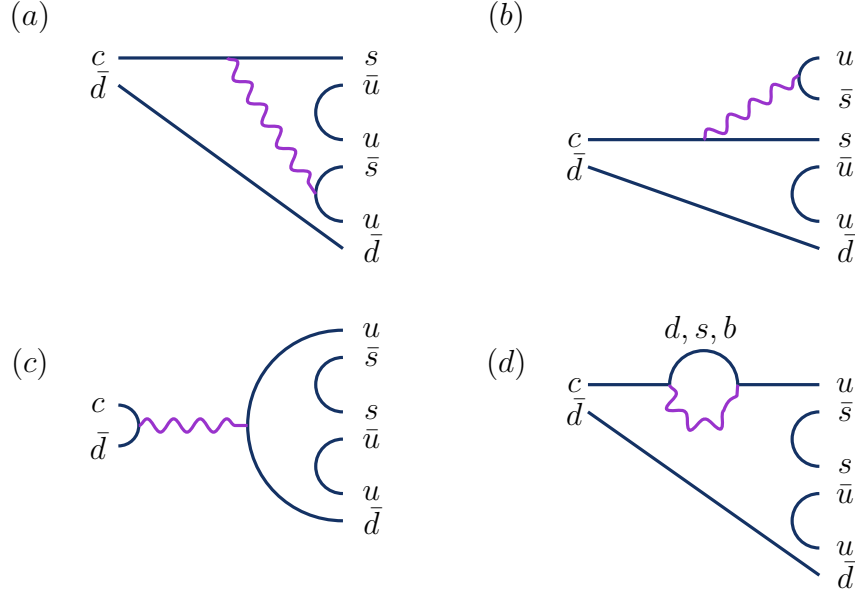


Figure 1.3: Some possible Feynman diagrams for the $D^+ \rightarrow K^- K^+ \pi^+$ decay. Smooth lines indicate fermion propagators while wavy lines indicate a W vector boson. Other possibilities (not shown) include an electroweak penguin decay and rescattering diagrams. For example, it would be possible to replace the s and $\bar{s}$ quarks in any of the diagrams by d and $\bar{d}$, and these quarks could subsequently annihilate in a final state interaction and rescatter to $s\bar{s}$, leading to the $K^- K^+ \pi^+$ final state.

in Fig. 1.3 will have varying levels of colour and OZI-suppression², but are all leading order. Unlike in neutral D meson decays, there is no possibility for W -exchange diagrams. The Feynman rules give the same combination of CKM elements for the amplitudes in (a) and (b), $V_{cs}^* V_{us}$, but the annihilation diagram (c) has the slightly different element $V_{cd}^* V_{ud}$, and similar matrix elements would result from diagrams where $udd\bar{d}$ is produced in the weak decay then rescattered to $us\bar{s}$.

Both QCD and electroweak penguin diagrams are possible in singly Cabibbo-suppressed charm decays. These are of particular importance since the presence of heavy virtual particles such as the b quark in the loop means that the QCD penguin diagram (d) may have a different weak phase to the tree diagrams. If the tree and penguin diagrams

²The OZI rule [37] states that any strongly occurring process with a Feynman diagram that can be split in two by cutting only internal gluon lines will be suppressed.

also have different strong phases, the resulting CP violating effect might be observable experimentally. The diagram (d) features a linear combination of products of CKM matrix elements $V_{cb}^*V_{ub}$, $V_{cs}^*V_{us}$ and $V_{cd}^*V_{ud}$, of which the most interesting is the $V_{cb}^*V_{ub}$ since this has a significantly different weak phase to the others.

In addition to predictions for branching ratios, the expected CP asymmetry in the Standard Model in the decay $D^+ \rightarrow K^*(892)^0 K^+$ with $K^*(892)^0 \rightarrow K^- \pi^+$ is calculated in Ref. [38]. The value obtained is $(0.28 \pm 0.08)\%$. This is an important resonance in the $D^+ \rightarrow K^- K^+ \pi^+$ decay, making up just over one fifth of the Dalitz plot by fit fraction (see Sect. 1.10) [39].

Provided the data analysis is limited by statistical uncertainties and CPV exists in the $D^+ \rightarrow K^*(892)^0 K^+$ decay at a similar level to the predicted central value of 0.28%, it may be possible to obtain evidence for it with the data collected in 2011 and 2012 at the LHCb experiment. Unfortunately no equivalent prediction is made in the paper for the $D^+ \rightarrow \phi \pi^+$ decay mode, the study of which forms a major part of this thesis.

1.9 The need for New Physics and its possible effects in the flavour sector

The evidence for direct CP violation in D^0 decays found at LHCb [2] was followed by a plethora of phenomenological publications, but at the time of writing none of these provided concrete predictions for the expected CPV in $D^+ \rightarrow K^- K^+ \pi^+$ decays in the SM or in New Physics (NP) scenarios, despite the fact that, given the requirement to tag D^0 decays, this is the singly Cabibbo-suppressed charm decay with the highest yield at both LHCb and the B -factories.

However, there is good reason to believe some form of NP might exist, due to various problems with the SM. For example, there is no adequate explanation for baryogenesis.

The SM does not provide a particularly attractive dark matter candidate to account for the 24% or so of the Universe that we believe to be cold dark matter [40]. There is no justification for any of the 19 input parameters (coupling constants, quark masses, CKM parameters, etc) required by the theory. There is no explanation for why we see no CP violation in the strong interaction. There is the so-called hierarchy problem: the Higgs mechanism in the SM requires quadratic radiative corrections to the Higgs vacuum expectation value to cancel out to an absurdly high degree of precision [41].

The sensitivity of charm decays to NP depends on the nature of the charm decay, the degree to which the flavour structure and CP violation in the new physics are aligned with those in the Standard Model, and on the energy scale of the exotic contribution. Charm penguin decays are a unique way to probe for the presence of NP because these are the only decays of hadrons in which up-type quark loops are formed (top quarks do not hadronise). Heavy virtual particles, in the simplest case the W boson and b quark, enter into these penguin loops. While the contributions of these particles to the overall amplitude decrease as their masses increase, they are not constrained by the energy of the collision that produced the parent particle. Therefore, in principle, heavier virtual particles than those which could be found in direct searches for NP with existing accelerator technology could contribute to the loop.

Scenarios for new physics which could lead to CPV in charm include supersymmetry, extra dimensions, a fourth generation of quarks and leptons, and little Higgs theories. An introduction to the available models, and a discussion of the power of D^0 mixing to constrain NP scenarios, is given in Ref. [42]. For example, Grossman *et al* calculate the contributions to the Wilson coefficients [43] from up-squark-gluino loops in Ref [28] and find that these can lead to CP asymmetries of up to $\mathcal{O}(10^{-2})$, while Delaunay *et al* consider the contributions of extra dimensions in Ref. [44]. While there are some possibilities for new physics at tree level, for example in scenarios with multiple Higgs bosons such as two

Higgs doublet models [28, 45], the general consensus seems to be in line with the naive expectation: new physics is much more likely to enter into penguin loops than into tree decays [12, 28, 46].

1.10 The Dalitz plot

In Chapters 3 and 4, studies of $D^\pm$ meson decays to three pseudoscalar charged hadrons are described. In the rest frame of the D meson, the momenta of the daughters will lie in a plane. In a two-body decay, if the masses of parent and daughters are known, the magnitudes of the momenta of the daughters in the parent rest frame are fixed. In a three body decay, there are two additional degrees of freedom. The daughter particles can be paired in three possible ways, and the invariant masses of the pairs are labelled m_{12} , m_{23} and m_{13} . Any two of these are enough to remove the remaining degrees of freedom and to completely determine the decay kinematics in the parent particle rest frame. For example, the four-momentum of particle 3 is maximal when $m_{12} = m_1 + m_2$. The scatter plot formed by plotting m_{ij}^2 against m_{ik}^2 is referred to as a Dalitz plot. Energy conservation means that all of the points in this plot should lie within a well-defined kinematic limit. The Particle Data Group review [16] provides a diagram showing the shape of a typical Dalitz plot, which is reproduced as Fig. 1.4.

The density of points in a Dalitz plot, parameterised by the partial decay rate $d\Gamma$ of a particle of mass M , is related to the spin-averaged matrix element for the decay $\mathcal{M}$ into an element of the Dalitz plot $dm_{12}^2 dm_{13}^2$ by

$$d\Gamma = \frac{1}{(2\pi)^3} \frac{1}{8M} |\mathcal{M}|^2 dm_{12}^2 dm_{13}^2 \quad (1.41)$$

Therefore non-uniformities in a Dalitz plot provide invaluable insights into the nature of $\mathcal{M}$. They suggest the presence of intermediate two-body resonances, for example

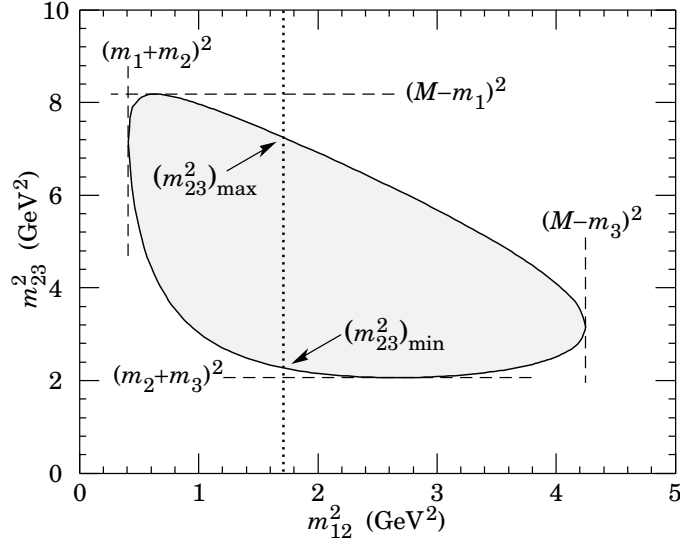


Figure 1.4: Dalitz plot for a typical three-body final state (of a B decay), in natural units with $c = 1$. [16].

$D^+ \rightarrow \phi\pi^+$, which is seen as a narrow horizontal band at low K^+K^- invariant mass in the $D^+ \rightarrow K^-K^+\pi^+$ Dalitz plot in Fig. 1.5. The other resonance clearly visible in this plot is the $K^*(892)^0$, which is responsible for the two vertically aligned lobes at a squared $K^-\pi^+$ invariant mass of $0.8 \text{ GeV}^2/c^4$.

The Dalitz plots of charm decays are usually made up of many such resonances, which often overlap. In general, final state interactions differ between resonances, meaning that their relative strong phases vary as the resonances interfere. If the Dalitz plot can be fitted satisfactorily with a simple parameterisation made up of a finite number of resonances, the relative strong phases of these resonances can be measured directly. Fitting the Dalitz plot for both a particle and an antiparticle separately also gives information about weak phases. For example, if one resonance is assumed to have no CP violation and is used as a reference, the strong and weak phases of the other resonances can be measured relative to it. This procedure is used in both the BaBar and CLEO-c searches for CP violation in the $D^+ \rightarrow K^-K^+\pi^+$ decay [39, 47]. If CP violation was found in a multi-body charm

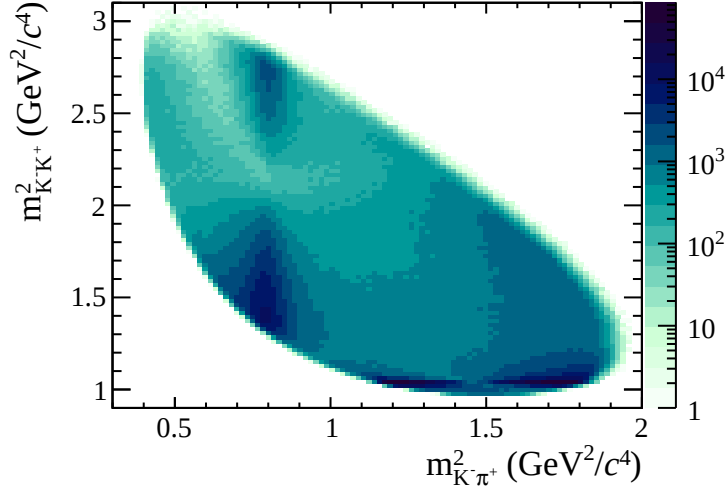


Figure 1.5: Dalitz plot of the $D^+ \rightarrow K^- K^+ \pi^+$ decay made with data collected at LHCb in 2011. The $K^*(892)^0$ and $\phi(1020)$ resonances are clearly visible in the vertical and horizontal directions respectively.

decay, an analysis of this type would be called for to investigate its nature.

There exist many techniques for measuring the phases and determining the contributions of different resonances in a Dalitz plot. The simplest is the isobar model, in which resonances are treated independently and then added together in a coherent sum. Following Ref. [48], the matrix element $\mathcal{M}_i$ for a resonance R of particles 1 and 2 with angular momentum L can be separated into

$$\mathcal{M}_i(L, m_{12}, m_{13}) = Z(L, \mathbf{p}_3, \mathbf{q}) F_M(L, \mathbf{p}_3) F_R(L, \mathbf{q}) T_R(m_{12}). \quad (1.42)$$

In this equation, $Z(\mathbf{p}_3, \mathbf{q})$ represents the angular distribution of R where $\mathbf{p}_3$ is the momentum of particle 3 in the rest frame of M and $\mathbf{q}$ is the momentum of particle 1 in the rest frame of R . $F_M(L, \mathbf{p}_3)$ represents the form factor for the $M \rightarrow R m_3$ decay, $F_R(L, \mathbf{q})$ represents the form factor for the $R \rightarrow m_1 m_2$ decay, and $T_R(m_{12})$ is a Breit-Wigner function representing the shape of the resonance when projected onto the m_{12} axis. The form factors are sometimes called Blatt-Weisskopf barrier or penetration factors, and depend

on the spin of the resonance involved. Slow moving decay products have difficulty generating sufficient angular momentum to conserve the spin of the resonance. The form factors account for this, and thereby ensure that the widths of resonances remain well-defined far from their thresholds [16]. The angular distribution Z is formed from the particle momenta and spin sums; precise expressions can be found in Ref. [48]. The overall matrix element for the three-body decay is then a sum of the isobar model matrix elements with relative phases δ_i ,

$$\mathcal{M} = \sum_i \mathcal{M}_i e^{i\delta_i}. \quad (1.43)$$

Unfortunately the isobar model violates unitarity and it is often difficult to describe scalar resonances with simple Breit-Wigner functions. More sophisticated approaches which avoid or ameliorate these problems include partial wave analysis [49] and the K -matrix procedure [50], or hybrids of these with the isobar model. A measure of how much a resonance contributes to the overall matrix element is given by its fit fraction, defined as the integral of its squared amplitude over the Dalitz plot divided by the integral of the square of the overall complex amplitude,

$$\frac{\int |M_i|^2 dm_{12}^2 dm_{13}^2}{\int |M|^2 dm_{12}^2 dm_{13}^2}. \quad (1.44)$$

Parameterising a Dalitz plot is a difficult problem and any such ‘amplitude analysis’ carries with it a large modelling uncertainty. To establish the existence of CP violation, therefore, model-independent techniques are preferable, although the simulation studies required to test these methods still rely on amplitude models. The remainder of this thesis describes the application of some model-independent approaches for CP violation searches in multi-body charm decays.

Chapter 2

The LHCb Detector

2.1 Introduction

The Letter of Intent for the LHCb experiment [51] at the Large Hadron Collider (LHC) was submitted in August 1995, following the approval of the LHC project by the CERN Council in December 1994. The LHC, a circular accelerator, was at the time foreseen to commence operation by colliding protons at a centre of mass energy of 10 TeV, with a later upgrade to 14 TeV. The LHCb detector was designed to make the most of the $b\bar{b}$ cross section, which peaks at high rapidity as shown in Fig. 2.1. A single-arm forward spectrometer with Ring Imaging Cherenkov counters and a silicon microvertex detector was envisaged. The site of this new experiment would be the cavern previously occupied by the DELPHI experiment at the Large Electron-Positron Collider, LEP.

The vision of the first pioneering collaborators was rewarded in 2010 with the accumulation of a substantial dataset for physics measurements. By mid 2011 the LHC machine was colliding protons in LHCb at a luminosity of $3.5 \times 10^{32} \text{ cm}^{-2}\text{s}^{-1}$, compared to the design value of $2 \times 10^{32} \text{ cm}^{-2}\text{s}^{-1}$, and in 2012 data were collected at luminosities of up to $6.0 \times 10^{32} \text{ cm}^{-2}\text{s}^{-1}$. The protons were packaged into bunches colliding at a maximum

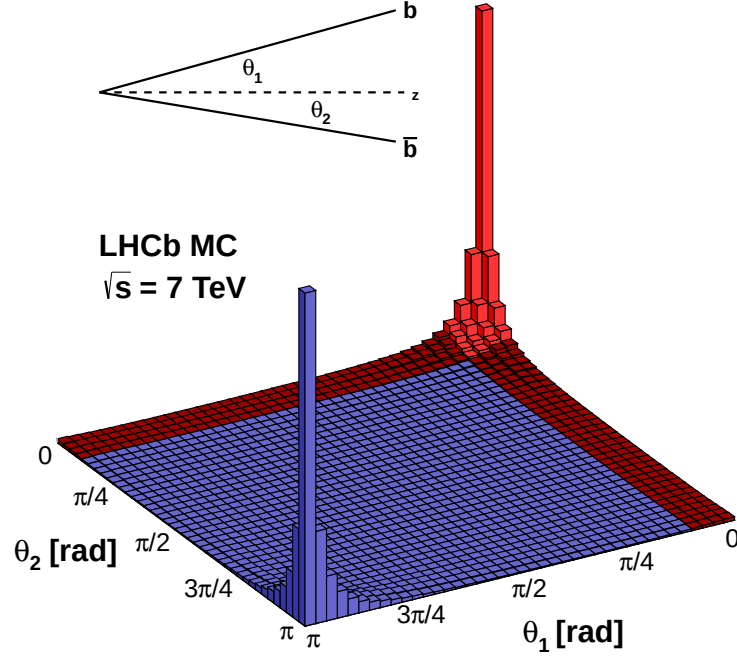


Figure 2.1: Plot showing a simulation of the relative cross section for the production of b quark pairs as a function of the angles θ_1 and θ_2 they make with the beam axis (z) in pp collisions at $\sqrt{s} = 7$ TeV [52]. The cross section clearly peaks at small angles, which translate to high rapidities.

frequency of 20 MHz and a centre-of-mass energy of 7 TeV in 2011 and 8 TeV in 2012. The general structure of the detector is shown in Fig. 2.2.

Before reaching the magnet, the products of pp collisions encounter the silicon strip vertex detector (VELO), the first Ring Imaging Cherenkov detector (RICH1), and the first tracking station, the Tracker Turicensis¹ (TT). The magnet is followed by three further tracking stations, the second Cherenkov detector (RICH2), the first of five muon detectors, the electromagnetic then hadronic calorimeters, and finally the remaining four muon chambers. The instrumented region extends to around 20 m in the $+z$ direction,

¹In Latin, *turicensis* pertains to Zurich.

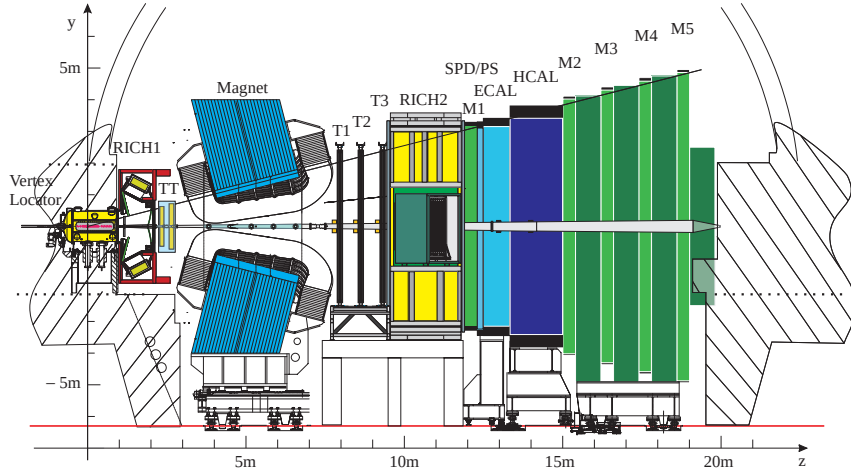


Figure 2.2: Plan of the LHCb experiment [53]. The labels TT and T1-T3 indicate the tracking stations, M1-M5 the muon detectors, RICH1 and RICH2 the Ring Imaging Cherenkov detectors, SPD/PS the scintillator pad/preshower detector (see Sect. 2.6) and ECAL and HCAL the electromagnetic and hadronic calorimeters respectively.

parallel to the proton beams, from the interaction point, which forms the zero of the coordinate system. The $+y$ direction is upwards towards the top of the cavern while the $+x$ direction is to the left for an observer looking along the $+z$ direction.

A microvertex detector is essential to isolate the pp collision points from each other and from the displaced decay vertices of B and D decays. The tracking system provides good momentum resolution $\Delta p/p$ of between 0.40% and 0.55%, which enables precision measurements of particle masses and analyses of Dalitz plots. Without excellent particle identification, decays of particles of similar mass to topologically identical final states would not be distinguishable. To avoid this, the RICHes test long-lived charged particles for consistency with kaon, pion and proton mass hypotheses. They perform well in the momentum range $5 < p < 100 \text{ GeV}/c$. On average, 96% of kaons are identified by these detectors as kaons at the 95% confidence level². A hardware trigger uses the calorimeters and muon system to activate the data acquisition system (DAQ) at a rate of up to 1 MHz,

²Unfortunately, 95% confidence is not usually enough for physics analysis, as Fig. 2.9 shows that around 10% of pions will be identified as kaons at this level.

and then software triggers reduce the data rate to between 2 and 4 kHz. The selected events are written to tape.

The detector covers an angular acceptance of ± 300 mrad in the bending plane of the magnet (the horizontal or x -direction) and ± 250 mrad in the non-bending plane (the vertical or y -direction). The main components are discussed in more detail in the following sections, mainly following the relevant Journal of Instrumentation paper, Ref. [53].

2.2 The LHC machine

The LHC machine consists of 1232 superconducting dipole magnets in a tunnel 27 km in circumference and 3.7 m in diameter on the Swiss/French border. Protons made by ionising hydrogen atoms are directed through the CERN accelerator complex and are injected into the LHC from the Super Proton Synchrotron with an energy of 450 GeV. The protons are accelerated further in a straight section of the LHC tunnel between the ALICE and CMS experiments. The collisions analysed in this thesis had a centre-of-mass energy of 7 TeV. The bunches of protons cross at the ATLAS, CMS, ALICE and LHCb experiments. Various crucial parts of the LHCb detector, notably the outer tracker and the trigger system, are more effective at lower luminosities than at those used by ATLAS and CMS. Therefore the event multiplicity is limited by “luminosity levelling” to around two pp interactions per bunch crossing event. This is achieved by moving one beam relative to another so that at LHCb the beams do not collide head-on, and the cross sectional area of overlap of the beams is smaller. The effective value of the beam amplitude (β^*) can also be adjusted. The instantaneous luminosity L is given by

$$L = \frac{fN^2S}{4\epsilon\beta^*} \quad (2.1)$$

where f is the frequency of pp collisions, N is the number of protons in the bunch, S is a geometrical factor, and ϵ is the emittance ($\epsilon\beta^* = \pi\sigma^2$ where $\pi\sigma^2$ is the cross sectional area of the beam). The emittance relates to the beam quality while the amplitude relates to the optics. The geometrical factor S accounts for the displacement of the beams needed to level the luminosity, and also the slight increase in the size of the interaction region due to the crossing angle of the beams, which is not quite 180° . It is a testament to the good performance of the LHC machine that in 2012, with luminosity levelling in place, the benchmark target of 2 fb^{-1} of data collected by LHCb per annum was surpassed, and around 22 fb^{-1} of data were collected by ATLAS and CMS.

2.3 The VELO

The LHCb vertex locator is a series of two sets of 21 roughly semicircular silicon modules (or ‘stations’) distributed around the pp interaction region as shown in Fig. 2.3. The sets move inwards along the x axis to within 8 mm of the beam during data taking, but are retracted to 3.8 cm from the beam axis for protection when the beam is not stable. When the VELO is closed the two halves overlap slightly. Each module contains two silicon strip sensors: an R-sensor, which measures the radial distance from the beam, and a ϕ -sensor, which determines the azimuthal angle in the $x - y$ plane. Tracks must cross at least three VELO stations to be reconstructed. The stations are arranged to ensure that this requirement is usually satisfied for tracks in the LHCb acceptance.

The sensors are essentially $p - n$ junctions, made of silicon enhanced by oxygen to improve the radiation tolerance. Doping the silicon with donor atoms such as phosphorus leads to an n -type material, with an excess of electrons. Conversely, a p -type material is created by doping with electron acceptors such as boron. A depletion region in which there are no free charge carriers is formed at the interface between p and n -type silicon because

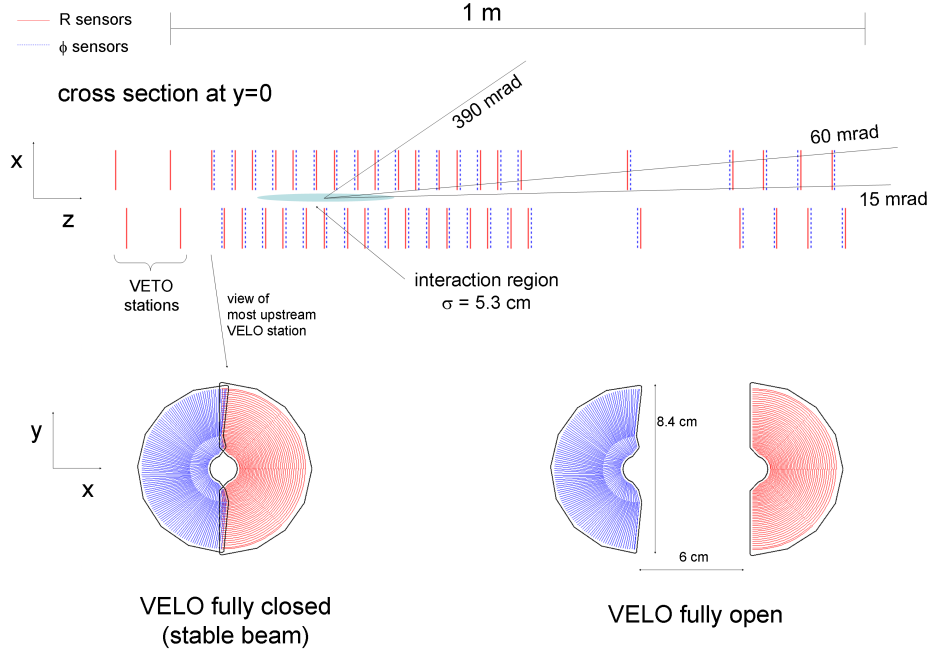


Figure 2.3: Plan of the LHCb vertex locator, showing the distribution of modules in the z -direction [53].

electrons near the interface tend to diffuse into the p-type silicon, leaving positive ions (holes) in the n -type region. The depletion region is enlarged on one side of the interface by applying a reverse biasing voltage. Electron-hole pairs created by the passage of a charged particle are separated by the electric field and move as an electrical current. The band gap is around 1.1 eV. When a high energy (minimum ionising) particle traverses a 300 μm thick silicon sensor, the Bethe-Bloch Equation [54] suggests that around 117 keV of energy will be lost, and the most probable number of electron-hole pairs generated, from the Landau distribution, is 23400. In the LHCb system, the depletion region is mostly in the n -type material, which comprises the bulk of the material of the sensor. The technology is referred to as oxygenated n^+ - on $-n$. The junction is formed by an implant of n -type material with high dopant concentration from which the charge is read out to aluminium strips, located at the front of the depleted n -bulk, and an implant of

p -type material situated at the back.

Within each module, the pitch or segmentation size of both R and ϕ sensors ranges from $38\,\mu\text{m}$ at the inner edge to around $100\,\mu\text{m}$ at the outer edge. As shown on the left of Fig. 2.4, the R sensors use concentric strips while the ϕ sensors use radial strips, with a discontinuity at a radius of $17.25\,\text{mm}$ to avoid the pitch becoming too large at the outer edge of the modules. Apart from this discontinuity, the pitch increases linearly with radial distance along the ϕ sensors. The sensors are $300\,\mu\text{m}$ thick and are connected with aluminium routing lines to 16 Beetle ASIC chips per sensor (32 per module). The 128-channel Beetle ASICs were designed to sample at the 40 MHz nominal LHC bunch crossing frequency and to read out the modules in a high radiation environment at the 1 MHz maximum rate of the hardware trigger. It takes 900 ns to read out one collision event. The analog front-end is formed by a low-noise charge-sensitive preamplifier, a pulse shaper and a buffer [55]. Events are pipelined, multiplexed, and read out via kapton cables to the data acquisition system (DAQ) via repeater boards.

The modules are enclosed within a vacuum vessel. Each detector half is placed inside a thin-walled aluminium box, and the boxes overlap when the VELO is closed. Aluminium was chosen for its short radiation length and good electrical conductivity. These “RF boxes” separate the primary LHC vacuum at $10^{-8}\,\text{mbar}$ from the secondary VELO vacuum of $10^{-4}\,\text{mb}$, and shield the VELO modules against electromagnetic interference from the LHC beams. The inner face of each box is corrugated to fit around the modules. The structure of the modules is made from carbon fibre and highly thermally conductive pyrolytic graphite, which transfers as much as 32 W to Al blocks cooled by CO_2 . This enables the VELO sensors to be kept at or below -5°C at all times. The cooling improves the performance of the electronics inside the vacuum, and permits operation in the high radiation environment. Irradiation can lead to the displacement of atoms from their lattice sites or to charge build-up in surface layers. The vital importance of cooling the

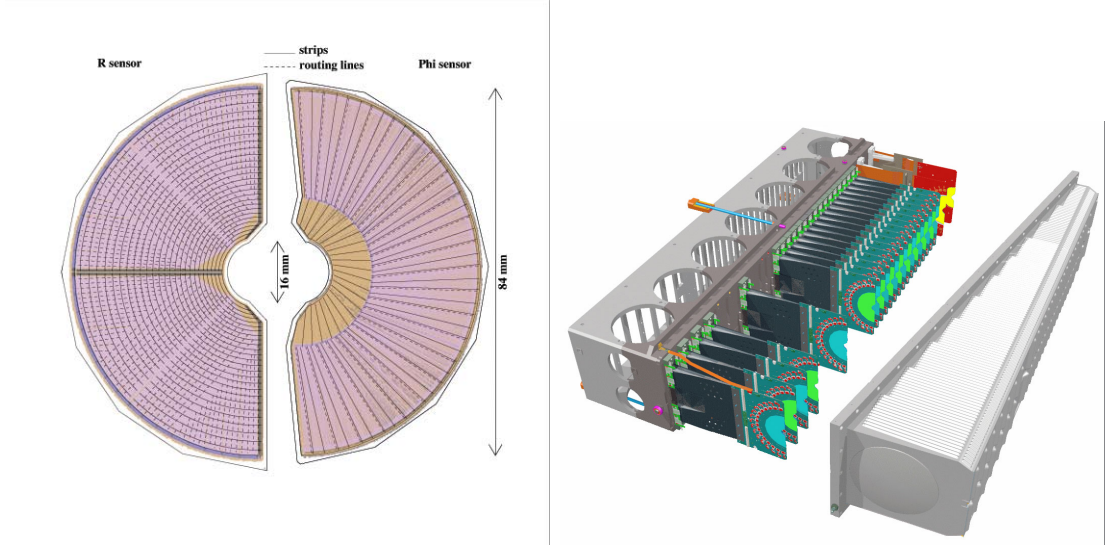


Figure 2.4: The geometry of the VELO sensors (left) and an illustration of the modules that make up one half of the subdetector with the RF box that fits over them (right), from Ref. [53]. The two modules with the lowest z -coordinates, shown in red and at the extreme top-right of the figure, form the pile-up system, described in Sect. 2.10.

VELO after exposure to radiation is illustrated by the plot of the temperature dependence of the leakage current in Fig. 2.5, taken from a recent publication on radiation damage in the sub-detector [56]. The depletion voltage of the sensors changes significantly with irradiation, and the maximum depletion voltage the sensors are designed to cope with, of 500 V, is expected to be needed only after three years of operation.

A key indicator of the performance of the VELO is the resolution with which the impact parameter of a track with respect to a pp collision vertex can be measured. It is shown in Fig. 2.5 that this quantity showed only small deviations from the expectation from simulations in the 2011 data taking period. The impact parameter resolution, which is $20\text{ }\mu\text{m}$ for a track with a typical transverse momentum of $3\text{ GeV}/c$, enables the lifetimes of most B and D mesons to be measured with uncertainties around of 50 fs, which compares favourably to the D^0 lifetime of 410 fs [16].

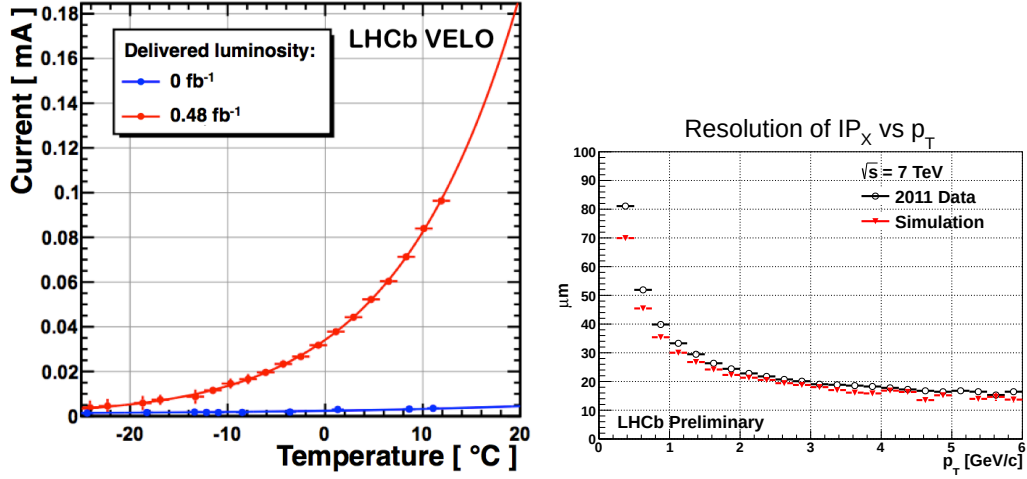


Figure 2.5: The temperature dependence of the bias current for a typical VELO sensor, left, with the nominal 150 V bias before and after around six months of LHC running, illustrating the effects of radiation damage [56]. The impact parameter resolution of the VELO in the x -direction, right, as a function of the transverse momentum p_T of the track [57].

2.4 The tracking system and magnet

The tracking system consists of the silicon Tracker Turicensis (TT) located upstream of the magnet (closer to the pp interaction region and VELO), and three tracking stations (T1-T3) immediately downstream of it. The inner part of these three stations (the Inner Tracker, IT) is silicon, while the outer part (the Outer Tracker, OT) is made of straw-tube drift chambers. The silicon detectors were designed to achieve good spatial resolution of around $50\text{ }\mu\text{m}$ and high signal-to-noise ratios while minimising the occupancy, material budget, cost and signal shaping time in a moderately high radiation environment, but one much lower than that of the VELO.

The TT is constructed from four layers of modules that each cover the height of the LHCb acceptance. It contains 143360 readout strips covering an active area of 8.4 m^2 . Each half-module consists of a row of seven silicon sensors arranged as shown on the left of Fig. 2.6. The architecture allows all infrastructure (front-end readout hybrids, cooling

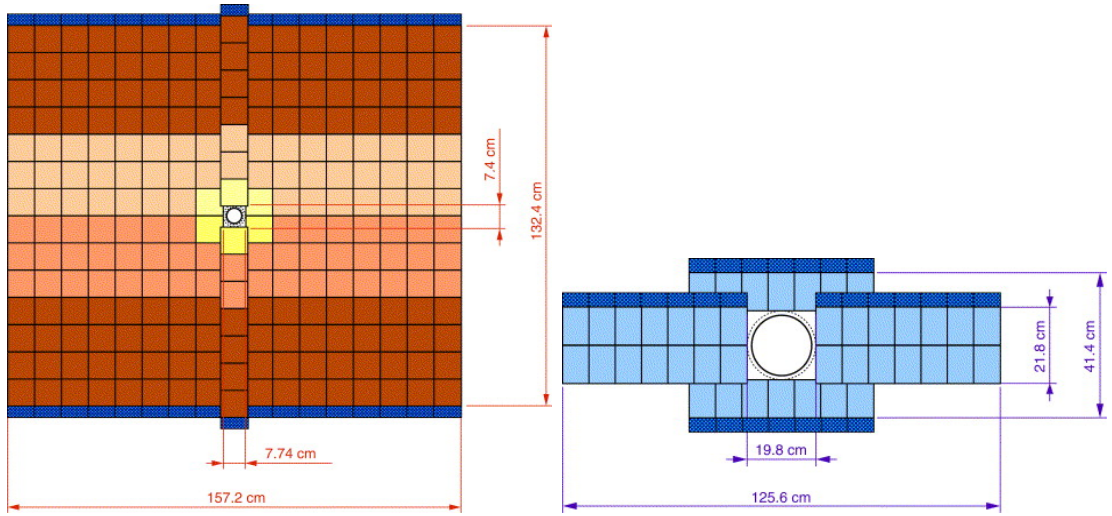


Figure 2.6: Layout of one of the TT layers, left, and an IT module, right [58]. The sensors in the half-modules which make up the TT layer are shown.

and support) to be kept outside the detector acceptance. The IT modules consist of either one or two silicon sensors that are connected via a pitch adapter to a kapton front-end readout hybrid. The silicon sensors are single sided p^+ -on- n sensors. In the the IT, the sensors are 7.6 cm wide and 11 cm long, and carry 384 readout strips with a strip pitch of 198 mm. For the TT, they are similarly sized and carry 512 readout strips with a strip pitch of 183 mm as shown on the right of Fig. 2.6. The TT and IT are kept below 5°C by aluminium and copper blocks cooled with C_6F_{14} . The IT is continually flushed with nitrogen to remove condensation.

The design of the OT was driven by the need to achieve momentum resolutions Δ_p/p of close to 0.4% to resolve the mass of reconstructed B-hadrons to within $10 \text{ MeV}/c^2$. This necessitated a rigid design so that the position of the straw-tubes can be guaranteed to a precision of $100 \mu\text{m}$ in the x -direction, and good electrical shielding of each tube to ensure low cross-talk and noise. Each OT station consists of two layers of drift-tubes with inner diameters of 4.9 mm, filled with a mixture of 70% Ar and 30% CO_2 . The gases are chosen to be easily ionised by charged particles. Each drift tube is made from two

strips of thin foils twisted together in a spiral. The inner (cathode) foil is made of carbon-doped polyimide (kapton) while the outer foil is a laminate of polyimide and aluminium. Electrons from the gas drift towards the anode. As the drift velocity v is known ($v = \mu E$ where E is the applied electric field and μ the mobility of the electrons), a measurement of the drift time with respect to the LHC clock allows the distance from the anode to be measured. The position of the ionisation event and hence the charged particle can thereby be resolved. The Al ensures fast signal transmission and good shielding, which is crucial to prevent cross talk and noise, whilst the polyimide is important to ensure the straw is gas-tight. By the end of 2011, typical momentum resolutions were around 0.5% for B -hadrons [59].

Both TT and IT are read out with Beetle front-end chips. The OT is read out through a series of front-end boards in which analog amplification and shaping is followed by digitisation, which is synchronised with the LHC clock. The data is transferred to the DAQ if a positive decision is received from the hardware trigger. The reconstruction software starts with single hits in one part of a sub-detector, referred to as track seeds. These are extrapolated and combined with hits in other parts of the detector. In general, the tracks are seeded in the VELO or tracking stations where the magnetic field is low. The track candidates are fitted with a Kalman filter which accounts for multiple scattering and corrects for energy losses. The tracking efficiency of the detector is measured using a tag-and-probe technique with $J/\psi \rightarrow \mu^+ \mu^-$ decays, and it is shown in Fig. 2.7.

Momentum measurement at LHCb depends on a powerful magnetic field: the integrated magnetic field for tracks of 10 m length, from the VELO to the front of RICH2, is 4 Tm. However, it is also necessary to keep the magnetic field lower than 2 mT inside the RICHes, because the image recorded by the photon detectors will be distorted if photoelectrons are deflected by the field. The magnet consists of a steel yoke surrounding two identical aluminium coils arranged with mirror symmetry about the horizontal plane

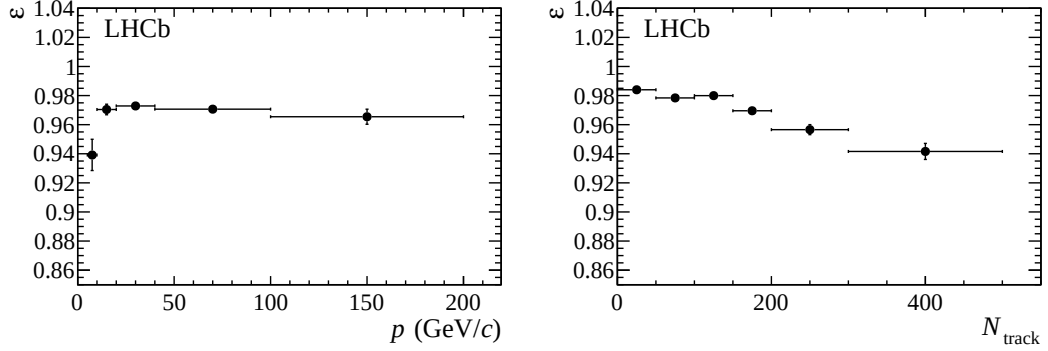


Figure 2.7: Tracking efficiency as a function of momentum (left) and number of tracks in the event (right) for data recorded in 2011. The tracking efficiency is defined here as the probability that the trajectory of a charged particle is reconstructed given that it has passed through the full tracking system, so the measure does not account for interactions with the detector material or decays in flight [57].

as shown in Fig. 2.8. The magnetic field was carefully mapped using Hall probes to a precision of approximately 4×10^{-4} and was found to agree with expectations to within 1%. The magnet polarity is reversible, so that certain detector asymmetry effects can be reversed and thereby measured and corrected for in physics analyses (see Chapter 3).

2.5 The RICHes

The two Ring Imaging Cherenkov detectors distinguish kaons from pions and protons. This is vital for separating the Cabibbo-favoured and suppressed decays described in Chapter 1, which is of paramount importance both in charm and B-physics, for example in the measurement of the CKM angle γ via the GLW/ADS methods [60]. The subdetectors rely on the Cherenkov radiation emitted at angle θ_c to the direction of motion of a particle travelling at velocity $v > c/n$ in a medium with refractive index $n > 1$. The Cherenkov angle θ_c is given by $\cos \theta_c = c/nv$. The ring resolution is then proportional to $\sigma_\theta/\sqrt{N}$ where σ_θ is the uncertainty on θ_c and N is the number of photoelectrons in the ring [16].

The RICH1 detector provides particle identification (PID) in the momentum range

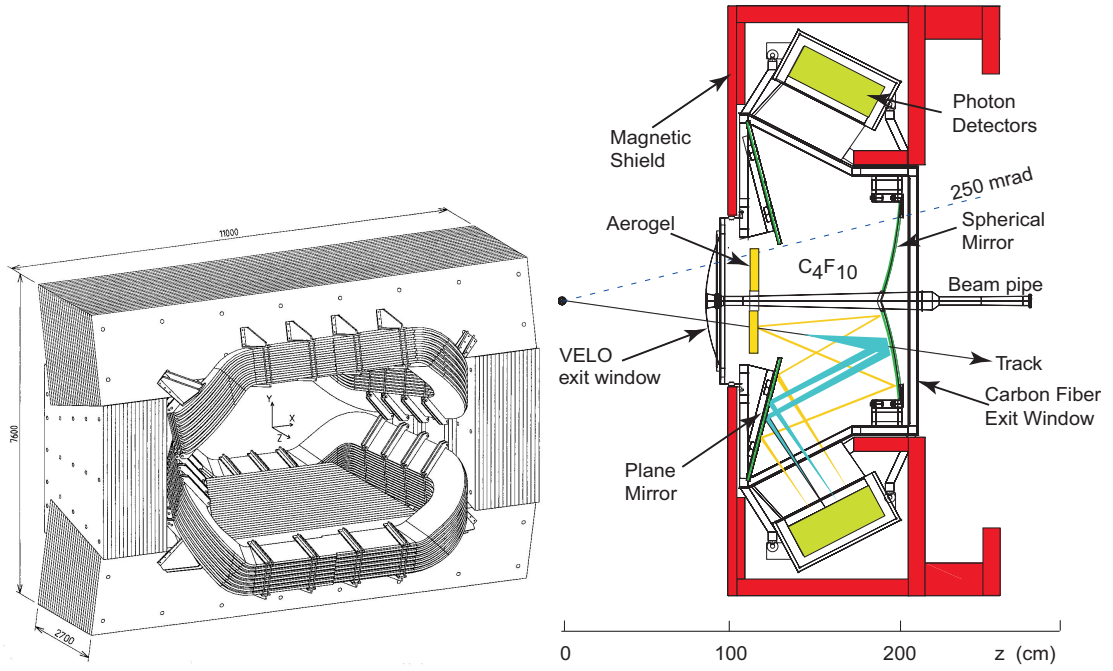


Figure 2.8: The LHCb magnet, left, and the RICH1 detector, right. [53].

$1 < p < 60 \text{ GeV}/c$ while RICH2 operates in a slightly reduced acceptance of ± 15 to $\pm 120 \text{ mrad}$ in the horizontal plane and $\pm 100 \text{ mrad}$ in the vertical plane, and identifies particles with momenta in the range $15 < p < 100 \text{ GeV}/c$. In both cases, the instrumentation is kept out of the detector acceptance by reflecting the light out of the chamber to hybrid photon detectors (HPDs) with spherical and flat mirrors. HPDs are used instead of photomultiplier tubes due to their superior spatial resolution and response time. To minimise the material budget in RICH1, these mirrors are made from carbon fibre reinforced polymers (CFRP) coated with thin films of Al and MgF_2 . In RICH2 they are glass.

RICH1 contains aerogel and C_4F_{10} while RICH2 contains CF_4 . Aerogel consists of grains of amorphous silicon dioxide with sizes ranging from 1 to 10 nm linked together in a three-dimensional structure filled by trapped air [61]. It has a refractive index intermediate between that of a gas and a liquid. The CFC gases are chosen for their refractive

indices, which are appropriate for the momentum spectrum of the decay products of charm and B particles. Given a reasonable quantum efficiency or number of primary photoelectrons generated per incident photon, a track passing through 5 cm of aerogel with refractive index $n = 1.03$ for light of wavelength 400 nm is expected to yield around 6.5 photoelectrons in a ring from a charged particle with $\beta = 1$. The corresponding yields for 95 cm of C_4F_{10} ($n = 1.0014$ at 400 nm) and 180 cm of CF_4 ($n = 1.0005$ at 400 nm) are 30 and 22 photoelectrons respectively. A likelihood fit is used to determine whether the ring best matches the expectation from a kaon, pion, or proton hypothesis. A set of likelihood variables describing how consistent a particle is with being a kaon, pion or proton is made available for data analysis, and is described further in Chapter 3.

The gases and aerogel in the RICH detectors are contained within large Al boxes. The RICH1 box is 300 μm thick inside the acceptance on the upstream side, and contains an aperture filled with CFRP in the acceptance on the downstream side to reduce the material budget. As RICH2 is larger, the pressure differential is greater so two 1 mm-thick carbon fibre and Al skins are separated by 30 mm of foam in the entrance and exit windows respectively.

The HPDs are arranged in a hexagonal pattern outside the RICHes. They are shielded from the magnetic field by large iron boxes. In RICH2 the stray magnetic field is reduced by these boxes from 15 mT to around 0.5 mT. In the HPDs, photoelectrons are released during the interaction of incident photons with the photocathode. They are accelerated by an applied voltage of 10 to 20 kV onto a reverse-biased, pixellated silicon anode, which results in the creation of an average of one electron-hole pair for every 3.6 eV of deposited energy. The HPDs are read out by integrated pixel chips. When tested, their quantum efficiency was found to be 5-10% higher than the minimum 20% required, and the “dark count rate” of fake signals from thermionic emission at the photocathode, ion feedback or electrostatic field emission was also satisfactory.

The silicon anodes of the HPD are bump bonded to the LHCbPIX1 binary readout ASIC and thence to the RICH electronics implemented on FPGAs. A series of algorithms converts the rings seen in the RICH to a likelihood for a kaon, proton, or pion mass hypothesis. The quantum efficiency and number of operational HPDs fluctuated with time during the 2011 run, and this was studied for the asymmetry measurements described in this thesis. The left plot of Fig. 2.9 shows that the performance of the detector slowly degraded through the 2011 data taking period. Furthermore, a difference in the particle identification efficiency between the halves of the RICHes on the left and right hand sides of the detector, when combined with the bending effect of the magnet on oppositely charged particles, produces a charge asymmetry in the particle identification efficiency. This is shown in the right plot of Fig. 2.9. These effects were found not to affect physics results significantly in 2011, largely because they can be neutralised by regularly reversing the polarity of the magnet, but they may cause complications in future. It should also be noted that the particle identification efficiency is strongly dependent on momentum: the kaon-pion discrimination is best in the range $10 < p < 50$ GeV and rapidly degrades outside this interval.

However, for hadrons with typical momenta, the particle identification power is excellent: Fig. 2.9 shows that kaons can be detected with a 95% efficiency with a misidentification rate of 5%. This is substantially better than the capability of any other LHC experiment.

2.6 The calorimeters

The calorimeters have the dual role of identifying and reconstructing photons, π^0 mesons and electrons, and measuring the transverse energy E_T of electron, photon and charged hadron showers for the hardware trigger. They operate by collecting scintillation light

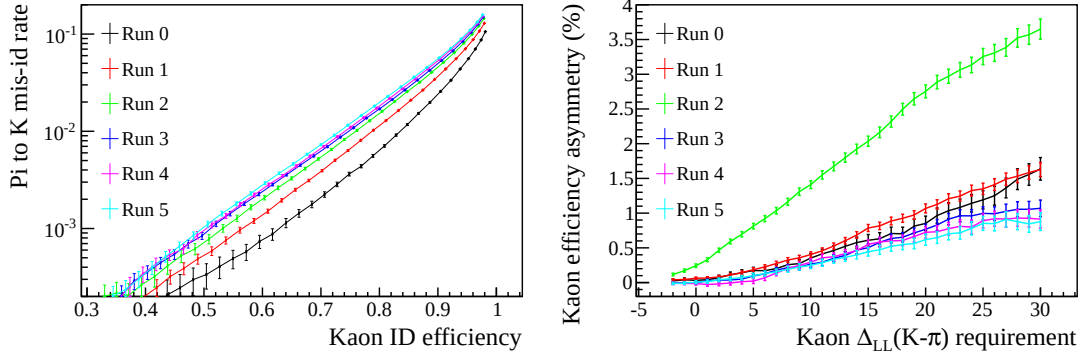


Figure 2.9: Left: the kaon ID efficiency plotted against the $\pi \rightarrow K$ misidentification rate for different requirements on the kaon likelihood variable. The highest probability for a kaon hypothesis, corresponding to the strictest likelihood requirement, is at the bottom-left corner of the plot. Each line corresponds to different running periods during 2011 for data taken with the magnet down. Right: the charge asymmetry in the identification efficiency as a function of the likelihood requirement for the same running periods. A high value on the x axis corresponds to a strict requirement on the likelihood for the particle to be a kaon. The asymmetry in the efficiency is particularly large in Run 2, perhaps due to some faulty HPDs on one side of the detector. The reverse polarity shows the opposite asymmetry effect, indicating that the asymmetry results from left-right differences across the detector. The effect of these asymmetries on the analysis described in Chapter 4 is considered by plotting the charge asymmetries as a function of time in 2011 in Sect. 4.10.10.

from particle interactions with dense material through optical fibres. There are three components: the preshower/scintillator pad detector (PS/SPD), the electromagnetic calorimeter (ECAL) and the hadronic calorimeter (HCAL). Different particles can be identified because they interact over different length scales, and give showers of light with different characteristic shapes.

The function of the PS/SPD is to distinguish electrons from charged hadrons and neutral pions. It consists of a 15 mm thick lead plate sandwiched between two layers of scintillator pads, before the ECAL. Charged particles, for example electrons, deposit energy in the first scintillator and can thus be distinguished from neutral particles, such as photons, which do not. Both electrons and photons then interact in the thin lead plate and the deposited energy is collected by the second scintillator. Hadrons have a

longer interaction length and therefore they pass through without depositing very much energy (although the hits they create are retained). Around 99.6% of pions do not deposit enough energy to meet the threshold to be identified as an electron, whilst at least 90% of electrons with momenta above 10 GeV/ c pass the threshold and can be detected. A correction is then made in the ECAL for the energy deposited in the lead plate.

The ECAL is a lead sampling scintillator. It is subdivided into inner, middle and outer sections of increasing cell size, a scheme also adopted in the PS/SPD. The total thickness of its 66 layers is 42 cm or 25 radiation lengths, enough for almost all the energy in an electromagnetic shower to be captured. This is required for good energy resolution. Each module is constructed from alternating layers of 2 mm thick lead, 120 μ m thick reflecting paper and 4 mm thick scintillator tiles. When excited by the passage of a charged particle, the polystyrene scintillator molecules release a small fraction of the excitation energy as optical photons. The transverse shower size (Molière radius) of the stack of modules is 3.5 cm. The energy resolution $\sigma(E)/E$ was determined using a test beam and improves from 3% to just over 1% as the momentum increases from 15 to 100 GeV/ c [62]. The hadronic calorimeter has similar structure but the absorber is iron rather than lead. It is divided into square cells of length 131.3 mm in the inner section and 262.6 mm in the outer section. Hadronic triggering does not require such good energy resolution, so to save space for the muon detectors the thickness of the HCAL is only 5.6 interaction lengths. The resolution is much worse than that of the ECAL, with $\sigma(E)/E$ varying as a function of momentum from 23% at 15 GeV/ c to 12% at 100 GeV/ c .

Each cell in both calorimeters is read out to an individual photomultiplier tube (PMT) by plastic wavelength-shifting fibres. The PS/SPD photomultipliers have multiple anodes, each of which covers several cells. The PMTs are encased in iron to shield them from stray magnetic fields. A pulse shaper takes the output of these tubes and removes the tail of any pulses extending beyond 25 ns, so that every LHC bunch crossing can be measured

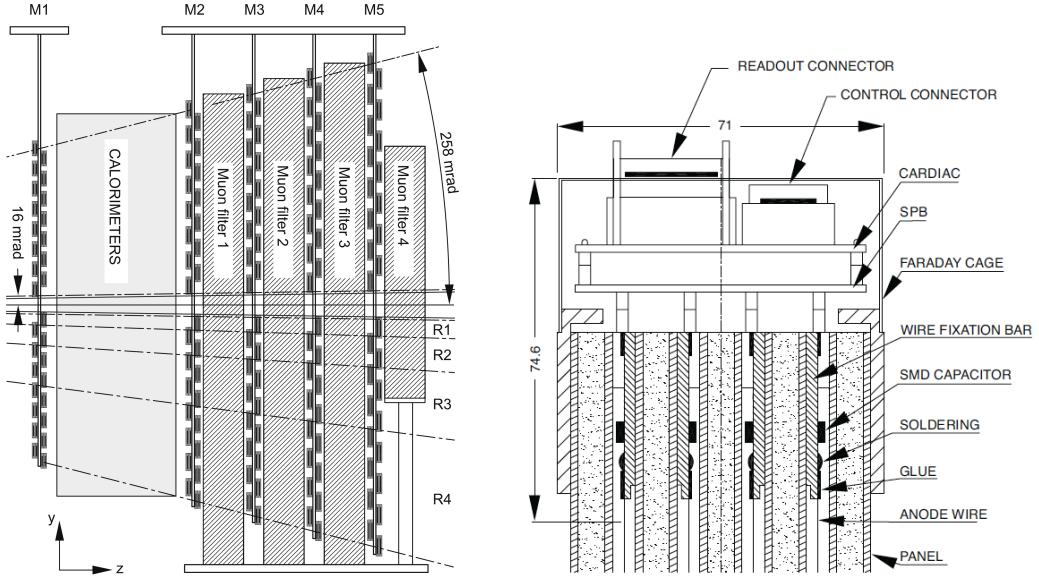


Figure 2.10: Diagram showing (left) the positions of the five LHCb muon stations, the calorimeters and the iron absorbers [63] and (right) the cross section through a wire chamber with the four gas gaps and the connection to the readout electronics. The SPB stands for the spark protection board while CARDIAC is the name of the front-end electronics [53].

and potentially activate the trigger. The front end board receives the resulting pulses and digitises them. The digital signals are refined slightly by FPGAs to reduce noise and then passed to the calorimeter readout cards in crates above the detector. These cards generate the final L0 trigger signal and pass the information on to the DAQ system.

2.7 The muon system

Muons are of fundamental importance to LHCb, as the easiest way to trigger the detector is on muons with high transverse momentum p_T , and because muons form part or all of the final state in flagship decay channels such as $B_s \rightarrow J/\psi\phi$ and $B_s \rightarrow \mu^+\mu^-$.

LHCb has five muon stations, one upstream in front of the calorimeters, and four downstream, behind them as shown on the left of Fig. 2.10. The first station is placed

upstream to improve the p_T resolution. The whole system consists of 1368 multi-wire proportional chambers (MWPCs) and 12 sets of three gas electron multiplier foils (referred to as triple-GEMs) in the region closest to the beam pipe in the most upstream station where the particle flux is highest. The downstream stations alternate with 80 cm thick iron absorbers. The detectors are divided into cells. Each cell provides a binary decision to the trigger, which requires aligned hits above the discriminator threshold in all five stations to fire. This means the efficiency of each station must exceed 95%. The spatial resolution is defined by the cell size, and is most precise for the first three stations in the bending plane of the magnet. The timing resolution is sufficient to distinguish consecutive LHC bunch crossings at 40 MHz.

Each triple-GEM detector consists of three copper-cladded kapton foils sandwiched between an anode and a cathode in a mixture of Ar, CO₂ and CF₄ in ratio 45 : 15 : 40. This combination of gases was found to give the detector an excellent time resolution of 3 ns. As the muons pass through the system they ionise the gas, and the ionisation electrons are attracted by the electric field towards the anode. The electrons that enter 70 μm wide holes in the foils are multiplied by the large electric field. The holes are 140 μm apart.

The MWPCs operate on a similar principle to the GEMs, except that a wire mesh is used instead of a perforated foil. They consist of two layers of closely spaced parallel anode wires between two parallel cathode plates as shown on the right of Fig. 2.10. The wires in one layer are perpendicular to those in the other. Ionisation electrons are attracted to the nearest wire, and hence the position of the particle can be resolved in two dimensions. Close to the wires, the electric field increases, which accelerates the electrons and leads them to cause secondary ionisation, a process known as avalanching. This avalanching is proportional to the energy of the incident particle. Thus the MWPC, in principle, allows a measurement of the particle energy, although in LHCb this is not used. Each MWPC

in the four most downstream muon stations contains four gas gaps with wires connected in OR, to optimise the efficiency, while the other muon station contains only two such gaps (or two triple-GEMs) in OR to minimise the material budget. In the MWPCs the time resolution is 5 ns. The same gases are used as in the triple-GEMs, but with ratio 40 : 55 : 5. The chambers and front-end electronics are enclosed in a Faraday cage.

The muon system is read out into front-end boards which amplify, time-align and shape the chamber signals. Logical ORs of the channels are taken before the signal is tagged with a code identifying the relevant pp bunch crossing and routed to the DAQ.

2.8 Material budget

Multiple scattering limits the momentum resolution of the detector, so it is extremely important to minimise the material budget before the calorimeters. The material in the VELO makes up 17.5% of a radiation length on average, with the largest contribution coming from the RF-foil. There is a strong variation in the amount of material with the azimuthal angle and radial distance from the beam pipe. The material in the detector up to the beginning of RICH2, including the entire tracking system, is shown in Fig 2.11. On average, particles pass through around 60% of a radiation length and 20% of an absorption length before entering RICH2 [64].

2.9 The DAQ and electronics

The LHCb detector is read out from analog front-end chips such as the Beetle or LHCbPIX1. The signals are digitised and sent to standardised readout boards known as TELL1s via optical links. The exception is the VELO, which sends analog information to TELL1s directly via kapton cables. Four pre-processing FPGAs perform common-mode rejection, zero-suppression and data compression as required. The resulting data

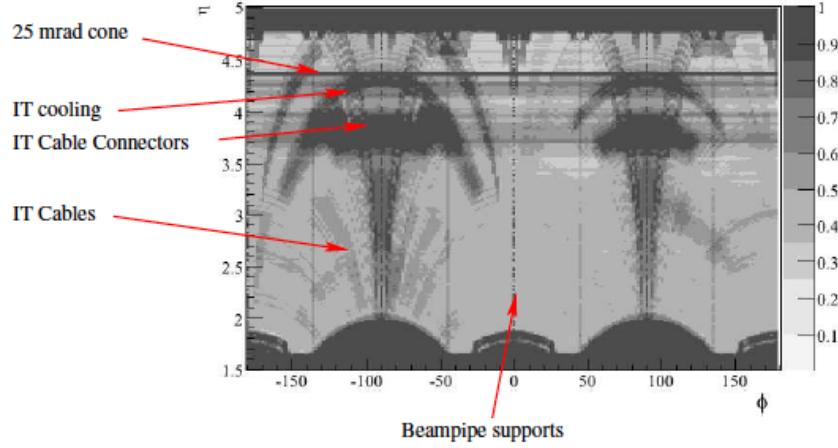


Figure 2.11: Radiation length in the LHCb detector as a function of pseudorapidity η and azimuthal angle around the beam axis ϕ , integrated up to $z = 930$ cm, with the effect of the IT labelled. The radiation length scale is truncated at one radiation length. [64].

fragments are collected by a fifth FPGA and formatted into a raw IP-packet that is subsequently sent to the Event Filter Farm (EFF) via 4Gb Ethernet ports. The EFF is the set of CPUs that perform the processing for the software trigger. The raw data selected by the trigger in the EFF is transferred to the CERN Tier-0 computing centre and subsequently distributed via the Large Computing Grid. The online system is synchronised with the Timing and Fast Control system (TFC) and operated via the Experiment Control System (ECS). The TFC ensures that the LHC machine clock and the trigger decisions are synchronised and that the trigger functions at an acceptable rate. The ECS ensures proper control and monitoring of all parts of the detector and is run by users in the control room with PVSS software.

2.10 The hardware trigger

The LHCb trigger operates in three stages. The Level-0 trigger (L0), implemented in custom hardware, operates at the LHC bunch crossing frequency and reduces the rate

from 40 MHz to 1 MHz. The High-Level Trigger (HLT1 and HLT2) is software based, and further reduces the rate to 2 or 3 kHz by reconstruction of tracks (in HLT1) and partial or full decay chains (in HLT2). The L0 trigger Decision Unit (L0DU) receives input via 24 high-speed optical links from three subdetectors at 40 MHz: the calorimeters and scintillator pad detectors, which trigger on electrons, photons or hadrons, the muon system, and, in the original design, the pile-up detector. The pile-up system, consisting of four VELO R-sensors upstream of the rest of the VELO, was to be used to locate the z-positions of primary vertices to measure the track multiplicity. This could enable the trigger to infer the probable number of pp interactions in a given bunch crossing and to remove overly complex events, but to date this subsystem has not been used except to measure the luminosity with beam-gas interactions [65, 66]. The L0 trigger decisions from each subdetector are combined in a logical OR to obtain the L0 decision. The L0DU itself is based on a TELL1 board. It instructs the DAQ system whether or not to read out the rest of the detector 4 μ s after an interaction.

The calorimeter trigger calculates the E_T of 2x2 groups of cells. These usually contain most of the energy deposited by a particle, but are too small to encompass overlapping showers. The highest E_T combination is found. The cause of the deposit, be it an electron, photon or hadron, is identified. A hadron should shower only in the HCAL and sometimes the ECAL, a photon should additionally leave a hit in a preshower cell, and an electron should leave hits in both a preshower and an SPD cell [66], as outlined in Sect. 2.6. The energy of this candidate, together with the total E_T in the HCAL and the number of hits in the SPD, is sent to the L0DU.

The muon detector is split into four and the muon tracks in each quadrant with the largest and second largest p_T are identified. Track finding starts from seed hits in the third muon station, and a track is formed if hits in all five muon stations can be aligned. The dedicated processors for the muon system each contain 192 elements (based on a

spatial division of each quadrant), and each run 96 tracking algorithms in parallel. Up to eight high- p_T track candidates (up to two from each quadrant) are sent to the L0DU.

It is possible for several trigger systems to give a positive signal on any given event. For example, a B or D meson could decay to several hadrons, of which one or more could pass the threshold to fire the calorimeter trigger, or a muon and some hadrons. Or alternatively two different decays from the same event could each result in a track which fires one of the triggers. If an event is triggered, all of the information about how this happened is saved to disk.

In this thesis, the hadronic Level-0 trigger systems (L0Hadron) are of particular importance, because these can be activated by the signal decay channels. The efficiency of the hadronic calorimeter trigger is shown as a function of p_T for sample decay channels in Fig. 2.12. The poor resolution is apparent: one would expect a fairly clear cut-off with p_T since the trigger makes its decision based on the transverse energy of the particle. However, the resolution is not the only reason for the smearing evident in the plot: the trigger has no information about the charge of the particle. Therefore the measured transverse energy of the particle depends strongly on which way it bends in the magnet. Particles of one charge, pointing into one side of the detector, will bend outwards for one magnet polarity and inwards for the other. If they bend inwards they are far less likely to have the threshold E_T required to activate the trigger. Therefore this trigger introduces a large left-right asymmetry for particles of a given charge which can be reversed by changing the magnet polarity. This must be considered when measurements of charge asymmetries for CP violation studies are attempted.

The threshold E_T for particles to activate the hadron hardware trigger was changed at various points through 2010 and 2011, but was usually around 3.5 GeV. Furthermore, the number of hits in the SPD was generally required to be below 600. Changes in the thresholds during the run reflect variations in the mean number of pp interactions per

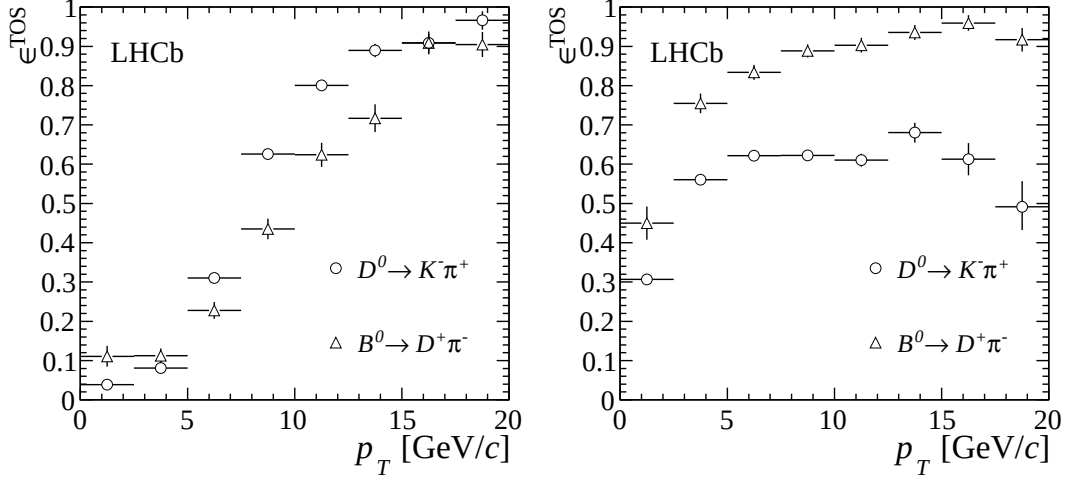


Figure 2.12: The efficiency of the hadronic level-0 trigger (left) and the 1-track inclusive software trigger (right) as a function of p_T for important B and D decay channels [66, 57].

bunch crossing. In principle, this could mean that data taken with one or the other magnet polarity could have a lower average threshold. This would affect how well various detector asymmetries discussed in Chapter 4 cancel when data taken with the two polarities are combined, leading to systematic biases on charge asymmetry measurements. No significant effect is observed, probably because the thresholds were kept constant for the majority of the data taking period. The configurations used in 2011 (where the statistical sensitivities of physics analyses to such issues are higher), and their relation to changes of the magnet polarity are summarised in Table 2.1.

2.11 The software trigger

The High Level Trigger (HLT) is a series of algorithms implemented in a C++ software package called Moore which runs on 26110 CPU cores in the Event Filter Farm [66]. In 2011, events were selected by the hardware triggers at an average rate of 870 kHz, slightly below the design rate of 1 MHz. The first stage of the HLT, referred to as HLT1,

reconstructs tracks starting from a three-dimensional pattern recognition which uses information from the VELO. The VELO tracks are continued through the tracking system to the OT and IT and a χ^2 for track quality is calculated from the Kalman filter track fit. For events selected by the muon hardware trigger, an attempt is made to match the VELO tracks with hits in the muon chambers. Accurate measurements of the momentum and p_T of hadrons and muons are performed: the invariant mass resolution of $J/\psi \rightarrow \mu^+\mu^-$ candidates was measured to be only 3% larger in the HLT than it is in the offline reconstruction. In most of 2010 and 2011, muonic charm and beauty decays were usually triggered by the presence of a high p_T muon. For most other decays, the inclusive displaced track trigger (Hlt1Track) requires one hadron, muon or electron track with a p_T greater than 1.7 GeV/ c , a momentum greater than 10 GeV/ c , a track fit $\chi^2/\text{ndf} < 2$ and an impact parameter with respect to the PV of at least 0.1 mm. This last requirement is highly efficient for the daughters of long-lived B and D^+ mesons, although less so for those of the shorter-lived D^0 and D_s^+ .

The second stage of the high level trigger consists of a series of selections designed to reconstruct particular decay modes or groups of decays. The full event information is used. For charm decays, the process is very similar to the offline reconstruction, except that no particle identification is used in the selection of tracks. Sometimes, to reduce the bandwidth, selections are prescaled. This is the case for one of the triggers used in the analysis described in Chapter 3. The prescaling means that the algorithms are only enabled for a fraction of the events for which a trigger decision has to be made.

As the HLT is purely software, it can evolve as more experience of data-taking is acquired and the priorities of the experiment change. In 2011, the HLT had approximately 30 ms to make each decision. Adjustable parameters in the algorithms are controlled by Trigger Configuration Keys (TCKs). More specific information on the trigger for the 2010 run can be found in Chapter 3.

Run interval	Main TCK	Moore	Magnet polarity	Int. Lumi (pb^{-1})
87219-87977	0x360032	v12r3	Down	7.4
89333-90207	0x5A0032	v12r5	Up	43.0
90256-92000	0x5A0032	v12r5	Down	40.2
92001-92735	0x6D0032	v12r6p1	Down	68.1
92821-93282	0x730035	v12r6p1	Down	84.3
93398-94386	0x730035	v12r6p1	Up	138.9
95948-97028	0x760037	v12r8	Up	70.3
97114-97992	0x760037	v12r8	Down	74.2
98002-98882	0x760037	v12r8	Down	117.4
98900-100256	0x760037	v12r8	Up	36.7
101373-101862	0x790037	v12r9p1	Up	64.9
101891-102452	0x790038	v12r9p1	Down	97.0
102499-102907	0x790038	v12r9p1	Up	82.9
103049-103686	0x790038	v12r9p1	Down	112.4
103686-104414	0x790038	v12r9p1	Up	46.5

Table 2.1: Main running periods in 2011 with the magnet polarity and trigger configuration key. In practice, the trigger configurations used for all of these keys are very similar, or identical. The horizontal lines correspond to the division into running periods described in Sect. 4.10.10, indicated by the vertical lines in Fig. 4.40.

2.12 Event and detector simulation

A full Monte Carlo simulation of proton-proton collisions and their interaction with the LHCb detector exists, and it is used principally to optimise event selections and estimate efficiencies. The pp collisions are simulated with PYTHIA 6.4 [67] with a specific LHCb configuration [68]. The most frequent production mechanisms for b and c quarks are the leading order $2 \rightarrow 2$ QCD processes reproduced from Ref. [68] in Fig. 2.13(a) and 2.13(b). However, other non-negligible processes such as flavour excitation or gluon-gluon splitting are also simulated. To generate standard ‘minimum bias’ events, diffractive and elastic processes are also activated. In the LHCb configuration, the track multiplicity and fraction of excited states are adjusted in accordance with the results of measurements at LEP and CDF.

Each simulated event is usually forced to contain the particular decay mode under

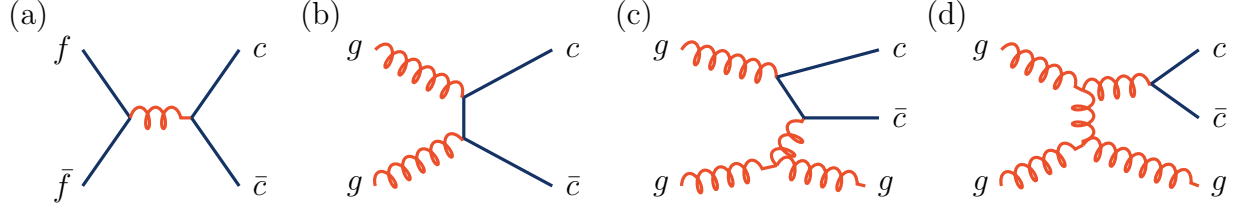


Figure 2.13: Processes for $c\bar{c}$ production implemented in Pythia 6: tree-level processes at lowest order (a, b) and higher order (c, d) [68].

study. Decays of hadronic particles, including, for example, representations of their Dalitz plot distributions and simulations of K , D or B mixing are described by EVTGEN [69]. Selection cuts are applied to the generated decays to save CPU time in later stages of the simulation. Usually, the daughters of B or D hadrons are simply required to be contained inside the detector acceptance. In the next phase, the interactions of the generated particles with the detector and its response are simulated using the GEANT4 toolkit [70] as described in Ref. [71]. An XML geometry database is used to store the detector description. Together with information on the detector alignment stored in the Conditions Database (also XML), this encodes all of the information needed to model the detector. The simulation is managed by the Gaudi-based [72] Gauss software application. The detector response is converted into the same format as that produced by the detector readout by another application, named Boole, so that the simulated events can be reconstructed in the same way as real pp collisions. The only difference between data and simulation in the context of the software is that in simulated data information about the generated events is also stored and can be matched to reconstructed signal when the data are analysed.

2.13 Reconstruction and analysis software

Raw data from the LHCb DAQ system is processed using the Brunel software package. This handles pattern recognition, track fitting, reconstruction of Cherenkov rings in the RICH system, association of reconstructed particles to ‘true’ information from the generator in the case of simulated events, and performance monitoring. A raw pp collision event is stored as a collection of ‘raw banks’, each of which contains the information from one TELL1 board. The banks are converted to new data structures stored in the so-called Transient Event Store or TES. This is a dynamic database of event information which serves as the source of particles for the reconstruction of individual decay channels. This reconstruction is handled by the DaVinci analysis framework. Particles satisfying the criteria to be charged pions or kaons, protons, muons, electrons, or photons are taken from the TES and combined to form composite candidates. Selection criteria are applied to isolate signal from background. This is performed first in the HLT2 algorithms, and then again offline in so-called ‘stripping’ algorithms. More CPU time is available in the stripping step, and therefore a wider range of selection criteria than that available in the trigger can be applied and the vertex fitting can be done more accurately. For example, particle identification information from the RICH detectors is available to the stripping algorithms, but not usually in the HLT. The output of the stripping selections is distributed on the Large Computing Grid for offline analysis. While the raw events selected by the trigger are also stored, they are not made accessible for analysis in order to avoid the need to store many replicas of the same data and to avoid the need for each user to ‘strip’ the data themselves. For charm decays, to save disk space, the files available for analysis contain only the tracks of the charm decay selected by the stripping algorithm, instead of the full event. The raw events are periodically ‘restripped’ to allow data to be reanalysed with different signal selection criteria.

For each candidate that is selected by a stripping algorithm, some information about

how the trigger algorithms selected the event is stored by the software. If the event was triggered by a daughter of the candidate that the HLT2 algorithm in question was designed to select, the candidate is labelled as ‘TOS’, meaning ‘triggered on signal’. If, by contrast, the event was triggered by a particle which does not form part of the signal candidate, then the candidate is labelled as ‘TIS’, meaning ‘triggered independently of signal’. Candidates can be both TIS and TOS, if several triggers were activated by the same event, or neither, if they cannot be satisfactorily categorised. If they are neither TIS nor TOS, the trigger was probably activated by a partially reconstructed signal candidate. Such events should not be used in data analysis. Furthermore, ‘TIS’ candidates are not always fully ‘independent of the signal’ because the track which activated the trigger can be correlated to the signal candidate. Nevertheless, this categorisation is an invaluable analysis tool, as will become apparent in Chapters 3 and 4.

The LHCb analysis framework is continually evolving as running conditions change and our understanding of the interaction of particles with detector material advances as more demanding analyses are performed. The relative stability of the trigger in 2011 and 2012 compared to 2010 has enabled closer study of its properties, described in part in Chapter 4. However, the good performance of the detector and the well-developed analysis software also made it possible to produce an impressive catalogue of physics results from the first data taking period in 2010, and one example is presented in the next chapter.

Chapter 3

Search for CP violation in

$D^+ \rightarrow K^- K^+ \pi^+$ decays with data collected at LHCb in 2010

3.1 Introduction

In the 35 pb^{-1} of data collected at LHCb in 2010, around 370,000 $D^+ \rightarrow K^- K^+ \pi^+$ decays were selected for studies of CP violation. This sample was of similar size to the datasets available at the B -factories BaBar and Belle at the time. However, in their searches for CPV, BaBar and Belle chose to restrict themselves to the $\phi(1020)$ and $K^*(892)^0$ resonances [73, 74]. Only CLEO-c had performed a full amplitude analysis and model-dependent search for CPV using the whole Dalitz plot [47], with around 20,000 decays. Therefore there was an opportunity to search for CPV with a much greater level of precision than had been achieved before, particularly in those areas of the $D^+ \rightarrow K^- K^+ \pi^+$ Dalitz plot that BaBar and Belle had not investigated. The publication that resulted from the analysis described here [10] was followed by a more comprehensive study from

BaBar in 2012 [39], but, as described in Chapter 5, there is still much scope for further work in this area.

To avoid the various problems and systematic uncertainties associated with model dependence discussed earlier in this thesis, we chose to take inspiration from a BaBar analysis of a different decay mode [75] to search for CPV in a model-independent way [76].

In this method the Dalitz plot is split into bins and a CP asymmetry variable

$$\mathcal{S}_{CP}^i = \frac{N^i(D^+) - \alpha N^i(D^-)}{\sqrt{N^i(D^+) + \alpha^2 N^i(D^-)}} , \quad \alpha = \frac{N_{\text{tot}}(D^+)}{N_{\text{tot}}(D^-)}, \quad (3.1)$$

is defined, where $N^i(D^+)$ and $N^i(D^-)$ are the numbers of $D^\pm$ candidates in the i^{th} bin and α is the ratio between the total D^+ and D^- yields, $N_{\text{tot}}(D^+)$ and $N_{\text{tot}}(D^-)$ respectively. The parameter α removes the contribution from charge asymmetries that do not vary across the Dalitz plot. The charge asymmetry in the production of $D^\pm$ mesons in pp collisions, and, to first order, the charge asymmetries in the detection efficiency of kaons and pions fall into this category. At the time of the analysis, neither were measured. This normalisation also means that there is no sensitivity to a CPV that is constant across the Dalitz plot, but such a CPV is *a priori* unlikely because of the different strong phases of the many two-particle resonances involved.

In the absence of asymmetries that vary across the Dalitz plot, the $\mathcal{S}_{CP}^i$ values in the Dalitz plot bins will be distributed according to a Gaussian distribution with zero mean and unit width. A χ^2 test is used to perform a numerical comparison between the bins of the D^+ and the D^- Dalitz plots ($\chi^2 = \sum (\mathcal{S}_{CP}^i)^2$). The number of degrees of freedom is the number of bins minus one (due to the constraint of the overall D^+/D^- normalisation). The p -value that results from this test is defined as the probability of obtaining, for a given number of degrees of freedom and under the assumption of no CPV, a χ^2 that is at least as high as the value observed [77]. It measures the degree to which we are confident

that the differences between the D^+ and D^- Dalitz plots are driven only by statistical fluctuations. The smaller the p -value, the lower the probability that the null hypothesis, that there is no CPV in the dataset, is true. In the absence of any effect, the p -values observed in a large number of tests should be uniformly distributed between zero and one.

If there is a large CP violating signal, the p -value from this test could be converted into a significance assuming Gaussian behaviour. Unfortunately, if no CPV is found there is no model-independent mechanism to determine a limit. Model-independent limits are obtained in Chapter 4 for a predefined region within the Dalitz plot, but here the aim is to search for CPV anywhere in the Dalitz plot distribution.

However, it is possible to compare the results to simulation studies in which an artificial CP asymmetry is introduced into an assumed amplitude model for the decay. Since such simulations are clearly model-dependent, they are only used as a guide to the sensitivity of the method, and not in the determination of the p -values that constitute the results of the analysis.

The technique requires careful checks to prove that we are not sensitive to local asymmetries that could be induced by sources such as the difference in the K -nucleon inelastic cross-section, differences in the reconstruction or trigger efficiencies, left-right detector asymmetries, etc. These effects are investigated in the two control channels $D^+ \rightarrow K^- \pi^+ \pi^+$ and $D_s^+ \rightarrow K^- K^+ \pi^+$. The analysis was performed blind, in the sense that the signal decay mode was only analysed once there was confidence that artificial asymmetries could not affect the result.

The optimum sensitivity to CPV is obtained with bins of a similar size to the area over which the asymmetry extends in the Dalitz plot. Two types of binning scheme are employed. The first is a simple regular grid of equally sized bins. The second attempts to allow for the highly non-uniform distribution of events over the $D^+ \rightarrow K^- K^+ \pi^+$ Dalitz plot, which is dominated by the $\phi\pi^+$ and $\bar{K}^*(892)^0 K^+$ resonances. This “adaptive

binning” scheme uses bins of different sizes to obtain roughly the same number of events in each bin. This means that variations in the statistical significance of a signal in a set of bins would indicate variations in the strength of the signal rather than variations in the event yields, making the results easier to interpret. The total number of bins is varied within these schemes, and simulation studies are used to motivate adjustments to the boundaries between bins which increase the sensitivity.

The work done in this chapter was in close collaboration with my academic supervisor and colleagues from several institutes in Rio de Janeiro. I was principally responsible for the sensitivity studies and the publication of the results, and while I was involved in the studies of the control modes and the determination of the selection criteria I was not their main author.

This chapter continues with a description of the procedure used to obtain a clean unbiased sample of $D^+ \rightarrow K^- K^+ \pi^+$ decays. This is followed by a description of the simulation studies used to test the sensitivity of the method and to define the binning schemes. Finally, there is an explanation of the cross checks performed using the control decay modes and a presentation of the results obtained in the signal channel. In all of the following text, charge conjugate decays are implied where appropriate. The kaon with opposite charge to the D^+ meson is referred to as the K^- or ‘opposite-sign kaon’ and the kaon with the same charge is labelled as the K^+ or ‘same-sign kaon’.

3.2 Dataset and selection

The data sample used in this analysis consists of approximately 35 pb^{-1} of data collected between 25 June and 30 October 2010. As discussed in the previous section, the detector can introduce biases into the Dalitz plot or anomalous asymmetries between D^+ and D^- decays, which could easily be confused with CP violation. To ensure that none

of the dataset is biased, well-defined trigger and selection criteria that lead to no such asymmetries when applied separately to the control decay modes are used.

The potential detector asymmetries are further complicated by the rapidly changing running conditions and resultant changes in the trigger as the LHC instantaneous luminosity increased through the year. A total of 10 different hardware trigger configurations and 19 different software trigger configurations were used in the collection of the data sample.

Approximately half of the dataset was taken with the magnet polarity down and half with polarity up. In the magnetic field, positively charged particles will bend in one direction (either left or right) and negatively charged particles will bend in the opposite direction. Since the detector is not necessarily left/right symmetric it is important that the magnet polarity is regularly reversed. Reversing the polarity helps to cancel any effect due to left/right differences in the detector. To this end the final results are calculated for each magnet polarity separately, compared, and then combined in a weighted average at the end of the analysis. In the data collected in 2010, the statistical sensitivity was not high enough to study the left-right asymmetries in detail, but the control modes are used to show that it does not affect the results, and a fuller treatment can be found in Chapter 4.

The trigger algorithms which yield the highest rate of signal decays are investigated. The majority of signal in this dataset is from events which activate the hardware calorimeter trigger, the first-level software trigger, and then one of the second-level software algorithms designed to select charm events.

At the hardware stage of the trigger, it is required that the signal decay itself activate the hadron calorimeter trigger, or that another particle in the event activate this hardware trigger or the photon, electron or muon trigger systems (or more than one of these systems). In 2010, the hadron trigger required one or more transverse energy (E_T)

deposits in the calorimeter of at least 2.6 or 3.6 GeV, depending on the configuration. In addition, the number of hits in the scintillating pad detector (SPD) must be less than a threshold value (900, 600 or 450), to exclude very large events which would take too long to process. The criteria are summarised in Table 3.1. As discussed in Chapter 2, the energy resolution of the calorimeter is of order 1 GeV, which is very large compared to the E_T of the average decay product of a D meson. Whether or not the hadron trigger is activated by a typical particle is therefore, to a large extent, effectively a matter of chance.

Run range	Mag	Lumi (nb ⁻¹)	TCK	Details
74367-75350	Down	86	0x10001F	Hadron $E_T > 2.26$ GeV
75351-75725	Up	193	0x13001F	Hadron $E_T > 2.26$ GeV
76790-77623	Down	1002	0x17001F	Hadron $E_T > 2.26$ GeV
77623-78287	Up	1585	0x19001F	Hadron $E_T > 2.26$ GeV
78287-78330	Down	281	0x190024	Hadron $E_T > 2.26$ GeV, SPD < 600
79571-80173	Up	5295	0x1E0030	Hadron $E_T > 2.6$ GeV, SPD < 900
(79753-79754)	Up	25	0x1F0031	Hadron $E_T > 3.6$ GeV, SPD < 450
80210-80883	Up	11038	002A/002C	Hadron $E_T > 3.6$ GeV, SPD < 450/900
81312-81764	Down	17582	002A/002C	Hadron $E_T > 3.6$ GeV, SPD < 450/900

Table 3.1: Significantly different hardware trigger configurations during the 2010 run. The column labelled ‘Mag’ specifies the magnet polarity. TCK stands for “Trigger configuration key” and relates to how the different triggers are classified. The SPD multiplicity is the number of hits received at the scintillating pad detector. In the last part of the data taking, runs 80210-81764, regular changes between the TCKs 002A and 002C were made, but the difference in SPD multiplicity threshold between the TCKs does not make a large difference to the physics (unlike, for example, the hadron E_T requirement).

Between 25 June and 29 August 2010, the first-level software trigger used to select most candidate events required one hadron track with a transverse momentum $p_T > 2.5$ GeV/ c and a second track with $p_T > 1.0$ GeV/ c to form a loosely defined vertex. An alternative algorithm required a single hadron track with $p_T > 5$ GeV/ c . From 22 September, following a pause in data taking, these triggers were replaced with a single algorithm, which required a good quality track (defined as a track having $\chi^2/\text{ndf} < 3$ and at least nine VELO

hits) to pass kinematic thresholds. The χ^2/ndf of the track is determined from the Kalman filter track fit method [78]. An example set of thresholds is transverse momentum $p_T > 1250 \text{ MeV}/c$, momentum $p > 12.5 \text{ GeV}/c$, impact parameter $IP > 0.125 \text{ mm}$ and $IP\chi^2 > 50$ where the latter criteria are with respect to the proton-proton interaction point or primary vertex (PV). The impact parameter χ^2 of a track with respect to a given vertex is the increase in the χ^2 of the vertex caused by including the track in that vertex. The χ^2 of a vertex is large if the tracks that form it do not intersect (or come close to intersecting) at a single point. If the track in question comes from the decay of a D^+ meson rather than from the PV, it causes a large increase in the χ^2 of the PV when it is included in the calculation, and therefore the χ^2 is likely to pass the selection requirement. The χ^2 of a quantity such as impact parameter or vertex separation is strongly correlated to the value of the quantity itself, but also accounts for how well measured the variable happens to be for that particular track or vertex; it is fairly similar to value/error on value)². At this stage, some signal decays also activate only muon or electron triggers, but this data sample is too small for a detailed study of the associated biases to be carried out, so it is not used in the analysis.

Dedicated second-level software trigger algorithms exist to select charged $D_{(s)}^+ \rightarrow hhh$ decays, where h represents a charged kaon or pion. For data taken between 22 September and 4 October, the principal algorithm only selected candidates in narrow mass ranges of $1844 < m < 1894 \text{ MeV}/c^2$ and $1943 < m < 1993 \text{ MeV}/c^2$. A secondary algorithm selected candidates with masses in the range $1700 < m < 2100 \text{ MeV}/c^2$, but this was only run on one event in 100. The restriction has unfortunate consequences for the determination of the signal yield after the selection, but knowing the yields precisely is not critical to the analysis. On and after 4 October, the allowed mass range in the main algorithm was changed to $1800 < m < 2040 \text{ MeV}/c^2$. The most important selection criteria used by these algorithms to reduce the event rate are the requirements that the daughter tracks have

$p_T > 500 \text{ MeV}/c$ and $IP\chi^2 > 4$ with respect to the PV.

Other triggers such as those aimed at B decays also select a significant number of candidates not selected by the signal triggers. However, the charge asymmetries found in signal which triggered these algorithms are not consistent with those in the rest of the data sample. Since the algorithms are not designed to select prompt charm this is not surprising. Therefore only ‘TIS’ events from these triggers, in which the algorithm was activated by particles that do not form part of the D^+ candidate, are accepted. Trigger algorithms designed to select $\phi(1020)$ mesons provide a fourth source of $K^-K^+\pi^+$ candidates. However, because the inclusion of signal from these algorithms would distort the Dalitz plot (due to the ϕ mass cut) they are not used.

Following this detailed consideration, the dataset is divided into three parts, Samples 1, 2 and 3. Data in Sample 1 were collected prior to 29 August, in Sample 2 between 22 September and 4 October, and in Sample 3 after 4 October. There are significant changes in algorithms at all stages of the trigger between Sample 1 and Sample 2. The only major difference between Sample 2 and Sample 3 is that the final stage of the trigger has a more restrictive mass window for $K^-K^+\pi^+$ candidates in Sample 2.

In the stripping algorithms for the $D_{(s)}^+ \rightarrow K^-K^+\pi^+$ and $D^+ \rightarrow K^-\pi^+\pi^+$ decays (see Sect. 2.13), the same selection criteria are used for the control and signal decays to ensure that no biases exist in the signal decay that are not also present in the control channels. In addition, care is taken to use criteria that do not preferentially select one area of the Dalitz plot instead of another. For example, sensitivity to CP violation is expected to be highest where resonances interfere, and this is often at the edge of the Dalitz plot where one track has a low momentum in the D^+ rest frame and therefore points back to the PV. A selection designed purely to optimise the signal to background ratio would reject these tracks before making D^+ candidates because they are very difficult to distinguish from background tracks coming from the pp interaction. This would seriously impair

the sensitivity of the analysis to CPV. Instead, it is still possible to reject most of the background by requiring that any two of the three tracks that form the D^+ candidate have a large impact parameter with respect to the PV.

The events selected in the stripping lines satisfy the criteria summarised in Table 3.2. The requirement on the number of tracks in the event is necessary to reduce the CPU consumption of the stripping algorithm. This CPU time is determined by the number of possible combinations of tracks which could be used to make a D^+ candidate. It is enormously reduced by the requirements on each track listed in the first part of the table. Thus, to keep the CPU time under control, loose requirements on the impact parameter χ^2 with respect to the PV of all the tracks are unavoidable despite the need to maintain a uniform efficiency across the Dalitz plot.

The vertex χ^2 is the χ^2 of the vertex fit and measures how closely the three tracks meet. The distance of closest approach χ^2 between two tracks is similar in practise, but it is determined from the geometry of the tracks and the uncertainties on their positions before the vertex fitting is performed. The vertex separation χ^2 is the χ^2 of a composite of two vertices under the usually false assumption that they coincide, so a larger value of this quantity indicates that the vertices are further apart. The $\Delta_{LL}(K - \pi)$ variable is a likelihood from the RICH system (see Sect. 2.5). The rings of Cherenkov light produced in the RICH detectors are compared to the rings expected of kaons, pions and protons. The reconstruction algorithm considers all tracks in the event, which means that overlapping rings can usually be identified as originating from multiple particles. If the radius of the ring is fully compatible with a kaon mass hypothesis and the ring contains a large number of hits, the likelihood for the kaon hypothesis will be large. A poorly defined ring or one with an anomalous radius will lead to the associated track being assigned a likelihood close to zero. Tracks with rings that are more compatible with a pion mass hypothesis than a kaon hypothesis are assigned negative $\Delta_{LL}(K - \pi)$ values. Information

Selection criterion	Requirement
Total number of tracks in full event	< 350
Track χ^2/ndf	< 5
Track transverse momentum (p_T)	$> 250 \text{ MeV}/c$
Track momentum	$> 2000 \text{ MeV}/c$
Minimum impact parameter χ^2 to any primary vertex (PV)	> 4
Kaon $\Delta_{LL}(K - \pi)$	> 3
Pion $\Delta_{LL}(K - \pi)$	< 10
Maximum distance of closest approach of tracks (DOCA) χ^2	< 50
At least two tracks with minimum impact parameter χ^2 to any PV	> 10
Scalar sum of the p_T of the daughters	$> 1800 \text{ MeV}/c$
Vertex fit χ^2/ndf	< 10
p_T of D candidate	$> 1000 \text{ MeV}/c$
Mass m ($K^- K^+ \pi^+$ candidates)	$1840 < m < 2040 \text{ MeV}/c^2$
Mass m ($K^- \pi^+ \pi^+$ candidates)	$1840 < m < 1940 \text{ MeV}/c^2$
Vertex separation χ^2 with respect to any PV	> 100
Impact Parameter χ^2 with respect to the associated PV	< 15
DIRA	> 0

Table 3.2: Variables and selection criteria used in the stripping algorithms to select the $D^+ \rightarrow K^- K^+ \pi^+$ candidates. The horizontal lines separate different types of criterion: requirements on the whole event, on tracks, on track combinations and on the candidate after the vertex fit.

from other sub-detectors is not incorporated into this variable. The efficiency of the particle identification requirements is calibrated using D^{*+} -tagged $D^0 \rightarrow K^- \pi^+$ decays. The last selection criterion, given the name ‘DIRA’ in LHCb software, is the cosine of the angle between the momentum vector of a candidate and the displacement vector from the primary vertex to its decay vertex. It is calculated in three dimensions, not only in the transverse plane. This is a useful consistency check as it should of course have a value of 1.

After the stripping selection, the $D^+ \rightarrow K^- K^+ \pi^+$ candidates in Samples 1 and 3 have a purity of approximately 69% and 86%. The purity of Sample 2 is expected to be approximately the same as that of Sample 3 but cannot be measured directly due to the trigger used, as discussed above. It is particularly important to reduce background from

charm decays, since this background is unlikely to be uniformly distributed across the Dalitz plot so it could lead to an artificial variation of the charge asymmetry. Therefore additional requirements are applied. These cuts are not implemented in the stripping algorithms so that their values could be tuned and in order to allow the backgrounds to be studied more carefully.

To reduce the background due to $D^+ \rightarrow K^- \pi^+ \pi^+$ decays in the $D_s^+ \rightarrow K^- K^+ \pi^+$ control sample, the requirement on $\Delta_{LL}(K - \pi)$ of the kaons is tightened, requiring $\Delta_{LL}(K - \pi) > 7$. Figure 3.1 shows that there is a peak at the D^+ mass in the $K^- \pi^+ \pi^+$ invariant mass distribution for selected $K^- K^+ \pi^+$ candidates. This is particularly prominent when the $\Delta_{LL}(K - \pi)$ requirement on the same-sign kaon is loose, for example at $\Delta_{LL}(K - \pi) > 3$, indicated by the black solid line in the figure. The particle identification requirement that $\Delta_{LL}(K - \pi) > 7$ is chosen. Increasing the cut value further, for example from 7 to 10, reduces the signal efficiency by approximately 14%, which is unacceptable. The opposite-sign kaon is required to satisfy the same criterion in order to cancel any charge asymmetries in the particle identification efficiency. Similarly, in order to reduce the contribution of background from $D_s^+ \rightarrow K^- K^+ K^+$ decays, the $\Delta_{LL}(K - \pi)$ of the pion is required to be smaller than 3.

It is not particularly important to reduce the contribution from D^+ decays where the D^+ meson is produced in the decay of a B meson, because the sensitivity of these decays to CP violation in the B system (for example, the semileptonic flavour specific asymmetry) is already small. These decays are characterised by the D^+ decay having a high impact parameter with respect to the PV, since B^0 mesons with a typical energy of 50 GeV will fly around 5 mm on average before decaying into a D meson. The set of candidates which are consistent with coming from B decays also contain a high proportion of mis-reconstructed background, so it is desirable to suppress them. Thus the D^+ is required to have an impact parameter χ^2 of less than 12 with respect to the PV at which it is produced. After this

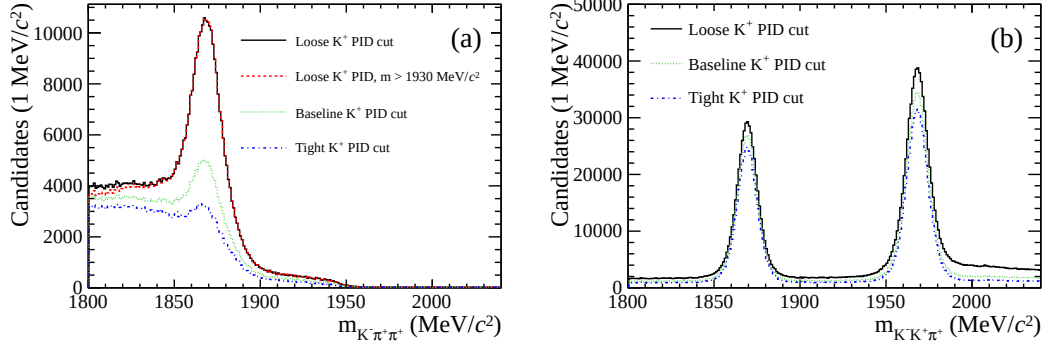


Figure 3.1: The invariant mass $m_{K^-\pi^+\pi^+}$ (a) for selected $K^-K^+\pi^+$ candidates that are reconstructed as $D^+ \rightarrow K^-\pi^+\pi^+$. The pion mass is assigned to the kaon with the same charge as the D^+ . The black solid line which overlaps the red dashed line corresponds to candidates that pass all selection criteria except for the requirement on the same-sign kaon, which is looser at $\Delta_{LL}(K-\pi) > 3$. The distribution peaks at the D^+ mass, indicating the presence of a significant background from $D^+ \rightarrow K^-\pi^+\pi^+$ decays. However, almost all of the background candidates are in the red dashed histogram, which is made from decays with $K^-K^+\pi^+$ invariant masses above $1.93 \text{ GeV}/c^2$. This indicates that the $K^-\pi^+\pi^+$ background is only significant under the $D_s^+ \rightarrow K^-K^+\pi^+$ control mode. The dashed lines in green and blue correspond to events satisfying the requirement that the same-sign kaon has $\Delta_{LL}(K-\pi) > 7$, which is the cut used in the main analysis, and 10, respectively. The invariant mass $m_{K^-K^+\pi^+}$ for the same events is given in (b) to show the efficiency loss associated with the various requirements.

requirement, the fraction of D^+ from B decays is found to be 4.5% in a large sample of simulated $D^+ \rightarrow K^-\pi^+\pi^+$ decays.

The resulting datasets contain signal samples with purities of 82% in Sample 1 and 92% in Sample 3. The lower purity in Sample 1 is due to the looser trigger requirements, and can be improved to 88% by increasing the requirement on the minimum sum of the p_T of the daughters from 1800 to 2800 MeV/c with very little loss in efficiency. Therefore this requirement is adopted in all three data samples. A summary of the additional cuts is given in Table 3.3. The efficiencies of these cuts relative to the stripping selection, and the resulting purities for the different decay modes, are shown in Table 3.4, for Samples 1 and 3. Additional cuts on other variables were investigated but led to no significant gain. The overall efficiency for Sample 3 is evaluated in the simulated dataset to be $(1.62 \pm 0.03)\%$,

Selection criterion	Requirement
Kaon $\Delta_{LL}(K - \pi)$	> 7
Pion $\Delta_{LL}(K - \pi)$	< 3
Impact Parameter χ^2 with respect to the associated PV	< 12
Scalar sum of the p_T of the daughters	$> 2800 \text{ MeV}/c$

Table 3.3: Additional cuts applied after the stripping selection to improve the signal purities.

but this should be treated only as a guide because the trigger and particle identification systems were not represented accurately in the simulation in 2010.

Decay	Sample 1		Sample 3	
	Efficiency	Purity	Efficiency	Purity
$D^+ \rightarrow K^- K^+ \pi^+$	77%	88%	79%	92%
$D_s^+ \rightarrow K^- K^+ \pi^+$	74%	89%	74%	92%
$D^+ \rightarrow K^- \pi^+ \pi^+$	77%	98%	79%	98%

Table 3.4: Efficiency and purity of different samples after the full offline selection, measured using data. The efficiency is calculated relative to the yield of candidates passing the stripping cuts. The numerator and denominator are determined by counting candidates inside a mass window. The purity is estimated from the fit (see Sect. 3.3) within the same window. The width of each window is four times the width σ of the relevant mass peak: $(1869.4 \pm 12.7) \text{ MeV}/c^2$ for $D^+ \rightarrow K^- K^+ \pi^+$, $(1868.9 \pm 16.1) \text{ MeV}/c^2$ for $D^+ \rightarrow K^- \pi^+ \pi^+$, and $(1968.2 \pm 14.1) \text{ MeV}/c^2$ for $D_s^+ \rightarrow K^- K^+ \pi$.

3.3 Mass spectra and backgrounds

The yields of selected signal candidates are determined from fits to the invariant mass distributions, shown in Fig. 3.2. The yields, given in Table 3.5, are not used directly in the analysis, but give appropriate sizes for the simulated samples used in the sensitivity studies. Furthermore, the fits allow a signal region of the mass distribution to be defined, and the proportion of background in this region to be determined. A double Gaussian peak is used to describe the $K^- K^+ \pi^+$ signal, whilst the background is described by a

quadratic polynomial component and a single Gaussian for the contamination from the $D^{*+} \rightarrow D^0(K^-K^+)\pi^+$ decay to the right of the D_s^+ peak, just visible at $2010 \text{ MeV}/c^2$ in Fig. 3.2(b). All fit parameters are floated except for the mass of the D^{*+} , which is fixed at $2010 \text{ MeV}/c^2$. The quadratic component of the fit polynomial is small, of order 10^{-6} , indicating that the background would be adequately described by a linear shape. The fit is performed simultaneously to the D^+ and D^- samples. The means and widths are summarised in Table 3.5 while the full fit parameters are listed in Appendix A.

In Sample 2, the yield cannot be calculated directly from a mass fit, because there was a mass cut in the Hlt2 algorithm that produces most of the signal: it selects only candidates in a $\pm 25 \text{ MeV}/c^2$ window around the nominal values of the D^+ and D_s^+ masses. To estimate the yield, the background to signal ratio B/S in the mass window for Samples 2 and 3 are compared for $D^+ \rightarrow K^-K^+\pi^+$ candidates triggered by the prescaled algorithm with the wider mass window described in Sect 3.2 (which was also run while the data in Sample 3 were collected). In Sample 2, $B/S = 0.070 \pm 0.006$ and in Sample 3 $B/S = 0.079 \pm 0.004$, so it is concluded that the difference in background levels between the samples is negligible. The yield in Sample 2 is then inferred as the total number of candidates in the mass window in the whole of Sample 2 times the purity in Sample 3.

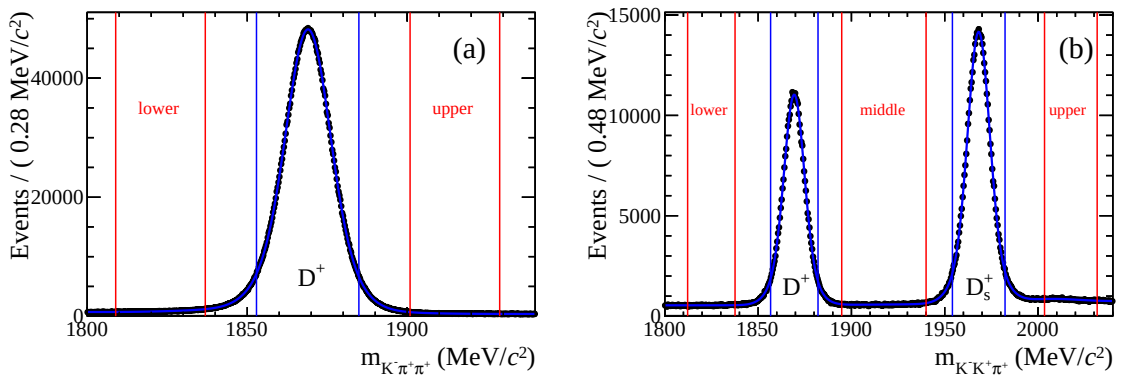


Figure 3.2: Mass fits to the (a) $K^- \pi^+ \pi^+$ and (b) $K^- K^+ \pi^+$ final states: Samples 1 and 3, D^+ and D^- combined. The intervals in invariant mass that define the signal and sideband regions used in Sect. 3.5 are labelled.

Decay	Fitted yield in Sample 1+3	Mean (MeV/ c^2)	Width (MeV/ c^2)
$D^+ \rightarrow K^- K^+ \pi^+$	$(3.284 \pm 0.006) \times 10^5$	1869.27 ± 0.01	6.35 ± 0.06
$D_s^+ \rightarrow K^- K^+ \pi^+$	$(4.615 \pm 0.012) \times 10^5$	1968.17 ± 0.01	7.05 ± 0.04
$D^+ \rightarrow K^- \pi^+ \pi^+$	$(3.378 \pm 0.004) \times 10^6$	1868.99 ± 0.01	8.00 ± 0.05

Table 3.5: Yields (S), means and widths of the fitted signals in the three decay modes after the final selection.

	Sample 1	Sample 2	Sample 3	Total
$D^+ \rightarrow K^- K^+ \pi^+$	84,667	65,781	253,446	403,894
$D_s^+ \rightarrow K^- K^+ \pi^+$	126,206	91,664	346,068	563,938
$D^+ \rightarrow K^- \pi^+ \pi^+$	858,356	687,197	2,294,315	3,839,868

Table 3.6: Number of candidates ($S+B$) in the signal windows described in the text after the final selection, for use in the subsequent analysis.

Based on these fits, narrow signal windows of approximately $\pm 2\sigma$ around the fitted masses are chosen, where σ is the appropriately weighted average of the widths of the two Gaussian distributions. The Dalitz plots are constructed only from candidates in this range. For the signal mode, this is 1856.7 MeV/ c^2 to 1882.1 MeV/ c^2 . For the $D_s^+ \rightarrow K^- K^+ \pi^+$ control mode we use 1954.1 MeV/ c^2 to 1982.3 MeV/ c^2 , and for the $D^+ \rightarrow K^- \pi^+ \pi^+$ decay the range is 1852.9 MeV/ c^2 to 1884.9 MeV/ c^2 . These windows are labelled on the mass distributions in Fig. 3.2.

The expected background consists of random three-track combinations, two-body resonances such as $K^*(892)^0$ and ϕ combined with an additional random track, and backgrounds from other charm decays. The latter generally result from four-body decays in which a track is missing, or three-body decays in which a kaon is misidentified as a pion. The main charm background in the $K^- K^+ \pi^+$ spectrum is from the $D^+ \rightarrow K^- \pi^+ \pi^+$ decay: the incorrect assignment of the kaon mass to the pion leads to a smeared distribution at a higher mass which partially overlaps with the $D_s^+ \rightarrow K^- K^+ \pi^+$ signal region, but not with the $D^+ \rightarrow K^- K^+ \pi^+$ mass peak. The four body, Cabibbo-favoured decay

$\bar{D}^0 \rightarrow K^+\pi^-\pi^+\pi^-$ where the π^- is lost and a π^+ is misidentified as a K^+ meson could be present to some degree in the signal region. There is no veto in the reconstruction on four-body vertices, so if four tracks form a vertex and three of them can be combined in such a way as to pass the selection criteria, these three tracks will form a $D^\pm$ candidate. A simulated sample of these decays, from the full LHCb simulation, is reconstructed as $D^+ \rightarrow K^-K^+\pi^+$ and the efficiency with which they pass the offline selection is calculated to be $(5.5 \pm 0.7) \times 10^{-6}$. This compares to 1.6% for signal decays in Sect. 3.2. The branching ratio of the background is approximately ten times higher than that for the signal [16] and the cross section for D^0 meson production is on the same order of magnitude as that for D^+ production [79], so the expected contamination of the sample is around 0.4%. This is far too small to affect the results.

The backgrounds in the control decay modes are also studied. One particular type of background arises when the same track is used twice, and two signal candidates are made from the same real particles. This is concentrated at the one point in the Dalitz plot where two of the daughter particles are kinematically identical in the D^+ meson rest frame, as in this case they also have the same kinematics in the rest frame of the detector. In the $D^+ \rightarrow K^-\pi^+\pi^+$ Dalitz plot this could occur along the line of symmetry of the Dalitz plot, as there are two identical pions. In this chapter, the Dalitz plot for this decay is folded over by plotting the maximum $K^-\pi^+$ invariant mass on the horizontal axis and the minimum $K^-\pi^+$ invariant mass on the vertical axis, and in this case the background lies along the upper edge of the plot. It is therefore removed in this control channel by requiring that each component of the momentum of the two pions in the detector rest frame differs by more than 1%. The background cannot appear in the $K^-K^+\pi^+$ decay channels because the K^- and π^+ $\Delta_{LL}(K - \pi)$ requirements are mutually exclusive, and oppositely charged kaons must bend in opposite directions in the magnetic field.

The Dalitz plots of the upper and lower mass sidebands of the D^+ signal decay are

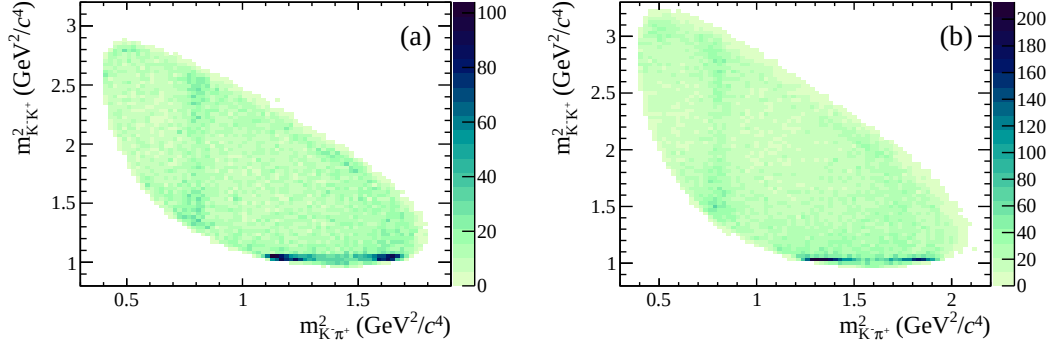


Figure 3.3: Dalitz plot distribution for $K^- K^+ \pi^+$ mass sidebands, (a) with invariant mass from 1812 to 1837 MeV/ c^2 and (b) with invariant mass from 1895 to 1940 MeV/ c^2 .

shown in Fig. 3.3. The left plot corresponds to D^+ invariant masses ranging from 1812 to 1837 MeV/ c^2 and the right plot corresponds to masses from 1895 to 1940 MeV/ c^2 . In both plots the ϕ and $K^*(892)^0$ resonances appear. The charge asymmetries in these sidebands are studied in Sect. 3.5.

3.4 Sensitivity studies and binning choice

Simulations are used to verify that CPV can be detected with the strategy outlined in Sect. 3.1 without producing false positive signals, and to devise and test suitable binning schemes for the Dalitz plot. The simulated Dalitz plots are also used to quantify the sensitivity to possible manifestations of CPV, where the sensitivity to a given level of CPV is defined as the probability of observing it with a significance of three Gaussian standard deviations.

The CLEO-c amplitude model (fit B) [47] forms the basis of these simulations. The model is of the isobar type described in Chapter 1. A probability density function is calculated by squaring the amplitude, and events are simulated from this p.d.f. with no consideration of the proton-proton collision, detector or trigger. A comparison of the model with the Dalitz plot of selected signal candidates is shown in Fig. 3.4. The

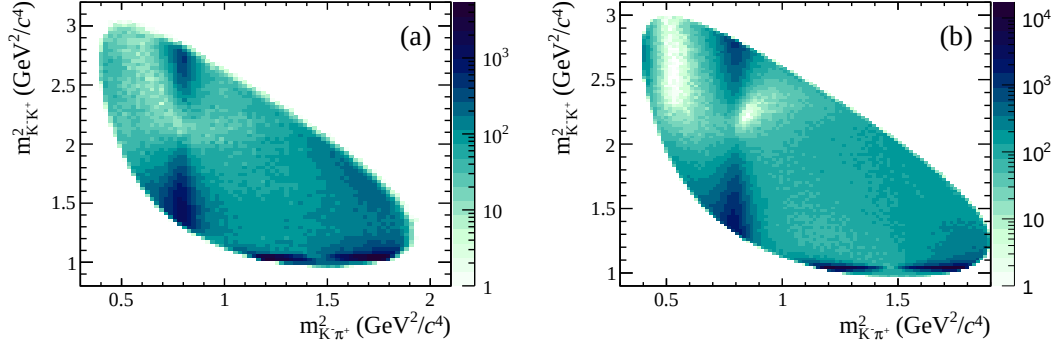


Figure 3.4: Dalitz plots from data (a) and simulation (b) for the $D^+ \rightarrow K^- K^+ \pi^+$ decay. It is clear that the amplitude model in the simulation is not perfect, but this is not surprising since it is based on 20,000 signal decays recorded at CLEO-c while in data there are 20 times this number. Since the physics results do not depend directly on the generated Dalitz plot, this is not critical.

Resonance	Amplitude	Relative phase	Fit fraction
$\overline{K}^*(892)^0$	1 (fixed)	0 (fixed)	$25.7 \pm 0.5^{+0.4+0.1}_{-0.3-1.2}$
$\overline{K}^*_0(1430)^0$	$4.56 \pm 0.13^{+0.10+0.42}_{-0.01-0.39}$	$70 \pm 6^{+1+16}_{-6-23}$	$18.8 \pm 1.2^{+0.6+3.2}_{-0.1-3.4}$
$\kappa(800)$	$2.30 \pm 0.13^{+0.01+0.52}_{-0.11-0.29}$	$-87 \pm 6^{+2+15}_{-3-10}$	$7.0 \pm 0.8^{+0.0+3.5}_{-0.6-1.9}$
$\overline{K}^*_2(1430)^0$	$7.6 \pm 0.8^{+0.5+2.4}_{-0.6-4.8}$	$171 \pm 4^{+0+24}_{-2-11}$	$1.7 \pm 0.4^{+0.3+1.2}_{-0.2-0.7}$
$\phi(1020)$	$1.166 \pm 0.015^{+0.001+0.025}_{-0.009-0.009}$	$-163 \pm 3^{+1+14}_{-1-5}$	$27.8 \pm 0.4^{+0.1+0.2}_{-0.3-0.4}$
$a_0(1450)^0$	$1.50 \pm 0.10^{+0.09+0.92}_{-0.06-0.33}$	$116 \pm 2^{+1+7}_{-1-14}$	$4.6 \pm 0.6^{+0.5+7.2}_{-0.3-1.8}$
$\phi(1680)$	$1.86 \pm 0.20^{+0.02+0.62}_{-0.08-0.77}$	$-112 \pm 6^{+3+19}_{-4-12}$	$0.51 \pm 0.11^{+0.01+0.37}_{-0.04-0.15}$

Table 3.7: The CLEO-c amplitude model “B” [47] used in the simulation studies. The uncertainties are statistical, experimental systematic and model systematic respectively. The κ resonance is sometimes referred to as the $K_0(800)$.

amplitudes and phases of the resonances used in this model are reproduced in Table 3.7. The phases of the resonances are defined relative to a reference, which is the $\overline{K}^*(892)^0$. For simplicity, only resonant modes with fit fractions greater than 2% are included in these pseudo-experiments. Simple representations of the efficiency and background are applied to the model, and then many different simulated datasets are generated to test the analysis techniques.

The full LHCb Monte Carlo simulation is used to determine the variation of the reconstruction and selection efficiency across the Dalitz plot. This simulation is generated with a uniform distribution of events in the Dalitz plot: the amplitude model built into EVTGEN [69] contains only a non-resonant component. An efficiency function is determined from a two-dimensional second order polynomial fit to the Dalitz plot distribution of events from this simulation that survive the selection cuts and trigger requirements, shown in Fig. 3.5. The simulation emulates a trigger which is representative of the configuration used towards the end of 2010 when most of the data were taken. Of the individual triggers available, those listed in Sect. 3.2 for Sample 3 are required. Depletions at the corners of the plot are observed. This is where one particle has low momentum and the other two have high momenta in the D^+ rest frame, and the particle with low momentum fails the selection criterion that requires it to have a high impact parameter with respect to the primary vertex. The effect is particularly pronounced at the top-left corner, where the pion has a low momentum in the D^+ rest frame. There is no reason for this depletion of the corners of the Dalitz plot to affect positive particles more than negative particles or vice versa, so it cannot bias the results of the analysis. This explains why no efficiency correction is applied to the data. However, if an area with low efficiency contained CPV, the statistical sensitivity to the CPV would be reduced and it would be more likely to escape undetected.

The efficiency is fitted in ‘square’ Dalitz coordinates [80, 81] so that it can be applied to the toy pseudo-experiments with an unbinned maximum likelihood fit. In this representation, one of the invariant mass axes of the Dalitz plot is replaced by the cosine of the helicity angle θ . If the particles in the decay are labelled 1, 2 and 3, the helicity angle is defined as the angle between the momentum of particle 1 and the momentum of particle 3 in the rest frame of a resonance formed by particles 1 and 2. In this case the pion is particle 1, the opposite-sign kaon is particle 2, and the system is illustrated in Fig. 3.6.

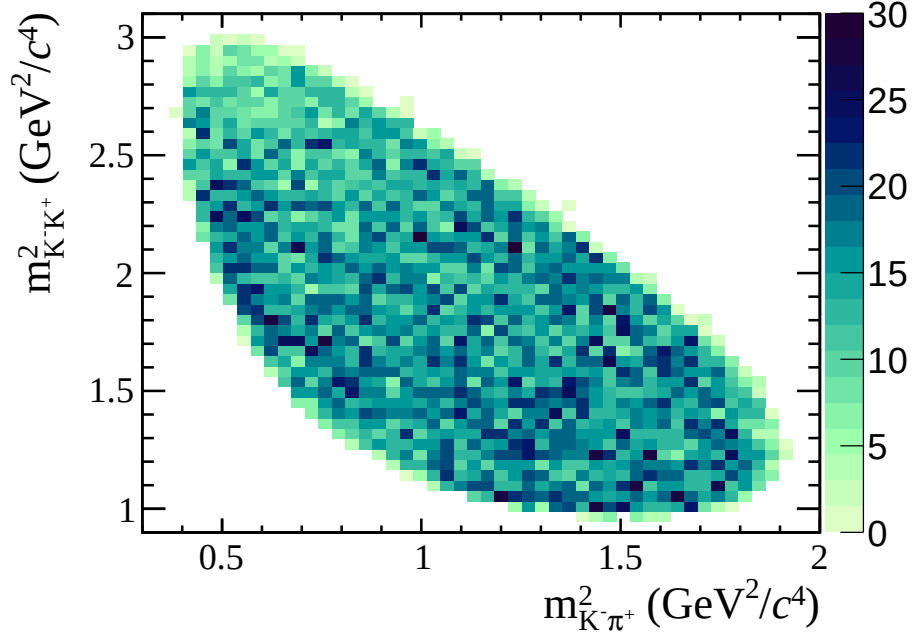


Figure 3.5: The Dalitz plot of simulated signal candidates generated with a flat distribution in phase space, then reconstructed in the same way as the data.

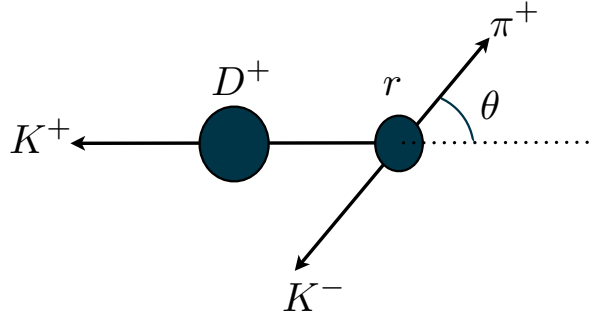


Figure 3.6: Definition of the helicity angle θ for the signal decay mode. The letter r indicates a hypothetical resonance formed by the K^- and π^+ , for example the $\overline{K}^*(892)^0$.

The advantage of the square representation of the Dalitz plot is that the kinematic limit becomes rectangular, as shown in Fig. 3.7, and so the phase space is easier to parameterise with an empirical function. However, the density of a non-resonant Dalitz plot is no longer uniform between the limits. The efficiency over most of the space ϵ_{DP} is

parameterised as

$$\begin{aligned} \epsilon_{DP} = & 1 + b_1(m_{K^-\pi^+}^2 - 1.15) + b_2(m_{K^-\pi^+}^2 - 1.15)^2 + \\ & c_1 \cos \theta + c_2(1.5 \cos^2 \theta - 0.5) + d_1 \cos \theta(m_{K^-\pi^+}^2 - 1.15) \end{aligned} \quad (3.2)$$

and then it is modified at the edges of the phase space, leading to an overall efficiency ϵ given by

$$\epsilon = \begin{cases} \epsilon_{DP} & -0.97 < \cos \theta < 0.97 \\ \epsilon_{DP} \cos(18.0 \times (\cos \theta - 0.97)) & -1.00 < \cos \theta < -0.97 \\ \epsilon_{DP} \cos(25.0 \times (-\cos \theta - 0.97)) & 0.97 < \cos \theta < 1.0 \end{cases}$$

This function is multiplied by the transformation function t relating square to linear Dalitz plot coordinates, which for this decay is (ignoring constant multiplicative factors)

$$\begin{aligned} t = & \left(\frac{1}{m_{K^-\pi^+}^2} \right) \left((m_{K^-\pi^+}^2 - m_{K^-}^2 - m_{\pi^+}^2)^2 - 4m_{K^-}^2 m_{\pi^+}^2 \right)^{\frac{1}{2}} \times \\ & \left((m_{D^+}^2 - m_{K^+}^2 - m_{K^-\pi^+}^2)^2 - 4m_{K^+}^2 m_{K^-\pi^+}^2 \right)^{\frac{1}{2}}, \end{aligned} \quad (3.3)$$

where the K^- and K^+ refer to the kaon with the opposite sign and same sign to that of the D^+ respectively. This formula is derived in Appendix B. The overall function is then fitted to the square Dalitz plot of simulated events. The χ^2/ndf of the projections of the fit in the $m_{K^-\pi^+}^2$ plane is 145/94, and that of the projection in the $\cos \theta$ plane is 105/94. The results are shown in Table 3.8 and the fits in Figs. 3.7 and 3.8. The absolute value of the efficiency is estimated in Sect 3.2 but it is not accurate due to differences between particle identification and trigger efficiencies in simulated and real data samples. It is in any case irrelevant to the analysis.

A simple model for the background is inferred by inspection of the Dalitz plots of the

Parameter	Value	Statistical uncertainty
b_1	0.136	0.026
b_2	-0.138	0.068
c_1	-0.079	0.017
c_2	-0.056	0.021
d_1	0.180	0.044

Table 3.8: The values of the parameters used to model the variation of the efficiency across the Dalitz plot in Eq. 3.3, from the two-dimensional fit shown in Fig. 3.7.

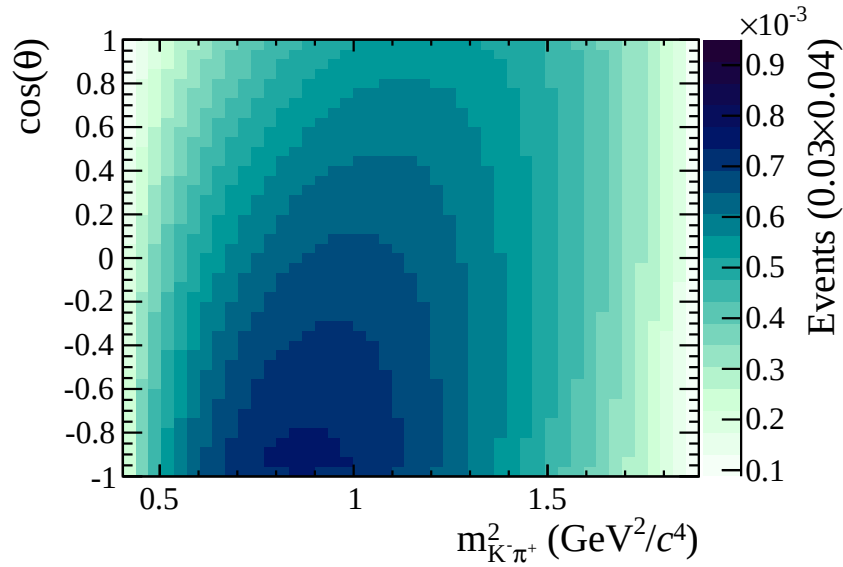


Figure 3.7: The two-dimensional fit to the density of data points in Dalitz space, which is the efficiency function multiplied by the transformation function from linear to square Dalitz coordinates. If the efficiency was uniform across the Dalitz plot, this function would be symmetric about $\cos \theta = 0$ where θ is the helicity angle. Instead, an area of low efficiency at the top of the Dalitz plot is apparent.

sidebands of the $D^+ \rightarrow K^- K^+ \pi^+$ signal, shown in Fig. 3.3. It is composed of random combinations of K^- , K^+ , and π^+ tracks, ϕ resonances with π^+ tracks, and $\overline{K}^*(892)^0$ resonances with K^+ tracks. The CLEO-c amplitude model has large uncertainties, as do the background and efficiency models, so the sensitivity studies are repeated for a range of different models.

Pseudo-experiments with large numbers of events are produced as described above to

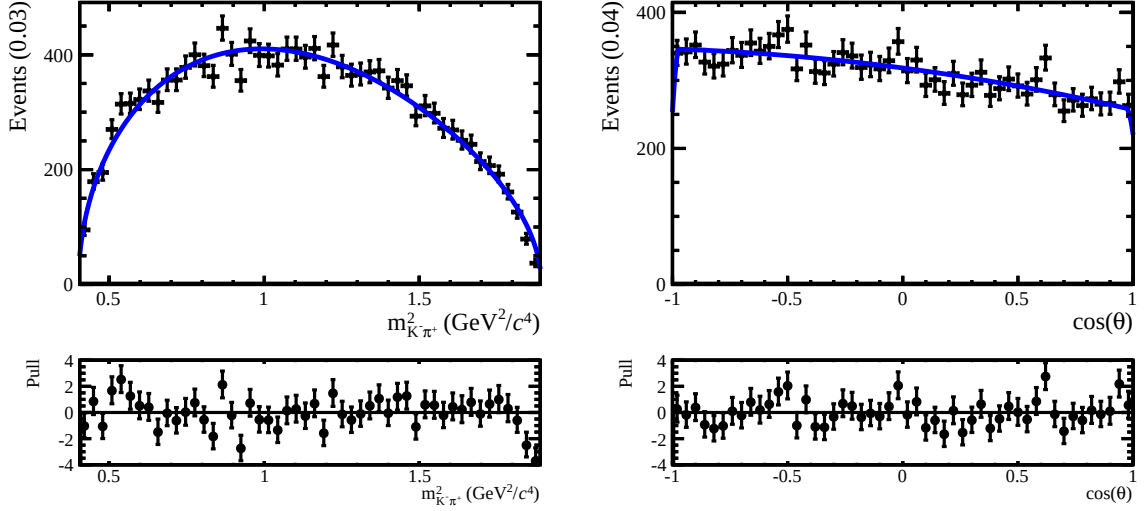


Figure 3.8: Fits and normalised residuals for the projections of the density of data points in Dalitz space, which is the efficiency function multiplied by the transformation function from linear to square Dalitz coordinates.

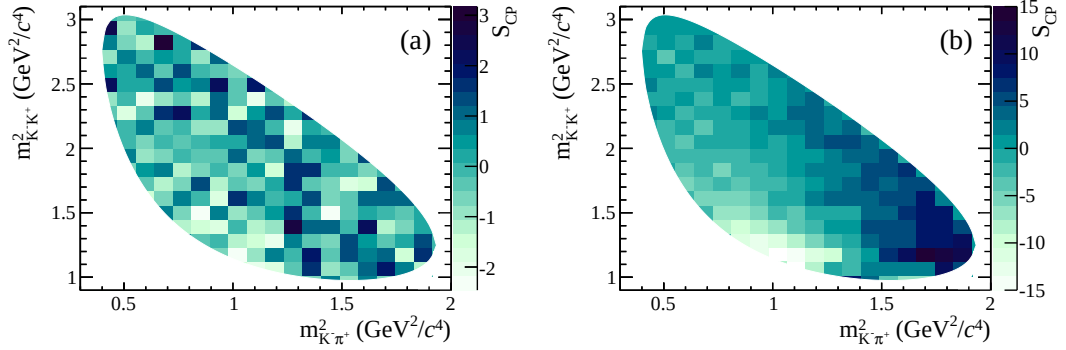


Figure 3.9: The variation of $\mathcal{S}_{CP}$ across the Dalitz plot in a Monte Carlo pseudo-experiment with a large number of events with (a) no CPV and (b) a 4° CPV in the $\phi\pi$ phase. Note the difference in colour scale between (a) and (b).

investigate how CPV would be observed in the Dalitz plot. Fig. 3.9(a) illustrates the values of the $\mathcal{S}_{CP}$ variable observed with 8×10^7 events and no CPV. This dataset is approximately 50 times larger than the data sample under study. The resulting χ^2/ndf is 253.4/218, giving a p -value for consistency with no CPV of 5.0%. This test shows that the method by itself is very unlikely to yield false positive results. Fig. 3.9(b) shows an

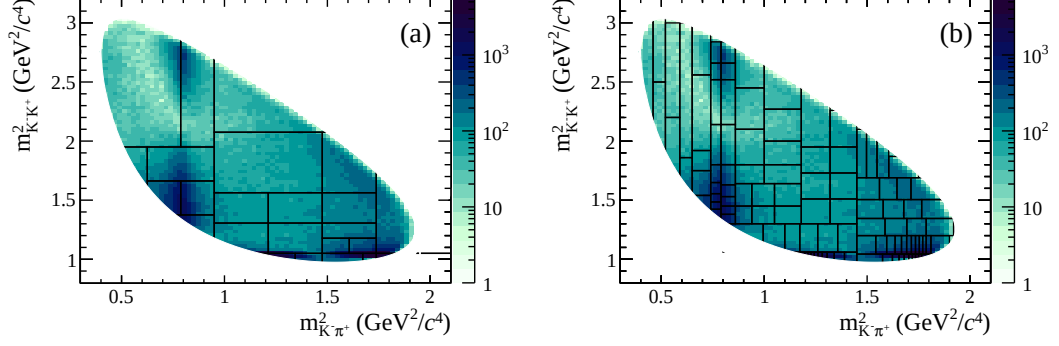


Figure 3.10: Layout of the (a) “Adaptive I” and (b) “Adaptive II” binnings on the Dalitz plot of data.

example test using 5×10^7 events with a CP violating phase difference of 4° between the amplitudes for the $\phi(1020)\pi^+$ component in D^+ and D^- decays. The p -value in this case is less than 10^{-100} . The CPV is clearly visible, and is spread over a broad area of the plot, changing sign from left to right. This sign change means the CPV causes only a 0.1% difference in the total decay rate between D^+ and D^- . This illustrates the strength of the method, as the asymmetry would be much more difficult to detect in a measurement that integrated over the Dalitz plot. Even with no systematic uncertainties, to see an 0.1% asymmetry with a significance of at least three Gaussian standard deviations (i.e. to measure a small asymmetry with an uncertainty of 0.033%) would require 9×10^6 signal decays. With the method and much smaller signal sample used here we would observe this signal at the same 3σ significance level with 76% probability, as shown in Table 3.9 below.

The sensitivity to a particular manifestation of CPV depends on the choice of binning. The fact that the region of CP violation in most of the pseudo-experiments covers a broad area of the Dalitz plot suggests that the optimal number of bins for this type of asymmetry is low. It is clear that the right compromise depends on the nature of the signal, which is *a priori* unknown, and on the size of the data sample. The results of toy studies with

reasonable values for injected CP asymmetries and varying numbers of bins are shown in Fig. 3.11.

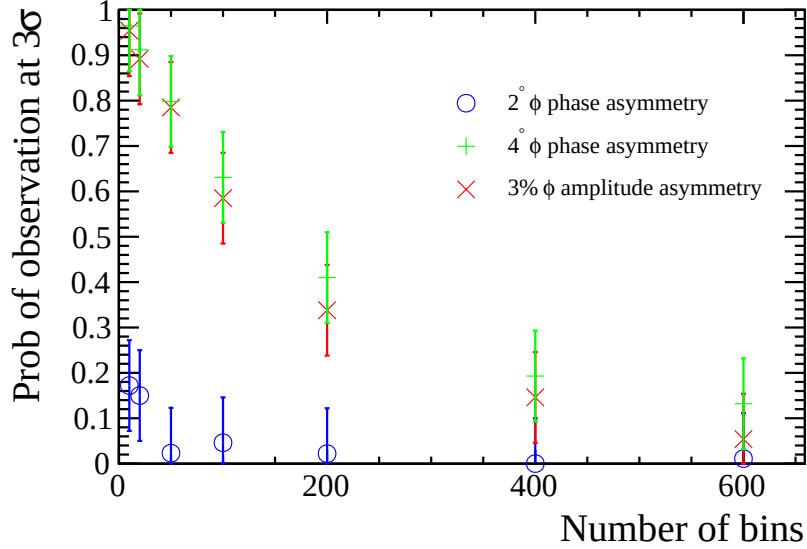


Figure 3.11: Variation of the sensitivity, defined as the probability of obtaining evidence for a given CP asymmetry at the 3σ level, with the number of bins for binnings generated with the adaptive algorithm.

From these studies, it was concluded that somewhere between 10 and 50 bins would give the highest sensitivity. Once the asymmetries are resolved, each bin adds a degree of freedom without changing the χ^2 value for consistency with no CPV. However, if CP asymmetries change sign within a bin, they will be diluted, because asymmetries in different parts of the bin will cancel out. Similarly, the sensitivity is reduced if only a small part of a large bin has any CPV in it, because the denominator of the $\mathcal{S}_{CP}$ variable will probably increase much more than the numerator. To avoid effects due to excessive fluctuations and non-Gaussian uncertainties, adaptive bins that contain fewer than 50 candidates are not used anywhere in the analysis. Such bins do not exist in the main dataset although one or two bins in the sidebands and in the data subsamples are rejected for this reason.

The binnings are chosen to reflect the highly non-uniform structure of the Dalitz plot. A simple algorithm was devised to generate bins of approximately equal population without separating D^+ and D^- . This algorithm takes the Dalitz plot, or a part of it, and calculates the total number of events in it. The longest side of this region is then bisected to create two bins from one. The number of events in each of the bins that result is calculated, and the largest bin is split in half along its longest side. This procedure is repeated until the desired number of bins is reached. Therefore in a perfectly rectangular Dalitz plot and in the limit of a large number of bins, the number of events per bin should vary by no more than a factor of two. However, the kinematic limit of the conventional Dalitz plots used here, and the small number of bins, mean that the number of events can vary by significantly more than this. Nevertheless, the variation in events per bin is considerably less than that which would have been obtained using a simple regular grid pattern.

The algorithm works well in the “square Dalitz plot” formalism for fairly flat Dalitz plots, as the kinematic limit becomes rectangular. However, for low numbers of bins and very non-uniform Dalitz plots it becomes very difficult to bin around the resonances in the square Dalitz plot, because they no longer follow horizontal and vertical lines. Therefore it was decided to use the conventional form of the Dalitz plot in this case.

Two binnings that are found to have good sensitivity to the simulated asymmetries contain 25 bins (“Adaptive I”) arranged as shown in Fig. 3.10(a), and 106 bins (“Adaptive II”) arranged as shown in Fig. 3.10(b). In Adaptive I, a simulation of the strong phase across the Dalitz plot relative to the $\overline{K}^*(892)^0$ resonance in the CLEO-c amplitude model, shown in Fig. 3.12, is used to refine the results of the algorithm. If the strong phase varies significantly across a bin, CP asymmetries are more likely to change sign within the bin. This could prevent the asymmetries being observed. Therefore the bin boundaries are adjusted to minimise changes in the strong phase within bins. The model-dependence

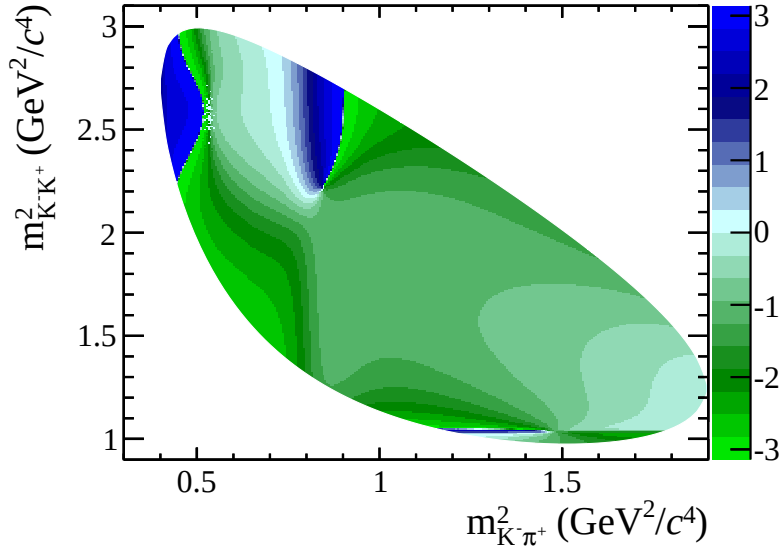


Figure 3.12: Histogram showing the strong phase variation relative to the $\overline{K}^*(892)^0$ resonance in the CLEO Dalitz model. The relative phase difference between $-\pi$ and π is of course zero. There is a small cluster of empty bins at the top of the plot in which the phase could not be determined due to the limited size of the simulated sample.

of this simulation can, in principle, influence the binning and therefore the sensitivity to CPV, but it cannot introduce model-dependence into the final results as no artificial signal could result purely from the choice of binning. Two further binning schemes, “Uniform I” and “Uniform II”, are defined. These use regular arrays of rectangular bins of equal size.

The adaptive binnings are used to determine the sensitivity to several manifestations of CPV. In Sect. 3.3, the yield of $D^\pm \rightarrow K^\mp K^\pm \pi^\pm$ decays was calculated to be approximately 370,000 and the fraction of background in the mass window was 8.5%. Roughly the same number of events were generated for each toy simulation. With 200 null test experiments of this type, including no asymmetries, no CP -violating signals are observed at the 3σ level with the Adaptive I or Adaptive II schemes. The expected number of pseudo-experiments which would show evidence for CPV is 0.3.

With the chosen binnings, a number of sets of 100 pseudo-experiments with different

CPV	Adaptive I		Adaptive II	
	$P(3\sigma)$	$\langle S \rangle$	$P(3\sigma)$	$\langle S \rangle$
no CPV	0	0.84σ	1%	0.84σ
6° in $\phi(1020)$ phase	99%	7.0σ	98%	5.2σ
5° in $\phi(1020)$ phase	97%	5.5σ	79%	3.8σ
4° in $\phi(1020)$ phase	76%	3.8σ	41%	2.7σ
3° in $\phi(1020)$ phase	38%	2.8σ	12%	1.9σ
2° in $\phi(1020)$ phase	5%	1.6σ	2%	1.2σ
6.3% in $\kappa(800)$ magnitude	16%	1.9σ	24%	2.2σ
11% in $\kappa(800)$ magnitude	83%	4.2σ	95%	5.6σ

Table 3.9: Results from sets of 100 pseudo-experiments with different CP asymmetries and Adaptive I and II binnings. Each pseudo-experiment has the same statistical sensitivity to CPV as the data. $P(3\sigma)$ is the fraction of pseudo-experiments in which evidence for CPV at the 3σ level was obtained (not to be confused with the p -value for consistency with the no-CPV hypothesis). $\langle S \rangle$ is the mean significance with which CPV is observed.

Model	Adaptive I		Adaptive II	
	$P(3\sigma)$	$\langle S \rangle$	$P(3\sigma)$	$\langle S \rangle$
B (baseline)	76%	3.8σ	41%	2.7σ
A	84%	4.3σ	47%	2.9σ
B2 (add $f_0(980)$)	53%	3.2σ	24%	2.2σ
B3 (vary $\bar{K}_0^*(1430)^0$ magn.)	82%	4.0σ	41%	2.8σ
B4 (vary $\bar{K}_0^*(1430)^0$ phase)	73%	3.7σ	38%	2.7σ
B (different background)	84%	4.2σ	35%	2.7σ
B (different background)	83%	4.0σ	38%	2.9σ

Table 3.10: Results from sets of 100 pseudo-experiments with a CPV of 4° in the phase of the $\phi(1020)$ resonance and different Dalitz plot models. Each pseudo-experiment has the same statistical sensitivity to CPV as the data. $P(3\sigma)$ is the probability of obtaining evidence for CPV at the 3σ level. $\langle S \rangle$ is the mean significance with which CPV is observed.

CP -violating asymmetries were produced. The probability of observing a given signal in either the $\phi(1020)$ or $\kappa(800)$ resonances with 3σ significance was calculated in samples of the same size as the dataset. The results are given in Table 3.9. It is clear that both binning schemes are sensitive to large CP -violating asymmetries. It appears that the Adaptive I scheme is be more sensitive to CPV in the ϕ resonance while Adaptive II is

more sensitive to CPV in the κ .

For comparison, the asymmetries in the ϕ phase and κ magnitude measured by the CLEO collaboration using the same amplitude model were $(6 \pm 6_{-2}^{+0+6})^\circ$ and $(-12 \pm 12_{-1-10}^{+6+2})\%$,¹ where the uncertainties are statistical, systematic and model-dependent, respectively. Table 3.9 suggests that, assuming their model, we would be at least 95% confident of detecting the central values of these asymmetries.

The sensitivity of the results to variations in the Dalitz plot model and the background is investigated, and example results for the CP asymmetry in the $\phi(1020)$ phase are shown in Table 3.10. In this table, models A and B are taken directly from the CLEO paper. The other models are based on CLEO's B fit: model B2 includes an $f_0(980)$ contribution that accounts for approximately 8% of events, and models B3 and B4 are variations of the $\overline{K}^*_0(1430)^0$ amplitude and phase within their uncertainties. The baseline background model contains ϕ , $\overline{K}^*(892)^0$ and non-resonant contributions in equal proportions, while the penultimate and last rows of Table 3.10 contain higher proportions of non-resonant background. The table shows that the background model makes a significant but not critical difference to the results. Also, as expected, the sensitivity to CPV in the resonances of an amplitude model depends quite strongly on the details of the model. This provides further justification for our model-independent approach. However, a reasonable level of sensitivity is retained in all the cases we tested. Thus, when taken together, the studies show that the method works well. It does not yield fake signals, and should be sensitive to any large CPV that varies significantly across the Dalitz plot even if it does not occur precisely in the way investigated here.

¹The conventions used in the CLEO paper to define asymmetry are different, so the asymmetries in Table II of Ref. [47] have been multiplied by two in order to be comparable with those given above.

3.5 Studies of the control decay channels and related cross-checks

The sensitivity to asymmetries that are not due to CP violation is investigated in two control channels, $D^+ \rightarrow K^- \pi^+ \pi^+$ and $D_s^+ \rightarrow K^- K^+ \pi^+$, and in the mass sidebands of these decay modes and of the signal decay. Because the control channels are Cabibbo favoured, there is no significant interference between tree and loop diagrams expected. Therefore we can be confident that any charge asymmetries we observe in these decay modes will be due to detector effects rather than CPV. Any momentum-dependent asymmetry in the detection efficiency of the daughter particles, or an asymmetric background with an uneven distribution across the Dalitz plot, could lead to a spurious signal.

The two control decay modes are complementary. The $D^+ \rightarrow K^- \pi^+ \pi^+$ decay has ten times the branching ratio of the Cabibbo-suppressed signal. Furthermore, the interaction asymmetry of kaons with detector material is expected to be more apparent in this channel, because in the signal decay the presence of positive and negative kaons will tend to cancel the effect. The $D_s^+ \rightarrow K^- K^+ \pi^+$ decay has similar kinematic characteristics and a similar yield to the signal. While the interference effects in the two decays differ (the scalar resonances have higher fit fractions in the D^+ than the D_s^+ Dalitz plots [82]) the detector effects are expected to be very similar. In addition, it is also important to check the mass sidebands of these control channels, and the signal, for anomalous asymmetries due to the backgrounds described in Sect. 3.3.

Many different adaptive and uniform binnings with varying numbers of bins are defined for $D^+ \rightarrow K^- \pi^+ \pi^+$ and $D_s^+ \rightarrow K^- K^+ \pi^+$ and their sidebands. Detector efficiency variations are expected to vary slowly across the Dalitz plot so a low number of bins is most appropriate, as illustrated in Figs. 3.13 and 3.14. However, backgrounds can be sharply peaked in the Dalitz plot, so these are better studied with a large number of bins

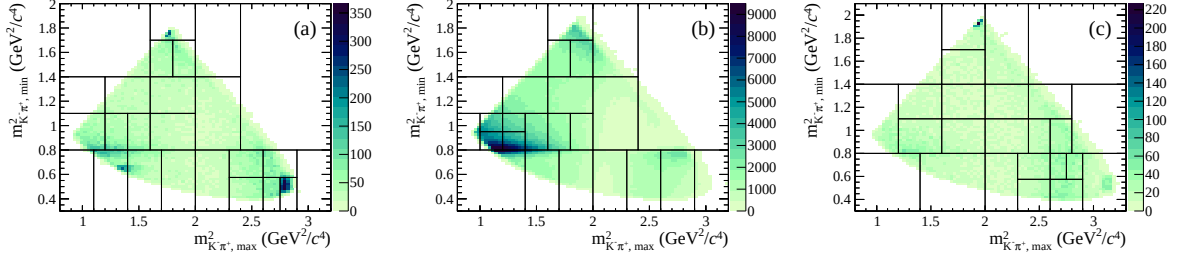


Figure 3.13: The Dalitz plots in data for the $K^-\pi^+\pi^+$ final state, with the binning superimposed, for the lower sideband (a), the D^+ signal window (b), and the upper sideband (c). The charge conjugate decay is included in each plot.

to avoid washing out any associated asymmetries. In each test, the p -value for consistency with no asymmetry variation across the Dalitz plot is calculated for samples 1–3 and each magnet polarity separately.

In the $D^+ \rightarrow K^-\pi^+\pi^+$ decay channel with 25 adaptive bins, the χ^2/ndf (p -value) for consistency with no asymmetries that vary across the Dalitz plot is found to be 23.5/24 (49%) for all of the data taken with magnet polarity up and 49.9/24 (0.15%) for data taken with the magnet down. The associated normalised residual distributions are shown in Fig. 3.15 and the distribution of $\mathcal{S}_{CP}$ values across the Dalitz plot in Fig. 3.16. In the final results, the combination of asymmetries measured in data taken with positive and negative magnet polarity helps to cancel differences in efficiency across the bending plane of the magnet, which induce detector asymmetries as discussed in Section 3.2 and Chapter 4. The overall χ^2/ndf and p -value is 32/24 (12.2%). The distribution of $\mathcal{S}_{CP}$ values across the Dalitz plot is shown in Fig 3.17. Table 3.11 compares the χ^2/ndf for compatibility with no asymmetry variation across the Dalitz plot in different running periods for the two magnet polarities. A possible deviation from the expected uniform distribution of the p -value in the magnet down dataset is found for both run periods, but there is no corresponding effect in the magnet up sample and when combined the data do not show a significant bias. Some detector asymmetries, for example due to the left-right

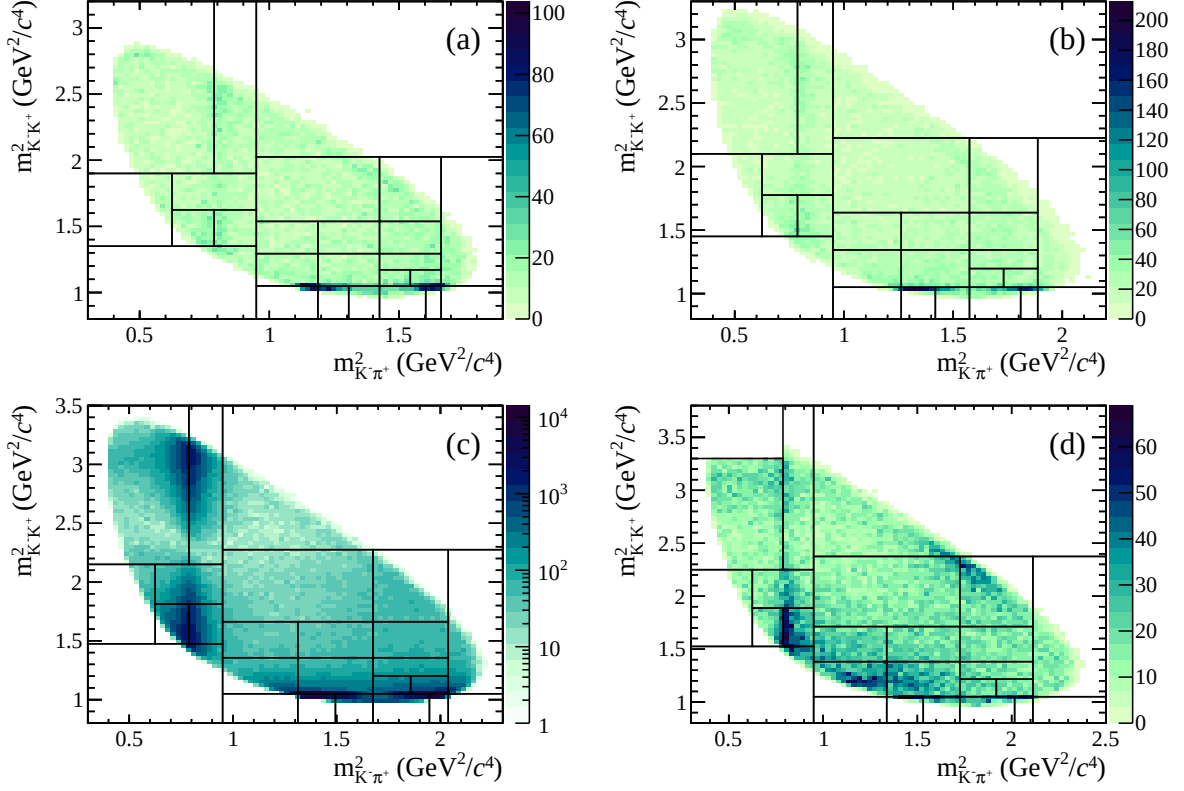


Figure 3.14: The Dalitz plots in data for the $K^-K^+\pi^+$ final state, with the binning superimposed, for the lower sideband (a), the middle sideband (b), the D_s^+ signal window (c), and the upper sideband (d). In the upper sideband, the top-left corner of the Dalitz plot is cut out to remove the contribution from $D^{*+} \rightarrow D^0(K^-K^+)\pi^+$. The charge conjugate decay is included in the plot.

differences in the particle identification efficiency mentioned in Sect. 2.5, are expected to reverse sign when the magnet polarity changes. Other effects, for example those due to the kaon interaction asymmetry, are not expected to depend on the magnetic field. Therefore the combined effect of both sources of asymmetry could produce a weak signal in one magnet polarity and no signal in the other. These potential asymmetries are discussed in more detail in Chapter 4. There is no means to determine the mechanism driving the asymmetry precisely with the limited statistical sensitivity of the 2010 dataset.

The studies are repeated with a large number of bins, both adaptive and uniform, to test for highly localised effects. Sharply peaked fake asymmetries could lead to effects that

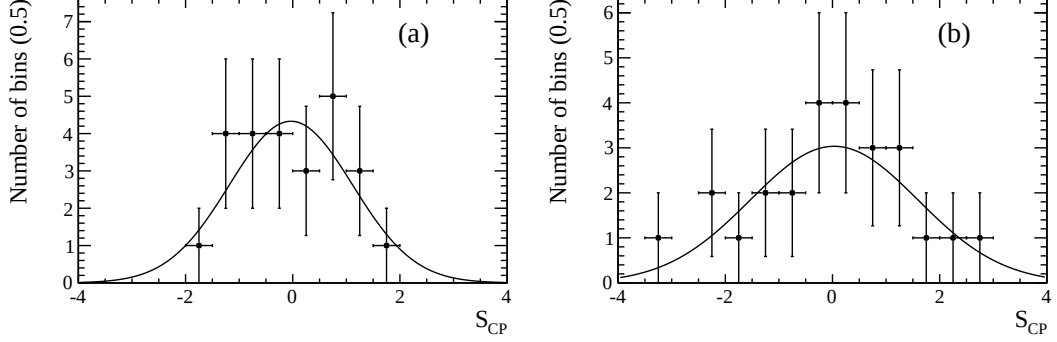


Figure 3.15: The normalised residual distributions for the $D^+ \rightarrow K^- \pi^+ \pi^+$ control mode in the magnet up (left) and magnet down (right) data, using 25 bins defined by the adaptive binning algorithm. The distributions are fitted with single Gaussian functions. For the magnet down sample there is a hint that the width differs from one ($\sigma = 1.42 \pm 0.20$), corresponding to the low χ^2 probability described in the text.

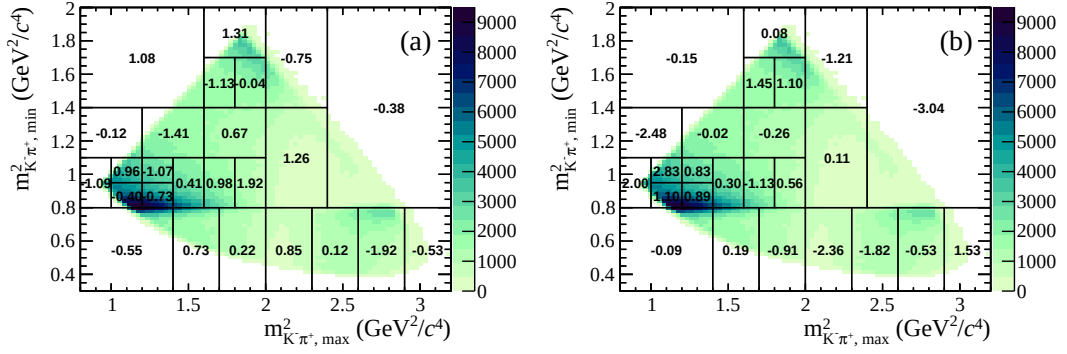


Figure 3.16: Plots showing the distribution of the S_{CP} variable across the Dalitz plot for the $D_s^+ \rightarrow K^- K^+ \pi^+$ control mode in (a) the magnet up and (b) the magnet down data, using a 25-bin scheme produced with the adaptive binning algorithm. The grid is superposed onto the Dalitz plot of the entire dataset.

would be washed out in large bins. However, when a large number of small bins are used, no p -values below 10% are observed. This is not surprising since, as discussed before, the sensitivity to slowly varying asymmetries is reduced with larger numbers of bins: in the absence of extreme anomalies, the number of degrees of freedom increases more quickly than the χ^2 . An example normalised residual distribution is given in Fig. 3.17 and the p -values are summarised in Table 3.12. The downward trend in p -values seen in this table is

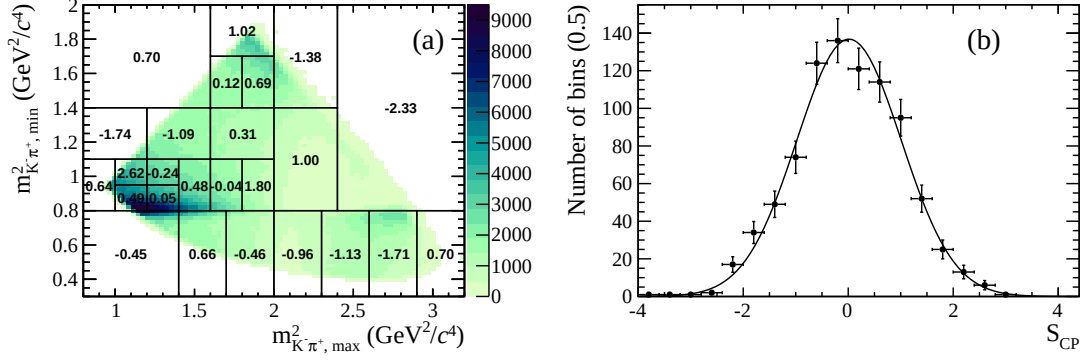


Figure 3.17: (a) Dalitz plot of $D^+ \rightarrow K^- \pi^+ \pi^+$, showing the 25-bin adaptive scheme with the $\mathcal{S}_{CP}$ values, with both magnet polarities combined. (b) Distribution of $\mathcal{S}_{CP}^i$ values from $D^+ \rightarrow K^- \pi^+ \pi^+$ from a test with 900 uniform bins. The mean of the fitted Gaussian distribution is 0.015 ± 0.034 and the width is 0.996 ± 0.023 .

	Magnet up	Magnet down	Combination
All	23/24 (49.2%)	50/24 (0.1%)	32/24 (12.2%)
Sample 1	25/24 (42.7%)	43/24 (1.0%)	32/24 (12.6%)
Sample 2	19/24 (75.7%)	-	-
Sample 3	20/24 (72.0%)	43/24 (1.0%)	33/24 (10.2%)

Table 3.11: χ^2/ndf and p -values for tests of various subsamples of the $D^+ \rightarrow K^- \pi^+ \pi^+$ control mode. The adaptive binning scheme with 25 bins shown in Fig. 3.16 is used.

an indication that any artificial asymmetry effects are slowly varying rather than sharply peaked. Since the lowest p -values are still above 1%, these slowly varying asymmetries must also be small.

	1300 bins	900 bins	400 bins	100 bins	25 bins
Uniform	73.8	17.7	72.6	54.6	1.7
Adaptive	81.7	57.4	65.8	30.0	12.2

Table 3.12: Results (p -values, in %) from tests with the $D^+ \rightarrow K^- \pi^+ \pi^+$ control channel using the uniform and adaptive binning schemes. The values correspond to tests performed on the whole dataset in the mass windows defined in Sect. 3.2. There is no evidence for any asymmetry. The high p -values seen for large numbers of bins also suggest that there are no sharply peaked asymmetries in the Dalitz plot that would be washed out in tests with fewer bins.

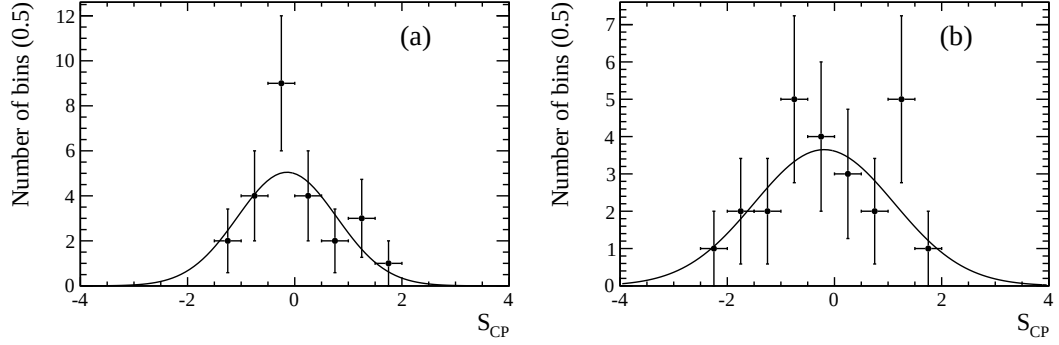


Figure 3.18: The normalised residual distributions for the $D_s^+ \rightarrow K^- K^+ \pi^+$ control mode in (a) the magnet up and (b) the magnet down data samples. The distributions are fitted with single Gaussian functions.

	Magnet up	Magnet down	Combination
All	16/24 (88.9%)	31/24 (15.5%)	26/24 (34.3%)
Sample 1	21/23 (59.0%)	24/23 (42.0%)	22/24 (58.6%)
Sample 2	21/24 (63.2%)	-	-
Sample 3	27/24 (30.7%)	26/24 (35.5%)	33/24 (10.1%)

Table 3.13: χ^2/ndf and p -values for tests of various subsamples of the $D_s^+ \rightarrow K^- K^+ \pi^+$ control mode. The adaptive binning scheme with 25 bins is used.

The $D_s^+ \rightarrow K^- K^+ \pi^+$ decay is tested with a version of the same binning scheme proposed for the signal decay, scaled up by the ratio of the available phase space in the control decay mode compared to the signal. The associated normalised residual distributions are shown in Fig. 3.18 and the distributions of the $\mathcal{S}_{CP}$ variable across the Dalitz plots in Fig. 3.19. The results are summarised in Table 3.13.

Due to the smaller sample size and to the high density of events along the ϕ and the $\bar{K}^*(892)^0$ bands, regular grid of bins are defined differently for this decay. The Dalitz plot is divided into three zones, as shown in Fig. 3.20. Each zone is further divided into 300, 100 or 30 bins of the same size. The results are given in Table 3.14. A χ^2/ndf of 16.0/24 (89%) is found for magnet up data and 31.0/24 (16%) for magnet down data. There is no evidence of any asymmetry in the D_s^+ control mode.

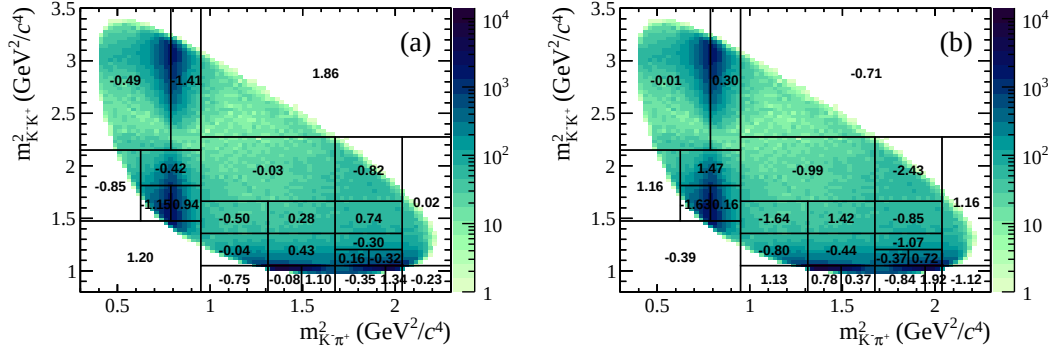


Figure 3.19: Plots showing the distribution of $\mathcal{S}_{CP}$ in the Dalitz plot for the $D_s^+ \rightarrow K^- K^+ \pi^+$ control mode in (a) the magnet up and (b) the magnet down data samples.

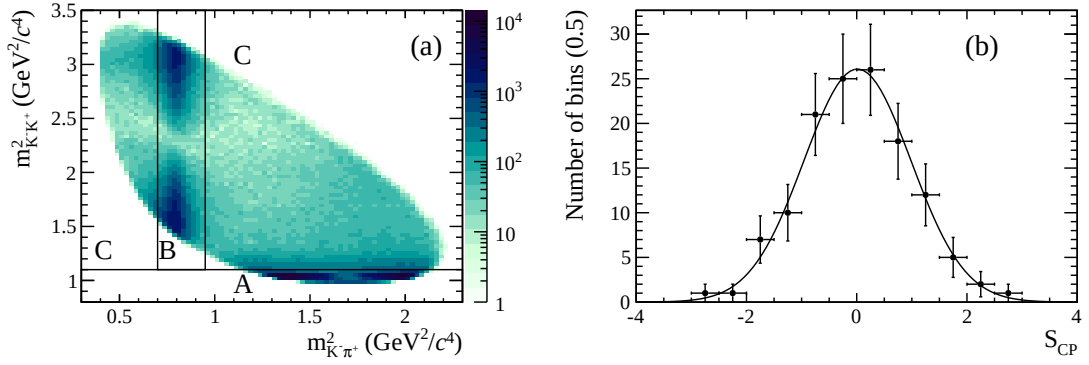


Figure 3.20: The Dalitz plot (a) of the $D_s^+ \rightarrow K^- K^+ \pi^+$ decay, showing the three regions referred to in the text. The distribution (b) of $\mathcal{S}_{CP}^i$ values from $D_s^+ \rightarrow K^- K^+ \pi^+$ with 129 adaptive bins. The fitted mean is -0.01 ± 0.08 and the width is 0.96 ± 0.06 .

Bins per zone	Zone A	Zone B	Zone C
300	20.1	25.3	14.5
100	41.7	84.6	89.5
30	66.0	62.5	24.6

Table 3.14: Results (p -values, in %) from studies of the $D_s^+ \rightarrow K^- K^+ \pi^+$ control channel using uniform binning schemes. The values correspond to tests performed separately on the zones A-C shown in Fig. 3.20, with Samples 1-3 and both magnet polarities combined.

Similar tests are carried out in the mass sidebands of the $D_{(s)}^+ \rightarrow K^- K^+ \pi^+$ signal shown in Fig. 3.2. In view of the smaller sample sizes, the data is not divided into trigger subsamples and only 25 candidates of each charge are required for a bin to be used in the calculation of the χ^2/ndf .

There are additional sources of background from D^{*+} decays that affects certain sidebands but cannot affect the signal region. The $D^{*+} \rightarrow D^0(K^- K^+) \pi^+$ background in the upper $K^- K^+ \pi^+$ sideband peaks in the upper-left corner of the Dalitz plot. This corner is removed as shown in Fig. 3.14. There is also some background in the lower $K^- \pi^+ \pi^+$ sideband from mis-reconstructed decays such as $D^{*+} \rightarrow D^0(K^- \pi^+ \pi^0) \pi^+$ or from $D^{*+} \rightarrow D^0(K^- K^+) \pi^+$ where the K^+ meson is mis-identified as a π^+ . To suppress these cases, a cut designed to suppress $D^{*+} \rightarrow D^0 \pi^+$ decays is applied that exploits the small amount of energy released in this process. Candidates that satisfy $m(K^- \pi^+ \pi^+) - m(K^- \pi^+) - m(\pi^+) < 10 \text{ MeV}/c^2$ are removed.

Table 3.15 gives the χ^2/ndf values for consistency with no asymmetries that vary across the Dalitz plot in magnet up and magnet down data and in their combination, for all subsamples of data tested with 25 bins. The table also includes the corresponding numbers for the control modes. There is no subsample with a χ^2 probability below 25% in data taken with both magnet polarities. However, the upper $K^- K^+ \pi^+$ sideband does have a low p -value (1%) in the magnet up data. This could be due to misreconstructed $D^+ \rightarrow K^- \pi^+ \pi^+$ decays. It is far from the signal region so cannot affect the results.

The particle identification requirements are tightened to verify that background from misreconstructed charm decays does not bias the charge asymmetry. The p -values are shown in Table 3.16. There is no clear pattern, so it is concluded that there is no evidence for significant asymmetries in the background.

The possibility of a bias in the Dalitz plot of D decays that originate from B decays due to some unknown second order effect is investigated by dividing the data set according

	All	Magnet up	Magnet down
$K^- \pi^+ \pi^+$: lower	15/23 (91.0%)	9/23 (99.7%)	29/23 (18.2%)
$K^- \pi^+ \pi^+$: D^+	34/24 (9.2%)	23/24 (49.2%)	50/24 (0.1%)
$K^- \pi^+ \pi^+$: upper	25/23 (35.3%)	20/23 (66.2%)	21/23 (56.1%)
$K^- K^+ \pi^+$: lower	34/24 (8.7%)	25/23 (32.7%)	33/24 (10.1%)
$K^- K^+ \pi^+$: middle	23/24 (50.8%)	27/24 (31.4%)	28/24 (27.7%)
$K^- K^+ \pi^+$: D_s^+	26/24 (34.4%)	16/24 (88.9%)	31/24 (15.5%)
$K^- K^+ \pi^+$: upper	26/22 (26.5%)	39/22 (1.3%)	21/22 (50.7%)

Table 3.15: Summary of χ^2/ndf and p -values in tests of the control decay channels and sidebands with 25 bins. The low p -value in the magnet down data sample for the $D^+ \rightarrow K^- \pi^+ \pi^+$ decay also appears in Table 3.11 and is discussed earlier in the text.

Final state	Nominal	$\Delta_{LL}(K - \pi) > 10$	$\Delta_{LL}(K - \pi) > 15$	$\Delta_{LL}(K - \pi) > 20$
$K^- \pi^+ \pi^+$: lower	14.6/23 (91%)	16.6/23 (83%)	25.7/22 (27%)	28.2/22 (17%)
$K^- \pi^+ \pi^+$: D^+	33.6/24 (9%)	41.9/24 (1%)	41.3/24 (2%)	30.4/24 (17%)
$K^- \pi^+ \pi^+$: upper	25.0/23 (35%)	18.7/23 (72%)	27.2/23 (25%)	29.1/23 (18%)
$K^- K^+ \pi^+$: lower	33.9/24 (9%)	22.1/23 (51%)	20.0/23 (64%)	10.0/17 (90%)
$K^- K^+ \pi^+$: middle	23.2/24 (51%)	26.8/24 (31%)	17.6/23 (78%)	37.8/21 (1%)
$K^- K^+ \pi^+$: D_s^+	26.2/24 (34%)	26.3/24 (34%)	38.5/24 (3%)	31.8/24 (13%)
$K^- K^+ \pi^+$: upper	25.7/22 (26%)	24.6/22 (32%)	19.0/20 (52%)	10.7/13 (64%)

Table 3.16: Variation of the χ^2/ndf and p -value with the kaon $\Delta_{LL}(K - \pi)$ requirement for the control decay modes and their sidebands. Magnet up and magnet down data are combined.

to the impact parameter χ^2 of the D candidate. The candidates with higher χ^2 are likely to contain a higher proportion of B decay products. The results are shown in Table 3.17.

There is no evidence for any effect.

The internal consistency of the tests performed suggests that any significant variation of the charge asymmetry across the $D^+ \rightarrow K^- K^+ \pi^+$ Dalitz plot is likely to be due to CP violation.

	$\chi^2_{IP} < 6$	$\chi^2_{IP} > 6$
$D^+ \rightarrow K^- \pi^+ \pi^+$	8.5	88.9
$D_s^+ \rightarrow K^- K^+ \pi^+$	52.0	30.6

Table 3.17: Results (p -values, in %) in the $D^+ \rightarrow K^- \pi^+ \pi^+$ and $D_s^+ \rightarrow K^- K^+ \pi^+$ samples divided according to the impact parameter χ^2 (χ^2_{IP}) with respect to the primary vertex. The adaptive binning scheme with 25 bins is used. While the p -values seen in the $D^+ \rightarrow K^- \pi^+ \pi^+$ decay are rather different depending on the χ^2_{IP} , this difference is assumed to be a purely statistical effect since the p -values are both far above the level that would indicate a significant asymmetry.

3.6 Results and conclusion

With confidence that there is no evidence for anomalous asymmetries in the control channels $D^+ \rightarrow K^- \pi^+ \pi^+$ and $D_s^+ \rightarrow K^- K^+ \pi^+$ and in the sidebands of the $K^- K^+ \pi^+$ mass spectrum, the signal sample was unblinded. It consists of 403,871 candidates selected within the $K^- K^+ \pi^+$ mass window from 1856.7 to 1882.1 MeV/ c^2 , of which 200,273 are D^+ and 203,598 are D^- . Therefore the normalisation factor α in the equation for S_{CP} is $N_{\text{tot}}(D^+)/N_{\text{tot}}(D^-) = 0.984 \pm 0.003$.

The adaptive binnings described in Sect. 3.4 and shown in Fig. 3.10, with 25 and 106 bins, and ‘uniform’ binnings with 200 and 530 bins of equal size, were applied to the data. For each binning choice with N_{bins} bins, the $\chi^2/\text{ndf} = \sum_i \frac{(\mathcal{S}_{CP}^i)^2}{(N_{\text{bins}}-1)}$ is calculated and the p -value is obtained.

The p -values are shown in Table 3.20. The variation of the $\mathcal{S}_{CP}^i$ values across the Dalitz plot for the four binning schemes are shown in Fig. 3.21. Fig. 3.22 contains the distributions of $\mathcal{S}_{CP}^i$ and the corresponding Gaussian fits. As for the control modes, the samples are split by running period and magnet polarity. The results for the Adaptive I scheme are shown in Table 3.18 and for the Adaptive II scheme in Table 3.19. In all the tests, the p -values obtained do not suggest that any CPV is present, and the $\mathcal{S}_{CP}^i$ distributions are well fitted by Gaussian functions, the mean and width of which are

	Magnet up	Magnet down	Combination
All	36/24 (6.0%)	27/24 (28.4%)	32/24 (12.6%)
Sample 1	18/24 (78.5%)	21/24 (62.5%)	15/24 (90.8%)
Sample 2	23/24 (49.2%)	-	-
Sample 3	25/24 (41.6%)	25/24 (40.2%)	35/24 (7.5%)

Table 3.18: χ^2/ndf values and p -values for tests of various subsamples of the $D^+ \rightarrow K^- K^+ \pi^+$ signal decay, using the Adaptive I binning scheme.

	Magnet up	Magnet down	Combination
All	147/105 (0.4%)	100/105 (63.3%)	123/105 (10.6%)
Sample 1	92/105 (82.2%)	107/105 (41.6%)	121/105 (14.1%)
Sample 2	94/105 (76.5%)	-	-
Sample 3	128/105 (6.3%)	111/105 (33.0%)	129/105 (5.7%)

Table 3.19: χ^2/ndf and probabilities for tests of various subsamples of the $D^+ \rightarrow K^- K^+ \pi^+$ signal decay, using the Adaptive II binning scheme.

consistent with 0 and 1 respectively.

There is no evidence for CP violation in the data sample of $D^+ \rightarrow K^- K^+ \pi^+$ collected at LHCb in 2010. The simulation studies suggest that if a CP violating difference of 5° in the phase of the ϕ between the D^+ and D^- decay exists, there is a reasonable chance that it could be observed in this dataset with a significance of three Gaussian standard deviations. Similarly, evidence for CPV could be obtained if an 11% magnitude difference between the $D^+ \rightarrow \kappa(800)K^+$ and $D^- \rightarrow \kappa(800)K^-$ exists. It can be concluded that such large effects are unlikely.

Binning	Fitted mean	Fitted width	χ^2/ndf	p -value (%)
Adaptive I	0.01 ± 0.23	1.13 ± 0.16	32.0/24	12.6
Adaptive II	-0.024 ± 0.010	1.078 ± 0.074	123.4/105	10.6
Uniform I	-0.043 ± 0.073	0.929 ± 0.051	191.3/198	82.1
Uniform II	-0.039 ± 0.045	1.011 ± 0.034	519.5/529	60.5

Table 3.20: Fitted means and widths, χ^2/ndf and p -values for consistency with no CPV for the $D^+ \rightarrow K^- K^+ \pi^+$ decay mode with four different binnings.

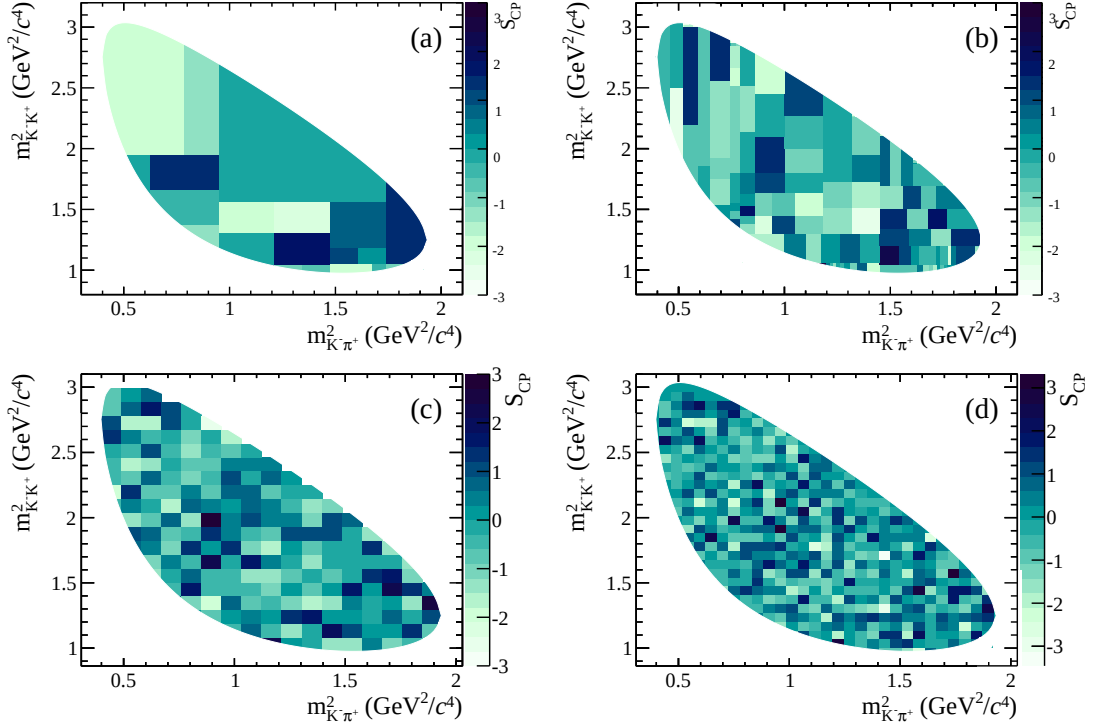


Figure 3.21: Distribution of $\mathcal{S}_{CP}^i$ in the Dalitz plot for “adaptive I” (top-left), “adaptive II” (top-right) and “uniform I” (bottom-left) and “uniform II” (bottom-right) binnings.

This is the first time a search for CPV with this technique used an adaptive binning with fewer than 100 bins. These small modifications were shown to greatly increase the sensitivity of the method and the analysis was repeated as part of the recent study of this decay mode at the BaBar experiment [39].

Unfortunately, to apply this technique to the larger datasets now available at LHCb would require a much more careful treatment of the detector asymmetries, since the statistical sensitivity to fake asymmetries is now enormously higher. With approximately $N = 370,000$ signal events and around $n = 20$ bins in the Dalitz plot needed to resolve any plausible effect, the precision achievable with the data taken in 2010 can be estimated by $\sqrt{n}/\sqrt{N} \equiv 0.7\%$. In 2011 the integrated luminosity recorded was 30 times higher than in 2010, and so the scale of the sensitivity should increase by a factor $\sqrt{30} \equiv 5.5$, to

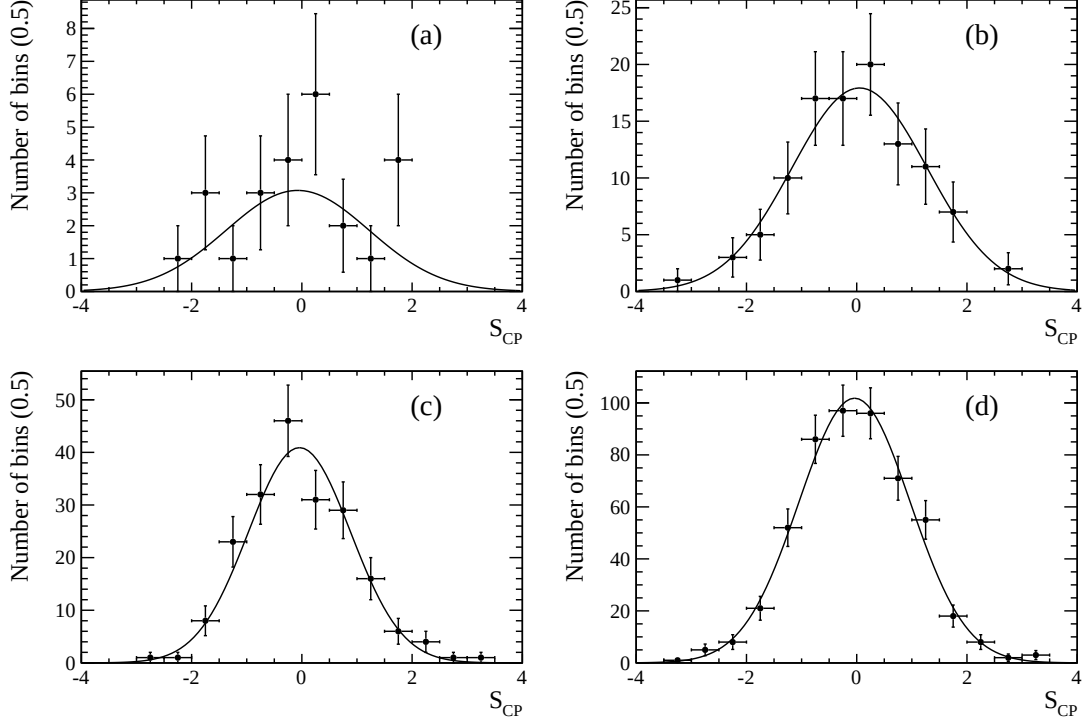


Figure 3.22: Normalised residual distributions of $\mathcal{S}_{CP}^i$ for (a) “adaptive I”, (b) “adaptive II”, (c) “uniform I” and (d) “uniform II” binnings. The means and widths of the distributions are given in Table 3.20.

0.13%. To enable control of the backgrounds and detector effects at below the 10^{-3} level, a different method is employed in the subsequent search for CPV which forms the subject of Chapter 4. This new method only applies to part of the Dalitz plot, but, despite the challenges presented by the larger dataset, the sensitivity achieved is very close to this naive estimate.

Chapter 4

Search for CP violation in $D^+ \rightarrow \phi\pi^+$ decays with data collected at LHCb in 2011

4.1 Introduction

The $D^+ \rightarrow \phi\pi^+$ decay is one of the most abundant singly Cabibbo suppressed decays of the D^+ meson that proceeds via a resonant state. The advantage of the ϕ resonance is that it decays symmetrically, to two oppositely charged kaons with approximately equal momenta. Therefore, unlike in resonances such as the $K^*(892)^0$, systematic uncertainties from the interaction of final state particles with the detector tend to cancel out. The most recent searches for CPV in this channel were conducted at the Belle and BaBar experiments [74, 39]. In the more precise measurement, at Belle, a CP asymmetry of $(+0.51 \pm 0.28 \pm 0.05)\%$ was observed in a sample of $(237.5 \pm 0.6) \times 10^3$ decays. This analysis is based on a data sample approximately four times larger.

In this chapter, the raw charge asymmetry, defined in Chapter 1 as

$$A_{\text{raw}} = \frac{N_{D^+} - N_{D^-}}{N_{D^+} + N_{D^-}} \quad (4.1)$$

for signal yields $N_{D^\pm}$ of $D^\pm$ decays, is calculated in a region of the $D^+ \rightarrow K^- K^+ \pi^+$ Dalitz plot around the ϕ resonance, defined by the $K^- K^+$ invariant mass ($m_{K^- K^+}$) range $1000 < m_{K^- K^+} < 1040 \text{ MeV}/c^2$. However, in order to distinguish the CP -violating asymmetry from asymmetries introduced by the pp initial state, a knowledge of the $D^\pm$ production asymmetry is required. In a closely related analysis, this was measured using the $D^+ \rightarrow K_s^0 \pi^+$ decay (in which no large CPV is expected) and found to be $(-0.96 \pm 0.26 \pm 0.18)\%$. The production asymmetry is expected to depend on the D^+ kinematics. The data were compatible with such variation, but the data sample was too small to demonstrate this conclusively [8]. This measurement is interesting in its own right to theorists in quantum chromodynamics [83]. Approximately, the CP asymmetry is the raw charge asymmetry in the $D^+ \rightarrow \phi \pi^+$ decay minus the production asymmetry. However, small systematic biases due to asymmetries in the detection of the pion [84] can be substantially reduced by instead taking the difference in raw asymmetries between the $K_s^0 \pi^+$ and $\phi \pi^+$ final states, so that effects due to the pions in the two final states tend to cancel.

There are two subtleties here, both concerning CPV in the $D^+ \rightarrow K_s^0 \pi^+$ decay. The CPV in the D^+ decay via interference of the Cabibbo-favoured and doubly-Cabibbo suppressed amplitudes to the final state is expected to be small, perhaps around $\mathcal{O}(10^{-4})$, and is ignored. The most recent search for CPV in this decay is also from the Belle collaboration [85], who find a CP asymmetry of $(0.018 \pm 0.094 \pm 0.067)\%$. The expected CPV in the neutral kaon system, $A_{CP}(K^0/\bar{K}^0)$, is calculated in the Belle article to be $(0.345 \pm 0.008)\%$. However, as explained in Sect 1.6, it is not expected to be the same at LHCb due to the different decay time dependence of the reconstruction efficiency. It is

calculated in Sect. 4.8 and subtracted, so the CP asymmetry in the charm system is

$$A_{CP}(D^+ \rightarrow \phi\pi^+) = A_{\text{raw}}(D^+ \rightarrow \phi\pi^+) - A_{\text{raw}}(D^+ \rightarrow K_s^0\pi^+) + A_{CP}(K^0/\bar{K}^0). \quad (4.2)$$

The large size of the available data sample at LHCb in 2011 should bring the statistical uncertainty on A_{CP} well below 0.2%. This means that systematic biases must be studied very carefully in control decay modes in which no CPV is expected, and cancelled by measuring the differences in asymmetries between different final states or by searching in one area of the Dalitz plot relative to another. While the principles employed are the same as in Chapter 3, the level of precision required is much higher as the dataset used is around an order of magnitude larger.

A search for CPV in the $D_s^+ \rightarrow K_s^0\pi^+$ decay using the $D_s^+ \rightarrow \phi\pi^+$ decay is performed concurrently. The relevant observable is

$$A_{CP}(D_s^+ \rightarrow K_s^0\pi^+) = A_{\text{raw}}(D_s^+ \rightarrow K_s^0\pi^+) + A_{CP}(K^0/\bar{K}^0) - A_{\text{raw}}(D_s^+ \rightarrow \phi\pi^+). \quad (4.3)$$

The $D_s^+ \rightarrow K_s^0\pi^+$ channel is also a singly Cabibbo suppressed decay mode, with the same possibility of contributions from penguin loops as the $D^+ \rightarrow \phi\pi^+$ decay, but the number of signal candidates is substantially lower than that in the other channels. This is partly due to the lower D_s^+ production cross section compared to the D^+ cross section [9] and partly because only K_s^0 mesons with very short decay times are used in this analysis. In Eq. 4.3, the effect of the CPV in the neutral kaon system has a sign opposite to that in Eq. 4.2 relative to the raw asymmetry in the $D^+ \rightarrow K_s^0\pi^+$ decay because the D_s^+ decays to a K^0 meson while the D^+ decays to a $\bar{K}^0$.

Within the Standard Model, the CPV in singly Cabibbo suppressed charm decays

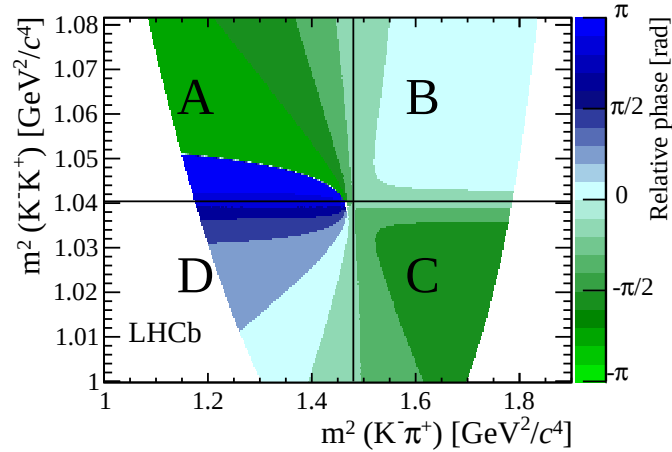


Figure 4.1: The variation of the overall phase of the D^+ decay amplitude in the ϕ mass region of the Dalitz plot, from a simulation study based on the CLEO-c amplitude model in which the phase is defined relative to the $K^*(892)^0$ resonance.

with contributing tree and penguin amplitudes is expected to be [86]

$$A_{CP} = \left| \text{Im} \left(\frac{V_{ub}V_{cb}^*}{V_{us}V_{cs}^*} \right) \right| R \sin \delta_S \quad (4.4)$$

where R is a number of order one that depends on the relevant Wilson coefficients [87, 43], δ_S is the strong phase difference between tree and penguin amplitudes, and V_{ij} are elements of the CKM matrix. The relevant Feynman diagrams are shown in Sect. 1.8. In the region of the ϕ resonance in the $D^+ \rightarrow K^- K^+ \pi^+$ Dalitz plot, several other amplitudes contribute to the overall matrix element and interfere with the ϕ resonance [39, 47]. If one of these has a component with a weak phase that differs from that of the ϕ meson, this should lead to a CP -violating asymmetry if there are also different strong phases, which is generally the case. However, a recent amplitude analysis of this decay mode from the CLEO-c collaboration [47] yields a matrix element with a relative strong phase that varies rapidly across the ϕ region, as shown in Fig. 4.1. This variation is expected in vector resonances [88, 89]. The isobar amplitude model favoured by CLEO-c (fit ‘B’ in

Ref. [47]) contains major contributions from the ϕ , $K^*(892)^0$, $K_0^*(1430)^0$ and κ resonances, and the phase is measured relative to that of the $K^*(892)^0$. The variation in this strong phase means that the CP asymmetry could change sign between different regions of the ϕ resonance, leading to the asymmetries cancelling when the different parts of the ϕ mass resonance are combined to calculate A_{CP} . This leads me to define a complementary observable which I have called $A_{CP|S}$. The area around the ϕ resonance in the Dalitz plot is split into four rectangular regions $A - D$ defined clockwise from the top-left as shown in Fig. 4.1. As in Chapter 3, the division is designed so that the change in phase within each region is minimised. A difference between the two diagonals, each made of two regions with similar phases, is calculated as follows:

$$A_{CP|S} = \frac{1}{2} (A_{\text{raw}}(A) + A_{\text{raw}}(C) - A_{\text{raw}}(B) - A_{\text{raw}}(D)). \quad (4.5)$$

In Sect. 4.6, this observable is found to be more sensitive to certain types of CPV than A_{CP} . Furthermore, it is not affected by the $D^\pm$ production asymmetry and will be shown to be very robust against detector asymmetries.

After an overview of the event selection, descriptions of the determination of the yield and the CPV in the neutral kaon system are presented. The results and systematic uncertainties follow, and a brief discussion concludes the chapter.

4.2 Dataset

The data sample used in this analysis corresponds to an integrated luminosity of 1.0 fb^{-1} of pp collisions at a centre of mass energy of 7 TeV, and was collected in 2011. The polarity of the LHCb magnetic field was changed several times during the run, and in the end the magnet-down sample comprised $589.9 \pm 0.95 \text{ pb}^{-1}$ and the magnet-up sample $435.4 \pm 0.8 \text{ pb}^{-1}$ (with statistical uncertainties only). There are software trigger algorithms

designed to collect both the $K_s^0\pi^+$ and $\phi\pi^+$ final states. Fully simulated signal samples are available for all of the signal and many of the background decay modes listed in Table 4.1. The simulated samples were specifically designed to model the 2011 dataset. All real and simulated events were processed with the same version of the reconstruction software.

Only ‘long’ tracks, which contain hits in both the VELO and the tracking stations, were used. The sample of $D^+ \rightarrow K_s^0\pi^+$ decays where the pion daughters of the K_s^0 originate outside the VELO was ignored, because it corresponds to only around 2% of the data available and it is subject to additional systematic effects, for example due to the asymmetric interaction of the K_s^0 with detector material. The low yield of such decays in the dataset is largely due to problems with the stripping and trigger algorithms which have since been rectified. In the reconstruction process, the K_s^0 meson mass was constrained to be the same as the nominal value [16] in order to improve the resolution of the D^+ mass distribution (although the effect of this constraint is actually very small).

4.3 Triggers

At the hardware stage, just over half of the signal decays in both final states are triggered by the hadron calorimeter trigger, ‘L0Hadron’. Roughly equal proportions of this sample are TIS, meaning that the trigger is activated by a particle that is not one of the daughters of the D^+ signal, and TOS, meaning that it is activated by a kaon or pion from the signal decay (see Chapter 2). As discussed in Chapter 3, there are several effects which could introduce charge asymmetry biases into the trigger. It is thought that the observed asymmetries are related to the alignment and homogeneity of the calorimeter (for L0) and tracking system (for HLT1), coupled to the magnetic field which causes an uneven distribution of positive and negative particles across these detectors. This is discussed further in Sect. 4.10.1. There could also be effects from the different material interaction

Decay	Branching ratio	Available number of simulated events
$D^+ \rightarrow K_s^0 \pi^+$	$(1.47 \pm 0.07)\%$	12500k
$D_s^+ \rightarrow K_s^0 \pi^+$	$(1.21 \pm 0.08) \times 10^{-3}$	300k
$D^+ \rightarrow \phi \pi^+$	$(2.65 \pm 0.09) \times 10^{-3}$	5000k
$D_s^+ \rightarrow \phi \pi^+$	$(4.5 \pm 0.4)\%$	2000k
$D_s^+ \rightarrow K_s^0 K^+$	$(1.48 \pm 0.08)\%$	1000k
$D^+ \rightarrow \bar{K}^0 e^+ \nu_e$	$(8.83 \pm 0.22)\%$	0
$D^+ \rightarrow \bar{K}^0 \mu^+ \nu_\mu$	$(9.2 \pm 0.6)\%$	0
$D_s^+ \rightarrow \phi K^+$	$(9.0 \pm 2.1) \times 10^{-5}$	0
$D^+ \rightarrow K^- \pi^+ \pi^+$	$(9.13 \pm 0.19)\%$	10000k
$D_s^+ \rightarrow K^0 \pi^+ \pi^0$	$(1.00 \pm 0.18)\%$	1000k
$D_s^+ \rightarrow K^- K^+ \pi^+ \pi^0$	$(5.6 \pm 0.5)\%$	0
$D_s^+ \rightarrow \phi e^+ \nu_e$	$(2.49 \pm 0.14)\%$	0
$\Lambda_c^+ \rightarrow \Lambda_0 \pi^+$	$(1.07 \pm 0.28)\%$	1000k
$\Lambda_c^+ \rightarrow K_s^0 p$	$(2.3 \pm 0.6)\%$	1000k
$D^+ \rightarrow K_L^0 \pi^+$	$(1.46 \pm 0.05)\%$	-

Table 4.1: Branching ratios of decays to relevant signal and background final states. The cross section for D_s^+ production is slightly less than half that for D^+ production, and the lifetime is shorter so the reconstruction and selection efficiencies will tend to be slightly lower [16].

cross sections of positive and negative particles with detector material.

The biases introduced into the trigger are studied with the Cabibbo-favoured $D^+ \rightarrow K^- \pi^+ \pi^+$ decay, which is a convenient control channel with a very high yield of pure signal decays. The studies are performed twice: once in order to determine the data sample to use, and once (described in Sect. 4.10) to determine the systematic uncertainty in the analysis.

In addition to the stripping selection, which is the same as that in $D^+ \rightarrow \phi \pi^+$ except for particle identification criteria and is described in Sect. 4.4, particles from the $D^+ \rightarrow K^- \pi^+ \pi^+$ decay are required to have momentum $p > 12 \text{ GeV}/c$, the D^+ impact parameter χ^2 must be less than 9, and the kaon must have $\Delta_{LL}(K - \pi) > 12$. These criteria suppress momentum-dependent material interaction asymmetries, D from B decays, and $D_s^+ \rightarrow \pi^- \pi^+ \pi^+$ backgrounds respectively. All data collected with the magnet polarity

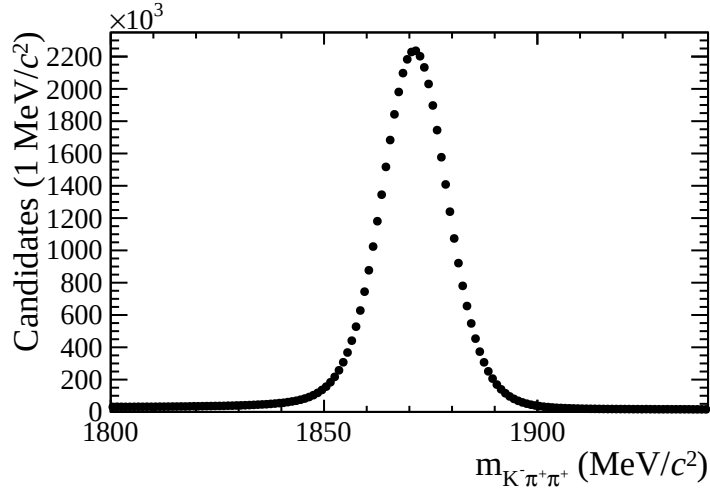


Figure 4.2: $D^+ \rightarrow K^- \pi^+ \pi^+$ mass distribution for selected candidates.

up and an approximately equally sized sample of data taken with the magnet down are used. The candidates that fall in a mass window from $1850 < m < 1890 \text{ MeV}/c^2$ are 1.5% background, so yields and asymmetries were determined by counting candidates in this window. The asymmetry in the background differs from that in the signal by at most an estimated 2%, so the effect of the background on the measured asymmetry is at most $2\% \times 1.5\% \approx 0.03\%$ and can be ignored for this preliminary study, although in Sect. 4.10 it is accounted for. The mass distribution is shown in Figure 4.2.

A sample of decays that is approximately unbiased by the trigger can be created by requiring at least one track in a charge-symmetric pair chosen from the final state particles to activate both the hadron hardware trigger and the one-track first level software trigger. Signal decays in events that are not triggered in this way can be tested against this minimally biased sample to determine whether or not the corresponding data samples are also unbiased. The hardware trigger is considered to be more important than the software trigger for this study because the asymmetries introduced by the software trigger will be the same as those studied in the determination of the pion tracking efficiency asymmetry, which are on average very small [84].

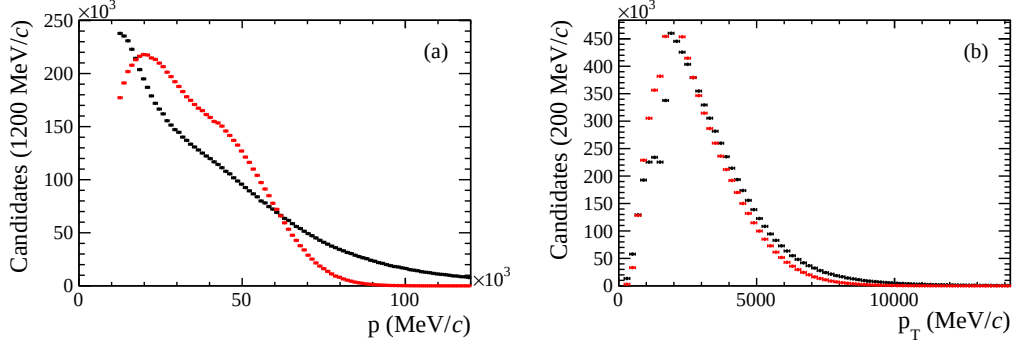


Figure 4.3: Distributions of (a) p and (b) p_T of kaons in red and the pion selected with the kaon to form a charge-symmetric pair of particles in black. The lower p_T pion in each decay is selected with 70% probability.

In the $D^+ \rightarrow K^- \pi^+ \pi^+$ decay, the charge-symmetric pair of particles must be created from the kaon and one of the pions. In order to create a sample of pions with similar kinematics to the kaons, for 70% of candidates the pion with lower p_T is selected, and for the remaining 30% the pion with higher p_T is used. This brings the pion p_T distribution into close agreement with that of the kaon, as shown in Fig. 4.3(b). A more sophisticated reweighting is not necessary at the level of precision this study requires. The momentum distributions, in Fig 4.3(a), remain rather different, but this is less important since the calorimeter trigger threshold is based on transverse energy. When the pions are instead chosen with equal probability, the measured raw asymmetry changes by $(0.043 \pm 0.051)\%$ compared to the case where the lower p_T pion is more likely to be selected, so it is concluded that the method is robust against kinematic differences.

A trigger-unbiased sample of $D^+ \rightarrow K^- \pi^+ \pi^+$ decays is thus isolated and its charge asymmetry is shown in the top row of Table 4.2. Differently triggered samples are then tested against it. Their asymmetries are detailed in Table 4.2. Only datasets from well-defined logical pathways through the trigger which can be easily understood are considered. The samples are often slightly statistically correlated, but the effect of this is not important. Only differences in the asymmetries between rows in the table are relevant,

Sample	Raw asymmetry (%)
(L0Hadron+HLT1) TOS on +/- pair (30/70)	-1.750 ± 0.037
(L0Hadron+HLT1) TOS on +/- pair (50/50)	-1.707 ± 0.035
(L0Hadron+HLT1) TOS on other pion	-1.240 ± 0.042
L0GlobalTIS, HLT1TOS	-1.854 ± 0.022
L0HadronTIS, HLT1TOS	-1.807 ± 0.029
L0MuonTIS, HLT1TOS	-1.866 ± 0.038
L0PhotonTIS, HLT1TOS	-1.877 ± 0.067
L0ElectronTIS, HLT1TOS	-1.918 ± 0.045

Table 4.2: Raw asymmetries in differently triggered samples of $D^+ \rightarrow K^- \pi^+ \pi^+$ decays. The first row shows results from the sample in which the low- p_T pion is chosen with 70% probability, while in the second row the pion are chosen from the two possibilities with equal probability. HLT1 stands for the first-level software trigger. The abbreviation ‘TOS’ indicates that the trigger is activated by a particle that forms part of the signal decay, while ‘TIS’ indicates that it is activated by another particle in the event. A label ‘Global TIS’ indicates a logical OR of the data samples in the last four rows of the table.

not the absolute values.

The data samples which are triggered at the hardware stage by a particle which does not form part of the signal decay could be biased by “associated production”, in which the D^+ meson is produced in association with a pion or a $\bar{D}$ hadron which activates the trigger. The data is classified as ‘TIS’ in the software with respect to the signal decay (see Sect. 2.13), but because the trigger may be activated by a particle with a charge that is correlated to the signal, the samples may not actually be ‘independent of the signal’. However, the results in Table 4.2 suggest that the proportion of events for which this is true is small, or the bias inherent in these events is small, or both. Experimentally, we find the raw asymmetry in the data that is TIS with respect to hadron, electron, photon or muon triggers to be different to that in the unbiased sample by $0.104 \pm 0.043\%$. While this is not a negligible effect, any biases should have the same sign for the $D_{(s)}^+ \rightarrow K_s^0 \pi^+$ and $D_{(s)}^+ \rightarrow \phi \pi^+$ final states, so should cancel out to a very good approximation when the difference is calculated. Therefore the TIS data is safe to use in the analysis. A systematic

uncertainty for possible failures in this cancellation is assigned in Sect. 4.10.

The set of candidates triggered only by the pion at the hardware level is found to have an anomalous asymmetry in the $D^+ \rightarrow K^- \pi^+ \pi^+$ control mode. The raw asymmetry in the third row of Table 4.2 is very different from that in the other rows. Therefore this data is considered to be biased and is not used. The set of candidates discarded corresponds to around 10% of the total number of $D^+ \rightarrow \phi \pi^+$ signal decays, and a similar proportion of the $D^+ \rightarrow K_s^0 \pi^+$ control sample.

For the sake of ease of interpretation, it is required that the same track activates both hardware and first-level software trigger stages in the case that a daughter of the signal D^+ activates the hadronic hardware trigger. The quantity of data lost makes less than an 0.01% difference to the overall statistical uncertainty. This requirement is not applied to data that was TIS with respect to the hardware trigger.

Thus we can define a charge-unbiased trigger sequence. Signal candidates are used if a K_s^0 or ϕ daughter track activates both hardware and first-level software trigger stages (and the same track must fire both triggers, although it is not excluded that both tracks fire either trigger). Alternatively or in addition, signal candidates can be TIS with respect to the hardware trigger provided that one of the tracks from the D^+ decay then activates the first-level software trigger. The second-level software trigger is required to find the signal decay in all cases. This requirement substantially improves the purity of the data samples. Furthermore, many second-level triggers select other decays in specific mass intervals, and this could distort the invariant mass distribution of the triggered signal, making it more difficult to determine the signal yields. It is assumed that any effect in a D^+ decay will be very similar in a D_s^+ decay.

4.4 Signal selection criteria

The stripping algorithms for the two final states used in the analysis are slightly different. The selection criteria are detailed in Table 4.3 and the more important requirements are discussed here. The selection proceeds on the same principle as that in Chapter 3.

The $\phi\pi^+$ final state is reconstructed by combining two oppositely charged tracks that are identified by the RICH detectors as kaons with a track identified as a pion. The scalar sum of the transverse momenta p_T of the daughter particles must exceed $2.8 \text{ GeV}/c$.

To reconstruct the $K_s^0\pi^+$ final state, pairs of oppositely charged tracks with a pion mass hypothesis are combined to form K_s^0 candidates. Accepted candidates are then combined with a third charged track, the bachelor pion, to form a $D_{(s)}^+$ candidate, with the mass of the K_s^0 meson constrained to its world average value in the kinematic fit. Only those K_s^0 candidates with $p_T > 700 \text{ MeV}/c$ and unconstrained invariant mass within $35 \text{ MeV}/c^2$ of the world average K_s^0 meson mass [16] are retained.

Both the K_s^0 and $D_{(s)}^+$ candidates are required to have a vertex fit with an acceptable χ^2/ndf . All daughter particles must have momentum $p > 2 \text{ GeV}/c$ and $p_T > 250 \text{ MeV}/c$. Impact parameter (IP) requirements are used to ensure that none of the daughters of the $D_{(s)}^+$ originate at any primary vertex (PV) in the event, and the K_s^0 meson decay vertex must be at least 10 mm downstream of the PV with which it is associated. The bachelor pion in both final states must have $p > 5 \text{ GeV}/c$ and $p_T > 500 \text{ MeV}/c$ and must not come from any PV. The number of PVs in each event in this data sample follows (approximately) a Poisson distribution with a mean of around two. This is a sufficiently small number that the probability of associating a fully reconstructed signal candidate to the wrong PV is negligible. A PV is formed by a minimum of five tracks, and a typical 25-track vertex has a resolution of $13 \mu\text{m}$ in the transverse plane and $71 \mu\text{m}$ in the z -direction [57]. For comparison, the interaction region has a transverse size of around $100 \mu\text{m}$ and a longitudinal size of around 10 cm .

Stripping criterion	$\phi\pi^+$ value	$K_s^0 \pi^+$ value
D_s^+, D^+ mass	$1800 < M < 2040 \text{ MeV}/c^2$	$1770 < M < 2070 \text{ MeV}/c^2$
D_s^+, D^+ vertex separation χ^2	> 100	> 30
D_s^+, D^+ IP χ^2 w.r.t. PV	< 15	< 15
D_s^+, D^+ p_T	> 1000	> 1000
D_s^+, D^+ DIRA	> 0.98	-
D_s^+, D^+ vertex χ^2/ndf	< 10	< 10
K_s^0 vertex χ^2	-	< 10
K_s^0 DoCA χ^2	-	< 25
K_s^0 IP χ^2	-	> 8
K_s^0 mass	-	$462.6 < M < 532.6 \text{ MeV}/c^2$
$K_s^0 p_T$	-	> 700
$K_s^0 Z_{diff}$	-	> 10
$\Sigma_{p_T}(\text{daughters})$	$> 2800 \text{ MeV}/c$	$> 1000 \text{ MeV}/c$
DoCA χ^2	-	< 11
DoCA	< 0.5	-
all dau IP χ^2	> 4	> 15
all dau p_T	$> 250 \text{ MeV}/c$	$> 250 \text{ MeV}/c$
all dau p	$> 2000 \text{ MeV}/c$	$> 2000 \text{ MeV}/c$
bachelor $\pi^+ p_T$	-	$> 500 \text{ MeV}/c$
bachelor $\pi^+ p$	-	$> 5000 \text{ MeV}/c$
K_s^0 dau IP χ^2	-	> 50
K_s^0 dau $\Delta_{LL}(K - \pi)$	-	< 10
IP χ^2 of two out of three dau.	> 10	-
$K \Delta_{LL}(K - \pi)$	> 7	-
bachelor $\pi^+ \Delta_{LL}(K - \pi)$	< 3	< 0
K, π Track χ^2/ndf	< 5.0	< 4.0
bachelor π^+ Track χ^2/ndf	-	< 3.0
Num. tracks in event	< 500	-
Clone Distance	5000	5000

Table 4.3: D_s^+, D^+ Stripping selections. In the table, IP represents impact parameter, ‘dau’ represents a stable daughter particle (a charged kaon or pion), the ‘bachelor’ is the pion from the D^+ , and ‘ndf’ stands for the number of degrees of freedom. The $\Delta_{LL}(K - \pi)$ is the likelihood variable for a kaon mass hypothesis from the particle identification system. The clone distance requirement is a standard veto applied by default to all reconstructed tracks, based on the Kullback-Liebler clone distance [90]. The Z_{diff} criterion in the K_s^0 stripping algorithm is defined as the distance in the z -direction travelled by the K_s^0 before it decays. The distance of closest approach (DoCA) requirement in the $\phi\pi^+$ case is a requirement on the maximum of the three possible distances of closest approach of the two kaons and the pion; for the $D^+ \rightarrow K_s^0 \pi^+$ the requirement is on the distance of closest approach of the K_s^0 meson and the pion. The ‘DIRA’ is the cosine of the angle between the momentum vector of a candidate and the displacement vector from the primary vertex to its decay vertex, as defined in Chapter 3.

Criterion	$\phi\pi^+$ value	$K_s^0\pi^+$ value
ϕ mass window	$1.0 < m < 1.04 \text{ GeV}/c^2$	-
D^+ IP χ^2	< 9	< 9
D^+ DOCA	*	< 0.5
D^+ DIRA	*	> 0.98
Bach. π^+ p	> 5000	*
Bach. π^+ p_T	> 500	*
Bach. π^+ $IP\chi^2$	> 15	*
Bach. π^+ track χ^2	< 3	*
Kaon track χ^2	< 4	-
Bach. π^+ $\Delta_{LL}(e - \pi)$	< 0	< 0
Bach. π^+ isMuon	FALSE	FALSE
Kaon $\Delta_{LL}(e - \pi)$	< 0	-
Kaon isMuon	FALSE	-
Kaon $\Delta_{LL}(K - \pi)$	> 12	-
Pion $\Delta_{LL}(K - \pi)$	< 0	*

Table 4.4: Offline selection criteria applied in addition to the stripping selections. Where the value in the table is *, the same requirement is applied in the stripping algorithm in the relevant decay mode. The isMuon criterion is satisfied if, given a track reconstructed in the tracking system, a number of hits in the muon stations are also found [91].

In addition to the stripping selection, some important additional requirements, listed in Table 4.4, are imposed before the data sample is analysed, to reduce backgrounds from random track combinations and partially reconstructed charm and B decays. The IP χ^2 of the $D_{(s)}^+$ with respect to the primary vertex is required to be lower than 9 in both final states to suppress D^+ from B decays. Also, the K^-K^+ invariant mass is restricted to the ϕ region by requiring $1.0 < m_{K^-K^+} < 1.04 \text{ GeV}/c^2$. Backgrounds from the semileptonic charm decays $D^+ \rightarrow K_s^0 l^+ \nu$ and $D^+ \rightarrow \phi l^+ \nu$ ($l = e, \mu$) are suppressed by requiring the bachelor pion to have an insufficient number of hits in the muon stations to be classified as a muon, and by requiring that $\Delta_{LL}(e - \pi) < 0$ so the particle is more likely to be a pion than an electron. These requirements are also applied to the daughters of the ϕ meson with no loss in statistical precision since the statistical uncertainty is limited by the $D^+ \rightarrow K_s^0 \pi^+$ decay mode. To avoid reflections from $D^+ \rightarrow K^- \pi^+ \pi^+$ under the

D_s^+ peak, the $\Delta_{LL}(K - \pi) > 7$ requirement on the ϕ meson daughters is tightened to $\Delta_{LL}(K - \pi) > 12$. Proton likelihood requirements are investigated for both decay modes but are found to have little effect.

Further requirements are applied to make the selections of $D_{(s)}^+ \rightarrow \phi\pi^+$ and $D_{(s)}^+ \rightarrow K_s^0\pi^+$ more similar than their respective stripping selections. This is particularly important for the bachelor pion, since the analysis relies on asymmetries due to this pion cancelling between final states. The requirements on the pion p_T , p , IP χ^2 and track χ^2/ndf are all tightened for the $\phi\pi^+$ final state to be the same as the requirements on the $D_{(s)}^+ \rightarrow K_s^0\pi^+$ decays, and the requirements on the track χ^2 of the K_s^0 daughters are also applied to the ϕ kaons. The efficiency of these criteria on selected candidates with invariant masses in the range $1850 < m < 1890 \text{ MeV}/c^2$ (i.e. the approximate efficiency on D^+ signal) relative to the stripping selection is 85.3%. The DIRA and DoCA requirements on the D^+ in the $\phi\pi^+$ selection defined in the caption of Table 4.3 are also applied to the $K_s^0\pi^+$ final state. These criteria have an efficiency of 97.6% relative to the stripping selection.

Fiducial requirements [2] are applied to exclude regions with a large tracking efficiency asymmetry. These are explained in Sect. 4.7. In addition, to ensure that only areas of kinematic space where both final states can be detected are used, the D^+ candidate is required to have $1.5 < p_T < 20.0 \text{ GeV}/c$ and pseudorapidity η in the range $2.2 < \eta < 4.4$. These criteria remove around 2% of $\phi\pi^+$ candidates, mostly at high p_T and low η , and 6% of $K_s^0\pi^+$ candidates, mostly at low p_T and high η . Table 4.5 gives the number of $D^+ \rightarrow \phi\pi^+$ candidates remaining after the various selection criteria, to indicate the efficiency of the more important selection requirements.

After all requirements are applied, there are three major remaining differences between the selections for the two final states. The sum of the p_T of the three daughters must be greater than $2800 \text{ MeV}/c$ in the $\phi\pi^+$ case while in the $K_s^0\pi^+$ case the p_T of the K_s^0 must

Raw stripping output	6,229,688
Add Hlt2 TOS requirement	3,595,106
Add kaon $\Delta_{LL}(K - \pi) > 9$ and D^+ IP $\chi^2 < 9$	3,052,612
Add μ^-, e^- ID	2,576,949
Add pion $\Delta_{LL}(K - \pi) < 0$	2,437,032
Add track χ^2 cuts	2,422,290
Add kaon $\Delta_{LL}(K - \pi) > 12$	2,094,378
Add π^+ IP χ^2, p, p_T cuts	2,040,618
Add full trigger requirements	1,647,771

Table 4.5: Table of $D^+ \rightarrow \phi\pi^+$ candidates in a mass window of $1845 < m < 1895 \text{ MeV}/c^2$ remaining after successive offline selection requirements

exceed $700 \text{ MeV}/c$. Since the measurement will be binned in the p_T of the $D_{(s)}^+$ meson (see Section 4.7) the differences in p_T within bins will be small, and therefore this is not a problem. There are also some selection criteria applied to the K_s^0 meson or its daughters that are not applied to the ϕ . For example the IP χ^2 of the daughters of the K_s^0 meson is subject to a much tighter requirement than that on the daughters of the ϕ . Since these requirements apply to a charge-symmetric pair of particles, this cannot easily affect charge asymmetries. Lastly, the vertex separation χ^2 of the D^+ from its PV must be > 100 in the $\phi\pi^+$ case but only > 30 in the $K_s^0\pi^+$ case. Tightening it in the $K_s^0\pi^+$ case is undesirable since the number of selected $D_{(s)}^+ \rightarrow K_s^0\pi^+$ decays limits the statistical precision of the final results. The effect of this last discrepancy is considered as a systematic uncertainty in Sect. 4.10.

After the selection, the remaining background falls into three categories. In both $K_s^0\pi^+$ and $\phi\pi^+$ final states, there is a combinatoric component and an irreducible background from $D_s^+ \rightarrow \phi\pi^+\pi^0$ or $D_s^+ \rightarrow K_s^0\pi^+\pi^0$ decays that peaks to the left of the D^+ peak, at the low mass end of the spectra. This is greatly reduced by requiring that the net momentum vector of the final state point to the PV, but cannot be eliminated altogether as the π^0 is sometimes produced at rest, or almost at rest, in the centre-of-mass frame

of the decay. In the $D_{(s)}^+ \rightarrow K_s^0 \pi^+$ decays there is additionally a cross-feed background from $D_s^+ \rightarrow K_s^0 K^+$ where the kaon is misidentified as a pion. The branching ratio for the $D_s^+ \rightarrow \phi K^+$ decay is much smaller than that for $D_s^+ \rightarrow K_s^0 K^+$ so this does not affect the $D_{(s)}^+ \rightarrow \phi \pi^+$ decay modes. Where simulated data samples of potential background contaminants are available, they are reconstructed as if they were signal decays and the mass distributions are shown in Fig. 4.4. The distributions are fitted with Crystal Ball functions $f(m)$, defined by [92]

$$f(m) \propto \begin{cases} \exp\left(-\frac{(m-\mu)^2}{2\sigma^2}\right) & \frac{x-\mu}{\sigma} > -\alpha \\ \left(\frac{n}{|\alpha|} - |\alpha| - \frac{(m-\mu)}{\sigma}\right)^{-n} & \frac{x-\mu}{\sigma} < -\alpha \end{cases}$$

where μ , α , σ and n are free parameters, and the normalisation factor in the two cases is chosen to ensure continuity and unitarity. In the equation the tail is assumed to be on the left hand side of the function at lower invariant mass, as in Fig. 4.4(a), but a negative value of α and a reversal of the inequality sign would give a tail on the right hand side at higher invariant mass, as in Fig. 4.4(c).

The K_s^0 and ϕ meson mass distributions for candidates selected using mass windows around the D^+ and D_s^+ masses are shown in Fig. 4.5. The K_s^0 signal appears purer than the ϕ due to the S-wave under the ϕ mass. The differences in the Dalitz plot structure between D_s^+ and D^+ mesons are not really apparent from this plot, because only the $K^- K^+$ projection is shown. The mass windows applied to the K_s^0 and ϕ mesons to select only signal candidates are given in Tables 4.3 and 4.4 respectively. It is clear that the $D^+ \rightarrow K_s^0 \pi^+$ decay has no large background contamination from $D^+ \rightarrow \pi^- \pi^+ \pi^+$ decays, which is as expected due to the requirements on the z -displacement of the decay vertex of the K_s^0 meson from that of the $D_{(s)}^+$ candidate and on the impact parameter of the K_s^0 meson daughters with respect to the PV. As a cross check, in Section 4.10.7 the ϕ mass window is widened to see if there is significant variation in the measured raw asymmetry

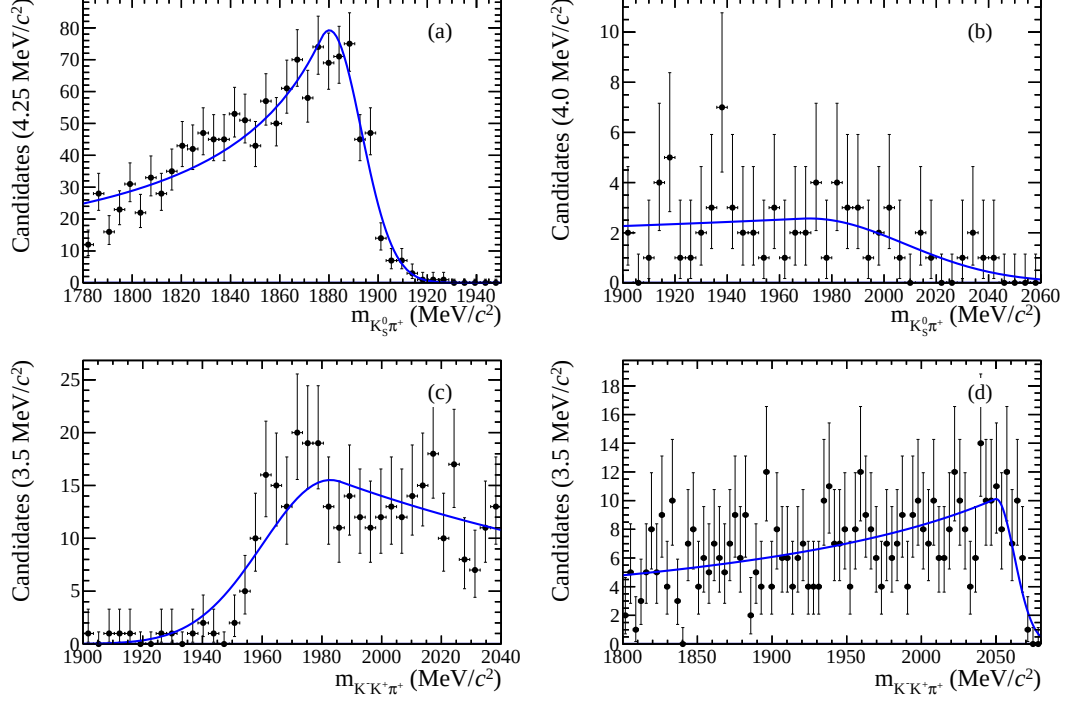


Figure 4.4: Cross feeds in the $K_s^0 \pi^+$ final state, from (a) $D_s^+ \rightarrow K_s^0 K^+$ and (b) $\Lambda_c^+ \rightarrow \Lambda^0(p^+ \pi^+) \pi^+$ decays, and in the $\phi \pi^+$ final state, from (c) $D^+ \rightarrow K^- \pi^+ \pi^+$ and (d) $\Lambda_c^+ \rightarrow p^+ K^- \pi^+ \pi^+$ decays. The decay modes are reconstructed and selected from simulated samples as if they were $K_s^0 \pi^+$ or $\phi \pi^+$ particle combinations respectively, then fitted with Crystal Ball functions. The $D_s^+ \rightarrow K_s^0 K^+$ decay is handled in the invariant mass fit to the $K_s^0 \pi^+$ candidates, while the $D^+ \rightarrow K^- \pi^+ \pi^+$ decay is suppressed by particle identification requirements. It is clear that the Λ_c^+ decays give broad backgrounds that would be absorbed by the combinatoric background component. In these plots hardware and first-level software trigger requirements are not applied, to increase the sample sizes.

with $K^- K^+$ invariant mass.

The proportion of events with more than one D^+ candidate is negligible, at 0.02% in the $\phi \pi^+$ final state and 0.006% in the $K_s^0 \pi^+$ final state. These events are retained, but as many of them are likely to be background they are considered as a source of systematic uncertainty in Sect. 4.10.5.

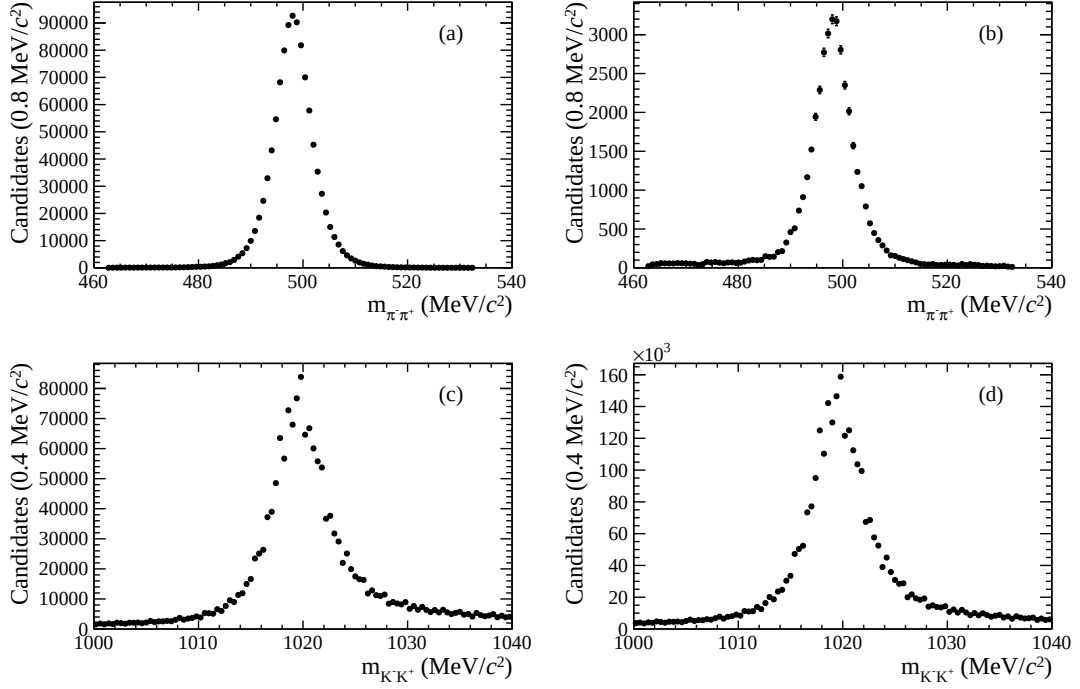


Figure 4.5: Invariant mass distribution of the K_s^0 mesons, for (a) selected candidates in the D^+ region of the $K_s^0 \pi^+$ mass spectrum, and (b) selected candidates in the D_s^+ region (within 20 MeV/c^2 of the D_s^+ mass), and ϕ meson mass distribution for (c) selected candidates in the D^+ region and (d) in the D_s^+ region of the $\phi\pi^+$ invariant mass spectrum.

4.5 Yield determination and background modelling

The shapes of the $D_{(s)}^+ \rightarrow K_s^0 \pi^+$ mass peaks are described by single ‘Cruiff’ functions $f(m)$ [93],

$$f(m) \propto \exp \left(\frac{-(m - \mu)^2}{2\sigma + (m - \mu)^2 \alpha_{L,R}} \right) \quad (4.6)$$

with the mean D^+ meson masses defined by the free parameter μ , the width by σ , and the tails by α_L and α_R . The parameter α_L is used for $m < \mu$ and α_R for $m > \mu$. In the $\phi\pi^+$ final state, the larger sample size means that the Cruiff functions are not sufficient to describe the data by themselves, and so Crystal Ball functions, defined in Sect. 4.4, are added to the Cruiff functions to account for the more prominent tails of the mass

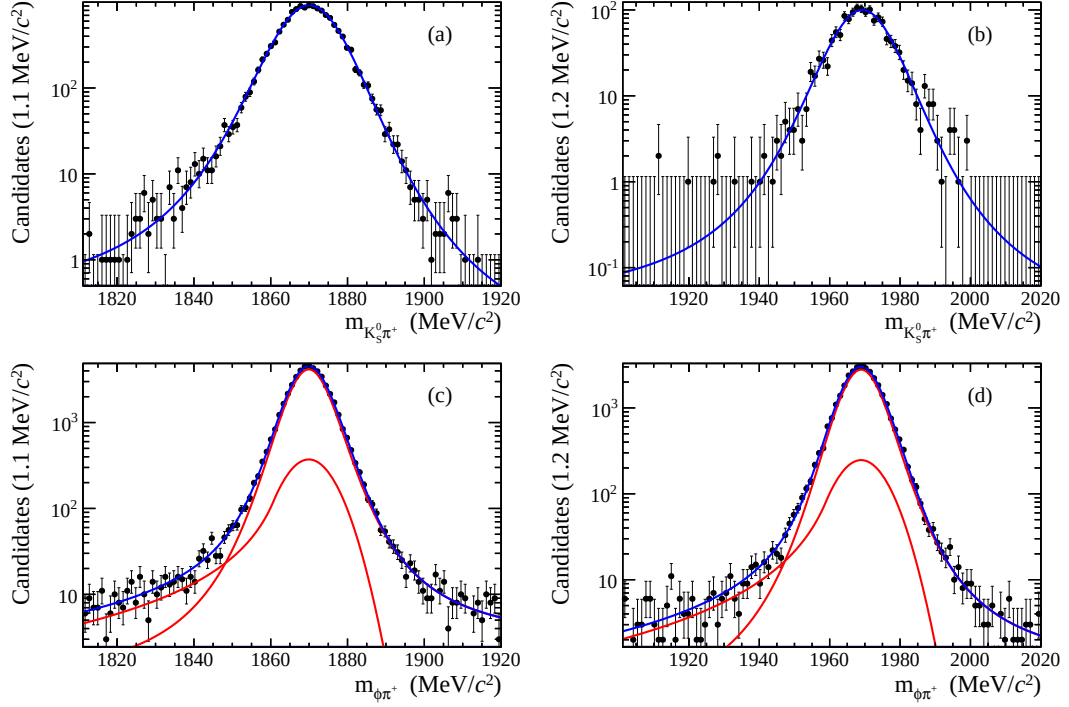


Figure 4.6: Fits to the four decay modes in simulated pp collision events, (a) $D^+ \rightarrow K_s^0 \pi^+$, (b) $D_s^+ \rightarrow K_s^0 \pi^+$, (c) $D^+ \rightarrow \phi \pi^+$ and (d) $D_s^+ \rightarrow \phi \pi^+$. The simulated events are reconstructed in the same way as the real data. To increase the statistics in these plots the full trigger and offline selection was not applied: they are made from the output of the stripping algorithms.

distribution. The signal lineshapes are tested on simulated data and found to describe them well, as shown in Fig. 4.6.

The $D^+ \rightarrow K^- \pi^+ \pi^+$ mass distribution, which has a still larger number of candidates, is studied to check that the difference in the parameterisation required between the final states is not due to background contaminations. Since a large radiative tail is apparent in the distribution in Fig. 4.7, it is also expected in the $D_{(s)}^+ \rightarrow \phi \pi^+$ signal decays. As in Chapter 3, the possibility of contamination from $D^+ \rightarrow K^- \pi^+ \pi^+$ decays in the $K^- K^+ \pi^+$ invariant mass distribution is studied by reconstructing the $D_s^+ \rightarrow K^- K^+ \pi^+$ candidates as $D^+ \rightarrow K^- \pi^+ \pi^+$ decays and investigating whether or not there is a peak at the D^+ meson mass. Fig. 4.8 shows that there is no significant peak at the D^+ mass and hence no

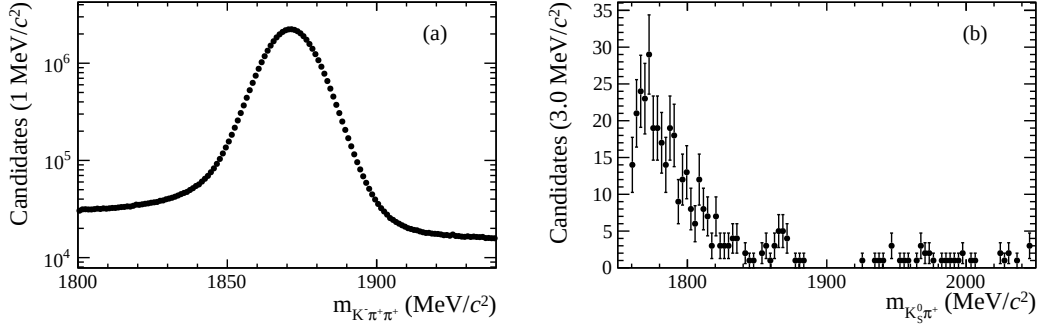


Figure 4.7: Invariant mass distribution (a) for $D^+ \rightarrow K^- \pi^+ \pi^+$ candidates on a logarithmic scale with a similar selection to the signal. The radiative tail is clearly apparent. Invariant mass distribution (b) for the $D_s^+ \rightarrow K_s^0 \pi^+ \pi^0$ background as it appears in the full LHCb simulation. This background is strongly suppressed by the requirement on the IP χ^2 of the $D_{(s)}^+$ candidate.

large background. This is expected given that only the ϕ region of the $D^+ \rightarrow K^- K^+ \pi^+$ Dalitz plot is used and that the particle identification requirements are stricter than those in Chapter 3.

The backgrounds in the $K^- K^+ \pi^+$ and $K_s^0 \pi^+$ mass spectra are each fitted with a straight line and an additional Gaussian component centred at low mass to account for background from partially reconstructed $D_s^+ \rightarrow K_s^0(\phi) \pi^+ \pi^0$ decays. This background mostly lies outside the interval in invariant mass that is fitted. A simulated sample of these decays is generated and candidates passing the stripping selection for the $K_s^0 \pi^+$ final state are distributed as shown in Fig. 4.7(b).

In the $D_{(s)}^+ \rightarrow K_s^0 \pi^+$ case there is also a component from cross-feed from the $D_s^+ \rightarrow K_s^0 K^+$ decay mode, where the K^+ meson is misidentified as a pion. In the fit to data, the cross-feed yield and its charge asymmetry are allowed to float but the shape is fixed from the simulation. It is modelled by a Crystal Ball function. The yield is found to be small, at 6014 ± 817 candidates, or 0.57% of the yield of $D^+ \rightarrow K_s^0 \pi^+$ decays.

The two final states are fitted independently. In each case, the dataset is divided

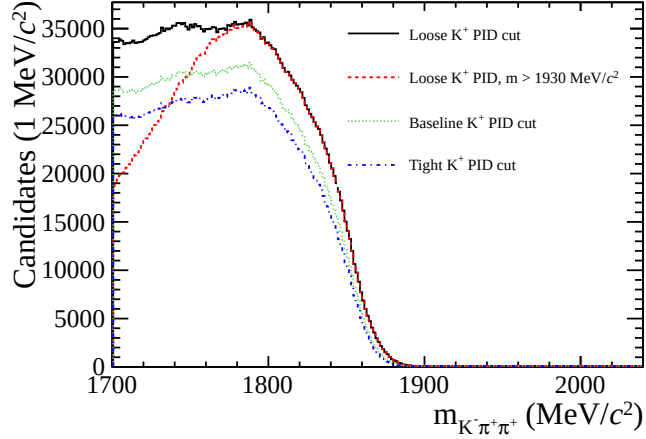


Figure 4.8: Selected candidates, with the pion mass assigned to the same-sign kaon as in Chapter 3, Fig. 3.1. There is no peak at the D^+ meson mass, indicating that there is no significant background from $D^+ \rightarrow K^- \pi^+ \pi^+$ decays.

into four subsamples according to the magnet polarity and charge of the $D_{(s)}^+$: magnet-up positive, magnet-up negative, magnet-down positive and magnet-down negative. All of these subsamples are fitted simultaneously with a probability density function which has peaks at both the D^+ and D_s^+ masses. Free parameters are introduced to allow the masses, widths and yields of the $D_{(s)}^\pm$ and background to vary independently between the four subsamples. These parameters enter as asymmetries between pairs of subsamples, for example as raw charge asymmetries between D^+ and D^- , or as differences between the D^+ mass in magnet up data and the D^+ mass in magnet down data.

In order to maximise the stability of the fit, some of the parameters are shared between D^+ and D_s^+ decays, for example the difference between the left and right tail parameters of the Cruijff function, and the α and n parameters of the Crystal Ball. All of the free fit parameters are detailed in Appendix C. The yields of signal decays are reproduced with the mean and widths of the mass distribution in Table 4.6 and the fits are shown in Fig. 4.9.

The charge asymmetries in the four decay modes are blinded by applying unknown

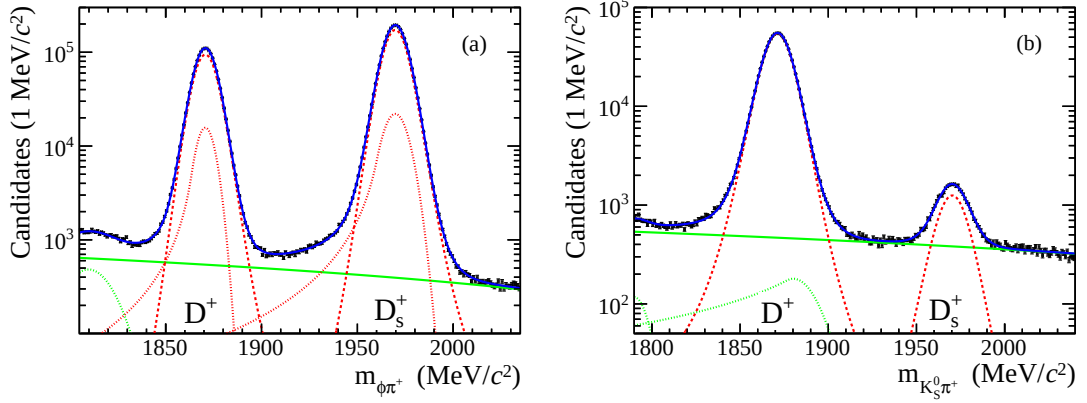


Figure 4.9: Invariant mass distribution of selected (a) $\phi\pi^+$ and (b) $K_s^0\pi^+$ candidates. All of the data is shown irrespective of its charge or the polarity of the magnet. The data are represented by symbols with error bars. The red dashed and dotted peaks indicate the components of the signal decays, the green solid line represents the combinatorial background shape, the green dotted lines represent backgrounds from specific decays, and the blue solid lines show the sum of all fit components.

Decay mode	Signal yield	Mean (MeV/c^2)	Width (MeV/c^2)
$D^\pm \rightarrow \phi\pi^+$	$(1.576 \pm 0.002) \times 10^6$	1870.72 ± 0.01	5.45 ± 0.02
$D_s^\pm \rightarrow \phi\pi^+$	$(3.010 \pm 0.002) \times 10^6$	1969.74 ± 0.01	5.65 ± 0.01
$D^\pm \rightarrow K_s^0\pi^+$	$(1.058 \pm 0.001) \times 10^6$	1871.20 ± 0.01	7.03 ± 0.03
$D_s^\pm \rightarrow K_s^0\pi^+$	$(2.562 \pm 0.024) \times 10^4$	1970.3 ± 0.1	7.48 ± 0.08

Table 4.6: Numbers of signal candidates in the four decay modes from the mass fits, and the means and widths of the corresponding peaks.

constant offsets generated from a Gaussian distribution with a mean of 0.005 and a width of 0.02 for the $K_s^0\pi^+$ final state and a mean of 0.005 and a width of 0.01 for the $\phi\pi^+$ final state. These values are chosen to be significantly larger than the expected CPV, but small enough not to destabilise the fit. The offsets are different for D^+ and D_s^+ mesons. They are, however, kept the same for each magnet polarity and between kinematic bins, so that these subsamples can be compared without unblinding. The blinding is performed using the RooFit framework with the RooUnblindPrecision class [94].

The global fits to the two data samples described here are validated by generating

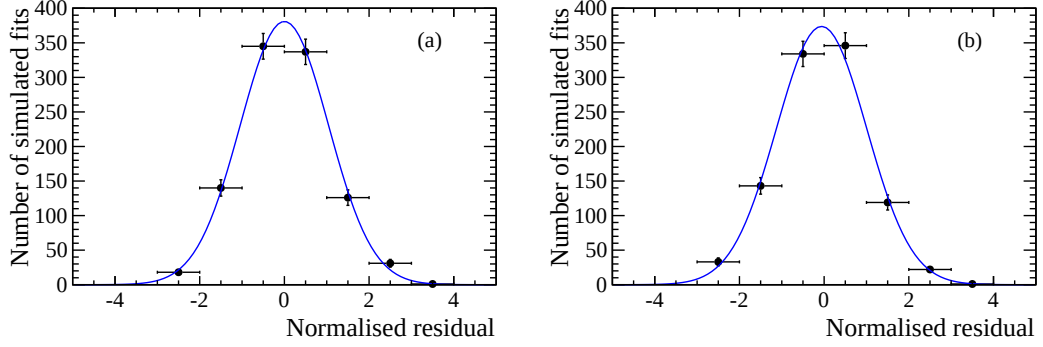


Figure 4.10: Normalised residual distributions from toy simulations of the raw charge asymmetry in the $K_s^0\pi^+$ final states in data taken with the magnet polarity down, (a) D^+ , (b), D_s^+ . The mean and width of the Gaussian fits feature in Table 4.7.

and fitting 1000 simulated samples with the yields subject to Poisson fluctuations about the measured signal yields. The samples are not simulated *ab initio* by modelling pp collisions, but simply by generating candidates randomly from the probability density function used to fit the mass distribution. In the case of the $K_s^0\pi^+$ final state, 998 out of 1000 simulated samples have convergent fits with accurate error matrices, while the others do not have accurate error matrices but still converge. The normalised residual distributions of the raw asymmetries are shown in Figs. 4.10 and 4.11, and the means and widths of the residual distributions are given in Table 4.7. All fits are included in the residual plots irrespective of the accuracy of the error matrix. There is no indication of any bias or imperfect determination of uncertainties.

However, the fit to the $\phi\pi^+$ final state was found to be less stable. The fit to data converges to give an accurate error matrix, but a lower percentage of fits to simulated samples converge than in the $K_s^0\pi^+$ case. In 1000 samples, 865 have convergent fits with accurate Hesse error matrices, while the other 135 have convergent fits but do not have accurate Hesse error matrices. The normalised residual distribution of the blinded raw asymmetry parameters for the 865 convergent fits are shown in Figures 4.12 and 4.13. The means and widths of the residual distributions are summarised in Table 4.7. There is no

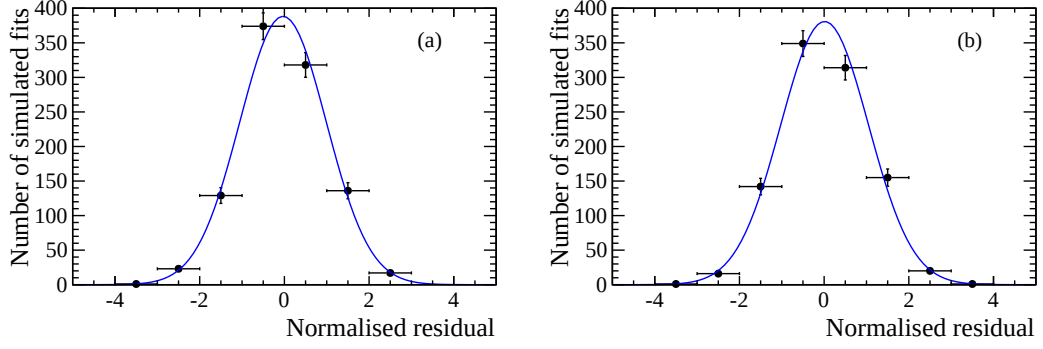


Figure 4.11: Normalised residual distributions from toy simulations of the raw charge asymmetry for the $K_S^0\pi^+$ final states in magnet up data, (a) D^+ , (b) D_s^+ . The mean and width of the Gaussian fits feature in Table 4.7.

	Mean	Width
$D^+ \rightarrow K_S^0\pi^+$, MD	-0.021 ± 0.032	1.005 ± 0.022
$D^+ \rightarrow K_S^0\pi^+$, MU	0.025 ± 0.031	0.985 ± 0.022
$D_s^+ \rightarrow K_S^0\pi^+$, MD	0.036 ± 0.032	1.012 ± 0.023
$D_s^+ \rightarrow K_S^0\pi^+$, MU	-0.021 ± 0.032	1.010 ± 0.023
$D^+ \rightarrow \phi\pi^+$, MD	-0.038 ± 0.035	1.026 ± 0.026
$D^+ \rightarrow \phi\pi^+$, MU	-0.019 ± 0.035	1.026 ± 0.024
$D_s^+ \rightarrow \phi\pi^+$, MD	-0.014 ± 0.035	1.024 ± 0.026
$D_s^+ \rightarrow \phi\pi^+$, MU	0.016 ± 0.035	0.989 ± 0.027

Table 4.7: Gaussian fit parameters of the normalised residual distribution of the raw asymmetries (Figs. 4.10 to 4.13) in the simulation studies for the four decay modes and the two magnet polarities (labelled MD and MU).

indication of bias or poor determination of uncertainties in the fits in which an accurate error matrix is obtained.

The possibility of bias introduced by the fit to the $\phi\pi^+$ final state is studied using the simulations. The unblinded raw asymmetry from the fit to the data is compared with the mean value from the fits to all 1000 simulated distributions in Table 4.8. There are no significant differences between the means, so it is concluded that no bias on the asymmetry is introduced by the fit.

The signal purity of the D^+ mass peak is calculated in a mass window from 1840 to

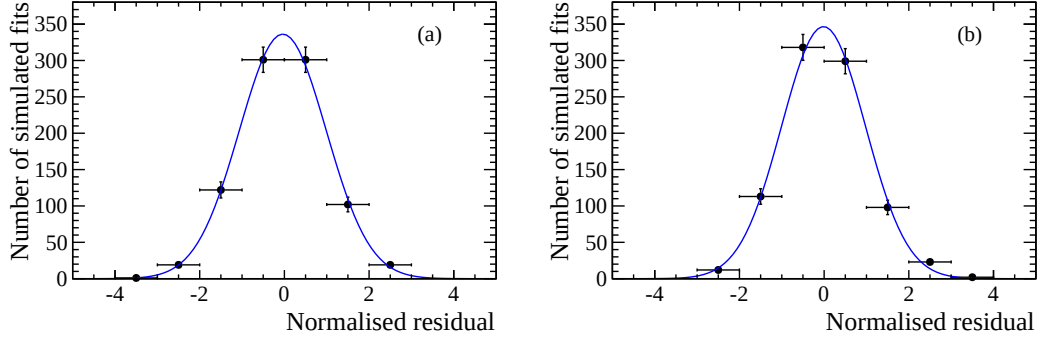


Figure 4.12: Normalised residual distributions of the raw asymmetry in the $\phi\pi^+$ final states in magnet-down data: (a) D^+ , (b) D_s^+ . Only the fits with accurate error matrices are shown. The means and widths of the Gaussian fit are given in Table 4.7.

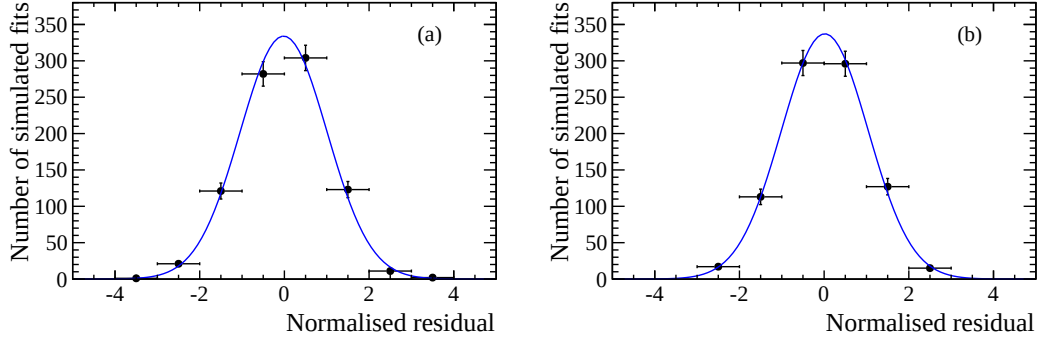


Figure 4.13: Normalised residual distributions of the raw asymmetry in the $\phi\pi^+$ final states in magnet-up data: (a) D^+ , (b) D_s^+ . Only the fits with accurate error matrices are shown. The means and widths of the Gaussian fit are given in Table 4.7.

Sample	A_{raw} in fit to data (%)	Mean A_{raw} in 1000 toys (%)	Bias (sigma)
D^+ magnet up	-1.100 ± 0.127	-1.101 ± 0.004	-0.33
D_s^+ magnet up	-0.770 ± 0.076	-0.771 ± 0.003	-0.28
D^+ magnet down	-0.297 ± 0.127	-0.299 ± 0.004	-0.71
D_s^+ magnet down	-0.093 ± 0.076	-0.093 ± 0.003	+0.30

Table 4.8: Investigation of the bias in the fit to the $\phi\pi^+$ final state using toy simulations. The unblinded raw asymmetries from data are used as the starting points for the simulations. No bias on the raw asymmetry A_{raw} is found.

1900 MeV/ c^2 and is approximately 98% for $\phi\pi^+$ and 97% for $K_s^0\pi^+$. The yields and raw asymmetries are cross-checked with a sideband subtraction procedure under the assumption of a linear background.

The mass fits described above are repeated in 12 bins of p_T and η . For reasons explained in Sect. 4.7, the binned fits are used to determine the results for A_{CP} . The plots of the particle mis-identification rates in Sect. 4.10.5, Fig. 4.30 show that the yield of cross-feed from $D_s^+ \rightarrow K_s^0 K^+$ is likely to be concentrated at high momentum. Therefore the contribution of this cross-feed is ignored in the lowest six bins of D^+ p_T .

The binned fits have lower statistics than the global fit. Therefore, in the $D_{(s)}^+ \rightarrow \phi\pi^+$ decays, the n parameter and the relative fraction of the Crystal Ball function are fixed to the value found in the global fit. Also, the asymmetry in the $D_s^+ \rightarrow \phi\pi^+\pi^0$ background is fixed to 0 for cases where the yield of this background is less than 100. This is only the case in the extreme bottom-left and top-right bins of p_T and η so does not significantly affect the measured asymmetries.

In the $D_{(s)}^+ \rightarrow K_s^0\pi^+$ decays, the charge asymmetry in the $D_s^+ \rightarrow K_s^0\pi^+\pi^0$ final state is fixed to 0 for cases where the yield is below 100 to keep the parameters from becoming ill-defined at low yields. This is found to be necessary in most bins. Furthermore, the asymmetry in the cross-feed from $D_s^+ \rightarrow K_s^0 K^+$ decays is also fixed to zero when the yield of the cross-feed is below 100; this is true for one or two mid-range p_T bins at low η where the particle mis-identification rates are lowest (see Fig. 4.30). As in the case of the fits to the $\phi\pi^+$ final state, these minor changes do not affect the overall measured charge asymmetry.

The fits to individual bins are reproduced in Appendix D.2, and the variation of the mean and width of the mass peaks between bins in the two D^+ decay modes is tabulated in Appendix C, Table C.3. There is no need to perform the calculation of $A_{CP}|_S$ in these bins because the decay mode is not being compared to another decay mode which has a different

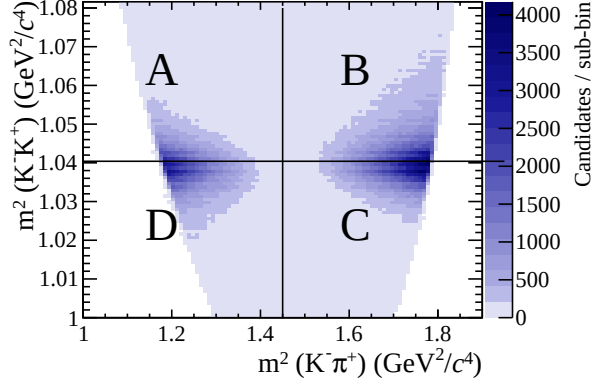


Figure 4.14: The distribution of signal candidates across the ϕ region in selected $D^+ \rightarrow K^- K^+ \pi^+$ decays, with the four zones $A - D$ labelled.

distribution in p_T and η after the triggering and signal selection process. In fact, the background is so low in the $D_{(s)}^+ \rightarrow \phi \pi^+$ channels that the fit is unnecessary, and the charge asymmetry in the $D^+ \rightarrow \phi \pi^+$ decay can be calculated by counting D^+ and D^- candidates in a mass interval defined around the D^+ meson mass of $1845 < m < 1895 \text{ MeV}/c^2$. Therefore, the yields for $A_{CP}|_S$ are evaluated using this simple technique. The systematic uncertainty that arises from ignoring the background is determined in Sect. 4.10.5 by comparing the raw asymmetries that result from the fitting and counting methods, and is found to be small. The resolution in the Dalitz plot is improved by constraining the D^+ mass to the nominal value [16]. This procedure has a complicated effect on the background distribution, so cannot be used unless the background is negligible. The candidates are distributed in the ϕ region of the $D^+ \rightarrow K^- K^+ \pi^+$ Dalitz plot as shown in Fig. 4.14. For the measurement of A_{CP} , the background in the $D_{(s)}^+ \rightarrow K_s^0 \pi^+$ channels are not negligible so the results are taken from fits in all decay modes, for consistency, and the $D_{(s)}^+$ meson masses are left free.

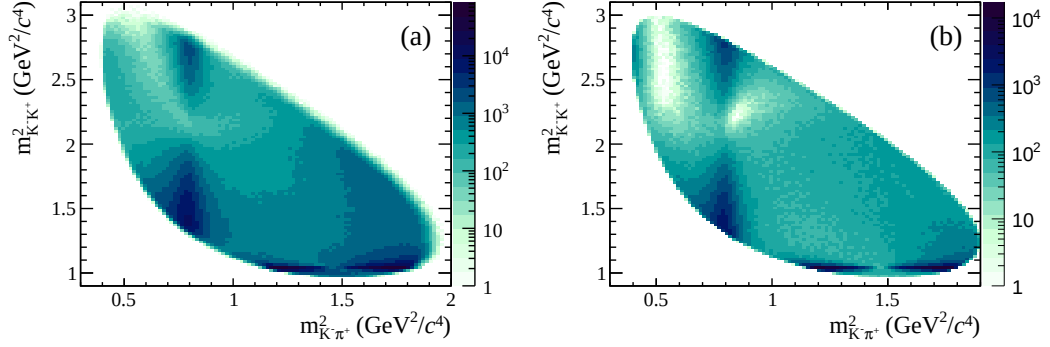


Figure 4.15: Selected data (a) and generated (b) Dalitz plots of the $D^+ \rightarrow K^- K^+ \pi^+$ decay. It is clear that the simulated model is not perfect, but this is not surprising since it includes no background or efficiency corrections and is based on 20,000 signal decays recorded at CLEO-c [47] while in the LHCb dataset there are around 5 million. Since none of the physics results depend on the generated Dalitz plot, and the differences in the ϕ region are not too large, this is not critical.

4.6 Motivation for the $A_{CP|S}$ variable

In order to determine the sensitivity of the variables A_{CP} and $A_{CP|S}$ to plausible types of CP violation, Dalitz plots of the $D^+ \rightarrow K^- K^+ \pi^+$ decay were simulated with the Laura++ package [95] from the CLEO-c Dalitz model B in Ref. [47]. The model is identical to that in Chapter 3, and is described in Table 3.7 in Sect. 3.4. The simulation is based only on the amplitude model, with no representation of the pp interaction or detector. However, unlike in Chapter 3, the background and efficiency were ignored in these studies. This is because the efficiency will not vary significantly across the small region of the Dalitz plot used in this analysis, so will have no effect, and the background is negligible compared to the signal. The Dalitz plots of the data and the simulation are compared in Fig. 4.15.

The key use of this model is to verify that, as found in Chapter 3 and shown in Fig. 4.1, the relative strong phase changes sign across the ϕ resonance and that this affects the sensitivity to CPV. The strong phase here is the phase of the fitted complex amplitude in the Dalitz model, defined relative to the $K^*(892)^0$. It may or may not be equivalent to the

relative strong phase associated directly with the CP violating asymmetry in Eq. 1.16: that depends on the nature of the CPV. As discussed in Sect. 4.1, there is a diagonal symmetry in Fig. 4.1: the strong phases in the top left and bottom right regions are similar, and the phase in the top right and bottom left regions are also similar. Therefore one might anticipate that the quantity

$$A_{CP|S} = \frac{1}{2} ((A_{\text{raw}}(A) + A_{\text{raw}}(C)) - (A_{\text{raw}}(B) + A_{\text{raw}}(D))) \quad (4.7)$$

has good sensitivity to some types of CPV.

To see if this is true, plausible types of CPV are introduced into the amplitude model, and a number of simulated Dalitz plots are produced. The first test involves generating 20 pseudo-experiments with an artificial CP -violating weak phase of 3° introduced into the ϕ resonance. The ϕ has a strong phase of -163° relative to the reference $K^{*0}(892)$ in the CLEO-c Dalitz model [47], and so to generate this CPV the phase is changed to 161.5° for D^+ decays and 164.5° for D^- decays. Almost 750,000 decays of each charge are generated in each pseudo-experiment, which is roughly the same as the signal yield in data, and the CP violating observables A_{CP} and $A_{CP|S}$ are calculated. The results in a randomly selected pseudo-experiment, in the ϕ region defined in the analysis, are

$$A_{CP} = (0.01 \pm 0.08)\% \quad (4.8)$$

$$A_{CP|S} = (-0.88 \pm 0.17)\%.$$

In the absence of CPV both quantities are expected to be zero. Overall, the mean value of $A_{CP|S}$ recorded was -1.02% . If one considers only the statistical uncertainty on the simulated sample, 90% of the toy studies yielded a value of $A_{CP|S}$ five Gaussian standard deviations σ from zero, and 100% gave a result 3σ from zero. When the statistical uncertainty on the control decay mode is added to the uncertainty on A_{CP} in data, and

Type of CPV	mean A_{CP} in 20 tests (%)	mean $A_{CP S}$ in 20 tests (%)
3° in relative ϕ phase	-0.01 (0.1σ)	-1.02 (5.1σ)
0.8% in ϕ amplitude	-0.50 (2.5σ)	-0.02 (0.1σ)
4° in $K_0^*(1430)^0$ phase	0.52 (2.6σ)	-0.89 (4.5σ)
4° in κ phase	0.70 (3.5σ)	0.10 (0.5σ)

Table 4.9: Expected values of observables for different types of CPV introduced into the Dalitz model, and the significance with which the CPV could be seen in this analysis if it exists. The degree of CP violation in the pseudo-experiment was chosen to give an expected result of significance varying from three to five Gaussian standard deviations in at least one observable. The expected uncertainties used to calculate the significance are all 0.2% on both A_{CP} and $A_{CP|S}$. This is an estimate of the precision achievable in the real analysis; the statistical uncertainties on the means in the table are all negligible. The κ resonance is sometimes referred to as the $K_0^*(800)$.

the systematic uncertainties are considered, the overall uncertainties on A_{CP} and $A_{CP|S}$ are both expected to be around 0.2%. Thus it is estimated that this CPV could be observed with 5.1σ significance. On the other hand, no A_{CP} values were over 3σ from zero and only one over 2σ , so the sensitivity of A_{CP} to this CPV is essentially zero.

Another set of pseudo-experiments have a 4° CPV introduced into the phase of the $K^*(1430)^0$. The mean value of A_{CP} is 0.52% and the mean value of $A_{CP|S}$ is -0.89%. This signal would be seen with 2.6σ significance in A_{CP} and 4.5σ in $A_{CP|S}$.

A third set of simulations use an 0.8% CPV in the amplitude of the ϕ . The mean value of A_{CP} is -0.50% and the mean value of $A_{CP|S}$ is -0.02%. There would be a hint of a signal in A_{CP} , with a result 2.5σ from zero, but $A_{CP|S}$ is not sensitive. Some additional pseudo-experiments were also generated and the results are summarised in Table 4.9. It is clear from this table that, while not always a better observable, $A_{CP|S}$ is a very useful complement to A_{CP} .

4.7 Techniques to reduce susceptibility to systematic biases

This section explains some of the techniques used in the analysis to minimise its systematic uncertainties. The dominant biases are due to the fact that oppositely charged particles bend in opposite directions in the magnetic field so traverse different parts of the detector and are not necessarily detected with the same efficiency. However, any effect will be reversed when the magnetic field is changed from one polarity to the other. Therefore, the yield extraction is performed separately for each polarity and the results combined with a simple average, defined as

$$A_{\text{raw}} = \frac{A_{\text{raw}}^{\uparrow} + A_{\text{raw}}^{\downarrow}}{2} \quad (4.9)$$

where $A_{\text{raw}}^{\uparrow}$ and $A_{\text{raw}}^{\downarrow}$ represent the raw asymmetries in magnet up and magnet down data respectively. Since more data were collected with the down than the up polarity, a weighted average would lead to imperfect cancellation of these detector asymmetries.

For the measurement of A_{CP} , the signal yields are measured in 12 bins of transverse momentum p_T and pseudorapidity η using binned likelihood fits to the distribution of the invariant masses m , where m is either $m_{K^-K^+\pi^+}$ or $m_{K_S^0\pi^+}$. The binning is chosen to keep roughly equal numbers of events in each two-dimensional bin. Several alternative binning schemes are used as cross checks, and this is described in Sect. 4.10.2. The values of A_{CP} in each bin are calculated and a weighted average over the bins is performed. This procedure is adopted because the detector acceptance and different kinematics of the two decays result in different distributions of reconstructed signal over the $p_T - \eta$ space, as shown in Fig. 4.16, and the $D^\pm$ production asymmetry may also vary over this space [8]. If the calculation was unbinned, the variation of the production asymmetry

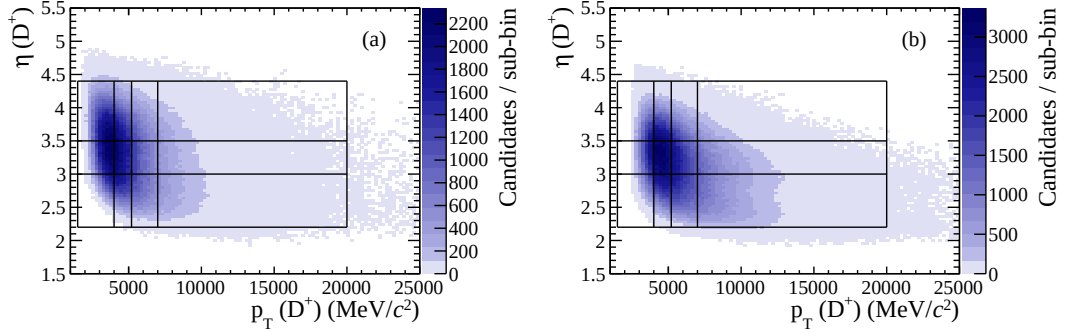


Figure 4.16: Distributions of transverse momentum p_T and pseudorapidity η for (a) $D^+ \rightarrow K_S^0 \pi^+$ and (b) $D^+ \rightarrow \phi \pi^+$ candidates with the bins represented by black lines. Candidates that do not fall into a bin are not used in the analysis.

over the phase space would cause a bias on the result, because the average production asymmetry would be different for the two final states. By contrast, with the binned approach adopted, the uncertainty on the CP asymmetry will be dominated by the decay mode with the lowest yield in that bin, so, for example, bins where only one decay mode is present would contribute with no statistical weight to the average. The binning thus ensures that only the region of kinematic overlap is used to calculate the asymmetry. To avoid any anomalies at the edges of the kinematic space where the variations within bins are most significant, the selection requirements $1.5 < p_T < 20 \text{ GeV}/c$ and $2.2 < \eta < 4.4$ are applied. Usually only one decay mode is detected outside of the allowed region so defined.

The increased phase space available to the $D_{(s)}^+ \rightarrow K_S^0 \pi^+$ decays compared to the $D_{(s)}^+ \rightarrow \phi \pi^+$ decays leads to slightly different momentum spectra for the bachelor pion in the two cases. Four kinematic distributions for the pion from the D^+ decays are reproduced as Figure 4.17 below. The differences are small, and will be substantially smaller within each bin of $D_{(s)}^+$ p_T and η , so the variation of the pion tracking efficiency asymmetry with these quantities should have little effect.

For a different perspective on the same effects, the opening angles between the daughter

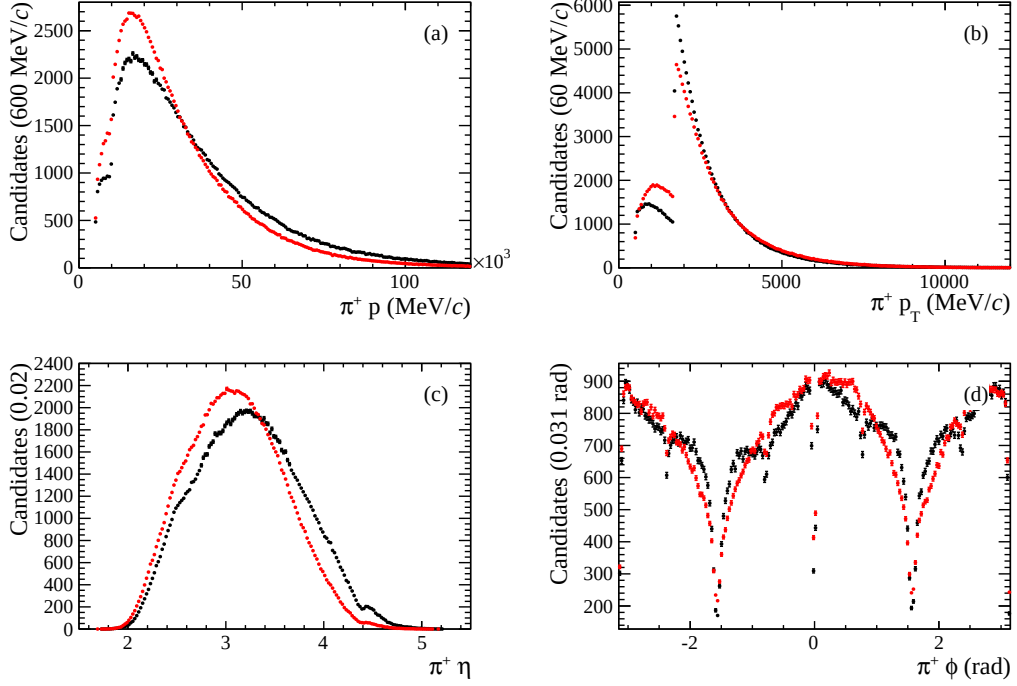


Figure 4.17: 1D spectra for the pion kinematics, (a) momentum p , (b) transverse momentum p_T , (c) pseudorapidity η , (d) azimuthal angle ϕ around the beam axis. The $\phi = 0$ direction corresponds to the $+x$ direction. In each case the spectrum from the $\phi\pi^+$ final state is in red and from the $K_s^0\pi^+$ final state is in black, and the plots are scaled to contain the same total number of entries. No background subtraction is applied. In the p_T spectrum the p_T threshold of the first-level software trigger at $1.7\text{ GeV}/c$ is clearly visible.

tracks are calculated for the two decay modes, and the results are compared in Fig. 4.18. The difference between the two final states is clear. However, the largest difference is seen in Fig. 4.18(a) which shows the opening angles between the daughter tracks of the K_s^0 or ϕ mesons. These are approximately charge-symmetric so differences between the two final states do not affect the results. The effects of the differences in Fig. 4.18(b) and Fig. 4.18(c) are investigated by using various different binnings in the kinematics of the pion to cross-check the value of A_{CP} , and this is described in Sect. 4.10.2.

Before the results were unblinded, a preliminary investigation of the variation of the asymmetry results between bins was performed. The results in the different bins were

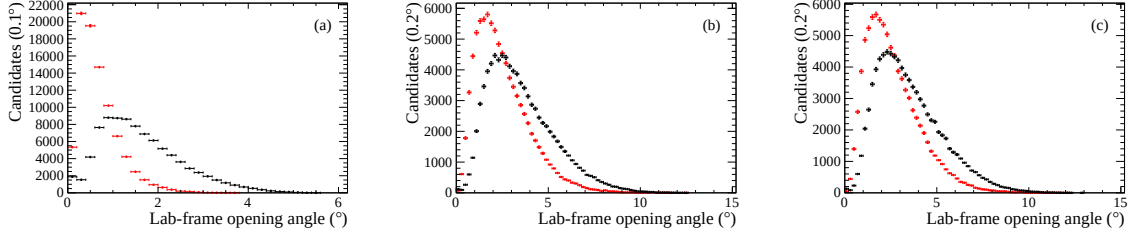


Figure 4.18: Opening angles in the lab frame, with $D^+ \rightarrow \phi\pi^+$ decays in red and $D^+ \rightarrow K_s^0\pi^+$ decays in black: (a), angle between the K_s^0 or ϕ daughters, (b) angle between the same-sign K_s^0 or ϕ daughter and the bachelor pion and (c) angle between the opposite-sign K_s^0 or ϕ daughter and the bachelor pion.

found to be statistically compatible. This was repeated after unblinding and the results are discussed in Sect. 4.9 and Sect. 4.10.2.

An increased understanding of the effect of the LHCb detector on the charge asymmetry can be obtained by plotting the charge asymmetry as a function of particle momenta in the bending plane of the magnet and parallel to the beam axis. The daughters of the ϕ and K_s^0 mesons are charge-symmetric, so it is most useful to do this for the bachelor pions. The plots are reproduced in Figs. 4.19 to 4.22.

These figures suggest that cuts should be applied to both final states to remove areas of high charge asymmetry [2]. The precise requirements chosen are taken from Ref. [84]. They are

$$|p_x| \leq \alpha(p_z - p_0), \quad \alpha = 0.317, p_0 = 2400 \text{ MeV}/c \quad (4.10)$$

for all bachelor tracks, in order to remove the “edge region” that is outside the fiducial region defined by the black lines in the plots on the left of Figs. 4.19 to 4.22. There is also the requirement that

$$p_1 - \beta_1 p_z < |p_x| < p_2 + \beta_2 p_z, \quad p_1 = 418 \text{ MeV}/c, p_2 = 497 \text{ MeV}/c, \beta_1 = 0.01397, \beta_2 = 0.01605 \quad (4.11)$$

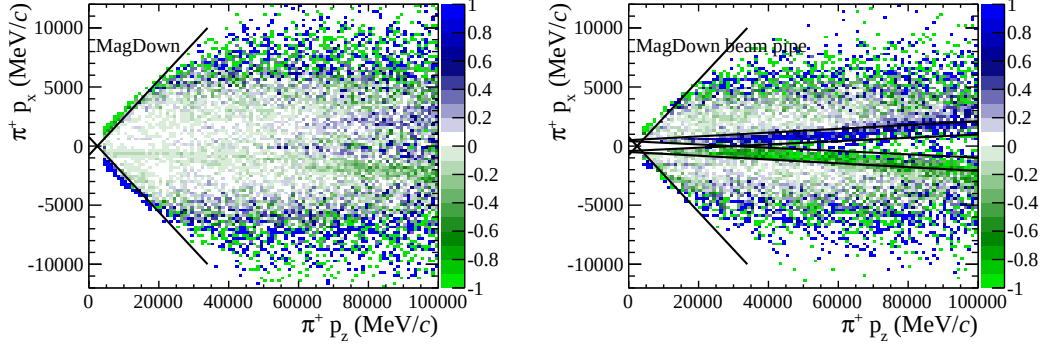


Figure 4.19: Plots of the charge asymmetry variation with p_x, p_z for the bachelor pion in $D^+ \rightarrow K_s^0 \pi^+$, magnet-down. The left plot shows all bachelor pions, the right shows the region of the beam pipe, defined as $|p_y/p_z| < 0.02$ for the y - and z -components of the pion momentum. It is clear that there are some large localised asymmetries, for example for pions with low z -momentum and high x -momentum. The effect approximately cancels when the two detector halves (positive and negative p_x) are combined, but for the avoidance of doubt the most asymmetric regions are removed by the fiducial cuts that are labelled on the plot.

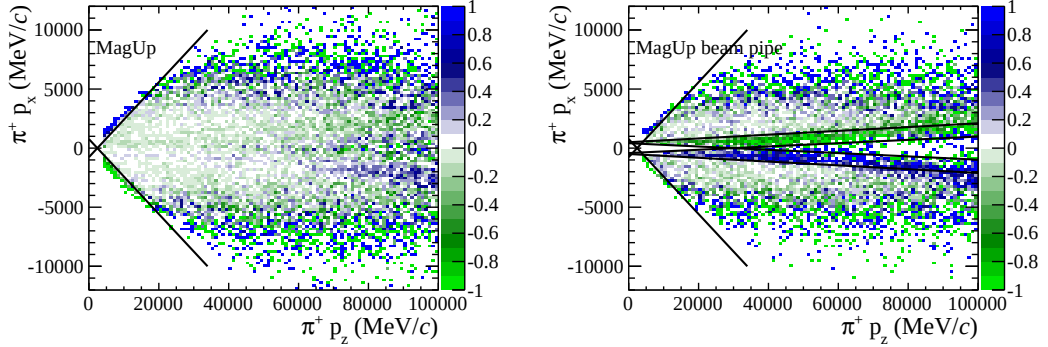


Figure 4.20: Plots of the charge asymmetry variation with p_x, p_z for the bachelor pion in $D^+ \rightarrow K_s^0 \pi^+$, magnet-up. The left plot shows all bachelor pions, the right shows the region of the beam pipe, defined as $|p_y/p_z| < 0.02$ for the y - and z -components of the pion momentum. The same effects as in Fig. 4.19 are observed, except that, as expected, the asymmetries have opposite sign. This verifies that they will cancel to a good approximation when the two magnet polarities are averaged.

which is only applied to events in the region of the beam pipe, defined by $|p_y/p_z| < 0.02$.

This region is shown in the plots on the right of each figure.

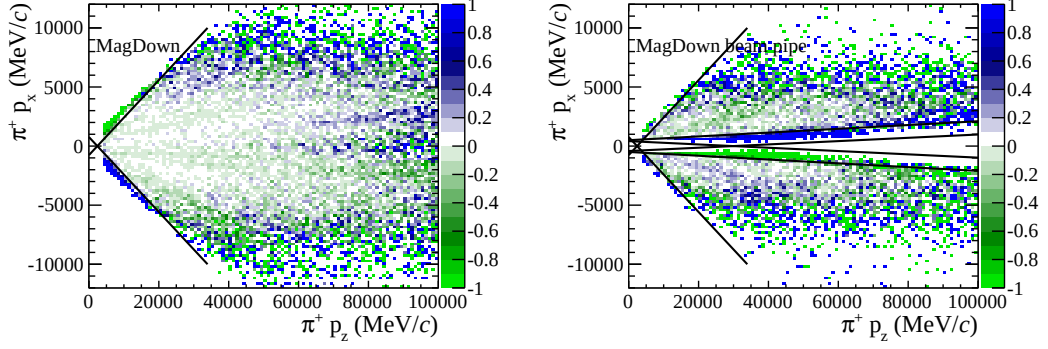


Figure 4.21: Plots of the charge asymmetry variation with p_x, p_z for the bachelor pion in $D^+ \rightarrow \phi\pi^+$, magnet-down. The left plot shows all bachelor pions, the right shows the region of the beam pipe, defined as $|p_y/p_z| < 0.02$ for the y - and z -components of the pion momentum. The effects are broadly the same as in the $D^+ \rightarrow K_s^0\pi^+$ decay mode, so should also cancel to a good approximation when the asymmetries in the two decay channels are subtracted.

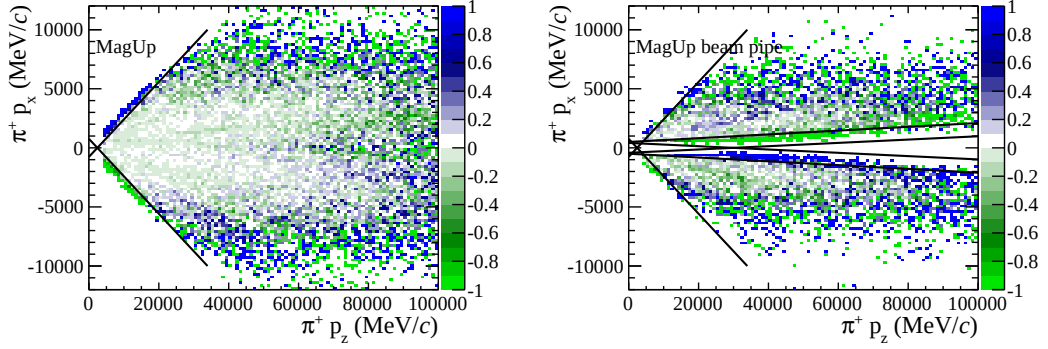


Figure 4.22: Plots of the charge asymmetry variation with p_x, p_z for the bachelor pion in $D^+ \rightarrow \phi\pi^+$, magnet-up. The left plot shows all bachelor pions, the right shows the region of the beam pipe, defined as $|p_y/p_z| < 0.02$ for the y - and z -components of the pion momentum.

4.8 CP asymmetries in neutral kaon decays

Following CPLEAR [96] and Grossman and Nir [29], the CPV in the decay of the neutral kaon into two pions $A_{CP}(K^0/\bar{K}^0)$ depends on the decay time acceptance $F(t)$ of the K_s^0 meson as

$$A_{CP}(K^0/\bar{K}^0) = \frac{\int_0^\infty F(t) D_{\pi\pi}(t) dt}{\int_0^\infty F(t) S_{\pi\pi}(t) dt} \quad (4.12)$$

where S and D are proportional to the sum and difference of the K^0 and $\bar{K}^0$ decay times to the $\pi^-\pi^+$ final state. The derivation of this formula is outlined in Sect. 1.6. Neglecting terms of $\mathcal{O}(\epsilon^2)$ and direct CP violation in kaon decays, this can be written as

$$A_{CP}(K^0/\bar{K}^0) = 2\text{Re}(\epsilon) \left[1 - \frac{\int_0^\infty F(t) e^{-\frac{1}{2}(\Gamma_S + \Gamma_L)t} \left(\cos \Delta m t + \frac{\text{Im}(\epsilon)}{\text{Re}(\epsilon)} \sin \Delta m t \right) dt}{\int_0^\infty F(t) e^{-\Gamma_S t} dt} \right] \quad (4.13)$$

This equation will be used in the calculations below. There is a systematic effect from the interaction of K_L^0 mesons with detector material known as regeneration that is discussed in Section 4.10. It is found to have only a very small effect.

In LHCb the distribution of decay times is driven purely by acceptance effects; the actual K_S^0 lifetime is irrelevant. Therefore the K_S^0 meson decay time is fitted with a totally empirical function for both the lower and the upper decay time acceptances (describing the distribution on the left and on the right of the peak in Fig. 4.23 respectively). The lower lifetime acceptance results from the requirement that the K_S^0 decay vertex is displaced in the z -direction from the D^+ decay vertex by at least 10mm, and by the requirements on the impact parameter χ^2 of the K_S^0 daughters. The upper acceptance is the result of the geometry of the vertex detector, since K_S^0 mesons which decay outside the VELO are not used in this analysis. Neither acceptance results in a sharp cut-off since both requirements are on longitudinal (z) displacement, while the K_S^0 can also travel in the transverse direction before decaying. In the case of the upper acceptance the functional form is a series of three exponential decay curves in different decay time regimes, which is chosen so that the exponential decay of the K_S^0 can be factored out of the equation. Three is the minimum number of exponentials required to describe the data reasonably well. The fit to a dataset with 200 bins gives a rather poor χ^2/ndf of just over 6. However, the decay times over which the CP violation varies significantly are much longer than the decay times of interest here, so the fit is good enough to get the scale of the CP-violating

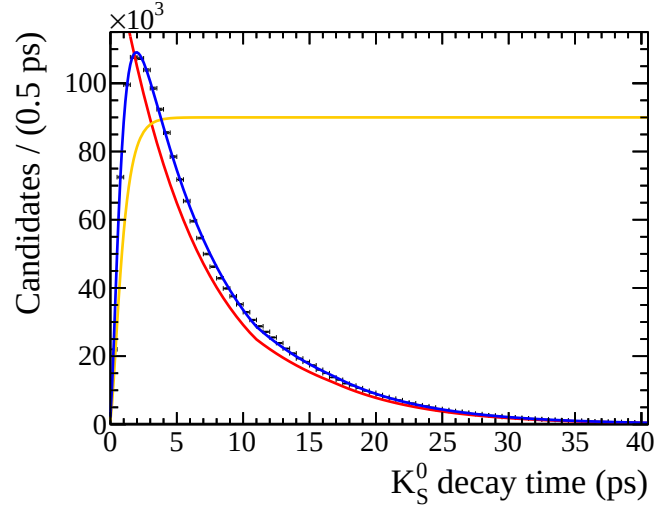


Figure 4.23: The K_s^0 decay time distribution with a fit shown in blue. The lower acceptance function, given in the first bracket of Equation 4.16, is shown in orange and the second part, the three exponential decays that make up the upper acceptance, is shown in red. The lower acceptance function has an arbitrary normalisation applied to make it visible on the plot. The nominal lifetime of the K_s^0 meson is 89.5 ps [16], much larger than the decay times observed here.

effects.

The fitted function is:

$$G(t) = \left(1 - e^{\frac{t-\alpha}{\beta}}\right)^2 e^{-\gamma_1 t} \quad (t < c_1) \quad (4.14)$$

$$G(t) = \left(1 - e^{\frac{t-\alpha}{\beta}}\right)^2 \left(e^{(-\gamma_1-\gamma_2)c_1} e^{-\gamma_2 t}\right) \quad (c_1 < t < c_2) \quad (4.15)$$

$$G(t) = \left(1 - e^{\frac{t-\alpha}{\beta}}\right)^2 \left(e^{(-\gamma_1-\gamma_2)c_1} e^{(-\gamma_2-\gamma_3)c_2} e^{-\gamma_3 t}\right) \quad (t > c_2) \quad (4.16)$$

for $t > \alpha$. The quantities α , β , γ_1 , γ_2 , γ_3 , c_1 and c_2 are free parameters. The actual decay time can be factorised out of the γ_i to obtain an acceptance function, which is then used in Eq. 4.13 to determine the CP violation.

The observed CPV is -2.82×10^{-4} , which is substantially smaller than the statistical uncertainties on our measurements. As a cross check, an alternative empirical function

Parameter	Fitted value	Uncertainty
α	-0.0818	0.0023
β	-0.6935	0.0040
γ_1	0.1601	0.0004
γ_2	0.1212	0.0006
γ_3	0.1436	0.0003
c_1	10.93	0.02
c_2	16.75	0.01

Table 4.10: Fit parameters used to describe the K_s^0 meson decay time acceptance.

which also allows the K_s^0 exponential decay to be factored out,

$$G(t) = \left(1 - e^{\frac{t-\alpha}{\beta}}\right)^2 (\delta e^{-\gamma_1 t} + (1 - \delta)e^{-\gamma_2 t}), \quad (4.17)$$

is used to fit the decay time distribution and the calculation is repeated. The lower decay time acceptance is the same as the baseline function, but this is not as important as the behaviour at longer decay times when the kaons have more of a chance to mix. The CP asymmetry obtained is -3.2×10^{-4} , which is in line with the previous value. The fit is shown in Figure 4.24. A systematic uncertainty on this result equal to the central value is assigned, so $A_{CP}(K^0/\bar{K}^0) = (-2.8 \pm 2.8) \times 10^{-4}$.

4.9 CP asymmetry results

The analysis is unblinded and the values of A_{CP} , $A_{CP}|_S$ and $A_{CP}(D_s^+ \rightarrow K_s^0 \pi^+)$ are calculated. We correct for the CPV in the neutral kaon system, which is -0.028% with negligible statistical uncertainty, so, as in Sect. 4.1,

$$A_{CP}(D^+ \rightarrow \phi \pi^+) = A_{\text{raw}}(D^+ \rightarrow \phi \pi^+) - (A_{\text{raw}}(D^+ \rightarrow K_s^0 \pi^+) - A_{CP}(K^0/\bar{K}^0)). \quad (4.18)$$

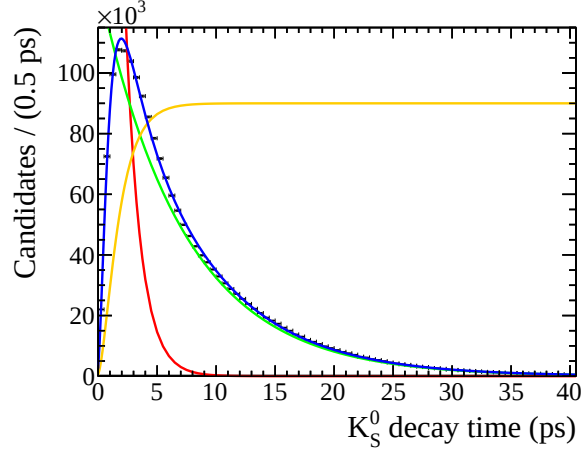


Figure 4.24: Alternative fit to the K_S^0 decay time distribution, with the combined fit shown in blue, the two constituent exponential decays in green and red and the lower acceptance function, the first term in Equation 4.17, in orange. The lower acceptance function has an arbitrary normalisation applied to make it visible on the plot.

The result is

$$A_{CP}(D^+ \rightarrow \phi\pi^+) = (-0.039 \pm 0.138)\%$$

where the uncertainty is statistical only. The result for $A_{CP}|_S$, given by,

$$A_{CP}|_S = \frac{1}{2} ((A_{\text{raw}}(A) + A_{\text{raw}}(C)) - (A_{\text{raw}}(B) + A_{\text{raw}}(D))), \quad (4.19)$$

is calculated to be

$$A_{CP}|_S = (-0.177 \pm 0.166)\%.$$

The CP asymmetry in $D_s^+ \rightarrow K_S^0\pi^+$, given by

$$A_{CP}(D_s^+ \rightarrow K_S^0\pi^+) = (A_{\text{raw}}(D_s^+ \rightarrow K_S^0\pi^+) + A_{CP}(K^0/\bar{K}^0) - A_{\text{raw}}(D_s^+ \rightarrow \phi\pi^+)), \quad (4.20)$$

is calculated in the same way, and is

$$A_{CP}(D_s^+ \rightarrow K_S^0\pi^+) = (0.607 \pm 0.827)\%.$$

Decay mode	Magnet up	Magnet down	Average
$D^+ \rightarrow \phi\pi^+$	-1.104 ± 0.127	-0.299 ± 0.106	-0.702 ± 0.082
$D^+ \rightarrow K_S^0\pi^+$	-0.866 ± 0.161	-0.679 ± 0.133	-0.773 ± 0.104
$D_s^+ \rightarrow K_S^0\pi^+$	1.234 ± 1.264	-0.890 ± 1.058	0.185 ± 0.825
$D_s^+ \rightarrow \phi\pi^+$	-0.771 ± 0.091	-0.093 ± 0.076	-0.432 ± 0.059

Table 4.11: Raw asymmetries in the four decay modes, in %. No correction for the kaon CPV is applied; inserting it would lead to an average asymmetry in $D^+ \rightarrow K_S^0\pi^+$ of $(-0.745 \pm 0.104)\%$ and in $D_s^+ \rightarrow K_S^0\pi^+$ of $(0.157 \pm 0.825)\%$. The results are weighted averages over the 12 kinematic bins.

There is no evidence of CP violation in either the D^+ or the D_s^+ decay.

The raw asymmetries in the four decay modes are calculated separately, by performing a weighted average over the asymmetries in each kinematic bin determined in the fits, and are given in Table 4.11. The asymmetries are consistent with the values expected from measurements of the D^+ and D_s^+ production asymmetries [8, 84], although a direct comparison is not appropriate because the production asymmetries are weighted to account for the variation of the production cross sections with p_T and η . We have more confidence in the fits in the separate bins than in the global fit to all bins, because the mean and width of the mass distribution changes with p_T and η , so the results in the bins are likely to be more precise. The asymmetries calculated in data taken with the two magnet polarities separately are not expected to be consistent, as discussed in detail in Sect. 4.10.1. In the $D^+ \rightarrow \phi\pi^+$ decay mode, the value of A_{CP} is $-0.443 \pm 0.212\%$ in magnet up data and 0.364 ± 0.176 in magnet down data, a difference of just less than 3σ , or $0.807 \pm 0.276\%$.

The raw asymmetry in the $D^+ \rightarrow \phi\pi^+$ decay mode, defined by counting candidates in a mass window from $1845 < m < 1895 \text{ MeV}/c^2$, is $(-0.673 \pm 0.080)\%$. This value is $(-1.050 \pm 0.122)\%$ in magnet up data and $(-0.296 \pm 0.102)\%$ in magnet down data. The agreement with the fitted raw asymmetry, in the first line of Table 4.11, is excellent. This is expected because the background is low and linear. This is a vital consistency

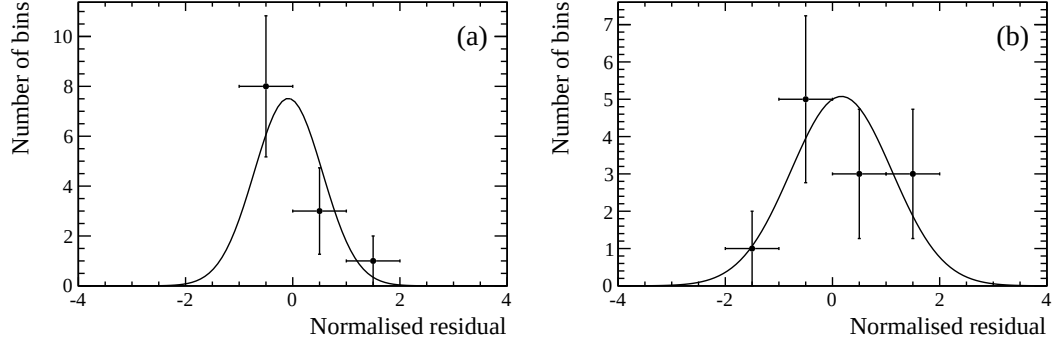


Figure 4.25: Normalised residual distribution of A_{CP} in bins. In each bin the average of the asymmetries in the two magnet polarities is taken and divided by its uncertainty, and plotted in the above histograms, for (a) D^+ and (b) D_s^+ . The D^+ distribution has mean -0.08 ± 0.18 and width 0.64 ± 0.13 . While the width is rather narrow (it is expected to be 1.0) this is assumed to be a statistical anomaly. The D_s^+ distribution has mean 0.17 ± 0.27 and width 0.94 ± 0.19 .

check, because the results for $A_{CP}|_S$ are calculated by exactly this method of counting candidates and ignoring the background altogether.

The values of A_{CP} with magnet polarity differences in each bin are given in Table 4.12. The fit in each bin is independent. The normalised residuals of A_{CP} in each bin are plotted in Figure 4.25, and the width of the distributions are consistent with 1, as expected. The χ^2/ndf values for consistency of all of the bins with the averages of A_{CP} are 0.37 in the D^+ decay and 1.04 in the D_s^+ decay, corresponding to p -values of 97% and 41% respectively. Thus there is no indication of any systematic difference between the bins. The means and widths of the mass distributions in the 12 bins are reproduced in Appendix C as Table C.3. The width is significantly higher at high η , as the resolution of the detector decreases, and the mean mass also increases slightly with η , but the effect is negligibly small.

Bin	Magnet up	Magnet down	Average
0	-1.30 ± 1.12	1.00 ± 0.92	-0.15 ± 0.72
1	0.51 ± 0.69	-0.53 ± 0.57	-0.01 ± 0.44
2	-0.75 ± 0.69	0.33 ± 0.58	-0.21 ± 0.45
3	-0.77 ± 0.75	0.49 ± 0.61	-0.14 ± 0.48
4	-0.23 ± 0.60	0.40 ± 0.50	0.09 ± 0.39
5	0.50 ± 0.67	0.77 ± 0.56	0.63 ± 0.44
6	-0.06 ± 0.69	0.61 ± 0.56	0.27 ± 0.44
7	-1.26 ± 0.67	0.67 ± 0.56	-0.30 ± 0.44
8	-1.06 ± 0.82	0.78 ± 0.69	-0.14 ± 0.54
9	-0.98 ± 0.65	0.38 ± 0.54	-0.30 ± 0.42
10	0.40 ± 0.84	-0.19 ± 0.70	0.11 ± 0.55
11	-0.66 ± 1.17	0.18 ± 0.98	-0.24 ± 0.76

Table 4.12: Values of $A_{CP}(D^+ \rightarrow \phi\pi^+)$ in bins of p_T and η , from the fit. Bins 0, 3, 6, 9 contain data with the lowest values of η and increasing values of p_T . Bins 1, 4, 7, 10 represent intermediate η values, and 2, 5, 8 and 11 represent high η values.

4.10 Systematic uncertainties and cross checks

Where possible, the systematic uncertainties in this analysis were determined before unblinding the results. The calculations were then repeated after unblinding and the results updated, since the blinding offsets can have small effects on the mass fitting. No significant changes were observed. The methods were kept the same and the unblinded results are quoted here. The various sources of systematic uncertainty are grouped into those due to differences in the selection criteria or kinematics between decay modes, those due to trigger efficiency asymmetries, uncertainties on the yield determination and background modelling, resolution in the Dalitz plot, and material interaction effects. Several additional cross checks are described. The systematic uncertainties are summarised in Tables 4.38 and 4.39 at the end of this section. The overall systematic uncertainties, for comparison with the individual uncertainties described below, are 0.14% for A_{CP} in both D^+ and D_s^+ decays, and 0.18% for $A_{CP|S}$.

4.10.1 Introduction to detector asymmetries

This analysis method is constructed to ensure that systematic biases on the raw charge asymmetries cancel as far as possible. Systematic uncertainties are assigned for residual non-cancellation. A major source of uncertainty relates to the fact that each polarity of the magnetic field bends oppositely charged particles in opposite directions so they pass through different parts of the detector which will not necessarily have the same efficiencies. The principle is illustrated in Fig. 4.26.

The raw asymmetry variation with the azimuthal angle around the beam axis ϕ is shown in Fig. 4.27(a). The $\phi = 0$ ('left', $x < 0$) and $\phi = \pm\pi$ ('right', $x > 0$) directions are in the bending plane of the magnet: the magnet bends particles in the xz plane and does not change the y component of their momentum. The asymmetry mostly cancels when data in the full range of ϕ are combined. However, small differences in the tracking efficiency or acceptance between the two halves of the detector lead to imperfections in this cancellation. These are reduced by the subtraction of the asymmetries in the two final states in Eq. 4.2 but not eliminated as the two decays are not kinematically identical. In the data taken with one magnet polarity, the imperfections bias the charge asymmetry, but when the magnet polarity is reversed the bias on the asymmetry changes sign because the particles are deflected in the opposite directions.

The values of A_{CP} in $D^+ \rightarrow \phi\pi^+$ decays are found to differ by $(0.81 \pm 0.28)\%$ between the data taken with magnet polarity up and data taken with polarity down, so the scale of the effect is half of this difference or $(0.41 \pm 0.14)\%$. As the bias changes sign when the magnet polarity is reversed, it is removed, to a very good approximation, by combining results obtained with opposite magnet polarities in a simple average with equal weights.

The systematic uncertainty in A_{CP} associated with the cancellation of this left/right asymmetry is determined by considering how imperfections in the cancellation could arise. One clue is given by the data sample of candidates which are triggered by the bachelor

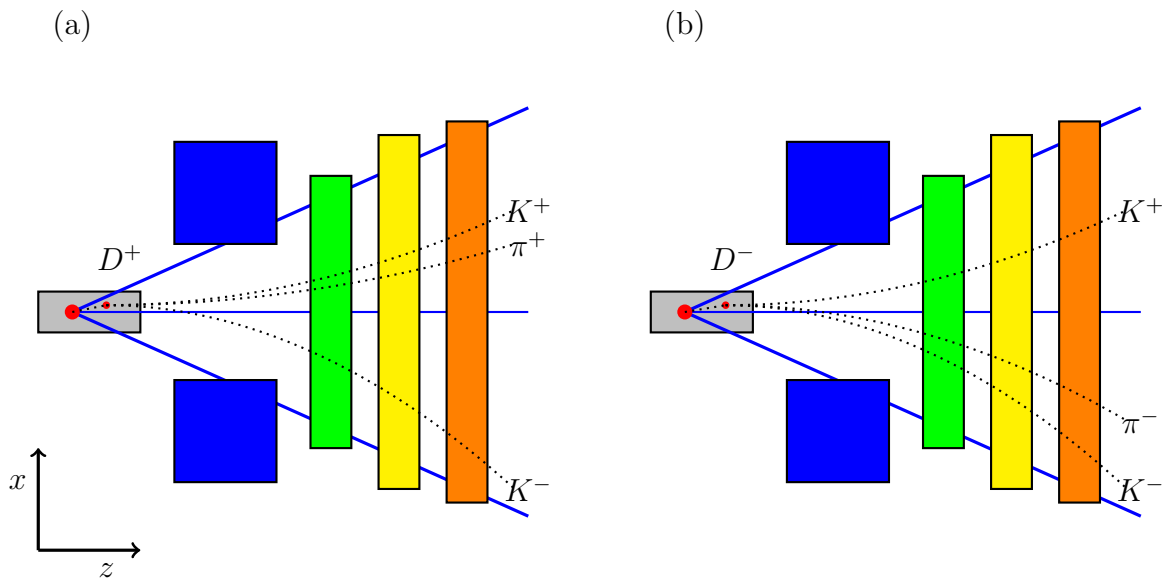


Figure 4.26: Cartoon showing the possible paths of tracks indicated by dotted lines through the LHCb detector from vertices indicated by red dots, (a) of a D^+ decay and (b) of a D^- decay, inspired by Ref. [97]. The trajectories of the K^- and K^+ are the same but that of the π^+ changes.

pion in the hardware trigger. These candidates were found to be biased in Sect. 4.3 and so are not used in the analysis. The bias may result from an imperfect cancellation of the enormous left/right asymmetry of up to $\pm 60\%$ shown in Fig. 4.27(b) when the data samples with pions pointing into the left and right sides of the detector are summed. Alternatively, it may be due to a material interaction asymmetry of positive and negative pions with the calorimeter. Both of these sources of bias should cancel to a good approximation when the charge asymmetries in the signal $D^+ \rightarrow \phi\pi^+$ and control $D^+ \rightarrow K_S^0\pi^+$ decay are subtracted. However, the fact that the results in the two magnet polarities are inconsistent with a significance of just under three Gaussian standard deviations indicates that the cancellation between final states is not perfect, so a more detailed study is required. This is performed by first testing the consistency of the asymmetries with different treatments of the kinematics in the two final states, and second by studying the different triggers involved. These are discussed in turn below, followed by an explanation

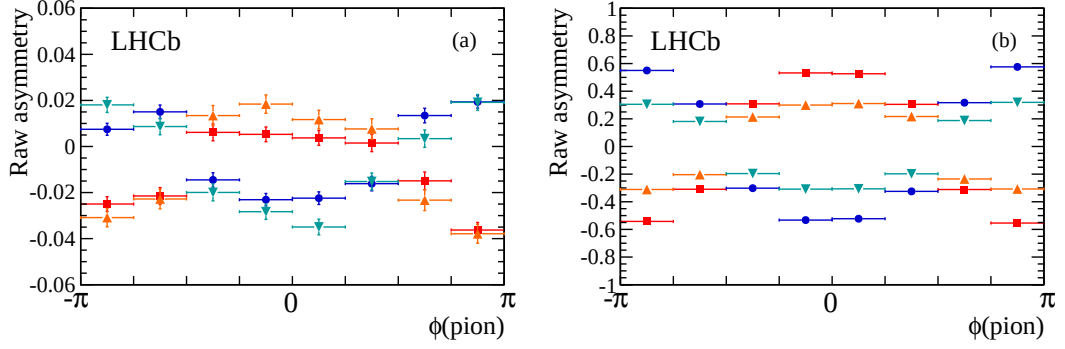


Figure 4.27: The raw charge asymmetry for (a) candidates selected with the trigger requirements defined in Sect. 4.2 and (b) signal candidates triggered by the bachelor pion at the hardware level. In each plot, the asymmetry is shown in eight bins of azimuthal angle ϕ . The asymmetry for $D^+ \rightarrow \phi\pi^+$ is shown in red with square markers for magnet up data and in dark blue with circular markers for magnet down data. The asymmetry for $D^+ \rightarrow K_s^0\pi^+$ is shown in orange with upward pointing triangles for magnet up data and in light blue with downward pointing triangles for magnet down data. The different vertical scales in (a) and (b) reflect the large differences in asymmetry between the two datasets.

of the systematic uncertainty on $A_{CP}|_S$.

4.10.2 Investigation of kinematic effects

While the kinematic binning in (p_T, η) of the D^+ described in Sect. 4.7 substantially reduces the effect of differences in the kinematic distributions of the two modes, some residual differences remain. If this implies that more tracks from one decay than from the other travel through an asymmetric part of the detector, a systematic bias could result.

The possibility of such a bias is studied by applying several different kinematic binning schemes to the data. A reminder of the baseline binning scheme is shown in Fig. 4.28, together with one of the cross-checking schemes, which uses 3×4 p_T, η bins instead of 4×3 . Perhaps more important cross checks are performed using a finer binning with 8×6 p_T, η bins, and with schemes in which the pion kinematics are also binned.

The measured asymmetry is found to be stable with variations in the binning, suggest-

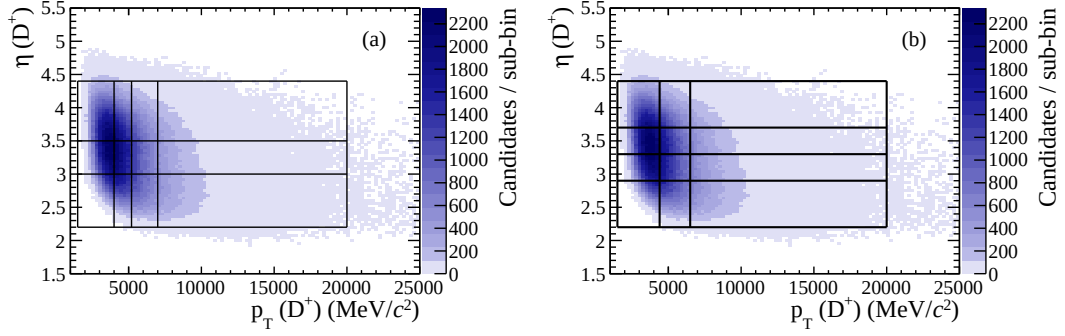


Figure 4.28: Binning schemes superimposed on the distribution of p_T and η of the $D^+ \rightarrow K_S^0 \pi^+$ candidates in (a) the baseline and (b) one of the cross-checking configurations.

Binning	Change in A_{CP} ($\times 10^{-4}$)
Baseline 12 bins ($4 \times D_{(s)}^+ p_T$, $3 \times D_{(s)}^+ \eta$)	0.0 ± 0.0
No binning	8.3 ± 3.7
12 bins ($3 \times D_{(s)}^+ p_T$, $4 \times D_{(s)}^+ \eta$)	0.6 ± 1.7
48 bins ($8 \times D_{(s)}^+ p_T$, $6 \times D_{(s)}^+ \eta$)	-2.9 ± 1.1
192 bins ($2 \times \pi^+ p$, $8 \times \pi^+ \phi$, $4 \times D_{(s)}^+ p_T$, $3 \times D_{(s)}^+ \eta$)	-2.4 ± 1.5
180 bins ($3 \times \pi^+ p_T$, $5 \times \pi^+ \eta$, $4 \times D_{(s)}^+ p_T$, $3 \times D_{(s)}^+ \eta$)	3.5 ± 2.6
1440 bins ($3 \times \pi^+ p_T$, $5 \times \pi^+ \eta$, $8 \times \pi^+ \phi$, $4 \times D_{(s)}^+ p_T$, $3 \times D_{(s)}^+ \eta$)	2.5 ± 1.6

Table 4.13: Changes to the final result observed with various alternative kinematic binning schemes. The statistical uncertainties are determined by subtracting the uncertainties on the alternative result and the default result in quadrature.

ing that the detector asymmetries are small. The results are summarised in Table 4.13. The difference between results obtained with magnet up and magnet down data decreases by up to 0.2% in the schemes in which the pion kinematics are binned. The largest discrepancy in raw asymmetry, as expected, results from using no kinematic binning, as this does not account for any variation of the $D^\pm$ production asymmetry across the kinematic region. This is clearly too crude, but the other binning choices are reasonable. The largest difference of the raw asymmetry in a non-trivial binning scheme from the baseline, of 0.035%, is assigned as a systematic uncertainty on the asymmetry due to residual differences between decay modes and appears in Table 4.38.

	Magnet up	Magnet down	Average
$D^+ \rightarrow K_s^0 \pi^+$, with fid. cuts	-0.885 ± 0.163	-0.687 ± 0.135	-0.786 ± 0.106
$D^+ \rightarrow K_s^0 \pi^+$, no fid. cuts	-0.887 ± 0.163	-0.726 ± 0.134	-0.807 ± 0.105
$\Delta(\text{with/without fid. cuts})$	0.002 ± 0.017	0.039 ± 0.016	0.021 ± 0.011
$D^+ \rightarrow \phi \pi^+$, with fid. cuts	-1.100 ± 0.127	-0.297 ± 0.106	-0.698 ± 0.083
$D^+ \rightarrow \phi \pi^+$, no fid. cuts	-1.108 ± 0.126	-0.304 ± 0.105	-0.706 ± 0.082
$\Delta(\text{with/without fid. cuts})$	0.009 ± 0.015	0.007 ± 0.013	0.008 ± 0.010

Table 4.14: The effect of fiducial cuts on the charge asymmetries in the two final states. The third and last rows give the differences between the values in the previous two rows.

The differences between final states could have particularly large effects on A_{CP} in regions of phase space where the charge asymmetry is already large. Applying the fiducial cuts described in Sect. 4.7 to remove the regions of high asymmetry shown in Figs. 4.19 to 4.22 makes a difference of 0.021% to the asymmetry in the $D^+ \rightarrow K_s^0 \pi^+$ decay, mostly due to the magnet down sample, and an 0.008% difference in the $D^+ \rightarrow \phi \pi^+$ decay. However, it is possible that the cuts prevent small biases from cancelling out within a detector half. Therefore the differences in asymmetry between applying and leaving out the requirements, added in quadrature, are assigned as a systematic uncertainty. This takes the value of 0.022% and also appears in Table 4.38.

4.10.3 Investigation of the effect of the trigger

Table 4.15 gives the final results as calculated by sideband subtraction for the different trigger types. The magnet polarity differences in the data appear to result mostly from the muon, electron and photon triggers. This is consistent with our expectation from the control decay modes. As explained in Sect. 2.13, data in which a particle from the signal candidate activates the trigger is referred to as ‘TOS’ while data in which the trigger is fired by a particle which does not form part of the signal decay is called ‘TIS’.

Table 4.16 presents the raw asymmetries in the differently triggered data samples in

	Magnet up	Magnet down	Average	Difference
Overall	-0.40 ± 0.21	0.41 ± 0.18	0.01 ± 0.14	-0.81 ± 0.28
TOSMuHadTIS	-0.27 ± 0.24	0.26 ± 0.20	-0.00 ± 0.15	-0.53 ± 0.31
ϕ/K_s^0 TOS	-0.36 ± 0.70	0.09 ± 0.58	-0.14 ± 0.45	-0.45 ± 0.90
Hadron TIS	-0.02 ± 0.31	0.46 ± 0.25	0.22 ± 0.20	-0.48 ± 0.40
Muon TIS	-0.52 ± 0.38	0.23 ± 0.32	-0.15 ± 0.25	-0.74 ± 0.50
Electron TIS	-0.48 ± 0.47	1.01 ± 0.40	0.26 ± 0.31	-1.49 ± 0.62
Photon TIS	-1.32 ± 0.69	1.08 ± 0.58	-0.12 ± 0.45	-2.40 ± 0.90
Pion TOS	0.13 ± 0.55	1.57 ± 0.46	0.85 ± 0.36	-1.44 ± 0.72

Table 4.15: A_{CP} values for the different hardware trigger types calculated by sideband subtraction in the baseline kinematic binning scheme, without correction for CPV in the neutral kaon system. The TOSMuHadTIS row indicates what the result would be if the photon and electron triggers were excluded from the analysis. As discussed in Sect. 4.3, the “Pion TOS” data, the sample of decays triggered only by the pion at the hardware stage, are not used because we do not have sufficient confidence in the cancellation between final states in this data.

Trigger sample	Magnet up	Magnet down	Average	Difference
Overall	-1.06 ± 0.13	-0.31 ± 0.11	-0.69 ± 0.08	-0.76 ± 0.17
ϕ TOS	-0.94 ± 0.34	-0.33 ± 0.28	-0.63 ± 0.22	-0.61 ± 0.44
Hadron TIS	-0.72 ± 0.18	-0.20 ± 0.15	-0.46 ± 0.12	-0.52 ± 0.24
Muon TIS	-1.53 ± 0.23	-0.12 ± 0.20	-0.83 ± 0.15	-1.41 ± 0.30
Electron TIS	-1.01 ± 0.28	-0.35 ± 0.23	-0.68 ± 0.18	-0.67 ± 0.36
Photon TIS	-1.37 ± 0.41	-0.43 ± 0.34	-0.90 ± 0.26	-0.94 ± 0.53
Pion TOS	0.12 ± 0.25	1.09 ± 0.20	0.61 ± 0.16	-0.97 ± 0.32
Overall	-0.85 ± 0.16	-0.69 ± 0.13	-0.77 ± 0.10	-0.16 ± 0.20
K_s^0 TOS	-1.14 ± 0.53	-0.65 ± 0.44	-0.90 ± 0.35	-0.49 ± 0.69
Hadron TIS	-0.75 ± 0.22	-0.63 ± 0.19	-0.69 ± 0.15	-0.12 ± 0.29
Muon TIS	-1.25 ± 0.27	-0.25 ± 0.23	-0.75 ± 0.18	-0.99 ± 0.36
Electron TIS	-0.70 ± 0.35	-1.28 ± 0.29	-0.99 ± 0.23	0.59 ± 0.46
Photon TIS	-0.24 ± 0.51	-1.35 ± 0.43	-0.79 ± 0.33	1.11 ± 0.67
Pion TOS	0.30 ± 0.44	-0.80 ± 0.37	-0.25 ± 0.29	1.10 ± 0.57

Table 4.16: Raw asymmetries in differently triggered datasets at the hardware stage, in %, for the two magnet polarities for the $D^+ \rightarrow \phi\pi^+$ signal channel (top) and the $D^+ \rightarrow K_s^0\pi^+$ control channel (bottom), using a weighted average over bins. All yields are calculated by sideband subtraction in the baseline kinematic bins.

the $D^+ \rightarrow \phi\pi^+$ and $D^+ \rightarrow K_s^0\pi^+$ decays separately. There is an additional contribution to the discrepancy between magnet up and magnet down data in the individual final

states from an effect specific to events from the muon hardware trigger. In the 2011 running period and in the simulation, the positions of the muon pads in stations were incorrectly approximated. This shifted the transverse momentum estimate of the positive and negative muons in opposite directions. Then, due to the p_T cut in the muon hardware trigger, a detector asymmetry was introduced. This is larger at low p_T . Unfortunately the LHCb data structure prevents a correction for this effect being made in this analysis, because the muon tracks which activated the trigger are not stored in datasets available for analysis. It is clear that the most significant discrepancy between magnet up and magnet down data occurs in the events which activated the muon trigger. However, this discrepancy largely cancels in the subtraction when A_{CP} is calculated.

Residual biases from the trigger are studied further using the $D^+ \rightarrow K^- \pi^+ \pi^+$ control channel. The charge asymmetries in the differently triggered datasets are given in Table 4.17. Since a more precise study is required than that described in Sect. 4.3, the full dataset is used, the full offline selection is applied and the asymmetries are calculated by sideband subtraction, resulting in slightly different raw asymmetries to those in Table 4.2. The sample contains approximately 57 million $D^+ \rightarrow K^- \pi^+ \pi^+$ decays. The data triggered by the K_s^0 or ϕ mesons at the hardware level is clearly charge-symmetric to a good approximation, and is assumed to be unbiased. However, in data triggered by another particle in the event, the particle that activates the trigger may easily be correlated to the signal decay, as discussed in Sect. 4.3. For example, a signal decay is often accompanied by a $D^\pm$ meson of the opposite charge. If this meson decays to a charged hadron, electron or muon, the daughter particle, which is more likely to have a charge opposite to that of the signal $D^\pm$, could fire the trigger. The different kinematics and acceptance of the two final states studied in this analysis mean that the cancellation of charge-asymmetric trigger efficiencies between them may not be complete.

Small but significant discrepancies between data from different triggers are observed,

Trigger type	Magnet up	Magnet down	Average	Difference
Hadron	-2.04 ± 0.03	-1.97 ± 0.03	-2.00 ± 0.02	-0.07 ± 0.04
Muon	-2.36 ± 0.04	-1.61 ± 0.04	-1.98 ± 0.03	-0.75 ± 0.05
Electron	-2.10 ± 0.05	-2.20 ± 0.04	-2.15 ± 0.03	0.11 ± 0.06
Photon	-1.94 ± 0.07	-2.23 ± 0.06	-2.08 ± 0.05	0.29 ± 0.09
Overall average	-2.13 ± 0.02	-1.94 ± 0.02	-2.03 ± 0.01	-0.19 ± 0.03

Table 4.17: Raw charge asymmetries in samples of the $D^+ \rightarrow K^- \pi^+ \pi^+$ control decay in which a particle that does not form part of the signal decay activated various hardware triggers.

indicating that the hardware triggers may introduce small biases into the dataset. A systematic uncertainty equal to the maximum deviation from the average charge asymmetry of $(-2.03 \pm 0.01)\%$ in any of the triggers is assigned. The maximum deviation is in the electron trigger, and is 0.114%. This is the dominant systematic uncertainty in Table 4.38. The precision with which effects cancel between $\phi\pi^+$ and $K_s^0\pi^+$ final states in the analysis cannot be quantified accurately and therefore the most conservative approach is adopted: there is assumed to be no cancellation at all.

There is a small additional systematic uncertainty related to the fact that the proportions of signal decays from the various triggers in the two final states are different and the asymmetries associated with the triggers are slightly different. 92.7% of $D^+ \rightarrow K_s^0\pi^+$ candidates are TIS and 10.3% are TOS (the categories are not mutually exclusive), while 90.0% of $D^+ \rightarrow \phi\pi^+$ candidates are TIS and 14.7% are TOS. The difference in asymmetries between TIS and TOS data is measured in the $D^+ \rightarrow K^- \pi^+ \pi^+$ decay where the sample size is high enough that the effects are unlikely to be statistical fluctuations. It is 0.104%, from Table 4.2. This is multiplied by the largest difference in TOS fraction, of 4.4%, to obtain a systematic uncertainty of 0.004%. However, the existing uncertainty for trigger-related effects of 0.114% is large enough that such effects can be subsumed into it, and no additional uncertainty on the result is assigned.

4.10.4 Generic systematic uncertainty on $A_{CP|S}$

The $A_{CP|S}$ observable is inherently robust against systematic uncertainties. Any effect that does not vary across the Dalitz plot will cancel in the subtraction in Eq. 4.5, and effects that do vary with $K^-\pi^+$ or K^-K^+ invariant mass across the ϕ region will also cancel when the regions are combined in the diagonal difference. To investigate the differences within the ϕ resonance, the asymmetries in the four regions and $A_{CP|S}$ are presented in Table 4.18 for the $D^+ \rightarrow \phi\pi^+$ decay. The two magnet polarities are not particularly consistent: overall, the difference between magnet polarities is $1.06 \pm 0.33\%$, just over 3σ . However, when the data taken with both magnet polarities is averaged, the χ^2/ndf for consistency of the four regions is $1.54/3 = 0.51$. This excellent agreement is expected, as only quantities that vary between the diagonals of the Dalitz plot region would lead to significant systematic biases on $A_{CP|S}$. To be sure no such effects exist, $A_{CP|S}$ is calculated in the $D_s^+ \rightarrow \phi\pi^+$ control channel, which has similar kinematics to the signal despite the different Dalitz plot distributions in the decays. The result is $(-0.120 \pm 0.119)\%$. The statistical uncertainty in this result, added in quadrature to the central value, gives a measure of the precision with which detector effects are known to cancel out and is assigned as the main systematic uncertainty in $A_{CP|S}$. The value is 0.169% , which appears in Table 4.39.

4.10.5 Systematic biases on yield determination and background contamination

The yields in all four decay modes are cross-checked by sideband subtraction. Since each fit in an individual $p_T - \eta$ bin is independent it is necessary to cross check each one separately. The signal and sideband regions are defined in Table 4.19. Unlike the window used in the calculation of $A_{CP|S}$, the priority in defining these mass ranges is to encompass

	Magnet up	Magnet down	Average
A	-1.15 ± 0.31	-0.46 ± 0.26	-0.80 ± 0.20
B	-1.45 ± 0.21	0.18 ± 0.18	-0.63 ± 0.14
C	-0.52 ± 0.24	-0.95 ± 0.20	-0.73 ± 0.15
D	-1.02 ± 0.25	-0.08 ± 0.21	-0.55 ± 0.17
A_{raw}	-1.04 ± 0.12	-0.29 ± 0.10	-0.67 ± 0.08
$A_{CP} _S$	0.40 ± 0.26	-0.75 ± 0.21	-0.18 ± 0.17

Table 4.18: The raw asymmetries in the four different regions in the $D^+ \rightarrow \phi\pi^+$ decay, with appropriate abbreviations, for magnet up and magnet down data are given, together with the global average value (i.e. the raw asymmetry in the $D^+ \rightarrow \phi\pi^+$ decay as calculated by counting in a mass window after constraining the D^+ meson mass to the nominal value) and the value of $A_{CP}|_S$. A comparison of the asymmetries in the regions of the D^+ and D_s^+ decays is given later in Table 4.28.

as much of the signal in the signal mass windows as possible, without compromising the statistical precision by using windows for the sidebands that are too small. The χ^2/ndf values for consistency of the fitted and sideband-subtracted results are given in Table 4.20.

The agreement between fits and sideband subtraction is excellent in the $D_{(s)}^+ \rightarrow \phi\pi^+$ final state and in the $D_s^+ \rightarrow K_s^0\pi^+$ decay. In the $D^+ \rightarrow K_s^0\pi^+$ decay, the agreement between fitted and sideband subtracted results is significantly less good than in $D^+ \rightarrow \phi\pi^+$, which is expected because there is a peaking background from the $D_s^+ \rightarrow K_s^0K^+$ decay which is ignored in the sideband subtraction. However, the weighted average raw asymmetry from the fit is $(-0.773 \pm 0.104)\%$ while from sideband subtraction it is $(-0.748 \pm 0.103)\%$, so any bias on the averaged asymmetry is small.

In the signal $D^+ \rightarrow \phi\pi^+$ decay channel, the average raw asymmetries obtained by fitting and sideband subtraction differ by 0.033%. This is adopted as a systematic uncertainty for the modelling of the mass distribution, and appears in Table 4.38.

If the background is ignored in the $\phi\pi^+$ final state it makes very little difference. Therefore, as stipulated in Section 4.5, $A_{CP}|_S$ will be calculated in a mass window. This is defined by eye, for the D_s^+ control channel, as $1940 < m < 1990 \text{ MeV}/c^2$, and for the

Mass interval	Range for $\phi\pi^+$ (MeV/ c^2)	Range for $K_s^0\pi^+$ (MeV/ c^2)
Low sideband	[1810, 1830]	[1800, 1830]
D^+ window	[1830, 1900]	[1830, 1910]
Middle sideband	[1900, 1920]	[1910, 1945]
D_s^+ window	[1920, 2005]	[1945, 1995]
High sideband	[2005, 2030]	[1995, 2035]

Table 4.19: Signal and sideband regions for the sideband subtraction in the two final states.

Decay mode	χ^2/ndf
$D^+ \rightarrow \phi\pi^+$	0.95
$D_s^+ \rightarrow \phi\pi^+$	0.92
$D^+ \rightarrow K_s^0\pi^+$	14.77
$D_s^+ \rightarrow K_s^0\pi^+$	0.88

Table 4.20: Values of χ^2/ndf for consistency of the fitted and sideband subtracted raw asymmetries in each decay channel. The χ^2 is calculated by summing the squares of the difference between the fit and the sideband subtraction divided by the square of the uncertainties subtracted in quadrature.

signal $D^+ \rightarrow \phi\pi^+$ decay as $1845 < m < 1895 \text{ MeV}/c^2$. These ranges are tighter than the mass window used to calculate the yields and raw asymmetries by sideband subtraction in the interests of keeping the signal pure.

The yields and raw asymmetries from counting, sideband subtraction, and fitting are compared in Table 4.21. The results are weighted averages over the p_T , η bins. The systematic uncertainty that arises from ignoring the background in $A_{CP}|_S$ is equal to the difference between the raw asymmetry in the fitted result and counted result, which is 0.007%. This value appears in Table 4.39.

To cross check the systematic uncertainty assigned for possible imperfections in the modelling of the mass distributions, the order of the background polynomial is changed from one to two. The fits to the whole p_T, η space are repeated and yield good results, shown in Fig. 4.29. The raw asymmetries are given in Table 4.22, and show only very

	Fit	Sideband-subtract	Counting
Yield (total) $\times 10^6$	3.0699 ± 0.0018	3.0671 ± 0.0017	3.0618 ± 0.0017
Raw asym. (mag-av) (%)	-0.4180 ± 0.0586	-0.4140 ± 0.0594	-0.4112 ± 0.0582
Yield (mag-up) $\times 10^6$	1.2461 ± 0.0011	1.2452 ± 0.0011	1.2427 ± 0.0011
Raw asym (mag-up) (%)	-0.7611 ± 0.0903	-0.7619 ± 0.0915	-0.7603 ± 0.0897
Yield (mag-down) $\times 10^6$	1.8237 ± 0.0013	1.8219 ± 0.0012	1.8191 ± 0.0013
Raw asym (mag-down) (%)	-0.0744 ± 0.0747	-0.0659 ± 0.0756	-0.0620 ± 0.0741

Table 4.21: Yields and raw asymmetries as determined by fitting, sideband subtraction and counting, for the $D_s^+ \rightarrow \phi\pi^+$ decay. It is clear that ignoring the background in the counting technique makes very little difference.

	Magnet up	Magnet down	Average
$D^+ \rightarrow \phi\pi^+$, Cruijff, linear bkg	-1.100 ± 0.127	-0.297 ± 0.106	-0.698 ± 0.083
$D^+ \rightarrow \phi\pi^+$, Cruijff, quad bkg	-1.113 ± 0.126	-0.339 ± 0.105	-0.726 ± 0.082
$\Delta(1\text{st}/2\text{nd order})$	0.013 ± 0.013	0.042 ± 0.011	0.028 ± 0.008
$D^+ \rightarrow K_s^0\pi^+$, Cruijff, linear bkg	-0.885 ± 0.163	-0.687 ± 0.135	-0.786 ± 0.106
$D^+ \rightarrow K_s^0\pi^+$, Cruijff, quad bkg	-0.888 ± 0.165	-0.689 ± 0.135	-0.789 ± 0.107
$\Delta(1\text{st}/2\text{nd order})$	0.004 ± 0.022	0.002 ± 0.015	0.003 ± 0.013

Table 4.22: Table of asymmetries in the D^+ decay, in %, with different choices of mass fitting function. Uncertainties on the differences are subtracted in quadrature as they are fully correlated.

small differences between background orders. The largest difference to a magnet-averaged value, 0.028%, is smaller than the existing systematic uncertainty for the mass fitting of 0.033% so no additional uncertainty is assigned.

The mis-identification rates from the calibration of the particle identification system can also be used to check that the cross-feed in the $D^+ \rightarrow K_s^0\pi^+$ mode from $D_s^+ \rightarrow K_s^0K^+$ decays in the fit is correctly accounted for. They are shown in bins of particle momentum in Fig. 4.30 for the cuts in use in this analysis. The bulk of the data lies in the high-efficiency region, so from this plot the rate of real kaons being mis-identified as pions is roughly estimated as 3%. The branching ratios of $D^+ \rightarrow K_s^0\pi^+$ and $D_s^+ \rightarrow K_s^0K^+$ decays are very similar and the reconstruction efficiencies for $D_s^+ \rightarrow K_s^0K^+$ are assumed to be

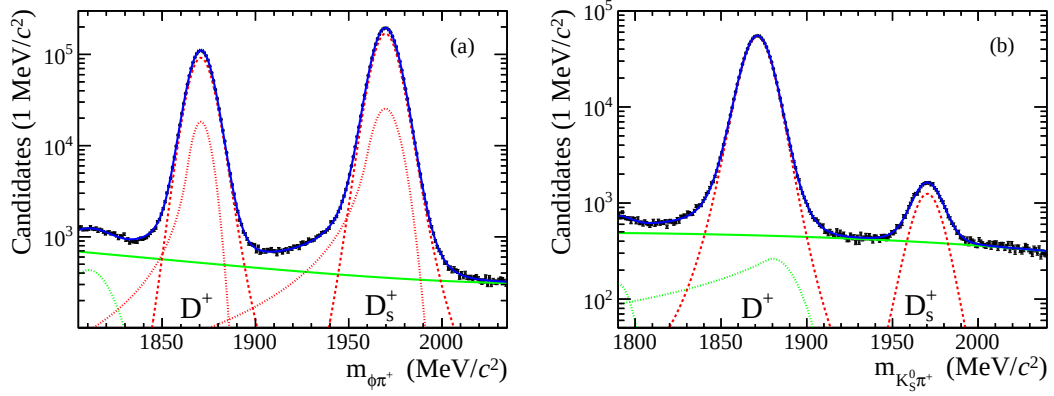


Figure 4.29: Fits to the whole p_T - η space with second order background polynomial, (a) for $\phi\pi^+$ final states and (b) for $K_S^0\pi^+$ final states.

	Magnet up	Magnet down	Average
No cross-feed	-0.880 ± 0.155	-0.684 ± 0.130	-0.782 ± 0.101
With cross-feed	-0.885 ± 0.163	-0.687 ± 0.135	-0.786 ± 0.106

Table 4.23: Raw asymmetries with and without the cross-feed contribution from $D_s^+ \rightarrow K_S^0 K^+$ to the $D^+ \rightarrow K_S^0 \pi^+$ decay.

the same as for $D_s^+ \rightarrow K_S^0 \pi^+$. All cross-feed candidates are assumed conservatively to lie under the D^+ mass peak. Therefore the only difference between cross-feed and signal are the D_s^+/D^+ cross section ratio (0.27) [9] and the mis-identification rate, 3%. Multiplying these numbers together gives 0.4%, a reasonable upper bound on the contamination from $D_s^+ \rightarrow K_S^0 K^+$ decays. The upper bound on the difference in asymmetry between $D^+ \rightarrow K_S^0 \pi^+$ and $D_s^+ \rightarrow K_S^0 K^+$ channels is then about 2%, so the effect on the asymmetry result is estimated at 0.008%.

To check this value, the data is fitted without this cross feed contribution included. The fit is shown in Fig. 4.31(a). The difference in raw asymmetries with and without the component is 0.004%, from Table 4.23. We take the larger difference, 0.008%, as a conservative systematic uncertainty, and this value features in Table 4.38.

There are a few other potential backgrounds that are not explicitly accounted for in

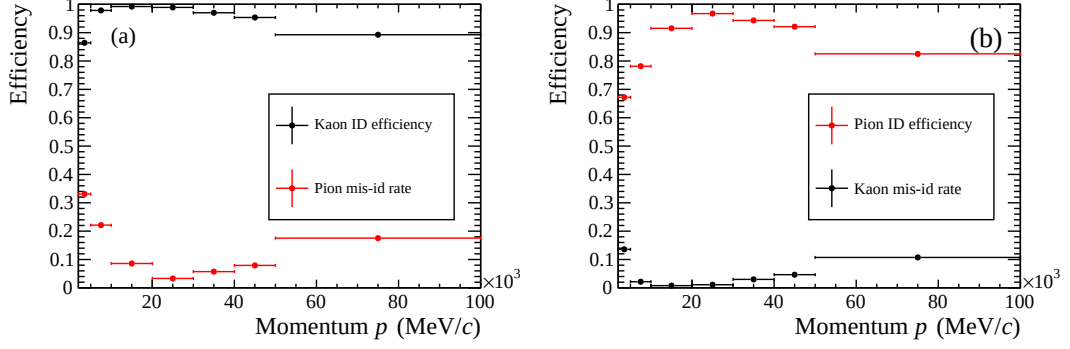


Figure 4.30: Magnet-averaged efficiencies of (a) selecting kaons and rejecting pions for $\Delta_{LL}(K - \pi) > 0$ and (b) selecting pions and rejecting kaons for $\Delta_{LL}(K - \pi) < 0$.

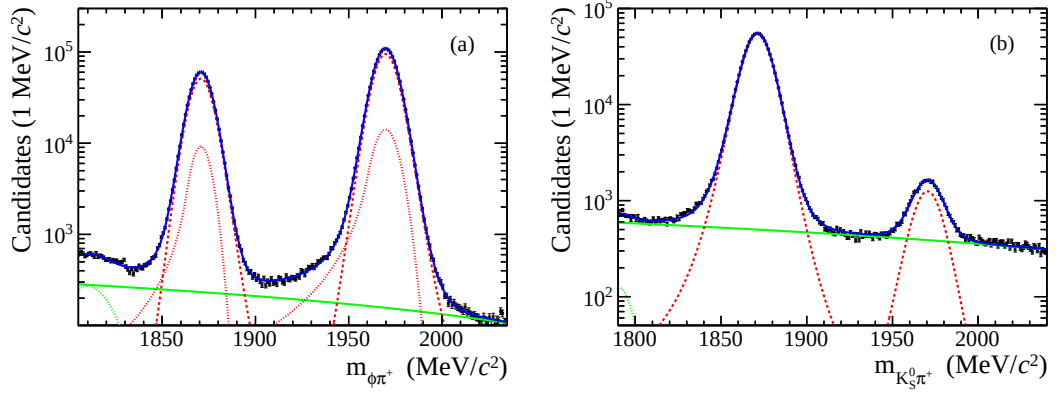


Figure 4.31: Fits to (a) the $\phi\pi^+$ decay mode with a tighter kaon identification requirement ($\Delta_{LL}(K - \pi) > 20$) and (b) the $K_s^0\pi^+$ final state with cross-feed ignored.

the fit. The $D^+ \rightarrow K^- \pi^+ \pi^+$ decay could potentially lead to a reflection at high mass in the $\phi\pi^+$ mass spectrum. The tight kaon identification requirements should exclude most of this already and Fig. 4.8 demonstrates that no significant background exists. However, tightening the kaon identification requirements is still a useful cross check, since it also verifies that the charge asymmetry is independent of the particular requirements used. Thus the kaon ID cut is tightened from $\Delta_{LL}(K - \pi) > 12$ to $\Delta_{LL}(K - \pi) > 20$, which removes around 45% of the dataset. The fit to the mass distribution of the remaining candidates is in Fig. 4.31b. The raw asymmetries change slightly, but not significantly,

	Magnet up	Magnet down	Average
$D^+ \rightarrow K_s^0 \pi^+$, standard	-0.885 ± 0.163	-0.687 ± 0.135	-0.786 ± 0.106
$D^+ \rightarrow K_s^0 \pi^+$, tight proton ID	-0.990 ± 0.172	-0.611 ± 0.142	-0.800 ± 0.111
$\Delta(\text{standard/tight})$	0.105 ± 0.053	0.077 ± 0.044	0.014 ± 0.034
$D^+ \rightarrow \phi \pi^+$, standard	-1.100 ± 0.127	-0.297 ± 0.106	-0.698 ± 0.083
$D^+ \rightarrow \phi \pi^+$, tight proton ID	-1.095 ± 0.129	-0.278 ± 0.108	-0.687 ± 0.084
$\Delta(\text{standard/tight})$	0.005 ± 0.025	0.019 ± 0.021	0.012 ± 0.017
$D^+ \rightarrow \phi \pi^+$, tight kaon ID	-1.230 ± 0.170	-0.133 ± 0.142	-0.681 ± 0.111
$\Delta(\text{standard/tight})$	0.130 ± 0.114	0.164 ± 0.094	0.017 ± 0.074

Table 4.24: Table of asymmetries, in %, with different particle identification requirements. For the differences, the uncertainties on the asymmetries for the different criteria are subtracted in quadrature as the datasets overlap.

as shown in Table 4.24.

Another potential background is from Λ_c decays, either to $\Lambda^0 \pi^+$ or to $p K^- \pi^+$. Requirements on the proton likelihood from the RICH system are introduced to suppress this background by vetoing particles consistent with a proton mass hypothesis. The cuts are 90% efficient on the $\phi \pi^+$ dataset and 62% efficient on the $K_s^0 \pi^+$ dataset. The fits to the mass distribution of the remaining candidates are in Fig. 4.32. The raw asymmetries that result from these cuts are also shown in Table 4.24. No significant change in asymmetry is observed so these cuts are not included in the baseline selection criteria.

The differences in charge asymmetries between the rows of Table 4.24 for separate magnet polarities, while not statistically significant, could be due to time-dependent inhomogeneities in the RICH detectors, which are discussed briefly in Sect. 2.5. The differences that remain after the polarities are averaged are fully consistent with zero. Therefore no additional systematic uncertainty is assigned, apart from the 0.008% determined for the cross-feed.

It is likely that there is a small fraction of D from B decays in the sample. B and D mesons have different production asymmetries. Differences between the fraction of D from B in the two final states would lead to a difference in the average production

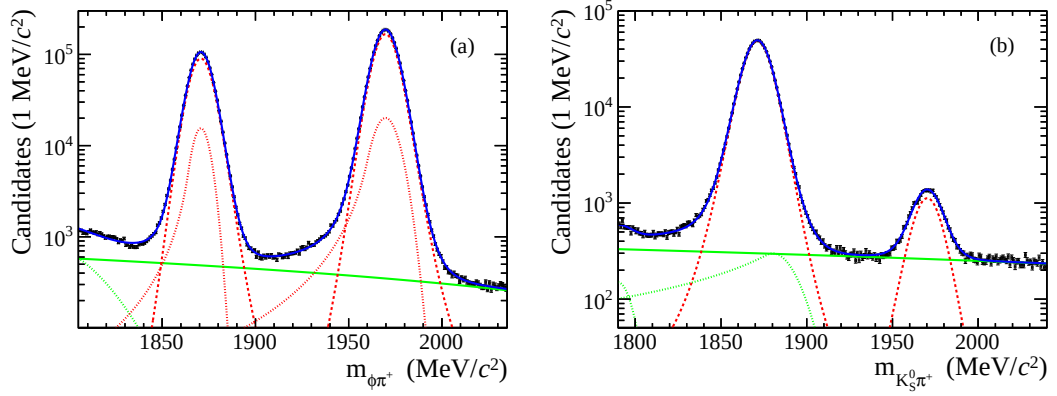


Figure 4.32: Fits to (a) the invariant mass distributions of the $\phi\pi^+$ and (b) the $K_s^0\pi^+$ final states with tighter proton PID requirements as explained in the caption of Table 4.24.

asymmetry, which would fake a signal of CP violation.

The $B^\pm$ production asymmetry is assumed to be $(-0.8 \pm 0.7)\%$ [60]. This is given the opposite convention to the asymmetries we calculate here,

$$A_{prod} \sim \frac{N_{B^-} - N_{B^+}}{N_{B^-} + N_{B^+}} \quad (4.21)$$

The B^0 and B_s^0 production asymmetries have been measured to be $(-1.5 \pm 1.3)\%$ and $(-3 \pm 6)\%$ [98]. However, B^+ and B^0 decay to D^- and B^- and $\bar{B}^0$ decay to D^+ so the effective D from B production asymmetries for D 's from B^+ and B^0 are still $(-0.8 \pm 0.7)\%$ and $-(1.5 \pm 1.3)\%$. Unfortunately the Λ_b production asymmetry is not measured. For the purposes of this study, the D from B production asymmetry is assumed to be -1.5% . The D^+ production asymmetry is $(-0.96 \pm 0.32)\%$ [8], and the D_s^+ production asymmetry is $(-0.33 \pm 0.24)\%$ [84].

The reconstruction, trigger and selection efficiencies for prompt D decays, which originate from the PV, and D from B decays, are calculated from simulation and shown in Table 4.25. From Ref. [79], the D^+ cross section in the LHCb acceptance is $(717 \pm 109) \mu\text{b}$, the D_s^+ cross section is $(194 \pm 38) \mu\text{b}$ and from Ref. [99] the cross section to produce hadrons

Decay mode	Prompt efficiency	D from B Efficiency
$D^+ \rightarrow K_s^0 \pi^+$	$(1.57 \pm 0.04) \times 10^{-4}$	$(0.92 \pm 0.11) \times 10^{-4}$
$D_s^+ \rightarrow K_s^0 \pi^+$	$1.04 \pm 0.19) \times 10^{-4}$	$(0.93 \pm 0.54) \times 10^{-4}$
$D^+ \rightarrow \phi \pi^+$	$(14.46 \pm 0.32) \times 10^{-4}$	$(7.58 \pm 0.80) \times 10^{-4}$
$D_s^+ \rightarrow \phi \pi^+$	$(8.46 \pm 0.24) \times 10^{-4}$	$(6.25 \pm 0.59) \times 10^{-4}$

Table 4.25: Reconstruction, trigger and selection efficiencies for prompt and D from B charm.

Decay mode	$\sigma(\text{prompt}) (\mu\text{b})$	$\sigma(\text{D from B}) (\mu\text{b})$
$D^+ \rightarrow K_s^0 \pi^+$	10.68 ± 1.62	0.255 ± 0.048
$D_s^+ \rightarrow K_s^0 \pi^+$	0.23 ± 0.05	0.014 ± 0.003
$D^+ \rightarrow \phi \pi^+$	1.95 ± 0.29	0.047 ± 0.009
$D_s^+ \rightarrow \phi \pi^+$	4.50 ± 0.88	0.273 ± 0.051

Table 4.26: Cross sections for prompt and D from B decay multiplied by the branching ratio to the decay mode listed.

containing a b -quark is $(75.3 \pm 14.1) \mu\text{b}$. The Particle Data Group [16] gives the relevant branching ratios, and thus the expected fraction of D from B decays in the sample can be estimated without relying on the cross sections in the simulation, which may not be accurate. The same procedure is used for the D_s^+ modes.

The cross sections for prompt and D from B particles are expected to be as shown in Table 4.26. The fraction of D from B decays expected in the four decays under study is given by

$$f = \frac{\sigma_B \epsilon_B}{\sigma_D \epsilon_D + \sigma_B \epsilon_B} \quad (4.22)$$

where σ is the cross section and $\epsilon_{D,B}$ the efficiency for prompt and D from B decays respectively. The fractions are given in Table 4.27. It is clear in this table that the LHCb simulation underestimates the ratio of the production of prompt charm to charm from B decays. The efficiency of the requirement in the simulation that the decay products are found within the acceptance of the LHCb detector is assumed to be the same for each pair of D^+ and D_s^+ decay channels; it is unlikely to differ by more than 5% so will not

Decay mode	f	f in LHCb MC	$A_{prod.}$	$A_{prod.}$ (MC)
$D^+ \rightarrow K_s^0 \pi^+$	$(1.39 \pm 0.37)\%$	$(4.65 \pm 0.53)\%$	-1.007%	-1.023%
$D_s^+ \rightarrow K_s^0 \pi^+$	$(5.14 \pm 3.24)\%$	$(9.38 \pm 5.15)\%$	-0.390%	-0.440%
$D^+ \rightarrow \phi \pi^+$	$(1.23 \pm 0.32)\%$	$(4.25 \pm 0.44)\%$	-1.006%	-1.021%
$D_s^+ \rightarrow \phi \pi^+$	$(4.29 \pm 1.18)\%$	$(8.08 \pm 0.73)\%$	-0.380%	-0.425%

Table 4.27: Fraction of D from B decays f , and overall (combined) production asymmetry based on the initial conservative guesses of the prompt and D from B production asymmetries above.

affect the results significantly.

The overall difference in effective production asymmetry between particles reconstructed and selected in the two final states of interest is then the systematic uncertainty. For D^+ this is 0.001%, as calculated from the measured cross sections and efficiencies, and 0.002% as calculated from the simulation. For D_s^+ it is 0.010% from the cross sections and 0.015% from the simulation. The larger value, of 0.002% for the D^+ decays and 0.015% for the D_s^+ decays, is assigned as a systematic uncertainty in each case. These values appear in Table 4.38.

In the $D^+ \rightarrow \phi \pi^+$ dataset, 0.018% of the events have more than one signal candidate in the mass peak. In the $D^+ \rightarrow K_s^0 \pi^+$ decay this fraction is 0.006%. An upper bound on the expected number of multiple candidates is given by the efficiency multiplied by the branching ratio for $D^+ \rightarrow \phi \pi^+$ or $D^+ \rightarrow K_s^0 \pi^+$, assuming that every D^+ candidate has a corresponding D^- candidate partner which also points into the detector. This is $3.8 \times 10^{-4}\%$ for $\phi \pi^+$ and $2.3 \times 10^{-4}\%$ for $K_s^0 \pi^+$. The number of multiple candidates observed is larger than that expected, perhaps due to background from multiple pions being paired with the same ϕ candidate, but the effect is negligible.

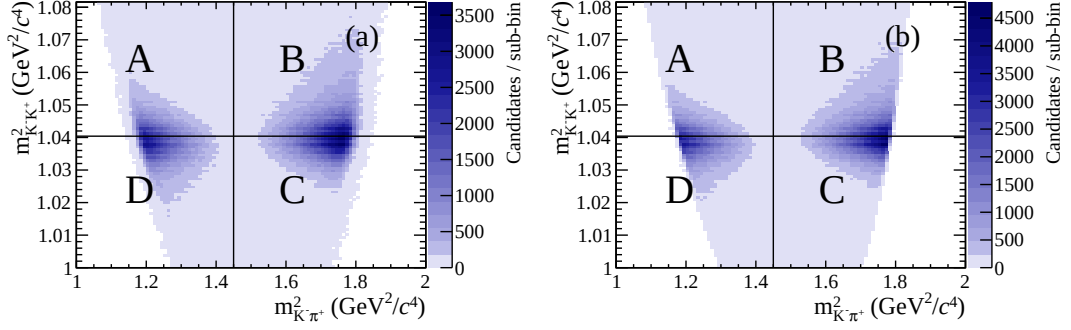


Figure 4.33: The ϕ resonance in the $D^+ \rightarrow K^- K^+ \pi^+$ Dalitz plot with the regions defined by solid black lines, with (a) no mass constraint and (b) with the D^+ mass constrained to the nominal value. The improvement in resolution in the Dalitz plot is apparent.

4.10.6 Systematic biases due to resolution effects

The resolution in the Dalitz plot of the $D_{(s)}^+ \rightarrow K^- K^+ \pi^+$ decay can be improved by constraining the $D_{(s)}^+$ mass to the world average value [16]. It was noted in Sect. 4.5 that the measured mass of the D meson differs between magnet down and magnet up data and between D^+ and D^- . The difference is small, around $0.2 \text{ MeV}/c^2$, and the effect of the mass constraint on $A_{CP}|_S$ is small. However, if the reconstruction is charge-asymmetric, it is better, particularly for $A_{CP}|_S$, to constrain the mass so that the kinematic limits of the Dalitz plots for D^- and D^+ are constrained to be the same. This removes small artificial asymmetry effects at the edges where the overlap of the Dalitz plots of the $D_{(s)}^+$ and $D_{(s)}^-$ decays is incomplete.

The asymmetries in the four regions which make up $A_{CP}|_S$ in $D_{(s)}^+ \rightarrow \phi \pi^+$ decays are tabulated with and without the mass constraint for the two magnet polarities separately and their arithmetic average in Table 4.28. There are relatively large differences in individual magnet polarities between results with and without the mass constraint in the individual regions. This is because the difference in the masses between D^+ and D^- mesons is of opposite sign for each magnet polarity, so the mass constraint has a much

Region	$D_s^+ A_{\text{raw}} (\text{cstr.})$	$D_s^+ A_{\text{raw}} (\text{w/o cstr.})$	$D^+ A_{\text{raw}} (\text{cstr.})$	$D^+ A_{\text{raw}} (\text{w/o cstr.})$
MU A_{raw}	-0.76 ± 0.09	-0.78 ± 0.09	-1.04 ± 0.12	-1.05 ± 0.12
MU: A	-0.78 ± 0.18	-0.56 ± 0.17	-1.15 ± 0.31	-0.93 ± 0.31
MU: B	-1.40 ± 0.20	-1.20 ± 0.20	-1.45 ± 0.22	-1.31 ± 0.21
MU: C	0.11 ± 0.20	-0.04 ± 0.20	-0.52 ± 0.24	-0.71 ± 0.24
MU: D	-0.89 ± 0.15	-1.15 ± 0.16	-1.02 ± 0.25	-1.16 ± 0.26
MU: $A_{CP S}$	0.81 ± 0.18	0.88 ± 0.18	0.40 ± 0.26	0.42 ± 0.26
MD A_{raw}	-0.06 ± 0.08	-0.06 ± 0.07	-0.29 ± 0.10	-0.27 ± 0.10
MD: A	-0.07 ± 0.15	-0.33 ± 0.14	-0.46 ± 0.26	-0.93 ± 0.26
MD: B	0.53 ± 0.17	0.26 ± 0.17	0.18 ± 0.18	-0.09 ± 0.18
MD: C	-1.21 ± 0.17	-0.96 ± 0.17	-0.95 ± 0.20	-0.61 ± 0.20
MD: D	0.29 ± 0.13	0.54 ± 0.13	-0.08 ± 0.21	0.32 ± 0.21
MD: $A_{CP S}$	-1.05 ± 0.15	-1.03 ± 0.15	-0.75 ± 0.21	-0.88 ± 0.21
Av: A_{raw}	-0.41 ± 0.06	-0.42 ± 0.06	-0.67 ± 0.08	-0.66 ± 0.08
Av: A	-0.43 ± 0.11	-0.44 ± 0.11	-0.80 ± 0.20	-0.93 ± 0.20
Av: B	-0.44 ± 0.13	-0.47 ± 0.13	-0.64 ± 0.14	-0.70 ± 0.14
Av: C	-0.55 ± 0.13	-0.50 ± 0.13	-0.74 ± 0.15	-0.66 ± 0.16
Av: D	-0.30 ± 0.10	-0.32 ± 0.10	-0.55 ± 0.17	-0.42 ± 0.17
$A_{CP S}$	-0.12 ± 0.12	-0.09 ± 0.12	-0.18 ± 0.17	-0.23 ± 0.17

Table 4.28: Raw asymmetries, in %, in the regions of the ϕ resonance, and values of A_{raw} and $A_{CP|S}$, for both D^+ and D_s^+ decays with and without (‘w/o’) a mass constraint (‘cstr.’). The results in magnet up and magnet down data are labelled MU and MD respectively. The last section shows that when the average of the magnet polarities is taken the results in the four regions are statistically compatible.

smaller effect on the results when the magnet polarities are averaged. The Dalitz plot distributions before the D^+ meson mass is constrained are shown for the ϕ region in the signal and control decay mode in Fig. 4.34.

The systematic uncertainty assigned for resolution effects in the Dalitz plot is the difference between the average values of $A_{CP|S}$ with and without the mass constraint. This is 0.056% for $A_{CP|S}$, 0.007% in A_{CP} for the D^+ decay and 0.006% for A_{CP} in the D_s^+ decay. These values appear in Tables 4.38 and 4.39.

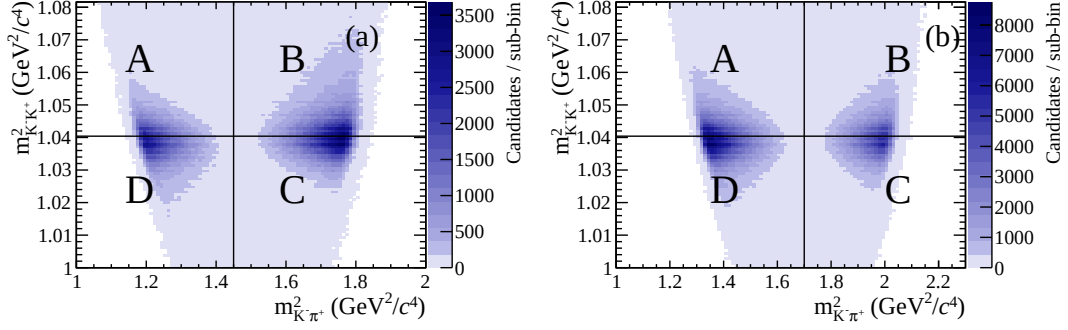


Figure 4.34: The ϕ region of (a) the D^+ Dalitz plot and (b) the D_s^+ Dalitz plot with the regions labelled.

4.10.7 Systematic biases due to charged kaon interaction asymmetries

In matter, both charged and neutral kaons interact asymmetrically: $\bar{K}^0$ and K^- mesons can be absorbed in hyperon production processes such as $\bar{K}^0 + p \rightarrow \Lambda^0 + \pi^+$ or $K^- + p \rightarrow \Lambda^0 + \pi^0$, while K^0 and K^+ mesons can only scatter elastically or undergo charge exchange. In the neutral kaon system this is known as regeneration and is discussed in Sect. 4.10.8, while the effect on charged kaons is explained here. In the case of charged pions, by contrast, the asymmetry is smaller and independent of momentum, because in the limit of isospin symmetry there is no difference between the quark and the antiquark in the pion, so each are equally likely to undergo a strong interaction independently of their flavour.

If the two charged kaons in the ϕ meson decay have identical kinematics, the interaction asymmetry will cancel between them. However, the kaon interaction with detector material is known to be strongly momentum dependent: it decreases rapidly as momentum increases. The same-sign and opposite-sign kaons in the $D_{(s)}^+ \rightarrow \phi \pi^+$ decay have slightly different momentum spectra. This is because the two lobes of the ϕ resonance are distorted due to the $D_{(s)}^+ \rightarrow K^- K^+ \pi^+$ S-wave interfering with the ϕ (if there was

no S-wave, the resonance as shown in Fig. 4.34 would have a vertical axis of symmetry, implying identical kinematics for the same-sign and opposite-sign kaons). The correlation between the momenta of the two kaons is shown in Fig. 4.35. The small differences between the distributions lead to a small systematic uncertainty. This can be studied with the regions used to calculate $A_{CP}|_S$. It is investigated in this section using the $D_s^+ \rightarrow \phi\pi^+$ control decay channel. The kinematics of the final state particles in the D_s^+ decay are shown in Sect. 4.10.12 to be almost identical to those from the D^+ decay so any effect will be the same in both channels.

While there are no statistically significant differences between the regions of the ϕ resonance in Table 4.28 when the two magnet polarities are averaged, there is a larger difference, of $(0.14 \pm 0.12)\%$, between the left and right halves of the ϕ resonance (areas of high and low $K^-\pi^+$ invariant mass as shown in Fig. 4.34) in the D_s^+ decay, which could be explained by a kaon instrumental asymmetry. There are much larger differences in the momentum spectra between decays with high and low $K^-\pi^+$ masses, shown in Fig. 4.36, than between the same-sign and opposite-sign kaons in the ϕ region as a whole, in Fig. 4.37. There are also large differences in the p_T spectra between the regions of higher and lower $K^-\pi^+$ invariant mass, shown in Fig. 4.38. These differences are important as the amount of material the particles can interact with before reaching the calorimeter depends on their p_T .

In order to make the mean momentum difference between the two kaons greater and thereby increase the effect of the instrumental asymmetry, the ϕ region is widened from $1.0 < m_{K^-K^+} < 1.04 \text{ GeV}/c^2$ to $0.98 < m_{K^-K^+} < 1.06 \text{ GeV}/c^2$ and the mass fits are rerun (without the kinematic binning). As shown in Table 4.29, the average raw asymmetry changes by 0.031% in the D^+ decay and by 0.002% in the D_s^+ decay. These values are assigned as the systematic uncertainties in the A_{CP} measurements for asymmetric interactions of the kaons with the detector material, and feature in Table 4.38.

	Magnet up	Magnet down	Average
$D^+ \rightarrow \phi\pi^+$, $1.00 < m < 1.04$ GeV	-1.100 ± 0.127	-0.297 ± 0.106	-0.698 ± 0.083
$D^+ \rightarrow \phi\pi^+$, $0.98 < m < 1.06$ GeV	-1.111 ± 0.120	-0.348 ± 0.100	-0.729 ± 0.078
$\Delta(\text{standard/wide } D^+)$	0.011 ± 0.041	0.051 ± 0.034	0.031 ± 0.027
$D_s^+ \rightarrow \phi\pi^+$, $1.00 < m < 1.04$ GeV	-0.770 ± 0.092	-0.093 ± 0.076	-0.432 ± 0.059
$D_s^+ \rightarrow \phi\pi^+$, $0.98 < m < 1.06$ GeV	-0.774 ± 0.087	-0.093 ± 0.072	-0.433 ± 0.057
$\Delta(\text{standard/wide } D_s^+)$	0.004 ± 0.027	0.001 ± 0.023	0.002 ± 0.018

Table 4.29: Change in asymmetry, in %, with the width of the ϕ region in the $D_{(s)}^+ \rightarrow K^- K^+ \pi^+$ Dalitz plot.

The kaon interaction asymmetry is studied in Ref. [100] using a data driven method based on $D^+ \rightarrow K^- \pi^+ \pi^+$ decays, partly inspired by this analysis. In this study, the ratio of $K^- \pi^+$ and $K^+ \pi^-$ detection efficiencies is measured by computing the difference in raw asymmetry between the $D^+ \rightarrow K^- \pi^+ \pi^+$ and $D^+ \rightarrow K_s^0 \pi^+$ decay modes, which is entirely caused by the charged kaon. The results of this study, in Table 4.30, are used to correct the measured raw asymmetries in the different regions for the differences. This is done by again binning the signal decays in two dimensions according to the momentum of the two kaons, and correcting the yield of both D^+ and D^- decays in each bin separately for the number of negative kaons that are not detected due to the kaon asymmetry. As negative kaons are more likely to interact strongly with material in the detector than the positive kaons they are more likely to be lost, and if this is the case the D candidate is not reconstructed. The effect of this correction on the raw asymmetries in the Dalitz plot regions is shown in Table 4.31. The left and right regions are in closer agreement following the correction. However, as discussed before, $A_{CP|S}$ is robust against these asymmetries, because a kaon asymmetry that affects, for example, region A will be cancelled out by one that affects region C , so within each diagonal there is cancellation of the asymmetry. The values of $A_{CP|S}$ in $D_s^+ \rightarrow \phi\pi^+$ before and after the correction differ by 0.009%, which is assigned as the systematic uncertainty in $A_{CP|S}$ for this interaction effect and features in Table 4.39.

Momentum range	$\epsilon_{K^+\pi^-}/\epsilon_{K^-\pi^+}$ (%)
$5 < p < 12$ GeV	1.065 ± 0.011
$12 < p < 20$ GeV	1.026 ± 0.005
$20 < p < 30$ GeV	1.012 ± 0.004
$30 < p < 50$ GeV	1.020 ± 0.004
$50 < p < 100$ GeV	1.023 ± 0.005

Table 4.30: Ratio of reconstruction efficiency for $K^+\pi^-$ and $K^-\pi^+$, measured using the difference between the $D^+ \rightarrow K^-\pi^+\pi^+$ and the $D^+ \rightarrow K_s^0\pi^+$ decay [100].

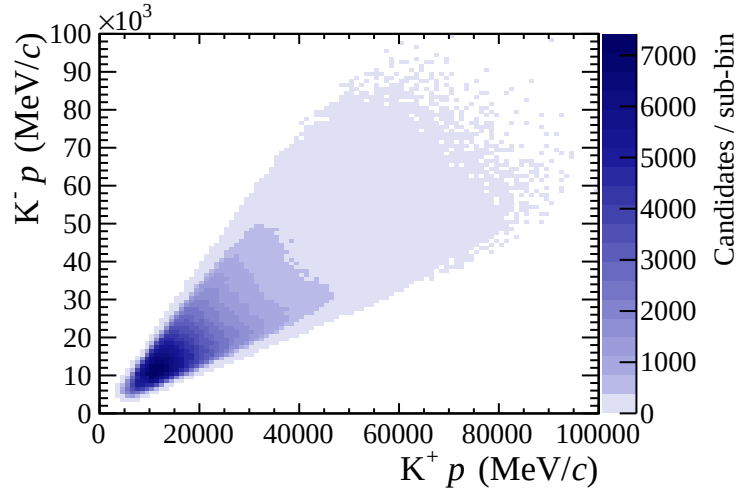


Figure 4.35: Correlation of same-sign and opposite sign kaon momenta, showing that in LHCb the boost means that most D decays have kaon daughters with similar momenta in the lab frame.

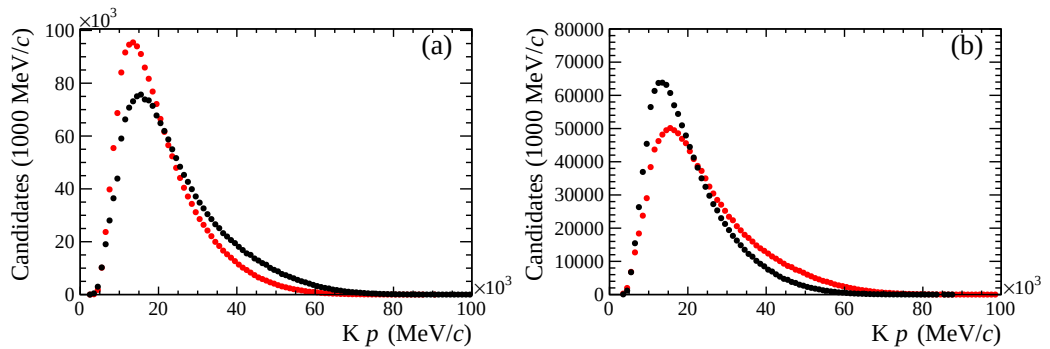


Figure 4.36: The momentum spectra of the same-sign (black) and opposite-sign (red) kaons on the (a) left and (b) right sides of the ϕ resonance, from the $D_s^+ \rightarrow \phi\pi^+$ control channel.

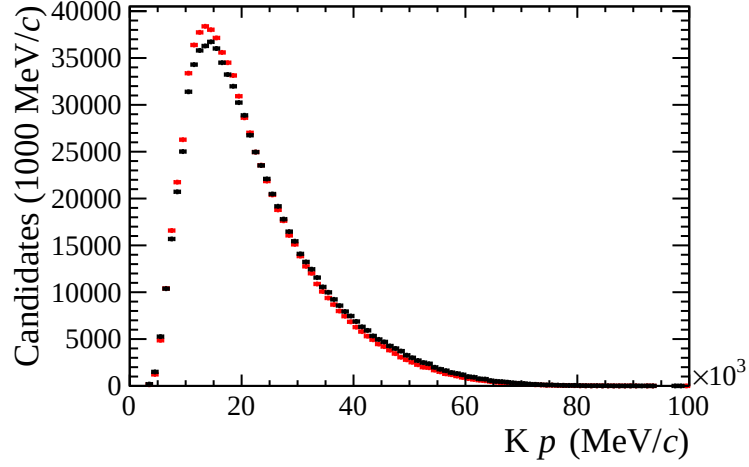


Figure 4.37: Momentum spectra of K^+ (in red) and K^- (in black) from $D^+ \rightarrow \phi\pi^+$ decays only (D^- decays are not included).

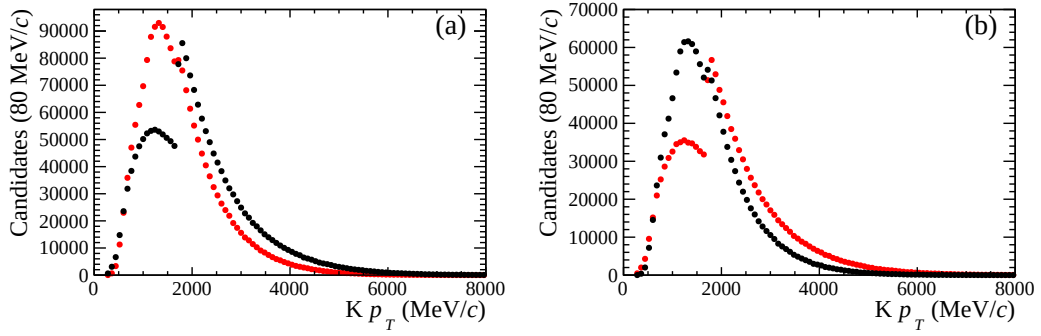


Figure 4.38: The transverse momentum spectra of the same-sign (black) and opposite-sign (red) kaons on (a) the left side and (b) the right side of the ϕ resonance, from the $D_s^+ \rightarrow \phi\pi^+$ control channel. The first-level software trigger threshold is more apparent for the same-sign kaon in (a) and the opposite-sign kaon in (b).

It is also important to show that $A_{CP}|_S$ is robust against variation of charge asymmetries with K^-K^+ invariant mass $m_{K^-K^+}$ in the Dalitz plot. The cancellation should be the same as for left-right differences. This is tested by changing the width of the ϕ region in the $D_s^+ \rightarrow K^-K^+\pi^+$ Dalitz plot, first narrowing and then widening it and recalculating the value of $A_{CP}|_S$. The raw asymmetries in the four zones for a ϕ region

Region	Before correction	After correction
Left	-0.36 ± 0.08	$-0.44 \pm 0.08 \pm 0.14$
Right	-0.50 ± 0.09	$-0.41 \pm 0.09 \pm 0.14$
A	-0.43 ± 0.11	$-0.52 \pm 0.11 \pm 0.14$
B	-0.44 ± 0.13	$-0.34 \pm 0.13 \pm 0.13$
C	-0.55 ± 0.13	$-0.47 \pm 0.13 \pm 0.14$
D	-0.30 ± 0.10	$-0.39 \pm 0.10 \pm 0.14$
A_{raw}	-0.41 ± 0.06	$-0.43 \pm 0.06 \pm 0.13$
$A_{CP S}$	-0.12 ± 0.12	$-0.13 \pm 0.12 \pm 0.05$
χ^2/ndf	$2.42/3 = 0.81$	$1.35/3 = 0.45$

Table 4.31: Differences in raw asymmetry in % across the ϕ region in the $D_s^+ \rightarrow K^- K^+ \pi^+$ Dalitz plot before and after a correction for the kaon asymmetry is applied. The ‘left’ region is the combination of A and D while the ‘right’ region is the combination of B and C . The second uncertainties in the right hand column are due to the statistical uncertainty on the determination of the interaction asymmetry, which partly cancels in the calculation of $A_{CP|S}$. The last row gives the χ^2/ndf for compatibility of the four regions.

Region	$1000 < m_{K^-K^+} < 1040 \text{ MeV}/c^2$	$1015 < m_{K^-K^+} < 1025 \text{ MeV}/c^2$	$m_{K^-K^+} < 1075 \text{ MeV}/c^2$
A	-0.43 ± 0.11	-0.39 ± 0.14	-0.38 ± 0.10
B	-0.44 ± 0.13	-0.33 ± 0.16	-0.53 ± 0.11
C	-0.55 ± 0.13	-0.50 ± 0.15	-0.51 ± 0.13
D	-0.30 ± 0.10	-0.35 ± 0.11	-0.34 ± 0.10
A_{raw}	-0.41 ± 0.06	-0.39 ± 0.07	-0.43 ± 0.05
$A_{CP S}$	-0.12 ± 0.12	-0.11 ± 0.14	-0.01 ± 0.11
χ^2/ndf	$2.42/3 = 0.81$	$0.87/3 = 0.29$	$2.00/3 = 0.67$

Table 4.32: Values of the raw asymmetry in % for different widths of the ϕ region in the $D_s^+ \rightarrow K^- K^+ \pi^+$ Dalitz plot. The default width is $1000 < m_{K^-K^+} < 1040 \text{ MeV}/c^2$. The last row gives the χ^2/ndf for compatibility of the four regions. No correction for the kaon asymmetry is applied.

of $1015 < m_{K^-K^+} < 1025 \text{ MeV}/c^2$ and for a region of $m_{K^-K^+} < 1075 \text{ MeV}/c^2$ with no lower cut-off are compared to the default values in Table 4.32. Neither of these variations significantly affects $A_{CP|S}$ so no additional systematic uncertainty is assigned.

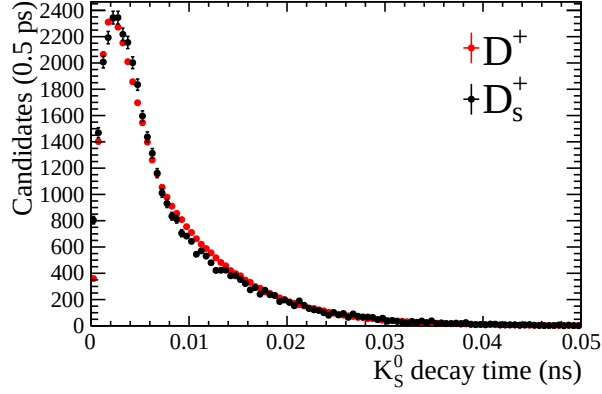


Figure 4.39: Decay time distributions of the K_S^0 from D^+ (in red) and D_s^+ (in black) decays. The small difference between the two curves seen at around 0.01 ns is probably due to the larger energy release in the D_s^+ decay compared to the D^+ decay. It will have a negligible effect on the CP -violating asymmetry.

4.10.8 Systematic uncertainties due to the neutral kaon

In this analysis, the CPV in the neutral kaon system is assumed to be the same, except with opposite sign, for the D^+ and D_s^+ to $K_S^0 \pi^+$ decays. If the decay time distribution of the K_S^0 differs substantially between these modes the CPV will not be the same. Fig. 4.39 shows that the distributions are virtually identical, so this is not a concern.

The interaction of a neutral kaon with detector material can change its flavour. This phenomenon is known as regeneration [101]. In the absence of hard scattering, the amplitudes for forward scattering of the neutral kaons from adjacent atoms of detector material can interfere, and this ‘coherent’ or dispersive regeneration can lead to quite substantial mixing-like effects if there is a large amount of dense material in the path of the kaons. Alternatively, in incoherent regeneration, nuclei scatter the kaons elastically but the scattering is diffractive rather than coherent between nuclei. In inelastic regeneration, the nucleus becomes excited or disintegrates. This is an absorptive process, and for K^0 and $\bar{K}^0$ mesons the inelastic interaction should be equivalent to the interaction of charged kaons. In this analysis, the effects of these processes on charge asymmetries are small

because 30% of the neutral kaons pass through no material at all before they decay, and the remainder traverse a few millimetres of aluminium and silicon at most.

The difference in interaction cross sections between K^0 and $\bar{K}^0$ follows the scaling law

$$\Delta\sigma = -\frac{23.2A^{0.758}}{[p \text{ (GeV}/c)]^{0.614}} \text{ mb} \quad (4.23)$$

for a particle of momentum p traversing material with atomic mass number A . This can be related to the asymmetry in the imaginary part of the forward scattering amplitude f via the optical theorem,

$$\Delta\sigma_{tot} = \frac{4\pi}{p} \text{Im}\Delta f. \quad (4.24)$$

The real part of the forward scattering amplitude is related to the imaginary part by dispersion relations. For kaons with momenta well above 1 GeV/ c , $\arg(\Delta f) = -2.18$ rad. The asymmetry in the forward scattering amplitudes (Δf) can be inserted into a formula for a regeneration parameter r which behaves in a similar way to the CPV parameter ϵ ,

$$r = -\frac{\pi\mathcal{N}\Delta f}{m\left(\Delta m - \frac{i}{2}(\Gamma_L - \Gamma_S)\right)} \quad (4.25)$$

where $\Gamma_{L,S}$ and Δm are the widths and the mass difference of the K_S^0 and K_L^0 states defined in Sect. 1.6, $\mathcal{N}$ is the number density of nucleons in the material and m is the K_S^0 meson mass. One can then repeat the calculation in Sect. 1.6 accounting for regeneration as well as CPV to obtain a formula for the asymmetry as a function of time,

$$A(t) = 2\text{Re}(\epsilon) - 2e^{-\frac{1}{2}\Delta\Gamma t} (\text{Re}(\epsilon) \cos \Delta m t + \text{Im}(\epsilon) \sin \Delta m t) - \\ 2 \sum_{j=1}^n \left(e^{-\frac{1}{2}\Delta\Gamma t_j} (r_j \cos \Delta m t_j + r'_j \sin \Delta m t_j) - e^{-\frac{1}{2}\Delta\Gamma t_{j-1}} (r_j \cos \Delta m t_{j-1} + r'_j \sin \Delta m t_{j-1}) \right) \quad (4.26)$$

where the sum is over the different layers of detector material j traversed by the kaons

ϕ angle	$p[2, 20]$ GeV		$p > 20$ GeV	
	UP	DOWN	UP	DOWN
$[0, \frac{1}{4}\pi]$	0.875 ± 0.014	1.126 ± 0.014	0.941 ± 0.019	1.047 ± 0.017
$[\frac{1}{4}\pi, \frac{1}{2}\pi]$	0.934 ± 0.015	1.081 ± 0.017	0.926 ± 0.022	1.043 ± 0.019
$[\frac{1}{2}\pi, \frac{3}{4}\pi]$	1.017 ± 0.019	0.960 ± 0.015	1.072 ± 0.026	0.935 ± 0.018
$[\frac{3}{4}\pi, \pi]$	1.102 ± 0.015	0.879 ± 0.012	1.066 ± 0.020	0.946 ± 0.016
$[\pi, \frac{5}{4}\pi]$	1.127 ± 0.018	0.878 ± 0.011	1.079 ± 0.022	0.938 ± 0.016
$[\frac{5}{4}\pi, \frac{3}{2}\pi]$	1.064 ± 0.020	0.934 ± 0.013	1.046 ± 0.025	0.967 ± 0.019
$[\frac{3}{2}\pi, \frac{7}{4}\pi]$	0.933 ± 0.019	1.041 ± 0.018	0.978 ± 0.024	1.037 ± 0.021
$[\frac{7}{4}\pi, 2\pi]$	0.869 ± 0.015	1.142 ± 0.015	0.924 ± 0.019	1.066 ± 0.018

Table 4.33: Pion efficiency ratio ($\epsilon(\pi^+)/\epsilon(\pi^-)$) as a function of momentum and azimuthal angle, from the D_s^+ production asymmetry analysis [102]

up to the decay time t , and $t_{j-1} = 0$ when $j = 1$. The material each neutral kaon in the analysis passes through is determined to a precision of 10%, and the above formulae are then used to calculate the asymmetry due to regeneration associated with each $K_s^0\pi^+$ candidate. Histograms of the asymmetries for each kinematic bin are produced and the overall effect on the results is determined to be $(-0.039 \pm 0.004)\%$ for $D^+ \rightarrow K_s^0\pi^+$. The uncertainty is that due to the material map, compared to which other uncertainties are expected to be negligible. By symmetry, the corresponding result for $D_s^+ \rightarrow K_s^0\pi^+$ is $(+0.039 \pm 0.004)\%$. The central values are assigned as systematic uncertainties on A_{CP} and feature in Table 4.38.

4.10.9 Cross-check: effect of pion tracking efficiencies

In the analysis of the production asymmetry of the D_s^+ meson at LHCb [84], the asymmetry in the pion tracking efficiency, which one would expect to be responsible for much of the difference in charge asymmetry between magnet polarities, is measured directly. The measurement is for a different decay channel, $D^0 \rightarrow K^-\pi^+\pi^-\pi^+$, and so there will be significant differences in the kinematics compared to the D^+ decays used here, but the

measured efficiencies are nevertheless a useful guide to the scale of the effects. They are reproduced with their uncertainties in Table 4.33. When the asymmetry difference between the $\phi\pi^+$ and $K_S^0\pi^+$ final states is taken, the pion asymmetry largely cancels. However, because the momentum distributions are not quite the same, and the pion asymmetry has a weak dependence on momentum, the cancellation will not be complete. As a cross check, the likely size of any effect is investigated.

The value of A_{CP} in D kinematic bin i and magnet/pion momentum bin j , corrected by the pion efficiencies $\epsilon^\pm(j)$, is

$$A_{CP}(i, j) = \frac{\frac{N_\phi^+(i, j)}{\epsilon^+(j)} - \frac{N_\phi^-(i, j)}{\epsilon^-(j)}}{\frac{N_\phi^+(i, j)}{\epsilon^+(j)} + \frac{N_\phi^-(i, j)}{\epsilon^-(j)}} - \frac{\frac{N_{K_S^0}^+(i, j)}{\epsilon^+(j)} - \frac{N_{K_S^0}^-(i, j)}{\epsilon^-(j)}}{\frac{N_{K_S^0}^+(i, j)}{\epsilon^+(j)} + \frac{N_{K_S^0}^-(i, j)}{\epsilon^-(j)}}. \quad (4.27)$$

In the determination of A_{CP} , the raw asymmetry is fitted directly. To correct the raw asymmetry into an efficiency-corrected raw asymmetry A_{effcorr} , a new parameter δ is introduced by writing $\epsilon^+ = \epsilon(1 + \delta)$ and $\epsilon^- = \epsilon(1 - \delta)$ so that the average efficiency ϵ cancels and in each bin

$$A_{\text{effcorr}} = \frac{\frac{N^+}{1+\delta} - \frac{N^-}{1-\delta}}{\frac{N^+}{1+\delta} + \frac{N^-}{1-\delta}}. \quad (4.28)$$

This rearranges to

$$A_{\text{effcorr}} = \frac{A_{\text{raw}} - \delta}{1 - A_{\text{raw}}\delta}. \quad (4.29)$$

$A_{\text{effcorr}, K_S^0}$ is of course the D^+ production asymmetry. Therefore in each kinematic bin

$$\Delta A_{CP} = A_{\text{effcorr}, \phi} - A_{\text{effcorr}, K_S^0} = \frac{A_{\text{raw}, \phi} - \delta}{1 - A_{\text{raw}, \phi}\delta} - \frac{A_{\text{raw}, K_S^0} - \delta}{1 - A_{\text{raw}, K_S^0}\delta}. \quad (4.30)$$

The pion efficiency asymmetry and the raw asymmetry are both small enough that a

Bin	p_T (GeV)	η	Magnet-up	Magnet-down	Average
0	[2, 4]	[2.2, 3]	0.992 ± 0.006	1.007 ± 0.005	1.000 ± 0.004
1	[2, 4]	[3, 3.5]	0.997 ± 0.005	1.003 ± 0.004	1.000 ± 0.003
2	[2, 4]	[3.5, 4.75]	1.002 ± 0.007	0.998 ± 0.006	1.000 ± 0.004
3	[4, 5.2]	[2.2, 3]	0.994 ± 0.005	1.006 ± 0.004	1.000 ± 0.003
4	[4, 5.2]	[3, 3.5]	1.001 ± 0.006	1.001 ± 0.005	1.001 ± 0.004
5	[4, 5.2]	[3.5, 4.75]	1.003 ± 0.007	0.997 ± 0.006	1.000 ± 0.005
6	[5.2, 7]	[2.2, 3]	0.997 ± 0.005	1.004 ± 0.004	1.001 ± 0.003
7	[5.2, 7]	[3, 3.5]	1.003 ± 0.006	1.000 ± 0.005	1.001 ± 0.004
8	[5.2, 7]	[3.5, 4.75]	1.002 ± 0.007	0.996 ± 0.006	0.999 ± 0.005
9	[7, 18]	[2.2, 3]	0.997 ± 0.005	1.005 ± 0.004	1.001 ± 0.003
10	[7, 18]	[3, 3.5]	1.002 ± 0.007	0.998 ± 0.005	1.000 ± 0.004
11	[7, 18]	[3.5, 4.75]	1.005 ± 0.007	0.996 ± 0.006	1.001 ± 0.005
12	[2, 18]	[2.2, 4.75]	1.000 ± 0.006	1.001 ± 0.005	1.000 ± 0.004

Table 4.34: Average efficiency ratios ($\epsilon^{\pi^+}/\epsilon^{\pi^-}$) in bins of D^+ p_T and η , with a global weighted average over 192 bins (16 bins of pion kinematics, 12 of D kinematics) in the last row. The uncertainties in each row of the table are correlated.

first order expansion in these parameters can be performed. This gives

$$\Delta A_{CP} \sim (A_{\text{raw},\phi} - A_{\text{raw},K_S^0})(1 - \delta^2) + \delta(A_{\text{raw},\phi}^2 - A_{\text{raw},K_S^0}^2). \quad (4.31)$$

Thus terms containing δ are second order corrections to ΔA_{CP} . From the efficiency ratios in Table 4.34, δ is at most 0.6% and therefore terms in $\delta^2 A_{\text{raw}}$ or $A_{\text{raw}}^2 \delta$ will be negligible, so the asymmetry in pion tracking efficiency will have no appreciable effect.

4.10.10 Cross-check: dependence of asymmetries on running period

The dataset is divided using technical stops and magnet polarity changes to create six running periods specified in Fig. 4.40, and the raw asymmetry as a function of time through 2011 is plotted for the $D^+ \rightarrow \phi\pi^+$ and $D^+ \rightarrow K_S^0\pi^+$ decays in Fig. 4.41. Each running period is chosen to contain some magnet up and some magnet down data, and

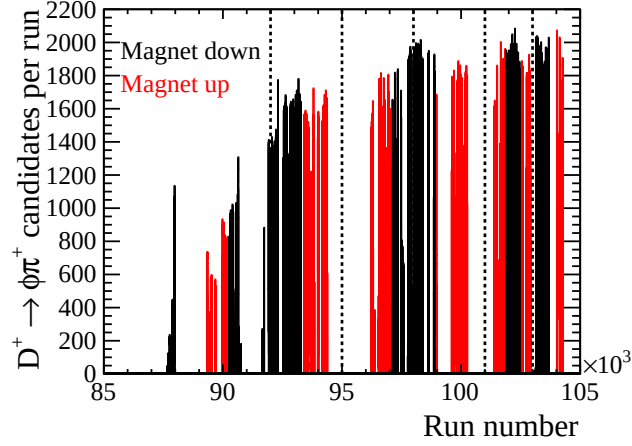


Figure 4.40: Histogram showing the data collected in each run in 2011, showing the division into the six running periods and the distribution of data taken with each magnet polarity. Magnet up data is shown in red, magnet down in black. This figure is inspired by Ref. [102]. Additional information about the running periods can be found in Table 2.1.

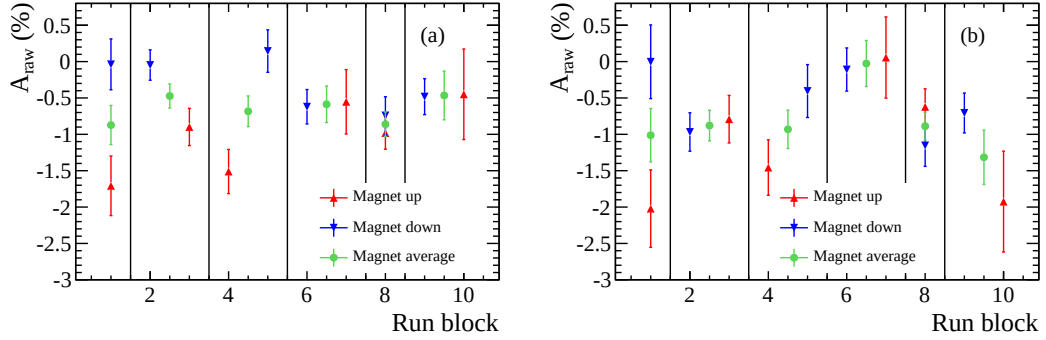


Figure 4.41: The raw asymmetry in (a) $D^+ \rightarrow \phi\pi^+$ and (b) $D^+ \rightarrow K_s^0\pi^+$ (right) split into six running periods specified in Fig 4.40. The results of flat line fits are given in Table 4.35

the average within each period is computed.

It can be seen that the detector effects may vary with time: within each magnet polarity, the raw asymmetries in the run blocks are not consistent. However, when the magnet polarities are averaged with equal weight, the underlying asymmetry is consistent with a constant value, as it should be. For $D^+ \rightarrow \phi\pi^+$, the p -value for consistency with no dependence on running period is 59% while for $D^+ \rightarrow K_s^0\pi^+$ it is 12%. Even if the raw

	Fitted Asymmetry (%)	χ^2/ndf
Magnet up	-1.07 ± 0.13	7.5/5
Magnet down	-0.32 ± 0.10	9.6/5
Simple Average	-0.67 ± 0.09	3.8/5
Magnet up	-0.93 ± 0.16	13.1/5
Magnet down	-0.66 ± 0.13	10.0/5
Simple Average	-0.84 ± 0.11	8.7/5

Table 4.35: χ^2/ndf values for the consistency of the raw charge asymmetries in the different running periods, determined from fits of horizontal lines to Fig. 4.41(a) ($D^+ \rightarrow \phi\pi^+$) above the first line, and Fig 4.41(b) ($D^+ \rightarrow K_s^0\pi^+$) below it. The fitted asymmetries are in good agreement with the raw asymmetries in Table 4.11. While the χ^2/ndf values for fits to data taken with individual magnet polarities are poor, the effects disappear as expected when the polarities are averaged.

	Fitted Asymmetry(%)	χ^2/ndf
Magnet up	-0.13 ± 0.20	4.6/5
Magnet down	0.31 ± 0.16	7.0/5
Simple Average	0.16 ± 0.13	6.1/5

Table 4.36: χ^2/ndf values for fits of flat lines to the A_{CP} values as a function of time in Fig. 4.42.

asymmetries in individual decay modes vary with time, A_{CP} should be stable for each magnet polarity and on average. The asymmetries are shown in Fig. 4.42 and the results of fits of horizontal lines to the raw asymmetries in the run blocks are in Table 4.36.

While there is no evidence for any time dependence of the magnet-averaged asymmetries, mechanisms for such effects exist. The cancellation of systematic effects between magnet up and magnet down data may be impaired by time-dependent changes, since magnet up and magnet down datasets were not collected concurrently. However, while there are some differences between running periods, for example due to HPDs in the RICH detectors operating for only part of the year, the effect of this is not considered to be sufficiently large to assign an additional systematic uncertainty.

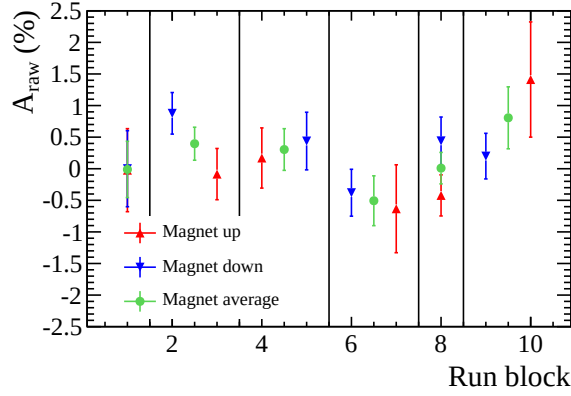


Figure 4.42: The values of A_{CP} in the six different run blocks specified in Fig 4.40. The results of flat line fits are given in Table 4.36.

4.10.11 Checks for effects on A_{CP} due to differences in selection criteria between $D^+ \rightarrow \phi\pi^+$ and $D^+ \rightarrow K_s^0\pi^+$ decays

Some of the selection requirements could introduce asymmetries into the dataset, and the kinematic differences between decay modes mean that these may not cancel in the subtraction used to calculate A_{CP} . The selection requirement on the vertex separation χ^2 between the primary vertex (PV) and the D^+ decay vertex in the $K_s^0\pi^+$ final state is looser than in the $\phi\pi^+$ final state, and this leads to a difference in the D^+ decay time distribution between final states. To check that this does not bias the results, the value of A_{CP} is calculated in five bins of D^+ decay time. The results are shown in Fig. 4.43. No significant decay time dependence is observed so there is no associated systematic uncertainty.

It is possible that while the selection criteria for the two final states are the same, the kinematic differences between them could still result in a bias. For example, in a purely hypothetical and rather exaggerated scenario, if the efficiency of the track χ^2 requirement is 80% for $D^+ \rightarrow \phi\pi^+$, 85% for $D^- \rightarrow \phi\pi^+$, 85% for $D^+ \rightarrow K_s^0\pi^+$ and 95% for $D^- \rightarrow K_s^0\pi^+$, an artificial asymmetry would result. If there was no asymmetry in

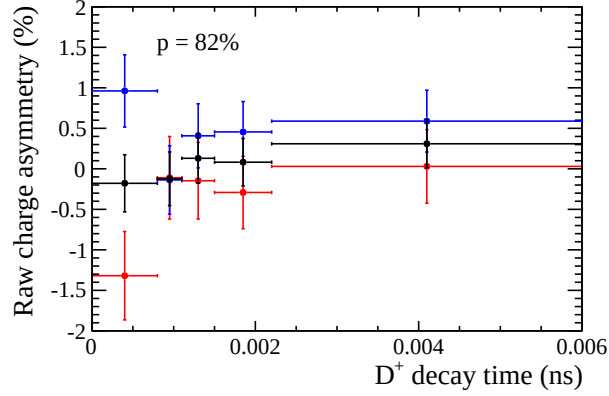


Figure 4.43: Value of A_{CP} in bins of D^+ decay time, calculated by sideband subtraction, for magnet up data in red, magnet down data in blue and their average in black. The p -value is that for consistency of the magnet averaged A_{CP} value with no dependence on decay time.

either decay before this criterion was applied,

$$A_{CP} \approx \frac{1/0.8 - 1/0.85}{1/0.8 + 1/0.85} - \frac{1/0.85 - 1/0.95}{1/0.85 + 1/0.95} \quad (4.32)$$

which is -2.5% . Therefore the dependence of A_{CP} on certain key variables is checked and is shown in Fig. 4.44. The pion track quality, identification likelihood variable, p_T and impact parameter χ^2 with respect to the PV are all investigated. The p -value for consistency of the magnet-averaged A_{CP} value with no dependence on the variable is shown on the plot. The only moderately low p -value occurs in the pion p_T , and this is a kinematic variable studied in Sect. 4.10.2. Thus no additional systematic uncertainties are assigned.

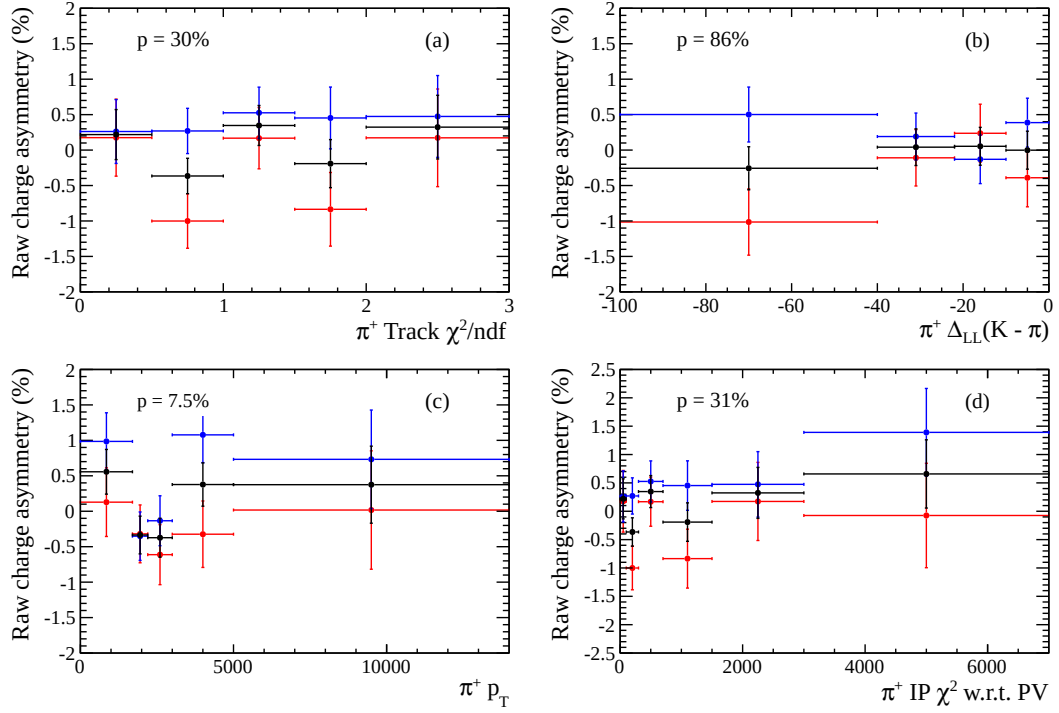


Figure 4.44: Values of A_{CP} in bins of (a) pion track χ^2/ndf , (b) pion identification likelihood, (c) pion p_T and (d) pion impact parameter χ^2 with respect to the PV. The p -value for consistency of the magnet averaged A_{CP} values with no dependence on the variable in question is shown on the plot. The results are calculated by sideband subtraction, for magnet up data in red, magnet up data in blue and their average in black

4.10.12 Checks for effects on $A_{CP}|_S$ due to kinematic differences between D_s^+ and D^+ decays

For the measurement of $A_{CP}|_S$, it is important to consider whether there any detector effects in the D^+ decay which would not appear in the D_s^+ decay, because the D_s^+ decay is used to show that $A_{CP}|_S$ is robust against such biases. Since the D^+ and D_s^+ mesons decay to the same final state and have similar masses, kinematic differences are expected to be small. If the differences between the kinematics of the final state particles in the two decays are smaller than kinematic differences between regions of the D_s^+ ϕ resonance, we will have a crude upper bound on detector effects due to those differences. The

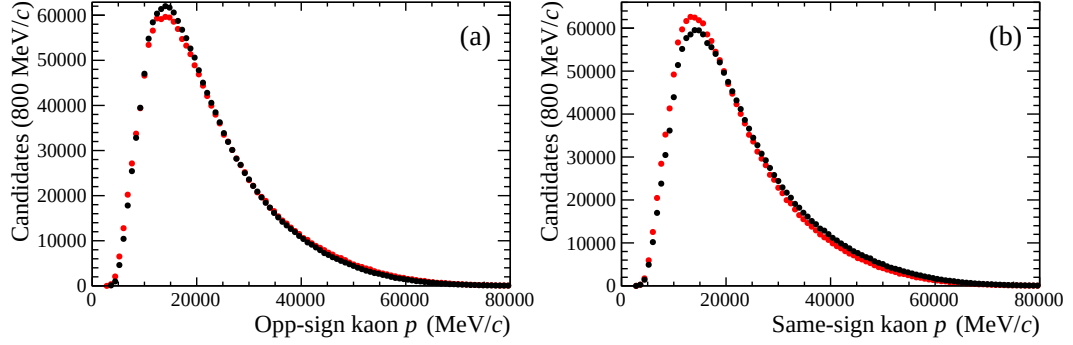


Figure 4.45: Momentum distributions for (a) the opposite-sign kaon and (b) the same-sign kaon. The particles from the D^+ decay are shown in red while those from the D_s^+ decay are shown in black. The histograms are scaled to contain the same total number of entries.

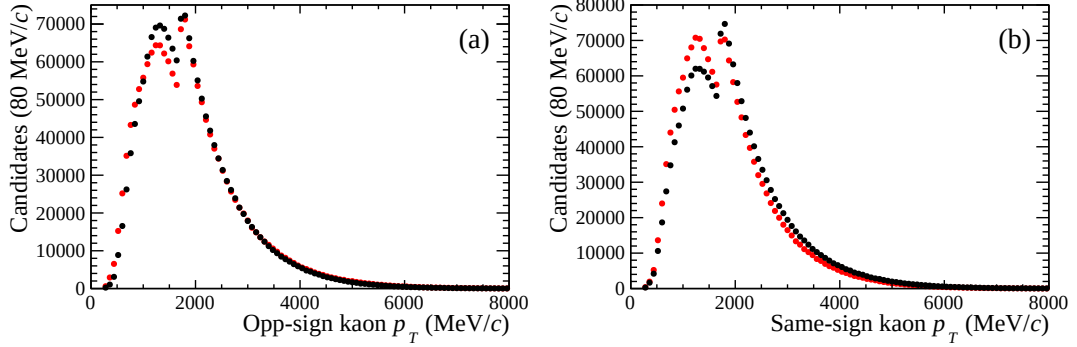


Figure 4.46: Transverse momentum distributions for (a) the opposite-sign kaon and (b) the same-sign kaon. The particles from the D^+ decay are shown in red while those from the D_s^+ decay are shown in black. The threshold at 1.7 GeV/c is due to the trigger. The histograms are scaled to contain the same total number of entries.

momentum, transverse momentum, and azimuthal angle distributions for the final state particles are plotted in Figs 4.45, 4.46, 4.47, and 4.48. The differences observed are small, and significantly smaller than the differences between the particles seen in, for example, Fig. 4.36 and Fig. 4.38. Therefore they can have no non-negligible effects, and any statistically significant deviation from the behaviour observed in $D_s^+ \rightarrow \phi\pi^+$ in $D^+ \rightarrow \phi\pi^+$ would be evidence of CP violation.

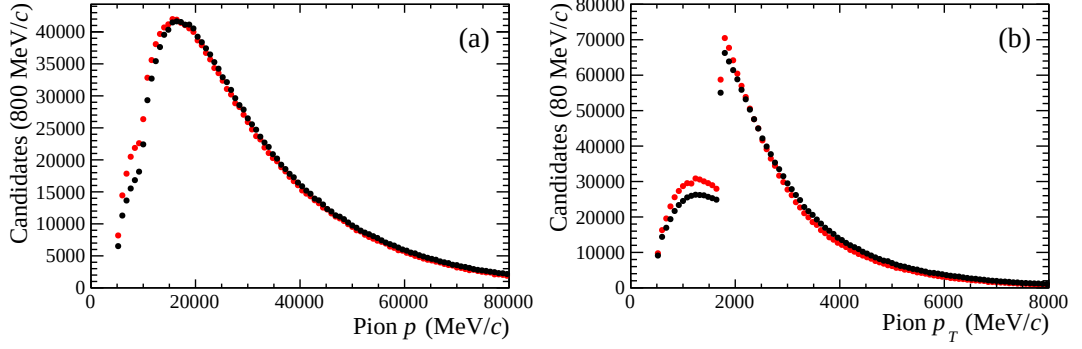


Figure 4.47: Momentum (a) and transverse momentum distributions (b) for the pion. The particles from the D^+ decay are shown in red while those from the D_s^+ decay are shown in black.

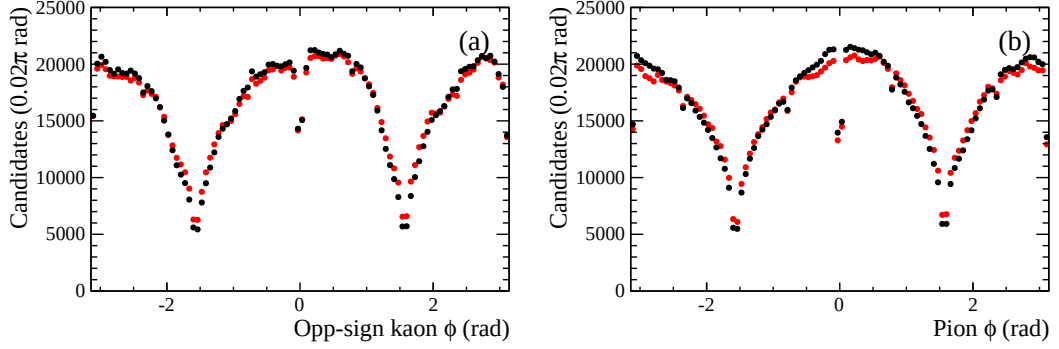


Figure 4.48: Azimuthal angle distributions for (a) the opposite-sign kaon (b) and the pion. The particles from the D^+ decay are shown in red while those from the D_s^+ decay are shown in black.

4.10.13 Cross-check: difference in raw asymmetries between

$$D_s^+ \rightarrow \phi\pi^+ \text{ and } D_s^+ \rightarrow \pi^-\pi^+\pi^+ \text{ decays}$$

As a further cross check, the difference in raw asymmetry between the $D_s^+ \rightarrow \phi\pi^+$ and $D_s^+ \rightarrow \pi^-\pi^+\pi^+$ decays is calculated. Since these are both Cabibbo-favoured tree-level decays, this quantity is expected to be zero. The $D_s^+ \rightarrow \pi^-\pi^+\pi^+$ decay has reasonably similar kinematic properties and a similar yield in our dataset to the $D^+ \rightarrow K_s^0\pi^+$ decay, and the $D_s^+ \rightarrow \phi\pi^+$ is very similar to the corresponding D^+ decay. Thus the kinematic

differences between the final states in the D_s^+ control decays are similar to those in the D^+ signal channels.

The $D_s^+ \rightarrow \pi^- \pi^+ \pi^+$ decay is reconstructed using the same selection as that used for the signal decays. The hardware trigger must be activated by a particle which does not form part of the signal decay, or by the π^- meson, or by a randomly selected π^+ meson. In the last case, a π^+ meson is chosen at random from the two available, and only the trigger decision on the selected π^+ meson is considered. This is a similar procedure to that used to select $D^+ \rightarrow K^- \pi^+ \pi^+$ decays in Sect. 4.3. The resulting sample has a large background due to random pions from the primary vertex. To remove this, the regions of the $D_s^+ \rightarrow \pi^- \pi^+ \pi^+$ Dalitz plot in which one of the pions has a low momentum in the D_s^+ rest frame are excluded from the sample by removing the areas of the Dalitz plot below the $f_0(980)$ resonance. The requirement on $\pi^- \pi^+$ invariant mass $m_{\pi^- \pi^+}^2 > 0.75 \text{ GeV}^2/c^4$ is applied to both $\pi^- \pi^+$ meson pairs. The mass distribution of the candidates that remain is fitted with a Cruijff function in the 12 kinematic bins described in Sect. 4.7 and the raw charge asymmetries in the D_s^+ decay are calculated.

The weighted average of the raw asymmetry differences in the 12 kinematic bins shown in Table 4.37 is $(0.22 \pm 0.12)\%$. The systematic uncertainty on this is similar to that on the main analysis, or 0.13%, so the result differs from zero by 1.3 standard deviations. Using statistical uncertainties only, the χ^2/ndf for consistency of the results in all 12 bins with zero is 15.8/12 leading to a p -value of 20%.

To mitigate the problem of a high background in the $D_s^+ \rightarrow \pi^- \pi^+ \pi^+$ decay, a boosted decision tree (BDT) [103] from the TMVA toolkit [104] is trained on a small subset of the data and then applied to the whole sample. Thirteen kinematic variables are passed to the BDT. Examples include the daughter p_T and impact parameter χ^2 with respect to the PV, and the separation χ^2 between the PV and the D_s^+ vertex. The BDT returns a single weight for each candidate which ranges from -1 if it is fully compatible with background

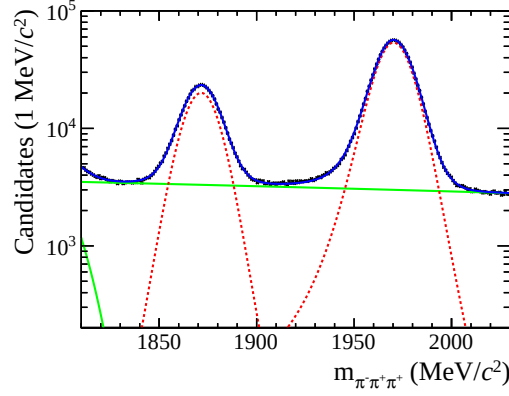


Figure 4.49: Fit to the distribution of selected $\pi^-\pi^+\pi^+$ candidate invariant masses, on a logarithmic scale.

bin	$\Delta A_{\text{raw}} (\%)$
0	-0.73 ± 0.88
1	0.24 ± 0.52
2	0.07 ± 0.53
3	1.05 ± 0.49
4	0.03 ± 0.37
5	0.18 ± 0.42
6	0.05 ± 0.37
7	0.69 ± 0.35
8	0.05 ± 0.43
9	0.08 ± 0.26
10	0.61 ± 0.31
11	-0.72 ± 0.50

Table 4.37: Values of the difference in raw asymmetry ΔA_{raw} between $D_s^+ \rightarrow \phi\pi^+$ and $D_s^+ \rightarrow \pi^-\pi^+\pi^+$ decay modes, in the bins of p_T and η shown in Fig. 4.16. Bins 0, 3, 6, 9 contain data with the lowest values of η and increasing values of p_T . Bins 1, 4, 7, 10 represent intermediate η values, and 2, 5, 8 and 11 represent high η values.

to +1 if it is fully compatible with signal, and this is used as a selection criterion. No information about charge asymmetries is given to the tree during training. The same BDT selection is applied to both the $\pi^-\pi^+\pi^+$ and $\phi\pi^+$ final states. This ensures the asymmetry is not affected by differences in selection cuts between final states. For reasonable cuts on the BDT criterion, the tree is highly efficient on the $\phi\pi^+$ decay mode.

The difference in raw asymmetries is found to depend quite strongly on the BDT cut, suggesting that the background in the $D_s^+ \rightarrow \pi^- \pi^+ \pi^+$ sample is asymmetric, and that this has a relatively strong effect on the measured asymmetry. The BDT criterion is chosen to be 0.2, which has an efficiency of 67.1% on sideband-subtracted $D_s^+ \rightarrow \pi^- \pi^+ \pi^+$ signal decays and 28.6% on the mass sidebands (i.e. it rejects just over 2/3 of the background for a loss of 1/3 of the signal). Asymmetries are then calculated using a sideband subtraction procedure. The end result is that the difference in raw asymmetries between $D_s^+ \rightarrow \phi \pi^+$ and $D_s^+ \rightarrow \pi^- \pi^+ \pi^+$ is $(0.08 \pm 0.12)\%$ for a BDT cut of 0.2. This is well within 1σ of zero, even when the systematic uncertainty is ignored.

As a further check, this asymmetry difference in the dataset selected without the BDT is calculated by sideband subtraction in the same 1440 bins as used in Table 4.13 and is found to be $(0.205 \pm 0.211)\%$ in magnet up data, $(0.008 \pm 0.176)\%$ in magnet down data, and $(0.107 \pm 0.137)\%$ in the average of the two. This is also very consistent with zero. It is concluded that there are no large asymmetries which would also exist in the signal channels, and that the analysis method is sound.

4.10.14 Summary tables of systematic uncertainties

The systematic uncertainties in A_{CP} are tabulated in Table 4.38. The systematic due to CPV in the kaon system was determined in Sect. 4.8. The overall systematic uncertainty is calculated by summing the individual uncertainties in quadrature. The uncertainty in A_{CP} is 0.14% in both the $D^+ \rightarrow \phi \pi^+$ decay and the $D_s^+ \rightarrow K_s^0 \pi^+$ decay. The systematic uncertainties in $A_{CP}|_S$ are summarised in Table 4.39. The total uncertainty is 0.18%, compared to a statistical uncertainty of 0.17%.

Systematic effect	Subsection	$A_{CP}(D^+)$	$A_{CP}(D_s^+)$
Kaon CP violation	4.8	0.028	0.028
Kinematic binning	4.10.2	0.035	0.035
Fiducial effects	4.10.2	0.022	0.022
Trigger asymmetries	4.10.3	0.114	0.114
Fitting	4.10.5	0.033	0.033
Cross-feed	4.10.5	0.008	0.000
D from B	4.10.5	0.002	0.015
Mass constraint	4.10.6	0.007	0.006
Kaon asymmetry	4.10.7	0.031	0.002
Regeneration	4.10.8	0.039	0.039
Total		0.138	0.136

Table 4.38: Summary of systematic uncertainties on A_{CP} values, all in %, with the subsection of the text in which they are discussed.

Systematic effect	Subsection	Value in %
D_s^+ decay	4.10.4	0.169
Backgrounds	4.10.5	0.007
D from B	4.10.5	0.003
Mass constraint	4.10.6	0.056
Kaon asymmetry	4.10.7	0.009
Total		0.178

Table 4.39: Summary of systematic uncertainties on $A_{CP}|_S$, all in %, with the subsection of the text in which they are discussed.

4.11 Discussion and conclusions

A model-independent search for CP violation in the $D^+ \rightarrow \phi\pi^+$ decay mode is performed. No evidence of CPV is found, either overall or in the Dalitz plot distribution. A concurrent search in the $D_s^+ \rightarrow K_s^0\pi^+$ decay also yields a null result. The CP asymmetry in the ϕ region of the $D^+ \rightarrow K^-K^+\pi^+$ Dalitz plot is

$$A_{CP}(D^+ \rightarrow \phi\pi^+) = (-0.04 \pm 0.14 \pm 0.14)\%,$$

the value of $A_{CP}|_S$ is

$$A_{CP}|_S = (-0.18 \pm 0.17 \pm 0.18)\%$$

and the CP asymmetry in the $D_s^+ \rightarrow K_s^0 \pi^+$ decay is

$$A_{CP}(D_s^+ \rightarrow K_s^0 \pi^+) = (0.61 \pm 0.83 \pm 0.14)\%.$$

In all cases the uncertainties are statistical and systematic, respectively. Any CPV in the $D^+ \rightarrow K_s^0 \pi^+$ and $D_s^+ \rightarrow \phi \pi^+$ decays is assumed to be negligible. Both decays are predominantly Cabibbo-favoured, but the $D^+ \rightarrow K_s^0 \pi^+$ decay has a doubly Cabibbo suppressed amplitude which could in principle interfere with the Cabibbo favoured decay. Any CPV from this is expected to be very small in the Standard Model (at most 0.01% [105]), and any enhancements from new physics would need to enter at tree level, which seems very unlikely.

These model-independent results indicate that any CPV in the ϕ resonance is probably small. In principle, a larger CPV in the ϕ could be cancelled by an effect of opposite sign in the underlying scalar resonances, but the lack of evidence for CPV in $A_{CP}|_S$ as well as A_{CP} suggests that this is unlikely. This result and the most recent search for CPV in neutral D meson decays at LHCb [4] are the only two searches for CP violation in singly Cabibbo suppressed charm decays to achieve an overall precision below 0.2%.

Chapter 5

Conclusions and outlook

It appears that there is no large CP violation in the Cabibbo-suppressed $D^+ \rightarrow K^- K^+ \pi^+$ decay. However, CP -violating asymmetries at the 0.1% level are not excluded anywhere in the Dalitz plot, and significantly larger CPV could exist far from the region of the ϕ resonance, provided that it is small enough to escape detection in the data collected at LHCb in 2010.

The prospects for a search in the same decay mode using data collected in 2012 at the higher centre of mass energy of $\sqrt{s} = 8 \text{ TeV}$ are very good. Our understanding of the LHCb detector has improved substantially since the inception of the data taking period in 2010. For example, techniques to calibrate the particle identification system to remove charge asymmetries due to inefficiencies in the RICH detectors now exist, and there is a measurement of the charge asymmetry in the interactions of kaons with detector material in the 2011 dataset [100], which could be easily extended to the data collected in 2012. Furthermore, the triggering of the detector on K_s^0 mesons which decay outside the VELO has been greatly improved. This means a much larger sample of the important $D^+ \rightarrow K_s^0 \pi^+$ control decay mode is available for further study, and if the analysis described in this thesis were repeated, it would probably be the $D^+ \rightarrow \phi \pi^+$ signal decay, not the

control channel, that would limit its statistical precision.

In data from the 2012 run, at least 8 million $D^+ \rightarrow K^- K^+ \pi^+$ decays in the ϕ region of the Dalitz plot should be useable in analysis. There should also be at least 10 million $D^+ \rightarrow K_s^0 \pi^+$ decays, although this number is more difficult to predict since the selection efficiency for the long-lived K_s^0 mesons is not well known. Nonetheless, a statistical uncertainty on A_{CP} of around 0.05% may be within reach. The systematic uncertainty can be expected to scale with the statistical uncertainty, since the precision with which systematic effects can be studied increases as larger samples of control channel decays become available. Thus A_{CP} should be measurable with a combined uncertainty below 0.1%. The precision on $A_{CP|S}$ should also be at the 0.1% level.

The model-independent techniques applied in this thesis to search for CP violation are applicable to several other analyses. For example, the method outlined in Chapter 3 is currently being used to search for CP violation in the Cabibbo-suppressed $D^+ \rightarrow \pi^- \pi^+ \pi^+$ decay at LHCb. Moreover, using the measurement of the detector-related kaon asymmetry [100], it should be possible to extend the analysis of the $D^+ \rightarrow \phi \pi^+$ decay described in Chapter 4 to other parts of the $D^+ \rightarrow K^- K^+ \pi^+$ Dalitz plot. For instance, the corresponding asymmetry in $D^+ \rightarrow K^*(892)^0 K^+$ could be measured by calculating the double difference

$$\begin{aligned} A_{CP}(D^+ \rightarrow K^*(892)^0 K^+) &= A_{\text{raw}}(D^+ \rightarrow K^*(892)^0 K^+) - A_{\text{raw}}(D_s^+ \rightarrow K^*(892)^0 K^+) \\ &\quad - A_{\text{raw}}(D^+ \rightarrow K_s^0 \pi^+) + A_{CP}(K^0/\bar{K}^0) + A_{\text{raw}}(D_s^+ \rightarrow \phi \pi^+). \end{aligned} \quad (5.1)$$

The second term in the equation uses the Dalitz plot of the $D_s^+ \rightarrow K^- K^+ \pi^+$ control channel to cancel any detector asymmetries, given an appropriate kinematic binning, and the last two terms cancel the difference in production charge asymmetry between signal and control channels. A similar measurement of CPV in the $D^+ \rightarrow K_s^0 K^+$ decay,

where the $K^*(892)^0$ is replaced by a K_s^0 meson in Eq. 5.1, is already in progress. The systematic uncertainties in these measurements will be larger than in the case of the $D^+ \rightarrow \phi\pi^+$ decay, but the method should still be robust and statistically limited by the signal decay. A combined uncertainty of 0.1% may be possible in the $D^+ \rightarrow K^*(892)^0 K^+$ decay using data collected in 2012. Since the $K^*(892)^0$ is a vector resonance, the concept of $A_{CP}|_S$ is equally as useful as in the $D^+ \rightarrow \phi\pi^+$ decay, and it should also be possible to obtain an accurate result for this observable. The CP -violating asymmetry in the $D^+ \rightarrow K^*(892)^0 K^+$ decay is predicted to be 0.3% given favourable combinations of strong and weak phases [38].

If evidence that direct CP violation in D^0 decays exists is resurrected by updates to the latest LHCb results [3, 4], and the quantity

$$\Delta A_{CP} = A_{\text{raw}}(D^{*+} \rightarrow D^0(K^- K^+)\pi^+) - A_{\text{raw}}(D^{*+} \rightarrow D^0(\pi^- \pi^+)\pi^+) \quad (5.2)$$

does in fact differ from zero, the next logical step would be to establish direct CPV in one single Cabibbo-suppressed decay mode. The simplest channel for which this is viable given the statistical sensitivities that can be achieved is of course the $D^+ \rightarrow \phi\pi^+$ decay, which is why it is studied in this thesis. However it would also be possible to make an accurate measurement of CPV in the $D^0 \rightarrow K^- K^+$ decay. The procedure would be to calculate, along the same lines as Eq. 5.1,

$$\begin{aligned} A_{CP}(D^0 \rightarrow K^- K^+) &= A_{\text{raw}}(D^{*+} \rightarrow D^0(K^- K^+)\pi^+) - A_{\text{raw}}(D^{*+} \rightarrow D^0(K^- \pi^+)\pi^+) \\ &\quad + A_{\text{raw}}(D^+ \rightarrow K^- \pi^+ \pi^+) - A_{\text{raw}}(D^+ \rightarrow K_s^0 \pi^+) + A_{CP}(K^0/\bar{K}^0) \end{aligned} \quad (5.3)$$

The Cabibbo-favoured $D^{*+} \rightarrow D^0(K^- \pi^+)\pi^+$ decay is used as a control mode to cancel the D^{*+} production asymmetry, but the detector asymmetry in its $K^- \pi^+$ final state

must then be cancelled using the two D^+ decays. Unfortunately, this would be a rather challenging analysis. Unlike those in Eq. 5.1, the four decay modes have quite different kinematic properties, and therefore a complicated binning or reweighting scheme would be necessary. The signal yield of tagged $D^0 \rightarrow K^- K^+$ decays is slightly higher than the yield of $D^+ \rightarrow \phi \pi^+$ decays, but not as large as in the whole $D^+ \rightarrow K^- K^+ \pi^+$ Dalitz plot. This measurement, while more complicated, should have a lower statistical uncertainty than the asymmetry difference between $K^- K^+$ and $\pi^- \pi^+$ final states, because the smaller $D^0 \rightarrow \pi^+ \pi^-$ sample does not need to be used.

If CP violation is established in multi-body charm decays, an amplitude analysis will be required to determine which resonance in the Dalitz plot the CPV originates from, and then to investigate whether the weak phase associated with the CPV is compatible with the Standard Model prediction, or requires another explanation. Since phases in a Dalitz plot must be measured relative to a reference resonance, only weak phases relative to this reference can be determined. It is possible that theoretical input could be used to assign a resonance in which no CPV is expected as the reference. Unfortunately, amplitude analyses using data samples of the size now available are likely to prove challenging. It is to be hoped that model uncertainties will scale with statistical uncertainties in such studies, but this cannot be guaranteed.

In the longer term, the planned upgrade to the LHCb detector in 2018 [106] should enable enormous samples of charm decays to be collected. The aim is to replace the existing hardware trigger with one able to activate detector readout at much higher rates than 1 MHz, and ultimately, perhaps, to dispense with the hardware trigger altogether. The output rate of the final-stage software trigger is foreseen to be around 20 kHz, a factor of six more than that available at present. The signal yield of $D^+ \rightarrow \phi \pi^+$ decays in 50 fb^{-1} of data collected with an upgraded detector is predicted to be around 500 million [59]. It seems likely that insights into CP violation in charm decays will soon be within reach.

Appendix A

Parameters for the mass fit in Chapter 3

Background yield	314032 ± 938
D^+ signal yield	327872 ± 683
D_s^+ yield	463070 ± 863
$A_{raw}(D^+)$	-0.006 ± 0.002
$A_{raw}(D_s^+)$	-0.004 ± 0.002
A_{raw} (background)	0.002 ± 0.004
Fraction of D^{*+}	0.060 ± 0.004
Linear background slope	$(6.7 \pm 0.1) \times 10^{-4}$
Asymmetry (D^+/D^-) in bkg. slope	$(0.2 \pm 3.0) \times 10^{-5}$
Quadratic bkg. component	$(3.8 \pm 1.0) \times 10^{-6}$
Width of D^{*+}	$18 \pm 1 \text{ MeV}/c^2$
Fraction of Gaussian 1 in D^+ distribution	0.61 ± 0.03
Fraction of Gaussian 1 in D_s^+ distribution	0.67 ± 0.01
Mean of Gaussian peak (D^+)	$1869.27 \pm 0.01 \text{ MeV}/c^2$
Mean of Gaussian peak (D_s^+)	$1968.17 \pm 0.01 \text{ MeV}/c^2$
Width of Peak 1 (D^+)	$5.04 \pm 0.06 \text{ MeV}/c^2$
Width of Peak 1 (D_s^+)	$5.60 \pm 0.04 \text{ MeV}/c^2$
Ratio of widths of Gaussian 1 and Gaussian 2 (D^+)	1.67 ± 0.02
Ratio of widths of Gaussian 1 and Gaussian 2 (D_s^+)	1.80 ± 0.02
Difference (D^+/D^-) in means (D^+)	$0.02 \pm 0.01 \text{ MeV}/c^2$
Difference (D^+/D^-) in means (D_s^+)	$0.01 \pm 0.01 \text{ MeV}/c^2$
Difference (D^+/D^-) in widths (D^+)	$0.023 \pm 0.010 \text{ MeV}/c^2$
Difference (D^+/D^-) in widths (D_s^+)	$0.002 \pm 0.009 \text{ MeV}/c^2$

Table A.1: Fit parameters for the fit to the $D^+ \rightarrow K^- K^+ \pi^+$ mass distribution in Chapter 3. The ν parameters are yields, the A_{raw} parameters are charge asymmetries. The χ^2/ndf is $314/177 = 1.77$.

Appendix B

Transformation from linear to square Dalitz plot coordinates

This derivation follows Ref. [80]. The density of candidates in the Dalitz plot can be written

$$dG = \frac{dm_{12}^2 dm_{13}^2}{M^3} \quad (\text{B.1})$$

where M is the mass of the parent particle, m_i is the mass of the i^{th} decay product and m_{ij} is the combined invariant mass of a pair of daughters. Let $\cos \theta_1$ be the helicity angle of particle 1 in the (1,2) rest frame, p be the momentum of particle 3 in the rest frame of M , P be its momentum in the (1,2) rest frame, and q be the momentum of 1 in the (1,2) rest frame. Then in the (1,2) rest frame, one can find the invariant mass of particle 1 and 2 with a scalar product of four-vectors,

$$m_{13}^2 = m_1^2 + m_3^2 + 2E_1' E_3' + 2Pq \cos \theta_1 \quad (\text{B.2})$$

where E'_i is the energy of the i^{th} particle in the (1,2) rest frame and E_i will be its energy in the rest frame of M . Then

$$dm_{13}^2 = Pq d(\cos \theta_1) \quad (\text{B.3})$$

for fixed m_{12} . Now, converting between (1,2) and M rest frames,

$$P = \gamma(p + \beta E_3) \quad (\text{B.4})$$

and

$$\gamma = \frac{(M - E_3)}{m_{12}}; \beta = \frac{p}{M - E_3} \quad (\text{B.5})$$

since the energy of the (1,2) system in the rest frame of M is of course $M - E_3$.

Thus we have

$$P = \frac{M - E_3}{m_{12}} \left(p + \frac{p}{M - E_3} E_3 \right) = \frac{Mp}{m_{12}} \quad (\text{B.6})$$

and so

$$dm_{13}^2 = \frac{M}{m_{12}} p q d \cos \theta_1 \quad (\text{B.7})$$

and

$$dG = \frac{pq}{m_{12}} \frac{d \cos \theta_1 dm_{12}^2}{M^2} \quad (\text{B.8})$$

with, from the Particle Data Group review [16] or a tedious manipulation,

$$p = \frac{\sqrt{(M^2 - (m_3 + m_{12})^2)(M^2 - (m_3 - m_{12})^2)}}{2M} \quad (\text{B.9})$$

and

$$q = \frac{\sqrt{(m_{12}^2 - (m_1 + m_2)^2)(m_{12}^2 - (m_1 - m_2)^2)}}{2m_{12}}. \quad (\text{B.10})$$

Appendix C

Fit parameters for mass fit in

Chapter 4

Tables C.1 and C.2 give the fit results for the single fits to the whole sample of $\phi\pi^+$ and $K_S^0\pi^+$ decays respectively. In the fits to the 12 bins of p_T and η , the mean and width of the mass distributions for D^+ vary as shown in Table C.3.

A_{raw} comb. bkg (MagDown)	0.016 ± 0.007
A_{raw} comb. bkg (MagUp)	0.013 ± 0.009
$A_{raw} D^+$ (MagDown)	-0.003 ± 0.001
$A_{raw} D^+$ (MagUp)	-0.011 ± 0.001
$A_{raw} D_s^+$ (MagDown)	-0.0009 ± 0.0008
$A_{raw} D_s^+$ (MagUp)	-0.0077 ± 0.0009
$A_{raw} \pi^0$ bkg.	-0.08 ± 0.02
Comb. bkg yield (MagDown)	64809 ± 1922
Comb. bkg yield (MagUp)	43210 ± 1380
π^0 background yield	4898 ± 253
D^+ signal yield (MagDown)	931390 ± 1189
D^+ signal yield (MagUp)	645512 ± 937
D_s^+ signal yield (MagDown)	1788464 ± 1698
D_s^+ signal yield (MagUp)	1221692 ± 1330
Background slope	-0.37 ± 0.02
π^0 bkg. width	$12.5 \pm 0.7 \text{ MeV}/c^2$
π^0 bkg mean	$1809.8 \pm 0.9 \text{ MeV}/c^2$
Cruiff $\alpha: D^+$	0.071 ± 0.001
Cruiff $\alpha: D_s^+$	0.0768 ± 0.0007
Left-right difference in Cruiff α	0.0089 ± 0.0007
Fraction of Cruiff	0.869 ± 0.007
$D^+ \mu$ (MagDown)	$1870.676 \pm 0.007 \text{ MeV}/c^2$
$D^+ \mu$ (MagUp)	$1870.756 \pm 0.008 \text{ MeV}/c^2$
$D_s^+ \mu$ (MagDown)	$1969.724 \pm 0.006 \text{ MeV}/c^2$
$D_s^+ \mu$ (MagUp)	$1969.824 \pm 0.007 \text{ MeV}/c^2$
D^+ Cruiff σ	$5.45 \pm 0.02 \text{ MeV}/c^2$
D_s^+ Cruiff σ	$5.65 \pm 0.01 \text{ MeV}/c^2$
Crystal ball width offset (cf. to Cruiff)	$0.72 \pm 0.07 \text{ MeV}/c^2$
Difference (D^+/D^-) in means (MagDown)	$-0.225 \pm 0.004 \text{ MeV}/c^2$
Difference (D^+/D^-) in means (MagUp)	$0.239 \pm 0.005 \text{ MeV}/c^2$
Difference (D^+/D^-) in widths (MagDown)	$0.020 \pm 0.003 \text{ MeV}/c^2$
Difference (D^+/D^-) in widths (MagUp)	$-0.003 \pm 0.004 \text{ MeV}/c^2$
Crystal Ball α	1.49 ± 0.02
Crystal Ball n	1.8 ± 0.1

Table C.1: Fit parameters from the fit to the $\phi\pi^+$ final state. The abbreviation ‘comb.’ is used to represent combinatorial background, A_{raw} a raw charge asymmetry, and ‘ π^0 ’ indicates the fit parameters relating to the background from $D_s^+ \rightarrow \phi\pi^+\pi^0$. The Cruiff μ , σ and α parameters are defined in Eq. 4.6 and the Crystal Ball parameters are defined in Eq. 4.4. The charge asymmetries are unblinded in this table.

A_{raw} comb. bkg (MagDown)	0.015 ± 0.006
A_{raw} comb. bkg (MagUp)	0.006 ± 0.008
A_{raw} D^+ (MagDown)	-0.007 ± 0.001
A_{raw} D^+ (MagUp)	-0.009 ± 0.002
A_{raw} D_s^+ (MagDown)	-0.009 ± 0.011
A_{raw} D_s^+ (MagUp)	0.016 ± 0.013
A_{raw} (π^0 background)	0.10 ± 0.10
A_{raw} (reflection)	0.00 ± 0.06
Comb. bkg. yield (MagDown)	63883 ± 566
Comb. bkg. yield (MagUp)	43575 ± 485
π^0 background yield	539 ± 58
Reflection yield	6014 ± 706
D^+ signal yield (MagDown)	623281 ± 949
D^+ signal yield (MagUp)	434470 ± 862
D_s^+ signal yield (MagDown)	15146 ± 149
D_s^+ signal yield (MagUp)	10474 ± 108
Background slope	-0.251 ± 0.011
D^+ Cruijff α_L	0.108 ± 0.001
D^+ Cruijff α_R	0.091 ± 0.001
D^+ μ (MagDown)	$1871.11 \pm 0.01 \text{ MeV}/c^2$
D^+ μ (MagUp)	$1871.30 \pm 0.01 \text{ MeV}/c^2$
D_s^+ μ (MagDown)	$1970.2 \pm 0.1 \text{ MeV}/c^2$
D_s^+ μ (MagUp)	$1970.4 \pm 0.1 \text{ MeV}/c^2$
D^+ Cruijff σ_L	$7.03 \pm 0.03 \text{ MeV}/c^2$
D^+ Cruijff σ_R	$7.44 \pm 0.02 \text{ MeV}/c^2$
D_s^+ Cruijff σ	$7.48 \pm 0.08 \text{ MeV}/c^2$
Difference (D^+/D^-) in means (D^+ , MagDown)	$-0.29 \pm 0.01 \text{ MeV}/c^2$
Difference (D^+/D^-) in means (D^+ , MagUp)	$0.27 \pm 0.01 \text{ MeV}/c^2$
Difference (D^+/D^-) in widths (D^+ , MagDown)	$0.02 \pm 0.01 \text{ MeV}/c^2$
Difference (D^+/D^-) in widths (D^+ , MagUp)	$-0.01 \pm 0.01 \text{ MeV}/c^2$

Table C.2: Fit parameters from the fit to the $\phi\pi^+$ final state. The abbreviation ‘comb.’ is used to represent combinatorial background, A_{raw} a raw charge asymmetry, and ‘ π^0 ’ indicates the fit parameters relating to the background from $D_s^+ \rightarrow \phi\pi^+\pi^0$. The mean and width of this background were fixed to the values observed in the $\phi\pi^+$ final state to preserve fit stability. The Cruijff μ , σ and α parameters are defined in Eq. 4.6, except that in this case the widths on the left and the right halves of the distribution are allowed to differ in the case of the D^+ decay. Due to the lower yield of D_s^+ decays, the tail parameters of the Cruijff used to describe the D_s^+ mass peak are shared with those of the D^+ . The charge asymmetries are unblinded in this table.

Bin	Mean ($D^+ \rightarrow K_s^0 \pi^+$)	Width ($D^+ \rightarrow K_s^0 \pi^+$)	Mean ($D^+ \rightarrow \phi \pi^+$)	Width ($D^+ \rightarrow \phi \pi^+$)
0	1871.19 ± 0.04	5.67 ± 0.05	1870.64 ± 0.03	4.33 ± 0.04
1	1871.24 ± 0.02	6.40 ± 0.03	1870.70 ± 0.02	4.99 ± 0.04
2	1871.45 ± 0.02	7.41 ± 0.03	1870.90 ± 0.03	5.78 ± 0.08
3	1871.15 ± 0.03	6.03 ± 0.04	1870.70 ± 0.02	4.60 ± 0.06
4	1871.18 ± 0.03	6.84 ± 0.03	1870.72 ± 0.02	5.27 ± 0.03
5	1871.37 ± 0.03	8.02 ± 0.04	1870.88 ± 0.02	6.22 ± 0.04
6	1871.14 ± 0.03	6.42 ± 0.04	1870.68 ± 0.01	4.88 ± 0.02
7	1871.14 ± 0.03	7.36 ± 0.04	1870.69 ± 0.02	5.60 ± 0.03
8	1871.27 ± 0.04	8.51 ± 0.06	1870.87 ± 0.03	6.43 ± 0.04
9	1871.06 ± 0.04	7.24 ± 0.04	1870.64 ± 0.01	5.44 ± 0.02
10	1871.00 ± 0.05	8.21 ± 0.06	1870.64 ± 0.02	6.12 ± 0.03
11	1871.33 ± 0.07	9.57 ± 0.09	1870.81 ± 0.04	6.64 ± 0.06

Table C.3: The variation of the mean and width of the $D^+ \rightarrow K_s^0 \pi^+$ and $D^+ \rightarrow \phi \pi^+$ mass distributions across the 12 kinematic bins shown in Fig. 4.16. The values in the table are averages over the two magnet polarities.

Appendix D

Additional mass fits for Chapter 4

D.1 Charge-separated projections

This appendix contains the mass fits to the $D_{(s)}^+ \rightarrow \phi\pi^+$ and $D_{(s)}^+ \rightarrow K_s^0\pi^+$ datasets analysed in Chapter 4 separated by the charge of the $D_{(s)}^+$ candidate.

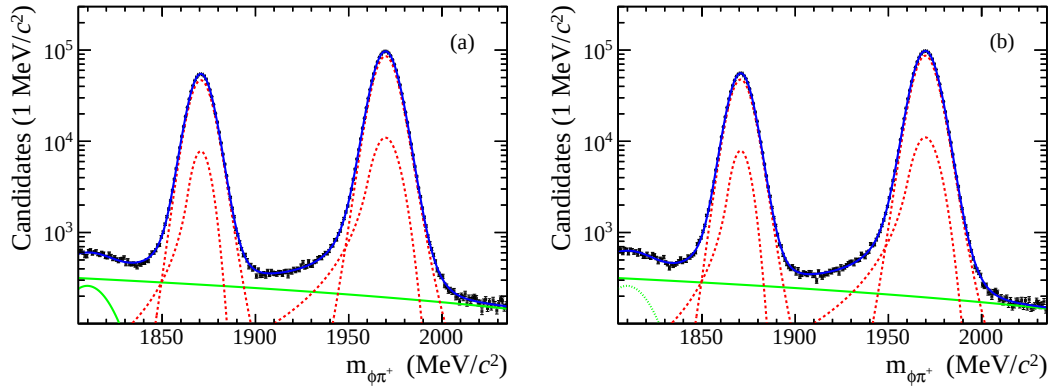


Figure D.1: Invariant mass distribution of the $\phi\pi^+$ final states, (a) D^+ , (b) D^- , over the whole p_T - η range.

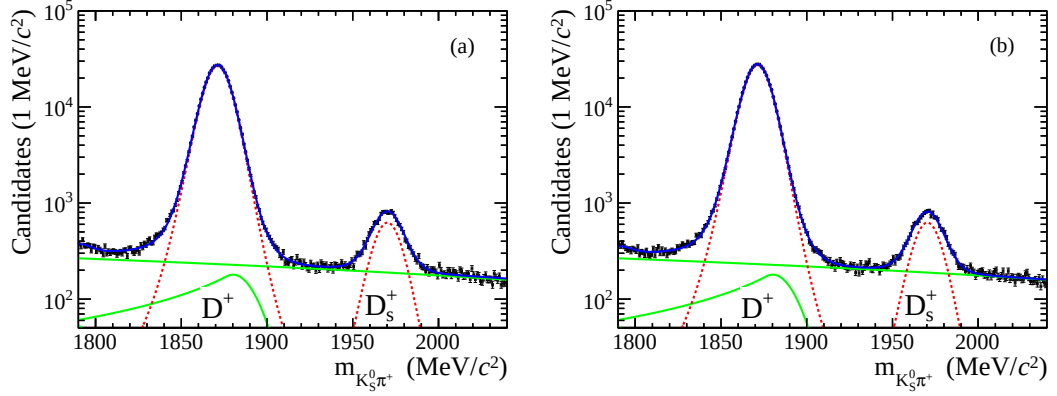


Figure D.2: Invariant mass distribution of the $K_s^0 \pi^+$ final states, (a) D^+ , (b) D^- , over the whole p_T - η range.

D.2 Binned fits

This appendix contains the mass fits to the $D_{(s)}^+ \rightarrow \phi \pi^+$ and $D_{(s)}^+ \rightarrow K_s^0 \pi^+$ datasets analysed in Chapter 4 in the 12 kinematic bins. Bins 0, 3, 6, 9 contain data with the lowest values of η and increasing values of p_T . The intermediate η values are fitted in bins 1, 4, 7, 10, and high η values in 2, 5, 8 and 11.

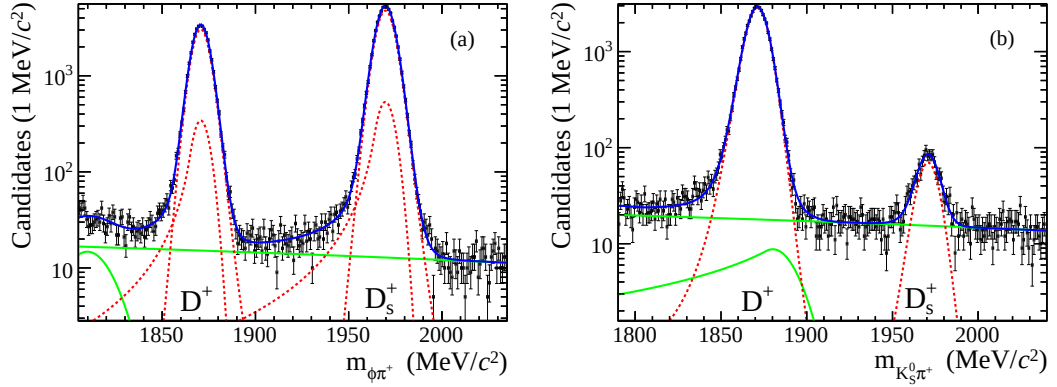


Figure D.3: Fit results: bin 0: (a) $\phi \pi^+$ final states and (b) $K_s^0 \pi^+$ final states.

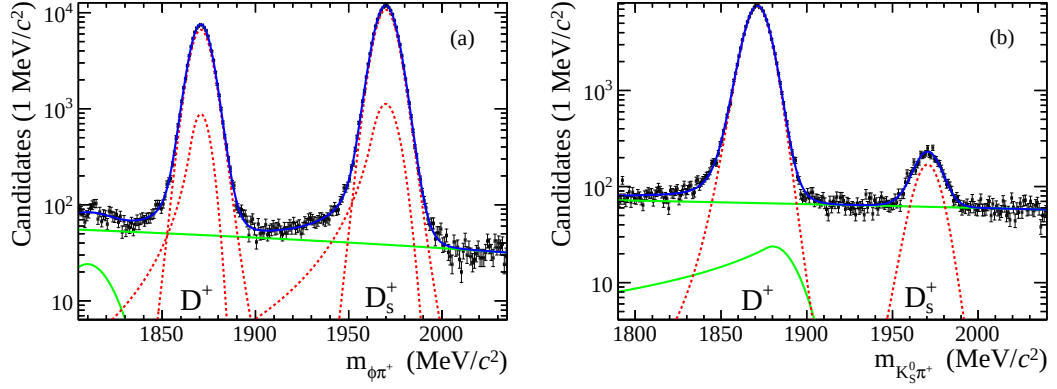


Figure D.4: Fit results: bin 1: (a) $\phi\pi^+$ final states and (b) $K_s^0\pi^+$ final states.

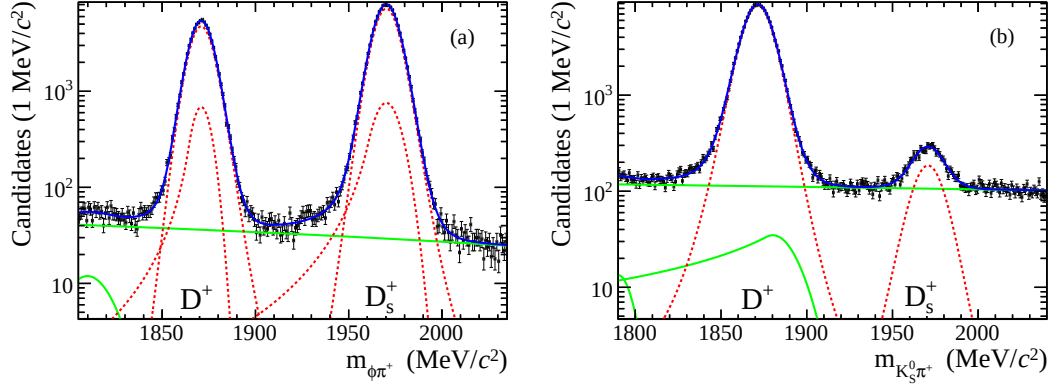


Figure D.5: Fit results: bin 2: (a) $\phi\pi^+$ final states and (b) $K_s^0\pi^+$ final states.

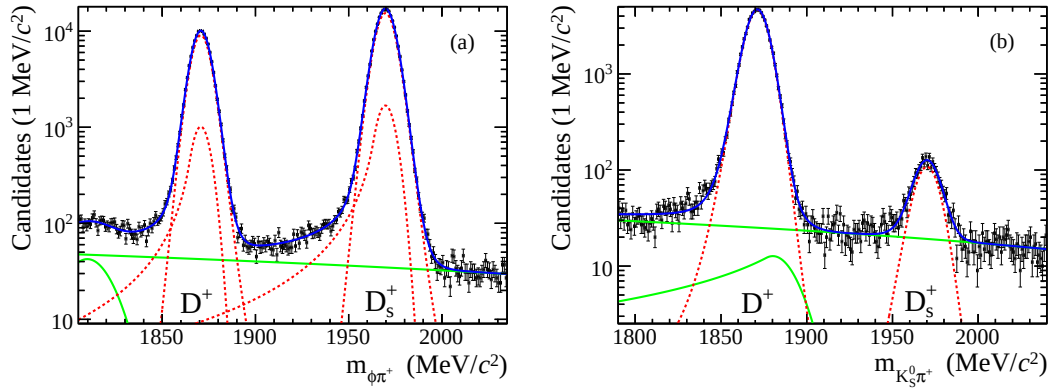


Figure D.6: Fit results: bin 3: (a) $\phi\pi^+$ final states and (b) $K_s^0\pi^+$ final states.

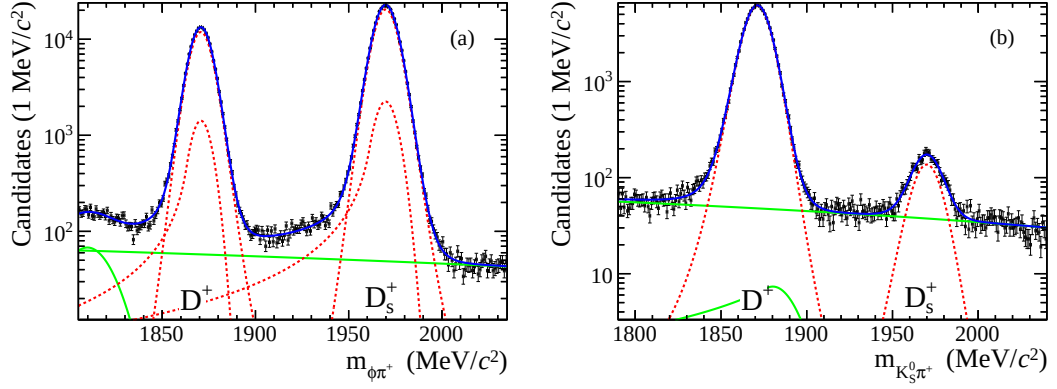


Figure D.7: Fit results: bin 4: (a) $\phi\pi^+$ final states and (b) $K_s^0\pi^+$ final states.

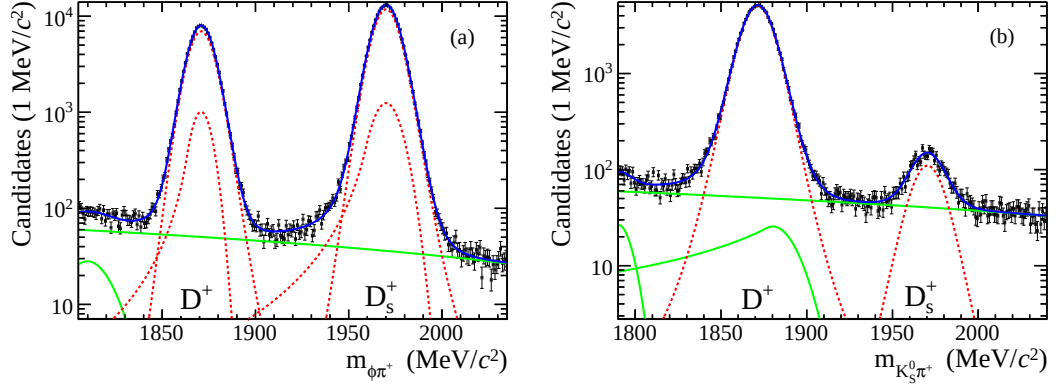


Figure D.8: Fit results: bin 5: (a) $\phi\pi^+$ final states and (b) $K_s^0\pi^+$ final states.

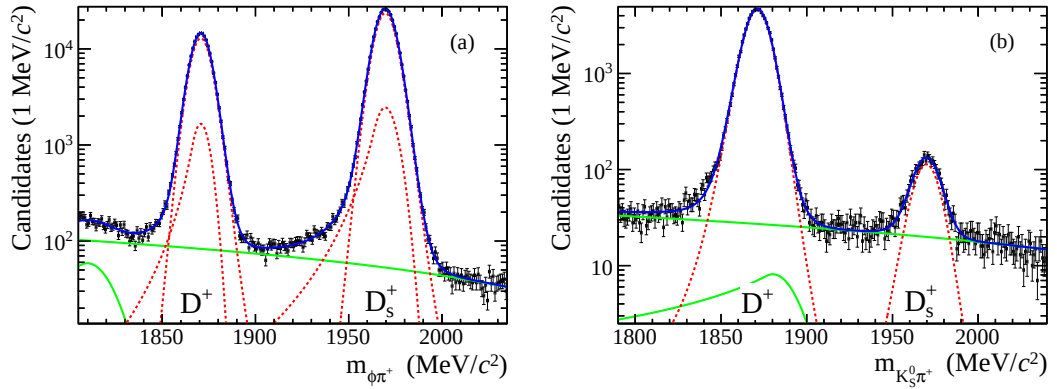


Figure D.9: Fit results: bin 6: (a) $\phi\pi^+$ final states and (b) $K_s^0\pi^+$ final states.

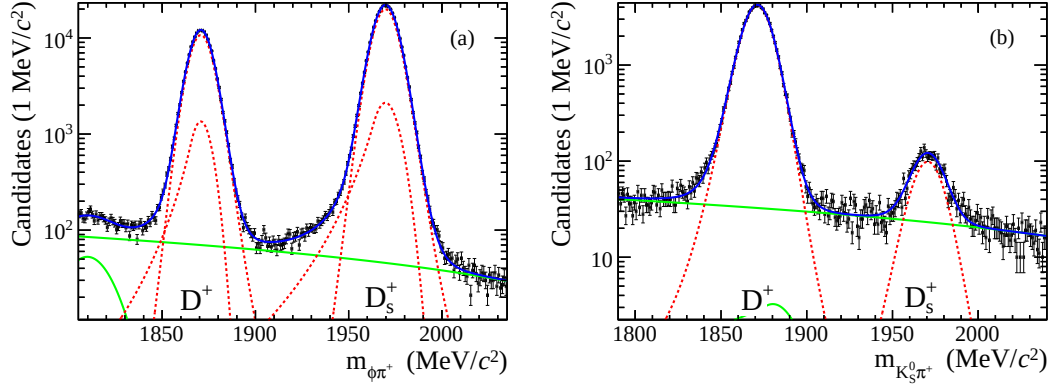


Figure D.10: Fit results: bin 7: (a) $\phi\pi^+$ final states and (b) $K_s^0\pi^+$ final states.

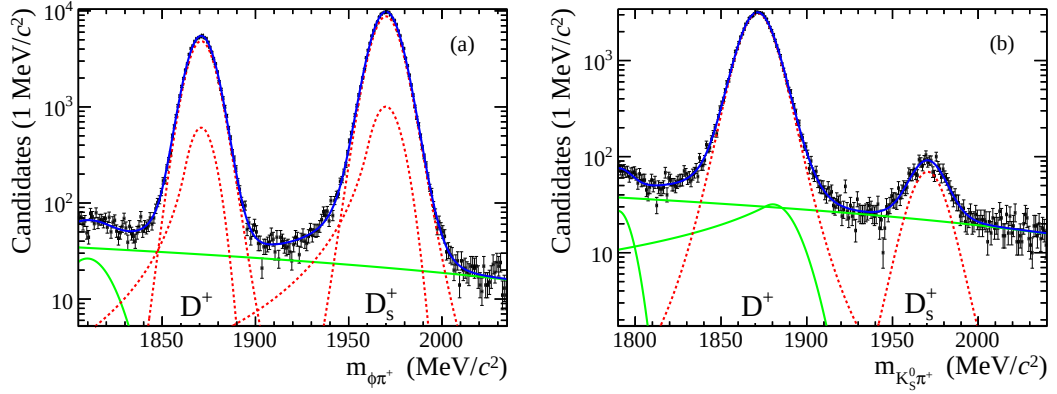


Figure D.11: Fit results: bin 8: (a) $\phi\pi^+$ final states and (b) $K_s^0\pi^+$ final states.

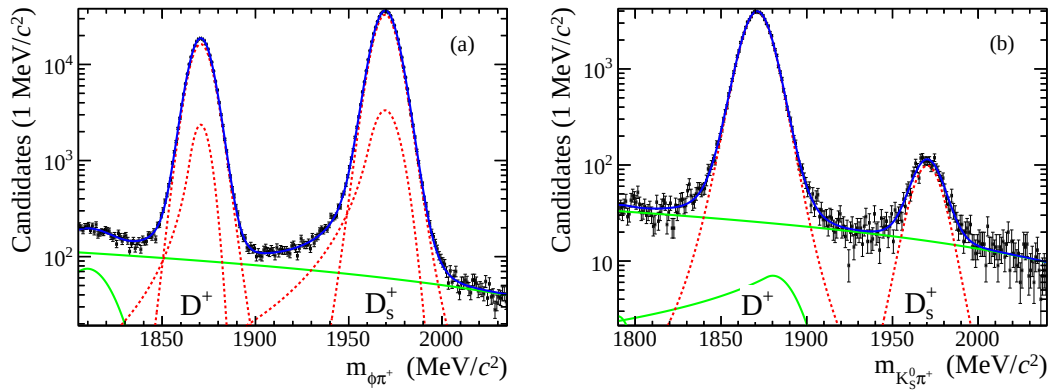


Figure D.12: Fit results: bin 9: (a) $\phi\pi^+$ final states and (b) $K_s^0\pi^+$ final states.

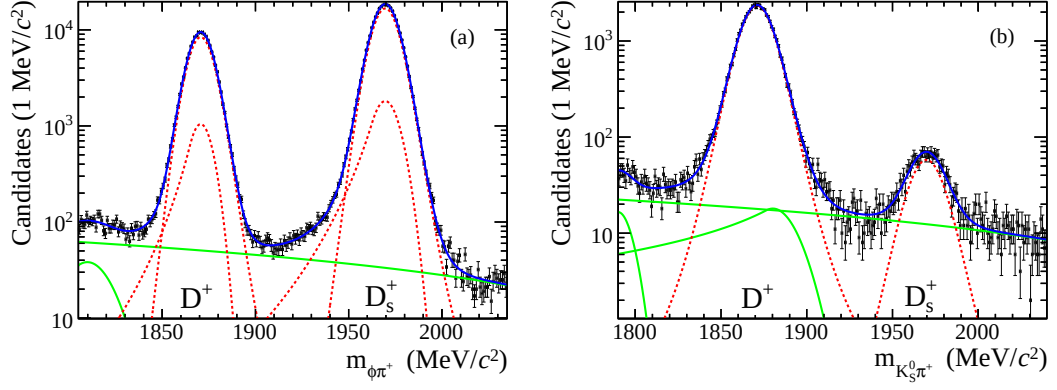


Figure D.13: Fit results: bin 10: (a) $\phi\pi^+$ final states and (b) $K_s^0\pi^+$ final states.

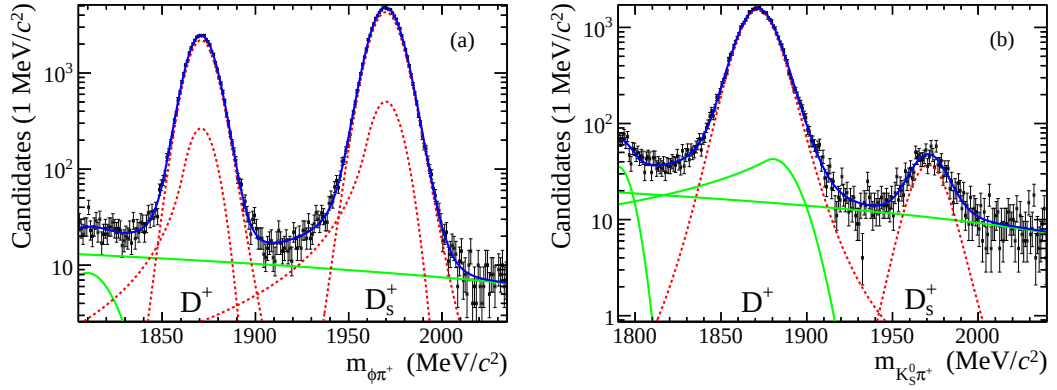


Figure D.14: Fit results: bin 11: (a) $\phi\pi^+$ final states and (b) $K_s^0\pi^+$ final states.

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