

Future flavour physics experiments

Neville Harnew*

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The current status of flavour physics and the prospects for present and future experiments will be reviewed. Measurements in B -physics, in which sensitive probes of new physics are the CKM angle γ , the B_s mixing phase ϕ_s , and the branching ratios of the rare decays $B_{(s)}^0 \rightarrow \mu^+ \mu^-$, will be highlighted. Topics in charm and kaon physics, in which the measurements of A_{CP} and the branching ratios of the rare decays $K \rightarrow \pi \nu \bar{\nu}$ are key measurements, will be discussed. Finally the complementarity of the future heavy flavour experiments, the LHCb upgrade and Belle-II, will be summarised.

1 Introduction

Flavour physics holds the key to some of today's most important issues in particle physics, namely the indirect search for dark matter and the mechanism of CP-violation. In the quark sector, the CKM matrix describes CP-violation in the Standard Model (SM) but gives rise to too small a level of asymmetry to explain the observed dominance of matter over antimatter in the Universe. In particular, (non)-consistency tests of the CKM mechanism provide an excellent framework to discover sources of New Physics (NP).

We know that sources of NP must exist, but as yet there is no knowledge of the effects or the scale in the quark sector. The absence to date of NP signals at ATLAS and CMS makes a strong argument to pursue searches in heavy flavour decays via rare processes, such as flavour-changing neutral currents (FCNCs). These are accessed via box and loop (penguin) decay processes which allow a probe of masses significantly beyond the kinematic limit [1]. History has shown that such indirect searches provide a powerful discovery tool for such high masses.

There are several key observables that will be the focus of future experimental measurements which will be discussed below. To demonstrate consistency of the CKM mechanism, measurements of the CP angle γ will need to be significantly improved. The weak phase in the B_s

system, ϕ_s , and ΔA_{CP} in the charm system indicate CP-violating effects in the SM which are expected to be very small, and where future experiments will probe down to SM expectations. These experiments will also improve the precision of $|V_{ub}|$ and allow checks on lepton universality, including the decay $B^0 \rightarrow D^{(*)} \tau \nu$. The branching ratios of $B_{(s)}^0 \rightarrow \mu^+ \mu^-$, the parameter P'_5 in $B^0 \rightarrow K^* \mu^+ \mu^-$ and the rare kaon decay $K \rightarrow \pi \nu \bar{\nu}$ are measurements in which large NP effects can be expected.

2 The B physics programme


2.1 The experiments

2.1.1 LHCb and the LHCb Upgrade

The LHCb detector [2] is a single-arm forward spectrometer designed to study CP violation in B -hadron decays at the LHC. LHCb covers a polar angular aperture between approximately 10 and 300 mrad (250 mrad) in the bending (non-bending) plane and exploits the sharply peaked forward-backward $b\bar{b}$ production cross section.

Up to 2018, LHCb will have accumulated $\sim 8 \text{ fb}^{-1}$ of integrated luminosity, and beyond this the data-doubling time becomes prohibitive. A compelling physics case has been made for improved precision and extra sensitivity to the rarest decay modes. The LHCb detector will therefore be upgraded in the long shutdown (LS2) of the LHC during 2018–20 [3]. The subdetector readout electronics will be upgraded to a 40 MHz rate and all trigger decisions will be made in software, giving significant efficiency improvements. The detector will also be upgraded to run at a luminosity of up to

* Corresponding authors E-mail: Neville.Harnew@physics.ox.ac.uk
University of Oxford, Denys Wilkinson Building, Keble Road, Oxford
OX1 3RH, UK

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$2 \times 10^{33} \text{ cm}^{-2}\text{s}^{-1}$, a factor of 5 increase. A combination of these improvements will allow around an order of magnitude increase in precision compared to where we stand today.

2.1.2 KEKB and Belle-II

KEKB collides 7 GeV e^- on 4 GeV e^+ and runs mainly on the $\Upsilon(4S) \rightarrow B\bar{B}$ with a possibility to run on the $\Upsilon(5S) \rightarrow B_s\bar{B}_s$. Both the KEKB accelerator and the Belle detector [4] are undergoing a major upgrade with the aim to start physics data-taking in 2017–2018 at a peak luminosity of $\sim 10^{36} \text{ cm}^{-2}\text{s}^{-1}$, approximately 40 times higher than its predecessor. The expectation is that Belle-II will accumulate 50 ab^{-1} in ~ 5 years giving approximately 50 times the current Belle data.

Whilst LHCb has the benefit of the raw data rate, Belle-II has several significant advantages. Firstly e^+e^- collisions benefit from a relatively clean environment and also the $B\bar{B}$'s are produced in a quantum correlated state. The trigger is very efficient and the tagging efficiency is high with respect to a pp machine (about $\times 15$). Another significant advantage over LHCb is the excellent reconstruction of neutrals: γ , π^0 , K_L and neutrinos via missing energy. The physics programme of Belle-II is broad, giving flavour-physics measurements which are unique, but also complementary to LHCb. A description of the Belle-II physics programme can be found in Ref. [5].

2.2 A consistent picture of CKM measurements

Imposing unitarity constraints on the CKM matrix gives the condition $V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0$, which can be represented by the so-called “unitarity triangle” when plotted in the complex plane. A consistency test of the SM requires that many different fits to the unitarity triangle all result in a common apex and, if not, this will indicate additional amplitudes from NP. The current constraints on the parameters of the unitarity triangle are shown in Fig. 1 [6]. Whilst there is good general consistency with the CKM parametrization, the current measurements are dominated by box or loop processes. The measurements solely from tree processes still have large uncertainties, in particular from the left side of the triangle ($|V_{ub}|/|V_{cb}|$) and the angle γ .

It is important to measure γ with high statistical power in a variety of complementary channels to compare tree (SM dominated) and loop (sensitive to NP) diagrams. As an example of tree-dominated processes, the evaluation of γ via the $B \rightarrow DK$ family of decays

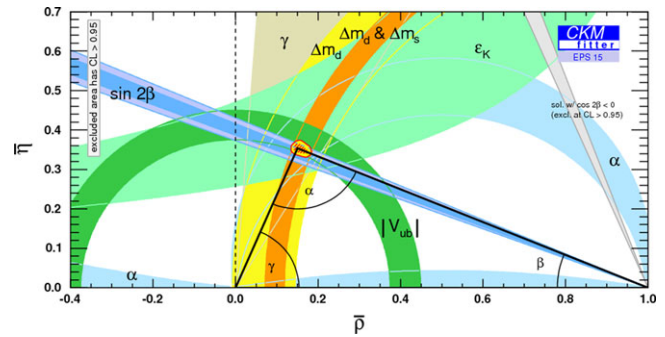


Figure 1 The experimental constraints on the sides and angles of the unitarity triangle from the CKMfitter group [6], represented on an Argand diagram. The base of the triangle is aligned along the real axis ($\bar{\rho}$), and is conventionally normalized to unity. The height of the apex of the triangle is plotted on the imaginary axis ($\bar{\eta}$). The experimental constraints on the three angles, α (light blue), β (violet) and γ (grey) are given by 95% confidence level (CL) bands. The darker blue band shows the 68% CL for β . Constraints on the triangle sides from measurements of $|V_{ub}|$ (dark green) and the B_d and B_s mixing frequencies (Δm_d and Δm_s respectively) are shown by the orange band at 95% CL. The 95% confidence constraint from measurements of indirect CP violation in the kaon system, the $|\epsilon_K|$ parameter (light green), is also shown. The dashed red region shows the 68% CL for the combination, which constrains the apex of the triangle.

gives extremely small theoretical uncertainty [7]. Hence measurements of these modes determine the “Standard Model” value of γ .

LHCb’s current best measurement of γ is from a combination of results from $B \rightarrow DK$ and $B \rightarrow D\pi$ decays which gives γ to be 72.6° with a confidence interval at the 68% level of $[55.4^\circ, 82.3^\circ]$ [8]. This is already a more significant measurement than BaBar and Belle combined, but still has large uncertainties.

In the future, the statistical reach in γ of the LHCb upgrade will be $\sim 1\%$ [9]. The corresponding measurement for Belle-II is expected to be $\sim 2\text{--}3\%$ [5]. To keep systematic uncertainty at or below those levels requires an exceptionally good understanding of detector effects.

For the triangle left side, the measurement of $|V_{ub}|$ in semileptonic B decays has for several years had an internal inconsistency between the exclusive measurement $B^0 \rightarrow \pi^- \mu^+ \nu$ and the inclusive measurement $B^0/B^+ \rightarrow X_{u\ell} \mu^+ \nu$ [10], namely $V_{ub} = (4.41 \pm 0.23) \times 10^{-3}$ (inclusive) and $V_{ub} = (3.28 \pm 0.29) \times 10^{-3}$ (exclusive). Similar effects have also been seen in the inclusive and exclusive measurements of V_{cb} [10], with $V_{cb} = (42.2 \pm 0.7) \times 10^{-3}$ (inclusive) and $V_{cb} = (39.5 \pm 0.8) \times 10^{-3}$ (exclusive). The $\mathcal{O}(3\sigma)$ significance is enticing, but not yet enough to confirm NP, and more measurements and lattice calculation

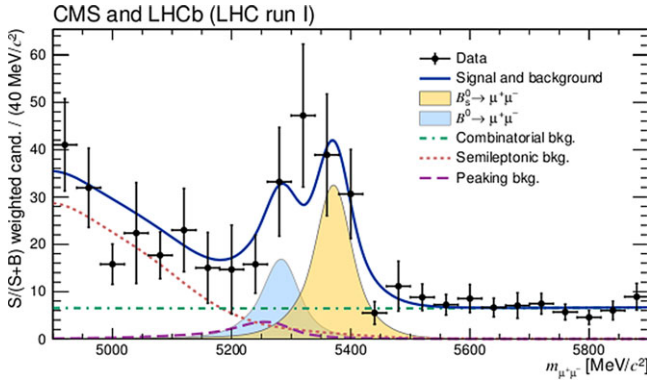


Figure 2 Combined CMS and LHCb di-muon mass combination for $B_{(s)} \rightarrow \mu^+ \mu^-$ [17].

improvements are necessary. LHCb has recently entered the game by measuring $|V_{ub}|$ in $\Lambda_b \rightarrow p \mu^- \bar{\nu}$ decays to be $|V_{ub}| = (3.27 \pm 0.23) \times 10^{-3}$ [11]. This measurement is 3.5σ below the inclusive measurement and agrees well with the current exclusive average. Hence future measurements of $|V_{ub}|$ and $|V_{cb}|$ will resolve these discrepancies and can potentially provide exciting indications of NP. Inclusive measurements of $|V_{ub}|$ from Belle-II at the few percent level will be possible.

2.3 $B_s \rightarrow \mu^+ \mu^-$ and $B^0 \rightarrow \mu^+ \mu^-$

The $B_s \rightarrow \mu^+ \mu^-$ decay is a loop process with a branching ratio (BR) of $(3.65 \pm 0.23) \times 10^{-9}$ in the SM [12]. This decay is extremely rare due to the absence of tree-level FCNCs, helicity suppression and CKM-matrix suppression. The decay $B^0 \rightarrow \mu^+ \mu^-$ is similarly suppressed and has a BR approximately 30 less, $(1.07 \pm 0.10) \times 10^{-10}$ [13]. The decays can be strongly enhanced in NP models, and are especially sensitive to high $\tan \beta$ parameter space in the minimal supersymmetric model (MSSM) [14], where the rates go as $\sim \tan^6 \beta$. Searches over 30 years have given approximately an order of magnitude improvement every ~ 5 years.

Data from CMS [15] and LHCb [16] have been combined [17] and the resulting di-muon mass measurement is shown in Fig. 2. The peaks show 3.0σ and 6.2σ excesses in the $B^0 \rightarrow \mu^+ \mu^-$ and $B_s \rightarrow \mu^+ \mu^-$ channels, respectively. These measurements are consistent with SM expectations, although the larger than expected BR for the B^0 decay is intriguing.

The LHCb upgrade and CMS experiments will continue to measure the ratio of BRs ($B^0 \rightarrow \mu^+ \mu^-$)/($B_s \rightarrow \mu^+ \mu^-$) with unrivaled precision. An ambitious goal of these experiments will be to search for other leptonic decays, for example $B_s \rightarrow \tau^+ \tau^-$, a channel which is much

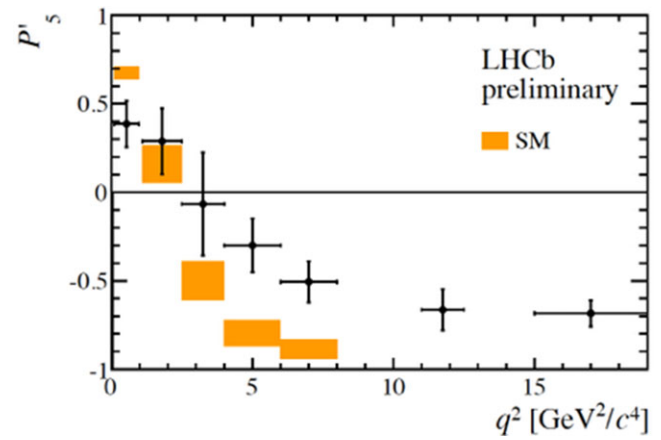


Figure 3 The P'_5 parameter of the LHCb angular analysis of $B^0 \rightarrow K^{*0} \mu^+ \mu^-$ [20] compared to SM expectations [19].

harder experimentally, but more sensitive to models incorporating extensions of the Higgs sector.

2.4 Angular analyses of $B^0 \rightarrow K^{*0} \mu^+ \mu^-$

The rare decay $B^0 \rightarrow K^{*0} \mu^+ \mu^-$ is a FCNC process that proceeds via loop and box amplitudes in the SM. In extensions of the SM, contributions from new particles can modify the angular distributions of the decay products. The current world-best measurements are made by LHCb [18] and good agreement has been found with SM parameterizations in most observables. However a local discrepancy from theoretical calculations [19] has been observed as a function of di-muon effective mass squared (q^2) for one of the observables, the so-called P'_5 parameter. This result has been confirmed by recent analysis of the full 3.0 fb^{-1} data sample [20], shown in Fig. 3, demonstrating a tension with the SM prediction at a level of 2.9σ in each of the $4.0 < q^2 < 6.0 \text{ GeV}^2$ and $6.0 < q^2 < 8.0 \text{ GeV}^2$ bins. A naïve combination of these deviations, based on a probability with two degrees of freedom and assuming the SM predictions in the two bins are uncorrelated, yields a local tension of 3.7σ . This is an interesting result that could be a hint of NP; however improved measurements are needed from both the LHCb upgrade and Belle-II. Better theoretical QCD calculations with improved uncertainties are also required.

2.5 Lepton universality in B decays

Lepton universality dictates that the $B^\pm \rightarrow K^\pm \mu^+ \mu^-$ and $B^\pm \rightarrow K^\pm e^+ e^-$ decays should have same BR to within a factor 10^{-3} ; however the ratio R_K of the BRs is sensitive to lepton flavour-violating NP contributions. LHCb

measures R_K to be $0.745^{+0.090}_{-0.074} (\text{stat}) \pm 0.036 (\text{syst})$, with hints of a deficit of $B^\pm \rightarrow K^\pm \mu^+ \mu^-$ compared to the expectation [21], currently a 2.6σ tension. The expected precision from both Belle-II and the LHCb upgrade will improve the errors by an order of magnitude and hence will resolve this issue.

There is also an excess measured by the BaBar collaboration of $\bar{B} \rightarrow D^{(*)} \tau^- \bar{\nu}_\tau$ decays relative to $\bar{B} \rightarrow D^{(*)} \ell^- \bar{\nu}_\ell$, where ℓ is a muon or electron. The measurements, $R(D) = 0.440 \pm 0.058 \pm 0.042$ and $R(D^*) = 0.332 \pm 0.024 \pm 0.018$, exceed the SM expectations by 2.0σ and 2.7σ , respectively [22]. The ratios are sensitive to NP contributions from a charged Higgs boson and, taken together, these results disagree with SM expectations at the 3.4σ level, although the excess cannot be explained by a charged Higgs boson within the type II two-Higgs-doublet model [23]. A recent Belle result lies between the SM expectation and the measurement from BaBar and is compatible with both [24]. Belle-II and possibly future LHCb results will be able to resolve this issue.

2.6 CP violation in B_s mixing

The D0 experiment has observed an anomalous di-muon asymmetry indicating CP violation in B_s mixing [25], the so-called A_{SL} measurement. A_{SL} is the difference of the numbers of B_s^0 decaying into μ^+ and μ^- , divided by the sum, integrated over the B_s^0 lifetime. The D0 result of $A_{SL} = -0.00957 \pm 0.00251 (\text{stat}) \pm 0.00146 (\text{syst})$, observed in 6.1 fb^{-1} of data, differs by 3.2σ from the SM prediction. This result has not yet been confirmed or refuted by separate measurements in the B^0 and B_s systems from the BaBar [26] and LHCb [27] experiments. Much improved measurements are required from the LHCb upgrade and Belle-II.

2.7 $B_s \rightarrow J/\psi \phi$ and $B_s \rightarrow \phi \phi$

The $B_s - \bar{B}_s$ mixing process introduces a small CP-violating weak phase whose predicted value in the SM, $\phi_s = -0.042 \pm 0.001 \text{ rad}$, is theoretically very clean [28]. However ϕ_s could be much larger than the SM prediction if NP contributes to $B_s - \bar{B}_s$ transitions. This phase can be measured in the tree decay process $B_s \rightarrow J/\psi \phi$ through the interference of the direct decay with the decay involving mixing. A compilation of results from hadron collider experiments is shown in Fig. 4 [29]. Here the constraints are dominated by the LHCb result, $\phi_s = -0.058 \pm 0.049 \pm 0.006 \text{ rad}$ [30], but with important contributions from ATLAS and CMS.

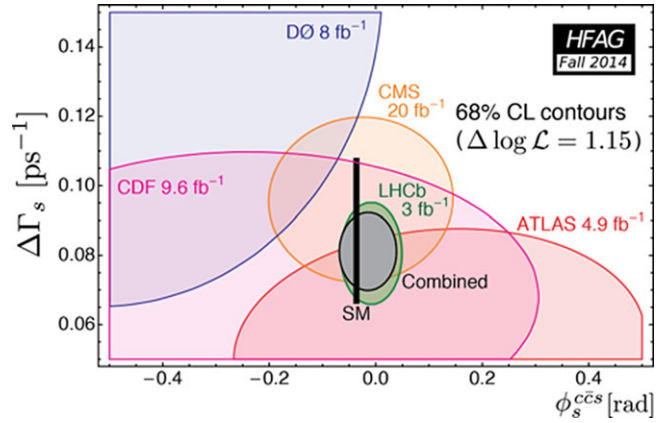


Figure 4 Contours of allowed regions in the $\Delta\Gamma_s, \phi_s$ plane of $B_s \rightarrow J/\psi \phi$ from LHCb, ATLAS, CMS and the Tevatron experiments [29]. $\Delta\Gamma_s$ is the width difference between B_s eigenstates.

Deviations from SM predictions can also be expected in the FCNC decay $B_s \rightarrow \phi \phi$ which again involves the interference of direct and mixing amplitudes. The upper limit of CP violation expected in the SM is $\sim 2\%$ [31], hence the observation of any significant CP violation in $B_s \rightarrow \phi \phi$ is a signature for NP. LHCb's current measurement for ϕ_s in the $B_s \rightarrow \phi \phi$ channel in 3 fb^{-1} of data is $-0.17 \pm 0.15 \pm 0.03 \text{ rad}$ [32], hence the large errors mean that no CP violation of significance can yet be observed. However the LHCb upgrade will bring the precision on this down to $\sim 0.02 \text{ rad}$ [9], to the same level as the current theoretical uncertainty.

3 Charm physics

3.1 The experiments

The LHCb and Belle-II experiments plan a full programme of charm physics measurements. Charm is produced from decays of b quarks and directly from gluon-gluon fusion interactions in LHCb and from the continuum in Belle-II. A dedicated experiment running at the IHEP e^+e^- charm-factory, BES III [35], has already collected an unprecedented data sample on the J/ψ , $\psi(2S)$, $\psi(3770)$ and $\psi(4040)$ resonances. The experiment will also run at the tau-pair threshold for a new precision tau mass measurement. Looking towards the future, BES III plans to collect data at centre-of-mass energies of 4260 MeV and 4360 MeV to conduct spectroscopic studies of the “XYZ” states [36], and also run at 4170 MeV in order to study the D_s meson. BES III is scheduled to collect data for around another eight to ten years.

3.2 CP violation in charm mixing

An important and topical area in charm physics is the search for CP violation. CP-violating effects are predicted to be very small in the SM, with a theoretical expectation of up to a few $\times 10^{-3}$ [33]. LHCb has recently made measurements of charm mixing and CP violation in the parameter $\Delta A_{CP} = A_{CP}(K^+K^-) - A_{CP}(\pi^+\pi^-) = +0.14 \pm 0.16(\text{stat}) \pm 0.08(\text{syst})\%$ [34], where $A_{CP}(f)$ is the difference in D^0 and \bar{D}^0 decaying into final state f , divided by the sum. Whilst no CP violation is yet observed, there is still much scope for NP effects. Improvements are also needed in the precision of $x = \Delta m/\Gamma$ which the LHCb upgrade and Belle-II will provide. At the required level of $\mathcal{O}(10^{-3})$ precision, several complementary A_{CP} measurements will be required to resolve NP from SM contributions.

4 $K \rightarrow \pi \nu \bar{\nu}$ experiments

The current holy grail in kaon physics is the measurement of the BRs of the super-rare decays $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ and $K_L \rightarrow \pi^0 \nu \bar{\nu}$, which are suppressed by the CKM $s \rightarrow d$ coupling and are very sensitive to contributions from physics beyond the SM. The SM predictions for these BRs are $(9.11 \pm 0.72) \times 10^{-11}$ and $(3.00 \pm 0.30) \times 10^{-11}$, respectively [37]. The next-generation experiments will measure these decays for the first time.

The $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ decay will be measured by NA62 [38], a dedicated experiment at CERN which has now started running. The measurement is a major experimental challenge since the final state has two neutrinos and only one detectable particle. The aim is to collect 100 events at the SM BR during 2015-16, with < 10 events background.

The KOTO experiment [39] at J-PARC will measure the very challenging $K_L \rightarrow \pi^0 \nu \bar{\nu}$ decay. Approximately 100 hours of data have been taken which has achieved similar sensitivity to the current limit of 2.6×10^{-8} at 90% confidence from the KEK-E391a experiment [40]. The next KOTO run is expected in 2015 and should improve the limit by a factor of ~ 20 , and then onwards towards the SM sensitivity.

5 Possible future facilities

5.1 Future circular colliders

The HL-LHC will deliver more luminosity than the upgraded LHCb can take, but will nevertheless provide the world's most abundant source of b and c hadrons. Hence

there remains the possibility of a dedicated flavour experiment beyond the LHCb upgrade.

A study of the FCC programme at CERN, the Future Circular Collider, is ongoing [41]. Possible modes of operation of the FCC are the collisions of e^+e^- (which includes a Higgs factory, *TeraZ* running on the Z^0 pole, *OkuW* at the WW threshold, the *MegaTop* top factory), pp , ep or heavy ions. The e^+e^- option is in principle especially interesting for flavour physics. *TeraZ* gives $\mathcal{O}(10^{12})$ Z events in 1 year, hence huge samples can be recorded in $Z \rightarrow b\bar{b}, c\bar{c}$ and $\tau^+\tau^-$. By way of example, *TeraZ* can deliver more than 20k $B_s \rightarrow \tau^+\tau^-$ events giving a $< 10\%$ precision on the SM BR; NP models can change the $B_s \rightarrow \tau^+\tau^-$ BR by large factors. Conversely, flavour physics options at the ILC/CLIC and a μ -collider seem to be rather marginal to their respective programmes since they concentrate on high-energy running where the cross-sections for b and c production are small.

At any future pp machine, the cross-section $\sigma(pp \rightarrow b\bar{b}X)$ increases slowly beyond $\sqrt{s} = 14$ TeV up to 100 TeV and all SM physics is boosted into the forward region. This does not preclude flavour physics measurements, but it may become harder to argue for a dedicated experiment.

5.2 Future τ -charm factories

There are several proposals for a next generation $e^+e^- \tau$ -charm factory, to go beyond the lifespan of BES-III. A facility at the Budker Institute of Nuclear Physics (BINP) in Russia [42] is in principle approved but the funding (400M Euros plus the detector) is unclear. This machine will operate at total energies from 2 to 5 GeV with an unprecedented luminosity of $10^{35} \text{ cm}^{-2}\text{s}^{-1}$ and with longitudinal polarization of the electrons. The major physics aims will be measurement of CP-violation in the decays of charmed particles and a hunt for NP in the decay of the tau lepton, for example flavour violation.

Other options being considered are for τ -charm factories at the Cabibbo Laboratory, Italy [43] and HIEPAF, China [44]. These machines aim for $\sqrt{s} = 2\text{--}7$ GeV and peak luminosities $\sim 10^{35} \text{ cm}^{-2}\text{s}^{-1}$. Physics programmes primarily focus on QCD and hadronic physics with some unique potential for charm and (polarised) τ physics.

6 Summary

The future of the flavour physics programme has been presented. In the medium term, the LHCb experiment is performing a high-statistics study of CP violation with

Table 1 A subjective comparison of key measurements in flavour physics. $\checkmark\checkmark$ represents world-leading, \checkmark represents high potential, but less precise, ? represents to be determined.

	LHCb Upgrade	Belle-II	ATLAS/CMS
CKM angle γ	$\checkmark\checkmark$	$\checkmark\checkmark$	
B_s weak phase ϕ_s	$\checkmark\checkmark$		\checkmark
$ V_{ub} $	$\checkmark?$	$\checkmark\checkmark$	
$B_{(s)}^0 \rightarrow \mu^+ \mu^-$	$\checkmark\checkmark$		$\checkmark\checkmark$
ΔA_{CP}	$\checkmark\checkmark$	\checkmark	
$D^{(*)} \tau \nu$	$\checkmark?$	$\checkmark\checkmark$	
P_5'	$\checkmark\checkmark$	$\checkmark\checkmark$	\checkmark
$B^0 \rightarrow \tau \bar{\nu}$		$\checkmark\checkmark$	
Flavour violation in τ decay	\checkmark	$\checkmark\checkmark$	\checkmark

unprecedented precision, providing a sensitive test of the SM and physics beyond. These measurements are complemented in certain important channels by ATLAS and CMS. During the next 5 years the Belle-II experiment and the LHCb upgrade will come online, each improving precision by at least a factor 10 from where we are today. These experiments are competing yet complementary, with their relative performance of key measurements summarized in Table 1. Some measurements will be unique to each experiment whereas others allow cross-checks. The table is subjective both in terms of performance and specified observables; a selection of key measurements could equally have included $\sin 2\beta$, $\tau \rightarrow \mu \nu$ and A_{SL} in B^0 etc.

In summary, many NP scenarios predict discoveries in flavour physics, which gives it an interesting and exciting future. Proposed upgrades of current experiments and the construction of new facilities will extend the flavour physics programme for many years to come.

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Key words. Flavour physics, CP-violation, rare decays, LHCb, Belle-II, charm- τ factory.

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