

# Search for heavy neutral leptons in B-meson decays

---



## The LHCb collaboration

*Full author list at the end of the paper*

*E-mail:* [spencer.collaviti@epfl.ch](mailto:spencer.collaviti@epfl.ch)

**ABSTRACT:** A search for long-lived heavy neutral leptons produced in B-meson decays and decaying to a  $\mu^\pm\pi^\mp$  final state is performed with data collected by the LHCb experiment in proton-proton collisions at a centre-of-mass energy of 13 TeV, corresponding to an integrated luminosity of  $5\text{ fb}^{-1}$ . The results are interpreted in both lepton-number-conserving and lepton-number-violating scenarios. No significant excess is observed. Constraints are placed on the squared mixing element  $|U_{\mu N}|^2$  to the active muon neutrino, under the assumption that couplings to other lepton flavours are negligible, in the mass range of 1.6–5.5 GeV.

**KEYWORDS:** Exotics, Beyond Standard Model, Hadron-Hadron Scattering

**ARXIV EPRINT:** [2512.14551](https://arxiv.org/abs/2512.14551)

---

**Contents**

<b>1</b>	<b>Introduction</b>	<b>1</b>
<b>2</b>	<b>LHCb detector, trigger and simulation</b>	<b>3</b>
<b>3</b>	<b>Event selection</b>	<b>4</b>
<b>4</b>	<b>Signal description</b>	<b>7</b>
<b>5</b>	<b>Background estimation</b>	<b>10</b>
<b>6</b>	<b>Signal extraction</b>	<b>11</b>
<b>7</b>	<b>Systematic uncertainties</b>	<b>14</b>
<b>8</b>	<b>Results and conclusions</b>	<b>14</b>
	<b>The LHCb collaboration</b>	<b>22</b>

---

**1 Introduction**

The Standard Model (SM) of particle physics, despite its remarkable success in describing the fundamental forces and particles of the Universe, leaves several crucial questions unanswered, including: the nature of dark matter [1], the matter-antimatter asymmetry in the Universe [2], and the origin of neutrino masses [3]. These gaps in the current understanding suggest the existence of new physics beyond the SM, already established by the discovery of neutrino oscillations [4], which provided the experimental evidence for nonzero neutrino masses.

Heavy neutral leptons (HNLs, denoted by  $N$ ) are hypothetical fermions that are singlets under all SM gauge groups and appear as right-handed neutrinos in type-I seesaw extensions of the SM [5–7]. In these frameworks, the neutrino sector contains both Dirac and Majorana mass terms, with the latter enabling lepton-number violation. The mixing between HNLs and active neutrinos depends on the ratio of Dirac to Majorana mass scales, inducing suppressed couplings  $U_{\ell N}$  ( $\ell = e, \mu, \tau$ ) that permit HNL production in weak decays of hadrons and gauge bosons, and subsequent decays back into SM particles via the same interaction [8, 9]. If the HNL is a Majorana particle, lepton-number-violating signatures such as same-sign dimuons are possible.

The Minimal Neutrino Standard Model ( $\nu$ MSM) provides a benchmark framework, augmenting the SM with three singlet HNL states [6, 7]. In this model, two  $\mathcal{O}(\text{GeV})$  mass<sup>1</sup> HNLs can generate the needed amount of baryon asymmetry via low-scale leptogenesis, while an  $\mathcal{O}(\text{keV})$  state can account for dark matter through resonant production [10, 11]. However, successful leptogenesis in the  $\nu$ MSM typically requires total mixing  $U^2 \equiv \sum_{\ell} |U_{\ell N}|^2 \lesssim 10^{-6}$  for HNL masses,  $m_N$ , of  $\mathcal{O}(\text{GeV})$  [12, 13], below the sensitivity of this analysis. In contrast,

---

<sup>1</sup>Natural units with  $\hbar = c = 1$  are used throughout.

scenarios with more HNLs or additional interactions, such as models with symmetry-protected low-scale seesaw mechanisms (e.g. an inverse seesaw with approximate lepton-number symmetry), flavour-structured models with dominant muon mixing, or frameworks with gauged difference between baryon and lepton number predict  $|U_{\mu N}|^2 \sim 10^{-5}\text{--}10^{-4}$  for GeV-scale HNLs while remaining consistent with light-neutrino masses and cosmological constraints [14–16]. This search is therefore formulated in a model-agnostic way in the  $(m_N, |U_{\mu N}|^2)$  plane, targeting the large-mixing regime relevant to these scenarios. The lifetime of a given HNL,  $\tau_N$ , depends on the HNL mass and the elements of the mixing matrix. In particular, the lifetime varies as  $\tau_N \sim |U_{\ell N}|^{-2} m_N^{-5}$  [6]. Hence, for sufficiently low values of mixing-matrix elements, even HNLs in the GeV–TeV range can be long-lived ( $\tau_N \gtrsim 1$  ps).

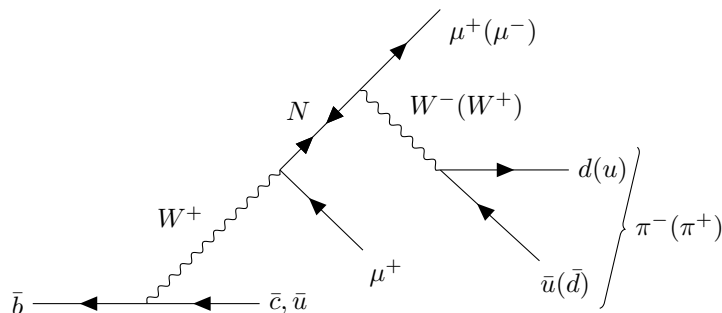
Searches for HNLs have been performed by several experiments using a comprehensive set of methodologies. The most stringent constraints on the mixing-matrix elements for HNLs with masses up to about 2 GeV were set by beam-dump experiments looking at HNLs produced from D and K meson decays, e.g. by the PS191 [17], E949 [18], CHARM [19], NuTeV [20] and BEBC [21] experiments. Searches at B Factories were conducted by the BaBar [22] and Belle [23, 24] experiments, searching for HNLs produced by B mesons ( $m_N \lesssim 6$  GeV). At the CERN Large Hadron Collider (LHC), limits on heavy neutral leptons have been set by the CMS [25–31], ATLAS [32, 33] and LHCb [34, 35] experiments on HNLs produced from B mesons, as well as from W and Z bosons (either real or virtual).

The search presented in this paper targets long-lived HNLs produced in B-meson decays and with lifetimes corresponding to a significant decay probability within the LHCb detector’s acceptance. The analysis is based on proton-proton (pp) collision data recorded at a centre-of-mass energy of 13 TeV with the LHCb detector during 2016–2018 (Run 2), corresponding to an integrated luminosity of  $\mathcal{L} = 5.04 \pm 0.10 \text{ fb}^{-1}$ . A search is performed for HNLs produced in both fully reconstructed leptonic  $B_{(c)}^+ \rightarrow \mu^+ N$  and partially reconstructed semileptonic  $B \rightarrow \mu^+ N X$  decays, where X represents additional unreconstructed particles, and where the HNL decays to  $\mu^+ \pi^-$ .<sup>2</sup> The search takes the form of a bump hunt in the invariant mass of the HNL decay products. A Feynman diagram for the searched HNL production and decay modes is shown in figure 1. The muons from the B meson and N decays may have the same sign, enabling sensitivity to lepton-number-violating processes induced by a Majorana-type mass term. Majorana- and Dirac-like (i.e. lepton-number violating and conserving) cases are treated independently in the search. The search is sensitive only to HNLs that mix with muon neutrinos, and therefore the results are interpreted in terms of the  $|U_{\mu N}|^2$  mixing-matrix element. Couplings with other lepton species are assumed to be negligible, that is:  $U_{eN} = U_{\tau N} = 0$ .

The search focuses on an HNL mass range extending from just above the charm-meson mass, up to the mass of the  $B_c^+$  meson. For HNLs in this mass range, B-meson decays are the dominant HNL production mode at the LHC [36]. The production of HNLs from beauty baryons has been calculated in ref. [37] and is expected to be suppressed relative to production from beauty mesons [36]. Baryonic production is therefore neglected in this analysis. Some small peripheral sensitivity contribution is nonetheless expected, but is not considered in the computed limits, making them somewhat conservative. Although the b-quark fragmentation

---

<sup>2</sup>The inclusion of charge-conjugate processes is implied throughout.



**Figure 1.** Feynman diagram for the inclusive HNL production from  $\bar{b}$  quarks and its subsequent decay  $N \rightarrow \mu^\pm \pi^\mp$ . This diagram represents various decay channels depending on the hadronisation of the  $\bar{b}$  quark. The  $\bar{b}$  quark and other quarks ( $\bar{c}$  or  $\bar{u}$ ) can either form the initial-state meson or appear in the final state. If the HNL is of a Majorana nature, the two muons in the final state can have the same sign.

fraction to  $B_c^+$  mesons is small at the LHC [38], HNL production from leptonic  $B_c^+$  decays is enhanced by the ratio of the CKM matrix elements  $|V_{cb}|^2/|V_{ub}|^2$  compared to production from leptonic  $B^+$  decays, and thus makes an important contribution to the analysis.

## 2 LHCb detector, trigger and simulation

The LHCb detector [39, 40] is a single-arm forward spectrometer covering the pseudorapidity range  $2 < \eta < 5$ , designed for the study of particles containing b or c quarks. The detector used for this analysis includes a high-precision tracking system consisting of a silicon-strip vertex detector (VELO) surrounding the pp interaction region [41], a large-area silicon-strip detector (TT) located upstream of a dipole magnet with a bending power of about 4 T m, and three stations of silicon-strip detectors and straw drift tubes (IT and OT) [42] placed downstream of the magnet. Different track types are reconstructed based on the subdetectors registering charged particle hits. Tracks formed with the track segments in the vertex detector, upstream and downstream tracking stations are referred to as *long* tracks, while those having hits only in the upstream and downstream tracking stations are called *downstream* tracks. Compared to downstream tracks, the long tracks have better momentum,  $p$ , and impact parameter, IP, resolution relative to the primary pp collision, PV. For long tracks, the momentum resolution varies from 0.5% at low momentum to 1.0% at 200 GeV, while the impact parameter resolution is  $(15 + 29/p_T) \mu\text{m}$ , where  $p_T$  is the component of the momentum transverse to the beam, in GeV.

Different types of charged hadrons are distinguished using information from two ring-imaging Cherenkov detectors [43], providing particle identification (PID). Muons are identified by a system composed of alternating layers of iron and multiwire proportional chambers [44]. Photons, electrons and hadrons are identified by a calorimeter system consisting of scintillating-pad (SPD) and preshower (PS) detectors, an electromagnetic and a hadronic calorimeter [45]. The SPD identifies charged particles, aids in separating electrons from photons, and measures event multiplicity through the number of hits ( $n_{\text{SPD}}$ ).

The online event selection is performed by a trigger [46], which consists of a hardware stage, based on information from the calorimeter and muon systems, followed by a software stage, which applies a full event reconstruction. The variable  $n_{\text{SPD}}$  is used in the hardware trigger stage (L0) for a global event cut (GEC). Specifically, the single-muon lines apply  $n_{\text{SPD}} < 450$  and dimuon lines  $n_{\text{SPD}} < 900$ . To harmonise efficiencies, an offline  $n_{\text{SPD}} < 450$  requirement is imposed on all events. Triggered data further undergo a centralised, offline processing step [47].

Simulation is used to model the effects of the detector acceptance and the imposed selection requirements. In the simulation, pp collisions are generated using PYTHIA [48, 49] with a specific LHCb configuration [50]. Decays of unstable particles are described by EVTGEN [51], in which final-state radiation is generated using PHOTOS [52]. The interaction of the generated particles with the detector, and its response, are implemented using the GEANT4 toolkit [53, 54] as described in ref. [55].

Several simulated samples of HNL decays are produced considering different mass hypotheses,  $m_N = 1.6, 2.0, 3.0, 4.0, 5.0$  and  $5.5$  GeV, and lifetimes,  $\tau_N = 10, 100$  and  $1000$  ps. This set of lifetimes has been chosen to cover the decay-time acceptance of the LHCb detector for displaced HNL decays to *long* or *downstream* tracks. An independent sample is generated for each HNL mass, lifetime and B-meson type:  $B^0, B^+, B_s^0$  or  $B_c^+$ . To model the total signal, the relevant mesons and decay modes are merged together taking into account the relative b-quark fragmentation fractions to the different B-meson species,  $f_s/f_u$  and  $f_c/f_u$ , measured by the LHCb collaboration [38, 56], and the branching-ratio predictions of B decays to HNLs taken from ref. [36]. The branching fractions of various decay channels, weighted by their corresponding fragmentation fractions, are presented in figure 2. These values depend on the HNL mass  $m_N$ , and are calculated for a mixing parameter of  $|U_{\mu N}|^2 = 10^{-4}$ .

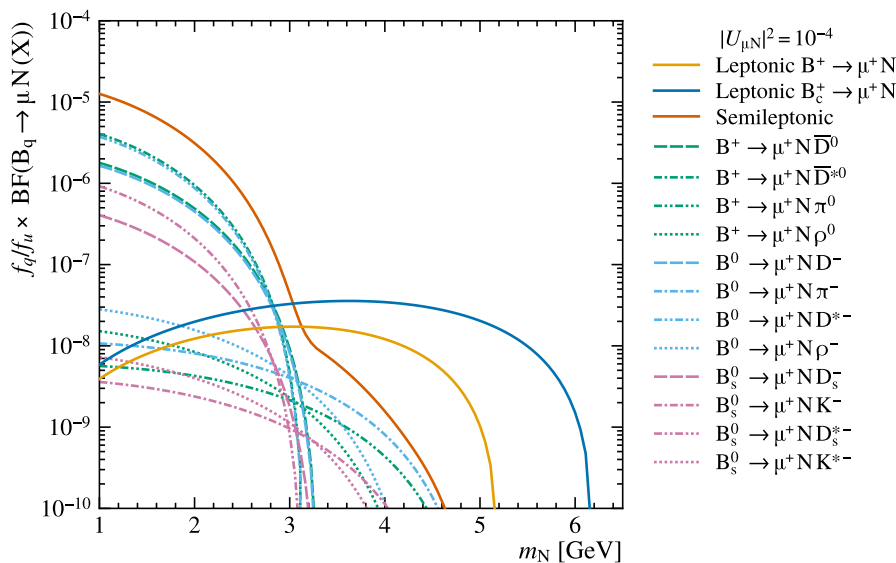
Both the opposite sign (OS) lepton-number-conserving  $\mu^+\mu^-$  and same sign (SS) lepton-number-violating  $\mu^+\mu^+$  decay channels are simulated. All B-meson decays involving HNLs and  $N \rightarrow \mu\pi$  decays are simulated neglecting HNL spin and polarisation. The same simplified model was used in previous searches of HNLs from B decays at the Belle [23], LHCb [34], and CMS [29] experiments.

### 3 Event selection

The flight distance of the HNL is a key observable for identifying displaced decays in the LHCb detector. It is defined as  $\text{FD}(N) \equiv \sqrt{(x_N - x_B)^2 + (y_N - y_B)^2 + (z_N - z_B)^2}$ , representing the spatial separation between the B-meson and N decay vertices. Owing to the forward geometry of the detector, the longitudinal component,  $\text{FD}_z(N) = z_N - z_B$ , provides an effective proxy for the full three-dimensional distance.

In each event, multiple pp interactions are reconstructed. The PV that fits best to the flight direction of the B candidate is taken as the PV associated to the B decay.

Candidate  $B \rightarrow \mu N (\rightarrow \mu\pi)(X)$  decays are separated into two analysis categories, referred to as *long* and *downstream*. The *long* category includes  $N \rightarrow \mu\pi$  decays that occur within the VELO and are reconstructed with *long* tracks, which offer superior mass, momentum, and vertex resolution. In this category, candidates must have  $\text{FD}_z(N)$  greater than 20 mm.



**Figure 2.** Branching fractions of various B-meson channels corresponding to different B-meson types,  $B^0$ ,  $B^+$ ,  $B_s^0$  or  $B_c^+$ , weighted by the corresponding fragmentation fraction. These values depend on the HNL mass,  $m_N$ , and are calculated for a mixing parameter of  $|U_{\mu N}|^2 = 10^{-4}$ . The solid red “Semileptonic” line is the sum of all semileptonic decay channels, i.e. the sum of all the specific decays below the semileptonic line in the legend.

The *downstream* category is composed of candidates that decay after the VELO and are reconstructed using *downstream* tracks. This is sensitive to HNLs with  $FD_z(N) \gtrsim 70$  cm.

The muon candidates from the signal decay are required to pass the muon-based L0 hardware trigger lines. These trigger lines accept events with either one or two muon candidates having a  $p_T$  above specific thresholds. For single muon candidates, the thresholds are 1.30 GeV in 2016, 1.70 GeV in 2017, and 1.75 GeV in 2018. For dimuon candidates, the product of their transverse momenta must exceed 1.69 GeV<sup>2</sup> in 2016 and 3.24 GeV<sup>2</sup> in 2017 and 2018.

In the subsequent software trigger, at least one of the muon candidates is required to have  $p_T > 1.1$  GeV and  $p > 6.0$  GeV. The muon candidates that satisfy these momentum criteria are also required to have associated tracks with good track-fit quality and to be inconsistent with originating from any PV in the event.<sup>3</sup>

At the second software trigger stage, the *long* category is required to pass either an inclusive topological selection targeting displaced b-hadron vertices or an inclusive selection for displaced  $N \rightarrow \mu\pi$  decays. The *downstream* category is selected with a trigger specifically developed for this analysis that selects  $B \rightarrow \mu N (\rightarrow \mu\pi)$  candidates with same-sign muons. In this trigger, the pion and muon candidates that form the HNL candidate are required to have  $p_T > 250$  MeV and a momentum exceeding 2 GeV and 3 GeV, respectively. The resulting HNL candidate must have  $p_T > 700$  MeV and is combined with a long muon candidate to form a B candidate. The reconstructed B momentum is required to be aligned with the displacement vector from the associated PV to the B secondary vertex, in the sense that the

<sup>3</sup>The size of the impact parameter is measured relative to its uncertainty with the variable  $\chi_{IP}^2$ , defined as the difference in the vertex-fit  $\chi^2$  of a given PV reconstructed with and without the particle being considered.

relative angle  $\theta$  satisfies  $\cos\theta > 0.99$ . This trigger is prescaled by a factor of five, effectively analysing 20% of these candidates.

In the offline selection, a  $B \rightarrow \mu N(\rightarrow \mu\pi)(X)$  candidate must satisfy loose kinematic and PID requirements before being processed by a dedicated and bespoke multivariate analysis (MVA). The N candidate is formed from two oppositely charged tracks, which must be either both long tracks or both downstream tracks. These tracks, identified as a pion candidate and a muon candidate, are required to pass the same momentum and transverse momentum selections as in the downstream trigger for the second software stage, and to have a large impact parameter with respect to the associated PV, selecting those consistent with a long-lived N and rejecting prompt tracks from the primary pp interaction. The two tracks are required to originate from a common vertex with good fit  $\chi^2$ , and the vertex is required to be significantly displaced from the associated PV, as quantified by  $FD_z(N)$ . The N candidate with  $p_T > 700$  MeV and  $m_N > 1.5$  GeV is combined with a long  $\mu$  candidate to form a B candidate, requiring a common vertex with good fit  $\chi^2$ . The B momentum is required to pass the same alignment criteria with the associated PV as in the downstream trigger. The mass of the B candidate,  $m(\mu\mu\pi)$ , should be in the wide range  $1.5 < m(\mu\mu\pi) < 6.5$  GeV. These requirements are sufficiently loose to still select partially reconstructed  $B \rightarrow \mu N(\rightarrow \mu\pi)(X)$  decays efficiently.

A fiducial volume (FV) selection removes candidates in low-acceptance regions, requiring final-state tracks with  $2.0 < \eta < 4.5$  and N candidates with  $p_T > 1$  GeV and  $p > 15$  GeV. This selection achieves an efficiency exceeding 90% for  $m_N \gtrsim 2$  GeV.

A multivariate analysis is performed to suppress combinatorial background, which dominates in the whole  $\mu\pi$  mass range, except for the region below 2 GeV, where peaking backgrounds from charm meson decays are also present. A neural network (NN) classifier, implemented using PYTORCH [57], is trained for each *reconstruction category* in the analysis. These reconstruction categories are defined by each of the two muon charge configurations (SS and OS), three B-decay modes ( $B \rightarrow \mu NX$ ,  $B^+ \rightarrow \mu N$ , and  $B_c^+ \rightarrow \mu N$ ), and two analysis displacement categories (long and downstream). This gives nine reconstruction categories in total (no OS downstream data are collected). Each classifier is trained using simulated HNL samples as signal proxy and candidates in the upper  $m(\mu\mu\pi)$  sideband in data as background proxy. The fully reconstructed leptonic  $B^+ \rightarrow \mu N$ , and  $B_c^+ \rightarrow \mu N$  categories are combined for the purpose of the NN training.

For fully reconstructed leptonic decays, the upper sideband corresponds to the  $m(\mu\mu\pi)$  region at least  $3\sigma$  (55.5 MeV) above the  $B^+$  mass peak, excluding the  $B_c^+$  signal region defined as  $\pm 3\sigma$  ( $\pm 76.8$  MeV) around the  $B_c^+$  peak, with  $\sigma$  the mass resolution. Partially reconstructed  $B \rightarrow \mu NX$  semileptonic decays are dominated by modes involving an unreconstructed D meson; therefore, the sideband is defined as the region where  $m(\mu\mu\pi) > m_{B^+} - m_{D^0}$ . A small fraction of signal  $B \rightarrow \mu NX$  decays, with  $X = \pi, \rho$ , may enter this sideband, but their contribution is expected to be negligible. To avoid biases, a 15% portion of both the signal and background proxy datasets is reserved from training, and used solely to evaluate the NN's classification performance.

Variables with high discrimination power are used to train the classifiers. These include the B-candidate flight distance, the  $p_T$  of all final-state particles, the  $\chi_{IP}^2$  of the N candidate and

its decay products, the N-candidate decay vertex  $\chi^2$ , and the angle between the momentum and displacement vector from the origin vertex to the decay vertex for the N candidate. For fully reconstructed leptonic decays, the angle between the momentum and displacement vector for the B-meson candidate is also used. The simulated signal samples for the SS and OS categories show no significant differences and are therefore combined for training. In contrast, background samples show different kinematic characteristics between SS and OS categories and are treated separately.

To maximise discrimination power across the full mass range, particularly between simulated mass values, a novel NN-based approach is employed, in which the classifier is parametrised by a physics variable, the HNL mass [58]. In the NN training, the parametrised mass feature is set to the true value of the generated HNL mass for the signal proxy, while, for the background, it is arbitrarily sampled from the simulated mass values. This approach allows the classifier to smoothly interpolate between simulated mass values and eliminates the need for separate classifiers trained at individual masses. The NN hyperparameters are tuned via Bayesian optimisation employing a Gaussian process [59], using classification accuracy as the optimisation metric. An independent set of optimal hyperparameter values is determined for each category. No sign of overtraining is observed in the classifier outputs.

Since the level of combinatorial background changes with the probed  $m_N$  values, multiple working points are defined to optimise the classifier’s performance. For each simulated  $m_N$  value, the optimal requirement on the classifier output is determined and interpolated across the mass range. The working point is selected to maximise the Punzi figure of merit [60], defined as

$$\text{FOM}(m_N) = \frac{\varepsilon(m_N)}{\sqrt{N_{\text{bkg}}(m_N) + \frac{3}{2}}}, \quad (3.1)$$

where  $\varepsilon(m_N)$  is the signal efficiency for a given  $m_N$  value. The expected background yield,  $N_{\text{bkg}}(m_N)$ , is extrapolated from the  $m(\mu\mu\pi)$  upper mass sideband into a window of  $m_N \pm 3\sigma_{m_N}$ , with  $\sigma_{m_N} = 25$  MeV, corresponding to the largest mass resolution measured in fits across the simulated HNL mass values. Variations of  $\sigma_{m_N}$  yield consistent results. The optimal requirements are then relaxed, if necessary, to ensure that at least approximately 30 candidates are selected in the signal region, to ensure stable fits, even if this leads to a suboptimal FOM.

## 4 Signal description

The signal yield  $N_{\text{sig}}$  expected in the selected data sample for each of the considered  $B_q \rightarrow \mu N(X)$  decays, where q indicates the non-b quark flavour, is given by

$$N_{\text{sig}} = \mathcal{L} \sigma(\text{pp} \rightarrow B^\pm) \frac{f_q}{f_u} \mathcal{B}(B_q \rightarrow \mu N(X)) \mathcal{B}(N \rightarrow \mu\pi) \frac{\varepsilon(\text{FV}_N)}{\varepsilon(\text{FV}_{B^\pm})} \varepsilon_{\text{sel}}, \quad (4.1)$$

where the various factors are explained in the following.

The total integrated luminosity of the analysed data samples is  $\mathcal{L} = 5.04 \pm 0.10 \text{ fb}^{-1}$ . The inclusive cross-section at  $\sqrt{s} = 13 \text{ TeV}$ ,  $\sigma(\text{pp} \rightarrow B^\pm) = 86.6 \pm 6.4 \mu\text{b}$ , was measured by the LHCb experiment [61] in the fiducial volume  $\text{FV}_{B^\pm}$  defined by  $2.0 < y(B^\pm) < 4.5$

and  $p_T(B^\pm) < 40 \text{ GeV}$ , where  $y$  is the rapidity. The ratio of geometrical acceptances  $\varepsilon(\text{FV}_N)/\varepsilon(\text{FV}_{B^\pm})$  is introduced to correct for the small mismatch between the fiducial volume selections. Imposing the  $B^\pm$  fiducial requirements on top of the analysis selection is found to be  $> 99.5\%$  efficient, indicating that any residual effect is negligible. The ratio is determined using the `RapidSim` fast-simulation toolkit [62]. For this, B mesons are generated with a momentum spectrum predicted by fixed-order next-to-leading-log (FONLL) calculations [63], and `RapidSim` subsequently models the detector’s geometric acceptance. This fast-simulation approach makes it feasible to determine the acceptance in fine steps of  $m_N$ , which is crucial for modelling the sharp acceptance drops near phase-space boundaries. As only the ratio is used, common assumptions largely cancel, reducing uncertainties in the modelled B-meson production spectrum. The statistical uncertainty on the acceptance ratio is approximately 0.5%, and the results are validated against the full LHCb simulation at several benchmark  $m_N$  values.

The factor  $f_q/f_u$  denotes the ratio of fragmentation fractions of the b quark to the  $B_q$  and  $B^\pm$  mesons. The ratio  $f_d/f_u$  is assumed to be unity due to isospin symmetry, while  $f_s/f_u = 0.244 \pm 0.012$  and  $f_c/f_u = (7.56 \pm 1.78) \times 10^{-3}$  are taken from LHCb measurements [38, 56]. The  $B_s^0$  and  $B_c^+$  fragmentation fractions are determined in the range  $4 < p_T < 25 \text{ GeV}$  and in the ranges  $2.0 < \eta < 5.0$  and  $2.5 < \eta < 4.5$ , respectively. These fiducial volumes are then slightly different to the  $B^\pm$  cross-section fiducial volume. The dependence of the fragmentation functions on  $p_T$  and  $\eta$  is small [38, 56], and thus any residual bias due to the fiducial volume difference is subleading compared to the quoted experimental uncertainties on  $f_q/f_u$ . As a result, the fiducial volume difference is neglected.

The signal selection efficiency  $\varepsilon_{\text{sel}}$  encodes the effects of all online and offline requirements for signal decays produced within the FV of the analysis and is determined in simulation as a function of HNL mass and lifetime. Efficiencies for alternative lifetimes are obtained from simulated samples through a weighting procedure, in which each candidate  $i$  is assigned a weight

$$w_{\tau'}^i \equiv \frac{\tau_{\text{gen}}}{\tau'} \frac{e^{-t_i/\tau'}}{e^{-t_i/\tau_{\text{gen}}}} \quad (4.2)$$

based on the generated lifetime of the sample,  $\tau_{\text{gen}}$ , the target lifetime,  $\tau'$  and the true decay time of the candidate in the event,  $t_i$ .

To ensure the realistic modelling of the detector and trigger responses, several corrections are applied. The simulation of the hardware trigger is corrected to match the performance observed in data. This correction is determined using a control sample of events containing muon pairs that were collected using triggers independent of those muons, ensuring an unbiased dataset for the efficiency measurement. The hardware trigger efficiency,  $\varepsilon_{\text{L0}}$ , is then measured on this control sample by calculating the fraction of events in which the muons under study also satisfy the hardware trigger requirements. By comparing the efficiencies measured in data and simulation, correction weights,  $w_{\text{L0}}$ , are derived. These weights are parametrised as a function of the maximum and minimum  $p_T$  of the two signal muons to accurately adjust the simulation.

The efficiency of the GEC on the number of SPD hits,  $n_{\text{SPD}}$ , is determined from simulation that is corrected to match the distribution in data. Specifically, the simulated SPD multiplicity

is rescaled event-by-event by a global factor,  $k_{n_{\text{SPD}}}$ , chosen such that the efficiency of the  $n_{\text{SPD}} < 450$  requirement matches that observed in data measured with dimuon triggers using  $n_{\text{SPD}} < 900$ . After this correction, a 10% relative uncertainty is assigned to the GEC efficiency to cover residual data-simulation differences; this is treated as a correlated nuisance across categories.

To correct for differences in the PID response between data and simulation, per-particle calibration weights, denoted as  $w_{\text{PID}}$ , are applied to the final-state particles of each simulated signal candidate. These weights are derived from high-statistics control samples [64] and are defined as the ratio of the PID efficiency measured in data to that in simulation. The weights are determined as a function of each particle’s momentum and pseudorapidity to account for kinematic variations in the detector performance. The muon identification weights are calibrated using a pure sample of  $J/\psi \rightarrow \mu^+ \mu^-$  decays, while the pion weights are derived using pions from  $D^{*+} \rightarrow D^0(\rightarrow K^- \pi^+) \pi^+$  decays selected only applying kinematic requirements. The total PID correction for a given signal candidate,  $w_{\text{PID}}^i$ , is the product of the individual weights applied to each of its three final-state particles.

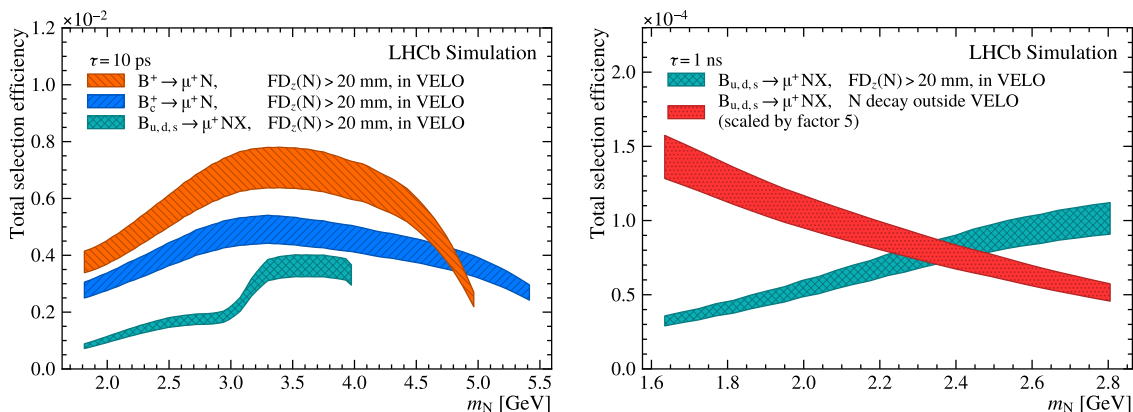
The total selection efficiency  $\varepsilon_{\text{sel}}$  for a sample of a given HNL mass and lifetime is therefore defined as

$$\varepsilon_{\text{sel}}(m_N, \tau') = \frac{\sum_i^{N_{\text{sel}}} w_{\tau'}^i w_{L0}^i w_{\text{PID}}^i}{N_{\text{gen}}}, \quad (4.3)$$

where  $N_{\text{gen}}$  and  $N_{\text{sel}}$  are the number of generated and selected signal events within the FV, respectively. A cubic spline is employed to interpolate  $\varepsilon_{\text{sel}}$  between simulated HNL mass points. The selection efficiencies are determined for all reconstruction categories scanning the 2D plane of relevant HNL masses and lifetimes, in the ranges  $m_N \in [1.6, 5.5]$  GeV and  $\tau_N \in [1 \text{ ps}, 10 \text{ ns}]$ , respectively.

For the long categories, the selection efficiencies  $\varepsilon_{\text{sel}}$  are maximal for values of  $m_N$  between 3 and 4 GeV where the HNL is heavy enough to provide high transverse momentum to the secondary muon, yet light enough to allow the primary muon (from the B meson) to also have a relatively large  $p_T$ . Moreover, the efficiencies are significantly larger for  $B^+ \rightarrow \mu^+ N$  than for  $B_c^+ \rightarrow \mu^+ N$  because the  $B^+$  lifetime is about three times larger than the  $B_c^+$  lifetime, making the impact parameter requirements more effective. On the other hand, the efficiency for the downstream category is larger for low  $m_N$  as the primary muon gets a larger share of the energy, and the first-stage software trigger is more efficient.

As an example, the total selection efficiencies for the different same-sign reconstruction modes are shown in figure 3 for HNL lifetimes of 10 ps and 1 ns as a function of  $m_N$ . Opposite-sign efficiencies are similar. For a lifetime of 10 ps, HNLs are sufficiently short-lived that downstream reconstruction is not efficient. At a lifetime of 1 ns, the analysis is only sensitive to the more abundantly-produced light ( $m_N < 3$  GeV) HNLs due to a weaker HNL-SM coupling. In this regime, HNL production is dominated by  $B_{u,d,s} \rightarrow \mu^+ N X$  decays. As a result, and for reasons of legibility, the downstream category is not shown on figure 3 (left), and, similarly, the decays  $B_c^+ \rightarrow \mu^+ N$  and  $B^+ \rightarrow \mu^+ N$  are not shown on figure 3 (right). An efficiency of the order of 0.5% is achieved for the 10 ps lifetime, with comparable values for all production modes of the long category. For the 1 ns lifetime, the total efficiency is highly reduced. After correcting for the prescale factor of five, and at low  $m_N$ , the downstream-track



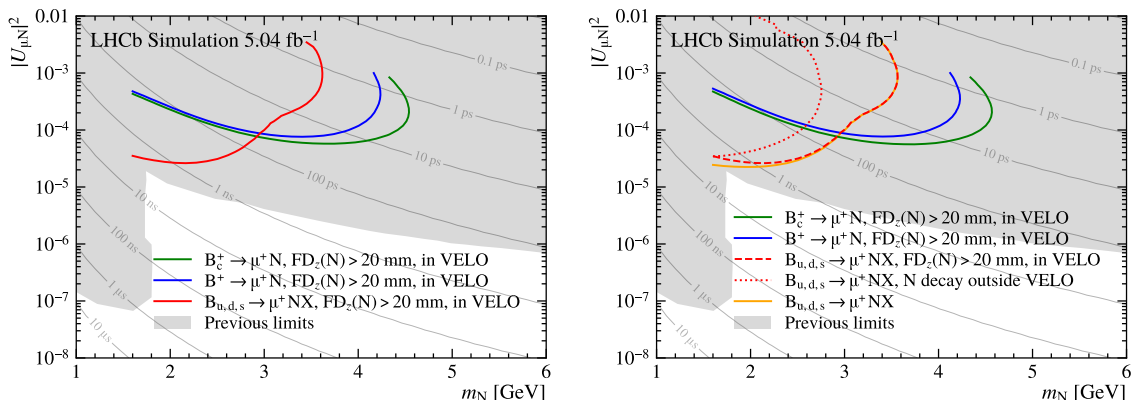
**Figure 3.** Total selection efficiency for HNL events with two same-sign muons, shown for HNL lifetimes of (left) 10 ps and (right) 1 ns. Coloured bands represent the allowed range of values within  $\pm 1\sigma$  of the combined statistical and systematic uncertainties. For a direct comparison between reconstruction categories, the downstream-track efficiency is multiplied by a factor of five, corresponding to the rescaling factor of the dedicated trigger.

selection is approximately three times as efficient as the long-track selection for an HNL lifetime of 1 ns. Due to the relatively large  $b \rightarrow c$  coupling, most  $B_{u,d,s} \rightarrow \mu^+NX$  decays will include a charm meson in the B decay products when kinematically allowed. This produces a softer momentum spectrum for HNL masses below this kinematic threshold, and a harder spectrum for those above, where the accompanying decay products are much lighter. This is the cause of the kink in the  $B_{u,d,s} \rightarrow \mu^+NX$  efficiency at around 3 GeV.

Figure 4 shows the sensitivity of each reconstruction category, obtained assuming no background. Below 3 GeV, the semileptonic *long* categories are expected to have the most competitive sensitivity in both SS and OS signatures. The contribution of the *downstream* category is significant for HNL masses of about 2 GeV. The sensitivity from fully reconstructed leptonic categories becomes dominant above 3 GeV.

### 5 Background estimation

The combinatorial background is described by a simple smooth function (exponential or linear), whose parameters are determined in the final fit in a sliding  $\mu\pi$  mass window, as described in section 6. A peaking background contribution due to  $D^0 \rightarrow K^- \pi^+$  and  $D^0 \rightarrow \pi^- \pi^+$  decays is estimated for the semileptonic *long* category. In these D decays, a peak appears in the  $\mu\pi$  invariant mass through the misidentification of the  $K^-$ ,  $\pi^-$  or  $\pi^+$  as a muon. In fully reconstructed leptonic decays, more stringent requirements on the  $\mu\mu\pi$  invariant mass suppress the misidentified background. The peaking background contribution is found to be negligible for the semileptonic *downstream* category due to the short lifetime of charm mesons. A data-driven ABCD method [65–67] (named after the four subsamples used in this approach, labelled A, B, C, and D) is employed to estimate these charm peaking background yields. The background levels from a control region of prompt-like decays, i.e. candidates with  $FD_z < 20$  mm, are extrapolated into the signal region. The use of this prompt control region is justified because the parameter space for prompt HNLs with masses up to 2 GeV is already



**Figure 4.** Sensitivity estimate of various reconstruction categories of the analysis for the (left) OS and (right) SS event categories, assuming no background. Lifetimes, shown by the grey contours, and previous limits are for a Majorana-natured HNL. The most stringent limits in this mass range are from the CMS and BEBC collaborations.

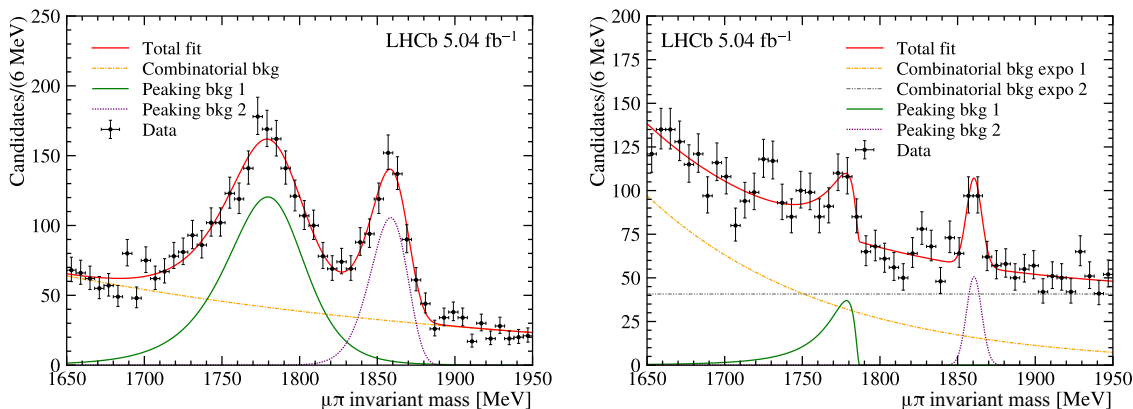
strongly constrained by dedicated searches at other experiments [23–25, 32]. Therefore, any prompt candidates in this mass range are expected to originate predominantly from charm meson decays rather than genuine HNL signals, making this region suitable as a background-dominated control sample for the ABCD method.

The signal and control regions are defined using two statistically independent variables: the HNL flight distance  $FD_z(N)$  and the invariant mass  $m(\mu\mu\pi)$ . The  $FD_z(N)$  variable divides the sample into displaced (regions A and C, with  $FD_z(N) \geq 20$  mm) and prompt (regions B and D, with  $FD_z(N) < 20$  mm) categories, while the invariant mass  $m(\mu\mu\pi)$  divides the sample into signal (regions A and B) and sideband (regions C and D) regions. Mass peaks from  $D^0 \rightarrow K^- \pi^+$  and  $D^0 \rightarrow \pi^- \pi^+$  are observed in the control regions. The two peaks in the  $\mu\pi$  spectrum in these categories are described with two Johnson  $S_U$  distributions [68], while the combinatorial background is modelled with an exponential function (two for the OS case). Figure 5 shows the data distributions in region D for the SS and OS categories, with the corresponding fits.

Peaking-background yields in region A are predicted with an ABCD extrapolation,  $N_A^{\text{pred}} = N_B \times (N_C/N_D)$ , where  $N_X$  are the peaking yields obtained from invariant-mass fits in regions X. Their full uncertainties are propagated. As a result,  $N_A^{\text{pred}}$  is found to be consistent with zero, but is nonetheless used as a constrained nuisance parameter in the final mass fit. The shape parameters of the Johnson  $S_U$  probability density function (PDF) are measured in the most populated region D and fixed when fitting regions A, B, and C. The exponential shape parameters are free to vary in each region. The statistical independence of  $FD_z(N)$  and  $m(\mu\mu\pi)$  is verified by applying the ABCD method to a subdivision of regions B and D.

## 6 Signal extraction

To search for evidence of HNLs, a bump hunt is performed blindly in sliding windows across the whole  $m(\mu\pi)$  spectrum. The HNL mass hypotheses in this spectrum,  $m_N$ , are scanned



**Figure 5.** Distribution of the  $\mu\pi$  mass in the control region D for the (left) SS and (right) OS *long* categories, showing fits with two Johnson  $S_U$  distributions for peaking backgrounds from charm meson decays and either one (left) or two (right) exponentials for the combinatorial background.

in steps of  $\frac{1}{2}\sigma_{m_N}$ , where  $\sigma_{m_N}$  is the mass resolution at each  $m_N$  value. For each hypothesis, the local search window is defined as  $|m - m_N| < 7\sigma_{m_N}$ .

The size of the local search window, the signal mass model, and the mass steps depend on the value of  $m_N$ . For a set of mass points, the signal mass model is extracted from simulated samples and modelled by a modified Crystal Ball function [69] with tails on both sides of the peak. Between simulated mass points, the signal PDF is interpolated using the moment-morphing technique [70]. No dependence of the signal shape on lifetime is observed.

The combinatorial background is modelled using an exponential function,  $\mathcal{B}_{\text{comb}}(m, N_{\text{comb}}, \alpha_{\text{comb}}) \propto e^{-\alpha_{\text{comb}}m}$ , which is treated as the *baseline* model. For a small decay constant, this function approximates a linear shape. To assess the systematic uncertainty associated with this choice, an *alternative*, explicitly linear, model,  $\mathcal{B}_{\text{comb}}(m, N_{\text{comb}}, \alpha_{\text{comb}}) \propto (1 + \alpha_{\text{comb}}m)$ , is used. The difference between the results obtained with the baseline and alternative models is used to quantify the corresponding systematic, as detailed in section 7. In both cases, the normalisation  $N_{\text{comb}}$  and the shape parameter  $\alpha_{\text{comb}}$  are allowed to vary in each fit and are independent between the analysis categories.

When the search window overlaps with the peaking background region, defined between 1650 and 1950 MeV, two peaking background PDFs are also included for the semileptonic *long* categories of the search (both SS and OS). Their shape parameters are fixed as described in the previous section, while the expected yield from the ABCD method is incorporated as a Gaussian prior.

For each interpretation of the HNL nature (Dirac or Majorana), the different reconstruction categories,  $i$ , are fitted simultaneously using a common yield parameter,  $N_{\text{sig}}$ . The total PDF for each reconstruction category is expressed as

$$\mathcal{P}_i(m; m_N, N_{\text{sig}}, \theta) = \frac{N_{\text{sig}}\epsilon_i\mathcal{P}_i^{\text{sig}}(m; m_N, \theta_{\text{sig}}) + \sum_{k=1}^3 N_{\text{bkg},k:i}\mathcal{P}_i^{\text{bkg},k}(m; m_N, \theta_{\text{bkg}})}{N_{\text{sig}}\epsilon_i + \sum_{k=1}^3 N_{\text{bkg},k:i}}, \quad (6.1)$$

with  $k$  distinguishing the three components of background: combinatorial ( $k = 1$ ), and the two peaking backgrounds ( $k = 2, 3$ ). In this equation,  $\mathcal{P}_i^{\text{sig}}$  and the set of  $\mathcal{P}_i^{\text{bkg},k}$  are the

signal and background model PDFs,  $\epsilon_i$  is the fraction of all HNL candidates that are in reconstruction category  $i$ , the set of  $N_{\text{bkg},k:i}$  are the background yields in category  $i$  and background component  $k$ , and the nuisance parameters (exponential slopes, etc.) are denoted by  $\theta \equiv (\theta_{\text{sig}}, \theta_{\text{bkg}})$ . When peaking background is not present, i.e. for all reconstruction categories except the semileptonic long categories, or when the peaking background is outside of the HNL mass window, the peaking background yield is forced to be identically zero, i.e.  $N_{\text{bkg},2:i} = N_{\text{bkg},3:i} = 0$ .

The extended likelihood is

$$\mathcal{L}_i(m_N, N_{\text{sig}}, \theta) = \frac{N_i^{N_{\text{obs}:i}} e^{-N_i}}{N_{\text{obs}:i}!} \mathcal{C}_{\epsilon_i}(\theta_{\text{sig}}) \mathcal{C}_{\text{bkg}:i}(\theta_{\text{bkg}}) \prod_{j=1}^{N_{\text{obs}:i}} \mathcal{P}_i(m_j; m_N, N_{\text{sig}}, \theta), \quad (6.2)$$

where  $N_{\text{obs}:i}$  is the observed number of candidates in the reconstruction category,  $N_i$  is the total yield;  $N_i = N_{\text{sig}:i} + \sum_{k=1}^3 N_{\text{bkg},k:i}$ , and  $m_j$  the invariant mass of observed event  $j$ . The  $\mathcal{C}_{\epsilon_i}$  factor represents the Gaussian prior on the event fraction in reconstruction category  $i$

$$\mathcal{C}_{\epsilon_i}(\theta_{\text{sig}}) = \frac{1}{\sqrt{2\pi}\sigma_{\epsilon_i}} \exp\left(-\frac{(\mu_{\epsilon_i} - \epsilon_i)^2}{2\sigma_{\epsilon_i}^2}\right), \quad (6.3)$$

where the central value,  $\mu_{\epsilon_i}$ , and uncertainty,  $\sigma_{\epsilon_i}$ , of  $\epsilon_i$  are obtained from simulation. The factors  $\mathcal{C}_{\text{bkg}:i}$  are the Gaussian priors on the peaking backgrounds normalisations, defined as

$$\mathcal{C}_{\text{bkg}:i}(\theta_{\text{bkg}}) = \prod_{k=2}^3 \frac{1}{\sqrt{2\pi}\sigma_{N_{\text{bkg},k:i}}} \exp\left(-\frac{(\mu_{N_{\text{bkg},k:i}} - N_{\text{bkg},k:i})^2}{2\sigma_{N_{\text{bkg},k:i}}^2}\right), \quad (6.4)$$

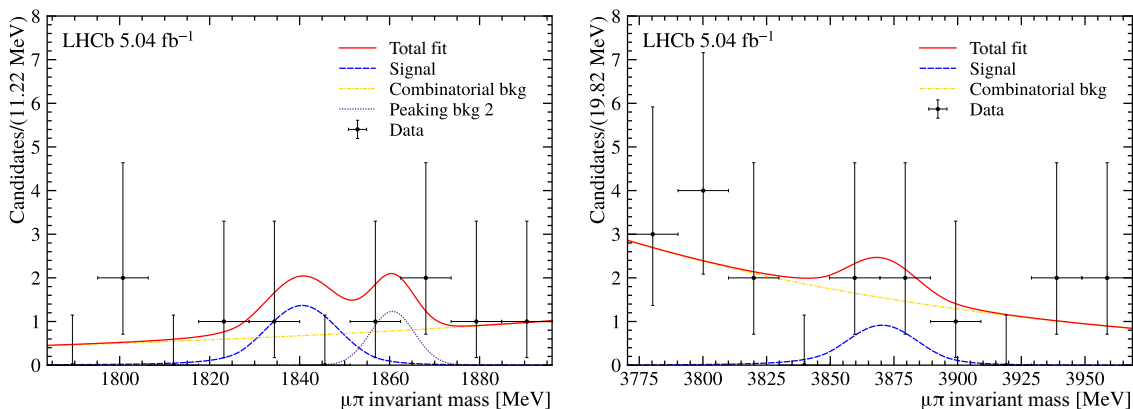
when reconstruction categories contain peaking background, and set to one elsewhere. In this definition,  $\mu_{N_{\text{bkg},k:i}}$  and  $\sigma_{N_{\text{bkg},k:i}}$  are the central values and uncertainties of the peaking background yield.

The combined likelihood for the simultaneous fit of different reconstruction categories is expressed by

$$\mathcal{L}(m_N, N_{\text{sig}}, \theta) = \prod_{i=1}^{N_{\text{cat}}} \mathcal{L}_i(m_N, N_{\text{sig}}, \theta). \quad (6.5)$$

The fit is implemented using the ZFIT library [71], and yields are not constrained to be positive. Examples of fits to the  $\mu\pi$  mass spectra in the signal region are shown in figure 6 for two mass ranges: one with peaking background contributions (left) and one without (right).

For each mass hypothesis, several values of the  $|U_{\mu N}|^2$  coupling are tested to determine upper limits. These tested couplings, denoted  $|U_{\mu N}|^2(\text{tested})$ , are used to compute the signal efficiency in each reconstruction category, which depends on the HNL lifetime and therefore on  $|U_{\mu N}|^2$ . The CL<sub>s</sub> method [72] is used to translate the fitted signal yield  $N_{\text{sig}}$  into a 95% confidence level (CL) upper limit on the muonic HNL coupling,  $|U_{\mu N}|^2$ , evaluated at the fixed signal efficiency. This value is denoted as  $|U_{\mu N}|^2(\text{measured})$ . The 95% CL exclusion region is defined as the region where  $|U_{\mu N}|^2(\text{measured})$  lies below  $|U_{\mu N}|^2(\text{tested})$ . To determine the global significance of any deviation, the look-elsewhere effect is accounted for following the method of ref. [73]. In essence, the number of crossings of the observed limit curve over the expected limit is used to estimate the effective number of statistically independent test masses considered.



**Figure 6.** Examples of mass distributions obtained in the signal region for the OS *long* category, with fits for Majorana HNLs. The plots correspond to the inclusive (left) and the leptonic  $B^+$  (right) reconstruction categories.

## 7 Systematic uncertainties

The systematic uncertainties are summarised in table 1. Relative uncertainties are quoted on the squared coupling,  $|U_{\mu N}|^2$ , except for the fragmentation fractions, which are given relative to their baseline values (since their impact on  $|U_{\mu N}|^2$  is mass dependent). All systematic uncertainties enter the likelihood as Gaussian priors.

The leading external systematic uncertainties arise from the inclusive  $\sigma(pp \rightarrow B^\pm)$  cross-section (7.4%) and the  $B_c^+$  fragmentation fraction (24% for HNLs from  $B_c^+$ ). The integrated luminosity (2.0%) and the  $B_s^0$  fragmentation ratio (4.9%) are also included as external constraints. The leading detector-related uncertainty is assigned to the GEC efficiency (10%), derived from the data-driven  $k_{n_{SPD}}$ -scaling procedure and the observed spread across HNL masses.

The contribution due to the signal mass modelling is evaluated with pseudoexperiments by varying the signal-shape parameters according to their covariance from simulation fits; this yields a 5.9% relative impact on  $|U_{\mu N}|^2$ . The background parametrisation uncertainty is assessed by generating samples with one functional form and fitting with an alternative form, giving a contribution of 2.0%.

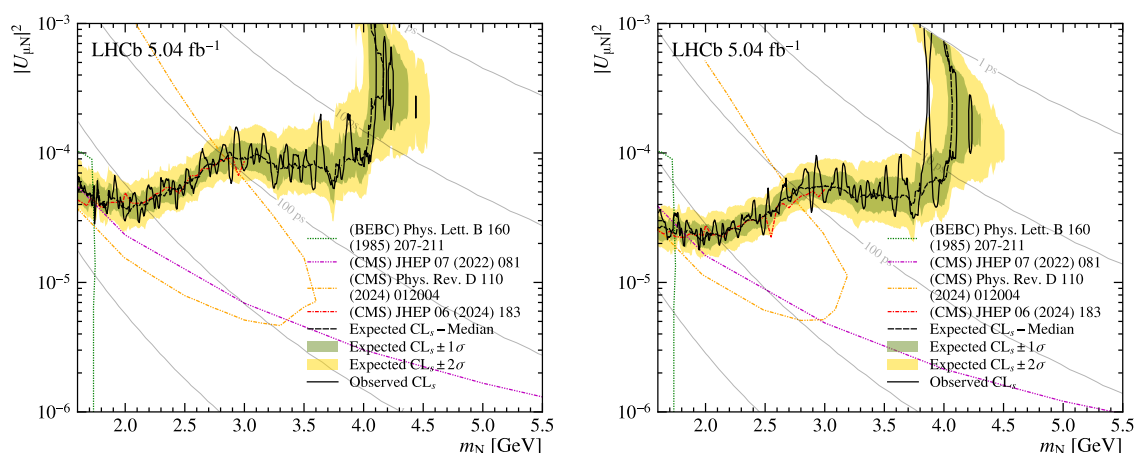
Statistical uncertainties in the efficiency corrections (L0, PID) are propagated as additional Gaussian nuisances. External inputs and the GEC efficiency are taken as correlated across categories; shape-related nuisances are treated as uncorrelated between categories.

## 8 Results and conclusions

A search for HNLs has been performed using a dataset corresponding to an integrated luminosity of  $\mathcal{L} = 5.04 \pm 0.10 \text{ fb}^{-1}$  of proton-proton collision data collected with the LHCb detector between 2016 and 2018. The search targets HNLs produced in beauty-meson decays with subsequent decays into a  $\mu^\pm \pi^\mp$  final state, probing HNL masses in the range of 1.6 to 5.5 GeV and their coupling to muon neutrinos.

Source	Baseline value	Rel. uncertainty [%]
$\sigma(pp \rightarrow B^+) [\mu\text{b}]$	$86.6 \pm 6.4$	7.4
Integrated luminosity [ $\text{fb}^{-1}$ ]	$5.04 \pm 0.10$	2.0
$B_c^+$ fragmentation fraction ( $f_c/f_u$ ) [ $\times 10^{-3}$ ]	$7.6 \pm 1.8$	—
$B_s^0$ fragmentation fraction ( $f_s/f_u$ )	$0.244 \pm 0.012$	—
GEC efficiency	—	10
Signal shape modelling	—	5.9
Background shape modelling	—	2.0

**Table 1.** Summary of systematic uncertainties on the HNL coupling  $|U_{\mu N}|^2$ , including baseline values and relative uncertainties in percent. Relative uncertainties, when reported, are defined based on the impact on  $|U_{\mu N}|^2$ . Relative uncertainties for fragmentation functions are not reported as this depends on the HNL mass considered.



**Figure 7.** (Left) Combination of all the OS search categories that corresponds to a Dirac-like HNL. (Right) Combination of all the SS and OS search categories that corresponds to a Majorana-like HNL. Lifetime contours are shown in grey.

The analysis combines fully reconstructed leptonic decays,  $B_{(c)}^+ \rightarrow \mu^+ N$ , and partially reconstructed inclusive semileptonic decays,  $B \rightarrow \mu^+ N X$ . Analysing final states with both same-sign and opposite-sign muons ensures sensitivity to both Majorana and Dirac HNL scenarios. A machine learning approach, featuring a neural network parametrised by the HNL mass, enhances signal discrimination. Using both *long* and *downstream* track categories provides sensitivity across a wide range of HNL lifetimes, corresponding to decay lengths from approximately 2 cm to 2 m.

The highest local excess has a  $2.5\sigma$  significance and is observed at  $m_N = 2.93$  GeV in the Dirac OS case. Taking into account the look-elsewhere effect, the probability of observing a local fluctuation of at least  $2.5\sigma$  is estimated to be 38%, lowering it to a global statistical significance of  $0.3\sigma$  (one-sided). Therefore, the observed results are compatible with statistical fluctuations.

Upper limits are set at the 95% confidence level on the mixing parameter squared,  $|U_{\mu N}|^2$ , as a function of the HNL mass  $m_N$ , and are reported in figure 7. These limits exclude values

of  $|U_{\mu N}|^2$  down to the  $10^{-5}$ – $10^{-4}$  level. This represents more than an order of magnitude improvement over past LHCb limits. The limits are a valuable cross-check to the existing limits in this region. They also complement searches from ATLAS and CMS which are typically more sensitive at higher masses from on-shell W boson decays, and previous fixed-target experiments where all masses above the D-meson threshold ( $\sim 1.7$  GeV) are inaccessible. The limits reported here do not probe the leptogenesis-favoured  $\nu$ MSM region but exclude significant parameter space in scenarios with three HNLs or additional interactions, such as symmetry-protected low-scale seesaws, flavour-structured models with dominant muon mixing, or frameworks with gauged  $B - L$  (baryon minus lepton number), which predict larger mixings compatible with light-neutrino masses and cosmological constraints [14, 15].

The techniques developed, including peaking background control in inclusive B decays, the treatment of downstream tracks, and a mass-parametrised neural network, provide a robust framework for future HNL searches. Significant sensitivity improvements [74] are expected utilising advancements in displaced vertex reconstruction [75] and the larger datasets from the LHCb Upgrade I [76] and II [77].

## Acknowledgments

We express our gratitude to our colleagues in the CERN accelerator departments for the excellent performance of the LHC. We thank the technical and administrative staff at the LHCb institutes. We acknowledge support from CERN and from the national agencies: ARC (Australia); CAPES, CNPq, FAPERJ and FINEP (Brazil); MOST and NSFC (China); CNRS/IN2P3 (France); BMFT, DFG and MPG (Germany); INFN (Italy); NWO (Netherlands); MNiSW and NCN (Poland); MCID/IFA (Romania); MICIU and AEI (Spain); SNSF and SER (Switzerland); NASU (Ukraine); STFC (U.K.); DOE NP and NSF (U.S.A.). We acknowledge the computing resources that are provided by ARDC (Australia), CBPF (Brazil), CERN, IHEP and LZU (China), IN2P3 (France), KIT and DESY (Germany), INFN (Italy), SURF (Netherlands), Polish WLCG (Poland), IFIN-HH (Romania), PIC (Spain), CSCS (Switzerland), and GridPP (U.K.). We are indebted to the communities behind the multiple open-source software packages on which we depend. Individual groups or members have received support from Key Research Program of Frontier Sciences of CAS, CAS PIFI, CAS CCEPP, Minciencias (Colombia); EPLANET, Marie Skłodowska-Curie Actions, ERC and NextGenerationEU (European Union); A\*MIDEX, ANR, IPhU and Labex P2IO, and Région Auvergne-Rhône-Alpes (France); Alexander-von-Humboldt Foundation (Germany); ICSC (Italy); Severo Ochoa and María de Maeztu Units of Excellence, GVA, XuntaGal, GENCAT, InTalent-Inditex and Prog. Atracción Talento CM (Spain); SRC (Sweden); the Leverhulme Trust, the Royal Society and UKRI (U.K.).

**Data Availability Statement.** Data associated to the plots in this publication are made available on the CERN document server at <https://cds.cern.ch/record/2951445>.

**Code Availability Statement.** This article has no associated code or the code will not be deposited.

**Open Access.** This article is distributed under the terms of the Creative Commons Attribution License ([CC-BY4.0](https://creativecommons.org/licenses/by/4.0/)), which permits any use, distribution and reproduction in any medium, provided the original author(s) and source are credited.

## References

- [1] J. Silk et al., *Particle Dark Matter: Observations, Models and Searches*, Cambridge Univ. Press, Cambridge (2010) [[DOI:10.1017/CB09780511770739](https://doi.org/10.1017/CB09780511770739)] [[INSPIRE](#)].
- [2] G.R. Farrar and M.E. Shaposhnikov, *Baryon asymmetry of the universe in the standard electroweak theory*, *Phys. Rev. D* **50** (1994) 774 [[hep-ph/9305275](#)] [[INSPIRE](#)].
- [3] S. Bilenky, *Neutrino oscillations: From a historical perspective to the present status*, *Nucl. Phys. B* **908** (2016) 2 [[arXiv:1602.00170](#)] [[INSPIRE](#)].
- [4] SUPER-KAMIOKANDE collaboration, *Evidence for oscillation of atmospheric neutrinos*, *Phys. Rev. Lett.* **81** (1998) 1562 [[hep-ex/9807003](#)] [[INSPIRE](#)].
- [5] P. Minkowski,  $\mu \rightarrow e\gamma$  at a Rate of One Out of  $10^9$  Muon Decays?, *Phys. Lett. B* **67** (1977) 421 [[INSPIRE](#)].
- [6] T. Asaka, S. Blanchet and M. Shaposhnikov, *The  $\nu$ MSM, dark matter and neutrino masses*, *Phys. Lett. B* **631** (2005) 151 [[hep-ph/0503065](#)] [[INSPIRE](#)].
- [7] T. Asaka and M. Shaposhnikov, *The  $\nu$ MSM, dark matter and baryon asymmetry of the universe*, *Phys. Lett. B* **620** (2005) 17 [[hep-ph/0505013](#)] [[INSPIRE](#)].
- [8] S.F. King, *Neutrino mass models*, *Rept. Prog. Phys.* **67** (2004) 107 [[hep-ph/0310204](#)] [[INSPIRE](#)].
- [9] G. Altarelli and F. Feruglio, *Models of neutrino masses and mixings*, *New J. Phys.* **6** (2004) 106 [[hep-ph/0405048](#)] [[INSPIRE](#)].
- [10] M. Fukugita and T. Yanagida, *Baryogenesis Without Grand Unification*, *Phys. Lett. B* **174** (1986) 45 [[INSPIRE](#)].
- [11] L. Canetti, M. Drewes, T. Frossard and M. Shaposhnikov, *Dark Matter, Baryogenesis and Neutrino Oscillations from Right Handed Neutrinos*, *Phys. Rev. D* **87** (2013) 093006 [[arXiv:1208.4607](#)] [[INSPIRE](#)].
- [12] J. Klarić, M. Shaposhnikov and I. Timiryasov, *Reconciling resonant leptogenesis and baryogenesis via neutrino oscillations*, *Phys. Rev. D* **104** (2021) 055010 [[arXiv:2103.16545](#)] [[INSPIRE](#)].
- [13] P. Hernandez, J. Lopez-Pavon, N. Rius and S. Sandner, *Bounds on right-handed neutrino parameters from observable leptogenesis*, *JHEP* **12** (2022) 012 [[arXiv:2207.01651](#)] [[INSPIRE](#)].
- [14] M. Drewes, Y. Georis and J. Klarić, *Mapping the Viable Parameter Space for Testable Leptogenesis*, *Phys. Rev. Lett.* **128** (2022) 051801 [[arXiv:2106.16226](#)] [[INSPIRE](#)].
- [15] M. Drewes, Y. Georis, J. Klarić and A. Wendels, *On the collider-testability of the type-I seesaw model with 3 right-handed neutrinos*, *JHEP* **03** (2025) 176 [[arXiv:2407.13620](#)] [[INSPIRE](#)].

- [16] S.S.K. A., S. Das, A. Das and S. Mandal, *Right-handed neutrino production from  $Z'$  interactions in forward search experiments*, *Phys. Rev. D* **112** (2025) 115045 [[arXiv:2508.10734](#)] [[INSPIRE](#)].
- [17] G. Bernardi et al., *Further limits on heavy neutrino couplings*, *Phys. Lett. B* **203** (1988) 332 [[INSPIRE](#)].
- [18] E949 collaboration, *Search for heavy neutrinos in  $K^+ \rightarrow \mu^+ \nu_H$  decays*, *Phys. Rev. D* **91** (2015) 052001 [*Erratum ibid.* **91** (2015) 059903] [[arXiv:1411.3963](#)] [[INSPIRE](#)].
- [19] CHARM collaboration, *A Search for Decays of Heavy Neutrinos in the Mass Range 0.5-GeV to 2.8-GeV*, *Phys. Lett. B* **166** (1986) 473 [[INSPIRE](#)].
- [20] NUTEV and E815 collaborations, *Search for neutral heavy leptons in a high-energy neutrino beam*, *Phys. Rev. Lett.* **83** (1999) 4943 [[hep-ex/9908011](#)] [[INSPIRE](#)].
- [21] WA66 collaboration, *Search for heavy neutrino decays in the BEBC beam dump experiment*, *Phys. Lett. B* **160** (1985) 207 [[INSPIRE](#)].
- [22] BABAR collaboration, *Search for heavy neutral leptons using tau lepton decays at BaBar*, *Phys. Rev. D* **107** (2023) 052009 [[arXiv:2207.09575](#)] [[INSPIRE](#)].
- [23] BELLE collaboration, *Search for heavy neutrinos at Belle*, *Phys. Rev. D* **87** (2013) 071102 [*Erratum ibid.* **95** (2017) 099903] [[arXiv:1301.1105](#)] [[INSPIRE](#)].
- [24] BELLE collaboration, *Search for a Heavy Neutrino in  $\tau$  Decays at Belle*, *Phys. Rev. Lett.* **131** (2023) 211802 [[arXiv:2212.10095](#)] [[INSPIRE](#)].
- [25] CMS collaboration, *Search for heavy neutral leptons in events with three charged leptons in proton-proton collisions at  $\sqrt{s} = 13$  TeV*, *Phys. Rev. Lett.* **120** (2018) 221801 [[arXiv:1802.02965](#)] [[INSPIRE](#)].
- [26] CMS collaboration, *Search for heavy Majorana neutrinos in same-sign dilepton channels in proton-proton collisions at  $\sqrt{s} = 13$  TeV*, *JHEP* **01** (2019) 122 [[arXiv:1806.10905](#)] [[INSPIRE](#)].
- [27] CMS collaboration, *Search for long-lived heavy neutral leptons with displaced vertices in proton-proton collisions at  $\sqrt{s} = 13$  TeV*, *JHEP* **07** (2022) 081 [[arXiv:2201.05578](#)] [[INSPIRE](#)].
- [28] CMS collaboration, *Search for long-lived heavy neutral leptons decaying in the CMS muon detectors in proton-proton collisions at  $s=13$  TeV*, *Phys. Rev. D* **110** (2024) 012004 [[arXiv:2402.18658](#)] [[INSPIRE](#)].
- [29] CMS collaboration, *Search for long-lived heavy neutrinos in the decays of B mesons produced in proton-proton collisions at  $\sqrt{s} = 13$  TeV*, *JHEP* **06** (2024) 183 [[arXiv:2403.04584](#)] [[INSPIRE](#)].
- [30] CMS collaboration, *Search for heavy neutral leptons in final states with electrons, muons, and hadronically decaying tau leptons in proton-proton collisions at  $\sqrt{s} = 13$  TeV*, *JHEP* **06** (2024) 123 [[arXiv:2403.00100](#)] [[INSPIRE](#)].
- [31] CMS collaboration, *Review of searches for vector-like quarks, vector-like leptons, and heavy neutral leptons in proton-proton collisions at  $\sqrt{s} = 13$  TeV at the CMS experiment*, *Phys. Rept.* **1115** (2025) 570 [[arXiv:2405.17605](#)] [[INSPIRE](#)].
- [32] ATLAS collaboration, *Search for heavy neutral leptons in decays of W bosons produced in 13 TeV pp collisions using prompt and displaced signatures with the ATLAS detector*, *JHEP* **10** (2019) 265 [[arXiv:1905.09787](#)] [[INSPIRE](#)].
- [33] ATLAS collaboration, *Search for heavy neutral leptons in decays of W bosons using a dilepton displaced vertex in  $\sqrt{s} = 13$  TeV pp collisions with the ATLAS detector*, *Phys. Rev. Lett.* **131** (2023) 061803 [[arXiv:2204.11988](#)] [[INSPIRE](#)].

- [34] LHCb collaboration, *Search for Majorana neutrinos in  $B^- \rightarrow \pi^+ \mu^- \mu^-$  decays*, *Phys. Rev. Lett.* **112** (2014) 131802 [[arXiv:1401.5361](#)] [[INSPIRE](#)].
- [35] LHCb collaboration, *Search for heavy neutral leptons in  $W^+ \rightarrow \mu^+ \mu^\pm \text{jet}$  decays*, *Eur. Phys. J. C* **81** (2021) 248 [[arXiv:2011.05263](#)] [[INSPIRE](#)].
- [36] K. Bondarenko, A. Boyarsky, D. Gorbunov and O. Ruchayskiy, *Phenomenology of GeV-scale Heavy Neutral Leptons*, *JHEP* **11** (2018) 032 [[arXiv:1805.08567](#)] [[INSPIRE](#)].
- [37] S. Ramazanov, *Semileptonic decays of charmed and beauty baryons with sterile neutrinos in the final state*, *Phys. Rev. D* **79** (2009) 077701 [[arXiv:0810.0660](#)] [[INSPIRE](#)].
- [38] LHCb collaboration, *Measurement of the  $B_c^-$  meson production fraction and asymmetry in 7 and 13 TeV pp collisions*, *Phys. Rev. D* **100** (2019) 112006 [[arXiv:1910.13404](#)] [[INSPIRE](#)].
- [39] LHCb collaboration, *The LHCb Detector at the LHC, 2008 JINST* **3** S08005 [[INSPIRE](#)].
- [40] LHCb collaboration, *LHCb Detector Performance*, *Int. J. Mod. Phys. A* **30** (2015) 1530022 [[arXiv:1412.6352](#)] [[INSPIRE](#)].
- [41] R. Aaij et al., *Performance of the LHCb Vertex Locator, 2014 JINST* **9** P09007 [[arXiv:1405.7808](#)] [[INSPIRE](#)].
- [42] LHCb OUTER TRACKER GROUP collaboration, *Improved performance of the LHCb Outer Tracker in LHC Run 2, 2017 JINST* **12** P11016 [[arXiv:1708.00819](#)] [[INSPIRE](#)].
- [43] LHCb RICH GROUP collaboration, *Performance of the LHCb RICH detector at the LHC*, *Eur. Phys. J. C* **73** (2013) 2431 [[arXiv:1211.6759](#)] [[INSPIRE](#)].
- [44] A.A. Alves Jr. et al., *Performance of the LHCb muon system, 2013 JINST* **8** P02022 [[arXiv:1211.1346](#)] [[INSPIRE](#)].
- [45] C. Abellán Beteta et al., *Calibration and performance of the LHCb calorimeters in Run 1 and 2 at the LHC*, [arXiv:2008.11556](#) [[INSPIRE](#)].
- [46] R. Aaij et al., *The LHCb Trigger and its Performance in 2011, 2013 JINST* **8** P04022 [[arXiv:1211.3055](#)] [[INSPIRE](#)].
- [47] N.A. Grieser et al., *The LHCb Stripping Project: Sustainable Legacy Data Processing for High-Energy Physics*, *Comput. Softw. Big Sci.* **9** (2025) 21 [[arXiv:2509.05294](#)] [[INSPIRE](#)].
- [48] T. Sjöstrand, S. Mrenna and P.Z. Skands, *A Brief Introduction to PYTHIA 8.1*, *Comput. Phys. Commun.* **178** (2008) 852 [[arXiv:0710.3820](#)] [[INSPIRE](#)].
- [49] T. Sjöstrand, S. Mrenna and P.Z. Skands, *PYTHIA 6.4 Physics and Manual*, *JHEP* **05** (2006) 026 [[hep-ph/0603175](#)] [[INSPIRE](#)].
- [50] LHCb collaboration, *Handling of the generation of primary events in Gauss, the LHCb simulation framework*, *J. Phys. Conf. Ser.* **331** (2011) 032047 [[INSPIRE](#)].
- [51] D.J. Lange, *The EvtGen particle decay simulation package*, *Nucl. Instrum. Meth. A* **462** (2001) 152 [[INSPIRE](#)].
- [52] N. Davidson, T. Przedzinski and Z. Was, *PHOTOS interface in C++: Technical and Physics Documentation*, *Comput. Phys. Commun.* **199** (2016) 86 [[arXiv:1011.0937](#)] [[INSPIRE](#)].
- [53] J. Allison et al., *Geant4 developments and applications*, *IEEE Trans. Nucl. Sci.* **53** (2006) 270 [[INSPIRE](#)].
- [54] GEANT4 collaboration, *Geant4: A simulation toolkit*, *Nucl. Instrum. Meth. A* **506** (2003) 250 [[INSPIRE](#)].

- [55] LHCb collaboration, *The LHCb simulation application, Gauss: Design, evolution and experience*, *J. Phys. Conf. Ser.* **331** (2011) 032023 [INSPIRE].
- [56] LHCb collaboration, *Measurement of  $b$  hadron fractions in 13 TeV  $pp$  collisions*, *Phys. Rev. D* **100** (2019) 031102 [arXiv:1902.06794] [INSPIRE].
- [57] A. Paszke et al., *PyTorch: An Imperative Style, High-Performance Deep Learning Library*, arXiv:1912.01703 [INSPIRE].
- [58] P. Baldi et al., *Parameterized neural networks for high-energy physics*, *Eur. Phys. J. C* **76** (2016) 235 [arXiv:1601.07913] [INSPIRE].
- [59] M. Balandat et al., *BoTorch: A Framework for Efficient Monte-Carlo Bayesian Optimization*, arXiv:1910.06403.
- [60] G. Punzi, *Sensitivity of searches for new signals and its optimization*, *eConf C* **030908** (2003) MODT002 [physics/0308063] [INSPIRE].
- [61] LHCb collaboration, *Measurement of the  $B^\pm$  production cross-section in  $pp$  collisions at  $\sqrt{s} = 7$  and 13 TeV*, *JHEP* **12** (2017) 026 [arXiv:1710.04921] [INSPIRE].
- [62] G.A. Cowan, D.C. Craik and M.D. Needham, *RapidSim: an application for the fast simulation of heavy-quark hadron decays*, *Comput. Phys. Commun.* **214** (2017) 239 [arXiv:1612.07489] [INSPIRE].
- [63] M. Cacciari, M. Greco and P. Nason, *The  $p_T$  spectrum in heavy-flavour hadroproduction*, *JHEP* **05** (1998) 007 [hep-ph/9803400] [INSPIRE].
- [64] L. Anderlini et al., *The PIDCalib package*, LHCb-PUB-2016-021 (2016) [INSPIRE].
- [65] O. Behnke eds., *Data analysis in high energy physics: A practical guide to statistical methods*, Wiley-VCH, Weinheim, Germany (2013).
- [66] D0 collaboration, *Search for high mass top quark production in  $p\bar{p}$  collisions at  $\sqrt{s} = 1.8$  TeV*, *Phys. Rev. Lett.* **74** (1995) 2422 [hep-ex/9411001] [INSPIRE].
- [67] CDF collaboration, *A Measurement of  $\sigma B(W \rightarrow e\nu)$  and  $\sigma B(Z^0 \rightarrow e^+e^-)$  in  $p\bar{p}$  Collisions at  $\sqrt{s} = 1800$  GeV*, *Phys. Rev. D* **44** (1991) 29 [INSPIRE].
- [68] N.L. Johnson, *Systems of frequency curves generated by methods of translation*, *Biometrika* **36** (1949) 149 [INSPIRE].
- [69] T. Skwarnicki, *A study of the radiative CASCADE transitions between the Upsilon-Prime and Upsilon resonances*, Ph.D. thesis, Cracow, INP, Poland (1986) [INSPIRE].
- [70] M. Baak, S. Gadatsch, R. Harrington and W. Verkerke, *Interpolation between multi-dimensional histograms using a new non-linear moment morphing method*, *Nucl. Instrum. Meth. A* **771** (2015) 39 [arXiv:1410.7388] [INSPIRE].
- [71] J. Eschle, A. Puig Navarro, R. Silva Coutinho and N. Serra, *zfit: scalable pythonic fitting*, arXiv:1910.13429 [DOI:10.1016/j.softx.2020.100508] [INSPIRE].
- [72] G. Cowan, K. Cranmer, E. Gross and O. Vitells, *Asymptotic formulae for likelihood-based tests of new physics*, *Eur. Phys. J. C* **71** (2011) 1554 [Erratum *ibid.* **73** (2013) 2501] [arXiv:1007.1727] [INSPIRE].
- [73] E. Gross and O. Vitells, *Trial factors for the look elsewhere effect in high energy physics*, *Eur. Phys. J. C* **70** (2010) 525 [arXiv:1005.1891] [INSPIRE].

- [74] S. Collaviti, A. Merli and L. Shchutska, *LHCb Upgrade 1: Results and prospects for triggers with very displaced vertices with focus on HNLs*, in *Feebly interacting particles: FIPs at LHCb*, (2025) [[arXiv:2510.05257](#)].
- [75] LHCb collaboration, *Long-lived particle reconstruction downstream of the LHCb magnet*, *Eur. Phys. J. C* **85** (2025) 7 [Erratum *ibid.* **85** (2025) 310] [[arXiv:2211.10920](#)] [[INSPIRE](#)].
- [76] LHCb collaboration, *The LHCb Upgrade I*, 2024 *JINST* **19** P05065 [[arXiv:2305.10515](#)] [[INSPIRE](#)].
- [77] LHCb collaboration, *LHCb Upgrade II Scoping Document*, CERN-LHCC-2024-010 (2024).

## The LHCb collaboration


































R. Aaij<sup>38</sup>, A.S.W. Abdelmotteleb<sup>58</sup>, C. Abellan Beteta<sup>52</sup>, F. Abudinén<sup>58</sup>, T. Ackernley<sup>62</sup>, A.A. Adefisoye<sup>70</sup>, B. Adeva<sup>48</sup>, M. Adinolfi<sup>56</sup>, P. Adlarson<sup>86</sup>, C. Agapopoulou<sup>14</sup>, C.A. Aidala<sup>88</sup>, Z. Ajaltouni<sup>11</sup>, S. Akar<sup>11</sup>, K. Akiba<sup>38</sup>, P. Albicocco<sup>28</sup>, J. Albrecht<sup>19,g</sup>, R. Aleksiejunas<sup>82</sup>, F. Alessio<sup>50</sup>, P. Alvarez Cartelle<sup>57</sup>, R. Amalric<sup>16</sup>, S. Amato<sup>3</sup>, J.L. Amey<sup>56</sup>, Y. Amhis<sup>14</sup>, L. An<sup>6</sup>, L. Anderlini<sup>27</sup>, M. Andersson<sup>52</sup>, P. Andreola<sup>52</sup>, M. Andreotti<sup>26</sup>, S. Andres Estrada<sup>45</sup>, A. Anelli<sup>31,50,p</sup>, D. Ao<sup>7</sup>, C. Arata<sup>12</sup>, F. Archilli<sup>37,v</sup>, Z. Areg<sup>70</sup>, M. Argenton<sup>26</sup>, S. Arguedas Cuendis<sup>9,50</sup>, L. Arnone<sup>31,p</sup>, A. Artamonov<sup>44</sup>, M. Artuso<sup>70</sup>, E. Aslanides<sup>13</sup>, R. Ataíde Da Silva<sup>51</sup>, M. Atzeni<sup>66</sup>, B. Audurier<sup>12</sup>, J.A. Authier<sup>15</sup>, D. Bacher<sup>65</sup>, I. Bachiller Perea<sup>51</sup>, S. Bachmann<sup>22</sup>, M. Bachmayer<sup>51</sup>, J.J. Back<sup>58</sup>, P. Baladron Rodriguez<sup>48</sup>, V. Balagura<sup>15</sup>, A. Balboni<sup>26</sup>, W. Baldini<sup>26</sup>, Z. Baldwin<sup>80</sup>, L. Balzani<sup>19</sup>, H. Bao<sup>7</sup>, J. Baptista de Souza Leite<sup>2</sup>, C. Barbero Pretel<sup>48,12</sup>, M. Barbetti<sup>27</sup>, I.R. Barbosa<sup>71</sup>, R.J. Barlow<sup>64</sup>, M. Barnyakov<sup>25</sup>, S. Barsuk<sup>14</sup>, W. Barter<sup>60</sup>, J. Bartz<sup>70</sup>, S. Bashir<sup>40</sup>, B. Batsukh<sup>5</sup>, P.B. Battista<sup>14</sup>, A. Bay<sup>51</sup>, A. Beck<sup>66</sup>, M. Becker<sup>19</sup>, F. Bedeschi<sup>35</sup>, I.B. Bediaga<sup>2</sup>, N.A. Behling<sup>19</sup>, S. Belin<sup>48</sup>, A. Bellavista<sup>25</sup>, K. Belous<sup>44</sup>, I. Belov<sup>29</sup>, I. Belyaev<sup>36</sup>, E. Ben-Haim<sup>16</sup>, G. Benane<sup>13</sup>, G. Bencivenni<sup>28</sup>, A. Berezhnoy<sup>44</sup>, R. Bernet<sup>52</sup>, S. Bernet Andres<sup>47</sup>, A. Bertolin<sup>33</sup>, F. Betti<sup>60</sup>, J. Bex<sup>57</sup>, O. Bezshyyko<sup>87</sup>, S. Bhattacharya<sup>81</sup>, J. Bhom<sup>41</sup>, M.S. Bieker<sup>18</sup>, N.V. Biesuz<sup>26</sup>, A. Biolchini<sup>38</sup>, M. Birch<sup>63</sup>, F.C.R. Bishop<sup>10</sup>, A. Bitadze<sup>64</sup>, A. Bizzeti<sup>27,q</sup>, T. Blake<sup>58,c</sup>, F. Blanc<sup>51</sup>, J.E. Blank<sup>19</sup>, S. Blusk<sup>70</sup>, V. Bocharnikov<sup>44</sup>, J.A. Boelhauve<sup>19</sup>, O. Boente Garcia<sup>50</sup>, T. Boettcher<sup>69</sup>, A. Bohare<sup>60</sup>, A. Boldyrev<sup>44</sup>, C. Bolognani<sup>84</sup>, R. Bolzonella<sup>26,m</sup>, R.B. Bonacci<sup>1</sup>, N. Bondar<sup>44,50</sup>, A. Bordelius<sup>50</sup>, F. Borgato<sup>33,50</sup>, S. Borghi<sup>64</sup>, M. Borsato<sup>31,p</sup>, J.T. Borsuk<sup>85</sup>, E. Bottalico<sup>62</sup>, S.A. Bouchiba<sup>51</sup>, M. Bovill<sup>65</sup>, T.J.V. Bowcock<sup>62</sup>, A. Boyer<sup>50</sup>, C. Bozzi<sup>26</sup>, J.D. Brandenburg<sup>89</sup>, A. Brea Rodriguez<sup>51</sup>, N. Breer<sup>19</sup>, J. Brodzicka<sup>41</sup>, J. Brown<sup>62</sup>, D. Brundu<sup>32</sup>, E. Buchanan<sup>60</sup>, M. Burgos Marcos<sup>84</sup>, A.T. Burke<sup>64</sup>, C. Burr<sup>50</sup>, C. Buti<sup>27</sup>, J.S. Butter<sup>57</sup>, J. Buytaert<sup>50</sup>, W. Byczynski<sup>50</sup>, S. Cadeddu<sup>32</sup>, H. Cai<sup>76</sup>, Y. Cai<sup>5</sup>, A. Caillet<sup>16</sup>, R. Calabrese<sup>26,m</sup>, S. Calderon Ramirez<sup>9</sup>, L. Calefice<sup>46</sup>, M. Calvi<sup>31,p</sup>, M. Calvo Gomez<sup>47</sup>, P. Camargo Magalhaes<sup>2,a</sup>, J.I. Cambon Bouzas<sup>48</sup>, P. Campana<sup>28</sup>, A.F. Campoverde Quezada<sup>7</sup>, S. Capelli<sup>31</sup>, M. Caporale<sup>25</sup>, L. Capriotti<sup>26</sup>, R. Caravaca-Mora<sup>9</sup>, A. Carbone<sup>25,k</sup>, L. Carcedo Salgado<sup>48</sup>, R. Cardinale<sup>29,n</sup>, A. Cardini<sup>32</sup>, P. Carniti<sup>31</sup>, L. Carus<sup>22</sup>, A. Casais Vidal<sup>66</sup>, R. Caspary<sup>22</sup>, G. Casse<sup>62</sup>, M. Cattaneo<sup>50</sup>, G. Cavallero<sup>26</sup>, V. Cavallini<sup>26,m</sup>, S. Celani<sup>50</sup>, I. Celestino<sup>35,t</sup>, S. Cesare<sup>30,o</sup>, A.J. Chadwick<sup>62</sup>, I. Chahrour<sup>88</sup>, H. Chang<sup>4,d</sup>, M. Charles<sup>16</sup>, Ph. Charpentier<sup>50</sup>, E. Chatzianagnostou<sup>38</sup>, R. Cheaib<sup>81</sup>, M. Chefdeville<sup>10</sup>, C. Chen<sup>57</sup>, J. Chen<sup>51</sup>, S. Chen<sup>5</sup>, Z. Chen<sup>7</sup>, A. Chen Hu<sup>63</sup>, M. Cherif<sup>12</sup>, A. Chernov<sup>41</sup>, S. Chernyshenko<sup>54</sup>, X. Chiotopoulos<sup>84</sup>, V. Chobanova<sup>45</sup>, S. Cholak<sup>51</sup>, M. Chrzaszcz<sup>41</sup>, A. Chubykin<sup>44</sup>, V. Chulikov<sup>28,36,50</sup>, P. Ciambrome<sup>28</sup>, X. Cid Vidal<sup>48</sup>, G. Ciezarek<sup>50</sup>, P. Cifra<sup>38</sup>, P.E.L. Clarke<sup>60</sup>, M. Clemencic<sup>50</sup>, H.V. Cliff<sup>57</sup>, J. Closier<sup>50</sup>, C. Cocha Toapaxi<sup>22</sup>, V. Coco<sup>50</sup>, J. Cogan<sup>13</sup>, E. Cogneras<sup>11</sup>, L. Cojocariu<sup>43</sup>, S. Collaviti<sup>51</sup>, P. Collins<sup>50</sup>, T. Colombo<sup>50</sup>, M. Colonna<sup>19</sup>, A. Comerma-Montells<sup>46</sup>, L. Congedo<sup>24</sup>, J. Connaughton<sup>58</sup>, A. Contu<sup>32</sup>, N. Cooke<sup>61</sup>, G. Cordova<sup>35,t</sup>, C. Coronel<sup>67</sup>, I. Corredoira<sup>12</sup>, A. Correia<sup>16</sup>, G. Corti<sup>50</sup>, J. Cottee Meldrum<sup>56</sup>, B. Couturier<sup>50</sup>, D.C. Craik<sup>52</sup>, M. Cruz Torres<sup>2,h</sup>,

E. Curras Rivera [ID](#)<sup>51</sup>, R. Currie [ID](#)<sup>60</sup>, C. D'Ambrosio [ID](#)<sup>63</sup>, C.L. Da Silva [ID](#)<sup>69</sup>, S. Dadabaev [ID](#)<sup>44</sup>,  
 X. Dai [ID](#)<sup>4</sup>, E. Dall'Occo [ID](#)<sup>50</sup>, J. Dalseno [ID](#)<sup>45</sup>, J. Daniel [ID](#)<sup>11</sup>, G. Darze [ID](#)<sup>3</sup>, A. Davidson [ID](#)<sup>58</sup>,  
 J.E. Davies [ID](#)<sup>64</sup>, O. De Aguiar Francisco [ID](#)<sup>64</sup>, C. De Angelis [ID](#)<sup>32,l</sup>, F. De Benedetti [ID](#)<sup>50</sup>,  
 J. de Boer [ID](#)<sup>38</sup>, K. De Bruyn [ID](#)<sup>83</sup>, S. De Capua [ID](#)<sup>64</sup>, M. De Cian [ID](#)<sup>64,50</sup>,  
 U. De Freitas Carneiro Da Graca [ID](#)<sup>2,b</sup>, E. De Lucia [ID](#)<sup>28</sup>, J.M. De Miranda [ID](#)<sup>2</sup>, L. De Paula [ID](#)<sup>3</sup>,  
 M. De Serio [ID](#)<sup>24,i</sup>, P. De Simone [ID](#)<sup>28</sup>, F. De Vellis [ID](#)<sup>19</sup>, J.A. de Vries [ID](#)<sup>84</sup>, F. Debernardis [ID](#)<sup>24</sup>,  
 D. Decamp [ID](#)<sup>10</sup>, S. Dekkers [ID](#)<sup>1</sup>, L. Del Buono [ID](#)<sup>16</sup>, B. Delaney [ID](#)<sup>66</sup>, H.-P. Dembinski [ID](#)<sup>19</sup>, J. Deng [ID](#)<sup>8</sup>,  
 V. Denysenko [ID](#)<sup>52</sup>, O. Deschamps [ID](#)<sup>11</sup>, F. Dettori [ID](#)<sup>32,l</sup>, B. Dey [ID](#)<sup>81</sup>, P. Di Nezza [ID](#)<sup>28</sup>, I. Diachkov [ID](#)<sup>44</sup>,  
 S. Didenko [ID](#)<sup>44</sup>, S. Ding [ID](#)<sup>70</sup>, Y. Ding [ID](#)<sup>51</sup>, L. Dittmann [ID](#)<sup>22</sup>, V. Dobishuk [ID](#)<sup>54</sup>, A.D. Docheva [ID](#)<sup>61</sup>,  
 A. Doheny [ID](#)<sup>58</sup>, C. Dong [ID](#)<sup>4,d</sup>, A.M. Donohoe [ID](#)<sup>23</sup>, F. Dordei [ID](#)<sup>32</sup>, A.C. dos Reis [ID](#)<sup>2</sup>, A.D. Dowling [ID](#)<sup>70</sup>,  
 L. Dreyfus [ID](#)<sup>13</sup>, W. Duan [ID](#)<sup>74</sup>, P. Duda [ID](#)<sup>85</sup>, L. Dufour [ID](#)<sup>50</sup>, V. Duk [ID](#)<sup>34</sup>, P. Durante [ID](#)<sup>50</sup>,  
 M.M. Duras [ID](#)<sup>85</sup>, J.M. Durham [ID](#)<sup>69</sup>, O.D. Durmus [ID](#)<sup>81</sup>, A. Dziurda [ID](#)<sup>41</sup>, A. Dzyuba [ID](#)<sup>44</sup>, S. Easo [ID](#)<sup>59</sup>,  
 E. Eckstein [ID](#)<sup>18</sup>, U. Egede [ID](#)<sup>1</sup>, A. Egorychev [ID](#)<sup>44</sup>, V. Egorychev [ID](#)<sup>44</sup>, S. Eisenhardt [ID](#)<sup>60</sup>, E. Ejopu [ID](#)<sup>62</sup>,  
 L. Eklund [ID](#)<sup>86</sup>, M. Elashri [ID](#)<sup>67</sup>, D. Elizondo Blanco [ID](#)<sup>9</sup>, J. Ellbracht [ID](#)<sup>19</sup>, S. Ely [ID](#)<sup>63</sup>, A. Ene [ID](#)<sup>43</sup>,  
 J. Eschle [ID](#)<sup>70</sup>, S. Esen [ID](#)<sup>22</sup>, T. Evans [ID](#)<sup>38</sup>, F. Fabiano [ID](#)<sup>32</sup>, S. Faghih [ID](#)<sup>67</sup>, L.N. Falcao [ID](#)<sup>31,p</sup>,  
 B. Fang [ID](#)<sup>7</sup>, R. Fantechi [ID](#)<sup>35</sup>, L. Fantini [ID](#)<sup>34,s</sup>, M. Faria [ID](#)<sup>51</sup>, K. Farmer [ID](#)<sup>60</sup>, F. Fassin [ID](#)<sup>83,38</sup>,  
 D. Fazzini [ID](#)<sup>31,p</sup>, L. Felkowski [ID](#)<sup>85</sup>, M. Feng [ID](#)<sup>5,7</sup>, A. Fernandez Casani [ID](#)<sup>49</sup>, M. Fernandez Gomez [ID](#)<sup>48</sup>,  
 A.D. Fernez [ID](#)<sup>68</sup>, F. Ferrari [ID](#)<sup>25,k</sup>, F. Ferreira Rodrigues [ID](#)<sup>3</sup>, M. Ferrillo [ID](#)<sup>52</sup>, M. Ferro-Luzzi [ID](#)<sup>50</sup>,  
 S. Filippov [ID](#)<sup>44</sup>, R.A. Fini [ID](#)<sup>24</sup>, M. Fiorini [ID](#)<sup>26,m</sup>, M. Firlej [ID](#)<sup>40</sup>, K.L. Fischer [ID](#)<sup>65</sup>, D.S. Fitzgerald [ID](#)<sup>88</sup>,  
 C. Fitzpatrick [ID](#)<sup>64</sup>, T. Fiutowski [ID](#)<sup>40</sup>, F. Fleuret [ID](#)<sup>15</sup>, A. Fomin [ID](#)<sup>53</sup>, M. Fontana [ID](#)<sup>25</sup>,  
 L.A. Foreman [ID](#)<sup>64</sup>, R. Forty [ID](#)<sup>50</sup>, D. Foulds-Holt [ID](#)<sup>60</sup>, V. Franco Lima [ID](#)<sup>3</sup>, M. Franco Sevilla [ID](#)<sup>68</sup>,  
 M. Frank [ID](#)<sup>50</sup>, E. Franzoso [ID](#)<sup>26,m</sup>, G. Frau [ID](#)<sup>64</sup>, C. Frei [ID](#)<sup>50</sup>, D.A. Friday [ID](#)<sup>64,50</sup>, J. Fu [ID](#)<sup>7</sup>,  
 T. Fulghesu [ID](#)<sup>13</sup>, Q. Führung [ID](#)<sup>19,57,g</sup>, G. Galati [ID](#)<sup>24</sup>, M.D. Galati [ID](#)<sup>38</sup>, A. Gallas Torreira [ID](#)<sup>48</sup>,  
 D. Galli [ID](#)<sup>25,k</sup>, S. Gambetta [ID](#)<sup>60</sup>, M. Gandelman [ID](#)<sup>3</sup>, P. Gandini [ID](#)<sup>30</sup>, B. Ganie [ID](#)<sup>64</sup>, H. Gao [ID](#)<sup>7</sup>,  
 R. Gao [ID](#)<sup>65</sup>, T.Q. Gao [ID](#)<sup>57</sup>, Y. Gao [ID](#)<sup>8</sup>, Y. Gao [ID](#)<sup>6</sup>, Y. Gao [ID](#)<sup>8</sup>, L.M. Garcia Martin [ID](#)<sup>51</sup>,  
 P. Garcia Moreno [ID](#)<sup>46</sup>, J. García Pardiñas [ID](#)<sup>66</sup>, P. Gardner [ID](#)<sup>68</sup>, L. Garrido [ID](#)<sup>46</sup>, C. Gaspar [ID](#)<sup>50</sup>,  
 A. Gavrikov [ID](#)<sup>33</sup>, L.L. Gerken [ID](#)<sup>19</sup>, E. Gersabeck [ID](#)<sup>20</sup>, M. Gersabeck [ID](#)<sup>20</sup>, T. Gershon [ID](#)<sup>58</sup>,  
 S. Ghizzo [ID](#)<sup>29,n</sup>, Z. Ghorbanimoghaddam [ID](#)<sup>56</sup>, F.I. Giasemis [ID](#)<sup>16,f</sup>, V. Gibson [ID](#)<sup>57</sup>, H.K. Giemza [ID](#)<sup>42</sup>,  
 A.L. Gilman [ID](#)<sup>67</sup>, M. Giovannetti [ID](#)<sup>28</sup>, A. Gioventù [ID](#)<sup>46</sup>, L. Girardey [ID](#)<sup>64,59</sup>, M.A. Giza [ID](#)<sup>41</sup>,  
 F.C. Glaser [ID](#)<sup>14,22</sup>, V.V. Gligorov [ID](#)<sup>16</sup>, L. Golinka-Bezshyyko [ID](#)<sup>87</sup>, E. Golobardes [ID](#)<sup>47</sup>,  
 D. Golubkov [ID](#)<sup>44</sup>, A. Golutvin [ID](#)<sup>63,50</sup>, S. Gomez Fernandez [ID](#)<sup>46</sup>, W. Gomulka [ID](#)<sup>40</sup>,  
 F. Goncalves Abrantes [ID](#)<sup>65</sup>, M. Goncerz [ID](#)<sup>41</sup>, G. Gong [ID](#)<sup>4,d</sup>, I. Gonçalves Vaz [ID](#)<sup>50</sup>, J.A. Gooding [ID](#)<sup>19</sup>,  
 I.V. Gorelov [ID](#)<sup>44</sup>, C. Gotti [ID](#)<sup>31</sup>, E. Govorkova [ID](#)<sup>66</sup>, J.P. Grabowski [ID](#)<sup>30</sup>, L.A. Granado Cardoso [ID](#)<sup>50</sup>,  
 E. Graugés [ID](#)<sup>46</sup>, E. Graverini [ID](#)<sup>51,u</sup>, L. Grazette [ID](#)<sup>58</sup>, G. Graziani [ID](#)<sup>27</sup>, A.T. Grecu [ID](#)<sup>43</sup>,  
 N.A. Grieser [ID](#)<sup>67</sup>, L. Grillo [ID](#)<sup>61</sup>, S. Gromov [ID](#)<sup>44</sup>, C. Gu [ID](#)<sup>15</sup>, M. Guarise [ID](#)<sup>26</sup>, L. Guerry [ID](#)<sup>11</sup>,  
 A.-K. Guseinov [ID](#)<sup>51</sup>, E. Gushchin [ID](#)<sup>44</sup>, Y. Guz [ID](#)<sup>6,50</sup>, T. Gys [ID](#)<sup>50</sup>, C. Göbel [ID](#)<sup>71</sup>, K. Habermann [ID](#)<sup>18</sup>,  
 T. Hadavizadeh [ID](#)<sup>1</sup>, C. Hadjivasiliou [ID](#)<sup>68</sup>, G. Haefeli [ID](#)<sup>51</sup>, C. Haen [ID](#)<sup>50</sup>, S. Haken [ID](#)<sup>57</sup>, G. Hallett [ID](#)<sup>58</sup>,  
 P.M. Hamilton [ID](#)<sup>68</sup>, J. Hammerich [ID](#)<sup>62</sup>, Q. Han [ID](#)<sup>33</sup>, X. Han [ID](#)<sup>22,50</sup>, S. Hansmann-Menzemer [ID](#)<sup>22</sup>,  
 L. Hao [ID](#)<sup>7</sup>, N. Harnew [ID](#)<sup>65</sup>, T.H. Harris [ID](#)<sup>1</sup>, M. Hartmann [ID](#)<sup>14</sup>, S. Hashmi [ID](#)<sup>40</sup>, J. He [ID](#)<sup>7,e</sup>,  
 A. Hedes [ID](#)<sup>64</sup>, F. Hemmer [ID](#)<sup>50</sup>, C. Henderson [ID](#)<sup>67</sup>, R. Henderson [ID](#)<sup>14</sup>, R.D.L. Henderson [ID](#)<sup>1</sup>,  
 A.M. Hennequin [ID](#)<sup>50</sup>, K. Hennessy [ID](#)<sup>62</sup>, L. Henry [ID](#)<sup>51</sup>, J. Herd [ID](#)<sup>63</sup>, P. Herrero Gascon [ID](#)<sup>22</sup>,  
 J. Heuel [ID](#)<sup>17</sup>, A. Heyn [ID](#)<sup>13</sup>, A. Hicheur [ID](#)<sup>3</sup>, G. Hijano Mendizabal [ID](#)<sup>52</sup>, J. Horswill [ID](#)<sup>64</sup>, R. Hou [ID](#)<sup>8</sup>,  
 Y. Hou [ID](#)<sup>11</sup>, D.C. Houston [ID](#)<sup>61</sup>, N. Howarth [ID](#)<sup>62</sup>, W. Hu [ID](#)<sup>7</sup>, X. Hu [ID](#)<sup>4</sup>, W. Hulsbergen [ID](#)<sup>38</sup>,

R.J. Hunter [id](#)<sup>58</sup>, M. Hushchyn [id](#)<sup>44</sup>, D. Hutchcroft [id](#)<sup>62</sup>, M. Idzik [id](#)<sup>40</sup>, D. Ilin [id](#)<sup>44</sup>, P. Ilten [id](#)<sup>67</sup>, A. Iniukhin [id](#)<sup>44</sup>, A. Iohner [id](#)<sup>10</sup>, A. Ishteev [id](#)<sup>44</sup>, K. Ivshin [id](#)<sup>44</sup>, H. Jage [id](#)<sup>17</sup>, S.J. Jaimes Elles [id](#)<sup>78,49,50</sup>, S. Jakobsen [id](#)<sup>50</sup>, T. Jakoubek [id](#)<sup>79</sup>, E. Jans [id](#)<sup>38</sup>, B.K. Jashal [id](#)<sup>49</sup>, A. Jawahery [id](#)<sup>68</sup>, C. Jayaweera [id](#)<sup>55</sup>, V. Jevtic [id](#)<sup>19</sup>, Z. Jia [id](#)<sup>16</sup>, E. Jiang [id](#)<sup>68</sup>, X. Jiang [id](#)<sup>5,7</sup>, Y. Jiang [id](#)<sup>7</sup>, Y.J. Jiang [id](#)<sup>6</sup>, E. Jimenez Moya [id](#)<sup>9</sup>, N. Jindal [id](#)<sup>89</sup>, M. John [id](#)<sup>65</sup>, A. John Rubesh Rajan [id](#)<sup>23</sup>, D. Johnson [id](#)<sup>55</sup>, C.R. Jones [id](#)<sup>57</sup>, S. Joshi [id](#)<sup>42</sup>, B. Jost [id](#)<sup>50</sup>, J. Juan Castella [id](#)<sup>57</sup>, N. Jurik [id](#)<sup>50</sup>, I. Juszcak [id](#)<sup>41</sup>, K. Kalecinska [id](#)<sup>40</sup>, D. Kaminaris [id](#)<sup>51</sup>, S. Kandybei [id](#)<sup>53</sup>, M. Kane [id](#)<sup>60</sup>, Y. Kang [id](#)<sup>4,d</sup>, C. Kar [id](#)<sup>11</sup>, M. Karacson [id](#)<sup>50</sup>, A. Kauniskangas [id](#)<sup>51</sup>, J.W. Kautz [id](#)<sup>67</sup>, M.K. Kazanecki [id](#)<sup>41</sup>, F. Keizer [id](#)<sup>50</sup>, M. Kenzie [id](#)<sup>57</sup>, T. Ketel [id](#)<sup>38</sup>, B. Khanji [id](#)<sup>70</sup>, A. Kharisova [id](#)<sup>44</sup>, S. Kholodenko [id](#)<sup>63,50</sup>, G. Khreich [id](#)<sup>14</sup>, T. Kirn [id](#)<sup>17</sup>, V.S. Kirsebom [id](#)<sup>31,p</sup>, O. Kitouni [id](#)<sup>66</sup>, S. Klaver [id](#)<sup>39</sup>, N. Kleijne [id](#)<sup>35,t</sup>, D.K. Klekots [id](#)<sup>87</sup>, K. Klimaszewski [id](#)<sup>42</sup>, M.R. Kmiec [id](#)<sup>42</sup>, T. Knospe [id](#)<sup>19</sup>, R. Kolb [id](#)<sup>22</sup>, S. Koliiev [id](#)<sup>54</sup>, L. Kolk [id](#)<sup>19</sup>, A. Konoplyannikov [id](#)<sup>6</sup>, P. Kopciewicz [id](#)<sup>50</sup>, P. Koppenburg [id](#)<sup>38</sup>, A. Korchin [id](#)<sup>53</sup>, M. Korolev [id](#)<sup>44</sup>, I. Kostiuk [id](#)<sup>38</sup>, O. Kot [id](#)<sup>54</sup>, S. Kotriakhova [id](#), E. Kowalczyk [id](#)<sup>68</sup>, A. Kozachuk [id](#)<sup>44</sup>, P. Kravchenko [id](#)<sup>44</sup>, L. Kravchuk [id](#)<sup>44</sup>, O. Kravcov [id](#)<sup>82</sup>, M. Kreps [id](#)<sup>58</sup>, P. Krokovny [id](#)<sup>44,44</sup>, W. Krupa [id](#)<sup>70</sup>, W. Krzemien [id](#)<sup>42</sup>, O. Kshyvanskyi [id](#)<sup>54</sup>, S. Kubis [id](#)<sup>85</sup>, M. Kucharczyk [id](#)<sup>41</sup>, V. Kudryavtsev [id](#)<sup>44,44</sup>, E. Kulikova [id](#)<sup>44</sup>, A. Kupsc [id](#)<sup>86</sup>, V. Kushnir [id](#)<sup>53</sup>, B. Kutsenko [id](#)<sup>13</sup>, J. Kvapil [id](#)<sup>69</sup>, I. Kyryllin [id](#)<sup>53</sup>, D. Lacarrere [id](#)<sup>50</sup>, P. Laguarda Gonzalez [id](#)<sup>46</sup>, A. Lai [id](#)<sup>32</sup>, A. Lampis [id](#)<sup>32</sup>, D. Lancierini [id](#)<sup>63</sup>, C. Landesa Gomez [id](#)<sup>48</sup>, J.J. Lane [id](#)<sup>1</sup>, G. Lanfranchi [id](#)<sup>28</sup>, C. Langenbruch [id](#)<sup>22</sup>, J. Langer [id](#)<sup>19</sup>, T. Latham [id](#)<sup>58</sup>, F. Lazzari [id](#)<sup>35,50,u</sup>, C. Lazzeroni [id](#)<sup>55</sup>, R. Le Gac [id](#)<sup>13</sup>, H. Lee [id](#)<sup>62</sup>, A. Leflat [id](#)<sup>44</sup>, R. Lefèvre [id](#)<sup>11</sup>, S. Legotin [id](#)<sup>44</sup>, M. Lehuraux [id](#)<sup>58</sup>, E. Lemos Cid [id](#)<sup>50</sup>, O. Leroy [id](#)<sup>13</sup>, T. Lesiak [id](#)<sup>41</sup>, E.D. Lesser [id](#)<sup>50</sup>, B. Leverington [id](#)<sup>22</sup>, A. Li [id](#)<sup>4,d</sup>, C. Li [id](#)<sup>4,d</sup>, C. Li [id](#)<sup>13</sup>, H. Li [id](#)<sup>74</sup>, J. Li [id](#)<sup>8</sup>, K. Li [id](#)<sup>77</sup>, L. Li [id](#)<sup>64</sup>, M. Li [id](#)<sup>8</sup>, P. Li [id](#)<sup>7</sup>, P.-R. Li [id](#)<sup>75</sup>, Q. Li [id](#)<sup>5,7</sup>, T. Li [id](#)<sup>73</sup>, T. Li [id](#)<sup>74</sup>, Y. Li [id](#)<sup>8</sup>, Y. Li [id](#)<sup>5</sup>, Y. Li [id](#)<sup>4</sup>, Z. Lian [id](#)<sup>4,d</sup>, Q. Liang [id](#)<sup>8</sup>, X. Liang [id](#)<sup>70</sup>, Z. Liang [id](#)<sup>32</sup>, S. Libralon [id](#)<sup>49</sup>, A. Lightbody [id](#)<sup>12</sup>, C. Lin [id](#)<sup>7</sup>, T. Lin [id](#)<sup>59</sup>, R. Lindner [id](#)<sup>50</sup>, H. Linton [id](#)<sup>63</sup>, R. Litvinov [id](#)<sup>32</sup>, D. Liu [id](#)<sup>8</sup>, F.L. Liu [id](#)<sup>1</sup>, G. Liu [id](#)<sup>74</sup>, K. Liu [id](#)<sup>75</sup>, S. Liu [id](#)<sup>5</sup>, W. Liu [id](#)<sup>8</sup>, Y. Liu [id](#)<sup>60</sup>, Y. Liu [id](#)<sup>75</sup>, Y.L. Liu [id](#)<sup>63</sup>, G. Loachamin Ordonez [id](#)<sup>71</sup>, I. Lobo [id](#)<sup>1</sup>, A. Lobo Salvia [id](#)<sup>46</sup>, A. Loi [id](#)<sup>32</sup>, T. Long [id](#)<sup>57</sup>, F.C.L. Lopes [id](#)<sup>2,a</sup>, J.H. Lopes [id](#)<sup>3</sup>, A. Lopez Huertas [id](#)<sup>46</sup>, C. Lopez Iribarnegaray [id](#)<sup>48</sup>, Q. Lu [id](#)<sup>15</sup>, C. Lucarelli [id](#)<sup>50</sup>, D. Lucchesi [id](#)<sup>33,r</sup>, M. Lucio Martinez [id](#)<sup>49</sup>, Y. Luo [id](#)<sup>6</sup>, A. Lupato [id](#)<sup>33,j</sup>, E. Luppi [id](#)<sup>26,m</sup>, K. Lynch [id](#)<sup>23</sup>, X.-R. Lyu [id](#)<sup>7</sup>, S. López Soliño [id](#)<sup>48</sup>, G.M. Ma [id](#)<sup>4,d</sup>, H. Ma [id](#)<sup>73</sup>, S. Maccolini [id](#)<sup>19</sup>, F. Machefer [id](#)<sup>14</sup>, F. Maciuc [id](#)<sup>43</sup>, B. Mack [id](#)<sup>70</sup>, I. Mackay [id](#)<sup>65</sup>, L.M. Mackey [id](#)<sup>70</sup>, L.R. Madhan Mohan [id](#)<sup>57</sup>, M.J. Madurai [id](#)<sup>55</sup>, D. Magdalinski [id](#)<sup>38</sup>, D. Maisuzenko [id](#)<sup>44</sup>, J.J. Malczewski [id](#)<sup>41</sup>, S. Malde [id](#)<sup>65</sup>, L. Malentacca [id](#)<sup>50</sup>, A. Malinin [id](#)<sup>44</sup>, T. Maltsev [id](#)<sup>44</sup>, G. Manca [id](#)<sup>32,l</sup>, G. Mancinelli [id](#)<sup>13</sup>, C. Mancuso [id](#)<sup>14</sup>, R. Manera Escalero [id](#)<sup>46</sup>, F.M. Manganella [id](#)<sup>37</sup>, D. Manuzzi [id](#)<sup>25</sup>, D. Marangotto [id](#)<sup>30,o</sup>, J.F. Marchand [id](#)<sup>10</sup>, R. Marchevski [id](#)<sup>51</sup>, U. Marconi [id](#)<sup>25</sup>, E. Mariani [id](#)<sup>16</sup>, S. Mariani [id](#)<sup>50</sup>, C. Marin Benito [id](#)<sup>46</sup>, J. Marks [id](#)<sup>22</sup>, A.M. Marshall [id](#)<sup>56</sup>, L. Martel [id](#)<sup>65</sup>, G. Martelli [id](#)<sup>34</sup>, G. Martellotti [id](#)<sup>36</sup>, L. Martinazzoli [id](#)<sup>50</sup>, M. Martinelli [id](#)<sup>31,p</sup>, D. Martinez Gomez [id](#)<sup>83</sup>, D. Martinez Santos [id](#)<sup>45</sup>, F. Martinez Vidal [id](#)<sup>49</sup>, A. Martorell i Granollers [id](#)<sup>47</sup>, A. Massafferri [id](#)<sup>2</sup>, R. Matev [id](#)<sup>50</sup>, A. Mathad [id](#)<sup>50</sup>, V. Matiunin [id](#)<sup>44</sup>, C. Matteuzzi [id](#)<sup>70</sup>, K.R. Mattioli [id](#)<sup>15</sup>, A. Mauri [id](#)<sup>63</sup>, E. Maurice [id](#)<sup>15</sup>, J. Mauricio [id](#)<sup>46</sup>, P. Mayencourt [id](#)<sup>51</sup>, J. Mazon de Cos [id](#)<sup>49</sup>, M. Mazurek [id](#)<sup>42</sup>, M. McCann [id](#)<sup>63</sup>, N.T. McHugh [id](#)<sup>61</sup>, A. McNab [id](#)<sup>64</sup>, R. McNulty [id](#)<sup>23</sup>, B. Meadows [id](#)<sup>67</sup>, G. Meier [id](#)<sup>19</sup>, D. Melnychuk [id](#)<sup>42</sup>, D. Mendoza Granada [id](#)<sup>16</sup>, P. Menendez Valdes Perez [id](#)<sup>48</sup>, F.M. Meng [id](#)<sup>4,d</sup>, M. Merk [id](#)<sup>38,84</sup>, A. Merli [id](#)<sup>51,30</sup>, L. Meyer Garcia [id](#)<sup>68</sup>, D. Miao [id](#)<sup>5,7</sup>, H. Miao [id](#)<sup>7</sup>, M. Mikhasenko [id](#)<sup>80</sup>, D.A. Milanese [id](#)<sup>78,y</sup>, A. Minotti [id](#)<sup>31,p</sup>, E. Minucci [id](#)<sup>28</sup>, T. Miralles [id](#)<sup>11</sup>, B. Mitreska [id](#)<sup>64</sup>,

D.S. Mitzel [ID](#)<sup>19</sup>, R. Mocanu [ID](#)<sup>43</sup>, A. Modak [ID](#)<sup>59</sup>, L. Moeser [ID](#)<sup>19</sup>, R.D. Moise [ID](#)<sup>17</sup>,  
 E.F. Molina Cardenas [ID](#)<sup>88</sup>, T. Mombächer [ID](#)<sup>67</sup>, M. Monk [ID](#)<sup>57</sup>, S. Monteil [ID](#)<sup>11</sup>, A. Morcillo Gomez [ID](#)<sup>48</sup>,  
 G. Morello [ID](#)<sup>28</sup>, M.J. Morello [ID](#)<sup>35,t</sup>, M.P. Morgenthaler [ID](#)<sup>22</sup>, A. Moro [ID](#)<sup>31,p</sup>, J. Moron [ID](#)<sup>40</sup>,  
 W. Morren [ID](#)<sup>38</sup>, A.B. Morris [ID](#)<sup>50</sup>, A.G. Morris [ID](#)<sup>13</sup>, R. Mountain [ID](#)<sup>70</sup>, Z.M. Mu [ID](#)<sup>6</sup>,  
 E. Muhammad [ID](#)<sup>58</sup>, F. Muheim [ID](#)<sup>60</sup>, M. Mulder [ID](#)<sup>83</sup>, R. Murta [ID](#)<sup>63</sup>, F. Muñoz-Rojas [ID](#)<sup>9</sup>,  
 V. Mytrochenko [ID](#)<sup>53</sup>, K. Müller [ID](#)<sup>52</sup>, P. Naik [ID](#)<sup>62</sup>, T. Nakada [ID](#)<sup>51</sup>, R. Nandakumar [ID](#)<sup>59</sup>, T. Nanut [ID](#)<sup>50</sup>,  
 I. Nasteva [ID](#)<sup>3</sup>, M. Needham [ID](#)<sup>60</sup>, E. Nekrasova [ID](#)<sup>44</sup>, N. Neri [ID](#)<sup>30,o</sup>, S. Neubert [ID](#)<sup>18</sup>, N. Neufeld [ID](#)<sup>50</sup>,  
 P. Neustroev [ID](#)<sup>44</sup>, J. Nicolini [ID](#)<sup>50</sup>, D. Nicotra [ID](#)<sup>84</sup>, E.M. Niel [ID](#)<sup>15</sup>, N. Nikitin [ID](#)<sup>44</sup>, L. Nisi [ID](#)<sup>19</sup>,  
 Q. Niu [ID](#)<sup>75</sup>, P. Nogarolli [ID](#)<sup>3</sup>, P. Nogga [ID](#)<sup>18</sup>, C. Normand [ID](#)<sup>56</sup>, J. Novoa Fernandez [ID](#)<sup>48</sup>, G. Nowak [ID](#)<sup>67</sup>,  
 C. Nunez [ID](#)<sup>88</sup>, H.N. Nur [ID](#)<sup>61</sup>, R.H. O’Neil [ID](#)<sup>50</sup>, A. Oblakowska-Mucha [ID](#)<sup>40</sup>, V. Obraztsov [ID](#)<sup>44</sup>,  
 T. Oeser [ID](#)<sup>17</sup>, A. Okhotnikov [ID](#)<sup>44</sup>, O. Okhrimenko [ID](#)<sup>54</sup>, R. Oldeman [ID](#)<sup>32,l</sup>, F. Oliva [ID](#)<sup>60,50</sup>,  
 E. Olivart Pino [ID](#)<sup>46</sup>, M. Olocco [ID](#)<sup>19</sup>, J.S. Ordonez Soto [ID](#)<sup>11</sup>, D. Osthus [ID](#)<sup>19</sup>,  
 J.M. Otalora Goicochea [ID](#)<sup>3</sup>, P. Owen [ID](#)<sup>52</sup>, A. Oyanguren [ID](#)<sup>49</sup>, O. Ozcelik [ID](#)<sup>50</sup>, F. Paciolla [ID](#)<sup>35,w</sup>,  
 A. Padee [ID](#)<sup>42</sup>, K.O. Padeken [ID](#)<sup>18</sup>, B. Pagare [ID](#)<sup>48</sup>, T. Pajero [ID](#)<sup>50</sup>, A. Palano [ID](#)<sup>24</sup>, L. Palini [ID](#)<sup>30</sup>,  
 M. Palutan [ID](#)<sup>28</sup>, C. Pan [ID](#)<sup>76</sup>, X. Pan [ID](#)<sup>4,d</sup>, S. Panebianco [ID](#)<sup>12</sup>, S. Paniskaki [ID](#)<sup>50,33</sup>, G. Panshin [ID](#)<sup>5</sup>,  
 L. Paolucci [ID](#)<sup>64</sup>, A. Papanestis [ID](#)<sup>59</sup>, M. Pappagallo [ID](#)<sup>24,i</sup>, L.L. Pappalardo [ID](#)<sup>26</sup>, C. Pappenheimer [ID](#)<sup>67</sup>,  
 C. Parkes [ID](#)<sup>64</sup>, D. Parmar [ID](#)<sup>80</sup>, G. Passaleva [ID](#)<sup>27</sup>, D. Passaro [ID](#)<sup>35,50,t</sup>, A. Pastore [ID](#)<sup>24</sup>, M. Patel [ID](#)<sup>63</sup>,  
 J. Patoc [ID](#)<sup>65</sup>, C. Patrignani [ID](#)<sup>25,k</sup>, A. Paul [ID](#)<sup>70</sup>, C.J. Pawley [ID](#)<sup>84</sup>, A. Pellegrino [ID](#)<sup>38</sup>, J. Peng [ID](#)<sup>5,7</sup>,  
 X. Peng [ID](#)<sup>75</sup>, M. Pepe Altarelli [ID](#)<sup>28</sup>, S. Perazzini [ID](#)<sup>25</sup>, D. Pereima [ID](#)<sup>44</sup>, H. Pereira Da Costa [ID](#)<sup>69</sup>,  
 M. Pereira Martinez [ID](#)<sup>48</sup>, A. Pereiro Castro [ID](#)<sup>48</sup>, C. Perez [ID](#)<sup>47</sup>, P. Perret [ID](#)<sup>11</sup>, A. Perrevoort [ID](#)<sup>83</sup>,  
 A. Perro [ID](#)<sup>50,13</sup>, M.J. Peters [ID](#)<sup>67</sup>, K. Petridis [ID](#)<sup>56</sup>, A. Petrolini [ID](#)<sup>29,n</sup>, S. Pezzulo [ID](#)<sup>29,n</sup>, J.P. Pfaller [ID](#)<sup>67</sup>,  
 H. Pham [ID](#)<sup>70</sup>, L. Pica [ID](#)<sup>35,t</sup>, M. Piccini [ID](#)<sup>34</sup>, L. Piccolo [ID](#)<sup>32</sup>, B. Pietrzyk [ID](#)<sup>10</sup>, G. Pietrzyk [ID](#)<sup>14</sup>,  
 R.N. Pilato [ID](#)<sup>62</sup>, D. Pinci [ID](#)<sup>36</sup>, F. Pisani [ID](#)<sup>50</sup>, M. Pizzichemi [ID](#)<sup>31,50,p</sup>, V.M. Placinta [ID](#)<sup>43</sup>,  
 M. Plo Casasus [ID](#)<sup>48</sup>, T. Poeschl [ID](#)<sup>50</sup>, F. Polci [ID](#)<sup>16</sup>, M. Poli Lener [ID](#)<sup>28</sup>, A. Poluektov [ID](#)<sup>13</sup>,  
 N. Polukhina [ID](#)<sup>44</sup>, I. Polyakov [ID](#)<sup>64</sup>, E. Polycarpo [ID](#)<sup>3</sup>, S. Ponce [ID](#)<sup>50</sup>, D. Popov [ID](#)<sup>7,50</sup>, K. Popp [ID](#)<sup>19</sup>,  
 S. Poslavskii [ID](#)<sup>44</sup>, K. Prasanth [ID](#)<sup>60</sup>, C. Prouve [ID](#)<sup>45</sup>, D. Provenzano [ID](#)<sup>32,50,l</sup>, V. Pugatch [ID](#)<sup>54</sup>,  
 A. Puicercus Gomez [ID](#)<sup>50</sup>, G. Punzi [ID](#)<sup>35,u</sup>, J.R. Pybus [ID](#)<sup>69</sup>, Q.Q. Qian [ID](#)<sup>6</sup>, W. Qian [ID](#)<sup>7</sup>, N. Qin [ID](#)<sup>4,d</sup>,  
 R. Quagliani [ID](#)<sup>50</sup>, R.I. Rabadan Trejo [ID](#)<sup>58</sup>, R. Racz [ID](#)<sup>82</sup>, J.H. Rademacker [ID](#)<sup>56</sup>,  
 M. Ramírez García [ID](#)<sup>88</sup>, M. Rama [ID](#)<sup>35</sup>, V. Ramos De Oliveira [ID](#)<sup>71</sup>, M. Ramos Pernas [ID](#)<sup>58</sup>,  
 M.S. Rangel [ID](#)<sup>3</sup>, F. Ratnikov [ID](#)<sup>44,44</sup>, G. Raven [ID](#)<sup>39</sup>, M. Rebollo De Miguel [ID](#)<sup>49</sup>, F. Redi [ID](#)<sup>30,j</sup>,  
 J. Reich [ID](#)<sup>56</sup>, F. Reiss [ID](#)<sup>20</sup>, Z. Ren [ID](#)<sup>7</sup>, P.K. Resmi [ID](#)<sup>65</sup>, M. Ribalda Galvez [ID](#)<sup>46</sup>, R. Ribatti [ID](#)<sup>51</sup>,  
 G. Ricart [ID](#)<sup>15,12</sup>, D. Riccardi [ID](#)<sup>35,t</sup>, S. Ricciardi [ID](#)<sup>59</sup>, K. Richardson [ID](#)<sup>66</sup>, M. Richardson-Slipper [ID](#)<sup>57</sup>,  
 F. Riehn [ID](#)<sup>19</sup>, K. Rinnert [ID](#)<sup>62</sup>, P. Robbe [ID](#)<sup>14,50</sup>, G. Robertson [ID](#)<sup>61</sup>, E. Rodrigues [ID](#)<sup>62</sup>,  
 A. Rodriguez Alvarez [ID](#)<sup>46</sup>, E. Rodriguez Fernandez [ID](#)<sup>48</sup>, J.A. Rodriguez Lopez [ID](#)<sup>78</sup>,  
 E. Rodriguez Rodriguez [ID](#)<sup>50</sup>, J. Roensch [ID](#)<sup>19</sup>, A. Rogachev [ID](#)<sup>44</sup>, A. Rogovskiy [ID](#)<sup>59</sup>, D.L. Rolf [ID](#)<sup>19</sup>,  
 P. Roloff [ID](#)<sup>50</sup>, V. Romanovskiy [ID](#)<sup>67</sup>, A. Romero Vidal [ID](#)<sup>48</sup>, G. Romolini [ID](#)<sup>26,50</sup>, F. Ronchetti [ID](#)<sup>51</sup>,  
 T. Rong [ID](#)<sup>6</sup>, M. Rotondo [ID](#)<sup>28</sup>, S.R. Roy [ID](#)<sup>22</sup>, M.S. Rudolph [ID](#)<sup>70</sup>, M. Ruiz Diaz [ID](#)<sup>22</sup>,  
 R.A. Ruiz Fernandez [ID](#)<sup>48</sup>, J. Ruiz Vidal [ID](#)<sup>84</sup>, J.J. Saavedra-Arias [ID](#)<sup>9</sup>, J.J. Saborido Silva [ID](#)<sup>48</sup>,  
 S.E.R. Sacha Emile R. [ID](#)<sup>50</sup>, N. Sagidova [ID](#)<sup>44</sup>, D. Sahoo [ID](#)<sup>81</sup>, N. Sahoo [ID](#)<sup>55</sup>, B. Saitta [ID](#)<sup>32</sup>,  
 M. Salomoni [ID](#)<sup>31,50,p</sup>, I. Sanderswood [ID](#)<sup>49</sup>, R. Santacesaria [ID](#)<sup>36</sup>, C. Santamarina Rios [ID](#)<sup>48</sup>,  
 M. Santimaria [ID](#)<sup>28</sup>, L. Santoro [ID](#)<sup>2</sup>, E. Santovetti [ID](#)<sup>37</sup>, A. Saputi [ID](#)<sup>26,50</sup>, D. Saranin [ID](#)<sup>44</sup>,  
 A. Sarnatskiy [ID](#)<sup>83</sup>, G. Sarpis [ID](#)<sup>50</sup>, M. Sarpis [ID](#)<sup>82</sup>, C. Satriano [ID](#)<sup>36</sup>, A. Satta [ID](#)<sup>37</sup>, M. Saur [ID](#)<sup>75</sup>,  
 D. Savrina [ID](#)<sup>44,44</sup>, H. Sazak [ID](#)<sup>17</sup>, F. Sborzacchi [ID](#)<sup>50,28</sup>, A. Scarabotto [ID](#)<sup>19</sup>, S. Schael [ID](#)<sup>17</sup>, S. Scherl [ID](#)<sup>62</sup>,

M. Schiller [ID](#)<sup>22</sup>, H. Schindler [ID](#)<sup>50</sup>, M. Schmelling [ID](#)<sup>21</sup>, B. Schmidt [ID](#)<sup>50</sup>, N. Schmidt [ID](#)<sup>69</sup>,  
 S. Schmitt [ID](#)<sup>66</sup>, H. Schmitz<sup>18</sup>, O. Schneider [ID](#)<sup>51</sup>, A. Schopper [ID](#)<sup>63</sup>, N. Schulte [ID](#)<sup>19</sup>, M.H. Schune [ID](#)<sup>14</sup>,  
 G. Schwering [ID](#)<sup>17</sup>, B. Sciascia [ID](#)<sup>28</sup>, A. Sciuccati [ID](#)<sup>50</sup>, G. Scriven [ID](#)<sup>84</sup>, I. Segal [ID](#)<sup>80</sup>, S. Sellam [ID](#)<sup>48</sup>,  
 A. Semennikov [ID](#)<sup>44</sup>, T. Senger [ID](#)<sup>52</sup>, M. Senghi Soares [ID](#)<sup>39</sup>, A. Sergi [ID](#)<sup>29,n</sup>, N. Serra [ID](#)<sup>52</sup>, L. Sestini [ID](#)<sup>27</sup>,  
 A. Seuthe [ID](#)<sup>19</sup>, B. Sevilla Sanjuan [ID](#)<sup>47</sup>, Y. Shang [ID](#)<sup>6</sup>, D.M. Shangase [ID](#)<sup>88</sup>, M. Shapkin [ID](#)<sup>44</sup>,  
 R.S. Sharma [ID](#)<sup>70</sup>, I. Shchemerov [ID](#)<sup>44</sup>, L. Shchutska [ID](#)<sup>51</sup>, T. Shears [ID](#)<sup>62</sup>, L. Shekhtman [ID](#)<sup>44,44</sup>,  
 Z. Shen [ID](#)<sup>38</sup>, S. Sheng [ID](#)<sup>5,7</sup>, V. Shevchenko [ID](#)<sup>44</sup>, B. Shi [ID](#)<sup>7</sup>, Q. Shi [ID](#)<sup>7</sup>, W.S. Shi [ID](#)<sup>74</sup>, Y. Shimizu [ID](#)<sup>14</sup>,  
 E. Shmanin [ID](#)<sup>25</sup>, R. Shorkin [ID](#)<sup>44</sup>, J.D. Shupperd [ID](#)<sup>70</sup>, R. Silva Coutinho [ID](#)<sup>2</sup>, G. Simi [ID](#)<sup>33,r</sup>,  
 S. Simone [ID](#)<sup>24,i</sup>, M. Singha [ID](#)<sup>81</sup>, N. Skidmore [ID](#)<sup>58</sup>, T. Skwarnicki [ID](#)<sup>70</sup>, M.W. Slater [ID](#)<sup>55</sup>, E. Smith [ID](#)<sup>66</sup>,  
 K. Smith [ID](#)<sup>69</sup>, M. Smith [ID](#)<sup>63</sup>, L. Soares Lavra [ID](#)<sup>60</sup>, M.D. Sokoloff [ID](#)<sup>67</sup>, F.J.P. Soler [ID](#)<sup>61</sup>,  
 A. Solomin [ID](#)<sup>56</sup>, A. Solovev [ID](#)<sup>44</sup>, K. Solovieva [ID](#)<sup>20</sup>, N.S. Sommerfeld [ID](#)<sup>18</sup>, R. Song [ID](#)<sup>1</sup>, Y. Song [ID](#)<sup>51</sup>,  
 Y. Song [ID](#)<sup>4,d</sup>, Y.S. Song [ID](#)<sup>6</sup>, F.L. Souza De Almeida [ID](#)<sup>46</sup>, B. Souza De Paula [ID](#)<sup>3</sup>, K.M. Sowa [ID](#)<sup>40</sup>,  
 E. Spadaro Norella [ID](#)<sup>29,n</sup>, E. Spedicato [ID](#)<sup>25</sup>, J.G. Speer [ID](#)<sup>19</sup>, P. Spradlin [ID](#)<sup>61</sup>, F. Stagni [ID](#)<sup>50</sup>,  
 M. Stahl [ID](#)<sup>80</sup>, S. Stahl [ID](#)<sup>50</sup>, S. Stanislaus [ID](#)<sup>65</sup>, M. Stefaniak [ID](#)<sup>89</sup>, E.N. Stein [ID](#)<sup>50</sup>, O. Steinkamp [ID](#)<sup>52</sup>,  
 D. Strelalina [ID](#)<sup>44</sup>, Y. Su [ID](#)<sup>7</sup>, F. Suljik [ID](#)<sup>65</sup>, J. Sun [ID](#)<sup>32</sup>, J. Sun [ID](#)<sup>64</sup>, L. Sun [ID](#)<sup>76</sup>, D. Sundfeld [ID](#)<sup>2</sup>,  
 W. Sutcliffe [ID](#)<sup>52</sup>, P. Svirha [ID](#)<sup>79</sup>, V. Svintozelskiy [ID](#)<sup>49</sup>, K. Swientek [ID](#)<sup>40</sup>, F. Swystun [ID](#)<sup>57</sup>,  
 A. Szabelski [ID](#)<sup>42</sup>, T. Szumlak [ID](#)<sup>40</sup>, S. T'Jampens [ID](#)<sup>10</sup>, Y. Tan [ID](#)<sup>4</sup>, Y. Tang [ID](#)<sup>76</sup>, Y.T. Tang [ID](#)<sup>7</sup>,  
 M.D. Tat [ID](#)<sup>22</sup>, J.A. Teixeira Jimenez [ID](#)<sup>48</sup>, A. Terentev [ID](#)<sup>44</sup>, F. Terzuoli [ID](#)<sup>35,w</sup>, F. Teubert [ID](#)<sup>50</sup>,  
 E. Thomas [ID](#)<sup>50</sup>, D.J.D. Thompson [ID](#)<sup>55</sup>, A.R. Thomson-Strong [ID](#)<sup>60</sup>, H. Tilquin [ID](#)<sup>63</sup>, V. Tisserand [ID](#)<sup>11</sup>,  
 M. Tobin [ID](#)<sup>5,50</sup>, T.T. Todorov [ID](#)<sup>20</sup>, L. Tomassetti [ID](#)<sup>26,m</sup>, G. Tonani [ID](#)<sup>30</sup>, X. Tong [ID](#)<sup>6</sup>, T. Tork [ID](#)<sup>30</sup>,  
 D. Torres Machado [ID](#)<sup>2</sup>, L. Toscano [ID](#)<sup>19</sup>, D.Y. Tou [ID](#)<sup>4,d</sup>, C. Trippel [ID](#)<sup>47</sup>, G. Tuci [ID](#)<sup>22</sup>, N. Tuning [ID](#)<sup>38</sup>,  
 L.H. Uecker [ID](#)<sup>22</sup>, A. Ukleja [ID](#)<sup>40</sup>, D.J. Unverzagt [ID](#)<sup>22</sup>, A. Upadhyay [ID](#)<sup>50</sup>, B. Urbach [ID](#)<sup>60</sup>,  
 A. Usachov [ID](#)<sup>38</sup>, A. Ustyuzhanin [ID](#)<sup>44</sup>, U. Uwer [ID](#)<sup>22</sup>, V. Vagnoni [ID](#)<sup>25,50</sup>, V. Valcarce Cadenas [ID](#)<sup>48</sup>,  
 G. Valenti [ID](#)<sup>25</sup>, N. Valls Canudas [ID](#)<sup>50</sup>, J. van Eldik [ID](#)<sup>50</sup>, H. Van Hecke [ID](#)<sup>69</sup>, E. van Herwijnen [ID](#)<sup>63</sup>,  
 C.B. Van Hulse [ID](#)<sup>48,z</sup>, R. Van Laak [ID](#)<sup>51</sup>, M. van Veghel [ID](#)<sup>84</sup>, G. Vasquez [ID](#)<sup>52</sup>, R. Vazquez Gomez [ID](#)<sup>46</sup>,  
 P. Vazquez Regueiro [ID](#)<sup>48</sup>, S. Vecchi [ID](#)<sup>26</sup>, J. Velilla Serna [ID](#)<sup>49</sup>, J.J. Velthuis [ID](#)<sup>56</sup>, M. Veltri [ID](#)<sup>27,x</sup>,  
 A. Venkateswaran [ID](#)<sup>51</sup>, M. Verdoglia [ID](#)<sup>32</sup>, M. Vesterinen [ID](#)<sup>58</sup>, W. Vetens [ID](#)<sup>70</sup>, D. Vico Benet [ID](#)<sup>65</sup>,  
 P. Vidrier Villalba [ID](#)<sup>46</sup>, M. Vieites Diaz [ID](#)<sup>48</sup>, X. Vilasis-Cardona [ID](#)<sup>47</sup>, E. Vilella Figueras [ID](#)<sup>62</sup>,  
 A. Villa [ID](#)<sup>25</sup>, P. Vincent [ID](#)<sup>16</sup>, B. Vivacqua [ID](#)<sup>3</sup>, F.C. Volle [ID](#)<sup>55</sup>, D. vom Bruch [ID](#)<sup>13</sup>, N. Voropaev [ID](#)<sup>44</sup>,  
 K. Vos [ID](#)<sup>84</sup>, C. Vrahas [ID](#)<sup>60</sup>, C. Vázquez Sierra [ID](#)<sup>45</sup>, J. Wagner [ID](#)<sup>19</sup>, J. Walsh [ID](#)<sup>35</sup>, E.J. Walton [ID](#)<sup>1,58</sup>,  
 G. Wan [ID](#)<sup>6</sup>, A. Wang [ID](#)<sup>7</sup>, B. Wang [ID](#)<sup>5</sup>, C. Wang [ID](#)<sup>22</sup>, G. Wang [ID](#)<sup>8</sup>, H. Wang [ID](#)<sup>75</sup>, J. Wang [ID](#)<sup>7</sup>,  
 J. Wang [ID](#)<sup>5</sup>, J. Wang [ID](#)<sup>4,d</sup>, J. Wang [ID](#)<sup>76</sup>, M. Wang [ID](#)<sup>50</sup>, N.W. Wang [ID](#)<sup>7</sup>, R. Wang [ID](#)<sup>56</sup>, X. Wang [ID](#)<sup>8</sup>,  
 X. Wang [ID](#)<sup>74</sup>, X.W. Wang [ID](#)<sup>63</sup>, Y. Wang [ID](#)<sup>77</sup>, Y. Wang [ID](#)<sup>6</sup>, Y.H. Wang [ID](#)<sup>75</sup>, Z. Wang [ID](#)<sup>14</sup>,  
 Z. Wang [ID](#)<sup>30</sup>, J.A. Ward [ID](#)<sup>58,1</sup>, M. Waterlaet [ID](#)<sup>50</sup>, N.K. Watson [ID](#)<sup>55</sup>, D. Websdale [ID](#)<sup>63</sup>, Y. Wei [ID](#)<sup>6</sup>,  
 Z. Weida [ID](#)<sup>7</sup>, J. Wendel [ID](#)<sup>45</sup>, B.D.C. Westhenry [ID](#)<sup>56</sup>, C. White [ID](#)<sup>57</sup>, M. Whitehead [ID](#)<sup>61</sup>, E. Whiter [ID](#)<sup>55</sup>,  
 A.R. Wiederhold [ID](#)<sup>64</sup>, D. Wiedner [ID](#)<sup>19</sup>, M.A. Wiegertjes [ID](#)<sup>38</sup>, C. Wild [ID](#)<sup>65</sup>, G. Wilkinson [ID](#)<sup>65,50</sup>,  
 M.K. Wilkinson [ID](#)<sup>67</sup>, M. Williams [ID](#)<sup>66</sup>, M.J. Williams [ID](#)<sup>50</sup>, M.R.J. Williams [ID](#)<sup>60</sup>, R. Williams [ID](#)<sup>57</sup>,  
 S. Williams [ID](#)<sup>56</sup>, Z. Williams [ID](#)<sup>56</sup>, F.F. Wilson [ID](#)<sup>59</sup>, M. Winn [ID](#)<sup>12</sup>, W. Wislicki [ID](#)<sup>42</sup>, M. Witek [ID](#)<sup>41</sup>,  
 L. Witola [ID](#)<sup>19</sup>, T. Wolf [ID](#)<sup>22</sup>, E. Wood [ID](#)<sup>57</sup>, G. Wormser [ID](#)<sup>14</sup>, S.A. Wotton [ID](#)<sup>57</sup>, H. Wu [ID](#)<sup>70</sup>, J. Wu [ID](#)<sup>8</sup>,  
 X. Wu [ID](#)<sup>76</sup>, Y. Wu [ID](#)<sup>6,57</sup>, Z. Wu [ID](#)<sup>7</sup>, K. Wyllie [ID](#)<sup>50</sup>, S. Xian [ID](#)<sup>74</sup>, Z. Xiang [ID](#)<sup>5</sup>, Y. Xie [ID](#)<sup>8</sup>,  
 T.X. Xing [ID](#)<sup>30</sup>, A. Xu [ID](#)<sup>35,t</sup>, L. Xu [ID](#)<sup>4,d</sup>, M. Xu [ID](#)<sup>50</sup>, Z. Xu [ID](#)<sup>50</sup>, Z. Xu [ID](#)<sup>7</sup>, Z. Xu [ID](#)<sup>5</sup>, S. Yadav [ID](#)<sup>26</sup>,  
 K. Yang [ID](#)<sup>63</sup>, X. Yang [ID](#)<sup>6</sup>, Y. Yang [ID](#)<sup>7</sup>, Y. Yang [ID](#)<sup>81</sup>, Z. Yang [ID](#)<sup>6</sup>, V. Yeroshenko [ID](#)<sup>14</sup>, H. Yeung [ID](#)<sup>64</sup>,  
 H. Yin [ID](#)<sup>8</sup>, X. Yin [ID](#)<sup>7</sup>, C.Y. Yu [ID](#)<sup>6</sup>, J. Yu [ID](#)<sup>73</sup>, X. Yuan [ID](#)<sup>5</sup>, Y Yuan [ID](#)<sup>5,7</sup>, J.A. Zamora Saa [ID](#)<sup>72</sup>,

M. Zavertyaev <sup>21</sup>, M. Zdybal <sup>41</sup>, F. Zenesini <sup>25</sup>, C. Zeng <sup>5,7</sup>, M. Zeng <sup>4,d</sup>, C. Zhang <sup>6</sup>,  
D. Zhang <sup>8</sup>, J. Zhang <sup>7</sup>, L. Zhang <sup>4,d</sup>, R. Zhang <sup>8</sup>, S. Zhang <sup>65</sup>, S. L. Zhang <sup>73</sup>, Y. Zhang <sup>6</sup>,  
Y.Z. Zhang <sup>4,d</sup>, Z. Zhang <sup>4,d</sup>, Y. Zhao <sup>22</sup>, A. Zhelezov <sup>22</sup>, S.Z. Zheng <sup>6</sup>, X.Z. Zheng <sup>4,d</sup>,  
Y. Zheng <sup>7</sup>, T. Zhou <sup>6</sup>, X. Zhou <sup>8</sup>, Y. Zhou <sup>7</sup>, V. Zhovkovska <sup>58</sup>, L.Z. Zhu <sup>7</sup>, X. Zhu <sup>4,d</sup>,  
X. Zhu <sup>8</sup>, Y. Zhu <sup>17</sup>, V. Zhukov <sup>17</sup>, J. Zhuo <sup>49</sup>, Q. Zou <sup>5,7</sup>, D. Zuliani <sup>33,r</sup>, G. Zunica <sup>28</sup>

<sup>1</sup> School of Physics and Astronomy, Monash University, Melbourne, Australia

<sup>2</sup> Centro Brasileiro de Pesquisas Físicas (CBPF), Rio de Janeiro, Brazil

<sup>3</sup> Universidade Federal do Rio de Janeiro (UFRJ), Rio de Janeiro, Brazil

<sup>4</sup> Department of Engineering Physics, Tsinghua University, Beijing, China

<sup>5</sup> Institute Of High Energy Physics (IHEP), Beijing, China

<sup>6</sup> School of Physics State Key Laboratory of Nuclear Physics and Technology, Peking University, Beijing, China

<sup>7</sup> University of Chinese Academy of Sciences, Beijing, China

<sup>8</sup> Institute of Particle Physics, Central China Normal University, Wuhan, Hubei, China

<sup>9</sup> Consejo Nacional de Rectores (CONARE), San Jose, Costa Rica

<sup>10</sup> Université Savoie Mont Blanc, CNRS, IN2P3-LAPP, Annecy, France

<sup>11</sup> Université Clermont Auvergne, CNRS/IN2P3, LPC, Clermont-Ferrand, France

<sup>12</sup> Université Paris-Saclay, Centre d'Etudes de Saclay (CEA), IRFU, Saclay, France, Gif-Sur-Yvette, France

<sup>13</sup> Aix Marseille Univ, CNRS/IN2P3, CPPM, Marseille, France

<sup>14</sup> Université Paris-Saclay, CNRS/IN2P3, IJCLab, Orsay, France

<sup>15</sup> Laboratoire Leprince-Ringuet, CNRS/IN2P3, Ecole Polytechnique, Institut Polytechnique de Paris, Palaiseau, France

<sup>16</sup> Laboratoire de Physique Nucléaire et de Hautes Énergies (LPNHE), Sorbonne Université, CNRS/IN2P3, F-75005 Paris, France

<sup>17</sup> I. Physikalisches Institut, RWTH Aachen University, Aachen, Germany

<sup>18</sup> Universität Bonn — Helmholtz-Institut für Strahlen und Kernphysik, Bonn, Germany

<sup>19</sup> Fakultät Physik, Technische Universität Dortmund, Dortmund, Germany

<sup>20</sup> Physikalisches Institut, Albert-Ludwigs-Universität Freiburg, Freiburg, Germany

<sup>21</sup> Max-Planck-Institut für Kernphysik (MPIK), Heidelberg, Germany

<sup>22</sup> Physikalisches Institut, Ruprecht-Karls-Universität Heidelberg, Heidelberg, Germany

<sup>23</sup> School of Physics, University College Dublin, Dublin, Ireland

<sup>24</sup> INFN Sezione di Bari, Bari, Italy

<sup>25</sup> INFN Sezione di Bologna, Bologna, Italy

<sup>26</sup> INFN Sezione di Ferrara, Ferrara, Italy

<sup>27</sup> INFN Sezione di Firenze, Firenze, Italy

<sup>28</sup> INFN Laboratori Nazionali di Frascati, Frascati, Italy

<sup>29</sup> INFN Sezione di Genova, Genova, Italy

<sup>30</sup> INFN Sezione di Milano, Milano, Italy

<sup>31</sup> INFN Sezione di Milano-Bicocca, Milano, Italy

<sup>32</sup> INFN Sezione di Cagliari, Monserrato, Italy

<sup>33</sup> INFN Sezione di Padova, Padova, Italy

<sup>34</sup> INFN Sezione di Perugia, Perugia, Italy

<sup>35</sup> INFN Sezione di Pisa, Pisa, Italy

<sup>36</sup> INFN Sezione di Roma La Sapienza, Roma, Italy

<sup>37</sup> INFN Sezione di Roma Tor Vergata, Roma, Italy

<sup>38</sup> Nikhef National Institute for Subatomic Physics, Amsterdam, Netherlands

<sup>39</sup> Nikhef National Institute for Subatomic Physics and VU University Amsterdam, Amsterdam, Netherlands

<sup>40</sup> AGH — University of Krakow, Faculty of Physics and Applied Computer Science, Kraków, Poland

<sup>41</sup> Henryk Niewodniczanski Institute of Nuclear Physics Polish Academy of Sciences, Kraków, Poland

<sup>42</sup> National Center for Nuclear Research (NCBJ), Warsaw, Poland

<sup>43</sup> Horia Hulubei National Institute of Physics and Nuclear Engineering, Bucharest-Magurele, Romania

- <sup>44</sup> Authors affiliated with an institute formerly covered by a cooperation agreement with CERN.
- <sup>45</sup> Universidade da Coruña, A Coruña, Spain
- <sup>46</sup> ICCUB, Universitat de Barcelona, Barcelona, Spain
- <sup>47</sup> La Salle, Universitat Ramon Llull, Barcelona, Spain
- <sup>48</sup> Instituto Galego de Física de Altas Enerxías (IGFAE), Universidade de Santiago de Compostela, Santiago de Compostela, Spain
- <sup>49</sup> Instituto de Física Corpuscular, Centro Mixto Universidad de Valencia — CSIC, Valencia, Spain
- <sup>50</sup> European Organization for Nuclear Research (CERN), Geneva, Switzerland
- <sup>51</sup> Institute of Physics, Ecole Polytechnique Fédérale de Lausanne (EPFL), Lausanne, Switzerland
- <sup>52</sup> Physik-Institut, Universität Zürich, Zürich, Switzerland
- <sup>53</sup> NSC Kharkiv Institute of Physics and Technology (NSC KIPT), Kharkiv, Ukraine
- <sup>54</sup> Institute for Nuclear Research of the National Academy of Sciences (KINR), Kyiv, Ukraine
- <sup>55</sup> School of Physics and Astronomy, University of Birmingham, Birmingham, U.K.
- <sup>56</sup> H.H. Wills Physics Laboratory, University of Bristol, Bristol, U.K.
- <sup>57</sup> Cavendish Laboratory, University of Cambridge, Cambridge, U.K.
- <sup>58</sup> Department of Physics, University of Warwick, Coventry, U.K.
- <sup>59</sup> STFC Rutherford Appleton Laboratory, Didcot, U.K.
- <sup>60</sup> School of Physics and Astronomy, University of Edinburgh, Edinburgh, U.K.
- <sup>61</sup> School of Physics and Astronomy, University of Glasgow, Glasgow, U.K.
- <sup>62</sup> Oliver Lodge Laboratory, University of Liverpool, Liverpool, U.K.
- <sup>63</sup> Imperial College London, London, U.K.
- <sup>64</sup> Department of Physics and Astronomy, University of Manchester, Manchester, U.K.
- <sup>65</sup> Department of Physics, University of Oxford, Oxford, U.K.
- <sup>66</sup> Massachusetts Institute of Technology, Cambridge, MA, United States
- <sup>67</sup> University of Cincinnati, Cincinnati, OH, United States
- <sup>68</sup> University of Maryland, College Park, MD, United States
- <sup>69</sup> Los Alamos National Laboratory (LANL), Los Alamos, NM, United States
- <sup>70</sup> Syracuse University, Syracuse, NY, United States
- <sup>71</sup> Pontificia Universidade Católica do Rio de Janeiro (PUC-Rio),<sup>aa</sup> Rio de Janeiro, Brazil
- <sup>72</sup> Universidad Andres Bello,<sup>ab</sup> Santiago, Chile
- <sup>73</sup> School of Physics and Electronics,<sup>ac</sup> Hunan University, Changsha City, China
- <sup>74</sup> State Key Laboratory of Nuclear Physics and Technology,<sup>ad</sup> South China Normal University, Guangzhou, China., Guangzhou, China
- <sup>75</sup> Lanzhou University,<sup>ae</sup> Lanzhou, China
- <sup>76</sup> School of Physics and Technology,<sup>af</sup> Wuhan University, Wuhan, China
- <sup>77</sup> Henan Normal University,<sup>ag</sup> Xinxiang, China
- <sup>78</sup> Departamento de Física,<sup>ah</sup> Universidad Nacional de Colombia, Bogota, Colombia
- <sup>79</sup> Institute of Physics of the Czech Academy of Sciences,<sup>ai</sup> Prague, Czech Republic
- <sup>80</sup> Ruhr Universitaet Bochum,<sup>aj</sup> Fakultae f. Physik und Astronomie, Bochum, Germany
- <sup>81</sup> Eotvos Lorand University,<sup>ak</sup> Budapest, Hungary
- <sup>82</sup> Faculty of Physics,<sup>al</sup> Vilnius University, Vilnius, Lithuania
- <sup>83</sup> Van Swinderen Institute,<sup>am</sup> University of Groningen, Groningen, Netherlands
- <sup>84</sup> Universiteit Maastricht,<sup>an</sup> Maastricht, Netherlands
- <sup>85</sup> Tadeusz Kosciuszko Cracow University of Technology,<sup>ao</sup> Cracow, Poland
- <sup>86</sup> Department of Physics and Astronomy,<sup>ap</sup> Uppsala University, Uppsala, Sweden
- <sup>87</sup> Taras Schevchenko University of Kyiv,<sup>aq</sup> Faculty of Physics, Kyiv, Ukraine
- <sup>88</sup> University of Michigan,<sup>ar</sup> Ann Arbor, MI, United States
- <sup>89</sup> Ohio State University,<sup>as</sup> Columbus, United States

<sup>a</sup> Associated to: Universidade Estadual de Campinas (UNICAMP), Campinas, Brazil

<sup>b</sup> Associated to: Centro Federal de Educação Tecnológica Celso Suckow da Fonseca, Rio De Janeiro, Brazil

<sup>c</sup> Associated to: Department of Physics and Astronomy, University of Victoria, Victoria, Canada

<sup>d</sup> Associated to: Center for High Energy Physics, Tsinghua University, Beijing, China

- <sup>e</sup> Associated to: *Hangzhou Institute for Advanced Study, UCAS, Hangzhou, China*
- <sup>f</sup> Associated to: *LIP6, Sorbonne Université, Paris, France*
- <sup>g</sup> Associated to: *Lamarr Institute for Machine Learning and Artificial Intelligence, Dortmund, Germany*
- <sup>h</sup> Associated to: *Universidad Nacional Autónoma de Honduras, Tegucigalpa, Honduras*
- <sup>i</sup> Associated to: *Università di Bari, Bari, Italy*
- <sup>j</sup> Associated to: *Università di Bergamo, Bergamo, Italy*
- <sup>k</sup> Associated to: *Università di Bologna, Bologna, Italy*
- <sup>l</sup> Associated to: *Università di Cagliari, Cagliari, Italy*
- <sup>m</sup> Associated to: *Università di Ferrara, Ferrara, Italy*
- <sup>n</sup> Associated to: *Università di Genova, Genova, Italy*
- <sup>o</sup> Associated to: *Università degli Studi di Milano, Milano, Italy*
- <sup>p</sup> Associated to: *Università degli Studi di Milano-Bicocca, Milano, Italy*
- <sup>q</sup> Associated to: *Università di Modena e Reggio Emilia, Modena, Italy*
- <sup>r</sup> Associated to: *Università di Padova, Padova, Italy*
- <sup>s</sup> Associated to: *Università di Perugia, Perugia, Italy*
- <sup>t</sup> Associated to: *Scuola Normale Superiore, Pisa, Italy*
- <sup>u</sup> Associated to: *Università di Pisa, Pisa, Italy*
- <sup>v</sup> Associated to: *Università di Roma Tor Vergata, Roma, Italy*
- <sup>w</sup> Associated to: *Università di Siena, Siena, Italy*
- <sup>x</sup> Associated to: *Università di Urbino, Urbino, Italy*
- <sup>y</sup> Associated to: *Universidad de Ingeniería y Tecnología (UTEC), Lima, Peru*
- <sup>z</sup> Associated to: *Universidad de Alcalá, Alcalá de Henares, Spain*
- <sup>aa</sup> Associated to 3
- <sup>ab</sup> Associated to 52
- <sup>ac</sup> Associated to 8
- <sup>ad</sup> Associated to 4
- <sup>ae</sup> Associated to 5
- <sup>af</sup> Associated to 4
- <sup>ag</sup> Associated to 8
- <sup>ah</sup> Associated to 16
- <sup>ai</sup> Associated to 64
- <sup>aj</sup> Associated to 19
- <sup>ak</sup> Associated to 50
- <sup>al</sup> Associated to 20
- <sup>am</sup> Associated to 38
- <sup>an</sup> Associated to 38
- <sup>ao</sup> Associated to 41
- <sup>ap</sup> Associated to 61
- <sup>aq</sup> Associated to 14
- <sup>ar</sup> Associated to 70
- <sup>as</sup> Associated to 69