



Observation of the semileptonic decay $B^+ \rightarrow p\bar{p}\mu^+\nu_\mu$

LHCb collaboration[†]

Abstract

The Cabibbo-suppressed semileptonic decay $B^+ \rightarrow p\bar{p}\mu^+\nu_\mu$ is observed for the first time using a sample of pp collisions corresponding to an integrated luminosity of 1.0, 2.0 and 1.9 fb⁻¹ at centre-of-mass energies of 7, 8 and 13 TeV, respectively. The differential branching fraction is measured as a function of the $p\bar{p}$ invariant mass using the decay mode $B^+ \rightarrow (J/\psi \rightarrow \mu^+\mu^-)K^+$ for normalisation. The total branching fraction is measured to be

$$\mathcal{B}(B^+ \rightarrow p\bar{p}\mu^+\nu_\mu) = (5.27_{-0.24}^{+0.23} \pm 0.21 \pm 0.15) \times 10^{-6},$$

where the first uncertainty is statistical, the second systematic and the third is from the uncertainty on the normalisation branching fraction.

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[†]Authors are listed at the end of this paper.

1 Introduction

Studies of semileptonic B meson decays have recently generated interest due to a number of anomalies in experimental results. Measurements of the observables $R(D)$ and $R(D^*)$ [1–6] have shown hints of lepton non-universality with a combined significance of over 3σ [7]. To probe the flavour structure of possible new physics contributions to these decay modes, it is desirable to make analogous measurements for decays involving different quark-level processes, such as $b \rightarrow u$ transitions. To that end, the decay mode $B^+ \rightarrow p\bar{p}l^+\nu_l$ is promising experimentally, particularly when performing the measurement at a hadron collider. The requirement of a proton anti-proton pair in the final state should significantly reduce combinatorial background, which would otherwise be significant for final states with pions.

Semileptonic decays of B mesons to a final state containing multiple baryons are as yet unobserved. A theoretical model of $B^+ \rightarrow p\bar{p}l^+\nu_l$ decays has been constructed with perturbative QCD (pQCD) [8]. This model is based on studies of several fully hadronic $B \rightarrow Y\bar{Y}'X$ decays where Y and \bar{Y}' represent baryons and X one or more mesons. By fitting the angular distributions and decay rates of the hadronic modes [9, 10] the authors of these papers estimate the differential rate of the $B^+ \rightarrow p\bar{p}l^+\nu_l$ decays. They also predict the total branching fraction of the $B^+ \rightarrow p\bar{p}l^+\nu_l$ decay to be $(1.04 \pm 0.38) \times 10^{-4}$ for $l = \mu, e$ leptons. This prediction motivated a search by the Belle collaboration for $B^+ \rightarrow p\bar{p}l^+\nu_l$ decays [11], who found evidence for the $B^+ \rightarrow p\bar{p}e^+\nu_e$ decay mode with 3.0σ significance. The branching fraction was measured to be $(8.2^{+3.7}_{-3.2} \pm 0.6) \times 10^{-6}$, two orders of magnitude smaller than the prediction.

The measurements of the fully hadronic modes show features that merit further investigation. It is surprising that the branching fractions of decays of B mesons to final states comprising only two baryons are suppressed compared to those of two baryons and one or more extra final state particles [12]. For example, the branching fraction of $B^0 \rightarrow p\bar{p}$ is two orders of magnitude smaller than that of the similar $B^0 \rightarrow p\bar{p}\pi^+\pi^-$ decay [12, 13]. Furthermore, the invariant mass distributions of the baryon pair in $B \rightarrow Y\bar{Y}'X$ decays show the so-called threshold enhancement effect. This is a characteristic shape that peaks at low values [14–17]. Understanding the dynamics that leads to such features is difficult in fully hadronic decays, due to the interaction of the two baryons with the extra hadrons. It is therefore desirable to study semileptonic decays, such as $B^+ \rightarrow p\bar{p}\mu^+\nu_\mu$, where such final-state interactions are absent.

In this paper, the first observation of the decay $B^+ \rightarrow p\bar{p}\mu^+\nu_\mu$ is presented. As the dynamics of the transition are not known, the branching fraction is measured in bins of $p\bar{p}$ invariant mass. These bins are then summed to obtain a measurement of the total branching fraction. The decay $B^+ \rightarrow J/\psi K^+$, with $J/\psi \rightarrow \mu^+\mu^-$ is chosen as the normalisation mode as it is fully reconstructed and can pass similar selection requirements to the signal. The branching fraction within a bin i is

$$\mathcal{B}_i(B^+ \rightarrow p\bar{p}\mu^+\nu_\mu) = \frac{N_i(B^+ \rightarrow p\bar{p}\mu^+\nu_\mu)}{N(B^+ \rightarrow (J/\psi \rightarrow \mu^+\mu^-)K^+)} \times \frac{\epsilon(B^+ \rightarrow (J/\psi \rightarrow \mu^+\mu^-)K^+)}{\epsilon_i(B^+ \rightarrow p\bar{p}\mu^+\nu_\mu)} \times \mathcal{B}(B^+ \rightarrow (J/\psi \rightarrow \mu^+\mu^-)K^+), \quad (1)$$

where $N_i(B^+ \rightarrow p\bar{p}\mu^+\nu_\mu)$ is the yield of $B^+ \rightarrow p\bar{p}\mu^+\nu_\mu$ candidates in bin i , $N(B^+ \rightarrow (J/\psi \rightarrow \mu^+\mu^-)K^+)$ is the total yield of $B^+ \rightarrow J/\psi K^+$ candidates and ϵ represents the product of the detector acceptance and the reconstruction and selection

43 efficiencies of the two modes. The branching fractions of $B^+ \rightarrow J/\psi K^+$ and $J/\psi \rightarrow \mu^+ \mu^-$
 44 decays are taken from Ref. [12].

45 The signal yields are extracted from fits to a variable called the corrected mass, which
 46 accounts for the unreconstructed neutrino in the signal decay. It is defined by [18]

$$m_{\text{corr}} = |p'_T| + \sqrt{|p'_T|^2 + m_{\text{vis}}^2}, \quad (2)$$

47 where $|p'_T|$ is defined as the magnitude of the reconstructed $p\bar{p}\mu^+$ momentum transverse
 48 to the B flight direction and m_{vis}^2 as the square of the $p\bar{p}\mu^+$ invariant mass.

49 This study uses the data collected with the LHCb detector in proton-proton collisions
 50 in 2011, 2012 and 2016. This corresponds to integrated luminosities of 1.0, 2.0 and 1.9 fb $^{-1}$
 51 at centre-of-mass energies of 7, 8 and 13 TeV, respectively. The 2011 and 2012 data sets
 52 are treated together and collectively referred as the Run 1 data set. Charge conjugate
 53 processes are implied throughout this paper.

54 2 Detector and simulation

55 The LHCb detector [19, 20] is a single-arm forward spectrometer covering the
 56 pseudorapidity range $2 < \eta < 5$, designed for the study of particles containing b or
 57 c quarks. The detector includes a high-precision tracking system consisting of a silicon-
 58 strip vertex detector surrounding the pp interaction region [21], a large-area silicon-strip
 59 detector located upstream of a dipole magnet with a bending power of about 4 Tm, and
 60 three stations of silicon-strip detectors and straw drift tubes [22, 23] placed downstream
 61 of the magnet. The tracking system provides a measurement of the momentum, p , of
 62 charged particles with a relative uncertainty that varies from 0.5% at low momentum
 63 to 1.0% at 200 GeV/ c . The minimum distance of a track to a primary vertex (PV), the
 64 impact parameter (IP), is measured with a resolution of $(15 + 29/p_T)$ μm , where p_T is
 65 the component of the momentum transverse to the beam in GeV/ c . Different types of
 66 charged hadrons are distinguished using information from two ring-imaging Cherenkov
 67 (RICH) detectors [24]. Photons, electrons and hadrons are identified by a calorimeter
 68 system consisting of scintillating-pad and preshower detectors, an electromagnetic and a
 69 hadronic calorimeter. Muons are identified by a system composed of alternating layers of
 70 iron and multiwire proportional chambers [25].

71 The online event selection is performed by a trigger [26], which consists of a hardware
 72 stage that performs some basic selection, followed by a software stage, which applies a
 73 full event reconstruction. At the first level, a track consistent with being a muon with
 74 significant p_T is required to be present in the event. Subsequently in the software stage,
 75 two tracks are required to form a secondary vertex with significant displacement from a
 76 pp interaction vertex. A multivariate algorithm [27] is used to identify vertices that are
 77 consistent with the decay of a b hadron.

78 Simulation is used to determine the efficiency of the signal mode and estimate the
 79 shapes of the signal and several backgrounds modes in the fits to the m_{corr} distribution.
 80 In the simulation, pp collisions are generated using PYTHIA [28] with a specific LHCb
 81 configuration [29]. Decays of unstable particles are described by EVTGEN [30], in which
 82 final-state radiation is generated using PHOTOS [31]. The interaction of the generated par-
 83 ticles with the detector, and its response, are implemented using the GEANT4 toolkit [32],

84 as described in Ref. [33]. The generated B meson p and p_T spectra are corrected to match
 85 the data distributions. A boosted decision tree (BDT) reweighter [34] is trained on samples
 86 of $B^+ \rightarrow J/\psi K^+$ data and simulation, independent of those used for the normalisation
 87 of the branching fraction. This is then used to correct all of the simulation used in the
 88 analysis.

89 3 Selection

90 Signal candidates are constructed from three charged tracks which are required to be
 91 of good quality and have a large IP with respect to any PV. The tracks must also have
 92 particle identification criteria consistent with their particle hypothesis. The requirement
 93 for positive proton identification in turn enforces a minimum value of p of 18 GeV/ c such
 94 that they are above the threshold for radiating in the RICH. Similarly, the muons must
 95 have p above 3 GeV/ c to propagate through the muon stations. All the tracks must have
 96 p_T larger than 1.5 GeV/ c and form a good quality vertex significantly displaced from the
 97 PV with which the candidate is associated. The signal muon must have fired the hardware
 98 trigger and the reconstructed B^+ candidate formed by the three tracks must be consistent
 99 with the object that fired the software trigger. Potential decays of η_c , J/ψ and $\psi(2S)$
 100 mesons to $p\bar{p}$ are vetoed with cuts on the $p\bar{p}$ invariant mass of ± 50 MeV/ c^2 around their
 101 respective known masses [12].

102 The selection of the $B^+ \rightarrow (J/\psi \rightarrow \mu^+\mu^-)K^+$ normalisation mode is aligned with that
 103 of the signal to reduce systematic uncertainties. The cuts on the signal protons are applied
 104 to the kaon and the muon of opposite sign ($K^+\mu^-$), with the exception of the particle
 105 identification criteria. The selection of the other muon is the same as that of the muon in
 106 the signal decay.

107 Further selection is used to reduce several sources of backgrounds relative to the signal.
 108 In total there are five variables to which selection is applied, with the chosen cuts on each
 109 optimised together. These variables, and the backgrounds targeted by them are described
 110 in the following paragraphs.

111 The largest background contribution comes from a melange of partially reconstructed
 112 decays producing two protons and a muon in the final state. It is expected that the
 113 largest among these originates in $b \rightarrow c$ quark transitions. The most pernicious is
 114 $B \rightarrow \bar{\Lambda}_c^- p \mu^+ \nu_\mu X$ decays, where X represents any number of charged or neutral pions
 115 (including none) and the $\bar{\Lambda}_c^-$ decays to a final state including one proton. The other major
 116 background arises from $B \rightarrow p\bar{p}DX$ decays, where the D meson may be of any variety
 117 (D^0 , D^+ , D^{*+} , *etc.*) and ultimately decays to a final state with a muon. The contribution
 118 of $B \rightarrow p\bar{\Lambda}_c^- X$ decays with the $\bar{\Lambda}_c^-$ decaying semileptonically is comparatively small, as
 119 the semileptonic branching fraction is dominated by $\bar{\Lambda}_c^- \rightarrow \Lambda l^- \bar{\nu}_l$ decays. The Λ baryon
 120 flies a sufficient distance within the detector before decaying such that the resulting proton
 121 is not associated with the B decay vertex. Another source of partially reconstructed
 122 background is formed of $B \rightarrow p\bar{p}\mu^+\nu_\mu X$ decays, where X denotes one or more charged
 123 or neutral pions. These decays may proceed with intermediate N^* or Δ resonances and
 124 could naively be expected to have similar branching fractions to the signal.

125 If any of these partially reconstructed decay modes produces more than three charged
 126 tracks, it can be efficiently dealt with by an isolation technique. Once a signal candidate
 127 has been constructed, the other tracks in the event close to the B decay vertex are

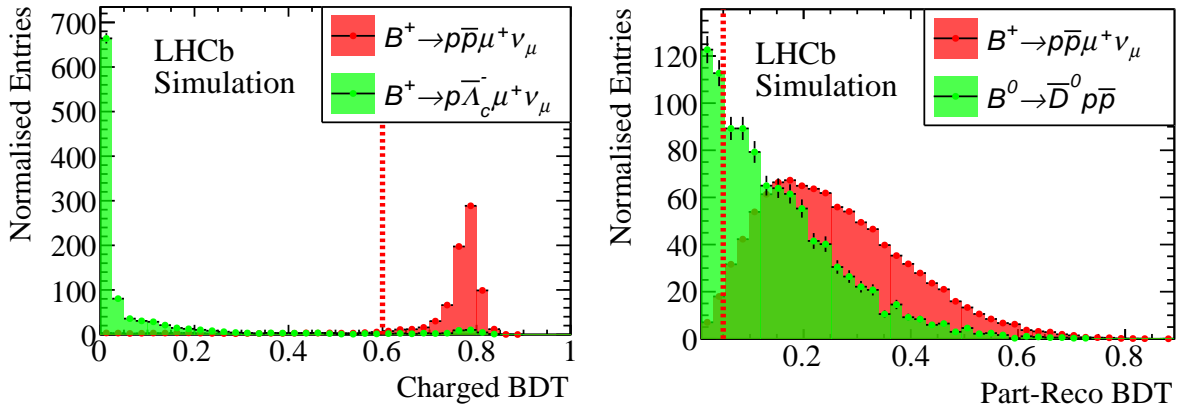


Figure 1: The result of training the (left) charged-isolation BDT and the (right) part-reco BDT. The chosen cut values are indicated by the red line. For some events there are no additional tracks near the B -decay vertex; these events are accepted and do not appear in the charged BDT output. The background samples shown here have the Λ_c^+ and \bar{D}^0 decaying via $\Lambda_c^+ \rightarrow pK^+\pi^-$ and $\bar{D}^0 \rightarrow \mu^+X$. The part-reco BDT is trained on a mixture of background modes with only one shown here for illustration.

128 examined. A BDT is used to identify those nearby tracks that can be associated with
 129 the signal candidate decay-vertex. If the candidate is truly signal, there should be few
 130 other tracks that can be associated with it and the BDT should classify them with a low
 131 score. On the other hand, the extra track(s) from a partially reconstructed decay will give
 132 a high score if such tracks are found. The isolation algorithm returns the BDT output
 133 for the four tracks most likely to have come from the B vertex. These four numbers are
 134 themselves combined into a single BDT classifier, known as the charged-isolation BDT.
 135 This BDT is trained on simulation to discriminate signal from $B^+ \rightarrow \bar{\Lambda}_c^- p\mu^+\nu_\mu$, which
 136 is expected to be the largest decay mode with extra charged tracks. The efficacy of this
 137 BDT in reducing such background is shown in Fig. 1. On its own, the indicated cut point
 138 on the charged BDT score rejects 80% of the major background decay $B \rightarrow \bar{\Lambda}_c^- p\mu^+\nu_\mu X$,
 139 whilst retaining 93% of the signal.

140 For those partially reconstructed final states with only additional neutral particles,
 141 further suppression is achieved by considering the kinematics of the decays. An additional
 142 BDT, the so called part-reco BDT, considers 11 variables: the impact parameter signifi-
 143 cance of the three final-state tracks, the $p\bar{p}$ pair and the B^+ candidate with respect to the
 144 PV; the impact parameters of the tracks with respect to the fitted B^+ decay vertex; the
 145 χ^2 of the B^+ vertex fit; the angle between the B^+ candidate momentum and displacement
 146 vectors; and the difference between the p and \bar{p} momenta. The part-reco BDT is trained
 147 on simulation in order to discriminate signal from a mixture of all the considered background
 148 modes. The result of this training is shown in Fig. 1. The selection on the part-reco BDT
 149 output removes 18% of the decays $B \rightarrow p\bar{p}D$ and keeps 98% of the signal.

150 An additional background arises from particles that are misidentified as protons
 151 (misID). The particle identification requirements on the proton tracks are therefore further
 152 tightened. The background due to the muon being another misidentified particle is
 153 considered and is reduced to a negligible amount with only a loose particle identification
 154 requirement.

155 In addition to the two BDTs and proton identification criteria, one further quantity

156 is considered. The uncertainty on the corrected mass of the candidate is powerful in
 157 improving the separation between signal and background [35]. It is calculated from the
 158 estimated uncertainties on the positions of the B^+ primary and secondary vertices, and the
 159 momenta of the tracks. Selecting lower values of the corrected-mass uncertainty produces
 160 a sharper peak for the signal mode in the corrected mass distribution, which will aid the
 161 discrimination of the signal from background in the fit to determine the yield. Therefore,
 162 in total the selection uses five quantities (two BDTs, the proton PID, the muon PID
 163 and the corrected-mass uncertainty). In order to ascertain the optimal cut point, a five
 164 dimensional grid search is performed using pseudoexperiments. Data sets are generated
 165 from the simulation samples with the expected proportions of each background. The
 166 expected signal amount is taken from the central value of the $B^+ \rightarrow p\bar{p}e^+\nu_e$ branching
 167 fraction reported by the Belle collaboration [11]. For the backgrounds, the current averages
 168 for the branching fractions are used if they have been measured. For those backgrounds
 169 that have not been measured, their branching fractions are estimated relative to that
 170 expected for the signal, accounting for different CKM matrix elements and the available
 171 phase space. For each set of cuts in the grid, the selection is applied to the simulation
 172 to estimate the efficiency for each component. The efficiency of the PID cuts on the
 173 simulation is estimated with a method based on data control samples [36]. For each data
 174 set the m_{corr} variable is generated and the expected relative uncertainty on the signal
 175 yield is found by a fit to the simulated data. These fits are not binned in $m(p\bar{p})$ but
 176 consider the entire sample as a whole. The set of cuts that produces the smallest relative
 177 uncertainty on the signal yield is chosen.

178 4 Signal and normalisation yields

179 The yields of the signal and normalisation modes are ascertained with unbinned extended
 180 maximum-likelihood fits. In the case of the normalisation mode, the invariant mass
 181 distribution of the $J/\psi K^+$ candidates is fitted. The 2011, 2012 and 2016 data sets are
 182 fitted separately and then the yields combined. These fits are shown in Fig. 2.

183 For the signal mode, the corrected mass is fitted. The distribution of this variable peaks
 184 at the known B^+ rest mass for candidates where one massless particle is not reconstructed.
 185 On the other hand, candidates from partially reconstructed decays that are missing one or
 186 more massive particles in addition to the neutrino have wide distributions concentrated at
 187 lower corrected mass values. The Run 1 and 2016 data are combined and fitted together
 188 to improve the fit stability.

189 The shapes for the signal component and contributions from partially reconstructed
 190 decays are determined using simulation. The shape of the signal probability density
 191 function (PDF) is parametrised by the sum of four bifurcated Gaussian functions with
 192 a common mean. The parameters of the Gaussian functions as well as their relative
 193 fractions are all fixed in the fit. All of the background PDFs are accounted for with kernel
 194 density estimation [37]. The shape of the proton misID background comes from a separate
 195 independent data sample in which the particle identification requirements on one of the
 196 protons have been removed. Using this data sample, the expected number of proton misID
 197 candidates can be estimated and used as a constraint in the fit. A background component
 198 due to random combinations of protons and muons, referred to as the combinatorial
 199 background, is included in the fit. A sample of data for which the B^+ decay vertex quality

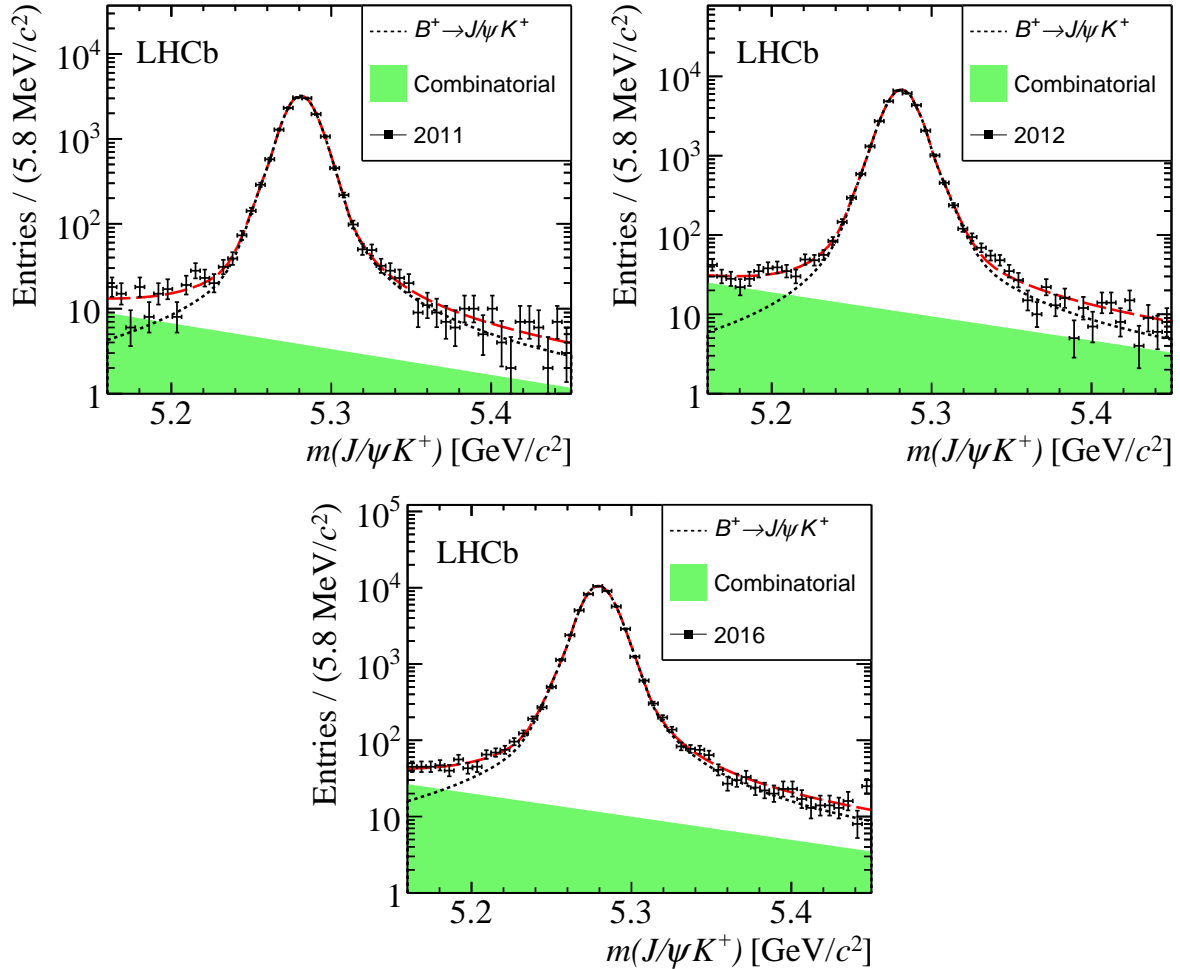


Figure 2: Distribution of $m(J/\psi K^+)$ with the fit result shown for the (top left) 2011 data, (top right) 2012 and (bottom) 2016.

200 selection has been reversed is used to estimate the shape of this background.

201 The yields of the signal, proton misID, combinatorial and partially reconstructed decays
 202 are determined by the fit, as are the relative fractions of each partially reconstructed
 203 mode. All of the fit parameters are free with the exception of the misID yield which is
 204 constrained.

205 The fit in each $m(p\bar{p})$ bin is performed independently. The m_{corr} distributions in
 206 each bin, and the resulting fits are shown in Fig. 3. In each bin the fits are validated
 207 using pseudoexperiments. An ensemble of 10^5 data sets is generated and fitted with the
 208 component yields taken from the fits to data. Some small biases on the signal yield are
 209 found and these are considered as a source of systematic uncertainty.

210 5 Efficiency

211 The efficiencies for the signal and normalisation modes to be reconstructed and selected are
 212 both assessed with simulation. Corrections are applied to account for known differences
 213 between data and simulation in the track-reconstruction efficiency [38] and the efficiency

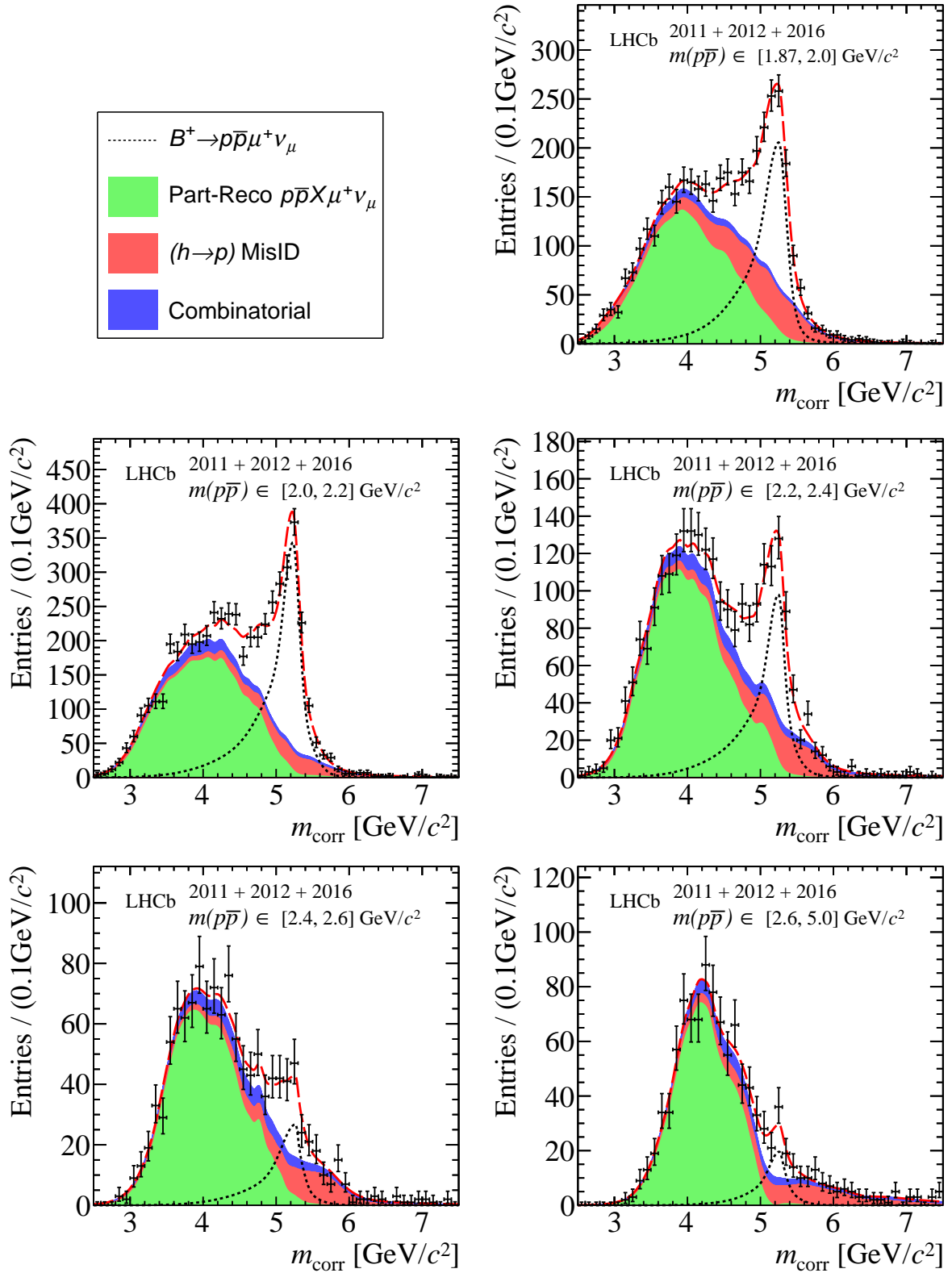


Figure 3: Distributions of m_{corr} in each $m(p\bar{p})$ bin with the fit results shown.

Table 1: The relative efficiencies for Run 1 and 2016 and the weighted combination of both.

$m(p\bar{p})_i$ [GeV/c ²]	$\epsilon(B \rightarrow p\bar{p}\mu\nu)_i/\epsilon(B \rightarrow J/\psi K)$		
	Run 1	2016	Run 1 & 2016
Bin 1: 1.87 – 2.0	0.369 ± 0.022	0.567 ± 0.032	0.477 ± 0.024
Bin 2: 2.0 – 2.2	0.366 ± 0.020	0.513 ± 0.027	0.446 ± 0.021
Bin 3: 2.2 – 2.4	0.358 ± 0.020	0.504 ± 0.026	0.438 ± 0.021
Bin 4: 2.4 – 2.6	0.361 ± 0.021	0.519 ± 0.027	0.447 ± 0.021
Bin 5: 2.6 – 5.0	0.350 ± 0.020	0.489 ± 0.024	0.426 ± 0.020

of the hardware trigger [39]. The efficiency of the particle identification requirements on each track is evaluated with data [36] and applied to the simulation.

The binning in $m(p\bar{p})$ reduces the dependence on the model of the B^+ decay when calculating the efficiency of the signal mode. However, as the selection cuts on kinematic quantities of the candidates, there is still some residual dependence on the dynamics of the decay. The simulation is therefore weighted to represent the pQCD model of Ref. [8] as the current best estimate of how the decay proceeds. This weighting corrects the distribution of the invariant mass of the $\mu^+\nu_\mu$ system. The variation of the parameters of this model is considered as a source of systematic uncertainty.

The ratio of selection efficiencies between the signal and normalisation modes in each bin of $m(p\bar{p})$ is shown in Table 1. These efficiencies are presented separately for the Run 1 and 2016 samples. They are combined to form an overall efficiency ratio, accounting for the difference in sample sizes between Run 1 and 2016. This combination is calculated using the measured B^+ production cross-sections [40] and integrated luminosities of each data set.

6 Systematic uncertainties

The systematic uncertainties can be split into two categories: those that affect the calculation of the ratio of efficiencies of the signal and normalisation modes and those that may change the determination of the signal yield in the fit. For the former, each of the corrections to the simulation contributes a source of uncertainty both from the limited sizes of the samples used to derive the corrections and from the method of deriving them. The parameters of the BDT reweighter used to correct the distributions of p and p_T of the B^+ are altered and the relative efficiencies recalculated. An additional uncertainty due to any residual differences between data and simulation is determined using the $B^+ \rightarrow J/\psi K^+$ decay mode. The difference in efficiency when cutting on the two BDTs and corrected-mass uncertainty is compared between data and simulation for the mode.

To account for the uncertainty in the correction of the simulation for the reconstruction efficiency of each track, the applied weights are varied within their uncertainties and the relative efficiencies recalculated. Similarly, an uncertainty is assessed for the particle identification weights applied to each track. The uncertainty due to the limited simulation sample sizes used to calculate the efficiencies is also included.

A further uncertainty is due to the physics model that the simulation is weighted to represent. The model affects the kinematic distributions of the daughter tracks which

247 feeds into the efficiency calculation as these distributions are cut on. Due to the model
 248 being unproven, a conservative uncertainty is taken. New sets of weights for the simulation
 249 are created that sample extreme variations of the model parameters ($\pm 5\sigma$), and for each
 250 variation the efficiency is recalculated. Despite this extreme test, the systematic due to
 251 the physics model is not dominant, which reflects the flat selection efficiency over the
 252 kinematic ranges in which the final-state particles lie within each bin of $m(p\bar{p})$. Finally,
 253 the uncertainties on the B^+ production cross-section [40] and integrated luminosities of
 254 the data samples are combined to give the systematic uncertainty on the averaging of the
 255 efficiencies when combining Run 1 and 2016.

256 In the corrected mass fit, uncertainties arise from potential variations in the shapes
 257 of the components. This variation is assessed with pseudoexperiments. Data sets are
 258 generated with the nominal fit model and then fitted with both the nominal model and
 259 an alternative. The width of the distribution of differences between the nominal and
 260 alternative fits gives the uncertainty. For those components that rely on kernel density
 261 estimators, a systematic is assessed for the choice of smoothing parameter by varying it.
 262 The uncertainty due to the choice of model for the signal shape is found by replacing the
 263 nominal PDF with one constructed with kernel density estimators. The uncertainty due
 264 to the limited sizes of the simulation samples is determined by generating new simulation
 265 from the nominal fit PDFs with the same statistics and making alternative PDFs with
 266 those samples. Similarly, an estimate of the uncertainty on the shape of the proton
 267 misID background component is assessed. For the shape of the combinatorial background
 268 component, an alternative data sample is trialled which requires the two protons to be of
 269 the same charge. Finally, the small biases in the fit noted in Sec. 4 are included.

270 A summary of the systematic uncertainties is presented in Table 2. They are given as
 271 relative uncertainties on the branching fraction with the combination accounting for the
 272 correlation of the uncertainties between the two data sets. The correlations of the total
 273 uncertainties between the bins is shown in Fig. 5 and the covariance matrix is presented
 274 in Table 4, both in the appendix.

275 7 Results

276 The fitted yields for the signal mode are presented in Table 3. The extracted yields of the
 277 normalisation channel are $14\,930 \pm 260$ for 2011, $31\,380 \pm 190$ for 2012 and $49\,270 \pm 250$
 278 for 2016. Combining these with the efficiency ratios from Sec. 5, the differential branching
 279 fraction in each $m(p\bar{p})$ bin is calculated relative to the branching fraction of the normali-
 280 sation mode. The results are presented in Table 3. The relative differential branching
 281 fractions are summed over the bins, with the correlation of the systematic uncertainties
 282 between the bins accounted for, to give the total relative branching fraction of

$$\frac{\mathcal{B}(B^+ \rightarrow p\bar{p}\mu^+\nu_\mu)}{\mathcal{B}(B^+ \rightarrow (J/\psi \rightarrow \mu^+\mu^-)K^+)} = (8.75 \pm 0.39 \pm 0.35) \times 10^{-2},$$

283 where the first uncertainty is statistical and the second systematic. Multiplying this by
 284 the current average of the normalisation branching fraction [12] leads to

$$\mathcal{B}(B^+ \rightarrow p\bar{p}\mu^+\nu_\mu) = (5.27_{-0.24}^{+0.23} \pm 0.21 \pm 0.15) \times 10^{-6},$$

285 where the third uncertainty is from the normalisation branching fraction. Finally, the
 286 absolute differential branching fraction as a function of $m(p\bar{p})$ is shown in Fig. 4, where

Table 2: A summary of the systematic uncertainties on the differential branching fractions. The contributions pertaining to the efficiency estimate are first, those for the yield extraction are below. The particle identification and tracking efficiency uncertainties are assumed to be 100% correlated between Run 1 and 2016. The total correlations of the uncertainties between the bins is shown in Fig. 5.

Source	Relative uncertainties on \mathcal{B} [%]				
	Bin 1	Bin 2	Bin 3	Bin 4	Bin 5
Kinematic reweighting	0.69	0.56	0.39	0.50	0.39
Data-simulation agreement	0.40	0.40	0.40	0.40	0.40
Tracking efficiency	2.74	2.74	2.74	2.74	2.74
Particle identification	1.01	0.68	1.30	1.05	1.67
Simulation sample size	3.63	3.18	3.15	3.15	2.98
Physics model	0.28	0.57	0.56	0.42	0.32
Run 1 and 2016 combination	2.06	1.63	1.65	1.74	1.63
Kernel smoothing	0.02	1.12	2.66	7.91	3.46
Signal model	0.59	2.02	2.97	4.81	9.92
Simulation sample size	0.32	0.02	0.31	2.38	5.18
misID model	0.91	0.13	0.56	5.22	13.53
Combinatorial model	0.90	1.17	1.21	8.51	4.68
Fit bias	0.21	0.13	0.95	2.46	7.84
Total systematic uncertainty	5.33	5.24	6.45	15.58	20.81
Total statistical uncertainty	9.1	5.5	12.5	25.3	29.8

287 the indicated uncertainties include statistical, systematic and normalisation uncertainty
288 contributions. As expected from the theory model and the analogous hadronic decays, the
289 differential distribution peaks at a very low value and falls off sharply. The measured total
290 branching fraction agrees with the previous measurement from the Belle collaboration
291 and represents the first observation of the $B^+ \rightarrow p\bar{p}\mu^+\nu_\mu$ decay mode.

Table 3: Number of observed $B^+ \rightarrow p\bar{p}\mu^+\nu_\mu$ candidates and differential branching fraction in each bin of $m(p\bar{p})$. In the centre column the uncertainties are statistical only. In the right the first uncertainties are statistical, the second systematic and the third from the normalisation branching fractions.

$m(p\bar{p})$ [GeV/c ²]	Signal Yield	$d\mathcal{B}(B^+ \rightarrow p\bar{p}\mu^+\nu_\mu)/dm(p\bar{p})$ [$\times 10^{-6}$ GeV ⁻¹ c ²]
Bin 1: 1.87 – 2.0	1208_{-110}^{+110}	$12.86_{-1.17}^{+1.18} \pm 0.69 \pm 0.38$
Bin 2: 2.0 – 2.2	1826_{-110}^{+97}	$12.88_{-0.74}^{+0.69} \pm 0.68 \pm 0.38$
Bin 3: 2.2 – 2.4	526_{-64}^{+67}	$3.78_{-0.46}^{+0.48} \pm 0.24 \pm 0.11$
Bin 4: 2.4 – 2.6	148_{-35}^{+40}	$1.038_{-0.248}^{+0.279} \pm 0.162 \pm 0.030$
Bin 5: 2.6 – 5.0	88_{-26}^{+26}	$0.0542_{-0.0160}^{+0.0160} \pm 0.0113 \pm 0.0016$

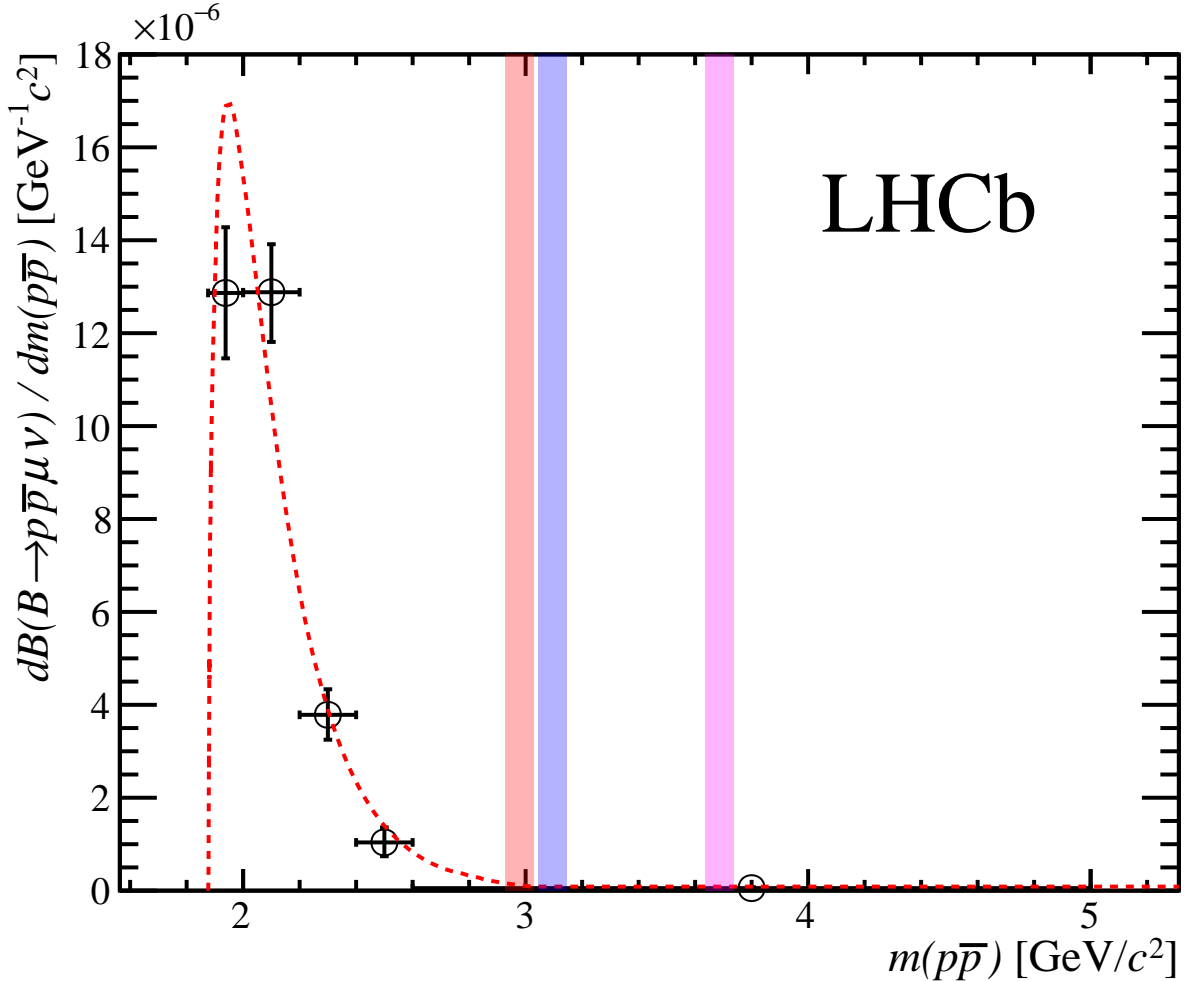


Figure 4: Differential branching fraction as a function of the $p\bar{p}$ invariant mass. The $\eta_c \rightarrow p\bar{p}$, $J/\psi \rightarrow p\bar{p}$ and $\psi(2S) \rightarrow p\bar{p}$ vetoes are indicated by the (left) red, (middle) blue and (right) pink bands, respectively. The red dashed line represents the prediction of the pQCD model normalised to the observed branching fraction [8].

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311 8 Appendix

Figure 5: The correlations in the uncertainties between bins of $p\bar{p}$ mass.

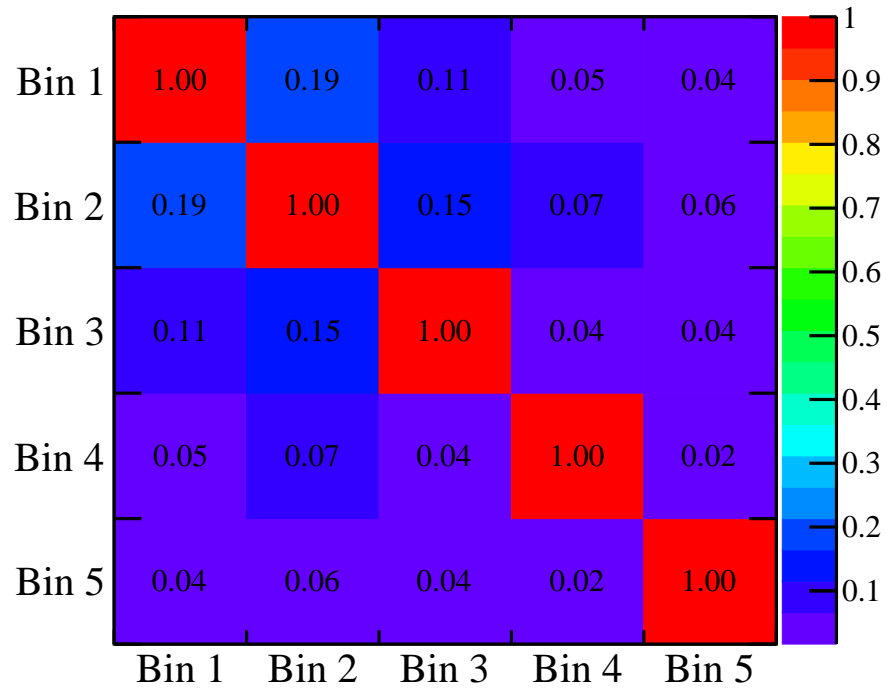


Table 4: The covariance matrix for bins of $m(p\bar{p})$.

$m(p\bar{p})$ [GeV/ c^2]	Bin 1 1.87 – 2.0	Bin 2 2.0 – 2.2	Bin 3 2.2 – 2.4	Bin 4 2.4 – 2.6	Bin 5 2.6 – 5.0
1.87 – 2.0	1.991×10^{-12}	2.800×10^{-13}	8.532×10^{-14}	2.307×10^{-14}	1.249×10^{-15}
2.0 – 2.2	2.800×10^{-13}	1.106×10^{-12}	8.332×10^{-14}	2.264×10^{-14}	1.211×10^{-15}
2.2 – 2.4	8.532×10^{-14}	8.332×10^{-14}	2.945×10^{-13}	6.905×10^{-15}	3.771×10^{-16}
2.4 – 2.6	2.307×10^{-14}	2.264×10^{-14}	6.905×10^{-15}	9.638×10^{-14}	1.011×10^{-16}
2.6 – 5.0	1.249×10^{-15}	1.211×10^{-15}	3.771×10^{-16}	1.011×10^{-16}	3.901×10^{-16}

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405 C.A. Aidala⁷⁸, S. Aiola²⁴, Z. Ajaltouni⁸, S. Akar⁶², P. Albicocco²¹, J. Albrecht¹³, F. Alessio⁴⁵,
406 M. Alexander⁵⁶, A. Alfonso Alberio⁴³, G. Alkhazov³⁶, P. Alvarez Cartelle⁵⁸, A.A. Alves Jr⁴⁴,
407 S. Amato², Y. Amhis¹⁰, L. An²⁰, L. Anderlini²⁰, G. Andreassi⁴⁶, M. Andreotti¹⁹, F. Archilli¹⁵,
408 J. Arnau Romeu⁹, A. Artamonov⁴², M. Artuso⁶⁵, K. Arzymatov⁴⁰, E. Aslanides⁹, M. Atzeni⁴⁷,
409 B. Audurier²⁵, S. Bachmann¹⁵, J.J. Back⁵³, S. Baker⁵⁸, V. Balagura^{10,b}, W. Baldini^{19,45},
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411 G. Bassi²⁷, V. Batozskaya³⁴, B. Batsukh⁶⁵, A. Battig¹³, A. Bay⁴⁶, M. Becker¹³, F. Bedeschi²⁷,
412 I. Bediaga¹, A. Beiter⁶⁵, L.J. Bel³⁰, V. Belavin⁴⁰, S. Belin²⁵, N. Bely⁴, V. Bellec⁴⁶, K. Belous⁴²,
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419 C. Bozzi¹⁹, M.J. Bradley⁵⁸, S. Braun¹⁵, A. Brea Rodriguez⁴⁴, M. Brodski⁴⁵, J. Brodzicka³²,
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422 L. Calero Diaz²¹, S. Cali²¹, R. Calladine⁵⁰, M. Calvi^{23,i}, M. Calvo Gomez^{43,m}, A. Camboni⁴³,
423 P. Campana²¹, D.H. Campora Perez⁴⁵, L. Capriotti^{18,e}, A. Carbone^{18,e}, G. Carboni²⁸,
424 R. Cardinale^{22,h}, A. Cardini²⁵, P. Carniti^{23,i}, K. Carvalho Akiba³⁰, A. Casais Vidal⁴⁴,
425 G. Casse⁵⁷, M. Cattaneo⁴⁵, G. Cavallero⁴⁵, R. Cenci^{27,p}, J. Cerasoli⁹, M.G. Chapman⁵¹,
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427 C. Chen³, S. Chen²⁵, A. Chernov³², S.-G. Chitic⁴⁵, V. Chobanova⁴⁴, M. Chruszcz³²,
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429 P.E.L. Clarke⁵⁵, M. Clemencic⁴⁵, H.V. Cliff⁵², J. Closier⁴⁵, J.L. Cobbedick⁵⁹, V. Coco⁴⁵,
430 J.A.B. Coelho¹⁰, J. Cogan⁹, E. Cogneras⁸, L. Cojocariu³⁵, P. Collins⁴⁵, T. Colombo⁴⁵,
431 A. Comerma-Montells¹⁵, A. Contu²⁵, N. Cooke⁵⁰, G. Coombs⁵⁶, S. Coquereau⁴³, G. Corti⁴⁵,
432 C.M. Costa Sobral⁵³, B. Couturier⁴⁵, D.C. Craik⁶¹, J. Crkovska⁶⁴, A. Crocombe⁵³,
433 M. Cruz Torres¹, R. Currie⁵⁵, C.L. Da Silva⁶⁴, E. Dall'Occo³⁰, J. Dalseno^{44,51}, C. D'Ambrosio⁴⁵,
434 A. Danilina³⁷, P. d'Argent¹⁵, A. Davis⁵⁹, O. De Aguiar Francisco⁴⁵, K. De Bruyn⁴⁵,
435 S. De Capua⁵⁹, M. De Cian⁴⁶, J.M. De Miranda¹, L. De Paula², M. De Serio^{17,d}, P. De Simone²¹,
436 J.A. de Vries³⁰, C.T. Dean⁶⁴, W. Dean⁷⁸, D. Decamp⁷, L. Del Buono¹¹, B. Delaney⁵²,
437 H.-P. Dembinski¹⁴, M. Demmer¹³, A. Dendek³³, V. Denysenko⁴⁷, D. Derkach⁷⁵, O. Deschamps⁸,
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449 M. Fuehring¹³, W. Funk⁴⁵, E. Gabriel⁵⁵, A. Gallas Torreira⁴⁴, D. Galli^{18,e}, S. Gallorini²⁶,
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451 J. García Pardiñas⁴⁷, B. Garcia Plana⁴⁴, F.A. Garcia Rosales¹⁰, J. Garra Tico⁵², L. Garrido⁴³,

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 460 T.H. Hancock⁶⁰, S. Hansmann-Menzemer¹⁵, N. Harnew⁶⁰, T. Harrison⁵⁷, R. Hart³⁰, C. Hasse⁴⁵,
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 463 M. Hilton⁵⁹, P.H. Hopchev⁴⁶, J. Hu¹⁵, W. Hu⁶, W. Huang⁴, W. Hulsbergen³⁰, T. Humair⁵⁸,
 464 R.J. Hunter⁵³, M. Hushchyn⁷⁵, D. Hutchcroft⁵⁷, D. Hynds³⁰, P. Ibis¹³, M. Idzik³³, P. Ilten⁵⁰,
 465 A. Inglessi³⁶, A. Inyakin⁴², K. Ivshin³⁶, R. Jacobsson⁴⁵, S. Jakobsen⁴⁵, J. Jalocha⁶⁰, E. Jans³⁰,
 466 B.K. Jashal⁷⁷, A. Jawahery⁶³, V. Jevtic¹³, F. Jiang³, M. John⁶⁰, D. Johnson⁴⁵, C.R. Jones⁵²,
 467 B. Jost⁴⁵, N. Jurik⁶⁰, S. Kandybei⁴⁸, M. Karacson⁴⁵, J.M. Kariuki⁵¹, N. Kazeev⁷⁵, M. Kecke¹⁵,
 468 F. Keizer^{52,52}, M. Kelsey⁶⁵, M. Kenzie⁵², T. Ketel³¹, B. Khanji⁴⁵, A. Kharisova⁷⁶, K.E. Kim⁶⁵,
 469 T. Kirn¹², V.S. Kirsebom⁴⁶, S. Klaver²¹, K. Klimaszewski³⁴, S. Koliiev⁴⁹, A. Kondybayeva⁷⁴,
 470 A. Konoplyannikov³⁷, P. Kopciwicz³³, R. Kopečna¹⁵, P. Koppenburg³⁰, I. Kostiuk^{30,49},
 471 O. Kot⁴⁹, S. Kotriakhova³⁶, L. Kravchuk³⁹, R.D. Krawczyk⁴⁵, M. Kreps⁵³, F. Kress⁵⁸,
 472 S. Kretzschmar¹², P. Krokovny^{41,x}, W. Krupa³³, W. Krzemien³⁴, W. Kucewicz^{32,l},
 473 M. Kucharczyk³², V. Kudryavtsev^{41,x}, H.S. Kuindersma³⁰, G.J. Kunde⁶⁴, T. Kvaratskheliya³⁷,
 474 D. Lacarrere⁴⁵, G. Lafferty⁵⁹, A. Lai²⁵, D. Lancierini⁴⁷, J.J. Lane⁵⁹, G. Lanfranchi²¹,
 475 C. Langenbruch¹², T. Latham⁵³, F. Lazzari^{27,v}, C. Lazzeroni⁵⁰, R. Le Gac⁹, R. Lefèvre⁸,
 476 A. Leflat³⁸, F. Lemaître⁴⁵, O. Leroy⁹, T. Lesiak³², B. Leverington¹⁵, H. Li⁶⁸, X. Li⁶⁴, Y. Li⁵,
 477 Z. Li⁶⁵, X. Liang⁶⁵, R. Lindner⁴⁵, V. Lisovskyi¹⁰, G. Liu⁶⁸, X. Liu³, D. Loh⁵³, A. Loi²⁵,
 478 J. Lomba Castro⁴⁴, I. Longstaff⁵⁶, J.H. Lopes², G. Loustau⁴⁷, G.H. Lovell⁵², Y. Lu⁵,
 479 D. Lucchesi^{26,o}, M. Lucio Martinez³⁰, Y. Luo³, A. Lupato²⁶, E. Luppi^{19,g}, O. Lupton⁵³,
 480 A. Lusiani²⁷, X. Lyu⁴, S. Maccolini^{18,e}, F. Machefert¹⁰, F. Maciuc³⁵, V. Macko⁴⁶,
 481 P. Mackowiak¹³, S. Maddrell-Mander⁵¹, L.R. Madhan Mohan⁵¹, O. Maev^{36,45}, A. Maevskiy⁷⁵,
 482 D. Maisuzenko³⁶, M.W. Majewski³³, S. Malde⁶⁰, B. Malecki⁴⁵, A. Malinin⁷³, T. Maltsev^{41,x},
 483 H. Malygina¹⁵, G. Manca^{25,f}, G. Mancinelli⁹, R. Manera Escalero⁴³, D. Manuzzi^{18,e},
 484 D. Marangotto^{24,q}, J. Maratas^{8,w}, J.F. Marchand⁷, U. Marconi¹⁸, S. Mariani²⁰,
 485 C. Marin Benito¹⁰, M. Marinangeli⁴⁶, P. Marino⁴⁶, J. Marks¹⁵, P.J. Marshall⁵⁷, G. Martellotti²⁹,
 486 L. Martinazzoli⁴⁵, M. Martinelli²³, D. Martinez Santos⁴⁴, F. Martinez Vidal⁷⁷, A. Massafferri¹,
 487 M. Materok¹², R. Matev⁴⁵, A. Mathad⁴⁷, Z. Mathe⁴⁵, V. Matiunin³⁷, C. Matteuzzi²³,
 488 K.R. Mattioli⁷⁸, A. Mauri⁴⁷, E. Maurice^{10,b}, M. McCann^{58,45}, L. McConnell¹⁶, A. McNab⁵⁹,
 489 R. McNulty¹⁶, J.V. Mead⁵⁷, B. Meadows⁶², C. Meaux⁹, G. Meier¹³, N. Meinert⁷¹,
 490 D. Melnychuk³⁴, S. Meloni^{23,i}, M. Merk³⁰, A. Merli²⁴, M. Mikhasenko⁴⁵, D.A. Milanese⁷⁰,
 491 E. Millard⁵³, M.-N. Minard⁷, O. Mineev³⁷, L. Minzoni^{19,g}, S.E. Mitchell⁵⁵, B. Mitreska⁵⁹,
 492 D.S. Mitzel⁴⁵, A. Mödden¹³, A. Mogini¹¹, R.D. Moise⁵⁸, T. Mombächer¹³, I.A. Monroy⁷⁰,
 493 S. Monteil⁸, M. Morandin²⁶, G. Morello²¹, M.J. Morello^{27,t}, J. Moron³³, A.B. Morris⁹,
 494 A.G. Morris⁵³, R. Mountain⁶⁵, H. Mu³, F. Muheim⁵⁵, M. Mukherjee⁶, M. Mulder³⁰, D. Müller⁴⁵,
 495 K. Müller⁴⁷, V. Müller¹³, C.H. Murphy⁶⁰, D. Murray⁵⁹, P. Muzzetto²⁵, P. Naik⁵¹, T. Nakada⁴⁶,
 496 R. Nandakumar⁵⁴, A. Nandi⁶⁰, T. Nanut⁴⁶, I. Nasteva², M. Needham⁵⁵, N. Neri^{24,q},
 497 S. Neubert¹⁵, N. Neufeld⁴⁵, R. Newcombe⁵⁸, T.D. Nguyen⁴⁶, C. Nguyen-Mau^{46,n}, E.M. Niel¹⁰,
 498 S. Nieswand¹², N. Nikitin³⁸, N.S. Nolte⁴⁵, C. Nunez⁷⁸, A. Oblakowska-Mucha³³, V. Obraztsov⁴²,
 499 S. Ogilvy⁵⁶, D.P. O’Hanlon¹⁸, R. Oldeman^{25,f}, C.J.G. Onderwater⁷², J. D. Osborn⁷⁸,
 500 A. Ossowska³², J.M. Otalora Goicochea², T. Ovsiannikova³⁷, P. Owen⁴⁷, A. Oyanguren⁷⁷,
 501 P.R. Pais⁴⁶, T. Pajero^{27,t}, A. Palano¹⁷, M. Palutan²¹, G. Panshin⁷⁶, A. Papanestis⁵⁴,

502 M. Pappagallo⁵⁵, L.L. Pappalardo^{19,g}, C. Pappenheimer⁶², W. Parker⁶³, C. Parkes⁵⁹,
503 G. Passaleva^{20,45}, A. Pastore¹⁷, M. Patel⁵⁸, C. Patrignani^{18,e}, A. Pearce⁴⁵, A. Pellegrino³⁰,
504 M. Pepe Altarelli⁴⁵, S. Perazzini¹⁸, D. Pereima³⁷, P. Perret⁸, L. Pescatore⁴⁶, K. Petridis⁵¹,
505 A. Petrolini^{22,h}, A. Petrov⁷³, S. Petrucci⁵⁵, M. Petruzzo^{24,q}, B. Pietrzyk⁷, G. Pietrzyk⁴⁶,
506 M. Pikiés³², M. Pili⁶⁰, D. Pinci²⁹, J. Pinzino⁴⁵, F. Pisani⁴⁵, A. Piucci¹⁵, V. Placinta³⁵,
507 S. Playfer⁵⁵, J. Plews⁵⁰, M. Plo Casasus⁴⁴, F. Polci¹¹, M. Poli Lener²¹, M. Poliaková⁶⁵,
508 A. Poluektov⁹, N. Polukhina^{74,c}, I. Polyakov⁶⁵, E. Polycarpo², G.J. Pomery⁵¹, S. Ponce⁴⁵,
509 A. Popov⁴², D. Popov⁵⁰, S. Poslavskii⁴², K. Prasanth³², L. Promberger⁴⁵, C. Prouve⁴⁴,
510 V. Pugatch⁴⁹, A. Puig Navarro⁴⁷, H. Pullen⁶⁰, G. Punzi^{27,p}, W. Qian⁴, J. Qin⁴, R. Quagliani¹¹,
511 B. Quintana⁸, N.V. Raab¹⁶, R.I. Rabadan Trejo⁹, B. Rachwał³³, J.H. Rademacker⁵¹,
512 M. Rama²⁷, M. Ramos Pernas⁴⁴, M.S. Rangel², F. Ratnikov^{40,75}, G. Raven³¹, M. Reboud⁷,
513 F. Redi⁴⁶, F. Reiss¹¹, C. Remon Alepuz⁷⁷, Z. Ren³, V. Renaudin⁶⁰, S. Ricciardi⁵⁴,
514 S. Richards⁵¹, K. Rinnert⁵⁷, P. Robbe¹⁰, A. Robert¹¹, A.B. Rodrigues⁴⁶, E. Rodrigues⁶²,
515 J.A. Rodriguez Lopez⁷⁰, M. Roehrken⁴⁵, S. Roiser⁴⁵, A. Rollings⁶⁰, V. Romanovskiy⁴²,
516 M. Romero Lamas⁴⁴, A. Romero Vidal⁴⁴, J.D. Roth⁷⁸, M. Rotondo²¹, M.S. Rudolph⁶⁵,
517 T. Ruf⁴⁵, J. Ruiz Vidal⁷⁷, J. Ryzka³³, J.J. Saborido Silva⁴⁴, N. Sagidova³⁶, B. Saitta^{25,f},
518 C. Sanchez Gras³⁰, C. Sanchez Mayordomo⁷⁷, B. Sanmartin Sedes⁴⁴, R. Santacesaria²⁹,
519 C. Santamarina Rios⁴⁴, M. Santimaria²¹, E. Santovetti^{28,j}, G. Sarpis⁵⁹, A. Sarti²⁹,
520 C. Satriano^{29,s}, A. Satta²⁸, M. Saur⁴, D. Savrina^{37,38}, L.G. Scantlebury Smead⁶⁰, S. Schael¹²,
521 M. Schellenberg¹³, M. Schiller⁵⁶, H. Schindler⁴⁵, M. Schmelling¹⁴, T. Schmelzer¹³, B. Schmidt⁴⁵,
522 O. Schneider⁴⁶, A. Schopper⁴⁵, H.F. Schreiner⁶², M. Schubiger³⁰, S. Schulte⁴⁶, M.H. Schune¹⁰,
523 R. Schwemmer⁴⁵, B. Sciascia²¹, A. Sciubba^{29,k}, S. Sellam⁶⁶, A. Semennikov³⁷, A. Sergi^{50,45},
524 N. Serra⁴⁷, J. Serrano⁹, L. Sestini²⁶, A. Seuthe¹³, P. Seyfert⁴⁵, D.M. Shangase⁷⁸, M. Shapkin⁴²,
525 T. Shears⁵⁷, L. Shekhtman^{41,x}, V. Shevchenko^{73,74}, E. Shmanin⁷⁴, J.D. Shupperd⁶⁵,
526 B.G. Siddi¹⁹, R. Silva Coutinho⁴⁷, L. Silva de Oliveira², G. Simi^{26,o}, S. Simone^{17,d}, I. Skiba¹⁹,
527 N. Skidmore¹⁵, T. Skwarnicki⁶⁵, M.W. Slater⁵⁰, J.G. Smeaton⁵², A. Smetkina³⁷, E. Smith¹²,
528 I.T. Smith⁵⁵, M. Smith⁵⁸, A. Snoch³⁰, M. Soares¹⁸, L. Soares Lavoura¹, M.D. Sokoloff⁶²,
529 F.J.P. Soler⁵⁶, B. Souza De Paula², B. Spaan¹³, E. Spadaro Norella^{24,q}, P. Spradlin⁵⁶,
530 F. Stagni⁴⁵, M. Stahl⁶², S. Stahl⁴⁵, P. Stefko⁴⁶, S. Stefkova⁵⁸, O. Steinkamp⁴⁷, S. Stemmlé¹⁵,
531 O. Stenyakin⁴², M. Stepanova³⁶, H. Stevens¹³, A. Stocchi¹⁰, S. Stone⁶⁵, S. Stracka²⁷,
532 M.E. Stramaglia⁴⁶, M. Straticiuc³⁵, S. Strovkov⁷⁶, J. Sun³, L. Sun⁶⁹, Y. Sun⁶³, P. Svihra⁵⁹,
533 K. Swientek³³, A. Szabelski³⁴, T. Szumlak³³, M. Szymanski⁴, S. Taneja⁵⁹, Z. Tang³,
534 T. Tekampe¹³, G. Tellarini¹⁹, F. Teubert⁴⁵, E. Thomas⁴⁵, K.A. Thomson⁵⁷, M.J. Tilley⁵⁸,
535 V. Tisserand⁸, S. T'Jampens⁷, M. Tobin⁵, S. Tolk⁴⁵, L. Tomassetti^{19,g}, D. Tonelli²⁷, D.Y. Tou¹¹,
536 E. Tournefier⁷, M. Traill⁵⁶, M.T. Tran⁴⁶, C. Trippl⁴⁶, A. Trisovic⁵², A. Tsaregorodtsev⁹,
537 G. Tuci^{27,45,p}, A. Tully⁴⁶, N. Tuning³⁰, A. Ukleja³⁴, A. Usachov¹⁰, A. Ustyuzhanin^{40,75},
538 U. Uwer¹⁵, A. Vagner⁷⁶, V. Vagnoni¹⁸, A. Valassi⁴⁵, G. Valenti¹⁸, M. van Beuzekom³⁰,
539 H. Van Hecke⁶⁴, E. van Herwijnen⁴⁵, C.B. Van Hulse¹⁶, M. van Veghel⁷², R. Vazquez Gomez⁴³,
540 P. Vazquez Regueiro⁴⁴, C. Vázquez Sierra³⁰, S. Vecchi¹⁹, J.J. Velthuis⁵¹, M. Veltri^{20,r},
541 A. Venkateswaran⁶⁵, M. Vernet⁸, M. Veronesi³⁰, M. Vesterinen⁵³, J.V. Viana Barbosa⁴⁵,
542 D. Vieira⁴, M. Vieites Diaz⁴⁶, H. Viemann⁷¹, X. Vilasis-Cardona^{43,m}, A. Vitkovskiy³⁰,
543 V. Volkov³⁸, A. Vollhardt⁴⁷, D. Vom Bruch¹¹, A. Vorobyev³⁶, V. Vorobyev^{41,x}, N. Voropaev³⁶,
544 R. Waldi⁷¹, J. Walsh²⁷, J. Wang³, J. Wang⁶⁹, J. Wang⁵, M. Wang³, Y. Wang⁶, Z. Wang⁴⁷,
545 D.R. Ward⁵², H.M. Wark⁵⁷, N.K. Watson⁵⁰, D. Websdale⁵⁸, A. Weiden⁴⁷, C. Weisser⁶¹,
546 B.D.C. Westhenry⁵¹, D.J. White⁵⁹, M. Whitehead¹², D. Wiedner¹³, G. Wilkinson⁶⁰,
547 M. Wilkinson⁶⁵, I. Williams⁵², M. Williams⁶¹, M.R.J. Williams⁵⁹, T. Williams⁵⁰, F.F. Wilson⁵⁴,
548 M. Winn¹⁰, W. Wislicki³⁴, M. Witek³², G. Wormser¹⁰, S.A. Wotton⁵², H. Wu⁶⁵, K. Wyllie⁴⁵,
549 Z. Xiang⁴, D. Xiao⁶, Y. Xie⁶, H. Xing⁶⁸, A. Xu³, L. Xu³, M. Xu⁶, Q. Xu⁴, Z. Xu⁷, Z. Xu³,
550 Z. Yang³, Z. Yang⁶³, Y. Yao⁶⁵, L.E. Yeomans⁵⁷, H. Yin⁶, J. Yu^{6,aa}, X. Yuan⁶⁵,
551 O. Yushchenko⁴², K.A. Zarebski⁵⁰, M. Zavertyaev^{14,c}, M. Zdybal³², M. Zeng³, D. Zhang⁶,

552 L. Zhang³, S. Zhang³, W.C. Zhang^{3,z}, Y. Zhang⁴⁵, A. Zhelezov¹⁵, Y. Zheng⁴, X. Zhou⁴,
553 Y. Zhou⁴, X. Zhu³, V. Zhukov^{12,38}, J.B. Zonneveld⁵⁵, S. Zucchelli^{18,e}.

554 ¹*Centro Brasileiro de Pesquisas Físicas (CBPF), Rio de Janeiro, Brazil*

555 ²*Universidade Federal do Rio de Janeiro (UFRJ), Rio de Janeiro, Brazil*

556 ³*Center for High Energy Physics, Tsinghua University, Beijing, China*

557 ⁴*University of Chinese Academy of Sciences, Beijing, China*

558 ⁵*Institute Of High Energy Physics (IHEP), Beijing, China*

559 ⁶*Institute of Particle Physics, Central China Normal University, Wuhan, Hubei, China*

560 ⁷*Univ. Grenoble Alpes, Univ. Savoie Mont Blanc, CNRS, IN2P3-LAPP, Annecy, France*

561 ⁸*Université Clermont Auvergne, CNRS/IN2P3, LPC, Clermont-Ferrand, France*

562 ⁹*Aix Marseille Univ, CNRS/IN2P3, CPPM, Marseille, France*

563 ¹⁰*LAL, Univ. Paris-Sud, CNRS/IN2P3, Université Paris-Saclay, Orsay, France*

564 ¹¹*LPNHE, Sorbonne Université, Paris Diderot Sorbonne Paris Cité, CNRS/IN2P3, Paris, France*

565 ¹²*I. Physikalisches Institut, RWTH Aachen University, Aachen, Germany*

566 ¹³*Fakultät Physik, Technische Universität Dortmund, Dortmund, Germany*

567 ¹⁴*Max-Planck-Institut für Kernphysik (MPIK), Heidelberg, Germany*

568 ¹⁵*Physikalisches Institut, Ruprecht-Karls-Universität Heidelberg, Heidelberg, Germany*

569 ¹⁶*School of Physics, University College Dublin, Dublin, Ireland*

570 ¹⁷*INFN Sezione di Bari, Bari, Italy*

571 ¹⁸*INFN Sezione di Bologna, Bologna, Italy*

572 ¹⁹*INFN Sezione di Ferrara, Ferrara, Italy*

573 ²⁰*INFN Sezione di Firenze, Firenze, Italy*

574 ²¹*INFN Laboratori Nazionali di Frascati, Frascati, Italy*

575 ²²*INFN Sezione di Genova, Genova, Italy*

576 ²³*INFN Sezione di Milano-Bicocca, Milano, Italy*

577 ²⁴*INFN Sezione di Milano, Milano, Italy*

578 ²⁵*INFN Sezione di Cagliari, Monserrato, Italy*

579 ²⁶*INFN Sezione di Padova, Padova, Italy*

580 ²⁷*INFN Sezione di Pisa, Pisa, Italy*

581 ²⁸*INFN Sezione di Roma Tor Vergata, Roma, Italy*

582 ²⁹*INFN Sezione di Roma La Sapienza, Roma, Italy*

583 ³⁰*Nikhef National Institute for Subatomic Physics, Amsterdam, Netherlands*

584 ³¹*Nikhef National Institute for Subatomic Physics and VU University Amsterdam, Amsterdam,
585 Netherlands*

586 ³²*Henryk Niewodniczanski Institute of Nuclear Physics Polish Academy of Sciences, Kraków, Poland*

587 ³³*AGH - University of Science and Technology, Faculty of Physics and Applied Computer Science,
588 Kraków, Poland*

589 ³⁴*National Center for Nuclear Research (NCBJ), Warsaw, Poland*

590 ³⁵*Horia Hulubei National Institute of Physics and Nuclear Engineering, Bucharest-Magurele, Romania*

591 ³⁶*Petersburg Nuclear Physics Institute NRC Kurchatov Institute (PNPI NRC KI), Gatchina, Russia*

592 ³⁷*Institute of Theoretical and Experimental Physics NRC Kurchatov Institute (ITEP NRC KI), Moscow,
593 Russia, Moscow, Russia*

594 ³⁸*Institute of Nuclear Physics, Moscow State University (SINP MSU), Moscow, Russia*

595 ³⁹*Institute for Nuclear Research of the Russian Academy of Sciences (INR RAS), Moscow, Russia*

596 ⁴⁰*Yandex School of Data Analysis, Moscow, Russia*

597 ⁴¹*Budker Institute of Nuclear Physics (SB RAS), Novosibirsk, Russia*

598 ⁴²*Institute for High Energy Physics NRC Kurchatov Institute (IHEP NRC KI), Protvino, Russia,
599 Protvino, Russia*

600 ⁴³*ICCUB, Universitat de Barcelona, Barcelona, Spain*

601 ⁴⁴*Instituto Galego de Física de Altas Enerxías (IGFAE), Universidade de Santiago de Compostela,
602 Santiago de Compostela, Spain*

603 ⁴⁵*European Organization for Nuclear Research (CERN), Geneva, Switzerland*

604 ⁴⁶*Institute of Physics, Ecole Polytechnique Fédérale de Lausanne (EPFL), Lausanne, Switzerland*

605 ⁴⁷*Physik-Institut, Universität Zürich, Zürich, Switzerland*

606 ⁴⁸*NSC Kharkiv Institute of Physics and Technology (NSC KIPT), Kharkiv, Ukraine*

607 ⁴⁹*Institute for Nuclear Research of the National Academy of Sciences (KINR), Kyiv, Ukraine*

608 ⁵⁰ *University of Birmingham, Birmingham, United Kingdom*
 609 ⁵¹ *H.H. Wills Physics Laboratory, University of Bristol, Bristol, United Kingdom*
 610 ⁵² *Cavendish Laboratory, University of Cambridge, Cambridge, United Kingdom*
 611 ⁵³ *Department of Physics, University of Warwick, Coventry, United Kingdom*
 612 ⁵⁴ *STFC Rutherford Appleton Laboratory, Didcot, United Kingdom*
 613 ⁵⁵ *School of Physics and Astronomy, University of Edinburgh, Edinburgh, United Kingdom*
 614 ⁵⁶ *School of Physics and Astronomy, University of Glasgow, Glasgow, United Kingdom*
 615 ⁵⁷ *Oliver Lodge Laboratory, University of Liverpool, Liverpool, United Kingdom*
 616 ⁵⁸ *Imperial College London, London, United Kingdom*
 617 ⁵⁹ *Department of Physics and Astronomy, University of Manchester, Manchester, United Kingdom*
 618 ⁶⁰ *Department of Physics, University of Oxford, Oxford, United Kingdom*
 619 ⁶¹ *Massachusetts Institute of Technology, Cambridge, MA, United States*
 620 ⁶² *University of Cincinnati, Cincinnati, OH, United States*
 621 ⁶³ *University of Maryland, College Park, MD, United States*
 622 ⁶⁴ *Los Alamos National Laboratory (LANL), Los Alamos, United States*
 623 ⁶⁵ *Syracuse University, Syracuse, NY, United States*
 624 ⁶⁶ *Laboratory of Mathematical and Subatomic Physics , Constantine, Algeria, associated to ²*
 625 ⁶⁷ *Pontificia Universidade Católica do Rio de Janeiro (PUC-Rio), Rio de Janeiro, Brazil, associated to ²*
 626 ⁶⁸ *South China Normal University, Guangzhou, China, associated to ³*
 627 ⁶⁹ *School of Physics and Technology, Wuhan University, Wuhan, China, associated to ³*
 628 ⁷⁰ *Departamento de Física , Universidad Nacional de Colombia, Bogota, Colombia, associated to ¹¹*
 629 ⁷¹ *Institut für Physik, Universität Rostock, Rostock, Germany, associated to ¹⁵*
 630 ⁷² *Van Swinderen Institute, University of Groningen, Groningen, Netherlands, associated to ³⁰*
 631 ⁷³ *National Research Centre Kurchatov Institute, Moscow, Russia, associated to ³⁷*
 632 ⁷⁴ *National University of Science and Technology “MISIS”, Moscow, Russia, associated to ³⁷*
 633 ⁷⁵ *National Research University Higher School of Economics, Moscow, Russia, associated to ⁴⁰*
 634 ⁷⁶ *National Research Tomsk Polytechnic University, Tomsk, Russia, associated to ³⁷*
 635 ⁷⁷ *Instituto de Física Corpuscular, Centro Mixto Universidad de Valencia - CSIC, Valencia, Spain,*
 636 *associated to ⁴³*
 637 ⁷⁸ *University of Michigan, Ann Arbor, United States, associated to ⁶⁵*

638 ^a *Universidade Federal do Triângulo Mineiro (UFMT), Uberaba-MG, Brazil*
 639 ^b *Laboratoire Leprince-Ringuet, Palaiseau, France*
 640 ^c *P.N. Lebedev Physical Institute, Russian Academy of Science (LPI RAS), Moscow, Russia*
 641 ^d *Università di Bari, Bari, Italy*
 642 ^e *Università di Bologna, Bologna, Italy*
 643 ^f *Università di Cagliari, Cagliari, Italy*
 644 ^g *Università di Ferrara, Ferrara, Italy*
 645 ^h *Università di Genova, Genova, Italy*
 646 ⁱ *Università di Milano Bicocca, Milano, Italy*
 647 ^j *Università di Roma Tor Vergata, Roma, Italy*
 648 ^k *Università di Roma La Sapienza, Roma, Italy*
 649 ^l *AGH - University of Science and Technology, Faculty of Computer Science, Electronics and*
 650 *Telecommunications, Kraków, Poland*
 651 ^m *LIFAELS, La Salle, Universitat Ramon Llull, Barcelona, Spain*
 652 ⁿ *Hanoi University of Science, Hanoi, Vietnam*
 653 ^o *Università di Padova, Padova, Italy*
 654 ^p *Università di Pisa, Pisa, Italy*
 655 ^q *Università degli Studi di Milano, Milano, Italy*
 656 ^r *Università di Urbino, Urbino, Italy*
 657 ^s *Università della Basilicata, Potenza, Italy*
 658 ^t *Scuola Normale Superiore, Pisa, Italy*
 659 ^u *Università di Modena e Reggio Emilia, Modena, Italy*
 660 ^v *Università di Siena, Siena, Italy*
 661 ^w *MSU - Iligan Institute of Technology (MSU-IIT), Iligan, Philippines*
 662 ^x *Novosibirsk State University, Novosibirsk, Russia*
 663 ^y *Sezione INFN di Trieste, Trieste, Italy*

664 ^z*School of Physics and Information Technology, Shaanxi Normal University (SNNU), Xi'an, China*

665 ^{aa}*Physics and Micro Electronic College, Hunan University, Changsha City, China*

666 [†]*Deceased*