

First observation of the $\Lambda_b^0 \rightarrow D^+ D^- \Lambda$ decay



The LHCb collaboration

E-mail: yanxi.wu@cern.ch

ABSTRACT: The $\Lambda_b^0 \rightarrow D^+ D^- \Lambda$ decay is observed for the first time using proton-proton collision data collected by the LHCb experiment at a center-of-mass energy of 13 TeV, corresponding to an integrated luminosity of 5.3 fb^{-1} . Using the $B^0 \rightarrow D^+ D^- K_S^0$ decay as a reference channel, the product of the relative production cross-section and decay branching fractions is measured to be

$$\mathcal{R} = \frac{\sigma_{\Lambda_b^0}}{\sigma_{B^0}} \times \frac{\mathcal{B}(\Lambda_b^0 \rightarrow D^+ D^- \Lambda)}{\mathcal{B}(B^0 \rightarrow D^+ D^- K_S^0)} = 0.179 \pm 0.022 \pm 0.014,$$

where the first uncertainty is statistical and the second is systematic. The known branching fraction of the reference channel, $\mathcal{B}(B^0 \rightarrow D^+ D^- K_S^0)$, and the cross-section ratio, $\sigma_{\Lambda_b^0}/\sigma_{B^0}$, previously measured by LHCb are used to derive the branching fraction of the $\Lambda_b^0 \rightarrow D^+ D^- \Lambda$ decay

$$\mathcal{B}(\Lambda_b^0 \rightarrow D^+ D^- \Lambda) = (1.24 \pm 0.15 \pm 0.10 \pm 0.28 \pm 0.11) \times 10^{-4},$$

where the third and fourth contributions are due to uncertainties of $\mathcal{B}(B^0 \rightarrow D^+ D^- K_S^0)$ and $\sigma_{\Lambda_b^0}/\sigma_{B^0}$, respectively. Inspection of the $D^+ \Lambda$ and $D^+ D^-$ invariant-mass distributions suggests a rich presence of intermediate resonances in the decay. The $\Lambda_b^0 \rightarrow D^{*+} D^- \Lambda$ decay is also observed for the first time as a partially reconstructed component in the $D^+ D^- \Lambda$ invariant mass spectrum.

KEYWORDS: B Physics, Branching fraction, Flavour Physics, Hadron-Hadron Scattering

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1 Introduction

Beauty baryons containing at least one b quark have rich phenomenology, but most of them have not been fully explored yet. The large sample of beauty baryons produced at the Large Hadron Collider (LHC) provides an unprecedented opportunity to enrich our knowledge of beauty baryons and better understand strong and weak interactions. The $b \rightarrow c$ transition underlies the main decay modes of beauty baryons. From the late 1990s to the early 2010s, beauty baryon decays involving charmed baryons in the final state were almost exclusively known and long considered dominant [1–3]. Since 2014, however, decays with a c quark hadronizing into a meson instead of a baryon have been commonly discovered by the LHCb experiment, with sizable branching fractions as well [4–6]. Among these, $b \rightarrow c\bar{c}s$ transitions provided the place to observe the first decays into systems made of a baryon and a charmonium resonance [7–10]. For such final states, a significant contribution due to intermediate pentaquark states has been established [11–14]. Another class of decays that originate from $b \rightarrow c\bar{c}s$ transitions is the decay of a Λ_b^0 baryon into a charmed baryon and an anti-charmed meson [15], which allows a precise measurement of the Λ_b^0 baryon mass to be performed due to the limited phase space of the reaction.

This paper presents the first observation of the $\Lambda_b^0 \rightarrow D^+ D^- \Lambda$ decay,¹ referred to hereafter as the signal channel. This decay is of interest as it can proceed via two types of two-body intermediate states: one involving a charmed baryon and an anti-charm meson, and the other through charmonium(-like) states. As discussed in ref. [16], a $D^+ D^-$ bound state can be produced near the $D^+ D^-$ mass threshold, and open-charmed pentaquark states with quark content $\bar{c}sudd$ might be present in the $D^- \Lambda$ final state. Figure 1 shows the example diagrams resulting in these intermediate states that might contribute to the $\Lambda_b^0 \rightarrow D^+ D^- \Lambda$

¹The inclusion of charge-conjugate modes is always implied.

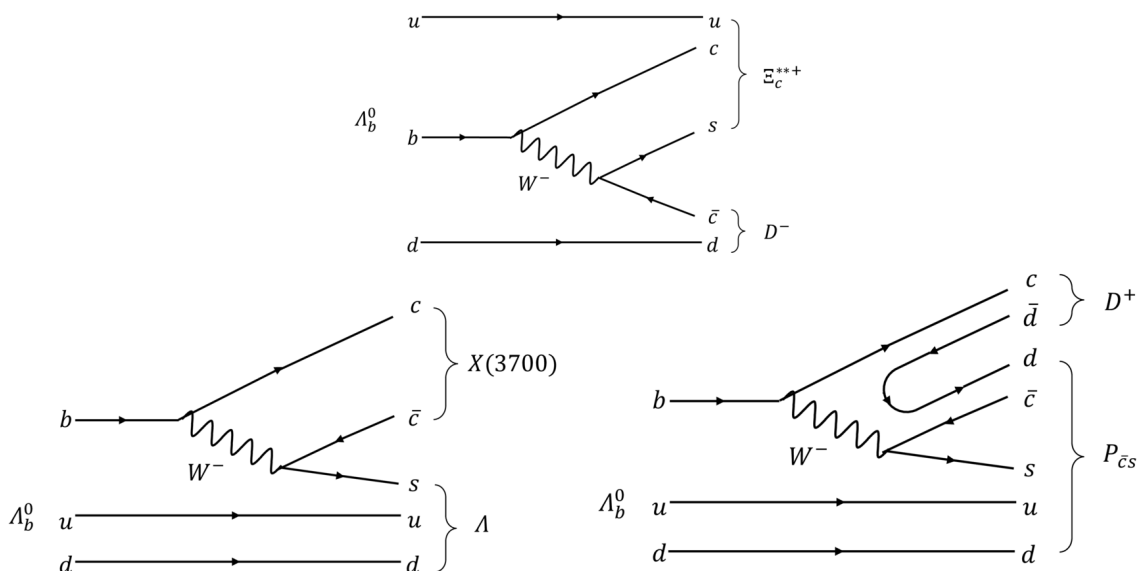


Figure 1. Example diagrams resulting in intermediate states that might contribute to the $\Lambda_b^0 \rightarrow D^+ D^- \Lambda$ decay.

decay, which originates from a $b \rightarrow \bar{c}s$ transition. These include the Ξ_c^{***} baryon decaying to $D^+ \Lambda$, the $X(3700)$ state decaying to $D^+ D^-$ and pentaquark states $P_{\bar{c}s}$ decaying to $D^- \Lambda$.

There is no previous experimental information about the signal channel $\Lambda_b^0 \rightarrow D^+ D^- \Lambda$. In the context of three-body B-meson decays, the doubly Cabibbo-suppressed decay $B^0 \rightarrow D^0 K^+ \pi^-$, for example, has a branching fraction on the order of 10^{-6} [17], the color-suppressed decay $B \rightarrow D^+ D^- K$ is around 10^{-4} [18], and the Cabibbo-allowed decay $B^0 \rightarrow D^*(2010)^- \pi^+ \pi^0$ is at the 10^{-2} level [19]. Therefore, it can be expected that the branching fraction of $\Lambda_b^0 \rightarrow D^+ D^- \Lambda$, also a color-suppressed decay, could be comparable to these orders of magnitude.

This analysis is performed using proton-proton (pp) collision data collected by the LHCb experiment from 2016 to 2018 at a center-of-mass energy of 13 TeV, corresponding to an integrated luminosity of 5.3 fb^{-1} . The branching fraction \mathcal{B} of the $\Lambda_b^0 \rightarrow D^+ D^- \Lambda$ decay is determined by taking the $B^0 \rightarrow D^+ D^- K_S^0$ decay as a reference channel. The latter has a decay topology similar to that of the signal channel, allowing for the cancellation of some systematic uncertainties in the branching fraction measurement. The primary measured quantity is the product of the relative production cross-section between Λ_b^0 and B^0 hadrons and their decay branching fraction ratio, defined as

$$\mathcal{R} \equiv \frac{\sigma_{\Lambda_b^0}}{\sigma_{B^0}} \times \frac{\mathcal{B}(\Lambda_b^0 \rightarrow D^+ D^- \Lambda)}{\mathcal{B}(B^0 \rightarrow D^+ D^- K_S^0)}, \quad (1.1)$$

where $\sigma_{\Lambda_b^0}$ (σ_{B^0}) is the production cross-section of the Λ_b^0 (B^0) hadron, and \mathcal{B} denotes the branching fractions. The branching fraction of the $\Lambda_b^0 \rightarrow D^+ D^- \Lambda$ decay is then derived using the value of the cross-section ratio, $\sigma_{\Lambda_b^0}/\sigma_{B^0}$, previously measured at the LHCb experiment [20] and the known branching fraction of the reference channel [17].

2 Detector and data samples

The LHCb detector [21, 22] 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 includes a high-precision tracking system consisting of a silicon-strip vertex detector surrounding the pp interaction region, a large-area silicon-strip detector 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 placed downstream of the magnet. The tracking system provides a measurement of the momentum, p , of charged particles with a relative uncertainty that varies from 0.5% at low momentum to 1.0% at 200 GeV/ c . The minimum distance of a track to a primary pp collision vertex (PV), the impact parameter, is measured with a resolution of $(15 + 29/p_T) \mu\text{m}$, where p_T is the component of the momentum transverse to the beam, in GeV/ c . Different types of charged hadrons are distinguished using information from two ring-imaging Cherenkov detectors. Photons, electrons and hadrons are identified by a calorimeter system consisting of scintillating-pad and preshower detectors, an electromagnetic and a hadronic calorimeter.

The online event selection is performed by a trigger, 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. At the hardware trigger stage, events are required to have a hadron with a transverse energy above 3.5 GeV in the calorimeters. The software trigger requires a two-, three- or four-track secondary vertex with a significant displacement from any PV. At least one charged particle from the secondary vertex must have a $p_T > 1.6$ GeV/ c and be inconsistent with originating from any PV.

Simulation samples are required to model the effects of the detector acceptance and the imposed selection requirements, and to study the invariant mass distributions of reconstructed $\Lambda_b^0 \rightarrow D^+ D^- \Lambda$ and $B^0 \rightarrow D^+ D^- K_S^0$ decays. The simulation samples are generated with Λ_b^0 or B^0 signal decays uniformly distributed in the $D^+ D^- \Lambda$ or $D^+ D^- K_S^0$ phase space. In the simulation, pp collisions are generated using PYTHIA [23, 24] with a specific LHCb configuration [25]. Decays of unstable particles are described by EVTGEN [26], in which final-state radiation is generated using PHOTOS [27]. The interaction of the generated particles with the detector, and its response, are implemented using the GEANT4 toolkit [28, 29] as described in ref. [30].

3 Selection of candidates

In the offline reconstruction, charged tracks of kaons, pions and protons are combined to form $D^+ \rightarrow K^- \pi^+ \pi^+$, $\Lambda \rightarrow p \pi^-$ and $K_S^0 \rightarrow \pi^+ \pi^-$ decays, which are then used to build the $\Lambda_b^0 \rightarrow D^+ D^- \Lambda$ and $B^0 \rightarrow D^+ D^- K_S^0$ candidates. It is worth noting that the Λ and K_S^0 candidates (collectively referred to as the V^0 particles) are reconstructed according to two different categories. In the LL category, they decay closely enough to the PV such that the final-state particles are reconstructed using the full tracking system. In the DD category, the V^0 particles decay downstream of the vertex detector. Consequently, the V^0 candidates have better momentum, mass and vertex resolution in the LL category than in the DD one, while the V^0 candidates in the DD category have higher efficiency.

A series of selection criteria are applied to the formed beauty-hadron candidates to suppress the background. The selection starts with loose requirements on kinematics, particle identification (PID) and variables that exploit the relatively long lifetime of beauty hadrons. Firstly, all final-state particles are required to have good track-fit quality and be displaced from any PV. Furthermore, these particles must have $p_T > 0.1 \text{ GeV}/c$ and $p > 2 \text{ GeV}/c$, and be identified with a high significance as a pion, a kaon or a proton, using information from the tracking system and PID detectors. The scalar sum of p_T of the D^\pm candidates' decay products must be larger than $1.8 \text{ GeV}/c$, with at least one of these having $p_T > 0.5 \text{ GeV}/c$ and $p > 5 \text{ GeV}/c$. The D^+ and V^0 candidates are required to have a good-quality decay vertex that is significantly displaced from any PV. The invariant mass of D^+ candidates should lie within $25 \text{ MeV}/c^2$ of the known mass [17]. Moreover, V^0 candidates should have $p_T > 250 \text{ MeV}/c$ and an invariant mass within $6.6 (5.4) \text{ MeV}/c^2$ of the known masses [17] for the $DD (LL)$ category. The beauty hadron candidate formed by combining the D^\pm and V^0 hadrons must have a good decay vertex displaced from its associated PV, which is defined as the PV that is the most compatible with the flight direction of the beauty candidate. Additionally, its decay time is required to be greater than 0.2 ps , and its momentum must point back to the associated PV. The final-state tracks of the Λ_b^0 baryon must have a scalar p_T sum larger than $5 \text{ GeV}/c$, and at least one of the final-state particles must have p_T larger than $1.7 \text{ GeV}/c$ and p larger than $10 \text{ GeV}/c$, and at least two of them must have p_T larger than $0.5 \text{ GeV}/c$ and p larger than $5 \text{ GeV}/c$. A kinematic fit to the whole decay chain is performed with the D^+ and V^0 constrained to their known masses [17] and the beauty-candidate momentum constrained to point back to the associated PV [31], which helps to improve the beauty-candidate mass resolution.

To further suppress the combinatorial background, a Boosted Decision Tree (BDT) [32, 33] classifier implemented in the TMVA toolkit [34, 35] is employed. Given the similar topology of the $\Lambda_b^0 \rightarrow D^+ D^- \Lambda$ and $B^0 \rightarrow D^+ D^- K_S^0$ decays, the BDT classifier is trained using $\Lambda_b^0 \rightarrow D^+ D^- \Lambda$ samples and is applied to both decay modes, helping to cancel certain systematic uncertainties associated with the efficiency determination in the branching fraction measurement. The BDT classifier training uses candidate Λ_b^0 decays in the high mass sideband ($5.80 < m(D^+ D^- \Lambda) < 6.15 \text{ GeV}/c^2$) in data, which serves as a proxy for the background, and simulated $\Lambda_b^0 \rightarrow D^+ D^- \Lambda$ signal decays. The training is performed separately for the LL and DD categories. The BDT classifier combines variables including the beauty-hadron decay topology, PID information of final-state particles and kinematic properties of the Λ_b^0 , D^\pm , Λ and final-state candidates, to discriminate between the signal and the background. The optimal requirement on the BDT response is determined by maximising the Punzi figure of merit $\epsilon/(\frac{5}{2} + \sqrt{B})$ [36], where ϵ is the signal efficiency and B is the background yield in the data signal region. The signal region is chosen as $\pm 25 \text{ MeV}/c^2$ around the known Λ_b^0 mass [17]. The signal efficiency ϵ is estimated from simulated samples, and the background yield B is estimated by a linear extrapolation of the yield in the high-mass data sideband to the signal region. The requirements on the BDT response are optimized separately for the signal and the reference channels but are found to be similar. The optimal requirement on the BDT response rejects about 99% of the combinatorial background while maintaining a signal efficiency of about 80%.

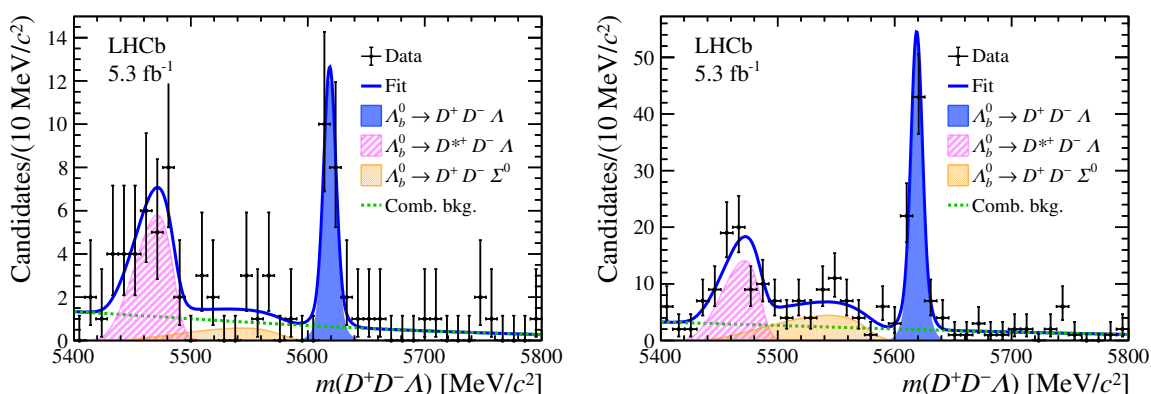


Figure 2. Invariant mass distribution of $\Lambda_b^0 \rightarrow D^+ D^- \Lambda$ candidates near the signal region with the fit results superimposed, for the (left) LL and (right) DD categories, respectively.

The background from the $K_S^0 \rightarrow \pi^+ \pi^-$ decay, which may be reconstructed as the $\Lambda \rightarrow p \pi^-$ decay due to misidentification of a pion as a proton, is investigated. This cross-feed background is suppressed by imposing a tight PID requirement on the proton track if the $p \pi^-$ invariant mass under the $\pi^+ \pi^-$ hypothesis is consistent with the K_S^0 meson mass. The remaining cross-feed background in the $B^0 \rightarrow D^+ D^- K_S^0$ decay is found to be negligible. The background from $\Lambda_b^0 \rightarrow D^+ K^+ \pi^- \pi^- \Lambda$, $\Lambda_b^0 \rightarrow K^- \pi^+ \pi^+ D^- \Lambda$ and $\Lambda_b^0 \rightarrow K^- \pi^+ \pi^+ K^+ \pi^- \pi^- \Lambda$ decays is referred to hereafter as the non-double-charm (NDC) background. This background involves the same set of final-state particles as the signal decays but there is only one or no intermediate D^\pm meson. The NDC background is largely suppressed by the imposed requirement on the D^\pm invariant mass. However, any residual NDC background can produce a peak in the $D^+ D^- \Lambda$ invariant mass distribution, and its yield is estimated based on the number of candidates in the D^\pm mass sidebands, positioned within a range of 35 to 90 MeV/c^2 from the known D^\pm mass. The fraction of the NDC background in the Λ_b^0 sample is estimated from a fit to the $D^+ D^- \Lambda$ invariant mass distribution in the D^\pm mass sidebands and extrapolating to the signal region. It is determined to be $(6 \pm 7)\%$ and $(6 \pm 3)\%$ for the LL and DD categories, respectively. Similar results are measured for the $B^0 \rightarrow D^+ D^- K_S^0$ decay channel. This method aligns with that used in refs. [37, 38]. The obtained NDC yield is then subtracted from the total beauty-hadron yield.

4 Signal yield determination

The invariant mass distributions of the Λ_b^0 and B^0 candidates after applying all the aforementioned selection requirements are shown in figures 2 and 3, respectively. The distributions are characterized by three significant peaking structures, one for the signal decay and the other two for partially reconstructed beauty-hadron decays, and a wide smooth combinatorial background. These components are fit with an extended unbinned maximum-likelihood method to determine the Λ_b^0 and B^0 signal yields.

The signal peak is described by the sum of two Gaussian functions sharing the same mean value. The common mean and the average resolution of the two Gaussian functions are free

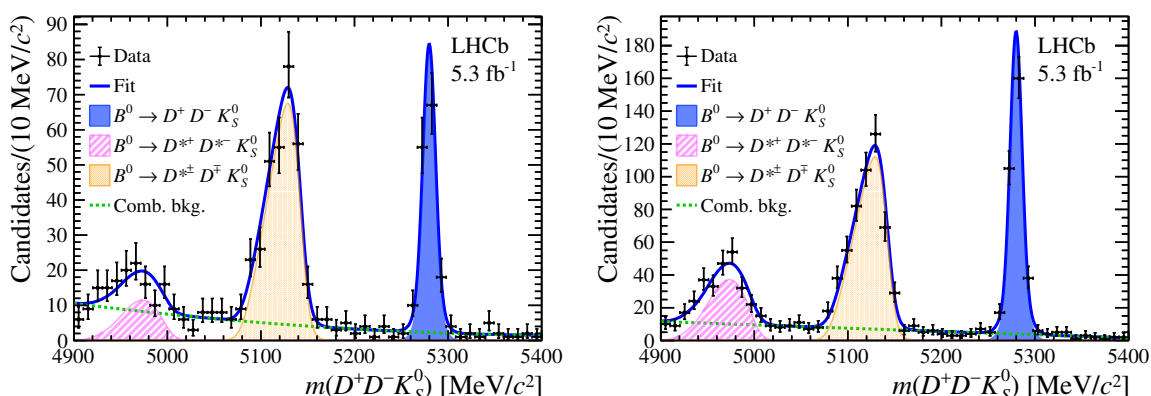


Figure 3. Invariant mass distribution of $B^0 \rightarrow D^+ D^- K_S^0$ candidates with the fit results superimposed, for the (left) LL and (right) DD categories, respectively.

parameters in the fit, while the relative fractions of the two components and the ratio of their widths are fixed to the values obtained from the simulation. In figure 2, the peaking background closer to the signal peak originates from the $\Lambda_b^0 \rightarrow D^+ D^- \Sigma^0 (\rightarrow \Lambda \gamma)$ decay where the γ is not included. The left peaking background is consistent with $\Lambda_b^0 \rightarrow D^{*\pm} (\rightarrow D^\pm \pi^0) D^\mp \Lambda$ decays with the π^0 not included. In figure 3, the partially reconstructed backgrounds in the $B^0 \rightarrow D^+ D^- K_S^0$ mass spectrum are consistent with the $B^0 \rightarrow D^{*+} D^{*-} K_S^0$ and $B^0 \rightarrow D^{*\pm} D^\mp K_S^0$ decays, where the π^0 in the $D^{*\pm} \rightarrow D^\pm \pi^0$ decay is not included. The shapes of the partially reconstructed backgrounds are obtained from a fast simulation [39], and convolved with the experimental resolution. The combinatorial background is modelled empirically by slowly varying functions, namely the ARGUS function [40] for the $\Lambda_b^0 \rightarrow D^+ D^- \Lambda$ mode and a second-order polynomial for the $B^0 \rightarrow D^+ D^- K_S^0$ mode, with all parameters free in the fit. The fit of $m(D^+ D^- \Lambda)$ distribution is performed over a larger range than what is shown in figure 2 to better constrain the combinatorial background. The fit is performed simultaneously for the LL and DD samples, and the mean of the signal Gaussians is shared.

The fit results are shown in figure 2 for $\Lambda_b^0 \rightarrow D^+ D^- \Lambda$ candidates and in figure 3 for the $B^0 \rightarrow D^+ D^- K_S^0$ candidates. After the subtraction of the aforementioned NDC background, the signal yields for the $\Lambda_b^0 \rightarrow D^+ D^- \Lambda$ and $B^0 \rightarrow D^+ D^- K_S^0$ decays are determined to be 18 ± 5 and 128 ± 12 for the LL category, 69 ± 9 and 296 ± 18 for the DD category, respectively. The statistical significance of the $\Lambda_b^0 \rightarrow D^+ D^- \Lambda$ decay evaluated using the likelihood-ratio test [41] exceeds 16 standard deviations (σ) after considering systematics. Thus, this represents the first observation of the $\Lambda_b^0 \rightarrow D^+ D^- \Lambda$ decay mode. The left peaking structure in the $D^+ D^- \Lambda$ invariant mass distributions exhibits a statistical significance of 9σ using the same method as above. This structure is consistent with the $\Lambda_b^0 \rightarrow D^{*+} D^- \Lambda$ decay, being thus observed for the first time in the $D^+ D^- \Lambda$ invariant mass spectrum.

5 Branching fraction measurement

The branching fraction of the $\Lambda_b^0 \rightarrow D^+ D^- \Lambda$ decay is measured with respect to that of the $B^0 \rightarrow D^+ D^- K_S^0$ decay as

$$\mathcal{R} = \frac{N_{\Lambda_b^0}^{\text{corr}}}{N_{B^0}^{\text{corr}}} \times \frac{\mathcal{B}(K_S^0 \rightarrow \pi^+ \pi^-)}{\mathcal{B}(\Lambda \rightarrow p \pi^-)}, \quad (5.1)$$

where $N_{X_b}^{\text{corr}}$ is the efficiency corrected yield of the $X_b = \Lambda_b^0$ or B^0 decay. The branching fractions $\mathcal{B}(\Lambda \rightarrow p \pi^-)$ and $\mathcal{B}(K_S^0 \rightarrow \pi^+ \pi^-)$ are taken from ref. [17]. The efficiency corrected yield is determined as

$$N_{X_b}^{\text{corr}} = \sum_i \frac{w_i}{\epsilon_i}, \quad (5.2)$$

where the sum runs over all the selected candidates in the signal or reference channel. The weight w_i assigned to each candidate is calculated using the invariant mass fit result following the sPlot technique [42], which is used to statistically subtract the background contribution in the data sample. The ϵ_i denotes the total experimental efficiency, which is calculated as a function of the final-state phase-space coordinates, represented by the two-dimensional plot of the two-body invariant mass distributions $m(D^+ D^-)$ and $m(D^+ V^0)$, and it is estimated for the LL and DD categories separately. The efficiency function is determined using simulated samples, which have been calibrated such that the distributions of several key variables match the data, including the PID response, Λ_b^0 kinematics and the total charged-track multiplicity. The relative variation of the total experimental efficiency across the phsp space is around 20% for both the signal and reference channels in the LL and DD categories.

Thus, \mathcal{R} is determined to be 0.172 ± 0.047 and 0.181 ± 0.025 for the LL and DD categories, respectively, where the uncertainties are statistical.

6 Systematic uncertainties

The systematic uncertainties on the branching fraction measurement, apart from external inputs, are generally related to either the signal yields or the efficiencies. Due to the similar topology of the signal and reference decays, many sources of systematic uncertainties are either cancelled or largely suppressed in the ratio of branching fractions. The remaining systematic uncertainties are outlined below and summarized in table 1.

The determination of the signal yields in the Λ_b^0 and B^0 decay channels is affected by the choice of the fit models for the various components, which in turn influences the branching fraction measurement. To test the signal model, alternative fits are performed by either fixing all the shape parameters to those obtained from the simulation or by using a Hypatia function [43] with the parameters of mean and resolution floated in the fit. In order to study the systematic uncertainty associated with the combinatorial background modelling, the range of the beauty-hadron invariant mass used in the fit is modified. The relative deviation of the branching fraction obtained in these alternative fits from the baseline result is found to be 3.4% at most, which is taken to be the systematic uncertainty due to the invariant mass modelling.

The distributions of the discriminating variables used in the BDT classifier are found to be consistent between the simulation and background-subtracted data of the reference channel. Additionally, given the overlap of the distributions of discriminating variables between the signal and reference channels in simulation, no corresponding systematic uncertainties are quoted. To validate the effect of the possible overtraining of the BDT classifier on the beauty-hadron invariant mass distribution, a fit is performed excluding the candidates used in the BDT training. The relative difference of the new branching fraction with respect to the baseline result is found to be 2.5% and is taken as the corresponding uncertainty.

The estimated NDC background fractions in the signal and reference channels suffer from the limited size of the data samples. These uncertainties are propagated to the branching fraction measurement causing a relative uncertainty of 4.5%.

The efficiencies are estimated from simulated samples, so systematic contributions arise due to the limited size of the samples, and due to the imperfect simulation of the detector response and particle kinematics. The relative uncertainty due to the limited size of the simulation samples is 3.9%. Corrections of the simulation samples for their different PID response and beauty-hadron kinematic distributions than in data are subject to uncertainties. Specifically, the systematic uncertainty associated with the corrections of the PID response is evaluated using alternative correction templates [44] and measuring the relative change of efficiencies, which is found to be negligible. The uncertainties on the corrections of the Λ_b^0 distributions are propagated to the branching fraction measurement using pseudoexperiments. For every pseudoexperiment, the correction factor in each bin of the Λ_b^0 transverse momentum and rapidity is varied following a Gaussian distribution. The mean and width of the Gaussian function are taken as the baseline correction factor and its uncertainty. Also, the branching fraction is calculated for each pseudoexperiment, and then a set of branching fractions is obtained, whose standard deviation is taken as the systematic uncertainty, calculated to be 1.5%.

The hardware-trigger response is approximately modelled in the simulation, therefore, a data-driven calibration is performed to align the efficiency in the simulation with that in the data [45]. The uncertainties on the calibration factors are propagated to the branching fraction measurement, resulting in a relative uncertainty of 0.5%.

The experimental efficiency is measured in bins of the final-state phase space. The choice of the binning scheme introduces another source of systematic uncertainty. The efficiency, recalculated using coarser bins, results in a relative change in the branching fraction of 2.6%. This value is thus quoted as a systematic uncertainty.

Besides the contributions outlined above, there are also further uncertainties due to the external inputs. They come from the limited knowledge of the branching fractions of the intermediate decays $\Lambda \rightarrow p\pi^-$, $K_S^0 \rightarrow \pi^+\pi^-$ and that of the reference channel $B^0 \rightarrow D^+D^-K^0$ [18]. Benefiting from the precise measurement of branching fractions of $\Lambda \rightarrow p\pi^-$ and $K_S^0 \rightarrow \pi^+\pi^-$ [17], the uncertainties associated with these two intermediate decays are small, at 0.9% relatively. However, experimental knowledge about the branching fraction of the reference channel $B^0 \rightarrow D^+D^-K^0$ is quite limited, resulting in a large uncertainty of 23.1%, which dominates the overall uncertainties. The precision of the branching fraction measurement of $\Lambda_b^0 \rightarrow D^+D^-\Lambda$ can be greatly enhanced once the measurement of

Source	Relative uncertainty (%)
Modelling of the invariant mass distribution	3.4
BDT classifier training	2.5
Subtraction of NDC background	4.5
Size of simulation samples	3.9
Corrections to simulation samples	1.5
Trigger efficiency	0.5
Binning scheme of two-body invariant mass	2.6
Branching fraction ratio of $\Lambda \rightarrow p\pi^-$ and $K_S^0 \rightarrow \pi^+\pi^-$	0.9
Branching fraction of $B^0 \rightarrow D^+D^-K^0$	23.1
Beauty-hadron production cross-section ratio	9.1
Total systematic uncertainty	7.8
Total uncertainty due to external inputs	24.7

Table 1. Summary of relative systematic uncertainties and uncertainties from external inputs on the branching fraction measurement.

$B^0 \rightarrow D^+D^-K^0$ is significantly improved. Finally, another source is the uncertainty from the measurement of the beauty-hadron production cross-section ratio performed by LHCb, which is 9.1% [20]. The total uncertainty due to the external inputs is 24.7%, which is the dominant uncertainty compared with the statistical and systematic ones.

7 Results and summary

The product of the ratio of branching fractions and the corresponding beauty-hadron production cross-section is measured to be

$$\mathcal{R} = \frac{\sigma_{\Lambda_b^0}}{\sigma_{B^0}} \times \frac{\mathcal{B}(\Lambda_b^0 \rightarrow D^+D^-\Lambda)}{\mathcal{B}(B^0 \rightarrow D^+D^-K_S^0)} = 0.179 \pm 0.022 \pm 0.014,$$

where the first uncertainty is statistical and the second is systematic. This result represents a weighted average of the LL and DD samples, with weights calculated using the statistical uncertainties.

The relative production cross-section $\sigma_{\Lambda_b^0}/\sigma_{B^0}$ is equal to the ratio of hadronization fractions, $f_{\Lambda_b^0}/f_{B^0}$, which has been measured by LHCb as a function of the p_T of the Λ_b^0 baryon [20]. Averaging over the p_T distribution of the Λ_b^0 baryon in data gives $\sigma_{\Lambda_b^0}/\sigma_{B^0} = 0.541 \pm 0.048$. Using the known branching fraction of $\mathcal{B}(B^0 \rightarrow D^+D^-K^0)$ [18] and assuming equal probabilities for observing a K^0 meson as a K_S^0 or K_L^0 mass eigenstate, the $\Lambda_b^0 \rightarrow D^+D^-\Lambda$ absolute branching fraction is determined to be

$$\mathcal{B}(\Lambda_b^0 \rightarrow D^+D^-\Lambda) = (1.24 \pm 0.15 \pm 0.10 \pm 0.28 \pm 0.11) \times 10^{-4},$$

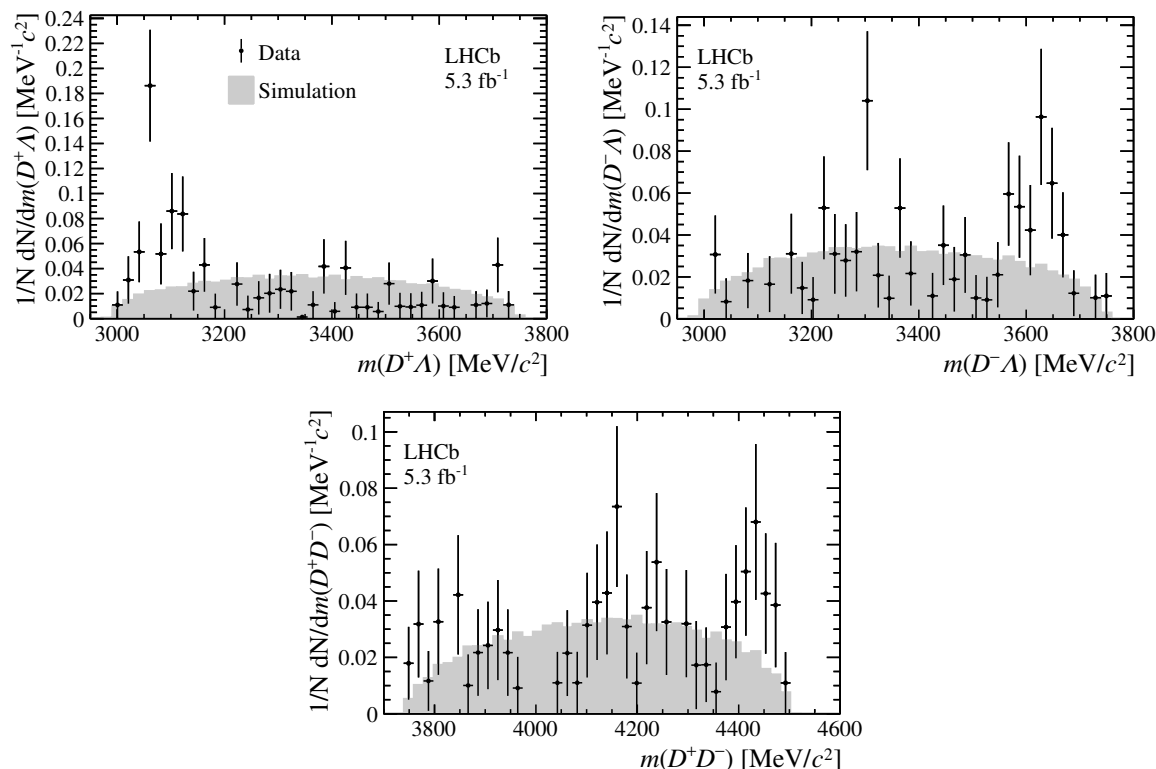


Figure 4. Normalized and background-subtracted invariant mass distributions of the (left) $D^+\Lambda$, (right) $D^-\Lambda$ and (bottom) D^+D^- systems in the $\Lambda_b^0 \rightarrow D^+D^-\Lambda$ decay, compared with the distributions in simulation samples.

where the first uncertainty is statistical, the second is systematic, and the third and fourth come from the uncertainties on the $B^0 \rightarrow D^+D^-K_S^0$ branching fraction and the beauty-hadron production cross-section ratio [20], respectively.

As emphasized in figures 4 and 5, where the invariant mass distributions $m(D^+D^-)$, $m(D^+V^0)$ and $m(D^-V^0)$ are shown, these decays are particularly noteworthy for their potential in probing possible resonant structures. These invariant mass distributions, in which the combinatorial background is subtracted using the sPlot technique, strongly depart from the phase space distributions obtained in simulation. Such deviations suggest the presence of a variety of resonant structures. For example, excited Ξ_c^+ states around $3055 \text{ MeV}/c^2$ are very likely to be included in the $m(D^+\Lambda)$ distribution, as shown in the top left plot of figure 4. Additionally, the $D\bar{D}$ bound state $X(3700)$, predicted by the theory in ref. [16], may exist in the $m(D^+D^-)$ distribution. However, as shown in the bottom plot of figure 4, the current statistics do not allow for a definitive conclusion. Furthermore, pentaquark states could potentially contribute to the $m(D^-\Lambda)$ distribution. These open the door to future discoveries in upcoming studies with larger datasets.

In summary, the $\Lambda_b^0 \rightarrow D^+D^-\Lambda$ decay is observed for the first time using proton-proton collision data collected by the LHCb experiment at a center-of-mass energy of 13 TeV, corresponding to an integrated luminosity of 5.3 fb^{-1} . The branching fraction of the $\Lambda_b^0 \rightarrow D^+D^-\Lambda$ decay is determined, which is a key step towards probing potential intermediate resonant

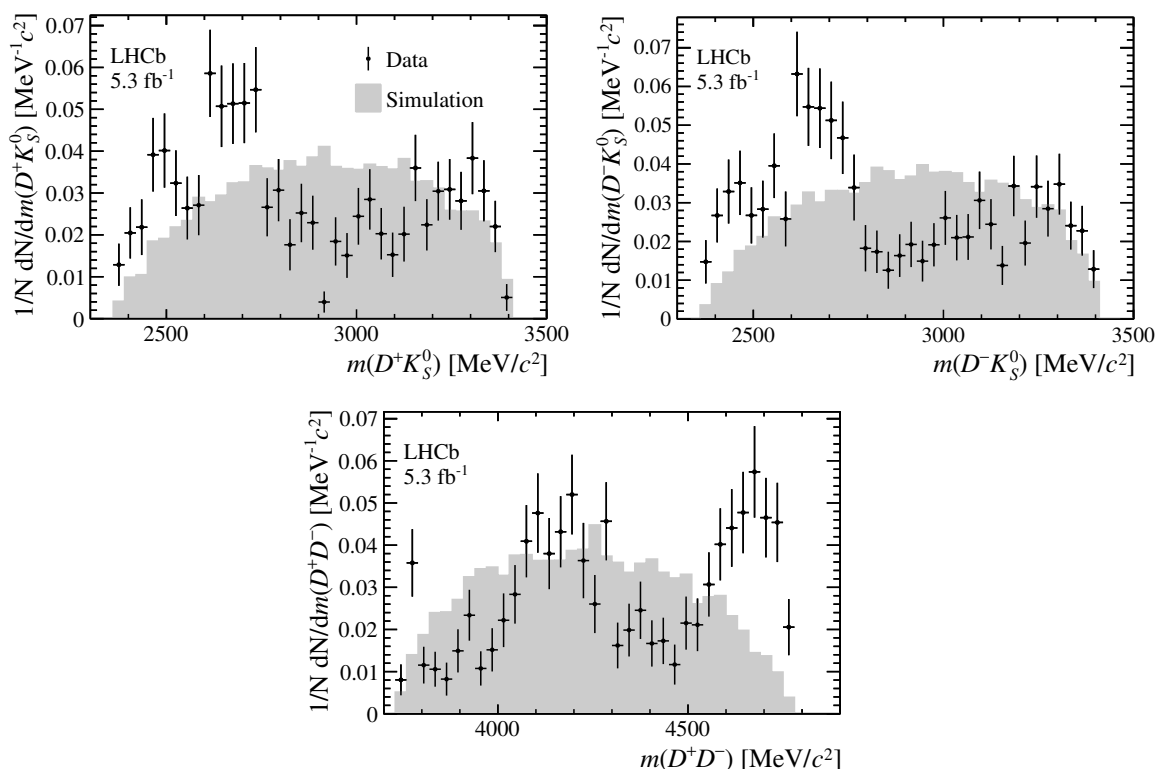


Figure 5. Normalized and background-subtracted invariant mass distributions of the (left) $D^+K_S^0$, (right) $D^-K_S^0$ and (bottom) D^+D^- systems in the $B^0 \rightarrow D^+D^-K_S^0$ decay, compared with the distributions in the simulation sample.

states. The peaking structure in the $D^+D^-\Lambda$ invariant mass distribution, which is consistent with the $\Lambda_b^0 \rightarrow D^{*+}D^-\Lambda$ decay, is also reported. Future studies will be needed to measure the branching fraction of the $\Lambda_b^0 \rightarrow D^{*+}D^-\Lambda$ decay. The indications of various resonant structures in the $\Lambda_b^0 \rightarrow D^+D^-\Lambda$ decay also call for future exploration in similar decay channels, like the $\Lambda_b^0 \rightarrow D^0\bar{D}^0\Lambda$ decay.

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Fiorini [ID](#)^{23,l}, K.M. Fischer [ID](#)⁶¹, D.S. Fitzgerald [ID](#)⁸⁰, C. Fitzpatrick [ID](#)⁶⁰, F. Fleuret [ID](#)¹⁴, M. Fontana [ID](#)²², L.F. Foreman [ID](#)⁶⁰, R. Forty [ID](#)⁴⁶, D. Foulds-Holt [ID](#)⁵³, M. Franco Sevilla [ID](#)⁶⁴, M. Frank [ID](#)⁴⁶, E. Franzoso [ID](#)^{23,l}, G. Frau [ID](#)¹⁹, C. Frei [ID](#)⁴⁶, D.A. Friday [ID](#)⁶⁰, J. Fu [ID](#)⁷, Q. Fuehring [ID](#)¹⁷, Y. Fujii [ID](#)¹, T. Fulghesu [ID](#)¹⁵, E. Gabriel [ID](#)³⁵, G. Galati [ID](#)^{21,h}, M.D. Galati [ID](#)³⁵, A. Gallas Torreira [ID](#)⁴⁴, D. Galli [ID](#)^{22,j}, S. Gambetta [ID](#)⁵⁶, M. Gandelman [ID](#)³, P. Gandini [ID](#)²⁷, H. Gao [ID](#)⁷, R. Gao [ID](#)⁶¹, Y. Gao [ID](#)⁸, Y. Gao [ID](#)⁶, Y. Gao⁸, M. Garau [ID](#)^{29,k}, L.M. Garcia Martin [ID](#)⁴⁷, P. Garcia Moreno [ID](#)⁴³, J. García Pardiñas [ID](#)⁴⁶, K.G. Garg [ID](#)⁸, L. Garrido [ID](#)⁴³, C. Gaspar [ID](#)⁴⁶, R.E. Geertsema [ID](#)³⁵, L.L. Gerken [ID](#)¹⁷, E. Gersabeck [ID](#)⁶⁰, M. Gersabeck [ID](#)⁶⁰, T. Gershon [ID](#)⁵⁴, Z. Ghorbanimoghaddam⁵², L. Giambastiani [ID](#)³⁰, F.I. Giasemis [ID](#)^{15,e}, V. Gibson [ID](#)⁵³, H.K. Gienza [ID](#)³⁹, A.L. Gilman [ID](#)⁶¹, M. Giovannetti [ID](#)²⁵, A. Gioventù [ID](#)⁴³, P. Gironella Gironell [ID](#)⁴³, C. Giugliano [ID](#)^{23,l}, M.A. Giza [ID](#)³⁸, E.L. Gkougkousis [ID](#)⁵⁹, F.C. Glaser [ID](#)^{13,19}, V.V. Gligorov [ID](#)¹⁵, C. Göbel [ID](#)⁶⁷, E. Golobardes [ID](#)⁴², D. Golubkov [ID](#)⁴¹, A. Golutvin [ID](#)^{59,41,46}, A. Gomes [ID](#)^{2,a,†}, S. Gomez Fernandez [ID](#)⁴³, F. Goncalves Abrantes [ID](#)⁶¹, M. Goncerz [ID](#)³⁸, G. Gong [ID](#)⁴, J.A. Gooding [ID](#)¹⁷, I.V. Gorelov [ID](#)⁴¹, C. Gotti [ID](#)²⁸, J.P. Grabowski [ID](#)⁷³, L.A. Granado Cardoso [ID](#)⁴⁶, E. Graugés [ID](#)⁴³, E. Graverini [ID](#)^{47,t}, L. Grazette [ID](#)⁵⁴, G. Graziani [ID](#), A.T. Greco [ID](#)⁴⁰, L.M. Greeven [ID](#)³⁵, N.A. Grieser [ID](#)⁶³, L. Grillo [ID](#)⁵⁷, S. Gromov [ID](#)⁴¹, C. Gu [ID](#)¹⁴, M. Guarise [ID](#)²³, M. Guittiere [ID](#)¹³, V. Guliaeva [ID](#)⁴¹, P.A. Günther [ID](#)¹⁹, A.-K. Guseinov [ID](#)⁴⁷, E. Gushchin [ID](#)⁴¹, Y. Guz [ID](#)^{6,41,46}, T. Gys [ID](#)⁴⁶, K. Habermann [ID](#)⁷³, T. Hadavizadeh [ID](#)¹, C. Hadjivasiliou [ID](#)⁶⁴, G. Haefeli [ID](#)⁴⁷, C. Haen [ID](#)⁴⁶, J. Haimberger [ID](#)⁴⁶, M. Hajheidari⁴⁶, M.M. Halvorsen [ID](#)⁴⁶, P.M. Hamilton [ID](#)⁶⁴, J. Hammerich [ID](#)⁵⁸, Q. Han [ID](#)⁸, X. Han [ID](#)¹⁹, S. Hansmann-Menzemer [ID](#)¹⁹, L. Hao [ID](#)⁷, N. Harnew [ID](#)⁶¹, T. Harrison [ID](#)⁵⁸, M. Hartmann [ID](#)¹³, J. He [ID](#)^{7,c}, K. Heijhoff [ID](#)³⁵, F. Hemmer [ID](#)⁴⁶, C. Henderson [ID](#)⁶³, R.D.L. Henderson [ID](#)^{1,54}, A.M. Hennequin [ID](#)⁴⁶, K. Hennessy [ID](#)⁵⁸, L. Henry [ID](#)⁴⁷, J. Herd [ID](#)⁵⁹, P. Herrero Gascon [ID](#)¹⁹, J. Heuel [ID](#)¹⁶, A. Hicheur [ID](#)³, G. Hijano Mendizabal⁴⁸, D. Hill [ID](#)⁴⁷, S.E. Hollitt [ID](#)¹⁷, J. Horswill [ID](#)⁶⁰, R. Hou [ID](#)⁸, Y. Hou [ID](#)¹⁰, N. Howarth⁵⁸, J. Hu¹⁹, J. Hu [ID](#)⁶⁹, W. Hu [ID](#)⁶, X. Hu [ID](#)⁴, W. Huang [ID](#)⁷, W. Hulsbergen [ID](#)³⁵, R.J. Hunter [ID](#)⁵⁴, M. Hushchyn [ID](#)⁴¹, D. Hutchcroft [ID](#)⁵⁸, D. Ilin [ID](#)⁴¹, P. Ilten [ID](#)⁶³, A. Inglessi [ID](#)⁴¹, A. Iniukhin [ID](#)⁴¹, A. Ishteev [ID](#)⁴¹, K. Ivshin [ID](#)⁴¹, R. Jacobsson [ID](#)⁴⁶, H. Jage [ID](#)¹⁶, S.J. Jaimes Elles [ID](#)^{45,72}, S. Jakobsen [ID](#)⁴⁶, E. Jans [ID](#)³⁵, B.K. Jashal [ID](#)⁴⁵, A. Jawahery [ID](#)^{64,46},

V. Jevtic [ID](#)¹⁷, E. Jiang [ID](#)⁶⁴, X. Jiang [ID](#)^{5,7}, Y. Jiang [ID](#)⁷, Y.J. Jiang [ID](#)⁶, M. John [ID](#)⁶¹, D. Johnson [ID](#)⁵¹, C.R. Jones [ID](#)⁵³, T.P. Jones [ID](#)⁵⁴, S. Joshi [ID](#)³⁹, B. Jost [ID](#)⁴⁶, N. Jurik [ID](#)⁴⁶, I. Juszcak [ID](#)³⁸, D. Kaminaris [ID](#)⁴⁷, S. Kandybei [ID](#)⁴⁹, Y. Kang [ID](#)⁴, M. Karacson [ID](#)⁴⁶, D. Karpenkov [ID](#)⁴¹, A. Kauniskangas [ID](#)⁴⁷, J.W. Kautz [ID](#)⁶³, F. Keizer [ID](#)⁴⁶, M. Kenzie [ID](#)⁵³, T. Ketel [ID](#)³⁵, B. Khanji [ID](#)⁶⁶, A. Kharisova [ID](#)⁴¹, S. Kholodenko [ID](#)³², G. Khreich [ID](#)¹³, T. Kirn [ID](#)¹⁶, V.S. Kirsebom [ID](#)^{28,p}, O. Kitouni [ID](#)⁶², S. Klaver [ID](#)³⁶, N. Klejne [ID](#)^{32,s}, K. Klimaszewski [ID](#)³⁹, M.R. Kmiec [ID](#)³⁹, S. Koliiev [ID](#)⁵⁰, L. Kolk [ID](#)¹⁷, A. Konoplyannikov [ID](#)⁴¹, P. Kopciewicz [ID](#)^{37,46}, P. Koppenburg [ID](#)³⁵, M. Korolev [ID](#)⁴¹, I. Kostiuk [ID](#)³⁵, O. Kot [ID](#)⁵⁰, S. Kotriakhova [ID](#), A. Kozachuk [ID](#)⁴¹, P. Kravchenko [ID](#)⁴¹, L. Kravchuk [ID](#)⁴¹, M. Kreps [ID](#)⁵⁴, S. Kretzschmar [ID](#)¹⁶, P. Krokovny [ID](#)⁴¹, W. Krupa [ID](#)⁶⁶, W. Krzemien [ID](#)³⁹, J. Kubat [ID](#)¹⁹, S. Kubis [ID](#)⁷⁷, W. Kucewicz [ID](#)³⁸, M. Kucharczyk [ID](#)³⁸, V. Kudryavtsev [ID](#)⁴¹, E. Kulikova [ID](#)⁴¹, A. Kupsc [ID](#)⁷⁹, B.K. Kutsenko [ID](#)¹², D. Lacarrere [ID](#)⁴⁶, A. Lai [ID](#)²⁹, A. Lampis [ID](#)²⁹, D. Lancierini [ID](#)⁵³, C. Landesa Gomez [ID](#)⁴⁴, J.J. Lane [ID](#)¹, R. Lane [ID](#)⁵², C. Langenbruch [ID](#)¹⁹, J. Langer [ID](#)¹⁷, O. Lantwin [ID](#)⁴¹, T. Latham [ID](#)⁵⁴, F. Lazzari [ID](#)^{32,t}, C. Lazzeroni [ID](#)⁵¹, R. Le Gac [ID](#)¹², R. Lefèvre [ID](#)¹¹, A. Leflat [ID](#)⁴¹, S. Legotin [ID](#)⁴¹, M. Lehuraux [ID](#)⁵⁴, E. Lemos Cid [ID](#)⁴⁶, O. Leroy [ID](#)¹², T. Lesiak [ID](#)³⁸, B. Leverington [ID](#)¹⁹, A. Li [ID](#)⁴, H. Li [ID](#)⁶⁹, K. Li [ID](#)⁸, L. Li [ID](#)⁶⁰, P. Li [ID](#)⁴⁶, P.-R. Li [ID](#)⁷⁰, S. Li [ID](#)⁸, T. Li [ID](#)^{5,d}, T. Li [ID](#)⁶⁹, Y. Li [ID](#)⁸, Y. Li [ID](#)⁵, Z. Li [ID](#)⁶⁶, Z. Lian [ID](#)⁴, X. Liang [ID](#)⁶⁶, S. Libralon [ID](#)⁴⁵, C. Lin [ID](#)⁷, T. Lin [ID](#)⁵⁵, R. Lindner [ID](#)⁴⁶, V. Lisovskyi [ID](#)⁴⁷, R. Litvinov [ID](#)^{29,k}, F.L. Liu [ID](#)¹, G. Liu [ID](#)⁶⁹, K. Liu [ID](#)⁷⁰, Q. Liu [ID](#)⁷, S. Liu [ID](#)^{5,7}, Y. Liu [ID](#)⁵⁶, Y. Liu [ID](#)⁷⁰, Y.L. Liu [ID](#)⁵⁹, A. Lobo Salvia [ID](#)⁴³, A. Loi [ID](#)²⁹, J. Lomba Castro [ID](#)⁴⁴, T. Long [ID](#)⁵³, J.H. Lopes [ID](#)³, A. Lopez Huertas [ID](#)⁴³, S. López Soliño [ID](#)⁴⁴, G.H. Lovell [ID](#)⁵³, C. Lucarelli [ID](#)^{24,m}, D. Lucchesi [ID](#)^{30,q}, S. Luchuk [ID](#)⁴¹, M. Lucio Martinez [ID](#)⁷⁶, V. Lukashenko [ID](#)^{35,50}, Y. Luo [ID](#)⁶, A. Lupato [ID](#)³⁰, E. Luppi [ID](#)^{23,l}, K. Lynch [ID](#)²⁰, X.-R. Lyu [ID](#)⁷, G.M. Ma [ID](#)⁴, R. Ma [ID](#)⁷, S. Maccolini [ID](#)¹⁷, F. Machefer [ID](#)¹³, F. Maciuc [ID](#)⁴⁰, B.M. Mack [ID](#)⁶⁶, I. Mackay [ID](#)⁶¹, L.M. Mackey [ID](#)⁶⁶, L.R. Madhan Mohan [ID](#)⁵³, M.M. Madurai [ID](#)⁵¹, A. Maevskiy [ID](#)⁴¹, D. Magdalinski [ID](#)³⁵, D. Maisuzenko [ID](#)⁴¹, M.W. Majewski [ID](#)³⁷, J.J. Malczewski [ID](#)³⁸, S. Malde [ID](#)⁶¹, B. Malecki [ID](#)^{38,46}, L. Malentacca [ID](#)⁴⁶, A. Malinin [ID](#)⁴¹, T. Maltsev [ID](#)⁴¹, G. Manca [ID](#)^{29,k}, G. Mancinelli [ID](#)¹², C. Mancuso [ID](#)^{27,13,o}, R. Manera Escalero [ID](#)⁴³, D. Manuzzi [ID](#)²², D. Marangotto [ID](#)^{27,o}, J.F. Marchand [ID](#)¹⁰, R. Marchevski [ID](#)⁴⁷, U. Marconi [ID](#)²², S. Mariani [ID](#)⁴⁶, C. Marin Benito [ID](#)⁴³, J. Marks [ID](#)¹⁹, A.M. Marshall [ID](#)⁵², P.J. Marshall [ID](#)⁵⁸, G. Martelli [ID](#)^{31,r}, G. Martellotti [ID](#)³³, L. Martinazzoli [ID](#)⁴⁶, M. Martinelli [ID](#)^{28,p}, D. Martinez Santos [ID](#)⁴⁴, F. Martinez Vidal [ID](#)⁴⁵, A. Massafferri [ID](#)², M. Materok [ID](#)¹⁶, R. Matev [ID](#)⁴⁶, A. Mathad [ID](#)⁴⁶, V. Matiunin [ID](#)⁴¹, C. Matteuzzi [ID](#)⁶⁶, K.R. Mattioli [ID](#)¹⁴, A. Mauri [ID](#)⁵⁹, E. Maurice [ID](#)¹⁴, J. Mauricio [ID](#)⁴³, P. Mayencourt [ID](#)⁴⁷, M. Mazurek [ID](#)³⁹, M. McCann [ID](#)⁵⁹, L. McConnell [ID](#)²⁰, T.H. McGrath [ID](#)⁶⁰, N.T. McHugh [ID](#)⁵⁷, A. McNab [ID](#)⁶⁰, R. McNulty [ID](#)²⁰, B. Meadows [ID](#)⁶³, G. Meier [ID](#)¹⁷, D. Melnychuk [ID](#)³⁹, M. Merk [ID](#)^{35,76}, A. Merli [ID](#)^{27,o}, L. Meyer Garcia [ID](#)³, D. Miao [ID](#)^{5,7}, H. Miao [ID](#)⁷, M. Mikhasenko [ID](#)^{73,f}, D.A. Milanese [ID](#)⁷², A. Minotti [ID](#)^{28,p}, E. Minucci [ID](#)⁶⁶, T. Miralles [ID](#)¹¹, B. Mitreska [ID](#)¹⁷, D.S. Mitzel [ID](#)¹⁷, A. Modak [ID](#)⁵⁵, A. Mödden [ID](#)¹⁷, R.A. Mohammed [ID](#)⁶¹, R.D. Moise [ID](#)¹⁶, S. Mokhnenko [ID](#)⁴¹, T. Mombächer [ID](#)⁴⁶, M. Monk [ID](#)^{54,1}, S. Monteil [ID](#)¹¹, A. Morcillo Gomez [ID](#)⁴⁴, G. Morello [ID](#)²⁵, M.J. Morello [ID](#)^{32,s}, M.P. Morgenthaler [ID](#)¹⁹, A.B. Morris [ID](#)⁴⁶, A.G. Morris [ID](#)¹², R. Mountain [ID](#)⁶⁶, H. Mu [ID](#)⁴, Z.M. Mu [ID](#)⁶, E. Muhammad [ID](#)⁵⁴, F. Muheim [ID](#)⁵⁶, M. Mulder [ID](#)⁷⁵, K. Müller [ID](#)⁴⁸, F. Muñoz-Rojas [ID](#)⁹, R. Murta [ID](#)⁵⁹, P. Naik [ID](#)⁵⁸, T. Nakada [ID](#)⁴⁷, R. Nandakumar [ID](#)⁵⁵, T. Nanut [ID](#)⁴⁶, I. Nasteva [ID](#)³, M. Needham [ID](#)⁵⁶, N. Neri [ID](#)^{27,o}, S. Neubert [ID](#)⁷³, N. Neufeld [ID](#)⁴⁶, P. Neustroev [ID](#)⁴¹, J. Nicolini [ID](#)^{17,13}, D. Nicotra [ID](#)⁷⁶, E.M. Niel [ID](#)⁴⁷, N. Nikitin [ID](#)⁴¹, P. Nogga [ID](#)⁷³, N.S. Nolte [ID](#)⁶², C. Normand [ID](#)⁵², J. Novoa Fernandez [ID](#)⁴⁴, G. Nowak [ID](#)⁶³, C. Nunez [ID](#)⁸⁰,

H.N. Nur [ID](#)⁵⁷, A. Oblakowska-Mucha [ID](#)³⁷, V. Obraztsov [ID](#)⁴¹, T. Oeser [ID](#)¹⁶, S. Okamura [ID](#)^{23,l,46}, A. Okhotnikov [ID](#)⁴¹, R. Oldeman [ID](#)^{29,k}, F. Oliva [ID](#)⁵⁶, M. Olocco [ID](#)¹⁷, C.J.G. Onderwater [ID](#)⁷⁶, R.H. O’Neil [ID](#)⁵⁶, J.M. Otalora Goicochea [ID](#)³, P. Owen [ID](#)⁴⁸, A. Oyanguren [ID](#)⁴⁵, O. Ozcelik [ID](#)⁵⁶, K.O. Padeken [ID](#)⁷³, B. Pagare [ID](#)⁵⁴, P.R. Pais [ID](#)¹⁹, T. Pajero [ID](#)⁶¹, A. Palano [ID](#)²¹, M. Palutan [ID](#)²⁵, G. Panshin [ID](#)⁴¹, L. Paolucci [ID](#)⁵⁴, A. Papanestis [ID](#)⁵⁵, M. Pappagallo [ID](#)^{21,h}, L.L. Pappalardo [ID](#)^{23,l}, C. Pappenheimer [ID](#)⁶³, C. Parkes [ID](#)⁶⁰, B. Passalacqua [ID](#)²³, G. Passaleva [ID](#)²⁴, D. Passaro [ID](#)^{32,s}, A. Pastore [ID](#)²¹, M. Patel [ID](#)⁵⁹, J. Patoc [ID](#)⁶¹, C. Patrignani [ID](#)^{22,j}, C.J. Pawley [ID](#)⁷⁶, A. Pellegrino [ID](#)³⁵, M. Pepe Altarelli [ID](#)²⁵, S. Perazzini [ID](#)²², D. Pereima [ID](#)⁴¹, A. Pereiro Castro [ID](#)⁴⁴, P. Perret [ID](#)¹¹, A. Perro [ID](#)⁴⁶, K. Petridis [ID](#)⁵², A. Petrolini [ID](#)^{26,n}, S. Petrucci [ID](#)⁵⁶, J.P. Pfaller [ID](#)⁶³, H. Pham [ID](#)⁶⁶, L. Pica [ID](#)^{32,s}, M. Piccini [ID](#)³¹, B. Pietrzyk [ID](#)¹⁰, G. Pietrzyk [ID](#)¹³, D. Pinci [ID](#)³³, F. Pisani [ID](#)⁴⁶, M. Pizzichemi [ID](#)^{28,p}, V. Placinta [ID](#)⁴⁰, M. Plo Casasus [ID](#)⁴⁴, F. Polci [ID](#)^{15,46}, M. Poli Lener [ID](#)²⁵, A. Poluektov [ID](#)¹², N. Polukhina [ID](#)⁴¹, I. Polyakov [ID](#)⁴⁶, E. Polycarpo [ID](#)³, S. Ponce [ID](#)⁴⁶, D. Popov [ID](#)⁷, S. Poslavskii [ID](#)⁴¹, K. Prasanth [ID](#)³⁸, C. Prouve [ID](#)⁴⁴, V. Pugatch [ID](#)⁵⁰, G. Punzi [ID](#)^{32,t}, W. Qian [ID](#)⁷, N. Qin [ID](#)⁴, S. Qu [ID](#)⁴, R. Quagliani [ID](#)⁴⁷, R.I. Rabadan Trejo [ID](#)⁵⁴, J.H. Rademacker [ID](#)⁵², M. Rama [ID](#)³², M. Ramírez García [ID](#)⁸⁰, M. Ramos Pernas [ID](#)⁵⁴, M.S. Rangel [ID](#)³, F. Ratnikov [ID](#)⁴¹, G. Raven [ID](#)³⁶, M. Rebollo De Miguel [ID](#)⁴⁵, F. Redi [ID](#)^{27,i}, J. Reich [ID](#)⁵², F. Reiss [ID](#)⁶⁰, Z. Ren [ID](#)⁷, P.K. Resmi [ID](#)⁶¹, R. Ribatti [ID](#)^{32,s}, G.R. Ricart [ID](#)^{14,81}, D. Riccardi [ID](#)^{32,s}, S. Ricciardi [ID](#)⁵⁵, K. Richardson [ID](#)⁶², M. Richardson-Slipper [ID](#)⁵⁶, K. Rinnert [ID](#)⁵⁸, P. Robbe [ID](#)¹³, G. Robertson [ID](#)⁵⁷, E. Rodrigues [ID](#)⁵⁸, E. Rodriguez Fernandez [ID](#)⁴⁴, J.A. Rodriguez Lopez [ID](#)⁷², E. Rodriguez Rodriguez [ID](#)⁴⁴, A. Rogovskiy [ID](#)⁵⁵, D.L. Rolf [ID](#)⁴⁶, P. Roloff [ID](#)⁴⁶, V. Romanovskiy [ID](#)⁴¹, M. Romero Lamas [ID](#)⁴⁴, A. Romero Vidal [ID](#)⁴⁴, G. Romolini [ID](#)²³, F. Ronchetti [ID](#)⁴⁷, M. Rotondo [ID](#)²⁵, S.R. Roy [ID](#)¹⁹, M.S. Rudolph [ID](#)⁶⁶, T. Ruf [ID](#)⁴⁶, M. Ruiz Diaz [ID](#)¹⁹, R.A. Ruiz Fernandez [ID](#)⁴⁴, J. Ruiz Vidal [ID](#)^{79,z}, A. Ryzhikov [ID](#)⁴¹, J. Ryzka [ID](#)³⁷, J.J. Saavedra-Arias [ID](#)⁹, J.J. Saborido Silva [ID](#)⁴⁴, R. Sadek [ID](#)¹⁴, N. Sagidova [ID](#)⁴¹, D. Sahoo [ID](#)⁷⁴, N. Sahoo [ID](#)⁵¹, B. Saitta [ID](#)^{29,k}, M. Salomoni [ID](#)^{28,p}, C. Sanchez Gras [ID](#)³⁵, I. Sanderswood [ID](#)⁴⁵, R. Santacesaria [ID](#)³³, C. Santamarina Rios [ID](#)⁴⁴, M. Santimaria [ID](#)²⁵, L. Santoro [ID](#)², E. Santovetti [ID](#)³⁴, A. Saputi [ID](#)^{23,46}, D. Saranin [ID](#)⁴¹, G. Sarpis [ID](#)⁵⁶, M. Sarpis [ID](#)⁷³, A. Sarti [ID](#)³³, C. Satriano [ID](#)^{33,u}, A. Satta [ID](#)³⁴, M. Saur [ID](#)⁶, D. Savrina [ID](#)⁴¹, H. Sazak [ID](#)¹⁶, L.G. Scantlebury Smead [ID](#)⁶¹, A. Scarabotto [ID](#)¹⁷, S. Schael [ID](#)¹⁶, S. Scherl [ID](#)⁵⁸, A.M. Schertz [ID](#)⁷⁴, M. Schiller [ID](#)⁵⁷, H. Schindler [ID](#)⁴⁶, M. Schmelling [ID](#)¹⁸, B. Schmidt [ID](#)⁴⁶, S. Schmitt [ID](#)¹⁶, H. Schmitz [ID](#)⁷³, O. Schneider [ID](#)⁴⁷, A. Schopper [ID](#)⁴⁶, N. Schulte [ID](#)¹⁷, S. Schulte [ID](#)⁴⁷, M.H. Schune [ID](#)¹³, R. Schwemmer [ID](#)⁴⁶, G. Schwering [ID](#)¹⁶, B. Sciascia [ID](#)²⁵, A. Sciuccati [ID](#)⁴⁶, S. Sellam [ID](#)⁴⁴, A. Semennikov [ID](#)⁴¹, T. Senger [ID](#)⁴⁸, M. Senghi Soares [ID](#)³⁶, A. Sergi [ID](#)²⁶, N. Serra [ID](#)⁴⁸, L. Sestini [ID](#)³⁰, A. Seuthe [ID](#)¹⁷, Y. Shang [ID](#)⁶, D.M. Shangase [ID](#)⁸⁰, M. Shapkin [ID](#)⁴¹, R.S. Sharma [ID](#)⁶⁶, I. Shchemerov [ID](#)⁴¹, L. Shchutska [ID](#)⁴⁷, T. Shears [ID](#)⁵⁸, L. Shekhtman [ID](#)⁴¹, Z. Shen [ID](#)⁶, S. Sheng [ID](#)^{5,7}, V. Shevchenko [ID](#)⁴¹, B. Shi [ID](#)⁷, E.B. Shields [ID](#)^{28,p}, Y. Shimizu [ID](#)¹³, E. Shmanin [ID](#)⁴¹, R. Shorkin [ID](#)⁴¹, J.D. Shupperd [ID](#)⁶⁶, R. Silva Coutinho [ID](#)⁶⁶, G. Simi [ID](#)³⁰, S. Simone [ID](#)^{21,h}, N. Skidmore [ID](#)⁵⁴, T. Skwarnicki [ID](#)⁶⁶, M.W. Slater [ID](#)⁵¹, J.C. Smallwood [ID](#)⁶¹, E. Smith [ID](#)⁶², K. Smith [ID](#)⁶⁵, M. Smith [ID](#)⁵⁹, A. Snoch [ID](#)³⁵, L. Soares Lavra [ID](#)⁵⁶, M.D. Sokoloff [ID](#)⁶³, F.J.P. Soler [ID](#)⁵⁷, A. Solomin [ID](#)^{41,52}, A. Solovev [ID](#)⁴¹, I. Solovyyev [ID](#)⁴¹, R. Song [ID](#)¹, Y. Song [ID](#)⁴⁷, Y. Song [ID](#)⁴, Y.S. Song [ID](#)⁶, F.L. Souza De Almeida [ID](#)⁶⁶, B. Souza De Paula [ID](#)³, E. Spadaro Norella [ID](#)^{27,o}, E. Spedicato [ID](#)²², J.G. Speer [ID](#)¹⁷, E. Spiridenkov [ID](#)⁴¹, P. Spradlin [ID](#)⁵⁷, V. Sriskaran [ID](#)⁴⁶, F. Stagni [ID](#)⁴⁶, M. Stahl [ID](#)⁴⁶, S. Stahl [ID](#)⁴⁶, S. Stanislaus [ID](#)⁶¹, E.N. Stein [ID](#)⁴⁶, O. Steinkamp [ID](#)⁴⁸, O. Stenyakin [ID](#)⁴¹, H. Stevens [ID](#)¹⁷, D. Strelakina [ID](#)⁴¹, Y. Su [ID](#)⁷, F. Suljik [ID](#)⁶¹, J. Sun [ID](#)²⁹, L. Sun [ID](#)⁷¹, Y. Sun [ID](#)⁶⁴, W. Sutcliffe [ID](#)⁴⁸,

P.N. Swallow [ID](#)⁵¹, F. Swystun [ID](#)⁵³, A. Szabelski [ID](#)³⁹, T. Szumlak [ID](#)³⁷, Y. Tan [ID](#)⁴, S. Taneja [ID](#)⁶⁰, M.D. Tat [ID](#)⁶¹, A. Terentev [ID](#)⁴⁸, F. Terzuoli [ID](#)^{32,w}, F. Teubert [ID](#)⁴⁶, E. Thomas [ID](#)⁴⁶, D.J.D. Thompson [ID](#)⁵¹, H. Tilquin [ID](#)⁵⁹, V. Tisserand [ID](#)¹¹, S. T'Jampens [ID](#)¹⁰, M. Tobin [ID](#)⁵, L. Tomassetti [ID](#)^{23,l}, G. Tonani [ID](#)^{27,o,46}, X. Tong [ID](#)⁶, D. Torres Machado [ID](#)², L. Toscano [ID](#)¹⁷, D.Y. Tou [ID](#)⁴, C. Trippel [ID](#)⁴², G. Tuci [ID](#)¹⁹, N. Tuning [ID](#)³⁵, L.H. Uecker [ID](#)¹⁹, A. Ukleja [ID](#)³⁷, D.J. Unverzagt [ID](#)¹⁹, E. Ursov [ID](#)⁴¹, A. Usachov [ID](#)³⁶, A. Ustyuzhanin [ID](#)⁴¹, U. Uwer [ID](#)¹⁹, V. Vagnoni [ID](#)²², A. Valassi [ID](#)⁴⁶, G. Valenti [ID](#)²², N. Valls Canudas [ID](#)⁴², H. Van Hecke [ID](#)⁶⁵, E. van Herwijnen [ID](#)⁵⁹, C.B. Van Hulse [ID](#)^{44,y}, R. Van Laak [ID](#)⁴⁷, M. van Veghel [ID](#)³⁵, R. Vazquez Gomez [ID](#)⁴³, P. Vazquez Regueiro [ID](#)⁴⁴, C. Vázquez Sierra [ID](#)⁴⁴, S. Vecchi [ID](#)²³, J.J. Velhuis [ID](#)⁵², M. Veltri [ID](#)^{24,x}, A. Venkateswaran [ID](#)⁴⁷, M. Vesterinen [ID](#)⁵⁴, M. Vieites Diaz [ID](#)⁴⁶, X. Vilasis-Cardona [ID](#)⁴², E. Vilella Figueras [ID](#)⁵⁸, A. Villa [ID](#)²², P. Vincent [ID](#)¹⁵, F.C. Volle [ID](#)¹³, D. vom Bruch [ID](#)¹², V. Vorobyev⁴¹, N. Voropaev [ID](#)⁴¹, K. Vos [ID](#)⁷⁶, G. Vouters¹⁰, C. Vrahas [ID](#)⁵⁶, J. Wagner [ID](#)¹⁷, J. Walsh [ID](#)³², E.J. Walton [ID](#)^{1,54}, G. Wan [ID](#)⁶, C. Wang [ID](#)¹⁹, G. Wang [ID](#)⁸, J. Wang [ID](#)⁶, J. Wang [ID](#)⁵, J. Wang [ID](#)⁴, J. Wang [ID](#)⁷¹, M. Wang [ID](#)²⁷, N.W. Wang [ID](#)⁷, R. Wang [ID](#)⁵², X. Wang [ID](#)⁶⁹, X.W. Wang [ID](#)⁵⁹, Y. Wang [ID](#)⁸, Z. Wang [ID](#)¹³, Z. Wang [ID](#)⁴, Z. Wang [ID](#)²⁷, J.A. Ward [ID](#)^{54,1}, M. Waterlaat⁴⁶, N.K. Watson [ID](#)⁵¹, D. Websdale [ID](#)⁵⁹, Y. Wei [ID](#)⁶, B.D.C. Westhenry [ID](#)⁵², D.J. White [ID](#)⁶⁰, M. Whitehead [ID](#)⁵⁷, A.R. Wiederhold [ID](#)⁵⁴, D. Wiedner [ID](#)¹⁷, G. Wilkinson [ID](#)⁶¹, M.K. Wilkinson [ID](#)⁶³, M. Williams [ID](#)⁶², M.R.J. Williams [ID](#)⁵⁶, R. Williams [ID](#)⁵³, F.F. Wilson [ID](#)⁵⁵, W. Wislicki [ID](#)³⁹, M. Witek [ID](#)³⁸, L. Witola [ID](#)¹⁹, C.P. Wong [ID](#)⁶⁵, G. Wormser [ID](#)¹³, S.A. Wotton [ID](#)⁵³, H. Wu [ID](#)⁶⁶, J. Wu [ID](#)⁸, Y. Wu [ID](#)⁶, K. Wyllie [ID](#)⁴⁶, S. Xian⁶⁹, Z. Xiang [ID](#)⁵, Y. Xie [ID](#)⁸, A. Xu [ID](#)³², J. Xu [ID](#)⁷, L. Xu [ID](#)⁴, L. Xu [ID](#)⁴, M. Xu [ID](#)⁵⁴, Z. Xu [ID](#)¹¹, Z. Xu [ID](#)⁷, Z. Xu [ID](#)⁵, D. Yang [ID](#)⁴, S. Yang [ID](#)⁷, X. Yang [ID](#)⁶, Y. Yang [ID](#)^{26,n}, Z. Yang [ID](#)⁶, Z. Yang [ID](#)⁶⁴, V. Yeroshenko [ID](#)¹³, H. Yeung [ID](#)⁶⁰, H. Yin [ID](#)⁸, C.Y. Yu [ID](#)⁶, J. Yu [ID](#)⁶⁸, X. Yuan [ID](#)⁵, E. Zaffaroni [ID](#)⁴⁷, M. Zavertyaev [ID](#)¹⁸, M. Zdybal [ID](#)³⁸, M. Zeng [ID](#)⁴, C. Zhang [ID](#)⁶, D. Zhang [ID](#)⁸, J. Zhang [ID](#)⁷, L. Zhang [ID](#)⁴, S. Zhang [ID](#)⁶⁸, S. Zhang [ID](#)⁶, Y. Zhang [ID](#)⁶, Y.Z. Zhang [ID](#)⁴, Y. Zhao [ID](#)¹⁹, A. Zharkova [ID](#)⁴¹, A. Zhelezov [ID](#)¹⁹, X.Z. Zheng [ID](#)⁴, Y. Zheng [ID](#)⁷, T. Zhou [ID](#)⁶, X. Zhou [ID](#)⁸, Y. Zhou [ID](#)⁷, V. Zhovkovska [ID](#)⁵⁴, L.Z. Zhu [ID](#)⁷, X. Zhu [ID](#)⁴, X. Zhu [ID](#)⁸, V. Zhukov [ID](#)¹⁶, J. Zhuo [ID](#)⁴⁵, Q. Zou [ID](#)^{5,7}, D. Zuliani [ID](#)³⁰, G. Zunica [ID](#)⁴⁷

¹ School of Physics and Astronomy, Monash University, Melbourne, Australia

² Centro Brasileiro de Pesquisas Físicas (CBPF), Rio de Janeiro, Brazil

³ Universidade Federal do Rio de Janeiro (UFRJ), Rio de Janeiro, Brazil

⁴ Center for High Energy Physics, Tsinghua University, Beijing, China

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

⁶ School of Physics State Key Laboratory of Nuclear Physics and Technology, Peking University, Beijing, China

⁷ University of Chinese Academy of Sciences, Beijing, China

⁸ Institute of Particle Physics, Central China Normal University, Wuhan, Hubei, China

⁹ Consejo Nacional de Rectores (CONARE), San Jose, Costa Rica

¹⁰ Université Savoie Mont Blanc, CNRS, IN2P3-LAPP, Annecy, France

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

¹² Aix Marseille Univ, CNRS/IN2P3, CPPM, Marseille, France

¹³ Université Paris-Saclay, CNRS/IN2P3, IJCLab, Orsay, France

¹⁴ Laboratoire Leprince-Ringuet, CNRS/IN2P3, Ecole Polytechnique, Institut Polytechnique de Paris, Palaiseau, France

¹⁵ LPNHE, Sorbonne Université, Paris Diderot Sorbonne Paris Cité, CNRS/IN2P3, Paris, France

¹⁶ I. Physikalisches Institut, RWTH Aachen University, Aachen, Germany

¹⁷ Fakultät Physik, Technische Universität Dortmund, Dortmund, Germany

- ¹⁸ *Max-Planck-Institut für Kernphysik (MPIK), Heidelberg, Germany*
- ¹⁹ *Physikalisches Institut, Ruprecht-Karls-Universität Heidelberg, Heidelberg, Germany*
- ²⁰ *School of Physics, University College Dublin, Dublin, Ireland*
- ²¹ *INFN Sezione di Bari, Bari, Italy*
- ²² *INFN Sezione di Bologna, Bologna, Italy*
- ²³ *INFN Sezione di Ferrara, Ferrara, Italy*
- ²⁴ *INFN Sezione di Firenze, Firenze, Italy*
- ²⁵ *INFN Laboratori Nazionali di Frascati, Frascati, Italy*
- ²⁶ *INFN Sezione di Genova, Genova, Italy*
- ²⁷ *INFN Sezione di Milano, Milano, Italy*
- ²⁸ *INFN Sezione di Milano-Bicocca, Milano, Italy*
- ²⁹ *INFN Sezione di Cagliari, Monserrato, Italy*
- ³⁰ *Università degli Studi di Padova, Università e INFN, Padova, Padova, Italy*
- ³¹ *INFN Sezione di Perugia, Perugia, Italy*
- ³² *INFN Sezione di Pisa, Pisa, Italy*
- ³³ *INFN Sezione di Roma La Sapienza, Roma, Italy*
- ³⁴ *INFN Sezione di Roma Tor Vergata, Roma, Italy*
- ³⁵ *Nikhef National Institute for Subatomic Physics, Amsterdam, Netherlands*
- ³⁶ *Nikhef National Institute for Subatomic Physics and VU University Amsterdam, Amsterdam, Netherlands*
- ³⁷ *AGH — University of Krakow, Faculty of Physics and Applied Computer Science, Kraków, Poland*
- ³⁸ *Henryk Niewodniczanski Institute of Nuclear Physics Polish Academy of Sciences, Kraków, Poland*
- ³⁹ *National Center for Nuclear Research (NCBJ), Warsaw, Poland*
- ⁴⁰ *Horia Hulubei National Institute of Physics and Nuclear Engineering, Bucharest-Magurele, Romania*
- ⁴¹ *Affiliated with an institute covered by a cooperation agreement with CERN*
- ⁴² *DS4DS, La Salle, Universitat Ramon Llull, Barcelona, Spain*
- ⁴³ *ICCUB, Universitat de Barcelona, Barcelona, Spain*
- ⁴⁴ *Instituto Galego de Física de Altas Enerxías (IGFAE), Universidade de Santiago de Compostela, Santiago de Compostela, Spain*
- ⁴⁵ *Instituto de Física Corpuscular, Centro Mixto Universidad de Valencia — CSIC, Valencia, Spain*
- ⁴⁶ *European Organization for Nuclear Research (CERN), Geneva, Switzerland*
- ⁴⁷ *Institute of Physics, Ecole Polytechnique Fédérale de Lausanne (EPFL), Lausanne, Switzerland*
- ⁴⁸ *Physik-Institut, Universität Zürich, Zürich, Switzerland*
- ⁴⁹ *NSC Kharkiv Institute of Physics and Technology (NSC KIPT), Kharkiv, Ukraine*
- ⁵⁰ *Institute for Nuclear Research of the National Academy of Sciences (KINR), Kyiv, Ukraine*
- ⁵¹ *University of Birmingham, Birmingham, United Kingdom*
- ⁵² *H.H. Wills Physics Laboratory, University of Bristol, Bristol, United Kingdom*
- ⁵³ *Cavendish Laboratory, University of Cambridge, Cambridge, United Kingdom*
- ⁵⁴ *Department of Physics, University of Warwick, Coventry, United Kingdom*
- ⁵⁵ *STFC Rutherford Appleton Laboratory, Didcot, United Kingdom*
- ⁵⁶ *School of Physics and Astronomy, University of Edinburgh, Edinburgh, United Kingdom*
- ⁵⁷ *School of Physics and Astronomy, University of Glasgow, Glasgow, United Kingdom*
- ⁵⁸ *Oliver Lodge Laboratory, University of Liverpool, Liverpool, United Kingdom*
- ⁵⁹ *Imperial College London, London, United Kingdom*
- ⁶⁰ *Department of Physics and Astronomy, University of Manchester, Manchester, United Kingdom*
- ⁶¹ *Department of Physics, University of Oxford, Oxford, United Kingdom*
- ⁶² *Massachusetts Institute of Technology, Cambridge, MA, United States*
- ⁶³ *University of Cincinnati, Cincinnati, OH, United States*
- ⁶⁴ *University of Maryland, College Park, MD, United States*
- ⁶⁵ *Los Alamos National Laboratory (LANL), Los Alamos, NM, United States*
- ⁶⁶ *Syracuse University, Syracuse, NY, United States*
- ⁶⁷ *Pontifícia Universidade Católica do Rio de Janeiro (PUC-Rio), Rio de Janeiro, Brazil, associated to ³*
- ⁶⁸ *School of Physics and Electronics, Hunan University, Changsha City, China, associated to ⁸*

- ⁶⁹ *Guangdong Provincial Key Laboratory of Nuclear Science, Guangdong-Hong Kong Joint Laboratory of Quantum Matter, Institute of Quantum Matter, South China Normal University, Guangzhou, China, associated to* ⁴
- ⁷⁰ *Lanzhou University, Lanzhou, China, associated to* ⁵
- ⁷¹ *School of Physics and Technology, Wuhan University, Wuhan, China, associated to* ⁴
- ⁷² *Departamento de Física, Universidad Nacional de Colombia, Bogota, Colombia, associated to* ¹⁵
- ⁷³ *Universität Bonn — Helmholtz-Institut für Strahlen und Kernphysik, Bonn, Germany, associated to* ¹⁹
- ⁷⁴ *Eotvos Lorand University, Budapest, Hungary, associated to* ⁴⁶
- ⁷⁵ *Van Swinderen Institute, University of Groningen, Groningen, Netherlands, associated to* ³⁵
- ⁷⁶ *Universiteit Maastricht, Maastricht, Netherlands, associated to* ³⁵
- ⁷⁷ *Tadeusz Kosciuszko Cracow University of Technology, Cracow, Poland, associated to* ³⁸
- ⁷⁸ *Universidad de Coruña, A Coruna, Spain, associated to* ⁴²
- ⁷⁹ *Department of Physics and Astronomy, Uppsala University, Uppsala, Sweden, associated to* ⁵⁷
- ⁸⁰ *University of Michigan, Ann Arbor, MI, United States, associated to* ⁶⁶
- ⁸¹ *Departement de Physique Nucleaire (SPhN), Gif-Sur-Yvette, France*

^a *Universidade de Brasília, Brasília, Brazil*

^b *Centro Federal de Educação Tecnológica Celso Suckow da Fonseca, Rio De Janeiro, Brazil*

^c *Hangzhou Institute for Advanced Study, UCAS, Hangzhou, China*

^d *School of Physics and Electronics, Henan University, Kaifeng, China*

^e *LIP6, Sorbonne Universite, Paris, France*

^f *Excellence Cluster ORIGINS, Munich, Germany*

^g *Universidad Nacional Autónoma de Honduras, Tegucigalpa, Honduras*

^h *Università di Bari, Bari, Italy*

ⁱ *Università degli studi di Bergamo, Bergamo, Italy*

^j *Università di Bologna, Bologna, Italy*

^k *Università di Cagliari, Cagliari, Italy*

^l *Università di Ferrara, Ferrara, Italy*

^m *Università di Firenze, Firenze, Italy*

ⁿ *Università di Genova, Genova, Italy*

^o *Università degli Studi di Milano, Milano, Italy*

^p *Università di Milano Bicocca, Milano, Italy*

^q *Università di Padova, Padova, Italy*

^r *Università di Perugia, Perugia, Italy*

^s *Scuola Normale Superiore, Pisa, Italy*

^t *Università di Pisa, Pisa, Italy*

^u *Università della Basilicata, Potenza, Italy*

^v *Università di Roma Tor Vergata, Roma, Italy*

^w *Università di Siena, Siena, Italy*

^x *Università di Urbino, Urbino, Italy*

^y *Universidad de Alcalá, Alcalá de Henares, Spain*

^z *Department of Physics/Division of Particle Physics, Lund, Sweden*

[†] *Deceased*