

RECEIVED: October 24, 2022

REVISED: November 29, 2022

ACCEPTED: December 19, 2022

PUBLISHED: July 7, 2023

Measurement of the ratio of branching fractions $\mathcal{B}(B_c^+ \rightarrow B_s^0 \pi^+) / \mathcal{B}(B_c^+ \rightarrow J/\psi \pi^+)$



The LHCb collaboration

E-mail: qi.shi@cern.ch

ABSTRACT: The ratio of branching fractions of $B_c^+ \rightarrow B_s^0 \pi^+$ and $B_c^+ \rightarrow J/\psi \pi^+$ decays is measured with proton-proton collision data of a centre-of-mass energy of 13 TeV. The data were collected with the LHCb experiment during 2016–2018, corresponding to an integrated luminosity of 5.4 fb^{-1} . The B_s^0 mesons are reconstructed via the decays $B_s^0 \rightarrow J/\psi \phi$ and $B_s^0 \rightarrow D_s^- \pi^+$. The ratio of branching fractions is measured to be $\mathcal{B}(B_c^+ \rightarrow B_s^0 \pi^+) / \mathcal{B}(B_c^+ \rightarrow J/\psi \pi^+) = 91 \pm 10 \pm 8 \pm 3$ where the first uncertainty is statistical, the second is systematic and the third is due to the knowledge of the branching fractions of the intermediate state decays.

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

ARXIV EPRINT: [2210.12000](https://arxiv.org/abs/2210.12000)

Contents

1	Introduction	1
2	Detector and simulation	2
3	Event selection	3
4	Signal yields and efficiencies	4
5	Systematic uncertainties	5
6	Results	7
7	Discussion of $\mathcal{B}(B_c^+ \rightarrow B_s^0 \pi^+)$	8
	The LHCb collaboration	12

1 Introduction

The $B_c^{(*)+}$ family of mesons is the only one formed by two different heavy flavour quarks ($\bar{b}c$). Both the \bar{b} quark and the c quark can each decay with the other as a spectator, leading to final states such as $J/\psi\pi^+$ and $B_s^0\pi^+$. In addition, the \bar{b} quark and the c quark can annihilate via a W^+ boson, allowing pure leptonic final states such as $\tau^+\nu_\tau$.

The $B_c^+ \rightarrow B_s^0\pi^+$ decay¹ was first observed in 2013 by the LHCb collaboration [1], and can be used to tag the initial flavour of the B_s^0 meson with the charge of the accompanying π^+ meson. The $B_c^+ \rightarrow B_s^0\pi^+$ decay is also the first observed case of one B meson decaying weakly into another B meson. This property makes the decay ideal for testing theoretical models. The branching fraction of the $B_c^+ \rightarrow B_s^0\pi^+$ decay should be large as it is a Cabibbo-favoured decay. There are several predictions for the branching fraction of the $B_c^+ \rightarrow B_s^0\pi^+$ decay based on QCD sum rules or quark-potential models, which range between 2.5% and 16.4% [2–9]. A precise measurement of the branching fraction of the $B_c^+ \rightarrow B_s^0\pi^+$ decay will improve the understanding of the B_c^+ theory models.

The $B_c^+ \rightarrow \tau^+\nu_\tau$ decay is highly sensitive to new physics effects [10–12] but experimental accessibility to this mode is limited. Due to the large branching fraction of the $B_c^+ \rightarrow B_s^0\pi^+$ decay, its improved measurement contributes to a more stringent limit on the $B_c^+ \rightarrow \tau^+\nu_\tau$ decay via the B_c^+ total decay width, depending on the theoretical model assumed [11, 13, 14].

In this paper, the ratio between the branching fractions of the $B_c^+ \rightarrow B_s^0\pi^+$ and $B_c^+ \rightarrow J/\psi\pi^+$ decays is measured, using proton-proton (pp) collision data collected with the LHCb experiment between 2016 and 2018 at a centre-of-mass energy of 13 TeV, corresponding

¹Inclusion of charge conjugate processes is implied throughout this paper.

Decay	Branching fraction [%]
$D_s^- \rightarrow K^+ K^- \pi^-$	5.38 ± 0.10
$B_s^0 \rightarrow D_s^- \pi^+$	0.298 ± 0.014
$B_s^0 \rightarrow J/\psi \phi$	0.104 ± 0.004
$\phi \rightarrow K^+ K^-$	49.1 ± 0.5
$J/\psi \rightarrow \mu^+ \mu^-$	5.961 ± 0.033

Table 1. Branching fractions of intermediate-state decays [15].

to an integrated luminosity of 5.4 fb^{-1} . The ratio of branching fractions is measured separately using the $B_s^0 \rightarrow J/\psi(\rightarrow \mu^+ \mu^-) \phi(\rightarrow K^+ K^-)$ and $B_s^0 \rightarrow D_s^-(\rightarrow K^+ K^- \pi^-) \pi^+$ decays. These two measurements are then combined. The ratio of branching fractions is evaluated as

$$\mathcal{R}_X \equiv \frac{\mathcal{B}(B_c^+ \rightarrow B_s^0 \pi^+)}{\mathcal{B}(B_c^+ \rightarrow J/\psi \pi^+)} = \frac{N_{B_c^+ \rightarrow B_s^0 \pi^+}}{N_{B_c^+ \rightarrow J/\psi \pi^+}} \cdot \frac{\epsilon_{B_c^+ \rightarrow J/\psi \pi^+}}{\epsilon_{B_c^+ \rightarrow B_s^0 \pi^+}} \cdot \frac{1}{\mathcal{R}_{\text{int}}^X}, \quad (1.1)$$

where N is the signal yield, ϵ is the total efficiency to reconstruct these decays, and $\mathcal{R}_{\text{int}}^X$ is the ratio of branching fractions of the corresponding intermediate state decays, as shown in table 1. The X represents the final state of the B_s^0 decay, $J/\psi \phi$ or $D_s^- \pi^+$. The superscripts or subscripts $J/\psi \phi$ and $D_s^- \pi^+$ are used to indicate the $B_c^+ \rightarrow B_s^0(\rightarrow J/\psi \phi) \pi^+$ and $B_c^+ \rightarrow B_s^0(\rightarrow D_s^- \pi^+) \pi^+$ decay modes. The $\mathcal{R}_{\text{int}}^X$ are defined as

$$\mathcal{R}_{\text{int}}^{J/\psi \phi} \equiv \mathcal{B}(B_s^0 \rightarrow J/\psi \phi) \cdot \mathcal{B}(\phi \rightarrow K^+ K^-), \quad (1.2)$$

$$\mathcal{R}_{\text{int}}^{D_s^- \pi^+} \equiv \mathcal{B}(B_s^0 \rightarrow D_s^- \pi^+) \cdot \mathcal{B}(D_s^- \rightarrow K^+ K^- \pi^-) / \mathcal{B}(J/\psi \rightarrow \mu^+ \mu^-) \quad (1.3)$$

with corresponding values of $\mathcal{R}_{\text{int}}^{J/\psi \phi} = (5.11 \pm 0.20) \times 10^{-4}$ and $\mathcal{R}_{\text{int}}^{D_s^- \pi^+} = (2.69 \pm 0.14) \times 10^{-3}$.

2 Detector and simulation

The LHCb detector [16, 17] 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 [18], a large-area silicon-strip detector located upstream of a dipole magnet with a bending power of about 4 Tm, and three stations of silicon-strip detectors and straw drift tubes placed downstream of the magnet [19]. 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 (IP), 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 [20]. Photons, electrons and hadrons are identified by a calorimeter system consisting of scintillating-pad and preshower

detectors, an electromagnetic and a hadronic calorimeter. Muons are identified by a system composed of alternating layers of iron and multiwire proportional chambers [21]. The online event selection is performed by a trigger [22], 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.

Simulation is required to model the effects of the detector acceptance and the imposed selection requirements. In the simulation, pp collisions are generated using PYTHIA 8 [23, 24] with a specific LHCb configuration [25]. A dedicated generator BCVEGPY [26] is used to simulate the production of B_c^+ mesons. Decays of unstable particles are described by EVTGEN [27], in which final-state radiation is generated using PHOTOS [28]. The interaction of the generated particles with the detector, and its response, are implemented using the GEANT4 toolkit [29, 30] as described in ref. [31].

3 Event selection

In the $B_c^+ \rightarrow B_s^0 \pi^+$ decay mode, the B_s^0 meson is reconstructed using two decay modes, $B_s^0 \rightarrow J/\psi \phi$ and $B_s^0 \rightarrow D_s^- \pi^+$, with the intermediate states selected based on the $D_s^- \rightarrow K^+ K^- \pi^-$, $J/\psi \rightarrow \mu^+ \mu^-$ and $\phi \rightarrow K^+ K^-$ decays. The reconstructed B_s^0 candidates are selected using the boosted decision tree (BDT) [32–34] classifier used in refs. [1, 35], with the same working points. In the $B_c^+ \rightarrow J/\psi \pi^+$ decay channel, the J/ψ mesons are reconstructed using a pair of oppositely charged muons. The selected B_s^0 and J/ψ candidates are combined with a track identified as a pion to reconstruct the B_c^+ candidates. These candidates and all intermediate states are required to have good vertex-fit quality. All final state particles (pions, kaons and muons) are required to have a good track-fit quality and high transverse momentum. Particle identification (PID) information is used to suppress misidentified tracks. The reconstructed masses of intermediate state particles are required to be within three times the expected mass resolution of their known masses [15]. A second boosted decision tree classifier taken from refs. [35, 36] is used to further distinguish signal B_c^+ mesons from combinatorial background. The vertex fit quality, transverse momentum and topological information are used in all BDT classifiers.

In the offline selection, trigger signatures are associated with reconstructed particles. Selection requirements can therefore be made on the trigger selection itself and on whether the event was selected at trigger level because of the signal candidate (denoted TOS), or because of the decay products of the b - or c -hadrons produced together with the signal B_c^+ meson (denoted TIS). For the $B_c^+ \rightarrow B_s^0(\rightarrow J/\psi \phi) \pi^+$ decay, the reconstructed J/ψ mesons are required to pass the hardware trigger that selects a muon or a pair of muons with high p_T (the muon TOS trigger). For the $B_c^+ \rightarrow B_s^0(\rightarrow D_s^- \pi^+) \pi^+$ decay, hadronic triggers are avoided due to the complexity of simulating the detector response of many-body final states overlapping in the calorimeter. Instead, events containing $B_c^+ \rightarrow B_s^0 \pi^+$ decays are required to pass the trigger in case there is a muon or pair of muons in the rest of the event, not related to the B_c^+ daughter particles (the muon TIS trigger). This requirement gives better control of trigger efficiencies, even though it reduces the signal yields. In the $\mathcal{R}_{J/\psi \phi}$ case, the TOS trigger requirement is applied to the $B_c^+ \rightarrow B_s^0 \pi^+$ and $B_c^+ \rightarrow J/\psi \pi^+$ decays, and in the $\mathcal{R}_{D_s^- \pi^+}$ case, the TIS trigger requirement is applied.

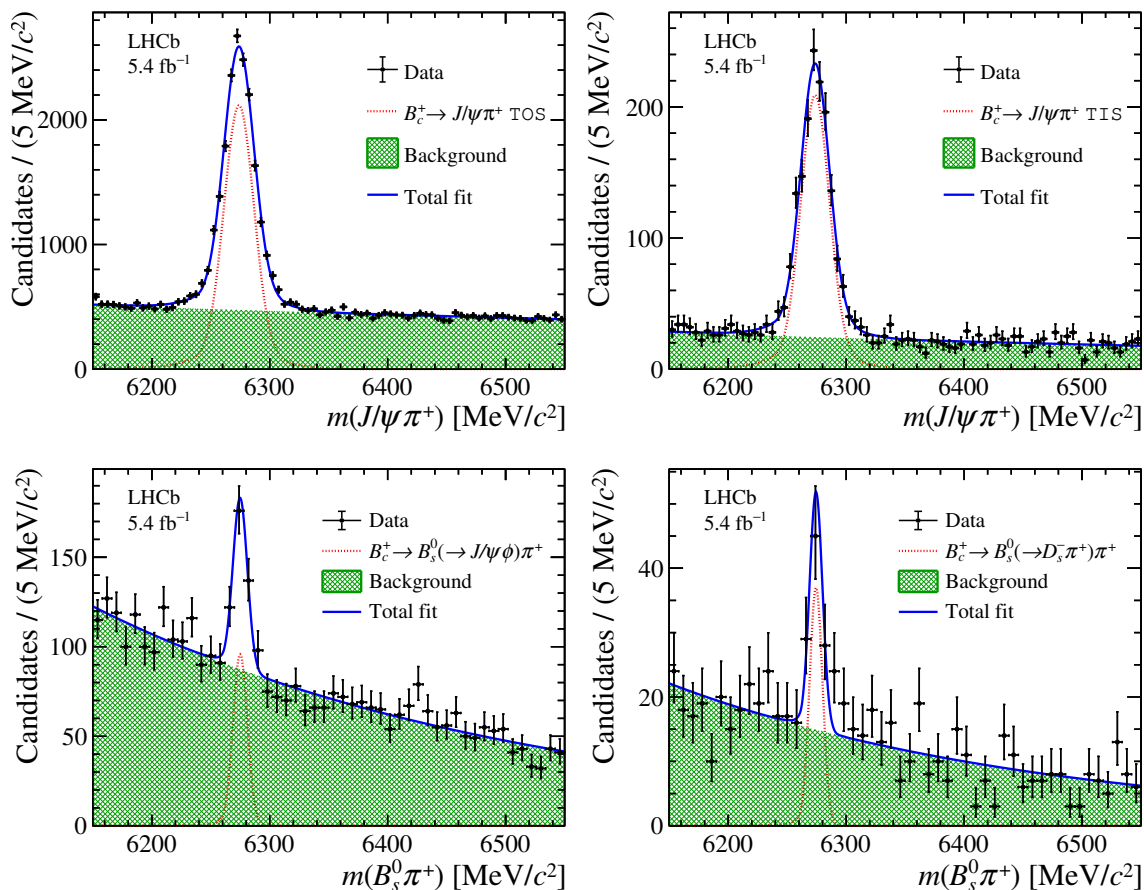


Figure 1. Invariant-mass distributions of B_c^+ candidates: (top left) $B_c^+ \rightarrow J/\psi\pi^+$ TOS, (top right) $B_c^+ \rightarrow J/\psi\pi^+$ TIS, (bottom left) $B_c^+ \rightarrow B_s^0(\rightarrow J/\psi\phi)\pi^+$, and (bottom right) $B_c^+ \rightarrow B_s^0(\rightarrow D_s^-\pi^+)\pi^+$. The black dots represent the data, the blue line represents the results of the total fit, and the red dashed line and green shaded area show the signal and combinatorial background components, respectively.

4 Signal yields and efficiencies

The signal yields are determined from unbinned maximum-likelihood fits to the B_c^+ candidate invariant-mass distributions. The invariant mass spectrum of B_c^+ -meson candidates is obtained from a fit to the whole decay chain with the masses of B_s^0 , J/ψ , and D_s^- mesons constrained to their known values [15], as described in ref. [37]. For the $B_c^+ \rightarrow J/\psi\pi^+$ decay, the signal component is modelled using the sum of two double-sided Crystal Ball (DSCB) functions [38] with a common peak position. For the $B_c^+ \rightarrow B_s^0\pi^+$ decay, one DSCB function is sufficient to model the signal shape. The tail parameters of all DSCB functions are determined from simulation, as detailed in ref. [35]. In both cases the combinatorial background is modelled with an exponential function. The fit results are shown in figure 1, and the signal yields are summarised in table 2.

The total efficiency is calculated as the product of the geometrical detector acceptance and of the efficiencies related to particle reconstruction, event selection, particle identification

Decay channel	Signal yields
$B_c^+ \rightarrow J/\psi\pi^+$ (TOS)	14641 ± 195
$B_c^+ \rightarrow J/\psi\pi^+$ (TIS)	1376 ± 45
$B_c^+ \rightarrow B_s^0(\rightarrow J/\psi\phi)\pi^+$	186 ± 25
$B_c^+ \rightarrow B_s^0(\rightarrow D_s^-\pi^+)\pi^+$	65 ± 12

Table 2. Yields of the normalisation and signal decay modes.

Decay channel	Efficiency [%]
$B_c^+ \rightarrow J/\psi\pi^+$ (TOS)	1.6141 ± 0.0028
$B_c^+ \rightarrow J/\psi\pi^+$ (TIS)	0.15846 ± 0.00063
$B_c^+ \rightarrow B_s^0(\rightarrow J/\psi\phi)\pi^+$	0.4526 ± 0.0013
$B_c^+ \rightarrow B_s^0(\rightarrow D_s^-\pi^+)\pi^+$	0.02801 ± 0.00028

Table 3. Total efficiencies of the $B_c^+ \rightarrow J/\psi\pi^+$ and $B_c^+ \rightarrow B_s^0\pi^+$ decay modes. The uncertainties are due to the finite size of the simulated samples.

and trigger decision. The efficiencies are determined using simulation calibrated with data. Since the number of final-state particles is different between the signal and normalisation modes (five and three, respectively), accurate modelling of the track reconstruction efficiency is important. For every event, a track-by-track correction to the track reconstruction efficiency of all final states is applied using a calibration sample of $J/\psi \rightarrow \mu^+\mu^-$ decays [39]. The PID information used in the event selection is corrected with high-yield calibration samples ($D^{*+} \rightarrow D^0\pi^+$ with $D^0 \rightarrow K^-\pi^+$ decays for hadrons, and the $J/\psi \rightarrow \mu^+\mu^-$ decay for muons) [40]. The total efficiencies are listed in table 3.

5 Systematic uncertainties

The measurement is affected by the systematic uncertainty in the determination of signal yields and efficiencies, as summarised in table 4.

The systematic uncertainty due to the signal lineshape modelling is studied using pseudoexperiments. The signal candidates in the fully simulated samples are mixed with background events that are randomly generated with the exponential shape and fraction determined from the fits to the data. The same fit model used for the data fit is applied to these samples. The difference between the fitted value of the signal yield ratio $N_{B_c^+ \rightarrow B_s^0\pi^+}/N_{B_c^+ \rightarrow J/\psi\pi^+}$ and the generated ratio in simulated samples is taken as the systematic uncertainty, 3.0% for $\mathcal{R}_{J/\psi\phi}$ and 4.4% for $\mathcal{R}_{D_s^-\pi^+}$. The systematic uncertainty of the background lineshape is estimated by using a first-order polynomial function as an alternative shape, and the difference with the default result is taken as the systematic uncertainty, which is 5.5% for $\mathcal{R}_{J/\psi\phi}$ and 4.5% for $\mathcal{R}_{D_s^-\pi^+}$.

	$\mathcal{R}_{J/\psi\phi}$ [%]	$\mathcal{R}_{D_s^- \pi^+}$ [%]
Signal model	3.0	4.4
Background model	5.5	4.5
$B_c^+ \rightarrow B_s^{*0} \pi^+$ component	3.2	3.1
Data-simulation agreement	2.3	4.8
Tracking efficiency	3.2	6.0
Simulation sample size	0.3	1.1
Trigger	1.0	1.0
Total	8.1	10.5

Table 4. Relative systematic uncertainties in the ratio of the branching fractions where the symbol $\mathcal{R}_{J/\psi\phi}$ indicates the ratio of branching fractions measured with the $B_c^+ \rightarrow B_s^0(\rightarrow J/\psi\phi)\pi^+$ decay channel and $\mathcal{R}_{D_s^- \pi^+}$ that using the $B_c^+ \rightarrow B_s^0(\rightarrow D_s^- \pi^+)\pi^+$ decay.

The B_c^+ mesons can also decay to a $B_s^{*0} \pi^+$ state, followed by the $B_s^{*0} \rightarrow B_s^0 \gamma$ decay. This final state, with an unobserved photon, mimics the signal but with the reconstructed $m(B_s^0 \pi^+)$ shifted to lower values by the mass difference between B_s^{*0} and B_s^0 mesons to a good approximation. In this case, the B_c^+ mass resolution is almost unaffected [1, 41]. To estimate the impact of this potential partially reconstructed decay, an alternative fit to the $m(B_s^0 \pi^+)$ mass distribution is performed including an additional $B_s^{*0} \pi^+$ component. The fit model for $B_c^+ \rightarrow B_s^{*0} \pi^+$ is a DSCB function with the same tail parameters as in the default fit. The mass resolution is assumed to be the same as the signal and the mass shift is fixed to the known mass difference between B_s^0 and B_s^{*0} mesons, $48.5_{-1.5}^{+1.8} \text{ MeV}/c^2$ [15]. The difference in the signal yield ratio is taken as the relevant systematic uncertainty, which is 3.2% for $\mathcal{R}_{J/\psi\phi}$ and 3.1% for $\mathcal{R}_{D_s^- \pi^+}$.

As some efficiencies are determined from simulated samples, any discrepancy between data and simulated events can introduce a bias. Distributions of kinematic variables in simulation and in background-subtracted data using the *sPlot* technique [42] are compared. The differences of the efficiencies between the unchanged simulation and after the alignment between data and simulation are 2.3% for $\mathcal{R}_{J/\psi\phi}$ and 4.8% for $\mathcal{R}_{D_s^- \pi^+}$, respectively, which are taken as systematic uncertainties.

The tracking efficiency, which is determined on data calibration samples, has a systematic uncertainty of 1% per track. Due to the hadronic interactions and the uncertainty of the LHCb material-budget in simulation, there is 1.1% additional uncertainty for kaons and 1.4% additional uncertainty for pions. The uncertainties for the same particles in numerator and denominator largely cancel in the ratio. Therefore, the systematic uncertainty is found to be 3.2% for the $\mathcal{R}_{J/\psi\phi}$ measurement and 6.0% for $\mathcal{R}_{D_s^- \pi^+}$.

The efficiencies determined from simulated events have uncertainties due to the limited size of the samples. The relative uncertainty in the total efficiency ratio $\epsilon(B_c^+ \rightarrow J/\psi\pi^+)/\epsilon(B_c^+ \rightarrow B_s^0\pi^+)$ is considered as the systematic uncertainty, the value is 0.3% for $\mathcal{R}_{J/\psi\phi}$ and 1.1% for $\mathcal{R}_{D_s^- \pi^+}$. The imperfect simulation of the trigger system can also cause a bias in the trigger selection efficiency. An uncertainty of 1.0% is assigned to the trigger

selection following ref. [43]. Other potential sources of systematic uncertainty, such as those associated with the PID calibration, are found to be negligible. A summary of the systematic uncertainties is given in table 4.

6 Results

The ratio of the total branching fractions, including the branching fractions of the intermediate states, is determined as

$$\mathcal{R}_{J/\psi\phi}^{\text{tot}} \equiv \frac{N_{B_c^+ \rightarrow B_s^0(\rightarrow J/\psi\phi)\pi^+}}{N_{B_c^+ \rightarrow J/\psi\pi^+}} \cdot \frac{\epsilon_{B_c^+ \rightarrow J/\psi\pi^+}}{\epsilon_{B_c^+ \rightarrow B_s^0(\rightarrow J/\psi\phi)\pi^+}}, \quad (6.1)$$

$$\mathcal{R}_{D_s^- \pi^+}^{\text{tot}} \equiv \frac{N_{B_c^+ \rightarrow B_s^0(\rightarrow D_s^- \pi^+)\pi^+}}{N_{B_c^+ \rightarrow J/\psi\pi^+}} \cdot \frac{\epsilon_{B_c^+ \rightarrow J/\psi\pi^+}}{\epsilon_{B_c^+ \rightarrow B_s^0(\rightarrow D_s^- \pi^+)\pi^+}}, \quad (6.2)$$

and are measured to be

$$\begin{aligned} \mathcal{R}_{J/\psi\phi}^{\text{tot}} &= 0.0453 \pm 0.0061 \text{ (stat)} \pm 0.0037 \text{ (syst)}, \\ \mathcal{R}_{D_s^- \pi^+}^{\text{tot}} &= 0.267 \pm 0.050 \text{ (stat)} \pm 0.028 \text{ (syst)}, \end{aligned}$$

in each decay mode. Accounting for the branching fractions of the intermediate state decays, as shown in table 1, the ratio between the branching fractions of the $B_c^+ \rightarrow B_s^0 \pi^+$ and $B_c^+ \rightarrow J/\psi \pi^+$ decays is

$$\begin{aligned} \mathcal{R}_{J/\psi\phi} &= 89 \pm 12 \text{ (stat)} \pm 7 \text{ (syst)} \pm 4 \text{ (}\mathcal{B}\text{)}, \\ \mathcal{R}_{D_s^- \pi^+} &= 99 \pm 19 \text{ (stat)} \pm 10 \text{ (syst)} \pm 5 \text{ (}\mathcal{B}\text{)}, \end{aligned}$$

for the two decay modes considered. The third uncertainty is due to the knowledge of the branching fractions of intermediate state decays (denoted \mathcal{B} hereafter).

The ratio of the branching fractions measured using the two decay modes can then be combined using the BLUE method [44]. The systematic uncertainties due to the signal lineshape, background lineshape, $B_c^+ \rightarrow B_s^{*0} \pi^+$ component, data-simulation agreement, tracking efficiency and trigger decision are considered to be 100% correlated between the two decay modes, while the uncertainty due to limited simulation sample size is uncorrelated. Uncertainties in this ratio arise from knowledge of the branching fractions of intermediate state decays, which is the uncertainty of \mathcal{R}_{int} . The uncertainties from $\mathcal{R}_{\text{int}}^{J/\psi\phi}$ and $\mathcal{R}_{\text{int}}^{D_s^- \pi^+}$ are considered uncorrelated. The combined result is

$$\mathcal{R} = \frac{\mathcal{B}(B_c^+ \rightarrow B_s^0 \pi^+)}{\mathcal{B}(B_c^+ \rightarrow J/\psi \pi^+)} = 91 \pm 10 \text{ (stat)} \pm 8 \text{ (syst)} \pm 3 \text{ (}\mathcal{B}\text{)}.$$

This is the first direct measurement of the ratio of branching fractions $\mathcal{B}(B_c^+ \rightarrow B_s^0 \pi^+)/\mathcal{B}(B_c^+ \rightarrow J/\psi \pi^+)$.

7 Discussion of $\mathcal{B}(B_c^+ \rightarrow B_s^0 \pi^+)$

The branching fraction of the $B_c^+ \rightarrow B_s^0 \pi^+$ decay can be extracted from this result with the knowledge of $\mathcal{B}(B_c^+ \rightarrow J/\psi \pi^+)$. The branching fraction of the $B_c^+ \rightarrow J/\psi \pi^+$ decay is predicted to be $(0.291_{-0.050}^{+0.043})\%$ [45] with a B_c^+ lifetime of 0.453 ps. Using this input and the B_c^+ lifetime of 0.510 ps taken from ref. [15], the branching fraction of the $B_c^+ \rightarrow B_s^0 \pi^+$ decay is found to be

$$\mathcal{B}(B_c^+ \rightarrow B_s^0 \pi^+) = \left(30.0 \pm 3.3 (\text{stat}) \pm 2.6 (\text{syst}) \pm 1.0 (\mathcal{B})_{-5.5}^{+4.6} (B_c^+ \rightarrow J/\psi \pi^+)\right) \%, \quad (7.1)$$

where the fourth uncertainty is the uncertainty from the prediction of $\mathcal{B}(B_c^+ \rightarrow J/\psi \pi^+)$.

The branching fraction of the $B_c^+ \rightarrow J/\psi \pi^+$ decay can also be determined from the theoretical prediction of $\mathcal{B}(B_c^+ \rightarrow J/\psi \mu^+ \nu_\mu)$ and the measurement of $\mathcal{B}(B_c^+ \rightarrow J/\psi \pi^+)/\mathcal{B}(B_c^+ \rightarrow J/\psi \mu^+ \nu_\mu) = 0.0469 \pm 0.0028 \pm 0.0046$ [46]. The average of several theoretical predictions for $\mathcal{B}(B_c^+ \rightarrow J/\psi \mu^+ \nu_\mu)$, as considered in ref. [47], is $\mathcal{B}(B_c^+ \rightarrow J/\psi \mu^+ \nu_\mu) = (1.95 \pm 0.46)\%$. Using these inputs, the value of $\mathcal{B}(B_c^+ \rightarrow J/\psi \pi^+)$ is found to be $(0.091 \pm 0.024)\%$. The branching fraction of the $B_c^+ \rightarrow B_s^0 \pi^+$ decay is determined to be

$$\mathcal{B}(B_c^+ \rightarrow B_s^0 \pi^+) = (8.3 \pm 0.9 (\text{stat}) \pm 0.7 (\text{syst}) \pm 0.3 (\mathcal{B}) \pm 2.2 (B_c^+ \rightarrow J/\psi \pi^+)) \%. \quad (7.2)$$

The fourth uncertainty in eq. (7.2) is due to the uncertainty on the value of $\mathcal{B}(B_c^+ \rightarrow J/\psi \pi^+)$.

Equations (7.1) and (7.2) show a discrepancy in $\mathcal{B}(B_c^+ \rightarrow B_s^0 \pi^+)$ which is larger than the quoted uncertainties, due to different predictions for the value of $\mathcal{B}(B_c^+ \rightarrow J/\psi \pi^+)$. Until this discrepancy is resolved, caution is advised when converting the measured ratio into a measurement of $\mathcal{B}(B_c^+ \rightarrow B_s^0 \pi^+)$. However, irrespective of this discrepancy, either value of the branching fraction $\mathcal{B}(B_c^+ \rightarrow J/\psi \pi^+)$ considered here results in the $B_c^+ \rightarrow B_s^0 \pi^+$ decay having the largest branching fraction of all B_c^+ decays measured to date.

Acknowledgments

We express our gratitude to our colleagues in the CERN accelerator departments for the excellent performance of the LHC. We thank the technical and administrative staff at the LHCb institutes. We acknowledge support from CERN and from the national agencies: CAPES, CNPq, FAPERJ and FINEP (Brazil); MOST and NSFC (China); CNRS/IN2P3 (France); BMBF, DFG and MPG (Germany); INFN (Italy); NWO (Netherlands); MNiSW and NCN (Poland); MEN/IFA (Romania); MICINN (Spain); SNSF and SER (Switzerland); NASU (Ukraine); STFC (United Kingdom); DOE NP and NSF (U.S.A.). We acknowledge the computing resources that are provided by CERN, IN2P3 (France), KIT and DESY (Germany), INFN (Italy), SURF (Netherlands), PIC (Spain), GridPP (United Kingdom), CSCS (Switzerland), IFIN-HH (Romania), CBPF (Brazil), Polish WLCG (Poland) and NERSC (U.S.A.). We are indebted to the communities behind the multiple open-source software packages on which we depend. Individual groups or members have received support from ARC and ARDC (Australia); Minciencias (Colombia); AvH Foundation (Germany); EPLANET, Marie Skłodowska-Curie Actions and ERC (European Union); A*MIDEX,

ANR, IPhU and Labex P2IO, and Région Auvergne-Rhône-Alpes (France); Key Research Program of Frontier Sciences of CAS, CAS PIFI, CAS CCEPP, Fundamental Research Funds for the Central Universities, and Sci. & Tech. Program of Guangzhou (China); GVA, XuntaGal, GENCAT and Prog. Atracción Talento, CM (Spain); SRC (Sweden); the Leverhulme Trust, the Royal Society and UKRI (United Kingdom).

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

References

- [1] LHCb collaboration, *Observation of the decay $B_c^+ \rightarrow B_s^0 \pi^+$* , *Phys. Rev. Lett.* **111** (2013) 181801 [[arXiv:1308.4544](https://arxiv.org/abs/1308.4544)] [[INSPIRE](#)].
- [2] V.V. Kiselev, A.E. Kovalsky and A.K. Likhoded, *B_c decays and lifetime in QCD sum rules*, *Nucl. Phys. B* **585** (2000) 353 [[hep-ph/0002127](https://arxiv.org/abs/hep-ph/0002127)] [[INSPIRE](#)].
- [3] I.P. Gouz et al., *Prospects for the B_c studies at LHCb*, *Phys. Atom. Nucl.* **67** (2004) 1559 [[hep-ph/0211432](https://arxiv.org/abs/hep-ph/0211432)] [[INSPIRE](#)].
- [4] M.A. Ivanov, J.G. Korner and P. Santorelli, *Exclusive semileptonic and nonleptonic decays of the B_c meson*, *Phys. Rev. D* **73** (2006) 054024 [[hep-ph/0602050](https://arxiv.org/abs/hep-ph/0602050)] [[INSPIRE](#)].
- [5] A.Y. Anisimov, I.M. Narodetsky, C. Semay and B. Silvestre-Brac, *The B_c meson lifetime in the light front constituent quark model*, *Phys. Lett. B* **452** (1999) 129 [[hep-ph/9812514](https://arxiv.org/abs/hep-ph/9812514)] [[INSPIRE](#)].
- [6] P. Colangelo and F. De Fazio, *Using heavy quark spin symmetry in semileptonic B_c decays*, *Phys. Rev. D* **61** (2000) 034012 [[hep-ph/9909423](https://arxiv.org/abs/hep-ph/9909423)] [[INSPIRE](#)].
- [7] D. Ebert, R.N. Faustov and V.O. Galkin, *Weak decays of the B_c meson to B_s and B mesons in the relativistic quark model*, *Eur. Phys. J. C* **32** (2003) 29 [[hep-ph/0308149](https://arxiv.org/abs/hep-ph/0308149)] [[INSPIRE](#)].
- [8] R. Dhir, N. Sharma and R.C. Verma, *Flavor dependence of B_c^+ meson form factors and $B_c \rightarrow PP$ decays*, *J. Phys. G* **35** (2008) 085002 [[INSPIRE](#)].
- [9] S. Naimuddin et al., *Nonleptonic two-body B_c -meson decays*, *Phys. Rev. D* **86** (2012) 094028 [[INSPIRE](#)].
- [10] C. Murgui, A. Peñuelas, M. Jung and A. Pich, *Global fit to $b \rightarrow c \tau \nu$ transitions*, *JHEP* **09** (2019) 103 [[arXiv:1904.09311](https://arxiv.org/abs/1904.09311)] [[INSPIRE](#)].
- [11] R. Alonso, B. Grinstein and J. Martin Camalich, *Lifetime of B_c^- Constrains Explanations for Anomalies in $B \rightarrow D^{(*)} \tau \nu$* , *Phys. Rev. Lett.* **118** (2017) 081802 [[arXiv:1611.06676](https://arxiv.org/abs/1611.06676)] [[INSPIRE](#)].
- [12] X.-Q. Li, Y.-D. Yang and X. Zhang, *Revisiting the one leptoquark solution to the $R(D^{(*)})$ anomalies and its phenomenological implications*, *JHEP* **08** (2016) 054 [[arXiv:1605.09308](https://arxiv.org/abs/1605.09308)] [[INSPIRE](#)].
- [13] A. Celis, M. Jung, X.-Q. Li and A. Pich, *Scalar contributions to $b \rightarrow c(u) \tau \nu$ transitions*, *Phys. Lett. B* **771** (2017) 168 [[arXiv:1612.07757](https://arxiv.org/abs/1612.07757)] [[INSPIRE](#)].
- [14] M. Beneke and G. Buchalla, *B_c meson lifetime*, *Phys. Rev. D* **53** (1996) 4991 [[hep-ph/9601249](https://arxiv.org/abs/hep-ph/9601249)] [[INSPIRE](#)].

- [15] PARTICLE DATA GROUP collaboration, *Review of Particle Physics*, *PTEP* **2022** (2022) 083C01 [INSPIRE].
- [16] LHCb collaboration, *The LHCb detector at the LHC*, 2008 *JINST* **3** S08005 [INSPIRE].
- [17] LHCb collaboration, *LHCb detector performance*, *Int. J. Mod. Phys. A* **30** (2015) 1530022 [arXiv:1412.6352] [INSPIRE].
- [18] R. Aaij et al., *Performance of the LHCb Vertex Locator*, 2014 *JINST* **9** P09007 [arXiv:1405.7808] [INSPIRE].
- [19] LHCb OUTER TRACKER GROUP collaboration, *Performance of the LHCb Outer Tracker*, 2014 *JINST* **9** P01002 [arXiv:1311.3893] [INSPIRE].
- [20] LHCb RICH GROUP collaboration, *Performance of the LHCb RICH detector at the LHC*, *Eur. Phys. J. C* **73** (2013) 2431 [arXiv:1211.6759] [INSPIRE].
- [21] A.A. Alves Jr. et al., *Performance of the LHCb muon system*, 2013 *JINST* **8** P02022 [arXiv:1211.1346] [INSPIRE].
- [22] R. Aaij et al., *The LHCb trigger and its performance in 2011*, 2013 *JINST* **8** P04022 [arXiv:1211.3055] [INSPIRE].
- [23] T. Sjöstrand, S. Mrenna and P.Z. Skands, *A Brief Introduction to PYTHIA 8.1*, *Comput. Phys. Commun.* **178** (2008) 852 [arXiv:0710.3820] [INSPIRE].
- [24] T. Sjöstrand, S. Mrenna and P.Z. Skands, *PYTHIA 6.4 Physics and Manual*, *JHEP* **05** (2006) 026 [hep-ph/0603175] [INSPIRE].
- [25] LHCb collaboration, *Handling of the generation of primary events in Gauss, the LHCb simulation framework*, *J. Phys. Conf. Ser.* **331** (2011) 032047 [INSPIRE].
- [26] C.-H. Chang, J.-X. Wang and X.-G. Wu, *An upgraded version of the generator BCVEGPY2.0 for hadronic production of B_c meson and its excited states*, *Comput. Phys. Commun.* **175** (2006) 624 [hep-ph/0604238] [INSPIRE].
- [27] D.J. Lange, *The EvtGen particle decay simulation package*, *Nucl. Instrum. Meth. A* **462** (2001) 152 [INSPIRE].
- [28] N. Davidson, T. Przedzinski and Z. Was, *PHOTOS interface in C++: Technical and Physics Documentation*, *Comput. Phys. Commun.* **199** (2016) 86 [arXiv:1011.0937] [INSPIRE].
- [29] J. Allison et al., *Geant4 developments and applications*, *IEEE Trans. Nucl. Sci.* **53** (2006) 270 [INSPIRE].
- [30] GEANT4 collaboration, *Geant4: A simulation toolkit*, *Nucl. Instrum. Meth. A* **506** (2003) 250 [INSPIRE].
- [31] LHCb collaboration, *The LHCb simulation application, Gauss: Design, evolution and experience*, *J. Phys. Conf. Ser.* **331** (2011) 032023 [INSPIRE].
- [32] L. Breiman, J. Friedman, R.A. Olshen and C.J. Stone, *Classification and regression trees*, Chapman and Hall/CRC (1984) [INSPIRE].
- [33] Y. Freund and R.E. Schapire, *A decision-theoretic generalization of on-line learning and an application to boosting*, *J. Comput. Syst. Sci.* **55** (1997) 119 [INSPIRE].
- [34] J.H. Friedman, *Greedy function approximation: A gradient boosting machine*, *Annals Statist.* **29** (2001) 1189 [INSPIRE].

- [35] LHCb collaboration, *Precision measurement of the B_c^+ meson mass*, *JHEP* **07** (2020) 123 [[arXiv:2004.08163](#)] [[INSPIRE](#)].
- [36] LHCb collaboration, *Measurement of B_c^+ production in proton-proton collisions at $\sqrt{s} = 8$ TeV*, *Phys. Rev. Lett.* **114** (2015) 132001 [[arXiv:1411.2943](#)] [[INSPIRE](#)].
- [37] W.D. Hulsbergen, *Decay chain fitting with a Kalman filter*, *Nucl. Instrum. Meth. A* **552** (2005) 566 [[physics/0503191](#)] [[INSPIRE](#)].
- [38] T. Skwarnicki, *A study of the radiative CASCADE transitions between the Upsilon-Prime and Upsilon resonances*, Ph.D. Thesis, Institute of Nuclear Physics, Kraków, Poland (1986) [[INSPIRE](#)].
- [39] LHCb collaboration, *Measurement of the track reconstruction efficiency at LHCb*, *2015 JINST* **10** P02007 [[arXiv:1408.1251](#)] [[INSPIRE](#)].
- [40] R. Aaij et al., *Selection and processing of calibration samples to measure the particle identification performance of the LHCb experiment in Run 2*, *EPJ Tech. Instrum.* **6** (2019) 1 [[arXiv:1803.00824](#)] [[INSPIRE](#)].
- [41] LHCb collaboration, *Observation of an excited B_c^+ state*, *Phys. Rev. Lett.* **122** (2019) 232001 [[arXiv:1904.00081](#)] [[INSPIRE](#)].
- [42] M. Pivk and F.R. Le Diberder, *SPlot: A Statistical tool to unfold data distributions*, *Nucl. Instrum. Meth. A* **555** (2005) 356 [[physics/0402083](#)] [[INSPIRE](#)].
- [43] LHCb collaboration, *Measurement of the J/ψ pair production cross-section in pp collisions at $\sqrt{s} = 13$ TeV*, *JHEP* **06** (2017) 047 [Erratum *ibid.* **10** (2017) 068] [[arXiv:1612.07451](#)] [[INSPIRE](#)].
- [44] A. Valassi, *Combining correlated measurements of several different physical quantities*, *Nucl. Instrum. Meth. A* **500** (2003) 391 [[INSPIRE](#)].
- [45] C.-F. Qiao, P. Sun, D. Yang and R.-L. Zhu, *B_c exclusive decays to charmonium and a light meson at next-to-leading order accuracy*, *Phys. Rev. D* **89** (2014) 034008 [[arXiv:1209.5859](#)] [[INSPIRE](#)].
- [46] LHCb collaboration, *Measurement of the ratio of B_c^+ branching fractions to $J/\psi\pi^+$ and $J/\psi\mu^+\nu_\mu$* , *Phys. Rev. D* **90** (2014) 032009 [[arXiv:1407.2126](#)] [[INSPIRE](#)].
- [47] LHCb collaboration, *Measurement of the B_c^- meson production fraction and asymmetry in 7 and 13 TeV pp collisions*, *Phys. Rev. D* **100** (2019) 112006 [[arXiv:1910.13404](#)] [[INSPIRE](#)].

The LHCb collaboration

R. Aaij [ID](#)³², A.S.W. Abdelmotteleb [ID](#)⁵⁰, C. Abellan Beteta⁴⁴, F. Abudinén [ID](#)⁵⁰, T. Ackernley [ID](#)⁵⁴, B. Adeva [ID](#)⁴⁰, M. Adinolfi [ID](#)⁴⁸, P. Adlarson [ID](#)⁷⁷, H. Afsharnia⁹, C. Agapopoulou [ID](#)¹³, C.A. Aidala [ID](#)⁷⁸, Z. Ajaltouni⁹, S. Akar [ID](#)⁵⁹, K. Akiba [ID](#)³², P. Albicocco [ID](#)²³, J. Albrecht [ID](#)¹⁵, F. Alessio [ID](#)⁴², M. Alexander [ID](#)⁵³, A. Alfonso Alberro [ID](#)³⁹, Z. Aliouche [ID](#)⁵⁶, P. Alvarez Cartelle [ID](#)⁴⁹, R. Amalric [ID](#)¹³, S. Amato [ID](#)², J.L. Amey [ID](#)⁴⁸, Y. Amhis [ID](#)^{11,42}, L. An [ID](#)⁴², L. Anderlini [ID](#)²², M. Andersson [ID](#)⁴⁴, A. Andreianov [ID](#)³⁸, M. Andreotti [ID](#)²¹, D. Andreou [ID](#)⁶², D. Ao [ID](#)⁶, F. Archilli [ID](#)¹⁷, A. Artamonov [ID](#)³⁸, M. Artuso [ID](#)⁶², E. Aslanides [ID](#)¹⁰, M. Atzeni [ID](#)⁴⁴, B. Audurier [ID](#)¹², I.B. Bachiller Perea [ID](#)⁸, S. Bachmann [ID](#)¹⁷, M. Bachmayer [ID](#)⁴³, J.J. Back [ID](#)⁵⁰, A. Bailly-reyre¹³, P. Baladron Rodriguez [ID](#)⁴⁰, V. Balagura [ID](#)¹², W. Baldini [ID](#)^{21,42}, J. Baptista de Souza Leite [ID](#)¹, M. Barbetti [ID](#)^{22,j}, R.J. Barlow [ID](#)⁵⁶, S. Barsuk [ID](#)¹¹, W. Barter [ID](#)⁵², M. Bartolini [ID](#)⁴⁹, F. Baryshnikov [ID](#)³⁸, J.M. Basels [ID](#)¹⁴, G. Bassi [ID](#)^{29,p}, B. Batsukh [ID](#)⁴, A. Battig [ID](#)¹⁵, A. Bay [ID](#)⁴³, A. Beck [ID](#)⁵⁰, M. Becker [ID](#)¹⁵, F. Bedeschi [ID](#)²⁹, I.B. Bediaga [ID](#)¹, A. Beiter⁶², V. Belavin³⁸, S. Belin [ID](#)⁴⁰, V. Bellee [ID](#)⁴⁴, K. Belous [ID](#)³⁸, I. Belov [ID](#)³⁸, I. Belyaev [ID](#)³⁸, G. Benane [ID](#)¹⁰, G. Bencivenni [ID](#)²³, E. Ben-Haim [ID](#)¹³, A. Berezhnoy [ID](#)³⁸, R. Bernet [ID](#)⁴⁴, S. Bernet Andres [ID](#)⁷⁶, D. Berninghoff¹⁷, H.C. Bernstein⁶², C. Bertella [ID](#)⁵⁶, A. Bertolin [ID](#)²⁸, C. Betancourt [ID](#)⁴⁴, F. Betti [ID](#)⁴², Ia. Bezshyiko [ID](#)⁴⁴, S. Bhasin [ID](#)⁴⁸, J. Bhom [ID](#)³⁵, L. Bian [ID](#)⁶⁸, M.S. Bieker [ID](#)¹⁵, N.V. Biesuz [ID](#)²¹, S. Bifani [ID](#)⁴⁷, P. Billoir [ID](#)¹³, A. Biolchini [ID](#)³², M. Birch [ID](#)⁵⁵, F.C.R. Bishop [ID](#)⁴⁹, A. Bitadze [ID](#)⁵⁶, A. Bizzeti [ID](#), M.P. Blago [ID](#)⁴⁹, T. Blake [ID](#)⁵⁰, F. Blanc [ID](#)⁴³, J.E. Blank [ID](#)¹⁵, S. Blusk [ID](#)⁶², D. Bobulska [ID](#)⁵³, J.A. Boelhauve [ID](#)¹⁵, O. Boente Garcia [ID](#)¹², T. Boettcher [ID](#)⁵⁹, A. Boldyrev [ID](#)³⁸, C.S. Bolognani [ID](#)⁷⁴, R. Bolzonella [ID](#)^{21,i}, N. Bondar [ID](#)^{38,42}, F. Borgato [ID](#)²⁸, S. Borghi [ID](#)⁵⁶, M. Borsato [ID](#)¹⁷, J.T. Borsuk [ID](#)³⁵, S.A. Bouchiba [ID](#)⁴³, T.J.V. Bowcock [ID](#)⁵⁴, A. Boyer [ID](#)⁴², C. Bozzi [ID](#)²¹, M.J. Bradley⁵⁵, S. Braun [ID](#)⁶⁰, A. Brea Rodriguez [ID](#)⁴⁰, J. Brodzicka [ID](#)³⁵, A. Brossa Gonzalo [ID](#)⁴⁰, J. Brown [ID](#)⁵⁴, D. Brundu [ID](#)²⁷, A. Buonaura [ID](#)⁴⁴, L. Buonincontri [ID](#)²⁸, A.T. Burke [ID](#)⁵⁶, C. Burr [ID](#)⁴², A. Bursche⁶⁶, A. Butkevich [ID](#)³⁸, J.S. Butter [ID](#)³², J. Buytaert [ID](#)⁴², W. Byczynski [ID](#)⁴², S. Cadeddu [ID](#)²⁷, H. Cai⁶⁸, R. Calabrese [ID](#)^{21,i}, L. Calefice [ID](#)¹⁵, S. Cali [ID](#)²³, M. Calvi [ID](#)^{26,m}, M. Calvo Gomez [ID](#)⁷⁶, P. Campana [ID](#)²³, D.H. Campora Perez [ID](#)⁷⁴, A.F. Campoverde Quezada [ID](#)⁶, S. Capelli [ID](#)^{26,m}, L. Capriotti [ID](#)²⁰, A. Carbone [ID](#)^{20,g}, G. Carboni [ID](#)³¹, R. Cardinale [ID](#)^{24,k}, A. Cardini [ID](#)²⁷, P. Carniti [ID](#)^{26,m}, L. Carus¹⁴, A. Casais Vidal [ID](#)⁴⁰, R. Caspary [ID](#)¹⁷, G. Casse [ID](#)⁵⁴, M. Cattaneo [ID](#)⁴², G. Cavallero [ID](#)⁵⁵, V. Cavallini [ID](#)^{21,i}, S. Celani [ID](#)⁴³, J. Cerasoli [ID](#)¹⁰, D. Cervenkov [ID](#)⁵⁷, A.J. Chadwick [ID](#)⁵⁴, I. Chahrour [ID](#)⁷⁸, M.G. Chapman⁴⁸, M. Charles [ID](#)¹³, Ph. Charpentier [ID](#)⁴², C.A. Chavez Barajas [ID](#)⁵⁴, M. Chefdeville [ID](#)⁸, C. Chen [ID](#)³, S. Chen [ID](#)⁴, A. Chernov [ID](#)³⁵, S. Chernyshenko [ID](#)⁴⁶, V. Chobanova [ID](#)⁴⁰, S. Cholak [ID](#)⁴³, M. Chrzaszcz [ID](#)³⁵, A. Chubykin [ID](#)³⁸, V. Chulikov [ID](#)³⁸, P. Ciambriano [ID](#)²³, M.F. Cicala [ID](#)⁵⁰, X. Cid Vidal [ID](#)⁴⁰, G. Ciezarek [ID](#)⁴², G. Ciullo [ID](#)^{i,21}, P.E.L. Clarke [ID](#)⁵², M. Clemencic [ID](#)⁴², H.V. Cliff [ID](#)⁴⁹, J. Closier [ID](#)⁴², J.L. Cobbledick [ID](#)⁵⁶, V. Coco [ID](#)⁴², J.A.B. Coelho [ID](#)¹¹, J. Cogan [ID](#)¹⁰, E. Cogneras [ID](#)⁹, L. Cojocariu [ID](#)³⁷, P. Collins [ID](#)⁴², T. Colombo [ID](#)⁴², L. Congedo [ID](#)¹⁹, A. Contu [ID](#)²⁷, N. Cooke [ID](#)⁴⁷, I. Corredoira [ID](#)⁴⁰, G. Corti [ID](#)⁴², B. Couturier [ID](#)⁴², D.C. Craik [ID](#)⁴⁴, M. Cruz Torres [ID](#)^{1,e}, R. Currie [ID](#)⁵², C.L. Da Silva [ID](#)⁶¹, S. Dadabaev [ID](#)³⁸, L. Dai [ID](#)⁶⁵, X. Dai [ID](#)⁵, E. Dall’Occo [ID](#)¹⁵, J. Dalseno [ID](#)⁴⁰, C. D’Ambrosio [ID](#)⁴², J. Daniel [ID](#)⁹, A. Danilina [ID](#)³⁸, P. d’Argent [ID](#)¹⁹, J.E. Davies [ID](#)⁵⁶, A. Davis [ID](#)⁵⁶, O. De Aguiar Francisco [ID](#)⁵⁶, J. de Boer [ID](#)⁴², K. De Bruyn [ID](#)⁷³, S. De Capua [ID](#)⁵⁶,

M. De Cian [ID](#)⁴³, U. De Freitas Carneiro Da Graca [ID](#)¹, E. De Lucia [ID](#)²³, J.M. De Miranda [ID](#)¹, L. De Paula [ID](#)², M. De Serio [ID](#)^{19,f}, D. De Simone [ID](#)⁴⁴, P. De Simone [ID](#)²³, F. De Vellis [ID](#)¹⁵, J.A. de Vries [ID](#)⁷⁴, C.T. Dean [ID](#)⁶¹, F. Debernardis [ID](#)^{19,f}, D. Decamp [ID](#)⁸, V. Dedu [ID](#)¹⁰, L. Del Buono [ID](#)¹³, B. Delaney [ID](#)⁵⁸, H.-P. Dembinski [ID](#)¹⁵, V. Denysenko [ID](#)⁴⁴, O. Deschamps [ID](#)⁹, F. Dettori [ID](#)^{27,h}, B. Dey [ID](#)⁷¹, P. Di Nezza [ID](#)²³, I. Diachkov [ID](#)³⁸, S. Didenko [ID](#)³⁸, L. Dieste Maronas⁴⁰, S. Ding [ID](#)⁶², V. Dobishuk [ID](#)⁴⁶, A. Dolmatov³⁸, C. Dong [ID](#)³, A.M. Donohoe [ID](#)¹⁸, F. Dordei [ID](#)²⁷, A.C. dos Reis [ID](#)¹, L. Douglas⁵³, A.G. Downes [ID](#)⁸, P. Duda [ID](#)⁷⁵, M.W. Dudek [ID](#)³⁵, L. Dufour [ID](#)⁴², V. Duk [ID](#)⁷², P. Durante [ID](#)⁴², M.M. Duras [ID](#)⁷⁵, J.M. Durham [ID](#)⁶¹, D. Dutta [ID](#)⁵⁶, A. Dziurda [ID](#)³⁵, A. Dzyuba [ID](#)³⁸, S. Easo [ID](#)⁵¹, U. Egede [ID](#)⁶³, V. Egorychev [ID](#)³⁸, C. Eirea Orro⁴⁰, S. Eisenhardt [ID](#)⁵², E. Ejopu [ID](#)⁵⁶, S. Ek-In [ID](#)⁴³, L. Eklund [ID](#)⁷⁷, J. Ellbracht [ID](#)¹⁵, S. Ely [ID](#)⁵⁵, A. Ene [ID](#)³⁷, E. Epple [ID](#)⁵⁹, S. Escher [ID](#)¹⁴, J. Eschle [ID](#)⁴⁴, S. Esen [ID](#)⁴⁴, T. Evans [ID](#)⁵⁶, F. Fabiano [ID](#)^{27,h}, L.N. Falcao [ID](#)¹, Y. Fan [ID](#)⁶, B. Fang [ID](#)^{11,68}, L. Fantini [ID](#)^{72,o}, M. Faria [ID](#)⁴³, S. Farry [ID](#)⁵⁴, D. Fazzini [ID](#)^{26,m}, L.F. Felkowski [ID](#)⁷⁵, M. Feo [ID](#)⁴², M. Fernandez Gomez [ID](#)⁴⁰, A.D. Fernez [ID](#)⁶⁰, F. Ferrari [ID](#)²⁰, L. Ferreira Lopes [ID](#)⁴³, F. Ferreira Rodrigues [ID](#)², S. Ferreres Sole [ID](#)³², M. Ferrillo [ID](#)⁴⁴, M. Ferro-Luzzi [ID](#)⁴², S. Filippov [ID](#)³⁸, R.A. Fini [ID](#)¹⁹, M. Fiorini [ID](#)^{21,i}, M. Firlej [ID](#)³⁴, K.M. Fischer [ID](#)⁵⁷, D.S. Fitzgerald [ID](#)⁷⁸, C. Fitzpatrick [ID](#)⁵⁶, T. Fiutowski [ID](#)³⁴, F. Fleuret [ID](#)¹², M. Fontana [ID](#)¹³, F. Fontanelli [ID](#)^{24,k}, R. Forty [ID](#)⁴², D. Foulds-Holt [ID](#)⁴⁹, V. Franco Lima [ID](#)⁵⁴, M. Franco Sevilla [ID](#)⁶⁰, M. Frank [ID](#)⁴², E. Franzoso [ID](#)^{21,i}, G. Frau [ID](#)¹⁷, C. Frei [ID](#)⁴², D.A. Friday [ID](#)⁵³, J. Fu [ID](#)⁶, Q. Fuehring [ID](#)¹⁵, T. Fulghesu [ID](#)¹³, E. Gabriel [ID](#)³², G. Galati [ID](#)^{19,f}, M.D. Galati [ID](#)³², A. Gallas Torreira [ID](#)⁴⁰, D. Galli [ID](#)^{20,g}, S. Gambetta [ID](#)^{52,42}, Y. Gan [ID](#)³, M. Gandelman [ID](#)², P. Gandini [ID](#)²⁵, Y. Gao [ID](#)⁷, Y. Gao [ID](#)⁵, M. Garau [ID](#)^{27,h}, L.M. Garcia Martin [ID](#)⁵⁰, P. Garcia Moreno [ID](#)³⁹, J. García Pardiñas [ID](#)^{26,m}, B. Garcia Plana⁴⁰, F.A. Garcia Rosales [ID](#)¹², L. Garrido [ID](#)³⁹, C. Gaspar [ID](#)⁴², R.E. Geertsema [ID](#)³², D. Gerick¹⁷, L.L. Gerken [ID](#)¹⁵, E. Gersabeck [ID](#)⁵⁶, M. Gersabeck [ID](#)⁵⁶, T. Gershon [ID](#)⁵⁰, L. Giambastiani [ID](#)²⁸, V. Gibson [ID](#)⁴⁹, H.K. Gienza [ID](#)³⁶, A.L. Gilman [ID](#)⁵⁷, M. Giovannetti [ID](#)^{23,s}, A. Gioventù [ID](#)⁴⁰, P. Gironella Gironell [ID](#)³⁹, C. Giugliano [ID](#)^{21,i}, M.A. Giza [ID](#)³⁵, K. Gizdov [ID](#)⁵², E.L. Gkougkousis [ID](#)⁴², V.V. Gligorov [ID](#)^{13,42}, C. Göbel [ID](#)⁶⁴, E. Golobardes [ID](#)⁷⁶, D. Golubkov [ID](#)³⁸, A. Golutvin [ID](#)^{55,38}, A. Gomes [ID](#)^{1,a}, S. Gomez Fernandez [ID](#)³⁹, F. Goncalves Abrantes [ID](#)⁵⁷, M. Goncerz [ID](#)³⁵, G. Gong [ID](#)³, I.V. Gorelov [ID](#)³⁸, C. Gotti [ID](#)²⁶, J.P. Grabowski [ID](#)⁷⁰, T. Grammatico [ID](#)¹³, L.A. Granado Cardoso [ID](#)⁴², E. Graugés [ID](#)³⁹, E. Graverini [ID](#)⁴³, G. Graziani [ID](#), A.T. Grecu [ID](#)³⁷, L.M. Greeven [ID](#)³², N.A. Grieser [ID](#)⁵⁹, L. Grillo [ID](#)⁵³, S. Gromov [ID](#)³⁸, B.R. Gruberg Cazon [ID](#)⁵⁷, C. Gu [ID](#)³, M. Guarise [ID](#)^{21,i}, M. Guittiere [ID](#)¹¹, P.A. Günther [ID](#)¹⁷, E. Gushchin [ID](#)³⁸, A. Guth¹⁴, Y. Guz [ID](#)³⁸, T. Gys [ID](#)⁴², T. Hadavizadeh [ID](#)⁶³, C. Hadjivasiliou [ID](#)⁶⁰, G. Haefeli [ID](#)⁴³, C. Haen [ID](#)⁴², J. Haimberger [ID](#)⁴², S.C. Haines [ID](#)⁴⁹, T. Halewood-leagas [ID](#)⁵⁴, M.M. Halvorsen [ID](#)⁴², P.M. Hamilton [ID](#)⁶⁰, J. Hammerich [ID](#)⁵⁴, Q. Han [ID](#)⁷, X. Han [ID](#)¹⁷, E.B. Hansen [ID](#)⁵⁶, S. Hansmann-Menzemer [ID](#)¹⁷, L. Hao [ID](#)⁶, N. Harnew [ID](#)⁵⁷, T. Harrison [ID](#)⁵⁴, C. Hasse [ID](#)⁴², M. Hatch [ID](#)⁴², J. He [ID](#)^{6,c}, K. Heijhoff [ID](#)³², F.H. Hemmer [ID](#)⁴², C. Henderson [ID](#)⁵⁹, R.D.L. Henderson [ID](#)^{63,50}, A.M. Hennequin [ID](#)⁵⁸, K. Hennessy [ID](#)⁵⁴, L. Henry [ID](#)⁴², J. Herd [ID](#)⁵⁵, J. Heuel [ID](#)¹⁴, A. Hicheur [ID](#)², D. Hill [ID](#)⁴³, M. Hilton [ID](#)⁵⁶, S.E. Hollitt [ID](#)¹⁵, J. Horswill [ID](#)⁵⁶, R. Hou [ID](#)⁷, Y. Hou [ID](#)⁸, J. Hu¹⁷, J. Hu [ID](#)⁶⁶, W. Hu [ID](#)⁵, X. Hu [ID](#)³, W. Huang [ID](#)⁶, X. Huang⁶⁸, W. Hulsbergen [ID](#)³², R.J. Hunter [ID](#)⁵⁰, M. Hushchyn [ID](#)³⁸, D. Hutchcroft [ID](#)⁵⁴, P. Ibis [ID](#)¹⁵, M. Idzik [ID](#)³⁴, D. Ilin [ID](#)³⁸, P. Ilten [ID](#)⁵⁹, A. Inglessi [ID](#)³⁸, A. Iniukhin [ID](#)³⁸, A. Ishteev [ID](#)³⁸, K. Ivshin [ID](#)³⁸, R. Jacobsson [ID](#)⁴², H. Jage [ID](#)¹⁴, S.J. Jaimes Elles [ID](#)⁴¹, S. Jakobsen [ID](#)⁴², E. Jans [ID](#)³²,

B.K. Jashal [ID](#)⁴¹, A. Jawahery [ID](#)⁶⁰, V. Jevtic [ID](#)¹⁵, E. Jiang [ID](#)⁶⁰, X. Jiang [ID](#)^{4,6}, Y. Jiang [ID](#)⁶,
 M. John [ID](#)⁵⁷, D. Johnson [ID](#)⁵⁸, C.R. Jones [ID](#)⁴⁹, T.P. Jones [ID](#)⁵⁰, B. Jost [ID](#)⁴², N. Jurik [ID](#)⁴²,
 I. Juszczak [ID](#)³⁵, S. Kandybei [ID](#)⁴⁵, Y. Kang [ID](#)³, M. Karacson [ID](#)⁴², D. Karpenkov [ID](#)³⁸, M. Karpov [ID](#)³⁸,
 J.W. Kautz [ID](#)⁵⁹, F. Keizer [ID](#)⁴², D.M. Keller [ID](#)⁶², M. Kenzie [ID](#)⁵⁰, T. Ketel [ID](#)³², B. Khanji [ID](#)¹⁵,
 A. Kharisova [ID](#)³⁸, S. Kholodenko [ID](#)³⁸, G. Khreich [ID](#)¹¹, T. Kirn [ID](#)¹⁴, V.S. Kirsebom [ID](#)⁴³,
 O. Kitouni [ID](#)⁵⁸, S. Klaver [ID](#)³³, N. Kleijne [ID](#)^{29,p}, K. Klimaszewski [ID](#)³⁶, M.R. Kmieć [ID](#)³⁶,
 S. Koliiev [ID](#)⁴⁶, L. Kolk [ID](#)¹⁵, A. Kondybayeva [ID](#)³⁸, A. Konoplyannikov [ID](#)³⁸, P. Kopciewicz [ID](#)³⁴,
 R. Kopecna¹⁷, P. Koppenburg [ID](#)³², M. Korolev [ID](#)³⁸, I. Kostiuk [ID](#)^{32,46}, O. Kot⁴⁶, S. Kotriakhova [ID](#),
 A. Kozachuk [ID](#)³⁸, P. Kravchenko [ID](#)³⁸, L. Kravchuk [ID](#)³⁸, R.D. Krawczyk [ID](#)⁴², M. Kreps [ID](#)⁵⁰,
 S. Kretzschmar [ID](#)¹⁴, P. Krokovny [ID](#)³⁸, W. Krupa [ID](#)³⁴, W. Krzemien [ID](#)³⁶, J. Kubat¹⁷, S. Kubis [ID](#)⁷⁵,
 W. Kucewicz [ID](#)³⁵, M. Kucharczyk [ID](#)³⁵, V. Kudryavtsev [ID](#)³⁸, A. Kupsc [ID](#)⁷⁷, D. Lacarrere [ID](#)⁴²,
 G. Lafferty [ID](#)⁵⁶, A. Lai [ID](#)²⁷, A. Lampis [ID](#)^{27,h}, D. Lancierini [ID](#)⁴⁴, C. Landesa Gomez [ID](#)⁴⁰,
 J.J. Lane [ID](#)⁵⁶, R. Lane [ID](#)⁴⁸, C. Langenbruch [ID](#)¹⁴, J. Langer [ID](#)¹⁵, O. Lantwin [ID](#)³⁸, T. Latham [ID](#)⁵⁰,
 F. Lazzari [ID](#)^{29,q}, M. Lazzaroni [ID](#)^{25,l}, R. Le Gac [ID](#)¹⁰, S.H. Lee [ID](#)⁷⁸, R. Lefèvre [ID](#)⁹, A. Leflat [ID](#)³⁸,
 S. Legotin [ID](#)³⁸, P. Lenisa [ID](#)^{i,21}, O. Leroy [ID](#)¹⁰, T. Lesiak [ID](#)³⁵, B. Leverington [ID](#)¹⁷, A. Li [ID](#)³,
 H. Li [ID](#)⁶⁶, K. Li [ID](#)⁷, P. Li [ID](#)¹⁷, P.-R. Li [ID](#)⁶⁷, S. Li [ID](#)⁷, T. Li [ID](#)⁴, T. Li [ID](#)⁶⁶, Y. Li [ID](#)⁴, Z. Li [ID](#)⁶²,
 X. Liang [ID](#)⁶², C. Lin [ID](#)⁶, T. Lin [ID](#)⁵¹, R. Lindner [ID](#)⁴², V. Lisovskyi [ID](#)¹⁵, R. Litvinov [ID](#)^{27,h},
 G. Liu [ID](#)⁶⁶, H. Liu [ID](#)⁶, Q. Liu [ID](#)⁶, S. Liu [ID](#)^{4,6}, A. Lobo Salvia [ID](#)³⁹, A. Loi [ID](#)²⁷, R. Lollini [ID](#)⁷²,
 J. Lomba Castro [ID](#)⁴⁰, I. Longstaff⁵³, J.H. Lopes [ID](#)², A. Lopez Huertas [ID](#)³⁹, S. López Soliño [ID](#)⁴⁰,
 G.H. Lovell [ID](#)⁴⁹, Y. Lu [ID](#)^{4,b}, C. Lucarelli [ID](#)^{22,j}, D. Lucchesi [ID](#)^{28,n}, S. Luchuk [ID](#)³⁸,
 M. Lucio Martinez [ID](#)⁷⁴, V. Lukashenko [ID](#)^{32,46}, Y. Luo [ID](#)³, A. Lupato [ID](#)⁵⁶, E. Luppi [ID](#)^{21,i},
 A. Lusiani [ID](#)^{29,p}, K. Lynch [ID](#)¹⁸, X.-R. Lyu [ID](#)⁶, R. Ma [ID](#)⁶, S. Maccolini [ID](#)¹⁵, F. Machefert [ID](#)¹¹,
 F. Maciuc [ID](#)³⁷, I. Mackay [ID](#)⁵⁷, V. Macko [ID](#)⁴³, L.R. Madhan Mohan [ID](#)⁴⁸, A. Maevskiy [ID](#)³⁸,
 D. Maisuzenko [ID](#)³⁸, M.W. Majewski³⁴, J.J. Malczewski [ID](#)³⁵, S. Malde [ID](#)⁵⁷, B. Malecki [ID](#)^{35,42},
 A. Malinin [ID](#)³⁸, T. Maltsev [ID](#)³⁸, G. Manca [ID](#)^{27,h}, G. Mancinelli [ID](#)¹⁰, C. Mancuso [ID](#)^{11,25,l},
 R. Manera Escalero³⁹, D. Manuzzi [ID](#)²⁰, C.A. Manzari [ID](#)⁴⁴, D. Marangotto [ID](#)^{25,l}, J.F. Marchand [ID](#)⁸,
 U. Marconi [ID](#)²⁰, S. Mariani [ID](#)^{22,j}, C. Marin Benito [ID](#)^{39,42}, J. Marks [ID](#)¹⁷, A.M. Marshall [ID](#)⁴⁸,
 P.J. Marshall⁵⁴, G. Martelli [ID](#)^{72,o}, G. Martellotti [ID](#)³⁰, L. Martinazzoli [ID](#)^{42,m}, M. Martinelli [ID](#)^{26,m},
 D. Martinez Santos [ID](#)⁴⁰, F. Martinez Vidal [ID](#)⁴¹, A. Massafferri [ID](#)¹, M. Materok [ID](#)¹⁴, R. Matev [ID](#)⁴²,
 A. Mathad [ID](#)⁴⁴, V. Matiunin [ID](#)³⁸, C. Matteuzzi [ID](#)²⁶, K.R. Mattioli [ID](#)¹², A. Mauri [ID](#)³²,
 E. Maurice [ID](#)¹², J. Mauricio [ID](#)³⁹, M. Mazurek [ID](#)⁴², M. McCann [ID](#)⁵⁵, L. McConnell [ID](#)¹⁸,
 T.H. McGrath [ID](#)⁵⁶, N.T. McHugh [ID](#)⁵³, A. McNab [ID](#)⁵⁶, R. McNulty [ID](#)¹⁸, J.V. Mead [ID](#)⁵⁴,
 B. Meadows [ID](#)⁵⁹, G. Meier [ID](#)¹⁵, D. Melnychuk [ID](#)³⁶, S. Meloni [ID](#)^{26,m}, M. Merk [ID](#)^{32,74}, A. Merli [ID](#)^{25,l},
 L. Meyer Garcia [ID](#)², D. Miao [ID](#)^{4,6}, M. Mikhasenko [ID](#)^{70,d}, D.A. Milanes [ID](#)⁶⁹, E. Millard⁵⁰,
 M. Milovanovic [ID](#)⁴², M.-N. Minard^{8,†}, A. Minotti [ID](#)^{26,m}, T. Miralles [ID](#)⁹, S.E. Mitchell [ID](#)⁵²,
 B. Mitreska [ID](#)⁵⁶, D.S. Mitzel [ID](#)¹⁵, A. Mödden [ID](#)¹⁵, R.A. Mohammed [ID](#)⁵⁷, R.D. Moise [ID](#)¹⁴,
 S. Mokhnenko [ID](#)³⁸, T. Mombächer [ID](#)⁴⁰, M. Monk [ID](#)^{50,63}, I.A. Monroy [ID](#)⁶⁹, S. Monteil [ID](#)⁹,
 G. Morello [ID](#)²³, M.J. Morello [ID](#)^{29,p}, J. Moron [ID](#)³⁴, A.B. Morris [ID](#)⁴², A.G. Morris [ID](#)⁵⁰,
 R. Mountain [ID](#)⁶², H. Mu [ID](#)³, E. Muhammad [ID](#)⁵⁰, F. Muheim [ID](#)⁵², M. Mulder [ID](#)⁷³, K. Müller [ID](#)⁴⁴,
 C.H. Murphy [ID](#)⁵⁷, D. Murray [ID](#)⁵⁶, R. Murta [ID](#)⁵⁵, P. Muzzetto [ID](#)^{27,h}, P. Naik [ID](#)⁴⁸, T. Nakada [ID](#)⁴³,
 R. Nandakumar [ID](#)⁵¹, T. Nanut [ID](#)⁴², I. Nasteva [ID](#)², M. Needham [ID](#)⁵², N. Neri [ID](#)^{25,l}, S. Neubert [ID](#)⁷⁰,
 N. Neufeld [ID](#)⁴², P. Neustroev³⁸, R. Newcombe⁵⁵, J. Nicolini [ID](#)^{15,11}, E.M. Niel [ID](#)⁴³, S. Nieswand¹⁴,
 N. Nikitin [ID](#)³⁸, N.S. Nolte [ID](#)⁵⁸, C. Normand [ID](#)^{8,h,27}, J. Novoa Fernandez [ID](#)⁴⁰, G.N. Nowak [ID](#)⁵⁹,

C. Nunez [ID](#)⁷⁸, A. Oblakowska-Mucha [ID](#)³⁴, V. Obraztsov [ID](#)³⁸, T. Oeser [ID](#)¹⁴, D.P. O’Hanlon [ID](#)⁴⁸, S. Okamura [ID](#)^{21,i}, R. Oldeman [ID](#)^{27,h}, F. Oliva [ID](#)⁵², C.J.G. Onderwater [ID](#)⁷³, R.H. O’Neil [ID](#)⁵², J.M. Otalora Goicochea [ID](#)², T. Ovsianikova [ID](#)³⁸, P. Owen [ID](#)⁴⁴, A. Oyanguren [ID](#)⁴¹, O. Ozcelik [ID](#)⁵², K.O. Padeken [ID](#)⁷⁰, B. Pagare [ID](#)⁵⁰, P.R. Pais [ID](#)⁴², T. Pajero [ID](#)⁵⁷, A. Palano [ID](#)¹⁹, M. Palutan [ID](#)²³, Y. Pan [ID](#)⁵⁶, G. Panshin [ID](#)³⁸, L. Paolucci [ID](#)⁵⁰, A. Papanestis [ID](#)⁵¹, M. Pappagallo [ID](#)^{19,f}, L.L. Pappalardo [ID](#)^{21,i}, C. Pappenheimer [ID](#)⁵⁹, W. Parker [ID](#)⁶⁰, C. Parkes [ID](#)⁵⁶, B. Passalacqua [ID](#)^{21,i}, G. Passaleva [ID](#)²², A. Pastore [ID](#)¹⁹, M. Patel [ID](#)⁵⁵, C. Patrignani [ID](#)^{20,g}, C.J. Pawley [ID](#)⁷⁴, A. Pearce [ID](#)⁴², A. Pellegrino [ID](#)³², M. Pepe Altarelli [ID](#)⁴², S. Perazzini [ID](#)²⁰, D. Pereima [ID](#)³⁸, A. Pereiro Castro [ID](#)⁴⁰, P. Perret [ID](#)⁹, K. Petridis [ID](#)⁴⁸, A. Petrolini [ID](#)^{24,k}, A. Petrov [ID](#)³⁸, S. Petrucci [ID](#)⁵², M. Petruzzo [ID](#)²⁵, H. Pham [ID](#)⁶², A. Philippov [ID](#)³⁸, R. Piandani [ID](#)⁶, L. Pica [ID](#)^{29,p}, M. Piccini [ID](#)⁷², B. Pietrzyk [ID](#)⁸, G. Pietrzyk [ID](#)¹¹, M. Pili [ID](#)⁵⁷, D. Pinci [ID](#)³⁰, F. Pisani [ID](#)⁴², M. Pizzichemi [ID](#)^{26,m,42}, V. Placinta [ID](#)³⁷, J. Plews [ID](#)⁴⁷, M. Plo Casasus [ID](#)⁴⁰, F. Polci [ID](#)^{13,42}, M. Poli Lener [ID](#)²³, M. Poliakov [ID](#)⁶², A. Poluektov [ID](#)¹⁰, N. Polukhina [ID](#)³⁸, I. Polyakov [ID](#)⁴², E. Polycarpo [ID](#)², S. Ponce [ID](#)⁴², D. Popov [ID](#)^{6,42}, S. Popov [ID](#)³⁸, S. Poslavskii [ID](#)³⁸, K. Prasanth [ID](#)³⁵, L. Promberger [ID](#)¹⁷, C. Prouve [ID](#)⁴⁰, V. Pugatch [ID](#)⁴⁶, V. Puill [ID](#)¹¹, G. Punzi [ID](#)^{29,q}, H.R. Qi [ID](#)³, W. Qian [ID](#)⁶, N. Qin [ID](#)³, S. Qu [ID](#)³, R. Quagliani [ID](#)⁴³, N.V. Raab [ID](#)¹⁸, B. Rachwal [ID](#)³⁴, J.H. Rademacker [ID](#)⁴⁸, R. Rajagopalan [ID](#)⁶², M. Rama [ID](#)²⁹, M. Ramos Pernas [ID](#)⁵⁰, M.S. Rangel [ID](#)², F. Ratnikov [ID](#)³⁸, G. Raven [ID](#)^{33,42}, M. Rebollo De Miguel [ID](#)⁴¹, F. Redi [ID](#)⁴², J. Reich [ID](#)⁴⁸, F. Reiss [ID](#)⁵⁶, C. Remon Alepuz [ID](#)⁴¹, Z. Ren [ID](#)³, P.K. Resmi [ID](#)¹⁰, R. Ribatti [ID](#)^{29,p}, A.M. Ricci [ID](#)²⁷, S. Ricciardi [ID](#)⁵¹, K. Richardson [ID](#)⁵⁸, M. Richardson-Slipper [ID](#)⁵², K. Rinnert [ID](#)⁵⁴, P. Robbe [ID](#)¹¹, G. Robertson [ID](#)⁵², A.B. Rodrigues [ID](#)⁴³, E. Rodrigues [ID](#)⁵⁴, E. Rodriguez Fernandez [ID](#)⁴⁰, J.A. Rodriguez Lopez [ID](#)⁶⁹, E. Rodriguez Rodriguez [ID](#)⁴⁰, D.L. Rolf [ID](#)⁴², A. Rollings [ID](#)⁵⁷, P. Roloff [ID](#)⁴², V. Romanovskiy [ID](#)³⁸, M. Romero Lamas [ID](#)⁴⁰, A. Romero Vidal [ID](#)⁴⁰, J.D. Roth [ID](#)^{78,†}, M. Rotondo [ID](#)²³, M.S. Rudolph [ID](#)⁶², T. Ruf [ID](#)⁴², R.A. Ruiz Fernandez [ID](#)⁴⁰, J. Ruiz Vidal [ID](#)⁴¹, A. Ryzhikov [ID](#)³⁸, J. Ryzka [ID](#)³⁴, J.J. Saborido Silva [ID](#)⁴⁰, N. Sagidova [ID](#)³⁸, N. Sahoo [ID](#)⁴⁷, B. Saitta [ID](#)^{27,h}, M. Salomoni [ID](#)⁴², C. Sanchez Gras [ID](#)³², I. Sanderswood [ID](#)⁴¹, R. Santacesaria [ID](#)³⁰, C. Santamarina Rios [ID](#)⁴⁰, M. Santimaria [ID](#)²³, E. Santovetti [ID](#)^{31,s}, D. Saranin [ID](#)³⁸, G. Sarpis [ID](#)¹⁴, M. Sarpis [ID](#)⁷⁰, A. Sarti [ID](#)³⁰, C. Satriano [ID](#)^{30,r}, A. Satta [ID](#)³¹, M. Saur [ID](#)¹⁵, D. Savrina [ID](#)³⁸, H. Sazak [ID](#)⁹, L.G. Scantlebury Smead [ID](#)⁵⁷, A. Scarabotto [ID](#)¹³, S. Schael [ID](#)¹⁴, S. Scherl [ID](#)⁵⁴, M. Schiller [ID](#)⁵³, H. Schindler [ID](#)⁴², M. Schmelling [ID](#)¹⁶, B. Schmidt [ID](#)⁴², S. Schmitt [ID](#)¹⁴, O. Schneider [ID](#)⁴³, A. Schopper [ID](#)⁴², M. Schubiger [ID](#)³², S. Schulte [ID](#)⁴³, M.H. Schune [ID](#)¹¹, R. Schwemmer [ID](#)⁴², B. Sciascia [ID](#)^{23,42}, A. Sciucati [ID](#)⁴², S. Sellam [ID](#)⁴⁰, A. Semennikov [ID](#)³⁸, M. Senghi Soares [ID](#)³³, A. Sergi [ID](#)^{24,k}, N. Serra [ID](#)⁴⁴, L. Sestini [ID](#)²⁸, A. Seuthe [ID](#)¹⁵, Y. Shang [ID](#)⁵, D.M. Shangase [ID](#)⁷⁸, M. Shapkin [ID](#)³⁸, I. Shchemerov [ID](#)³⁸, L. Shchutka [ID](#)⁴³, T. Shears [ID](#)⁵⁴, L. Shekhtman [ID](#)³⁸, Z. Shen [ID](#)⁵, S. Sheng [ID](#)^{4,6}, V. Shevchenko [ID](#)³⁸, B. Shi [ID](#)⁶, Q. Shi [ID](#)⁶, E.B. Shields [ID](#)^{26,m}, Y. Shimizu [ID](#)¹¹, E. Shmanin [ID](#)³⁸, R. Shorkin [ID](#)³⁸, J.D. Shupperd [ID](#)⁶², B.G. Siddi [ID](#)^{21,i}, R. Silva Coutinho [ID](#)⁶², G. Simi [ID](#)²⁸, S. Simone [ID](#)^{19,f}, M. Singla [ID](#)⁶³, N. Skidmore [ID](#)⁵⁶, R. Skuza [ID](#)¹⁷, T. Skwarnicki [ID](#)⁶², M.W. Slater [ID](#)⁴⁷, J.C. Smallwood [ID](#)⁵⁷, J.G. Smeaton [ID](#)⁴⁹, E. Smith [ID](#)⁴⁴, K. Smith [ID](#)⁶¹, M. Smith [ID](#)⁵⁵, A. Snoch [ID](#)³², L. Soares Lavra [ID](#)⁹, M.D. Sokoloff [ID](#)⁵⁹, F.J.P. Soler [ID](#)⁵³, A. Solomin [ID](#)^{38,48}, A. Solovev [ID](#)³⁸, I. Solovyev [ID](#)³⁸, R. Song [ID](#)⁶³, F.L. Souza De Almeida [ID](#)², B. Souza De Paula [ID](#)², B. Spaan [ID](#)^{15,†}, E. Spadaro Norella [ID](#)^{25,l}, E. Spedicato [ID](#)²⁰, E. Spiridenkov [ID](#)³⁸, P. Spradlin [ID](#)⁵³, V. Sriskaran [ID](#)⁴², F. Stagni [ID](#)⁴², M. Stahl [ID](#)⁴², S. Stahl [ID](#)⁴², S. Stanislaus [ID](#)⁵⁷, E.N. Stein [ID](#)⁴², O. Steinkamp [ID](#)⁴⁴, O. Stenyakin [ID](#)³⁸, H. Stevens [ID](#)¹⁵, S. Stone [ID](#)^{62,†},

D. Strelakina ^{1b38}, Y.S. Su ^{6b6}, F. Suljik ^{57b57}, J. Sun ^{27b27}, L. Sun ^{68b68}, Y. Sun ^{60b60}, P. Svihra ^{56b56}, P.N. Swallow ^{47b47}, K. Swientek ^{34b34}, A. Szabelski ^{36b36}, T. Szumlak ^{34b34}, M. Szymanski ^{42b42}, Y. Tan ^{3b3}, S. Taneja ^{56b56}, M.D. Tat ^{57b57}, A. Terentev ^{38b38}, F. Teubert ^{42b42}, E. Thomas ^{42b42}, D.J.D. Thompson ^{47b47}, K.A. Thomson ^{54b54}, H. Tilquin ^{55b55}, V. Tisserand ^{9b9}, S. T'Jampens ^{8b8}, M. Tobin ^{4b4}, L. Tomassetti ^{21,i21,i}, G. Tonani ^{25,l25,l}, X. Tong ^{5b5}, D. Torres Machado ^{1b1}, D.Y. Tou ^{3b3}, S.M. Trilov ^{48b48}, C. Tripll ^{43b43}, G. Tuci ^{6b6}, A. Tully ^{43b43}, N. Tuning ^{32b32}, A. Ukleja ^{36b36}, D.J. Unverzagt ^{17b17}, A. Usachov ^{33b33}, A. Ustyuzhanin ^{38b38}, U. Uwer ^{17b17}, A. Vagner ^{38b38}, V. Vagnoni ^{20b20}, A. Valassi ^{42b42}, G. Valenti ^{20b20}, N. Valls Canudas ^{76b76}, M. Van Dijk ^{43b43}, H. Van Hecke ^{61b61}, E. van Herwijnen ^{55b55}, C.B. Van Hulse ^{40,u40,u}, M. van Veghel ^{73b73}, R. Vazquez Gomez ^{39b39}, P. Vazquez Regueiro ^{40b40}, C. Vázquez Sierra ^{42b42}, S. Vecchi ^{21b21}, J.J. Velthuis ^{48b48}, M. Veltri ^{22,t22,t}, A. Venkateswaran ^{43b43}, M. Veronesi ^{32b32}, M. Vesterinen ^{50b50}, D. Vieira ^{59b59}, M. Vieites Diaz ^{43b43}, X. Vilasis-Cardona ^{76b76}, E. Vilella Figueras ^{54b54}, A. Villa ^{20b20}, P. Vincent ^{13b13}, F.C. Volle ^{11b11}, D. vom Bruch ^{10b10}, A. Vorobyev ^{38b38}, V. Vorobyev ^{38b38}, N. Voropaev ^{38b38}, K. Vos ^{74b74}, C. Vrahas ^{52b52}, R. Waldi ^{17b17}, J. Walsh ^{29b29}, G. Wan ^{5b5}, C. Wang ^{17b17}, G. Wang ^{7b7}, J. Wang ^{5b5}, J. Wang ^{4b4}, J. Wang ^{3b3}, J. Wang ^{68b68}, M. Wang ^{25b25}, R. Wang ^{48b48}, X. Wang ^{66b66}, Y. Wang ^{7b7}, Z. Wang ^{44b44}, Z. Wang ^{3b3}, Z. Wang ^{6b6}, J.A. Ward ^{50,63b50,63}, N.K. Watson ^{47b47}, D. Websdale ^{55b55}, Y. Wei ^{5b5}, B.D.C. Westhenry ^{48b48}, D.J. White ^{56b56}, M. Whitehead ^{53b53}, A.R. Wiederhold ^{50b50}, D. Wiedner ^{15b15}, G. Wilkinson ^{57b57}, M.K. Wilkinson ^{59b59}, I. Williams ^{49b49}, M. Williams ^{58b58}, M.R.J. Williams ^{52b52}, R. Williams ^{49b49}, F.F. Wilson ^{51b51}, W. Wislicki ^{36b36}, M. Witek ^{35b35}, L. Witola ^{17b17}, C.P. Wong ^{61b61}, G. Wormser ^{11b11}, S.A. Wotton ^{49b49}, H. Wu ^{62b62}, J. Wu ^{7b7}, K. Wyllie ^{42b42}, Z. Xiang ^{6b6}, D. Xiao ^{7b7}, Y. Xie ^{7b7}, A. Xu ^{5b5}, J. Xu ^{6b6}, L. Xu ^{3b3}, L. Xu ^{3b3}, M. Xu ^{50b50}, Q. Xu ^{6b6}, Z. Xu ^{9b9}, Z. Xu ^{6b6}, D. Yang ^{3b3}, S. Yang ^{6b6}, X. Yang ^{5b5}, Y. Yang ^{6b6}, Z. Yang ^{5b5}, Z. Yang ^{60b60}, L.E. Yeomans ^{54b54}, V. Yeroshenko ^{11b11}, H. Yeung ^{56b56}, H. Yin ^{7b7}, J. Yu ^{65b65}, X. Yuan ^{62b62}, E. Zaffaroni ^{43b43}, M. Zavertyaev ^{16b16}, M. Zdybal ^{35b35}, O. Zenaiev ^{42b42}, M. Zeng ^{3b3}, C. Zhang ^{5b5}, D. Zhang ^{7b7}, L. Zhang ^{3b3}, S. Zhang ^{65b65}, S. Zhang ^{5b5}, Y. Zhang ^{5b5}, Y. Zhang ^{57b57}, A. Zharkova ^{38b38}, A. Zhelezov ^{17b17}, Y. Zheng ^{6b6}, T. Zhou ^{5b5}, X. Zhou ^{6b6}, Y. Zhou ^{6b6}, V. Zhovkovska ^{11b11}, X. Zhu ^{3b3}, X. Zhu ^{7b7}, Z. Zhu ^{6b6}, V. Zhukov ^{14,38b14,38}, Q. Zou ^{4,6b4,6}, S. Zucchelli ^{20,g20,g}, D. Zuliani ^{28b28}, G. Zunica ^{56b56}

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

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

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

⁴ Institute Of High Energy Physics (IHEP), Beijing, China

⁵ School of Physics State Key Laboratory of Nuclear Physics and Technology, Peking University, Beijing, China

⁶ University of Chinese Academy of Sciences, Beijing, China

⁷ Institute of Particle Physics, Central China Normal University, Wuhan, Hubei, China

⁸ Université Savoie Mont Blanc, CNRS, IN2P3-LAPP, Annecy, France

⁹ Université Clermont Auvergne, CNRS/IN2P3, LPC, Clermont-Ferrand, France

¹⁰ Aix Marseille Univ, CNRS/IN2P3, CPPM, Marseille, France

¹¹ Université Paris-Saclay, CNRS/IN2P3, IJCLab, Orsay, France

¹² Laboratoire Leprince-Ringuet, CNRS/IN2P3, Ecole Polytechnique, Institut Polytechnique de Paris, Palaiseau, France

¹³ LPNHE, Sorbonne Université, Paris Diderot Sorbonne Paris Cité, CNRS/IN2P3, Paris, France

¹⁴ I. Physikalisches Institut, RWTH Aachen University, Aachen, Germany

¹⁵ Fakultät Physik, Technische Universität Dortmund, Dortmund, Germany

- ¹⁶ *Max-Planck-Institut für Kernphysik (MPIK), Heidelberg, Germany*
- ¹⁷ *Physikalisches Institut, Ruprecht-Karls-Universität Heidelberg, Heidelberg, Germany*
- ¹⁸ *School of Physics, University College Dublin, Dublin, Ireland*
- ¹⁹ *INFN Sezione di Bari, Bari, Italy*
- ²⁰ *INFN Sezione di Bologna, Bologna, Italy*
- ²¹ *INFN Sezione di Ferrara, Ferrara, Italy*
- ²² *INFN Sezione di Firenze, Firenze, Italy*
- ²³ *INFN Laboratori Nazionali di Frascati, Frascati, Italy*
- ²⁴ *INFN Sezione di Genova, Genova, Italy*
- ²⁵ *INFN Sezione di Milano, Milano, Italy*
- ²⁶ *INFN Sezione di Milano-Bicocca, Milano, Italy*
- ²⁷ *INFN Sezione di Cagliari, Monserrato, Italy*
- ²⁸ *Università degli Studi di Padova, Università e INFN, Padova, Padova, Italy*
- ²⁹ *INFN Sezione di Pisa, Pisa, Italy*
- ³⁰ *INFN Sezione di Roma La Sapienza, Roma, Italy*
- ³¹ *INFN Sezione di Roma Tor Vergata, Roma, Italy*
- ³² *Nikhef National Institute for Subatomic Physics, Amsterdam, Netherlands*
- ³³ *Nikhef National Institute for Subatomic Physics and VU University Amsterdam, Amsterdam, Netherlands*
- ³⁴ *AGH - University of Science and Technology, Faculty of Physics and Applied Computer Science, Kraków, Poland*
- ³⁵ *Henryk Niewodniczanski Institute of Nuclear Physics Polish Academy of Sciences, Kraków, Poland*
- ³⁶ *National Center for Nuclear Research (NCBJ), Warsaw, Poland*
- ³⁷ *Horia Hulubei National Institute of Physics and Nuclear Engineering, Bucharest-Magurele, Romania*
- ³⁸ *Affiliated with an institute covered by a cooperation agreement with CERN*
- ³⁹ *ICCUB, Universitat de Barcelona, Barcelona, Spain*
- ⁴⁰ *Instituto Galego de Física de Altas Enerxías (IGFAE), Universidade de Santiago de Compostela, Santiago de Compostela, Spain*
- ⁴¹ *Instituto de Física Corpuscular, Centro Mixto Universidad de Valencia - CSIC, Valencia, Spain*
- ⁴² *European Organization for Nuclear Research (CERN), Geneva, Switzerland*
- ⁴³ *Institute of Physics, Ecole Polytechnique Fédérale de Lausanne (EPFL), Lausanne, Switzerland*
- ⁴⁴ *Physik-Institut, Universität Zürich, Zürich, Switzerland*
- ⁴⁵ *NSC Kharkiv Institute of Physics and Technology (NSC KIPT), Kharkiv, Ukraine*
- ⁴⁶ *Institute for Nuclear Research of the National Academy of Sciences (KINR), Kyiv, Ukraine*
- ⁴⁷ *University of Birmingham, Birmingham, United Kingdom*
- ⁴⁸ *H.H. Wills Physics Laboratory, University of Bristol, Bristol, United Kingdom*
- ⁴⁹ *Cavendish Laboratory, University of Cambridge, Cambridge, United Kingdom*
- ⁵⁰ *Department of Physics, University of Warwick, Coventry, United Kingdom*
- ⁵¹ *STFC Rutherford Appleton Laboratory, Didcot, United Kingdom*
- ⁵² *School of Physics and Astronomy, University of Edinburgh, Edinburgh, United Kingdom*
- ⁵³ *School of Physics and Astronomy, University of Glasgow, Glasgow, United Kingdom*
- ⁵⁴ *Oliver Lodge Laboratory, University of Liverpool, Liverpool, United Kingdom*
- ⁵⁵ *Imperial College London, London, United Kingdom*
- ⁵⁶ *Department of Physics and Astronomy, University of Manchester, Manchester, United Kingdom*
- ⁵⁷ *Department of Physics, University of Oxford, Oxford, United Kingdom*
- ⁵⁸ *Massachusetts Institute of Technology, Cambridge, MA, United States*
- ⁵⁹ *University of Cincinnati, Cincinnati, OH, United States*
- ⁶⁰ *University of Maryland, College Park, MD, United States*
- ⁶¹ *Los Alamos National Laboratory (LANL), Los Alamos, NM, United States*
- ⁶² *Syracuse University, Syracuse, NY, United States*
- ⁶³ *School of Physics and Astronomy, Monash University, Melbourne, Australia, associated to ⁵⁰*
- ⁶⁴ *Pontifícia Universidade Católica do Rio de Janeiro (PUC-Rio), Rio de Janeiro, Brazil, associated to ²*

- ⁶⁵ *Physics and Micro Electronic College, Hunan University, Changsha City, China, associated to* ⁷
- ⁶⁶ *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* ³
- ⁶⁷ *Lanzhou University, Lanzhou, China, associated to* ⁴
- ⁶⁸ *School of Physics and Technology, Wuhan University, Wuhan, China, associated to* ³
- ⁶⁹ *Departamento de Fisica, Universidad Nacional de Colombia, Bogota, Colombia, associated to* ¹³
- ⁷⁰ *Universität Bonn - Helmholtz-Institut für Strahlen und Kernphysik, Bonn, Germany, associated to* ¹⁷
- ⁷¹ *Eotvos Lorand University, Budapest, Hungary, associated to* ⁴²
- ⁷² *INFN Sezione di Perugia, Perugia, Italy, associated to* ²¹
- ⁷³ *Van Swinderen Institute, University of Groningen, Groningen, Netherlands, associated to* ³²
- ⁷⁴ *Universiteit Maastricht, Maastricht, Netherlands, associated to* ³²
- ⁷⁵ *Tadeusz Kosciuszko Cracow University of Technology, Cracow, Poland, associated to* ³⁵
- ⁷⁶ *DS4DS, La Salle, Universitat Ramon Llull, Barcelona, Spain, associated to* ³⁹
- ⁷⁷ *Department of Physics and Astronomy, Uppsala University, Uppsala, Sweden, associated to* ⁵³
- ⁷⁸ *University of Michigan, Ann Arbor, MI, United States, associated to* ⁶²

^a *Universidade de Brasília, Brasília, Brazil*

^b *Central South U., Changsha, China*

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

^d *Excellence Cluster ORIGINS, Munich, Germany*

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

^f *Università di Bari, Bari, Italy*

^g *Università di Bologna, Bologna, Italy*

^h *Università di Cagliari, Cagliari, Italy*

ⁱ *Università di Ferrara, Ferrara, Italy*

^j *Università di Firenze, Firenze, Italy*

^k *Università di Genova, Genova, Italy*

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

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

ⁿ *Università di Padova, Padova, Italy*

^o *Università di Perugia, Perugia, Italy*

^p *Scuola Normale Superiore, Pisa, Italy*

^q *Università di Pisa, Pisa, Italy*

^r *Università della Basilicata, Potenza, Italy*

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

^t *Università di Urbino, Urbino, Italy*

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

[†] *Deceased*