



**HAL**  
open science

## Observation of an excited $B_{c^+}$ state

Roel Aaij, Carlos Abellán Beteta, Bernardo Adeva, Marco Adinolfi, Christine Angela Aidala, Ziad Ajaltouni, Simon Akar, Pietro Albicocco, Johannes Albrecht, Federico Alessio, et al.

► **To cite this version:**

Roel Aaij, Carlos Abellán Beteta, Bernardo Adeva, Marco Adinolfi, Christine Angela Aidala, et al.. Observation of an excited  $B_{c^+}$  state. Phys.Rev.Lett., 2019, 122 (23), pp.232001. 10.1103/PhysRevLett.122.232001 . hal-02101690

**HAL Id: hal-02101690**

**<https://hal.science/hal-02101690>**

Submitted on 7 Sep 2023

**HAL** is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.



# Observation of an excited $B_c^+$ state

LHCb collaboration<sup>†</sup>

## Abstract

Using  $pp$  collision data corresponding to an integrated luminosity of  $8.5 \text{ fb}^{-1}$  recorded by the LHCb experiment at centre-of-mass energies of  $\sqrt{s} = 7, 8$  and  $13 \text{ TeV}$ , the observation of an excited  $B_c^+$  state in the  $B_c^+ \pi^+ \pi^-$  invariant-mass spectrum is reported. The observed peak has a mass of  $6841.2 \pm 0.6 \text{ (stat)} \pm 0.1 \text{ (syst)} \pm 0.8 \text{ (} B_c^+ \text{) MeV}/c^2$ , where the last uncertainty is due to the limited knowledge of the  $B_c^+$  mass. It is consistent with expectations of the  $B_c^*(2^3S_1)^+$  state reconstructed without the low-energy photon from the  $B_c^*(1^3S_1)^+ \rightarrow B_c^+ \gamma$  decay following  $B_c^*(2^3S_1)^+ \rightarrow B_c^*(1^3S_1)^+ \pi^+ \pi^-$ . A second state is seen with a global (local) statistical significance of  $2.2 \sigma$  ( $3.2 \sigma$ ) and a mass of  $6872.1 \pm 1.3 \text{ (stat)} \pm 0.1 \text{ (syst)} \pm 0.8 \text{ (} B_c^+ \text{) MeV}/c^2$ , and is consistent with the  $B_c(2^1S_0)^+$  state. These mass measurements are the most precise to date.

Published in Phys. Rev. Lett. 122 (2019) 232001

© 2019 CERN for the benefit of the LHCb collaboration. CC-BY-4.0 licence.

<sup>†</sup>Authors are listed at the end of this Letter.



The  $B_c$  meson family is unique in the Standard Model as its states are formed from two heavy quarks of different flavours. The spectrum of masses of  $B_c$  mesons can reveal information on heavy-quark dynamics and improve the understanding of the strong interaction. Specifically, it provides tests of nonrelativistic quark-potential models [1–13], which have been successfully applied to quarkonium, since the  $B_c$  family shares properties with both the charmonium and bottomonium systems. The  $B_c$  family is predicted to have a rich spectroscopy by various potential models [1–13] and lattice quantum chromodynamics [12]. However, the  $B_c$  mesons are much less explored compared to quarkonia due to the small production rate, since their predominant production mechanism requires the production of both  $c\bar{c}$  and  $b\bar{b}$  pairs. The ground state meson,  $B_c^+$ , was first observed by the CDF experiment [14] at the Tevatron collider. Knowledge of the properties of the  $B_c^+$  meson has been greatly advanced by the LHCb experiment with the measurement of the  $B_c^+$  mass, lifetime and production rate [15–20], and the discovery and precise measurement of the branching fractions of several new decay channels [16, 21–30]. Charge conjugation is implied throughout this Letter.

Excited  $B_c^+$  states that lie below the threshold for decay into a beauty and charm meson pair are expected to have decay widths smaller than a few hundred keV [3, 4]. Depending on its mass, an excited  $B_c^+$  resonance may undergo either cascade radiative or pionic decays to the  $B_c^+$  state, which decays weakly. The second  $S$ -wave  $B_c$  state occurs as either a pseudoscalar ( $0^-$ ) or a vector ( $1^-$ ) spin state, *i.e.*, the singlet  $B_c(2^1S_0)^+$  or the triplet  $B_c(2^3S_1)^+$ . The  $B_c(2^1S_0)^+$  and  $B_c(2^3S_1)^+$  states are denoted as  $B_c(2S)^+$  and  $B_c^*(2S)^+$ , respectively. The  $B_c(2S)^+$  state decays directly to  $B_c^+\pi^+\pi^-$ , while the  $B_c^*(2S)^+$  state decays to  $B_c(1^3S_1)^+\pi^+\pi^-$ , followed by the  $B_c(1^3S_1)^+ \rightarrow B_c^+\gamma$  electromagnetic transition. The low-energy photon produced in this decay is not considered in this analysis, since the reconstruction efficiency for such photons is too low to be useful with the current data sample. The  $B_c(1^3S_1)^+$  state is denoted as  $B_c^{*+}$  hereafter. The transitions among the  $B_c^{(*)}(2S)^+$  and  $B_c^{*+}$  states are illustrated in Fig. 1. Decays of both  $B_c^{(*)}(2S)^+$  states produce a narrow peak in the  $B_c^+\pi^+\pi^-$  invariant-mass spectrum [31, 32], however, the  $B_c^*(2S)^+$  state peaks at  $M(B_c^*(2S)^+)_{\text{rec}} = M(B_c^*(2S)^+) - \Delta M(B_c^{*+})$  due to the missing photon, where  $\Delta M(B_c^{*+})$  is the mass difference between the intermediate state  $B_c^{*+}$  and the  $B_c^+$  meson. Since the  $B_c^{*+}$  state has not been observed yet, the quantity  $\Delta M(B_c^{*+})$  is unknown and the value of  $M(B_c^*(2S)^+)$  can not be determined with this technique at the moment. Taking into account the unreconstructed photon, the mass difference between the two peaks in the  $B_c^+\pi^+\pi^-$  mass distribution originating from the two  $B_c^{(*)}(2S)^+$  states,  $M(B_c(2S)^+) - M(B_c^*(2S)^+)_{\text{rec}}$ , is predicted to be in the range 11 to 53 MeV/ $c^2$  [1–13]. The production cross-section of the  $B_c^*(2S)^+$  state is predicted to be twice as large as that of the  $B_c(2S)^+$  state [8, 31, 33, 34], while the branching fractions of the decays  $B_c(2S)^+ \rightarrow B_c^+\pi^+\pi^-$  and  $B_c^*(2S)^+ \rightarrow B_c^{*+}\pi^+\pi^-$  are expected to be similar [8, 34].

With the large samples of  $B_c^+$  mesons produced at the Large Hadron Collider, the ATLAS collaboration first reported the observation of a signal in the  $B_c^+\pi^+\pi^-$  mass distribution peaking at a value of  $6842 \pm 4$  (stat)  $\pm 5$  (syst) MeV/ $c^2$  using  $pp$  collision data at  $\sqrt{s} = 7$  and 8 TeV corresponding to a luminosity of 24 fb $^{-1}$  [35]. Due to large mass resolution and low signal yield, no determination could be made as to whether the observed peak was either the  $B_c(2S)^+$ , the  $B_c^*(2S)^+$  state, or a combination of the two states. The LHCb experiment also performed a search for excited  $B_c^+$  states in the  $B_c^+\pi^+\pi^-$  mass distribution using  $pp$  collision data at centre-of-mass energy of  $\sqrt{s} = 8$  TeV, corresponding to an integrated luminosity of 2 fb $^{-1}$ . No evidence of any signal was

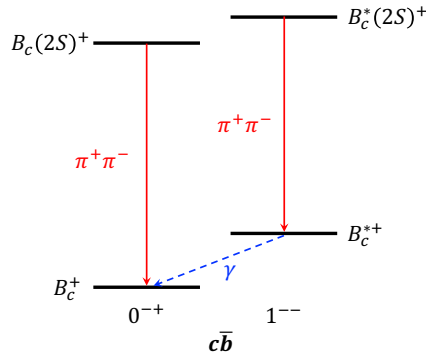


Figure 1: Transitions among the  $B_c^{(*)}(2S)^+$  and  $B_c^{(*)+}$  states.

found [36]. Recently, the CMS collaboration reported the observation of the  $B_c(2S)^+$  and  $B_c^*(2S)^+$  states [37], in which the mass of the  $B_c(2S)^+$  state and the mass difference between the two peaks were measured to be  $6871.0 \pm 1.2$  (stat)  $\pm 0.8$  (syst)  $\pm 0.8$  ( $B_c^+$ ) MeV/ $c^2$  and  $29.0 \pm 1.5$  (stat)  $\pm 0.7$  (syst) MeV/ $c^2$ , respectively. The third uncertainty is due to the limited knowledge of the  $B_c^+$  mass.

This Letter presents an updated search for excited  $B_c$  mesons in the  $B_c^+ \pi^+ \pi^-$  mass distribution. The analysis makes use of Run 1 and Run 2 data collected by the LHCb experiment from 2011 to 2018 at centre-of-mass energies of  $\sqrt{s} = 7, 8$  and 13 TeV, corresponding to integrated luminosities of about 1.0, 2.0 and 5.5 fb $^{-1}$ , respectively.

The LHCb detector [38, 39] is a single-arm forward spectrometer covering the pseudorapidity range  $2 < \eta < 5$ , designed for the study of particles containing  $b$  and/or  $c$  quarks. The detector elements that are particularly relevant to this analysis are: a silicon-strip vertex detector surrounding the  $pp$  interaction region that allows  $c$  and  $b$  hadrons to be identified from their characteristically long flight distance; a tracking system that 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/ $c$ ; and two ring-imaging Cherenkov detectors that are able to discriminate between different species of charged hadrons. The minimum distance of a track to a primary 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/ $c$ . 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 stage, events are required to have at least one muon with high transverse momentum,  $p_T$ , or a hadron with high transverse energy. At the software stage, two muon tracks or three charged tracks are required to have high  $p_T$  and to form a secondary vertex with a significant displacement from the interaction point. The momentum scale in data is calibrated using the  $J/\psi$  and  $B^+$  mesons [40] with well-known masses.

Simulated samples are used to model the signal behaviour. In the simulation,  $pp$  collisions are generated using PYTHIA 6 [41] with a specific LHCb configuration [42]. The generator BCVEGPy [33] is used to simulate the production of  $B_c^+$  mesons. Decays of unstable particles are described by EVTGEN [43], in which final-state radiation is

generated using PHOTOS [44]. The interaction of the generated particles with the detector, and its response, are implemented using the GEANT4 toolkit [45] as described in Ref. [46].

To form the  $B_c^{(*)}(2S)^+$  candidates, first the intermediate  $B_c^+$  state is reconstructed from the  $B_c^+ \rightarrow J/\psi \pi^+$  decay. The  $J/\psi$  candidates are reconstructed with a pair of oppositely charged particles identified as muons. The muons are required to have  $p_T > 550 \text{ MeV}/c$  and good track-fit quality. They are required to form a common decay vertex with an invariant mass in the range  $[3040, 3140] \text{ MeV}/c^2$ , corresponding to approximately six times the  $J/\psi$  mass resolution. The  $J/\psi$  candidate is combined with a charged pion to form the  $B_c^+$  candidate. Each particle is associated to the PV that has the smallest value of  $\chi_{\text{IP}}^2$ , where  $\chi_{\text{IP}}^2$  is defined as the difference in the vertex-fit  $\chi^2$  of a given PV reconstructed with and without the particle under consideration. The pion must have  $p_T > 1000 \text{ MeV}/c$ , good track-fit quality, and be inconsistent with originating from any PV. The  $B_c^+$  candidate is required to have a good-quality vertex, a trajectory consistent with coming from its associated PV, and a decay time larger than  $0.2 \text{ ps}$ .

To further suppress background, a boosted decision tree (BDT) [47, 48] classifier is used, as done in the  $B_c^+$  production measurement [20]. The input variables of the BDT classifier are taken to be the  $p_T$  of each muon, the  $J/\psi$  meson and the charged pion; the decay length, decay time and vertex-fit  $\chi^2$  of the  $B_c^+$  meson; and the  $\chi_{\text{IP}}^2$  of the muons, the pion, the  $J/\psi$  meson and the  $B_c^+$  meson with respect to the associated PV. The BDT classifier is trained using signal candidates from simulation and background candidates from the upper sideband of the  $J/\psi \pi^+$  mass distribution in data, corresponding to the range  $[6370, 6600] \text{ MeV}/c^2$ . The BDT threshold is chosen to maximise  $S/\sqrt{S+B}$ , where  $S$  and  $B$  are the expected yields of signal and background in the range  $M(J/\psi \pi^+) \in [6251, 6301] \text{ MeV}/c^2$ , respectively. This mass window corresponds to around four times the resolution of  $M(J/\psi \pi^+)$ . To improve the signal-to-background ratio in the  $B_c^{(*)}(2S)^+$  search, the transverse momentum of the  $B_c^+$  meson is required to be larger than  $10 \text{ GeV}/c$ .

An unbinned maximum-likelihood fit is performed to the  $M(J/\psi \pi^+)$  distribution. To improve the mass resolution, the mass  $M(J/\psi \pi^+)$  is calculated by constraining the  $J/\psi$  mass to its known value [49] and the  $B_c^+$  meson to originate from the associated PV [50]. The signal component is described by a Gaussian function with asymmetric power-law tails [51]. The parameters of the tails are determined from the simulation, while the mean and width of the Gaussian function are left free in the fit. The combinatorial background is modelled with an exponential function. The contamination from the Cabibbo-suppressed decay  $B_c^+ \rightarrow J/\psi K^+$ , with the kaon misidentified as a pion, is modelled by a Gaussian function with asymmetric power-law tails. The parameters of this Gaussian function are fixed according to the simulation, except that the mean is constrained relative to that of the  $B_c^+ \rightarrow J/\psi \pi^+$  signal. The invariant-mass distribution of the  $J/\psi \pi^+$  candidates is shown in Fig. 2. The  $B_c^+$  signal yield is  $3785 \pm 73$ . The fitted  $B_c^+$  mass and mass resolution are  $6273.7 \pm 0.3 \text{ MeV}/c^2$  and  $15.1 \pm 0.3 \text{ MeV}/c^2$ , respectively.

To reconstruct the  $B_c^{(*)}(2S)^+$  candidates,  $B_c^+$  candidates with  $M(J/\psi \pi^+) \in [6200, 6320] \text{ MeV}/c^2$  are combined with a pair of oppositely charged particles identified as pions. These pion candidates are required to originate from the PV, and each have  $p_T > 300 \text{ MeV}/c$ ,  $p > 1500 \text{ MeV}/c$ , and a good track-fit quality. The  $B_c^{(*)}(2S)^+$  candidate is required to have a good vertex-fit quality. To improve the mass resolution, a fit [50] is performed in which the  $J/\psi$  and  $B_c^+$  masses are constrained to their known values [49] and the daughters of the  $B_c^{(*)}(2S)^+$  meson are required to point

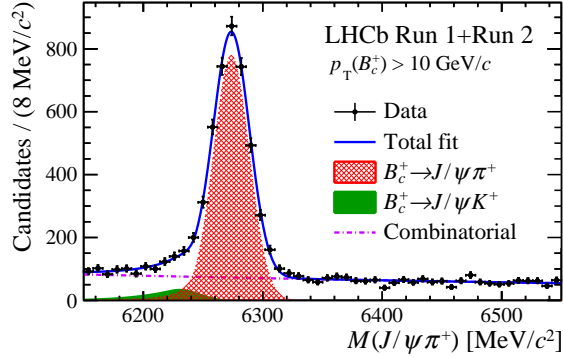


Figure 2: Invariant-mass distribution of the selected  $B_c^+$  candidates. The fit results are overlaid.

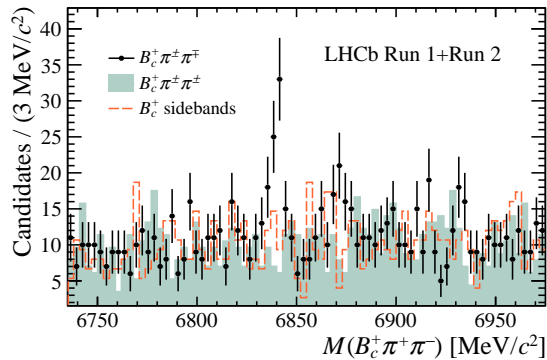


Figure 3: Invariant-mass  $M(B_c^+ \pi^+ \pi^-)$  distributions for the data and same-sign samples with the distribution of the  $B_c^+$  mass sidebands overlaid.

to the associated PV. The  $\chi^2$  per number of degrees of freedom of this fit must be smaller than nine. The value of  $M(B_c^+ \pi^+ \pi^-) - M(B_c^+) - M(\pi^+ \pi^-)$  is required to be smaller than  $200 \text{ MeV}/c^2$ . To ensure that the selection does not produce any artificial peaks in the  $M(B_c^+ \pi^+ \pi^-)$  spectrum, the same requirements are applied to a same-sign sample, constructed from  $B_c^+ \pi^+ \pi^+$  or  $B_c^+ \pi^- \pi^-$  combinations. The efficiency of the selections is found to change smoothly with the invariant mass  $M(B_c^+ \pi \pi)$  and no peaks are seen in the same-sign sample.

The  $M(B_c^+ \pi^+ \pi^-)$  distribution in the data sample after all the selections are applied is shown in Fig. 3, with those of the same-sign sample and a sample drawn from the  $B_c^+$  sidebands ( $M(J/\psi \pi^+) \in [6150, 6200] \cup [6320, 6550] \text{ MeV}/c^2$ ) superimposed for comparison. The same-sign and  $B_c^+$  mass sideband distributions are scaled to the opposite-sign distribution in the sideband region,  $M(B_c^+ \pi^+ \pi^-) \in [6735, 6825] \cup [6895, 6975] \text{ MeV}/c^2$ . The  $M(B_c^+ \pi^+ \pi^-)$  distribution presents an obvious peak at approximately  $6840 \text{ MeV}/c^2$ , and a less significant structure at about  $6870 \text{ MeV}/c^2$ .

The masses and yields of the  $B_c^{(*)}(2S)^+$  peaks are determined using an unbinned maximum-likelihood fit to the distribution of the mass difference,  $\Delta M \equiv M(B_c^+ \pi^+ \pi^-) - M(B_c^+)$ , to eliminate the dependence on the reconstructed  $B_c^+$  mass. Here the mass  $M(B_c^+ \pi^+ \pi^-)$  is calculated with no constraint on the  $B_c^+$  mass, but

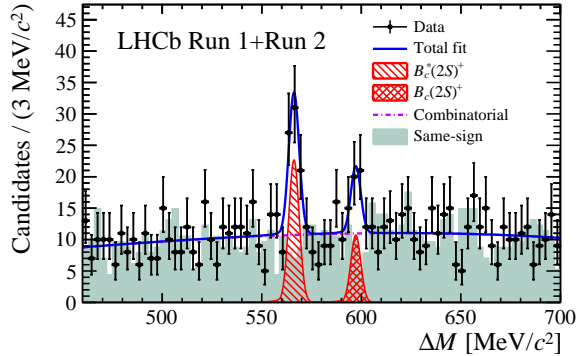


Figure 4: Distribution of  $\Delta M = M(B_c^+ \pi^+ \pi^-) - M(B_c^+)$  with the fit results overlaid. The same-sign distribution has been normalized to the data in the  $B_c^{(*)}(2S)^+$  sideband region.

Table 1: Results of the fit to the  $\Delta M$  distribution. Uncertainties are statistical only.

	$B_c^*(2S)^+$	$B_c(2S)^+$
Signal yield	$51 \pm 10$	$24 \pm 9$
Peak $\Delta M$ value ( $\text{MeV}/c^2$ )	$566.2 \pm 0.6$	$597.2 \pm 1.3$
Resolution ( $\text{MeV}/c^2$ )	$2.6 \pm 0.5$	$2.5 \pm 1.0$
Local significance	$6.8 \sigma$	$3.2 \sigma$
Global significance	$6.3 \sigma$	$2.2 \sigma$

only constraining the  $J/\psi$  mass to its known value [49] and requiring the  $B_c^{(*)}(2S)^+$  meson to come from the associated PV [50]. Each  $B_c^{(*)}(2S)^+$  peak is modelled by a Gaussian function with asymmetric power-law tails [51]. The tail parameters are fixed to the values determined from simulation, while the Gaussian mean and width are treated as free parameters. The combinatorial background is described by a second-order polynomial function.

The fit to the  $\Delta M$  distribution is shown in Fig. 4, and the results are summarised in Table 1. The  $B_c^*(2S)^+$  signal yield is determined to be  $51 \pm 10$  (stat), corresponding to a local statistical significance of  $6.8 \sigma$ . The significance is evaluated with a likelihood-based test, in which the likelihood distribution of the background-only hypothesis is obtained using pseudoexperiments [52]. The yield of the  $B_c(2S)^+$  state is  $24 \pm 9$  (stat) with a local statistical significance of  $3.2 \sigma$ . The Gaussian widths of the two peaks are consistent with the expectation of negligible resonance widths. The mass difference between the two peaks is measured to be  $31.1 \pm 1.4$  (stat)  $\text{MeV}/c^2$ . Taking the known  $B_c^+$  mass,  $M(B_c^+) = 6274.9 \pm 0.8 \text{ MeV}/c^2$  [53], the quantities  $M(B_c^*(2S)^+)_{\text{rec}}$  and  $M(B_c(2S)^+)$  are determined to be  $6841.1 \pm 0.6$  (stat)  $\pm 0.8 (B_c^+) \text{ MeV}/c^2$  and  $6872.1 \pm 1.3$  (stat)  $\pm 0.8 (B_c^+) \text{ MeV}/c^2$ , respectively. The second uncertainty is due to the limited knowledge of the  $B_c^+$  mass. After considering the look-elsewhere effect in the predicted mass regions [54],  $M(B_c^+ \pi^+ \pi^-) \in [6790, 6895] \text{ MeV}/c^2$  for the  $B_c^*(2S)^+$  state, and  $M(B_c^+ \pi^+ \pi^-) \in [6845, 6895] \text{ MeV}/c^2$  for the  $B_c(2S)^+$  state [1–10, 55], the global statistical significances of the two states are determined to be  $6.3 \sigma$  and  $2.2 \sigma$ , respectively.



Several sources of systematic uncertainty on the determination of the mass difference  $\Delta M$  are studied. The dominant contribution is from the uncertainty on the momentum scale, which is due to imperfections in the description of the magnetic field and the imperfect alignment of the subdetectors. The uncertainty of the momentum calibration is estimated using other particles, such as  $K_S^0$  and  $\mathcal{Y}$  mesons, and leads to an uncertainty of  $0.12 \text{ MeV}/c^2$  on the  $\Delta M$  measurements. The unreconstructed photon emitted in the  $B_c^*(2S)^+$  decay chain could be an additional source of systematic uncertainty. Studies on simulated events show that the missing photon introduces a small bias, and a correction of  $+0.08 \text{ MeV}/c^2$ , with negligible uncertainty, is applied to the fitted value of the  $B_c^*(2S)^+$  mass peak. All other systematic uncertainties are negligible and are briefly described as follows. The effects of the imperfect modelling of the signal and background components are estimated by using alternative models. The alternative model for the signal peaks uses Hypatia functions [56], while for the background the alternative model consists of a sum of two threshold functions, each of the form  $(\Delta M - m_t)^p \times e^{-C \cdot (\Delta M - m_t)}$ , where  $p$  and  $C$  are free parameters, and  $m_t$  represents the threshold, which is taken to be  $2m_{\pi^\pm}$ . The changes in  $\Delta M$  obtained with the alternative models are found to be negligible. The effect of final-state radiation is also studied with simulated events and the associated uncertainty on the fitted mass values is found to be negligible. The total systematic uncertainty on  $\Delta M$  for both the  $B_c(2S)^+$  and  $B_c^*(2S)^+$  states of  $0.12 \text{ MeV}/c^2$  is fully correlated, and therefore cancels in the mass difference of the two peaks.

In conclusion, using  $pp$  collision data collected by the LHCb experiment at centre-of-mass energies of  $\sqrt{s} = 7, 8$  and  $13 \text{ TeV}$ , corresponding to an integrated luminosity of  $8.5 \text{ fb}^{-1}$ , a peaking structure consistent with the  $B_c^*(2S)^+$  state is observed in the  $B_c^+ \pi^+ \pi^-$  mass spectrum with a global (local) statistical significance of  $6.3 \sigma$  ( $6.8 \sigma$ ). The mass associated with the  $B_c^*(2S)^+$  state, for which the low-energy photon in the intermediate decay  $B_c^{*+} \rightarrow B_c^+ \gamma$  is not reconstructed, is measured to be

$$6841.2 \pm 0.6 \text{ (stat)} \pm 0.1 \text{ (syst)} \pm 0.8 (B_c^+) \text{ MeV}/c^2,$$

where the last uncertainty is due to the limited knowledge of the  $B_c^+$  mass. It is equal to  $M(B_c^*(2S)^+)_{\text{rec}} = M(B_c^*(2S)^+) - (M(B_c^{*+}) - M(B_c^+))$ . The mass difference between the  $B_c^*(2S)^+$  and  $B_c^{*+}$  state is determined to be  $566.3 \pm 0.6 \text{ (stat)} \pm 0.1 \text{ (syst)} \text{ MeV}/c^2$ . The data also show a hint for a second structure consistent with the  $B_c(2S)^+$  state with a global (local) statistical significance of  $2.2 \sigma$  ( $3.2 \sigma$ ). Assuming this peak is due to the  $B_c(2S)^+$  state, its mass is measured to be

$$6872.1 \pm 1.3 \text{ (stat)} \pm 0.1 \text{ (syst)} \pm 0.8 (B_c^+) \text{ MeV}/c^2.$$

The mass difference between the  $B_c(2S)^+$  and  $B_c^+$  state is  $597.2 \pm 1.3 \text{ (stat)} \pm 0.1 \text{ (syst)} \text{ MeV}/c^2$ . The mass difference of the two  $B_c^{(*)}(2S)^+$  peaks is determined to be

$$31.0 \pm 1.4 \text{ (stat)} \pm 0.0 \text{ (syst)} \text{ MeV}/c^2,$$

in which both the uncertainty from the  $B_c^+$  mass and the systematic uncertainty cancel. The mass measurements are the most precise to date, and are consistent with the results from the CMS collaboration [37]. They are also within the range of the theoretical predictions [1–13].

## Acknowledgements

We thank Chao-Hsi Chang and Xing-Gang Wu for frequent and interesting discussions on the production of the  $B_c$  mesons. 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); MSHE (Russia); MinECo (Spain); SNSF and SER (Switzerland); NASU (Ukraine); STFC (United Kingdom); NSF (USA). 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), RRCKI and Yandex LLC (Russia), CSCS (Switzerland), IFIN-HH (Romania), CBPF (Brazil), PL-GRID (Poland) and OSC (USA). 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 AvH Foundation (Germany); EPLANET, Marie Skłodowska-Curie Actions and ERC (European Union); ANR, Labex P2IO and OCEVU, and Région Auvergne-Rhône-Alpes (France); Key Research Program of Frontier Sciences of CAS, CAS PIFI, and the Thousand Talents Program (China); RFBR, RSF and Yandex LLC (Russia); GVA, XuntaGal and GENCAT (Spain); the Royal Society and the Leverhulme Trust (United Kingdom); Laboratory Directed Research and Development program of LANL (USA).

## References

- [1] S. S. Gershtein *et al.*, *Production cross-section and spectroscopy of  $B_c$  mesons*, Sov. J. Nucl. Phys. **48** (1988) 327, Yad. Fiz. **48** (1988) 515.
- [2] Y.-Q. Chen and Y.-P. Kuang, *Improved QCD-motivated heavy quark potentials with explicit  $\Lambda_{\overline{MS}}$  dependence*, Phys. Rev. **D46** (1992) 1165, Erratum *ibid.* **D47** (1993) 350.
- [3] E. J. Eichten and C. Quigg, *Mesons with beauty and charm: Spectroscopy*, Phys. Rev. **D49** (1994) 5845, [arXiv:hep-ph/9402210](#).
- [4] S. S. Gershtein, V. V. Kiselev, A. K. Likhoded, and A. V. Tkabladze,  *$B_c$  spectroscopy*, Phys. Rev. **D51** (1995) 3613, [arXiv:hep-ph/9406339](#).
- [5] S. N. Gupta and J. M. Johnson,  *$B_c$  spectroscopy in a quantum-chromodynamic potential model*, Phys. Rev. **D53** (1996) 312, [arXiv:hep-ph/9511267](#).
- [6] L. P. Fulcher, *Phenomenological predictions of the properties of the  $B_c$  system*, Phys. Rev. **D60** (1999) 074006, [arXiv:hep-ph/9806444](#).
- [7] D. Ebert, R. N. Faustov, and V. O. Galkin, *Properties of heavy quarkonia and  $B_c$  mesons in the relativistic quark model*, Phys. Rev. **D67** (2003) 014027, [arXiv:hep-ph/0210381](#).

- [8] S. Godfrey, *Spectroscopy of  $B_c$  mesons in the relativized quark model*, Phys. Rev. **D70** (2004) 054017, [arXiv:hep-ph/0406228](#).
- [9] K.-W. Wei and X.-H. Guo, *Mass spectra of doubly heavy mesons in Regge phenomenology*, Phys. Rev. **D81** (2010) 076005.
- [10] A. Abd El-Hady, J. R. Spence, and J. P. Vary, *Radiative decays of  $B_c$  mesons in a Bethe-Salpeter model*, Phys. Rev. **D71** (2005) 034006, [arXiv:hep-ph/0603139](#).
- [11] J. Zeng, J. W. Van Orden, and W. Roberts, *Heavy mesons in a relativistic model*, Phys. Rev. **D52** (1995) 5229, [arXiv:hep-ph/9412269](#).
- [12] C. T. H. Davies *et al.*,  *$B_c$  spectroscopy from lattice QCD*, Phys. Lett. **B382** (1996) 131, [arXiv:hep-lat/9602020](#).
- [13] R. J. Dowdall, C. T. H. Davies, T. C. Hammant, and R. R. Horgan, *Precise heavy-light meson masses and hyperfine splittings from lattice QCD including charm quarks in the sea*, Phys. Rev. **D86** (2012) 094510, [arXiv:1207.5149](#).
- [14] CDF collaboration, F. Abe *et al.*, *Observation of the  $B_c$  meson in  $p\bar{p}$  collisions at  $\sqrt{s} = 1.8$  TeV*, Phys. Rev. Lett. **81** (1998) 2432, [arXiv:hep-ex/9805034](#); CDF collaboration, F. Abe *et al.*, *Observation of  $B_c$  mesons in  $p\bar{p}$  collisions at  $\sqrt{s} = 1.8$  TeV*, Phys. Rev. **D58** (1998) 112004, [arXiv:hep-ex/9804014](#).
- [15] LHCb collaboration, R. Aaij *et al.*, *Measurements of  $B_c^+$  production and mass with the  $B_c^+ \rightarrow J/\psi \pi^+$  decay*, Phys. Rev. Lett. **109** (2012) 232001, [arXiv:1209.5634](#).
- [16] LHCb collaboration, R. Aaij *et al.*, *Observation of  $B_c^+ \rightarrow J/\psi D_s^+$  and  $B_c^+ \rightarrow J/\psi D_s^{*+}$  decays*, Phys. Rev. **D87** (2013) 112012, [arXiv:1304.4530](#).
- [17] LHCb collaboration, R. Aaij *et al.*, *First observation of a baryonic  $B_c^+$  decay*, Phys. Rev. Lett. **113** (2014) 152003, [arXiv:1408.0971](#).
- [18] LHCb collaboration, R. Aaij *et al.*, *Measurement of the  $B_c^+$  meson lifetime using  $B_c^+ \rightarrow J/\psi \mu^+ \nu_\mu X$  decays*, Eur. Phys. J. **C74** (2014) 2839, [arXiv:1401.6932](#).
- [19] LHCb collaboration, R. Aaij *et al.*, *Measurement of the lifetime of the  $B_c^+$  meson using the  $B_c^+ \rightarrow J/\psi \pi^+$  decay mode*, Phys. Lett. **B742** (2015) 29, [arXiv:1411.6899](#).
- [20] LHCb collaboration, R. Aaij *et al.*, *Measurement of  $B_c^+$  production in proton-proton collisions at  $\sqrt{s} = 8$  TeV*, Phys. Rev. Lett. **114** (2015) 132001, [arXiv:1411.2943](#).
- [21] LHCb collaboration, R. Aaij *et al.*, *First observation of the decay  $B_c^+ \rightarrow J/\psi \pi^+ \pi^- \pi^+$* , Phys. Rev. Lett. **108** (2012) 251802, [arXiv:1204.0079](#).
- [22] LHCb collaboration, R. Aaij *et al.*, *Observation of the decay  $B_c^+ \rightarrow \psi(2S)\pi^+$* , Phys. Rev. **D87** (2013) 071103(R), [arXiv:1303.1737](#).
- [23] LHCb collaboration, R. Aaij *et al.*, *First observation of the decay  $B_c^+ \rightarrow J/\psi K^+$* , JHEP **09** (2013) 075, [arXiv:1306.6723](#).
- [24] LHCb collaboration, R. Aaij *et al.*, *Observation of the decay  $B_c^+ \rightarrow B_s^0 \pi^+$* , Phys. Rev. Lett. **111** (2013) 181801, [arXiv:1308.4544](#).

- [25] LHCb collaboration, R. Aaij *et al.*, *Observation of the decay  $B_c^+ \rightarrow J/\psi K^+ K^- \pi^+$* , JHEP **11** (2013) 094, [arXiv:1309.0587](#).
- [26] LHCb collaboration, R. Aaij *et al.*, *Evidence for the decay  $B_c^+ \rightarrow J/\psi 3\pi^+ 2\pi^-$* , JHEP **05** (2014) 148, [arXiv:1404.0287](#).
- [27] LHCb collaboration, R. Aaij *et al.*, *Measurement of the branching fraction ratio  $\mathcal{B}(B_c^+ \rightarrow \psi(2S)\pi^+)/\mathcal{B}(B_c^+ \rightarrow J/\psi\pi^+)$* , Phys. Rev. **D92** (2015) 057007, [arXiv:1507.03516](#).
- [28] LHCb collaboration, R. Aaij *et al.*, *Measurement of the ratio of branching fractions  $\mathcal{B}(B_c^+ \rightarrow J/\psi K^+)/\mathcal{B}(B_c^+ \rightarrow J/\psi \pi^+)$* , JHEP **09** (2016) 153, [arXiv:1607.06823](#).
- [29] LHCb collaboration, R. Aaij *et al.*, *Observation of  $B_c^+ \rightarrow J/\psi D^{(*)} K^{(*)}$  decays*, Phys. Rev. **D95** (2017) 032005, [arXiv:1612.07421](#).
- [30] LHCb collaboration, R. Aaij *et al.*, *Observation of  $B_c^+ \rightarrow D^0 K^+$  decays*, Phys. Rev. Lett. **118** (2017) 111803, [arXiv:1701.01856](#).
- [31] Y.-N. Gao *et al.*, *Experimental prospects of the  $B_c$  studies of the LHCb experiment*, Chin. Phys. Lett. **27** (2010) 061302.
- [32] A. Berezhnoy and A. Likhoded, *The observation possibility of  $B_c$  excitations at LHC*, PoS **QFTHEP2013** (2013) 051, [arXiv:1307.5993](#).
- [33] C.-H. Chang, X.-Y. Wang, and X.-G. Wu, *BCVEGPY2.2: A newly upgraded version for hadronic production of the meson  $B_c$  and its excited states*, Comput. Phys. Commun. **197** (2015) 335, [arXiv:1507.05176](#).
- [34] I. P. Gouz *et al.*, *Prospects for the  $B_c$  studies at LHCb*, Phys. Atom. Nucl. **67** (2004) 1559, [arXiv:hep-ph/0211432](#).
- [35] ATLAS collaboration, G. Aad *et al.*, *Observation of an excited  $B_c^\pm$  meson state with the ATLAS detector*, Phys. Rev. Lett. **113** (2014) 212004, [arXiv:1407.1032](#).
- [36] LHCb collaboration, R. Aaij *et al.*, *Search for excited  $B_c^+$  states*, JHEP **01** (2018) 138, [arXiv:1712.04094](#).
- [37] CMS collaboration, A. M. Sirunyan *et al.*, *Observation of two excited  $B_c^+$  states and measurement of the  $B_c^+(2S)$  mass in  $pp$  collisions at  $\sqrt{s} = 13$  TeV*, [arXiv:1902.00571](#).
- [38] LHCb collaboration, A. A. Alves Jr. *et al.*, *The LHCb detector at the LHC*, JINST **3** (2008) S08005.
- [39] LHCb collaboration, R. Aaij *et al.*, *LHCb detector performance*, Int. J. Mod. Phys. **A30** (2015) 1530022, [arXiv:1412.6352](#).
- [40] LHCb collaboration, R. Aaij *et al.*, *Measurement of  $b$ -hadron masses*, Phys. Lett. **B708** (2012) 241, [arXiv:1112.4896](#).
- [41] T. Sjöstrand, S. Mrenna, and P. Skands, *PYTHIA 6.4 physics and manual*, JHEP **05** (2006) 026, [arXiv:hep-ph/0603175](#).

- [42] I. Belyaev *et al.*, *Handling of the generation of primary events in Gauss, the LHCb simulation framework*, J. Phys. Conf. Ser. **331** (2011) 032047.
- [43] D. J. Lange, *The EvtGen particle decay simulation package*, Nucl. Instrum. Meth. **A462** (2001) 152.
- [44] P. Golonka and Z. Was, *PHOTOS Monte Carlo: A precision tool for QED corrections in Z and W decays*, Eur. Phys. J. **C45** (2006) 97, [arXiv:hep-ph/0506026](#).
- [45] Geant4 collaboration, J. Allison *et al.*, *Geant4 developments and applications*, IEEE Trans. Nucl. Sci. **53** (2006) 270.
- [46] M. Clemencic *et al.*, *The LHCb simulation application, Gauss: Design, evolution and experience*, J. Phys. Conf. Ser. **331** (2011) 032023.
- [47] L. Breiman, J. H. Friedman, R. A. Olshen, and C. J. Stone, *Classification and regression trees*, Wadsworth international group, Belmont, California, USA, 1984.
- [48] 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.
- [49] Particle Data Group, C. Patrignani *et al.*, *Review of particle physics*, Chin. Phys. **C40** (2016) 100001.
- [50] W. D. Hulsbergen, *Decay chain fitting with a Kalman filter*, Nucl. Instrum. Meth. **A552** (2005) 566, [arXiv:physics/0503191](#).
- [51] T. Skwarnicki, *A study of the radiative cascade transitions between the Upsilon-prime and Upsilon resonances*, PhD thesis, Institute of Nuclear Physics, Krakow, 1986, DESY-F31-86-02.
- [52] G. Cowan, K. Cranmer, E. Gross, and O. Vitells, *Asymptotic formulae for likelihood-based tests of new physics*, Eur. Phys. J. **C71** (2011) 1554, Erratum *ibid.* **C73** (2013) 2501, [arXiv:1007.1727](#).
- [53] Particle Data Group, M. Tanabashi *et al.*, *Review of particle physics*, Phys. Rev. **D98** (2018) 030001.
- [54] E. Gross and O. Vitells, *Trial factors for the look elsewhere effect in high energy physics*, Eur. Phys. J. **C70** (2010) 525, [arXiv:1005.1891](#).
- [55] A. K. Rai and P. C. Vinodkumar, *Properties of B<sub>c</sub> meson*, Pramana **66** (2006) 953, [arXiv:hep-ph/0606194](#).
- [56] D. Martínez Santos and F. Dupertuis, *Mass distributions marginalized over per-event errors*, Nucl. Instrum. Meth. **A764** (2014) 150, [arXiv:1312.5000](#).

## LHCb collaboration

R. Aaij<sup>29</sup>, C. Abellán Beteta<sup>46</sup>, B. Adeva<sup>43</sup>, M. Adinolfi<sup>50</sup>, C.A. Aidala<sup>77</sup>, Z. Ajaltouni<sup>7</sup>, S. Akar<sup>61</sup>, P. Albicocco<sup>20</sup>, J. Albrecht<sup>12</sup>, F. Alessio<sup>44</sup>, M. Alexander<sup>55</sup>, A. Alfonso Alberio<sup>42</sup>, G. Alkhazov<sup>35</sup>, P. Alvarez Cartelle<sup>57</sup>, A.A. Alves Jr<sup>43</sup>, S. Amato<sup>2</sup>, Y. Amhis<sup>9</sup>, L. An<sup>19</sup>, L. Anderlini<sup>19</sup>, G. Andreassi<sup>45</sup>, M. Andreotti<sup>18</sup>, J.E. Andrews<sup>62</sup>, F. Archilli<sup>29</sup>, J. Arnau Romeu<sup>8</sup>, A. Artamonov<sup>41</sup>, M. Artuso<sup>63</sup>, K. Arzymatov<sup>39</sup>, E. Aslanides<sup>8</sup>, M. Atzeni<sup>46</sup>, B. Audurier<sup>24</sup>, S. Bachmann<sup>14</sup>, J.J. Back<sup>52</sup>, S. Baker<sup>57</sup>, V. Balagura<sup>9,b</sup>, W. Baldini<sup>18,44</sup>, A. Baranov<sup>39</sup>, R.J. Barlow<sup>58</sup>, S. Barsuk<sup>9</sup>, W. Barter<sup>57</sup>, M. Bartolini<sup>21</sup>, F. Baryshnikov<sup>73</sup>, V. Batozskaya<sup>33</sup>, B. Batsukh<sup>63</sup>, A. Battig<sup>12</sup>, V. Battista<sup>45</sup>, A. Bay<sup>45</sup>, F. Bedeschi<sup>26</sup>, I. Bediaga<sup>1</sup>, A. Beiter<sup>63</sup>, L.J. Bel<sup>29</sup>, S. Belin<sup>24</sup>, N. Bely<sup>4</sup>, V. Bellee<sup>45</sup>, N. Belloli<sup>22,i</sup>, K. Belous<sup>41</sup>, G. Bencivenni<sup>20</sup>, E. Ben-Haim<sup>10</sup>, S. Benson<sup>29</sup>, S. Beranek<sup>11</sup>, A. Berezhnoy<sup>37</sup>, R. Bernet<sup>46</sup>, D. Berninghoff<sup>14</sup>, E. Bertholet<sup>10</sup>, A. Bertolin<sup>25</sup>, C. Betancourt<sup>46</sup>, F. Betti<sup>17,e</sup>, M.O. Bettler<sup>51</sup>, I.a. Bezshyiko<sup>46</sup>, S. Bhasin<sup>50</sup>, J. Bhom<sup>31</sup>, M.S. Bieker<sup>12</sup>, S. Bifani<sup>49</sup>, P. Billoir<sup>10</sup>, A. Birnkraut<sup>12</sup>, A. Bizzeti<sup>19,u</sup>, M. Bjørn<sup>59</sup>, M.P. Blago<sup>44</sup>, T. Blake<sup>52</sup>, F. Blanc<sup>45</sup>, S. Blusk<sup>63</sup>, D. Bobulska<sup>55</sup>, V. Bocci<sup>28</sup>, O. Boente Garcia<sup>43</sup>, T. Boettcher<sup>60</sup>, A. Bondar<sup>40,x</sup>, N. Bondar<sup>35</sup>, S. Borghi<sup>58,44</sup>, M. Borisyak<sup>39</sup>, M. Borsato<sup>14</sup>, M. Boubdir<sup>11</sup>, T.J.V. Bowcock<sup>56</sup>, C. Bozzi<sup>18,44</sup>, S. Braun<sup>14</sup>, M. Brodski<sup>44</sup>, J. Brodzicka<sup>31</sup>, A. Brossa Gonzalo<sup>52</sup>, D. Brundu<sup>24,44</sup>, E. Buchanan<sup>50</sup>, A. Buonaura<sup>46</sup>, C. Burr<sup>58</sup>, A. Bursche<sup>24</sup>, J. Buytaert<sup>44</sup>, W. Byczynski<sup>44</sup>, S. Cadeddu<sup>24</sup>, H. Cai<sup>67</sup>, R. Calabrese<sup>18,g</sup>, S. Cali<sup>20</sup>, R. Calladine<sup>49</sup>, M. Calvi<sup>22,i</sup>, M. Calvo Gomez<sup>42,m</sup>, A. Camboni<sup>42,m</sup>, P. Campana<sup>20</sup>, D.H. Campora Perez<sup>44</sup>, L. Capriotti<sup>17,e</sup>, A. Carbone<sup>17,e</sup>, G. Carboni<sup>27</sup>, R. Cardinale<sup>21</sup>, A. Cardini<sup>24</sup>, P. Carniti<sup>22,i</sup>, K. Carvalho Akiba<sup>2</sup>, G. Casse<sup>56</sup>, M. Cattaneo<sup>44</sup>, G. Cavallero<sup>21</sup>, R. Cenci<sup>26,p</sup>, M.G. Chapman<sup>50</sup>, M. Charles<sup>10,44</sup>, Ph. Charpentier<sup>44</sup>, G. Chatzikonstantinidis<sup>49</sup>, M. Chefdeville<sup>6</sup>, V. Chekalina<sup>39</sup>, C. Chen<sup>3</sup>, S. Chen<sup>24</sup>, S.-G. Chitic<sup>44</sup>, V. Chobanova<sup>43</sup>, M. Chrzaszcz<sup>44</sup>, A. Chubykin<sup>35</sup>, P. Ciambone<sup>20</sup>, X. Cid Vidal<sup>43</sup>, G. Ciezarek<sup>44</sup>, F. Cindolo<sup>17</sup>, P.E.L. Clarke<sup>54</sup>, M. Clemencic<sup>44</sup>, H.V. Cliff<sup>51</sup>, J. Closier<sup>44</sup>, V. Coco<sup>44</sup>, J.A.B. Coelho<sup>9</sup>, J. Cogan<sup>8</sup>, E. Cogneras<sup>7</sup>, L. Cojocariu<sup>34</sup>, P. Collins<sup>44</sup>, T. Colombo<sup>44</sup>, A. Comerma-Montells<sup>14</sup>, A. Contu<sup>24</sup>, G. Coombs<sup>44</sup>, S. Coquereau<sup>42</sup>, G. Corti<sup>44</sup>, C.M. Costa Sobral<sup>52</sup>, B. Couturier<sup>44</sup>, G.A. Cowan<sup>54</sup>, D.C. Craik<sup>60</sup>, A. Crocombe<sup>52</sup>, M. Cruz Torres<sup>1</sup>, R. Currie<sup>54</sup>, C.L. Da Silva<sup>78</sup>, E. Dall'Occo<sup>29</sup>, J. Dalseno<sup>43,50</sup>, C. D'Ambrosio<sup>44</sup>, A. Danilina<sup>36</sup>, P. d'Argent<sup>14</sup>, A. Davis<sup>58</sup>, O. De Aguiar Francisco<sup>44</sup>, K. De Bruyn<sup>44</sup>, S. De Capua<sup>58</sup>, M. De Cian<sup>45</sup>, J.M. De Miranda<sup>1</sup>, L. De Paula<sup>2</sup>, M. De Serio<sup>16,d</sup>, P. De Simone<sup>20</sup>, J.A. de Vries<sup>29</sup>, C.T. Dean<sup>55</sup>, W. Dean<sup>77</sup>, D. Decamp<sup>6</sup>, L. Del Buono<sup>10</sup>, B. Delaney<sup>51</sup>, H.-P. Dembinski<sup>13</sup>, M. Demmer<sup>12</sup>, A. Dendek<sup>32</sup>, D. Derkach<sup>74</sup>, O. Deschamps<sup>7</sup>, F. Desse<sup>9</sup>, F. Dettori<sup>24</sup>, B. Dey<sup>68</sup>, A. Di Canto<sup>44</sup>, P. Di Nezza<sup>20</sup>, S. Didenko<sup>73</sup>, H. Dijkstra<sup>44</sup>, F. Dordei<sup>24</sup>, M. Dorigo<sup>26,y</sup>, A.C. dos Reis<sup>1</sup>, A. Dosil Suárez<sup>43</sup>, L. Douglas<sup>55</sup>, A. Dovbnya<sup>47</sup>, K. Dreimanis<sup>56</sup>, L. Dufour<sup>44</sup>, G. Dujany<sup>10</sup>, P. Durante<sup>44</sup>, J.M. Durham<sup>78</sup>, D. Dutta<sup>58</sup>, R. Dzhelyadin<sup>41,†</sup>, M. Dziewiecki<sup>14</sup>, A. Dziurda<sup>31</sup>, A. Dzyuba<sup>35</sup>, S. Easo<sup>53</sup>, U. Egede<sup>57</sup>, V. Egorychev<sup>36</sup>, S. Eidelman<sup>40,x</sup>, S. Eisenhardt<sup>54</sup>, U. Eitschberger<sup>12</sup>, R. Ekelhof<sup>12</sup>, L. Eklund<sup>55</sup>, S. Ely<sup>63</sup>, A. Ene<sup>34</sup>, S. Escher<sup>11</sup>, S. Esen<sup>29</sup>, T. Evans<sup>61</sup>, A. Falabella<sup>17</sup>, C. Färber<sup>44</sup>, N. Farley<sup>49</sup>, S. Farry<sup>56</sup>, D. Fazzini<sup>22,i</sup>, M. Féo<sup>44</sup>, P. Fernandez Declara<sup>44</sup>, A. Fernandez Prieto<sup>43</sup>, F. Ferrari<sup>17,e</sup>, L. Ferreira Lopes<sup>45</sup>, F. Ferreira Rodrigues<sup>2</sup>, S. Ferreres Sole<sup>29</sup>, M. Ferro-Luzzi<sup>44</sup>, S. Filippov<sup>38</sup>, R.A. Fini<sup>16</sup>, M. Fiorini<sup>18,g</sup>, M. Firlej<sup>32</sup>, C. Fitzpatrick<sup>44</sup>, T. Fiutowski<sup>32</sup>, F. Fleuret<sup>9,b</sup>, M. Fontana<sup>44</sup>, F. Fontanelli<sup>21,h</sup>, R. Forty<sup>44</sup>, V. Franco Lima<sup>56</sup>, M. Frank<sup>44</sup>, C. Frei<sup>44</sup>, J. Fu<sup>23,q</sup>, W. Funk<sup>44</sup>, E. Gabriel<sup>54</sup>, A. Gallas Torreira<sup>43</sup>, D. Galli<sup>17,e</sup>, S. Gallorini<sup>25</sup>, S. Gambetta<sup>54</sup>, Y. Gan<sup>3</sup>, M. Gandelman<sup>2</sup>, P. Gandini<sup>23</sup>, Y. Gao<sup>3</sup>, L.M. Garcia Martin<sup>76</sup>, J. García Pardiñas<sup>46</sup>, B. Garcia Plana<sup>43</sup>, J. Garra Tico<sup>51</sup>, L. Garrido<sup>42</sup>, D. Gascon<sup>42</sup>, C. Gaspar<sup>44</sup>, G. Gazzoni<sup>7</sup>, D. Gerick<sup>14</sup>, E. Gersabeck<sup>58</sup>, M. Gersabeck<sup>58</sup>, T. Gershon<sup>52</sup>, D. Gerstel<sup>8</sup>, Ph. Ghez<sup>6</sup>, V. Gibson<sup>51</sup>, O.G. Girard<sup>45</sup>, P. Gironella Gironell<sup>42</sup>, L. Giubega<sup>34</sup>, K. Gizdov<sup>54</sup>, V.V. Gligorov<sup>10</sup>, C. Göbel<sup>65</sup>, D. Golubkov<sup>36</sup>, A. Golutvin<sup>57,73</sup>, A. Gomes<sup>1,a</sup>, I.V. Gorelov<sup>37</sup>, C. Gotti<sup>22,i</sup>, E. Govorkova<sup>29</sup>,

J.P. Grabowski<sup>14</sup>, R. Graciani Diaz<sup>42</sup>, L.A. Granado Cardoso<sup>44</sup>, E. Graugés<sup>42</sup>, E. Graverini<sup>46</sup>,  
 G. Graziani<sup>19</sup>, A. Grecu<sup>34</sup>, R. Greim<sup>29</sup>, P. Griffith<sup>24</sup>, L. Grillo<sup>58</sup>, L. Gruber<sup>44</sup>,  
 B.R. Gruberg Cazon<sup>59</sup>, C. Gu<sup>3</sup>, E. Gushchin<sup>38</sup>, A. Guth<sup>11</sup>, Yu. Guz<sup>41,44</sup>, T. Gys<sup>44</sup>,  
 T. Hadavizadeh<sup>59</sup>, C. Hadjivasiliou<sup>7</sup>, G. Haefeli<sup>45</sup>, C. Haen<sup>44</sup>, S.C. Haines<sup>51</sup>, P.M. Hamilton<sup>62</sup>,  
 Q. Han<sup>68</sup>, X. Han<sup>14</sup>, T.H. Hancock<sup>59</sup>, S. Hansmann-Menzemer<sup>14</sup>, N. Harnew<sup>59</sup>, T. Harrison<sup>56</sup>,  
 C. Hasse<sup>44</sup>, M. Hatch<sup>44</sup>, J. He<sup>4</sup>, M. Hecker<sup>57</sup>, K. Heinicke<sup>12</sup>, A. Heister<sup>12</sup>, K. Hennessy<sup>56</sup>,  
 L. Henry<sup>76</sup>, M. Heß<sup>70</sup>, J. Heuel<sup>11</sup>, A. Hicheur<sup>64</sup>, R. Hidalgo Charman<sup>58</sup>, D. Hill<sup>59</sup>, M. Hilton<sup>58</sup>,  
 P.H. Hopchev<sup>45</sup>, J. Hu<sup>14</sup>, W. Hu<sup>68</sup>, W. Huang<sup>4</sup>, Z.C. Huard<sup>61</sup>, W. Hulsbergen<sup>29</sup>, T. Humair<sup>57</sup>,  
 M. Hushchyn<sup>74</sup>, D. Hutchcroft<sup>56</sup>, D. Hynds<sup>29</sup>, P. Ibis<sup>12</sup>, M. Idzik<sup>32</sup>, P. Ilten<sup>49</sup>, A. Inglessi<sup>35</sup>,  
 A. Inyakin<sup>41</sup>, K. Ivshin<sup>35</sup>, R. Jacobsson<sup>44</sup>, S. Jakobsen<sup>44</sup>, J. Jalocha<sup>59</sup>, E. Jans<sup>29</sup>, B.K. Jashal<sup>76</sup>,  
 A. Jawahery<sup>62</sup>, F. Jiang<sup>3</sup>, M. John<sup>59</sup>, D. Johnson<sup>44</sup>, C.R. Jones<sup>51</sup>, C. Joram<sup>44</sup>, B. Jost<sup>44</sup>,  
 N. Jurik<sup>59</sup>, S. Kandybei<sup>47</sup>, M. Karacson<sup>44</sup>, J.M. Kariuki<sup>50</sup>, S. Karodia<sup>55</sup>, N. Kazeev<sup>74</sup>,  
 M. Kecke<sup>14</sup>, F. Keizer<sup>51</sup>, M. Kelsey<sup>63</sup>, M. Kenzie<sup>51</sup>, T. Ketel<sup>30</sup>, B. Khanji<sup>44</sup>, A. Kharisova<sup>75</sup>,  
 C. Khurewathanakul<sup>45</sup>, K.E. Kim<sup>63</sup>, T. Kirn<sup>11</sup>, V.S. Kirsebom<sup>45</sup>, S. Klaver<sup>20</sup>,  
 K. Klimaszewski<sup>33</sup>, S. Koliiev<sup>48</sup>, M. Kolpin<sup>14</sup>, R. Kopecna<sup>14</sup>, P. Koppenburg<sup>29</sup>, I. Kostiuik<sup>29,48</sup>,  
 S. Kotriakhova<sup>35</sup>, M. Kozeiha<sup>7</sup>, L. Kravchuk<sup>38</sup>, M. Kreps<sup>52</sup>, F. Kress<sup>57</sup>, S. Kretzschmar<sup>11</sup>,  
 P. Krokovny<sup>40,x</sup>, W. Krupa<sup>32</sup>, W. Krzemien<sup>33</sup>, W. Kucewicz<sup>31,l</sup>, M. Kucharczyk<sup>31</sup>,  
 V. Kudryavtsev<sup>40,x</sup>, G.J. Kunde<sup>78</sup>, A.K. Kuonen<sup>45</sup>, T. Kvaratskheliya<sup>36</sup>, D. Lacarrere<sup>44</sup>,  
 G. Lafferty<sup>58</sup>, A. Lai<sup>24</sup>, D. Lancierini<sup>46</sup>, G. Lanfranchi<sup>20</sup>, C. Langenbruch<sup>11</sup>, T. Latham<sup>52</sup>,  
 C. Lazzeroni<sup>49</sup>, R. Le Gac<sup>8</sup>, R. Lefèvre<sup>7</sup>, A. Leflat<sup>37</sup>, F. Lemaitre<sup>44</sup>, O. Leroy<sup>8</sup>, T. Lesiak<sup>31</sup>,  
 B. Leverington<sup>14</sup>, H. Li<sup>66</sup>, P.-R. Li<sup>4,ab</sup>, X. Li<sup>78</sup>, Y. Li<sup>5</sup>, Z. Li<sup>63</sup>, X. Liang<sup>63</sup>, T. Likhomanenko<sup>72</sup>,  
 R. Lindner<sup>44</sup>, F. Lionetto<sup>46</sup>, V. Lisovskyi<sup>9</sup>, G. Liu<sup>66</sup>, X. Liu<sup>3</sup>, D. Loh<sup>52</sup>, A. Loi<sup>24</sup>, I. Longstaff<sup>55</sup>,  
 J.H. Lopes<sup>2</sup>, G. Loustau<sup>46</sup>, G.H. Lovell<sup>51</sup>, D. Lucchesi<sup>25,o</sup>, M. Lucio Martinez<sup>43</sup>, Y. Luo<sup>3</sup>,  
 A. Lupato<sup>25</sup>, E. Luppi<sup>18,g</sup>, O. Lupton<sup>52</sup>, A. Lusiani<sup>26</sup>, X. Lyu<sup>4</sup>, F. Machefert<sup>9</sup>, F. Maciuc<sup>34</sup>,  
 V. Macko<sup>45</sup>, P. Mackowiak<sup>12</sup>, S. Maddrell-Mander<sup>50</sup>, O. Maev<sup>35,44</sup>, K. Maguire<sup>58</sup>,  
 D. Maisuzenko<sup>35</sup>, M.W. Majewski<sup>32</sup>, S. Malde<sup>59</sup>, B. Malecki<sup>44</sup>, A. Malinin<sup>72</sup>, T. Maltsev<sup>40,x</sup>,  
 H. Malygina<sup>14</sup>, G. Manca<sup>24,f</sup>, G. Mancinelli<sup>8</sup>, D. Marangotto<sup>23,q</sup>, J. Maratas<sup>7,w</sup>,  
 J.F. Marchand<sup>6</sup>, U. Marconi<sup>17</sup>, C. Marin Benito<sup>9</sup>, M. Marinangeli<sup>45</sup>, P. Marino<sup>45</sup>, J. Marks<sup>14</sup>,  
 P.J. Marshall<sup>56</sup>, G. Martellotti<sup>28</sup>, M. Martinelli<sup>44,22,i</sup>, D. Martinez Santos<sup>43</sup>,  
 F. Martinez Vidal<sup>76</sup>, A. Massafferri<sup>1</sup>, M. Materok<sup>11</sup>, R. Matev<sup>44</sup>, A. Mathad<sup>46</sup>, Z. Mathe<sup>44</sup>,  
 V. Matiunin<sup>36</sup>, C. Matteuzzi<sup>22</sup>, K.R. Mattioli<sup>77</sup>, A. Mauri<sup>46</sup>, E. Maurice<sup>9,b</sup>, B. Maurin<sup>45</sup>,  
 M. McCann<sup>57,44</sup>, A. McNab<sup>58</sup>, R. McNulty<sup>15</sup>, J.V. Mead<sup>56</sup>, B. Meadows<sup>61</sup>, C. Meaux<sup>8</sup>,  
 N. Meinert<sup>70</sup>, D. Melnychuk<sup>33</sup>, M. Merk<sup>29</sup>, A. Merli<sup>23,q</sup>, E. Michielin<sup>25</sup>, D.A. Milanes<sup>69</sup>,  
 E. Millard<sup>52</sup>, M.-N. Minard<sup>6</sup>, O. Mineev<sup>36</sup>, L. Minzoni<sup>18,g</sup>, D.S. Mitzel<sup>14</sup>, A. Mödden<sup>12</sup>,  
 A. Mogini<sup>10</sup>, R.D. Moise<sup>57</sup>, T. Mombächer<sup>12</sup>, I.A. Monroy<sup>69</sup>, S. Monteil<sup>7</sup>, M. Morandin<sup>25</sup>,  
 G. Morello<sup>20</sup>, M.J. Morello<sup>26,t</sup>, J. Moron<sup>32</sup>, A.B. Morris<sup>8</sup>, R. Mountain<sup>63</sup>, F. Muheim<sup>54</sup>,  
 M. Mukherjee<sup>68</sup>, M. Mulder<sup>29</sup>, D. Müller<sup>44</sup>, J. Müller<sup>12</sup>, K. Müller<sup>46</sup>, V. Müller<sup>12</sup>,  
 C.H. Murphy<sup>59</sup>, D. Murray<sup>58</sup>, P. Naik<sup>50</sup>, T. Nakada<sup>45</sup>, R. Nandakumar<sup>53</sup>, A. Nandi<sup>59</sup>,  
 T. Nanut<sup>45</sup>, I. Nasteva<sup>2</sup>, M. Needham<sup>54</sup>, N. Neri<sup>23,q</sup>, S. Neubert<sup>14</sup>, N. Neufeld<sup>44</sup>,  
 R. Newcombe<sup>57</sup>, T.D. Nguyen<sup>45</sup>, C. Nguyen-Mau<sup>45,n</sup>, S. Nieswand<sup>11</sup>, R. Niet<sup>12</sup>, N. Nikitin<sup>37</sup>,  
 N.S. Nolte<sup>44</sup>, A. Oblakowska-Mucha<sup>32</sup>, V. Obraztsov<sup>41</sup>, S. Ogilvy<sup>55</sup>, D.P. O’Hanlon<sup>17</sup>,  
 R. Oldeman<sup>24,f</sup>, C.J.G. Onderwater<sup>71</sup>, J. D. Osborn<sup>77</sup>, A. Ossowska<sup>31</sup>, J.M. Otalora Goicochea<sup>2</sup>,  
 T. Ovsiannikova<sup>36</sup>, P. Owen<sup>46</sup>, A. Oyanguren<sup>76</sup>, P.R. Pais<sup>45</sup>, T. Pajero<sup>26,t</sup>, A. Palano<sup>16</sup>,  
 M. Palutan<sup>20</sup>, G. Panshin<sup>75</sup>, A. Papanestis<sup>53</sup>, M. Pappagallo<sup>54</sup>, L.L. Pappalardo<sup>18,g</sup>,  
 W. Parker<sup>62</sup>, C. Parkes<sup>58,44</sup>, G. Passaleva<sup>19,44</sup>, A. Pastore<sup>16</sup>, M. Patel<sup>57</sup>, C. Patrignani<sup>17,e</sup>,  
 A. Pearce<sup>44</sup>, A. Pellegrino<sup>29</sup>, G. Penso<sup>28</sup>, M. Pepe Altarelli<sup>44</sup>, S. Perazzini<sup>17</sup>, D. Pereima<sup>36</sup>,  
 P. Perret<sup>7</sup>, L. Pescatore<sup>45</sup>, K. Petridis<sup>50</sup>, A. Petrolini<sup>21,h</sup>, A. Petrov<sup>72</sup>, S. Petrucci<sup>54</sup>,  
 M. Petruzzo<sup>23,q</sup>, B. Pietrzyk<sup>6</sup>, G. Pietrzyk<sup>45</sup>, M. Pikies<sup>31</sup>, M. Pili<sup>59</sup>, D. Pinci<sup>28</sup>, J. Pinzino<sup>44</sup>,  
 F. Pisani<sup>44</sup>, A. Piucci<sup>14</sup>, V. Placinta<sup>34</sup>, S. Playfer<sup>54</sup>, J. Plews<sup>49</sup>, M. Plo Casasus<sup>43</sup>, F. Polci<sup>10</sup>,  
 M. Poli Lener<sup>20</sup>, M. Poliakhova<sup>63</sup>, A. Poluektov<sup>8</sup>, N. Polukhina<sup>73,c</sup>, I. Polyakov<sup>63</sup>, E. Polcarpo<sup>2</sup>,

G.J. Pomery<sup>50</sup>, S. Ponce<sup>44</sup>, A. Popov<sup>41</sup>, D. Popov<sup>49,13</sup>, S. Poslavskii<sup>41</sup>, E. Price<sup>50</sup>, C. Prouve<sup>43</sup>, V. Pugatch<sup>48</sup>, A. Puig Navarro<sup>46</sup>, H. Pullen<sup>59</sup>, G. Punzi<sup>26,p</sup>, W. Qian<sup>4</sup>, J. Qin<sup>4</sup>, R. Quagliani<sup>10</sup>, B. Quintana<sup>7</sup>, N.V. Raab<sup>15</sup>, B. Rachwal<sup>32</sup>, J.H. Rademacker<sup>50</sup>, M. Rama<sup>26</sup>, M. Ramos Pernas<sup>43</sup>, M.S. Rangel<sup>2</sup>, F. Ratnikov<sup>39,74</sup>, G. Raven<sup>30</sup>, M. Ravonel Salzgeber<sup>44</sup>, M. Reboud<sup>6</sup>, F. Redi<sup>45</sup>, S. Reichert<sup>12</sup>, F. Reiss<sup>10</sup>, C. Remon Alepuz<sup>76</sup>, Z. Ren<sup>3</sup>, V. Renaudin<sup>59</sup>, S. Ricciardi<sup>53</sup>, S. Richards<sup>50</sup>, K. Rinnert<sup>56</sup>, P. Robbe<sup>9</sup>, A. Robert<sup>10</sup>, A.B. Rodrigues<sup>45</sup>, E. Rodrigues<sup>61</sup>, J.A. Rodriguez Lopez<sup>69</sup>, M. Roehrken<sup>44</sup>, S. Roiser<sup>44</sup>, A. Rollings<sup>59</sup>, V. Romanovskiy<sup>41</sup>, A. Romero Vidal<sup>43</sup>, J.D. Roth<sup>77</sup>, M. Rotondo<sup>20</sup>, M.S. Rudolph<sup>63</sup>, T. Ruf<sup>44</sup>, J. Ruiz Vidal<sup>76</sup>, J.J. Saborido Silva<sup>43</sup>, N. Sagidova<sup>35</sup>, B. Saitta<sup>24,f</sup>, V. Salustino Guimaraes<sup>65</sup>, C. Sanchez Gras<sup>29</sup>, C. Sanchez Mayordomo<sup>76</sup>, B. Sanmartin Sedes<sup>43</sup>, R. Santacesaria<sup>28</sup>, C. Santamarina Rios<sup>43</sup>, M. Santimaria<sup>20,44</sup>, E. Santovetti<sup>27,j</sup>, G. Sarpis<sup>58</sup>, A. Sarti<sup>20,k</sup>, C. Satriano<sup>28,s</sup>, A. Satta<sup>27</sup>, M. Saur<sup>4</sup>, D. Savrina<sup>36,37</sup>, S. Schael<sup>11</sup>, M. Schellenberg<sup>12</sup>, M. Schiller<sup>55</sup>, H. Schindler<sup>44</sup>, M. Schmelling<sup>13</sup>, T. Schmelzer<sup>12</sup>, B. Schmidt<sup>44</sup>, O. Schneider<sup>45</sup>, A. Schopper<sup>44</sup>, H.F. Schreiner<sup>61</sup>, M. Schubiger<sup>45</sup>, S. Schulte<sup>45</sup>, M.H. Schune<sup>9</sup>, R. Schwemmer<sup>44</sup>, B. Sciascia<sup>20</sup>, A. Sciubba<sup>28,k</sup>, A. Semennikov<sup>36</sup>, E.S. Sepulveda<sup>10</sup>, A. Sergi<sup>49,44</sup>, N. Serra<sup>46</sup>, J. Serrano<sup>8</sup>, L. Sestini<sup>25</sup>, A. Seuthe<sup>12</sup>, P. Seyfert<sup>44</sup>, M. Shapkin<sup>41</sup>, T. Shears<sup>56</sup>, L. Shekhtman<sup>40,x</sup>, V. Shevchenko<sup>72</sup>, E. Shmanin<sup>73</sup>, B.G. Siddi<sup>18</sup>, R. Silva Coutinho<sup>46</sup>, L. Silva de Oliveira<sup>2</sup>, G. Simi<sup>25,o</sup>, S. Simone<sup>16,d</sup>, I. Skiba<sup>18</sup>, N. Skidmore<sup>14</sup>, T. Skwarnicki<sup>63</sup>, M.W. Slater<sup>49</sup>, J.G. Smeaton<sup>51</sup>, E. Smith<sup>11</sup>, I.T. Smith<sup>54</sup>, M. Smith<sup>57</sup>, M. Soares<sup>17</sup>, I. Soares Lavra<sup>1</sup>, M.D. Sokoloff<sup>61</sup>, F.J.P. Soler<sup>55</sup>, B. Souza De Paula<sup>2</sup>, B. Spaan<sup>12</sup>, E. Spadaro Norella<sup>23,q</sup>, P. Spradlin<sup>55</sup>, F. Stagni<sup>44</sup>, M. Stahl<sup>14</sup>, S. Stahl<sup>44</sup>, P. Stefko<sup>45</sup>, S. Stefkova<sup>57</sup>, O. Steinkamp<sup>46</sup>, S. Stemmle<sup>14</sup>, O. Stenyakin<sup>41</sup>, M. Stepanova<sup>35</sup>, H. Stevens<sup>12</sup>, A. Stocchi<sup>9</sup>, S. Stone<sup>63</sup>, S. Stracka<sup>26</sup>, M.E. Stramaglia<sup>45</sup>, M. Straticiu<sup>34</sup>, U. Straumann<sup>46</sup>, S. Strokov<sup>75</sup>, J. Sun<sup>3</sup>, L. Sun<sup>67</sup>, Y. Sun<sup>62</sup>, K. Swientek<sup>32</sup>, A. Szabelski<sup>33</sup>, T. Szumlak<sup>32</sup>, M. Szymanski<sup>4</sup>, Z. Tang<sup>3</sup>, T. Tekampe<sup>12</sup>, G. Tellarini<sup>18</sup>, F. Teubert<sup>44</sup>, E. Thomas<sup>44</sup>, M.J. Tilley<sup>57</sup>, V. Tisserand<sup>7</sup>, S. T'Jampens<sup>6</sup>, M. Tobin<sup>5</sup>, S. Tolk<sup>44</sup>, L. Tomassetti<sup>18,g</sup>, D. Tonelli<sup>26</sup>, D.Y. Tou<sup>10</sup>, R. Tourinho Jadallah Aoude<sup>1</sup>, E. Tournefier<sup>6</sup>, M. Traill<sup>55</sup>, M.T. Tran<sup>45</sup>, A. Trisovic<sup>51</sup>, A. Tsaregorodtsev<sup>8</sup>, G. Tuci<sup>26,44,p</sup>, A. Tully<sup>51</sup>, N. Tuning<sup>29</sup>, A. Ukleja<sup>33</sup>, A. Usachov<sup>9</sup>, A. Ustyuzhanin<sup>39,74</sup>, U. Uwer<sup>14</sup>, A. Vagner<sup>75</sup>, V. Vagnoni<sup>17</sup>, A. Valassi<sup>44</sup>, S. Valat<sup>44</sup>, G. Valenti<sup>17</sup>, M. van Beuzekom<sup>29</sup>, H. Van Hecke<sup>78</sup>, E. van Herwijnen<sup>44</sup>, C.B. Van Hulse<sup>15</sup>, J. van Tilburg<sup>29</sup>, M. van Veghel<sup>29</sup>, R. Vazquez Gomez<sup>44</sup>, P. Vazquez Regueiro<sup>43</sup>, C. Vázquez Sierra<sup>29</sup>, S. Vecchi<sup>18</sup>, J.J. Velthuis<sup>50</sup>, M. Veltri<sup>19,r</sup>, A. Venkateswaran<sup>63</sup>, M. Vernet<sup>7</sup>, M. Veronesi<sup>29</sup>, M. Vesterinen<sup>52</sup>, J.V. Viana Barbosa<sup>44</sup>, D. Vieira<sup>4</sup>, M. Vieites Diaz<sup>43</sup>, H. Viemann<sup>70</sup>, X. Vilasis-Cardona<sup>42,m</sup>, A. Vitkovskiy<sup>29</sup>, M. Vitti<sup>51</sup>, V. Volkov<sup>37</sup>, A. Vollhardt<sup>46</sup>, D. Vom Bruch<sup>10</sup>, B. Voneki<sup>44</sup>, A. Vorobyev<sup>35</sup>, V. Vorobyev<sup>40,x</sup>, N. Voropaev<sup>35</sup>, R. Waldi<sup>70</sup>, J. Walsh<sup>26</sup>, J. Wang<sup>5</sup>, M. Wang<sup>3</sup>, Y. Wang<sup>68</sup>, Z. Wang<sup>46</sup>, D.R. Ward<sup>51</sup>, H.M. Wark<sup>56</sup>, N.K. Watson<sup>49</sup>, D. Websdale<sup>57</sup>, A. Weiden<sup>46</sup>, C. Weissner<sup>60</sup>, M. Whitehead<sup>11</sup>, G. Wilkinson<sup>59</sup>, M. Wilkinson<sup>63</sup>, I. Williams<sup>51</sup>, M. Williams<sup>60</sup>, M.R.J. Williams<sup>58</sup>, T. Williams<sup>49</sup>, F.F. Wilson<sup>53</sup>, M. Winn<sup>9</sup>, W. Wislicki<sup>33</sup>, M. Witek<sup>31</sup>, G. Wormser<sup>9</sup>, S.A. Wotton<sup>51</sup>, K. Wyllie<sup>44</sup>, D. Xiao<sup>68</sup>, Y. Xie<sup>68</sup>, H. Xing<sup>66</sup>, A. Xu<sup>3</sup>, M. Xu<sup>68</sup>, Q. Xu<sup>4</sup>, Z. Xu<sup>6</sup>, Z. Xu<sup>3</sup>, Z. Yang<sup>3</sup>, Z. Yang<sup>62</sup>, Y. Yao<sup>63</sup>, L.E. Yeomans<sup>56</sup>, H. Yin<sup>68</sup>, J. Yu<sup>68,aa</sup>, X. Yuan<sup>63</sup>, O. Yushchenko<sup>41</sup>, K.A. Zarebski<sup>49</sup>, M. Zavertyaev<sup>13,c</sup>, M. Zeng<sup>3</sup>, D. Zhang<sup>68</sup>, L. Zhang<sup>3</sup>, W.C. Zhang<sup>3,z</sup>, Y. Zhang<sup>44</sup>, A. Zhelezov<sup>14</sup>, Y. Zheng<sup>4</sup>, X. Zhu<sup>3</sup>, V. Zhukov<sup>11,37</sup>, J.B. Zonneveld<sup>54</sup>, S. Zucchelli<sup>17,e</sup>.

<sup>1</sup>Centro Brasileiro de Pesquisas Físicas (CBPF), Rio de Janeiro, Brazil

<sup>2</sup>Universidade Federal do Rio de Janeiro (UFRJ), Rio de Janeiro, Brazil

<sup>3</sup>Center for High Energy Physics, Tsinghua University, Beijing, China

<sup>4</sup>University of Chinese Academy of Sciences, Beijing, China

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

<sup>6</sup>Univ. Grenoble Alpes, Univ. Savoie Mont Blanc, CNRS, IN2P3-LAPP, Annecy, France

<sup>7</sup>Université Clermont Auvergne, CNRS/IN2P3, LPC, Clermont-Ferrand, France



- <sup>8</sup> Aix Marseille Univ, CNRS/IN2P3, CPPM, Marseille, France
- <sup>9</sup> LAL, Univ. Paris-Sud, CNRS/IN2P3, Université Paris-Saclay, Orsay, France
- <sup>10</sup> LPNHE, Sorbonne Université, Paris Diderot Sorbonne Paris Cité, CNRS/IN2P3, Paris, France
- <sup>11</sup> I. Physikalisches Institut, RWTH Aachen University, Aachen, Germany
- <sup>12</sup> Fakultät Physik, Technische Universität Dortmund, Dortmund, Germany
- <sup>13</sup> Max-Planck-Institut für Kernphysik (MPIK), Heidelberg, Germany
- <sup>14</sup> Physikalisches Institut, Ruprecht-Karls-Universität Heidelberg, Heidelberg, Germany
- <sup>15</sup> School of Physics, University College Dublin, Dublin, Ireland
- <sup>16</sup> INFN Sezione di Bari, Bari, Italy
- <sup>17</sup> INFN Sezione di Bologna, Bologna, Italy
- <sup>18</sup> INFN Sezione di Ferrara, Ferrara, Italy
- <sup>19</sup> INFN Sezione di Firenze, Firenze, Italy
- <sup>20</sup> INFN Laboratori Nazionali di Frascati, Frascati, Italy
- <sup>21</sup> INFN Sezione di Genova, Genova, Italy
- <sup>22</sup> INFN Sezione di Milano-Bicocca, Milano, Italy
- <sup>23</sup> INFN Sezione di Milano, Milano, Italy
- <sup>24</sup> INFN Sezione di Cagliari, Monserrato, Italy
- <sup>25</sup> INFN Sezione di Padova, Padova, Italy
- <sup>26</sup> INFN Sezione di Pisa, Pisa, Italy
- <sup>27</sup> INFN Sezione di Roma Tor Vergata, Roma, Italy
- <sup>28</sup> INFN Sezione di Roma La Sapienza, Roma, Italy
- <sup>29</sup> Nikhef National Institute for Subatomic Physics, Amsterdam, Netherlands
- <sup>30</sup> Nikhef National Institute for Subatomic Physics and VU University Amsterdam, Amsterdam, Netherlands
- <sup>31</sup> Henryk Niewodniczanski Institute of Nuclear Physics Polish Academy of Sciences, Kraków, Poland
- <sup>32</sup> AGH - University of Science and Technology, Faculty of Physics and Applied Computer Science, Kraków, Poland
- <sup>33</sup> National Center for Nuclear Research (NCBJ), Warsaw, Poland
- <sup>34</sup> Horia Hulubei National Institute of Physics and Nuclear Engineering, Bucharest-Magurele, Romania
- <sup>35</sup> Petersburg Nuclear Physics Institute NRC Kurchatov Institute (PNPI NRC KI), Gatchina, Russia
- <sup>36</sup> Institute of Theoretical and Experimental Physics NRC Kurchatov Institute (ITEP NRC KI), Moscow, Russia, Moscow, Russia
- <sup>37</sup> Institute of Nuclear Physics, Moscow State University (SINP MSU), Moscow, Russia
- <sup>38</sup> Institute for Nuclear Research of the Russian Academy of Sciences (INR RAS), Moscow, Russia
- <sup>39</sup> Yandex School of Data Analysis, Moscow, Russia
- <sup>40</sup> Budker Institute of Nuclear Physics (SB RAS), Novosibirsk, Russia
- <sup>41</sup> Institute for High Energy Physics NRC Kurchatov Institute (IHEP NRC KI), Protvino, Russia, Protvino, Russia
- <sup>42</sup> ICCUB, Universitat de Barcelona, Barcelona, Spain
- <sup>43</sup> Instituto Galego de Física de Altas Enerxías (IGFAE), Universidade de Santiago de Compostela, Santiago de Compostela, Spain
- <sup>44</sup> European Organization for Nuclear Research (CERN), Geneva, Switzerland
- <sup>45</sup> Institute of Physics, Ecole Polytechnique Fédérale de Lausanne (EPFL), Lausanne, Switzerland
- <sup>46</sup> Physik-Institut, Universität Zürich, Zürich, Switzerland
- <sup>47</sup> NSC Kharkiv Institute of Physics and Technology (NSC KIPT), Kharkiv, Ukraine
- <sup>48</sup> Institute for Nuclear Research of the National Academy of Sciences (KINR), Kyiv, Ukraine
- <sup>49</sup> University of Birmingham, Birmingham, United Kingdom
- <sup>50</sup> H.H. Wills Physics Laboratory, University of Bristol, Bristol, United Kingdom
- <sup>51</sup> Cavendish Laboratory, University of Cambridge, Cambridge, United Kingdom
- <sup>52</sup> Department of Physics, University of Warwick, Coventry, United Kingdom
- <sup>53</sup> STFC Rutherford Appleton Laboratory, Didcot, United Kingdom
- <sup>54</sup> School of Physics and Astronomy, University of Edinburgh, Edinburgh, United Kingdom
- <sup>55</sup> School of Physics and Astronomy, University of Glasgow, Glasgow, United Kingdom
- <sup>56</sup> Oliver Lodge Laboratory, University of Liverpool, Liverpool, United Kingdom
- <sup>57</sup> Imperial College London, London, United Kingdom
- <sup>58</sup> School of Physics and Astronomy, University of Manchester, Manchester, United Kingdom

- <sup>59</sup> *Department of Physics, University of Oxford, Oxford, United Kingdom*  
<sup>60</sup> *Massachusetts Institute of Technology, Cambridge, MA, United States*  
<sup>61</sup> *University of Cincinnati, Cincinnati, OH, United States*  
<sup>62</sup> *University of Maryland, College Park, MD, United States*  
<sup>63</sup> *Syracuse University, Syracuse, NY, United States*  
<sup>64</sup> *Laboratory of Mathematical and Subatomic Physics, Constantine, Algeria, associated to <sup>2</sup>*  
<sup>65</sup> *Pontifícia Universidade Católica do Rio de Janeiro (PUC-Rio), Rio de Janeiro, Brazil, associated to <sup>2</sup>*  
<sup>66</sup> *South China Normal University, Guangzhou, China, associated to <sup>3</sup>*  
<sup>67</sup> *School of Physics and Technology, Wuhan University, Wuhan, China, associated to <sup>3</sup>*  
<sup>68</sup> *Institute of Particle Physics, Central China Normal University, Wuhan, Hubei, China, associated to <sup>3</sup>*  
<sup>69</sup> *Departamento de Física, Universidad Nacional de Colombia, Bogota, Colombia, associated to <sup>10</sup>*  
<sup>70</sup> *Institut für Physik, Universität Rostock, Rostock, Germany, associated to <sup>14</sup>*  
<sup>71</sup> *Van Swinderen Institute, University of Groningen, Groningen, Netherlands, associated to <sup>29</sup>*  
<sup>72</sup> *National Research Centre Kurchatov Institute, Moscow, Russia, associated to <sup>36</sup>*  
<sup>73</sup> *National University of Science and Technology "MISIS", Moscow, Russia, associated to <sup>36</sup>*  
<sup>74</sup> *National Research University Higher School of Economics, Moscow, Russia, associated to <sup>39</sup>*  
<sup>75</sup> *National Research Tomsk Polytechnic University, Tomsk, Russia, associated to <sup>36</sup>*  
<sup>76</sup> *Instituto de Física Corpuscular, Centro Mixto Universidad de Valencia - CSIC, Valencia, Spain, associated to <sup>42</sup>*  
<sup>77</sup> *University of Michigan, Ann Arbor, United States, associated to <sup>63</sup>*  
<sup>78</sup> *Los Alamos National Laboratory (LANL), Los Alamos, United States, associated to <sup>63</sup>*

- <sup>a</sup> *Universidade Federal do Triângulo Mineiro (UFMT), Uberaba-MG, Brazil*  
<sup>b</sup> *Laboratoire Leprince-Ringuet, Palaiseau, France*  
<sup>c</sup> *P.N. Lebedev Physical Institute, Russian Academy of Science (LPI RAS), Moscow, Russia*  
<sup>d</sup> *Università di Bari, Bari, Italy*  
<sup>e</sup> *Università di Bologna, Bologna, Italy*  
<sup>f</sup> *Università di Cagliari, Cagliari, Italy*  
<sup>g</sup> *Università di Ferrara, Ferrara, Italy*  
<sup>h</sup> *Università di Genova, Genova, Italy*  
<sup>i</sup> *Università di Milano Bicocca, Milano, Italy*  
<sup>j</sup> *Università di Roma Tor Vergata, Roma, Italy*  
<sup>k</sup> *Università di Roma La Sapienza, Roma, Italy*  
<sup>l</sup> *AGH - University of Science and Technology, Faculty of Computer Science, Electronics and Telecommunications, Kraków, Poland*  
<sup>m</sup> *LIFAEELS, La Salle, Universitat Ramon Llull, Barcelona, Spain*  
<sup>n</sup> *Hanoi University of Science, Hanoi, Vietnam*  
<sup>o</sup> *Università di Padova, Padova, Italy*  
<sup>p</sup> *Università di Pisa, Pisa, Italy*  
<sup>q</sup> *Università degli Studi di Milano, Milano, Italy*  
<sup>r</sup> *Università di Urbino, Urbino, Italy*  
<sup>s</sup> *Università della Basilicata, Potenza, Italy*  
<sup>t</sup> *Scuola Normale Superiore, Pisa, Italy*  
<sup>u</sup> *Università di Modena e Reggio Emilia, Modena, Italy*  
<sup>w</sup> *MSU - Iligan Institute of Technology (MSU-IIT), Iligan, Philippines*  
<sup>x</sup> *Novosibirsk State University, Novosibirsk, Russia*  
<sup>y</sup> *Sezione INFN di Trieste, Trieste, Italy*  
<sup>z</sup> *School of Physics and Information Technology, Shaanxi Normal University (SNNU), Xi'an, China*  
<sup>aa</sup> *Physics and Micro Electronic College, Hunan University, Changsha City, China*  
<sup>ab</sup> *Lanzhou University, Lanzhou, China*

† *Deceased*