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Measurement of the branching fraction ratio $\mathcal{B}(B_c^+ \to \psi(2S)\pi^+)/\mathcal{B}(B_c^+ \to J/\psi\pi^+)$

R. Aaij *et al.*[*]
(LHCb collaboration)

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Using pp collision data collected by LHCb at center-of-mass energies $\sqrt{s} = 7$ TeV and 8 TeV, corresponding to an integrated luminosity of 3 fb^{-1}, the ratio of the branching fraction of the $B_c^+ \to \psi(2S)\pi^+$ decay relative to that of the $B_c^+ \to J/\psi\pi^+$ decay is measured to be $0.268 \pm 0.032(\text{stat}) \pm 0.007(\text{syst}) \pm 0.006(\text{BF})$. The first uncertainty is statistical, the second is systematic, and the third is due to the uncertainties on the branching fractions of the $J/\psi \to \mu^+\mu^-$ and $\psi(2S) \to \mu^+\mu^-$ decays. This measurement is consistent with the previous LHCb result, and the statistical uncertainty is halved.

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In the Standard Model of particle physics the B_c meson family is unique because it contains two different heavy flavor quarks, charm and beauty. The ground state of the B_c meson family has a rich set of decay modes since either constituent quark can decay with the other as a spectator, or they can annihilate to a virtual W boson. The search for new B_c^+ decay channels[1] and precise measurements of their branching fractions can improve the understanding of quantum chromodynamics (QCD) and can test various effective models. Many properties of the B_c^+ meson have been investigated by the LHCb experiment: the B_c^+ mass, lifetime and production rate have been measured [1–6], while several new decay channels have been observed [2,3,7–13]. The observation of the $B_c^+ \to \psi(2S)\pi^+$ decay was made with pp collision data at a center-of-mass energy of $\sqrt{s} = 7$ TeV, corresponding to an integrated luminosity of 1.0 fb^{-1} [8]. The ratio of the branching fraction of the $B_c^+ \to \psi(2S)\pi^+$ decay with respect to that of the $B_c^+ \to J/\psi\pi^+$ decay, defined as

$$R_{\mathcal{B}} \equiv \frac{\mathcal{B}(B_c^+ \to \psi(2S)\pi^+)}{\mathcal{B}(B_c^+ \to J/\psi\pi^+)}, \tag{1}$$

was measured to be $0.250 \pm 0.068(\text{stat}) \pm 0.014(\text{syst}) \pm 0.006(\text{BF})$. The first uncertainty is statistical, the second is systematic, and the third is due to the uncertainties on the branching fractions of the $J/\psi \to \mu^+\mu^-$ and $\psi(2S) \to \mu^+\mu^-$ decays. The statistical uncertainty is dominant. Several theoretical predictions for $R_{\mathcal{B}}$ based on different effective models [14–19] exist, and vary between 0.07 and 0.29.

The analysis presented here updates the previous LHCb measurement of $R_{\mathcal{B}}$ [8], using the full pp collision data collected by LHCb in 2011 and 2012 at $\sqrt{s} = 7$ TeV and 8 TeV, respectively, corresponding to an integrated luminosity of 3 fb^{-1}. Due to the increased data sample and an improved analysis method, the statistical uncertainty is reduced by half, allowing a more powerful test of the theories.

The LHCb detector [20,21] is a single-arm forward spectrometer covering the pseudorapidity range $2 < \eta < 5$, and is 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 [22], 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 [23] placed downstream of the magnet. The tracking system provides a measurement of 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 vertex (PV), the impact parameter, is measured with a resolution of $(15 + 29/p_{\text{T}})\mu$m, where p_{T} is the component of the track momentum transverse to the beam, in GeV/c. Different types of charged hadrons are distinguished using information from two ring-imaging Cherenkov detectors [24]. Photons, electrons, and hadrons are identified by a calorimeter system consisting of scintillating-pad and preshower detectors, an electromagnetic calorimeter, and a hadronic calorimeter. Muons are identified by a system composed of alternating layers of iron and multiwire proportional chambers [25]. The online event selection is performed by a trigger [26], 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.

In the $B_c^+ \to J/\psi\pi^+$ and $B_c^+ \to \psi(2S)\pi^+$ decay channels, the J/ψ and $\psi(2S)$ mesons are reconstructed through their decays into two muons. At least one muon with high

[*]Full author list given at end of the article.

[1]Charge conjugation is implied throughout the paper.

p_T is required in the hardware trigger. The software trigger requires a charged particle with $p_T > 1.7$ GeV/c, or $p_T > 1$ GeV/c if identified as a muon; alternatively a dimuon trigger requires two oppositely charged muons with $p_T > 500$ MeV/c, and the invariant mass of the muon pair greater than 2.95 GeV/c^2.

Further offline selections require a good quality muon track with $p_T > 550$ MeV/c, a good quality vertex for the reconstructed J/ψ or $\psi(2S)$ candidate, and the reconstructed J/ψ and $\psi(2S)$ masses to be within ± 100 MeV/c^2 of their known values [27]. The mass resolution for both resonances is 14 MeV/c^2. The muon track pair and the pion track are required to be inconsistent with originating from a PV. The pion track is required to be of good quality, and to have a p_T greater than 500 MeV/c. The particle identification (PID) information for pions is used to reduce the contamination from kaons and protons. The B_c^+ candidate is required to have a good quality vertex and a reconstructed mass within ± 500 MeV/c^2 of its known mass [27], which corresponds to more than ten times the mass resolution. To further separate signal from background, a boosted decision tree (BDT) selection using the AdaBoost algorithm [28,29] is applied. The selection uses more input variables and is more sophisticated compared to the previous analysis [8].

Simulated samples are generated to study the behavior of signal events. The B_c^+ signals are generated with a dedicated generator BCVEGPY [30,31] through the dominant hard subprocess $gg \to B_c^+ + b + \bar{c}$. The fragmentation and hadronization processes are simulated with PYTHIA [32,33]. The detector simulation is based on the GEANT4 package [34,35]. The BDT classifier uses information on the candidate's kinematic properties, decay length, vertex quality, impact parameter, and angle between the particle momentum and the vector from the primary to the secondary vertex. The distributions of the variables that are used in the BDT are similar for $B_c^+ \to J/\psi\pi^+$ and $B_c^+ \to \psi(2S)\pi^+$ decays. The simulated sample of $B_c^+ \to J/\psi\pi^+$ is used as the signal sample for the BDT training. The main background is combinatorial, and is represented by the upper sideband in the B_c^+ mass spectrum from the $B_c^+ \to J/\psi\pi^+$ data sample, requiring the reconstructed mass to be in the range $[6346, 6444]$ MeV/c^2. Since the upper sideband is used for the BDT training, the BDT could overperform in this region and distort the expected combinatorial background in the signal region. To avoid possible bias, two BDT classifiers are trained, denoted as BDT1 and BDT2 in the following. The $B_c^+ \to J/\psi\pi^+$ simulation and data samples are both split into two halves. One half of the simulated data sample and of the B_c^+ upper

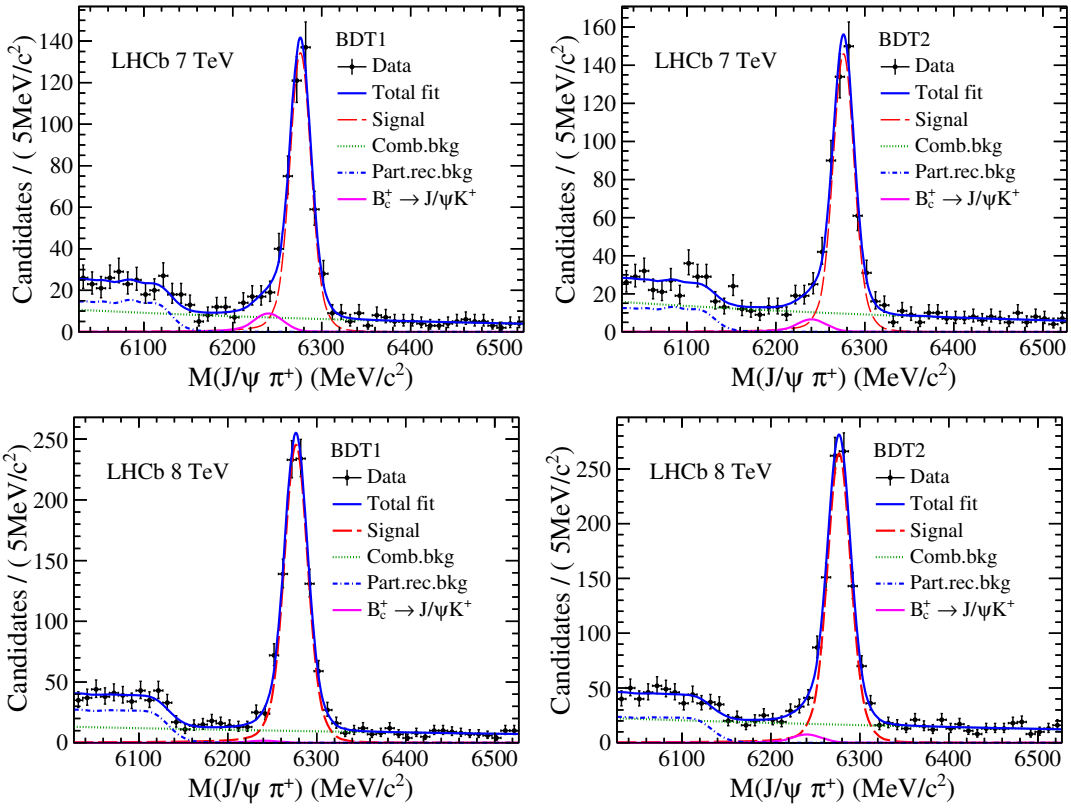

FIG. 1 (color online). Fit to the reconstructed B_c^+ mass distribution for $B_c^+ \to J/\psi\pi^+$ using (top) 2011 and (bottom) 2012 data samples. The plots on the left (right) correspond to the data selected with BDT1 (BDT2). Black points with error bars represent the data, and the various components are indicated in the keys.

sideband is used to train the BDT1 classifier, and the other half for BDT2. Each BDT classifier is applied to the other half of the $B_c^+ \to J/\psi\pi^+$ data sample, which is not used for its training. The $B_c^+ \to \psi(2S)\pi^+$ data sample is also split into two subsamples, one for each BDT classifier. The threshold value for the BDT response is chosen to maximize the signal significance. Finally, the $\mu^+\mu^-$ invariant mass window $[3030, 3170]$ MeV$/c^2$ is applied to J/ψ candidates, and $[3620, 3760]$ MeV$/c^2$ to $\psi(2S)$ candidates.

After the full selection, the background in the $B_c^+ \to J/\psi\pi^+$ sample consists of three categories: combinatorial background; partially reconstructed background, mainly from $B_c^+ \to J/\psi\rho^+$ decays with $\rho^+ \to \pi^+\pi^0$, where the π^0 is not reconstructed; and contamination from the Cabibbo-suppressed decay, $B_c^+ \to J/\psi K^+$, with the kaon misidentified as a pion. The background in the $B_c^+ \to \psi(2S)\pi^+$ sample consists of a combinatorial background and a partially reconstructed background. The contribution from $B_c^+ \to \psi(2S)K^+$ is negligible.

The signal yields are extracted from unbinned extended maximum likelihood fits to the invariant mass distributions of $J/\psi\pi^+$ or $\psi(2S)\pi^+$ in the range $[6027, 6527]$ MeV$/c^2$, as shown in Figs. 1 and 2 for 2011 and 2012 data, and are summarized in Tables I and II. To improve the B_c^+ mass resolution, the masses of J/ψ and $\psi(2S)$ candidates are constrained to their known values [27]. For the $B_c^+ \to J/\psi\pi^+$ channel, the signal probability density function is modeled by the sum of two double-sided Crystal Ball functions [36], with the same mean value and tail parameters determined from simulation; the combinatorial background is described with an exponential function; and the partially reconstructed background is modeled with the distribution of the B_c^+ invariant mass obtained from a simulated $B_c^+ \to J/\psi\rho^+$ sample using a kernel estimation [37]. This last shape is convolved with a Gaussian distribution to take into account a difference in mass resolution between data and simulation. For the $B_c^+ \to J/\psi K^+$ background, the shape of the B_c^+ mass distribution is modeled by a double-sided Crystal Ball function with parameters determined from simulation. For the $B_c^+ \to \psi(2S)\pi^+$ channel, due to the limited statistics, the signal shape is modeled by a single double-sided Crystal Ball function with the tail parameters determined from simulation; the combinatorial and partially reconstructed backgrounds are described with the same models as used for the $B_c^+ \to J/\psi\pi^+$ channel.

The total selection efficiency is the product of the detector geometrical acceptance, the trigger efficiency, the reconstruction and selection efficiency, the PID efficiency, and the BDT classifier efficiency. All efficiencies are determined using simulated samples. To account for any

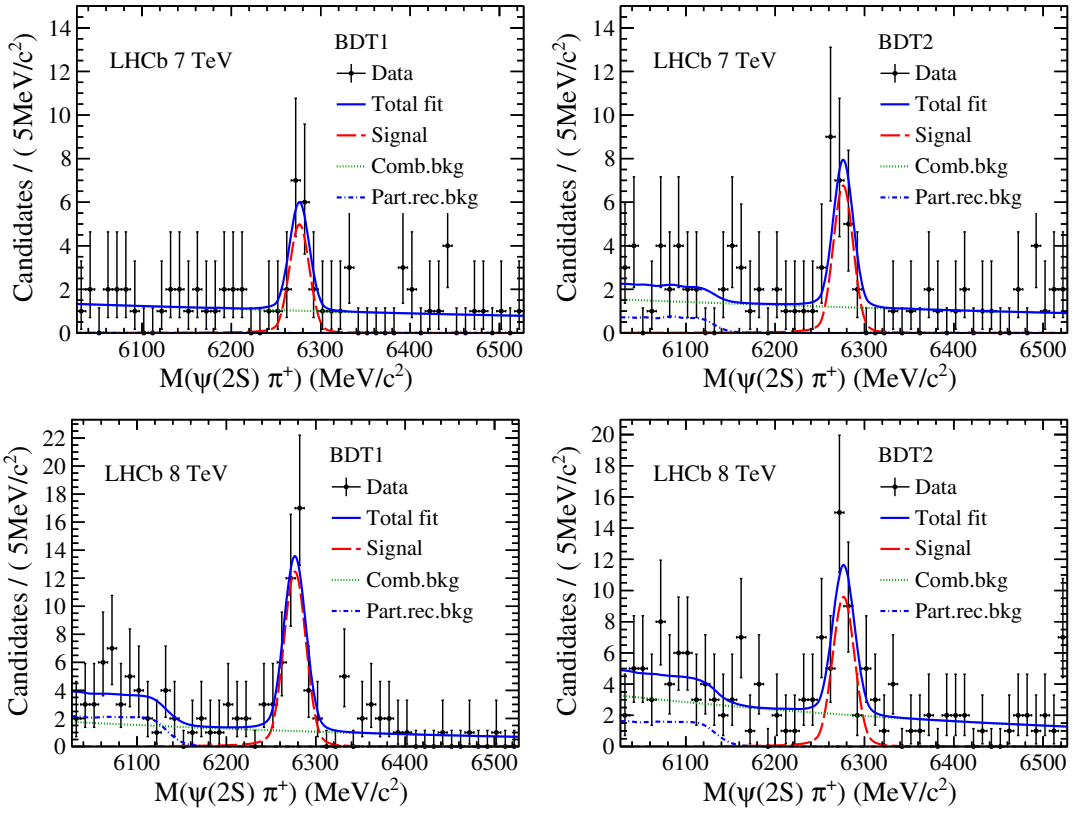

FIG. 2 (color online). Fit to the reconstructed B_c^+ mass distribution for $B_c^+ \to \psi(2S)\pi^+$ using (top) 2011 and (bottom) 2012 data samples. The plots on the left (right) correspond to the data selected with BDT1 (BDT2). Black points with error bars represent the data, and the various components are indicated in the keys.

TABLE I. Summary of the signal yields and efficiencies for the $B_c^+ \to J/\psi\pi^+$ decay.

	2011		2012	
	BDT1	BDT2	BDT1	BDT2
Yield	437 ± 24	475 ± 26	883 ± 34	950 ± 36
$\varepsilon_{\rm BDT}$	$(62.99 \pm 0.07)\%$	$(69.29 \pm 0.06)\%$	$(62.33 \pm 0.06)\%$	$(68.50 \pm 0.06)\%$
ε^*	$(1.392 \pm 0.003)\%$		$(1.339 \pm 0.003)\%$	

discrepancy between data and simulation, the PID efficiencies are calibrated using a π^+ sample from D^*-tagged $D^0 \to K^-\pi^+$ decays. The BDT classifier efficiencies of BDT1 and BDT2 are slightly different. After correcting for the BDT classifier efficiencies the signal yields of the subsamples are consistent within the statistical uncertainties. The BDT classifier efficiency, $\varepsilon_{\rm BDT}$, and the product of all other efficiencies, ε^*, are listed in Tables I and II.

Several sources of systematic uncertainty on the $R_{\mathcal{B}}$ measurement are studied and are summarized in Table III. To account for the uncertainty due to the signal shape modeling, the data are refitted with an alternative shape. The B_c^+ invariant mass distributions are modeled by a kernel estimation convolved with a Gaussian function, as determined from simulation. A difference of 0.6% from the nominal result is observed and is taken as a systematic uncertainty.

The modeling of the partially reconstructed background can also introduce a systematic uncertainty. This is estimated by reducing the fit range to $[6164, 6527]$ MeV$/c^2$ to exclude its contribution. A change of 2.4% in the result is observed. In the nominal fits, the parameters for $B_c^+ \to J/\psi K^+$ and the partially reconstructed background are fixed; the results change by less than 1% when these parameters are allowed to vary. The systematic uncertainty due to background modeling is estimated to be 2.4%.

Systematic uncertainties on the $R_{\mathcal{B}}$ measurement can be introduced by the BDT classifier efficiency if the simulation fails to describe the data. The distributions of all training variables from simulation and background-subtracted data are compared, where the background subtraction is performed using the *sPlot* technique, taking the B_c^+ invariant mass as the discriminating variable [38]. They are generally in agreement within statistical fluctuations. Only one variable, which describes the consistency between the pion track and the PV, indicates small differences between simulation and data. Therefore, the simulated sample is reweighed to match the data, and the BDT efficiencies are recalculated with the reweighed simulated sample. The result obtained with these BDT efficiencies is different from the nominal value by 0.2%, which is taken as the uncertainty from the BDT classifier.

The efficiencies determined from simulated samples have uncertainties due to the limited statistics. This leads to an uncertainty of 0.3%. An uncertainty of 1.1% is assigned due to imperfect simulation of the trigger, which is determined using data driven methods [39,40]. The B_c^+ lifetime of simulated samples is set according to the latest LHCb measurement [4]. To estimate the systematic uncertainty due to this, the B_c^+ lifetime is varied within the uncertainty of this measurement, and the change in the result, 0.1%, is taken as a systematic uncertainty. The total systematic uncertainty is 2.7%.

The ratio of the branching fractions with J/ψ and $\psi(2S)$ mesons decaying to dimuons, denoted as

$$R \equiv \frac{\mathcal{B}(B_c^+ \to \psi(2S)\pi^+, \psi(2S) \to \mu^+\mu^-)}{\mathcal{B}(B_c^+ \to J/\psi\pi^+, J/\psi \to \mu^+\mu^-)}, \tag{2}$$

is calculated as

$$R = \frac{N^{\rm cor}_{2011}(B_c^+ \to \psi(2S)\pi^+) + N^{\rm cor}_{2012}(B_c^+ \to \psi(2S)\pi^+)}{N^{\rm cor}_{2011}(B_c^+ \to J/\psi\pi^+) + N^{\rm cor}_{2012}(B_c^+ \to J/\psi\pi^+)}, \tag{3}$$

where $N^{\rm cor}_{2011\,(2012)}$ are the signal yields from 2011 (2012) after efficiency correction. The ratio is measured to be

$$R = 0.0354 \pm 0.0042(\text{stat}) \pm 0.0010(\text{syst}).$$

The ratio of the branching fractions of $B_c^+ \to \psi(2S)\pi^+$ and $B_c^+ \to J/\psi\pi^+$ is calculated as

TABLE II. Summary of the signal yields and efficiencies for the $B_c^+ \to \psi(2S)\pi^+$ decay.

	2011		2012	
	BDT1	BDT2	BDT1	BDT2
Yield	14.4 ± 4.5	19.6 ± 5.3	40.1 ± 7.1	30.8 ± 7.0
$\varepsilon_{\rm BDT}$	$(58.79 \pm 0.11)\%$	$(65.84 \pm 0.11)\%$	$(58.32 \pm 0.08)\%$	$(65.08 \pm 0.08)\%$
ε^*	$(1.631 \pm 0.006)\%$		$(1.529 \pm 0.005)\%$	

TABLE III. Summary of systematic uncertainties on the $R_{\mathcal{B}}$ measurement.

Component	Uncertainty
Signal shape	0.6%
Background shape	2.4%
BDT classifier	0.2%
Monte-Carlo statistics	0.3%
Trigger efficiency	1.1%
B_c^+ lifetime	0.1%
Total	2.7%

$$R_{\mathcal{B}} = R \times \frac{\mathcal{B}(J/\psi \to \mu^+\mu^-)}{\mathcal{B}(\psi(2S) \to \mu^+\mu^-)}. \quad (4)$$

Assuming electroweak universality, the $J/\psi \to \mu^+\mu^-$ and $\psi(2S) \to \mu^+\mu^-$ branching fractions can be substituted with the more precisely measured ones in the e^+e^- channel [27]. Using these values, the ratio $R_{\mathcal{B}}$ is measured to be

$$R_{\mathcal{B}} = 0.268 \pm 0.032(\text{stat}) \pm 0.007(\text{syst}) \pm 0.006(\text{BF}),$$

where the first uncertainty is statistical, the second is systematic, and the last term is due to the uncertainty on $\mathcal{B}(J/\psi \to e^+e^-)/\mathcal{B}(\psi(2S) \to e^+e^-)$. This result is in agreement with the previous LHCb result [8]. Our measurement is consistent with the predictions of nonrelativistic QCD at next-to-leading order $(0.26^{+0.05}_{-0.06})$ [18] and perturbative QCD based on k_T factorization $(0.29^{+0.17}_{-0.11})$ [19]. The result disfavors the theoretical calculations based on the relativistic quark model [14], the quark potential model [15], the relativistic constituent quark model [16], and the QCD relativistic potential model [17].

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R. Aaij,[38] B. Adeva,[37] M. Adinolfi,[46] A. Affolder,[52] Z. Ajaltouni,[5] S. Akar,[6] J. Albrecht,[9] F. Alessio,[38] M. Alexander,[51] S. Ali,[41] G. Alkhazov,[30] P. Alvarez Cartelle,[53] A. A. Alves Jr,[57] S. Amato,[2] S. Amerio,[22] Y. Amhis,[7] L. An,[3] J. Anderson,[40] G. Andreassi,[39] M. Andreotti,[16,g] J. E. Andrews,[58] R. B. Appleby,[54] O. Aquines Gutierrez,[10] F. Archilli,[38] P. d'Argent,[11] A. Artamonov,[35] M. Artuso,[59] E. Aslanides,[6] G. Auriemma,[25,n] M. Baalouch,[5] S. Bachmann,[11] J. J. Back,[48] A. Badalov,[36] C. Baesso,[60] W. Baldini,[16,38] R. J. Barlow,[54] C. Barschel,[38] S. Barsuk,[7] W. Barter,[38] V. Batozskaya,[28] V. Battista,[39] A. Bay,[39] L. Beaucourt,[4] J. Beddow,[51] F. Bedeschi,[23] I. Bediaga,[1] L. J. Bel,[41] V. Bellee,[39] I. Belyaev,[31] E. Ben-Haim,[8] G. Bencivenni,[18] S. Benson,[38] J. Benton,[46] A. Berezhnoy,[32] R. Bernet,[40] A. Bertolin,[22] M.-O. Bettler,[38] M. van Beuzekom,[41] A. Bien,[11] S. Bifani,[45] T. Bird,[54] A. Birnkraut,[9] A. Bizzeti,[17,i] T. Blake,[48] F. Blanc,[39] J. Blouw,[10] S. Blusk,[59] V. Bocci,[25] A. Bondar,[34] N. Bondar,[30,38] W. Bonivento,[15] S. Borghi,[54] M. Borsato,[7] T. J. V. Bowcock,[52] E. Bowen,[40] C. Bozzi,[16] S. Braun,[11] D. Brett,[54] M. Britsch,[10] T. Britton,[59] J. Brodzicka,[54] N. H. Brook,[46] A. Bursche,[40] J. Buytaert,[38] S. Cadeddu,[15] R. Calabrese,[16,g] M. Calvi,[20,k] M. Calvo Gomez,[36,p] P. Campana,[18] D. Campora Perez,[38] L. Capriotti,[54] A. Carbone,[14,e] G. Carboni,[24,l] R. Cardinale,[19,j] A. Cardini,[15] P. Carniti,[20] L. Carson,[50] K. Carvalho Akiba,[2,38] G. Casse,[52] L. Cassina,[20,k] L. Castillo Garcia,[38] M. Cattaneo,[38] Ch. Cauet,[9] G. Cavallero,[19] R. Cenci,[23,t] M. Charles,[8] Ph. Charpentier,[38] M. Chefdeville,[4] S. Chen,[54] S.-F. Cheung,[55] N. Chiapolini,[40] M. Chrzaszcz,[40] X. Cid Vidal,[38] G. Ciezarek,[41] P. E. L. Clarke,[50] M. Clemencic,[38] H. V. Cliff,[47] J. Closier,[38] V. Coco,[38] J. Cogan,[6] E. Cogneras,[5] V. Cogoni,[15,f] L. Cojocariu,[29] G. Collazuol,[22] P. Collins,[38] A. Comerma-Montells,[11] A. Contu,[15,38] A. Cook,[46] M. Coombes,[46] S. Coquereau,[8] G. Corti,[38] M. Corvo,[16,g] B. Couturier,[38] G. A. Cowan,[50] D. C. Craik,[48] A. Crocombe,[48] M. Cruz Torres,[60] S. Cunliffe,[53] R. Currie,[53] C. D'Ambrosio,[38] E. Dall'Occo,[41] J. Dalseno,[46] P. N. Y. David,[41] A. Davis,[57] K. De Bruyn,[41] S. De Capua,[54] M. De Cian,[11] J. M. De Miranda,[1] L. De Paula,[2] P. De Simone,[18] C.-T. Dean,[51] D. Decamp,[4] M. Deckenhoff,[9]

L. Del Buono,[8] N. Déléage,[4] M. Demmer,[9] D. Derkach,[55] O. Deschamps,[5] F. Dettori,[38] B. Dey,[21] A. Di Canto,[38] F. Di Ruscio,[24] H. Dijkstra,[38] S. Donleavy,[52] F. Dordei,[11] M. Dorigo,[39] A. Dosil Suárez,[37] D. Dossett,[48] A. Dovbnya,[43] K. Dreimanis,[52] L. Dufour,[41] G. Dujany,[54] F. Dupertuis,[39] P. Durante,[38] R. Dzhelyadin,[35] A. Dziurda,[26] A. Dzyuba,[30] S. Easo,[49,38] U. Egede,[53] V. Egorychev,[31] S. Eidelman,[34] S. Eisenhardt,[50] U. Eitschberger,[9] R. Ekelhof,[9] L. Eklund,[51] I. El Rifai,[5] Ch. Elsasser,[40] S. Ely,[59] S. Esen,[11] H. M. Evans,[47] T. Evans,[55] A. Falabella,[14] C. Färber,[38] C. Farinelli,[41] N. Farley,[45] S. Farry,[52] R. Fay,[52] D. Ferguson,[50] V. Fernandez Albor,[37] F. Ferrari,[14] F. Ferreira Rodrigues,[1] M. Ferro-Luzzi,[38] S. Filippov,[33] M. Fiore,[16,38,g] M. Fiorini,[16,g] M. Firlej,[27] C. Fitzpatrick,[39] T. Fiutowski,[27] K. Fohl,[38] P. Fol,[53] M. Fontana,[10] F. Fontanelli,[19,j] R. Forty,[38] O. Francisco,[2] M. Frank,[38] C. Frei,[38] M. Frosini,[17] J. Fu,[21] E. Furfaro,[24,l] A. Gallas Torreira,[37] D. Galli,[14,e] S. Gallorini,[22,38] S. Gambetta,[50] M. Gandelman,[2] P. Gandini,[55] Y. Gao,[3] J. García Pardiñas,[37] J. Garra Tico,[47] L. Garrido,[36] D. Gascon,[36] C. Gaspar,[38] R. Gauld,[55] L. Gavardi,[9] G. Gazzoni,[5] A. Geraci,[21,v] D. Gerick,[11] E. Gersabeck,[11] M. Gersabeck,[54] T. Gershon,[48] Ph. Ghez,[4] A. Gianelle,[22] S. Gianì,[39] V. Gibson,[47] O. G. Girard,[39] L. Giubega,[29] V. V. Gligorov,[38] C. Göbel,[60] D. Golubkov,[31] A. Golutvin,[53,31,38] A. Gomes,[1,b] C. Gotti,[20,k] M. Grabalosa Gándara,[5] R. Graciani Diaz,[36] L. A. Granado Cardoso,[38] E. Graugés,[36] E. Graverini,[40] G. Graziani,[17] A. Grecu,[29] E. Greening,[55] S. Gregson,[47] P. Griffith,[45] L. Grillo,[11] O. Grünberg,[63] B. Gui,[59] E. Gushchin,[33] Yu. Guz,[35,38] T. Gys,[38] T. Hadavizadeh,[55] C. Hadjivasiliou,[59] G. Haefeli,[39] C. Haen,[38] S. C. Haines,[47] S. Hall,[53] B. Hamilton,[58] X. Han,[11] S. Hansmann-Menzemer,[11] N. Harnew,[55] J. Harrison,[54] J. He,[38] T. Head,[39] V. Heijne,[41] K. Hennessy,[52] P. Henrard,[5] L. Henry,[8] J. A. Hernando Morata,[37] E. van Herwijnen,[38] M. Heß,[63] A. Hicheur,[2] D. Hill,[55] M. Hoballah,[5] C. Hombach,[54] W. Hulsbergen,[41] T. Humair,[53] N. Hussain,[55] D. Hutchcroft,[52] D. Hynds,[51] M. Idzik,[27] P. Ilten,[56] R. Jacobsson,[38] A. Jaeger,[11] J. Jalocha,[55] E. Jans,[41] A. Jawahery,[58] F. Jing,[3] M. John,[55] D. Johnson,[38] C. R. Jones,[47] C. Joram,[38] B. Jost,[38] N. Jurik,[59] S. Kandybei,[43] W. Kanso,[6] M. Karacson,[38] T. M. Karbach,[38,a] S. Karodia,[51] M. Kelsey,[59] I. R. Kenyon,[45] M. Kenzie,[38] T. Ketel,[42] B. Khanji,[20,38,k] C. Khurewathanakul,[39] S. Klaver,[54] K. Klimaszewski,[28] O. Kochebina,[7] M. Kolpin,[11] I. Komarov,[39] R. F. Koopman,[42] P. Koppenburg,[41,38] M. Kozeiha,[5] L. Kravchuk,[33] K. Kreplin,[11] M. Kreps,[48] G. Krocker,[11] P. Krokovny,[34] F. Kruse,[9] W. Kucewicz,[26,o] M. Kucharczyk,[26] V. Kudryavtsev,[34] A. K. Kuonen,[39] K. Kurek,[28] T. Kvaratskheliya,[31] D. Lacarrere,[38] G. Lafferty,[54] A. Lai,[15] D. Lambert,[50] G. Lanfranchi,[18] C. Langenbruch,[48] B. Langhans,[38] T. Latham,[48] C. Lazzeroni,[45] R. Le Gac,[6] J. van Leerdam,[41] J.-P. Lees,[4] R. Lefèvre,[5] A. Leflat,[32,38] J. Lefrançois,[7] O. Leroy,[6] T. Lesiak,[26] B. Leverington,[11] Y. Li,[7] T. Likhomanenko,[65,64] M. Liles,[52] R. Lindner,[38] C. Linn,[38] F. Lionetto,[40] B. Liu,[15] X. Liu,[3] D. Loh,[48] S. Lohn,[38] I. Longstaff,[51] J. H. Lopes,[2] D. Lucchesi,[22,r] M. Lucio Martinez,[37] H. Luo,[50] A. Lupato,[22] E. Luppi,[16,g] O. Lupton,[55] N. Lusardi,[21] A. Lusiani,[23] F. Machefert,[7] F. Maciuc,[29] O. Maev,[30] K. Maguire,[54] S. Malde,[55] A. Malinin,[64] G. Manca,[7] G. Mancinelli,[6] P. Manning,[59] A. Mapelli,[38] J. Maratas,[5] J. F. Marchand,[4] U. Marconi,[14] C. Marin Benito,[36] P. Marino,[23,38,t] R. Märki,[39] J. Marks,[11] G. Martellotti,[25] M. Martin,[6] M. Martinelli,[39] D. Martinez Santos,[37] F. Martinez Vidal,[66] D. Martins Tostes,[2] A. Massafferri,[1] R. Matev,[38] A. Mathad,[48] Z. Mathe,[38] C. Matteuzzi,[20] K. Matthieu,[11] A. Mauri,[40] B. Maurin,[39] A. Mazurov,[45] M. McCann,[53] J. McCarthy,[45] A. McNab,[54] R. McNulty,[12] B. Meadows,[57] F. Meier,[9] M. Meissner,[11] D. Melnychuk,[28] M. Merk,[41] D. A. Milanes,[62] M.-N. Minard,[4] D. S. Mitzel,[11] J. Molina Rodriguez,[60] I. A. Monroy,[62] S. Monteil,[5] M. Morandin,[22] P. Morawski,[27] A. Mordà,[6] M. J. Morello,[23,t] J. Moron,[27] A. B. Morris,[50] R. Mountain,[59] F. Muheim,[50] J. Müller,[9] K. Müller,[40] V. Müller,[9] M. Mussini,[14] B. Muster,[39] P. Naik,[46] T. Nakada,[39] R. Nandakumar,[49] A. Nandi,[55] I. Nasteva,[2] M. Needham,[50] N. Neri,[21] S. Neubert,[11] N. Neufeld,[38] M. Neuner,[11] A. D. Nguyen,[39] T. D. Nguyen,[39] C. Nguyen-Mau,[39,q] V. Niess,[5] R. Niet,[9] N. Nikitin,[32] T. Nikodem,[11] D. Ninci,[23] A. Novoselov,[35] D. P. O'Hanlon,[48] A. Oblakowska-Mucha,[27] V. Obraztsov,[35] S. Ogilvy,[51] O. Okhrimenko,[44] R. Oldeman,[15,f] C. J. G. Onderwater,[67] B. Osorio Rodrigues,[1] J. M. Otalora Goicochea,[2] A. Otto,[38] P. Owen,[53] A. Oyanguren,[66] A. Palano,[13,d] F. Palombo,[21,u] M. Palutan,[18] J. Panman,[38] A. Papanestis,[49] M. Pappagallo,[51] L. L. Pappalardo,[16,g] C. Pappenheimer,[57] C. Parkes,[54] G. Passaleva,[17] G. D. Patel,[52] M. Patel,[53] C. Patrignani,[19,j] A. Pearce,[54,49] A. Pellegrino,[41] G. Penso,[25,m] M. Pepe Altarelli,[38] S. Perazzini,[14,e] P. Perret,[5] L. Pescatore,[45] K. Petridis,[46] A. Petrolini,[19,j] M. Petruzzo,[21] E. Picatoste Olloqui,[36] B. Pietrzyk,[4] T. Pilař,[48] D. Pinci,[25] A. Pistone,[19] A. Piucci,[11] S. Playfer,[50] M. Plo Casasus,[37] T. Poikela,[38] F. Polci,[8] A. Poluektov,[48,34] I. Polyakov,[31] E. Polycarpo,[2] A. Popov,[35] D. Popov,[10,38] B. Popovici,[29] C. Potterat,[2] E. Price,[46] J. D. Price,[52] J. Prisciandaro,[39] A. Pritchard,[52] C. Prouve,[46] V. Pugatch,[44] A. Puig Navarro,[39] G. Punzi,[23,s] W. Qian,[4] R. Quagliani,[7,46] B. Rachwal,[26] J. H. Rademacker,[46] M. Rama,[23] M. S. Rangel,[2] I. Raniuk,[43] N. Rauschmayr,[38] G. Raven,[42] F. Redi,[53] S. Reichert,[54] M. M. Reid,[48] A. C. dos Reis,[1] S. Ricciardi,[49] S. Richards,[46] M. Rihl,[38] K. Rinnert,[52] V. Rives Molina,[36] P. Robbe,[7,38] A. B. Rodrigues,[1] E. Rodrigues,[54] J. A. Rodriguez Lopez,[62] P. Rodriguez Perez,[54] S. Roiser,[38] V. Romanovsky,[35] A. Romero Vidal,[37] J. W. Ronayne,[12]

M. Rotondo,[22] J. Rouvinet,[39] T. Ruf,[38] H. Ruiz,[36] P. Ruiz Valls,[66] J. J. Saborido Silva,[37] N. Sagidova,[30] P. Sail,[51] B. Saitta,[15,f] V. Salustino Guimaraes,[2] C. Sanchez Mayordomo,[66] B. Sanmartin Sedes,[37] R. Santacesaria,[25] C. Santamarina Rios,[37] M. Santimaria,[18] E. Santovetti,[24,l] A. Sarti,[18,m] C. Satriano,[25,n] A. Satta,[24] D. M. Saunders,[46] D. Savrina,[31,32] M. Schiller,[38] H. Schindler,[38] M. Schlupp,[9] M. Schmelling,[10] T. Schmelzer,[9] B. Schmidt,[38] O. Schneider,[39] A. Schopper,[38] M. Schubiger,[39] M.-H. Schune,[7] R. Schwemmer,[38] B. Sciascia,[18] A. Sciubba,[25,m] A. Semennikov,[31] N. Serra,[40] J. Serrano,[6] L. Sestini,[22] P. Seyfert,[20] M. Shapkin,[35] I. Shapoval,[16,43,g] Y. Shcheglov,[30] T. Shears,[52] L. Shekhtman,[34] V. Shevchenko,[64] A. Shires,[9] B. G. Siddi,[16] R. Silva Coutinho,[48] G. Simi,[22] M. Sirendi,[47] N. Skidmore,[46] I. Skillicorn,[51] T. Skwarnicki,[59] E. Smith,[55,49] E. Smith,[53] I. T. Smith,[50] J. Smith,[47] M. Smith,[54] H. Snoek,[41] M. D. Sokoloff,[57,38] F. J. P. Soler,[51] F. Soomro,[39] D. Souza,[46] B. Souza De Paula,[2] B. Spaan,[9] P. Spradlin,[51] S. Sridharan,[38] F. Stagni,[38] M. Stahl,[11] S. Stahl,[38] O. Steinkamp,[40] O. Stenyakin,[35] F. Sterpka,[59] S. Stevenson,[55] S. Stoica,[29] S. Stone,[59] B. Storaci,[40] S. Stracka,[23,t] M. Straticiuc,[29] U. Straumann,[40] L. Sun,[57] W. Sutcliffe,[53] K. Swientek,[27] S. Swientek,[9] V. Syropoulos,[42] M. Szczekowski,[28] P. Szczypka,[39,38] T. Szumlak,[27] S. T'Jampens,[4] A. Tayduganov,[6] T. Tekampe,[9] M. Teklishyn,[7] G. Tellarini,[16,g] F. Teubert,[38] C. Thomas,[55] E. Thomas,[38] J. van Tilburg,[41] V. Tisserand,[4] M. Tobin,[39] J. Todd,[57] S. Tolk,[42] L. Tomassetti,[16,g] D. Tonelli,[38] S. Topp-Joergensen,[55] N. Torr,[55] E. Tournefier,[4] S. Tourneur,[39] K. Trabelsi,[39] M. T. Tran,[39] M. Tresch,[40] A. Trisovic,[38] A. Tsaregorodtsev,[6] P. Tsopelas,[41] N. Tuning,[41,38] A. Ukleja,[28] A. Ustyuzhanin,[65,64] U. Uwer,[11] C. Vacca,[15,f] V. Vagnoni,[14] G. Valenti,[14] A. Vallier,[7] R. Vazquez Gomez,[18] P. Vazquez Regueiro,[37] C. Vázquez Sierra,[37] S. Vecchi,[16] J. J. Velthuis,[46] M. Veltri,[17,h] G. Veneziano,[39] M. Vesterinen,[11] B. Viaud,[7] D. Vieira,[2] M. Vieites Diaz,[37] X. Vilasis-Cardona,[36,p] A. Vollhardt,[40] D. Volyanskyy,[10] D. Voong,[46] A. Vorobyev,[30] V. Vorobyev,[34] C. Voß,[63] J. A. de Vries,[41] R. Waldi,[63] C. Wallace,[48] R. Wallace,[12] J. Walsh,[23] S. Wandernoth,[11] J. Wang,[59] D. R. Ward,[47] N. K. Watson,[45] D. Websdale,[53] A. Weiden,[40] M. Whitehead,[48] G. Wilkinson,[55,38] M. Wilkinson,[59] M. Williams,[38] M. P. Williams,[45] M. Williams,[56] T. Williams,[45] F. F. Wilson,[49] J. Wimberley,[58] J. Wishahi,[9] W. Wislicki,[28] M. Witek,[26] G. Wormser,[7] S. A. Wotton,[47] S. Wright,[47] K. Wyllie,[38] Y. Xie,[61] Z. Xu,[39] Z. Yang,[3] J. Yu,[61] X. Yuan,[34] O. Yushchenko,[35] M. Zangoli,[14] M. Zavertyaev,[10,c] L. Zhang,[3] Y. Zhang,[3] A. Zhelezov,[11] A. Zhokhov,[31] L. Zhong[3] and S. Zucchelli[14]

(LHCb collaboration)

[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]*LAPP, Université Savoie Mont-Blanc, CNRS/IN2P3, Annecy-Le-Vieux, France*
[5]*Clermont Université, Université Blaise Pascal, CNRS/IN2P3, LPC, Clermont-Ferrand, France*
[6]*CPPM, Aix-Marseille Université, CNRS/IN2P3, Marseille, France*
[7]*LAL, Université Paris-Sud, CNRS/IN2P3, Orsay, France*
[8]*LPNHE, Université Pierre et Marie Curie, Université Paris Diderot, CNRS/IN2P3, Paris, France*
[9]*Fakultät Physik, Technische Universität Dortmund, Dortmund, Germany*
[10]*Max-Planck-Institut für Kernphysik (MPIK), Heidelberg, Germany*
[11]*Physikalisches Institut, Ruprecht-Karls-Universität Heidelberg, Heidelberg, Germany*
[12]*School of Physics, University College Dublin, Dublin, Ireland*
[13]*Sezione INFN di Bari, Bari, Italy*
[14]*Sezione INFN di Bologna, Bologna, Italy*
[15]*Sezione INFN di Cagliari, Cagliari, Italy*
[16]*Sezione INFN di Ferrara, Ferrara, Italy*
[17]*Sezione INFN di Firenze, Firenze, Italy*
[18]*Laboratori Nazionali dell'INFN di Frascati, Frascati, Italy*
[19]*Sezione INFN di Genova, Genova, Italy*
[20]*Sezione INFN di Milano Bicocca, Milano, Italy*
[21]*Sezione INFN di Milano, Milano, Italy*
[22]*Sezione INFN di Padova, Padova, Italy*
[23]*Sezione INFN di Pisa, Pisa, Italy*
[24]*Sezione INFN di Roma Tor Vergata, Roma, Italy*
[25]*Sezione INFN di Roma La Sapienza, Roma, Italy*
[26]*Henryk Niewodniczanski Institute of Nuclear Physics Polish Academy of Sciences, Kraków, Poland*
[27]*AGH - University of Science and Technology, Faculty of Physics and Applied Computer Science, Kraków, Poland*
[28]*National Center for Nuclear Research (NCBJ), Warsaw, Poland*

[29]Horia Hulubei National Institute of Physics and Nuclear Engineering, Bucharest-Magurele, Romania
[30]Petersburg Nuclear Physics Institute (PNPI), Gatchina, Russia
[31]Institute of Theoretical and Experimental Physics (ITEP), Moscow, Russia
[32]Institute of Nuclear Physics, Moscow State University (SINP MSU), Moscow, Russia
[33]Institute for Nuclear Research of the Russian Academy of Sciences (INR RAN), Moscow, Russia
[34]Budker Institute of Nuclear Physics (SB RAS) and Novosibirsk State University, Novosibirsk, Russia
[35]Institute for High Energy Physics (IHEP), Protvino, Russia
[36]Universitat de Barcelona, Barcelona, Spain
[37]Universidad de Santiago de Compostela, Santiago de Compostela, Spain
[38]European Organization for Nuclear Research (CERN), Geneva, Switzerland
[39]Ecole Polytechnique Fédérale de Lausanne (EPFL), Lausanne, Switzerland
[40]Physik-Institut, Universität Zürich, Zürich, Switzerland
[41]Nikhef National Institute for Subatomic Physics, Amsterdam, The Netherlands
[42]Nikhef National Institute for Subatomic Physics and VU University Amsterdam, Amsterdam, The Netherlands
[43]NSC Kharkiv Institute of Physics and Technology (NSC KIPT), Kharkiv, Ukraine
[44]Institute for Nuclear Research of the National Academy of Sciences (KINR), Kyiv, Ukraine
[45]University of Birmingham, Birmingham, United Kingdom
[46]H.H. Wills Physics Laboratory, University of Bristol, Bristol, United Kingdom
[47]Cavendish Laboratory, University of Cambridge, Cambridge, United Kingdom
[48]Department of Physics, University of Warwick, Coventry, United Kingdom
[49]STFC Rutherford Appleton Laboratory, Didcot, United Kingdom
[50]School of Physics and Astronomy, University of Edinburgh, Edinburgh, United Kingdom
[51]School of Physics and Astronomy, University of Glasgow, Glasgow, United Kingdom
[52]Oliver Lodge Laboratory, University of Liverpool, Liverpool, United Kingdom
[53]Imperial College London, London, United Kingdom
[54]School of Physics and Astronomy, University of Manchester, Manchester, United Kingdom
[55]Department of Physics, University of Oxford, Oxford, United Kingdom
[56]Massachusetts Institute of Technology, Cambridge 02139, Massachusetts, USA
[57]University of Cincinnati, Cincinnati 45221, Ohio, USA
[58]University of Maryland, College Park, Maryland 20742, USA
[59]Syracuse University, Syracuse 13244, New York, USA
[60]Pontifícia Universidade Católica do Rio de Janeiro (PUC-Rio), Rio de Janeiro, Brazil, (associated with Universidade Federal do Rio de Janeiro (UFRJ), Rio de Janeiro, Brazil)
[61]Institute of Particle Physics, Central China Normal University, Wuhan, Hubei, China, (associated with Center for High Energy Physics, Tsinghua University, Beijing, China
[62]Departamento de Fisica, Universidad Nacional de Colombia, Bogota, Colombia, (associated with LPNHE, Université Pierre et Marie Curie, Université Paris Diderot, CNRS/IN2P3, Paris, France)
[63]Institut für Physik, Universität Rostock, Rostock, Germany, (associated with Physikalisches Institut, Ruprecht-Karls-Universität Heidelberg, Heidelberg, Germany)
[64]National Research Centre Kurchatov Institute, Moscow, Russia, (associated with Institute of Theoretical and Experimental Physics (ITEP), Moscow, Russia)
[65]Yandex School of Data Analysis, Moscow, Russia, (associated with Institute of Theoretical and Experimental Physics (ITEP), Moscow, Russia)
[66]Instituto de Fisica Corpuscular (IFIC), Universitat de Valencia-CSIC, Valencia, Spain, (associated with Universitat de Barcelona, Barcelona, Spain)
[67]Van Swinderen Institute, University of Groningen, Groningen, The Netherlands, (associated with Nikhef National Institute for Subatomic Physics, Amsterdam, The Netherlands)

[a]Deceased.
[b]Also at Universidade Federal do Triângulo Mineiro (UFTM), Uberaba-MG, Brazil.
[c]Also at P.N. Lebedev Physical Institute, Russian Academy of Science (LPI RAS), Moscow, Russia.
[d]Also at Università di Bari, Bari, Italy.
[e]Also at Università di Bologna, Bologna, Italy.
[f]Also at Università di Cagliari, Cagliari, Italy.
[g]Also at Università di Ferrara, Ferrara, Italy.
[h]Also at Università di Urbino, Urbino, Italy.
[i]Also at Università di Modena e Reggio Emilia, Modena, Italy.
[j]Also at Università di Genova, Genova, Italy.
[k]Also at Università di Milano Bicocca, Milano, Italy.

[l]Also at Università di Roma Tor Vergata, Roma, Italy.
[m]Also at Università di Roma La Sapienza, Roma, Italy.
[n]Also at Università della Basilicata, Potenza, Italy
[o]Also at AGH - University of Science and Technology, Faculty of Computer Science, Electronics and Telecommunications, Kraków, Poland.
[p]Also at LIFAELS, La Salle, Universitat Ramon Llull, Barcelona, Spain.
[q]Also at Hanoi University of Science, Hanoi, Viet Nam.
[r]Also at Università di Padova, Padova, Italy.
[s]Also at Università di Pisa, Pisa, Italy.
[t]Also at Scuola Normale Superiore, Pisa, Italy.
[u]Also at Università degli Studi di Milano, Milano, Italy.
[v]Also at Politecnico di Milano, Milano, Italy.