Measurement of D^0–$\bar{D}^0$ Mixing Parameters and Search for CP Violation Using $D^0 \to K^+\pi^-$ Decays

R. Aaij *et al.**
(LHCb Collaboration)

(Received 25 September 2013; published 18 December 2013)

Measurements of charm mixing parameters from the decay-time-dependent ratio of $D^0 \to K^+\pi^-$ to $D^0 \to K^-\pi^+$ rates and the charge-conjugate ratio are reported. The analysis uses data, corresponding to 3 fb^{-1} of integrated luminosity, from proton-proton collisions at 7 and 8 TeV center-of-mass energies recorded by the LHCb experiment. In the limit of charge-parity (CP) symmetry, the mixing parameters are determined to be $x'^2 = (5.5 \pm 4.9) \times 10^{-5}$, $y' = (4.8 \pm 1.0) \times 10^{-3}$, and $R_D = (3.568 \pm 0.066) \times 10^{-3}$. Allowing for CP violation, the measurement is performed separately for D^0 and $\bar{D}^0$ mesons yielding $A_D = (-0.7 \pm 1.9)\%$, for the direct CP-violating asymmetry, and $0.75 < |q/p| < 1.24$ at the 68.3% confidence level, for the parameter describing CP violation in mixing. This is the most precise determination of these parameters from a single experiment and shows no evidence for CP violation.

DOI: 10.1103/PhysRevLett.111.251801 PACS numbers: 11.30.Er, 12.15.Ff, 13.25.Ft, 14.40.Lb

Mass eigenstates of neutral charm mesons are linear combinations of flavor eigenstates $|D_{1,2}\rangle = p|D^0\rangle \pm q|\bar{D}^0\rangle$, where p and q are complex parameters. This results in D^0–$\bar{D}^0$ oscillation. In the limit of charge-parity (CP) symmetry, the oscillation is characterized by the difference in mass $\Delta m \equiv m_2 - m_1$ and decay width $\Delta\Gamma \equiv \Gamma_2 - \Gamma_1$ between the D mass eigenstates. These differences are usually expressed in terms of the dimensionless mixing parameters $x \equiv \Delta m/\Gamma$ and $y \equiv \Delta\Gamma/2\Gamma$, where Γ is the average decay width of neutral D mesons. If CP symmetry is violated, the oscillation rates for mesons produced as D^0 and $\bar{D}^0$ can differ, further enriching the phenomenology. Both short- and long-distance components of the amplitude contribute to the time evolution of neutral D mesons [1–3]. Short-distance amplitudes could include contributions from non-standard-model particles or interactions, possibly enhancing the average oscillation rate or the difference between D^0 and $\bar{D}^0$ meson rates. The study of CP violation in D^0 oscillation may lead to an improved understanding of possible dynamics beyond the standard model [4–7].

The first evidence for D^0–$\bar{D}^0$ oscillation was reported in 2007 [8,9]. By 2009, the hypothesis of no oscillation was excluded with significance in excess of 10 standard deviations [10] by combining results from different experiments [8,9,11–17]. In 2012, the LHCb experiment reported the first observation from a single measurement with greater than 5 standard deviation significance [18], which has been recently confirmed by the CDF experiment [19].

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

This Letter reports a search for CP violation in D^0–$\bar{D}^0$ mixing by comparing the decay-time-dependent ratio of $D^0 \to K^+\pi^-$ to $D^0 \to K^-\pi^+$ rates with the corresponding ratio for the charge-conjugate processes. An improved determination of the CP-averaged charm mixing parameters with respect to our previous measurement [18] is also reported. The analysis uses data corresponding to 1.0 fb^{-1} of integrated luminosity from $\sqrt{s} = 7$ TeV pp collisions recorded by LHCb during 2011 and 2.0 fb^{-1} from $\sqrt{s} = 8$ TeV collisions recorded during 2012. The neutral D flavor at production is determined from the charge of the low-momentum pion π_s^+ in the flavor-conserving strong-interaction decay $D^{*+} \to D^0\pi_s^+$. The inclusion of charge-conjugate processes is implicit unless stated otherwise. The $D^{*+} \to D^0(\to K^-\pi^+)\pi_s^+$ process is denoted as right sign (RS), and $D^{*+} \to D^0(\to K^+\pi^-)\pi_s^+$ is denoted as wrong sign (WS). The RS decay rate is dominated by a Cabibbo-favored amplitude. The WS rate arises from the interfering amplitudes of the doubly Cabibbo-suppressed $D^0 \to K^+\pi^-$ decay and the Cabibbo-favored $\bar{D}^0 \to K^+\pi^-$ decay following D^0–$\bar{D}^0$ oscillation, each of similar magnitude. In the limit of $|x|$, $|y| \ll 1$, and assuming negligible CP violation, the time-dependent ratio $R(t)$ of WS-to-RS decay rates is [1–4]

$$R(t) \approx R_D + \sqrt{R_D}\,y'\frac{t}{\tau} + \frac{x'^2 + y'^2}{4}\left(\frac{t}{\tau}\right)^2, \tag{1}$$

where t is the decay time, τ is the average D^0 lifetime, and R_D is the ratio of suppressed-to-favored decay rates. The parameters x' and y' depend linearly on the mixing parameters as $x' \equiv x\cos\delta + y\sin\delta$ and $y' \equiv y\cos\delta - x\sin\delta$, where δ is the strong-phase difference between the suppressed and favored amplitudes $\mathcal{A}(D^0 \to K^+\pi^-)/\mathcal{A}(\bar{D}^0 \to K^+\pi^-) = -\sqrt{R_D}e^{-i\delta}$. Allowing for CP violation, the WS rates $R^+(t)$ and $R^-(t)$ of initially produced D^0 and $\bar{D}^0$ mesons are functions of independent sets of mixing parameters $(R_D^\pm, x'^{2\pm}, y'^\pm)$. A difference between R_D^+ and R_D^- arises if the ratio between the magnitudes of suppressed and favored decay amplitudes is not CP symmetric (direct CP violation). Violation of CP symmetry either in mixing $|q/p| \neq 1$ or in the interference between mixing and decay amplitudes $\phi \equiv \arg[q\mathcal{A}(\bar{D}^0 \to K^+\pi^-)/p\mathcal{A}(D^0 \to K^+\pi^-)] - \delta \neq 0$ are usually referred to as indirect CP violation and would result in differences between (x'^{2+}, y'^+) and (x'^{2-}, y'^-).

The LHCb detector [20] is a single-arm forward spectrometer covering the pseudorapidity range $2 < \eta < 5$, designed for the study of particles containing b or c quarks. Detector components particularly relevant for this analysis are the silicon vertex detector, which provides reconstruction of displaced vertices of b- and c-hadron decays; the tracking system, which measures charged particle momenta with relative uncertainty that varies from 0.4% at 5 GeV/c to 0.6% at 100 GeV/c, corresponding to a typical mass resolution of approximately 8 MeV/c^2 for a two-body charm-meson decay; and the ring-imaging Cherenkov detectors, which provide kaon-pion discrimination [21]. The magnet polarity is periodically inverted, and approximately equal amounts of data are collected in each configuration to mitigate the effects of detection asymmetries. The online event-selection system (trigger) [22] consists of a first-level hardware stage based on information from the calorimeter and muon systems, followed by a software high-level trigger.

Events with D^{*+} candidates consistent with being produced at the pp collision point (primary vertex) are selected following Ref. [18]. In addition, a WS candidate is discarded if resulting from a D^0 candidate that, associated with another pion, also forms a RS candidate with $M(D^0\pi_s^+)$ within 3 MeV/c^2 of the known D^{*+} mass. This removes about 15% of the WS background with negligible signal loss. The two-body $D^0\pi_s^+$ mass $M(D^0\pi_s^+)$ is computed using the known D^0 and π^+ masses [23] and their reconstructed momenta [18]. In Ref. [18], we used events selected by the hardware trigger based on hadron calorimeter transverse-energy depositions that were geometrically matched with signal final-state tracks. In the present analysis, we distinguish two trigger categories. One category consists of events that meet the above trigger requirement (triggered-on-signal, TOS). The other comprises events with candidates failing the track-calorimeter matching and events selected based on muon hardware triggers decisions ($\overline{\text{TOS}}$). The two subsamples contribute approximately equal signal yields with similar purities. However, they require separate treatment due to their differing kinematic distributions and trigger-induced biases.

The RS and WS signal yields are determined by fitting the $M(D^0\pi_s^+)$ distribution of D^0 candidates with reconstructed mass within 24 MeV/c^2 of the known value. The time-integrated $M(D^0\pi_s^+)$ distributions are shown in Fig. 1. The smooth background is dominated by favored $\bar{D}^0 \to K^+\pi^-$ decays associated with random π_s^+ candidates. The sample contains 1.15×10^5 (1.14×10^5) signal WS D^0 ($\bar{D}^0$) decays and approximately 230 times more RS decays. Yield differences between D^0 and $\bar{D}^0$ decays are dominated by differences in charm-anticharm production rates and reconstruction efficiencies. Each sample is divided into 13 subsamples according to the candidate's decay time, and signal yields are determined for each using shape parametrizations determined from simulation and tuned to data [18]. We assume that for a given D^* meson flavor, the signal shapes are common to WS and RS decays, while the descriptions of the background can differ. The decay-time-dependent WS-to-RS yield ratios R^+ and R^- observed in the D^0 and $\bar{D}^0$ samples, respectively, and their difference are shown in Fig. 2. These are corrected for the relative efficiencies for reconstructing $K^-\pi^+$ and $K^+\pi^-$ final states.

The mixing parameters are determined by minimizing a χ^2 variable that includes terms for the difference between the observed and predicted ratios and for systematic deviations of parameters

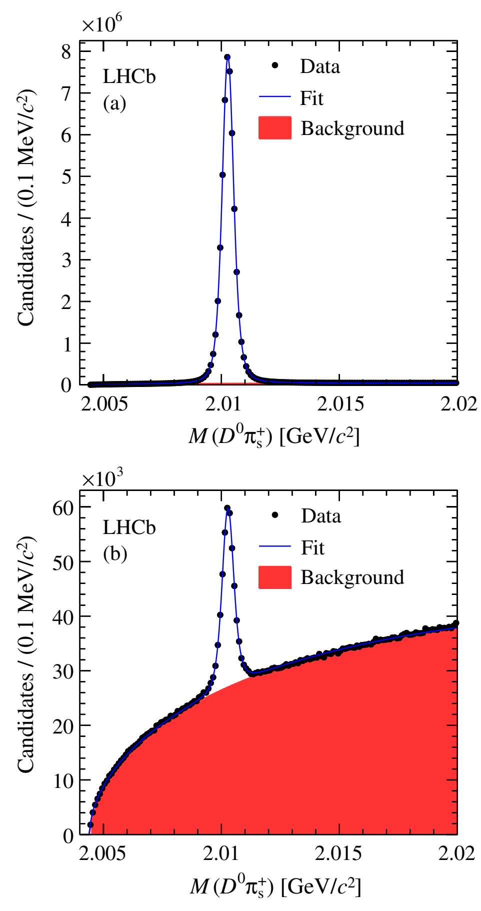

FIG. 1 (color online). Distribution of $M(D^0\pi_s^+)$ for selected (a) right-sign $D^0 \to K^-\pi^+$ and (b) wrong-sign $D^0 \to K^+\pi^-$ candidates.

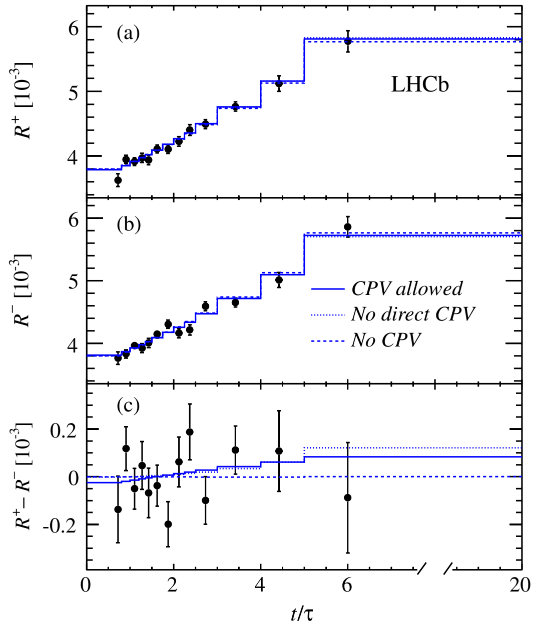

FIG. 2 (color online). Efficiency-corrected ratios of WS-to-RS yields for (a) D^{*+} decays, (b) D^{*-} decays, and (c) their differences as functions of decay time in units of D^0 lifetime. Projections of fits allowing for (dashed line) no *CP* violation (CPV), (dotted line) no direct *CP* violation, and (solid line) full *CP* violation are overlaid. The abscissa of the data points corresponds to the average decay time over the bin; the error bars indicate the statistical uncertainties.

$$\chi^2 = \sum_i \left[\left(\frac{r_i^+ - \epsilon_r^+ \tilde{R}_i^+}{\sigma_i^+} \right)^2 + \left(\frac{r_i^- - \epsilon_r^- \tilde{R}_i^-}{\sigma_i^-} \right)^2 \right] + \chi^2_\epsilon + \chi^2_B + \chi^2_p. \quad (2)$$

The measured WS-to-RS yield ratio and its statistical uncertainty in the decay-time bin i are denoted by $r_i^\pm$ and $\sigma_i^\pm$, respectively. The predicted value for the WS-to-RS yield ratio $\tilde{R}_i^\pm$ corresponds to the time integral over bin i of Eq. (1) including bin-specific corrections. These account for small biases due to the decay-time evolution of the approximately 3% fraction of signal candidates originating from b-hadron decays (Δ_B) and of the about 0.5% component of peaking background from RS decays in which both final-state particles are misidentified (Δ_p) [18]. The relative efficiency $\epsilon_r^\pm$ accounts for instrumental asymmetries in the $K\pi$ reconstruction efficiencies, mainly caused by K^- mesons having a larger interaction cross section with matter than K^+ mesons. These asymmetries are measured in data to be in the range 0.8%–1.2% with 0.2% precision and to be independent of decay time. They are derived from the efficiency ratio $\epsilon_r^+ = 1/\epsilon_r^- = \epsilon(K^+\pi^-)/\epsilon(K^-\pi^+)$, obtained from the product of $D^- \to K^+\pi^-\pi^-$ and $D^+ \to K_S^0(\to \pi^+\pi^-)\pi^+$ event yields divided by the product of the corresponding charge-conjugate decay yields. No *CP* violation is expected or experimentally observed [23] in these decays. Asymmetries due to *CP* violation in neutral kaons and their interaction cross sections with matter are negligible. The 1% asymmetry between D^+ and D^- production rates [24] cancels in this ratio, provided that the kinematic distributions are consistent across samples. We weight the $D^- \to K^+\pi^-\pi^-$ events so that their kinematic distributions match those in the $D^+ \to K_S^0\pi^+$ sample. Similarly, these samples are weighted as functions of $K\pi$ momentum to match the RS momentum spectra. The parameters associated with Δ_B, Δ_p, and ϵ_r are determined separately for TOS and $\overline{\text{TOS}}$ subsets and vary independently in the fit within their Gaussian constraints χ^2_B, χ^2_p, and χ^2_ϵ [18].

To avoid experimenters' bias in the *CP* violation parameters, the measurement technique is finalized by adding arbitrary offsets to the WS-to-RS yield ratios for the D^0 and $\bar{D}^0$ samples, designed to mimic the effect of different mixing parameters in the two samples. To rule out global systematic uncertainties not accounted for in Eq. (2), the data are first integrated over the whole decay-time spectrum and subsequently divided into statistically independent subsets according to criteria likely to reveal biases from specific instrumental effects. These include the number of primary vertices in the events, the K laboratory momentum, the π_s impact parameter χ^2 with respect to the primary vertex, the D^0 impact parameter χ^2 with respect to the primary vertex, the magnetic field orientation, and the hardware trigger category. The variations of the time-integrated charge asymmetry in WS-to-RS yield ratios are consistent with statistical fluctuations. Then, we investigate decay-time-dependent biases by dividing the time-binned sample according to the magnet polarity and the number of primary vertices per event. In the TOS sample, differences of WS-to-RS yield ratios as functions of decay time for opposite magnet polarities yield χ^2 values of 12, 17, and 14 (for 12 degrees of freedom), for events with one, two, and more than two primary vertices, respectively. The corresponding χ^2 values in the $\overline{\text{TOS}}$ sample, 9, 11, and 8, suggest a systematically better consistency. Hence, the statistical uncertainty of each of the WS-to-RS ratios in the TOS samples is increased by a factor of $\sqrt{17/12}$, following Ref. [23]. These scaled uncertainties are used in all subsequent fits. Independent analyses of the 2011 and 2012 data yield consistent results. The ratio between RS D^0 to $\bar{D}^0$ decay rates is independent of decay time with a 62% p value and a standard deviation of 0.16%, showing no evidence of correlations between particle identification or reconstruction efficiency and decay time.

Three fits are performed to the data shown in Fig. 2. The first allows direct and indirect *CP* violation, the second allows only indirect *CP* violation by constraining $R_D^\pm$ to a common value, and the third is a *CP*-conserving fit that constrains all mixing parameters to be the same in the D^0 and $\bar{D}^0$ samples. The fit results and their projections are shown in Table I and Fig. 2, respectively. Figure 3 shows the central values and confidence regions in the (x'^2, y') plane.

TABLE I. Results of fits to the data for different hypotheses on the *CP* symmetry [27]. The reported uncertainties are statistical and systematic, respectively; ndf indicates the number of degrees of freedom.

Parameter	Value
Direct and indirect *CP* violation	
R_D^+ (10^{-3})	$3.545 \pm 0.082 \pm 0.048$
y'^+ (10^{-3})	$5.1 \pm 1.2 \pm 0.7$
x'^{2+} (10^{-5})	$4.9 \pm 6.0 \pm 3.6$
R_D^- (10^{-3})	$3.591 \pm 0.081 \pm 0.048$
y'^- (10^{-3})	$4.5 \pm 1.2 \pm 0.7$
x'^{2-} (10^{-5})	$6.0 \pm 5.8 \pm 3.6$
χ^2/ndf	85.9/98
No direct *CP* violation	
R_D (10^{-3})	$3.568 \pm 0.058 \pm 0.033$
y'^+ (10^{-3})	$4.8 \pm 0.9 \pm 0.6$
x'^{2+} (10^{-5})	$6.4 \pm 4.7 \pm 3.0$
y'^- (10^{-3})	$4.8 \pm 0.9 \pm 0.6$
x'^{2-} (10^{-5})	$4.6 \pm 4.6 \pm 3.0$
χ^2/ndf	86.0/99
No *CP* violation	
R_D (10^{-3})	$3.568 \pm 0.058 \pm 0.033$
y' (10^{-3})	$4.8 \pm 0.8 \pm 0.5$
x'^2 (10^{-5})	$5.5 \pm 4.2 \pm 2.6$
χ^2/ndf	86.4/101

For each fit, 104 WS-to-RS ratio data points are used, corresponding to 13 ranges of decay time, distinguishing D^{*+} from D^{*-} decays, TOS from $\overline{\text{TOS}}$ decays, and 2011 data from 2012 data. The consistency with the hypothesis of *CP* symmetry is determined from the change in χ^2 between the fit without and with *CP* violation, taking into account the difference in number of degrees of freedom. The resulting p value, for the fit with direct and indirect (indirect only) *CP* violation allowed, is 91% (81%), showing that the data are compatible with *CP* symmetry.

The uncertainties incorporate both statistical and systematic contributions, since all relevant systematic effects depend on the true values of the mixing parameters, and are thus incorporated into the fit χ^2. These include the uncertainty in the fraction of charm mesons from b-hadron decays, and their bias on the observed decay time, the uncertainty in the fraction of peaking background, and the uncertainty in the determination of the instrumental asymmetry. The statistical uncertainty is determined in a separate fit and used to calculate the systematic component by subtraction in quadrature.

Direct *CP* violation would produce a nonzero intercept at $t = 0$ in the efficiency-corrected difference of WS-to-RS yield ratios between D^0 and $\bar{D}^0$ mesons shown in Fig. 2(c). It is parametrized by the asymmetry measured in the first fit $A_D \equiv (R_D^+ - R_D^-)/(R_D^+ + R_D^-) = (-0.7 \pm 1.9)\%$. Indirect *CP* violation results in a time dependence of the efficiency-corrected difference of yield ratios. The slope observed in Fig. 2(c) is about 5% of the individual slopes of Figs. 2(a) and 2(b) and is consistent with zero. From the results of the fit allowing for direct and indirect *CP* violation, a likelihood for $|q/p|$ is constructed using the relations $x'^{\pm} = |q/p|^{\pm 1}(x' \cos\phi \pm y' \sin\phi)$ and $y'^{\pm} = |q/p|^{\pm 1}(y' \cos\phi \mp x' \sin\phi)$. Confidence intervals are derived with a likelihood-ratio ordering and assuming that the correlations are independent of the true values of the mixing parameters. The magnitude of q/p is determined to be $0.75 < |q/p| < 1.24$ and $0.67 < |q/p| < 1.52$ at the 68.3% and 95.5% confidence levels, respectively. Significantly more stringent bounds on $|q/p|$ and additional information on ϕ are available by combining the present results with other measurements [10], in particular, when also using theoretical constraints, such as the relationship $\tan\phi = x(1 - |q/p|^2)/y(1 + |q/p|^2)$ [25,26],

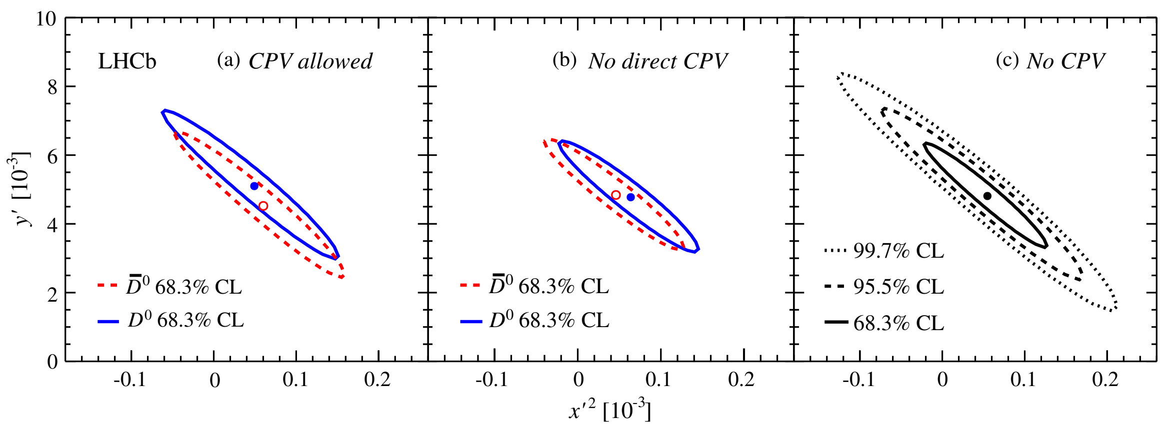

FIG. 3 (color online). Two-dimensional confidence regions in the (x'^2, y') plane obtained (a) without any restriction on *CP* violation, (b) assuming no direct *CP* violation, and (c) assuming *CP* conservation. The dashed (solid) curves in (a) and (b) indicate the contours of the mixing parameters associated with $\bar{D}^0$ (D^0) decays. The best-fit value for $\bar{D}^0$ (D^0) decays is shown with an open (filled) point. The solid, dashed, and dotted curves in (c) indicate the contours of *CP* -averaged mixing parameters at 68.3%, 95.5%, and 99.7% confidence level (CL), respectively. The best-fit value is shown with a point.

which applies in the limit that direct *CP* violation is negligible.

In summary, D^0–$\bar{D}^0$ oscillation is studied using $D^{*+} \to D^0(\to K^+\pi^-)\pi^+$ decays reconstructed in the full sample of pp collisions, corresponding to 3 fb^{-1} of integrated luminosity collected by the LHCb experiment in 2011 and 2012. Assuming *CP* conservation, the mixing parameters are measured to be $x'^2 = (5.5 \pm 4.9) \times 10^{-5}$, $y' = (4.8 \pm 1.0) \times 10^{-3}$, and $R_D = (3.568 \pm 0.066) \times 10^{-3}$. The observed parameters are consistent with, 2.5 times more precise than, and supersede the results based on a subset of the present data [18]. Studying D^0 and $\bar{D}^0$ decays separately shows no evidence for *CP* violation and provides the most stringent bounds on the parameters A_D and $|q/p|$ from a single experiment.

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); NSFC (China); CNRS/IN2P3 and Region Auvergne (France); BMBF, DFG, HGF, and MPG (Germany); SFI (Ireland); INFN (Italy); FOM and NWO (Netherlands); SCSR (Poland); MEN/IFA (Romania); MinES, Rosatom, RFBR, and NRC "Kurchatov Institute" (Russia); MinECo, XuntaGal, and GENCAT (Spain); SNSF and SER (Switzerland); NAS Ukraine (Ukraine); STFC (United Kingdom); and NSF (U.S.A.). We also acknowledge the support received from the ERC under FP7. The Tier1 computing centres are supported by IN2P3 (France), KIT and BMBF (Germany), INFN (Italy), NWO and SURF (Netherlands), PIC (Spain), and GridPP (United Kingdom). We are thankful for the computing resources put at our disposal by Yandex LLC (Russia), as well as to the communities behind the multiple open source software packages that we depend on.

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R. Aaij,[40] B. Adeva,[36] M. Adinolfi,[45] C. Adrover,[6] A. Affolder,[51] Z. Ajaltouni,[5] J. Albrecht,[9] F. Alessio,[37] M. Alexander,[50] S. Ali,[40] G. Alkhazov,[29] P. Alvarez Cartelle,[36] A. A. Alves, Jr.,[24] S. Amato,[2] S. Amerio,[21] Y. Amhis,[7] L. Anderlini,[17,a] J. Anderson,[39] R. Andreassen,[56] J. E. Andrews,[57] R. B. Appleby,[53] O. Aquines Gutierrez,[10] F. Archilli,[18] A. Artamonov,[34] M. Artuso,[58] E. Aslanides,[6] G. Auriemma,[24,b] M. Baalouch,[5] S. Bachmann,[11] J. J. Back,[47] A. Badalov,[35] C. Baesso,[59] V. Balagura,[30] W. Baldini,[16] R. J. Barlow,[53] C. Barschel,[37] S. Barsuk,[7] W. Barter,[46] Th. Bauer,[40] A. Bay,[38] J. Beddow,[50] F. Bedeschi,[22] I. Bediaga,[1] S. Belogurov,[30] K. Belous,[34] I. Belyaev,[30] E. Ben-Haim,[8] G. Bencivenni,[18] S. Benson,[49] J. Benton,[45] A. Berezhnoy,[31] R. Bernet,[39] M.-O. Bettler,[46] M. van Beuzekom,[40] A. Bien,[11] S. Bifani,[44] T. Bird,[53] A. Bizzeti,[17,c]

P. M. Bjørnstad,[53] T. Blake,[37] F. Blanc,[38] J. Blouw,[10] S. Blusk,[58] V. Bocci,[24] A. Bondar,[33] N. Bondar,[29] W. Bonivento,[15] S. Borghi,[53] A. Borgia,[58] T. J. V. Bowcock,[51] E. Bowen,[39] C. Bozzi,[16] T. Brambach,[9] J. van den Brand,[41] J. Bressieux,[38] D. Brett,[53] M. Britsch,[10] T. Britton,[58] N. H. Brook,[45] H. Brown,[51] A. Bursche,[39] G. Busetto,[21,d] J. Buytaert,[37] S. Cadeddu,[15] O. Callot,[7] M. Calvi,[20,e] M. Calvo Gomez,[35,f] A. Camboni,[35] P. Campana,[18,37] D. Campora Perez,[37] A. Carbone,[14,g] G. Carboni,[23,h] R. Cardinale,[19,i] A. Cardini,[15] H. Carranza-Mejia,[49] L. Carson,[52] K. Carvalho Akiba,[2] G. Casse,[51] L. Castillo Garcia,[37] M. Cattaneo,[37] Ch. Cauet,[9] R. Cenci,[57] M. Charles,[54] Ph. Charpentier,[37] S.-F. Cheung,[54] N. Chiapolini,[39] M. Chrzaszcz,[39,25] K. Ciba,[37] X. Cid Vidal,[37] G. Ciezarek,[52] P. E. L. Clarke,[49] M. Clemencic,[37] H. V. Cliff,[46] J. Closier,[37] C. Coca,[28] V. Coco,[40] J. Cogan,[6] E. Cogneras,[5] P. Collins,[37] A. Comerma-Montells,[35] A. Contu,[15,37] A. Cook,[45] M. Coombes,[45] S. Coquereau,[8] G. Corti,[37] B. Couturier,[37] G. A. Cowan,[49] D. C. Craik,[47] M. Cruz Torres,[59] S. Cunliffe,[52] R. Currie,[49] C. D'Ambrosio,[37] P. David,[8] P. N. Y. David,[40] A. Davis,[56] I. De Bonis,[4] K. De Bruyn,[40] S. De Capua,[53] M. De Cian,[11] J. M. De Miranda,[1] L. De Paula,[2] W. De Silva,[56] P. De Simone,[18] D. Decamp,[4] M. Deckenhoff,[9] L. Del Buono,[8] N. Déléage,[4] D. Derkach,[54] O. Deschamps,[5] F. Dettori,[41] A. Di Canto,[11] H. Dijkstra,[37] M. Dogaru,[28] S. Donleavy,[51] F. Dordei,[11] P. Dornan,[52] A. Dosil Suárez,[36] D. Dossett,[47] A. Dovbnya,[42] F. Dupertuis,[38] P. Durante,[37] R. Dzhelyadin,[34] A. Dziurda,[25] A. Dzyuba,[29] S. Easo,[48] U. Egede,[52] V. Egorychev,[30] S. Eidelman,[33] D. van Eijk,[40] S. Eisenhardt,[49] U. Eitschberger,[9] R. Ekelhof,[9] L. Eklund,[50,37] I. El Rifai,[5] Ch. Elsasser,[39] A. Falabella,[14,j] C. Färber,[11] C. Farinelli,[40] S. Farry,[51] D. Ferguson,[49] V. Fernandez Albor,[36] F. Ferreira Rodrigues,[1] M. Ferro-Luzzi,[37] S. Filippov,[32] M. Fiore,[16,j] C. Fitzpatrick,[37] M. Fontana,[10] F. Fontanelli,[19,i] R. Forty,[37] O. Francisco,[2] M. Frank,[37] C. Frei,[37] M. Frosini,[17,37,a] E. Furfaro,[23,h] A. Gallas Torreira,[36] D. Galli,[14,g] M. Gandelman,[2] P. Gandini,[58] Y. Gao,[3] J. Garofoli,[58] P. Garosi,[53] J. Garra Tico,[46] L. Garrido,[35] C. Gaspar,[37] R. Gauld,[54] E. Gersabeck,[11] M. Gersabeck,[53] T. Gershon,[47] Ph. Ghez,[4] V. Gibson,[46] L. Giubega,[28] V. V. Gligorov,[37] C. Göbel,[59] D. Golubkov,[30] A. Golutvin,[52,30,37] A. Gomes,[2] P. Gorbounov,[30,37] H. Gordon,[37] M. Grabalosa Gándara,[5] R. Graciani Diaz,[35] L. A. Granado Cardoso,[37] E. Graugés,[35] G. Graziani,[17] A. Grecu,[28] E. Greening,[54] S. Gregson,[46] P. Griffith,[44] L. Grillo,[11] O. Grünberg,[60] B. Gui,[58] E. Gushchin,[32] Yu. Guz,[34,37] T. Gys,[37] C. Hadjivasiliou,[58] G. Haefeli,[38] C. Haen,[37] S. C. Haines,[46] S. Hall,[52] B. Hamilton,[57] T. Hampson,[45] S. Hansmann-Menzemer,[11] N. Harnew,[54] S. T. Harnew,[45] J. Harrison,[53] T. Hartmann,[60] J. He,[37] T. Head,[37] V. Heijne,[40] K. Hennessy,[51] P. Henrard,[5] J. A. Hernando Morata,[36] E. van Herwijnen,[37] M. Heß,[60] A. Hicheur,[1] E. Hicks,[51] D. Hill,[54] M. Hoballah,[5] C. Hombach,[53] W. Hulsbergen,[40] P. Hunt,[54] T. Huse,[51] N. Hussain,[54] D. Hutchcroft,[51] D. Hynds,[50] V. Iakovenko,[43] M. Idzik,[26] P. Ilten,[12] R. Jacobsson,[37] A. Jaeger,[11] E. Jans,[40] P. Jaton,[38] A. Jawahery,[57] F. Jing,[3] M. John,[54] D. Johnson,[54] C. R. Jones,[46] C. Joram,[37] B. Jost,[37] M. Kaballo,[9] S. Kandybei,[42] W. Kanso,[6] M. Karacson,[37] T. M. Karbach,[37] I. R. Kenyon,[44] T. Ketel,[41] B. Khanji,[20] O. Kochebina,[7] I. Komarov,[38] R. F. Koopman,[41] P. Koppenburg,[40] M. Korolev,[31] A. Kozlinskiy,[40] L. Kravchuk,[32] K. Kreplin,[11] M. Kreps,[47] G. Krocker,[11] P. Krokovny,[33] F. Kruse,[9] M. Kucharczyk,[20,25,37,e] V. Kudryavtsev,[33] K. Kurek,[27] T. Kvaratskheliya,[30,37] V. N. La Thi,[38] D. Lacarrere,[37] G. Lafferty,[53] A. Lai,[15] D. Lambert,[49] R. W. Lambert,[41] E. Lanciotti,[37] G. Lanfranchi,[18] C. Langenbruch,[37] T. Latham,[47] C. Lazzeroni,[44] R. Le Gac,[6] J. van Leerdam,[40] J.-P. Lees,[4] R. Lefèvre,[5] A. Leflat,[31] J. Lefrançois,[7] S. Leo,[22] O. Leroy,[6] T. Lesiak,[25] B. Leverington,[11] Y. Li,[3] L. Li Gioi,[5] M. Liles,[51] R. Lindner,[37] C. Linn,[11] B. Liu,[3] G. Liu,[37] S. Lohn,[37] I. Longstaff,[50] J. H. Lopes,[2] N. Lopez-March,[38] H. Lu,[3] D. Lucchesi,[21,d] J. Luisier,[38] H. Luo,[49] O. Lupton,[54] F. Machefert,[7] I. V. Machikhiliyan,[30] F. Maciuc,[28] O. Maev,[29,37] S. Malde,[54] G. Manca,[15,k] G. Mancinelli,[6] J. Maratas,[5] U. Marconi,[14] P. Marino,[22,l] R. Märki,[38] J. Marks,[11] G. Martellotti,[24] A. Martens,[8] A. Martín Sánchez,[7] M. Martinelli,[40] D. Martinez Santos,[41,37] D. Martins Tostes,[2] A. Martynov,[31] A. Massafferri,[1] R. Matev,[37] Z. Mathe,[37] C. Matteuzzi,[20] E. Maurice,[6] A. Mazurov,[16,37,j] J. McCarthy,[44] A. McNab,[53] R. McNulty,[12] B. McSkelly,[51] B. Meadows,[56,54] F. Meier,[9] M. Meissner,[11] M. Merk,[40] D. A. Milanes,[8] M.-N. Minard,[4] J. Molina Rodriguez,[59] S. Monteil,[5] D. Moran,[53] P. Morawski,[25] A. Mordà,[6] M. J. Morello,[22,l] R. Mountain,[58] I. Mous,[40] F. Muheim,[49] K. Müller,[39] R. Muresan,[28] B. Muryn,[26] B. Muster,[38] P. Naik,[45] T. Nakada,[38] R. Nandakumar,[48] I. Nasteva,[1] M. Needham,[49] S. Neubert,[37] N. Neufeld,[37] A. D. Nguyen,[38] T. D. Nguyen,[38] C. Nguyen-Mau,[38,m] M. Nicol,[7] V. Niess,[5] R. Niet,[9] N. Nikitin,[31] T. Nikodem,[11] A. Nomerotski,[54] A. Novoselov,[34] A. Oblakowska-Mucha,[26] V. Obraztsov,[34] S. Oggero,[40] S. Ogilvy,[50] O. Okhrimenko,[43] R. Oldeman,[15,k] M. Orlandea,[28] J. M. Otalora Goicochea,[2] P. Owen,[52] A. Oyanguren,[35] B. K. Pal,[58] A. Palano,[13,n] M. Palutan,[18] J. Panman,[37] A. Papanestis,[48] M. Pappagallo,[50] C. Parkes,[53] C. J. Parkinson,[52] G. Passaleva,[17] G. D. Patel,[51] M. Patel,[52] G. N. Patrick,[48] C. Patrignani,[19,i] C. Pavel-Nicorescu,[28] A. Pazos Alvarez,[36] A. Pearce,[53]

A. Pellegrino,[40] G. Penso,[24,o] M. Pepe Altarelli,[37] S. Perazzini,[14,g] E. Perez Trigo,[36] A. Pérez-Calero Yzquierdo,[35] P. Perret,[5] M. Perrin-Terrin,[6] L. Pescatore,[44] E. Pesen,[61] G. Pessina,[20] K. Petridis,[52] A. Petrolini,[19,i] A. Phan,[58] E. Picatoste Olloqui,[35] B. Pietrzyk,[4] T. Pilař,[47] D. Pinci,[24] S. Playfer,[49] M. Plo Casasus,[36] F. Polci,[8] G. Polok,[25] A. Poluektov,[47,33] E. Polycarpo,[2] A. Popov,[34] D. Popov,[10] B. Popovici,[28] C. Potterat,[35] A. Powell,[54] J. Prisciandaro,[38] A. Pritchard,[51] C. Prouve,[7] V. Pugatch,[43] A. Puig Navarro,[38] G. Punzi,[22,p] W. Qian,[4] B. Rachwal,[25] J. H. Rademacker,[45] B. Rakotomiaramanana,[38] M. S. Rangel,[2] I. Raniuk,[42] N. Rauschmayr,[37] G. Raven,[41] S. Redford,[54] S. Reichert,[53] M. M. Reid,[47] A. C. dos Reis,[1] S. Ricciardi,[48] A. Richards,[52] K. Rinnert,[51] V. Rives Molina,[35] D. A. Roa Romero,[5] P. Robbe,[7] D. A. Roberts,[57] A. B. Rodrigues,[1] E. Rodrigues,[53] P. Rodriguez Perez,[36] S. Roiser,[37] V. Romanovsky,[34] A. Romero Vidal,[36] M. Rotondo,[21] J. Rouvinet,[38] T. Ruf,[37] F. Ruffini,[22] H. Ruiz,[35] P. Ruiz Valls,[35] G. Sabatino,[24,h] J. J. Saborido Silva,[36] N. Sagidova,[29] P. Sail,[50] B. Saitta,[15,k] V. Salustino Guimaraes,[2] B. Sanmartin Sedes,[36] R. Santacesaria,[24] C. Santamarina Rios,[36] E. Santovetti,[23,h] M. Sapunov,[6] A. Sarti,[18] C. Satriano,[24,b] A. Satta,[23] M. Savrie,[16,j] D. Savrina,[30,31] M. Schiller,[41] H. Schindler,[37] M. Schlupp,[9] M. Schmelling,[10] B. Schmidt,[37] O. Schneider,[38] A. Schopper,[37] M.-H. Schune,[7] R. Schwemmer,[37] B. Sciascia,[18] A. Sciubba,[24] M. Seco,[36] A. Semennikov,[30] K. Senderowska,[26] I. Sepp,[52] N. Serra,[39] J. Serrano,[6] P. Seyfert,[11] M. Shapkin,[34] I. Shapoval,[16,42,j] Y. Shcheglov,[29] T. Shears,[51] L. Shekhtman,[33] O. Shevchenko,[42] V. Shevchenko,[30] A. Shires,[9] R. Silva Coutinho,[47] M. Sirendi,[46] N. Skidmore,[45] T. Skwarnicki,[58] N. A. Smith,[51] E. Smith,[54,48] E. Smith,[52] J. Smith,[46] M. Smith,[53] M. D. Sokoloff,[56] F. J. P. Soler,[50] F. Soomro,[38] D. Souza,[45] B. Souza De Paula,[2] B. Spaan,[9] A. Sparkes,[49] P. Spradlin,[50] F. Stagni,[37] S. Stahl,[11] O. Steinkamp,[39] S. Stevenson,[54] S. Stoica,[28] S. Stone,[58] B. Storaci,[39] M. Straticiuc,[28] U. Straumann,[39] V. K. Subbiah,[37] L. Sun,[56] W. Sutcliffe,[52] S. Swientek,[9] V. Syropoulos,[41] M. Szczekowski,[27] P. Szczypka,[38,37] D. Szilard,[2] T. Szumlak,[26] S. T'Jampens,[4] M. Teklishyn,[7] E. Teodorescu,[28] F. Teubert,[37] C. Thomas,[54] E. Thomas,[37] J. van Tilburg,[11] V. Tisserand,[4] M. Tobin,[38] S. Tolk,[41] D. Tonelli,[37] S. Topp-Joergensen,[54] N. Torr,[54] E. Tournefier,[4,52] S. Tourneur,[38] M. T. Tran,[38] M. Tresch,[39] A. Tsaregorodtsev,[6] P. Tsopelas,[40] N. Tuning,[40,37] M. Ubeda Garcia,[37] A. Ukleja,[27] A. Ustyuzhanin,[52,q] U. Uwer,[11] V. Vagnoni,[14] G. Valenti,[14] A. Vallier,[7] R. Vazquez Gomez,[18] P. Vazquez Regueiro,[36] C. Vázquez Sierra,[36] S. Vecchi,[16] J. J. Velthuis,[45] M. Veltri,[17,r] G. Veneziano,[38] M. Vesterinen,[37] B. Viaud,[7] D. Vieira,[2] X. Vilasis-Cardona,[35,f] A. Vollhardt,[39] D. Volyanskyy,[10] D. Voong,[45] A. Vorobyev,[29] V. Vorobyev,[33] C. Voß,[60] H. Voss,[10] R. Waldi,[60] C. Wallace,[47] R. Wallace,[12] S. Wandernoth,[11] J. Wang,[58] D. R. Ward,[46] N. K. Watson,[44] A. D. Webber,[53] D. Websdale,[52] M. Whitehead,[47] J. Wicht,[37] J. Wiechczynski,[25] D. Wiedner,[11] L. Wiggers,[40] G. Wilkinson,[54] M. P. Williams,[47,48] M. Williams,[55] F. F. Wilson,[48] J. Wimberley,[57] J. Wishahi,[9] W. Wislicki,[27] M. Witek,[25] G. Wormser,[7] S. A. Wotton,[46] S. Wright,[46] S. Wu,[3] K. Wyllie,[37] Y. Xie,[49,37] Z. Xing,[58] Z. Yang,[3] X. Yuan,[3] O. Yushchenko,[34] M. Zangoli,[14] M. Zavertyaev,[10,s] F. Zhang,[3] L. Zhang,[58] W. C. Zhang,[12] Y. Zhang,[3] A. Zhelezov,[11] A. Zhokhov,[30] L. Zhong,[3] and A. Zvyagin[37]

(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 de Savoie, 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 Padova, Padova, Italy*
[22]*Sezione INFN di Pisa, Pisa, Italy*
[23]*Sezione INFN di Roma Tor Vergata, Roma, Italy*
[24]*Sezione INFN di Roma La Sapienza, Roma, Italy*
[25]*Henryk Niewodniczanski Institute of Nuclear Physics, Polish Academy of Sciences, Kraków, Poland*
[26]*AGH-University of Science and Technology, Faculty of Physics and Applied Computer Science, Kraków, Poland*
[27]*National Center for Nuclear Research (NCBJ), Warsaw, Poland*
[28]*Horia Hulubei National Institute of Physics and Nuclear Engineering, Bucharest-Magurele, Romania*
[29]*Petersburg Nuclear Physics Institute (PNPI), Gatchina, Russia*
[30]*Institute of Theoretical and Experimental Physics (ITEP), Moscow, Russia*
[31]*Institute of Nuclear Physics, Moscow State University (SINP MSU), Moscow, Russia*
[32]*Institute for Nuclear Research of the Russian Academy of Sciences (INR RAN), Moscow, Russia*
[33]*Budker Institute of Nuclear Physics (SB RAS) and Novosibirsk State University, Novosibirsk, Russia*
[34]*Institute for High Energy Physics (IHEP), Protvino, Russia*
[35]*Universitat de Barcelona, Barcelona, Spain*
[36]*Universidad de Santiago de Compostela, Santiago de Compostela, Spain*
[37]*European Organization for Nuclear Research (CERN), Geneva, Switzerland*
[38]*Ecole Polytechnique Fédérale de Lausanne (EPFL), Lausanne, Switzerland*
[39]*Physik-Institut, Universität Zürich, Zürich, Switzerland*
[40]*Nikhef National Institute for Subatomic Physics, Amsterdam, The Netherlands*
[41]*Nikhef National Institute for Subatomic Physics and VU University Amsterdam, Amsterdam, The Netherlands*
[42]*NSC Kharkiv Institute of Physics and Technology (NSC KIPT), Kharkiv, Ukraine*
[43]*Institute for Nuclear Research of the National Academy of Sciences (KINR), Kyiv, Ukraine*
[44]*University of Birmingham, Birmingham, United Kingdom*
[45]*H. H. Wills Physics Laboratory, University of Bristol, Bristol, United Kingdom*
[46]*Cavendish Laboratory, University of Cambridge, Cambridge, United Kingdom*
[47]*Department of Physics, University of Warwick, Coventry, United Kingdom*
[48]*STFC Rutherford Appleton Laboratory, Didcot, United Kingdom*
[49]*School of Physics and Astronomy, University of Edinburgh, Edinburgh, United Kingdom*
[50]*School of Physics and Astronomy, University of Glasgow, Glasgow, United Kingdom*
[51]*Oliver Lodge Laboratory, University of Liverpool, Liverpool, United Kingdom*
[52]*Imperial College London, London, United Kingdom*
[53]*School of Physics and Astronomy, University of Manchester, Manchester, United Kingdom*
[54]*Department of Physics, University of Oxford, Oxford, United Kingdom*
[55]*Massachusetts Institute of Technology, Cambridge, Massachusetts, United States*
[56]*University of Cincinnati, Cincinnati, Ohio, United States*
[57]*University of Maryland, College Park, Maryland, United States*
[58]*Syracuse University, Syracuse, New York, United States*
[59]*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]*
[60]*Institut für Physik, Universität Rostock, Rostock, Germany (associated with Physikalisches Institut, Ruprecht-Karls-Universität Heidelberg, Heidelberg, Germany)*
[61]*Celal Bayar University, Manisa, Turkey (associated with European Organization for Nuclear Research (CERN), Geneva, Switzerland)*

[a]Also at Università di Firenze, Firenze, Italy.
[b]Also at Università della Basilicata, Potenza, Italy.
[c]Also at Università di Modena e Reggio Emilia, Modena, Italy.
[d]Also at Università di Padova, Padova, Italy.
[e]Also at Università di Milano Bicocca, Milano, Italy.
[f]Also at LIFAELS, La Salle, Universitat Ramon Llull, Barcelona, Spain.
[g]Also at Università di Bologna, Bologna, Italy.
[h]Also at Università di Roma Tor Vergata, Roma, Italy.
[i]Also at Università di Genova, Genova, Italy.
[j]Also at Università di Ferrara, Ferrara, Italy.
[k]Also at Università di Cagliari, Cagliari, Italy.
[l]Also at Scuola Normale Superiore, Pisa, Italy.
[m]Also at Hanoi University of Science, Hanoi, Viet Nam.

[n]Also at Università di Bari, Bari, Italy.
[o]Also at Università di Roma La Sapienza, Roma, Italy.
[p]Also at Università di Pisa, Pisa, Italy.
[q]Also at Institute of Physics and Technology, Moscow, Russia.
[r]Also at Università di Urbino, Urbino, Italy.
[s]Also at P. N. Lebedev Physical Institute, Russian Academy of Science (LPI RAS), Moscow, Russia.