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Determination of the ratio of b-quark fragmentation fractions f_s/f_d in pp collisions at $\sqrt{s} = 7$ TeV with the ATLAS detector

The ATLAS Collaboration

Abstract

With an integrated luminosity of 2.47 fb^{-1} recorded by the ATLAS experiment at the LHC, the exclusive decays $B_s^0 \to J/\psi\phi$ and $B_d^0 \to J/\psi K^{*0}$ of B mesons produced in pp collisions at $\sqrt{s} = 7$ TeV are used to determine the ratio of fragmentation fractions f_s/f_d. From the observed yields of 6640 ± 100(stat) ± 220(sys) $B_s^0 \to J/\psi\phi$ events and 36290 ± 320(stat) ± 650(sys) $B_d^0 \to J/\psi K^{*0}$ events, the quantity $\frac{f_s}{f_d}\frac{\mathcal{B}(B_s^0 \to J/\psi\phi)}{\mathcal{B}(B_d^0 \to J/\psi K^{*0})}$ is estimated to be 0.199 ± 0.004(stat) ± 0.010(sys).

The production rate of B_s^0 (B_d^0) mesons is a product of the $b\bar{b}$ cross section, the instantaneous luminosity and the probability that the $\bar{b}$-quark is bound to an s-(d-) quark. The latter, denoted by the fragmentation fraction f_s (f_d), depends on the momentum-dependent parton distribution functions at the interaction point and the probability for a soft gluon splitting into $s\bar{s}$ ($d\bar{d}$). At the LHC, the soft gluon may fragment into $u\bar{u}$, $c\bar{c}$ and various types of diquark-antidiquark pairs with the respective fragmentation fractions constrained by $f_u + f_d + f_s + f_c + f_{\text{baryon}} = 1$. The fragmentation fraction is $O(40\%)$ for u- and d-quarks, $O(10\%)$ for s-quarks and at the percent level for c-quarks and baryons. Precise knowledge of the fragmentation fractions is essential for measuring b-hadron cross sections and branching fractions at the LHC. In particular for rare decays, such as the branching fraction measurement of $B_s^0 \to \mu^+\mu^-$ [1–3], a precise knowledge of f_s/f_d is important since it improves the sensitivity of searches for new physics processes beyond the Standard Model (SM). This Letter presents a measurement of f_s/f_d using $B_s^0 \to J/\psi\phi$ and $B_d^0 \to J/\psi K^{*0}$ decays.

The fragmentation ratio f_s/f_d is extracted from the $B_s^0 \to J/\psi\phi$ and $B_d^0 \to J/\psi K^{*0}$ signal yields, $N_{B_s^0}$ and $N_{B_d^0}$. These are corrected for the branching fractions of the relevant decays and for the relative efficiency $\mathcal{R}_{\text{eff}}$ that is expressed as a product of acceptance and selection efficiency ratios for the two modes and is determined from Monte Carlo (MC) simulations:

$$\frac{f_s}{f_d} = \frac{N_{B_s^0}}{N_{B_d^0}} \frac{\mathcal{B}(B_d^0 \to J/\psi K^{*0})}{\mathcal{B}(B_s^0 \to J/\psi\phi)} \frac{\mathcal{B}(K^{*0} \to K^+\pi^-)}{\mathcal{B}(\phi \to K^+K^-)} \mathcal{R}_{\text{eff}}, \tag{1}$$

where the J/ψ, ϕ and K^{*0} are reconstructed in their $J/\psi \to \mu^+\mu^-$, $\phi \to K^+K^-$ and $K^{*0} \to K^+\pi^-$ final states [4], respectively. The data sample consists of an integrated luminosity of 2.47 ± 0.04 fb^{-1} collected with the ATLAS detector at $\sqrt{s} = 7$ TeV pp collisions in 2011. The ATLAS multipurpose detector is described in detail in Ref. [5].

The PYTHIA 6 and 8 [6, 7] MC generators, adjusted to ATLAS data [8], are used to simulate background and signal events, respectively. The polarization parameters, taken from Ref. [9], for $B_s^0 \to J/\psi\phi$ and $B_d^0 \to J/\psi K^{*0}$ decays are specified individually in the simulations. The detector response for the generated events is simulated with GEANT4 [10, 11].

The $B_s^0 \to J/\psi\phi$ and $B_d^0 \to J/\psi K^{*0}$ signal candidates consist of two muons and two hadrons originating from a common secondary vertex. The J/ψ candidates are selected by a dimuon trigger requiring two oppositely charged muon candidates, each having a transverse momentum of $p_{\text{T}} > 4$ GeV. Reconstructed muon candidates are categorized either as combined or segment-tagged muons. A combined muon consists of an inner detector (ID) track combined with a muon spectrometer (MS) track using tight matching criteria, while a segment-tagged muon requires an ID track and track segments in the MS that are not reconstructed as an MS track [5]. Both muons, of which at least one must be a combined muon, are fitted to originate from the same two-track vertex. The vertex fit chi-square per degree of freedom (dof) is required to be $\chi^2/\text{dof} < 10$. To improve the sample purity, each muon track must have at least one hit in the pixel detector, more than five hits in the silicon strip detector and at least one hit in the transition radiation tracker that reduces the pseudorapidity coverage to $|\eta| < 2.0$ [12].

Since the dimuon mass resolution is different for muons reconstructed in the endcaps ($1.05 < |\eta| < 2.5$) and for muons reconstructed in the barrel ($|\eta| < 1.05$), all accepted J/ψ candidates are divided into three classes: two barrel muons (BB), one endcap and one barrel muon (EB), and two endcap muons (EE). The values of parameters describing the dimuon mass distribution around the J/ψ peak for the three pseudorapidity classes in data and $B_s^0 \to J/\psi\phi$ and $B_d^0 \to J/\psi K^{*0}$ MC signal samples are extracted from

maximum-likelihood fits. For data, the selected mass regions are 2.991–3.197 GeV for BB, 2.955–3.235 GeV for EB and 2.914–3.275 GeV for EE classes. The corresponding J/ψ mass regions in the simulations are adjusted such that the J/ψ selection efficiencies in data and MC simulations are the same.

The B_s^0 candidates are reconstructed by fitting J/ψ candidates with two particle tracks with opposite charges, with the kaon mass hypothesis, to a common four-track vertex and constraining the dimuon invariant mass to the J/ψ mass [9]. All combinations are accepted if $p_{\mathrm{T}}(B_s^0) > 8$ GeV, $\chi^2/\mathrm{dof} < 3$ for the vertex fit and the K^+K^- invariant mass lies in the range determined by ± 2 natural widths (Γ_ϕ) around the ϕ mass peak, yielding $1011 < m_{K^+K^-} < 1028$ MeV. The $m_{K^+K^-}$ distribution is modeled with a Breit-Wigner line shape convolved with a Crystal Ball function [13] and the selected mass window retains 85% of signal events.

The B_d^0 candidates are reconstructed in a similar way. Here, one track of the K^{*0} decay is assigned a kaon mass hypothesis and the other track a pion mass hypothesis. Since ATLAS has limited kaon/pion separation capability in the momentum range relevant for this analysis, both $K\pi$ mass assignment combinations are tested and the one with a mass closest to the K^{*0} mass is chosen, yielding the correct $K\pi$ selection for 86% of all K^{*0} candidates. The probability density function (PDF) for the invariant mass of the correctly selected $K\pi$ candidates is modeled with a relativistic Breit-Wigner line shape convolved with a Crystal Ball function. The PDF for the invariant mass of the events where the K and π are swapped is modeled with a Gaussian function. Since the peaking background from the decay $B_s^0 \to J/\psi\phi$ yields a natural threshold in the low-K^{*0}-mass region, the K^{*0} mass selection obtained from a maximum-likelihood fit is limited to $\pm\Gamma_{K^{*0}}$ around the K^{*0} mass peak, yielding a selected range of $847 < m_{K\pi} < 942$ MeV for data. In the simulations, the K^+K^- and $K\pi$ mass selections are adjusted such that efficiencies in data and MC simulations are the same.

The signal-to-background ratio for $B_s^0 \to J/\psi\phi$ and $B_d^0 \to J/\psi K^{*0}$ decays is optimized using three variables with high background suppression power: the B vertex fit χ^2/dof, the transverse decay length L_{xy}, defined as the projection of the vector pointing from the primary vertex (PV) [14] to the B decay secondary vertex in the transverse plane, and the pointing angle $\alpha = |\phi_{p_{\mathrm{T}}} - \phi_{L_{xy}}|$ between the transverse momentum of the B meson and the L_{xy}. If more than one PV candidate exists, the one with the highest sum of the squares of the constituent tracks transverse momenta, $\sum p_{\mathrm{T}}^2$, is used. The χ^2/dof, L_{xy} and α selection criteria is optimized using simulated $B_s^0 \to J/\psi\phi$ and $B_d^0 \to J/\psi K^{*0}$ events for signal and data sidebands for background. Before optimizing the selection, simulated distributions were matched with those in the data by applying data-driven corrections described below.

The MC tuning is performed on the event-based set of B_s^0 (B_d^0) kinematic variables (p_{T}, η) by dividing samples into subsets containing *even*-number or *odd*-number events to avoid possible correlations between weights and the B_s^0 (B_d^0) yield extraction. Data-driven weights are obtained by comparing sideband-subtracted $B_s^0 \to J/\psi\phi$ ($B_d^0 \to J/\psi K^{*0}$) p_{T} and η distributions from data with the corresponding ones from MC simulations in the signal region $5.32 < m_{J/\psi\phi} < 5.42$ ($5.21 < m_{J/\psi K^{*0}} < 5.35$) GeV. The sideband-subtracted sample is obtained by subtracting the underlying background under the signal region using the lower and upper sidebands defined in the ranges $5.20 < m_{J/\psi\phi} < 5.25$ ($5.09 < m_{J/\psi K^{*0}} < 5.16$) GeV and $5.48 < m_{J/\psi\phi} < 5.53$ ($5.40 < m_{J/\psi K^{*0}} < 5.47$) GeV, respectively.

For each bin (i) and (j) of the p_{T} and η distributions, a weight is determined as a product of a p_{T}-dependent

and η-dependent weights:

$$W_{ij}(p_{\mathrm{T}}, \eta) = \frac{n_i^{\mathrm{data}}(p_{\mathrm{T}})}{n_i^{\mathrm{MC}}(p_{\mathrm{T}})} \times \frac{n_j^{\mathrm{data}}(\eta)}{n_j^{\mathrm{MC}}(\eta)}, \tag{2}$$

where $n_i^{\mathrm{data/MC}}(p_{\mathrm{T}})$ is the normalized number of entries in the p_{T} bin i and $n_j^{\mathrm{data/MC}}(\eta)$ is that in the η bin j. The set of weights $W_{ij}(p_{\mathrm{T}}, \eta)$ is extracted by comparing the histograms of *odd* events in data and MC simulation. The procedure is repeated until the weights converge, which occurs after the second iteration. The combined weights are applied to *even* MC events. The resulting distributions for χ^2/dof, L_{xy} and α for data and simulations are in good agreement.

For both modes, the dominant background originates from a J/ψ produced at the PV plus two oppositely charged hadrons (direct J/ψ) [15]. Since the hadrons are not associated with any B_s^0 (B_d^0) decay, the $J/\psi K^+K^-$ ($J/\psi K^+\pi^-$) invariant-mass distribution does not peak but yields a decreasing mass spectrum. Another large background consists of two random low-momentum, oppositely charged muons combined with two random charged hadrons. Here, neither the dimuon mass distribution peaks at the J/ψ nor does the four-particle mass show any peaking structure. Inclusive decays $B \to J/\psi X$ where X is a single hadron or a collection of hadrons provide a source of background that is very similar to the signal. If X consists of exactly two charged-particle tracks (without any π^0), the mode is topologically indistinguishable from the signal mode. Self-cross-feed in which one or both hadrons from the ϕ (K^{*0}) decay are replaced with random hadrons is negligible. In addition, peaking backgrounds from $B_d^0 \to J/\psi K^{*0}$ and $B_d^0 \to J/\psi K^+\pi^-$ contribute to $B_s^0 \to J/\psi\phi$ while $B_d^0 \to J/\psi K^+\pi^-$ contributes to $B_d^0 \to J/\psi K^{*0}$.

To reduce the contribution of these backgrounds, the selection of χ^2/dof, L_{xy}, and α, is optimized for each mode separately by determining the maximum value of the sensitivity $S/\sqrt{S+B}$ as a function of selection value of the observable to be optimized, where S represents the signal yield obtained from simulation and B is the background extracted from data sidebands. The optimization for the B_s^0 (B_d^0) mode yields χ^2/dof < 2.4 (2.6), $L_{xy} > 0.26$ (0.30) mm and $\alpha < 0.14$ (0.12) rad. In combination with the J/ψ mass requirement, the χ^2/dof selection reduces the combinatorial background significantly, while the L_{xy} and α selections remove most of the direct J/ψ background.

In the final sample, the numbers of signal events $N_{B_s^0}$ and $N_{B_d^0}$ are extracted from unbinned extended maximum-likelihood fits to the $J/\psi K^+K^-$ and $J/\psi K^+\pi^-$ invariant-mass spectra, respectively. The PDF for B_s^0 signal is modeled with three Gaussian functions with a common mean value that is left free in the fit. The widths and fractions are fixed to the values obtained from the MC simulations. To account for possible width differences in the two narrowest Gaussian functions between data and simulation, an additional scale factor is introduced, which is left free in the fit. The PDF for the peaking background is modeled with a Crystal Ball function with parameters fixed in the fit to the values obtained in simulations. The peaking background yield of 652 ± 93 events is calculated from the B_d^0 signal yield and the selection efficiencies of both peaking background modes and is fixed in the fit to data. The remaining residual backgrounds are modeled with an exponential function where its two parameters are left free.

The B_d^0 signal PDF is the same as that for the B_s^0, except that the three Gaussian functions describe both the correctly reconstructed and swapped $K^+\pi^-$ samples. The PDF of the peaking background is modeled with a sum of Crystal Ball and Gaussian functions for which the relative $B_d^0 \to J/\psi K^+\pi^-$ yield with respect to that of the $B_d^0 \to J/\psi K^{*0}$ signal is determined from the corresponding branching fractions and selection efficiencies, yielding $(4.7 \pm 2.4)\%$. Most of the residual background is modeled with an

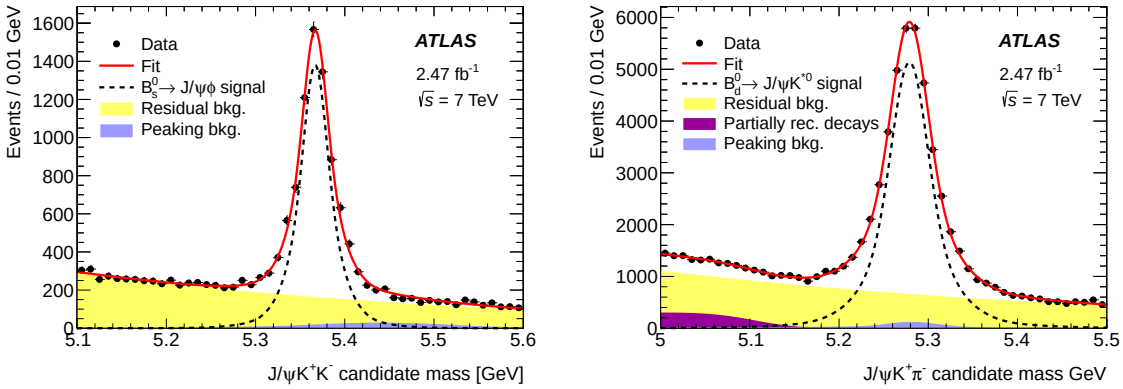

Figure 1: The invariant-mass spectra of $B_s^0 \to J/\psi\phi$ (left) and $B_d^0 \to J/\psi K^{*0}$ decays (right) for data (points with error bars), total fit (solid), signal (dashed), residual background (yellow shaded), partially reconstructed events (magenta shaded) and peaking background (blue shaded).

exponential function while partially reconstructed $B \to J/\psi X$ decays require parameterization with a complementary error function with all parameters left free for both functions.

The B_s^0 and B_d^0 yields are extracted in the mass range $5.1 < m_{B_s^0} < 5.6$ GeV and $5.0 < m_{B_d^0} < 5.5$ GeV, respectively. Figure 1 shows the measured $J/\psi\phi$ and $J/\psi K^{*0}$ invariant-mass spectra with fits overlaid. The total number of derived $B_s^0 \to J/\psi\phi$ and $B_d^0 \to J/\psi K^{*0}$ signal events from the fits are 6640 ± 100 and 36290 ± 320, respectively. The χ^2/dof of the B_s^0 (B_d^0) invariant-mass fit is 0.959 (0.945).

The additive systematic uncertainties result from the $B_s^0 \to J/\psi\phi$ and $B_d^0 \to J/\psi K^{*0}$ signal and background parameterizations. The contribution from the signal shape parameterization is calculated by varying the five fixed parameters within $\pm 1\sigma$ in a multivariate Gaussian function that takes into account all correlations. For the non-peaking backgrounds, the exponential function is replaced with a second-order polynomial for the B_s^0 while it is replaced with a second-order polynomial plus an error function for the B_d^0. The difference in signal yield with respect to the nominal fit is taken as a systematic error. For peaking backgrounds, the fixed parameters are varied by $\pm 1\sigma$ and the difference with respect to the nominal yield is taken as a systematic error. In addition, since S-wave contributions from $B_s^0 \to J/\psi K^+K^-$ and $B_s^0 \to J/\psi f_0(980)$ decays to $B_s^0 \to J/\psi\phi$ and $B_d^0 \to J/\psi K^{*0}$ are neglected in the fits, an uncertainty is derived using the ATLAS measured contribution of 2.4% [16] for $B_s^0 \to J/\psi\phi$, and the contribution of 1% for $B_d^0 \to J/\psi K^{*0}$ derived from the MC simulation. All additive systematic errors are added in quadrature, yielding total additive uncertainties of 220 $N_{B_s^0}$ and 650 $N_{B_d^0}$ events.

The multiplicative systematic uncertainty includes contributions from the relative efficiency and the branching fractions of the ϕ and K^{*0} decays. The uncertainty on the relative efficiency is dominated by the uncertainty on the ϕ/K^{*0} selection (3.5%) estimated as the difference between the nominal relative efficiency and the one where the ϕ/K^{*0} mass selection is not adjusted. Other uncertainties from the J/ψ selection (0.2%), reweighting (0.4%), B_s^0 and B_d^0 lifetimes (0.002%) and the contribution due to uncertainties in the polarization parameters (0.01%) are negligible. Table 1 summarizes the contributions of the additive and multiplicative systematic errors. Using Eq. (1) and the values listed in Table 1 yields

$$\frac{f_s}{f_d}\frac{\mathcal{B}(B_s^0 \to J/\psi\phi)}{\mathcal{B}(B_d^0 \to J/\psi K^{*0})} = 0.199 \pm 0.004(\text{stat}) \pm 0.010(\text{sys}). \quad (3)$$

Table 1: Extracted number of B_s^0 and B_d^0 mesons, relative efficiency for the two modes $\mathcal{R}_{\text{eff}}$, assumed values for the relevant ϕ and K^{*0} branching fractions, and resulting systematic uncertainties σ on $\frac{f_s}{f_d}\frac{\mathcal{B}(B_s^0\to J/\psi\phi)}{\mathcal{B}(B_d^0\to J/\psi K^{*0})}$.

Observable	Value	σ	Ref.
$N_{B_s^0}$	$6640 \pm 100 \pm 220$	3.3%	
$N_{B_d^0}$	$36290 \pm 320 \pm 650$	1.8%	
$\mathcal{R}_{\text{eff}}$	$0.799 \pm 0.001 \pm 0.028$	3.5%	
$\mathcal{B}(\phi \to K^+K^-)$	0.489 ± 0.005	1.0%	[9]
$\mathcal{B}(K^{*0} \to K^+\pi^-)$	0.66503 ± 0.00014	0.02%	[9]
Total		5.2%	

A perturbative QCD prediction [17] yields

$$\frac{\mathcal{B}(B_s^0 \to J/\psi\phi)}{\mathcal{B}(B_d^0 \to J/\psi K^{*0})} = 0.83^{+0.03}_{-0.02}(\omega_B)^{+0.01}_{-0.00}(f_M)^{+0.01}_{-0.02}(a_i)^{+0.01}_{-0.02}(m_c),$$

where the uncertainties result from the shape parameter ω_B of the B meson wave function, meson decay constants f_M, Gegenbauer moments a_i in the wave functions of the light vector mesons and the c-quark mass. Adding all contributions linearly yields a 7.1% theory error. Using this prediction, the ratio of fragmentation fractions is measured to be

$$\frac{f_s}{f_d} = 0.240 \pm 0.004(\text{stat}) \pm 0.013(\text{sys}) \pm 0.017(\text{th}). \tag{4}$$

However, f_s/f_d may depend on the p_{T} and η of the B meson, e.g. LHCb observes an f_s/f_d dependence on p_{T} but no dependence on η [18]. Figure 2 (left) shows the p_{T} dependence of f_s/f_d for ATLAS and that of other experiments. To investigate the p_{T} and η dependences of f_s/f_d, the data sample is divided into six bins in p_{T} in the range 8 GeV $< p_{\text{T}} <$ 50 GeV and four bins in η for $|\eta| < 2.5$ such that the number of events in each bin is approximately equal. The f_s/f_d distributions as a function of p_{T} and η have been fitted with a uniform (first-order polynomial) distribution yielding fit p-values 0.64 (0.74) and 0.76 (0.57), respectively. No significant f_s/f_d dependence on p_{T} and $|\eta|$ is seen at the present level of accuracy. Figure 2 (right) shows the ATLAS f_s/f_d measurement in comparison with results from LEP [19], CDF [19] and LHCb [18].

In summary, this Letter reports on the first ATLAS measurement of the quantity Eq. (3) from which the ratio of fragmentation fractions f_s/f_d is derived yielding Eq. (4). This result, which is obtained from measuring the ratio of event yields in the exclusive decays $B_s^0 \to J/\psi\phi$ and $B_d^0 \to J/\psi K^{*0}$ produced in LHC pp collisions at $\sqrt{s} = 7$ TeV for an integrated luminosity of 2.47 fb^{-1}, agrees with results from LHCb [18], CDF [20], and the LEP [19] average. The ATLAS data show no dependence on p_{T} nor on $|\eta|$ within the kinematic range tested.

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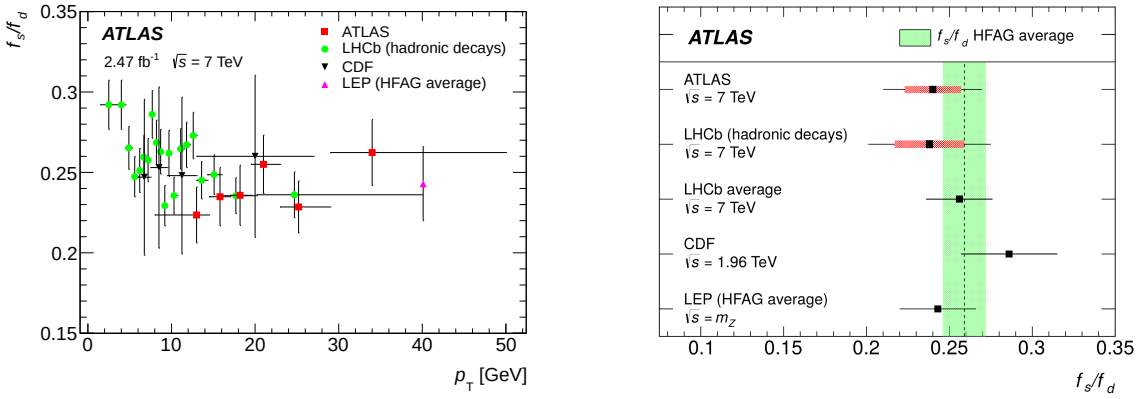

Figure 2: (Left) Measurements of f_s/f_d versus B meson p_{T} for CDF [20], LHCb [18] and ATLAS, where the ATLAS data points are plotted at the average p_{T} of the events in each bin. The error bars show statistical and systematic errors added in quadrature. The LEP ratio, taken from Ref. [19], is plotted at an approximate p_{T} in Z decays. (Right) Measurements of f_s/f_d (black and blue points with error bars) from LEP [19], CDF [19], LHCb [18] and ATLAS. The total experimental error (thin black) is added linearly to the theory error (thick red). The green-shaded region shows the HFAG average obtained using the blue points.

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G. Aad[85], B. Abbott[113], J. Abdallah[151], O. Abdinov[11], R. Aben[107], M. Abolins[90], O.S. AbouZeid[158], H. Abramowicz[153], H. Abreu[152], R. Abreu[116], Y. Abulaiti[146a,146b], B.S. Acharya[164a,164b,a], L. Adamczyk[38a], D.L. Adams[25], J. Adelman[108], S. Adomeit[100], T. Adye[131], A.A. Affolder[74], T. Agatonovic-Jovin[13], J. Agricola[54], J.A. Aguilar-Saavedra[126a,126f], S.P. Ahlen[22], F. Ahmadov[65,b], G. Aielli[133a,133b], H. Akerstedt[146a,146b], T.P.A. Åkesson[81], A.V. Akimov[96], G.L. Alberghi[20a,20b], J. Albert[169], S. Albrand[55], M.J. Alconada Verzini[71], M. Aleksa[30], I.N. Aleksandrov[65], C. Alexa[26a], G. Alexander[153], T. Alexopoulos[10], M. Alhroob[113], G. Alimonti[91a], L. Alio[85], J. Alison[31], S.P. Alkire[35], B.M.M. Allbrooke[149], P.P. Allport[74], A. Aloisio[104a,104b], A. Alonso[36], F. Alonso[71], C. Alpigiani[76], A. Altheimer[35], B. Alvarez Gonzalez[30], D. Álvarez Piqueras[167], M.G. Alviggi[104a,104b], B.T. Amadio[15], K. Amako[66], Y. Amaral Coutinho[24a], C. Amelung[23], D. Amidei[89], S.P. Amor Dos Santos[126a,126c], A. Amorim[126a,126b], S. Amoroso[48], N. Amram[153], G. Amundsen[23], C. Anastopoulos[139], L.S. Ancu[49], N. Andari[108], T. Andeen[35], C.F. Anders[58b], G. Anders[30], J.K. Anders[74], K.J. Anderson[31], A. Andreazza[91a,91b], V. Andrei[58a], S. Angelidakis[9], I. Angelozzi[107], P. Anger[44], A. Angerami[35], F. Anghinolfi[30], A.V. Anisenkov[109,c], N. Anjos[12], A. Annovi[124a,124b], M. Antonelli[47], A. Antonov[98], J. Antos[144b], F. Anulli[132a], M. Aoki[66], L. Aperio Bella[18], G. Arabidze[90], Y. Arai[66], J.P. Araque[126a], A.T.H. Arce[45], F.A. Arduh[71], J-F. Arguin[95], S. Argyropoulos[42], M. Arik[19a], A.J. Armbruster[30], O. Arnaez[30], V. Arnal[82], H. Arnold[48], M. Arratia[28], O. Arslan[21], A. Artamonov[97], G. Artoni[23], S. Asai[155], N. Asbah[42], A. Ashkenazi[153], B. Åsman[146a,146b], L. Asquith[149], K. Assamagan[25], R. Astalos[144a], M. Atkinson[165], N.B. Atlay[141], K. Augsten[128], M. Aurousseau[145b], G. Avolio[30], B. Axen[15], M.K. Ayoub[117], G. Azuelos[95,d], M.A. Baak[30], A.E. Baas[58a], M.J. Baca[18], C. Bacci[134a,134b], H. Bachacou[136], K. Bachas[154], M. Backes[30], M. Backhaus[30], P. Bagiacchi[132a,132b], P. Bagnaia[132a,132b], Y. Bai[33a], T. Bain[35], J.T. Baines[131], O.K. Baker[176], E.M. Baldin[109,c], P. Balek[129], T. Balestri[148], F. Balli[84], E. Banas[39], Sw. Banerjee[173], A.A.E. Bannoura[175], H.S. Bansil[18], L. Barak[30], E.L. Barberio[88], D. Barberis[50a,50b], M. Barbero[85], T. Barillari[101], M. Barisonzi[164a,164b], T. Barklow[143], N. Barlow[28], S.L. Barnes[84], B.M. Barnett[131], R.M. Barnett[15], Z. Barnovska[5], A. Baroncelli[134a], G. Barone[23], A.J. Barr[120], F. Barreiro[82], J. Barreiro Guimarães da Costa[57], R. Bartoldus[143], A.E. Barton[72], P. Bartos[144a], A. Basalaev[123], A. Bassalat[117], A. Basye[165], R.L. Bates[53], S.J. Batista[158], J.R. Batley[28], M. Battaglia[137], M. Bauce[132a,132b], F. Bauer[136], H.S. Bawa[143,e], J.B. Beacham[111], M.D. Beattie[72], T. Beau[80], P.H. Beauchemin[161], R. Beccherle[124a,124b], P. Bechtle[21], H.P. Beck[17,f], K. Becker[120], M. Becker[83], S. Becker[100], M. Beckingham[170], C. Becot[117], A.J. Beddall[19b], A. Beddall[19b], V.A. Bednyakov[65], C.P. Bee[148], L.J. Beemster[107], T.A. Beermann[175], M. Begel[25], J.K. Behr[120], C. Belanger-Champagne[87], W.H. Bell[49], G. Bella[153], L. Bellagamba[20a], A. Bellerive[29], M. Bellomo[86], K. Belotskiy[98], O. Beltramello[30], O. Benary[153], D. Benchekroun[135a], M. Bender[100], K. Bendtz[146a,146b], N. Benekos[10], Y. Benhammou[153], E. Benhar Noccioli[49], J.A. Benitez Garcia[159b], D.P. Benjamin[45], J.R. Bensinger[23], S. Bentvelsen[107], L. Beresford[120], M. Beretta[47], D. Berge[107], E. Bergeaas Kuutmann[166], N. Berger[5], F. Berghaus[169], J. Beringer[15], C. Bernard[22], N.R. Bernard[86], C. Bernius[110], F.U. Bernlochner[21], T. Berry[77], P. Berta[129], C. Bertella[83], G. Bertoli[146a,146b], F. Bertolucci[124a,124b], C. Bertsche[113], D. Bertsche[113], M.I. Besana[91a], G.J. Besjes[36], O. Bessidskaia Bylund[146a,146b], M. Bessner[42], N. Besson[136], C. Betancourt[48], S. Bethke[101], A.J. Bevan[76], W. Bhimji[15], R.M. Bianchi[125], L. Bianchini[23], M. Bianco[30], O. Biebel[100], D. Biedermann[16], S.P. Bieniek[78], M. Biglietti[134a], J. Bilbao De Mendizabal[49], H. Bilokon[47], M. Bindi[54], S. Binet[117], A. Bingul[19b], C. Bini[132a,132b], S. Biondi[20a,20b], C.W. Black[150], J.E. Black[143], K.M. Black[22], D. Blackburn[138], R.E. Blair[6], J.-B. Blanchard[136], J.E. Blanco[77], T. Blazek[144a], I. Bloch[42], C. Blocker[23], W. Blum[83,*], U. Blumenschein[54], G.J. Bobbink[107], V.S. Bobrovnikov[109,c], S.S. Bocchetta[81], A. Bocci[45],

C. Bock[100], M. Boehler[48], J.A. Bogaerts[30], D. Bogavac[13], A.G. Bogdanchikov[109], C. Bohm[146a], V. Boisvert[77], T. Bold[38a], V. Boldea[26a], A.S. Boldyrev[99], M. Bomben[80], M. Bona[76], M. Boonekamp[136], A. Borisov[130], G. Borissov[72], S. Borroni[42], J. Bortfeldt[100], V. Bortolotto[60a,60b,60c], K. Bos[107], D. Boscherini[20a], M. Bosman[12], J. Boudreau[125], J. Bouffard[2], E.V. Bouhova-Thacker[72], D. Boumediene[34], C. Bourdarios[117], N. Bousson[114], A. Boveia[30], J. Boyd[30], I.R. Boyko[65], I. Bozic[13], J. Bracinik[18], A. Brandt[8], G. Brandt[54], O. Brandt[58a], U. Bratzler[156], B. Brau[86], J.E. Brau[116], H.M. Braun[175,*], S.F. Brazzale[164a,164c], W.D. Breaden Madden[53], K. Brendlinger[122], A.J. Brennan[88], L. Brenner[107], R. Brenner[166], S. Bressler[172], K. Bristow[145c], T.M. Bristow[46], D. Britton[53], D. Britzger[42], F.M. Brochu[28], I. Brock[21], R. Brock[90], J. Bronner[101], G. Brooijmans[35], T. Brooks[77], W.K. Brooks[32b], J. Brosamer[15], E. Brost[116], J. Brown[55], P.A. Bruckman de Renstrom[39], D. Bruncko[144b], R. Bruneliere[48], A. Bruni[20a], G. Bruni[20a], M. Bruschi[20a], N. Bruscino[21], L. Bryngemark[81], T. Buanes[14], Q. Buat[142], P. Buchholz[141], A.G. Buckley[53], S.I. Buda[26a], I.A. Budagov[65], F. Buehrer[48], L. Bugge[119], M.K. Bugge[119], O. Bulekov[98], D. Bullock[8], H. Burckhart[30], S. Burdin[74], C.D. Burgard[48], B. Burghgrave[108], S. Burke[131], I. Burmeister[43], E. Busato[34], D. Büscher[48], V. Büscher[83], P. Bussey[53], J.M. Butler[22], A.I. Butt[3], C.M. Buttar[53], J.M. Butterworth[78], P. Butti[107], W. Buttinger[25], A. Buzatu[53], A.R. Buzykaev[109,c], S. Cabrera Urbán[167], D. Caforio[128], V.M. Cairo[37a,37b], O. Cakir[4a], N. Calace[49], P. Calafiura[15], A. Calandri[136], G. Calderini[80], P. Calfayan[100], L.P. Caloba[24a], D. Calvet[34], S. Calvet[34], R. Camacho Toro[31], S. Camarda[42], P. Camarri[133a,133b], D. Cameron[119], R. Caminal Armadans[165], S. Campana[30], M. Campanelli[78], A. Campoverde[148], V. Canale[104a,104b], A. Canepa[159a], M. Cano Bret[33e], J. Cantero[82], R. Cantrill[126a], T. Cao[40], M.D.M. Capeans Garrido[30], I. Caprini[26a], M. Caprini[26a], M. Capua[37a,37b], R. Caputo[83], R. Cardarelli[133a], F. Cardillo[48], T. Carli[30], G. Carlino[104a], L. Carminati[91a,91b], S. Caron[106], E. Carquin[32a], G.D. Carrillo-Montoya[30], J.R. Carter[28], J. Carvalho[126a,126c], D. Casadei[78], M.P. Casado[12], M. Casolino[12], E. Castaneda-Miranda[145b], A. Castelli[107], V. Castillo Gimenez[167], N.F. Castro[126a,g], P. Catastini[57], A. Catinaccio[30], J.R. Catmore[119], A. Cattai[30], J. Caudron[83], V. Cavaliere[165], D. Cavalli[91a], M. Cavalli-Sforza[12], V. Cavasinni[124a,124b], F. Ceradini[134a,134b], B.C. Cerio[45], K. Cerny[129], A.S. Cerqueira[24b], A. Cerri[149], L. Cerrito[76], F. Cerutti[15], M. Cerv[30], A. Cervelli[17], S.A. Cetin[19c], A. Chafaq[135a], D. Chakraborty[108], I. Chalupkova[129], P. Chang[165], J.D. Chapman[28], D.G. Charlton[18], C.C. Chau[158], C.A. Chavez Barajas[149], S. Cheatham[152], A. Chegwidden[90], S. Chekanov[6], S.V. Chekulaev[159a], G.A. Chelkov[65,h], M.A. Chelstowska[89], C. Chen[64], H. Chen[25], K. Chen[148], L. Chen[33d,i], S. Chen[33c], X. Chen[33f], Y. Chen[67], H.C. Cheng[89], Y. Cheng[31], A. Cheplakov[65], E. Cheremushkina[130], R. Cherkaoui El Moursli[135e], V. Chernyatin[25,*], E. Cheu[7], L. Chevalier[136], V. Chiarella[47], G. Chiarelli[124a,124b], G. Chiodini[73a], A.S. Chisholm[18], R.T. Chislett[78], A. Chitan[26a], M.V. Chizhov[65], K. Choi[61], S. Chouridou[9], B.K.B. Chow[100], V. Christodoulou[78], D. Chromek-Burckhart[30], J. Chudoba[127], A.J. Chuinard[87], J.J. Chwastowski[39], L. Chytka[115], G. Ciapetti[132a,132b], A.K. Ciftci[4a], D. Cinca[53], V. Cindro[75], I.A. Cioara[21], A. Ciocio[15], F. Cirotto[104a,104b], Z.H. Citron[172], M. Ciubancan[26a], A. Clark[49], B.L. Clark[57], P.J. Clark[46], R.N. Clarke[15], W. Cleland[125], C. Clement[146a,146b], Y. Coadou[85], M. Cobal[164a,164c], A. Coccaro[49], J. Cochran[64], L. Coffey[23], J.G. Cogan[143], L. Colasurdo[106], B. Cole[35], S. Cole[108], A.P. Colijn[107], J. Collot[55], T. Colombo[58c], G. Compostella[101], P. Conde Muiño[126a,126b], E. Coniavitis[48], S.H. Connell[145b], I.A. Connelly[77], V. Consorti[48], S. Constantinescu[26a], C. Conta[121a,121b], G. Conti[30], F. Conventi[104a,j], M. Cooke[15], B.D. Cooper[78], A.M. Cooper-Sarkar[120], T. Cornelissen[175], M. Corradi[20a], F. Corriveau[87,k], A. Corso-Radu[163], A. Cortes-Gonzalez[12], G. Cortiana[101], G. Costa[91a], M.J. Costa[167], D. Costanzo[139], D. Côté[8], G. Cottin[28], G. Cowan[77], B.E. Cox[84], K. Cranmer[110], G. Cree[29], S. Crépé-Renaudin[55], F. Crescioli[80], W.A. Cribbs[146a,146b], M. Crispin Ortuzar[120], M. Cristinziani[21], V. Croft[106], G. Crosetti[37a,37b], T. Cuhadar Donszelmann[139], J. Cummings[176], M. Curatolo[47], C. Cuthbert[150], H. Czirr[141], P. Czodrowski[3], S. D'Auria[53], M. D'Onofrio[74], M.J. Da Cunha Sargedas De Sousa[126a,126b], C. Da Via[84], W. Dabrowski[38a], A. Dafinca[120], T. Dai[89],

O. Dale[14], F. Dallaire[95], C. Dallapiccola[86], M. Dam[36], J.R. Dandoy[31], N.P. Dang[48], A.C. Daniells[18], M. Danninger[168], M. Dano Hoffmann[136], V. Dao[48], G. Darbo[50a], S. Darmora[8], J. Dassoulas[3], A. Dattagupta[61], W. Davey[21], C. David[169], T. Davidek[129], E. Davies[120,l], M. Davies[153], P. Davison[78], Y. Davygora[58a], E. Dawe[88], I. Dawson[139], R.K. Daya-Ishmukhametova[86], K. De[8], R. de Asmundis[104a], A. De Benedetti[113], S. De Castro[20a,20b], S. De Cecco[80], N. De Groot[106], P. de Jong[107], H. De la Torre[82], F. De Lorenzi[64], D. De Pedis[132a], A. De Salvo[132a], U. De Sanctis[149], A. De Santo[149], J.B. De Vivie De Regie[117], W.J. Dearnaley[72], R. Debbe[25], C. Debenedetti[137], D.V. Dedovich[65], I. Deigaard[107], J. Del Peso[82], T. Del Prete[124a,124b], D. Delgove[117], F. Deliot[136], C.M. Delitzsch[49], M. Deliyergiyev[75], A. Dell'Acqua[30], L. Dell'Asta[22], M. Dell'Orso[124a,124b], M. Della Pietra[104a,j], D. della Volpe[49], M. Delmastro[5], P.A. Delsart[55], C. Deluca[107], D.A. DeMarco[158], S. Demers[176], M. Demichev[65], A. Demilly[80], S.P. Denisov[130], D. Derendarz[39], J.E. Derkaoui[135d], F. Derue[80], P. Dervan[74], K. Desch[21], C. Deterre[42], P.O. Deviveiros[30], A. Dewhurst[131], S. Dhaliwal[23], A. Di Ciaccio[133a,133b], L. Di Ciaccio[5], A. Di Domenico[132a,132b], C. Di Donato[104a,104b], A. Di Girolamo[30], B. Di Girolamo[30], A. Di Mattia[152], B. Di Micco[134a,134b], R. Di Nardo[47], A. Di Simone[48], R. Di Sipio[158], D. Di Valentino[29], C. Diaconu[85], M. Diamond[158], F.A. Dias[46], M.A. Diaz[32a], E.B. Diehl[89], J. Dietrich[16], S. Diglio[85], A. Dimitrievska[13], J. Dingfelder[21], P. Dita[26a], S. Dita[26a], F. Dittus[30], F. Djama[85], T. Djobava[51b], J.I. Djuvsland[58a], M.A.B. do Vale[24c], D. Dobos[30], M. Dobre[26a], C. Doglioni[81], T. Dohmae[155], J. Dolejsi[129], Z. Dolezal[129], B.A. Dolgoshein[98,*], M. Donadelli[24d], S. Donati[124a,124b], P. Dondero[121a,121b], J. Donini[34], J. Dopke[131], A. Doria[104a], M.T. Dova[71], A.T. Doyle[53], E. Drechsler[54], M. Dris[10], E. Dubreuil[34], E. Duchovni[172], G. Duckeck[100], O.A. Ducu[26a,85], D. Duda[107], A. Dudarev[30], L. Duflot[117], L. Duguid[77], M. Dührssen[30], M. Dunford[58a], H. Duran Yildiz[4a], M. Düren[52], A. Durglishvili[51b], D. Duschinger[44], M. Dyndal[38a], C. Eckardt[42], K.M. Ecker[101], R.C. Edgar[89], W. Edson[2], N.C. Edwards[46], W. Ehrenfeld[21], T. Eifert[30], G. Eigen[14], K. Einsweiler[15], T. Ekelof[166], M. El Kacimi[135c], M. Ellert[166], S. Elles[5], F. Ellinghaus[175], A.A. Elliot[169], N. Ellis[30], J. Elmsheuser[100], M. Elsing[30], D. Emeliyanov[131], Y. Enari[155], O.C. Endner[83], M. Endo[118], J. Erdmann[43], A. Ereditato[17], G. Ernis[175], J. Ernst[2], M. Ernst[25], S. Errede[165], E. Ertel[83], M. Escalier[117], H. Esch[43], C. Escobar[125], B. Esposito[47], A.I. Etienvre[136], E. Etzion[153], H. Evans[61], A. Ezhilov[123], L. Fabbri[20a,20b], G. Facini[31], R.M. Fakhrutdinov[130], S. Falciano[132a], R.J. Falla[78], J. Faltova[129], Y. Fang[33a], M. Fanti[91a,91b], A. Farbin[8], A. Farilla[134a], T. Farooque[12], S. Farrell[15], S.M. Farrington[170], P. Farthouat[30], F. Fassi[135e], P. Fassnacht[30], D. Fassouliotis[9], M. Faucci Giannelli[77], A. Favareto[50a,50b], L. Fayard[117], P. Federic[144a], O.L. Fedin[123,m], W. Fedorko[168], S. Feigl[30], L. Feligioni[85], C. Feng[33d], E.J. Feng[6], H. Feng[89], A.B. Fenyuk[130], L. Feremenga[8], P. Fernandez Martinez[167], S. Fernandez Perez[30], J. Ferrando[53], A. Ferrari[166], P. Ferrari[107], R. Ferrari[121a], D.E. Ferreira de Lima[53], A. Ferrer[167], D. Ferrere[49], C. Ferretti[89], A. Ferretto Parodi[50a,50b], M. Fiascaris[31], F. Fiedler[83], A. Filipčič[75], M. Filipuzzi[42], F. Filthaut[106], M. Fincke-Keeler[169], K.D. Finelli[150], M.C.N. Fiolhais[126a,126c], L. Fiorini[167], A. Firan[40], A. Fischer[2], C. Fischer[12], J. Fischer[175], W.C. Fisher[90], E.A. Fitzgerald[23], N. Flaschel[42], I. Fleck[141], P. Fleischmann[89], S. Fleischmann[175], G.T. Fletcher[139], G. Fletcher[76], R.R.M. Fletcher[122], T. Flick[175], A. Floderus[81], L.R. Flores Castillo[60a], M.J. Flowerdew[101], A. Formica[136], A. Forti[84], D. Fournier[117], H. Fox[72], S. Fracchia[12], P. Francavilla[80], M. Franchini[20a,20b], D. Francis[30], L. Franconi[119], M. Franklin[57], M. Frate[163], M. Fraternali[121a,121b], D. Freeborn[78], S.T. French[28], F. Friedrich[44], D. Froidevaux[30], J.A. Frost[120], C. Fukunaga[156], E. Fullana Torregrosa[83], B.G. Fulsom[143], T. Fusayasu[102], J. Fuster[167], C. Gabaldon[55], O. Gabizon[175], A. Gabrielli[20a,20b], A. Gabrielli[132a,132b], G.P. Gach[38a], S. Gadatsch[30], S. Gadomski[49], G. Gagliardi[50a,50b], P. Gagnon[61], C. Galea[106], B. Galhardo[126a,126c], E.J. Gallas[120], B.J. Gallop[131], P. Gallus[128], G. Galster[36], K.K. Gan[111], J. Gao[33b,85], Y. Gao[46], Y.S. Gao[143,e], F.M. Garay Walls[46], F. 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J. Van Nieuwkoop[142], I. van Vulpen[107], M.C. van Woerden[30], M. Vanadia[132a,132b], W. Vandelli[30], R. Vanguri[122], A. Vaniachine[6], F. Vannucci[80], G. Vardanyan[177], R. Vari[132a], E.W. Varnes[7], T. Varol[40], D. Varouchas[80], A. Vartapetian[8], K.E. Varvell[150], F. Vazeille[34], T. Vazquez Schroeder[87], J. Veatch[7], L.M. Veloce[158], F. Veloso[126a,126c], T. Velz[21], S. Veneziano[132a], A. Ventura[73a,73b], D. Ventura[86], M. Venturi[169], N. Venturi[158], A. Venturini[23], V. Vercesi[121a], M. Verducci[132a,132b], W. Verkerke[107], J.C. Vermeulen[107], A. Vest[44], M.C. Vetterli[142,d], O. Viazlo[81], I. Vichou[165], T. Vickey[139], O.E. Vickey Boeriu[139], G.H.A. Viehhauser[120], S. Viel[15], R. Vigne[62], M. Villa[20a,20b], M. Villaplana Perez[91a,91b], E. Vilucchi[47], M.G. Vincter[29], V.B. Vinogradov[65], I. Vivarelli[149], F. Vives Vaque[3], S. Vlachos[10], D. Vladoiu[100], M. Vlasak[128], M. Vogel[32a], P. Vokac[128], G. Volpi[124a,124b], M. Volpi[88], H. von der Schmitt[101], H. von Radziewski[48], E. von Toerne[21], V. Vorobel[129], K. Vorobev[98], M. Vos[167], R. Voss[30], J.H. Vossebeld[74], N. Vranjes[13], M. Vranjes Milosavljevic[13], V. Vrba[127], M. Vreeswijk[107], R. Vuillermet[30], I. Vukotic[31], Z. Vykydal[128], P. Wagner[21], W. Wagner[175], H. Wahlberg[71], S. Wahrmund[44], J. Wakabayashi[103], J. Walder[72], R. Walker[100], W. Walkowiak[141], C. Wang[151], F. Wang[173], H. Wang[15], H. Wang[40], J. Wang[42], J. Wang[33a], K. Wang[87], R. Wang[6], S.M. Wang[151], T. Wang[21], T. Wang[35], X. Wang[176], C. Wanotayaroj[116], A. Warburton[87], C.P. Ward[28], D.R. Wardrope[78], A. Washbrook[46], C. Wasicki[42], P.M. Watkins[18], A.T. Watson[18], I.J. Watson[150], M.F. Watson[18], G. Watts[138], S. Watts[84], B.M. Waugh[78], S. Webb[84], M.S. Weber[17], S.W. Weber[174], J.S. Webster[31], A.R. Weidberg[120], B. Weinert[61], J. Weingarten[54], C. Weiser[48], H. Weits[107], P.S. Wells[30], T. Wenaus[25], T. Wengler[30], S. Wenig[30], N. Wermes[21], M. Werner[48], P. Werner[30], M. Wessels[58a], J. Wetter[161], K. Whalen[116], A.M. Wharton[72], A. White[8], M.J. White[1], R. White[32b], S. White[124a,124b], D. Whiteson[163], F.J. Wickens[131], W. Wiedenmann[173], M. Wielers[131], P. Wienemann[21], C. Wiglesworth[36], L.A.M. Wiik-Fuchs[21], A. Wildauer[101], H.G. Wilkens[30], H.H. Williams[122], S. Williams[107], C. Willis[90], S. Willocq[86], A. Wilson[89], J.A. Wilson[18], I. Wingerter-Seez[5], F. Winklmeier[116], B.T. Winter[21], M. Wittgen[143], J. Wittkowski[100], S.J. Wollstadt[83], M.W. Wolter[39], H. Wolters[126a,126c], B.K. Wosiek[39], J. Wotschack[30], M.J. Woudstra[84], K.W. Wozniak[39], M. Wu[55], M. Wu[31], S.L. Wu[173], X. Wu[49], Y. Wu[89], T.R. Wyatt[84], B.M. Wynne[46], S. Xella[36], D. Xu[33a], L. Xu[25], B. Yabsley[150], S. Yacoob[145a], R. Yakabe[67], M. Yamada[66], D. Yamaguchi[157], Y. Yamaguchi[118], A. Yamamoto[66], S. Yamamoto[155], T. Yamanaka[155], K. Yamauchi[103], Y. Yamazaki[67], Z. Yan[22], H. Yang[33e], H. Yang[173], Y. Yang[151], W-M. Yao[15], Y. Yasu[66], E. Yatsenko[5], K.H. Yau Wong[21], J. Ye[40], S. Ye[25], I. Yeletskikh[65], A.L. Yen[57], E. Yildirim[42], K. Yorita[171], R. Yoshida[6], K. Yoshihara[122], C. Young[143], C.J.S. Young[30], S. Youssef[22], D.R. Yu[15], J. Yu[8], J.M. Yu[89], J. Yu[114], L. Yuan[67], S.P.Y. Yuen[21], A. Yurkewicz[108], I. Yusuff[28,ak], B. Zabinski[39], R. Zaidan[63], A.M. Zaitsev[130,ab], J. Zalieckas[14], A. Zaman[148], S. Zambito[57], L. Zanello[132a,132b], D. Zanzi[88], C. Zeitnitz[175], M. Zeman[128], A. Zemla[38a], Q. Zeng[143], K. Zengel[23], O. Zenin[130], T. Ženiš[144a], D. Zerwas[117], D. Zhang[89], F. Zhang[173], H. Zhang[33c], J. Zhang[6], L. Zhang[48], R. Zhang[33b], X. Zhang[33d], Z. Zhang[117], X. Zhao[40], Y. Zhao[33d,117], Z. Zhao[33b], A. Zhemchugov[65], J. Zhong[120], B. Zhou[89], C. Zhou[45], L. Zhou[35], L. Zhou[40], N. Zhou[33f], C.G. Zhu[33d], H. Zhu[33a], J. Zhu[89], Y. Zhu[33b], X. Zhuang[33a], K. Zhukov[96], A. Zibell[174], D. Zieminska[61], N.I. Zimine[65], C. Zimmermann[83], S. Zimmermann[48], Z. Zinonos[54], M. Zinser[83], M. Ziolkowski[141], L. Živković[13], G. Zobernig[173], A. Zoccoli[20a,20b], M. zur Nedden[16], G. Zurzolo[104a,104b], L. Zwalinski[30].

[1] Department of Physics, University of Adelaide, Adelaide, Australia
[2] Physics Department, SUNY Albany, Albany NY, United States of America
[3] Department of Physics, University of Alberta, Edmonton AB, Canada
[4] [(a)] Department of Physics, Ankara University, Ankara; [(b)] Istanbul Aydin University, Istanbul; [(c)] Division of Physics, TOBB University of Economics and Technology, Ankara, Turkey
[5] LAPP, CNRS/IN2P3 and Université Savoie Mont Blanc, Annecy-le-Vieux, France
[6] High Energy Physics Division, Argonne National Laboratory, Argonne IL, United States of America

[7] Department of Physics, University of Arizona, Tucson AZ, United States of America
[8] Department of Physics, The University of Texas at Arlington, Arlington TX, United States of America
[9] Physics Department, University of Athens, Athens, Greece
[10] Physics Department, National Technical University of Athens, Zografou, Greece
[11] Institute of Physics, Azerbaijan Academy of Sciences, Baku, Azerbaijan
[12] Institut de Física d'Altes Energies and Departament de Física de la Universitat Autònoma de Barcelona, Barcelona, Spain
[13] Institute of Physics, University of Belgrade, Belgrade, Serbia
[14] Department for Physics and Technology, University of Bergen, Bergen, Norway
[15] Physics Division, Lawrence Berkeley National Laboratory and University of California, Berkeley CA, United States of America
[16] Department of Physics, Humboldt University, Berlin, Germany
[17] Albert Einstein Center for Fundamental Physics and Laboratory for High Energy Physics, University of Bern, Bern, Switzerland
[18] School of Physics and Astronomy, University of Birmingham, Birmingham, United Kingdom
[19] [(a)] Department of Physics, Bogazici University, Istanbul; [(b)] Department of Physics Engineering, Gaziantep University, Gaziantep; [(c)] Department of Physics, Dogus University, Istanbul, Turkey
[20] [(a)] INFN Sezione di Bologna; [(b)] Dipartimento di Fisica e Astronomia, Università di Bologna, Bologna, Italy
[21] Physikalisches Institut, University of Bonn, Bonn, Germany
[22] Department of Physics, Boston University, Boston MA, United States of America
[23] Department of Physics, Brandeis University, Waltham MA, United States of America
[24] [(a)] Universidade Federal do Rio De Janeiro COPPE/EE/IF, Rio de Janeiro; [(b)] Electrical Circuits Department, Federal University of Juiz de Fora (UFJF), Juiz de Fora; [(c)] Federal University of Sao Joao del Rei (UFSJ), Sao Joao del Rei; [(d)] Instituto de Fisica, Universidade de Sao Paulo, Sao Paulo, Brazil
[25] Physics Department, Brookhaven National Laboratory, Upton NY, United States of America
[26] [(a)] National Institute of Physics and Nuclear Engineering, Bucharest; [(b)] National Institute for Research and Development of Isotopic and Molecular Technologies, Physics Department, Cluj Napoca; [(c)] University Politehnica Bucharest, Bucharest; [(d)] West University in Timisoara, Timisoara, Romania
[27] Departamento de Física, Universidad de Buenos Aires, Buenos Aires, Argentina
[28] Cavendish Laboratory, University of Cambridge, Cambridge, United Kingdom
[29] Department of Physics, Carleton University, Ottawa ON, Canada
[30] CERN, Geneva, Switzerland
[31] Enrico Fermi Institute, University of Chicago, Chicago IL, United States of America
[32] [(a)] Departamento de Física, Pontificia Universidad Católica de Chile, Santiago; [(b)] Departamento de Física, Universidad Técnica Federico Santa María, Valparaíso, Chile
[33] [(a)] Institute of High Energy Physics, Chinese Academy of Sciences, Beijing; [(b)] Department of Modern Physics, University of Science and Technology of China, Anhui; [(c)] Department of Physics, Nanjing University, Jiangsu; [(d)] School of Physics, Shandong University, Shandong; [(e)] Department of Physics and Astronomy, Shanghai Key Laboratory for Particle Physics and Cosmology, Shanghai Jiao Tong University, Shanghai; [(f)] Physics Department, Tsinghua University, Beijing 100084, China
[34] Laboratoire de Physique Corpusculaire, Clermont Université and Université Blaise Pascal and CNRS/IN2P3, Clermont-Ferrand, France
[35] Nevis Laboratory, Columbia University, Irvington NY, United States of America
[36] Niels Bohr Institute, University of Copenhagen, Kobenhavn, Denmark
[37] [(a)] INFN Gruppo Collegato di Cosenza, Laboratori Nazionali di Frascati; [(b)] Dipartimento di Fisica, Università della Calabria, Rende, Italy

[38] [(a)] AGH University of Science and Technology, Faculty of Physics and Applied Computer Science, Krakow; [(b)] Marian Smoluchowski Institute of Physics, Jagiellonian University, Krakow, Poland
[39] Institute of Nuclear Physics Polish Academy of Sciences, Krakow, Poland
[40] Physics Department, Southern Methodist University, Dallas TX, United States of America
[41] Physics Department, University of Texas at Dallas, Richardson TX, United States of America
[42] DESY, Hamburg and Zeuthen, Germany
[43] Institut für Experimentelle Physik IV, Technische Universität Dortmund, Dortmund, Germany
[44] Institut für Kern- und Teilchenphysik, Technische Universität Dresden, Dresden, Germany
[45] Department of Physics, Duke University, Durham NC, United States of America
[46] SUPA - School of Physics and Astronomy, University of Edinburgh, Edinburgh, United Kingdom
[47] INFN Laboratori Nazionali di Frascati, Frascati, Italy
[48] Fakultät für Mathematik und Physik, Albert-Ludwigs-Universität, Freiburg, Germany
[49] Section de Physique, Université de Genève, Geneva, Switzerland
[50] [(a)] INFN Sezione di Genova; [(b)] Dipartimento di Fisica, Università di Genova, Genova, Italy
[51] [(a)] E. Andronikashvili Institute of Physics, Iv. Javakhishvili Tbilisi State University, Tbilisi; [(b)] High Energy Physics Institute, Tbilisi State University, Tbilisi, Georgia
[52] II Physikalisches Institut, Justus-Liebig-Universität Giessen, Giessen, Germany
[53] SUPA - School of Physics and Astronomy, University of Glasgow, Glasgow, United Kingdom
[54] II Physikalisches Institut, Georg-August-Universität, Göttingen, Germany
[55] Laboratoire de Physique Subatomique et de Cosmologie, Université Grenoble-Alpes, CNRS/IN2P3, Grenoble, France
[56] Department of Physics, Hampton University, Hampton VA, United States of America
[57] Laboratory for Particle Physics and Cosmology, Harvard University, Cambridge MA, United States of America
[58] [(a)] Kirchhoff-Institut für Physik, Ruprecht-Karls-Universität Heidelberg, Heidelberg; [(b)] Physikalisches Institut, Ruprecht-Karls-Universität Heidelberg, Heidelberg; [(c)] ZITI Institut für technische Informatik, Ruprecht-Karls-Universität Heidelberg, Mannheim, Germany
[59] Faculty of Applied Information Science, Hiroshima Institute of Technology, Hiroshima, Japan
[60] [(a)] Department of Physics, The Chinese University of Hong Kong, Shatin, N.T., Hong Kong; [(b)] Department of Physics, The University of Hong Kong, Hong Kong; [(c)] Department of Physics, The Hong Kong University of Science and Technology, Clear Water Bay, Kowloon, Hong Kong, China
[61] Department of Physics, Indiana University, Bloomington IN, United States of America
[62] Institut für Astro- und Teilchenphysik, Leopold-Franzens-Universität, Innsbruck, Austria
[63] University of Iowa, Iowa City IA, United States of America
[64] Department of Physics and Astronomy, Iowa State University, Ames IA, United States of America
[65] Joint Institute for Nuclear Research, JINR Dubna, Dubna, Russia
[66] KEK, High Energy Accelerator Research Organization, Tsukuba, Japan
[67] Graduate School of Science, Kobe University, Kobe, Japan
[68] Faculty of Science, Kyoto University, Kyoto, Japan
[69] Kyoto University of Education, Kyoto, Japan
[70] Department of Physics, Kyushu University, Fukuoka, Japan
[71] Instituto de Física La Plata, Universidad Nacional de La Plata and CONICET, La Plata, Argentina
[72] Physics Department, Lancaster University, Lancaster, United Kingdom
[73] [(a)] INFN Sezione di Lecce; [(b)] Dipartimento di Matematica e Fisica, Università del Salento, Lecce, Italy
[74] Oliver Lodge Laboratory, University of Liverpool, Liverpool, United Kingdom
[75] Department of Physics, Jožef Stefan Institute and University of Ljubljana, Ljubljana, Slovenia

[76] School of Physics and Astronomy, Queen Mary University of London, London, United Kingdom
[77] Department of Physics, Royal Holloway University of London, Surrey, United Kingdom
[78] Department of Physics and Astronomy, University College London, London, United Kingdom
[79] Louisiana Tech University, Ruston LA, United States of America
[80] Laboratoire de Physique Nucléaire et de Hautes Energies, UPMC and Université Paris-Diderot and CNRS/IN2P3, Paris, France
[81] Fysiska institutionen, Lunds universitet, Lund, Sweden
[82] Departamento de Fisica Teorica C-15, Universidad Autonoma de Madrid, Madrid, Spain
[83] Institut für Physik, Universität Mainz, Mainz, Germany
[84] School of Physics and Astronomy, University of Manchester, Manchester, United Kingdom
[85] CPPM, Aix-Marseille Université and CNRS/IN2P3, Marseille, France
[86] Department of Physics, University of Massachusetts, Amherst MA, United States of America
[87] Department of Physics, McGill University, Montreal QC, Canada
[88] School of Physics, University of Melbourne, Victoria, Australia
[89] Department of Physics, The University of Michigan, Ann Arbor MI, United States of America
[90] Department of Physics and Astronomy, Michigan State University, East Lansing MI, United States of America
[91] [(a)] INFN Sezione di Milano; [(b)] Dipartimento di Fisica, Università di Milano, Milano, Italy
[92] B.I. Stepanov Institute of Physics, National Academy of Sciences of Belarus, Minsk, Republic of Belarus
[93] National Scientific and Educational Centre for Particle and High Energy Physics, Minsk, Republic of Belarus
[94] Department of Physics, Massachusetts Institute of Technology, Cambridge MA, United States of America
[95] Group of Particle Physics, University of Montreal, Montreal QC, Canada
[96] P.N. Lebedev Institute of Physics, Academy of Sciences, Moscow, Russia
[97] Institute for Theoretical and Experimental Physics (ITEP), Moscow, Russia
[98] National Research Nuclear University MEPhI, Moscow, Russia
[99] D.V. Skobeltsyn Institute of Nuclear Physics, M.V. Lomonosov Moscow State University, Moscow, Russia
[100] Fakultät für Physik, Ludwig-Maximilians-Universität München, München, Germany
[101] Max-Planck-Institut für Physik (Werner-Heisenberg-Institut), München, Germany
[102] Nagasaki Institute of Applied Science, Nagasaki, Japan
[103] Graduate School of Science and Kobayashi-Maskawa Institute, Nagoya University, Nagoya, Japan
[104] [(a)] INFN Sezione di Napoli; [(b)] Dipartimento di Fisica, Università di Napoli, Napoli, Italy
[105] Department of Physics and Astronomy, University of New Mexico, Albuquerque NM, United States of America
[106] Institute for Mathematics, Astrophysics and Particle Physics, Radboud University Nijmegen/Nikhef, Nijmegen, Netherlands
[107] Nikhef National Institute for Subatomic Physics and University of Amsterdam, Amsterdam, Netherlands
[108] Department of Physics, Northern Illinois University, DeKalb IL, United States of America
[109] Budker Institute of Nuclear Physics, SB RAS, Novosibirsk, Russia
[110] Department of Physics, New York University, New York NY, United States of America
[111] Ohio State University, Columbus OH, United States of America
[112] Faculty of Science, Okayama University, Okayama, Japan
[113] Homer L. Dodge Department of Physics and Astronomy, University of Oklahoma, Norman OK,

United States of America
[114] Department of Physics, Oklahoma State University, Stillwater OK, United States of America
[115] Palacký University, RCPTM, Olomouc, Czech Republic
[116] Center for High Energy Physics, University of Oregon, Eugene OR, United States of America
[117] LAL, Université Paris-Sud and CNRS/IN2P3, Orsay, France
[118] Graduate School of Science, Osaka University, Osaka, Japan
[119] Department of Physics, University of Oslo, Oslo, Norway
[120] Department of Physics, Oxford University, Oxford, United Kingdom
[121] [(a)] INFN Sezione di Pavia; [(b)] Dipartimento di Fisica, Università di Pavia, Pavia, Italy
[122] Department of Physics, University of Pennsylvania, Philadelphia PA, United States of America
[123] National Research Centre "Kurchatov Institute" B.P.Konstantinov Petersburg Nuclear Physics Institute, St. Petersburg, Russia
[124] [(a)] INFN Sezione di Pisa; [(b)] Dipartimento di Fisica E. Fermi, Università di Pisa, Pisa, Italy
[125] Department of Physics and Astronomy, University of Pittsburgh, Pittsburgh PA, United States of America
[126] [(a)] Laboratório de Instrumentação e Física Experimental de Partículas - LIP, Lisboa; [(b)] Faculdade de Ciências, Universidade de Lisboa, Lisboa; [(c)] Department of Physics, University of Coimbra, Coimbra; [(d)] Centro de Física Nuclear da Universidade de Lisboa, Lisboa; [(e)] Departamento de Fisica, Universidade do Minho, Braga; [(f)] Departamento de Fisica Teorica y del Cosmos and CAFPE, Universidad de Granada, Granada (Spain); [(g)] Dep Fisica and CEFITEC of Faculdade de Ciencias e Tecnologia, Universidade Nova de Lisboa, Caparica, Portugal
[127] Institute of Physics, Academy of Sciences of the Czech Republic, Praha, Czech Republic
[128] Czech Technical University in Prague, Praha, Czech Republic
[129] Faculty of Mathematics and Physics, Charles University in Prague, Praha, Czech Republic
[130] State Research Center Institute for High Energy Physics, Protvino, Russia
[131] Particle Physics Department, Rutherford Appleton Laboratory, Didcot, United Kingdom
[132] [(a)] INFN Sezione di Roma; [(b)] Dipartimento di Fisica, Sapienza Università di Roma, Roma, Italy
[133] [(a)] INFN Sezione di Roma Tor Vergata; [(b)] Dipartimento di Fisica, Università di Roma Tor Vergata, Roma, Italy
[134] [(a)] INFN Sezione di Roma Tre; [(b)] Dipartimento di Matematica e Fisica, Università Roma Tre, Roma, Italy
[135] [(a)] Faculté des Sciences Ain Chock, Réseau Universitaire de Physique des Hautes Energies - Université Hassan II, Casablanca; [(b)] Centre National de l'Energie des Sciences Techniques Nucleaires, Rabat; [(c)] Faculté des Sciences Semlalia, Université Cadi Ayyad, LPHEA-Marrakech; [(d)] Faculté des Sciences, Université Mohamed Premier and LPTPM, Oujda; [(e)] Faculté des sciences, Université Mohammed V-Agdal, Rabat, Morocco
[136] DSM/IRFU (Institut de Recherches sur les Lois Fondamentales de l'Univers), CEA Saclay (Commissariat à l'Energie Atomique et aux Energies Alternatives), Gif-sur-Yvette, France
[137] Santa Cruz Institute for Particle Physics, University of California Santa Cruz, Santa Cruz CA, United States of America
[138] Department of Physics, University of Washington, Seattle WA, United States of America
[139] Department of Physics and Astronomy, University of Sheffield, Sheffield, United Kingdom
[140] Department of Physics, Shinshu University, Nagano, Japan
[141] Fachbereich Physik, Universität Siegen, Siegen, Germany
[142] Department of Physics, Simon Fraser University, Burnaby BC, Canada
[143] SLAC National Accelerator Laboratory, Stanford CA, United States of America
[144] [(a)] Faculty of Mathematics, Physics & Informatics, Comenius University, Bratislava; [(b)] Department

of Subnuclear Physics, Institute of Experimental Physics of the Slovak Academy of Sciences, Kosice, Slovak Republic
[145] [(a)] Department of Physics, University of Cape Town, Cape Town; [(b)] Department of Physics, University of Johannesburg, Johannesburg; [(c)] School of Physics, University of the Witwatersrand, Johannesburg, South Africa
[146] [(a)] Department of Physics, Stockholm University; [(b)] The Oskar Klein Centre, Stockholm, Sweden
[147] Physics Department, Royal Institute of Technology, Stockholm, Sweden
[148] Departments of Physics & Astronomy and Chemistry, Stony Brook University, Stony Brook NY, United States of America
[149] Department of Physics and Astronomy, University of Sussex, Brighton, United Kingdom
[150] School of Physics, University of Sydney, Sydney, Australia
[151] Institute of Physics, Academia Sinica, Taipei, Taiwan
[152] Department of Physics, Technion: Israel Institute of Technology, Haifa, Israel
[153] Raymond and Beverly Sackler School of Physics and Astronomy, Tel Aviv University, Tel Aviv, Israel
[154] Department of Physics, Aristotle University of Thessaloniki, Thessaloniki, Greece
[155] International Center for Elementary Particle Physics and Department of Physics, The University of Tokyo, Tokyo, Japan
[156] Graduate School of Science and Technology, Tokyo Metropolitan University, Tokyo, Japan
[157] Department of Physics, Tokyo Institute of Technology, Tokyo, Japan
[158] Department of Physics, University of Toronto, Toronto ON, Canada
[159] [(a)] TRIUMF, Vancouver BC; [(b)] Department of Physics and Astronomy, York University, Toronto ON, Canada
[160] Faculty of Pure and Applied Sciences, University of Tsukuba, Tsukuba, Japan
[161] Department of Physics and Astronomy, Tufts University, Medford MA, United States of America
[162] Centro de Investigaciones, Universidad Antonio Narino, Bogota, Colombia
[163] Department of Physics and Astronomy, University of California Irvine, Irvine CA, United States of America
[164] [(a)] INFN Gruppo Collegato di Udine, Sezione di Trieste, Udine; [(b)] ICTP, Trieste; [(c)] Dipartimento di Chimica, Fisica e Ambiente, Università di Udine, Udine, Italy
[165] Department of Physics, University of Illinois, Urbana IL, United States of America
[166] Department of Physics and Astronomy, University of Uppsala, Uppsala, Sweden
[167] Instituto de Física Corpuscular (IFIC) and Departamento de Física Atómica, Molecular y Nuclear and Departamento de Ingeniería Electrónica and Instituto de Microelectrónica de Barcelona (IMB-CNM), University of Valencia and CSIC, Valencia, Spain
[168] Department of Physics, University of British Columbia, Vancouver BC, Canada
[169] Department of Physics and Astronomy, University of Victoria, Victoria BC, Canada
[170] Department of Physics, University of Warwick, Coventry, United Kingdom
[171] Waseda University, Tokyo, Japan
[172] Department of Particle Physics, The Weizmann Institute of Science, Rehovot, Israel
[173] Department of Physics, University of Wisconsin, Madison WI, United States of America
[174] Fakultät für Physik und Astronomie, Julius-Maximilians-Universität, Würzburg, Germany
[175] Fachbereich C Physik, Bergische Universität Wuppertal, Wuppertal, Germany
[176] Department of Physics, Yale University, New Haven CT, United States of America
[177] Yerevan Physics Institute, Yerevan, Armenia
[178] Centre de Calcul de l'Institut National de Physique Nucléaire et de Physique des Particules (IN2P3), Villeurbanne, France

[a] Also at Department of Physics, King's College London, London, United Kingdom
[b] Also at Institute of Physics, Azerbaijan Academy of Sciences, Baku, Azerbaijan
[c] Also at Novosibirsk State University, Novosibirsk, Russia
[d] Also at TRIUMF, Vancouver BC, Canada
[e] Also at Department of Physics, California State University, Fresno CA, United States of America
[f] Also at Department of Physics, University of Fribourg, Fribourg, Switzerland
[g] Also at Departamento de Fisica e Astronomia, Faculdade de Ciencias, Universidade do Porto, Portugal
[h] Also at Tomsk State University, Tomsk, Russia
[i] Also at CPPM, Aix-Marseille Université and CNRS/IN2P3, Marseille, France
[j] Also at Universita di Napoli Parthenope, Napoli, Italy
[k] Also at Institute of Particle Physics (IPP), Canada
[l] Also at Particle Physics Department, Rutherford Appleton Laboratory, Didcot, United Kingdom
[m] Also at Department of Physics, St. Petersburg State Polytechnical University, St. Petersburg, Russia
[n] Also at Louisiana Tech University, Ruston LA, United States of America
[o] Also at Institucio Catalana de Recerca i Estudis Avancats, ICREA, Barcelona, Spain
[p] Also at Graduate School of Science, Osaka University, Osaka, Japan
[q] Also at Department of Physics, National Tsing Hua University, Taiwan
[r] Also at Department of Physics, The University of Texas at Austin, Austin TX, United States of America
[s] Also at Institute of Theoretical Physics, Ilia State University, Tbilisi, Georgia
[t] Also at CERN, Geneva, Switzerland
[u] Also at Georgian Technical University (GTU),Tbilisi, Georgia
[v] Also at Manhattan College, New York NY, United States of America
[w] Also at Hellenic Open University, Patras, Greece
[x] Also at Institute of Physics, Academia Sinica, Taipei, Taiwan
[y] Also at LAL, Université Paris-Sud and CNRS/IN2P3, Orsay, France
[z] Also at Academia Sinica Grid Computing, Institute of Physics, Academia Sinica, Taipei, Taiwan
[aa] Also at School of Physics, Shandong University, Shandong, China
[ab] Also at Moscow Institute of Physics and Technology State University, Dolgoprudny, Russia
[ac] Also at Section de Physique, Université de Genève, Geneva, Switzerland
[ad] Also at International School for Advanced Studies (SISSA), Trieste, Italy
[ae] Also at Department of Physics and Astronomy, University of South Carolina, Columbia SC, United States of America
[af] Also at School of Physics and Engineering, Sun Yat-sen University, Guangzhou, China
[ag] Also at Faculty of Physics, M.V.Lomonosov Moscow State University, Moscow, Russia
[ah] Also at National Research Nuclear University MEPhI, Moscow, Russia
[ai] Also at Department of Physics, Stanford University, Stanford CA, United States of America
[aj] Also at Institute for Particle and Nuclear Physics, Wigner Research Centre for Physics, Budapest, Hungary
[ak] Also at University of Malaya, Department of Physics, Kuala Lumpur, Malaysia
[*] Deceased