


## Elliptic Flow of Charm and Strange Hadrons in High-Multiplicity $p + \text{Pb}$ Collisions at $\sqrt{s_{\text{NN}}} = 8.16$ TeV

A. M. Sirunyan *et al.*\*  
(CMS Collaboration)

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The elliptic azimuthal anisotropy coefficient ( $v_2$ ) is measured for charm ( $D^0$ ) and strange ( $K_S^0$ ,  $\Lambda$ ,  $\Xi^-$ , and  $\Omega^-$ ) hadrons, using a data sample of  $p + \text{Pb}$  collisions collected by the CMS experiment, at a nucleon-nucleon center-of-mass energy of  $\sqrt{s_{\text{NN}}} = 8.16$  TeV. A significant positive  $v_2$  signal from long-range azimuthal correlations is observed for all particle species in high-multiplicity  $p + \text{Pb}$  collisions. The measurement represents the first observation of possible long-range collectivity for open heavy flavor hadrons in small systems. The results suggest that charm quarks have a smaller  $v_2$  than the lighter quarks, probably reflecting a weaker collective behavior. This effect is not seen in the larger PbPb collision system at  $\sqrt{s_{\text{NN}}} = 5.02$  TeV, also presented.

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There has been long-standing interest in the space-time evolution of the multiparticle production process in high energy collisions of hadrons [1]. The observation of strong collective flow, as inferred from the correlations in azimuthal angle ( $\phi$ ) of particles emitted over a wide pseudorapidity ( $\eta$ ) range in relativistic nucleus-nucleus (AA) collisions, has been one of the key signatures suggesting the formation of a strongly interacting quark-gluon plasma (QGP) between the initial impact of the colliding nuclei and final production of particles. As observed first at the Brookhaven National Laboratory (BNL) Relativistic Heavy Ion Collider (RHIC) [2,2–5] and later at the CERN Large Hadron Collider (LHC) [6–11], the QGP exhibits nearly ideal hydrodynamical behavior [12–14]. In recent years, the observation of similar correlations in events with high final-state particle multiplicity resulting from proton-proton ( $pp$ ) [15–17] and proton-lead ( $p + \text{Pb}$ ) [18–21] collisions at the LHC has raised the question whether a fluidlike QGP is also created in these smaller collision systems [22].

The azimuthal correlation structure of emitted particles is typically characterized by its Fourier components [23]. In hydrodynamic models, the second and third Fourier components, known as elliptic ( $v_2$ ) and triangular ( $v_3$ ) flow, respectively, most directly reflect the QGP response to the initial collision geometry and its fluctuations [24–26]. The properties of the long-range correlation associated with light-flavor and strange hadrons in small systems are found

to be similar to those observed in AA collisions. This includes, e.g., the particle species dependence [27–29] and multiparticle (or collective) nature [29–32] of the long-range correlation. More recently, such long-range correlations have also been observed in lighter systems at RHIC, including  $d\text{Au}$  [33–35] and  $^3\text{HeAu}$  [36]. While these measurements are consistent with a hydrodynamic expansion, alternative scenarios based on gluon saturation in the initial state also claim to capture the main features of the correlation data (recent reviews are provided in Refs. [37,38]).

The large masses of heavy quarks (charm and bottom) lead to their being produced in the early stages of the collision, and they thus probe the properties of the QGP through their interactions with the medium [39]. The elliptic flow results for  $D$  mesons in AA collisions measured at RHIC [40] and the LHC [41–43] suggest that charm quarks develop strong collective behavior, similar to the bulk production of light flavor particles from the QGP. In small systems, long-range correlation involving inclusive muons and  $J/\psi$  mesons have revealed hints of heavy flavor quark collectivity [44,45]. Observation of  $D$  meson  $v_2$  in the  $p + \text{Pb}$  system, and especially the comparison to the light-flavor and strange particle  $v_2$ , can impose further constraints on different interpretations related to the origin of the observed long-range collectivity. In particular, such measurements can provide key insights into properties of heavy quark interaction and thermalization within a hot QGP medium possibly formed at a significantly reduced system size.

This Letter presents the first measurements of the elliptic anisotropies of prompt  $D^0$  mesons and strange hadrons ( $K_S^0$ ,  $\Lambda$ ,  $\Xi^-$ , and  $\Omega^-$ ) in  $p + \text{Pb}$  collisions at a nucleon-nucleon center-of-mass energy of  $\sqrt{s_{\text{NN}}} = 8.16$  TeV. In all cases, particles and antiparticles are combined in the

\*Full author list given at the end of the Letter.

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measurements. The  $v_2$  harmonic of all particle species in high-multiplicity  $p + \text{Pb}$  events is determined in different intervals of transverse momentum ( $p_T$ ), via long-range two-particle correlations with charged particles. The  $v_2$  harmonics for the same strange hadrons are also measured in PbPb collisions at  $\sqrt{s_{\text{NN}}} = 5.02$  TeV for 30%–50% centrality (defined as the fraction of the total inelastic cross section, with 0% denoting the most central collisions), to compare with the previously published  $D^0$   $v_2$  results from these same collisions [43].

The central feature of the CMS apparatus is a superconducting solenoid of 6 m internal diameter, providing a magnetic field of 3.8 T. Within the solenoid volume, there are four primary subdetectors including a silicon pixel and strip tracker detector, a lead tungstate crystal electromagnetic calorimeter, and a brass and scintillator hadron calorimeter, each composed of a barrel and two endcap sections. Iron and quartz-fiber Cherenkov hadron forward calorimeters cover the range  $2.9 < |\eta| < 5.2$ . Muons are measured in gas-ionization detectors embedded in the steel flux-return yoke outside the solenoid. The silicon tracker measures charged particles within the range  $|\eta| < 2.5$ . For charged particles with  $1 < p_T < 10$  GeV and  $|\eta| < 1.4$ , the track resolutions are typically 1.5% in  $p_T$  and 25–90 (45–150)  $\mu\text{m}$  in the transverse (longitudinal) impact parameter [46]. A detailed description of the CMS detector, together with a definition of the coordinate system used and the relevant kinematic variables, can be found in Ref. [47].

The  $p + \text{Pb}$  data at  $\sqrt{s_{\text{NN}}} = 8.16$  TeV used in this analysis were collected by the CMS experiment in 2016, and correspond to an integrated luminosity of  $186 \text{ nb}^{-1}$ . The beam energies are 6.5 TeV for the protons and 2.56 TeV per nucleon for the lead nuclei. Because of the asymmetric beam conditions, particles selected in this Letter from midrapidity in the laboratory frame ( $|y_{\text{lab}}| < 1$ ) correspond to rapidity in the nucleon-nucleon center-of-mass frame of  $-1.46 < y_{\text{cm}} < 0.54$ , with positive rapidity corresponding to the proton beam direction. The event reconstruction, event selections, and triggers are identical to those described in Refs. [48,49]. A subset of PbPb data at  $\sqrt{s_{\text{NN}}} = 5.02$  TeV for 30%–50% centrality were also used and reprocessed using the same reconstruction algorithm as the  $p + \text{Pb}$  data.

The  $p + \text{Pb}$  data are analyzed for multiplicity ranges of  $N_{\text{trk}}^{\text{offline}} < 35$  and  $185 \leq N_{\text{trk}}^{\text{offline}} < 250$ , where  $N_{\text{trk}}^{\text{offline}}$  is the number of primary tracks [46] with  $|\eta| < 2.4$  and  $p_T > 0.4$  GeV. Events in the multiplicity region of  $N_{\text{trk}}^{\text{offline}} > 250$  is not included to avoid effects of multiple interactions in a single event (pileup). These bin boundaries correspond to fractional inelastic cross sections from 100% to 57%, and from 0.33% to 0.01%, respectively. The 30%–50% centrality PbPb data have an average  $N_{\text{trk}}^{\text{offline}}$  of 919.

The reconstruction and selection procedures for strange-hadron candidates in  $p + \text{Pb}$  collisions are identical to

those in Refs. [28,29,50]. Pairs of oppositely charged particle tracks that are detached from the primary vertex (i.e., having large significance of impact parameters) are selected to determine if they point to a common secondary vertex from the decay of a  $K_S^0$ , a  $\Lambda$  or a  $D^0$  candidate. The reconstruction efficiency for tracks with low momenta and large impact parameters is increased by using all tracks that pass the loose selection of Ref. [46]. The track pair is assumed to originate from  $\pi^+\pi^-$  in  $K_S^0$  reconstruction, while the assumption of  $\pi^-p(\pi^+\bar{p})$  is used in the  $\Lambda$  ( $\bar{\Lambda}$ ) reconstruction. To reconstruct  $\Xi^-$  and  $\Omega^-$  particles, a  $\Lambda$  candidate is combined with an additional particle of the correct sign, assuming the pion or kaon PDG mass [51], to define an additional vertex. The  $D^0$  mesons are reconstructed through the hadronic decay channel  $D^0 \rightarrow K^-\pi^+$ . In order to suppress the combinatorial background and improve the momentum and mass resolution, high-purity [46] tracks with  $p_T > 0.7$  GeV and  $|\eta| < 1.5$  are used. For each pair of selected tracks, two  $D^0$  candidates are considered by assuming one of the tracks has the pion mass while the other track has the kaon mass, and vice versa. Similar swapped-mass candidates are not required for strange hadrons since the two decay products are either the same mass (for  $K_S^0$ ) or so different in mass that momentum-sharing criteria can be used to identify which decay particle is the heavier one (for  $\Lambda$ ,  $\Xi^-$ , and  $\Omega^-$ ).

Several topological selections are applied to further reduce the combinatorial background. In particular, strange hadron and  $D^0$  candidates are selected according to the  $\chi^2$  probability of their decay vertex, the three-dimensional distance (normalized by its uncertainty) between the primary and decay vertices, and the pointing angle (defined as the angle between the line segment connecting the primary and decay vertices and the momentum vector of the reconstructed particle candidates in the plane transverse to the beam direction). The selection is optimized in each  $p_T$  bin, separately for different particle species, in order to maximize the statistical significance of the signal. For  $\Xi^-$  and  $\Omega^-$  reconstruction, these selections are applied to both the initial decay vertex and the subsequent decay vertex of  $\Lambda$ .

In the case of the  $D^0$  measurement, the selections on the pointing angle also suppress the fraction of nonprompt  $D^0$  production (from decays of  $b$  hadrons). Simulated event samples of PYTHIA 8.209 [52,53]  $D^0$  signal events, embedded into EPOS LHC [54] minimum bias  $p + \text{Pb}$  events, are used to estimate the nonprompt  $D^0$  contamination in data. By fitting the distributions of distance of closest approach of  $D^0$  total momentum vector to the primary vertex, using the probability distribution functions (pdf) for prompt and nonprompt  $D^0$  derived from simulation, the residual nonprompt fraction is found to be decreasing with  $p_T$  from 7% to 1%.

The azimuthal anisotropies of  $D^0$  mesons and strange hadrons are extracted from their long-range ( $|\Delta\eta| > 1$ )

two-particle azimuthal correlations with charged particles, as described in Refs. [28,29]. Taking the  $D^0$  meson as an example, the two-dimensional (2D) correlation function is constructed by pairing each  $D^0$  candidate with reference primary charged-particle tracks with  $0.3 < p_T < 3.0$  GeV (denoted “ref” particles), and calculating

$$\frac{1}{N_{D^0}} \frac{d^2 N^{\text{pair}}}{d\Delta\eta d\Delta\phi} = B(0, 0) \frac{S(\Delta\eta, \Delta\phi)}{B(\Delta\eta, \Delta\phi)}, \quad (1)$$

where  $\Delta\eta$  and  $\Delta\phi$  are the differences in  $\eta$  and  $\phi$  of each pair. The same-event pair distribution,  $S(\Delta\eta, \Delta\phi)$ , represents the yield of particle pairs normalized by the number of  $D^0$  candidates from the same event. The mixed-event pair yield distribution,  $B(\Delta\eta, \Delta\phi)$ , is constructed by pairing  $D^0$  candidates in each event with the reference primary charged-particle tracks from 20 different randomly selected events, from the same  $N_{\text{trk}}^{\text{offline}}$  range, and with a primary vertex falling in the same 2 cm wide range of reconstructed  $z$  coordinate. The analysis procedure is performed in each  $D^0$  candidate  $p_T$  range by dividing it into intervals of invariant mass. The correction for acceptance and efficiency (derived from PYTHIA+EPOS simulations) of the  $D^0$  meson yield is found to have negligible effect on the measurements, and thus is not applied. The  $\Delta\phi$  correlation functions averaged over  $|\Delta\eta| > 1$  (to remove short-range correlations such as jet fragmentation) is then obtained from the projection of 2D distributions and fitted by the first three terms of a Fourier series (including additional terms has a negligible effect):

$$\frac{1}{N_{D^0}} \frac{dN^{\text{pair}}}{d\Delta\phi} = \frac{N_{\text{assoc}}}{2\pi} \left( 1 + \sum_{n=1}^3 2V_{n\Delta} \cos(n\Delta\phi) \right). \quad (2)$$

Here,  $V_{n\Delta}$  are the Fourier coefficients and  $N_{\text{assoc}}$  represents the total number of pairs per  $D^0$  candidate. By assuming  $V_{n\Delta}$  to be the product of single-particle anisotropies [55],  $V_{n\Delta}(D^0, \text{ref}) = v_n(D^0)v_n(\text{ref})$ , the  $v_n$  anisotropy harmonics for  $D^0$  candidates can be extracted as a function of invariant mass,  $v_n(D^0) = V_{n\Delta}(D^0, \text{ref})/\sqrt{V_{n\Delta}(\text{ref}, \text{ref})}$ . Because of the limited amount of available data, only the elliptic anisotropy harmonic is measured. The residual contribution of back-to-back dijets to the measured  $v_2$  results is corrected by subtracting correlations from low-multiplicity  $p + \text{Pb}$  events, following an identical procedure established in Refs. [29,55]. The Fourier coefficients,  $V_{n\Delta}$ , extracted from events with  $N_{\text{trk}}^{\text{offline}} < 35$  are subtracted from those extracted from events with  $185 \leq N_{\text{trk}}^{\text{offline}} < 250$  after accounting for the jet yield ratio of the selected events. The subtraction is not performed for PbPb results as the back-to-back jet correlations are found to be negligible in events with centrality between 30% and 50% [49].

To extract the  $v_2$  values of the  $D^0$  meson signal ( $v_2^S$ ), a simultaneous fit to the invariant mass spectrum of  $D^0$  candidates and their  $v_2$  as a function of the invariant mass,  $v_2^{S+B}(m_{\text{inv}})$ , is performed in each  $p_T$  interval. The mass spectrum fit function is composed of three components: the sum of two Gaussian functions with the same mean but different widths for the  $D^0$  signal,  $S(m_{\text{inv}})$ , an additional Gaussian function to describe the invariant mass shape of  $D^0$  candidates with an incorrect mass assignment from the exchange of the pion and kaon designations,  $SW(m_{\text{inv}})$ , and a third-order polynomial to model the combinatorial background,  $B(m_{\text{inv}})$ . The width of  $SW(m_{\text{inv}})$  and the ratio of the yields of  $SW(m_{\text{inv}})$  and  $S(m_{\text{inv}})$  are fixed according to results obtained from PYTHIA+EPOS simulation studies. The  $v_2^{S+B}(m_{\text{inv}})$  distribution is fitted with

$$v_2^{S+B}(m_{\text{inv}}) = \alpha(m_{\text{inv}})v_2^S + [1 - \alpha(m_{\text{inv}})]v_2^B(m_{\text{inv}}), \quad (3)$$

where

$$\alpha(m_{\text{inv}}) = \frac{S(m_{\text{inv}}) + SW(m_{\text{inv}})}{S(m_{\text{inv}}) + SW(m_{\text{inv}}) + B(m_{\text{inv}})}. \quad (4)$$

Here  $v_2^B(m_{\text{inv}})$  for the background  $D^0$  candidates is modeled as a linear function of the invariant mass, and  $\alpha(m_{\text{inv}})$  is the  $D^0$  signal fraction. The  $K-\pi$  swapped component is included in the signal fraction because these candidates are from genuine  $D^0$  mesons and should have the same  $v_2$  value as that of the nonswapped  $D^0$  signal. Figure 1 shows an example of a simultaneous fit to the mass spectrum and  $v_2^{S+B}(m_{\text{inv}})$  in the  $p_T$  interval 4.2–5.0 GeV for the multiplicity range  $185 \leq N_{\text{trk}}^{\text{offline}} < 250$  in  $p + \text{Pb}$

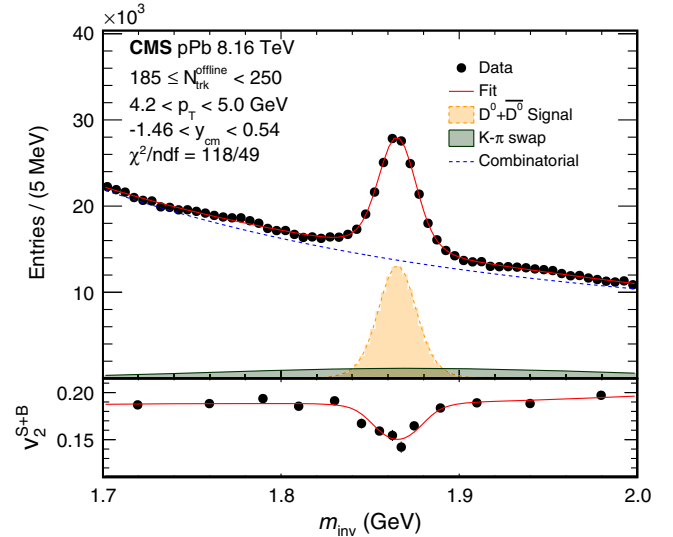


FIG. 1. Example of the simultaneous fit to the invariant mass spectrum and  $v_2^{S+B}(m_{\text{inv}})$  in the  $p_T$  interval 4.2–5.0 GeV for events with  $185 \leq N_{\text{trk}}^{\text{offline}} < 250$ .

collisions. The  $v_2$  values for the strange hadrons are extracted in the same way although no swapped-mass component is required.

As the residual contribution from nonprompt  $D^0$  mesons is small, no explicit correction is applied and a systematic uncertainty is quoted instead. Based on the prediction for AA collisions that  $B$  mesons have a smaller  $v_2$  than light-flavor particles, due to the larger mass of the  $b$  quark [56–58], the nonprompt  $D^0$   $v_2$  values are assumed to lie between 0 and those of strange hadrons. The maximum effect from nonprompt  $D^0$  mesons is thus estimated using the extracted nonprompt  $D^0$  fraction and the change in  $v_2^S$  is found to be smaller than 6%.

Other sources of systematic uncertainty in the  $D^0$   $v_2$  measurement in this analysis include the background mass pdf, the  $D^0$  meson yield correction (acceptance and efficiency correction), selection of the  $D^0$  candidates, and the background  $v_2$  pdf. No systematic effect has been observed while changing the background mass pdf to a second-order polynomial or an exponential function. To evaluate the uncertainties arising from the  $D^0$  meson yield correction, the  $v_2$  values are extracted from the corrected signal  $D^0$  distributions and compared to the uncorrected  $v_2$  values, yielding an uncertainty of 2%. The selection criteria for  $D^0$  candidates are also varied to tighter and looser values such that the  $D^0$  signal fraction,  $\alpha(m_{\text{inv}})$ , changes by 50% and a systematic uncertainty of 14% is evaluated from the variations of  $v_2$ . The systematic uncertainties from the background  $v_2$  pdf (20% for  $p_T < 2.4$  GeV and 4% for  $p_T > 2.4$  GeV) are evaluated by changing  $v_2^B(m_{\text{inv}})$  to a second-order polynomial function of the invariant mass and a constant value. Systematic uncertainties from trigger bias and effects of pileup are negligible.

For  $K_S^0$ ,  $\Lambda$ , and  $\Xi^-$  particles, the systematic uncertainties related to selection of reconstructed candidates (2% for  $K_S^0$  and  $\Lambda$  particles and 6% for  $\Xi^-$  particles) are evaluated in the same way as for  $D^0$  mesons. To test the procedure of extracting the signal  $v_2$ , a study using EPOS LHC [54]  $p + \text{Pb}$  events is performed and the extracted values are compared to the generator-level values. The agreement is found to be better than 6%. Systematic uncertainties for  $\Omega^-$  particles are quoted to be the same as those of  $\Xi^-$  particles.

Figure 2 shows the results of the  $v_2$  measurement of the prompt  $D^0$  meson with  $-1.46 < y_{\text{cm}} < 0.54$  for high-multiplicity ( $185 \leq N_{\text{trk}}^{\text{offline}} < 250$ )  $p + \text{Pb}$  collisions. The  $v_2$  results for strange hadrons are also shown for comparison. A clear mass ordering in the elliptic flow is observed in the low- $p_T$  region of  $\lesssim 2.5$  GeV, where heavier particle species have a smaller  $v_2$  signal at a given  $p_T$  value. For  $p_T > 2.5$  GeV,  $v_2$  values for  $\Lambda$ ,  $\Xi^-$ , and  $\Omega^-$  baryons, which are similar to each other, all become larger than those of  $D^0$  and  $K_S^0$  mesons, a trend which is also observed in 5.02 TeV  $p + \text{Pb}$  collisions [28].

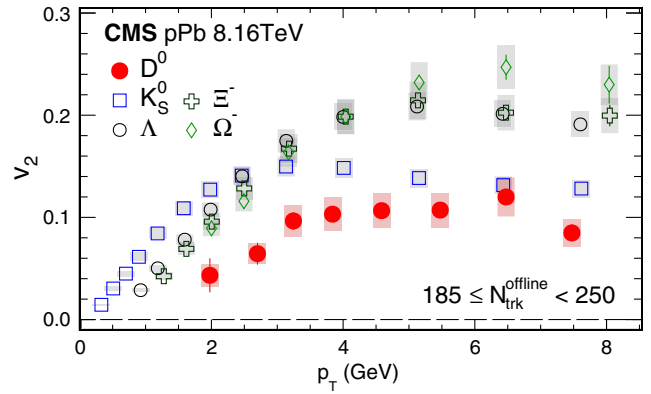


FIG. 2. Results of elliptic flow ( $v_2$ ) for  $D^0$  mesons, as well as  $K_S^0$ ,  $\Lambda$ ,  $\Xi^-$ , and  $\Omega^-$  particles, as functions of  $p_T$  for  $-1.46 < y_{\text{cm}} < 0.54$ , with  $185 \leq N_{\text{trk}}^{\text{offline}} < 250$  in  $p + \text{Pb}$  collisions at  $\sqrt{s_{\text{NN}}} = 8.16$  TeV. The error bars correspond to statistical uncertainties, while the shaded areas denote the systematic uncertainties.

The elliptic flow results corrected for residual jet correlations ( $v_2^{\text{sub}}$ ) are shown in Fig. 3 (upper left) for prompt  $D^0$  mesons as well as for strange hadrons as functions of  $p_T$  for  $p + \text{Pb}$  collisions with  $185 \leq N_{\text{trk}}^{\text{offline}} < 250$ . The reduction in the  $v_2$  values resulting from the correction is most significant in the high- $p_T$  region, with a 30%–40% reduction found for  $p_T > 5$  GeV. The prompt  $D^0$   $v_2^{\text{sub}}$  results show a clear trend of rising and declining with  $p_T$ . The same ordering in particle mass as seen in Fig. 2 is observed in the  $v_2^{\text{sub}}$  values in the lower- $p_T$  region. This behavior is consistent with the expectation of particle emission from a collective expanding source, which might indicate significant collective behavior of charm quarks in high-multiplicity  $p + \text{Pb}$  systems at LHC energies. Previously published  $v_2$  data for  $D^0$  meson in 30%–50% centrality PbPb collisions [43], together with new results for strange hadrons obtained in this Letter, are shown in Fig. 3 (lower left). A similar mass ordering to that in  $p + \text{Pb}$  collisions is seen, although the multiplicity range is much larger.

Motivated by the quark coalescence model [59–63], collectivity at the partonic level is investigated by studying the scaling properties of  $v_2^{\text{sub}}$  divided by the number of constituent quarks,  $n_q$ , as a function of transverse kinetic energy per constituent quark,  $KE_T/n_q$  (where  $KE_T = \sqrt{m^2 + p_T^2} - m$ ), for all hadronic species and systems measured (Fig. 3, right). In high-multiplicity  $p + \text{Pb}$  collisions, the results for strange hadrons tend to follow a universal trend in the region  $0.5 < KE_T/n_q < 1.5$  GeV, while the elliptic flow for  $D^0$  mesons is found to have smaller values. This could suggest that the collective behavior of charm quarks is weaker than that of the light-flavor and strange quarks in high-multiplicity  $p + \text{Pb}$  collisions at the LHC. For  $KE_T/n_q > 1.5$  GeV, no clear

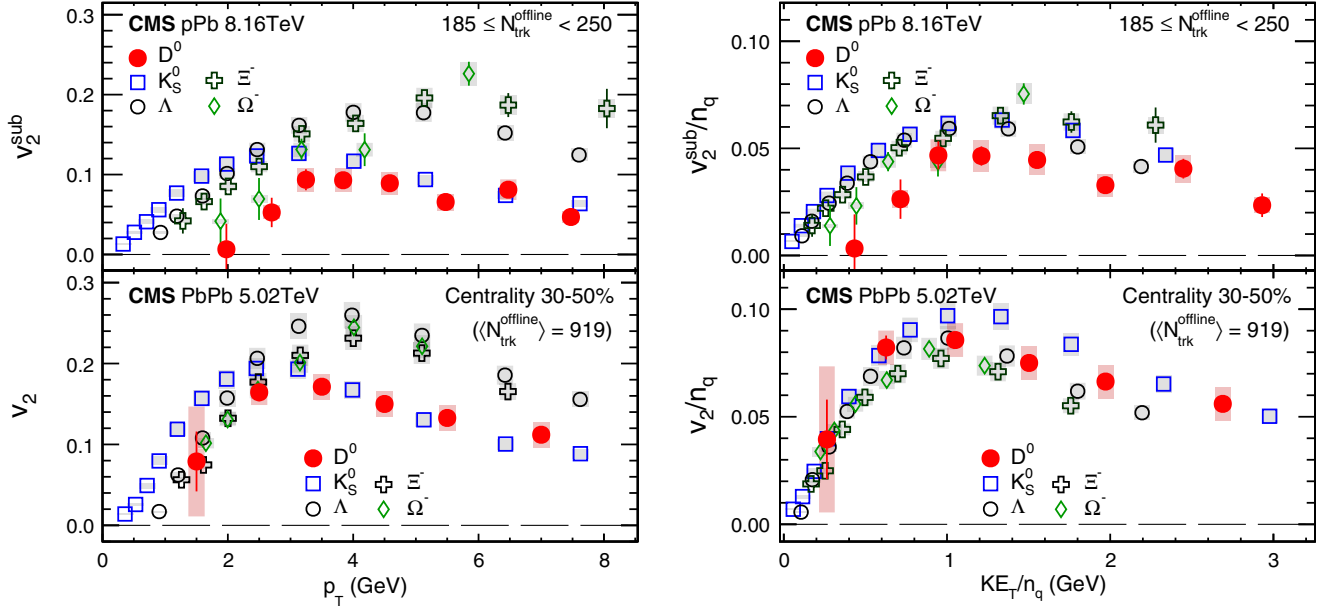


FIG. 3. Left:  $v_2^{\text{sub}}$  results for prompt  $D^0$  meson, as well as for strange hadrons, as functions of  $p_T$ , for  $-1.46 < y_{\text{cm}} < 0.54$  in  $p + \text{Pb}$  collisions at  $\sqrt{s_{\text{NN}}} = 8.16$  TeV with  $185 \leq N_{\text{trk}}^{\text{offline}} < 250$  (upper) and for  $-1 < y_{\text{cm}} < 1$  in  $\text{PbPb}$  collisions at  $\sqrt{s_{\text{NN}}} = 5.02$  TeV for 30%–50% centrality (lower). Right:  $n_q$ -scaled  $v_2^{\text{sub}}$  results. The  $D^0$   $v_2$  data in  $\text{PbPb}$  are taken from Ref. [43]. The error bars correspond to statistical uncertainties, while the shaded areas denote the systematic uncertainties.

universal scaling of  $v_2/n_q$  between mesons and baryons is observed. The behavior is qualitatively different in the larger  $\text{PbPb}$  collision system with centrality between 30% and 50%. The results for all particle species tend to follow a common trend in the  $KE_T/n_q < 1$  GeV region, indicating that  $D^0$  mesons develop a strong collective behavior similar to the bulk of the QGP.

In summary, the first measurements of elliptic azimuthal anisotropies for prompt  $D^0$  mesons, as well as  $K_S^0$ ,  $\Lambda$ ,  $\Xi^-$ ,  $\Omega^-$  hadrons, in high-multiplicity  $p + \text{Pb}$  collisions at  $\sqrt{s_{\text{NN}}} = 8.16$  TeV are presented. Significant positive  $v_2$  values are observed for  $D^0$  mesons with  $p_T > 2$  GeV. Comparing to strange-hadron results, the  $D^0$   $v_2$  values are found to be smaller at a given  $p_T$ , or at similar transverse kinetic energy per constituent quark, after normalizing  $v_2$  by the number of constituent quarks. The latter effect is not observed in the larger  $\text{PbPb}$  collision system. A possible interpretation is that, in high multiplicity  $p + \text{Pb}$  collisions, in contrast to larger nucleus-nucleus collision systems, the collective behavior of charm quarks is weaker than that of the light-flavor quarks.

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A. Mahmoud,<sup>26,i,j</sup> Y. Mohammed,<sup>26,j</sup> E. Salama,<sup>26,k,i</sup> S. Bhowmik,<sup>27</sup> A. Carvalho Antunes De Oliveira,<sup>27</sup> R. K. Dewanjee,<sup>27</sup> K. Ehataht,<sup>27</sup> M. Kadastik,<sup>27</sup> M. Raidal,<sup>27</sup> C. Veelken,<sup>27</sup> P. Eerola,<sup>28</sup> H. Kirschenmann,<sup>28</sup> J. Pekkanen,<sup>28</sup> M. Voutilainen,<sup>28</sup> J. Havukainen,<sup>29</sup> J. K. Heikkilä,<sup>29</sup> T. Järvinen,<sup>29</sup> V. Karimäki,<sup>29</sup> R. Kinnunen,<sup>29</sup> T. Lampén,<sup>29</sup> K. Lassila-Perini,<sup>29</sup> S. Laurila,<sup>29</sup> S. Lehti,<sup>29</sup> T. Lindén,<sup>29</sup> P. Luukka,<sup>29</sup> T. Mäenpää,<sup>29</sup> H. Siikonen,<sup>29</sup> E. Tuominen,<sup>29</sup> J. Tuominiemi,<sup>29</sup> T. Tuuva,<sup>30</sup> M. Besancon,<sup>31</sup> F. Couderc,<sup>31</sup> M. DeJardin,<sup>31</sup> D. Denegri,<sup>31</sup> J. L. Faure,<sup>31</sup> F. Ferri,<sup>31</sup> S. Ganjour,<sup>31</sup> A. Givernaud,<sup>31</sup> P. Gras,<sup>31</sup> G. Hamel de Monchenault,<sup>31</sup> P. Jarry,<sup>31</sup> C. Leloup,<sup>31</sup> E. Locci,<sup>31</sup> J. Malcles,<sup>31</sup> G. Negro,<sup>31</sup> J. Rander,<sup>31</sup> A. Rosowsky,<sup>31</sup> M. Ö. Sahin,<sup>31</sup> M. Titov,<sup>31</sup> A. Abdulsalam,<sup>32,l</sup> C. Amendola,<sup>32</sup> I. Antropov,<sup>32</sup> F. Beaudette,<sup>32</sup> P. Busson,<sup>32</sup> C. Charlot,<sup>32</sup> R. Granier de Cassagnac,<sup>32</sup> I. Kucher,<sup>32</sup> S. Lisniak,<sup>32</sup> A. Lobanov,<sup>32</sup> J. Martin Blanco,<sup>32</sup> M. Nguyen,<sup>32</sup> C. Ochando,<sup>32</sup> G. Ortona,<sup>32</sup> P. Pigard,<sup>32</sup> R. Salerno,<sup>32</sup> J. B. Sauvan,<sup>32</sup> Y. Sirois,<sup>32</sup> A. G. Stahl Leitner,<sup>32</sup> A. Zabi,<sup>32</sup> A. Zghiche,<sup>32</sup> J.-L. Agram,<sup>33,m</sup> J. Andrea,<sup>33</sup> D. Bloch,<sup>33</sup> J.-M. Brom,<sup>33</sup> E. C. Chabert,<sup>33</sup> V. Cherepanov,<sup>33</sup> C. Collard,<sup>33</sup> E. Conte,<sup>33,m</sup> J.-C. Fontaine,<sup>33,m</sup> D. Gelé,<sup>33</sup> U. Goerlach,<sup>33</sup> M. Jansová,<sup>33</sup> A.-C. Le Bihan,<sup>33</sup> N. Tonon,<sup>33</sup> P. Van Hove,<sup>33</sup> S. Gadrat,<sup>34</sup> S. Beauceron,<sup>35</sup> C. Bernet,<sup>35</sup> G. Boudoul,<sup>35</sup> N. Chanon,<sup>35</sup> R. Chierici,<sup>35</sup> D. Contardo,<sup>35</sup> P. Depasse,<sup>35</sup> H. El Mamouni,<sup>35</sup> J. Fay,<sup>35</sup> L. Finco,<sup>35</sup> S. Gascon,<sup>35</sup> M. Gouzevitch,<sup>35</sup> G. Grenier,<sup>35</sup> B. Ille,<sup>35</sup> F. Lagarde,<sup>35</sup> I. B. Laktineh,<sup>35</sup> H. Lattaud,<sup>35</sup> M. Lethuillier,<sup>35</sup> L. Mirabito,<sup>35</sup> A. L. Pequegnot,<sup>35</sup> S. Perries,<sup>35</sup> A. Popov,<sup>35,n</sup> V. Sordini,<sup>35</sup> M. Vander Donckt,<sup>35</sup> S. Viret,<sup>35</sup> S. Zhang,<sup>35</sup> T. Toriashvili,<sup>36,o</sup> Z. Tsamalaidze,<sup>37,h</sup> C. Autermann,<sup>38</sup> L. Feld,<sup>38</sup> M. K. Kiesel,<sup>38</sup> K. Klein,<sup>38</sup> M. Lipinski,<sup>38</sup> M. Preuten,<sup>38</sup> M. P. Rauch,<sup>38</sup> C. Schomakers,<sup>38</sup> J. Schulz,<sup>38</sup> M. Teroerde,<sup>38</sup> B. Wittmer,<sup>38</sup> V. Zhukov,<sup>38,n</sup> A. Albert,<sup>39</sup> D. Duchardt,<sup>39</sup> M. Endres,<sup>39</sup> M. Erdmann,<sup>39</sup> T. Esch,<sup>39</sup> R. Fischer,<sup>39</sup> S. Ghosh,<sup>39</sup> A. Güth,<sup>39</sup> T. Hebbeker,<sup>39</sup> C. Heidemann,<sup>39</sup> K. Hoepfner,<sup>39</sup> H. Keller,<sup>39</sup> S. Knutzen,<sup>39</sup> L. Mastrolorenzo,<sup>39</sup> M. Merschmeyer,<sup>39</sup> A. Meyer,<sup>39</sup> P. Millet,<sup>39</sup> S. Mukherjee,<sup>39</sup> T. Pook,<sup>39</sup> M. Radziej,<sup>39</sup> H. Reithler,<sup>39</sup> M. Rieger,<sup>39</sup> F. Scheuch,<sup>39</sup> A. Schmidt,<sup>39</sup> D. Teyssier,<sup>39</sup> G. Flügge,<sup>40</sup> O. Hlushchenko,<sup>40</sup> B. Kargoll,<sup>40</sup> T. Kress,<sup>40</sup> A. Künsken,<sup>40</sup> T. Müller,<sup>40</sup> A. Nehr Korn,<sup>40</sup> A. Nowack,<sup>40</sup> C. Pistone,<sup>40</sup> O. Pooth,<sup>40</sup> H. Sert,<sup>40</sup> A. Stahl,<sup>40,p</sup> M. Aldaya Martin,<sup>41</sup> T. Arndt,<sup>41</sup> C. Asawatangtrakuldee,<sup>41</sup> I. Babounikau,<sup>41</sup> K. Beernaert,<sup>41</sup> O. Behnke,<sup>41</sup> U. Behrens,<sup>41</sup> A. Bermúdez Martínez,<sup>41</sup> D. Bertsche,<sup>41</sup> A. A. Bin Anuar,<sup>41</sup> K. Borras,<sup>41,q</sup> V. Botta,<sup>41</sup> A. Campbell,<sup>41</sup> P. Connor,<sup>41</sup> C. Contreras-Campana,<sup>41</sup> F. Costanza,<sup>41</sup> V. Danilov,<sup>41</sup> A. De Wit,<sup>41</sup> M. M. Defranchis,<sup>41</sup> C. Diez Pardos,<sup>41</sup> D. Domínguez Damiani,<sup>41</sup> G. Eckerlin,<sup>41</sup> T. Eichhorn,<sup>41</sup> A. Elwood,<sup>41</sup> E. Eren,<sup>41</sup> E. Gallo,<sup>41,r</sup> A. Geiser,<sup>41</sup> J. M. Grados Luyando,<sup>41</sup> A. Grohsjean,<sup>41</sup> P. Gunnellini,<sup>41</sup> M. Guthoff,<sup>41</sup> M. Haranko,<sup>41</sup> A. Harb,<sup>41</sup> J. Hauk,<sup>41</sup> H. Jung,<sup>41</sup> M. Kasemann,<sup>41</sup> J. Keaveney,<sup>41</sup> C. Kleinwort,<sup>41</sup> J. Knolle,<sup>41</sup> D. Krücker,<sup>41</sup> W. Lange,<sup>41</sup> A. Lelek,<sup>41</sup> T. Lenz,<sup>41</sup> K. Lipka,<sup>41</sup> W. Lohmann,<sup>41,s</sup> R. Mankel,<sup>41</sup> I.-A. Melzer-Pellmann,<sup>41</sup> A. B. Meyer,<sup>41</sup> M. Meyer,<sup>41</sup> M. Missiroli,<sup>41</sup> G. Mittag,<sup>41</sup> J. Mnich,<sup>41</sup> V. Myronenko,<sup>41</sup> S. K. Pflitsch,<sup>41</sup> D. Pitzl,<sup>41</sup> A. Raspereza,<sup>41</sup> M. Savitskiy,<sup>41</sup> P. Saxena,<sup>41</sup> P. Schütze,<sup>41</sup> C. Schwanenberger,<sup>41</sup> R. Shevchenko,<sup>41</sup> A. Singh,<sup>41</sup> N. Stefaniuk,<sup>41</sup> H. Tholen,<sup>41</sup> A. Vagnerini,<sup>41</sup>



G. P. Van Onsem,<sup>41</sup> R. Walsh,<sup>41</sup> Y. Wen,<sup>41</sup> K. Wichmann,<sup>41</sup> C. Wissing,<sup>41</sup> O. Zenaiev,<sup>41</sup> R. Aggleton,<sup>42</sup> S. Bein,<sup>42</sup> A. Benecke,<sup>42</sup> V. Blobel,<sup>42</sup> M. Centis Vignali,<sup>42</sup> T. Dreyer,<sup>42</sup> E. Garutti,<sup>42</sup> D. Gonzalez,<sup>42</sup> J. Haller,<sup>42</sup> A. Hinzmann,<sup>42</sup> M. Hoffmann,<sup>42</sup> A. Karavdina,<sup>42</sup> G. Kasieczka,<sup>42</sup> R. Klanner,<sup>42</sup> R. Kogler,<sup>42</sup> N. Kovalchuk,<sup>42</sup> S. Kurz,<sup>42</sup> V. Kutzner,<sup>42</sup> J. Lange,<sup>42</sup> D. Marconi,<sup>42</sup> J. Multhaupt,<sup>42</sup> M. Niedziela,<sup>42</sup> D. Nowatschin,<sup>42</sup> A. Perieanu,<sup>42</sup> A. Reimers,<sup>42</sup> O. Rieger,<sup>42</sup> C. Scharf,<sup>42</sup> P. Schleper,<sup>42</sup> S. Schumann,<sup>42</sup> J. Schwandt,<sup>42</sup> J. Sonneveld,<sup>42</sup> H. Stadie,<sup>42</sup> G. Steinbrück,<sup>42</sup> F. M. Stober,<sup>42</sup> M. Stöver,<sup>42</sup> D. Troendle,<sup>42</sup> E. Usai,<sup>42</sup> A. Vanhoefer,<sup>42</sup> B. Vormwald,<sup>42</sup> M. Akbiyik,<sup>43</sup> C. Barth,<sup>43</sup> M. Baselga,<sup>43</sup> S. Baur,<sup>43</sup> E. Butz,<sup>43</sup> R. Caspart,<sup>43</sup> T. Chwalek,<sup>43</sup> F. Colombo,<sup>43</sup> W. De Boer,<sup>43</sup> A. Dierlamm,<sup>43</sup> N. Faltermann,<sup>43</sup> B. Freund,<sup>43</sup> M. Giffels,<sup>43</sup> M. A. Harrendorf,<sup>43</sup> F. Hartmann,<sup>43,p</sup> S. M. Heindl,<sup>43</sup> U. Husemann,<sup>43</sup> F. Kassel,<sup>43,p</sup> I. Katkov,<sup>43,n</sup> S. Kudella,<sup>43</sup> H. Mildner,<sup>43</sup> S. Mitra,<sup>43</sup> M. U. Mozer,<sup>43</sup> Th. Müller,<sup>43</sup> M. Plagge,<sup>43</sup> G. Quast,<sup>43</sup> K. Rabbertz,<sup>43</sup> M. Schröder,<sup>43</sup> I. Shvetsov,<sup>43</sup> G. Sieber,<sup>43</sup> H. J. Simonis,<sup>43</sup> R. Ulrich,<sup>43</sup> S. Wayand,<sup>43</sup> M. Weber,<sup>43</sup> T. Weiler,<sup>43</sup> S. Williamson,<sup>43</sup> C. Wöhrmann,<sup>43</sup> R. Wolf,<sup>43</sup> G. Anagnostou,<sup>44</sup> G. Daskalakis,<sup>44</sup> T. Gerasis,<sup>44</sup> A. Kyriakis,<sup>44</sup> D. Loukas,<sup>44</sup> G. Paspalaki,<sup>44</sup> I. Topsis-Giotis,<sup>44</sup> G. Karathanasis,<sup>45</sup> S. Kesisoglou,<sup>45</sup> P. Kontaxakis,<sup>45</sup> A. Panagiotou,<sup>45</sup> N. Saoulidou,<sup>45</sup> E. Tziaferi,<sup>45</sup> K. Vellidis,<sup>45</sup> K. Kousouris,<sup>46</sup> I. Papakrivopoulos,<sup>46</sup> G. Tsipolitis,<sup>46</sup> I. Evangelou,<sup>47</sup> C. Foudas,<sup>47</sup> P. Gianneios,<sup>47</sup> P. Katsoulis,<sup>47</sup> P. Kokkas,<sup>47</sup> S. Mallios,<sup>47</sup> N. Manthos,<sup>47</sup> I. Papadopoulos,<sup>47</sup> E. Paradas,<sup>47</sup> J. Strologas,<sup>47</sup> F. A. Triantis,<sup>47</sup> D. Tsitsonis,<sup>47</sup> M. Csanad,<sup>48</sup> N. Filipovic,<sup>48</sup> P. Major,<sup>48</sup> M. I. Nagy,<sup>48</sup> G. Pasztor,<sup>48</sup> O. Surányi,<sup>48</sup> G. I. Veres,<sup>48</sup> G. Bencze,<sup>49</sup> C. Hajdu,<sup>49</sup> D. Horvath,<sup>49,t</sup> Á. Hunyadi,<sup>49</sup> F. Sikler,<sup>49</sup> T. Á. Vámi,<sup>49</sup> V. Veszpremi,<sup>49</sup> G. Vesztergombi,<sup>49,au</sup> N. Beni,<sup>50</sup> S. Czellar,<sup>50</sup> J. Karancsi,<sup>50,v</sup> A. Makovec,<sup>50</sup> J. Molnar,<sup>50</sup> Z. Szillasi,<sup>50</sup> M. Bartók,<sup>51,u</sup> P. Raics,<sup>51</sup> Z. L. Trocsanyi,<sup>51</sup> B. Ujvari,<sup>51</sup> S. Choudhury,<sup>52</sup> J. R. Komaragiri,<sup>52</sup> P. C. Tiwari,<sup>52</sup> S. Bahinipati,<sup>53,w</sup> P. Mal,<sup>53</sup> K. Mandal,<sup>53</sup> A. Nayak,<sup>53,x</sup> D. K. Sahoo,<sup>53,w</sup> S. K. Swain,<sup>53</sup> S. Bansal,<sup>54</sup> S. B. Beri,<sup>54</sup> V. Bhatnagar,<sup>54</sup> S. Chauhan,<sup>54</sup> R. Chawla,<sup>54</sup> N. Dhingra,<sup>54</sup> R. Gupta,<sup>54</sup> A. Kaur,<sup>54</sup> A. Kaur,<sup>54</sup> M. Kaur,<sup>54</sup> S. Kaur,<sup>54</sup> R. Kumar,<sup>54</sup> P. Kumari,<sup>54</sup> M. Lohan,<sup>54</sup> A. Mehta,<sup>54</sup> K. Sandeep,<sup>54</sup> S. Sharma,<sup>54</sup> J. B. Singh,<sup>54</sup> G. Walia,<sup>54</sup> A. Bhardwaj,<sup>55</sup> B. C. Choudhary,<sup>55</sup> R. B. Garg,<sup>55</sup> M. Gola,<sup>55</sup> S. Keshri,<sup>55</sup> Ashok Kumar,<sup>55</sup> S. Malhotra,<sup>55</sup> M. Naimuddin,<sup>55</sup> P. Priyanka,<sup>55</sup> K. Ranjan,<sup>55</sup> Aashaq Shah,<sup>55</sup> R. Sharma,<sup>55</sup> R. Bhardwaj,<sup>56,y</sup> M. Bharti,<sup>56</sup> R. Bhattacharya,<sup>56</sup> S. Bhattacharya,<sup>56</sup> U. Bhawandeep,<sup>56,y</sup> D. Bhowmik,<sup>56</sup> S. Dey,<sup>56</sup> S. Dutt,<sup>56,y</sup> S. Dutta,<sup>56</sup> S. Ghosh,<sup>56</sup> K. Mondal,<sup>56</sup> S. Nandan,<sup>56</sup> A. Purohit,<sup>56</sup> P. K. Rout,<sup>56</sup> A. Roy,<sup>56</sup> S. Roy Chowdhury,<sup>56</sup> S. Sarkar,<sup>56</sup> M. Sharan,<sup>56</sup> B. Singh,<sup>56</sup> S. Thakur,<sup>56,y</sup> P. K. Behera,<sup>57</sup> R. Chudasama,<sup>58</sup> D. Dutta,<sup>58</sup> V. Jha,<sup>58</sup> V. Kumar,<sup>58</sup> P. K. Netrakanti,<sup>58</sup> L. M. Pant,<sup>58</sup> P. Shukla,<sup>58</sup> T. Aziz,<sup>59</sup> M. A. Bhat,<sup>59</sup> S. Dugad,<sup>59</sup> G. B. Mohanty,<sup>59</sup> N. Sur,<sup>59</sup> B. Sutar,<sup>59</sup> Ravindra Kumar Verma,<sup>59</sup> S. Banerjee,<sup>60</sup> S. Bhattacharya,<sup>60</sup> S. Chatterjee,<sup>60</sup> P. Das,<sup>60</sup> M. Guchait,<sup>60</sup> Sa. Jain,<sup>60</sup> S. Kumar,<sup>60</sup> M. Maity,<sup>60,z</sup> G. Majumder,<sup>60</sup> K. Mazumdar,<sup>60</sup> N. Sahoo,<sup>60</sup> T. Sarkar,<sup>60,z</sup> S. Chauhan,<sup>61</sup> S. Dube,<sup>61</sup> V. Hegde,<sup>61</sup> A. Kapoor,<sup>61</sup> K. Kothekar,<sup>61</sup> S. Pandey,<sup>61</sup> A. Rane,<sup>61</sup> S. Sharma,<sup>61</sup> S. Chenarani,<sup>62,aa</sup> E. Eskandari Tadavani,<sup>62</sup> S. M. Etesami,<sup>62,aa</sup> M. Khakzad,<sup>62</sup> M. Mohammadi Najafabadi,<sup>62</sup> M. Naseri,<sup>62</sup> F. Rezaei Hosseinabadi,<sup>62</sup> B. Safarzadeh,<sup>62,bb</sup> M. Zeinali,<sup>62</sup> M. Felcini,<sup>63</sup> M. Grunewald,<sup>63</sup> M. Abbrescia,<sup>64a,64b</sup> C. Calabria,<sup>64a,64b</sup> A. Colaleo,<sup>64a</sup> D. Creanza,<sup>64a,64c</sup> L. Cristella,<sup>64a,64b</sup> N. De Filippis,<sup>64a,64c</sup> M. De Palma,<sup>64a,64b</sup> A. Di Florio,<sup>64a,64b</sup> F. Errico,<sup>64a,64b</sup> L. Fiore,<sup>64a</sup> A. Gelmi,<sup>64a,64b</sup> G. Iaselli,<sup>64a,64c</sup> S. Lezki,<sup>64a,64b</sup> G. Maggi,<sup>64a,64c</sup> M. Maggi,<sup>64a</sup> G. Miniello,<sup>64a,64b</sup> S. My,<sup>64a,64b</sup> S. Nuzzo,<sup>64a,64b</sup> A. Pompili,<sup>64a,64b</sup> G. Pugliese,<sup>64a,64c</sup> R. Radogna,<sup>64a</sup> A. Ranieri,<sup>64a</sup> G. Selvaggi,<sup>64a,64b</sup> A. Sharma,<sup>64a</sup> L. Silvestris,<sup>64a,p</sup> R. Venditti,<sup>64a</sup> P. Verwilligen,<sup>64a</sup> G. Zito,<sup>64a</sup> G. Abbiendi,<sup>65a</sup> C. Battilana,<sup>65a,65b</sup> D. Bonacorsi,<sup>65a,65b</sup> L. Borgonovi,<sup>65a,65b</sup> S. Braibant-Giacomelli,<sup>65a,65b</sup> L. Brigliadori,<sup>65a,65b</sup> R. Campanini,<sup>65a,65b</sup> P. Capiluppi,<sup>65a,65b</sup> A. Castro,<sup>65a,65b</sup> F. R. Cavallo,<sup>65a</sup> S. S. Chhibra,<sup>65a,65b</sup> G. Codispoti,<sup>65a,65b</sup> M. Cuffiani,<sup>65a,65b</sup> G. M. Dallavalle,<sup>65a</sup> F. Fabbri,<sup>65a</sup> A. Fanfani,<sup>65a,65b</sup> P. Giacomelli,<sup>65a</sup> C. Grandi,<sup>65a</sup> L. Guiducci,<sup>65a,65b</sup> S. Marcellini,<sup>65a</sup> G. Masetti,<sup>65a</sup> A. Montanari,<sup>65a</sup> F. L. Navarra,<sup>65a,65b</sup> A. Perrotta,<sup>65a</sup> A. M. Rossi,<sup>65a,65b</sup> T. Rovelli,<sup>65a,65b</sup> G. P. Siroli,<sup>65a,65b</sup> N. Tosi,<sup>65a</sup> S. Albergo,<sup>66a,66b</sup> A. Di Mattia,<sup>66a</sup> R. Potenza,<sup>66a,66b</sup> A. Tricomi,<sup>66a,66b</sup> C. Tuve,<sup>66a,66b</sup> G. Barbagli,<sup>67a</sup> K. Chatterjee,<sup>67a,67b</sup> V. Ciulli,<sup>67a,67b</sup> C. Civinini,<sup>67a</sup> R. D'Alessandro,<sup>67a,67b</sup> E. Focardi,<sup>67a,67b</sup> G. Latino,<sup>67a</sup> P. Lenzi,<sup>67a,67b</sup> M. Meschini,<sup>67a</sup> S. Paoletti,<sup>67a</sup> L. Russo,<sup>67a,cc</sup> G. Sguazzoni,<sup>67a</sup> D. Strom,<sup>67a</sup> L. Viliani,<sup>67a</sup> L. Benussi,<sup>68</sup> S. Bianco,<sup>68</sup> F. Fabbri,<sup>68</sup> D. Piccolo,<sup>68</sup> F. Primavera,<sup>68,p</sup> F. Ferro,<sup>69a</sup> F. Ravera,<sup>69a,69b</sup> E. Robutti,<sup>69a</sup> S. Tosi,<sup>69a,69b</sup> A. Benaglia,<sup>70a</sup> A. Beschi,<sup>70a,70b</sup> L. Brianza,<sup>70a,70b</sup> F. Brivio,<sup>70a,70b</sup> V. Ciriolo,<sup>70a,70b,p</sup> S. Di Guida,<sup>70a,70b,p</sup> M. E. Dinardo,<sup>70a,70b</sup> S. Fiorendi,<sup>70a,70b</sup> S. Gennai,<sup>70a</sup> A. Ghezzi,<sup>70a,70b</sup> P. Govoni,<sup>70a,70b</sup> M. Malberti,<sup>70a,70b</sup> S. Malvezzi,<sup>70a</sup> A. Massironi,<sup>70a,70b</sup> D. Menasce,<sup>70a</sup> L. Moroni,<sup>70a</sup> M. Paganoni,<sup>70a,70b</sup> D. Pedrini,<sup>70a</sup> S. Ragazzi,<sup>70a,70b</sup> T. Tabarelli de Fatis,<sup>70a,70b</sup> S. Buontempo,<sup>71a</sup> N. Cavallo,<sup>71a,71c</sup> A. Di Crescenzo,<sup>71a,71b</sup> F. Fabozzi,<sup>71a,71c</sup> F. Fienga,<sup>71a,71b</sup> G. Galati,<sup>71a,71b</sup> A. O. M. Iorio,<sup>71a,71b</sup> W. A. Khan,<sup>71a</sup> L. Lista,<sup>71a</sup> S. Meola,<sup>71a,71d,p</sup> P. Paolucci,<sup>71a,p</sup> C. Sciacca,<sup>71a,71b</sup> E. Voevodina,<sup>71a,71b</sup> P. Azzi,<sup>72a</sup> N. Bacchetta,<sup>72a</sup> L. Benato,<sup>72a,72b</sup> D. Bisello,<sup>72a,72b</sup> A. Boletti,<sup>72a,72b</sup> A. Bragagnolo,<sup>72a</sup> R. Carlin,<sup>72a,72b</sup> P. Checchia,<sup>72a</sup> M. Dall'Osso,<sup>72a,72b</sup> P. De Castro Manzano,<sup>72a</sup> T. Dorigo,<sup>72a</sup> U. Dosselli,<sup>72a</sup>

F. Gasparini,<sup>72a,72b</sup> U. Gasparini,<sup>72a,72b</sup> A. Gozzelino,<sup>72a</sup> S. Lacaprra,<sup>72a</sup> P. Lujan,<sup>72a</sup> M. Margoni,<sup>72a,72b</sup>  
A. T. Meneguzzo,<sup>72a,72b</sup> P. Ronchese,<sup>72a,72b</sup> R. Rossin,<sup>72a,72b</sup> F. Simonetto,<sup>72a,72b</sup> A. Tiko,<sup>72a</sup> E. Torassa,<sup>72a</sup> M. Zanetti,<sup>72a,72b</sup>  
P. Zotto,<sup>72a,72b</sup> G. Zumerle,<sup>72a,72b</sup> A. Braghieri,<sup>73a</sup> A. Magnani,<sup>73a</sup> P. Montagna,<sup>73a,73b</sup> S. P. Ratti,<sup>73a,73b</sup> V. Re,<sup>73a</sup>  
M. Ressegotti,<sup>73a,73b</sup> C. Riccardi,<sup>73a,73b</sup> P. Salvini,<sup>73a</sup> I. Vai,<sup>73a,73b</sup> P. Vitulo,<sup>73a,73b</sup> L. Alunni Solestizi,<sup>74a,74b</sup> M. Biasini,<sup>74a,74b</sup>  
G. M. Bilei,<sup>74a</sup> C. Cecchi,<sup>74a,74b</sup> D. Ciangottini,<sup>74a,74b</sup> L. Fanò,<sup>74a,74b</sup> P. Lariccia,<sup>74a,74b</sup> E. Manoni,<sup>74a</sup> G. Mantovani,<sup>74a,74b</sup>  
V. Mariani,<sup>74a,74b</sup> M. Menichelli,<sup>74a</sup> A. Rossi,<sup>74a,74b</sup> A. Santocchia,<sup>74a,74b</sup> D. Spiga,<sup>74a</sup> K. Androsov,<sup>75a</sup> P. Azzurri,<sup>75a</sup>  
G. Bagliesi,<sup>75a</sup> L. Bianchini,<sup>75a</sup> T. Boccali,<sup>75a</sup> L. Borrello,<sup>75a</sup> R. Castaldi,<sup>75a</sup> M. A. Ciocci,<sup>75a,75b</sup> R. Dell'Orso,<sup>75a</sup> G. Fedi,<sup>75a</sup>  
L. Giannini,<sup>75a,75c</sup> A. Giassi,<sup>75a</sup> M. T. Grippo,<sup>75a</sup> F. Ligabue,<sup>75a,75c</sup> E. Manca,<sup>75a,75c</sup> G. Mandorli,<sup>75a,75c</sup> A. Messineo,<sup>75a,75b</sup>  
F. Palla,<sup>75a</sup> A. Rizzi,<sup>75a,75b</sup> P. Spagnolo,<sup>75a</sup> R. Tenchini,<sup>75a</sup> G. Tonelli,<sup>75a,75b</sup> A. Venturi,<sup>75a</sup> P. G. Verdini,<sup>75a</sup> L. Barone,<sup>76a,76b</sup>  
F. Cavallari,<sup>76a</sup> M. Cipriani,<sup>76a,76b</sup> N. Daci,<sup>76a</sup> D. Del Re,<sup>76a,76b</sup> E. Di Marco,<sup>76a,76b</sup> M. Diemoz,<sup>76a</sup> S. Gelli,<sup>76a,76b</sup>  
E. Longo,<sup>76a,76b</sup> B. Marzocchi,<sup>76a,76b</sup> P. Meridiani,<sup>76a</sup> G. Organtini,<sup>76a,76b</sup> F. Pandolfi,<sup>76a</sup> R. Paramatti,<sup>76a,76b</sup> F. Preiato,<sup>76a,76b</sup>  
S. Rahatlou,<sup>76a,76b</sup> C. Rovelli,<sup>76a</sup> F. Santanastasio,<sup>76a,76b</sup> N. Amapane,<sup>77a,77b</sup> R. Arcidiacono,<sup>77a,77c</sup> S. Argiro,<sup>77a,77b</sup>  
M. Arneodo,<sup>77a,77c</sup> N. Bartosik,<sup>77a</sup> R. Bellan,<sup>77a,77b</sup> C. Biino,<sup>77a</sup> N. Cartiglia,<sup>77a</sup> F. Cenna,<sup>77a,77b</sup> S. Cometti,<sup>77a</sup> M. Costa,<sup>77a,77b</sup>  
R. Covarelli,<sup>77a,77b</sup> N. Demaria,<sup>77a</sup> B. Kiani,<sup>77a,77b</sup> C. Mariotti,<sup>77a</sup> S. Maselli,<sup>77a</sup> E. Migliore,<sup>77a,77b</sup> V. Monaco,<sup>77a,77b</sup>  
E. Monteil,<sup>77a,77b</sup> M. Monteno,<sup>77a</sup> M. M. Obertino,<sup>77a,77b</sup> L. Pacher,<sup>77a,77b</sup> N. Pastrone,<sup>77a</sup> M. Pelliccioni,<sup>77a</sup>  
G. L. Pinna Angioni,<sup>77a,77b</sup> A. Romero,<sup>77a,77b</sup> M. Ruspa,<sup>77a,77c</sup> R. Sacchi,<sup>77a,77b</sup> K. Shchelina,<sup>77a,77b</sup> V. Sola,<sup>77a</sup>  
A. Solano,<sup>77a,77b</sup> D. Soldi,<sup>77a</sup> A. Staiano,<sup>77a</sup> S. Belforte,<sup>78a</sup> V. Candelise,<sup>78a,78b</sup> M. Casarsa,<sup>78a</sup> F. Cossutti,<sup>78a</sup>  
G. Della Ricca,<sup>78a,78b</sup> F. Vazzoler,<sup>78a,78b</sup> A. Zanetti,<sup>78a</sup> D. H. Kim,<sup>79</sup> G. N. Kim,<sup>79</sup> M. S. Kim,<sup>79</sup> J. Lee,<sup>79</sup> S. Lee,<sup>79</sup> S. W. Lee,<sup>79</sup>  
C. S. Moon,<sup>79</sup> Y. D. Oh,<sup>79</sup> S. Sekmen,<sup>79</sup> D. C. Son,<sup>79</sup> Y. C. Yang,<sup>79</sup> H. Kim,<sup>80</sup> D. H. Moon,<sup>80</sup> G. Oh,<sup>80</sup> J. Goh,<sup>81</sup> T. J. Kim,<sup>81</sup>  
S. Cho,<sup>82</sup> S. Choi,<sup>82</sup> Y. Go,<sup>82</sup> D. Gyun,<sup>82</sup> S. Ha,<sup>82</sup> B. Hong,<sup>82</sup> Y. Jo,<sup>82</sup> K. Lee,<sup>82</sup> K. S. Lee,<sup>82</sup> S. Lee,<sup>82</sup> J. Lim,<sup>82</sup> S. K. Park,<sup>82</sup>  
Y. Roh,<sup>82</sup> H. S. Kim,<sup>83</sup> J. Almond,<sup>84</sup> J. Kim,<sup>84</sup> J. S. Kim,<sup>84</sup> H. Lee,<sup>84</sup> K. Lee,<sup>84</sup> K. Nam,<sup>84</sup> S. B. Oh,<sup>84</sup> B. C. Radburn-Smith,<sup>84</sup>  
S. h. Seo,<sup>84</sup> U. K. Yang,<sup>84</sup> H. D. Yoo,<sup>84</sup> G. B. Yu,<sup>84</sup> H. Kim,<sup>85</sup> J. H. Kim,<sup>85</sup> J. S. H. Lee,<sup>85</sup> I. C. Park,<sup>85</sup> Y. Choi,<sup>86</sup> C. Hwang,<sup>86</sup>  
J. Lee,<sup>86</sup> I. Yu,<sup>86</sup> V. Dudenias,<sup>87</sup> A. Juodagalvis,<sup>87</sup> J. Vaitkus,<sup>87</sup> I. Ahmed,<sup>88</sup> Z. A. Ibrahim,<sup>88</sup> M. A. B. Md Ali,<sup>88,dd</sup>  
F. Mohamad Idris,<sup>88,ee</sup> W. A. T. Wan Abdullah,<sup>88</sup> M. N. Yusli,<sup>88</sup> Z. Zolkapli,<sup>88</sup> M. C. Duran-Osuna,<sup>89</sup> H. Castilla-Valdez,<sup>89</sup>  
E. De La Cruz-Burelo,<sup>89</sup> G. Ramirez-Sanchez,<sup>89</sup> I. Heredia-De La Cruz,<sup>89,ff</sup> R. I. Rabadan-Trejo,<sup>89</sup> R. Lopez-Fernandez,<sup>89</sup>  
J. Mejia Guisao,<sup>89</sup> R. Reyes-Almanza,<sup>89</sup> A. Sanchez-Hernandez,<sup>89</sup> S. Carrillo Moreno,<sup>90</sup> C. Oropeza Barrera,<sup>90</sup>  
F. Vazquez Valencia,<sup>90</sup> J. Eysermans,<sup>91</sup> I. Pedraza,<sup>91</sup> H. A. Salazar Ibarquen,<sup>91</sup> C. Uribe Estrada,<sup>91</sup> A. Morelos Pineda,<sup>92</sup>  
D. Krofcheck,<sup>93</sup> S. Bheesette,<sup>94</sup> P. H. Butler,<sup>94</sup> A. Ahmad,<sup>95</sup> M. Ahmad,<sup>95</sup> M. I. Asghar,<sup>95</sup> Q. Hassan,<sup>95</sup> H. R. Hoorani,<sup>95</sup>  
A. Saddique,<sup>95</sup> M. A. Shah,<sup>95</sup> M. Shoaib,<sup>95</sup> M. Waqas,<sup>95</sup> H. Bialkowska,<sup>96</sup> M. Bluj,<sup>96</sup> B. Boimska,<sup>96</sup> T. Frueboes,<sup>96</sup>  
M. Górski,<sup>96</sup> M. Kazana,<sup>96</sup> K. Nawrocki,<sup>96</sup> M. Szleper,<sup>96</sup> P. Traczyk,<sup>96</sup> P. Zalewski,<sup>96</sup> K. Bunkowski,<sup>97</sup> A. Byszuk,<sup>97,gg</sup>  
K. Doroba,<sup>97</sup> A. Kalinowski,<sup>97</sup> M. Konecki,<sup>97</sup> J. Krolikowski,<sup>97</sup> M. Misiura,<sup>97</sup> M. Olszewski,<sup>97</sup> A. Pyskir,<sup>97</sup> M. Walczak,<sup>97</sup>  
P. Bargassa,<sup>98</sup> C. Beirão Da Cruz E Silva,<sup>98</sup> A. Di Francesco,<sup>98</sup> P. Faccioli,<sup>98</sup> B. Galinhas,<sup>98</sup> M. Gallinaro,<sup>98</sup> J. Hollar,<sup>98</sup>  
N. Leonardo,<sup>98</sup> L. Lloret Iglesias,<sup>98</sup> M. V. Nemallapudi,<sup>98</sup> J. Seixas,<sup>98</sup> G. Strong,<sup>98</sup> O. Toldaiev,<sup>98</sup> D. Vadrucchio,<sup>98</sup> J. Varela,<sup>98</sup>  
S. Afanasiev,<sup>99</sup> P. Bunin,<sup>99</sup> M. Gavrilenko,<sup>99</sup> I. Golutvin,<sup>99</sup> I. Gorbunov,<sup>99</sup> A. Kamenev,<sup>99</sup> V. Karjavin,<sup>99</sup> A. Lanev,<sup>99</sup>  
A. Malakhov,<sup>99</sup> V. Matveev,<sup>99,hh,ii</sup> P. Moisenz,<sup>99</sup> V. Palichik,<sup>99</sup> V. Perelygin,<sup>99</sup> S. Shmatov,<sup>99</sup> S. Shulha,<sup>99</sup> N. Skatchkov,<sup>99</sup>  
V. Smirnov,<sup>99</sup> N. Voytishin,<sup>99</sup> A. Zarubin,<sup>99</sup> V. Golovtsov,<sup>100</sup> Y. Ivanov,<sup>100</sup> V. Kim,<sup>100,ij</sup> E. Kuznetsova,<sup>100,kk</sup> P. Levchenko,<sup>100</sup>  
V. Murzin,<sup>100</sup> V. Oreshkin,<sup>100</sup> I. Smirnov,<sup>100</sup> D. Sosnov,<sup>100</sup> V. Sulimov,<sup>100</sup> L. Uvarov,<sup>100</sup> S. Vavilov,<sup>100</sup> A. Vorobyev,<sup>100</sup>  
Yu. Andreev,<sup>101</sup> A. Dermenev,<sup>101</sup> S. Gninenko,<sup>101</sup> N. Golubev,<sup>101</sup> A. Karneyeu,<sup>101</sup> M. Kirsanov,<sup>101</sup> N. Krasnikov,<sup>101</sup>  
A. Pashenkov,<sup>101</sup> D. Tlisov,<sup>101</sup> A. Toropin,<sup>101</sup> V. Epshteyn,<sup>102</sup> V. Gavrilo,<sup>102</sup> N. Lychkovskaya,<sup>102</sup> V. Popov,<sup>102</sup>  
I. Pozdnyakov,<sup>102</sup> G. Safronov,<sup>102</sup> A. Spiridonov,<sup>102</sup> A. Stepenov,<sup>102</sup> V. Stolin,<sup>102</sup> M. Toms,<sup>102</sup> E. Vlasov,<sup>102</sup> A. Zhokin,<sup>102</sup>  
T. Aushv,<sup>103</sup> A. Bylinkin,<sup>103,ii</sup> R. Chistov,<sup>104,ll</sup> M. Danilov,<sup>104,ll</sup> P. Parygin,<sup>104</sup> D. Philippov,<sup>104</sup> S. Polikarpov,<sup>104,ll</sup>  
E. Tarkovskii,<sup>104</sup> V. Andreev,<sup>105</sup> M. Azarkin,<sup>105,ii</sup> I. Dremin,<sup>105,ii</sup> M. Kirakosyan,<sup>105,ii</sup> S. V. Rusakov,<sup>105</sup> A. Terkulov,<sup>105</sup>  
A. Baskakov,<sup>106</sup> A. Belyaev,<sup>106</sup> E. Boos,<sup>106</sup> A. Ershov,<sup>106</sup> A. Gribushin,<sup>106</sup> A. Kaminskiy,<sup>106,mmm</sup> O. Kodolova,<sup>106</sup>  
V. Korotkikh,<sup>106</sup> I. Lokhtin,<sup>106</sup> I. Miagkov,<sup>106</sup> S. Obraztsov,<sup>106</sup> S. Petrushanko,<sup>106</sup> V. Savrin,<sup>106</sup> A. Snigirev,<sup>106</sup>  
I. Vardanyan,<sup>106</sup> V. Blinov,<sup>107,nn</sup> T. Dimova,<sup>107,nn</sup> L. Kardapoltsev,<sup>107,nn</sup> D. Shtol,<sup>107,nn</sup> Y. Skovpen,<sup>107,nn</sup> I. Azhgirey,<sup>108</sup>  
I. Bayshev,<sup>108</sup> S. Bitioukov,<sup>108</sup> D. Elumakhov,<sup>108</sup> A. Godizov,<sup>108</sup> V. Kachanov,<sup>108</sup> A. Kalinin,<sup>108</sup> D. Konstantinov,<sup>108</sup>  
P. Mandrik,<sup>108</sup> V. Petrov,<sup>108</sup> R. Ryutin,<sup>108</sup> S. Slabospitskii,<sup>108</sup> A. Sobol,<sup>108</sup> S. Troshin,<sup>108</sup> N. Tyurin,<sup>108</sup> A. Uzunian,<sup>108</sup>  
A. Volkov,<sup>108</sup> A. Babaev,<sup>109</sup> S. Baidali,<sup>109</sup> P. Adzic,<sup>110,oo</sup> P. Cirkovic,<sup>110</sup> D. Devetak,<sup>110</sup> M. Dordevic,<sup>110</sup> J. Milosevic,<sup>110</sup>  
J. Alcaraz Maestre,<sup>111</sup> A. Álvarez Fernández,<sup>111</sup> I. Bachiller,<sup>111</sup> M. Barrio Luna,<sup>111</sup> J. A. Brochero Cifuentes,<sup>111</sup>

M. Cerrada,<sup>111</sup> N. Colino,<sup>111</sup> B. De La Cruz,<sup>111</sup> A. Delgado Peris,<sup>111</sup> C. Fernandez Bedoya,<sup>111</sup> J. P. Fernández Ramos,<sup>111</sup>  
 J. Flix,<sup>111</sup> M. C. Fouz,<sup>111</sup> O. Gonzalez Lopez,<sup>111</sup> S. Goy Lopez,<sup>111</sup> J. M. Hernandez,<sup>111</sup> M. I. Josa,<sup>111</sup> D. Moran,<sup>111</sup>  
 A. Pérez-Calero Yzquierdo,<sup>111</sup> J. Puerta Pelayo,<sup>111</sup> I. Redondo,<sup>111</sup> L. Romero,<sup>111</sup> M. S. Soares,<sup>111</sup> A. Triossi,<sup>111</sup>  
 C. Albajar,<sup>112</sup> J. F. de Trocóniz,<sup>112</sup> J. Cuevas,<sup>113</sup> C. Erice,<sup>113</sup> J. Fernandez Menendez,<sup>113</sup> S. Folgueras,<sup>113</sup>  
 I. Gonzalez Caballero,<sup>113</sup> J. R. González Fernández,<sup>113</sup> E. Palencia Cortezon,<sup>113</sup> V. Rodríguez Bouza,<sup>113</sup> S. Sanchez Cruz,<sup>113</sup>  
 P. Vischia,<sup>113</sup> J. M. Vizán García,<sup>113</sup> I. J. Cabrillo,<sup>114</sup> A. Calderon,<sup>114</sup> B. Chazin Quero,<sup>114</sup> J. Duarte Campderros,<sup>114</sup>  
 M. Fernandez,<sup>114</sup> P. J. Fernández Manteca,<sup>114</sup> A. García Alonso,<sup>114</sup> J. Garcia-Ferrero,<sup>114</sup> G. Gomez,<sup>114</sup> A. Lopez Virto,<sup>114</sup>  
 J. Marco,<sup>114</sup> C. Martinez Rivero,<sup>114</sup> P. Martinez Ruiz del Arbol,<sup>114</sup> F. Matorras,<sup>114</sup> J. Piedra Gomez,<sup>114</sup> C. Prieels,<sup>114</sup>  
 T. Rodrigo,<sup>114</sup> A. Ruiz-Jimeno,<sup>114</sup> L. Scodellaro,<sup>114</sup> N. Trevisani,<sup>114</sup> I. Vila,<sup>114</sup> R. Vilar Cortabitarte,<sup>114</sup> D. Abbaneo,<sup>115</sup>  
 B. Akgun,<sup>115</sup> E. Auffray,<sup>115</sup> P. Baillon,<sup>115</sup> A. H. Ball,<sup>115</sup> D. Barney,<sup>115</sup> J. Bendavid,<sup>115</sup> M. Bianco,<sup>115</sup> A. Bocci,<sup>115</sup> C. Botta,<sup>115</sup>  
 T. Camporesi,<sup>115</sup> M. Cepeda,<sup>115</sup> G. Cerminara,<sup>115</sup> E. Chapon,<sup>115</sup> Y. Chen,<sup>115</sup> G. Cucciati,<sup>115</sup> D. d'Enterria,<sup>115</sup>  
 A. Dabrowski,<sup>115</sup> V. Daponte,<sup>115</sup> A. David,<sup>115</sup> A. De Roeck,<sup>115</sup> N. Deelen,<sup>115</sup> M. Dobson,<sup>115</sup> T. du Pree,<sup>115</sup> M. Dünser,<sup>115</sup>  
 N. Dupont,<sup>115</sup> A. Elliott-Peisert,<sup>115</sup> P. Everaerts,<sup>115</sup> F. Fallavollita,<sup>115,pp</sup> D. Fasanella,<sup>115</sup> G. Franzoni,<sup>115</sup> J. Fulcher,<sup>115</sup>  
 W. Funk,<sup>115</sup> D. Gigi,<sup>115</sup> A. Gilbert,<sup>115</sup> K. Gill,<sup>115</sup> F. Glege,<sup>115</sup> D. Gulhan,<sup>115</sup> J. Hegeman,<sup>115</sup> V. Innocente,<sup>115</sup> A. Jafari,<sup>115</sup>  
 P. Janot,<sup>115</sup> O. Karacheban,<sup>115,s</sup> J. Kieseler,<sup>115</sup> A. Kornmayer,<sup>115</sup> M. Krammer,<sup>115,b</sup> C. Lange,<sup>115</sup> P. Lecoq,<sup>115</sup> C. Lourenço,<sup>115</sup>  
 L. Malgeri,<sup>115</sup> M. Mannelli,<sup>115</sup> F. Meijers,<sup>115</sup> J. A. Merlin,<sup>115</sup> S. Mersi,<sup>115</sup> E. Meschi,<sup>115</sup> P. Milenovic,<sup>115,qq</sup> F. Moortgat,<sup>115</sup>  
 M. Mulders,<sup>115</sup> J. Ngadiuba,<sup>115</sup> S. Orfanelli,<sup>115</sup> L. Orsini,<sup>115</sup> F. Pantaleo,<sup>115,p</sup> L. Pape,<sup>115</sup> E. Perez,<sup>115</sup> M. Peruzzi,<sup>115</sup>  
 A. Petrilli,<sup>115</sup> G. Petrucciani,<sup>115</sup> A. Pfeiffer,<sup>115</sup> M. Pierini,<sup>115</sup> F. M. Pitters,<sup>115</sup> D. Rabady,<sup>115</sup> A. Racz,<sup>115</sup> T. Reis,<sup>115</sup>  
 G. Rolandi,<sup>115,rr</sup> M. Rovere,<sup>115</sup> H. Sakulin,<sup>115</sup> C. Schäfer,<sup>115</sup> C. Schwick,<sup>115</sup> M. Seidel,<sup>115</sup> M. Selvaggi,<sup>115</sup> A. Sharma,<sup>115</sup>  
 P. Silva,<sup>115</sup> P. Sphicas,<sup>115,ss</sup> A. Stakia,<sup>115</sup> J. Steggemann,<sup>115</sup> M. Tosi,<sup>115</sup> D. Treille,<sup>115</sup> A. Tsirou,<sup>115</sup> V. Veckalns,<sup>115,tt</sup>  
 W. D. Zeuner,<sup>115</sup> W. Bertl,<sup>116,a</sup> L. Caminada,<sup>116,uu</sup> K. Deiters,<sup>116</sup> W. Erdmann,<sup>116</sup> R. Horisberger,<sup>116</sup> Q. Ingram,<sup>116</sup>  
 H. C. Kaestli,<sup>116</sup> D. Kotlinski,<sup>116</sup> U. Langenegger,<sup>116</sup> T. Rohe,<sup>116</sup> S. A. Wiederkehr,<sup>116</sup> M. Backhaus,<sup>117</sup> L. Bäni,<sup>117</sup>  
 P. Berger,<sup>117</sup> N. Chernyavskaya,<sup>117</sup> G. Dissertori,<sup>117</sup> M. Dittmar,<sup>117</sup> M. Donegà,<sup>117</sup> C. Dorfer,<sup>117</sup> C. Grab,<sup>117</sup> C. Heidegger,<sup>117</sup>  
 D. Hits,<sup>117</sup> J. Hoss,<sup>117</sup> T. Klijnsma,<sup>117</sup> W. Lustermann,<sup>117</sup> R. A. Manzoni,<sup>117</sup> M. Marionneau,<sup>117</sup> M. T. Meinhard,<sup>117</sup>  
 D. Meister,<sup>117</sup> F. Micheli,<sup>117</sup> P. Musella,<sup>117</sup> F. Nessi-Tedaldi,<sup>117</sup> J. Pata,<sup>117</sup> F. Pauss,<sup>117</sup> G. Perrin,<sup>117</sup> L. Perrozzi,<sup>117</sup>  
 S. Pigazzini,<sup>117</sup> M. Quittnat,<sup>117</sup> M. Reichmann,<sup>117</sup> D. Ruini,<sup>117</sup> D. A. Sanz Becerra,<sup>117</sup> M. Schönenberger,<sup>117</sup> L. Shchutska,<sup>117</sup>  
 V. R. Tavolaro,<sup>117</sup> K. Theofilatos,<sup>117</sup> M. L. Vesterbacka Olsson,<sup>117</sup> R. Wallny,<sup>117</sup> D. H. Zhu,<sup>117</sup> T. K. Aarrestad,<sup>118</sup>  
 C. Amsler,<sup>118,vv</sup> D. Brzhechko,<sup>118</sup> M. F. Canelli,<sup>118</sup> A. De Cosa,<sup>118</sup> R. Del Burgo,<sup>118</sup> S. Donato,<sup>118</sup> C. Galloni,<sup>118</sup> T. Hreus,<sup>118</sup>  
 B. Kilminster,<sup>118</sup> I. Neutelings,<sup>118</sup> D. Pinna,<sup>118</sup> G. Rauco,<sup>118</sup> P. Robmann,<sup>118</sup> D. Salerno,<sup>118</sup> K. Schweiger,<sup>118</sup> C. Seitz,<sup>118</sup>  
 Y. Takahashi,<sup>118</sup> A. Zucchetta,<sup>118</sup> Y. H. Chang,<sup>119</sup> K. y. Cheng,<sup>119</sup> T. H. Doan,<sup>119</sup> Sh. Jain,<sup>119</sup> R. Khurana,<sup>119</sup> C. M. Kuo,<sup>119</sup>  
 W. Lin,<sup>119</sup> A. Pozdnyakov,<sup>119</sup> S. S. Yu,<sup>119</sup> P. Chang,<sup>120</sup> Y. Chao,<sup>120</sup> K. F. Chen,<sup>120</sup> P. H. Chen,<sup>120</sup> W.-S. Hou,<sup>120</sup>  
 Arun Kumar,<sup>120</sup> Y. y. Li,<sup>120</sup> R.-S. Lu,<sup>120</sup> E. Paganis,<sup>120</sup> A. Psallidas,<sup>120</sup> A. Steen,<sup>120</sup> J. f. Tsai,<sup>120</sup> B. Asavapibhop,<sup>121</sup>  
 N. Srimanobhas,<sup>121</sup> N. Suwonjandee,<sup>121</sup> A. Bat,<sup>122</sup> F. Boran,<sup>122</sup> S. Cerci,<sup>122,ww</sup> S. Damarseckin,<sup>122</sup> Z. S. Demiroglu,<sup>122</sup>  
 C. Dozen,<sup>122</sup> I. Dumanoglu,<sup>122</sup> S. Girgis,<sup>122</sup> G. Gokbulut,<sup>122</sup> Y. Guler,<sup>122</sup> E. Gurbinar,<sup>122</sup> I. Hos,<sup>122,xx</sup> E. E. Kangal,<sup>122,yy</sup>  
 O. Kara,<sup>122</sup> A. Kayis Topaksu,<sup>122</sup> U. Kiminsu,<sup>122</sup> M. Oglakci,<sup>122</sup> G. Onengut,<sup>122</sup> K. Ozdemir,<sup>122,zz</sup> S. Ozturk,<sup>122,aaa</sup>  
 D. Sunar Cerci,<sup>122,ww</sup> B. Tali,<sup>122,ww</sup> U. G. Tok,<sup>122</sup> S. Turkcapar,<sup>122</sup> I. S. Zorbakir,<sup>122</sup> C. Zorbilmez,<sup>122</sup> B. Isildak,<sup>123,bbb</sup>  
 G. Karapinar,<sup>123,ccc</sup> M. Yalvac,<sup>123</sup> M. Zeyrek,<sup>123</sup> I. O. Atakisi,<sup>124</sup> E. Gülmez,<sup>124</sup> M. Kaya,<sup>124,ddd</sup> O. Kaya,<sup>124,eee</sup> S. Tekten,<sup>124</sup>  
 E. A. Yetkin,<sup>124,fff</sup> M. N. Agaras,<sup>125</sup> S. Atay,<sup>125</sup> A. Cakir,<sup>125</sup> K. Cankocak,<sup>125</sup> Y. Komurcu,<sup>125</sup> S. Sen,<sup>125,ggg</sup> B. Grynyov,<sup>126</sup>  
 L. Levchuk,<sup>127</sup> F. Ball,<sup>128</sup> L. Beck,<sup>128</sup> J. J. Brooke,<sup>128</sup> D. Burns,<sup>128</sup> E. Clement,<sup>128</sup> D. Cussans,<sup>128</sup> O. Davignon,<sup>128</sup>  
 H. Flacher,<sup>128</sup> J. Goldstein,<sup>128</sup> G. P. Heath,<sup>128</sup> H. F. Heath,<sup>128</sup> L. Kreczko,<sup>128</sup> D. M. Newbold,<sup>128,hhh</sup> S. Paramesvaran,<sup>128</sup>  
 B. Penning,<sup>128</sup> T. Sakuma,<sup>128</sup> D. Smith,<sup>128</sup> V. J. Smith,<sup>128</sup> J. Taylor,<sup>128</sup> A. Titterton,<sup>128</sup> A. Belyaev,<sup>129,iii</sup> C. Brew,<sup>129</sup>  
 R. M. Brown,<sup>129</sup> D. Cieri,<sup>129</sup> D. J. A. Cockerill,<sup>129</sup> J. A. Coughlan,<sup>129</sup> K. Harder,<sup>129</sup> S. Harper,<sup>129</sup> J. Linacre,<sup>129</sup> E. Olaiya,<sup>129</sup>  
 D. Petyt,<sup>129</sup> C. H. Shepherd-Themistocleous,<sup>129</sup> A. Thea,<sup>129</sup> I. R. Tomalin,<sup>129</sup> T. Williams,<sup>129</sup> W. J. Womersley,<sup>129</sup>  
 G. Auzinger,<sup>130</sup> R. Bainbridge,<sup>130</sup> P. Bloch,<sup>130</sup> J. Borg,<sup>130</sup> S. Breeze,<sup>130</sup> O. Buchmuller,<sup>130</sup> A. Bundock,<sup>130</sup> S. Casasso,<sup>130</sup>  
 D. Colling,<sup>130</sup> L. Corpe,<sup>130</sup> P. Dauncey,<sup>130</sup> G. Davies,<sup>130</sup> M. Della Negra,<sup>130</sup> R. Di Maria,<sup>130</sup> Y. Haddad,<sup>130</sup> G. Hall,<sup>130</sup>  
 G. Iles,<sup>130</sup> T. James,<sup>130</sup> M. Komm,<sup>130</sup> C. Laner,<sup>130</sup> L. Lyons,<sup>130</sup> A.-M. Magnan,<sup>130</sup> S. Malik,<sup>130</sup> A. Martelli,<sup>130</sup> J. Nash,<sup>130,jjj</sup>  
 A. Nikitenko,<sup>130,g</sup> V. Palladino,<sup>130</sup> M. Pesaresi,<sup>130</sup> A. Richards,<sup>130</sup> A. Rose,<sup>130</sup> E. Scott,<sup>130</sup> C. Seez,<sup>130</sup> A. Shtipliyski,<sup>130</sup>  
 T. Strebler,<sup>130</sup> S. Summers,<sup>130</sup> A. Tapper,<sup>130</sup> K. Uchida,<sup>130</sup> T. Virdee,<sup>130,p</sup> N. Wardle,<sup>130</sup> D. Winterbottom,<sup>130</sup> J. Wright,<sup>130</sup>  
 S. C. Zenz,<sup>130</sup> J. E. Cole,<sup>131</sup> P. R. Hobson,<sup>131</sup> A. Khan,<sup>131</sup> P. Kyberd,<sup>131</sup> C. K. Mackay,<sup>131</sup> A. Morton,<sup>131</sup> I. D. Reid,<sup>131</sup>

L. Teodorescu,<sup>131</sup> S. Zahid,<sup>131</sup> K. Call,<sup>132</sup> J. Dittmann,<sup>132</sup> K. Hatakeyama,<sup>132</sup> H. Liu,<sup>132</sup> C. Madrid,<sup>132</sup> B. McMaster,<sup>132</sup>  
 N. Pastika,<sup>132</sup> C. Smith,<sup>132</sup> R. Bartek,<sup>133</sup> A. Dominguez,<sup>133</sup> A. Buccilli,<sup>134</sup> S. I. Cooper,<sup>134</sup> C. Henderson,<sup>134</sup> P. Rumerio,<sup>134</sup>  
 C. West,<sup>134</sup> D. Arcaro,<sup>135</sup> T. Bose,<sup>135</sup> D. Gastler,<sup>135</sup> D. Rankin,<sup>135</sup> C. Richardson,<sup>135</sup> J. Rohlf,<sup>135</sup> L. Sulak,<sup>135</sup> D. Zou,<sup>135</sup>  
 G. Benelli,<sup>136</sup> X. Coubez,<sup>136</sup> D. Cutts,<sup>136</sup> M. Hadley,<sup>136</sup> J. Hakala,<sup>136</sup> U. Heintz,<sup>136</sup> J. M. Hogan,<sup>136,kkk</sup> K. H. M. Kwok,<sup>136</sup>  
 E. Laird,<sup>136</sup> G. Landsberg,<sup>136</sup> J. Lee,<sup>136</sup> Z. Mao,<sup>136</sup> M. Narain,<sup>136</sup> J. Pazzini,<sup>136</sup> S. Piperov,<sup>136</sup> S. Sagir,<sup>136,lll</sup> R. Syarif,<sup>136</sup>  
 D. Yu,<sup>136</sup> R. Band,<sup>137</sup> C. Brainerd,<sup>137</sup> R. Breedon,<sup>137</sup> D. Burns,<sup>137</sup> M. Calderon De La Barca Sanchez,<sup>137</sup> M. Chertok,<sup>137</sup>  
 J. Conway,<sup>137</sup> R. Conway,<sup>137</sup> P. T. Cox,<sup>137</sup> R. Erbacher,<sup>137</sup> C. Flores,<sup>137</sup> G. Funk,<sup>137</sup> W. Ko,<sup>137</sup> O. Kukral,<sup>137</sup> R. Lander,<sup>137</sup>  
 C. Mclean,<sup>137</sup> M. Mulhearn,<sup>137</sup> D. Pellett,<sup>137</sup> J. Pilot,<sup>137</sup> S. Shalhout,<sup>137</sup> M. Shi,<sup>137</sup> D. Stolp,<sup>137</sup> D. Taylor,<sup>137</sup> K. Tos,<sup>137</sup>  
 M. Tripathi,<sup>137</sup> Z. Wang,<sup>137</sup> F. Zhang,<sup>137</sup> M. Bachtis,<sup>138</sup> C. Bravo,<sup>138</sup> R. Cousins,<sup>138</sup> A. Dasgupta,<sup>138</sup> A. Florent,<sup>138</sup>  
 J. Hauser,<sup>138</sup> M. Ignatenko,<sup>138</sup> N. Mccoll,<sup>138</sup> S. Regnard,<sup>138</sup> D. Saltzberg,<sup>138</sup> C. Schnaible,<sup>138</sup> V. Valuev,<sup>138</sup> E. Bouvier,<sup>139</sup>  
 K. Burt,<sup>139</sup> R. Clare,<sup>139</sup> J. W. Gary,<sup>139</sup> S. M. A. Ghiasi Shirazi,<sup>139</sup> G. Hanson,<sup>139</sup> G. Karapostoli,<sup>139</sup> E. Kennedy,<sup>139</sup>  
 F. Lacroix,<sup>139</sup> O. R. Long,<sup>139</sup> M. Olmedo Negrete,<sup>139</sup> M. I. Paneva,<sup>139</sup> W. Si,<sup>139</sup> L. Wang,<sup>139</sup> H. Wei,<sup>139</sup> S. Wimpenny,<sup>139</sup>  
 B. R. Yates,<sup>139</sup> J. G. Branson,<sup>140</sup> S. Cittolin,<sup>140</sup> M. Derdzinski,<sup>140</sup> R. Gerosa,<sup>140</sup> D. Gilbert,<sup>140</sup> B. Hashemi,<sup>140</sup> A. Holzner,<sup>140</sup>  
 D. Klein,<sup>140</sup> G. Kole,<sup>140</sup> V. Krutelyov,<sup>140</sup> J. Letts,<sup>140</sup> M. Masciovecchio,<sup>140</sup> D. Olivito,<sup>140</sup> S. Padhi,<sup>140</sup> M. Pieri,<sup>140</sup> M. Sani,<sup>140</sup>  
 V. Sharma,<sup>140</sup> S. Simon,<sup>140</sup> M. Tadel,<sup>140</sup> A. Vartak,<sup>140</sup> S. Wasserbaech,<sup>140,mmm</sup> J. Wood,<sup>140</sup> F. Würthwein,<sup>140</sup> A. Yagil,<sup>140</sup>  
 G. Zevi Della Porta,<sup>140</sup> N. Amin,<sup>141</sup> R. Bhandari,<sup>141</sup> J. Bradmiller-Feld,<sup>141</sup> C. Campagnari,<sup>141</sup> M. Citron,<sup>141</sup> A. Dishaw,<sup>141</sup>  
 V. Dutta,<sup>141</sup> M. Franco Sevilla,<sup>141</sup> L. Gouskos,<sup>141</sup> R. Heller,<sup>141</sup> J. Incandela,<sup>141</sup> A. Ovcharova,<sup>141</sup> H. Qu,<sup>141</sup> J. Richman,<sup>141</sup>  
 D. Stuart,<sup>141</sup> I. Suarez,<sup>141</sup> S. Wang,<sup>141</sup> J. Yoo,<sup>141</sup> D. Anderson,<sup>142</sup> A. Bornheim,<sup>142</sup> J. M. Lawhorn,<sup>142</sup> H. B. Newman,<sup>142</sup>  
 T. Q. Nguyen,<sup>142</sup> M. Spiropulu,<sup>142</sup> J. R. Vlimant,<sup>142</sup> R. Wilkinson,<sup>142</sup> S. Xie,<sup>142</sup> Z. Zhang,<sup>142</sup> R. Y. Zhu,<sup>142</sup> M. B. Andrews,<sup>143</sup>  
 T. Ferguson,<sup>143</sup> T. Mudholkar,<sup>143</sup> M. Paulini,<sup>143</sup> M. Sun,<sup>143</sup> I. Vorobiev,<sup>143</sup> M. Weinberg,<sup>143</sup> J. P. Cumalat,<sup>144</sup> W. T. Ford,<sup>144</sup>  
 F. Jensen,<sup>144</sup> A. Johnson,<sup>144</sup> M. Krohn,<sup>144</sup> S. Leontsinis,<sup>144</sup> E. MacDonald,<sup>144</sup> T. Mulholland,<sup>144</sup> K. Stenson,<sup>144</sup>  
 K. A. Ulmer,<sup>144</sup> S. R. Wagner,<sup>144</sup> J. Alexander,<sup>145</sup> J. Chaves,<sup>145</sup> Y. Cheng,<sup>145</sup> J. Chu,<sup>145</sup> A. Datta,<sup>145</sup> K. Mcdermott,<sup>145</sup>  
 N. Mirman,<sup>145</sup> J. R. Patterson,<sup>145</sup> D. Quach,<sup>145</sup> A. Rinkevicius,<sup>145</sup> A. Ryd,<sup>145</sup> L. Skinnari,<sup>145</sup> L. Soffi,<sup>145</sup> S. M. Tan,<sup>145</sup>  
 Z. Tao,<sup>145</sup> J. Thom,<sup>145</sup> J. Tucker,<sup>145</sup> P. Wittich,<sup>145</sup> M. Zientek,<sup>145</sup> S. Abdullin,<sup>146</sup> M. Albrow,<sup>146</sup> M. Alyari,<sup>146</sup> G. Apollinari,<sup>146</sup>  
 A. Apresyan,<sup>146</sup> A. Apyan,<sup>146</sup> S. Banerjee,<sup>146</sup> L. A. T. Bauerdick,<sup>146</sup> A. Beretvas,<sup>146</sup> J. Berryhill,<sup>146</sup> P. C. Bhat,<sup>146</sup>  
 G. Bolla,<sup>146,a</sup> K. Burkett,<sup>146</sup> J. N. Butler,<sup>146</sup> A. Canepa,<sup>146</sup> G. B. Cerati,<sup>146</sup> H. W. K. Cheung,<sup>146</sup> F. Chlebana,<sup>146</sup>  
 M. Cremonesi,<sup>146</sup> J. Duarte,<sup>146</sup> V. D. Elvira,<sup>146</sup> J. Freeman,<sup>146</sup> Z. Geise,<sup>146</sup> E. Gottschalk,<sup>146</sup> L. Gray,<sup>146</sup> D. Green,<sup>146</sup>  
 S. Grünendahl,<sup>146</sup> O. Gutsche,<sup>146</sup> J. Hanlon,<sup>146</sup> R. M. Harris,<sup>146</sup> S. Hasegawa,<sup>146</sup> J. Hirschauer,<sup>146</sup> Z. Hu,<sup>146</sup> B. Jayatilaka,<sup>146</sup>  
 S. Jindariani,<sup>146</sup> M. Johnson,<sup>146</sup> U. Joshi,<sup>146</sup> B. Klima,<sup>146</sup> M. J. Kortelainen,<sup>146</sup> B. Kreis,<sup>146</sup> S. Lammel,<sup>146</sup> D. Lincoln,<sup>146</sup>  
 R. Lipton,<sup>146</sup> M. Liu,<sup>146</sup> T. Liu,<sup>146</sup> J. Lykken,<sup>146</sup> K. Maeshima,<sup>146</sup> J. M. Marraffino,<sup>146</sup> D. Mason,<sup>146</sup> P. McBride,<sup>146</sup>  
 P. Merkel,<sup>146</sup> S. Mrenna,<sup>146</sup> S. Nahn,<sup>146</sup> V. O'Dell,<sup>146</sup> K. Pedro,<sup>146</sup> O. Prokofyev,<sup>146</sup> G. Rakness,<sup>146</sup> L. Ristori,<sup>146</sup>  
 A. Savoy-Navarro,<sup>146,nnn</sup> B. Schneider,<sup>146</sup> E. Sexton-Kennedy,<sup>146</sup> A. Soha,<sup>146</sup> W. J. Spalding,<sup>146</sup> L. Spiegel,<sup>146</sup> S. Stoynev,<sup>146</sup>  
 J. Strait,<sup>146</sup> N. Strobbe,<sup>146</sup> L. Taylor,<sup>146</sup> S. Tkaczyk,<sup>146</sup> N. V. Tran,<sup>146</sup> L. Uplegger,<sup>146</sup> E. W. Vaandering,<sup>146</sup> C. Vernieri,<sup>146</sup>  
 M. Verzocchi,<sup>146</sup> R. Vidal,<sup>146</sup> M. Wang,<sup>146</sup> H. A. Weber,<sup>146</sup> A. Whitbeck,<sup>146</sup> D. Acosta,<sup>147</sup> P. Avery,<sup>147</sup> P. Bortignon,<sup>147</sup>  
 D. Bourilkov,<sup>147</sup> A. Brinkerhoff,<sup>147</sup> L. Cadamuro,<sup>147</sup> A. Carnes,<sup>147</sup> M. Carver,<sup>147</sup> D. Curry,<sup>147</sup> R. D. Field,<sup>147</sup> S. V. Gleyzer,<sup>147</sup>  
 B. M. Joshi,<sup>147</sup> J. Konigsberg,<sup>147</sup> A. Korytov,<sup>147</sup> P. Ma,<sup>147</sup> K. Matchev,<sup>147</sup> H. Mei,<sup>147</sup> G. Mitselmakher,<sup>147</sup> K. Shi,<sup>147</sup>  
 D. Sperka,<sup>147</sup> J. Wang,<sup>147</sup> S. Wang,<sup>147</sup> Y. R. Joshi,<sup>148</sup> S. Linn,<sup>148</sup> A. Ackert,<sup>149</sup> T. Adams,<sup>149</sup> A. Askew,<sup>149</sup> S. Hagopian,<sup>149</sup>  
 V. Hagopian,<sup>149</sup> K. F. Johnson,<sup>149</sup> T. Kolberg,<sup>149</sup> G. Martinez,<sup>149</sup> T. Perry,<sup>149</sup> H. Prosper,<sup>149</sup> A. Saha,<sup>149</sup> A. Santra,<sup>149</sup>  
 V. Sharma,<sup>149</sup> R. Yohay,<sup>149</sup> M. M. Baarmand,<sup>150</sup> V. Bhopatkar,<sup>150</sup> S. Colafranceschi,<sup>150</sup> M. Hohlmann,<sup>150</sup> D. Noonan,<sup>150</sup>  
 M. Rahmani,<sup>150</sup> T. Roy,<sup>150</sup> F. Yumiceva,<sup>150</sup> M. R. Adams,<sup>151</sup> L. Apanasevich,<sup>151</sup> D. Berry,<sup>151</sup> R. R. Betts,<sup>151</sup>  
 R. Cavanaugh,<sup>151</sup> X. Chen,<sup>151</sup> S. Dittmer,<sup>151</sup> O. Evdokimov,<sup>151</sup> C. E. Gerber,<sup>151</sup> D. A. Hangal,<sup>151</sup> D. J. Hofman,<sup>151</sup>  
 K. Jung,<sup>151</sup> J. Kamin,<sup>151</sup> C. Mills,<sup>151</sup> I. D. Sandoval Gonzalez,<sup>151</sup> M. B. Tonjes,<sup>151</sup> N. Varelas,<sup>151</sup> H. Wang,<sup>151</sup> Z. Wu,<sup>151</sup>  
 J. Zhang,<sup>151</sup> M. Alhousseini,<sup>152</sup> B. Bilki,<sup>152,ooo</sup> W. Clarida,<sup>152</sup> K. Dilsiz,<sup>152,ppp</sup> S. Durgut,<sup>152</sup> R. P. Gandrajula,<sup>152</sup>  
 M. Haytmyradov,<sup>152</sup> V. Khristenko,<sup>152</sup> J.-P. Merlo,<sup>152</sup> A. Mestvirishvili,<sup>152</sup> A. Moeller,<sup>152</sup> J. Nachtman,<sup>152</sup> H. Ogul,<sup>152,qqq</sup>  
 Y. Onel,<sup>152</sup> F. Ozok,<sup>152,rrr</sup> A. Penzo,<sup>152</sup> C. Snyder,<sup>152</sup> E. Tiras,<sup>152</sup> J. Wetzel,<sup>152</sup> B. Blumenfeld,<sup>153</sup> A. Cocoros,<sup>153</sup>  
 N. Eminizer,<sup>153</sup> D. Fehling,<sup>153</sup> L. Feng,<sup>153</sup> A. V. Gritsan,<sup>153</sup> W. T. Hung,<sup>153</sup> P. Maksimovic,<sup>153</sup> J. Roskes,<sup>153</sup> U. Sarica,<sup>153</sup>  
 M. Swartz,<sup>153</sup> M. Xiao,<sup>153</sup> C. You,<sup>153</sup> A. Al-bataineh,<sup>154</sup> P. Baringer,<sup>154</sup> A. Bean,<sup>154</sup> S. Boren,<sup>154</sup> J. Bowen,<sup>154</sup> J. Castle,<sup>154</sup>  
 S. Khalil,<sup>154</sup> A. Kropivnitskaya,<sup>154</sup> D. Majumder,<sup>154</sup> W. Mcbrayer,<sup>154</sup> M. Murray,<sup>154</sup> C. Rogan,<sup>154</sup> S. Sanders,<sup>154</sup>  
 E. Schmitz,<sup>154</sup> J. D. Tapia Takaki,<sup>154</sup> Q. Wang,<sup>154</sup> A. Ivanov,<sup>155</sup> K. Kaadze,<sup>155</sup> D. Kim,<sup>155</sup> Y. Maravin,<sup>155</sup> D. R. Mendis,<sup>155</sup>

T. Mitchell,<sup>155</sup> A. Modak,<sup>155</sup> A. Mohammadi,<sup>155</sup> L. K. Saini,<sup>155</sup> N. Skhirtladze,<sup>155</sup> F. Rebassoo,<sup>156</sup> D. Wright,<sup>156</sup> A. Baden,<sup>157</sup> O. Baron,<sup>157</sup> A. Belloni,<sup>157</sup> S. C. Eno,<sup>157</sup> Y. Feng,<sup>157</sup> C. Ferraioli,<sup>157</sup> N. J. Hadley,<sup>157</sup> S. Jabeen,<sup>157</sup> G. Y. Jeng,<sup>157</sup> R. G. Kellogg,<sup>157</sup> J. Kunkle,<sup>157</sup> A. C. Mignerey,<sup>157</sup> F. Ricci-Tam,<sup>157</sup> Y. H. Shin,<sup>157</sup> A. Skuja,<sup>157</sup> S. C. Tonwar,<sup>157</sup> K. Wong,<sup>157</sup> D. Abercrombie,<sup>158</sup> B. Allen,<sup>158</sup> V. Azzolini,<sup>158</sup> R. Barbieri,<sup>158</sup> A. Baty,<sup>158</sup> G. Bauer,<sup>158</sup> R. Bi,<sup>158</sup> S. Brandt,<sup>158</sup> W. Busza,<sup>158</sup> I. A. Cali,<sup>158</sup> M. D'Alfonso,<sup>158</sup> Z. Demiragli,<sup>158</sup> G. Gomez Ceballos,<sup>158</sup> M. Goncharov,<sup>158</sup> P. Harris,<sup>158</sup> D. Hsu,<sup>158</sup> M. Hu,<sup>158</sup> Y. Iiyama,<sup>158</sup> G. M. Innocenti,<sup>158</sup> M. Klute,<sup>158</sup> D. Kovalskyi,<sup>158</sup> Y.-J. Lee,<sup>158</sup> A. Levin,<sup>158</sup> P. D. Luckey,<sup>158</sup> B. Maier,<sup>158</sup> A. C. Marini,<sup>158</sup> C. McGinn,<sup>158</sup> C. Mironov,<sup>158</sup> S. Narayanan,<sup>158</sup> X. Niu,<sup>158</sup> C. Paus,<sup>158</sup> C. Roland,<sup>158</sup> G. Roland,<sup>158</sup> G. S. F. Stephans,<sup>158</sup> K. Sumorok,<sup>158</sup> K. Tatar,<sup>158</sup> D. Velicanu,<sup>158</sup> J. Wang,<sup>158</sup> T. W. Wang,<sup>158</sup> B. Wyslouch,<sup>158</sup> S. Zhaozhong,<sup>158</sup> A. C. Benvenuti,<sup>159</sup> R. M. Chatterjee,<sup>159</sup> A. Evans,<sup>159</sup> P. Hansen,<sup>159</sup> S. Kalafut,<sup>159</sup> Y. Kubota,<sup>159</sup> Z. Lesko,<sup>159</sup> J. Mans,<sup>159</sup> S. Nourbakhsh,<sup>159</sup> N. Ruckstuhl,<sup>159</sup> R. Rusack,<sup>159</sup> J. Turkewitz,<sup>159</sup> M. A. Wadud,<sup>159</sup> J. G. Acosta,<sup>160</sup> S. Oliveros,<sup>160</sup> E. Avdeeva,<sup>161</sup> K. Bloom,<sup>161</sup> D. R. Claes,<sup>161</sup> C. Fangmeier,<sup>161</sup> F. Golf,<sup>161</sup> R. Gonzalez Suarez,<sup>161</sup> R. Kamalieddin,<sup>161</sup> I. Kravchenko,<sup>161</sup> J. Monroy,<sup>161</sup> J. E. Siado,<sup>161</sup> G. R. Snow,<sup>161</sup> B. Stieger,<sup>161</sup> A. Godshalk,<sup>162</sup> C. Harrington,<sup>162</sup> I. Iashvili,<sup>162</sup> A. Kharchilava,<sup>162</sup> D. Nguyen,<sup>162</sup> A. Parker,<sup>162</sup> S. Rappoccio,<sup>162</sup> B. Roobahani,<sup>162</sup> E. Barberis,<sup>163</sup> C. Freer,<sup>163</sup> A. Hortiangtham,<sup>163</sup> D. M. Morse,<sup>163</sup> T. Orimoto,<sup>163</sup> R. Teixeira De Lima,<sup>163</sup> T. Wamorkar,<sup>163</sup> B. Wang,<sup>163</sup> A. Wisecarver,<sup>163</sup> D. Wood,<sup>163</sup> S. Bhattacharya,<sup>164</sup> O. Charaf,<sup>164</sup> K. A. Hahn,<sup>164</sup> N. Mucia,<sup>164</sup> N. Odell,<sup>164</sup> M. H. Schmitt,<sup>164</sup> K. Sung,<sup>164</sup> M. Trovato,<sup>164</sup> M. Velasco,<sup>164</sup> R. Bucci,<sup>165</sup> N. Dev,<sup>165</sup> M. Hildreth,<sup>165</sup> K. Hurtado Anampa,<sup>165</sup> C. Jessop,<sup>165</sup> D. J. Karmgard,<sup>165</sup> N. Kellams,<sup>165</sup> K. Lannon,<sup>165</sup> W. Li,<sup>165</sup> N. Loukas,<sup>165</sup> N. Marinelli,<sup>165</sup> F. Meng,<sup>165</sup> C. Mueller,<sup>165</sup> Y. Musienko,<sup>165,hh</sup> M. Planer,<sup>165</sup> A. Reinsvold,<sup>165</sup> R. Ruchti,<sup>165</sup> P. Siddireddy,<sup>165</sup> G. Smith,<sup>165</sup> S. Taroni,<sup>165</sup> M. Wayne,<sup>165</sup> A. Wightman,<sup>165</sup> M. Wolf,<sup>165</sup> A. Woodard,<sup>165</sup> J. Alimena,<sup>166</sup> L. Antonelli,<sup>166</sup> B. Bylsma,<sup>166</sup> L. S. Durkin,<sup>166</sup> S. Flowers,<sup>166</sup> B. Francis,<sup>166</sup> A. Hart,<sup>166</sup> C. Hill,<sup>166</sup> W. Ji,<sup>166</sup> T. Y. Ling,<sup>166</sup> W. Luo,<sup>166</sup> B. L. Winer,<sup>166</sup> H. W. Wulsin,<sup>166</sup> S. Cooperstein,<sup>167</sup> P. Elmer,<sup>167</sup> J. Hardenbrook,<sup>167</sup> P. Hebda,<sup>167</sup> S. Higginbotham,<sup>167</sup> A. Kalogeropoulos,<sup>167</sup> D. Lange,<sup>167</sup> M. T. Lucchini,<sup>167</sup> J. Luo,<sup>167</sup> D. Marlow,<sup>167</sup> K. Mei,<sup>167</sup> I. Ojalvo,<sup>167</sup> J. Olsen,<sup>167</sup> C. Palmer,<sup>167</sup> P. Piroué,<sup>167</sup> J. Salfeld-Nebgen,<sup>167</sup> D. Stickland,<sup>167</sup> C. Tully,<sup>167</sup> S. Malik,<sup>168</sup> S. Norberg,<sup>168</sup> A. Barker,<sup>169</sup> V. E. Barnes,<sup>169</sup> L. Gutay,<sup>169</sup> M. Jones,<sup>169</sup> A. W. Jung,<sup>169</sup> A. Khatiwada,<sup>169</sup> B. Mahakud,<sup>169</sup> D. H. Miller,<sup>169</sup> N. Neumeister,<sup>169</sup> C. C. Peng,<sup>169</sup> H. Qiu,<sup>169</sup> J. F. Schulte,<sup>169</sup> J. Sun,<sup>169</sup> F. Wang,<sup>169</sup> R. Xiao,<sup>169</sup> W. Xie,<sup>169</sup> T. Cheng,<sup>170</sup> J. Dolen,<sup>170</sup> N. Parashar,<sup>170</sup> Z. Chen,<sup>171</sup> K. M. Ecklund,<sup>171</sup> S. Freed,<sup>171</sup> F. J. M. Geurts,<sup>171</sup> M. Guilbaud,<sup>171</sup> M. Kilpatrick,<sup>171</sup> W. Li,<sup>171</sup> B. Michlin,<sup>171</sup> B. P. Padley,<sup>171</sup> J. Roberts,<sup>171</sup> J. Rorie,<sup>171</sup> W. Shi,<sup>171</sup> B. Tran,<sup>171</sup> Z. Tu,<sup>171</sup> J. Zabel,<sup>171</sup> A. Zhang,<sup>171</sup> A. Bodek,<sup>172</sup> P. de Barbaro,<sup>172</sup> R. Demina,<sup>172</sup> Y. t. Duh,<sup>172</sup> J. L. Dulemba,<sup>172</sup> C. Fallon,<sup>172</sup> T. Ferbel,<sup>172</sup> M. Galanti,<sup>172</sup> A. Garcia-Bellido,<sup>172</sup> J. Han,<sup>172</sup> O. Hindrichs,<sup>172</sup> A. Khukhunaishvili,<sup>172</sup> K. H. Lo,<sup>172</sup> P. Tan,<sup>172</sup> R. Taus,<sup>172</sup> M. Verzetti,<sup>172</sup> A. Agapitos,<sup>173</sup> J. P. Chou,<sup>173</sup> Y. Gershtein,<sup>173</sup> T. A. Gómez Espinosa,<sup>173</sup> E. Halkiadakis,<sup>173</sup> M. Heindl,<sup>173</sup> E. Hughes,<sup>173</sup> S. Kaplan,<sup>173</sup> R. Kunnawalkam Elayavalli,<sup>173</sup> S. Kyriacou,<sup>173</sup> A. Lath,<sup>173</sup> R. Montalvo,<sup>173</sup> K. Nash,<sup>173</sup> M. Osherson,<sup>173</sup> H. Saka,<sup>173</sup> S. Salur,<sup>173</sup> S. Schnetzer,<sup>173</sup> D. Sheffield,<sup>173</sup> S. Somalwar,<sup>173</sup> R. Stone,<sup>173</sup> S. Thomas,<sup>173</sup> P. Thomassen,<sup>173</sup> M. Walker,<sup>173</sup> A. G. Delannoy,<sup>174</sup> J. Heideman,<sup>174</sup> G. Riley,<sup>174</sup> K. Rose,<sup>174</sup> S. Spanier,<sup>174</sup> K. Thapa,<sup>174</sup> O. Bouhali,<sup>175,sss</sup> A. Castaneda Hernandez,<sup>175,sss</sup> A. Celik,<sup>175</sup> M. Dalchenko,<sup>175</sup> M. De Mattia,<sup>175</sup> A. Delgado,<sup>175</sup> S. Dildick,<sup>175</sup> R. Eusebi,<sup>175</sup> J. Gilmore,<sup>175</sup> T. Huang,<sup>175</sup> T. Kamon,<sup>175,ttt</sup> S. Luo,<sup>175</sup> R. Mueller,<sup>175</sup> Y. Pakhotin,<sup>175</sup> R. Patel,<sup>175</sup> A. Perloff,<sup>175</sup> L. Perniè,<sup>175</sup> D. Rathjens,<sup>175</sup> A. Safonov,<sup>175</sup> A. Tatarinov,<sup>175</sup> N. Akchurin,<sup>176</sup> J. Damgov,<sup>176</sup> F. De Guio,<sup>176</sup> P. R. Duderø,<sup>176</sup> S. Kunori,<sup>176</sup> K. Lamichhane,<sup>176</sup> S. W. Lee,<sup>176</sup> T. Mengke,<sup>176</sup> S. Muthumuni,<sup>176</sup> T. Peltola,<sup>176</sup> S. Undleeb,<sup>176</sup> I. Volobouev,<sup>176</sup> Z. Wang,<sup>176</sup> S. Greene,<sup>177</sup> A. Gurrola,<sup>177</sup> R. Janjam,<sup>177</sup> W. Johns,<sup>177</sup> C. Maguire,<sup>177</sup> A. Melo,<sup>177</sup> H. Ni,<sup>177</sup> K. Padeken,<sup>177</sup> J. D. Ruiz Alvarez,<sup>177</sup> P. Sheldon,<sup>177</sup> S. Tuo,<sup>177</sup> J. Velkovska,<sup>177</sup> M. Verweij,<sup>177</sup> Q. Xu,<sup>177</sup> M. W. Arenton,<sup>178</sup> P. Barria,<sup>178</sup> B. Cox,<sup>178</sup> R. Hirosky,<sup>178</sup> M. Joyce,<sup>178</sup> A. Ledovskoy,<sup>178</sup> H. Li,<sup>178</sup> C. Neu,<sup>178</sup> T. Sinthuprasith,<sup>178</sup> Y. Wang,<sup>178</sup> E. Wolfe,<sup>178</sup> F. Xia,<sup>178</sup> R. Harr,<sup>179</sup> P. E. Karchin,<sup>179</sup> N. Poudyal,<sup>179</sup> J. Sturdy,<sup>179</sup> P. Thapa,<sup>179</sup> S. Zaleski,<sup>179</sup> M. Brodski,<sup>180</sup> J. Buchanan,<sup>180</sup> C. Caillol,<sup>180</sup> D. Carlsmith,<sup>180</sup> S. Dasu,<sup>180</sup> L. Dodd,<sup>180</sup> S. Duric,<sup>180</sup> B. Gomber,<sup>180</sup> M. Grothe,<sup>180</sup> M. Herndon,<sup>180</sup> A. Hervé,<sup>180</sup> U. Hussain,<sup>180</sup> P. Klabbers,<sup>180</sup> A. Lanaro,<sup>180</sup> A. Levine,<sup>180</sup> K. Long,<sup>180</sup> R. Loveless,<sup>180</sup> T. Ruggles,<sup>180</sup> A. Savin,<sup>180</sup> N. Smith,<sup>180</sup> W. H. Smith,<sup>180</sup> and N. Woods<sup>180</sup>

(CMS Collaboration)

<sup>1</sup>Yerevan Physics Institute, Yerevan, Armenia<sup>2</sup>Institut für Hochenergiephysik, Wien, Austria

- <sup>3</sup>*Institute for Nuclear Problems, Minsk, Belarus*  
<sup>4</sup>*Universiteit Antwerpen, Antwerpen, Belgium*  
<sup>5</sup>*Vrije Universiteit Brussel, Brussel, Belgium*  
<sup>6</sup>*Université Libre de Bruxelles, Bruxelles, Belgium*  
<sup>7</sup>*Ghent University, Ghent, Belgium*  
<sup>8</sup>*Université Catholique de Louvain, Louvain-la-Neuve, Belgium*  
<sup>9</sup>*Centro Brasileiro de Pesquisas Físicas, Rio de Janeiro, Brazil*  
<sup>10</sup>*Universidade do Estado do Rio de Janeiro, Rio de Janeiro, Brazil*  
<sup>11a</sup>*Universidade Estadual Paulista, São Paulo, Brazil*  
<sup>11b</sup>*Universidade Federal do ABC, São Paulo, Brazil*  
<sup>12</sup>*Institute for Nuclear Research and Nuclear Energy, Bulgarian Academy of Sciences, Sofia, Bulgaria*  
<sup>13</sup>*University of Sofia, Sofia, Bulgaria*  
<sup>14</sup>*Beihang University, Beijing, China*  
<sup>15</sup>*Institute of High Energy Physics, Beijing, China*  
<sup>16</sup>*State Key Laboratory of Nuclear Physics and Technology, Peking University, Beijing, China*  
<sup>17</sup>*Tsinghua University, Beijing, China*  
<sup>18</sup>*Universidad de Los Andes, Bogota, Colombia*  
<sup>19</sup>*University of Split, Faculty of Electrical Engineering, Mechanical Engineering and Naval Architecture, Split, Croatia*  
<sup>20</sup>*University of Split, Faculty of Science, Split, Croatia*  
<sup>21</sup>*Institute Rudjer Boskovic, Zagreb, Croatia*  
<sup>22</sup>*University of Cyprus, Nicosia, Cyprus*  
<sup>23</sup>*Charles University, Prague, Czech Republic*  
<sup>24</sup>*Escuela Politecnica Nacional, Quito, Ecuador*  
<sup>25</sup>*Universidad San Francisco de Quito, Quito, Ecuador*  
<sup>26</sup>*Academy of Scientific Research and Technology of the Arab Republic of Egypt, Egyptian Network of High Energy Physics, Cairo, Egypt*  
<sup>27</sup>*National Institute of Chemical Physics and Biophysics, Tallinn, Estonia*  
<sup>28</sup>*Department of Physics, University of Helsinki, Helsinki, Finland*  
<sup>29</sup>*Helsinki Institute of Physics, Helsinki, Finland*  
<sup>30</sup>*Lappeenranta University of Technology, Lappeenranta, Finland*  
<sup>31</sup>*IRFU, CEA, Université Paris-Saclay, Gif-sur-Yvette, France*  
<sup>32</sup>*Laboratoire Leprince-Ringuet, Ecole polytechnique, CNRS/IN2P3, Université Paris-Saclay, Palaiseau, France*  
<sup>33</sup>*Université de Strasbourg, CNRS, IPHC UMR 7178, F-67000 Strasbourg, France*  
<sup>34</sup>*Centre de Calcul de l'Institut National de Physique Nucléaire et de Physique des Particules, CNRS/IN2P3, Villeurbanne, France*  
<sup>35</sup>*Université de Lyon, Université Claude Bernard Lyon 1, CNRS-IN2P3, Institut de Physique Nucléaire de Lyon, Villeurbanne, France*  
<sup>36</sup>*Georgian Technical University, Tbilisi, Georgia*  
<sup>37</sup>*Tbilisi State University, Tbilisi, Georgia*  
<sup>38</sup>*RWTH Aachen University, I. Physikalisches Institut, Aachen, Germany*  
<sup>39</sup>*RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany*  
<sup>40</sup>*RWTH Aachen University, III. Physikalisches Institut B, Aachen, Germany*  
<sup>41</sup>*Deutsches Elektronen-Synchrotron, Hamburg, Germany*  
<sup>42</sup>*University of Hamburg, Hamburg, Germany*  
<sup>43</sup>*Institut für Experimentelle Teilchenphysik, Karlsruhe, Germany*  
<sup>44</sup>*Institute of Nuclear and Particle Physics (INPP), NCSR Demokritos, Aghia Paraskevi, Greece*  
<sup>45</sup>*National and Kapodistrian University of Athens, Athens, Greece*  
<sup>46</sup>*National Technical University of Athens, Athens, Greece*  
<sup>47</sup>*University of Ioánnina, Ioánnina, Greece*  
<sup>48</sup>*MTA-ELTE Lendület CMS Particle and Nuclear Physics Group, Eötvös Loránd University, Budapest, Hungary*  
<sup>49</sup>*Wigner Research Centre for Physics, Budapest, Hungary*  
<sup>50</sup>*Institute of Nuclear Research ATOMKI, Debrecen, Hungary*  
<sup>51</sup>*Institute of Physics, University of Debrecen, Debrecen, Hungary*  
<sup>52</sup>*Indian Institute of Science (IISc), Bangalore, India*  
<sup>53</sup>*National Institute of Science Education and Research, Bhubaneswar, India*  
<sup>54</sup>*Panjab University, Chandigarh, India*  
<sup>55</sup>*University of Delhi, Delhi, India*  
<sup>56</sup>*Saha Institute of Nuclear Physics, HBNI, Kolkata, India*  
<sup>57</sup>*Indian Institute of Technology Madras, Madras, India*  
<sup>58</sup>*Bhabha Atomic Research Centre, Mumbai, India*  
<sup>59</sup>*Tata Institute of Fundamental Research-A, Mumbai, India*  
<sup>60</sup>*Tata Institute of Fundamental Research-B, Mumbai, India*

- <sup>61</sup>*Indian Institute of Science Education and Research (IISER), Pune, India*
- <sup>62</sup>*Institute for Research in Fundamental Sciences (IPM), Tehran, Iran*
- <sup>63</sup>*University College Dublin, Dublin, Ireland*
- <sup>64a</sup>*INFN Sezione di Bari, Bari, Italy*
- <sup>64b</sup>*Università di Bari, Bari, Italy*
- <sup>64c</sup>*Politecnico di Bari, Bari, Italy*
- <sup>65a</sup>*INFN Sezione di Bologna, Bologna, Italy*
- <sup>65b</sup>*Università di Bologna, Bologna, Italy*
- <sup>66a</sup>*INFN Sezione di Catania, Catania, Italy*
- <sup>66b</sup>*Università di Catania, Catania, Italy*
- <sup>67a</sup>*INFN Sezione di Firenze, Firenze, Italy*
- <sup>67b</sup>*Università di Firenze, Firenze, Italy*
- <sup>68</sup>*INFN Laboratori Nazionali di Frascati, Frascati, Italy*
- <sup>69a</sup>*INFN Sezione di Genova, Genova, Italy*
- <sup>69b</sup>*Università di Genova, Genova, Italy*
- <sup>70a</sup>*INFN Sezione di Milano-Bicocca, Milano, Italy*
- <sup>70b</sup>*Università di Milano-Bicocca, Milano, Italy*
- <sup>71a</sup>*INFN Sezione di Napoli, Napoli, Italy*
- <sup>71b</sup>*Università di Napoli 'Federico II', Napoli, Italy*
- <sup>71c</sup>*Università della Basilicata, Potenza, Italy*
- <sup>71d</sup>*Università G. Marconi, Roma, Italy*
- <sup>72a</sup>*INFN Sezione di Padova, Padova, Italy*
- <sup>72b</sup>*Università di Padova, Padova, Italy*
- <sup>72c</sup>*Università di Trento, Trento, Italy*
- <sup>73a</sup>*INFN Sezione di Pavia, Pavia, Italy*
- <sup>73b</sup>*Università di Pavia*
- <sup>74a</sup>*INFN Sezione di Perugia, Perugia, Italy*
- <sup>74b</sup>*Università di Perugia, Perugia, Italy*
- <sup>75a</sup>*INFN Sezione di Pisa, Pisa, Italy*
- <sup>75b</sup>*Università di Pisa, Pisa, Italy*
- <sup>75c</sup>*Scuola Normale Superiore di Pisa, Pisa, Italy*
- <sup>76a</sup>*INFN Sezione di Roma, Rome, Italy*
- <sup>76b</sup>*Sapienza Università di Roma, Rome, Italy*
- <sup>77a</sup>*INFN Sezione di Torino, Torino, Italy*
- <sup>77b</sup>*Università di Torino, Torino, Italy*
- <sup>77c</sup>*Università del Piemonte Orientale, Novara, Italy*
- <sup>78a</sup>*INFN Sezione di Trieste, Trieste, Italy*
- <sup>78b</sup>*Università di Trieste, Trieste, Italy*
- <sup>79</sup>*Kyungpook National University, Daegu, Korea*
- <sup>80</sup>*Chonnam National University, Institute for Universe and Elementary Particles, Kwangju, Korea*
- <sup>81</sup>*Hanyang University, Seoul, Korea*
- <sup>82</sup>*Korea University, Seoul, Korea*
- <sup>83</sup>*Sejong University, Seoul, Korea*
- <sup>84</sup>*Seoul National University, Seoul, Korea*
- <sup>85</sup>*University of Seoul, Seoul, Korea*
- <sup>86</sup>*Sungkyunkwan University, Suwon, Korea*
- <sup>87</sup>*Vilnius University, Vilnius, Lithuania*
- <sup>88</sup>*National Centre for Particle Physics, Universiti Malaya, Kuala Lumpur, Malaysia*
- <sup>89</sup>*Centro de Investigacion y de Estudios Avanzados del IPN, Mexico City, Mexico*
- <sup>90</sup>*Universidad Iberoamericana, Mexico City, Mexico*
- <sup>91</sup>*Benemerita Universidad Autonoma de Puebla, Puebla, Mexico*
- <sup>92</sup>*Universidad Autónoma de San Luis Potosí, San Luis Potosí, Mexico*
- <sup>93</sup>*University of Auckland, Auckland, New Zealand*
- <sup>94</sup>*University of Canterbury, Christchurch, New Zealand*
- <sup>95</sup>*National Centre for Physics, Quaid-I-Azam University, Islamabad, Pakistan*
- <sup>96</sup>*National Centre for Nuclear Research, Swierk, Poland*
- <sup>97</sup>*Institute of Experimental Physics, Faculty of Physics, University of Warsaw, Warsaw, Poland*
- <sup>98</sup>*Laboratório de Instrumentação e Física Experimental de Partículas, Lisboa, Portugal*
- <sup>99</sup>*Joint Institute for Nuclear Research, Dubna, Russia*
- <sup>100</sup>*Petersburg Nuclear Physics Institute, Gatchina (St. Petersburg), Russia*

- <sup>101</sup>*Institute for Nuclear Research, Moscow, Russia*
- <sup>102</sup>*Institute for Theoretical and Experimental Physics, Moscow, Russia*
- <sup>103</sup>*Moscow Institute of Physics and Technology, Moscow, Russia*
- <sup>104</sup>*National Research Nuclear University 'Moscow Engineering Physics Institute' (MEPhI), Moscow, Russia*
- <sup>105</sup>*P.N. Lebedev Physical Institute, Moscow, Russia*
- <sup>106</sup>*Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, Moscow, Russia*
- <sup>107</sup>*Novosibirsk State University (NSU), Novosibirsk, Russia*
- <sup>108</sup>*State Research Center of Russian Federation, Institute for High Energy Physics of NRC 'Kurchatov Institute', Protvino, Russia*
- <sup>109</sup>*National Research Tomsk Polytechnic University, Tomsk, Russia*
- <sup>110</sup>*University of Belgrade, Faculty of Physics and Vinca Institute of Nuclear Sciences, Belgrade, Serbia*
- <sup>111</sup>*Centro de Investigaciones Energéticas Medioambientales y Tecnológicas (CIEMAT), Madrid, Spain*
- <sup>112</sup>*Universidad Autónoma de Madrid, Madrid, Spain*
- <sup>113</sup>*Universidad de Oviedo, Oviedo, Spain*
- <sup>114</sup>*Instituto de Física de Cantabria (IFCA), CSIC-Universidad de Cantabria, Santander, Spain*
- <sup>115</sup>*CERN, European Organization for Nuclear Research, Geneva, Switzerland*
- <sup>116</sup>*Paul Scherrer Institut, Villigen, Switzerland*
- <sup>117</sup>*ETH Zurich—Institute for Particle Physics and Astrophysics (IPA), Zurich, Switzerland*
- <sup>118</sup>*Universität Zürich, Zurich, Switzerland*
- <sup>119</sup>*National Central University, Chung-Li, Taiwan*
- <sup>120</sup>*National Taiwan University (NTU), Taipei, Taiwan*
- <sup>121</sup>*Chulalongkorn University, Faculty of Science, Department of Physics, Bangkok, Thailand*
- <sup>122</sup>*Çukurova University, Physics Department, Science and Art Faculty, Adana, Turkey*
- <sup>123</sup>*Middle East Technical University, Physics Department, Ankara, Turkey*
- <sup>124</sup>*Bogazici University, Istanbul, Turkey*
- <sup>125</sup>*Istanbul Technical University, Istanbul, Turkey*
- <sup>126</sup>*Institute for Scintillation Materials of National Academy of Science of Ukraine, Kharkov, Ukraine*
- <sup>127</sup>*National Scientific Center, Kharkov Institute of Physics and Technology, Kharkov, Ukraine*
- <sup>128</sup>*University of Bristol, Bristol, United Kingdom*
- <sup>129</sup>*Rutherford Appleton Laboratory, Didcot, United Kingdom*
- <sup>130</sup>*Imperial College, London, United Kingdom*
- <sup>131</sup>*Brunel University, Uxbridge, United Kingdom*
- <sup>132</sup>*Baylor University, Waco, Texas 76798, USA*
- <sup>133</sup>*Catholic University of America, Washington, DC 20064, USA*
- <sup>134</sup>*The University of Alabama, Tuscaloosa, Alabama 35487, USA*
- <sup>135</sup>*Boston University, Boston, Massachusetts 02215, USA*
- <sup>136</sup>*Brown University, Providence, Rhode Island 02912, USA*
- <sup>137</sup>*University of California, Davis, California 95616, USA*
- <sup>138</sup>*University of California, Los Angeles, California 90095, USA*
- <sup>139</sup>*University of California, Riverside, Riverside, California 92521, USA*
- <sup>140</sup>*University of California, San Diego, La Jolla, California 92093, USA*
- <sup>141</sup>*University of California, Santa Barbara—Department of Physics, Santa Barbara, California 93106, USA*
- <sup>142</sup>*California Institute of Technology, Pasadena, California 91125, USA*
- <sup>143</sup>*Carnegie Mellon University, Pittsburgh, Pennsylvania 15213, USA*
- <sup>144</sup>*University of Colorado Boulder, Boulder, Colorado 80309, USA*
- <sup>145</sup>*Cornell University, Ithaca, New York 14853, USA*
- <sup>146</sup>*Fermi National Accelerator Laboratory, Batavia, New York 60510, USA*
- <sup>147</sup>*University of Florida, Gainesville, Florida 32611, USA*
- <sup>148</sup>*Florida International University, Miami, Florida 33199, USA*
- <sup>149</sup>*Florida State University, Tallahassee, Florida 32306, USA*
- <sup>150</sup>*Florida Institute of Technology, Melbourne, Florida 32901, USA*
- <sup>151</sup>*University of Illinois at Chicago (UIC), Chicago, Illinois 60607, USA*
- <sup>152</sup>*The University of Iowa, Iowa City, Iowa 52242, USA*
- <sup>153</sup>*Johns Hopkins University, Baltimore, Maryland 21218, USA*
- <sup>154</sup>*The University of Kansas, Lawrence, Kansas 66045, USA*
- <sup>155</sup>*Kansas State University, Manhattan, New York 66506, USA*
- <sup>156</sup>*Lawrence Livermore National Laboratory, Livermore, California 94551, USA*
- <sup>157</sup>*University of Maryland, College Park, Maryland 20742, USA*
- <sup>158</sup>*Massachusetts Institute of Technology, Cambridge, Massachusetts 02139, USA*
- <sup>159</sup>*University of Minnesota, Minneapolis, Minnesota 55455, USA*
- <sup>160</sup>*University of Mississippi, Oxford, Mississippi 38677, USA*



- <sup>161</sup>*University of Nebraska-Lincoln, Lincoln, Nebraska 68588, USA*  
<sup>162</sup>*State University of New York at Buffalo, Buffalo, New York 14260, USA*  
<sup>163</sup>*Northeastern University, Boston, Massachusetts 02115, USA*  
<sup>164</sup>*Northwestern University, Evanston, Illinois 60208, USA*  
<sup>165</sup>*University of Notre Dame, Notre Dame, Indiana 46556, USA*  
<sup>166</sup>*The Ohio State University, Columbus, Ohio 43210, USA*  
<sup>167</sup>*Princeton University, Princeton, New Jersey 08542, USA*  
<sup>168</sup>*University of Puerto Rico, Mayaguez, Puerto Rico 00681, USA*  
<sup>169</sup>*Purdue University, West Lafayette, Indiana 47907, USA*  
<sup>170</sup>*Purdue University Northwest, Hammond, Indiana 46323, USA*  
<sup>171</sup>*Rice University, Houston, Texas 77251, USA*  
<sup>172</sup>*University of Rochester, Rochester, New York 14627, USA*  
<sup>173</sup>*Rutgers, The State University of New Jersey, Piscataway, New Jersey 08854, USA*  
<sup>174</sup>*University of Tennessee, Knoxville, Tennessee 37996, USA*  
<sup>175</sup>*Texas A&M University, College Station, Texas 77843, USA*  
<sup>176</sup>*Texas Tech University, Lubbock, Texas 79409, USA*  
<sup>177</sup>*Vanderbilt University, Nashville, Tennessee 37235, USA*  
<sup>178</sup>*University of Virginia, Charlottesville, Virginia 22904, USA*  
<sup>179</sup>*Wayne State University, Detroit, Michigan 48202, USA*  
<sup>180</sup>*University of Wisconsin—Madison, Madison, Wisconsin 53706, USA*

<sup>a</sup>Deceased.

<sup>b</sup>Also at Vienna University of Technology, Vienna, Austria.

<sup>c</sup>Also at IRFU, CEA, Université Paris-Saclay, Gif-sur-Yvette, France.

<sup>d</sup>Also at Universidade Estadual de Campinas, Campinas, Brazil.

<sup>e</sup>Also at Federal University of Rio Grande do Sul, Porto Alegre, Brazil.

<sup>f</sup>Also at Université Libre de Bruxelles, Bruxelles, Belgium.

<sup>g</sup>Also at Institute for Theoretical and Experimental Physics, Moscow, Russia.

<sup>h</sup>Also at Joint Institute for Nuclear Research, Dubna, Russia.

<sup>i</sup>Also at British University in Egypt, Cairo, Egypt.

<sup>j</sup>Also at Fayoum University, El-Fayoum, Egypt.

<sup>k</sup>Also at Ain Shams University, Cairo, Egypt.

<sup>l</sup>Also at Department of Physics, King Abdulaziz University, Jeddah, Saudi Arabia.

<sup>m</sup>Also at Université de Haute Alsace, Mulhouse, France.

<sup>n</sup>Also at Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, Moscow, Russia.

<sup>o</sup>Also at Tbilisi State University, Tbilisi, Georgia.

<sup>p</sup>Also at CERN, European Organization for Nuclear Research, Geneva, Switzerland.

<sup>q</sup>Also at RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany.

<sup>r</sup>Also at University of Hamburg, Hamburg, Germany.

<sup>s</sup>Also at Brandenburg University of Technology, Cottbus, Germany

<sup>t</sup>Also at Institute of Nuclear Research ATOMKI, Debrecen, Hungary.

<sup>u</sup>Also at MTA-ELTE Lendület CMS Particle and Nuclear Physics Group, Eötvös Loránd University, Budapest, Hungary.

<sup>v</sup>Also at Institute of Physics, University of Debrecen, Debrecen, Hungary.

<sup>w</sup>Also at IIT Bhubaneswar, Bhubaneswar, India.

<sup>x</sup>Also at Institute of Physics, Bhubaneswar, India.

<sup>y</sup>Also at Shoolini University, Solan, India.

<sup>z</sup>Also at University of Visva-Bharati, Santiniketan, India.

<sup>aa</sup>Also at Isfahan University of Technology, Isfahan, Iran.

<sup>bb</sup>Also at Plasma Physics Research Center, Science and Research Branch, Islamic Azad University, Tehran, Iran.

<sup>cc</sup>Also at Università degli Studi di Siena, Siena, Italy.

<sup>dd</sup>Also at International Islamic University of Malaysia, Kuala Lumpur, Malaysia.

<sup>ee</sup>Also at Malaysian Nuclear Agency, MOSTI, Kajang, Malaysia.

<sup>ff</sup>Also at Consejo Nacional de Ciencia y Tecnología, Mexico city, Mexico.

<sup>gg</sup>Also at Warsaw University of Technology, Institute of Electronic Systems, Warsaw, Poland.

<sup>hh</sup>Also at Institute for Nuclear Research, Moscow, Russia.

<sup>ii</sup>Also at National Research Nuclear University 'Moscow Engineering Physics Institute' (MEPhI), Moscow, Russia.

<sup>jj</sup>Also at St. Petersburg State Polytechnical University, St. Petersburg, Russia.

<sup>kk</sup>Also at University of Florida, Gainesville, FL, USA.

<sup>ll</sup>Also at P.N. Lebedev Physical Institute, Moscow, Russia.

<sup>mmm</sup>Also at INFN Sezione di Padova, Università di Padova, Padova, Italy, Università di Trento, Trento, Italy.

- <sup>nn</sup> Also at Budker Institute of Nuclear Physics, Novosibirsk, Russia.
- <sup>oo</sup> Also at Faculty of Physics, University of Belgrade, Belgrade, Serbia.
- <sup>pp</sup> Also at INFN Sezione di Pavia, Università di Pavia, Pavia, Italy.
- <sup>qq</sup> Also at University of Belgrade, Faculty of Physics and Vinca Institute of Nuclear Sciences, Belgrade, Serbia.
- <sup>rr</sup> Also at Scuola Normale e Sezione dell'INFN, Pisa, Italy.
- <sup>ss</sup> Also at National and Kapodistrian University of Athens, Athens, Greece.
- <sup>tt</sup> Also at Riga Technical University.
- <sup>uu</sup> Also at Universität Zürich, Zurich, Switzerland.
- <sup>vv</sup> Also at Stefan Meyer Institute for Subatomic Physics.
- <sup>ww</sup> Also at Adiyaman University, Adiyaman, Turkey.
- <sup>xx</sup> Also at Istanbul Aydin University, Istanbul, Turkey.
- <sup>yy</sup> Also at Mersin University, Mersin, Turkey.
- <sup>zz</sup> Also at Piri Reis University, Istanbul, Turkey.
- <sup>aaa</sup> Also at Gaziosmanpasa University, Tokat, Turkey.
- <sup>bbb</sup> Also at Ozyegin University, Istanbul, Turkey.
- <sup>ccc</sup> Also at Izmir Institute of Technology, Izmir, Turkey.
- <sup>ddd</sup> Also at Marmara University, Istanbul, Turkey.
- <sup>eee</sup> Also at Kafkas University, Kars, Turkey.
- <sup>fff</sup> Also at Istanbul Bilgi University, Istanbul, Turkey.
- <sup>ggg</sup> Also at Hacettepe University, Ankara, Turkey.
- <sup>hhh</sup> Also at Rutherford Appleton Laboratory, Didcot, United Kingdom.
- <sup>iii</sup> Also at School of Physics and Astronomy, University of Southampton, Southampton, United Kingdom.
- <sup>jjj</sup> Also at Monash University, Faculty of Science, Clayton, Australia.
- <sup>kkk</sup> Also at Bethel University.
- <sup>lll</sup> Also at Karamanoğlu Mehmetbey University, Karaman, Turkey.
- <sup>mmm</sup> Also at Utah Valley University, Orem, USA.
- <sup>nnn</sup> Also at Purdue University, West Lafayette, IN, USA.
- <sup>ooo</sup> Also at Beykent University.
- <sup>ppp</sup> Also at Bingol University, Bingol, Turkey.
- <sup>qqq</sup> Also at Sinop University, Sinop, Turkey.
- <sup>rrr</sup> Also at Mimar Sinan University, Istanbul, Istanbul, Turkey.
- <sup>sss</sup> Also at Texas A&M University at Qatar, Doha, Qatar.
- <sup>ttt</sup> Also at Kyungpook National University.