

CERN-EP-2018-076
2018/08/29

CMS-HIN-17-003

Elliptic flow of charm and strange hadrons in high-multiplicity pPb collisions at $\sqrt{s_{\text{NN}}} = 8.16$ TeV

The CMS Collaboration*

Abstract

The elliptic azimuthal anisotropy coefficient (v_2) is measured for charm (D^0) and strange (K_S^0 , Λ , Ξ^- , and Ω^-) hadrons, using a data sample of pPb 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 pPb 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.

Published in Physical Review Letters as doi:10.1103/PhysRevLett.121.082301.

There has been longstanding 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 (ϕ) of particles emitted over a wide pseudorapidity (η) 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 BNL RHIC [2–5] and later at the CERN 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 (pPb) [18–21] collisions at the LHC has raised the question whether a fluid-like 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 dAu [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/ψ mesons have revealed hints of heavy flavor quark collectivity [44, 45]. Observation of D meson v_2 in the pPb 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 to 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 , Λ , Ξ^- , and Ω^-) in pPb 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 measurements. The v_2 harmonic of all particle species in high-multiplicity pPb 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) μm 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 pPb 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 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 is also used and reprocessed using the same reconstruction algorithm as the pPb data.

The pPb 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 pPb 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 Λ 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 π^-p ($\pi^+\bar{p}$) is used in the Λ ($\bar{\Lambda}$) reconstruction. To reconstruct Ξ^- and Ω^- particles, a Λ 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 Λ , Ξ^- and Ω^-).

Several topological selections are applied to further reduce the combinatorial background. In particular, strange hadron and D^0 candidates are selected according to the χ^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 sta-

tistical significance of the signal. For Ξ^- and Ω^- reconstruction, these selections are applied to both the initial decay vertex and the subsequent decay vertex of Λ .

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 pPb 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 η and ϕ 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_{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 pPb 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,

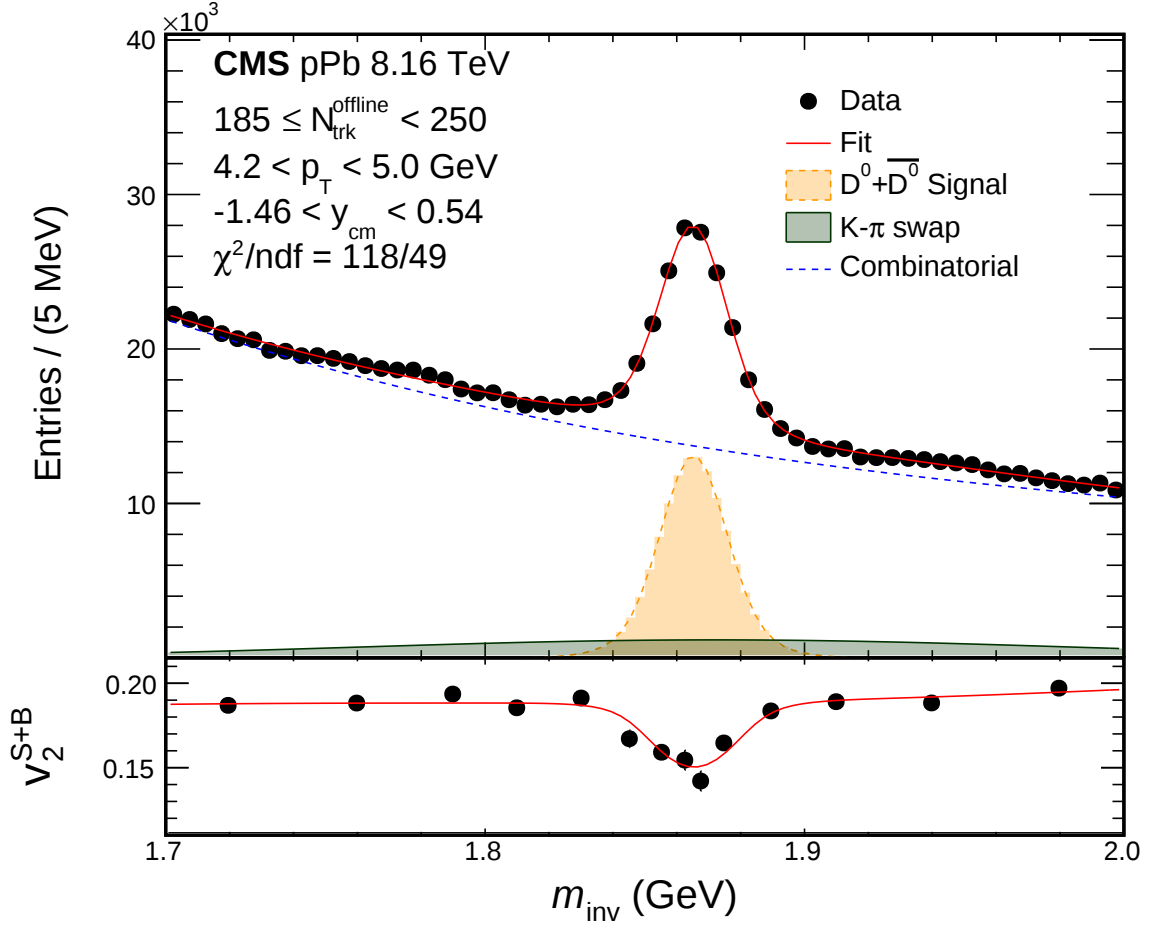


Figure 1: Example of the simultaneous fit to the invariant mass spectrum and $v_2^{S+B}(m_{\text{inv}})$ in the p_T interval 4.2–5.0 GeV for events with $185 \leq N_{\text{trk}}^{\text{offline}} < 250$.

$S(m_{\text{inv}})$, 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- π 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 non-swapped 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 pPb 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

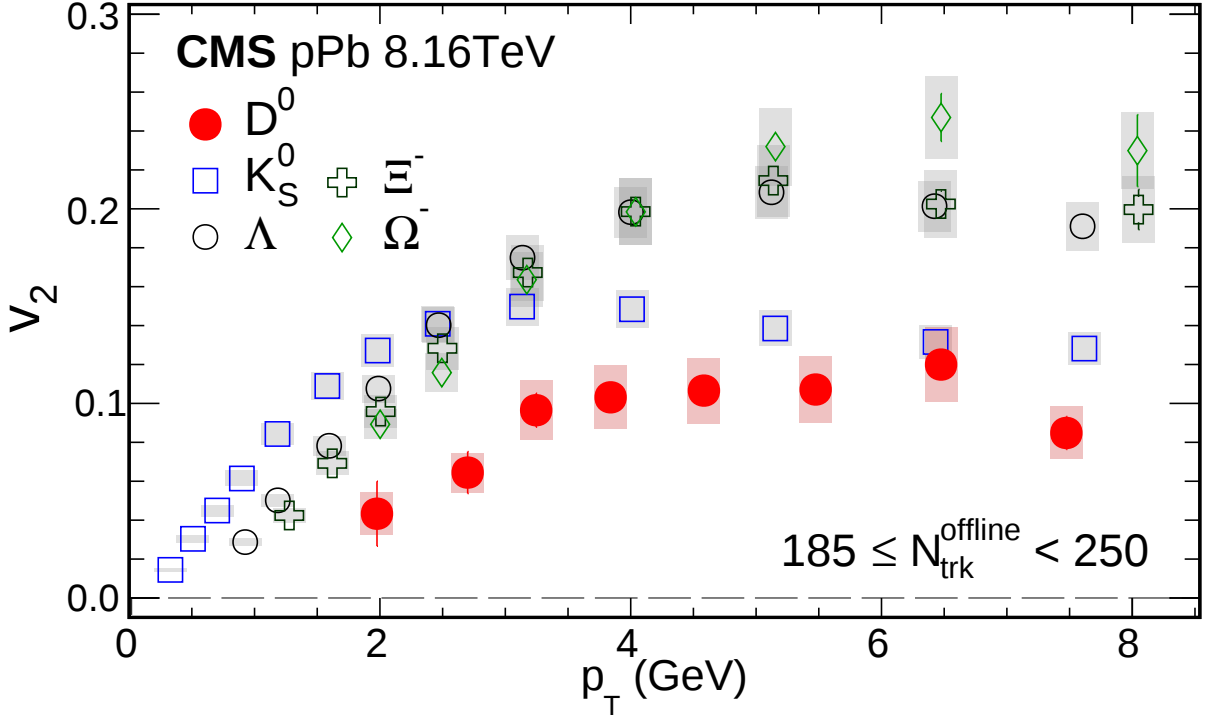


Figure 2: Results of elliptic flow (v_2) for D^0 mesons, as well as K_S^0 , Λ , Ξ^- , and Ω^- particles, as functions of p_T for $-1.46 < y_{cm} < 0.54$, with $185 \leq N_{trk}^{offline} < 250$ in pPb collisions at $\sqrt{s_{NN}} = 8.16$ TeV. The error bars correspond to statistical uncertainties, while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

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, $\alpha(m_{inv})$, 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 $v_2^B(m_{inv})$ 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 , Λ , and Ξ^- particles, the systematic uncertainties related to selection of reconstructed candidates (2% for K_S^0 and Λ particles and 6% for Ξ^- 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] pPb 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 Ω^- particles are quoted to be the same as those of Ξ^- particles.

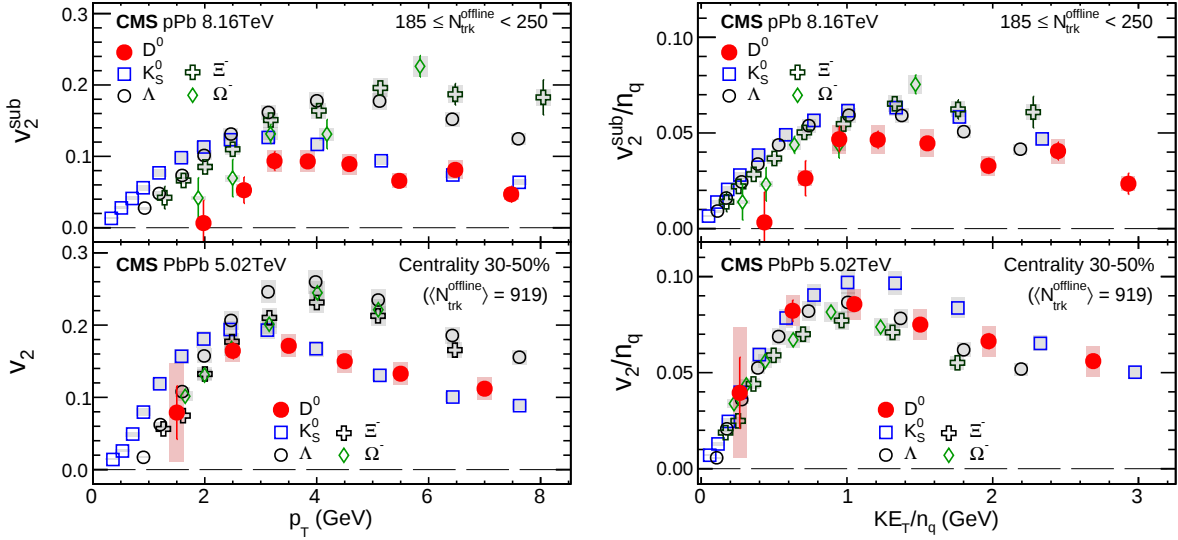


Figure 3: Left: the v_2^{sub} results for prompt D^0 meson, as well as for strange hadrons, as functions of p_T , for $-1.46 < y_{\text{cm}} < 0.54$ in pPb collisions at $\sqrt{s_{\text{NN}}} = 8.16$ TeV with $185 \leq N_{\text{trk}}^{\text{offline}} < 250$ (upper) and for $-1 < y_{\text{cm}} < 1$ in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

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 ($185 \leq N_{\text{trk}}^{\text{offline}} < 250$) pPb 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 Λ , Ξ^- , and Ω^- 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 pPb collisions [28].

The elliptic flow results corrected for residual jet correlations (v_2^{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 pPb 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^{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^{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 pPb 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 pPb 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^{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 pPb 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 pPb collisions at the LHC. For $KE_T/n_q > 1.5$ GeV, no clear universal scaling of v_2/n_q between mesons and baryons is observed. The behavior is qualitatively different in the larger 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 , Λ , Ξ^- , Ω^- hadrons, in high-multiplicity pPb collisions at $\sqrt{s_{NN}} = 8.16$ 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 PbPb collision system. A possible interpretation is that, in high-multiplicity pPb collisions, in contrast to larger nucleus-nucleus collision systems, the collective behavior of charm quarks is weaker than that of the light-flavor quarks.

Acknowledgments

We congratulate our colleagues in the CERN accelerator departments for the excellent performance of the LHC and thank the technical and administrative staffs at CERN and at other CMS institutes for their contributions to the success of the CMS effort. In addition, we gratefully acknowledge the computing centers and personnel of the Worldwide LHC Computing Grid for delivering so effectively the computing infrastructure essential to our analyses. Finally, we acknowledge the enduring support for the construction and operation of the LHC and the CMS detector provided by the following funding agencies: BMWFW and FWF (Austria); FNRS and FWO (Belgium); CNPq, CAPES, FAPERJ, and FAPESP (Brazil); MES (Bulgaria); CERN; CAS, MoST, and NSFC (China); COLCIENCIAS (Colombia); MSES and CSF (Croatia); RPF (Cyprus); SENESCYT (Ecuador); MoER, ERC IUT, and ERDF (Estonia); Academy of Finland, MEC, and HIP (Finland); CEA and CNRS/IN2P3 (France); BMBF, DFG, and HGF (Germany); GSRT (Greece); NKFI (Hungary); DAE and DST (India); IPM (Iran); SFI (Ireland); INFN (Italy); MSIP and NRF (Republic of Korea); LAS (Lithuania); MOE and UM (Malaysia); BUAP, CINVESTAV, CONACYT, LNS, SEP, and UASLP-FAI (Mexico); MBIE (New Zealand); PAEC (Pakistan); MSHE and NSC (Poland); FCT (Portugal); JINR (Dubna); MON, RosAtom, RAS and RFBR (Russia); MESTD (Serbia); SEIDI, CPAN, PCTI and FEDER (Spain); Swiss Funding Agencies (Switzerland); MST (Taipei); ThEPCenter, IPST, STAR, and NSTDA (Thailand); TUBITAK and TAEK (Turkey); NASU and SFFR (Ukraine); STFC (United Kingdom); DOE and NSF (USA).

References

- [1] W. Busza et al., “Charged particle multiplicity in π^- -nucleus interactions at 100 and 175 GeV/c.”, *Phys. Rev. Lett.* **34** (1975) 836, doi:10.1103/PhysRevLett.34.836.
- [2] PHOBOS Collaboration, “System size dependence of cluster properties from two-particle angular correlations in Cu+Cu and Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV”, *Phys. Rev. C* **81** (2010) 024904, doi:10.1103/PhysRevC.81.024904, arXiv:0812.1172.
- [3] STAR Collaboration, “Distributions of charged hadrons associated with high transverse momentum particles in pp and Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV”, *Phys. Rev. Lett.* **95**

- (2005) 152301, doi:10.1103/PhysRevLett.95.152301, arXiv:nucl-ex/0501016.
- [4] STAR Collaboration, “Long range rapidity correlations and jet production in high energy nuclear collisions”, *Phys. Rev. C* **80** (2009) 064912, doi:10.1103/PhysRevC.80.064912, arXiv:0909.0191.
- [5] PHOBOS Collaboration, “High transverse momentum triggered correlations over a large pseudorapidity acceptance in Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV”, *Phys. Rev. Lett.* **104** (2010) 062301, doi:10.1103/PhysRevLett.104.062301, arXiv:0903.2811.
- [6] CMS Collaboration, “Long-range and short-range dihadron angular correlations in central PbPb collisions at a nucleon-nucleon center of mass energy of 2.76 TeV”, *JHEP* **07** (2011) 076, doi:10.1007/JHEP07(2011)076, arXiv:1105.2438.
- [7] CMS Collaboration, “Centrality dependence of dihadron correlations and azimuthal anisotropy harmonics in PbPb collisions at $\sqrt{s_{NN}} = 2.76$ TeV”, *Eur. Phys. J. C* **72** (2012) 2012, doi:10.1140/epjc/s10052-012-2012-3, arXiv:1201.3158.
- [8] ALICE Collaboration, “Elliptic flow of charged particles in Pb-Pb collisions at 2.76 TeV”, *Phys. Rev. Lett.* **105** (2010) 252302, doi:10.1103/PhysRevLett.105.252302, arXiv:1011.3914.
- [9] ATLAS Collaboration, “Measurement of the azimuthal anisotropy for charged particle production in $\sqrt{s_{NN}} = 2.76$ TeV lead-lead collisions with the ATLAS detector”, *Phys. Rev. C* **86** (2012) 014907, doi:10.1103/PhysRevC.86.014907, arXiv:1203.3087.
- [10] CMS Collaboration, “Measurement of the elliptic anisotropy of charged particles produced in PbPb collisions at nucleon-nucleon center-of-mass energy = 2.76 TeV”, *Phys. Rev. C* **87** (2013) 014902, doi:10.1103/PhysRevC.87.014902, arXiv:1204.1409.
- [11] CMS Collaboration, “Studies of azimuthal dihadron correlations in ultra-central PbPb collisions at $\sqrt{s_{NN}} = 2.76$ TeV”, *JHEP* **02** (2014) 088, doi:10.1007/JHEP02(2014)088, arXiv:1312.1845.
- [12] J.-Y. Ollitrault, “Anisotropy as a signature of transverse collective flow”, *Phys. Rev. D* **46** (1992) 229, doi:10.1103/PhysRevD.46.229.
- [13] U. Heinz and R. Snellings, “Collective flow and viscosity in relativistic heavy-ion collisions”, *Ann. Rev. Nucl. Part. Sci.* **63** (2013) 123, doi:10.1146/annurev-nucl-102212-170540, arXiv:1301.2826.
- [14] C. Gale, S. Jeon, and B. Schenke, “Hydrodynamic modeling of heavy-ion collisions”, *Int. J. Mod. Phys. A* **28** (2013) 1340011, doi:10.1142/S0217751X13400113, arXiv:1301.5893.
- [15] CMS Collaboration, “Observation of long-range near-side angular correlations in proton-proton collisions at the LHC”, *JHEP* **09** (2010) 091, doi:10.1007/JHEP09(2010)091, arXiv:1009.4122.
- [16] ATLAS Collaboration, “Observation of long-range elliptic azimuthal anisotropies in $\sqrt{s} = 13$ and 2.76 TeV pp collisions with the ATLAS Detector”, *Phys. Rev. Lett.* **116** (2016) 172301, doi:10.1103/PhysRevLett.116.172301, arXiv:1509.04776.

- [17] CMS Collaboration, “Measurement of long-range near-side two-particle angular correlations in pp collisions at $\sqrt{s} = 13$ TeV”, *Phys. Rev. Lett.* **116** (2016) 172302, doi:10.1103/PhysRevLett.116.172302, arXiv:1510.03068.
- [18] CMS Collaboration, “Observation of long-range near-side angular correlations in proton-lead collisions at the LHC”, *Phys. Lett. B* **718** (2013) 795, doi:10.1016/j.physletb.2012.11.025, arXiv:1210.5482.
- [19] ALICE Collaboration, “Long-range angular correlations on the near and away side in pPb collisions at $\sqrt{s_{NN}} = 5.02$ TeV”, *Phys. Lett. B* **719** (2013) 29, doi:10.1016/j.physletb.2013.01.012, arXiv:1212.2001.
- [20] ATLAS Collaboration, “Observation of associated near-side and away-side long-range correlations in $\sqrt{s_{NN}} = 5.02$ TeV proton-lead collisions with the ATLAS detector”, *Phys. Rev. Lett.* **110** (2013) 182302, doi:10.1103/PhysRevLett.110.182302, arXiv:1212.5198.
- [21] LHCb Collaboration, “Measurements of long-range near-side angular correlations in $\sqrt{s_{NN}} = 5$ TeV proton-lead collisions in the forward region”, *Phys. Lett. B* **762** (2016) 473, doi:10.1016/j.physletb.2016.09.064, arXiv:1512.00439.
- [22] R. D. Weller and P. Romatschke, “One fluid to rule them all: viscous hydrodynamic description of event-by-event central p+p, p+Pb and Pb+Pb collisions at $\sqrt{s} = 5.02$ TeV”, *Phys. Lett. B* **774** (2017) 351, doi:10.1016/j.physletb.2017.09.077, arXiv:1701.07145.
- [23] S. Voloshin and Y. Zhang, “Flow study in relativistic nuclear collisions by Fourier expansion of azimuthal particle distributions”, *Z. Phys. C* **70** (1996) 665, doi:10.1007/s002880050141, arXiv:hep-ph/9407282.
- [24] B. H. Alver, C. Gombeaud, M. Luzum, and J.-Y. Ollitrault, “Triangular flow in hydrodynamics and transport theory”, *Phys. Rev. C* **82** (2010) 034913, doi:10.1103/PhysRevC.82.034913, arXiv:1007.5469.
- [25] B. Schenke, S. Jeon, and C. Gale, “Elliptic and triangular flow in event-by-event D=3+1 viscous hydrodynamics”, *Phys. Rev. Lett.* **106** (2011) 042301, doi:10.1103/PhysRevLett.106.042301, arXiv:1009.3244.
- [26] Z. Qiu, C. Shen, and U. Heinz, “Hydrodynamic elliptic and triangular flow in Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV”, *Phys. Lett. B* **707** (2012) 151, doi:10.1016/j.physletb.2011.12.041, arXiv:1110.3033.
- [27] ALICE Collaboration, “Long-range angular correlations of pi, K and p in p-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV”, *Phys. Lett. B* **726** (2013) 164, doi:10.1016/j.physletb.2013.08.024, arXiv:1307.3237.
- [28] CMS Collaboration, “Long-range two-particle correlations of strange hadrons with charged particles in pPb and PbPb collisions at LHC energies”, *Phys. Lett. B* **742** (2015) 200, doi:10.1016/j.physletb.2015.01.034, arXiv:1409.3392.
- [29] CMS Collaboration, “Evidence for collectivity in pp collisions at the LHC”, *Phys. Lett. B* **765** (2017) 193, doi:10.1016/j.physletb.2016.12.009, arXiv:1606.06198.

-
- [30] CMS Collaboration, “Evidence for collective multi-particle correlations in pPb collisions”, *Phys. Rev. Lett.* **115** (2015) 012301, doi:10.1103/PhysRevLett.115.012301, arXiv:1502.05382.
 - [31] ATLAS Collaboration, “Measurement of multi-particle azimuthal correlations in pp , p +Pb and low-multiplicity Pb+Pb collisions with the ATLAS detector”, *Eur. Phys. J. C* **77** (2017) 428, doi:10.1140/epjc/s10052-017-4988-1, arXiv:1705.04176.
 - [32] ATLAS Collaboration, “Measurement of long-range multiparticle azimuthal correlations with the subevent cumulant method in pp and p +Pb collisions with the ATLAS detector at the CERN Large Hadron Collider”, *Phys. Rev. C* **97** (2018) 024904, doi:10.1103/PhysRevC.97.024904, arXiv:1708.03559.
 - [33] PHENIX Collaboration, “Measurement of long-range angular correlation and quadrupole anisotropy of pions and (anti)protons in central d +Au collisions at $\sqrt{s_{NN}} = 200$ GeV”, *Phys. Rev. Lett.* **114** (2015) 192301, doi:10.1103/PhysRevLett.114.192301, arXiv:1404.7461.
 - [34] STAR Collaboration, “Long-range pseudorapidity dihadron correlations in d +Au collisions at $\sqrt{s_{NN}} = 200$ GeV”, *Phys. Lett. B* **747** (2015) 265, doi:10.1016/j.physletb.2015.05.075, arXiv:1502.07652.
 - [35] PHENIX Collaboration, “Measurements of multiparticle correlations in d +Au collisions at 200, 62.4, 39, and 19.6 GeV and p +Au collisions at 200 GeV and implications for collective behavior”, *Phys. Rev. Lett.* **120** (2018) 062302, doi:10.1103/PhysRevLett.120.062302, arXiv:1707.06108.
 - [36] PHENIX Collaboration, “Measurements of elliptic and triangular flow in high-multiplicity ^3He +Au collisions at $\sqrt{s_{NN}} = 200$ GeV”, *Phys. Rev. Lett.* **115** (2015) 142301, doi:10.1103/PhysRevLett.115.142301, arXiv:1507.06273.
 - [37] K. Dusling, W. Li, and B. Schenke, “Novel collective phenomena in high-energy proton–proton and proton–nucleus collisions”, *Int. J. Mod. Phys. E* **25** (2016) 1630002, doi:10.1142/S0218301316300022, arXiv:1509.07939.
 - [38] J. L. Nagle and W. A. Zajc, “Small system collectivity in relativistic hadron and nuclear collisions”, (2018). arXiv:1801.03477. Submitted to *Ann. Rev. Nucl. Part. Sci.*
 - [39] P. Braun-Munzinger, “Quarkonium production in ultra-relativistic nuclear collisions: Suppression versus enhancement”, *J. Phys. G* **34** (2007) S471, doi:10.1088/0954-3899/34/8/S36, arXiv:nucl-th/0701093.
 - [40] STAR Collaboration, “Measurement of D^0 azimuthal anisotropy at midrapidity in Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV”, *Phys. Rev. Lett.* **118** (2017) 212301, doi:10.1103/PhysRevLett.118.212301, arXiv:1701.06060.
 - [41] ALICE Collaboration, “Azimuthal anisotropy of D meson production in Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV”, *Phys. Rev. C* **90** (2014) 034904, doi:10.1103/PhysRevC.90.034904, arXiv:1405.2001.
 - [42] ALICE Collaboration, “D-meson azimuthal anisotropy in midcentral Pb-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV”, *Phys. Rev. Lett.* **120** (2018) 102301, doi:10.1103/PhysRevLett.120.102301, arXiv:1707.01005.

- [43] CMS Collaboration, “Measurement of prompt D^0 meson azimuthal anisotropy in PbPb collisions at $\sqrt{s_{NN}} = 5.02$ TeV”, (2017). [arXiv:1708.03497](#). Submitted to *Phys. Rev. Lett.*
- [44] ALICE Collaboration, “Forward-central two-particle correlations in p-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV”, *Phys. Lett. B* **753** (2016) 126, [doi:10.1016/j.physletb.2015.12.010](#), [arXiv:1506.08032](#).
- [45] ALICE Collaboration, “Search for collectivity with azimuthal J/ψ -hadron correlations in high multiplicity p-Pb collisions at $\sqrt{s_{NN}} = 5.02$ and 8.16 TeV”, *Phys. Lett. B* **780** (2018) 7, [doi:10.1016/j.physletb.2018.02.039](#), [arXiv:1709.06807](#).
- [46] CMS Collaboration, “Description and performance of track and primary-vertex reconstruction with the CMS tracker”, *JINST* **9** (2014) P10009, [doi:10.1088/1748-0221/9/10/P10009](#), [arXiv:1405.6569](#).
- [47] CMS Collaboration, “The CMS experiment at the CERN LHC”, *JINST* **3** (2008) S08004, [doi:10.1088/1748-0221/3/08/S08004](#).
- [48] CMS Collaboration, “Constraints on the chiral magnetic effect using charge-dependent azimuthal correlations in pPb and PbPb collisions at the LHC”, (2017). [arXiv:1708.01602](#). Submitted to *Phys. Rev. C*.
- [49] CMS Collaboration, “Observation of correlated azimuthal anisotropy fourier harmonics in pp and p+Pb collisions at the LHC”, *Phys. Rev. Lett.* **120** (2018) 092301, [doi:10.1103/PhysRevLett.120.092301](#), [arXiv:1709.09189](#).
- [50] CMS Collaboration, “Multiplicity and rapidity dependence of strange hadron production in pp, pPb, and PbPb collisions at the LHC”, *Phys. Lett. B* **768** (2017) 103, [doi:10.1016/j.physletb.2017.01.075](#), [arXiv:1605.06699](#).
- [51] Particle Data Group, C. Patrignani et al., “Review of particle physics”, *Chin. Phys. C* **40** (2016) 100001, [doi:10.1088/1674-1137/40/10/100001](#).
- [52] T. Sjöstrand, S. Mrenna and P. Skands, “A brief introduction to PYTHIA 8.1”, *Comput. Phys. Commun.* **178** (2008) 852, [doi:10.1016/j.cpc.2008.01.036](#), [arXiv:0710.3820](#).
- [53] CMS Collaboration, “Event generator tunes obtained from underlying event and multiparton scattering measurements”, *Eur. Phys. J. C* **76** (2016) 155, [doi:10.1140/epjc/s10052-016-3988-x](#), [arXiv:1512.00815](#).
- [54] T. Pierog et al., “EPOS LHC: Test of collective hadronization with data measured at the CERN Large Hadron Collider”, *Phys. Rev. C* **92** (2015) 034906, [doi:10.1103/PhysRevC.92.034906](#), [arXiv:1306.0121](#).
- [55] CMS Collaboration, “Multiplicity and transverse momentum dependence of two- and four-particle correlations in pPb and PbPb collisions”, *Phys. Lett. B* **724** (2013) 213, [doi:10.1016/j.physletb.2013.06.028](#), [arXiv:1305.0609](#).
- [56] M. Nahrgang et al., “Elliptic and triangular flow of heavy flavor in heavy-ion collisions”, *Phys. Rev. C* **91** (2015) 014904, [doi:10.1103/PhysRevC.91.014904](#), [arXiv:1410.5396](#).

- [57] M. He, R. J. Fries, and R. Rapp, “Heavy flavor at the Large Hadron Collider in a strong coupling approach”, *Phys. Lett. B* **735** (2014) 445, doi:10.1016/j.physletb.2014.05.050, arXiv:1401.3817.
- [58] J. Xu, J. Liao, and M. Gyulassy, “Bridging soft-hard transport properties of quark-gluon plasmas with CUJET3.0”, *JHEP* **02** (2016) 169, doi:10.1007/JHEP02(2016)169, arXiv:1508.00552.
- [59] D. Molnar and S. A. Voloshin, “Elliptic flow at large transverse momenta from quark coalescence”, *Phys. Rev. Lett.* **91** (2003) 092301, doi:10.1103/PhysRevLett.91.092301, arXiv:nucl-th/0302014.
- [60] V. Greco, C. M. Ko, and P. Levai, “Parton coalescence and antiproton/pion anomaly at RHIC”, *Phys. Rev. Lett.* **90** (2003) 202302, doi:10.1103/PhysRevLett.90.202302, arXiv:nucl-th/0301093.
- [61] R. J. Fries, B. Muller, C. Nonaka, and S. A. Bass, “Hadronization in heavy ion collisions: Recombination and fragmentation of partons”, *Phys. Rev. Lett.* **90** (2003) 202303, doi:10.1103/PhysRevLett.90.202303, arXiv:nucl-th/0301087.
- [62] STAR Collaboration, “Mass, quark-number, and $\sqrt{s_{NN}}$ dependence of the second and fourth flow harmonics in ultra-relativistic nucleus-nucleus collisions”, *Phys. Rev. C* **75** (2007) 054906, doi:10.1103/PhysRevC.75.054906, arXiv:nucl-ex/0701010.
- [63] PHENIX Collaboration, “Scaling properties of azimuthal anisotropy in Au+Au and Cu+Cu collisions at $\sqrt{s_{NN}} = 200$ GeV”, *Phys. Rev. Lett.* **98** (2007) 162301, doi:10.1103/PhysRevLett.98.162301, arXiv:nucl-ex/0608033.

A The CMS Collaboration

Yerevan Physics Institute, Yerevan, Armenia

A.M. Sirunyan, A. Tumasyan

Institut für Hochenergiephysik, Wien, Austria

W. Adam, F. Ambrogio, E. Asilar, T. Bergauer, J. Brandstetter, E. Brondolin, M. Dragicevic, J. Erö, A. Escalante Del Valle, M. Flechl, R. Frühwirth¹, V.M. Ghete, J. Hrubec, M. Jeitler¹, N. Krammer, I. Krätschmer, D. Liko, T. Madlener, I. Mikulec, N. Rad, H. Rohringer, J. Schieck¹, R. Schöfbeck, M. Spanring, D. Spitzbart, A. Taurok, W. Waltenberger, J. Wittmann, C.-E. Wulz¹, M. Zarucki

Institute for Nuclear Problems, Minsk, Belarus

V. Chekhovsky, V. Mossolov, J. Suarez Gonzalez

Universiteit Antwerpen, Antwerpen, Belgium

E.A. De Wolf, D. Di Croce, X. Janssen, J. Lauwers, M. Pieters, M. Van De Klundert, H. Van Haevermaet, P. Van Mechelen, N. Van Remortel

Vrije Universiteit Brussel, Brussel, Belgium

S. Abu Zeid, F. Blekman, J. D'Hondt, I. De Bruyn, J. De Clercq, K. Deroover, G. Flouris, D. Lontkovskyi, S. Lowette, I. Marchesini, S. Moortgat, L. Moreels, Q. Python, K. Skovpen, S. Tavernier, W. Van Doninck, P. Van Mulders, I. Van Parijs

Université Libre de Bruxelles, Bruxelles, Belgium

D. Beghin, B. Bilin, H. Brun, B. Clerbaux, G. De Lentdecker, H. Delannoy, B. Dorney, G. Fasanella, L. Favart, R. Goldouzian, A. Grebenyuk, A.K. Kalsi, T. Lenzi, J. Luetic, N. Postiau, E. Starling, L. Thomas, C. Vander Velde, P. Vanlaer, D. Vannerom, Q. Wang

Ghent University, Ghent, Belgium

T. Cornelis, D. Dobur, A. Fagot, M. Gul, I. Khvastunov², D. Poyraz, C. Roskas, D. Trocino, M. Tytgat, W. Verbeke, B. Vermassen, M. Vit, N. Zaganidis

Université Catholique de Louvain, Louvain-la-Neuve, Belgium

H. Bakhshiansohi, O. Bondu, S. Brochet, G. Bruno, C. Caputo, P. David, C. Delaere, M. Delcourt, B. Francois, A. Giammanco, G. Krintiras, V. Lemaitre, A. Magitteri, A. Mertens, M. Musich, K. Piotrkowski, A. Saggio, M. Vidal Marono, S. Wertz, J. Zobec

Centro Brasileiro de Pesquisas Fisicas, Rio de Janeiro, Brazil

F.L. Alves, G.A. Alves, L. Brito, G. Correia Silva, C. Hensel, A. Moraes, M.E. Pol, P. Rebello Teles

Universidade do Estado do Rio de Janeiro, Rio de Janeiro, Brazil

E. Belchior Batista Das Chagas, W. Carvalho, J. Chinellato³, E. Coelho, E.M. Da Costa, G.G. Da Silveira⁴, D. De Jesus Damiao, C. De Oliveira Martins, S. Fonseca De Souza, H. Malbouisson, D. Matos Figueiredo, M. Melo De Almeida, C. Mora Herrera, L. Mundim, H. Nogima, W.L. Prado Da Silva, L.J. Sanchez Rosas, A. Santoro, A. Sznajder, M. Thiel, E.J. Tonelli Manganote³, F. Torres Da Silva De Araujo, A. Vilela Pereira

Universidade Estadual Paulista ^a, Universidade Federal do ABC ^b, São Paulo, Brazil

S. Ahuja^a, C.A. Bernardes^a, L. Calligaris^a, T.R. Fernandez Perez Tomei^a, E.M. Gregores^b, P.G. Mercadante^b, S.F. Novaes^a, SandraS. Padula^a, D. Romero Abad^b

Institute for Nuclear Research and Nuclear Energy, Bulgarian Academy of Sciences, Sofia, Bulgaria

A. Aleksandrov, R. Hadjiiska, P. Iaydjiev, A. Marinov, M. Misheva, M. Rodozov, M. Shopova, G. Sultanov

University of Sofia, Sofia, Bulgaria

A. Dimitrov, L. Litov, B. Pavlov, P. Petkov

Beihang University, Beijing, China

W. Fang⁵, X. Gao⁵, L. Yuan

Institute of High Energy Physics, Beijing, China

M. Ahmad, J.G. Bian, G.M. Chen, H.S. Chen, M. Chen, Y. Chen, C.H. Jiang, D. Leggat, H. Liao, Z. Liu, F. Romeo, S.M. Shaheen, A. Spiezia, J. Tao, C. Wang, Z. Wang, E. Yazgan, H. Zhang, J. Zhao

State Key Laboratory of Nuclear Physics and Technology, Peking University, Beijing, China

Y. Ban, G. Chen, J. Li, L. Li, Q. Li, Y. Mao, S.J. Qian, D. Wang, Z. Xu

Tsinghua University, Beijing, China

Y. Wang

Universidad de Los Andes, Bogota, Colombia

C. Avila, A. Cabrera, C.A. Carrillo Montoya, L.F. Chaparro Sierra, C. Florez, C.F. González Hernández, M.A. Segura Delgado

University of Split, Faculty of Electrical Engineering, Mechanical Engineering and Naval Architecture, Split, Croatia

B. Courbon, N. Godinovic, D. Lelas, I. Puljak, T. Sculac

University of Split, Faculty of Science, Split, Croatia

Z. Antunovic, M. Kovac

Institute Rudjer Boskovic, Zagreb, Croatia

V. Brigljevic, D. Ferencek, K. Kadija, B. Mesic, A. Starodumov⁶, T. Susa

University of Cyprus, Nicosia, Cyprus

M.W. Ather, A. Attikis, G. Mavromanolakis, J. Mousa, C. Nicolaou, F. Ptochos, P.A. Razis, H. Rykaczewski

Charles University, Prague, Czech Republic

M. Finger⁷, M. Finger Jr.⁷

Escuela Politecnica Nacional, Quito, Ecuador

E. Ayala

Universidad San Francisco de Quito, Quito, Ecuador

E. Carrera Jarrin

Academy of Scientific Research and Technology of the Arab Republic of Egypt, Egyptian Network of High Energy Physics, Cairo, Egypt

M.A. Mahmoud^{8,9}, Y. Mohammed⁸, E. Salama^{9,10}

National Institute of Chemical Physics and Biophysics, Tallinn, Estonia

S. Bhowmik, A. Carvalho Antunes De Oliveira, R.K. Dewanjee, K. Ehataht, M. Kadastik, M. Raidal, C. Veelken

Department of Physics, University of Helsinki, Helsinki, Finland

P. Eerola, H. Kirschenmann, J. Pekkanen, M. Voutilainen

Helsinki Institute of Physics, Helsinki, Finland

J. Havukainen, J.K. Heikkilä, T. Järvinen, V. Karimäki, R. Kinnunen, T. Lampén, K. Lassila-Perini, S. Laurila, S. Lehti, T. Lindén, P. Luukka, T. Mäenpää, H. Siikonen, E. Tuominen, J. Tuominiemi

Lappeenranta University of Technology, Lappeenranta, Finland

T. Tuuva

IRFU, CEA, Université Paris-Saclay, Gif-sur-Yvette, France

M. Besancon, F. Couderc, M. Dejardin, D. Denegri, J.L. Faure, F. Ferri, S. Ganjour, A. Givernaud, P. Gras, G. Hamel de Monchenault, P. Jarry, C. Leloup, E. Locci, J. Malcles, G. Negro, J. Rander, A. Rosowsky, M.Ö. Sahin, M. Titov

Laboratoire Leprince-Ringuet, Ecole polytechnique, CNRS/IN2P3, Université Paris-Saclay, Palaiseau, France

A. Abdulsalam¹¹, C. Amendola, I. Antropov, F. Beaudette, P. Busson, C. Charlot, R. Granier de Cassagnac, I. Kucher, S. Lisniak, A. Lobanov, J. Martin Blanco, M. Nguyen, C. Ochando, G. Ortona, P. Pigard, R. Salerno, J.B. Sauvan, Y. Sirois, A.G. Stahl Leiton, A. Zabi, A. Zghiche

Université de Strasbourg, CNRS, IPHC UMR 7178, F-67000 Strasbourg, France

J.-L. Agram¹², J. Andrea, D. Bloch, J.-M. Brom, E.C. Chabert, V. Cherepanov, C. Collard, E. Conte¹², J.-C. Fontaine¹², D. Gelé, U. Goerlach, M. Jansová, A.-C. Le Bihan, N. Tonon, P. Van Hove

Centre de Calcul de l'Institut National de Physique Nucleaire et de Physique des Particules, CNRS/IN2P3, Villeurbanne, France

S. Gadrat

Université de Lyon, Université Claude Bernard Lyon 1, CNRS-IN2P3, Institut de Physique Nucléaire de Lyon, Villeurbanne, France

S. Beauceron, C. Bernet, G. Boudoul, N. Chanon, R. Chierici, D. Contardo, P. Depasse, H. El Mamouni, J. Fay, L. Finco, S. Gascon, M. Gouzevitch, G. Grenier, B. Ille, F. Lagarde, I.B. Laktineh, H. Lattaud, M. Lethuillier, L. Mirabito, A.L. Pequegnot, S. Perries, A. Popov¹³, V. Sordini, M. Vander Donckt, S. Viret, S. Zhang

Georgian Technical University, Tbilisi, Georgia

T. Toriashvili¹⁴

Tbilisi State University, Tbilisi, Georgia

Z. Tsamalaidze⁷

RWTH Aachen University, I. Physikalisches Institut, Aachen, Germany

C. Autermann, L. Feld, M.K. Kiesel, K. Klein, M. Lipinski, M. Preuten, M.P. Rauch, C. Schomakers, J. Schulz, M. Teroerde, B. Wittmer, V. Zhukov¹³

RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany

A. Albert, D. Duchardt, M. Endres, M. Erdmann, T. Esch, R. Fischer, S. Ghosh, A. Güth, T. Hebbeker, C. Heidemann, K. Hoepfner, H. Keller, S. Knutzen, L. Mastrolorenzo, M. Merschmeyer, A. Meyer, P. Millet, S. Mukherjee, T. Pook, M. Radziej, H. Reithler, M. Rieger, F. Scheuch, A. Schmidt, D. Teyssier

RWTH Aachen University, III. Physikalisches Institut B, Aachen, Germany

G. Flügge, O. Hlushchenko, B. Kargoll, T. Kress, A. Künsken, T. Müller, A. Nehr Korn, A. Nowack, C. Pistone, O. Pooth, H. Sert, A. Stahl¹⁵

Deutsches Elektronen-Synchrotron, Hamburg, Germany

M. Aldaya Martin, T. Arndt, C. Asawatangtrakuldee, I. Babounikau, K. Beernaert, O. Behnke, U. Behrens, A. Bermúdez Martínez, D. Bertsche, A.A. Bin Anuar, K. Borras¹⁶, V. Botta, A. Campbell, P. Connor, C. Contreras-Campana, F. Costanza, V. Danilov, A. De Wit, M.M. Defranchis, C. Diez Pardos, D. Domínguez Damiani, G. Eckerlin, T. Eichhorn, A. Elwood, E. Eren, E. Gallo¹⁷, A. Geiser, J.M. Grados Luyando, A. Grohsjean, P. Gunnellini, M. Guthoff, M. Haranko, A. Harb, J. Hauk, H. Jung, M. Kasemann, J. Keaveney, C. Kleinwort, J. Knolle, D. Krücker, W. Lange, A. Lelek, T. Lenz, K. Lipka, W. Lohmann¹⁸, R. Mankel, I.-A. Melzer-Pellmann, A.B. Meyer, M. Meyer, M. Missiroli, G. Mittag, J. Mnich, V. Myronenko, S.K. Pflitsch, D. Pitzl, A. Raspereza, M. Savitskyi, P. Saxena, P. Schütze, C. Schwanenberger, R. Shevchenko, A. Singh, N. Stefaniuk, H. Tholen, A. Vagnerini, G.P. Van Onsem, R. Walsh, Y. Wen, K. Wichmann, C. Wissing, O. Zenaiev

University of Hamburg, Hamburg, Germany

R. Aggleton, S. Bein, A. Benecke, V. Blobel, M. Centis Vignali, T. Dreyer, E. Garutti, D. Gonzalez, J. Haller, A. Hinzmann, M. Hoffmann, A. Karavdina, G. Kasieczka, R. Klanner, R. Kogler, N. Kovalchuk, S. Kurz, V. Kutzner, J. Lange, D. Marconi, J. Multhaupt, M. Niedziela, D. Nowatschin, A. Perieanu, A. Reimers, O. Rieger, C. Scharf, P. Schleper, S. Schumann, J. Schwandt, J. Sonneveld, H. Stadie, G. Steinbrück, F.M. Stober, M. Stöver, D. Troendle, E. Usai, A. Vanhoefer, B. Vormwald

Institut für Experimentelle Teilchenphysik, Karlsruhe, Germany

M. Akbiyik, C. Barth, M. Baselga, S. Baur, E. Butz, R. Caspart, T. Chwalek, F. Colombo, W. De Boer, A. Dierlamm, N. Faltermann, B. Freund, M. Giffels, M.A. Harrendorf, F. Hartmann¹⁵, S.M. Heindl, U. Husemann, F. Kassel¹⁵, I. Katkov¹³, S. Kudella, H. Mildner, S. Mitra, M.U. Mozer, Th. Müller, M. Plagge, G. Quast, K. Rabbertz, M. Schröder, I. Shvetsov, G. Sieber, H.J. Simonis, R. Ulrich, S. Wayand, M. Weber, T. Weiler, S. Williamson, C. Wöhrmann, R. Wolf

Institute of Nuclear and Particle Physics (INPP), NCSR Demokritos, Aghia Paraskevi, Greece

G. Anagnostou, G. Daskalakis, T. Gerasis, A. Kyriakis, D. Loukas, G. Paspalaki, I. Topsis-Giotis

National and Kapodistrian University of Athens, Athens, Greece

G. Karathanasis, S. Kesisoglou, P. Kontaxakis, A. Panagiotou, N. Saoulidou, E. Tziaferi, K. Vellidis

National Technical University of Athens, Athens, Greece

K. Kousouris, I. Papakrivopoulos, G. Tsipolitis

University of Ioánnina, Ioánnina, Greece

I. Evangelou, C. Foudas, P. Giannios, P. Katsoulis, P. Kokkas, S. Mallios, N. Manthos, I. Papadopoulos, E. Paradas, J. Strologas, F.A. Triantis, D. Tsitsonis

MTA-ELTE Lendület CMS Particle and Nuclear Physics Group, Eötvös Loránd University, Budapest, Hungary

M. Csanad, N. Filipovic, P. Major, M.I. Nagy, G. Pasztor, O. Surányi, G.I. Veres

Wigner Research Centre for Physics, Budapest, Hungary

G. Bencze, C. Hajdu, D. Horvath¹⁹, Á. Hunyadi, F. Sikler, T.Á. Vámi, V. Veszpremi, G. Vesztergombi[†]

Institute of Nuclear Research ATOMKI, Debrecen, Hungary

N. Beni, S. Czellar, J. Karancsi²¹, A. Makovec, J. Molnar, Z. Szillasi

Institute of Physics, University of Debrecen, Debrecen, Hungary

M. Bartók²⁰, P. Raics, Z.L. Trocsanyi, B. Ujvari

Indian Institute of Science (IISc), Bangalore, India

S. Choudhury, J.R. Komaragiri, P.C. Tiwari

National Institute of Science Education and Research, Bhubaneswar, India

S. Bahinipati²², P. Mal, K. Mandal, A. Nayak²³, D.K. Sahoo²², S.K. Swain

Panjab University, Chandigarh, India

S. Bansal, S.B. Beri, V. Bhatnagar, S. Chauhan, R. Chawla, N. Dhingra, R. Gupta, A. Kaur, A. Kaur, M. Kaur, S. Kaur, R. Kumar, P. Kumari, M. Lohan, A. Mehta, K. Sandeep, S. Sharma, J.B. Singh, G. Walia

University of Delhi, Delhi, India

A. Bhardwaj, B.C. Choudhary, R.B. Garg, M. Gola, S. Keshri, Ashok Kumar, S. Malhotra, M. Naimuddin, P. Priyanka, K. Ranjan, Aashaq Shah, R. Sharma

Saha Institute of Nuclear Physics, HBNI, Kolkata, India

R. Bhardwaj²⁴, M. Bharti, R. Bhattacharya, S. Bhattacharya, U. Bhawandeep²⁴, D. Bhowmik, S. Dey, S. Dutt²⁴, S. Dutta, S. Ghosh, K. Mondal, S. Nandan, A. Purohit, P.K. Rout, A. Roy, S. Roy Chowdhury, S. Sarkar, M. Sharan, B. Singh, S. Thakur²⁴

Indian Institute of Technology Madras, Madras, India

P.K. Behera

Bhabha Atomic Research Centre, Mumbai, India

R. Chudasama, D. Dutta, V. Jha, V. Kumar, P.K. Netrakanti, L.M. Pant, P. Shukla

Tata Institute of Fundamental Research-A, Mumbai, India

T. Aziz, M.A. Bhat, S. Dugad, G.B. Mohanty, N. Sur, B. Sutar, RavindraKumar Verma

Tata Institute of Fundamental Research-B, Mumbai, India

S. Banerjee, S. Bhattacharya, S. Chatterjee, P. Das, M. Guchait, Sa. Jain, S. Kumar, M. Maity²⁵, G. Majumder, K. Mazumdar, N. Sahoo, T. Sarkar²⁵

Indian Institute of Science Education and Research (IISER), Pune, India

S. Chauhan, S. Dube, V. Hegde, A. Kapoor, K. Kothekar, S. Pandey, A. Rane, S. Sharma

Institute for Research in Fundamental Sciences (IPM), Tehran, Iran

S. Chenarani²⁶, E. Eskandari Tadavani, S.M. Etesami²⁶, M. Khakzad, M. Mohammadi Najafabadi, M. Naseri, F. Rezaei Hosseinabadi, B. Safarzadeh²⁷, M. Zeinali

University College Dublin, Dublin, Ireland

M. Felcini, M. Grunewald

INFN Sezione di Bari ^a, Università di Bari ^b, Politecnico di Bari ^c, Bari, Italy

M. Abbrescia^{a,b}, C. Calabria^{a,b}, A. Colaleo^a, D. Creanza^{a,c}, L. Cristella^{a,b}, N. De Filippis^{a,c}, M. De Palma^{a,b}, A. Di Florio^{a,b}, F. Errico^{a,b}, L. Fiore^a, A. Gelmi^{a,b}, G. Iaselli^{a,c}, S. Lezki^{a,b}, G. Maggi^{a,c}, M. Maggi^a, G. Miniello^{a,b}, S. My^{a,b}, S. Nuzzo^{a,b}, A. Pompili^{a,b}, G. Pugliese^{a,c}, R. Radogna^a, A. Ranieri^a, G. Selvaggi^{a,b}, A. Sharma^a, L. Silvestris^{a,15}, R. Venditti^a, P. Verwilligen^a, G. Zito^a

INFN Sezione di Bologna ^a, Università di Bologna ^b, Bologna, Italy

G. Abbiendi^a, C. Battilana^{a,b}, D. Bonacorsi^{a,b}, L. Borgonovi^{a,b}, S. Braibant-Giacomelli^{a,b}, L. Brigliadori^{a,b}, R. Campanini^{a,b}, P. Capiluppi^{a,b}, A. Castro^{a,b}, F.R. Cavallo^a, S.S. Chhibra^{a,b},

G. Codispoti^{a,b}, M. Cuffiani^{a,b}, G.M. Dallavalle^a, F. Fabbri^a, A. Fanfani^{a,b}, P. Giacomelli^a, C. Grandi^a, L. Guiducci^{a,b}, S. Marcellini^a, G. Masetti^a, A. Montanari^a, F.L. Navarria^{a,b}, A. Perrotta^a, A.M. Rossi^{a,b}, T. Rovelli^{a,b}, G.P. Siroli^{a,b}, N. Tosi^a

INFN Sezione di Catania ^a, Università di Catania ^b, Catania, Italy

S. Albergo^{a,b}, A. Di Mattia^a, R. Potenza^{a,b}, A. Tricomi^{a,b}, C. Tuve^{a,b}

INFN Sezione di Firenze ^a, Università di Firenze ^b, Firenze, Italy

G. Barbagli^a, K. Chatterjee^{a,b}, V. Ciulli^{a,b}, C. Civinini^a, R. D'Alessandro^{a,b}, E. Focardi^{a,b}, G. Latino, P. Lenzi^{a,b}, M. Meschini^a, S. Paoletti^a, L. Russo^{a,28}, G. Sguazzoni^a, D. Strom^a, L. Viliani^a

INFN Laboratori Nazionali di Frascati, Frascati, Italy

L. Benussi, S. Bianco, F. Fabbri, D. Piccolo, F. Primavera¹⁵

INFN Sezione di Genova ^a, Università di Genova ^b, Genova, Italy

F. Ferro^a, F. Ravera^{a,b}, E. Robutti^a, S. Tosi^{a,b}

INFN Sezione di Milano-Bicocca ^a, Università di Milano-Bicocca ^b, Milano, Italy

A. Benaglia^a, A. Beschi^b, L. Brianza^{a,b}, F. Brivio^{a,b}, V. Ciriolo^{a,b,15}, S. Di Guida^{a,d,15}, M.E. Dinardo^{a,b}, S. Fiorendi^{a,b}, S. Gennai^a, A. Ghezzi^{a,b}, P. Govoni^{a,b}, M. Malberti^{a,b}, S. Malvezzi^a, A. Massironi^{a,b}, D. Menasce^a, L. Moroni^a, M. Paganoni^{a,b}, D. Pedrini^a, S. Ragazzi^{a,b}, T. Tabarelli de Fatis^{a,b}

INFN Sezione di Napoli ^a, Università di Napoli 'Federico II' ^b, Napoli, Italy, Università della Basilicata ^c, Potenza, Italy, Università G. Marconi ^d, Roma, Italy

S. Buontempo^a, N. Cavallo^{a,c}, A. Di Crescenzo^{a,b}, F. Fabozzi^{a,c}, F. Fienga^{a,b}, G. Galati^{a,b}, A.O.M. Iorio^{a,b}, W.A. Khan^a, L. Lista^a, S. Meola^{a,d,15}, P. Paolucci^{a,15}, C. Sciacca^{a,b}, E. Voevodina^{a,b}

INFN Sezione di Padova ^a, Università di Padova ^b, Padova, Italy, Università di Trento ^c, Trento, Italy

P. Azzi^a, N. Bacchetta^a, L. Benato^{a,b}, D. Bisello^{a,b}, A. Boletti^{a,b}, A. Bragagnolo, R. Carlin^{a,b}, P. Checchia^a, M. Dall'Osso^{a,b}, P. De Castro Manzano^a, T. Dorigo^a, U. Dosselli^a, F. Gasparini^{a,b}, U. Gasparini^{a,b}, A. Gozzelino^a, S. Lacaprara^a, P. Lujan, M. Margoni^{a,b}, A.T. Meneguzzo^{a,b}, P. Ronchese^{a,b}, R. Rossin^{a,b}, F. Simonetto^{a,b}, A. Tiko, E. Torassa^a, M. Zanetti^{a,b}, P. Zotto^{a,b}, G. Zumerle^{a,b}

INFN Sezione di Pavia ^a, Università di Pavia ^b, Pavia, Italy

A. Braghieri^a, A. Magnani^a, P. Montagna^{a,b}, S.P. Ratti^{a,b}, V. Re^a, M. Ressegotti^{a,b}, C. Riccardi^{a,b}, P. Salvini^a, I. Vai^{a,b}, P. Vitulo^{a,b}

INFN Sezione di Perugia ^a, Università di Perugia ^b, Perugia, Italy

L. Alunni Solestizi^{a,b}, M. Biasini^{a,b}, G.M. Bilei^a, C. Cecchi^{a,b}, D. Ciangottini^{a,b}, L. Fanò^{a,b}, P. Lariccia^{a,b}, E. Manoni^a, G. Mantovani^{a,b}, V. Mariani^{a,b}, M. Menichelli^a, A. Rossi^{a,b}, A. Santocchia^{a,b}, D. Spiga^a

INFN Sezione di Pisa ^a, Università di Pisa ^b, Scuola Normale Superiore di Pisa ^c, Pisa, Italy

K. Androsov^a, P. Azzurri^a, G. Bagliesi^a, L. Bianchini^a, T. Boccali^a, L. Borrello, R. Castaldi^a, M.A. Ciocci^{a,b}, R. Dell'Orso^a, G. Fedì^a, L. Giannini^{a,c}, A. Giassi^a, M.T. Grippo^a, F. Ligabue^{a,c}, E. Manca^{a,c}, G. Mandorli^{a,c}, A. Messineo^{a,b}, F. Palla^a, A. Rizzi^{a,b}, P. Spagnolo^a, R. Tenchini^a, G. Tonelli^{a,b}, A. Venturi^a, P.G. Verdini^a

INFN Sezione di Roma ^a, Sapienza Università di Roma ^b, Rome, Italy

L. Barone^{a,b}, F. Cavallari^a, M. Cipriani^{a,b}, N. Daci^a, D. Del Re^{a,b}, E. Di Marco^{a,b}, M. Diemoz^a,

S. Gelli^{a,b}, E. Longo^{a,b}, B. Marzocchi^{a,b}, P. Meridiani^a, G. Organtini^{a,b}, F. Pandolfi^a, R. Paramatti^{a,b}, F. Preiato^{a,b}, S. Rahatlou^{a,b}, C. Rovelli^a, F. Santanastasio^{a,b}

INFN Sezione di Torino ^a, Università di Torino ^b, Torino, Italy, Università del Piemonte Orientale ^c, Novara, Italy

N. Amapane^{a,b}, R. Arcidiacono^{a,c}, S. Argiro^{a,b}, M. Arneodo^{a,c}, N. Bartosik^a, R. Bellan^{a,b}, C. Biino^a, N. Cartiglia^a, F. Cenna^{a,b}, S. Cometti, M. Costa^{a,b}, R. Covarelli^{a,b}, N. Demaria^a, B. Kiani^{a,b}, C. Mariotti^a, S. Maselli^a, E. Migliore^{a,b}, V. Monaco^{a,b}, E. Monteil^{a,b}, M. Monteno^a, M.M. Obertino^{a,b}, L. Pacher^{a,b}, N. Pastrone^a, M. Pelliccioni^a, G.L. Pinna Angioni^{a,b}, A. Romero^{a,b}, M. Ruspa^{a,c}, R. Sacchi^{a,b}, K. Shchelina^{a,b}, V. Sola^a, A. Solano^{a,b}, D. Soldi, A. Staiano^a

INFN Sezione di Trieste ^a, Università di Trieste ^b, Trieste, Italy

S. Belforte^a, V. Candelise^{a,b}, M. Casarsa^a, F. Cossutti^a, G. Della Ricca^{a,b}, F. Vazzoler^{a,b}, A. Zanetti^a

Kyungpook National University

D.H. Kim, G.N. Kim, M.S. Kim, J. Lee, S. Lee, S.W. Lee, C.S. Moon, Y.D. Oh, S. Sekmen, D.C. Son, Y.C. Yang

Chonnam National University, Institute for Universe and Elementary Particles, Kwangju, Korea

H. Kim, D.H. Moon, G. Oh

Hanyang University, Seoul, Korea

J. Goh, T.J. Kim

Korea University, Seoul, Korea

S. Cho, S. Choi, Y. Go, D. Gyun, S. Ha, B. Hong, Y. Jo, K. Lee, K.S. Lee, S. Lee, J. Lim, S.K. Park, Y. Roh

Sejong University, Seoul, Korea

H.S. Kim

Seoul National University, Seoul, Korea

J. Almond, J. Kim, J.S. Kim, H. Lee, K. Lee, K. Nam, S.B. Oh, B.C. Radburn-Smith, S.h. Seo, U.K. Yang, H.D. Yoo, G.B. Yu

University of Seoul, Seoul, Korea

H. Kim, J.H. Kim, J.S.H. Lee, I.C. Park

Sungkyunkwan University, Suwon, Korea

Y. Choi, C. Hwang, J. Lee, I. Yu

Vilnius University, Vilnius, Lithuania

V. Dudenias, A. Juodagalvis, J. Vaitkus

National Centre for Particle Physics, Universiti Malaya, Kuala Lumpur, Malaysia

I. Ahmed, Z.A. Ibrahim, M.A.B. Md Ali²⁹, F. Mohamad Idris³⁰, W.A.T. Wan Abdullah, M.N. Yusli, Z. Zolkapli

Centro de Investigacion y de Estudios Avanzados del IPN, Mexico City, Mexico

Duran-Osuna, M. C., H. Castilla-Valdez, E. De La Cruz-Burelo, Ramirez-Sanchez, G., I. Heredia-De La Cruz³¹, Rabadan-Trejo, R. I., R. Lopez-Fernandez, J. Mejia Guisao, Reyes-Almanza, R, A. Sanchez-Hernandez

Universidad Iberoamericana, Mexico City, Mexico

S. Carrillo Moreno, C. Oropeza Barrera, F. Vazquez Valencia

Benemerita Universidad Autonoma de Puebla, Puebla, Mexico

J. Eysermans, I. Pedraza, H.A. Salazar Ibarguen, C. Uribe Estrada

Universidad Autónoma de San Luis Potosí, San Luis Potosí, Mexico

A. Morelos Pineda

University of Auckland, Auckland, New Zealand

D. Krofcheck

University of Canterbury, Christchurch, New Zealand

S. Bheesette, P.H. Butler

National Centre for Physics, Quaid-I-Azam University, Islamabad, Pakistan

A. Ahmad, M. Ahmad, M.I. Asghar, Q. Hassan, H.R. Hoorani, A. Saddique, M.A. Shah, M. Shoaib, M. Waqas

National Centre for Nuclear Research, Swierk, Poland

H. Bialkowska, M. Bluj, B. Boimska, T. Frueboes, M. Górski, M. Kazana, K. Nawrocki, M. Szleper, P. Traczyk, P. Zalewski

Institute of Experimental Physics, Faculty of Physics, University of Warsaw, Warsaw, Poland

K. Bunkowski, A. Byszuk³², K. Doroba, A. Kalinowski, M. Konecki, J. Krolikowski, M. Misiura, M. Olszewski, A. Pyskir, M. Walczak

Laboratório de Instrumentação e Física Experimental de Partículas, Lisboa, Portugal

P. Bargassa, C. Beirão Da Cruz E Silva, A. Di Francesco, P. Faccioli, B. Galinhas, M. Gallinaro, J. Hollar, N. Leonardo, L. Lloret Iglesias, M.V. Nemallapudi, J. Seixas, G. Strong, O. Toldaiev, D. Vadrucio, J. Varela

Joint Institute for Nuclear Research, Dubna, Russia

S. Afanasiev, P. Bunin, M. Gavrilenko, I. Golutvin, I. Gorbunov, A. Kamenev, V. Karjavin, A. Lanev, A. Malakhov, V. Matveev^{33,34}, P. Moisezenz, V. Palichik, V. Pereygin, S. Shmatov, S. Shulha, N. Skatchkov, V. Smirnov, N. Voytishin, A. Zarubin

Petersburg Nuclear Physics Institute, Gatchina (St. Petersburg), Russia

V. Golovtsov, Y. Ivanov, V. Kim³⁵, E. Kuznetsova³⁶, P. Levchenko, V. Murzin, V. Oreshkin, I. Smirnov, D. Sosnov, V. Sulimov, L. Uvarov, S. Vavilov, A. Vorobyev

Institute for Nuclear Research, Moscow, Russia

Yu. Andreev, A. Dermenev, S. Gninenko, N. Golubev, A. Karneyeu, M. Kirsanov, N. Krasnikov, A. Pashenkov, D. Tlisov, A. Toropin

Institute for Theoretical and Experimental Physics, Moscow, Russia

V. Epshteyn, V. Gavrilo, N. Lychkovskaya, V. Popov, I. Pozdnyakov, G. Safronov, A. Spiridonov, A. Stepenov, V. Stolin, M. Toms, E. Vlasov, A. Zhokin

Moscow Institute of Physics and Technology, Moscow, Russia

T. Aushev, A. Bylinkin³⁴

National Research Nuclear University 'Moscow Engineering Physics Institute' (MEPhI), Moscow, Russia

R. Chistov³⁷, M. Danilov³⁷, P. Parygin, D. Philippov, S. Polikarpov³⁷, E. Tarkovskii

P.N. Lebedev Physical Institute, Moscow, Russia

V. Andreev, M. Azarkin³⁴, I. Dremin³⁴, M. Kirakosyan³⁴, S.V. Rusakov, A. Terkulov

Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, Moscow, Russia

A. Baskakov, A. Belyaev, E. Boos, A. Ershov, A. Gribushin, A. Kaminskiy³⁸, O. Kodolova, V. Korotkikh, I. Lokhtin, I. Miagkov, S. Obraztsov, S. Petrushanko, V. Savrin, A. Snigirev, I. Vardanyan

Novosibirsk State University (NSU), Novosibirsk, Russia

V. Blinov³⁹, T. Dimova³⁹, L. Kardapoltsev³⁹, D. Shtol³⁹, Y. Skovpen³⁹

State Research Center of Russian Federation, Institute for High Energy Physics of NRC 'Kurchatov Institute', Protvino, Russia

I. Azhgirey, I. Bayshev, S. Bitioukov, D. Elumakhov, A. Godizov, V. Kachanov, A. Kalinin, D. Konstantinov, P. Mandrik, V. Petrov, R. Ryutin, S. Slabospitskii, A. Sobol, S. Troshin, N. Tyurin, A. Uzunian, A. Volkov

National Research Tomsk Polytechnic University, Tomsk, Russia

A. Babaev, S. Baidali

University of Belgrade, Faculty of Physics and Vinca Institute of Nuclear Sciences, Belgrade, Serbia

P. Adzic⁴⁰, P. Cirkovic, D. Devetak, M. Dordevic, J. Milosevic

Centro de Investigaciones Energéticas Medioambientales y Tecnológicas (CIEMAT), Madrid, Spain

J. Alcaraz Maestre, A. Álvarez Fernández, I. Bachiller, M. Barrio Luna, J.A. Brochero Cifuentes, M. Cerrada, N. Colino, B. De La Cruz, A. Delgado Peris, C. Fernandez Bedoya, J.P. Fernández Ramos, J. Flix, M.C. Fouz, O. Gonzalez Lopez, S. Goy Lopez, J.M. Hernandez, M.I. Josa, D. Moran, A. Pérez-Calero Yzquierdo, J. Puerta Pelayo, I. Redondo, L. Romero, M.S. Soares, A. Triossi

Universidad Autónoma de Madrid, Madrid, Spain

C. Albajar, J.F. de Trocóniz

Universidad de Oviedo, Oviedo, Spain

J. Cuevas, C. Erice, J. Fernandez Menendez, S. Folgueras, I. Gonzalez Caballero, J.R. González Fernández, E. Palencia Cortezon, V. Rodríguez Bouza, S. Sanchez Cruz, P. Vischia, J.M. Vizan Garcia

Instituto de Física de Cantabria (IFCA), CSIC-Universidad de Cantabria, Santander, Spain

I.J. Cabrillo, A. Calderon, B. Chazin Quero, J. Duarte Campderros, M. Fernandez, P.J. Fernández Manteca, A. García Alonso, J. Garcia-Ferrero, G. Gomez, A. Lopez Virto, J. Marco, C. Martinez Rivero, P. Martinez Ruiz del Arbol, F. Matorras, J. Piedra Gomez, C. Prieels, T. Rodrigo, A. Ruiz-Jimeno, L. Scodellaro, N. Trevisani, I. Vila, R. Vilar Cortabitarte

CERN, European Organization for Nuclear Research, Geneva, Switzerland

D. Abbaneo, B. Akgun, E. Auffray, P. Baillon, A.H. Ball, D. Barney, J. Bendavid, M. Bianco, A. Bocci, C. Botta, T. Camporesi, M. Cepeda, G. Cerminara, E. Chapon, Y. Chen, G. Cucciati, D. d'Enterria, A. Dabrowski, V. Daponte, A. David, A. De Roeck, N. Deelen, M. Dobson, T. du Pree, M. Dünser, N. Dupont, A. Elliott-Peisert, P. Everaerts, F. Fallavollita⁴¹, D. Fasanella, G. Franzoni, J. Fulcher, W. Funk, D. Gigi, A. Gilbert, K. Gill, F. Glege, D. Gulhan, J. Hegeman, V. Innocente, A. Jafari, P. Janot, O. Karacheban¹⁸, J. Kieseler, A. Kornmayer, M. Krammer¹,

C. Lange, P. Lecoq, C. Lourenço, L. Malgeri, M. Mannelli, F. Meijers, J.A. Merlin, S. Mersi, E. Meschi, P. Milenovic⁴², F. Moortgat, M. Mulders, J. Ngadiuba, S. Orfanelli, L. Orsini, F. Pantaleo¹⁵, L. Pape, E. Perez, M. Peruzzi, A. Petrilli, G. Petrucciani, A. Pfeiffer, M. Pierini, F.M. Pitters, D. Rabad, A. Racz, T. Reis, G. Rolandi⁴³, M. Rovere, H. Sakulin, C. Schäfer, C. Schwick, M. Seidel, M. Selvaggi, A. Sharma, P. Silva, P. Sphicas⁴⁴, A. Stakia, J. Steggemann, M. Tosi, D. Treille, A. Tsiros, V. Veckalns⁴⁵, W.D. Zeuner

Paul Scherrer Institut, Villigen, Switzerland

W. Bertl[†], L. Caminada⁴⁶, K. Deiters, W. Erdmann, R. Horisberger, Q. Ingram, H.C. Kaestli, D. Kotlinski, U. Langenegger, T. Rohe, S.A. Wiederkehr

ETH Zurich - Institute for Particle Physics and Astrophysics (IPA), Zurich, Switzerland

M. Backhaus, L. Bäni, P. Berger, N. Chernyavskaya, G. Dissertori, M. Dittmar, M. Donegà, C. Dorfer, C. Grab, C. Heidegger, D. Hits, J. Hoss, T. Klijnsma, W. Lustermann, R.A. Manzoni, M. Marionneau, M.T. Meinhard, D. Meister, F. Micheli, P. Musella, F. Nessi-Tedaldi, J. Pata, F. Pauss, G. Perrin, L. Perrozzi, S. Pigazzini, M. Quittnat, M. Reichmann, D. Ruini, D.A. Sanz Becerra, M. Schönenberger, L. Shchutska, V.R. Tavolaro, K. Theofilatos, M.L. Vesterbacka Olsson, R. Wallny, D.H. Zhu

Universität Zürich, Zurich, Switzerland

T.K. Aarrestad, C. Amsler⁴⁷, D. Brzhechko, M.F. Canelli, A. De Cosa, R. Del Burgo, S. Donato, C. Galloni, T. Hreus, B. Kilminster, I. Neutelings, D. Pinna, G. Rauco, P. Robmann, D. Salerno, K. Schweiger, C. Seitz, Y. Takahashi, A. Zucchetta

National Central University, Chung-Li, Taiwan

Y.H. Chang, K.y. Cheng, T.H. Doan, Sh. Jain, R. Khurana, C.M. Kuo, W. Lin, A. Pozdnyakov, S.S. Yu

National Taiwan University (NTU), Taipei, Taiwan

P. Chang, Y. Chao, K.F. Chen, P.H. Chen, W.-S. Hou, Arun Kumar, Y.y. Li, R.-S. Lu, E. Paganis, A. Psallidas, A. Steen, J.f. Tsai

Chulalongkorn University, Faculty of Science, Department of Physics, Bangkok, Thailand

B. Asavapibhop, N. Srimanobhas, N. Suwonjandee

Çukurova University, Physics Department, Science and Art Faculty, Adana, Turkey

A. Bat, F. Boran, S. Cerci⁴⁸, S. Damarcekin, Z.S. Demiroglu, C. Dozen, I. Dumanoglu, S. Girgis, G. Gokbulut, Y. Guler, E. Gurpinar, I. Hos⁴⁹, E.E. Kangal⁵⁰, O. Kara, A. Kayis Topaksu, U. Kiminsu, M. Oglakci, G. Onengut, K. Ozdemir⁵¹, S. Ozturk⁵², D. Sunar Cerci⁴⁸, B. Tali⁴⁸, U.G. Tok, S. Turkcapar, I.S. Zorbakir, C. Zorbilmez

Middle East Technical University, Physics Department, Ankara, Turkey

B. Isildak⁵³, G. Karapinar⁵⁴, M. Yalvac, M. Zeyrek

Bogazici University, Istanbul, Turkey

I.O. Atakisi, E. Gülmez, M. Kaya⁵⁵, O. Kaya⁵⁶, S. Tekten, E.A. Yetkin⁵⁷

Istanbul Technical University, Istanbul, Turkey

M.N. Agaras, S. Atay, A. Cakir, K. Cankocak, Y. Komurcu, S. Sen⁵⁸

Institute for Scintillation Materials of National Academy of Science of Ukraine, Kharkov, Ukraine

B. Grynyov

National Scientific Center, Kharkov Institute of Physics and Technology, Kharkov, Ukraine
L. Levchuk

University of Bristol, Bristol, United Kingdom

F. Ball, L. Beck, J.J. Brooke, D. Burns, E. Clement, D. Cussans, O. Davignon, H. Flacher, J. Goldstein, G.P. Heath, H.F. Heath, L. Kreczko, D.M. Newbold⁵⁹, S. Paramesvaran, B. Penning, T. Sakuma, D. Smith, V.J. Smith, J. Taylor, A. Titterton

Rutherford Appleton Laboratory, Didcot, United Kingdom

A. Belyaev⁶⁰, C. Brew, R.M. Brown, D. Cieri, D.J.A. Cockerill, J.A. Coughlan, K. Harder, S. Harper, J. Linacre, E. Olaiya, D. Petyt, C.H. Shepherd-Themistocleous, A. Thea, I.R. Tomalin, T. Williams, W.J. Womersley

Imperial College, London, United Kingdom

G. Auzinger, R. Bainbridge, P. Bloch, J. Borg, S. Breeze, O. Buchmuller, A. Bundock, S. Casasso, D. Colling, L. Corpe, P. Dauncey, G. Davies, M. Della Negra, R. Di Maria, Y. Haddad, G. Hall, G. Iles, T. James, M. Komm, C. Laner, L. Lyons, A.-M. Magnan, S. Malik, A. Martelli, J. Nash⁶¹, A. Nikitenko⁶, V. Palladino, M. Pesaresi, A. Richards, A. Rose, E. Scott, C. Seez, A. Shtipliyski, T. Strebler, S. Summers, A. Tapper, K. Uchida, T. Virdee¹⁵, N. Wardle, D. Winterbottom, J. Wright, S.C. Zenz

Brunel University, Uxbridge, United Kingdom

J.E. Cole, P.R. Hobson, A. Khan, P. Kyberd, C.K. Mackay, A. Morton, I.D. Reid, L. Teodorescu, S. Zahid

Baylor University, Waco, USA

K. Call, J. Dittmann, K. Hatakeyama, H. Liu, C. Madrid, B. McMaster, N. Pastika, C. Smith

Catholic University of America, Washington DC, USA

R. Bartek, A. Dominguez

The University of Alabama, Tuscaloosa, USA

A. Buccilli, S.I. Cooper, C. Henderson, P. Rumerio, C. West

Boston University, Boston, USA

D. Arcaro, T. Bose, D. Gastler, D. Rankin, C. Richardson, J. Rohlf, L. Sulak, D. Zou

Brown University, Providence, USA

G. Benelli, X. Coubez, D. Cutts, M. Hadley, J. Hakala, U. Heintz, J.M. Hogan⁶², K.H.M. Kwok, E. Laird, G. Landsberg, J. Lee, Z. Mao, M. Narain, J. Pazzini, S. Piperov, S. Sagir⁶³, R. Syarif, D. Yu

University of California, Davis, Davis, USA

R. Band, C. Brainerd, R. Breedon, D. Burns, M. Calderon De La Barca Sanchez, M. Chertok, J. Conway, R. Conway, P.T. Cox, R. Erbacher, C. Flores, G. Funk, W. Ko, O. Kukral, R. Lander, C. Mclean, M. Mulhearn, D. Pellett, J. Pilot, S. Shalhout, M. Shi, D. Stolp, D. Taylor, K. Tos, M. Tripathi, Z. Wang, F. Zhang

University of California, Los Angeles, USA

M. Bachtis, C. Bravo, R. Cousins, A. Dasgupta, A. Florent, J. Hauser, M. Ignatenko, N. Mccoll, S. Regnard, D. Saltzberg, C. Schnaible, V. Valuev

University of California, Riverside, Riverside, USA

E. Bouvier, K. Burt, R. Clare, J.W. Gary, S.M.A. Ghiasi Shirazi, G. Hanson, G. Karapostoli,

E. Kennedy, F. Lacroix, O.R. Long, M. Olmedo Negrete, M.I. Paneva, W. Si, L. Wang, H. Wei, S. Wimpenny, B.R. Yates

University of California, San Diego, La Jolla, USA

J.G. Branson, S. Cittolin, M. Derdzinski, R. Gerosa, D. Gilbert, B. Hashemi, A. Holzner, D. Klein, G. Kole, V. Krutelyov, J. Letts, M. Masciovecchio, D. Olivito, S. Padhi, M. Pieri, M. Sani, V. Sharma, S. Simon, M. Tadel, A. Vartak, S. Wasserbaech⁶⁴, J. Wood, F. Würthwein, A. Yagil, G. Zevi Della Porta

University of California, Santa Barbara - Department of Physics, Santa Barbara, USA

N. Amin, R. Bhandari, J. Bradmiller-Feld, C. Campagnari, M. Citron, A. Dishaw, V. Dutta, M. Franco Sevilla, L. Gouskos, R. Heller, J. Incandela, A. Ovcharova, H. Qu, J. Richman, D. Stuart, I. Suarez, S. Wang, J. Yoo

California Institute of Technology, Pasadena, USA

D. Anderson, A. Bornheim, J.M. Lawhorn, H.B. Newman, T.Q. Nguyen, M. Spiropulu, J.R. Vlimant, R. Wilkinson, S. Xie, Z. Zhang, R.Y. Zhu

Carnegie Mellon University, Pittsburgh, USA

M.B. Andrews, T. Ferguson, T. Mudholkar, M. Paulini, M. Sun, I. Vorobiev, M. Weinberg

University of Colorado Boulder, Boulder, USA

J.P. Cumalat, W.T. Ford, F. Jensen, A. Johnson, M. Krohn, S. Leontsinis, E. MacDonald, T. Mulholland, K. Stenson, K.A. Ulmer, S.R. Wagner

Cornell University, Ithaca, USA

J. Alexander, J. Chaves, Y. Cheng, J. Chu, A. Datta, K. McDermott, N. Mirman, J.R. Patterson, D. Quach, A. Rinkevicius, A. Ryd, L. Skinnari, L. Soffi, S.M. Tan, Z. Tao, J. Thom, J. Tucker, P. Wittich, M. Zientek

Fermi National Accelerator Laboratory, Batavia, USA

S. Abdullin, M. Albrow, M. Alyari, G. Apollinari, A. Apresyan, A. Apyan, S. Banerjee, L.A.T. Bauerdick, A. Beretvas, J. Berryhill, P.C. Bhat, G. Bolla[†], K. Burkett, J.N. Butler, A. Canepa, G.B. Cerati, H.W.K. Cheung, F. Chlebana, M. Cremonesi, J. Duarte, V.D. Elvira, J. Freeman, Z. Gecse, E. Gottschalk, L. Gray, D. Green, S. Grünendahl, O. Gutsche, J. Hanlon, R.M. Harris, S. Hasegawa, J. Hirschauer, Z. Hu, B. Jayatilaka, S. Jindariani, M. Johnson, U. Joshi, B. Klima, M.J. Kortelainen, B. Kreis, S. Lammel, D. Lincoln, R. Lipton, M. Liu, T. Liu, J. Lykken, K. Maeshima, J.M. Marraffino, D. Mason, P. McBride, P. Merkel, S. Mrenna, S. Nahn, V. O'Dell, K. Pedro, O. Prokofyev, G. Rakness, L. Ristori, A. Savoy-Navarro⁶⁵, B. Schneider, E. Sexton-Kennedy, A. Soha, W.J. Spalding, L. Spiegel, S. Stoynev, J. Strait, N. Strobbe, L. Taylor, S. Tkaczyk, N.V. Tran, L. Uplegger, E.W. Vaandering, C. Vernieri, M. Verzocchi, R. Vidal, M. Wang, H.A. Weber, A. Whitbeck

University of Florida, Gainesville, USA

D. Acosta, P. Avery, P. Bortignon, D. Bourilkov, A. Brinkerhoff, L. Cadamuro, A. Carnes, M. Carver, D. Curry, R.D. Field, S.V. Gleyzer, B.M. Joshi, J. Konigsberg, A. Korytov, P. Ma, K. Matchev, H. Mei, G. Mitselmakher, K. Shi, D. Sperka, J. Wang, S. Wang

Florida International University, Miami, USA

Y.R. Joshi, S. Linn

Florida State University, Tallahassee, USA

A. Ackert, T. Adams, A. Askew, S. Hagopian, V. Hagopian, K.F. Johnson, T. Kolberg, G. Martinez, T. Perry, H. Prosper, A. Saha, A. Santra, V. Sharma, R. Yohay

Florida Institute of Technology, Melbourne, USA

M.M. Baarmand, V. Bhopatkar, S. Colafranceschi, M. Hohlmann, D. Noonan, M. Rahmani, T. Roy, F. Yumiceva

University of Illinois at Chicago (UIC), Chicago, USA

M.R. Adams, L. Apanasevich, D. Berry, R.R. Betts, R. Cavanaugh, X. Chen, S. Dittmer, O. Evdokimov, C.E. Gerber, D.A. Hangal, D.J. Hofman, K. Jung, J. Kamin, C. Mills, I.D. Sandoval Gonzalez, M.B. Tonjes, N. Varelas, H. Wang, Z. Wu, J. Zhang

The University of Iowa, Iowa City, USA

M. Alhusseini, B. Bilki⁶⁶, W. Clarida, K. Dilsiz⁶⁷, S. Durgut, R.P. Gandrajula, M. Haytmyradov, V. Khristenko, J.-P. Merlo, A. Mestvirishvili, A. Moeller, J. Nachtman, H. Ogul⁶⁸, Y. Onel, F. Ozok⁶⁹, A. Penzo, C. Snyder, E. Tiras, J. Wetzel

Johns Hopkins University, Baltimore, USA

B. Blumenfeld, A. Cocoros, N. Eminizer, D. Fehling, L. Feng, A.V. Gritsan, W.T. Hung, P. Maksimovic, J. Roskes, U. Sarica, M. Swartz, M. Xiao, C. You

The University of Kansas, Lawrence, USA

A. Al-bataineh, P. Baringer, A. Bean, S. Boren, J. Bowen, J. Castle, S. Khalil, A. Kropivnitskaya, D. Majumder, W. Mcbrayer, M. Murray, C. Rogan, S. Sanders, E. Schmitz, J.D. Tapia Takaki, Q. Wang

Kansas State University, Manhattan, USA

A. Ivanov, K. Kaadze, D. Kim, Y. Maravin, D.R. Mendis, T. Mitchell, A. Modak, A. Mohammadi, L.K. Saini, N. Skhirtladze

Lawrence Livermore National Laboratory, Livermore, USA

F. Rebassoo, D. Wright

University of Maryland, College Park, USA

A. Baden, O. Baron, A. Belloni, S.C. Eno, Y. Feng, C. Ferraioli, N.J. Hadley, S. Jabeen, G.Y. Jeng, R.G. Kellogg, J. Kunkle, A.C. Mignerey, F. Ricci-Tam, Y.H. Shin, A. Skuja, S.C. Tonwar, K. Wong

Massachusetts Institute of Technology, Cambridge, USA

D. Abercrombie, B. Allen, V. Azzolini, R. Barbieri, A. Baty, G. Bauer, R. Bi, S. Brandt, W. Busza, I.A. Cali, M. D'Alfonso, Z. Demiragli, G. Gomez Ceballos, M. Goncharov, P. Harris, D. Hsu, M. Hu, Y. Iiyama, G.M. Innocenti, M. Klute, D. Kovalskyi, Y.-J. Lee, A. Levin, P.D. Luckey, B. Maier, A.C. Marini, C. McGinn, C. Mironov, S. Narayanan, X. Niu, C. Paus, C. Roland, G. Roland, G.S.F. Stephans, K. Sumorok, K. Tatar, D. Velicanu, J. Wang, T.W. Wang, B. Wyslouch, S. Zhaozhong

University of Minnesota, Minneapolis, USA

A.C. Benvenuti, R.M. Chatterjee, A. Evans, P. Hansen, S. Kalafut, Y. Kubota, Z. Lesko, J. Mans, S. Nourbakhsh, N. Ruckstuhl, R. Rusack, J. Turkewitz, M.A. Wadud

University of Mississippi, Oxford, USA

J.G. Acosta, S. Oliveros

University of Nebraska-Lincoln, Lincoln, USA

E. Avdeeva, K. Bloom, D.R. Claes, C. Fangmeier, F. Golf, R. Gonzalez Suarez, R. Kamalieddin, I. Kravchenko, J. Monroy, J.E. Siado, G.R. Snow, B. Stieger

State University of New York at Buffalo, Buffalo, USA

A. Godshalk, C. Harrington, I. Iashvili, A. Kharchilava, D. Nguyen, A. Parker, S. Rappoccio, B. Roozbahani

Northeastern University, Boston, USA

E. Barberis, C. Freer, A. Hortiangtham, D.M. Morse, T. Orimoto, R. Teixeira De Lima, T. Wamorkar, B. Wang, A. Wisecarver, D. Wood

Northwestern University, Evanston, USA

S. Bhattacharya, O. Charaf, K.A. Hahn, N. Mucia, N. Odell, M.H. Schmitt, K. Sung, M. Trovato, M. Velasco

University of Notre Dame, Notre Dame, USA

R. Bucci, N. Dev, M. Hildreth, K. Hurtado Anampa, C. Jessop, D.J. Karmgard, N. Kellams, K. Lannon, W. Li, N. Loukas, N. Marinelli, F. Meng, C. Mueller, Y. Musienko³³, M. Planer, A. Reinsvold, R. Ruchti, P. Siddireddy, G. Smith, S. Taroni, M. Wayne, A. Wightman, M. Wolf, A. Woodard

The Ohio State University, Columbus, USA

J. Alimena, L. Antonelli, B. Bylsma, L.S. Durkin, S. Flowers, B. Francis, A. Hart, C. Hill, W. Ji, T.Y. Ling, W. Luo, B.L. Winer, H.W. Wulsin

Princeton University, Princeton, USA

S. Cooperstein, P. Elmer, J. Hardenbrook, P. Hebda, S. Higginbotham, A. Kalogeropoulos, D. Lange, M.T. Lucchini, J. Luo, D. Marlow, K. Mei, I. Ojalvo, J. Olsen, C. Palmer, P. Piroué, J. Salfeld-Nebgen, D. Stickland, C. Tully

University of Puerto Rico, Mayaguez, USA

S. Malik, S. Norberg

Purdue University, West Lafayette, USA

A. Barker, V.E. Barnes, L. Gutay, M. Jones, A.W. Jung, A. Khatiwada, B. Mahakud, D.H. Miller, N. Neumeister, C.C. Peng, H. Qiu, J.F. Schulte, J. Sun, F. Wang, R. Xiao, W. Xie

Purdue University Northwest, Hammond, USA

T. Cheng, J. Dolen, N. Parashar

Rice University, Houston, USA

Z. Chen, K.M. Ecklund, S. Freed, F.J.M. Geurts, M. Guilbaud, M. Kilpatrick, W. Li, B. Michlin, B.P. Padley, J. Roberts, J. Rorie, W. Shi, B. Tran, Z. Tu, J. Zabel, A. Zhang

University of Rochester, Rochester, USA

A. Bodek, P. de Barbaro, R. Demina, Y.t. Duh, J.L. Dulemba, C. Fallon, T. Ferbel, M. Galanti, A. Garcia-Bellido, J. Han, O. Hindrichs, A. Khukhunaishvili, K.H. Lo, P. Tan, R. Taus, M. Verzetti

Rutgers, The State University of New Jersey, Piscataway, USA

A. Agapitos, J.P. Chou, Y. Gershtein, T.A. Gómez Espinosa, E. Halkiadakis, M. Heindl, E. Hughes, S. Kaplan, R. Kunnawalkam Elayavalli, S. Kyriacou, A. Lath, R. Montalvo, K. Nash, M. Osherson, H. Saka, S. Salur, S. Schnetzer, D. Sheffield, S. Somalwar, R. Stone, S. Thomas, P. Thomassen, M. Walker

University of Tennessee, Knoxville, USA

A.G. Delannoy, J. Heideman, G. Riley, K. Rose, S. Spanier, K. Thapa

Texas A&M University, College Station, USA

O. Bouhali⁷⁰, A. Castaneda Hernandez⁷⁰, A. Celik, M. Dalchenko, M. De Mattia, A. Delgado, S. Dildick, R. Eusebi, J. Gilmore, T. Huang, T. Kamon⁷¹, S. Luo, R. Mueller, Y. Pakhotin, R. Patel, A. Perloff, L. Perniè, D. Rathjens, A. Safonov, A. Tatarinov

Texas Tech University, Lubbock, USA

N. Akchurin, J. Damgov, F. De Guio, P.R. Duderov, S. Kunori, K. Lamichhane, S.W. Lee, T. Mengke, S. Muthumuni, T. Peltola, S. Undleeb, I. Volobouev, Z. Wang

Vanderbilt University, Nashville, USA

S. Greene, A. Gurrola, R. Janjam, W. Johns, C. Maguire, A. Melo, H. Ni, K. Padeken, J.D. Ruiz Alvarez, P. Sheldon, S. Tuo, J. Velkovska, M. Verweij, Q. Xu

University of Virginia, Charlottesville, USA

M.W. Arenton, P. Barria, B. Cox, R. Hirosky, M. Joyce, A. Ledovskoy, H. Li, C. Neu, T. Sinthuprasith, Y. Wang, E. Wolfe, F. Xia

Wayne State University, Detroit, USA

R. Harr, P.E. Karchin, N. Poudyal, J. Sturdy, P. Thapa, S. Zaleski

University of Wisconsin - Madison, Madison, WI, USA

M. Brodski, J. Buchanan, C. Caillol, D. Carlsmith, S. Dasu, L. Dodd, S. Duric, B. Gomber, M. Grothe, M. Herndon, A. Hervé, U. Hussain, P. Klabbers, A. Lanaro, A. Levine, K. Long, R. Loveless, T. Ruggles, A. Savin, N. Smith, W.H. Smith, N. Woods

†: Deceased

1: Also at Vienna University of Technology, Vienna, Austria

2: Also at IRFU, CEA, Université Paris-Saclay, Gif-sur-Yvette, France

3: Also at Universidade Estadual de Campinas, Campinas, Brazil

4: Also at Federal University of Rio Grande do Sul, Porto Alegre, Brazil

5: Also at Université Libre de Bruxelles, Bruxelles, Belgium

6: Also at Institute for Theoretical and Experimental Physics, Moscow, Russia

7: Also at Joint Institute for Nuclear Research, Dubna, Russia

8: Also at Fayoum University, El-Fayoum, Egypt

9: Now at British University in Egypt, Cairo, Egypt

10: Now at Ain Shams University, Cairo, Egypt

11: Also at Department of Physics, King Abdulaziz University, Jeddah, Saudi Arabia

12: Also at Université de Haute Alsace, Mulhouse, France

13: Also at Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, Moscow, Russia

14: Also at Tbilisi State University, Tbilisi, Georgia

15: Also at CERN, European Organization for Nuclear Research, Geneva, Switzerland

16: Also at RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany

17: Also at University of Hamburg, Hamburg, Germany

18: Also at Brandenburg University of Technology, Cottbus, Germany

19: Also at Institute of Nuclear Research ATOMKI, Debrecen, Hungary

20: Also at MTA-ELTE Lendület CMS Particle and Nuclear Physics Group, Eötvös Loránd University, Budapest, Hungary

21: Also at Institute of Physics, University of Debrecen, Debrecen, Hungary

22: Also at Indian Institute of Technology Bhubaneswar, Bhubaneswar, India

23: Also at Institute of Physics, Bhubaneswar, India

24: Also at Shoolini University, Solan, India

- 25: Also at University of Visva-Bharati, Santiniketan, India
- 26: Also at Isfahan University of Technology, Isfahan, Iran
- 27: Also at Plasma Physics Research Center, Science and Research Branch, Islamic Azad University, Tehran, Iran
- 28: Also at Università degli Studi di Siena, Siena, Italy
- 29: Also at International Islamic University of Malaysia, Kuala Lumpur, Malaysia
- 30: Also at Malaysian Nuclear Agency, MOSTI, Kajang, Malaysia
- 31: Also at Consejo Nacional de Ciencia y Tecnología, Mexico city, Mexico
- 32: Also at Warsaw University of Technology, Institute of Electronic Systems, Warsaw, Poland
- 33: Also at Institute for Nuclear Research, Moscow, Russia
- 34: Now at National Research Nuclear University 'Moscow Engineering Physics Institute' (MEPhI), Moscow, Russia
- 35: Also at St. Petersburg State Polytechnical University, St. Petersburg, Russia
- 36: Also at University of Florida, Gainesville, USA
- 37: Also at P.N. Lebedev Physical Institute, Moscow, Russia
- 38: Also at INFN Sezione di Padova ^a, Università di Padova ^b, Università di Trento (Trento) ^c, Padova, Italy
- 39: Also at Budker Institute of Nuclear Physics, Novosibirsk, Russia
- 40: Also at Faculty of Physics, University of Belgrade, Belgrade, Serbia
- 41: Also at INFN Sezione di Pavia ^a, Università di Pavia ^b, Pavia, Italy
- 42: Also at University of Belgrade, Faculty of Physics and Vinca Institute of Nuclear Sciences, Belgrade, Serbia
- 43: Also at Scuola Normale e Sezione dell'INFN, Pisa, Italy
- 44: Also at National and Kapodistrian University of Athens, Athens, Greece
- 45: Also at Riga Technical University, Riga, Latvia
- 46: Also at Universität Zürich, Zurich, Switzerland
- 47: Also at Stefan Meyer Institute for Subatomic Physics (SMI), Vienna, Austria
- 48: Also at Adiyaman University, Adiyaman, Turkey
- 49: Also at Istanbul Aydin University, Istanbul, Turkey
- 50: Also at Mersin University, Mersin, Turkey
- 51: Also at Piri Reis University, Istanbul, Turkey
- 52: Also at Gaziosmanpasa University, Tokat, Turkey
- 53: Also at Ozyegin University, Istanbul, Turkey
- 54: Also at Izmir Institute of Technology, Izmir, Turkey
- 55: Also at Marmara University, Istanbul, Turkey
- 56: Also at Kafkas University, Kars, Turkey
- 57: Also at Istanbul Bilgi University, Istanbul, Turkey
- 58: Also at Hacettepe University, Ankara, Turkey
- 59: Also at Rutherford Appleton Laboratory, Didcot, United Kingdom
- 60: Also at School of Physics and Astronomy, University of Southampton, Southampton, United Kingdom
- 61: Also at Monash University, Faculty of Science, Clayton, Australia
- 62: Also at Bethel University, St. Paul, USA
- 63: Also at Karamanoğlu Mehmetbey University, Karaman, Turkey
- 64: Also at Utah Valley University, Orem, USA
- 65: Also at Purdue University, West Lafayette, USA
- 66: Also at Beykent University, Istanbul, Turkey
- 67: Also at Bingol University, Bingol, Turkey
- 68: Also at Sinop University, Sinop, Turkey

69: Also at Mimar Sinan University, Istanbul, Istanbul, Turkey

70: Also at Texas A&M University at Qatar, Doha, Qatar

71: Also at Kyungpook National University, Daegu, Korea