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Measurement of the azimuthal anisotropy of neutral pions in PbPb collisions at $\sqrt{s_{NN}} = 2.76\,\text{TeV}$

The CMS Collaboration*

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Abstract

First measurements of the azimuthal anisotropy of neutral pions produced in PbPb collisions at a center-of-mass energy of $\sqrt{s_{NN}} = 2.76\,\text{TeV}$ are presented. The amplitudes of the second Fourier component (v_2) of the π^0 azimuthal distributions are extracted using an event-plane technique. The values of v_2 are studied as a function of the neutral pion transverse momentum (p_T) for different classes of collision centrality in the kinematic range $1.6 < p_\text{T} < 8.0\,\text{GeV}/c$, within the pseudorapidity interval $|\eta| < 0.8$. The CMS measurements of $v_2(p_\text{T})$ are similar to previously reported π^0 azimuthal anisotropy results from $\sqrt{s_{NN}} = 200\,\text{GeV}$ AuAu collisions at RHIC, despite a factor of $\sim$14 increase in the center-of-mass energy. In the momentum range $2.5 < p_\text{T} < 5.0\,\text{GeV}/c$, the neutral pion anisotropies are found to be smaller than those observed by CMS for inclusive charged particles.

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*See Appendix A for the list of collaboration members

A central goal of relativistic heavy-ion experiments is to create a deconfined phase of nuclear matter, the quark gluon plasma (QGP), at extreme temperatures and energy densities, and to characterize its properties. Observations at the Relativistic Heavy Ion Collider (RHIC) suggest that an extremely dense partonic medium with near-perfect fluid properties is formed [1–4]. These observations include the suppression of high-transverse-momentum (p_{T}) hadron production, referred to as "jet-quenching"; strong azimuthal anisotropies in bulk particle production at low p_{T}; and baryon-meson differences in hadron suppression patterns and azimuthal anisotropies at intermediate p_{T}. Measurements of the azimuthal correlations of the produced particles play a key role in understanding the dominant physics processes in each of these transverse momentum ranges.

At low p_{T} ($<$2 GeV/c), the azimuthal anisotropy of the emitted particles is understood to be the result of a collective hydrodynamic expansion of the medium, converting any initial-state spatial anisotropy (eccentricity of the nuclear overlap region) into a final-state momentum anisotropy [5, 6]. The strength of the anisotropy is characterized by the values of the Fourier coefficients, v_n, of the expansion of the particle yields given by $\frac{\mathrm{d}N}{\mathrm{d}\phi_R} \propto 1 + \sum_n 2v_n \cos n(\phi - \psi_{\mathrm{EP}})$, where ϕ is the azimuthal angle of the outgoing particles and ψ_{EP} is the event plane angle reconstructed using the beam direction, z, and the azimuthal direction of the maximum transverse energy in each event. The second Fourier coefficient, v_2, is referred to as elliptic flow. At higher transverse momentum ($p_{\mathrm{T}} \gtrsim 6$ GeV/c), the azimuthal anisotropies have been attributed to the path-length dependence of energy loss in the medium due to the asymmetry in the reaction zone [7–11]. In the intermediate p_{T} region, the RHIC data show an enhancement of baryon production [12, 13] and a larger v_2 of baryons as compared to mesons [14, 15]. This behavior has been interpreted as a signature of quark recombination as the dominant production mechanism of moderate p_{T} hadrons, which implies the existence of quark degrees of freedom in the medium produced at RHIC [16]. Recent theoretical calculations also show that the RHIC measurements of baryon and meson v_2 at low p_{T} can be described by model calculations based on thermal partons only. However, contributions from shower partons that are larger for mesons than for baryons must be included to explain the data in the intermediate p_{T} range [17].

The measurements of the elliptic anisotropy for inclusive charged particles, produced in PbPb collisions at a nucleon-nucleon center-of-mass energy of $\sqrt{s_{NN}} = 2.76$ TeV at the Large Hadron Collider (LHC), have been reported by ALICE [18], ATLAS [19], and CMS [20]. The measured v_2 coefficients exhibit similar strength and p_{T} dependence as those measured at RHIC in AuAu collisions [18, 21]. Differences in the elliptical flow of baryons and mesons can be indirectly tested via the comparison of the strength of the v_2 signals for π^0 mesons and inclusive charged particles.

This Letter presents the first measurement of elliptic flow of π^0 mesons as a function of p_{T} in PbPb collisions at a center-of-mass energy of $\sqrt{s_{NN}} = 2.76$ TeV. The data were recorded by the CMS experiment during the first LHC heavy-ion run in November 2010. The π^0 meson elliptic flow is measured in the pseudorapidity range $|\eta| < 0.8$, where η is defined as $\eta = -\ln[\tan(\theta/2)]$, and θ is the polar angle between the particle momentum and the anticlockwise beam direction. The measurement is performed over the full azimuthal coverage $0 < \phi < 2\pi$, and spans the range $1.6 < p_{\mathrm{T}} < 8.0$ GeV/c.

The detectors used for this analysis are the barrel Electromagnetic Calorimeter (ECAL) and the Hadron Forward (HF) calorimeter, which have an η acceptance of $|\eta| < 1.4$ and $2.9 < |\eta| < 5.2$, respectively. Despite a wider pseudorapidity coverage of the barrel ECAL, these results are restricted to $|\eta| < 0.8$ in order to allow a direct comparison with the charged particle elliptic flow results [20]. The barrel ECAL is located within a 3.8 T solenoidal magnetic field. The

ECAL is made of lead-tungstate crystals that have a short radiation length (0.89 cm), and a small Molière radius (2.19 cm). A more detailed description of the CMS experiment can be found elsewhere [22].

The minimum-bias event sample is collected using coincidences between the trigger signals from each side of the interaction point using the Beam Scintillation Counters (BSC) ($3.23 < |\eta| < 4.65$) or the HF. Such a coincidence of minimum-bias trigger with bunches colliding in the interaction region suppresses any events due to noise, cosmic rays, out-of-time triggers, and beam backgrounds. The trigger accepts (97 ± 3)% of the total inelastic PbPb cross section. Collision centrality, defined as the fraction of total inelastic nucleus-nucleus cross section, is calculated using the sum of transverse energy (E_{T}) in towers from HF at both positive and negative z positions [23]. In this Letter, we present results based on centrality intervals of 10% width, ranging from 20–30% (more central) to 70–80% (more peripheral). For the most central collisions (0–20%), a small signal-to-background ratio limits the identification of π^0 mesons.

The π^0 mesons are measured by reconstructing their decay photons ($\pi^0 \to \gamma\gamma$) in the barrel ECAL. Electromagnetic showers are found in the ECAL by forming clusters of contiguous crystals with a seed crystal having energy above a threshold of 200 MeV. Clusters are identified as photons on the basis of a shower shape requirement called the S4/S9 ratio. Photons are reconstructed using a 3×3 array of crystals, which contain on average 93% of the photon energy. The quantity S4 is the total energy in a 2×2 array (a sub-matrix of the 3×3 array) containing the crystal with the highest energy deposited and S9 is the total energy in the 3×3 crystal matrix. There are four possible 2×2 matrix combinations, and S4 is defined as the most energetic of these four combinations. Clusters with S9 > 400 MeV and S4/S9 > 0.87 are selected as photon candidates for π^0 meson reconstructed invariant mass, $m_{\gamma_i\gamma_j}$ calculations. The invariant mass of a photon pair (γ_i, γ_j) as measured in the ECAL is calculated from the energies and positions of the clusters, as given by $m_{\gamma_i\gamma_j} = \sqrt{2E_iE_j(1-\cos\theta_{ij})}$, where θ_{ij} is the opening angle between the two photons. Candidate pairs are formed from each photon cluster in an event in a particular p_{T} bin for the π^0 meson invariant mass calculation. A p_{T}-dependent opening angle requirement and a cluster pair separation cut are also applied to the π^0 meson invariant mass distribution. Pairs are selected with $\theta_{ij} > \frac{a}{p_{\mathrm{T}}} + \frac{b}{p_{\mathrm{T}}^2}$, where a and b are opening angle cut parameters obtained from a detailed PYTHIA 6.422 simulation [24]. The values of the parameters a and b are 0.17 GeV/c and -0.11 (GeV/c)^2, respectively. Further, a photon pair is rejected if the separation of the two photon clusters (distance is calculated based on the η and ϕ coordinates of the clusters and using 1.29 m radius of the ECAL) is less than a threshold distance at a certain p_{T}. The threshold distance between photon-clusters decreases monotonically from 15 cm at $p_{\mathrm{T}} \approx 1.6$ GeV/c to 5.0 cm at $p_{\mathrm{T}} \approx 8.0$ GeV/c. At sufficiently high p_{T}, photons from a nearly symmetric decay ($E_{\gamma_1} \approx E_{\gamma_2}$, where E_{γ_i} is the energy of a photon) can produce showers in the calorimeter that are reconstructed as a single cluster. In CMS, this effect becomes apparent at $p_{\mathrm{T}} > 8.0$ GeV/c. Consequently, results presented here are restricted to $p_{\mathrm{T}} < 8.0$ GeV/c.

The π^0 meson yields are extracted statistically by subtracting the combinatorial background from the π^0 candidate invariant mass distribution. The combinatorial background is estimated and subtracted using an event mixing technique, which forms pairs from photon candidates in different events. Each photon candidate is combined with all other photon candidates in three other events. The mixing of events is performed within intervals of centrality, z-vertex position and the event-plane angle [20] orientation to replicate the background from uncorrelated pairs. All selections applied to the combinations of same-event pairs are also applied to mixed-event pairs. Event mixing is done in six z-vertex intervals of width $\Delta z = 5.0$ cm in the range $|z| < 15$ cm. Similarly, the event-plane angle [20] is also divided into six intervals in the range

$0 < \psi_{\mathrm{EP}} < \pi$. The event-plane angle is determined from the HF, with flattening and resolution correction factors applied as in [20]. The π^0 reconstruction efficiencies as a function of p_{T}, centrality, and event-plane are studied by embedding simulated π^0 mesons in real events. A total of 100 k such events are analyzed, where each event has ten π^0 mesons embedded with a flat p_{T} and ϕ distribution over a range of $0.2 < p_{\mathrm{T}} < 10.0\,\mathrm{GeV}/c$ and $|\eta| < 1.0$ to avoid any edge effects. The results for π^0 meson elliptic flow are corrected for the dependence of the reconstruction efficiency on p_{T} for all centralities. In addition an in-plane versus out-of-plane dependence is observed for the π^0 meson reconstruction efficiency in more central collisions. Corrections for this effect range from 16% ($1.6 < p_{\mathrm{T}} < 2.0\,\mathrm{GeV}/c$) to 6% ($2.5 < p_{\mathrm{T}} < 3.0\,\mathrm{GeV}/c$) for the 20–30% centrality interval. For higher p_{T} intervals in this centrality class, such ϕ-dependent efficiency corrections are not needed. Similarly for the 40–50% and 50–60% centrality intervals, these corrections range from 7% ($1.6 < p_{\mathrm{T}} < 2.0\,\mathrm{GeV}/c$) to 4% ($2.5 < p_{\mathrm{T}} < 3.0\,\mathrm{GeV}/c$), while no ϕ-dependent efficiency corrections are needed for the more peripheral events.

Figure 1 (top panel) presents the π^0 meson invariant mass distribution before background subtraction for $2.5 < p_{\mathrm{T}} < 3.0\,\mathrm{GeV}/c$ for the 40-50% centrality interval. This panel shows the same-event distribution (solid circles) and the mixed-event normalized background (dashed line). For a given p_{T} bin, the mixed-event background distribution is normalized to the same-event signal distribution in the range 200–250 MeV/c. Different normalization regions such as 175–225 MeV/c and 225–275 MeV/c are also studied and no significant change in the resulting π^0 meson v_2 is observed. The middle panel of Fig. 1 shows the combinatorial-background-subtracted π^0 meson invariant mass distribution (solid circles) in the same p_{T} bin and centrality class. Over-subtraction is observed for higher mass regions, $m_{\gamma\gamma} > 250\,\mathrm{MeV}/c$. Investigations using PYTHIA and HYDJET (1.8) [25] simulations show that this effect can be attributed to a correlated conversion background (converted photons) which has a different shape than a purely combinatorial background. By definition, the event-mixing technique cannot account for the effect of a correlated conversion background. Open symbols in the middle panel correspond to HYDJET simulations, the result obtained without rejecting any converted photons. The background-subtracted mass spectrum predicted by simulations is seen to reproduce the data well. HYDJET simulation results also show that the over-subtraction at high invariant mass is eliminated when the clusters from the converted photons are suppressed, as shown in the bottom panel of Fig. 1. The event yield is calculated by integrating the data in a two standard deviations (σ, in units of mass) window around the mean (μ) of the distribution. The σ and μ are determined from a Gaussian fit to the combinatorial-background-subtracted π^0 meson invariant mass distribution for every p_{T} and centrality interval. To avoid any model dependence, no corrections to the data are applied in order to account for these converted photons; instead asymmetric mass integration ranges of $\mu - 2\sigma < m_{\gamma\gamma} < \mu$, and $\mu - 3\sigma < m_{\gamma\gamma} < \mu$ are employed to understand the systematic effect of the conversion contribution to the mass peak in the higher mass regions. Studies showed that the maximum effect of the correlated background on the yield extraction in the mass integration range is less than 16%. To obtain the dependence of π^0 meson production on azimuthal angle, the extracted yield is first measured in a given p_{T} bin as a function of the azimuthal angle between the π^0 meson trajectory and the event-plane orientation, ψ_{EP}, found as described in Ref. [20]. The measurement is performed in six equally spaced intervals of $\Delta\phi = \phi(\pi^0) - \psi_{\mathrm{EP}}$ in the range $0 < \Delta\phi < \pi/2$. The π^0 meson yields corrected for reconstruction efficiency are measured for each $\Delta\phi$ bin and the resulting angular distribution, $\mathrm{d}N/\mathrm{d}\Delta\phi$, is fitted with $N_0\,(1 + 2v_2 \cos 2\Delta\phi)$ to determine the strength of the modulation in the yield. We use an analytic linear χ^2 fitting procedure that matches the integral of $N_0\,(1 + 2v_2 \cos 2\Delta\phi)$ over each $\Delta\phi$ bin to the measured π^0 meson yield within the corresponding bin [14, 15].

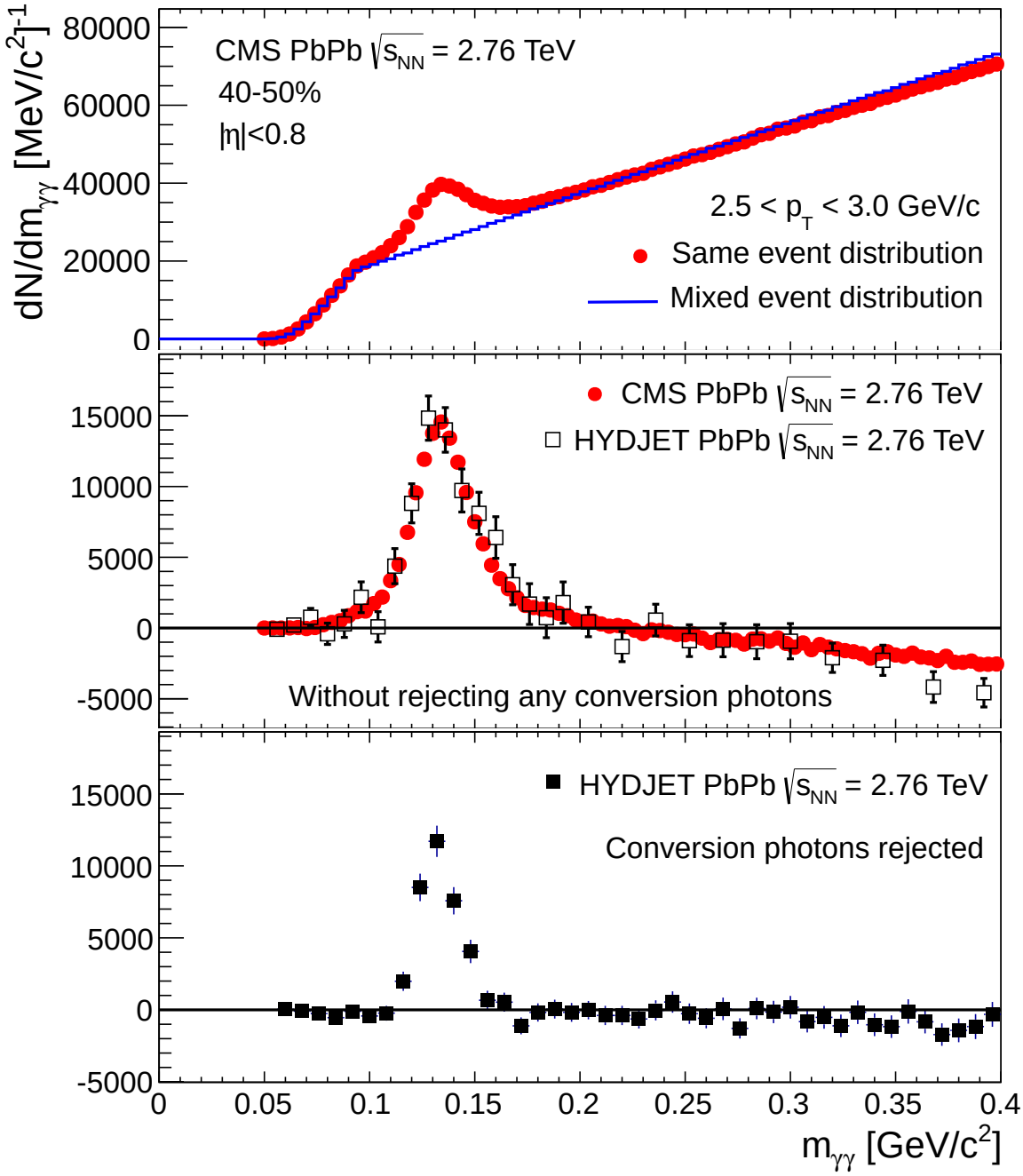

Figure 1: (Color online) Top panel: π^0 meson invariant mass distribution with combinatorial background for $2.5 < p_{\mathrm{T}} < 3.0\,\mathrm{GeV}/c$ for 40–50% centrality interval in PbPb collisions at $\sqrt{s_{NN}} = 2.76\,\mathrm{TeV}$. The solid line represents the combinatorial background estimated from the event-mixing technique. Middle panel: Combinatorial background-subtracted π^0 invariant mass distribution (solid circles) in the same p_{T} bin and centrality interval. Open squares show HYDJET simulation results. Bottom panel: HYDJET simulation results obtained after rejecting converted photons. The HYDJET simulation results have been scaled up by a factor of 556 to match the data.

Systematic uncertainties are assessed by varying the S4/S9 ratio and the mass integration ranges. A combination of the S4/S9 = 0.87 and $|m_{\gamma\gamma} - \mu| < 2.0\sigma$ mass integration range serves

as a reference in this analysis. The π^0 meson v_2 results are calculated for S4/S9 = 0.83 or 0.91 keeping the mass integration range at a reference value of $|m_{\gamma\gamma} - \mu| < 2.0\sigma$. In addition to asymmetric mass integration ranges, symmetric ranges such as $|m_{\gamma\gamma} - \mu| < 3.0\sigma$, and $|m_{\gamma\gamma} - \mu| < 1.5\sigma$ are used to determine the π^0 meson v_2 results for all centralities keeping S4/S9 fixed at 0.87. The largest observed differences in the v_2 results based on different S4/S9 ratio cuts and $m_{\gamma\gamma} - \mu$ ranges are used to determine the systematic uncertainty. The systematic uncertainty determined from the precision of the ϕ-efficiency curves obtained from the embedding procedure ranges from 18% to 4% from the lowest to the highest p_{T} intervals for 20–30% centrality. For 70–80% centrality, the systematic uncertainty varies from 7.2% to 9%. The total systematic uncertainties obtained upon adding all the sources listed above in quadrature vary from 21% ($1.6 < p_{\mathrm{T}} < 2.0\,\mathrm{GeV}/c$) to 31% ($6.0 < p_{\mathrm{T}} < 8.0\,\mathrm{GeV}/c$) for the 20–30% centrality interval. Similarly for 70–80% these uncertainties change from 9.6% ($1.6 < p_{\mathrm{T}} < 2.0\,\mathrm{GeV}/c$) to 33% ($6.0 < p_{\mathrm{T}} < 8.0\,\mathrm{GeV}/c$). Systematic uncertainties arising from the trigger efficiency are found to be negligible.

The π^0 meson $v_2(p_{\mathrm{T}})$ results are shown in Fig. 2 for six centrality classes from 20–30% to 70–80%. CMS π^0 meson v_2 results, shown as solid circles, are compared to PHENIX π^0 v_2 results [9], for AuAu collisions at $\sqrt{s_{NN}} = 200\,\mathrm{GeV}$, shown as open circles. Green (grey) shaded bands show the systematic uncertainties associated with the CMS π^0 meson (charged particle) v_2 measurements. Our measurement shows qualitatively similar features as observed at RHIC energies despite an order of magnitude increase in the center-of-mass energy and the corresponding larger contribution from hard-scattered partons to meson production [26]. This observation is consistent with the previously reported similarity in the elliptic flow results for inclusive charged particles at RHIC and LHC [18, 19].

Figure 2 also presents a comparison between CMS π^0 meson v_2 results (solid circles), and CMS inclusive charged particle v_2 [20] (open squares) as a function of p_{T} using the event-plane method. The π^0 meson v_2 is systematically lower than that for inclusive charged particles v_2 between $2.5 < p_{\mathrm{T}} < 5.0\,\mathrm{GeV}/c$ for mid-central collisions (20–60%). In more peripheral collisions (60-80%), the differences tend to decrease for π^0 mesons and inclusive charged particles, indicating a related origin of the elliptic anisotropy for all particle species. For particles with intermediate p_{T} at RHIC, the v_2 values of baryons are observed to be higher than those for mesons [14, 15]. The differences observed between the inclusive charged particle and π^0 meson results may be due to the contribution from baryons which would increase the overall v_2 of the inclusive charged particles, compared to that for neutral pions, assuming a baryon-meson v_2 splitting comparable to that seen at RHIC. The baryon enhancement at RHIC has a strong centrality dependence [12–14]. Therefore, a detailed measurement of v_2 of identified particles as a function of centrality is important for understanding the production mechanism and the path-length dependence of parton energy loss in the medium.

In summary, the CMS detector has been used to perform the first measurements of the azimuthal anisotropy of neutral pions in PbPb collisions at $\sqrt{s_{NN}} = 2.76\,\mathrm{TeV}$. The measurements of v_2 were presented as a function of p_{T} for six centralities, from 20–30% to 70–80% for $1.6 < p_{\mathrm{T}} < 8.0\,\mathrm{GeV}/c$. Results were compared with PHENIX π^0 meson [9] and CMS inclusive charged particle measurements [20]. It was found that the values of $v_2(p_{\mathrm{T}})$ for neutral pions measured at RHIC and the LHC were of comparable magnitude. These data may shed light on the hadronization mechanism at RHIC and LHC energies, and contribute to the understanding of the parton-medium interactions. In the collision centrality interval 20–60%, and in the momentum range $2.5 < p_{\mathrm{T}} < 5.0\,\mathrm{GeV}/c$, the magnitude of elliptic flow for neutral pions was found to be systematically lower than that for charged particles. This behavior is consistent with observations at lower collision energies, where this difference is found to be caused

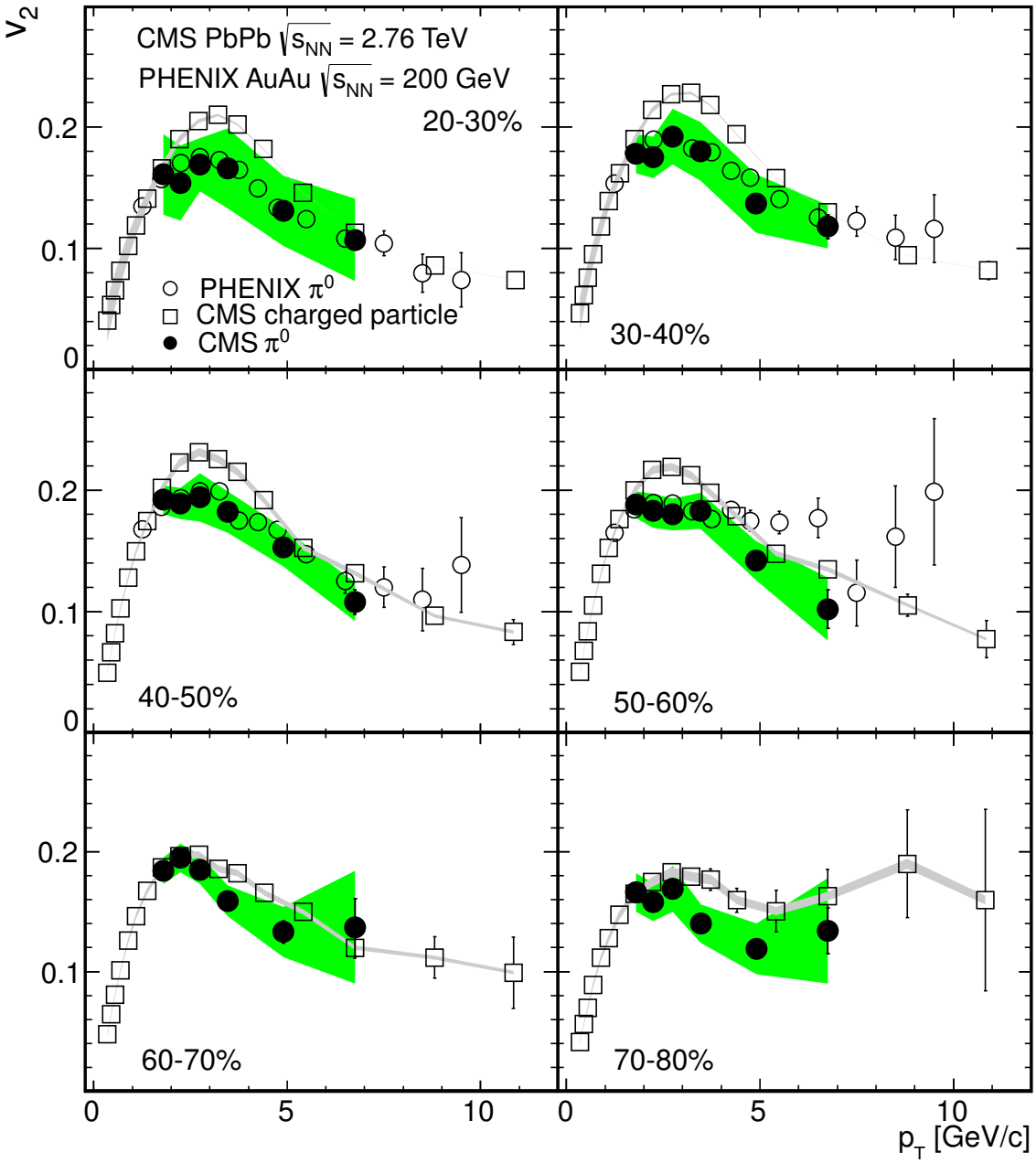

Figure 2: (Color online) CMS π^0 meson v_2 (solid circles) compared to PHENIX π^0 meson v_2 [9] (open circles) for mid-rapidity ($|\eta| < 0.8$ and $|\eta| < 0.35$, respectively) and CMS charged particle v_2 (open squares, $|\eta| < 0.8$). Results are presented as a function of p_T for six centrality intervals (20–30% to 70–80%). Green (grey) shaded bands represent systematic uncertainties associated with CMS π^0 meson (charged particle) v_2 measurements. Only statistical uncertainties are shown for the PHENIX results. The systematic uncertainties for the 50–60% centrality on the PHENIX data points are 10.4%.

by the larger elliptic flow of baryons compared to mesons. The differences tend to decrease for more peripheral collisions (60–80%) in the CMS data, where RHIC measurements are not available.

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A The CMS Collaboration

Yerevan Physics Institute, Yerevan, Armenia
S. Chatrchyan, V. Khachatryan, A.M. Sirunyan, A. Tumasyan

Institut für Hochenergiephysik der OeAW, Wien, Austria
W. Adam, E. Aguilo, T. Bergauer, M. Dragicevic, J. Erö, C. Fabjan[1], M. Friedl, R. Frühwirth[1], V.M. Ghete, J. Hammer, N. Hörmann, J. Hrubec, M. Jeitler[1], W. Kiesenhofer, V. Knünz, M. Krammer[1], I. Krätschmer, D. Liko, I. Mikulec, M. Pernicka[†], B. Rahbaran, C. Rohringer, H. Rohringer, R. Schöfbeck, J. Strauss, A. Taurok, W. Waltenberger, G. Walzel, E. Widl, C.-E. Wulz[1]

National Centre for Particle and High Energy Physics, Minsk, Belarus
V. Mossolov, N. Shumeiko, J. Suarez Gonzalez

Universiteit Antwerpen, Antwerpen, Belgium
S. Bansal, T. Cornelis, E.A. De Wolf, X. Janssen, S. Luyckx, L. Mucibello, S. Ochesanu, B. Roland, R. Rougny, M. Selvaggi, Z. Staykova, H. Van Haevermaet, P. Van Mechelen, N. Van Remortel, A. Van Spilbeeck

Vrije Universiteit Brussel, Brussel, Belgium
F. Blekman, S. Blyweert, J. D'Hondt, R. Gonzalez Suarez, A. Kalogeropoulos, M. Maes, A. Olbrechts, W. Van Doninck, P. Van Mulders, G.P. Van Onsem, I. Villella

Université Libre de Bruxelles, Bruxelles, Belgium
B. Clerbaux, G. De Lentdecker, V. Dero, A.P.R. Gay, T. Hreus, A. Léonard, P.E. Marage, T. Reis, L. Thomas, G. Vander Marcken, C. Vander Velde, P. Vanlaer, J. Wang

Ghent University, Ghent, Belgium
V. Adler, K. Beernaert, A. Cimmino, S. Costantini, G. Garcia, M. Grunewald, B. Klein, J. Lellouch, A. Marinov, J. Mccartin, A.A. Ocampo Rios, D. Ryckbosch, N. Strobbe, F. Thyssen, M. Tytgat, P. Verwilligen, S. Walsh, E. Yazgan, N. Zaganidis

Université Catholique de Louvain, Louvain-la-Neuve, Belgium
S. Basegmez, G. Bruno, R. Castello, L. Ceard, C. Delaere, T. du Pree, D. Favart, L. Forthomme, A. Giammanco[2], J. Hollar, V. Lemaitre, J. Liao, O. Militaru, C. Nuttens, D. Pagano, A. Pin, K. Piotrzkowski, N. Schul, J.M. Vizan Garcia

Université de Mons, Mons, Belgium
N. Beliy, T. Caebergs, E. Daubie, G.H. Hammad

Centro Brasileiro de Pesquisas Fisicas, Rio de Janeiro, Brazil
G.A. Alves, M. Correa Martins Junior, D. De Jesus Damiao, T. Martins, M.E. Pol, M.H.G. Souza

Universidade do Estado do Rio de Janeiro, Rio de Janeiro, Brazil
W.L. Aldá Júnior, W. Carvalho, A. Custódio, E.M. Da Costa, C. De Oliveira Martins, S. Fonseca De Souza, D. Matos Figueiredo, L. Mundim, H. Nogima, V. Oguri, W.L. Prado Da Silva, A. Santoro, L. Soares Jorge, A. Sznajder

Instituto de Fisica Teorica, Universidade Estadual Paulista, Sao Paulo, Brazil
T.S. Anjos[3], C.A. Bernardes[3], F.A. Dias[4], T.R. Fernandez Perez Tomei, E. M. Gregores[3], C. Lagana, F. Marinho, P.G. Mercadante[3], S.F. Novaes, Sandra S. Padula

Institute for Nuclear Research and Nuclear Energy, Sofia, Bulgaria
V. Genchev[5], P. Iaydjiev[5], S. Piperov, M. Rodozov, S. Stoykova, G. Sultanov, V. Tcholakov, R. Trayanov, M. Vutova

University of Sofia, Sofia, Bulgaria
A. Dimitrov, R. Hadjiiska, V. Kozhuharov, L. Litov, B. Pavlov, P. Petkov

Institute of High Energy Physics, Beijing, China
J.G. Bian, G.M. Chen, H.S. Chen, C.H. Jiang, D. Liang, S. Liang, X. Meng, J. Tao, J. Wang, X. Wang, Z. Wang, H. Xiao, M. Xu, J. Zang, Z. Zhang

State Key Lab. of Nucl. Phys. and Tech., Peking University, Beijing, China
C. Asawatangtrakuldee, Y. Ban, S. Guo, Y. Guo, W. Li, S. Liu, Y. Mao, S.J. Qian, H. Teng, D. Wang, L. Zhang, B. Zhu, W. Zou

Universidad de Los Andes, Bogota, Colombia
C. Avila, J.P. Gomez, B. Gomez Moreno, A.F. Osorio Oliveros, J.C. Sanabria

Technical University of Split, Split, Croatia
N. Godinovic, D. Lelas, R. Plestina[6], D. Polic, I. Puljak[5]

University of Split, Split, Croatia
Z. Antunovic, M. Kovac

Institute Rudjer Boskovic, Zagreb, Croatia
V. Brigljevic, S. Duric, K. Kadija, J. Luetic, S. Morovic

University of Cyprus, Nicosia, Cyprus
A. Attikis, M. Galanti, G. Mavromanolakis, J. Mousa, C. Nicolaou, F. Ptochos, P.A. Razis

Charles University, Prague, Czech Republic
M. Finger, M. Finger Jr.

Academy of Scientific Research and Technology of the Arab Republic of Egypt, Egyptian Network of High Energy Physics, Cairo, Egypt
Y. Assran[7], S. Elgammal[8], A. Ellithi Kamel[9], S. Khalil[8], M.A. Mahmoud[10], A. Radi[11,12]

National Institute of Chemical Physics and Biophysics, Tallinn, Estonia
M. Kadastik, M. Müntel, M. Raidal, L. Rebane, A. Tiko

Department of Physics, University of Helsinki, Helsinki, Finland
P. Eerola, G. Fedi, M. Voutilainen

Helsinki Institute of Physics, Helsinki, Finland
J. Härkönen, A. Heikkinen, V. Karimäki, R. Kinnunen, M.J. Kortelainen, T. Lampén, K. Lassila-Perini, S. Lehti, T. Lindén, P. Luukka, T. Mäenpää, T. Peltola, E. Tuominen, J. Tuominiemi, E. Tuovinen, D. Ungaro, L. Wendland

Lappeenranta University of Technology, Lappeenranta, Finland
K. Banzuzi, A. Karjalainen, A. Korpela, T. Tuuva

DSM/IRFU, CEA/Saclay, Gif-sur-Yvette, France
M. Besancon, S. Choudhury, M. Dejardin, D. Denegri, B. Fabbro, J.L. Faure, F. Ferri, S. Ganjour, A. Givernaud, P. Gras, G. Hamel de Monchenault, P. Jarry, E. Locci, J. Malcles, L. Millischer, A. Nayak, J. Rander, A. Rosowsky, I. Shreyber, M. Titov

Laboratoire Leprince-Ringuet, Ecole Polytechnique, IN2P3-CNRS, Palaiseau, France
S. Baffioni, F. Beaudette, L. Benhabib, L. Bianchini, M. Bluj[13], C. Broutin, P. Busson, C. Charlot, N. Daci, T. Dahms, L. Dobrzynski, R. Granier de Cassagnac, M. Haguenauer, P. Miné, C. Mironov, I.N. Naranjo, M. Nguyen, C. Ochando, P. Paganini, D. Sabes, R. Salerno, Y. Sirois, C. Veelken, A. Zabi

Institut Pluridisciplinaire Hubert Curien, Université de Strasbourg, Université de Haute Alsace Mulhouse, CNRS/IN2P3, Strasbourg, France
J.-L. Agram[14], J. Andrea, D. Bloch, D. Bodin, J.-M. Brom, M. Cardaci, E.C. Chabert, C. Collard, E. Conte[14], F. Drouhin[14], C. Ferro, J.-C. Fontaine[14], D. Gelé, U. Goerlach, P. Juillot, A.-C. Le Bihan, P. Van Hove

Centre de Calcul de l'Institut National de Physique Nucleaire et de Physique des Particules, CNRS/IN2P3, Villeurbanne, France, Villeurbanne, France
F. Fassi, D. Mercier

Université de Lyon, Université Claude Bernard Lyon 1, CNRS-IN2P3, Institut de Physique Nucléaire de Lyon, Villeurbanne, France
S. Beauceron, N. Beaupere, O. Bondu, G. Boudoul, J. Chasserat, R. Chierici[5], D. Contardo, P. Depasse, H. El Mamouni, J. Fay, S. Gascon, M. Gouzevitch, B. Ille, T. Kurca, M. Lethuillier, L. Mirabito, S. Perries, V. Sordini, Y. Tschudi, P. Verdier, S. Viret

Institute of High Energy Physics and Informatization, Tbilisi State University, Tbilisi, Georgia
Z. Tsamalaidze[15]

RWTH Aachen University, I. Physikalisches Institut, Aachen, Germany
G. Anagnostou, S. Beranek, M. Edelhoff, L. Feld, N. Heracleous, O. Hindrichs, R. Jussen, K. Klein, J. Merz, A. Ostapchuk, A. Perieanu, F. Raupach, J. Sammet, S. Schael, D. Sprenger, H. Weber, B. Wittmer, V. Zhukov[16]

RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany
M. Ata, J. Caudron, E. Dietz-Laursonn, D. Duchardt, M. Erdmann, R. Fischer, A. Güth, T. Hebbeker, C. Heidemann, K. Hoepfner, D. Klingebiel, P. Kreuzer, C. Magass, M. Merschmeyer, A. Meyer, M. Olschewski, P. Papacz, H. Pieta, H. Reithler, S.A. Schmitz, L. Sonnenschein, J. Steggemann, D. Teyssier, M. Weber

RWTH Aachen University, III. Physikalisches Institut B, Aachen, Germany
M. Bontenackels, V. Cherepanov, G. Flügge, H. Geenen, M. Geisler, W. Haj Ahmad, F. Hoehle, B. Kargoll, T. Kress, Y. Kuessel, A. Nowack, L. Perchalla, O. Pooth, P. Sauerland, A. Stahl

Deutsches Elektronen-Synchrotron, Hamburg, Germany
M. Aldaya Martin, J. Behr, W. Behrenhoff, U. Behrens, M. Bergholz[17], A. Bethani, K. Borras, A. Burgmeier, A. Cakir, L. Calligaris, A. Campbell, E. Castro, F. Costanza, D. Dammann, C. Diez Pardos, G. Eckerlin, D. Eckstein, G. Flucke, A. Geiser, I. Glushkov, P. Gunnellini, S. Habib, J. Hauk, G. Hellwig, H. Jung, M. Kasemann, P. Katsas, C. Kleinwort, H. Kluge, A. Knutsson, M. Krämer, D. Krücker, E. Kuznetsova, W. Lange, W. Lohmann[17], B. Lutz, R. Mankel, I. Marfin, M. Marienfeld, I.-A. Melzer-Pellmann, A.B. Meyer, J. Mnich, A. Mussgiller, S. Naumann-Emme, J. Olzem, H. Perrey, A. Petrukhin, D. Pitzl, A. Raspereza, P.M. Ribeiro Cipriano, C. Riedl, E. Ron, M. Rosin, J. Salfeld-Nebgen, R. Schmidt[17], T. Schoerner-Sadenius, N. Sen, A. Spiridonov, M. Stein, R. Walsh, C. Wissing

University of Hamburg, Hamburg, Germany
C. Autermann, V. Blobel, J. Draeger, H. Enderle, J. Erfle, U. Gebbert, M. Görner, T. Hermanns, R.S. Höing, K. Kaschube, G. Kaussen, H. Kirschenmann, R. Klanner, J. Lange, B. Mura, F. Nowak, T. Peiffer, N. Pietsch, D. Rathjens, C. Sander, H. Schettler, P. Schleper, E. Schlieckau, A. Schmidt, M. Schröder, T. Schum, M. Seidel, V. Sola, H. Stadie, G. Steinbrück, J. Thomsen, L. Vanelderen

Institut für Experimentelle Kernphysik, Karlsruhe, Germany
C. Barth, J. Berger, C. Böser, T. Chwalek, W. De Boer, A. Descroix, A. Dierlamm, M. Feindt, M. Guthoff[5], C. Hackstein, F. Hartmann, T. Hauth[5], M. Heinrich, H. Held, K.H. Hoffmann, S. Honc, I. Katkov[16], J.R. Komaragiri, P. Lobelle Pardo, D. Martschei, S. Mueller, Th. Müller, M. Niegel, A. Nürnberg, O. Oberst, A. Oehler, J. Ott, G. Quast, K. Rabbertz, F. Ratnikov, N. Ratnikova, S. Röcker, A. Scheurer, F.-P. Schilling, G. Schott, H.J. Simonis, F.M. Stober, D. Troendle, R. Ulrich, J. Wagner-Kuhr, S. Wayand, T. Weiler, M. Zeise

Institute of Nuclear Physics "Demokritos", Aghia Paraskevi, Greece
G. Daskalakis, T. Geralis, S. Kesisoglou, A. Kyriakis, D. Loukas, I. Manolakos, A. Markou, C. Markou, C. Mavrommatis, E. Ntomari

University of Athens, Athens, Greece
L. Gouskos, T.J. Mertzimekis, A. Panagiotou, N. Saoulidou

University of Ioánnina, Ioánnina, Greece
I. Evangelou, C. Foudas[5], P. Kokkas, N. Manthos, I. Papadopoulos, V. Patras

KFKI Research Institute for Particle and Nuclear Physics, Budapest, Hungary
G. Bencze, C. Hajdu[5], P. Hidas, D. Horvath[18], F. Sikler, V. Veszpremi, G. Vesztergombi[19]

Institute of Nuclear Research ATOMKI, Debrecen, Hungary
N. Beni, S. Czellar, J. Molnar, J. Palinkas, Z. Szillasi

University of Debrecen, Debrecen, Hungary
J. Karancsi, P. Raics, Z.L. Trocsanyi, B. Ujvari

Panjab University, Chandigarh, India
S.B. Beri, V. Bhatnagar, N. Dhingra, R. Gupta, M. Jindal, M. Kaur, M.Z. Mehta, N. Nishu, L.K. Saini, A. Sharma, J. Singh

University of Delhi, Delhi, India
Ashok Kumar, Arun Kumar, S. Ahuja, A. Bhardwaj, B.C. Choudhary, S. Malhotra, M. Naimuddin, K. Ranjan, V. Sharma, R.K. Shivpuri

Saha Institute of Nuclear Physics, Kolkata, India
S. Banerjee, S. Bhattacharya, S. Dutta, B. Gomber, Sa. Jain, Sh. Jain, R. Khurana, S. Sarkar, M. Sharan

Bhabha Atomic Research Centre, Mumbai, India
A. Abdulsalam, R.K. Choudhury, D. Dutta, S. Kailas, V. Kumar, P. Mehta, A.K. Mohanty[5], L.M. Pant, P. Shukla

Tata Institute of Fundamental Research - EHEP, Mumbai, India
T. Aziz, S. Ganguly, M. Guchait[20], M. Maity[21], G. Majumder, K. Mazumdar, G.B. Mohanty, B. Parida, K. Sudhakar, N. Wickramage

Tata Institute of Fundamental Research - HECR, Mumbai, India
S. Banerjee, S. Dugad

Institute for Research in Fundamental Sciences (IPM), Tehran, Iran
H. Arfaei, H. Bakhshiansohi[22], S.M. Etesami[23], A. Fahim[22], M. Hashemi, H. Hesari, A. Jafari[22], M. Khakzad, M. Mohammadi Najafabadi, S. Paktinat Mehdiabadi, B. Safarzadeh[24], M. Zeinali[23]

INFN Sezione di Bari [a], Università di Bari [b], Politecnico di Bari [c], Bari, Italy
M. Abbrescia[a,b], L. Barbone[a,b], C. Calabria[a,b,5], S.S. Chhibra[a,b], A. Colaleo[a], D. Creanza[a,c],

N. De Filippis[a,c,5], M. De Palma[a,b], L. Fiore[a], G. Iaselli[a,c], L. Lusito[a,b], G. Maggi[a,c], M. Maggi[a], B. Marangelli[a,b], S. My[a,c], S. Nuzzo[a,b], N. Pacifico[a,b], A. Pompili[a,b], G. Pugliese[a,c], G. Selvaggi[a,b], L. Silvestris[a], G. Singh[a,b], R. Venditti, G. Zito[a]

INFN Sezione di Bologna [a], Università di Bologna [b], Bologna, Italy
G. Abbiendi[a], A.C. Benvenuti[a], D. Bonacorsi[a,b], S. Braibant-Giacomelli[a,b], L. Brigliadori[a,b], P. Capiluppi[a,b], A. Castro[a,b], F.R. Cavallo[a], M. Cuffiani[a,b], G.M. Dallavalle[a], F. Fabbri[a], A. Fanfani[a,b], D. Fasanella[a,b,5], P. Giacomelli[a], C. Grandi[a], L. Guiducci[a,b], S. Marcellini[a], G. Masetti[a], M. Meneghelli[a,b,5], A. Montanari[a], F.L. Navarria[a,b], F. Odorici[a], A. Perrotta[a], F. Primavera[a,b], A.M. Rossi[a,b], T. Rovelli[a,b], G. Siroli[a,b], R. Travaglini[a,b]

INFN Sezione di Catania [a], Università di Catania [b], Catania, Italy
S. Albergo[a,b], G. Cappello[a,b], M. Chiorboli[a,b], S. Costa[a,b], 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], V. Ciulli[a,b], C. Civinini[a], R. D'Alessandro[a,b], E. Focardi[a,b], S. Frosali[a,b], E. Gallo[a], S. Gonzi[a,b], M. Meschini[a], S. Paoletti[a], G. Sguazzoni[a], A. Tropiano[a,5]

INFN Laboratori Nazionali di Frascati, Frascati, Italy
L. Benussi, S. Bianco, S. Colafranceschi[25], F. Fabbri, D. Piccolo

INFN Sezione di Genova [a], Università di Genova [b], Genova, Italy
P. Fabbricatore[a], R. Musenich[a], S. Tosi

INFN Sezione di Milano-Bicocca [a], Università di Milano-Bicocca [b], Milano, Italy
A. Benaglia[a,b,5], F. De Guio[a,b], L. Di Matteo[a,b,5], S. Fiorendi[a,b], S. Gennai[a,5], A. Ghezzi[a,b], S. Malvezzi[a], R.A. Manzoni[a,b], A. Martelli[a,b], A. Massironi[a,b,5], D. Menasce[a], L. Moroni[a], M. Paganoni[a,b], D. Pedrini[a], S. Ragazzi[a,b], N. Redaelli[a], S. Sala[a], T. Tabarelli de Fatis[a,b]

INFN Sezione di Napoli [a], Università di Napoli "Federico II" [b], Napoli, Italy
S. Buontempo[a], C.A. Carrillo Montoya[a], N. Cavallo[a,26], A. De Cosa[a,b,5], O. Dogangun[a,b], F. Fabozzi[a,26], A.O.M. Iorio[a], L. Lista[a], S. Meola[a,27], M. Merola[a,b], P. Paolucci[a,5]

INFN Sezione di Padova [a], Università di Padova [b], Università di Trento (Trento) [c], Padova, Italy
P. Azzi[a], N. Bacchetta[a,5], P. Bellan[a,b], D. Bisello[a,b], A. Branca[a,5], P. Checchia[a], T. Dorigo[a], U. Dosselli[a], F. Gasparini[a,b], A. Gozzelino[a], M. Gulmini[a,28], K. Kanishchev[a,c], S. Lacaprara[a], I. Lazzizzera[a,c], M. Margoni[a,b], G. Maron[a,28], A.T. Meneguzzo[a,b], M. Nespolo[a,5], J. Pazzini[a], P. Ronchese[a,b], F. Simonetto[a,b], E. Torassa[a], S. Vanini[a,b], P. Zotto[a,b], G. Zumerle[a,b]

INFN Sezione di Pavia [a], Università di Pavia [b], Pavia, Italy
M. Gabusi[a,b], S.P. Ratti[a,b], C. Riccardi[a,b], P. Torre[a,b], P. Vitulo[a,b]

INFN Sezione di Perugia [a], Università di Perugia [b], Perugia, Italy
M. Biasini[a,b], G.M. Bilei[a], L. Fanò[a,b], P. Lariccia[a,b], A. Lucaroni[a,b,5], G. Mantovani[a,b], M. Menichelli[a], A. Nappi[a,b], F. Romeo[a,b], A. Saha[a], A. Santocchia[a,b], A. Spiezia[a,b], S. Taroni[a,b,5]

INFN Sezione di Pisa [a], Università di Pisa [b], Scuola Normale Superiore di Pisa [c], Pisa, Italy
P. Azzurri[a,c], G. Bagliesi[a], T. Boccali[a], G. Broccolo[a,c], R. Castaldi[a], R.T. D'Agnolo[a,c], R. Dell'Orso[a], F. Fiori[a,b,5], L. Foà[a,c], A. Giassi[a], A. Kraan[a], F. Ligabue[a,c], T. Lomtadze[a], L. Martini[a,29], A. Messineo[a,b], F. Palla[a], A. Rizzi[a,b], A.T. Serban[a,30], P. Spagnolo[a], P. Squillacioti[a,5], R. Tenchini[a], G. Tonelli[a,b,5], A. Venturi[a,5], P.G. Verdini[a]

INFN Sezione di Roma [a], Università di Roma "La Sapienza" [b], Roma, Italy
L. Barone[a,b], F. Cavallari[a], D. Del Re[a,b,5], M. Diemoz[a], C. Fanelli, M. Grassi[a,b,5], E. Longo[a,b],

P. Meridiani[a,5], F. Micheli[a,b], S. Nourbakhsh[a,b], G. Organtini[a,b], R. Paramatti[a], S. Rahatlou[a,b], M. Sigamani[a], L. Soffi[a,b]

INFN Sezione di Torino [a], Università di Torino [b], Università del Piemonte Orientale (Novara) [c], Torino, Italy
N. Amapane[a,b], R. Arcidiacono[a,c], S. Argiro[a,b], M. Arneodo[a,c], C. Biino[a], N. Cartiglia[a], M. Costa[a,b], D. Dattola[a], N. Demaria[a], C. Mariotti[a,5], S. Maselli[a], E. Migliore[a,b], V. Monaco[a,b], M. Musich[a,5], M.M. Obertino[a,c], N. Pastrone[a], M. Pelliccioni[a], A. Potenza[a,b], A. Romero[a,b], R. Sacchi[a,b], A. Solano[a,b], A. Staiano[a], A. Vilela Pereira[a]

INFN Sezione di Trieste [a], Università di Trieste [b], Trieste, Italy
S. Belforte[a], V. Candelise[a,b], F. Cossutti[a], G. Della Ricca[a,b], B. Gobbo[a], M. Marone[a,b,5], D. Montanino[a,b,5], A. Penzo[a], A. Schizzi[a,b]

Kangwon National University, Chunchon, Korea
S.G. Heo, T.Y. Kim, S.K. Nam

Kyungpook National University, Daegu, Korea
S. Chang, D.H. Kim, G.N. Kim, D.J. Kong, H. Park, S.R. Ro, D.C. Son, T. Son

Chonnam National University, Institute for Universe and Elementary Particles, Kwangju, Korea
J.Y. Kim, Zero J. Kim, S. Song

Korea University, Seoul, Korea
S. Choi, D. Gyun, B. Hong, M. Jo, H. Kim, T.J. Kim, K.S. Lee, D.H. Moon, S.K. Park

University of Seoul, Seoul, Korea
M. Choi, J.H. Kim, C. Park, I.C. Park, S. Park, G. Ryu

Sungkyunkwan University, Suwon, Korea
Y. Cho, Y. Choi, Y.K. Choi, J. Goh, M.S. Kim, E. Kwon, B. Lee, J. Lee, S. Lee, H. Seo, I. Yu

Vilnius University, Vilnius, Lithuania
M.J. Bilinskas, I. Grigelionis, M. Janulis, A. Juodagalvis

Centro de Investigacion y de Estudios Avanzados del IPN, Mexico City, Mexico
H. Castilla-Valdez, E. De La Cruz-Burelo, I. Heredia-de La Cruz, R. Lopez-Fernandez, R. Magaña Villalba, J. Martínez-Ortega, A. Sánchez-Hernández, L.M. Villasenor-Cendejas

Universidad Iberoamericana, Mexico City, Mexico
S. Carrillo Moreno, F. Vazquez Valencia

Benemerita Universidad Autonoma de Puebla, Puebla, Mexico
H.A. Salazar Ibarguen

Universidad Autónoma de San Luis Potosí, San Luis Potosí, Mexico
E. Casimiro Linares, A. Morelos Pineda, M.A. Reyes-Santos

University of Auckland, Auckland, New Zealand
D. Krofcheck

University of Canterbury, Christchurch, New Zealand
A.J. Bell, P.H. Butler, R. Doesburg, S. Reucroft, H. Silverwood

National Centre for Physics, Quaid-I-Azam University, Islamabad, Pakistan
M. Ahmad, M.H. Ansari, M.I. Asghar, H.R. Hoorani, S. Khalid, W.A. Khan, T. Khurshid, S. Qazi, M.A. Shah, M. Shoaib

National Centre for Nuclear Research, Swierk, Poland
H. Bialkowska, B. Boimska, T. Frueboes, R. Gokieli, M. Górski, M. Kazana, K. Nawrocki, K. Romanowska-Rybinska, M. Szleper, G. Wrochna, P. Zalewski

Institute of Experimental Physics, Faculty of Physics, University of Warsaw, Warsaw, Poland
G. Brona, K. Bunkowski, M. Cwiok, W. Dominik, K. Doroba, A. Kalinowski, M. Konecki, J. Krolikowski

Laboratório de Instrumentação e Física Experimental de Partículas, Lisboa, Portugal
N. Almeida, P. Bargassa, A. David, P. Faccioli, P.G. Ferreira Parracho, M. Gallinaro, J. Seixas, J. Varela, P. Vischia

Joint Institute for Nuclear Research, Dubna, Russia
S. Afanasiev, P. Bunin, M. Gavrilenko, I. Golutvin, I. Gorbunov, A. Kamenev, V. Karjavin, G. Kozlov, A. Lanev, A. Malakhov, P. Moisenz, V. Palichik, V. Perelygin, S. Shmatov, V. Smirnov, A. Volodko, A. Zarubin

Petersburg Nuclear Physics Institute, Gatchina (St Petersburg), Russia
S. Evstyukhin, V. Golovtsov, Y. Ivanov, V. Kim, P. Levchenko, V. Murzin, V. Oreshkin, I. Smirnov, V. Sulimov, L. Uvarov, S. Vavilov, A. Vorobyev, An. Vorobyev

Institute for Nuclear Research, Moscow, Russia
Yu. Andreev, A. Dermenev, S. Gninenko, N. Golubev, M. Kirsanov, N. Krasnikov, V. Matveev, A. Pashenkov, D. Tlisov, A. Toropin

Institute for Theoretical and Experimental Physics, Moscow, Russia
V. Epshteyn, M. Erofeeva, V. Gavrilov, M. Kossov[5], N. Lychkovskaya, V. Popov, G. Safronov, S. Semenov, V. Stolin, E. Vlasov, A. Zhokin

Moscow State University, Moscow, Russia
A. Belyaev, E. Boos, A. Ershov, A. Gribushin, V. Klyukhin, O. Kodolova, V. Korotkikh, I. Lokhtin, A. Markina, S. Obraztsov, M. Perfilov, S. Petrushanko, A. Popov, L. Sarycheva[†], V. Savrin, A. Snigirev, I. Vardanyan

P.N. Lebedev Physical Institute, Moscow, Russia
V. Andreev, M. Azarkin, I. Dremin, M. Kirakosyan, A. Leonidov, G. Mesyats, S.V. Rusakov, A. Vinogradov

State Research Center of Russian Federation, Institute for High Energy Physics, Protvino, Russia
I. Azhgirey, I. Bayshev, S. Bitioukov, V. Grishin[5], V. Kachanov, D. Konstantinov, A. Korablev, V. Krychkine, V. Petrov, R. Ryutin, A. Sobol, L. Tourtchanovitch, S. Troshin, N. Tyurin, A. Uzunian, A. Volkov

University of Belgrade, Faculty of Physics and Vinca Institute of Nuclear Sciences, Belgrade, Serbia
P. Adzic[31], M. Djordjevic, M. Ekmedzic, D. Krpic[31], J. Milosevic

Centro de Investigaciones Energéticas Medioambientales y Tecnológicas (CIEMAT), Madrid, Spain
M. Aguilar-Benitez, J. Alcaraz Maestre, P. Arce, C. Battilana, E. Calvo, M. Cerrada, M. Chamizo

Llatas, N. Colino, B. De La Cruz, A. Delgado Peris, D. Domínguez Vázquez, C. Fernandez Bedoya, J.P. Fernández Ramos, A. Ferrando, J. Flix, M.C. Fouz, P. Garcia-Abia, O. Gonzalez Lopez, S. Goy Lopez, J.M. Hernandez, M.I. Josa, G. Merino, J. Puerta Pelayo, A. Quintario Olmeda, I. Redondo, L. Romero, J. Santaolalla, M.S. Soares, C. Willmott

Universidad Autónoma de Madrid, Madrid, Spain
C. Albajar, G. Codispoti, J.F. de Trocóniz

Universidad de Oviedo, Oviedo, Spain
H. Brun, J. Cuevas, J. Fernandez Menendez, S. Folgueras, I. Gonzalez Caballero, L. Lloret Iglesias, J. Piedra Gomez

Instituto de Física de Cantabria (IFCA), CSIC-Universidad de Cantabria, Santander, Spain
J.A. Brochero Cifuentes, I.J. Cabrillo, A. Calderon, S.H. Chuang, J. Duarte Campderros, M. Felcini[32], M. Fernandez, G. Gomez, J. Gonzalez Sanchez, A. Graziano, C. Jorda, A. Lopez Virto, J. Marco, R. Marco, C. Martinez Rivero, F. Matorras, F.J. Munoz Sanchez, T. Rodrigo, A.Y. Rodríguez-Marrero, A. Ruiz-Jimeno, L. Scodellaro, M. Sobron Sanudo, I. Vila, R. Vilar Cortabitarte

CERN, European Organization for Nuclear Research, Geneva, Switzerland
D. Abbaneo, E. Auffray, G. Auzinger, P. Baillon, A.H. Ball, D. Barney, J.F. Benitez, C. Bernet[6], G. Bianchi, P. Bloch, A. Bocci, A. Bonato, C. Botta, H. Breuker, T. Camporesi, G. Cerminara, T. Christiansen, J.A. Coarasa Perez, D. D'Enterria, A. Dabrowski, A. De Roeck, S. Di Guida, M. Dobson, N. Dupont-Sagorin, A. Elliott-Peisert, B. Frisch, W. Funk, G. Georgiou, M. Giffels, D. Gigi, K. Gill, D. Giordano, M. Giunta, F. Glege, R. Gomez-Reino Garrido, P. Govoni, S. Gowdy, R. Guida, M. Hansen, P. Harris, C. Hartl, J. Harvey, B. Hegner, A. Hinzmann, V. Innocente, P. Janot, K. Kaadze, E. Karavakis, K. Kousouris, P. Lecoq, Y.-J. Lee, P. Lenzi, C. Lourenço, T. Mäki, M. Malberti, L. Malgeri, M. Mannelli, L. Masetti, F. Meijers, S. Mersi, E. Meschi, R. Moser, M.U. Mozer, M. Mulders, P. Musella, E. Nesvold, T. Orimoto, L. Orsini, E. Palencia Cortezon, E. Perez, L. Perrozzi, A. Petrilli, A. Pfeiffer, M. Pierini, M. Pimiä, D. Piparo, G. Polese, L. Quertenmont, A. Racz, W. Reece, J. Rodrigues Antunes, G. Rolandi[33], T. Rommerskirchen, C. Rovelli[34], M. Rovere, H. Sakulin, F. Santanastasio, C. Schäfer, C. Schwick, I. Segoni, S. Sekmen, A. Sharma, P. Siegrist, P. Silva, M. Simon, P. Sphicas[35], D. Spiga, A. Tsirou, G.I. Veres[19], J.R. Vlimant, H.K. Wöhri, S.D. Worm[36], W.D. Zeuner

Paul Scherrer Institut, Villigen, Switzerland
W. Bertl, K. Deiters, W. Erdmann, K. Gabathuler, R. Horisberger, Q. Ingram, H.C. Kaestli, S. König, D. Kotlinski, U. Langenegger, F. Meier, D. Renker, T. Rohe, J. Sibille[37]

Institute for Particle Physics, ETH Zurich, Zurich, Switzerland
L. Bäni, P. Bortignon, M.A. Buchmann, B. Casal, N. Chanon, A. Deisher, G. Dissertori, M. Dittmar, M. Donegà, M. Dünser, J. Eugster, K. Freudenreich, C. Grab, D. Hits, P. Lecomte, W. Lustermann, A.C. Marini, P. Martinez Ruiz del Arbol, N. Mohr, F. Moortgat, C. Nägeli[38], P. Nef, F. Nessi-Tedaldi, F. Pandolfi, L. Pape, F. Pauss, M. Peruzzi, F.J. Ronga, M. Rossini, L. Sala, A.K. Sanchez, A. Starodumov[39], B. Stieger, M. Takahashi, L. Tauscher[†], A. Thea, K. Theofilatos, D. Treille, C. Urscheler, R. Wallny, H.A. Weber, L. Wehrli

Universität Zürich, Zurich, Switzerland
C. Amsler, V. Chiochia, S. De Visscher, C. Favaro, M. Ivova Rikova, B. Millan Mejias, P. Otiougova, P. Robmann, H. Snoek, S. Tupputi, M. Verzetti

National Central University, Chung-Li, Taiwan

Y.H. Chang, K.H. Chen, C.M. Kuo, S.W. Li, W. Lin, Z.K. Liu, Y.J. Lu, D. Mekterovic, A.P. Singh, R. Volpe, S.S. Yu

National Taiwan University (NTU), Taipei, Taiwan
P. Bartalini, P. Chang, Y.H. Chang, Y.W. Chang, Y. Chao, K.F. Chen, C. Dietz, U. Grundler, W.-S. Hou, Y. Hsiung, K.Y. Kao, Y.J. Lei, R.-S. Lu, D. Majumder, E. Petrakou, X. Shi, J.G. Shiu, Y.M. Tzeng, X. Wan, M. Wang

Cukurova University, Adana, Turkey
A. Adiguzel, M.N. Bakirci[40], S. Cerci[41], C. Dozen, I. Dumanoglu, E. Eskut, S. Girgis, G. Gokbulut, E. Gurpinar, I. Hos, E.E. Kangal, T. Karaman, G. Karapinar[42], A. Kayis Topaksu, G. Onengut, K. Ozdemir, S. Ozturk[43], A. Polatoz, K. Sogut[44], D. Sunar Cerci[41], B. Tali[41], H. Topakli[40], L.N. Vergili, M. Vergili

Middle East Technical University, Physics Department, Ankara, Turkey
I.V. Akin, T. Aliev, B. Bilin, S. Bilmis, M. Deniz, H. Gamsizkan, A.M. Guler, K. Ocalan, A. Ozpineci, M. Serin, R. Sever, U.E. Surat, M. Yalvac, E. Yildirim, M. Zeyrek

Bogazici University, Istanbul, Turkey
E. Gülmez, B. Isildak[45], M. Kaya[46], O. Kaya[46], S. Ozkorucuklu[47], N. Sonmez[48]

Istanbul Technical University, Istanbul, Turkey
K. Cankocak

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

University of Bristol, Bristol, United Kingdom
F. Bostock, J.J. Brooke, E. Clement, D. Cussans, H. Flacher, R. Frazier, J. Goldstein, M. Grimes, G.P. Heath, H.F. Heath, L. Kreczko, S. Metson, D.M. Newbold[36], K. Nirunpong, A. Poll, S. Senkin, V.J. Smith, T. Williams

Rutherford Appleton Laboratory, Didcot, United Kingdom
L. Basso[49], A. Belyaev[49], C. Brew, R.M. Brown, D.J.A. Cockerill, J.A. Coughlan, K. Harder, S. Harper, J. Jackson, B.W. Kennedy, E. Olaiya, D. Petyt, B.C. Radburn-Smith, C.H. Shepherd-Themistocleous, I.R. Tomalin, W.J. Womersley

Imperial College, London, United Kingdom
R. Bainbridge, G. Ball, R. Beuselinck, O. Buchmuller, D. Colling, N. Cripps, M. Cutajar, P. Dauncey, G. Davies, M. Della Negra, W. Ferguson, J. Fulcher, D. Futyan, A. Gilbert, A. Guneratne Bryer, G. Hall, Z. Hatherell, J. Hays, G. Iles, M. Jarvis, G. Karapostoli, L. Lyons, A.-M. Magnan, J. Marrouche, B. Mathias, R. Nandi, J. Nash, A. Nikitenko[39], A. Papageorgiou, J. Pela[5], M. Pesaresi, K. Petridis, M. Pioppi[50], D.M. Raymond, S. Rogerson, A. Rose, M.J. Ryan, C. Seez, P. Sharp[†], A. Sparrow, M. Stoye, A. Tapper, M. Vazquez Acosta, T. Virdee, S. Wakefield, N. Wardle, T. Whyntie

Brunel University, Uxbridge, United Kingdom
M. Chadwick, J.E. Cole, P.R. Hobson, A. Khan, P. Kyberd, D. Leggat, D. Leslie, W. Martin, I.D. Reid, P. Symonds, L. Teodorescu, M. Turner

Baylor University, Waco, USA
K. Hatakeyama, H. Liu, T. Scarborough

The University of Alabama, Tuscaloosa, USA
O. Charaf, C. Henderson, P. Rumerio

Boston University, Boston, USA
A. Avetisyan, T. Bose, C. Fantasia, A. Heister, J. St. John, P. Lawson, D. Lazic, J. Rohlf, D. Sperka, L. Sulak

Brown University, Providence, USA
J. Alimena, S. Bhattacharya, D. Cutts, A. Ferapontov, U. Heintz, S. Jabeen, G. Kukartsev, E. Laird, G. Landsberg, M. Luk, M. Narain, D. Nguyen, M. Segala, T. Sinthuprasith, T. Speer, K.V. Tsang

University of California, Davis, Davis, USA
R. Breedon, G. Breto, M. Calderon De La Barca Sanchez, S. Chauhan, M. Chertok, J. Conway, R. Conway, P.T. Cox, J. Dolen, R. Erbacher, M. Gardner, R. Houtz, W. Ko, A. Kopecky, R. Lander, T. Miceli, D. Pellett, F. Ricci-tam, B. Rutherford, M. Searle, J. Smith, M. Squires, M. Tripathi, R. Vasquez Sierra

University of California, Los Angeles, Los Angeles, USA
V. Andreev, D. Cline, R. Cousins, J. Duris, S. Erhan, P. Everaerts, C. Farrell, J. Hauser, M. Ignatenko, C. Jarvis, C. Plager, G. Rakness, P. Schlein[†], P. Traczyk, V. Valuev, M. Weber

University of California, Riverside, Riverside, USA
J. Babb, R. Clare, M.E. Dinardo, J. Ellison, J.W. Gary, F. Giordano, G. Hanson, G.Y. Jeng[51], H. Liu, O.R. Long, A. Luthra, H. Nguyen, S. Paramesvaran, J. Sturdy, S. Sumowidagdo, R. Wilken, S. Wimpenny

University of California, San Diego, La Jolla, USA
W. Andrews, J.G. Branson, G.B. Cerati, S. Cittolin, D. Evans, F. Golf, A. Holzner, R. Kelley, M. Lebourgeois, J. Letts, I. Macneill, B. Mangano, S. Padhi, C. Palmer, G. Petrucciani, M. Pieri, M. Sani, V. Sharma, S. Simon, E. Sudano, M. Tadel, Y. Tu, A. Vartak, S. Wasserbaech[52], F. Würthwein, A. Yagil, J. Yoo

University of California, Santa Barbara, Santa Barbara, USA
D. Barge, R. Bellan, C. Campagnari, M. D'Alfonso, T. Danielson, K. Flowers, P. Geffert, J. Incandela, C. Justus, P. Kalavase, S.A. Koay, D. Kovalskyi, V. Krutelyov, S. Lowette, N. Mccoll, V. Pavlunin, F. Rebassoo, J. Ribnik, J. Richman, R. Rossin, D. Stuart, W. To, C. West

California Institute of Technology, Pasadena, USA
A. Apresyan, A. Bornheim, Y. Chen, E. Di Marco, J. Duarte, M. Gataullin, Y. Ma, A. Mott, H.B. Newman, C. Rogan, M. Spiropulu[4], V. Timciuc, J. Veverka, R. Wilkinson, Y. Yang, R.Y. Zhu

Carnegie Mellon University, Pittsburgh, USA
B. Akgun, V. Azzolini, R. Carroll, T. Ferguson, Y. Iiyama, D.W. Jang, Y.F. Liu, M. Paulini, H. Vogel, I. Vorobiev

University of Colorado at Boulder, Boulder, USA
J.P. Cumalat, B.R. Drell, C.J. Edelmaier, W.T. Ford, A. Gaz, B. Heyburn, E. Luiggi Lopez, J.G. Smith, K. Stenson, K.A. Ulmer, S.R. Wagner

Cornell University, Ithaca, USA
J. Alexander, A. Chatterjee, N. Eggert, L.K. Gibbons, B. Heltsley, A. Khukhunaishvili, B. Kreis, N. Mirman, G. Nicolas Kaufman, J.R. Patterson, A. Ryd, E. Salvati, W. Sun, W.D. Teo, J. Thom, J. Thompson, J. Tucker, J. Vaughan, Y. Weng, L. Winstrom, P. Wittich

Fairfield University, Fairfield, USA
D. Winn

Fermi National Accelerator Laboratory, Batavia, USA
S. Abdullin, M. Albrow, J. Anderson, L.A.T. Bauerdick, A. Beretvas, J. Berryhill, P.C. Bhat, I. Bloch, K. Burkett, J.N. Butler, V. Chetluru, H.W.K. Cheung, F. Chlebana, V.D. Elvira, I. Fisk, J. Freeman, Y. Gao, D. Green, O. Gutsche, J. Hanlon, R.M. Harris, J. Hirschauer, B. Hooberman, S. Jindariani, M. Johnson, U. Joshi, B. Kilminster, B. Klima, S. Kunori, S. Kwan, C. Leonidopoulos, J. Linacre, D. Lincoln, R. Lipton, J. Lykken, K. Maeshima, J.M. Marraffino, S. Maruyama, D. Mason, P. McBride, K. Mishra, S. Mrenna, Y. Musienko[53], C. Newman-Holmes, V. O'Dell, O. Prokofyev, E. Sexton-Kennedy, S. Sharma, W.J. Spalding, L. Spiegel, P. Tan, L. Taylor, S. Tkaczyk, N.V. Tran, L. Uplegger, E.W. Vaandering, R. Vidal, J. Whitmore, W. Wu, F. Yang, F. Yumiceva, J.C. Yun

University of Florida, Gainesville, USA
D. Acosta, P. Avery, D. Bourilkov, M. Chen, T. Cheng, S. Das, M. De Gruttola, G.P. Di Giovanni, D. Dobur, A. Drozdetskiy, R.D. Field, M. Fisher, Y. Fu, I.K. Furic, J. Gartner, J. Hugon, B. Kim, J. Konigsberg, A. Korytov, A. Kropivnitskaya, T. Kypreos, J.F. Low, K. Matchev, P. Milenovic[54], G. Mitselmakher, L. Muniz, R. Remington, A. Rinkevicius, P. Sellers, N. Skhirtladze, M. Snowball, J. Yelton, M. Zakaria

Florida International University, Miami, USA
V. Gaultney, S. Hewamanage, L.M. Lebolo, S. Linn, P. Markowitz, G. Martinez, J.L. Rodriguez

Florida State University, Tallahassee, USA
T. Adams, A. Askew, J. Bochenek, J. Chen, B. Diamond, S.V. Gleyzer, J. Haas, S. Hagopian, V. Hagopian, M. Jenkins, K.F. Johnson, H. Prosper, V. Veeraraghavan, M. Weinberg

Florida Institute of Technology, Melbourne, USA
M.M. Baarmand, B. Dorney, M. Hohlmann, H. Kalakhety, I. Vodopiyanov

University of Illinois at Chicago (UIC), Chicago, USA
M.R. Adams, I.M. Anghel, L. Apanasevich, Y. Bai, V.E. Bazterra, R.R. Betts, I. Bucinskaite, J. Callner, R. Cavanaugh, C. Dragoiu, O. Evdokimov, L. Gauthier, C.E. Gerber, D.J. Hofman, S. Khalatyan, F. Lacroix, M. Malek, C. O'Brien, C. Silkworth, D. Strom, N. Varelas

The University of Iowa, Iowa City, USA
U. Akgun, E.A. Albayrak, B. Bilki[55], W. Clarida, F. Duru, S. Griffiths, J.-P. Merlo, H. Mermerkaya[56], A. Mestvirishvili, A. Moeller, J. Nachtman, C.R. Newsom, E. Norbeck, Y. Onel, F. Ozok, S. Sen, E. Tiras, J. Wetzel, T. Yetkin, K. Yi

Johns Hopkins University, Baltimore, USA
B.A. Barnett, B. Blumenfeld, S. Bolognesi, D. Fehling, G. Giurgiu, A.V. Gritsan, Z.J. Guo, G. Hu, P. Maksimovic, S. Rappoccio, M. Swartz, A. Whitbeck

The University of Kansas, Lawrence, USA
P. Baringer, A. Bean, G. Benelli, O. Grachov, R.P. Kenny Iii, M. Murray, D. Noonan, S. Sanders, R. Stringer, G. Tinti, J.S. Wood, V. Zhukova

Kansas State University, Manhattan, USA
A.F. Barfuss, T. Bolton, I. Chakaberia, A. Ivanov, S. Khalil, M. Makouski, Y. Maravin, S. Shrestha, I. Svintradze

Lawrence Livermore National Laboratory, Livermore, USA
J. Gronberg, D. Lange, D. Wright

University of Maryland, College Park, USA
A. Baden, M. Boutemeur, B. Calvert, S.C. Eno, J.A. Gomez, N.J. Hadley, R.G. Kellogg, M. Kirn,

T. Kolberg, Y. Lu, M. Marionneau, A.C. Mignerey, K. Pedro, A. Peterman, A. Skuja, J. Temple, M.B. Tonjes, S.C. Tonwar, E. Twedt

Massachusetts Institute of Technology, Cambridge, USA
A. Apyan, G. Bauer, J. Bendavid, W. Busza, E. Butz, I.A. Cali, M. Chan, V. Dutta, G. Gomez Ceballos, M. Goncharov, K.A. Hahn, Y. Kim, M. Klute, K. Krajczar[57], W. Li, P.D. Luckey, T. Ma, S. Nahn, C. Paus, D. Ralph, C. Roland, G. Roland, M. Rudolph, G.S.F. Stephans, F. Stöckli, K. Sumorok, K. Sung, D. Velicanu, E.A. Wenger, R. Wolf, B. Wyslouch, S. Xie, M. Yang, Y. Yilmaz, A.S. Yoon, M. Zanetti

University of Minnesota, Minneapolis, USA
S.I. Cooper, B. Dahmes, A. De Benedetti, G. Franzoni, A. Gude, S.C. Kao, K. Klapoetke, Y. Kubota, J. Mans, N. Pastika, R. Rusack, M. Sasseville, A. Singovsky, N. Tambe, J. Turkewitz

University of Mississippi, University, USA
L.M. Cremaldi, R. Kroeger, L. Perera, R. Rahmat, D.A. Sanders

University of Nebraska-Lincoln, Lincoln, USA
E. Avdeeva, K. Bloom, S. Bose, J. Butt, D.R. Claes, A. Dominguez, M. Eads, J. Keller, I. Kravchenko, J. Lazo-Flores, H. Malbouisson, S. Malik, G.R. Snow

State University of New York at Buffalo, Buffalo, USA
U. Baur, A. Godshalk, I. Iashvili, S. Jain, A. Kharchilava, A. Kumar, S.P. Shipkowski, K. Smith

Northeastern University, Boston, USA
G. Alverson, E. Barberis, D. Baumgartel, M. Chasco, J. Haley, D. Nash, D. Trocino, D. Wood, J. Zhang

Northwestern University, Evanston, USA
A. Anastassov, A. Kubik, N. Mucia, N. Odell, R.A. Ofierzynski, B. Pollack, A. Pozdnyakov, M. Schmitt, S. Stoynev, M. Velasco, S. Won

University of Notre Dame, Notre Dame, USA
L. Antonelli, D. Berry, A. Brinkerhoff, M. Hildreth, C. Jessop, D.J. Karmgard, J. Kolb, K. Lannon, W. Luo, S. Lynch, N. Marinelli, D.M. Morse, T. Pearson, R. Ruchti, J. Slaunwhite, N. Valls, M. Wayne, M. Wolf

The Ohio State University, Columbus, USA
B. Bylsma, L.S. Durkin, C. Hill, R. Hughes, R. Hughes, K. Kotov, T.Y. Ling, D. Puigh, M. Rodenburg, C. Vuosalo, G. Williams, B.L. Winer

Princeton University, Princeton, USA
N. Adam, E. Berry, P. Elmer, D. Gerbaudo, V. Halyo, P. Hebda, J. Hegeman, A. Hunt, P. Jindal, D. Lopes Pegna, P. Lujan, D. Marlow, T. Medvedeva, M. Mooney, J. Olsen, P. Piroué, X. Quan, A. Raval, B. Safdi, H. Saka, D. Stickland, C. Tully, J.S. Werner, A. Zuranski

University of Puerto Rico, Mayaguez, USA
J.G. Acosta, E. Brownson, X.T. Huang, A. Lopez, H. Mendez, S. Oliveros, J.E. Ramirez Vargas, A. Zatserklyaniy

Purdue University, West Lafayette, USA
E. Alagoz, V.E. Barnes, D. Benedetti, G. Bolla, D. Bortoletto, M. De Mattia, A. Everett, Z. Hu, M. Jones, O. Koybasi, M. Kress, A.T. Laasanen, N. Leonardo, V. Maroussov, P. Merkel, D.H. Miller, N. Neumeister, I. Shipsey, D. Silvers, A. Svyatkovskiy, M. Vidal Marono, H.D. Yoo, J. Zablocki, Y. Zheng

Purdue University Calumet, Hammond, USA
S. Guragain, N. Parashar

Rice University, Houston, USA
A. Adair, C. Boulahouache, K.M. Ecklund, F.J.M. Geurts, B.P. Padley, R. Redjimi, J. Roberts, J. Zabel

University of Rochester, Rochester, USA
B. Betchart, A. Bodek, Y.S. Chung, R. Covarelli, P. de Barbaro, R. Demina, Y. Eshaq, A. Garcia-Bellido, P. Goldenzweig, J. Han, A. Harel, D.C. Miner, D. Vishnevskiy, M. Zielinski

The Rockefeller University, New York, USA
A. Bhatti, R. Ciesielski, L. Demortier, K. Goulianos, G. Lungu, S. Malik, C. Mesropian

Rutgers, the State University of New Jersey, Piscataway, USA
S. Arora, A. Barker, J.P. Chou, C. Contreras-Campana, E. Contreras-Campana, D. Duggan, D. Ferencek, Y. Gershtein, R. Gray, E. Halkiadakis, D. Hidas, A. Lath, S. Panwalkar, M. Park, R. Patel, V. Rekovic, J. Robles, K. Rose, S. Salur, S. Schnetzer, C. Seitz, S. Somalwar, R. Stone, S. Thomas

University of Tennessee, Knoxville, USA
G. Cerizza, M. Hollingsworth, S. Spanier, Z.C. Yang, A. York

Texas A&M University, College Station, USA
R. Eusebi, W. Flanagan, J. Gilmore, T. Kamon[58], V. Khotilovich, R. Montalvo, I. Osipenkov, Y. Pakhotin, A. Perloff, J. Roe, A. Safonov, T. Sakuma, S. Sengupta, I. Suarez, A. Tatarinov, D. Toback

Texas Tech University, Lubbock, USA
N. Akchurin, J. Damgov, P.R. Dudero, C. Jeong, K. Kovitanggoon, S.W. Lee, T. Libeiro, Y. Roh, I. Volobouev

Vanderbilt University, Nashville, USA
E. Appelt, A.G. Delannoy, C. Florez, S. Greene, A. Gurrola, W. Johns, C. Johnston, P. Kurt, C. Maguire, A. Melo, M. Sharma, P. Sheldon, B. Snook, S. Tuo, J. Velkovska

University of Virginia, Charlottesville, USA
M.W. Arenton, M. Balazs, S. Boutle, B. Cox, B. Francis, J. Goodell, R. Hirosky, A. Ledovskoy, C. Lin, C. Neu, J. Wood, R. Yohay

Wayne State University, Detroit, USA
S. Gollapinni, R. Harr, P.E. Karchin, C. Kottachchi Kankanamge Don, P. Lamichhane, A. Sakharov

University of Wisconsin, Madison, USA
M. Anderson, M. Bachtis, D. Belknap, L. Borrello, D. Carlsmith, M. Cepeda, S. Dasu, E. Friis, L. Gray, K.S. Grogg, M. Grothe, R. Hall-Wilton, M. Herndon, A. Hervé, P. Klabbers, J. Klukas, A. Lanaro, C. Lazaridis, J. Leonard, R. Loveless, A. Mohapatra, I. Ojalvo, F. Palmonari, G.A. Pierro, I. Ross, A. Savin, W.H. Smith, J. Swanson

†: Deceased
1: Also at Vienna University of Technology, Vienna, Austria
2: Also at National Institute of Chemical Physics and Biophysics, Tallinn, Estonia
3: Also at Universidade Federal do ABC, Santo Andre, Brazil
4: Also at California Institute of Technology, Pasadena, USA

5: Also at CERN, European Organization for Nuclear Research, Geneva, Switzerland
6: Also at Laboratoire Leprince-Ringuet, Ecole Polytechnique, IN2P3-CNRS, Palaiseau, France
7: Also at Suez Canal University, Suez, Egypt
8: Also at Zewail City of Science and Technology, Zewail, Egypt
9: Also at Cairo University, Cairo, Egypt
10: Also at Fayoum University, El-Fayoum, Egypt
11: Also at British University, Cairo, Egypt
12: Now at Ain Shams University, Cairo, Egypt
13: Also at National Centre for Nuclear Research, Swierk, Poland
14: Also at Université de Haute-Alsace, Mulhouse, France
15: Now at Joint Institute for Nuclear Research, Dubna, Russia
16: Also at Moscow State University, Moscow, Russia
17: Also at Brandenburg University of Technology, Cottbus, Germany
18: Also at Institute of Nuclear Research ATOMKI, Debrecen, Hungary
19: Also at Eötvös Loránd University, Budapest, Hungary
20: Also at Tata Institute of Fundamental Research - HECR, Mumbai, India
21: Also at University of Visva-Bharati, Santiniketan, India
22: Also at Sharif University of Technology, Tehran, Iran
23: Also at Isfahan University of Technology, Isfahan, Iran
24: Also at Plasma Physics Research Center, Science and Research Branch, Islamic Azad University, Teheran, Iran
25: Also at Facoltà Ingegneria Università di Roma, Roma, Italy
26: Also at Università della Basilicata, Potenza, Italy
27: Also at Università degli Studi Guglielmo Marconi, Roma, Italy
28: Also at Laboratori Nazionali di Legnaro dell' INFN, Legnaro, Italy
29: Also at Università degli studi di Siena, Siena, Italy
30: Also at University of Bucharest, Faculty of Physics, Bucuresti-Magurele, Romania
31: Also at Faculty of Physics of University of Belgrade, Belgrade, Serbia
32: Also at University of California, Los Angeles, Los Angeles, USA
33: Also at Scuola Normale e Sezione dell' INFN, Pisa, Italy
34: Also at INFN Sezione di Roma; Università di Roma "La Sapienza", Roma, Italy
35: Also at University of Athens, Athens, Greece
36: Also at Rutherford Appleton Laboratory, Didcot, United Kingdom
37: Also at The University of Kansas, Lawrence, USA
38: Also at Paul Scherrer Institut, Villigen, Switzerland
39: Also at Institute for Theoretical and Experimental Physics, Moscow, Russia
40: Also at Gaziosmanpasa University, Tokat, Turkey
41: Also at Adiyaman University, Adiyaman, Turkey
42: Also at Izmir Institute of Technology, Izmir, Turkey
43: Also at The University of Iowa, Iowa City, USA
44: Also at Mersin University, Mersin, Turkey
45: Also at Ozyegin University, Istanbul, Turkey
46: Also at Kafkas University, Kars, Turkey
47: Also at Suleyman Demirel University, Isparta, Turkey
48: Also at Ege University, Izmir, Turkey
49: Also at School of Physics and Astronomy, University of Southampton, Southampton, United Kingdom
50: Also at INFN Sezione di Perugia; Università di Perugia, Perugia, Italy
51: Also at University of Sydney, Sydney, Australia

52: Also at Utah Valley University, Orem, USA
53: Also at Institute for Nuclear Research, Moscow, Russia
54: Also at University of Belgrade, Faculty of Physics and Vinca Institute of Nuclear Sciences, Belgrade, Serbia
55: Also at Argonne National Laboratory, Argonne, USA
56: Also at Erzincan University, Erzincan, Turkey
57: Also at KFKI Research Institute for Particle and Nuclear Physics, Budapest, Hungary
58: Also at Kyungpook National University, Daegu, Korea