Evidence for collective multi-particle correlations in pPb collisions

The CMS Collaboration

Abstract

The second-order azimuthal anisotropy Fourier harmonics, \( v_2 \), are obtained in pPb and PbPb collisions over a wide pseudorapidity (\( \eta \)) range based on correlations among six or more charged particles. The pPb data, corresponding to an integrated luminosity of 35 nb\(^{-1}\), were collected during the 2013 LHC pPb run at a nucleon-nucleon center-of-mass energy of 5.02 TeV by the CMS experiment. A sample of semi-peripheral PbPb collision data at \( \sqrt{s_{NN}} = 2.76 \) TeV, corresponding to an integrated luminosity of 2.5 \( \mu \)b\(^{-1}\) and covering a similar range of particle multiplicities as the pPb data, is also analyzed for comparison. The six- and eight-particle cumulant and the Lee-Yang zeros methods are used to extract the \( v_2 \) coefficients, extending previous studies of two- and four-particle correlations. For both the pPb and PbPb systems, the \( v_2 \) values obtained with correlations among more than four particles are consistent with previously published four-particle results. These data support the interpretation of a collective origin for the previously observed long-range (large \( \Delta \eta \)) correlations in both systems. The ratios of \( v_2 \) values corresponding to correlations including different numbers of particles are compared to theoretical predictions that assume a hydrodynamic behavior of a pPb system dominated by fluctuations in the positions of participant nucleons. These results provide new insights into the multi-particle dynamics of collision systems with a very small overlapping region.

Submitted to Physical Review Letters
Measurements at the CERN LHC have led to the discovery of two-particle azimuthal correlation structures at large relative pseudorapidity (long-range) in proton-proton (pp) [1] and proton-lead (pPb) [2–5] collisions. Similar long-range structure has also been observed for $\sqrt{s_{NN}} = 200$ GeV deuteron-gold (dAu) collisions at RHIC [6, 7]. The results extend previous studies of relativistic heavy ion collisions, such as for the copper-copper [8], gold-gold [8–12], and lead-lead (PbPb) [13–18] systems, where similar long-range, two-particle correlations at small relative azimuthal angle $|\Delta\phi| \approx 0$ were first observed. A fundamental question is whether the observed behavior results from correlations exclusively between particle pairs, or if it is a multi-particle, collective effect. It has been suggested that the hydrodynamic collective flow of a strongly interacting and expanding medium [19–21] is responsible for these long-range correlations in central and mid-central heavy ion collisions. The origin of the observed long-range correlations in collision systems with a small overlapping region, such as for pp and pPb collisions, is not clear since for these systems the formation of an extended hot medium is not necessarily expected. Various theoretical models have been proposed to interpret the pp [22, 23] and pPb results, including initial-state gluon saturation without any final state interactions [24, 25] and, similar to what is thought to occur in heavier systems, hydrodynamic behavior that develops in a conjectured high-density medium [26–28]. These models have been successful in describing different aspects of the previous experimental results.

To further investigate the multi-particle nature of the observed long-range correlation phenomena, in this Letter we present measurements of correlations among six or more charged particles for pPb collisions at a center-of-mass energy per nucleon pair of $\sqrt{s_{NN}} = 5.02$ TeV. The azimuthal dependence of particle production is typically characterized by an expansion in Fourier harmonics ($v_n$) [29]. In hydrodynamic models, the second ($v_2$) and third ($v_3$) harmonics, called “elliptic” and “triangular” flow [30], respectively, directly reflect the response to the initial collision geometry and fluctuations [31–33], providing insight into the fundamental transport properties of the medium. First attempts to establish the multi-particle nature of the correlations observed in pPb collisions were presented in Refs. [34, 35] by directly measuring four-particle azimuthal correlations, where the elliptic flow signal was obtained using the four-particle cumulant method [36]. However, four-particle correlations can still be affected by contributions from non-collective effects such as fragmentation of back-to-back jets. By extending the studies to six- and eight-particle cumulants [36] and by also obtaining results using the Lee-Yang zeros (LYZ) method, which involves correlations among all detected particles [37, 38], it is possible to further explore the collective nature of the correlations. High-statistics data obtained by the CMS experiment during the 2013 pPb run at the LHC are used. With a sample of very high final state multiplicity pPb collisions, the correlation data have been studied in a regime that is comparable to the charged particle multiplicity of the 50% most peripheral (semi-peripheral) PbPb collisions at $\sqrt{s_{NN}} = 2.76$ TeV.

The CMS detector comprises a number of subsystems [39]. The results in this Letter are mainly based on the silicon tracker information. The silicon tracker, located in the 3.8 T field of a superconducting solenoid, consists of 1440 silicon pixel and 15148 silicon strip detector modules. The silicon tracker measures charged particles within the pseudorapidity range $|\eta| < 2.5$, and provides an impact parameter resolution of $\approx 15 \mu m$ and a transverse momentum ($p_T$) resolution better than 1.5% at $p_T \approx 100$ GeV/c. The electromagnetic (ECAL) and hadron (HCAL) calorimeters are also located inside the solenoid and cover the pseudorapidity range $|\eta| < 3.0$. The HCAL barrel and endcaps are sampling calorimeters composed of brass and scintillator plates. The ECAL consists of lead tungstate crystals arranged in a quasiprojective geometry. Iron/quartz-fiber Čerenkov hadron forward (HF) calorimeters cover the range $2.9 < |\eta| < 5.2$ on either side of the interaction region. These HF calorimeters are azimuthally subdivided into
20° modular wedges and further segmented to form $0.175 \times 0.175 \text{ rad} \ (\Delta \eta \times \Delta \phi)$ “towers”. The detailed Monte Carlo (MC) simulation of the CMS detector response is based on GEANT4 [40].

The analysis is performed using data recorded by CMS during the LHC pPb run in 2013. The data set corresponds to an integrated luminosity of $35 \text{ nb}^{-1}$. The beam energies were 4 TeV for protons and 1.58 TeV per nucleon for lead nuclei, resulting in $\sqrt{s_{NN}} = 5.02 \text{ TeV}$. The beam directions were reversed during the run allowing a check of one potential source of systematic uncertainties. As a result of the energy difference between the colliding beams, the nucleon-nucleon center-of-mass in the pPb collisions is not at rest with respect to the laboratory frame. Massless particles emitted at $\eta_{cm} = 0$ in the nucleon-nucleon center-of-mass frame will be detected at $\eta = -0.465$ (clockwise proton beam) or 0.465 (counterclockwise proton beam) in the laboratory frame. A sample of $\sqrt{s_{NN}} = 2.76 \text{ TeV}$ PbPb data collected during the 2011 LHC heavy-ion run, corresponding to an integrated luminosity of $2.3 \mu \text{b}^{-1}$, is also analyzed for comparison purposes. The triggers and event selection, as well as track reconstruction and selection are summarized below and are identical to those used in Ref. [35].

Minimum bias (MB) pPb events were triggered by requiring at least one track with $p_T > 0.4 \text{ GeV}/c$ to be found in the pixel tracker for a pPb bunch crossing. Only a small fraction ($\sim 10^{-3}$) of all MB triggered events were recorded (i.e., the trigger was “prescaled”) because of hardware limits on the data acquisition rate. In order to select high-multiplicity pPb collisions, a dedicated high-multiplicity trigger was implemented using the CMS level-1 (L1) and high-level trigger (HLT) systems. At L1, three triggers requiring the total transverse energy summed over ECAL and HCAL to be greater than 20, 40, and 60 GeV were used since these cuts selected roughly the same events as the three HLT multiplicity selections discussed below. Online track reconstruction for the HLT was based on the three layers of pixel detectors, and required a track origin within a cylindrical region of length 30 cm along the beam and radius 0.2 cm perpendicular to the beam around the nominal interaction point. For each event, the vertex reconstructed with the highest number of pixel tracks was selected. The number of pixel tracks ($N_{\text{online trk}}$) with $|\eta| < 2.4$, $p_T > 0.4 \text{ GeV}/c$, and a distance of closest approach to this vertex of 0.4 cm or less, was determined for each event. Several high-multiplicity ranges were defined with prescale factors that were progressively reduced until, for the highest multiplicity events, no prescaling was applied.

In the offline analysis, hadronic collisions are selected by requiring a coincidence of at least one HF calorimeter tower containing more than 3 GeV of total energy in each of the HF detectors. Only towers within $3 < |\eta| < 5$ are used to avoid the edges of the HF acceptance. Events are also required to contain at least one reconstructed primary vertex within 15 cm of the nominal interaction point along the beam axis and within 0.15 cm transverse to the beam trajectory. At least two reconstructed tracks are required to be associated with the primary vertex. Beam related background is suppressed by rejecting events for which less than 25% of all reconstructed tracks pass the track selection criteria of this analysis. The pPb instantaneous luminosity provided by the LHC in the 2013 run resulted in an approximately 3% probability of at least one additional interaction occurring in the same bunch crossing. Following the procedure developed in Ref. [35] for rejecting such “pileup” events, a 99.8% purity of single-interaction events is achieved for the pPb collisions belonging to the highest multiplicity class studied in this Letter. In pPb interactions simulated with the EPOS [41] and HIJING [42] event generators, requiring at least one primary particle with total energy $E > 3 \text{ GeV}$ in each of the $\eta$ ranges $-5 < \eta < -3$ and $3 < \eta < 5$ is found to select 97–98% of the total inelastic hadronic cross section.

The CMS “high-quality” tracks, described in Ref. [43] are used in this analysis. Additionally, a reconstructed track is only considered as a candidate track from the primary vertex if the
significance of the separation along the beam axis (z) between the track and the best vertex, $d_z/\sigma(d_z)$, and the significance of the track-vertex impact parameter measured transverse to the beam, $d_T/\sigma(d_T)$, are each less than 3. The relative uncertainty in the transverse-momentum measurement, $\sigma(p_T)/p_T$, is required to be less than 10%. To ensure high tracking efficiency and to reduce the rate of incorrectly reconstructed tracks, only tracks within $|\eta| < 2.4$ and with $0.3 < p_T < 3.0$ GeV/c are used in the analysis. A different $p_T$ cutoff of 0.4 GeV/c is used in the multiplicity determination because of constraints on the online processing time for the HLT.

The entire pPb data set is divided into classes of reconstructed track multiplicity, $N_{\text{trk}}^{\text{offline}}$, where primary tracks with $|\eta| < 2.4$ and $p_T > 0.4$ GeV/c are counted. The multiplicity classification in this analysis is identical to that used in Ref. [35], where more details are provided including a table relating $N_{\text{trk}}^{\text{offline}}$ to the fraction of MB triggered events. A subset of semi-peripheral PbPb data collected during the 2011 LHC heavy-ion run with an MB trigger is also reanalyzed in order to directly compare the pPb and PbPb systems at the same track multiplicity. This PbPb sample is reprocessed using the same event selection and track reconstruction as for the present pPb analysis. A description of the 2011 PbPb data can be found in Ref. [44].

Extending the previous two- and four-particle azimuthal correlation measurements of Ref. [35], six- and eight-particle azimuthal correlations are evaluated in this analysis as follow:

\[
\langle\langle 6 \rangle\rangle \equiv \langle\langle e^{in(\phi_1+\phi_2+\phi_3-\phi_4-\phi_5-\phi_6)}\rangle\rangle,
\]
\[
\langle\langle 8 \rangle\rangle \equiv \langle\langle e^{in(\phi_1+\phi_2+\phi_3+\phi_4-\phi_5-\phi_6-\phi_7-\phi_8)}\rangle\rangle.
\]

Here $\phi_i$ ($i = 1, ..., 8$) are the azimuthal angles of one unique combination of multiple particles in an event, $n$ is the harmonic number, and $\langle\langle \cdot \cdot \cdot \rangle\rangle$ represents the average over all combinations from all events within a given multiplicity range. The corresponding cumulants, $c_n\{6\}$ and $c_n\{8\}$, are calculated as

\[
c_n\{6\} = \langle\langle 6 \rangle\rangle - 9 \cdot \langle\langle 4 \rangle\rangle \langle\langle 2 \rangle\rangle + 12 \cdot \langle\langle 2 \rangle\rangle^3,
\]
\[
c_n\{8\} = \langle\langle 8 \rangle\rangle - 16 \cdot \langle\langle 6 \rangle\rangle \langle\langle 2 \rangle\rangle - 18 \cdot \langle\langle 4 \rangle\rangle^2 + 144 \cdot \langle\langle 4 \rangle\rangle \langle\langle 2 \rangle\rangle^2 - 144 \langle\langle 2 \rangle\rangle^4.
\]

using the Q-cumulant method as formulated in Ref. [36], where $\langle\langle 2 \rangle\rangle$ and $\langle\langle 4 \rangle\rangle$ are defined similarly as in Eq. [1]. The Fourier harmonics $v_n$ that characterize the global azimuthal behavior can be related to the multi-particle correlations using

\[
v_n\{6\} = \frac{1}{\sqrt[4]{4}} c_n\{6\},
\]
\[
v_n\{8\} = \frac{1}{\sqrt[33]{33}} c_n\{8\}.
\]

To account for detector effects, such as the tracking efficiency, the Q-cumulant method was extended in Ref. [45] to allow for particles having different weights. Each reconstructed track is weighted by a correction factor to account for the reconstruction efficiency, detector acceptance, and fraction of misreconstructed tracks. This factor is derived as a function of $p_T$ and $\eta$, as described in Refs. [13] [44], based on MC simulations. The combined geometrical acceptance and efficiency for track reconstruction exceeds 60% for $p_T \approx 0.3$ GeV/c and $|\eta| < 2.4$. The efficiency is greater than 90% in the $|\eta| < 1$ region for $p_T > 0.6$ GeV/c. For the entire multiplicity range (up to $N_{\text{trk}}^{\text{offline}} \sim 350$) studied in this Letter, no dependence of the tracking efficiency on multiplicity is found and the rate of mis-reconstructed tracks remains at the 1–2% level. The software package provided by Ref. [45] is used to implement the weights of individual tracks in the cumulant calculations.
The LYZ method allows a direct study of the large-order behavior by using the asymptotic form of the cumulant expansion to relate locations of the zeros of a generating function to the azimuthal correlations. This method has been employed in previous CMS PbPb analyses. For each multiplicity bin, the $v_2$ harmonic averaged over $0.3 < p_T < 3.0 \text{ GeV/c}$ is found using an integral generating function. Similar to the cumulant methods, a weight is obtained with an $\eta$ gap of 2 units between the two particles. Possible residual non-flow effects resulting from back-to-back jet correlations are estimated using very low multiplicity events in Ref. [35]. Based on this analysis, such non-flow effects are expected to make a negligible contribution to $v_2 \{2\}$ in very high multiplicity events. In PbPb collisions, the $v_2$ values from all methods show an increase with multiplicity, while little multiplicity dependence is seen for the PbPb data. This difference might reflect the presence of a changing lenticular overlap geometry in PbPb collisions, which is presumably less prominent in pPb collisions, giving rise to a large (and varying) initial elliptic asymmetry in the PbPb system.

The effect of fluctuation-driven initial-state eccentricities on multi-particle cumulants has re-
Figure 1: The cumulant $c_2\{6\}$ and $-c_2\{8\}$ results as a function of $N_{\text{offline}}$ for PbPb (left) and pPb (right) reactions. Error bars and shaded areas denote statistical and systematic uncertainties, respectively.

Recently been explored in the context of hydrodynamic behavior of the resulting medium \[50,51\]. For fluctuation-driven initial-state conditions, ratios of $v_2$ values derived from various orders of multi-particle cumulants are predicted to follow a universal behavior \[50\]. In Fig. 3, ratios of $v_2\{6\}/v_2\{4\}$ (top) and $v_2\{8\}/v_2\{6\}$ (bottom) are calculated and plotted against $v_2\{4\}/v_2\{2\}$ in pPb collisions at $\sqrt{s_{\text{NN}}}=5.02$ TeV. The $v_2\{2\}$ and $v_2\{4\}$ data are taken from previously published CMS results \[35\]. The solid curves correspond to theoretical predictions for both large and small systems based on hydrodynamics and the assumption that the initial-state geometry is purely driven by fluctuations \[50\]. The ratios from PbPb collisions are also shown for comparison. Note that the geometry of very central PbPb collisions might be dominated by fluctuations, but for these semi-peripheral PbPb collisions the lenticular shape of the overlap region should also strongly contribute to the $v_2$ values. The CMS pPb data are consistent with the predictions within statistical and systematic uncertainties. The $v_2$ values are highly correlated as they are derived from the same data. The systematic uncertainties in the ratios presented in Fig. 3 are estimated to be 2.4% for $v_2\{4\}/v_2\{2\}$ for both pPb and PbPb collisions, 1% for $v_2\{6\}/v_2\{4\}$ in pPb and PbPb collisions, and 3.6% and 1% for $v_2\{8\}/v_2\{6\}$ in pPb and PbPb collisions, respectively.

Recently, other theoretical models based on quantum chromodynamics, and not involving hydrodynamics, have also been suggested to explain the observed multi-particle correlations in pPb collisions \[52,53\]. Unlike the descriptions based on hydrodynamic behavior, these models do not require significant final-state interactions among quarks and gluons. They suggest sim-
Figure 2: The $v_2$ values as a function of $N_{\text{offline}}^{\text{trk}}$. Open data points are published two- and four-particle $v_2$ results [35]. Solid data points are $v_2$ results obtained from six- and eight-particle cumulants, and LYZ methods, averaged over the particle $p_T$ range of 0.3–3.0 GeV/c, in PbPb at $\sqrt{s_{NN}} = 2.76$ TeV (left) and pPb at $\sqrt{s_{NN}} = 5.02$ TeV (right). Statistical and systematic uncertainties are indicated by the error bars and shaded regions, respectively.

In summary, multi-particle azimuthal correlations among six, eight, and all particles have been measured in pPb collisions at $\sqrt{s_{NN}} = 5.02$ TeV by the CMS experiment. The new measurements extend previous CMS two- and four-particle correlation analyses of pPb collisions and strongly constrain possible explanations for the observed correlations. A direct comparison of the correlation data for pPb and PbPb collisions is presented as a function of particle multiplicity. Averaging over the particle $p_T$ range of 0.3–3.0 GeV/c, multi-particle correlation signals are observed in both pPb and PbPb collisions. The second-order azimuthal anisotropy Fourier harmonic, $v_2$, is extracted using six- and eight-particle cumulants and using the LYZ method which involves all particles. The $v_2$ values obtained using correlation methods including four or more particles are consistent within $\pm 2\%$ for the PbPb system, and within $\pm 10\%$ for the pPb system. This measurement supports the collective nature of the observed correlations. The ratios of $v_2$ values obtained using different numbers of particles are found to be consistent with hydrodynamic model calculations for pPb collisions.

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
Figure 3: Cumulant ratios $v_2\{6\}/v_2\{4\}$ (top) and $v_2\{8\}/v_2\{6\}$ (bottom) as a function of $v_2\{4\}/v_2\{2\}$ in pPb collisions at √s_{NN} = 5.02 TeV and PbPb collisions at √s_{NN} = 2.76 TeV. Error bars and shaded areas denote statistical and systematic uncertainties, respectively. The solid curves show the expected behavior based on a hydrodynamics motivated study of the role of initial-state fluctuations [50].

FWO (Belgium); CNPq, CAPES, FAPERJ, and FAPESP (Brazil); MES (Bulgaria); CERN; CAS, MoST, and NSFC (China); COLCIENCIAS (Colombia); MSES and CSF (Croatia); RPF (Cyprus); 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); OTKA and NIH (Hungary); DAE and DST (India); IPM (Iran); SFI (Ireland); INFN (Italy); MSIP and NRF (Republic of Korea); LAS (Lithuania); MOE and UM (Malaysia); CINVESTAV, CONACYT, 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 and CPAN (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


References


Universidade Estadual Paulista $^a$, Universidade Federal do ABC $^b$, São Paulo, Brazil
C.A. Bernardes$^b$, S. Dogra$^a$, T.R. Fernandez Perez Tomei$^a$, E.M. Gregores$^b$, P.G. Mercadante$^b$, S.F. Novaes$^a$, Sandra S. Padula$^a$

Institute for Nuclear Research and Nuclear Energy, Sofia, Bulgaria
A. Aleksandrov, V. Genchev$^2$, R. Hadjiiska, P. Iaydjiev, A. Marinov, S. Piperov, M. Rodozov, S. Stoykova, G. Sultanov, M. Vutova

University of Sofia, Sofia, Bulgaria
A. Dimitrov, I. Glushkov, L. Litov, B. Pavlov, P. Petkov

Institute of High Energy Physics, Beijing, China

State Key Laboratory of Nuclear Physics and Technology, Peking University, Beijing, China
C. Asawatangtrakuldee, Y. Ban, S. Liu, Y. Mao, S.J. Qian, D. Wang, Z. Xu, F. Zhang$^5$, L. Zhang, W. Zou

Universidad de Los Andes, Bogota, Colombia
C. Avila, A. Cabrera, L.F. Chaparro Sierra, C. Florez, J.P. Gomez, B. Gomez Moreno, J.C. Sanabria

University of Split, Faculty of Electrical Engineering, Mechanical Engineering and Naval Architecture, Split, Croatia
N. Godinovic, D. Lelas, D. Polic, I. Puljak

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

Institute Rudjer Boskovic, Zagreb, Croatia
V. Brigljevic, K. Kadija, J. Luetic, D. Mekterovic, L. Sudic

University of Cyprus, Nicosia, Cyprus

Charles University, Prague, Czech Republic
M. Bodlak, M. Finger, M. Finger Jr.$^9$

Academy of Scientific Research and Technology of the Arab Republic of Egypt, Egyptian Network of High Energy Physics, Cairo, Egypt
Y. Assran$^{10}$, A. Ellithi Kamel$^{11}$, M.A. Mahmoud$^{12}$, A. Radi$^{13,14}$

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

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

Helsinki Institute of Physics, Helsinki, Finland

Lappeenranta University of Technology, Lappeenranta, Finland
J. Talvitie, T. Tuuva
The CMS Collaboration


University of Hamburg, Hamburg, Germany

Institut für Experimentelle Kernphysik, Karlsruhe, Germany

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

University of Athens, Athens, Greece
A. Agapitos, S. Kesisoglou, A. Panagiotou, N. Saoulidou, E. Stiliaris, E. Tziaferi

University of Ioánnina, Ioánnina, Greece

Wigner Research Centre for Physics, Budapest, Hungary
G. Bence, C. Hajdu, P. Hidas, D. Horvath, F. Sikler, V. Veszpremi, G. Vesztergombi, A.J. Zsigmond

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

University of Debrecen, Debrecen, Hungary
A. Makovec, P. Raics, Z.L. Trocsanyi, B. Ujvari

National Institute of Science Education and Research, Bhubaneswar, India
S.K. Swain

Panjab University, Chandigarh, India
S.B. Beri, V. Bhatnagar, R. Gupta, U. Bhandeep, A.K. Kalsi, M. Kaur, R. Kumar, M. Mittal, N. Nishu, J.B. Singh

University of Delhi, Delhi, India
Ashok Kumar, Arun Kumar, S. Ahuja, A. Bhardwaj, B.C. Choudhary, A. Kumar, S. Malhotra, M. Naimuddin, K. Ranjan, V. Sharma
Saha Institute of Nuclear Physics, Kolkata, India

Bhabha Atomic Research Centre, Mumbai, India
A. Abdul salam, D. Dutta, V. Kumar, A.K. Mohanty\textsuperscript{2}, L.M. Pant, P. Shukla, A. Topkar

Tata Institute of Fundamental Research, Mumbai, India

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

Institute for Research in Fundamental Sciences (IPM), Tehran, Iran
H. Bakhshiansohi, H. Behnamian, S.M. Etesami\textsuperscript{23}, A. Fahim\textsuperscript{24}, R. Goldouzian, M. Khakzad, M. Mohammadi Najafabadi, M. Naseri, S. Paktinat Mehdiabadi, F. Rezaei Hosseinabadi, B. Safarzadeh\textsuperscript{25}, M. Zeinali

University College Dublin, Dublin, Ireland
M. Felcini, M. Grunewald

INFN Sezione di Bari \textsuperscript{a}, Universit\`{a} di Bari \textsuperscript{b}, Politecnico di Bari \textsuperscript{c}, Bari, Italy
M. Abbrescia\textsuperscript{a,b}, C. Calabria\textsuperscript{a,b}, S.S. Chhibra\textsuperscript{a,b}, A. Colaleo\textsuperscript{a}, D. Creanza\textsuperscript{a,c}, L. Cristella\textsuperscript{a,b}, N. De Filippis\textsuperscript{a,c}, M. De Palma\textsuperscript{a,b}, L. Fiore\textsuperscript{a}, G. Iaselli\textsuperscript{a,c}, G. Maggi\textsuperscript{a,c}, M. Maggi\textsuperscript{a}, S. My\textsuperscript{a,c}, S. Nuzzo\textsuperscript{a,b}, A. Pompili\textsuperscript{a,b}, G. Pugliese\textsuperscript{a,c}, R. Radogna\textsuperscript{a,b,2}, G. Selvaggi\textsuperscript{a,b}, A. Sharma\textsuperscript{a}, L. Silvestris\textsuperscript{a,2}, R. Venditti\textsuperscript{a,b}, P. Verwilligen\textsuperscript{a}

INFN Sezione di Bologna \textsuperscript{a}, Universit\`{a} di Bologna \textsuperscript{b}, Bologna, Italy
G. Abbiendi\textsuperscript{a}, A.C. Benvenuti\textsuperscript{a}, D. Bonacorsi\textsuperscript{a,b}, S. Brabant-Giacomelli\textsuperscript{a,b}, L. Brigliadori\textsuperscript{a,b}, R. Campanini\textsuperscript{a,b}, P. Capiluppi\textsuperscript{a,b}, A. Castro\textsuperscript{a,b}, F.R. Cavallo\textsuperscript{a}, G. Codispoti\textsuperscript{a,b}, M. Cuffiani\textsuperscript{a,b}, G.M. Dallavalle\textsuperscript{a}, F. Fabbri\textsuperscript{a}, A. Fanfani\textsuperscript{a,b}, D. Fasanella\textsuperscript{a,b}, P. Giacomelli\textsuperscript{a}, C. Grandi\textsuperscript{a}, L. Guiducci\textsuperscript{a,b}, S. Marcellini\textsuperscript{a}, G. Masetti\textsuperscript{a}, A. Montanari\textsuperscript{a}, F.L. Navarra\textsuperscript{a,b}, A. Perrotta\textsuperscript{a}, A.M. Rossi\textsuperscript{a,b}, T. Rovelli\textsuperscript{a,b}, G.P. Siroli\textsuperscript{a,b}, N. Tosi\textsuperscript{a,b}, R. Travaglini\textsuperscript{a,b}

INFN Sezione di Catania \textsuperscript{a}, Universit\`{a} di Catania \textsuperscript{b}, CSFNSM \textsuperscript{c}, Catania, Italy
S. Albergo\textsuperscript{a,b}, G. Cappello\textsuperscript{a}, M. Chiorboli\textsuperscript{a,b}, S. Costa\textsuperscript{a,b}, F. Giordano\textsuperscript{a,2}, R. Potenza\textsuperscript{a,b}, A. Tricomi\textsuperscript{a,b}, C. Tuve\textsuperscript{a,b}

INFN Sezione di Firenze \textsuperscript{a}, Universit\`{a} di Firenze \textsuperscript{b}, Firenze, Italy
G. Barboglio\textsuperscript{a}, V. Ciulli\textsuperscript{a,b}, C. Civinini\textsuperscript{a}, R. D’Alessandro\textsuperscript{a,b}, E. Focardi\textsuperscript{a,b}, E. Gallo\textsuperscript{a}, S. Gonzi\textsuperscript{a,b}, V. Gori\textsuperscript{a,b}, P. Lenzi\textsuperscript{a,b}, M. Meschini\textsuperscript{a}, S. Paolletti\textsuperscript{a}, G. Squazzon\textsuperscript{a}, A. Tropiano\textsuperscript{a,b}

INFN Laboratori Nazionali di Frascati, Frascati, Italy
L. Benussi, S. Bianco, F. Fabbrica, D. Piccolo

INFN Sezione di Genova \textsuperscript{a}, Universit\`{a} di Genova \textsuperscript{b}, Genova, Italy
R. Ferretti\textsuperscript{a,b}, F. Ferro\textsuperscript{a}, M. Lo Vetere\textsuperscript{a,b}, E. Robutti\textsuperscript{a}, S. Tosi\textsuperscript{a,b}

INFN Sezione di Milano-Bicocca \textsuperscript{a}, Universit\`{a} di Milano-Bicocca \textsuperscript{b}, Milano, Italy
M.E. Dinaro\textsuperscript{a,b}, S. Fiorendi\textsuperscript{a,b}, S. Gennai\textsuperscript{a,2}, R. Gerosa\textsuperscript{a,b,2}, A. Ghezzi\textsuperscript{a,b}, P. Govoni\textsuperscript{a,b}, M.T. Lucchini\textsuperscript{a,b,2}, S. Malvezzi\textsuperscript{a}, R.A. Manzoni\textsuperscript{a,b}, A. Martelli\textsuperscript{a,b}, B. Marzocchi\textsuperscript{a,b,2}, D. Menasse\textsuperscript{a}, L. Moroni\textsuperscript{a}, M. Paganoni\textsuperscript{a,b}, D. Pedrini\textsuperscript{a}, S. Ragazzi\textsuperscript{a,b}, N. Redaelli\textsuperscript{a}, T. Tabarelli de Fatis\textsuperscript{a,b}
INFN Sezione di Napoli, Università di Napoli ‘Federico II’, Università della Basilicata (Potenza), Università G. Marconi (Roma), Napoli, Italy

INFN Sezione di Padova, Università di Padova, Università di Trento (Trento), Padova, Italy

INFN Sezione di Pavia, Università di Pavia, Pavia, Italy
M. Gabusi, S.P. Ratti, V. Re, C. Riccardi, P. Salvini, P. Vitulo

INFN Sezione di Perugia, Università di Perugia, Perugia, Italy
M. Biasini, G.M. Bilei, D. Ciangottini, L. Fanò, P. Lariccia, G. Mantovani, M. Menichelli, A. Saha, A. Santocchia, A. Spiezia

INFN Sezione di Pisa, Università di Pisa, Scuola Normale Superiore di Pisa, Pisa, Italy

INFN Sezione di Roma, Università di Roma, Roma, Italy

INFN Sezione di Torino, Università di Torino, Università del Piemonte Orientale (Novara), Torino, Italy

INFN Sezione di Trieste, Università di Trieste, Trieste, Italy
S. Belforte, V. Candelise, M. Casarsa, F. Cossutti, G. Della Ricca, B. Gobbo, C. La Licata, M. Marone, A. Schizzi, T. Umer, A. Zanetti

Kangwon National University, Chunchon, Korea
S. Chang, A. Kropivnitskaya, S.K. Nam

Kyungpook National University, Daegu, Korea
D.H. Kim, G.N. Kim, M.S. Kim, D.J. Kong, S. Lee, Y.D. Oh, H. Park, A. Sakharov, D.C. Son

Chonbuk National University, Jeonju, Korea
T.J. Kim, M.S. Ryu

Chonnam National University, Institute for Universe and Elementary Particles, Kwangju, Korea
J.Y. Kim, D.H. Moon, S. Song
Korea University, Seoul, Korea
S. Choi, D. Gyun, B. Hong, M. Jo, H. Kim, Y. Kim, B. Lee, K.S. Lee, S.K. Park, Y. Roh

Seoul National University, Seoul, Korea
H.D. Yoo

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

Sungkyunkwan University, Suwon, Korea

Vilnius University, Vilnius, Lithuania
A. Juodagalvis

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

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

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

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

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
P.H. Butler, S. Reucroft

National Centre for Physics, Quaid-I-Azam University, Islamabad, Pakistan
A. Ahmad, M. Ahmad, Q. Hassan, H.R. Hoorani, W.A. Khan, T. Khurshid, M. Shoaib

National Centre for Nuclear Research, Swierk, Poland

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

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

Joint Institute for Nuclear Research, Dubna, Russia

Paul Scherrer Institut, Villigen, Switzerland

Institute for Particle Physics, ETH Zurich, Zurich, Switzerland

Universität Zürich, Zurich, Switzerland

National Central University, Chung-Li, Taiwan

National Taiwan University (NTU), Taipei, Taiwan

Chulalongkorn University, Faculty of Science, Department of Physics, Bangkok, Thailand
B. Asavapibhop, G. Singh, N. Srimanobhas, N. Suwonjandee

Cukurova University, Adana, Turkey

Middle East Technical University, Physics Department, Ankara, Turkey

Bogazici University, Istanbul, Turkey
E.A. Albayrak, E. Gülmez, M. Kaya, O. Kaya, T. Yetkin

Istanbul Technical University, Istanbul, Turkey
K. Cankocak, F.I. Vardarlı

National Scientific Center, Kharkov Institute of Physics and Technology, Kharkov, Ukraine
L. Levchuk, P. Sorokin
University of Bristol, Bristol, United Kingdom

Rutherford Appleton Laboratory, Didcot, United Kingdom

Imperial College, London, United Kingdom

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

Baylor University, Waco, USA

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

Boston University, Boston, USA
A. Avetisyan, T. Bose, C. Fantasia, P. Lawson, C. Richardson, J. Rohlf, J. St. John, L. Sulak

Brown University, Providence, USA

University of California, Davis, Davis, USA

University of California, Los Angeles, USA

University of California, Riverside, Riverside, USA

University of California, San Diego, La Jolla, USA
University of California, Santa Barbara, Santa Barbara, USA

California Institute of Technology, Pasadena, USA

Carnegie Mellon University, Pittsburgh, USA
V. Azzolini, A. Calamba, B. Carlson, T. Ferguson, Y. Iiyama, M. Paulini, J. Russ, H. Vogel, I. Vorobiev

University of Colorado at Boulder, Boulder, USA

Cornell University, Ithaca, USA

Fairfield University, Fairfield, USA
D. Winn

Fermi National Accelerator Laboratory, Batavia, USA

University of Florida, Gainesville, USA

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

Florida State University, Tallahassee, USA

Florida Institute of Technology, Melbourne, USA
M.M. Baarmand, M. Hohlmann, H. Kalakhety, F. Yumiceva

University of Illinois at Chicago (UIC), Chicago, USA
M.R. Adams, L. Apanasevich, D. Berry, R.R. Betts, I. Bucinskaite, R. Cavanaugh, O. Evdokimov,
The University of Iowa, Iowa City, USA

Johns Hopkins University, Baltimore, USA

The University of Kansas, Lawrence, USA

Kansas State University, Manhattan, USA
I. Chakaberia, A. Ivanov, K. Kaadze, S. Khalil, M. Makouski, Y. Maravin, L.K. Saini, N. Skhirtladze, I. Svintradze

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

University of Maryland, College Park, USA

Massachusetts Institute of Technology, Cambridge, USA

University of Minnesota, Minneapolis, USA

University of Mississippi, Oxford, USA
J.G. Acosta, S. Oliveros

University of Nebraska-Lincoln, Lincoln, USA

State University of New York at Buffalo, Buffalo, USA
J. Dolen, A. Godshalk, I. Iashvili, A. Kharchilava, A. Kumar, S. Rappoccio

Northeastern University, Boston, USA

Northwestern University, Evanston, USA
University of Notre Dame, Notre Dame, USA

The Ohio State University, Columbus, USA

Princeton University, Princeton, USA

University of Puerto Rico, Mayaguez, USA
E. Brownson, S. Malik, H. Mendez, J.E. Ramirez Vargas

Purdue University, West Lafayette, USA

Purdue University Calumet, Hammond, USA
N. Parashar, J. Stupak

Rice University, Houston, USA
A. Adair, B. Akgun, K.M. Ecklund, F.J.M. Geurts, W. Li, B. Michlin, B.P. Padley, R. Redjimi, J. Roberts, J. Zabel

University of Rochester, Rochester, USA

The Rockefeller University, New York, USA
R. Ciesielski, L. Demortier, K. Goulianos, C. Mesropian

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

University of Tennessee, Knoxville, USA
K. Rose, S. Spanier, A. York

Texas A&M University, College Station, USA

Texas Tech University, Lubbock, USA
N. Akchurin, C. Cowden, J. Damgov, C. Dragoiu, P.R. Dudero, J. Faulkner, K. Kovitanggool, S. Kunori, S.W. Lee, T. Libeiro, I. Volobouev
Vanderbilt University, Nashville, USA

University of Virginia, Charlottesville, USA

Wayne State University, Detroit, USA
C. Clarke, R. Harr, P.E. Karchin, C. Kottachchi Kankanamge Don, P. Lamichhane, J. Sturdy

University of Wisconsin, Madison, USA

†: Deceased
1: Also at Vienna University of Technology, Vienna, Austria
2: Also at CERN, European Organization for Nuclear Research, Geneva, Switzerland
3: Also at Institut Pluridisciplinaire Hubert Curien, Université de Strasbourg, Université de Haute Alsace Mulhouse, CNRS/IN2P3, Strasbourg, France
4: Also at National Institute of Chemical Physics and Biophysics, Tallinn, Estonia
5: Also at Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, Moscow, Russia
6: Also at Universidade Estadual de Campinas, Campinas, Brazil
7: Also at Laboratoire Leprince-Ringuet, Ecole Polytechnique, IN2P3-CNRS, Palaiseau, France
8: Also at Université Libre de Bruxelles, Bruxelles, Belgium
9: Also at Joint Institute for Nuclear Research, Dubna, Russia
10: Also at Suez University, Suez, Egypt
11: Also at Cairo University, Cairo, Egypt
12: Also at Fayoum University, El-Fayoum, Egypt
13: Also at British University in Egypt, Cairo, Egypt
14: Now at Ain Shams University, Cairo, Egypt
15: Also at Université de Haute Alsace, Mulhouse, France
16: Also at Brandenburg University of Technology, Cottbus, Germany
17: Also at Institute of Nuclear Research ATOMKI, Debrecen, Hungary
18: Also at Eötvös Loránd University, Budapest, Hungary
19: Also at University of Debrecen, Debrecen, Hungary
20: Also at University of Visva-Bharati, Santiniketan, India
21: Now at King Abdulaziz University, Jeddah, Saudi Arabia
22: Also at University of Ruhuna, Matara, Sri Lanka
23: Also at Isfahan University of Technology, Isfahan, Iran
24: Also at University of Tehran, Department of Engineering Science, Tehran, Iran
25: Also at Plasma Physics Research Center, Science and Research Branch, Islamic Azad University, Tehran, Iran
26: Also at Università degli Studi di Siena, Siena, Italy
27: Also at Centre National de la Recherche Scientifique (CNRS) - IN2P3, Paris, France
28: Also at Purdue University, West Lafayette, USA
29: Also at International Islamic University of Malaysia, Kuala Lumpur, Malaysia
30: Also at Institute for Nuclear Research, Moscow, Russia
31: Also at St. Petersburg State Polytechnical University, St. Petersburg, Russia
32: Also at National Research Nuclear University "Moscow Engineering Physics Institute"; (MEPhI), Moscow, Russia
33: Also at INFN Sezione di Padova; Università di Padova; Università di Trento (Trento), Padova, Italy
34: Also at Faculty of Physics, University of Belgrade, Belgrade, Serbia
35: Also at Facoltà Ingegneria, Università di Roma, Roma, Italy
36: Also at Scuola Normale e Sezione dell’INFN, Pisa, Italy
37: Also at University of Athens, Athens, Greece
38: Also at Paul Scherrer Institut, Villigen, Switzerland
39: Also at Institute for Theoretical and Experimental Physics, Moscow, Russia
40: Also at Albert Einstein Center for Fundamental Physics, Bern, Switzerland
41: Also at Gaziosmanpasa University, Tokat, Turkey
42: Also at Adiyaman University, Adiyaman, Turkey
43: Also at Mersin University, Mersin, Turkey
44: Also at Cag University, Mersin, Turkey
45: Also at Piri Reis University, Istanbul, Turkey
46: Also at Anadolu University, Eskisehir, Turkey
47: Also at Ozyegin University, Istanbul, Turkey
48: Also at Izmir Institute of Technology, Izmir, Turkey
49: Also at Necmettin Erbakan University, Konya, Turkey
50: Also at Mimar Sinan University, Istanbul, Istanbul, Turkey
51: Also at Marmara University, Istanbul, Turkey
52: Also at Kafkas University, Kars, Turkey
53: Also at Yildiz Technical University, Istanbul, Turkey
54: Also at Rutherford Appleton Laboratory, Didcot, United Kingdom
55: Also at School of Physics and Astronomy, University of Southampton, Southampton, United Kingdom
56: Also at University of Belgrade, Faculty of Physics and Vinca Institute of Nuclear Sciences, Belgrade, Serbia
57: Also at Argonne National Laboratory, Argonne, USA
58: Also at Erzincan University, Erzincan, Turkey
59: Also at Texas A&M University at Qatar, Doha, Qatar
60: Also at Kyungpook National University, Daegu, Korea