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Evidence for similar collectivity of high transverse momentum particles in pPb and PbPb collisions

The CMS Collaboration*

Abstract

Charged hadron elliptic anisotropies (v_2) are presented over a wide transverse momentum (p_T) range for proton-lead (pPb) and lead-lead (PbPb) collisions at nucleon-nucleon center-of-mass energies of 8.16 and 5.02 TeV, respectively. The data were recorded by the CMS experiment and correspond to integrated luminosities of 186 nb^{-1} and 0.607 nb^{-1} for the pPb and PbPb systems, respectively. A four-particle cumulant analysis is performed using subevents separated in pseudorapidity to effectively suppress non-collective effects. At high p_T ($p_T > 8 \text{ GeV}$), significant positive v_2 values are observed that are similar between pPb and PbPb collisions at comparable charged particle multiplicities. This observation suggests a common origin for the multi-particle collectivity for high- p_T particles in the two systems.

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Strong azimuthal correlations among particles emitted over a wide range of polar angles in relativistic nucleus-nucleus (AA) collisions at the BNL RHIC [1–3] and CERN LHC [4–10] colliders indicate the formation of a quark-gluon plasma (QGP) that exhibits nearly ideal hydrodynamic behavior [11–13]. The second and third Fourier components of the particle azimuthal distribution, known as elliptic (v_2) and triangular (v_3) flow, respectively, reflect the response of the medium to the initial collision geometry, including its fluctuations, providing insights into the fundamental transport properties of the QGP medium [14, 15]. Similar correlations have been observed in high-multiplicity proton-proton (pp) [16–19] and proton-lead (pPb) [20–25] collisions at the LHC, as well as in deuteron-gold [26, 27] and helium-3-gold [28] collisions at RHIC. The properties of the observed long-range correlations in these systems have been found to be consistent with hydrodynamic descriptions of a QGP droplet [29, 30].

For a transverse momentum (p_T) greater than ~ 3 GeV, partons are not expected to be thermalized in the hot and dense medium created in heavy ion collisions, and a hydrodynamic picture is not applicable [13]. The observed azimuthal anisotropy of such particles in noncentral AA collisions is primarily attributed to the energy loss of high- p_T partons as they traverse the QGP medium, whose geometry reflects the lenticular shape of the collision overlap region [31, 32]. The extent of this energy loss depends on the path length, which, in turn, depends on the direction of the parton relative to the orientation of the medium [33–36]. Therefore, the study of azimuthal anisotropy in small systems, where the overlap geometry is not expected to have a dominant role, is of considerable interest [22, 37].

One of the challenges in analyzing azimuthal correlations, particularly in small colliding systems, is separating genuine collective effects from those arising from particles that are correlated as a result of other unrelated processes (such as jets and resonance decays). These so-called “nonflow” correlations that can be difficult to separate from the global flow anisotropies. The azimuthal correlations of high- p_T particles in small systems have been previously studied using two-particle correlations [38, 39]. In those analyses, corrections for nonflow correlations are made using the relative multiplicity dependence of flow and nonflow correlations. The nonflow correction is then based on assumptions about the evolution of nonflow from low to high multiplicity collisions, and about the dominance of nonflow in low multiplicity collisions.

This Letter presents a measurement of elliptic anisotropies for high- p_T particles in pPb collisions at a center-of-mass energy per nucleon pair $\sqrt{s_{NN}} = 8.16$ TeV, compared to those in lead-lead (PbPb) collisions at $\sqrt{s_{NN}} = 5.02$ TeV. The pPb and PbPb data were obtained using the CMS detector at the LHC in 2016 and 2018, corresponding to an integrated luminosities of 186 nb^{-1} and 0.607 nb^{-1} , respectively [40, 41]. The Q-cumulant multiparticle correlation technique is used based on “subevents” dividing particles into multiple pseudorapidity regions [42–44]. By increasing the number of subevents beyond two, this approach helps in suppressing nonflow effects in a data-driven way. The results are presented as a function of p_T based on 2-, 3-, and 4-subevent analyses. Tabulated results for this analysis can be accessed in the HEPdata record [45].

The central feature of the CMS apparatus [46, 47] is a superconducting solenoid with an internal diameter of 6 m, providing a magnetic field of 3.8 T. Within the solenoid volume are a silicon pixel and strip tracker [48, 49], a lead tungstate crystal electromagnetic calorimeter [50], and a brass and scintillator hadron calorimeter, each composed of a barrel and two endcap sections. For the run period relevant to this analysis, the silicon pixel and strip tracker provided coverage for $|\eta| < 2.4$. The hadron forward (HF) calorimeter [51] extends the pseudorapidity coverage provided by the barrel and endcap detectors, with the two halves, one on each end, providing coverage in the range $2.9 < |\eta| < 5.2$. The HF calorimeters are azimuthally subdivided into

20° modular wedges, which are further segmented to form 0.175×0.175 ($\Delta\eta \times \Delta\phi$) towers. The CMS apparatus can be used to detect and identify electrons, muons, photons, and hadrons [48, 52, 53]. A more detailed description of the CMS detector can be found in Ref. [46].

For pPb collisions, the beam energies for the proton and lead nuclei were 6.5 TeV and 2.56 TeV per nucleon, respectively, resulting in a center-of-mass energy of $\sqrt{s_{\text{NN}}} = 8.16$ TeV. Because of the asymmetric beam energies, the nucleon-nucleon center-of-mass in the pPb collisions was not at rest with respect to the laboratory frame but was moving in the direction of the proton beam with a rapidity shift of 0.465. Data were taken with the directions of the beams reversed for assessing possible systematic effects. The results in each direction were consistent with each other and were merged; results are reported using the convention that the positive pseudorapidity is defined by the proton-going direction.

To select high-multiplicity pPb collisions, a dedicated high-multiplicity trigger was implemented using the CMS level-1 (L1) [54] and high-level trigger (HLT) systems [55]. The HLT uses fast versions of the offline software. To trigger minimum bias (MB) pPb events, at least one of the two HF calorimeters was required to register an energy deposit above a threshold of 1 GeV. Additionally, at least one track with $p_{\text{T}} > 0.4$ GeV in the pixel tracker at HLT level was required.

In this analysis, pPb events were required to have a primary vertex within 15 cm of the nominal interaction point along the beam axis and 0.2 cm in the transverse direction. At least two reconstructed tracks must be associated with the primary vertex. Results are reported in ranges of $N_{\text{trk}}^{\text{offline}}$, corresponding to the measured track multiplicity with $p_{\text{T}} > 0.4$ GeV and $|\eta| < 2.4$, before correcting for the tracking efficiency. Table 1 of Back matter A.1 reports the mean multiplicity ($\langle N_{\text{trk}}^{\text{offline}} \rangle$) and multiplicity after correcting for tracking inefficiencies ($\langle N_{\text{trk}}^{\text{corrected}} \rangle$), for various $N_{\text{trk}}^{\text{offline}}$ ranges. A trigger efficiency plateau above 95% is observed in the $185 \leq N_{\text{trk}}^{\text{offline}} < 250$ range.

The PbPb MB events are selected based on signals surpassing readout threshold of 3 GeV on both sides of the HF calorimeters. The PbPb events are also required to have a primary vertex within 15 cm of the nominal interaction point along the beam axis and 0.2 cm in the transverse direction. Additionally, each HF detector must have at least two towers with an energy deposit of 4 GeV or more. The trigger, event reconstruction, and track selections considered in this analysis are the same as in previous CMS correlation analyses [19, 20, 22]. To perform correlation measurements, only tracks that originate from the primary vertex and meet the high-purity criteria discussed in Ref. [48] are used. The trigger and event selection efficiencies are found to be about 98% and above 95% for pPb and PbPb, respectively. Furthermore, for both cases, the impact parameter significance, i.e., the parameter value divided by its uncertainty, of the tracks with respect to the primary vertex in the longitudinal and transverse directions must be less than 3, and the relative p_{T} uncertainty must be less than 10% for the p_{T} range used.

To ensure high tracking efficiency and minimal background contamination, only tracks with $|\eta| < 2.4$ and with $p_{\text{T}} > 0.3$ GeV for pPb collisions and $p_{\text{T}} > 0.5$ GeV for PbPb collisions are used. The selected tracks are corrected for tracking efficiency and detector acceptance effects using simulated Monte Carlo samples generated by HIJING v1.35 [56] and HYDJET 1.9 [57] for pPb and PbPb collisions, respectively. The response of the CMS detector to these simulated events is based on GEANT4 [58]. In the measurement of correlations in pPb collisions, multiple interactions (pileup) in the recorded event are a source of background. The average number of collisions per bunch crossing in the pPb data varied between 0.1 and 0.25. The procedure used for identifying and rejecting pileup is similar to that described in Ref. [20]. The pileup is negligible in PbPb collisions.

The Q -cumulant method, as encoded in the MCORRELATIONS package [59], is used to determine the v_2 value. This method has been used to measure four-, six-, and eight-particle correlations in previous CMS publications [60, 61], with the multiparticle correlations being inherently less sensitive to few-particle correlations, such as those arising from jet fragmentation and back-to-back dijet correlations. In this method, the two- and four-particle correlators, $\langle\langle 2 \rangle\rangle$ and $\langle\langle 4 \rangle\rangle$, are defined as

$$\langle\langle 2 \rangle\rangle = \langle\langle e^{in(\phi_1 - \phi_2)} \rangle\rangle \quad \text{and} \quad \langle\langle 4 \rangle\rangle = \langle\langle e^{in(\phi_1 + \phi_2 - \phi_3 - \phi_4)} \rangle\rangle. \quad (1)$$

Here, ϕ_j ($j = 1, \dots, 4$) represents the azimuthal angles of four distinct particles in an event, and the notation $\langle\langle \dots \rangle\rangle$ signifies that the average is calculated first over all particles in an event, then across all events. The integer n denotes the order of Fourier harmonic, with $n = 2$ corresponding to elliptic flow [14]. The four-particle cumulant $c_n\{4\}$ is given as

$$c_n\{4\} = \langle\langle 4 \rangle\rangle - 2\langle\langle 2 \rangle\rangle^2. \quad (2)$$

The multiparticle cumulant method correlates each particle of interest (POI) with reference flow particles (RFPs). In this analysis, the RFPs for the cumulant method are charged hadrons within $|\eta| < 2.4$ and with 0.3 (0.5) $< p_T < 3.0$ GeV for pPb (PbPb) collisions. In order to reduce the contribution of minijets, an upper limit of $p_T < 3.0$ GeV is used for the RFPs [62]. The p_T ranges used for the POIs are given in Table 2 of Back matter A.2.

In the standard Q -cumulant analysis, the POI and RFP ranges overlap in η , potentially introducing nonflow contributions from short-range correlations. To suppress these effects, a subevent method [43] is used, where particles are selected from different η ranges, ensuring a pseudorapidity gap (difference in pseudorapidity values, $\Delta\eta$) between correlated particles. Statistical uncertainties are estimated using a bootstrap method [63]. Figure 1 illustrates how

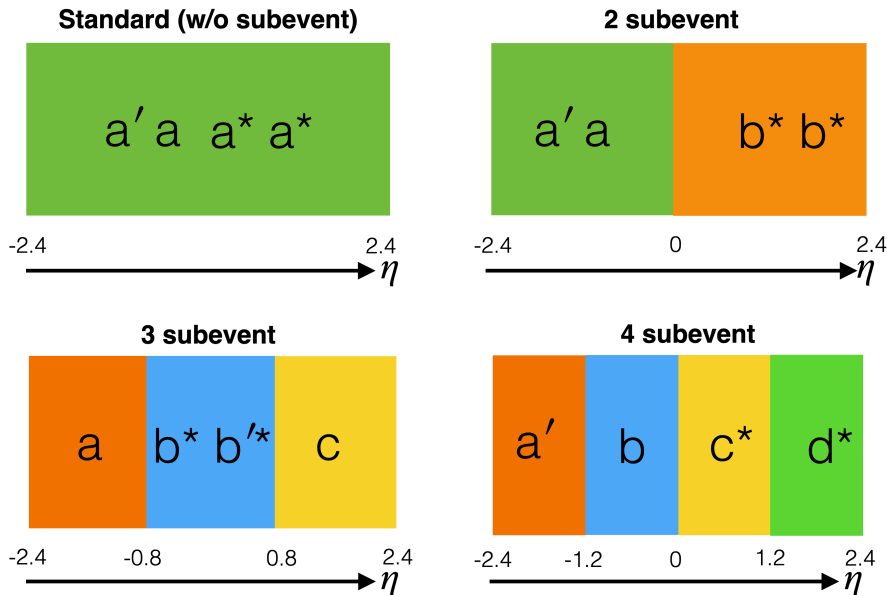


Figure 1: Different subevents in the CMS tracker acceptance used to correlate four particles. The denoted pseudorapidity ranges are used for the analysis. The letters denote the particles used in four-particle correlator. The asterisk (*) indicates particles with a negative azimuthal angle, and the prime symbol denotes the POI.

particle tracks are selected to construct four-particle cumulants. The upper left panel shows the case where all four particles are chosen from the same η range, leading to significant nonflow contributions from single jets. The upper right panel depicts the two-subevent method ($-2.4 < \eta < 0$ and $0 < \eta < 2.4$), which reduces nonflow effects by separating particles a and b into distinct η ranges. The three-subevent method (lower left) further suppresses dijet contributions by dividing into three η ranges ($-2.4 < \eta < -0.8$, $-0.8 < \eta < 0.8$ and $0.8 < \eta < 2.4$), while the four-subevent method (lower right) minimizes nonflow effects by assigning each particle to a distinct η range ($-2.4 < \eta < -1.2$, $-1.2 < \eta < 0$, $0 < \eta < 1.2$ and $1.2 < \eta < 2.4$).

The p_T dependence of the flow coefficients can be studied using p_T -differential cumulants, $d_n\{4\}$, given by

$$d_n\{4\} = \langle\langle 4' \rangle\rangle - 2\langle\langle 2' \rangle\rangle\langle\langle 2 \rangle\rangle, \quad (3)$$

where $\langle\langle 4' \rangle\rangle$ is a four-particle correlator with three RFPs and one POI and $\langle\langle 2' \rangle\rangle$ is a two-particle correlator with one RFP and one POI. In the following, we provide the specific $d_n\{4\}$ formulas for the two, three, and four subevent analyses. We use a notation where a , b , c , or d refers to the particle chosen in a specific subevent and the symbol “|” indicates a separation between subevents. In Eq.(4), e.g., the notation $a'a | b^*b^*$ in the four-particle correlator means the first two particles are required to be in the first subevent ($a'a$) while the last two are required to be in the second subevent (b^*b^*), where a' is the POI. Similarly, for the two-particle correlator, one particle in each subevent is required ($a' | b$).

The two-subevent differential cumulant can be expressed in terms of the correlators, with

$$d_n\{4\}_{2\text{sub}} = \langle\langle 4 \rangle^{a'a|b^*b^*} \rangle - 2\langle\langle 2 \rangle^{a'|b^*} \rangle\langle\langle 2 \rangle^{a|b^*} \rangle. \quad (4)$$

For the three subevent case, the correlator expansion depends on the POI pseudorapidity range, with

$$d_n\{4\}_{3\text{sub}} = \langle\langle 4 \rangle^{a|b^*b^*|c'} \rangle - 2\langle\langle 2 \rangle^{a|b^*} \rangle\langle\langle 2 \rangle^{b^*|c'} \rangle, \quad (5)$$

when the POI is in the range $0.8 < |\eta| < 2.4$ and

$$d_n\{4\}_{3\text{sub}} = \langle\langle 4 \rangle^{a|b^*b^*|c} \rangle - \langle\langle 2 \rangle^{a|b^*} \rangle\langle\langle 2 \rangle^{b^*|c} \rangle - \langle\langle 2 \rangle^{a|b^*} \rangle\langle\langle 2 \rangle^{b^*|c} \rangle, \quad (6)$$

when $|\eta| < 0.8$. In the latter case, we have two choices for the POI and, accordingly, two combinations for the product of two-particle correlators ($\langle\langle 2 \rangle^{a|b^*} \rangle\langle\langle 2 \rangle^{b^*|c} \rangle$ and $\langle\langle 2 \rangle^{a|b^*} \rangle\langle\langle 2 \rangle^{b^*|c} \rangle$). Similarly, in the case of four subevents, instead of taking twice the product of two-particle correlators, we incorporate two different choices ($\langle\langle 2 \rangle^{a'|c^*} \rangle\langle\langle 2 \rangle^{b|d^*} \rangle$ and $\langle\langle 2 \rangle^{a'|d^*} \rangle\langle\langle 2 \rangle^{b|c^*} \rangle$), with

$$d_n\{4\}_{4\text{sub}} = \langle\langle 4 \rangle^{a'|b|c^*|d^*} \rangle - \langle\langle 2 \rangle^{a'|c^*} \rangle\langle\langle 2 \rangle^{b|d^*} \rangle - \langle\langle 2 \rangle^{a'|d^*} \rangle\langle\langle 2 \rangle^{b|c^*} \rangle \quad (7)$$

when the POI is in the range $-2.4 < \eta < -1.2$ and similar equations for when the POI is in different η ranges. The differential $v_n\{4\}$ value can then be expressed as

$$v_n\{4\} = -d_n\{4\}/(-c_n\{4\})^{3/4}, \quad (8)$$

where $c_n\{4\}$ is the integral cumulant for RFPs [42]. The effectiveness of four-subevent method in nonflow removal is confirmed by a study done using generator level HIJING events (Figure 4 of Back matterA.3), where collective effects are absent and we expect zero values after nonflow removal.

The systematic uncertainties are evaluated as functions of p_T using alternative procedures for extracting the cumulants, following the Barlow procedure [64]. Systematic uncertainties due to

tracking inefficiency and track misreconstruction rate are studied by varying the track quality requirements. The selection thresholds on the significances of the transverse and longitudinal track impact parameters are varied from 2 to 5. In addition, the upper limit on the relative p_T uncertainty is varied from 5 to 10% (15%) for pPb (PbPb) collisions. The resulting systematic uncertainty varies up to 5% depending on multiplicity, p_T , and collision system. The sensitivity of the results to the primary vertex position along the beam axis (z_{vtx}) is determined by comparing events with different z_{vtx} locations from -15 cm to $+15$ cm. This systematic uncertainty is estimated to be $< 0.2\%$. The impact of pileup in pPb collisions is studied by varying the pileup selection of events using the distance among reconstructed vertices and their associated number of tracks. The corresponding systematic uncertainty is also found to be $< 0.1\%$. Systematic effects from event selections in PbPb collisions are found to be negligible. Systematic uncertainty from the different sources are added in quadrature to obtain the total systematic uncertainty shown as boxes in the figures.

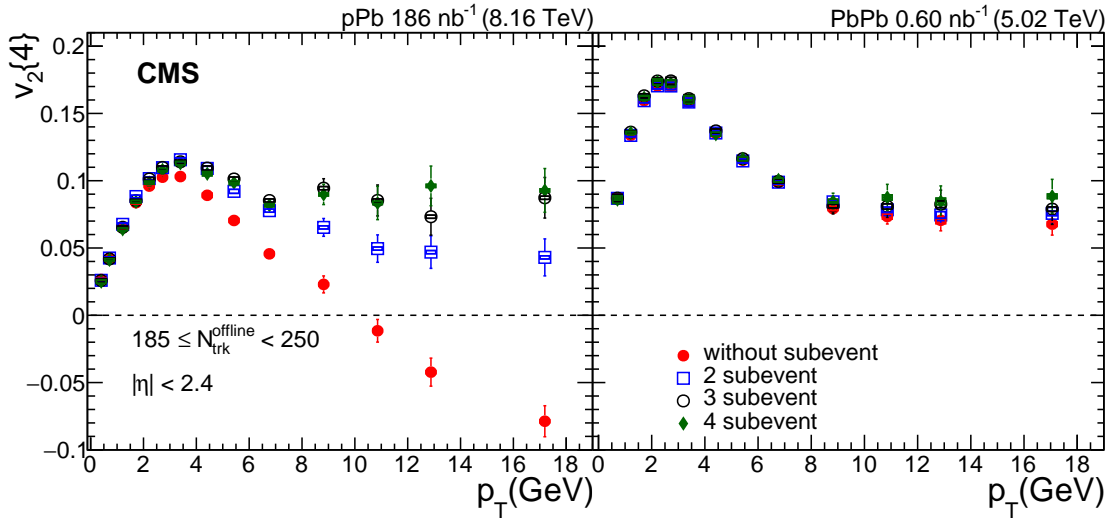


Figure 2: The $v_2\{4\}$ value vs. p_T with $185 \leq N_{\text{trk}}^{\text{offline}} < 250$ for pPb (left) and PbPb (right) collisions. The red, blue, black and green markers are for the cases where tracks are not divided into subevents, and divided into two, three and four subevents, respectively. The solid lines and boxes represent the statistical and systematic uncertainties, respectively.

The $v_2\{4\}$ results for the different subevent methods are shown for the $185 \leq N_{\text{trk}}^{\text{offline}} < 250$ range as function of p_T in Fig. 2. The left panel shows the results for pPb collisions and the right panel for PbPb collisions. The $v_2\{4\}$ is calculated for each p_T range of POI and the marker is placed at the mean p_T value. The standard $v_2\{4\}$ result (without subevents) becomes negative above $p_T \sim 10$ GeV for pPb collisions, which is not the case for the PbPb results. This is likely a consequence of selecting rare high-multiplicity pPb events with an increased nonflow contribution from jets, which results in a negative contribution to $v_2\{4\}$, when compared with PbPb events. Using the subevent method, this negative trend is heavily suppressed and positive values of $v_2\{4\}$ (negative value of $d_2\{4\}$) result up to $p_T \sim 17$ GeV, the upper limit of the current investigation. The three- and four-subevent results are in agreement with each other, suggesting a nearly complete removal of short range correlations.

The left plot in Fig. 3 compares the four-subevent $v_2\{4\}$ values as a function of p_T for pPb and PbPb collisions. We observe similar magnitudes of $v_2\{4\}$ in both collision systems at higher p_T , with nearly constant values above $p_T \sim 6$ GeV. In the right plot of Fig. 3, we show the four-subevent $v_2\{4\}$ for particles with $p_T > 6$ GeV as a function of $\langle N_{\text{trk}}^{\text{offline}} \rangle$ for pPb and PbPb

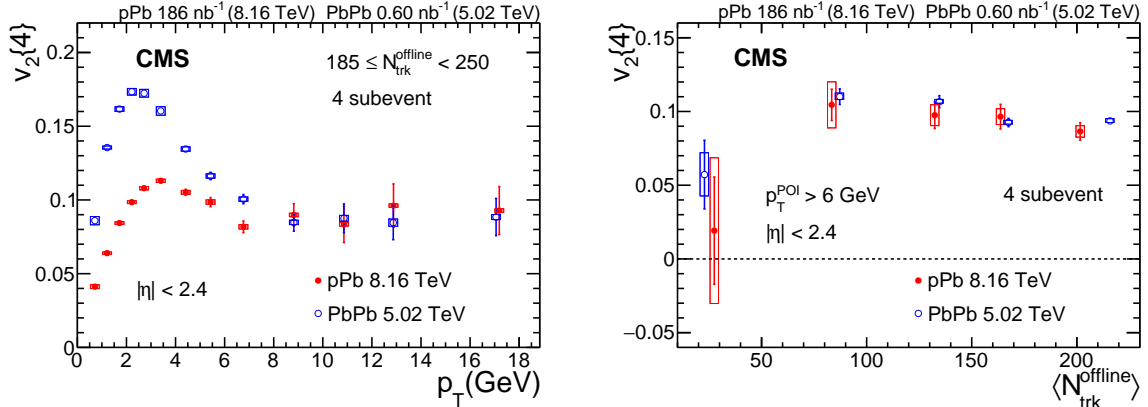


Figure 3: left: Comparison of pPb and PbPb four-subevent $v_2\{4\}$ values with $185 \leq N_{\text{trk}}^{\text{offline}} < 250$ vs. p_T . right: Comparison of pPb and PbPb four-subevent $v_2\{4\}$ values with $p_T^{\text{POI}} > 6$ GeV vs. $\langle N_{\text{trk}}^{\text{offline}} \rangle$. The solid lines and boxes represent the statistical and systematic uncertainties, respectively.

collisions. Figure 5 of Back matter A.4 shows the $v_2\{4\}$ results in terms of efficiency-corrected mean multiplicity ($\langle N_{\text{trk}}^{\text{corrected}} \rangle$). The $v_2\{4\}$ values and their $\langle N_{\text{trk}}^{\text{offline}} \rangle$ dependence for the two systems are again very similar.

Our results are unexpected, given the distinct nature and geometry of the medium formed in pPb as compared to PbPb collisions. The baryon/meson enhancement found at intermediate p_T disappears for $p_T > 6$ GeV in PbPb collisions [65]. This is consistent with the higher- p_T region studied here being well within the hard scattering regime where any azimuthal asymmetry is expected to arise through an energy loss mechanism, as opposed to hydrodynamic flow. High- p_T hadrons are significantly suppressed in PbPb collisions relative to pp collisions, indicating a path length dependent energy loss [66]. No such energy loss is apparent in pPb collisions, although it is important to note that nuclear modification measurements in small systems are complicated by uncertainties in the calculated number of binary nucleon-nucleon collisions [67, 68]. The larger $v_2\{4\}$ values observed for low multiplicity PbPb collisions below $p_T \sim 3$ GeV suggest a more lenticular collision geometry when compared to high-multiplicity pPb collisions. This, together with the energy loss argument, leads to an expectation of larger $v_2\{4\}$ values at high p_T for PbPb events. However, our observed high- p_T $v_2\{4\}$ values are similar for PbPb and pPb collisions. One potential origin of the $v_2\{4\}$ at high p_T could be the initial-state intrinsic transverse momentum asymmetries of unpolarized and polarized partons within an unpolarized nucleon, as explored in Ref. [69]. Further investigations, both in theory and in experiment are needed.

In summary, four-particle elliptic anisotropies ($v_2\{4\}$) are measured over a large range of transverse momentum (p_T) using multiparticle cumulant analyses based on the division of particle tracks into two, three, or four separate pseudorapidity ranges (“subevents”). Dividing the particles into separate subevents is shown to strongly suppress effects resulting from jet fragmentation. Significant and positive $v_2\{4\}$ values that extend to high p_T are found for high-multiplicity pPb events. Results are shown for proton-lead (pPb) and lead-lead (PbPb) collisions at nucleon-nucleon center-of-mass energies of 8.16 TeV and 5.02 TeV, respectively. Similar magnitudes of $v_2\{4\}$ values at $p_T > 8$ GeV are observed in pPb and PbPb collisions at comparable multiplicities. This observation suggests a common origin for the multi-particle collectivity for high- p_T particles in the two systems.

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A Back matter

A.1 Mapping between $N_{\text{trk}}^{\text{offline}}$ and $N_{\text{trk}}^{\text{corrected}}$ in pPb and PbPb collisions

Table 1 gives Average multiplicity ($\langle N_{\text{trk}}^{\text{offline}} \rangle$) and multiplicity corrected for tracking efficiency ($\langle N_{\text{trk}}^{\text{corrected}} \rangle$) values in various $N_{\text{trk}}^{\text{offline}}$ ranges for pPb and PbPb collisions. Uncertainties for the tracking efficiency corrected $N_{\text{trk}}^{\text{corrected}}$ are included.

Table 1: $\langle N_{\text{trk}}^{\text{offline}} \rangle$ and $\langle N_{\text{trk}}^{\text{corrected}} \rangle$ values in various $N_{\text{trk}}^{\text{offline}}$ ranges.

$N_{\text{trk}}^{\text{offline}}$ range	pPb		PbPb	
	$\langle N_{\text{trk}}^{\text{offline}} \rangle$	$\langle N_{\text{trk}}^{\text{corrected}} \rangle$	$\langle N_{\text{trk}}^{\text{offline}} \rangle$	$\langle N_{\text{trk}}^{\text{corrected}} \rangle$
(0, 60)	27	33±1	23	39±2
[60, 120)	83	101±4	87	152±6
[120, 150)	132	160±6	135	233±10
[150, 185)	164	198±7	168	287±12
[185, 250)	202	245±10	216	368±16

A.2 Mean p_T for different p_T bins in pPb and PbPb for $185 \leq N_{\text{trk}}^{\text{offline}} < 250$

Table 2 gives the mean p_T ($\langle p_T \rangle$) values for various p_T ranges used for the POIs in pPb and PbPb collisions. The difference is negligible except the last bin.

Table 2: $\langle p_T \rangle$ for p_T bins of POI in pPb and PbPb for $185 \leq N_{\text{trk}}^{\text{offline}} < 250$. All p_T values are given in units of GeV.

p_T range	pPb	PbPb
	$\langle p_T \rangle$	$\langle p_T \rangle$
0.3-0.5	0.40	
0.5-1.0	0.71	0.71
1.0-1.5	1.21	1.21
1.5-2.0	1.71	1.71
2.0-2.5	2.22	2.22
2.5-3.0	2.72	2.72
3.0-4.0	3.40	3.40
4.0-5.0	4.41	4.41
5.0-6.0	5.43	5.42
6.0-8.0	6.77	6.76
8.0-10.0	8.81	8.81
10.0-12.0	10.86	10.85
12.0-14.0	12.88	12.87
>14.0	17.19	17.06

A.3 Comparison of 4-subevent $d_2\{4\}$ in HIJING with data

Figure 4 compares four-subevent $d_2\{4\}$ results based on HIJING simulations with the experimental results. The HIJING results for $60 \leq N_{\text{trk}}^{\text{gen}} < 120$ are consistent with zero at high p_T ,

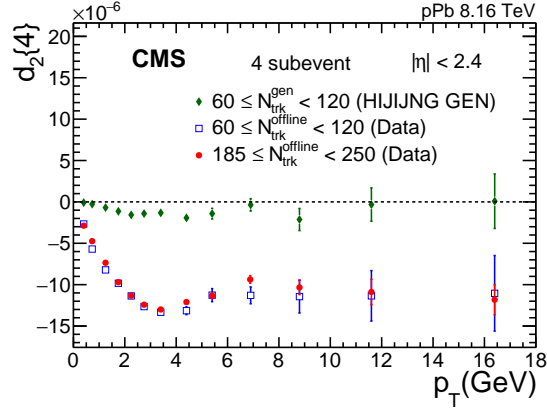


Figure 4: The four-subevent $d_2\{4\}$ values in generator level HIJING for $60 \leq N_{\text{trk}}^{\text{gen}} < 120$ shown by the closed green diamonds are compared to the experimental pPb results with $60 \leq N_{\text{trk}}^{\text{offline}} < 120$ (open blue squares) and $185 \leq N_{\text{trk}}^{\text{offline}} < 250$ (closed red circles).

suggesting complete removal of nonflow. Here $N_{\text{trk}}^{\text{gen}}$ is the measured track multiplicity with $p_T > 0.4 \text{ GeV}$ and $|\eta| < 2.4$ in generator level HIJING. For comparison, the experimental pPb four-subevent $d_2\{4\}$ values are shown for $60 \leq N_{\text{trk}}^{\text{gen}} < 120$ and $185 \leq N_{\text{trk}}^{\text{offline}} < 250$. The experimental results are found to have significantly negative values.

A.4 Plot shown in Fig. 3 (right), but with $\langle N_{\text{trk}}^{\text{corrected}} \rangle$ along the x-axis.

Figure 5 shows the four-subevent $v_2\{4\}$ results in terms of efficiency-corrected mean multiplicity ($\langle N_{\text{trk}}^{\text{corrected}} \rangle$) in pPb and PbPb collisions. The POI is taken with $p_T > 6 \text{ GeV}$. The high- p_T $v_2\{4\}$ values and their $\langle N_{\text{trk}}^{\text{offline}} \rangle$ dependence for the two systems are very similar.

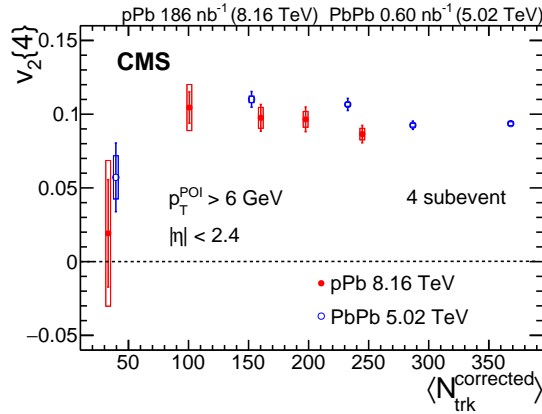




















Figure 5: Comparison of $v_2\{4\}$ values as a function of $\langle N_{\text{trk}}^{\text{corrected}} \rangle$ between pPb and PbPb collisions. The solid lines and boxes indicate the statistical and systematic uncertainties, respectively.

B The CMS Collaboration

Yerevan Physics Institute, Yerevan, Armenia

V. Chekhovsky, A. Hayrapetyan, V. Makarenko , A. Tumasyan¹ 














Institut für Hochenergiephysik, Vienna, Austria

W. Adam , J.W. Andrejkovic, L. Benato , T. Bergauer , S. Chatterjee , K. Damanakis , M. Dragicevic , P.S. Hussain , M. Jeitler² , N. Krammer , A. Li , D. Liko , I. Mikulec , J. Schieck² , R. Schöfbeck² , D. Schwarz , M. Sonawane , W. Waltenberger , C.-E. Wulz² 















Universiteit Antwerpen, Antwerpen, Belgium

T. Janssen , T. Van Laer, P. Van Mechelen 












Vrije Universiteit Brussel, Brussel, Belgium

N. Breugelmans, J. D'Hondt , S. Dansana , A. De Moor , M. Delcourt , F. Heyen, Y. Hong , S. Lowette , I. Makarenko , D. Müller , S. Tavernier , M. Tytgat³ , G.P. Van Onsem , S. Van Putte , D. Vannerom 
















Université Libre de Bruxelles, Bruxelles, Belgium

B. Bilin , B. Clerbaux , A.K. Das, I. De Bruyn , G. De Lentdecker , H. Evard , L. Favart , P. Gianneios , A. Khalilzadeh, F.A. Khan , K. Lee , A. Malara , M.A. Shahzad, L. Thomas , M. Vanden Bemden , C. Vander Velde , P. Vanlaer 










Ghent University, Ghent, Belgium

M. De Coen , D. Dobur , G. Gokbulut , J. Knolle , L. Lambrecht , D. Marckx , K. Mota Amarilo , K. Skovpen , N. Van Den Bossche , J. van der Linden , L. Wezenbeek 


















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

S. Bein , A. Benecke , A. Bethani , G. Bruno , C. Caputo , J. De Favereau De Jeneret , C. Delaere , I.S. Donertas , A. Giammanco , A.O. Guzel , Sa. Jain , V. Lemaitre, J. Lidrych , P. Mastrapasqua , T.T. Tran , S. Turkcapar 









Centro Brasileiro de Pesquisas Fisicas, Rio de Janeiro, Brazil

G.A. Alves , E. Coelho , G. Correia Silva , C. Hensel , T. Menezes De Oliveira , C. Mora Herrera⁴ , P. Rebello Teles , M. Soeiro, E.J. Tonelli Manganote⁵ , A. Vilela Pereira⁴ 

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

W.L. Aldá Júnior , M. Barroso Ferreira Filho , H. Brandao Malbouisson , W. Carvalho , J. Chinellato⁶, E.M. Da Costa , G.G. Da Silveira⁷ , D. De Jesus Damiao , S. Fonseca De Souza , R. Gomes De Souza, T. Laux Kuhn⁷ , M. Macedo , J. Martins , L. Mundim , H. Nogima , J.P. Pinheiro , A. Santoro , A. Sznajder , M. Thiel 

Universidade Estadual Paulista, Universidade Federal do ABC, São Paulo, Brazil

C.A. Bernardes⁷ , L. Calligaris , T.R. Fernandez Perez Tomei , E.M. Gregores , I. Maietto Silverio , P.G. Mercadante , S.F. Novaes , B. Orzari , Sandra S. Padula 

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

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




University of Sofia, Sofia, Bulgaria

A. Dimitrov , L. Litov , B. Pavlov , P. Petkov , A. Petrov , E. Shumka 

Instituto De Alta Investigación, Universidad de Tarapacá, Casilla 7 D, Arica, Chile

S. Keshri , D. Laroze , S. Thakur 













Beihang University, Beijing, China

T. Cheng , T. Javaid , L. Yuan 













Department of Physics, Tsinghua University, Beijing, China

Z. Hu , Z. Liang, J. Liu

Institute of High Energy Physics, Beijing, China

G.M. Chen⁸ , H.S. Chen⁸ , M. Chen⁸ , F. Iemmi , C.H. Jiang, A. Kapoor⁹ , H. Liao , Z.-A. Liu¹⁰ , R. Sharma¹¹ , J.N. Song¹⁰, J. Tao , C. Wang⁸, J. Wang , Z. Wang⁸, H. Zhang , J. Zhao 

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

A. Agapitos , Y. Ban , A. Carvalho Antunes De Oliveira , S. Deng , B. Guo, C. Jiang , A. Levin , C. Li , Q. Li , Y. Mao, S. Qian, S.J. Qian , X. Qin, X. Sun , D. Wang , H. Yang, Y. Zhao, C. Zhou 

Guangdong Provincial Key Laboratory of Nuclear Science and Guangdong-Hong Kong Joint Laboratory of Quantum Matter, South China Normal University, Guangzhou, China

S. Yang 




Sun Yat-Sen University, Guangzhou, China

Z. You 

University of Science and Technology of China, Hefei, China

K. Jaffel , N. Lu 

Nanjing Normal University, Nanjing, China

G. Bauer¹², B. Li¹³, H. Wang , K. Yi¹⁴ , J. Zhang 

Institute of Modern Physics and Key Laboratory of Nuclear Physics and Ion-beam Application (MOE) - Fudan University, Shanghai, China

Y. Li

Zhejiang University, Hangzhou, Zhejiang, China

Z. Lin , C. Lu , M. Xiao 

Universidad de Los Andes, Bogota, Colombia

C. Avila , D.A. Barbosa Trujillo, A. Cabrera , C. Florez , J. Fraga , J.A. Reyes Vega




Universidad de Antioquia, Medellin, Colombia

J. Jaramillo , C. Rendón , M. Rodriguez , A.A. Ruales Barbosa , J.D. Ruiz Alvarez 

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

D. Giljanovic , N. Godinovic , D. Lelas , A. Sculac 

University of Split, Faculty of Science, Split, Croatia

M. Kovac , A. Petkovic , T. Sculac 




Institute Rudjer Boskovic, Zagreb, Croatia

P. Bargassa , V. Brigljevic , B.K. Chitroda , D. Ferencek , K. Jakovcic, A. Starodumov¹⁵ , T. Susa 

University of Cyprus, Nicosia, Cyprus

A. Attikis , K. Christoforou , A. Hadjiagapiou, C. Leonidou , J. Mousa , C. Nicolaou, L. Paizanos, F. Ptochos , P.A. Razis , H. Rykaczewski, H. Saka , A. Stepennov 


Charles University, Prague, Czech Republic

M. Finger , M. Finger Jr. , A. Kveton 



Escuela Politecnica Nacional, Quito, Ecuador

E. Ayala 

Universidad San Francisco de Quito, Quito, Ecuador

E. Carrera Jarrin 








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

H. Abdalla¹⁶ , Y. Assran^{17,18}, B. El-mahdy 

Center for High Energy Physics (CHEP-FU), Fayoum University, El-Fayoum, Egypt

M. Abdullah Al-Mashad , M.A. Mahmoud 















National Institute of Chemical Physics and Biophysics, Tallinn, Estonia

K. Ehataht , M. Kadastik, T. Lange , C. Nielsen , J. Pata , M. Raidal , L. Tani , C. Veelken 

Department of Physics, University of Helsinki, Helsinki, Finland

H. Kirschenmann , K. Osterberg , M. Voutilainen 



















Helsinki Institute of Physics, Helsinki, Finland

S. Bharthuar , N. Bin Norjoharuddeen , E. Brücken , F. Garcia , P. Inkaew , K.T.S. Kallonen , T. Lampén , K. Lassila-Perini , S. Lehti , T. Lindén , M. Myllymäki , M.m. Rantanen , H. Siikonen , J. Tuominiemi 





























Lappeenranta-Lahti University of Technology, Lappeenranta, Finland

P. Luukka , H. Petrow 


















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

M. Besancon , F. Couderc , M. Dejardin , D. Denegri, J.L. Faure, F. Ferri , S. Ganjour , P. Gras , G. Hamel de Monchenault , M. Kumar , V. Lohezic , J. Malcles , F. Orlandi , L. Portales , A. Rosowsky , M.Ö. Sahin , A. Savoy-Navarro¹⁹ , P. Simkina , M. Titov , M. Tornago 

Laboratoire Leprince-Ringuet, CNRS/IN2P3, Ecole Polytechnique, Institut Polytechnique de Paris, Palaiseau, France

F. Beaudette , G. Boldrini , P. Busson , A. Cappati , C. Charlot , M. Chiusi , T.D. Cuisset , F. Damas , O. Davignon , A. De Wit , I.T. Ehle , B.A. Fontana Santos Alves , S. Ghosh , A. Gilbert , R. Granier de Cassagnac , A. Hakimi , B. Harikrishnan , L. Kalipoliti , G. Liu , M. Nguyen , C. Ochando , R. Salerno , J.B. Sauvan , Y. Sirois , L. Urda Gómez , E. Vernazza , A. Zabi , A. Zghiche 

























Université de Strasbourg, CNRS, IPHC UMR 7178, Strasbourg, France

J.-L. Agram²⁰ , J. Andrea , D. Apparú , D. Bloch , J.-M. Brom , E.C. Chabert , C. Collard , S. Falke , U. Goerlach , R. Haeberle , A.-C. Le Bihan , M. Meena , O. Poncet , G. Saha , M.A. Sessini , P. Van Hove , P. Vaucelle 




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

A. Di Florio 

Institut de Physique des 2 Infinis de Lyon (IP2I), Villeurbanne, France

D. Amram , S. Beauceron , B. Blancon , G. Boudoul , N. Chanon , D. Contardo , P. Depasse , C. Dozen²¹ , H. El Mamouni , J. Fay , S. Gascon , M. Gouzevitch , C. Greenberg , G. Grenier , B. Ille , E. Jourd'huy , I.B. Laktineh , M. Lethuillier , L. Mirabito , S. Perries , A. Purohit , M. Vander Donckt , P. Verdier , J. Xiao 



































Georgian Technical University, Tbilisi, Georgia

D. Chokheli , I. Lomidze , Z. Tsamalaidze²² 









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

V. Botta , S. Consuegra Rodríguez , L. Feld , K. Klein , M. Lipinski , D. Meuser , A. Pauls , D. Pérez Adán , N. Röwert , M. Teroerde 










































































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

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



































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

C. Dziwok , G. Flügge , T. Kress , A. Nowack , O. Pooth , A. Stahl , T. Ziemons , A. Zotz 






































Deutsches Elektronen-Synchrotron, Hamburg, Germany

H. Aarup Petersen , M. Aldaya Martin , J. Alimena , S. Amoroso , Y. An , J. Bach , S. Baxter , M. Bayatmakou , H. Becerril Gonzalez , O. Behnke , A. Belvedere , F. Blekman²⁴ , K. Borras²⁵ , A. Campbell , A. Cardini , C. Cheng , F. Colombina , M. De Silva , G. Eckerlin , D. Eckstein , L.I. Estevez Banos , E. Gallo²⁴ , A. Geiser , V. Guglielmi , M. Guthoff , A. Hinzmann , L. Jeppe , B. Kaech , M. Kasemann , C. Kleinwort , R. Kogler , M. Komm , D. Krücker , W. Lange , D. Leyva Pernia , K. Lipka²⁶ , W. Lohmann²⁷ , F. Lorkowski , R. Mankel , I.-A. Melzer-Pellmann , M. Mendizabal Morentin , A.B. Meyer , G. Milella , K. Moral Figueroa , A. Mussgiller , L.P. Nair , J. Niedziela , A. Nürnberg , Y. Otarid , J. Park , E. Ranken , A. Raspereza , D. Rastorguev , J. Rübenach , L. Rygaard , A. Saggio , M. Scham^{28,25} , S. Schnake²⁵ , P. Schütze , C. Schwanenberger²⁴ , D. Selivanova , K. Sharko , M. Shchedrolosiev , D. Stafford , F. Vazzoler , A. Ventura Barroso , R. Walsh , D. Wang , Q. Wang , K. Wichmann , L. Wiens²⁵ , C. Wissing , Y. Yang , S. Zakharov , A. Zimmermann Castro Santos 




University of Hamburg, Hamburg, Germany

A. Albrecht , S. Albrecht , M. Antonello , S. Bollweg , M. Bonanomi , P. Connor , K. El Morabit , Y. Fischer , E. Garutti , A. Grohsjean , J. Haller , D. Hundhausen , H.R. Jabusch , G. Kasieczka , P. Keicher , R. Klanner , W. Korcari , T. Kramer , C.c. Kuo , V. Kutzner , F. Labe , J. Lange , A. Lobanov , C. Matthies , L. Moureaux , M. Mrowietz , A. Nigamova , Y. Nissan , A. Paasch , K.J. Pena Rodriguez , T. Quadfasel , B. Raciti , M. Rieger , D. Savoie , J. Schindler , P. Schleper , M. Schröder , J. Schwandt , M. Sommerhalder , H. Stadie , G. Steinbrück , A. Tews , B. Wiederspan , M. Wolf 








Karlsruher Institut fuer Technologie, Karlsruhe, Germany

S. Brommer , E. Butz , T. Chwalek , A. Dierlamm , A. Droll, U. Elicabuk, N. Faltermann , M. Giffels , A. Gottmann , F. Hartmann²⁹ , R. Hofsaess , M. Horzela , U. Husemann , J. Kieseler , M. Klute , O. Lavoryk , J.M. Lawhorn , M. Link, A. Lintuluoto , S. Maier , S. Mitra , M. Mormile , Th. Müller , M. Neukum, M. Oh , E. Pfeffer , M. Presilla , G. Quast , K. Rabbertz , B. Regnery , N. Shadskiy , I. Shvetsov , H.J. Simonis , L. Sowa, L. Stockmeier, K. Tauqeer, M. Toms , B. Topko , N. Trevisani , R.F. Von Cube , M. Wassmer , S. Wieland , F. Wittig, R. Wolf , X. Zuo 

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

G. Anagnostou, G. Daskalakis , A. Kyriakis , A. Papadopoulos²⁹, A. Stakia 

National and Kapodistrian University of Athens, Athens, Greece

G. Melachroinos, Z. Painesis , I. Paraskevas , N. Saoulidou , K. Theofilatos , E. Tziaferi , K. Vellidis , I. Zisopoulos 






National Technical University of Athens, Athens, Greece

G. Bakas , T. Chatzistavrou, G. Karapostoli , K. Kousouris , I. Papakrivopoulos , E. Siamarkou, G. Tsipolitis , A. Zacharopoulou

University of Ioánnina, Ioánnina, Greece

I. Bestintzanos, I. Evangelou , C. Foudas, C. Kamtsikis, P. Katsoulis, P. Kokkas , P.G. Kosmoglou Kioseoglou , N. Manthos , I. Papadopoulos , J. Strologas 

HUN-REN Wigner Research Centre for Physics, Budapest, Hungary

C. Hajdu , D. Horvath^{30,31} , K. Márton, A.J. Rádl³² , F. Sikler , V. Veszpremi 

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

M. Csanád , K. Farkas , A. Fehérkuti³³ , M.M.A. Gadallah³⁴ , Á. Kadlecik , P. Major , G. Pásztor , G.I. Veres 




Faculty of Informatics, University of Debrecen, Debrecen, Hungary

B. Ujvari , G. Zilizi 













HUN-REN ATOMKI - Institute of Nuclear Research, Debrecen, Hungary

G. Bencze, S. Czellar, J. Molnar, Z. Szillasi

Karoly Robert Campus, MATE Institute of Technology, Gyongyos, Hungary

T. Csorgo³³ , F. Nemes³³ , T. Novak 

Panjab University, Chandigarh, India

S. Bansal , S.B. Beri, V. Bhatnagar , G. Chaudhary , S. Chauhan , N. Dhingra³⁵ , A. Kaur , A. Kaur , H. Kaur , M. Kaur , S. Kumar , T. Sheokand, J.B. Singh , A. Singla 

University of Delhi, Delhi, India















A. Ahmed , A. Bhardwaj , A. Chhetri , B.C. Choudhary , A. Kumar , A. Kumar , M. Naimuddin , K. Ranjan , M.K. Saini, S. Saumya 

Saha Institute of Nuclear Physics, HBNI, Kolkata, India

S. Baradia , S. Barman³⁶ , S. Bhattacharya , S. Das Gupta, S. Dutta , S. Dutta, S. Sarkar

Indian Institute of Technology Madras, Madras, India










M.M. Ameen , P.K. Behera , S.C. Behera , S. Chatterjee , G. Dash , P. Jana 

P. Kalbhor , S. Kamble , J.R. Komaragiri³⁷ , D. Kumar³⁷ , T. Mishra , B. Parida³⁸ , P.R. Pujahari , N.R. Saha , A. Sharma , A.K. Sikdar , R.K. Singh , P. Verma , S. Verma , A. Vijay 

Tata Institute of Fundamental Research-A, Mumbai, India

S. Dugad, G.B. Mohanty , M. Shelake, P. Suryadevara

Tata Institute of Fundamental Research-B, Mumbai, India

A. Bala , S. Banerjee , R.M. Chatterjee, M. Guchait , Sh. Jain , A. Jaiswal, S. Kumar , G. Majumder , K. Mazumdar , S. Parolia , A. Thachayath 

National Institute of Science Education and Research, An OCC of Homi Bhabha National Institute, Bhubaneswar, Odisha, India

S. Bahinipati³⁹ , C. Kar , D. Maity⁴⁰ , P. Mal , K. Naskar⁴⁰ , A. Nayak⁴⁰ , S. Nayak, K. Pal , P. Sadangi, S.K. Swain , S. Varghese⁴⁰ , D. Vats⁴⁰ 








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

S. Acharya⁴¹ , A. Alpana , S. Dube , B. Gomber⁴¹ , P. Hazarika , B. Kansal , A. Laha , B. Sahu⁴¹ , S. Sharma , K.Y. Vaish 

Isfahan University of Technology, Isfahan, Iran

H. Bakhshiansohi⁴² , A. Jafari⁴³ , M. Zeinali⁴⁴ 

































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

S. Bashiri, S. Chenarani⁴⁵ , S.M. Etesami , Y. Hosseini , M. Khakzad , E. Khazaie , M. Mohammadi Najafabadi , S. Tizchang⁴⁶ 






























University College Dublin, Dublin, Ireland

M. Felcini , M. Grunewald 







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

M. Abbrescia^{a,b} , A. Colaleo^{a,b} , D. Creanza^{a,c} , B. D'Anzi^{a,b} , N. De Filippis^{a,c} , M. De Palma^{a,b} , W. Elmetenawee^{a,b,47} , N. Ferrara^{a,b} , L. Fiore^a , G. Iaselli^{a,c} , L. Longo^a , M. Louka^{a,b} , G. Maggi^{a,c} , M. Maggi^a , I. Margjeka^a , V. Mastrapasqua^{a,b} , S. My^{a,b} , S. Nuzzo^{a,b} , A. Pellecchia^{a,b} , A. Pompili^{a,b} , G. Pugliese^{a,c} , R. Radogna^{a,b} , D. Ramos^a , A. Ranieri^a , L. Silvestris^a , F.M. Simone^{a,c} , Ü. Sözbilir^a , A. Stamerra^{a,b} , D. Troiano^{a,b} , R. Venditti^{a,b} , P. Verwilligen^a , A. Zaza^{a,b} 

















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

G. Abbiendi^a , C. Battilana^{a,b} , D. Bonacorsi^{a,b} , P. Capiluppi^{a,b} , A. Castro^{+a,b} , F.R. Cavallo^a , M. Cuffiani^{a,b} , G.M. Dallavalle^a , T. Diotallevi^{a,b} , F. Fabbri^a , A. Fanfani^{a,b} , D. Fasanella^a , P. Giacomelli^a , L. Giommi^{a,b} , C. Grandi^a , L. Guiducci^{a,b} , S. Lo Meo^{a,48} , M. Lorusso^{a,b} , L. Lunerti^a , S. Marcellini^a , G. Masetti^a , F.L. Navarria^{a,b} , G. Paggi^{a,b} , A. Perrotta^a , F. Primavera^{a,b} , A.M. Rossi^{a,b} , S. Rossi Tisbeni^{a,b} , T. Rovelli^{a,b} , G.P. Siroli^{a,b} 

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

S. Costa^{a,b,49} , A. Di Mattia^a , A. Lapertosa^a , R. Potenza^{a,b} , A. Tricomi^{a,b,49} , C. Tuve^{a,b} 

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





P. Assiouras^a , G. Barbagli^a , G. Bardelli^{a,b} , B. Camaiani^{a,b} , A. Cassese^a , R. Ceccarelli^a , V. Ciulli^{a,b} , C. Civinini^a , R. D'Alessandro^{a,b} , E. Focardi^{a,b} , T. Kello^a , G. Latino^{a,b} , P. Lenzi^{a,b} , M. Lizzo^a , M. Meschini^a , S. Paoletti^a 

A. Papanastassiou^{a,b}, G. Sguazzoni^a , L. Vilianni^a 










INFN Laboratori Nazionali di Frascati, Frascati, Italy

L. Benussi , S. Bianco , S. Meola⁵⁰ , D. Piccolo 









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

M. Alves Gallo Pereira^a , F. Ferro^a , E. Robutti^a , S. Tosi^{a,b} 










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

A. Benaglia^a , F. Brivio^a , F. Cetorelli^{a,b} , F. De Guio^{a,b} , M.E. Dinardo^{a,b} , P. Dini^a , S. Gennai^a , R. Gerosa^{a,b} , A. Ghezzi^{a,b} , P. Govoni^{a,b} , L. Guzzi^a , M.T. Lucchini^{a,b} , M. Malberti^a , S. Malvezzi^a , A. Massironi^a , D. Menasce^a , L. Moroni^a , M. Paganoni^{a,b} , S. Palluotto^{a,b} , D. Pedrini^a , A. Perego^{a,b} , B.S. Pinolini^a, G. Pizzati^{a,b} , S. Ragazzi^{a,b} , T. Tabarelli de Fatis^{a,b}










INFN Sezione di Napoli^a, Università di Napoli 'Federico II'^b, Napoli, Italy; Università della Basilicata^c, Potenza, Italy; Scuola Superiore Meridionale (SSM)^d, Napoli, Italy

S. Buontempo^a , A. Cagnotta^{a,b} , F. Carnevali^{a,b}, N. Cavallo^{a,c} , F. Fabozzi^{a,c} , A.O.M. Iorio^{a,b} , L. Lista^{a,b,51} , P. Paolucci^{a,29} , B. Rossi^a 










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

R. Ardino^a , P. Azzi^a , N. Bacchetta^{a,52} , D. Bisello^{a,b} , P. Bortignon^a , G. Bortolato^{a,b}, A. Bragagnolo^{a,b} , A.C.M. Bulla^a , P. Checchia^a , T. Dorigo^{a,53} , F. Gasparini^{a,b} , U. Gasparini^{a,b} , S. Giorgetti^a, A. Gozzelino^a , E. Lusiani^a , M. Margoni^{a,b} , A.T. Meneguzzo^{a,b} , M. Migliorini^{a,b} , J. Pazzini^{a,b} , P. Ronchese^{a,b} , R. Rossin^{a,b} , F. Simonetto^{a,b} , M. Tosi^{a,b} , A. Triossi^{a,b} , S. Ventura^a , M. Zanetti^{a,b} , P. Zotto^{a,b} , A. Zucchetta^{a,b} , G. Zumerle^{a,b}










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

A. Braghieri^a , S. Calzaferri^a , D. Fiorina^a , P. Montagna^{a,b} , V. Re^a , C. Riccardi^{a,b} , P. Salvini^a , I. Vai^{a,b} , P. Vitulo^{a,b} 










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



S. Ajmal^{a,b} , M.E. Ascioti^{a,b}, G.M. Bilei^a , C. Carrivale^{a,b}, D. Ciangottini^{a,b} , L. Fanò^{a,b} , M. Magherini^{a,b} , V. Mariani^{a,b} , M. Menichelli^a , F. Moscatelli^{a,54} , A. Rossi^{a,b} , A. Santocchia^{a,b} , D. Spiga^a , T. Tedeschi^{a,b}

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









































C. Aimè^a , C.A. Alexe^{a,c} , P. Asenov^{a,b} , P. Azzurri^a , G. Bagliesi^a , R. Bhattacharya^a , L. Bianchini^{a,b} , T. Boccali^a , E. Bossini^a , D. Bruschini^{a,c} , R. Castaldi^a , M.A. Ciocci^{a,b} , M. Cipriani^{a,b} , V. D'Amante^{a,d} , R. Dell'Orso^a , S. Donato^a , A. Giassi^a , F. Ligabue^{a,c} , A.C. Marini^a , D. Matos Figueiredo^a, A. Messineo^{a,b} , S. Mishra^a , V.K. Muraleedharan Nair Bindhu^{a,b,40} , M. Musich^{a,b} , S. Nandan^a , F. Palla^a , A. Rizzi^{a,b} , G. Rolandi^{a,c} , S. Roy Chowdhury^a , T. Sarkar^a , A. Scribano^a , P. Spagnolo^a , R. Tenchini^a , G. Tonelli^{a,b} , N. Turini^{a,d} , F. Vaselli^{a,c} , A. Venturi^a , P.G. Verdini^a

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








C. Baldenegro Barrera^{a,b} , P. Barria^a , C. Basile^{a,b} , F. Cavallari^a , L. Cunqueiro Mendez^{a,b} , D. Del Re^{a,b} , E. Di Marco^{a,b} , M. Diemoz^a , F. Errico^{a,b} , R. Gargiulo^{a,b}, E. Longo^{a,b} , L. Martikainen^{a,b} , J. Mijuskovic^{a,b} , G. Organtini^{a,b} , F. Pandolfi^a , R. Paramatti^{a,b} , C. Quaranta^{a,b} , S. Rahatlou^{a,b} , C. Rovelli^a

F. Santanastasio^{a,b} , L. Soffi^a , V. Vladimirov^{a,b}

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

N. Amapane^{a,b} , R. Arcidiacono^{a,c} , S. Argiro^{a,b} , M. Arneodo^{a,c} , N. Bartosik^a , R. Bellan^{a,b} , A. Bellora^{a,b} , C. Biino^a , C. Borca^{a,b} , N. Cartiglia^a , M. Costa^{a,b} , R. Covarelli^{a,b} , N. Demaria^a , L. Finco^a , M. Grippo^{a,b} , B. Kiani^{a,b} , F. Legger^a , F. Luongo^{a,b} , C. Mariotti^a , L. Markovic^{a,b} , S. Maselli^a , A. Mecca^{a,b} , L. Menzio^{a,b}, P. Meridiani^a , E. Migliore^{a,b} , M. Monteno^a , R. Mulargia^a , M.M. Obertino^{a,b} , G. Ortona^a , L. Pacher^{a,b} , N. Pastrone^a , M. Pelliccioni^a , M. Ruspa^{a,c} , F. Siviero^{a,b} , V. Sola^{a,b} , A. Solano^{a,b} , A. Staiano^a , C. Tarricone^{a,b} , D. Trocino^a , G. Umoret^{a,b} , R. White^{a,b} 

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

J. Babbar^{a,b} , S. Belforte^a , V. Candelise^{a,b} , M. Casarsa^a , F. Cossutti^a , K. De Leo^a , G. Della Ricca^{a,b} 





Kyungpook National University, Daegu, Korea

S. Dogra , J. Hong , B. Kim , J. Kim, D. Lee, H. Lee, S.W. Lee , C.S. Moon , Y.D. Oh , M.S. Ryu , S. Sekmen , B. Tae, Y.C. Yang 

Department of Mathematics and Physics - GWNu, Gangneung, Korea

M.S. Kim 

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

G. Bak , P. Gwak , H. Kim , D.H. Moon 

Hanyang University, Seoul, Korea

E. Asilar , J. Choi⁵⁵ , D. Kim , T.J. Kim , J.A. Merlin, Y. Ryou

Korea University, Seoul, Korea

S. Choi , S. Han, B. Hong , K. Lee, K.S. Lee , S. Lee , J. Yoo 

Kyung Hee University, Department of Physics, Seoul, Korea

J. Goh , S. Yang 








Sejong University, Seoul, Korea

H. S. Kim , Y. Kim, S. Lee




Seoul National University, Seoul, Korea

J. Almond, J.H. Bhyun, J. Choi , J. Choi, W. Jun , J. Kim , Y.W. Kim , S. Ko , H. Kwon , H. Lee , J. Lee , J. Lee , B.H. Oh , S.B. Oh , H. Seo , U.K. Yang, I. Yoon 

University of Seoul, Seoul, Korea

W. Jang , D.Y. Kang, Y. Kang , S. Kim , B. Ko, J.S.H. Lee , Y. Lee , I.C. Park , Y. Roh, I.J. Watson 

Yonsei University, Department of Physics, Seoul, Korea

S. Ha , K. Hwang , H.D. Yoo 

Sungkyunkwan University, Suwon, Korea

M. Choi , M.R. Kim , H. Lee, Y. Lee , I. Yu 

College of Engineering and Technology, American University of the Middle East (AUM), Dasman, Kuwait

T. Beyrouthy , Y. Gharbia 


Kuwait University - College of Science - Department of Physics, Safat, Kuwait

F. Alazemi 

Riga Technical University, Riga, Latvia

K. Dreimanis , A. Gaile , C. Munoz Diaz , D. Osite , G. Pikurs, A. Potrebko ,
M. Seidel , D. Sidiropoulos Kontos 

University of Latvia (LU), Riga, Latvia

N.R. Strautnieks 





Vilnius University, Vilnius, Lithuania

M. Ambrozas , A. Juodagalvis , A. Rinkevicius , G. Tamulaitis 








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

I. Yusuff⁵⁶ , Z. Zolkapli



Universidad de Sonora (UNISON), Hermosillo, Mexico

J.F. Benitez , A. Castaneda Hernandez , H.A. Encinas Acosta, L.G. Gallegos Maríñez,
M. León Coello , J.A. Murillo Quijada , A. Sehrawat , L. Valencia Palomo 

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

G. Ayala , H. Castilla-Valdez , H. Crotte Ledesma, E. De La Cruz-Burelo , I. Heredia-
De La Cruz⁵⁷ , R. Lopez-Fernandez , J. Mejia Guisao , C.A. Mondragon Herrera,
A. Sánchez Hernández 

Universidad Iberoamericana, Mexico City, Mexico

C. Oropeza Barrera , D.L. Ramirez Guadarrama, M. Ramírez García 

Benemerita Universidad Autonoma de Puebla, Puebla, Mexico

I. Bautista , F.E. Neri Huerta , I. Pedraza , H.A. Salazar Ibarguen , C. Uribe Estrada 

University of Montenegro, Podgorica, Montenegro

I. Bubanja , N. Raicevic 

University of Canterbury, Christchurch, New Zealand

P.H. Butler 

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

A. Ahmad , M.I. Asghar, A. Awais , M.I.M. Awan, H.R. Hoorani , W.A. Khan 







AGH University of Krakow, Krakow, Poland

V. Avati, L. Grzanka , M. Malawski 




National Centre for Nuclear Research, Swierk, Poland

H. Bialkowska , M. Bluj , M. Górski , M. Kazana , M. Szleper , P. Zalewski 

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

K. Bunkowski , K. Doroba , A. Kalinowski , M. Konecki , J. Krolikowski ,
A. Muhammad 

Warsaw University of Technology, Warsaw, Poland



P. Fokow , K. Pozniak , W. Zabolotny 

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

M. Araujo , D. Bastos , C. Beirão Da Cruz E Silva , A. Boletti , M. Bozzo ,
T. Camporesi , G. Da Molin , P. Faccioli , M. Gallinaro , J. Hollar , N. Leonardo 

G.B. Marozzo , A. Petrilli , M. Pisano , J. Seixas , J. Varela , J.W. Wulff 
































Faculty of Physics, University of Belgrade, Belgrade, Serbia

P. Adzic , P. Milenovic 

VINCA Institute of Nuclear Sciences, University of Belgrade, Belgrade, Serbia

D. Devetak, M. Dordevic , J. Milosevic , L. Nadderd , V. Rekovic, M. Stojanovic 













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

J. Alcaraz Maestre , Cristina F. Bedoya , J.A. Brochero Cifuentes , Oliver M. Carretero , M. Cepeda , M. Cerrada , N. Colino , B. De La Cruz , A. Delgado Peris , A. Escalante Del Valle , D. Fernández Del Val , J.P. Fernández Ramos , J. Flix , M.C. Fouz , O. Gonzalez Lopez , S. Goy Lopez , J.M. Hernandez , M.I. Josa , J. Llorente Merino , C. Martin Perez , E. Martin Viscasillas , D. Moran , C. M. Morcillo Perez , Á. Navarro Tobar , C. Perez Dengra , A. Pérez-Calero Yzquierdo , J. Puerta Pelayo , I. Redondo , S. Sánchez Navas , J. Sastre , J. Vazquez Escobar 



















Universidad Autónoma de Madrid, Madrid, Spain

J.F. de Trocóniz 

Universidad de Oviedo, Instituto Universitario de Ciencias y Tecnologías Espaciales de Asturias (ICTEA), Oviedo, Spain

B. Alvarez Gonzalez , J. Cuevas , J. Fernandez Menendez , S. Folgueras , I. Gonzalez Caballero , P. Leguina , E. Palencia Cortezon , J. Prado Pico , V. Rodríguez Bouza , A. Soto Rodríguez , A. Trapote , C. Vico Villalba , P. Vischia 

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

S. Bhowmik , S. Blanco Fernández , I.J. Cabrillo , A. Calderon , J. Duarte Campderros , M. Fernandez , G. Gomez , C. Lasiosa García , R. Lopez Ruiz , C. Martinez Rivero , P. Martinez Ruiz del Arbol , F. Matorras , P. Matorras Cuevas , E. Navarrete Ramos , J. Piedra Gomez , L. Scodellaro , I. Vila , J.M. Vizán Garcia 

University of Colombo, Colombo, Sri Lanka

B. Kailasapathy⁵⁸ , D.D.C. Wickramarathna 













University of Ruhuna, Department of Physics, Matara, Sri Lanka

W.G.D. Dharmaratna⁵⁹ , K. Liyanage , N. Perera 


































CERN, European Organization for Nuclear Research, Geneva, Switzerland

D. Abbaneo , C. Amendola , E. Auffray , G. Auzinger , J. Baechler, D. Barney , A. Bermúdez Martínez , M. Bianco , A.A. Bin Anuar , A. Bocci , L. Borgonovi , C. Botta , E. Brondolin , C.E. Brown , C. Caillol , G. Cerminara , N. Chernyavskaya , D. d'Enterria , A. Dabrowski , A. David , A. De Roeck , M.M. Defranchis , M. Deile , M. Dobson , G. Franzoni , W. Funk , S. Giani, D. Gigi, K. Gill , F. Glege , J. Hegeman , J.K. Heikkilä , B. Huber , V. Innocente , T. James , P. Janot , O. Kaluzinska , O. Karacheban²⁷ , G. Karathanasis , S. Laurila , P. Lecoq , E. Leutgeb , C. Lourenço , L. Malgeri , M. Mannelli , M. Matthewman, A. Mehta , F. Meijers , S. Mersi , E. Meschi , V. Milosevic , F. Monti , F. Moortgat , M. Mulders , I. Neutelings , S. Orfanelli, F. Pantaleo , G. Petrucciani , A. Pfeiffer , M. Pierini , H. Qu , D. Rabadý , B. Ribeiro Lopes , F. Riti , M. Rovere , H. Sakulin , R. Salvatico , S. Sanchez Cruz , S. Scarfi , C. Schwick, M. Selvaggi , A. Sharma , K. Shchelina , P. Silva , P. Sphicas⁶⁰ , A.G. Stahl Leitner , A. Steen , S. Summers , D. Treille , P. Tropea , D. Walter , J. Wanczyk⁶¹ , J. Wang, S. Wuchterl , P. Zehetner , P. Zejdl , W.D. Zeuner



















PSI Center for Neutron and Muon Sciences, Villigen, Switzerland

T. Bevilacqua⁶² , L. Caminada⁶² , A. Ebrahimi , W. Erdmann , R. Horisberger ,
Q. Ingram , H.C. Kaestli , D. Kotlinski , C. Lange , M. Missiroli⁶² , L. Noehte⁶² ,
T. Rohe , A. Samalan



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

T.K. Aarrestad , M. Backhaus , G. Bonomelli , A. Calandri , C. Cazzaniga ,
K. Datta , P. De Bryas Dexmiers D'archiac⁶¹ , A. De Cosa , G. Dissertori , M. Dittmar,
M. Donegà , F. Eble , M. Galli , K. Gedia , F. Glessgen , C. Grab , N. Härringer ,
T.G. Harte, D. Hits , W. Lustermann , A.-M. Lyon , R.A. Manzoni , M. Marchegiani ,
L. Marchese , A. Mascellani⁶¹ , F. Nessi-Tedaldi , F. Pauss , V. Perovic , S. Pigazzini ,
B. Ristic , R. Seidita , J. Steggemann⁶¹ , A. Tarabini , D. Valsecchi , R. Wallny 












Universität Zürich, Zurich, Switzerland

C. Amsler⁶³ , P. Bärttschi , M.F. Canelli , K. Cormier , M. Huwiler , W. Jin ,
A. Jofrehei , B. Kilminster , S. Leontsinis , S.P. Liehti , A. Macchiolo , P. Meiring ,
F. Meng , J. Motta , A. Reimers , P. Robmann, M. Senger , E. Shokr, F. Stäger ,
R. Tramontano 

National Central University, Chung-Li, Taiwan

C. Adloff⁶⁴, D. Bhowmik, C.M. Kuo, W. Lin, P.K. Rout , P.C. Tiwari³⁷ 


National Taiwan University (NTU), Taipei, Taiwan

L. Ceard, K.F. Chen , Z.g. Chen, A. De Iorio , W.-S. Hou , T.h. Hsu, Y.w. Kao,
S. Karmakar , G. Kole , Y.y. Li , R.-S. Lu , E. Paganis , X.f. Su , J. Thomas-Wilsker ,
L.s. Tsai, D. Tsionou, H.y. Wu, E. Yazgan 


















High Energy Physics Research Unit, Department of Physics, Faculty of Science, Chulalongkorn University, Bangkok, Thailand

C. Asawatangtrakuldee , N. Srimanobhas , V. Wachirapusanand 

Tunis El Manar University, Tunis, Tunisia

Y. Maghrbi 

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

D. Agyel , F. Boran , F. Dolek , I. Dumanoglu⁶⁵ , E. Eskut , Y. Guler⁶⁶ ,
E. Gurpinar Guler⁶⁶ , C. Isik , O. Kara, A. Kayis Topaksu , Y. Komurcu , G. Onengut ,
K. Ozdemir⁶⁷ , A. Polatoz , B. Tali⁶⁸ , U.G. Tok , E. Uslan , I.S. Zorbakir 

Middle East Technical University, Physics Department, Ankara, Turkey

G. Sokmen, M. Yalvac⁶⁹ 


Bogazici University, Istanbul, Turkey

B. Akgun , I.O. Atakisi , E. Gülmez , M. Kaya⁷⁰ , O. Kaya⁷¹ , S. Tekten⁷² 





Istanbul Technical University, Istanbul, Turkey

A. Cakir , K. Cankocak^{65,73} , G.G. Dincer⁶⁵ , S. Sen⁷⁴ 

Istanbul University, Istanbul, Turkey

O. Aydılek⁷⁵ , B. Hacısahinoglu , I. Hos⁷⁶ , B. Kaynak , S. Ozkorucuklu , O. Potok ,
H. Sert , C. Simsek , C. Zorbilmez 

Yildiz Technical University, Istanbul, Turkey

S. Cerci , B. Isildak⁷⁷ , D. Sunar Cerci , T. Yetkin 

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
















Ukraine

A. Boyaryntsev , B. Grynyov 

























National Science Centre, Kharkiv Institute of Physics and Technology, Kharkiv, Ukraine

L. Levchuk 












































University of Bristol, Bristol, United Kingdom

D. Anthony , J.J. Brooke , A. Bundock , F. Bury , E. Clement , D. Cussans , H. Flacher , M. Glowacki , J. Goldstein , H.F. Heath , M.-L. Holmberg , L. Kreczko , S. Paramesvaran , L. Robertshaw , V.J. Smith , K. Walkingshaw Pass


Rutherford Appleton Laboratory, Didcot, United Kingdom

A.H. Ball , K.W. Bell , A. Belyaev⁷⁸ , C. Brew , R.M. Brown , D.J.A. Cockerill , C. Cooke , A. Elliot , K.V. Ellis , K. Harder , S. Harper , J. Linacre , K. Manolopoulos , D.M. Newbold , E. Olaiya , D. Petyt , T. Reis , A.R. Sahasransu , G. Salvi , T. Schuh , C.H. Shepherd-Themistocleous , I.R. Tomalin , K.C. Whalen , T. Williams 




Imperial College, London, United Kingdom

I. Andreou , R. Bainbridge , P. Bloch , O. Buchmuller , C.A. Carrillo Montoya , G.S. Chahal⁷⁹ , D. Colling , J.S. Dancu , I. Das , P. Dauncey , G. Davies , M. Della Negra , S. Fayer , G. Fedi , G. Hall , A. Howard , G. Iles , C.R. Knight , P. Krueper , J. Langford , K.H. Law , J. León Holgado , L. Lyons , A.-M. Magnan , B. Maier , S. Mallios , M. Mieskolainen , J. Nash⁸⁰ , M. Pesaresi , P.B. Pradeep , B.C. Radburn-Smith , A. Richards , A. Rose , K. Savva , C. Seez , R. Shukla , A. Tapper , K. Uchida , G.P. Uttley , T. Virdee²⁹ , M. Vojinovic , N. Wardle , D. Winterbottom 

Brunel University, Uxbridge, United Kingdom

J.E. Cole , A. Khan , P. Kyberd , I.D. Reid 

Baylor University, Waco, Texas, USA

S. Abdullin , A. Brinkerhoff , E. Collins , M.R. Darwish , J. Dittmann , K. Hatakeyama , V. Hegde , J. Hiltbrand , B. McMaster , J. Samudio , S. Sawant , C. Sutantawibul , J. Wilson 





















Catholic University of America, Washington, DC, USA

R. Bartek , A. Dominguez , A.E. Simsek , S.S. Yu 




















The University of Alabama, Tuscaloosa, Alabama, USA

B. Bam , A. Buchot Perraguin , R. Chudasama , S.I. Cooper , C. Crovella , S.V. Gleyzer , E. Pearson , C.U. Perez , P. Rumerio⁸¹ , E. Usai , R. Yi 






Boston University, Boston, Massachusetts, USA

A. Akpinar , C. Cosby , G. De Castro , Z. Demiragli , C. Erice , C. Fangmeier , C. Fernandez Madrazo , E. Fontanesi , D. Gastler , F. Golf , S. Jeon , J. O'cain , I. Reed , J. Rohlf , K. Salyer , D. Sperka , D. Spitzbart , I. Suarez , A. Tsatsos , A.G. Zecchinelli 

Brown University, Providence, Rhode Island, USA












G. Barone , G. Benelli , D. Cutts , L. Gouskos , M. Hadley , U. Heintz , K.W. Ho , J.M. Hogan⁸² , T. Kwon , G. Landsberg , K.T. Lau , J. Luo , S. Mondal , T. Russell , S. Sagir⁸³ , X. Shen , F. Simpson , M. Stamenkovic , N. Venkatasubramanian 

University of California, Davis, Davis, California, USA




S. Abbott , B. Barton , C. Brainerd , R. Breedon , H. Cai 

M. Calderon De La Barca Sanchez , M. Chertok , M. Citron , J. Conway , P.T. Cox , R. Erbacher , F. Jensen , O. Kukral , G. Mocellin , M. Mulhearn , S. Ostrom , W. Wei , S. Yoo , F. Zhang 

















University of California, Los Angeles, California, USA

K. Adamidis, M. Bachtis , D. Campos, R. Cousins , A. Datta , G. Flores Avila , J. Hauser , M. Ignatenko , M.A. Iqbal , T. Lam , Y.f. Lo, E. Manca , A. Nunez Del Prado, D. Saltzberg , V. Valuev 

















University of California, Riverside, Riverside, California, USA

R. Clare , J.W. Gary , G. Hanson 










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

A. Aportela, A. Arora , J.G. Branson , S. Cittolin , S. Cooperstein , D. Diaz , J. Duarte , L. Giannini , Y. Gu, J. Guiang , R. Kansal , V. Krutelyov , R. Lee , J. Letts , M. Masciovecchio , F. Mokhtar , S. Mukherjee , M. Pieri , D. Primosch, M. Quinnan , V. Sharma , M. Tadel , E. Vourliotis , F. Würthwein , Y. Xiang , A. Yagil
















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

A. Barzdukas , L. Brennan , C. Campagnari , K. Downham , C. Grieco , M.M. Hussain, J. Incandela , J. Kim , A.J. Li , P. Masterson , H. Mei , J. Richman , S.N. Santpur , U. Sarica , R. Schmitz , F. Setti , J. Shephlock , D. Stuart , T.Á. Vámi , X. Yan , D. Zhang














California Institute of Technology, Pasadena, California, USA

S. Bhattacharya , A. Bornheim , O. Cerri, A. Latorre, J. Mao , H.B. Newman , G. Reales Gutiérrez, M. Spiropulu , J.R. Vlimant , C. Wang , S. Xie , R.Y. Zhu 
















Carnegie Mellon University, Pittsburgh, Pennsylvania, USA

J. Alison , S. An , P. Bryant , M. Cremonesi, V. Dutta , T. Ferguson , T.A. Gómez Espinosa , A. Harilal , A. Kallil Tharayil, C. Liu , T. Mudholkar , S. Murthy , P. Palit , K. Park, M. Paulini , A. Roberts , A. Sanchez , W. Terrill 

















University of Colorado Boulder, Boulder, Colorado, USA
























J.P. Cumalat , W.T. Ford , A. Hart , A. Hassani , N. Manganeli , J. Pearkes , C. Savard , N. Schonbeck , K. Stenson , K.A. Ulmer , S.R. Wagner , N. Zipper , D. Zuolo 

Cornell University, Ithaca, New York, USA




















J. Alexander , X. Chen , D.J. Cranshaw , J. Dickinson , J. Fan , X. Fan , S. Hogan , P. Kotamnives, J. Monroy , M. Oshiro , J.R. Patterson , M. Reid , A. Ryd , J. Thom , P. Wittich , R. Zou 

Fermi National Accelerator Laboratory, Batavia, Illinois, USA












M. Albrow , M. Alyari , O. Amram , G. Apollinari , A. Apresyan , L.A.T. Bauerdick , D. Berry , J. Berryhill , P.C. Bhat , K. Burkett , J.N. Butler , A. Canepa , G.B. Cerati , H.W.K. Cheung , F. Chlebana , G. Cummings , I. Dutta , V.D. Elvira , Y. Feng , J. Freeman , A. Gandrakota , Z. Gecse , L. Gray , D. Green, A. Grummer , S. Grünendahl , D. Guerrero , O. Gutsche , R.M. Harris , T.C. Herwig , J. Hirschauer , B. Jayatilaka , S. Jindariani , M. Johnson , U. Joshi , T. Klijsma , B. Klima , K.H.M. Kwok , S. Lammel , C. Lee , D. Lincoln , R. Lipton , T. Liu , C. Madrid , K. Maeshima , D. Mason , P. McBride , P. Merkel , S. Mrenna

S. Nahn , J. Ngadiuba , D. Noonan , S. Norberg, V. Papadimitriou , N. Pastika , K. Pedro , C. Pena⁸⁴ , F. Ravera , A. Reinsvold Hall⁸⁵ , L. Ristori , M. Safdari , E. Sexton-Kennedy , N. Smith , A. Soha , L. Spiegel , S. Stoynev , J. Strait , L. Taylor , S. Tkaczyk , N.V. Tran , L. Uplegger , E.W. Vaandering , I. Zoi 






University of Florida, Gainesville, Florida, USA

C. Aruta , P. Avery , D. Bourilkov , P. Chang , V. Cherepanov , R.D. Field, C. Huh , E. Koenig , M. Kolosova , J. Konigsberg , A. Korytov , K. Matchev , N. Menendez , G. Mitselmakher , K. Mohrman , A. Muthirakalayil Madhu , N. Rawal , S. Rosenzweig , Y. Takahashi , J. Wang 
























Florida State University, Tallahassee, Florida, USA

T. Adams , A. Al Kadhim , A. Askew , S. Bower , R. Hashmi , R.S. Kim , S. Kim , T. Kolberg , G. Martinez, H. Prosper , P.R. Prova, M. Wulansatiti , R. Yohay , J. Zhang











Florida Institute of Technology, Melbourne, Florida, USA

B. Alsufyani , S. Butalla , S. Das , T. Elkafrawy⁸⁶ , M. Hohlmann , E. Yanes












University of Illinois Chicago, Chicago, Illinois, USA

M.R. Adams , A. Baty , C. Bennett, R. Cavanaugh , R. Escobar Franco , O. Evdokimov , C.E. Gerber , M. Hawksworth, A. Hingrajiya, D.J. Hofman , J.h. Lee , D. S. Lemos , A.H. Merrit , C. Mills , S. Nanda , G. Oh , B. Ozek , D. Pilipovic , R. Pradhan , E. Prifti, T. Roy , S. Rudrabhatla , N. Singh, M.B. Tonjes , N. Varelas , M.A. Wadud , Z. Ye , J. Yoo 























The University of Iowa, Iowa City, Iowa, USA

M. Alhousseini , D. Blend, K. Dilsiz⁸⁷ , L. Emediato , G. Karaman , O.K. Köseyan , J.-P. Merlo, A. Mestvirishvili⁸⁸ , O. Neogi, H. Ogul⁸⁹ , Y. Onel , A. Penzo , C. Snyder, E. Tiras⁹⁰ 









Johns Hopkins University, Baltimore, Maryland, USA

B. Blumenfeld , L. Corcodilos , J. Davis , A.V. Gritsan , L. Kang , S. Kyriacou , P. Maksimovic , M. Roguljic , J. Roskes , S. Sekhar , M. Swartz 



















The University of Kansas, Lawrence, Kansas, USA

A. Abreu , L.F. Alcerro Alcerro , J. Anguiano , S. Arteaga Escatel , P. Baringer , A. Bean , Z. Flowers , D. Grove , J. King , G. Krintiras , M. Lazarovits , C. Le Mahieu , J. Marquez , M. Murray , M. Nickel , M. Pitt , S. Popescu⁹¹ , C. Rogan , C. Royon , S. Sanders , C. Smith , G. Wilson 
















Kansas State University, Manhattan, Kansas, USA










B. Allmond , R. Gujju Gurunadha , A. Ivanov , K. Kaadze , Y. Maravin , J. Natoli , D. Roy , G. Sorrentino 

University of Maryland, College Park, Maryland, USA

A. Baden , A. Belloni , J. Bistany-riebman, Y.M. Chen , S.C. Eno , N.J. Hadley , S. Jabeen , R.G. Kellogg , T. Koeth , B. Kronheim, Y. Lai , S. Lascio , A.C. Mignerey , S. Nabili , C. Palmer , C. Papageorgakis , M.M. Paranjpe, E. Popova⁹² , A. Shevelev , L. Wang , L. Zhang 

Massachusetts Institute of Technology, Cambridge, Massachusetts, USA














J. Bendavid , S. Bright-Thonney , I.A. Cali , P.c. Chou , M. D'Alfonso , J. Eysermans , C. Freer , G. Gomez-Ceballos , M. Goncharov, G. Grosso, P. Harris, D. Hoang, D. Kovalskyi , J. Krupa , L. Lavezzo , Y.-J. Lee , K. Long , C. Mcginn, A. Novak , M.I. Park 

C. Paus , C. Reissel , C. Roland , G. Roland , S. Rothman , G.S.F. Stephans ,
Z. Wang , B. Wyslouch , T. J. Yang 












University of Minnesota, Minneapolis, Minnesota, USA

B. Crossman , C. Kapsiak , M. Krohn , D. Mahon , J. Mans , B. Marzocchi ,
M. Revering , R. Rusack , R. Saradhy , N. Strobbe 




















University of Nebraska-Lincoln, Lincoln, Nebraska, USA

K. Bloom , D.R. Claes , G. Haza , J. Hossain , C. Joo , I. Kravchenko , A. Rohilla ,
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








State University of New York at Buffalo, Buffalo, New York, USA

H. Bandyopadhyay , L. Hay , H.w. Hsia , I. Iashvili , A. Kalogeropoulos ,
A. Kharchilava , M. Morris , D. Nguyen , S. Rappoccio , H. Rejeb Sfar, A. Williams ,
P. Young 


























Northeastern University, Boston, Massachusetts, USA

G. Alverson , E. Barberis , J. Bonilla , B. Bylsma, M. Campana , J. Dervan ,
Y. Haddad , Y. Han , I. Israr , A. Krishna , J. Li , M. Lu , R. Mccarthy ,
D.M. Morse , V. Nguyen , T. Orimoto , A. Parker , L. Skinnari , E. Tsai , D. Wood 









Northwestern University, Evanston, Illinois, USA

J. Bueghly, S. Dittmer , K.A. Hahn , D. Li , Y. Liu , M. Mcginnis , Y. Miao ,
D.G. Monk , M.H. Schmitt , A. Taliercio , M. Velasco

















University of Notre Dame, Notre Dame, Indiana, USA

G. Agarwal , R. Band , R. Bucci, S. Castells , A. Das , R. Goldouzian , M. Hildreth ,
K. Hurtado Anampa , T. Ivanov , C. Jessop , K. Lannon , J. Lawrence , N. Loukas ,
L. Lutton , J. Mariano, N. Marinelli, I. Mcalister, T. McCauley , C. Mcgrady , C. Moore ,
Y. Musienko²² , H. Nelson , M. Osherson , A. Piccinelli , R. Ruchti , A. Townsend ,
Y. Wan, M. Wayne , H. Yockey, M. Zarucki , L. Zygalá 

The Ohio State University, Columbus, Ohio, USA

A. Basnet , M. Carrigan , L.S. Durkin , C. Hill , M. Joyce , M. Nunez Ornelas , K. Wei,
D.A. Wenzl, B.L. Winer , B. R. Yates 



















Princeton University, Princeton, New Jersey, USA

H. Bouchamaoui , K. Coldham, P. Das , G. Dezoort , P. Elmer , A. Frankenthal ,
B. Greenberg , N. Haubrich , K. Kennedy, G. Kopp , S. Kwan , D. Lange ,
A. Loeliger , D. Marlow , I. Ojalvo , J. Olsen , D. Stickland , C. Tully , L.H. Vage




University of Puerto Rico, Mayaguez, Puerto Rico, USA

S. Malik , R. Sharma

Purdue University, West Lafayette, Indiana, USA










A.S. Bakshi , S. Chandra , R. Chawla , A. Gu , L. Gutay, M. Jones , A.W. Jung ,
A.M. Koshy, M. Liu , G. Negro , N. Neumeister , G. Paspalaki , S. Piperov ,
V. Scheurer, J.F. Schulte , J. Thieman , A. K. Viridi , F. Wang , A. Wildridge , W. Xie ,
Y. Yao 

Purdue University Northwest, Hammond, Indiana, USA

J. Dolen , N. Parashar , A. Pathak 

Rice University, Houston, Texas, USA



















D. Acosta , A. Agrawal , T. Carnahan , K.M. Ecklund , P.J. Fernández Manteca 

S. Freed, P. Gardner, F.J.M. Geurts , I. Krommydas , W. Li , J. Lin , O. Miguel Colin , B.P. Padley , R. Redjimi, J. Rotter , E. Yigitbasi , Y. Zhang 

University of Rochester, Rochester, New York, USA

A. Bodek , P. de Barbaro , R. Demina , J.L. Dulemba , A. Garcia-Bellido , O. Hindrichs , A. Khukhunaishvili , N. Parmar , P. Parygin⁹² , R. Taus 















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

B. Chiarito, J.P. Chou , S.V. Clark , D. Gadkari , Y. Gershtein , E. Halkiadakis , M. Heindl , C. Houghton , D. Jaroslowski , S. Konstantinou , I. Laflotte , A. Lath , R. Montalvo, K. Nash, J. Reichert , P. Saha , S. Salur , S. Schnetzer, S. Somalwar , R. Stone , S.A. Thayil , S. Thomas, J. Vora 










University of Tennessee, Knoxville, Tennessee, USA

D. Ally , A.G. Delannoy , S. Fiorendi , S. Higginbotham , T. Holmes , A.R. Kanuganti , N. Karunarathna , L. Lee , E. Nibigira , S. Spanier 

Texas A&M University, College Station, Texas, USA

D. Aebi , M. Ahmad , T. Akhter , K. Androsov⁶¹ , O. Bouhali⁹³ , R. Eusebi , J. Gilmore , T. Huang , T. Kamon⁹⁴ , H. Kim , S. Luo , R. Mueller , D. Overton , A. Safonov 

Texas Tech University, Lubbock, Texas, USA

N. Akchurin , J. Damgov , N. Gogate , A. Hussain , Y. Kazhykarim, K. Lamichhane , S.W. Lee , A. Mankel , T. Peltola , I. Volobouev 

Vanderbilt University, Nashville, Tennessee, USA

E. Appelt , Y. Chen , S. Greene, A. Gurrola , W. Johns , R. Kunnawalkam Elayavalli , A. Melo , D. Rathjens , F. Romeo , P. Sheldon , S. Tuo , J. Velkovska , J. Viinikainen 
























University of Virginia, Charlottesville, Virginia, USA

B. Cardwell , H. Chung, B. Cox , J. Hakala , R. Hirosky , A. Ledovskoy , C. Mantilla , C. Neu , C. Ramón Álvarez 


































Wayne State University, Detroit, Michigan, USA

S. Bhattacharya , P.E. Karchin 

University of Wisconsin - Madison, Madison, Wisconsin, USA





































A. Aravind , S. Banerjee , K. Black , T. Bose , E. Chavez , S. Dasu , P. Everaerts , C. Galloni, H. He , M. Herndon , A. Herve , C.K. Koraka , A. Lanaro, R. Loveless , J. Madhusudanan Sreekala , A. Mallampalli , A. Mohammadi , S. Mondal, G. Parida , L. Pétré , D. Pinna, A. Savin, V. Shang , V. Sharma , W.H. Smith , D. Teague, H.F. Tsoi , W. Vetens , A. Warden 

Authors affiliated with an international laboratory covered by a cooperation agreement with CERN

S. Afanasiev , V. Alexakhin , D. Budkouski , I. Golutvin[†] , I. Gorbunov , V. Karjavine , O. Kodolova⁹⁵ , V. Korenkov , A. Lanev , A. Malakhov , V. Matveev⁹⁶ , A. Nikitenko^{97,95} , V. Palichik , V. Perelygin , M. Savina , V. Shalaev , S. Shmatov , S. Shulha , V. Smirnov , O. Teryaev , N. Voytishin , B.S. Yuldashev⁹⁸ , A. Zarubin , I. Zhizhin , Yu. Andreev , A. Dermenev , S. Gninenko , N. Golubev , A. Karneyeu , D. Kirpichnikov , M. Kirsanov , N. Krasnikov , I. Tlisova , A. Toropin

Authors affiliated with an institute formerly covered by a cooperation agreement with CERN

G. Gavrillov , V. Golovtcov , Y. Ivanov , V. Kim⁹⁹ , P. Levchenko¹⁰⁰ , V. Murzin 

V. Oreshkin , D. Sosnov , V. Sulimov , L. Uvarov , A. Vorobyev[†], T. Aushhev , K. Ivanov , V. Gavrilov , N. Lychkovskaya , V. Popov , A. Zhokin , R. Chistov⁹⁹ , M. Danilov⁹⁹ , S. Polikarpov⁹⁹ , V. Andreev , M. Azarkin , M. Kirakosyan, A. Terkulov , E. Boos , A. Demiyarov , A. Ershov , A. Gribushin , L. Khein , V. Korotkikh, S. Obraztsov , S. Petrushanko , V. Savrin , A. Snigirev , I. Vardanyan , V. Blinov⁹⁹, T. Dimova⁹⁹ , A. Kozyrev⁹⁹ , O. Radchenko⁹⁹ , Y. Skovpen⁹⁹ , V. Kachanov , S. Slabospitskii , A. Uzunian , A. Babaev , V. Borshch , D. Druzhkin¹⁰¹ 

†: Deceased

¹Also at Yerevan State University, Yerevan, Armenia

²Also at TU Wien, Vienna, Austria

³Also at Ghent University, Ghent, Belgium

⁴Also at Universidade do Estado do Rio de Janeiro, Rio de Janeiro, Brazil

⁵Also at FACAMP - Faculdades de Campinas, Sao Paulo, Brazil

⁶Also at Universidade Estadual de Campinas, Campinas, Brazil

⁷Also at Federal University of Rio Grande do Sul, Porto Alegre, Brazil

⁸Also at University of Chinese Academy of Sciences, Beijing, China

⁹Also at China Center of Advanced Science and Technology, Beijing, China

¹⁰Also at University of Chinese Academy of Sciences, Beijing, China

¹¹Also at China Spallation Neutron Source, Guangdong, China

¹²Now at Henan Normal University, Xinxiang, China

¹³Also at University of Shanghai for Science and Technology, Shanghai, China

¹⁴Now at The University of Iowa, Iowa City, Iowa, USA

¹⁵Also at an institute formerly covered by a cooperation agreement with CERN

¹⁶Also at Cairo University, Cairo, Egypt

¹⁷Also at Suez University, Suez, Egypt

¹⁸Now at British University in Egypt, Cairo, Egypt

¹⁹Also at Purdue University, West Lafayette, Indiana, USA

²⁰Also at Université de Haute Alsace, Mulhouse, France

²¹Also at Istinye University, Istanbul, Turkey

²²Also at an international laboratory covered by a cooperation agreement with CERN

²³Also at The University of the State of Amazonas, Manaus, Brazil

²⁴Also at University of Hamburg, Hamburg, Germany

²⁵Also at RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany

²⁶Also at Bergische University Wuppertal (BUW), Wuppertal, Germany

²⁷Also at Brandenburg University of Technology, Cottbus, Germany

²⁸Also at Forschungszentrum Jülich, Juelich, Germany

²⁹Also at CERN, European Organization for Nuclear Research, Geneva, Switzerland

³⁰Also at HUN-REN ATOMKI - Institute of Nuclear Research, Debrecen, Hungary

³¹Now at Universitatea Babeş-Bolyai - Facultatea de Fizica, Cluj-Napoca, Romania

³²Also at MTA-ELTE Lendület CMS Particle and Nuclear Physics Group, Eötvös Loránd University, Budapest, Hungary

³³Also at HUN-REN Wigner Research Centre for Physics, Budapest, Hungary

³⁴Also at Physics Department, Faculty of Science, Assiut University, Assiut, Egypt

³⁵Also at Punjab Agricultural University, Ludhiana, India

³⁶Also at University of Visva-Bharati, Santiniketan, India

³⁷Also at Indian Institute of Science (IISc), Bangalore, India

³⁸Also at Amity University Uttar Pradesh, Noida, India

³⁹Also at IIT Bhubaneswar, Bhubaneswar, India

- ⁴⁰Also at Institute of Physics, Bhubaneswar, India
- ⁴¹Also at University of Hyderabad, Hyderabad, India
- ⁴²Also at Deutsches Elektronen-Synchrotron, Hamburg, Germany
- ⁴³Also at Isfahan University of Technology, Isfahan, Iran
- ⁴⁴Also at Sharif University of Technology, Tehran, Iran
- ⁴⁵Also at Department of Physics, University of Science and Technology of Mazandaran, Behshahr, Iran
- ⁴⁶Also at Department of Physics, Faculty of Science, Arak University, ARAK, Iran
- ⁴⁷Also at Helwan University, Cairo, Egypt
- ⁴⁸Also at Italian National Agency for New Technologies, Energy and Sustainable Economic Development, Bologna, Italy
- ⁴⁹Also at Centro Siciliano di Fisica Nucleare e di Struttura Della Materia, Catania, Italy
- ⁵⁰Also at Università degli Studi Guglielmo Marconi, Roma, Italy
- ⁵¹Also at Scuola Superiore Meridionale, Università di Napoli 'Federico II', Napoli, Italy
- ⁵²Also at Fermi National Accelerator Laboratory, Batavia, Illinois, USA
- ⁵³Also at Lulea University of Technology, Lulea, Sweden
- ⁵⁴Also at Consiglio Nazionale delle Ricerche - Istituto Officina dei Materiali, Perugia, Italy
- ⁵⁵Also at Institut de Physique des 2 Infinis de Lyon (IP2I), Villeurbanne, France
- ⁵⁶Also at Department of Applied Physics, Faculty of Science and Technology, Universiti Kebangsaan Malaysia, Bangi, Malaysia
- ⁵⁷Also at Consejo Nacional de Ciencia y Tecnología, Mexico City, Mexico
- ⁵⁸Also at Trincomalee Campus, Eastern University, Sri Lanka, Nilaveli, Sri Lanka
- ⁵⁹Also at Saegis Campus, Nugegoda, Sri Lanka
- ⁶⁰Also at National and Kapodistrian University of Athens, Athens, Greece
- ⁶¹Also at Ecole Polytechnique Fédérale Lausanne, Lausanne, Switzerland
- ⁶²Also at Universität Zürich, Zurich, Switzerland
- ⁶³Also at Stefan Meyer Institute for Subatomic Physics, Vienna, Austria
- ⁶⁴Also at Laboratoire d'Annecy-le-Vieux de Physique des Particules, IN2P3-CNRS, Annecy-le-Vieux, France
- ⁶⁵Also at Near East University, Research Center of Experimental Health Science, Mersin, Turkey
- ⁶⁶Also at Konya Technical University, Konya, Turkey
- ⁶⁷Also at Izmir Bakircay University, Izmir, Turkey
- ⁶⁸Also at Adiyaman University, Adiyaman, Turkey
- ⁶⁹Also at Bozok Universitetesi Rektörlüğü, Yozgat, Turkey
- ⁷⁰Also at Marmara University, Istanbul, Turkey
- ⁷¹Also at Milli Savunma University, Istanbul, Turkey
- ⁷²Also at Kafkas University, Kars, Turkey
- ⁷³Now at Istanbul Okan University, Istanbul, Turkey
- ⁷⁴Also at Hacettepe University, Ankara, Turkey
- ⁷⁵Also at Erzincan Binali Yildirim University, Erzincan, Turkey
- ⁷⁶Also at Istanbul University - Cerrahpasa, Faculty of Engineering, Istanbul, Turkey
- ⁷⁷Also at Yildiz Technical University, Istanbul, Turkey
- ⁷⁸Also at School of Physics and Astronomy, University of Southampton, Southampton, United Kingdom
- ⁷⁹Also at IPPP Durham University, Durham, United Kingdom
- ⁸⁰Also at Monash University, Faculty of Science, Clayton, Australia
- ⁸¹Also at Università di Torino, Torino, Italy
- ⁸²Also at Bethel University, St. Paul, Minnesota, USA

⁸³Also at Karamanoğlu Mehmetbey University, Karaman, Turkey

⁸⁴Also at California Institute of Technology, Pasadena, California, USA

⁸⁵Also at United States Naval Academy, Annapolis, Maryland, USA

⁸⁶Also at Ain Shams University, Cairo, Egypt

⁸⁷Also at Bingöl University, Bingöl, Turkey

⁸⁸Also at Georgian Technical University, Tbilisi, Georgia

⁸⁹Also at Sinop University, Sinop, Turkey

⁹⁰Also at Erciyes University, Kayseri, Turkey

⁹¹Also at Horia Hulubei National Institute of Physics and Nuclear Engineering (IFIN-HH), Bucharest, Romania

⁹²Now at another institute formerly covered by a cooperation agreement with CERN

⁹³Also at Texas A&M University at Qatar, Doha, Qatar

⁹⁴Also at Kyungpook National University, Daegu, Korea

⁹⁵Also at Yerevan Physics Institute, Yerevan, Armenia

⁹⁶Also at another international laboratory covered by a cooperation agreement with CERN

⁹⁷Also at Imperial College, London, United Kingdom

⁹⁸Also at Institute of Nuclear Physics of the Uzbekistan Academy of Sciences, Tashkent, Uzbekistan

⁹⁹Also at another institute formerly covered by a cooperation agreement with CERN

¹⁰⁰Also at Northeastern University, Boston, Massachusetts, USA

¹⁰¹Also at Universiteit Antwerpen, Antwerpen, Belgium