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Probing the chiral magnetic wave in pPb and PbPb collisions at $\sqrt{s_{\text{NN}}} = 5.02$ TeV using charge-dependent azimuthal anisotropies

The CMS Collaboration*

Abstract

Charge-dependent anisotropy Fourier coefficients (v_n) of particle azimuthal distributions are measured in pPb and PbPb collisions at $\sqrt{s_{\text{NN}}} = 5.02$ TeV with the CMS detector at the LHC. The normalized difference in the second-order anisotropy coefficients (v_2) between positively and negatively charged particles is found to depend linearly on the observed event charge asymmetry with comparable slopes for both pPb and PbPb collisions over a wide range of charged particle multiplicity. In PbPb, the third-order anisotropy coefficient, v_3 , shows a similar linear dependence with the same slope as seen for v_2 . The observed similarities between the v_2 slopes for pPb and PbPb, as well as the similar slopes for v_2 and v_3 in PbPb, are compatible with expectations based on local charge conservation in the decay of clusters or resonances, and constitute a challenge to the hypothesis that, at LHC energies, the observed charge asymmetry dependence of v_2 in heavy ion collisions arises from a chiral magnetic wave.

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1 Introduction

Observing macroscopic phenomena arising from quantum anomalies is a subject of interest for a wide range of physics communities, from magnetized relativistic matter in three-dimensional Dirac and Weyl materials [1–3] to hot plasma in the early universe or formed in relativistic heavy ion collisions [4–6]. In quantum chromodynamics, gluon fields within a localized region of space-time can form nontrivial topological configurations [7–10]. If approximate chiral symmetry is restored, the interactions of chiral quarks with these gluon fields can produce a chirality imbalance, violating the local P and CP symmetries [9, 10]. This anomalous chiral effect can manifest itself as an electric current along or opposite to a strong magnetic field [11–13]. The electric charge separation produced by these currents is known as the chiral magnetic effect (CME) [11]. The chiral separation effect (CSE) is a similar process, where the separation of the chiral charges along the magnetic field will be induced by a finite density of the net electric charges [14]. The coupling of electric and chiral charge densities and currents leads to a long-wavelength collective excitation, known as the chiral magnetic wave (CMW) [14–17].

In relativistic heavy ion (AA) collisions, a strong magnetic field and the restoration of the approximate chiral symmetry, both necessary conditions for creating a CMW, may be present. The magnetic field is produced by the spectator protons and is, on average, perpendicular to the reaction plane defined by the impact parameter and beam directions. The propagation of the CMW leads to an electric quadrupole moment, where additional positive (negative) charges are accumulated away from (close to) the reaction plane [14]. Following a hydrodynamic evolution of the medium formed in AA collisions, this electric quadrupole moment is expected to result in a charge-dependent variation of the second-order anisotropy coefficient (v_2) in the Fourier expansion of the final-state particle azimuthal distribution. More specifically, the v_2 coefficient will exhibit a linear dependence on the observed event charge asymmetry [14], $A_{\text{ch}} \equiv (N_+ - N_-)/(N_+ + N_-)$, where N_+ and N_- denote the number of positively and negatively charged hadrons in each event,

$$v_{2,\pm} = v_{2,\pm}^{\text{base}} \mp r A_{\text{ch}}. \quad (1)$$

Here $v_{2,\pm}^{\text{base}}$ represents the value in the absence of a charge quadrupole moment from the CMW for positively (+) and negatively (–) charged particles, and r denotes the slope parameter. In the presence of a CMW, the difference of v_2 values between positively and negatively charged particles will be proportional to A_{ch} . Similar charge-dependent effects from the CMW are not expected for the third-order anisotropy coefficient (v_3) [13].

Recent observations of the A_{ch} dependence of $v_{2,\pm}$ in AA collisions at RHIC at BNL and the CERN LHC are qualitatively consistent with expectations of the CMW mechanism [5, 18, 19]. However, the interpretation of the results remains inconclusive since alternative mechanisms have been proposed to generate charge-dependent v_2 coefficients without a CMW [20, 21]. For example, it has been shown that local charge conservation (LCC) in the decay of clusters or resonances can qualitatively describe the charge-dependent v_2 data [20]. Decay particles from a lower transverse momentum (p_T) resonance tend to have a larger rapidity separation, resulting in a daughter more likely to fall outside the detector acceptance, leading to a nonzero A_{ch} . Hence, this process generates a correlation between A_{ch} and the average p_T of charged particles, and therefore also between A_{ch} and the v_2 coefficient, since v_2 depends on p_T . The LCC mechanism also applies to all higher-order anisotropy Fourier coefficients (v_n).

This paper presents measurements of the A_{ch} dependence of the $\langle p_T \rangle$ and of the p_T -averaged v_n coefficients in pPb and PbPb collisions at $\sqrt{s_{\text{NN}}} = 5.02$ TeV, using data collected with the CMS experiment at the LHC. It has been shown that pp and pPb collisions with high charged-

particle multiplicities can generate large final-state azimuthal anisotropies, comparable to those in AA collisions at similar event multiplicities [22–35]. However, the CMW contribution to any A_{ch} -dependent v_2 signal is expected to be negligible in pPb collisions: the induced magnetic field is smaller than in PbPb collisions (albeit of the same order of magnitude) and, more importantly, its correlation with the harmonic event planes is vanishingly small [6, 36]. The recent observation of nearly identical charge-dependent azimuthal correlations in pPb and PbPb suggested significant contamination of background sources (e.g., LCC) to any CME induced signal [6, 37]. Therefore, a comparison between pPb and PbPb systems and their A_{ch} dependence of the $\langle p_T \rangle$ and the v_3 coefficient can differentiate between the CMW and LCC mechanisms. It is worth noting that a lack of experimental evidence for the CME [6, 37] does not necessarily imply the absence of the CMW, as the CME requires an initial chirality imbalance from topological QCD charges (which may be too weak to be observed), whereas the CMW only requires an initial net electric charge density [14, 16]. Therefore, the CME and CMW deserve independent experimental investigations.

2 The CMS detector

The central feature of the CMS apparatus is a superconducting solenoid of 6 m internal diameter, providing a magnetic field of 3.8 T. Within the solenoid volume, there are silicon pixel and strip tracker detectors, a lead tungstate crystal electromagnetic calorimeter, and a brass and scintillator hadron calorimeter. The silicon tracker measures charged particles within the pseudorapidity range $|\eta| < 2.5$. For charged particles with $1 < p_T < 10 \text{ GeV}/c$ and $|\eta| < 1.4$, the track resolutions are typically 1.5% in p_T and 25–90 (45–150) μm in the transverse (longitudinal) impact parameter [38]. Iron and quartz-fiber Cherenkov hadron forward (HF) calorimeters cover the range $2.9 < |\eta| < 5.2$. A detailed description of the CMS detector, together with a definition of the coordinate system used and the relevant kinematic variables, can be found in Ref. [39].

3 Event and track selections

The pPb data at $\sqrt{s_{\text{NN}}} = 5.02 \text{ TeV}$, collected in 2013 using the CMS detector, correspond to an integrated luminosity of 35 nb^{-1} . A subset of peripheral PbPb data at $\sqrt{s_{\text{NN}}} = 5.02 \text{ TeV}$ collected in 2015 (30–90% centrality, where centrality is defined as the fraction of the total inelastic cross section, with 0% denoting the most central collisions [40]), is also used. The sample is reconstructed with the same algorithm as the pPb data, in order to compare directly the two systems at similar multiplicities. The event reconstruction, event selection and the trigger, including the dedicated triggers to collect a large sample of high-multiplicity pPb events, are identical to those used in previous CMS particle correlation measurements [6, 22, 32]. In the offline analysis of pPb (PbPb) collisions, hadronic events are selected by requiring the presence of at least one (three) energy deposit(s) greater than 3 GeV in each of the two HF calorimeters. Events are also required to contain a primary vertex within 15 cm of the nominal interaction point along the beam axis and 0.15 cm in the transverse direction. In the pPb data sample, there is a 3% probability to have at least one additional interaction in the same bunch crossing (pileup). After the procedure used to reject pileup events is applied, the remaining sample has a purity of 99.8% for single collision events [32]. The pileup in PbPb data is negligible.

Primary tracks, i.e., tracks that originate at the primary vertex and satisfy the high-purity criteria of Ref. [38], are used to define the event charged-particle multiplicity ($N_{\text{trk}}^{\text{offline}}$) and to perform correlation measurements. In addition, the impact parameter significance of the tracks

with respect to the primary vertex in the beam and transverse direction is required to be less than 3. The relative uncertainty in p_T must be less than 10%. To ensure high tracking efficiency, only tracks with $|\eta| < 2.4$ and $p_T > 0.3 \text{ GeV}/c$ are used for A_{ch} and v_n measurements in this analysis. The pPb and PbPb data are compared in ranges of $N_{\text{trk}}^{\text{offline}}$, where primary tracks with $|\eta| < 2.4$ and $p_T > 0.4 \text{ GeV}/c$ are counted, in order to match the trigger selection criterion implemented at the HLT in pPb collisions.

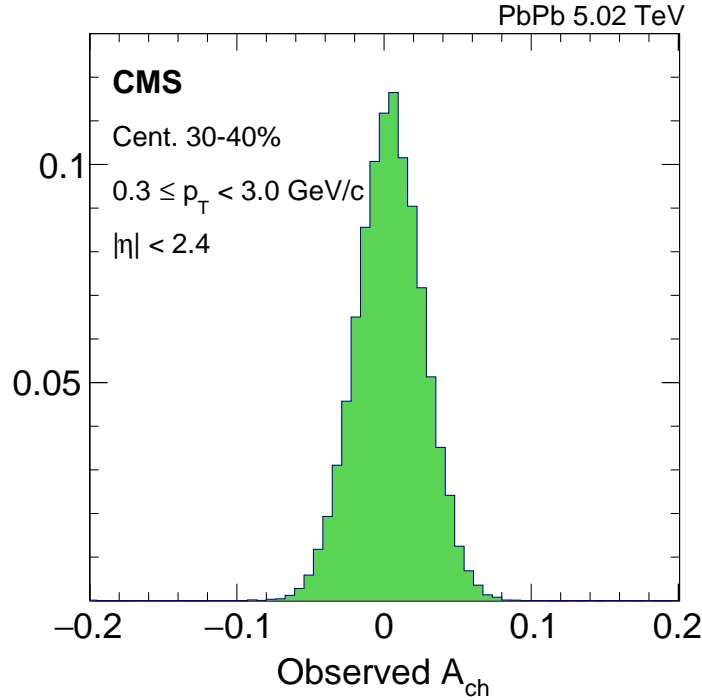


Figure 1: The event-by-event probability distribution observed in the charge asymmetry, A_{ch} , for PbPb collisions at $\sqrt{s_{\text{NN}}} = 5.02 \text{ TeV}$ within the 30–40% centrality range. The particles are selected between 0.3 to 3.0 GeV/c and having pseudorapidity $|\eta| < 2.4$.

4 Analysis technique

In each multiplicity or centrality class, events are further divided into several ranges of the observed event charge asymmetry, $A_{\text{ch}}^{\text{obs}}$, calculated based on the number of positively and negatively charged particles from primary tracks. An example of the $A_{\text{ch}}^{\text{obs}}$ distribution for PbPb data in the 30–40% centrality range is shown in Fig. 1. Within each $A_{\text{ch}}^{\text{obs}}$ range, the v_n coefficients are obtained separately for tracks with positive (v_n^+) and negative (v_n^-) charge, and with $|\eta| < 2.4$ and $0.3 < p_T < 3 \text{ GeV}/c$, using the two-particle cumulant method [41] with a pseudorapidity gap of at least 1 unit between the two particles to suppress the short-range correlations. Because of statistical limitations, the pseudorapidity gap chosen in this analysis is smaller than the value of 2 units typically used in other CMS correlation measurements, but results are found to be consistent between 1 and 2 units of pseudorapidity gap. Residual effects of short-range correlations may still contribute to the sum of the $v_n, v_n^- + v_n^+$, but not the difference since the effect is largely canceled out. However, this effect contributes to the pPb and PbPb systems similarly [32], so it has little impact on the comparison of the two systems.

The main physics observable of interest in this analysis is the slope parameter (r^{norm}) extracted by fitting a linear function to the normalized v_n differences, $(v_n^- - v_n^+) / (v_n^- + v_n^+)$, as a function

of the true event charge asymmetry value, $A_{\text{ch}}^{\text{true}}$, obtained by correcting $A_{\text{ch}}^{\text{obs}}$ for the detector acceptance and tracking efficiency. Based on Monte Carlo (MC) simulations, detector effects can be modeled as a Gaussian response of the $A_{\text{ch}}^{\text{true}}$ distribution within $|\eta| < 2.4$, with a width determined from the simulated $A_{\text{ch}}^{\text{obs}}$ distribution at a given $A_{\text{ch}}^{\text{true}}$ value. Combining the $A_{\text{ch}}^{\text{obs}}$ distribution in data with the response function from MC simulations, the predicted correlation between $A_{\text{ch}}^{\text{obs}}$ and $A_{\text{ch}}^{\text{true}}$ in data is calculated. The slope of a linear fit to this correlation is used to obtain the average $A_{\text{ch}}^{\text{true}}$ value in each selected $A_{\text{ch}}^{\text{obs}}$ range in data. The slope, which ranges from 0.6 to 0.8, is fit separately for each multiplicity or centrality selection. This procedure is validated using different MC generators, which give similar correction factors.

The systematic uncertainty related to the A_{ch} correction factors, based on the difference between EPOS LHC [42] and HYDJET++ [43] event generators, is estimated to be 1–7% ranging from high- to low-multiplicity events. To evaluate the systematic uncertainty related to the v_n measurement, the sensitivity of the results to different track selection criteria is studied. Varying the longitudinal and transverse track impact parameter selection criteria from the default three standard deviations to two or five, and the relative p_T uncertainty selection criterion from the default 10% to 5%, yields a systematic uncertainty of less than 2%. The longitudinal primary vertex position (z_{vtx}) has been varied, using ranges $|z_{\text{vtx}}| < 3$ cm and $3 < |z_{\text{vtx}}| < 15$ cm, where the difference with respect to the default range $|z_{\text{vtx}}| < 15$ cm is less than 2%. All of the systematic uncertainty sources are uncorrelated and were found to be similar for pPb and PbPb collisions. Therefore, the total systematic uncertainty is taken as the quadratic sum, and the same values are quoted for both pPb and PbPb systems.

5 Results

Figure 2 (left column) shows the $A_{\text{ch}}^{\text{true}}$ dependence of v_2 coefficients, averaged over $0.3 < p_T < 3$ GeV/c, for positively and negatively charged particles in the multiplicity range $185 \leq N_{\text{trk}}^{\text{offline}} < 220$ of pPb and PbPb collisions at $\sqrt{s_{\text{NN}}} = 5.02$ TeV. The normalized v_2 difference as a function of $A_{\text{ch}}^{\text{true}}$ is also shown. A trend of v_2^+ (v_2^-) decreasing (increasing) as $A_{\text{ch}}^{\text{true}}$ increases is observed for both pPb and PbPb collisions with an approximately linear dependence. A similar linear trend of elliptic anisotropy as a function of A_{ch} has been observed in AuAu [18] and PbPb [19] systems at lower collision energies, as shown in Fig. 3 for 30–40% centrality PbPb events. The linear slope parameter, r_2^{norm} , is extracted by a χ^2 fit to a linear function, which gives values of 0.149 ± 0.008 for pPb and 0.108 ± 0.005 for PbPb, in the multiplicity range $185 \leq N_{\text{trk}}^{\text{offline}} < 220$. A significant nonzero value of the linear slope parameter is observed in pPb collisions, even greater than that in PbPb collisions. Since the CMW effect is expected to be negligible in high-multiplicity pPb events, this observation might be caused, at LHC energies, by a mechanism unrelated to the CMW. The differences in the linear slope parameters observed in the pPb and PbPb systems remain to be understood.

The $\langle p_T \rangle$ for positively and negatively charged particles are also measured as functions of $A_{\text{ch}}^{\text{true}}$, in the multiplicity range $185 \leq N_{\text{trk}}^{\text{offline}} < 220$ of pPb and PbPb collisions at $\sqrt{s_{\text{NN}}} = 5.02$ TeV, and shown in Fig. 2 (right column). The normalized $\langle p_T \rangle$ difference as a function of $A_{\text{ch}}^{\text{true}}$ is obtained for the two systems with the slope parameters displayed in the figure. A similar linear $A_{\text{ch}}^{\text{true}}$ dependence of the $\langle p_T \rangle$ value to that of v_2 is observed. This behavior is qualitatively consistent with the expectation of the LCC effect from resonance decays. Since v_n has a strong dependence on particle p_T , a correlation between the p_T -averaged v_n and A_{ch} , as observed in Fig. 2 (left), can also be induced by the LCC mechanism.

The extracted normalized slope parameters for v_2 and $\langle p_T \rangle$ as functions of event multiplicity

in pPb and PbPb collisions are shown in Fig. 4. The r^{norm} values for both v_2 and $\langle p_T \rangle$ are found to have a weak dependence on the event multiplicity for both pPb and PbPb collisions, with values for $\langle p_T \rangle$ approximately half of those for v_2 . In the overlapping multiplicity range, normalized slope parameters are observed to be larger in pPb than PbPb collisions, which is not expected in the CMW context and may indicate a collision system dependence of the LCC or other mechanisms. The measured normalized slope parameters, as well as the absolute slope parameters, for each multiplicity or centrality range of pPb and PbPb collisions, are reported in Tables 1–3.

Table 1: The table summarizes the absolute and normalized slope parameters (r) from v_2 and $\langle p_T \rangle$ in ranges of multiplicity class, $N_{\text{trk}}^{\text{offline}}$, in pPb collisions at $\sqrt{s_{\text{NN}}} = 5.02$ TeV. The first uncertainty associated with the central values denotes statistical errors, while the second uncertainty represents the systematic uncertainty.

$N_{\text{trk}}^{\text{offline}}$	$r_{\langle v_2 \rangle}$	$r_{\langle v_2 \rangle}^{\text{norm}}$	$r_{\langle p_T \rangle}$	$r_{\langle p_T \rangle}^{\text{norm}}$
[120, 150)	$0.022 \pm 0.001 \pm 0.002$	$0.163 \pm 0.01 \pm 0.011$	$0.103 \pm 0.001 \pm 0.007$	$0.06 \pm 0 \pm 0.004$
[150, 185)	$0.02 \pm 0.001 \pm 0.001$	$0.145 \pm 0.008 \pm 0.009$	$0.105 \pm 0.001 \pm 0.007$	$0.06 \pm 0 \pm 0.004$
[185, 220)	$0.02 \pm 0.001 \pm 0.001$	$0.143 \pm 0.008 \pm 0.009$	$0.108 \pm 0.001 \pm 0.007$	$0.062 \pm 0.001 \pm 0.004$
[220, 260)	$0.022 \pm 0.002 \pm 0.001$	$0.153 \pm 0.012 \pm 0.009$	$0.111 \pm 0.002 \pm 0.007$	$0.063 \pm 0.001 \pm 0.004$

The charge asymmetry dependence of the v_3 coefficient for positively and negatively charged particles is also studied in PbPb collisions at $\sqrt{s_{\text{NN}}} = 5.02$ TeV, as shown in Fig. 5 (top) for the 30–40% centrality class. As found for the v_2 values, the v_3^+ (v_3^-) values also decrease (increase) as $A_{\text{ch}}^{\text{true}}$ increases. No v_3 results for pPb collisions are reported because of limited statistical precision. The normalized v_3 difference, $(v_3^- - v_3^+) / (v_3^- + v_3^+)$, is derived as a function of

Table 2: The table summarizes the absolute and normalized slope parameters (r) from v_2 and $\langle p_T \rangle$ in ranges of multiplicity class, $N_{\text{trk}}^{\text{offline}}$, in PbPb collisions at $\sqrt{s_{\text{NN}}} = 5.02$ TeV. The first uncertainty associated with the central values denotes statistical errors, while the second uncertainty represents the systematic uncertainty.

$N_{\text{trk}}^{\text{offline}}$	$r_{\langle v_2 \rangle}$	$r_{\langle v_2 \rangle}^{\text{norm}}$	$r_{\langle p_T \rangle}$	$r_{\langle p_T \rangle}^{\text{norm}}$
[90, 120)	$0.02 \pm 0.001 \pm 0.001$	$0.12 \pm 0.007 \pm 0.009$	$0.084 \pm 0.001 \pm 0.006$	$0.056 \pm 0 \pm 0.004$
[120, 150)	$0.023 \pm 0.001 \pm 0.002$	$0.131 \pm 0.006 \pm 0.009$	$0.084 \pm 0.001 \pm 0.006$	$0.056 \pm 0.001 \pm 0.004$
[150, 185)	$0.022 \pm 0.001 \pm 0.001$	$0.119 \pm 0.005 \pm 0.008$	$0.087 \pm 0.001 \pm 0.006$	$0.057 \pm 0.001 \pm 0.004$
[185, 220)	$0.022 \pm 0.001 \pm 0.001$	$0.108 \pm 0.005 \pm 0.007$	$0.087 \pm 0.001 \pm 0.006$	$0.058 \pm 0.001 \pm 0.004$
[220, 260)	$0.025 \pm 0.001 \pm 0.001$	$0.126 \pm 0.004 \pm 0.008$	$0.091 \pm 0.001 \pm 0.005$	$0.059 \pm 0.001 \pm 0.004$
[260, 300)	$0.025 \pm 0.001 \pm 0.001$	$0.122 \pm 0.004 \pm 0.007$	$0.093 \pm 0.001 \pm 0.005$	$0.06 \pm 0.001 \pm 0.003$
[300, 400)	$0.028 \pm 0 \pm 0.001$	$0.133 \pm 0.002 \pm 0.007$	$0.094 \pm 0.001 \pm 0.005$	$0.061 \pm 0 \pm 0.003$
[400, 500)	$0.03 \pm 0 \pm 0.001$	$0.141 \pm 0.002 \pm 0.007$	$0.099 \pm 0.001 \pm 0.005$	$0.064 \pm 0.001 \pm 0.003$

Table 3: The table summarizes the absolute and normalized slope parameters (r) from v_2 and v_3 in ranges of centrality class, in PbPb collisions at $\sqrt{s_{\text{NN}}} = 5.02$ TeV. The first uncertainty associated with the central values denotes statistical errors, while the second uncertainty represents the systematic uncertainty.

Centrality	$r_{\langle v_2 \rangle}$	$r_{\langle v_2 \rangle}^{\text{norm}}$	$r_{\langle v_3 \rangle}$	$r_{\langle v_3 \rangle}^{\text{norm}}$
30–40%	$0.032 \pm 0 \pm 0.001$	$0.162 \pm 0.001 \pm 0.006$	$0.01 \pm 0.0006 \pm 0.0004$	$0.149 \pm 0.008 \pm 0.006$
40–50%	$0.032 \pm 0 \pm 0.001$	$0.151 \pm 0.001 \pm 0.006$	$0.0102 \pm 0.0007 \pm 0.0004$	$0.15 \pm 0.01 \pm 0.006$
50–60%	$0.028 \pm 0 \pm 0.001$	$0.135 \pm 0.001 \pm 0.007$	$0.0083 \pm 0.001 \pm 0.0004$	$0.131 \pm 0.016 \pm 0.007$
60–70%	$0.024 \pm 0 \pm 0.002$	$0.126 \pm 0.002 \pm 0.008$	$0.0054 \pm 0.0016 \pm 0.0003$	$0.102 \pm 0.03 \pm 0.006$
70–80%	$0.022 \pm 0.001 \pm 0.002$	$0.136 \pm 0.004 \pm 0.011$	—	—
80–90%	$0.022 \pm 0.002 \pm 0.002$	$0.171 \pm 0.012 \pm 0.014$	—	—

$A_{\text{ch}}^{\text{true}}$ in PbPb collisions and compared with that for v_2 in Fig. 5 (bottom). The normalized slope parameter of v_3 , r_3^{norm} , agrees well with r_2^{norm} within statistical uncertainties. Charge-dependent higher harmonic v_n coefficients were measured in PbPb collisions at 2.76 TeV [5] and their magnitude was found to be smaller than that of the second order coefficient. We show in this paper that, once normalized, no difference is observed for the $A_{\text{ch}}^{\text{true}}$ dependence between the charge-dependent v_2 and v_3 .

The r_2^{norm} and r_3^{norm} values of PbPb collisions at $\sqrt{s_{\text{NN}}} = 5.02$ TeV are shown in Fig. 6, as functions of centrality in the range 30–90%. As found for r_2^{norm} , a moderate centrality dependence of r_3^{norm} is observed. Over the centrality range studied in this analysis, the r_2^{norm} and r_3^{norm} slope parameters are consistent with each other within uncertainties. The CMW effect is expected with respect to the reaction plane, which is approximated by the second-order event plane in AA collisions, but highly suppressed with respect to the third-order event plane [13]. The observation of the harmonic order independence, reflected in the similar r_2^{norm} and r_3^{norm} values, indicates an underlying physics mechanism unrelated to the CMW effect and, instead, can be qualitatively explained by the LCC effect [20].

Note that the results reported here and elsewhere [18, 19] used the same population of particles to measure both v_n and $A_{\text{ch}}^{\text{true}}$. However, the slope parameters are found to be reduced by about a factor of three, if the $A_{\text{ch}}^{\text{true}}$ and v_n values are determined by two distinct groups of randomly selected particles. This suggests that the observed correlations are not of a collective nature.

6 Summary

In summary, the charge-dependent Fourier coefficients of the azimuthal anisotropy have been measured in pPb and PbPb collisions at $\sqrt{s_{\text{NN}}} = 5.02$ TeV as functions of the charge asymmetry of the produced hadrons. The normalized differences in the v_2 coefficient between positively and negatively charged particles in pPb and PbPb, and that in the v_3 coefficient in PbPb collisions, are found to depend linearly on the charge asymmetry. The normalized slope parameters of the v_2 coefficient versus charge asymmetry in pPb collisions are found to be significant and similar to those in PbPb collisions over a wide range of charged particle multiplicities. The normalized slope parameters of the v_2 and v_3 coefficients in PbPb collisions show similar magnitudes for various centrality classes. A significant charged asymmetry dependence is also observed for the event-averaged transverse momenta of positively and negatively charged particles in both pPb and PbPb collisions. None of these observations, made at 5.02 TeV and within the CMS phase space window, are expected from the chiral magnetic wave as the dominant physics mechanism, while they are qualitatively consistent with predictions based on local charge conservation. The new measurements presented here indicate that, at LHC energies, the chiral magnetic wave is not the cause of the charge-dependent azimuthal anisotropies seen in pPb and PbPb collisions.

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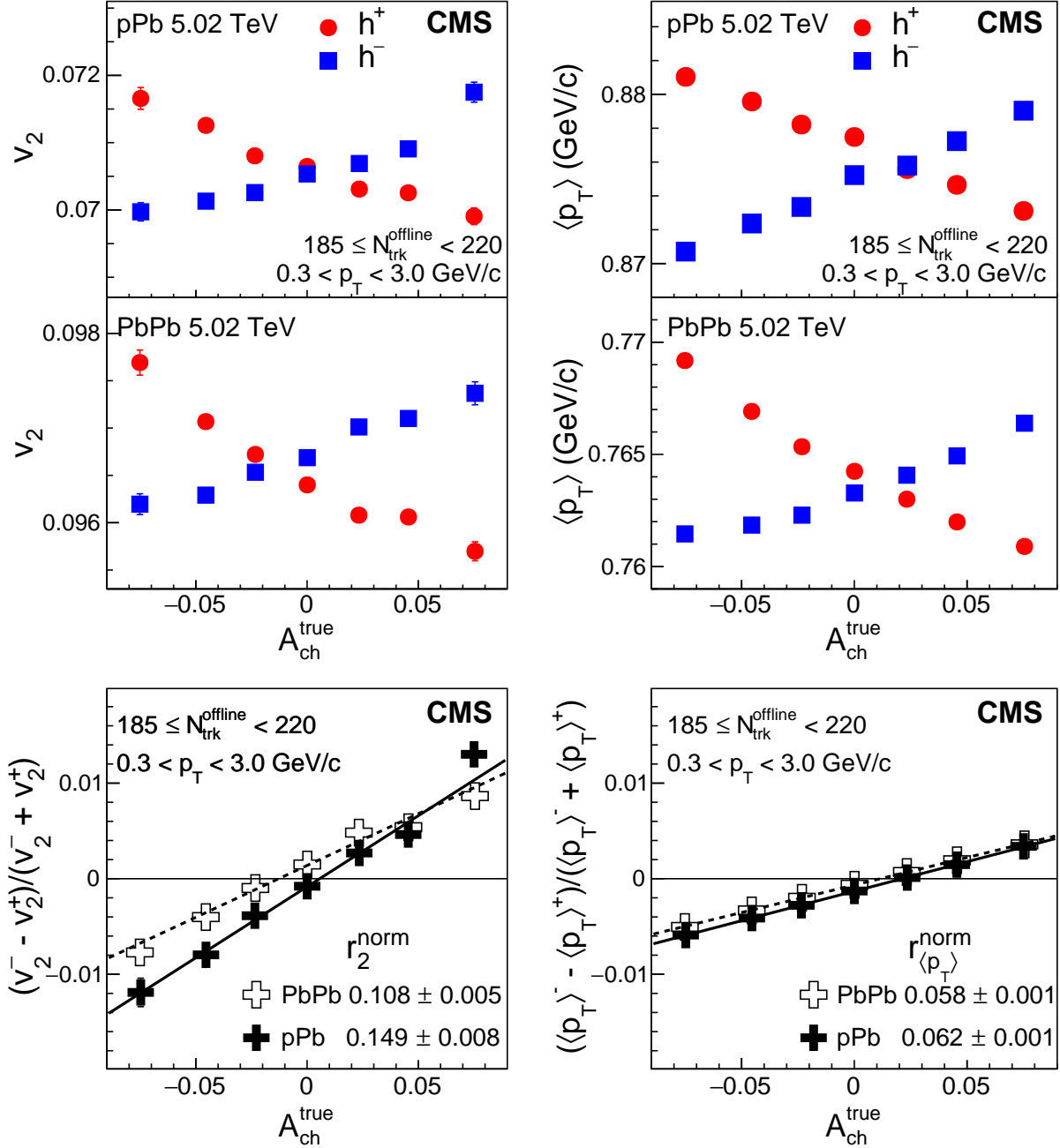


Figure 2: The elliptic anisotropy v_2 (top left) and event-averaged $\langle p_T \rangle$ (top right) for positively (h^+) and negatively (h^-) charged particles, and their normalized differences (bottom row), as functions of A_{ch}^{true} for the multiplicity range $185 \leq N_{trk}^{offline} < 220$ of pPb and PbPb collisions at $\sqrt{s_{NN}} = 5.02$ TeV. Statistical uncertainties are smaller than the marker size, while systematic uncertainties are not displayed.

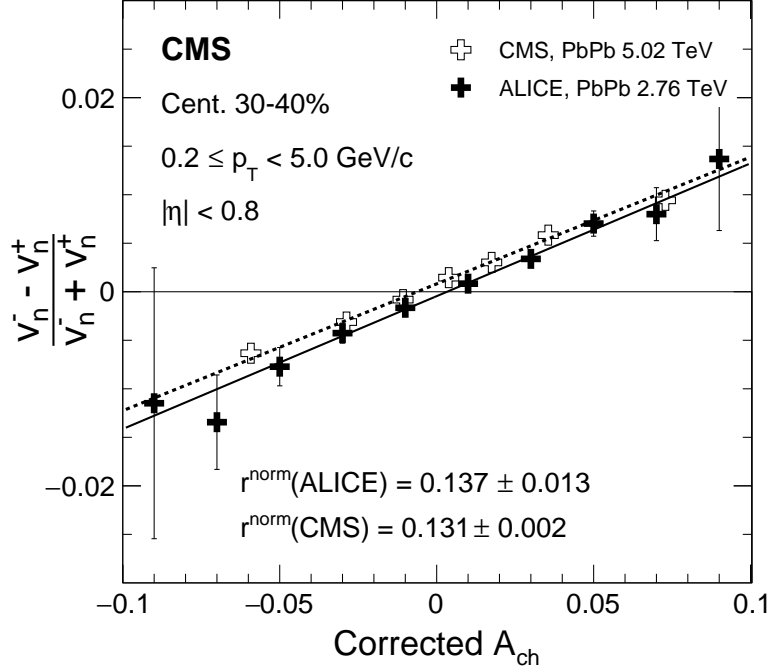


Figure 3: The normalized difference in elliptic flow v_2 between positive- and negative-charged particles, $(v_2^- - v_2^+)/ (v_2^- + v_2^+)$, as a function of charge asymmetry, is presented. The results are selected in centrality range 30–40% with particles within $|\eta| < 0.8$ and $0.2 \leq p_T < 5.0$ GeV, and are compared between the ALICE [19] and the CMS experiment in PbPb collisions at $\sqrt{s_{NN}} = 2.76$ TeV and 5.02 TeV, respectively. The bars represent statistical point-by-point uncertainties.

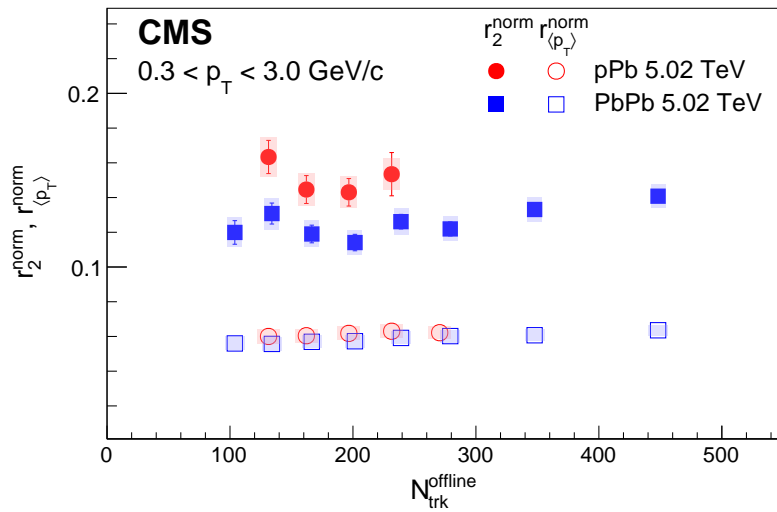


Figure 4: The linear slope parameters, r_2^{norm} , for v_2 (filled symbols) and $\langle p_T \rangle$ (open symbols) as functions of event multiplicity in pPb and PbPb collisions at $\sqrt{s_{NN}} = 5.02$ TeV. Statistical and systematic uncertainties are indicated by the error bars and shaded regions, respectively.

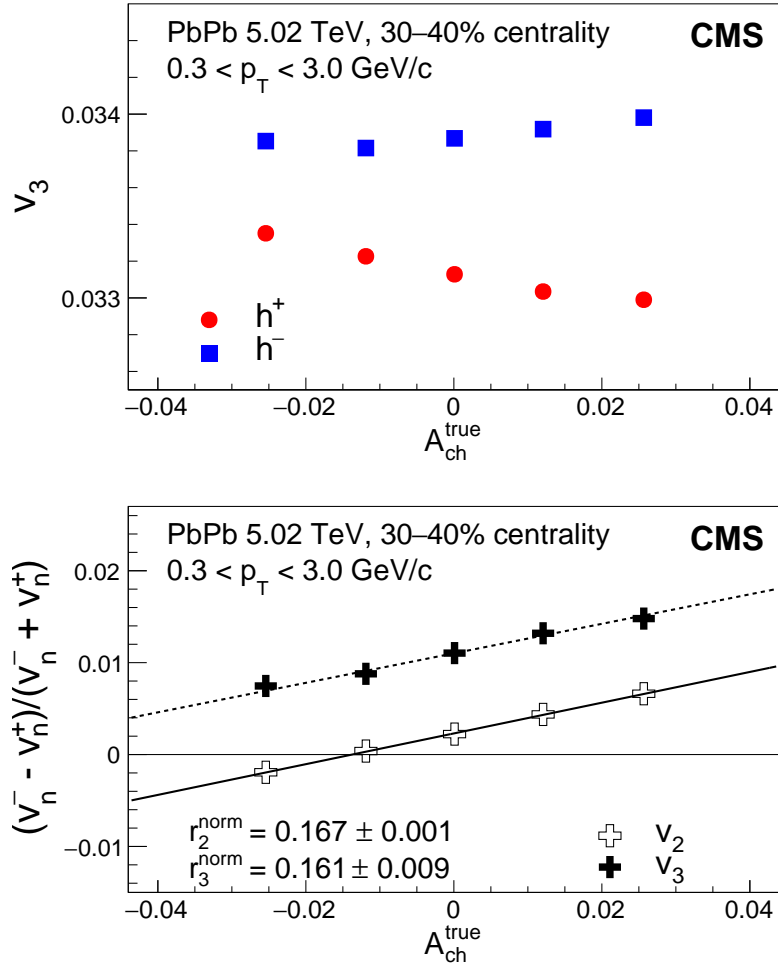


Figure 5: The v_3 coefficient for positively and negatively charged particles (top) and the normalized difference in v_n , $(v_n^- - v_n^+) / (v_n^- + v_n^+)$ (bottom), for $n = 2$ and 3 , as functions of true event charge asymmetry for the 30–40% centrality class in PbPb collisions at $\sqrt{s_{NN}} = 5.02$ TeV.

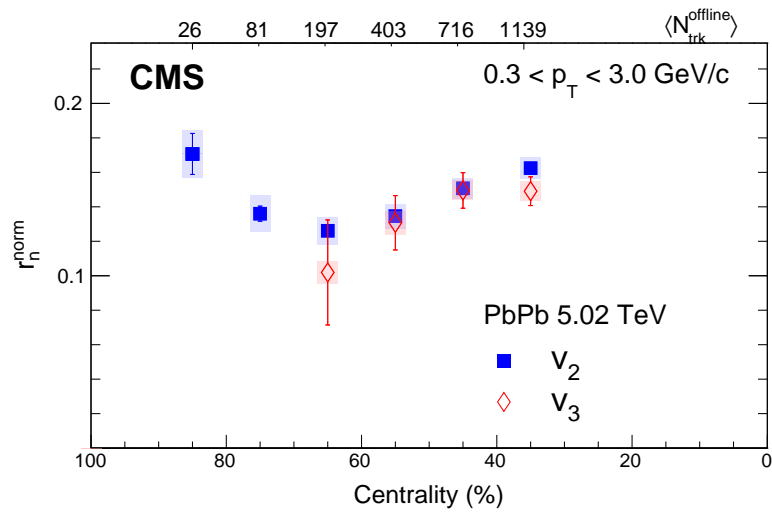


Figure 6: The linear slope parameters, r_2^{norm} and r_3^{norm} as functions of the centrality class in PbPb collisions. Average $N_{\text{trk}}^{\text{offline}}$ values for each centrality class are indicated on the top axis. Statistical and systematic uncertainties are indicated by the error bars and shaded regions, respectively.

A The CMS Collaboration

Yerevan Physics Institute, Yerevan, Armenia

A.M. Sirunyan, A. Tumasyan

Institut für Hochenergiephysik, Wien, Austria

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

Institute for Nuclear Problems, Minsk, Belarus

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

Universiteit Antwerpen, Antwerpen, Belgium

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

Vrije Universiteit Brussel, Brussel, Belgium

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

Université Libre de Bruxelles, Bruxelles, Belgium

H. Brun, B. Clerbaux, G. De Lentdecker, H. Delannoy, G. Fasanella, L. Favart, R. Goldouzian, A. Grebenyuk, G. Karapostoli, T. Lenzi, J. Luetic, T. Maerschalk, A. Marinov, A. Randle-conde, T. Seva, C. Vander Velde, P. Vanlaer, D. Vannerom, R. Yonamine, F. Zenoni, F. Zhang²

Ghent University, Ghent, Belgium

A. Cimmino, T. Cornelis, D. Dobur, A. Fagot, M. Gul, I. Khvastunov, D. Poyraz, C. Roskas, S. Salva, M. Tytgat, W. Verbeke, N. Zaganidis

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

H. Bakhshiansohi, O. Bondu, S. Brochet, G. Bruno, C. Caputo, A. Caudron, S. De Visscher, C. Delaere, M. Delcourt, B. Francois, A. Giammanco, A. Jafari, M. Komm, G. Krintiras, V. Lemaitre, A. Magitteri, A. Mertens, M. Musich, K. Piotrkowski, L. Quertenmont, M. Vidal Marono, S. Wertz

Université de Mons, Mons, Belgium

N. Bely

Centro Brasileiro de Pesquisas Fisicas, Rio de Janeiro, Brazil

W.L. Aldá Júnior, F.L. Alves, G.A. Alves, L. Brito, M. Correa Martins Junior, C. Hensel, A. Moraes, M.E. Pol, P. Rebello Teles

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

E. Belchior Batista Das Chagas, W. Carvalho, J. Chinellato³, A. Custódio, E.M. Da Costa, G.G. Da Silveira⁴, D. De Jesus Damiao, S. Fonseca De Souza, L.M. Huertas Guativa, H. Malbouisson, M. Melo De Almeida, C. Mora Herrera, L. Mundim, H. Nogima, A. Santoro, A. Sznajder, E.J. Tonelli Manganote³, F. Torres Da Silva De Araujo, A. Vilela Pereira

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

S. Ahuja^a, C.A. Bernardes^a, T.R. Fernandez Perez Tomei^a, E.M. Gregores^b, P.G. Mercadante^b, S.F. Novaes^a, Sandra S. Padula^a, D. Romero Abad^b, J.C. Ruiz Vargas^a

Institute for Nuclear Research and Nuclear Energy of Bulgaria Academy of Sciences

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

University of Sofia, Sofia, Bulgaria

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

Beihang University, Beijing, China

W. Fang⁵, X. Gao⁵

Institute of High Energy Physics, Beijing, China

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

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

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

Universidad de Los Andes, Bogota, Colombia

C. Avila, A. Cabrera, L.F. Chaparro Sierra, C. Florez, C.F. González Hernández, J.D. Ruiz Alvarez

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

B. Courbon, N. Godinovic, D. Lelas, I. Puljak, P.M. Ribeiro Cipriano, T. Sculac

University of Split, Faculty of Science, Split, Croatia

Z. Antunovic, M. Kovac

Institute Rudjer Boskovic, Zagreb, Croatia

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

University of Cyprus, Nicosia, Cyprus

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

Charles University, Prague, Czech Republic

M. Finger⁷, M. Finger Jr.⁷

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

Y. Assran^{8,9}, M.A. Mahmoud^{10,9}, A. Mahrous¹¹

National Institute of Chemical Physics and Biophysics, Tallinn, Estonia

R.K. Dewanjee, M. Kadastik, L. Perrini, M. Raidal, A. Tiko, C. Veelken

Department of Physics, University of Helsinki, Helsinki, Finland

P. Eerola, J. Pekkanen, M. Voutilainen

Helsinki Institute of Physics, Helsinki, Finland

J. Härkönen, T. Järvinen, V. Karimäki, R. Kinnunen, T. Lampén, K. Lassila-Perini, S. Lehti, T. Lindén, P. Luukka, E. Tuominen, J. Tuominiemi, E. Tuovinen

Lappeenranta University of Technology, Lappeenranta, Finland

J. Talvitie, T. Tuuva

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

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

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

A. Abdulsalam, I. Antropov, S. Baffioni, F. Beaudette, P. Busson, L. Cadamuro, C. Charlot, R. Granier de Cassagnac, M. Jo, S. Lisniak, A. Lobanov, J. Martin Blanco, M. Nguyen, C. Ochando, G. Ortona, P. Paganini, P. Pigard, S. Regnard, R. Salerno, J.B. Sauvan, Y. Sirois, A.G. Stahl Leiton, T. Strebler, Y. Yilmaz, A. Zabi, A. Zghiche

Université de Strasbourg, CNRS, IPHC UMR 7178, F-67000 Strasbourg, FranceJ.-L. Agram¹², J. Andrea, D. Bloch, J.-M. Brom, M. Buttignol, E.C. Chabert, N. Chanon, C. Collard, E. Conte¹², X. Coubez, J.-C. Fontaine¹², D. Gelé, U. Goerlach, M. Jansová, A.-C. Le Bihan, N. Taroni, P. Van Hove**Centre de Calcul de l'Institut National de Physique Nucleaire et de Physique des Particules, CNRS/IN2P3, Villeurbanne, France**

S. Gadrat

Université de Lyon, Université Claude Bernard Lyon 1, CNRS-IN2P3, Institut de Physique Nucléaire de Lyon, Villeurbanne, FranceS. Beauceron, C. Bernet, G. Boudoul, R. Chierici, D. Contardo, P. Depasse, H. El Mamouni, J. Fay, L. Finco, S. Gascon, M. Gouzevitch, G. Grenier, B. Ille, F. Lagarde, I.B. Laktineh, M. Lethuillier, L. Mirabito, A.L. Pequegnot, S. Perries, A. Popov¹³, V. Sordini, M. Vander Donckt, S. Viret**Georgian Technical University, Tbilisi, Georgia**T. Toriashvili¹⁴**Tbilisi State University, Tbilisi, Georgia**I. Bagaturia¹⁵**RWTH Aachen University, I. Physikalisches Institut, Aachen, Germany**C. Autermann, S. Beranek, L. Feld, M.K. Kiesel, K. Klein, M. Lipinski, M. Preuten, C. Schomakers, J. Schulz, T. Verlage, V. Zhukov¹³**RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany**

A. Albert, E. Dietz-Laursonn, D. Duchardt, M. Endres, M. Erdmann, S. Erdweg, T. Esch, R. Fischer, A. Güth, M. Hamer, T. Hebbeker, C. Heidemann, K. Hoepfner, S. Knutzen, M. Merschmeyer, A. Meyer, P. Millet, S. Mukherjee, M. Olschewski, K. Padeken, T. Pook, M. Radziej, H. Reithler, M. Rieger, F. Scheuch, D. Teyssier, S. Thüer

RWTH Aachen University, III. Physikalisches Institut B, Aachen, GermanyG. Flügge, B. Kargoll, T. Kress, A. Künsken, J. Lingemann, T. Müller, A. Nehr Korn, A. Nowack, C. Pistone, O. Pooth, A. Stahl¹⁶**Deutsches Elektronen-Synchrotron, Hamburg, Germany**M. Aldaya Martin, T. Arndt, C. Asawatangtrakuldee, K. Beernaert, O. Behnke, U. Behrens, A. Bermúdez Martínez, A.A. Bin Anuar, K. Borras¹⁷, V. Botta, A. Campbell, P. Connor, C. Contreras-Campana, F. Costanza, C. Diez Pardos, G. Eckerlin, D. Eckstein, T. Eichhorn,

E. Eren, E. Gallo¹⁸, J. Garay Garcia, A. Geiser, A. Gizhko, J.M. Grados Luyando, A. Grohsjean, P. Gunnellini, M. Guthoff, A. Harb, J. Hauk, M. Hempel¹⁹, H. Jung, A. Kalogeropoulos, M. Kasemann, J. Keaveney, C. Kleinwort, I. Korol, D. Krücker, W. Lange, A. Lelek, T. Lenz, J. Leonard, K. Lipka, W. Lohmann¹⁹, R. Mankel, I.-A. Melzer-Pellmann, A.B. Meyer, G. Mittag, J. Mnich, A. Mussgiller, E. Ntomari, D. Pitzl, A. Raspereza, B. Roland, M. Savitskyi, P. Saxena, R. Shevchenko, S. Spannagel, N. Stefaniuk, G.P. Van Onsem, R. Walsh, Y. Wen, K. Wichmann, C. Wissing, O. Zenaiev

University of Hamburg, Hamburg, Germany

S. Bein, V. Blobel, M. Centis Vignali, T. Dreyer, E. Garutti, D. Gonzalez, J. Haller, A. Hinzmann, M. Hoffmann, A. Karavdina, R. Klanner, R. Kogler, N. Kovalchuk, S. Kurz, T. Lapsien, I. Marchesini, D. Marconi, M. Meyer, M. Niedziela, D. Nowatschin, F. Pantaleo¹⁶, T. Peiffer, A. Perieanu, C. Scharf, P. Schleper, A. Schmidt, S. Schumann, J. Schwandt, J. Sonneveld, H. Stadie, G. Steinbrück, F.M. Stober, M. Stöver, H. Tholen, D. Troendle, E. Usai, L. Vanelderen, A. Vanhoefer, B. Vormwald

Institut für Experimentelle Kernphysik, Karlsruhe, Germany

M. Akbiyik, C. Barth, S. Baur, E. Butz, R. Caspart, T. Chwalek, F. Colombo, W. De Boer, A. Dierlamm, B. Freund, R. Friese, M. Giffels, A. Gilbert, D. Haitz, F. Hartmann¹⁶, S.M. Heindl, U. Husemann, F. Kassel¹⁶, S. Kudella, H. Mildner, M.U. Mozer, Th. Müller, M. Plagge, G. Quast, K. Rabbertz, M. Schröder, I. Shvetsov, G. Sieber, H.J. Simonis, R. Ulrich, S. Wayand, M. Weber, T. Weiler, S. Williamson, C. Wöhrmann, R. Wolf

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

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

National and Kapodistrian University of Athens, Athens, Greece

G. Karathanasis, S. Kesisoglou, A. Panagiotou, N. Saoulidou

National Technical University of Athens, Athens, Greece

K. Kousouris

University of Ioánnina, Ioánnina, Greece

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

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

M. Csanad, N. Filipovic, G. Pasztor, G.I. Veres²⁰

Wigner Research Centre for Physics, Budapest, Hungary

G. Bencze, C. Hajdu, D. Horvath²¹, Á. Hunyadi, F. Sikler, V. Veszpremi, A.J. Zsigmond

Institute of Nuclear Research ATOMKI, Debrecen, Hungary

N. Beni, S. Czellar, J. Karancsi²², A. Makovec, J. Molnar, Z. Szillasi

Institute of Physics, University of Debrecen, Debrecen, Hungary

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

Indian Institute of Science (IISc), Bangalore, India

S. Choudhury, J.R. Komaragiri

National Institute of Science Education and Research, Bhubaneswar, India

S. Bahinipati²³, S. Bhowmik, P. Mal, K. Mandal, A. Nayak²⁴, D.K. Sahoo²³, N. Sahoo, S.K. Swain

Panjab University, Chandigarh, India

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

University of Delhi, Delhi, India

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

Saha Institute of Nuclear Physics, HBNI, Kolkata, India

R. Bhardwaj, R. Bhattacharya, S. Bhattacharya, U. Bhawandeep, S. Dey, S. Dutt, S. Dutta, S. Ghosh, N. Majumdar, A. Modak, K. Mondal, S. Mukhopadhyay, S. Nandan, A. Purohit, A. Roy, D. Roy, S. Roy Chowdhury, S. Sarkar, M. Sharan, S. Thakur

Indian Institute of Technology Madras, Madras, India

P.K. Behera

Bhabha Atomic Research Centre, Mumbai, India

R. Chudasama, D. Dutta, V. Jha, V. Kumar, A.K. Mohanty¹⁶, P.K. Netrakanti, L.M. Pant, P. Shukla, A. Topkar

Tata Institute of Fundamental Research-A, Mumbai, India

T. Aziz, S. Dugad, B. Mahakud, S. Mitra, G.B. Mohanty, N. Sur, B. Sutar

Tata Institute of Fundamental Research-B, Mumbai, India

S. Banerjee, S. Bhattacharya, S. Chatterjee, P. Das, M. Guhait, Sa. Jain, S. Kumar, M. Maity²⁵, G. Majumder, K. Mazumdar, T. Sarkar²⁵, N. Wickramage²⁶

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

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

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

S. Chenarani²⁷, E. Eskandari Tadavani, S.M. Etesami²⁷, M. Khakzad, M. Mohammadi Najafabadi, M. Naseri, S. Paktinat Mehdiabadi²⁸, F. Rezaei Hosseinabadi, B. Safarzadeh²⁹, M. Zeinali

University College Dublin, Dublin, Ireland

M. Felcini, M. Grunewald

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

M. Abbrescia^{a,b}, C. Calabria^{a,b}, A. Colaleo^a, D. Creanza^{a,c}, L. Cristella^{a,b}, N. De Filippis^{a,c}, M. De Palma^{a,b}, F. Errico^{a,b}, L. Fiore^a, G. Iaselli^{a,c}, S. Lezki^{a,b}, G. Maggi^{a,c}, M. Maggi^a, G. Miniello^{a,b}, S. My^{a,b}, S. Nuzzo^{a,b}, A. Pompili^{a,b}, G. Pugliese^{a,c}, R. Radogna^a, A. Ranieri^a, G. Selvaggi^{a,b}, A. Sharma^a, L. Silvestris^{a,16}, R. Venditti^a, P. Verwilligen^a

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

G. Abbiendi^a, C. Battilana^{a,b}, D. Bonacorsi^{a,b}, S. Braibant-Giacomelli^{a,b}, R. Campanini^{a,b}, P. Capiluppi^{a,b}, A. Castro^{a,b}, F.R. Cavallo^a, S.S. Chhibra^a, G. Codispoti^{a,b}, M. Cuffiani^{a,b}, G.M. Dallavalle^a, F. Fabbri^a, A. Fanfani^{a,b}, D. Fasanella^{a,b}, P. Giacomelli^a, C. Grandi^a, L. Guiducci^{a,b}, S. Marcellini^a, G. Masetti^a, A. Montanari^a, F.L. Navarra^{a,b}, A. Perrotta^a, A.M. Rossi^{a,b}, T. Rovelli^{a,b}, G.P. Siroli^{a,b}, N. Tosi^a

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

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

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

G. Barbagli^a, K. Chatterjee^{a,b}, V. Ciulli^{a,b}, C. Civinini^a, R. D'Alessandro^{a,b}, E. Focardi^{a,b}, P. Lenzi^{a,b}, M. Meschini^a, S. Paoletti^a, L. Russo^{a,30}, G. Sguazzoni^a, D. Strom^a, L. Viliani^{a,b,16}

INFN Laboratori Nazionali di Frascati, Frascati, Italy

L. Benussi, S. Bianco, F. Fabbri, D. Piccolo, F. Primavera¹⁶

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

V. Calvelli^{a,b}, 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, L. Brianza^{a,b}, F. Brivio^{a,b}, V. Ciriolo^{a,b}, M.E. Dinardo^{a,b}, S. Fiorendi^{a,b}, S. Gennai^a, A. Ghezzi^{a,b}, P. Govoni^{a,b}, M. Malberti^{a,b}, S. Malvezzi^a, R.A. Manzoni^{a,b}, D. Menasce^a, L. Moroni^a, M. Paganoni^{a,b}, K. Pauwels^{a,b}, D. Pedrini^a, S. Pigazzini^{a,b,31}, S. Ragazzi^{a,b}, T. Tabarelli de Fatis^{a,b}

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

S. Buontempo^a, N. Cavallo^{a,c}, S. Di Guida^{a,d,16}, F. Fabozzi^{a,c}, F. Fienga^{a,b}, A.O.M. Iorio^{a,b}, W.A. Khan^a, L. Lista^a, S. Meola^{a,d,16}, P. Paolucci^{a,16}, C. Sciacca^{a,b}, F. Thyssen^a

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

P. Azzi^{a,16}, N. Bacchetta^a, L. Benato^{a,b}, M. Biasotto^{a,32}, A. Boletti^{a,b}, R. Carlin^{a,b}, P. Checchia^a, M. Dall'Osso^{a,b}, P. De Castro Manzano^a, T. Dorigo^a, U. Dosselli^a, F. Gasparini^{a,b}, U. Gasparini^{a,b}, A. Gozzelino^a, S. Lacaprara^a, M. Margoni^{a,b}, A.T. Meneguzzo^{a,b}, M. Michelotto^a, N. Pozzobon^{a,b}, P. Ronchese^{a,b}, R. Rossin^{a,b}, F. Simonetto^{a,b}, E. Torassa^a, M. Zanetti^{a,b}, P. Zotto^{a,b}, G. Zumerle^{a,b}

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

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

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

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

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

K. Androsov^a, P. Azzurri^{a,16}, G. Bagliesi^a, J. Bernardini^a, T. Boccali^a, L. Borrello, R. Castaldi^a, M.A. Ciocci^{a,b}, R. Dell'Orso^a, G. Fedi^a, L. Giannini^{a,c}, A. Giassi^a, M.T. Grippo^{a,30}, F. Ligabue^{a,c}, T. Lomtadze^a, E. Manca^{a,c}, G. Mandorli^{a,c}, L. Martini^{a,b}, A. Messineo^{a,b}, F. Palla^a, A. Rizzi^{a,b}, A. Savoy-Navarro^{a,33}, P. Spagnolo^a, R. Tenchini^a, G. Tonelli^{a,b}, A. Venturi^a, P.G. Verdini^a

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

L. Barone^{a,b}, F. Cavallari^a, M. Cipriani^{a,b}, N. Daci^a, D. Del Re^{a,b,16}, E. Di Marco^{a,b}, M. Diemoz^a, S. Gelli^{a,b}, E. Longo^{a,b}, F. Margaroli^{a,b}, B. Marzocchi^{a,b}, P. Meridiani^a, G. Organtini^{a,b}, R. Paramatti^{a,b}, F. Preiato^{a,b}, S. Rahatlou^{a,b}, C. Rovelli^a, F. Santanastasio^{a,b}

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

N. Amapane^{a,b}, R. Arcidiacono^{a,c}, S. Argiro^{a,b}, M. Arneodo^{a,c}, N. Bartosik^a, R. Bellan^{a,b}, C. Biino^a, N. Cartiglia^a, F. Cenna^{a,b}, M. Costa^{a,b}, R. Covarelli^{a,b}, A. Degano^{a,b}, N. Demaria^a, B. Kiani^{a,b}, C. Mariotti^a, S. Maselli^a, E. Migliore^{a,b}, V. Monaco^{a,b}, E. Monteil^{a,b}, M. Monteno^a

M.M. Obertino^{a,b}, L. Pacher^{a,b}, N. Pastrone^a, M. Pelliccioni^a, G.L. Pinna Angioni^{a,b}, F. Ravera^{a,b}, A. Romero^{a,b}, M. Ruspa^{a,c}, R. Sacchi^{a,b}, K. Shchelina^{a,b}, V. Sola^a, A. Solano^{a,b}, A. Staiano^a, P. Traczyk^{a,b}

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

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

Kyungpook National University, Daegu, Korea

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

Chonbuk National University, Jeonju, Korea

A. Lee

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

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

Hanyang University, Seoul, Korea

J.A. Brochero Cifuentes, J. Goh, T.J. Kim

Korea University, Seoul, Korea

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

Seoul National University, Seoul, Korea

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

University of Seoul, Seoul, Korea

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

Sungkyunkwan University, Suwon, Korea

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

Vilnius University, Vilnius, Lithuania

V. Dudenas, A. Juodagalvis, J. Vaitkus

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

I. Ahmed, Z.A. Ibrahim, M.A.B. Md Ali³⁴, F. Mohamad Idris³⁵, W.A.T. Wan Abdullah, M.N. Yusli, Z. Zolkapli

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

Duran-Osuna, M. C., H. Castilla-Valdez, E. De La Cruz-Burelo, Ramirez-Sanchez, G., I. Heredia-De La Cruz³⁶, Rabadan-Trejo, R. I., R. Lopez-Fernandez, J. Mejia Guisao, Reyes-Almanza, R, A. Sanchez-Hernandez

Universidad Iberoamericana, Mexico City, Mexico

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

Benemerita Universidad Autonoma de Puebla, Puebla, Mexico

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

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

A. Morelos Pineda

University of Auckland, Auckland, New Zealand

D. Krofcheck

University of Canterbury, Christchurch, New Zealand

P.H. Butler

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

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

National Centre for Nuclear Research, Swierk, Poland

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

Institute of Experimental Physics, Faculty of Physics, University of Warsaw, Warsaw, PolandK. Bunkowski, A. Byszuk³⁷, K. Doroba, A. Kalinowski, M. Konecki, J. Krolikowski, M. Misiura, M. Olszewski, A. Pyskir, M. Walczak**Laboratório de Instrumentação e Física Experimental de Partículas, Lisboa, Portugal**

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

Joint Institute for Nuclear Research, Dubna, RussiaS. Afanasiev, P. Bunin, M. Gavrilenko, I. Golutvin, I. Gorbunov, A. Kamenev, V. Karjavin, A. Lanev, A. Malakhov, V. Matveev^{38,39}, V. Palichik, V. Perelygin, S. Shmatov, S. Shulha, N. Skatchkov, V. Smirnov, N. Voytishin, A. Zarubin**Petersburg Nuclear Physics Institute, Gatchina (St. Petersburg), Russia**Y. Ivanov, V. Kim⁴⁰, E. Kuznetsova⁴¹, P. Levchenko, V. Murzin, V. Oreshkin, I. Smirnov, V. Sulimov, L. Uvarov, S. Vavilov, A. Vorobyev**Institute for Nuclear Research, Moscow, Russia**

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

Institute for Theoretical and Experimental Physics, Moscow, Russia

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

Moscow Institute of Physics and Technology, Moscow, RussiaT. Aushev, A. Bylinkin³⁹**National Research Nuclear University 'Moscow Engineering Physics Institute' (MEPhI), Moscow, Russia**M. Chadeeva⁴², P. Parygin, D. Philippov, S. Polikarpov, E. Popova, V. Rusinov**P.N. Lebedev Physical Institute, Moscow, Russia**V. Andreev, M. Azarkin³⁹, I. Dremin³⁹, M. Kirakosyan³⁹, A. Terkulov**Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, Moscow, Russia**

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

Novosibirsk State University (NSU), Novosibirsk, RussiaV. Blinov⁴³, D. Shtol⁴³, Y. Skovpen⁴³**State Research Center of Russian Federation, Institute for High Energy Physics, Protvino, Russia**

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

University of Belgrade, Faculty of Physics and Vinca Institute of Nuclear Sciences, Belgrade, SerbiaP. Adzic⁴⁴, P. Cirkovic, D. Devetak, M. Dordevic, J. Milosevic, V. Rekovic**Centro de Investigaciones Energéticas Medioambientales y Tecnológicas (CIEMAT), Madrid, Spain**

J. Alcaraz Maestre, A. Álvarez Fernández, M. Barrio Luna, M. Cerrada, N. Colino, B. De La Cruz, A. Delgado Peris, A. Escalante Del Valle, C. Fernandez Bedoya, J.P. Fernández Ramos, J. Flix, M.C. Fouz, P. Garcia-Abia, O. Gonzalez Lopez, S. Goy Lopez, J.M. Hernandez, M.I. Josa, A. Pérez-Calero Yzquierdo, J. Puerta Pelayo, A. Quintario Olmeda, I. Redondo, L. Romero, M.S. Soares

Universidad Autónoma de Madrid, Madrid, Spain

J.F. de Trocóniz, M. Missiroli, D. Moran

Universidad de Oviedo, Oviedo, Spain

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

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

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

CERN, European Organization for Nuclear Research, Geneva, SwitzerlandD. Abbaneo, E. Auffray, P. Baillon, A.H. Ball, D. Barney, M. Bianco, P. Bloch, A. Bocci, C. Botta, T. Camporesi, R. Castello, M. Cepeda, G. Cerminara, E. Chapon, Y. Chen, D. d'Enterria, A. Dabrowski, V. Daponte, A. David, M. De Gruttola, A. De Roeck, M. Dobson, B. Dorney, T. du Pree, M. Dünser, N. Dupont, A. Elliott-Peisert, P. Everaerts, F. Fallavollita, G. Franzoni, J. Fulcher, W. Funk, D. Gigi, K. Gill, F. Glege, D. Gulhan, P. Harris, J. Hegeman, V. Innocente, P. Janot, O. Karacheban¹⁹, J. Kieseler, H. Kirschenmann, V. Knünz, A. Kornmayer¹⁶, M.J. Kortelainen, M. Krammer¹, C. Lange, P. Lecoq, C. Lourenço, M.T. Lucchini, L. Malgeri, M. Mannelli, A. Martelli, F. Meijers, J.A. Merlin, S. Mersi, E. Meschi, P. Milenovic⁴⁵, F. Moortgat, M. Mulders, H. Neugebauer, S. Orfanelli, L. Orsini, L. Pape, E. Perez, M. Peruzzi, A. Petrilli, G. Petrucciani, A. Pfeiffer, M. Pierini, A. Racz, T. Reis, G. Rolandi⁴⁶, M. Rovere, H. Sakulin, C. Schäfer, C. Schwick, M. Seidel, M. Selvaggi, A. Sharma, P. Silva, P. Sphicas⁴⁷, A. Stakia, J. Steggemann, M. Stoye, M. Tosi, D. Treille, A. Triossi, A. Tsirou, V. Veckalns⁴⁸, M. Verweij, W.D. Zeuner**Paul Scherrer Institut, Villigen, Switzerland**W. Bertl[†], L. Caminada⁴⁹, K. Deiters, W. Erdmann, R. Horisberger, Q. Ingram, H.C. Kaestli, D. Kotlinski, U. Langenegger, T. Rohe, S.A. Wiederkehr**Institute for Particle Physics, ETH Zurich, Zurich, Switzerland**

F. Bachmair, L. Bäni, P. Berger, L. Bianchini, B. Casal, G. Dissertori, M. Dittmar, M. Donegà,

C. Grab, C. Heidegger, D. Hits, J. Hoss, G. Kasieczka, T. Klijsma, W. Lustermann, B. Mangano, M. Marionneau, M.T. Meinhard, D. Meister, F. Micheli, P. Musella, F. Nessi-Tedaldi, F. Pandolfi, J. Pata, F. Pauss, G. Perrin, L. Perrozzi, M. Quittnat, M. Reichmann, M. Schönenberger, L. Shchutska, V.R. Tavolaro, K. Theofilatos, M.L. Vesterbacka Olsson, R. Wallny, D.H. Zhu

Universität Zürich, Zurich, Switzerland

T.K. Aarrestad, C. AMSler⁵⁰, M.F. Canelli, A. De Cosa, R. Del Burgo, S. Donato, C. Galloni, T. Hreus, B. Kilminster, J. Ngadiuba, D. Pinna, G. Rauco, P. Robmann, D. Salerno, C. Seitz, Y. Takahashi, A. Zucchetta

National Central University, Chung-Li, Taiwan

V. Candelise, T.H. Doan, Sh. Jain, R. Khurana, C.M. Kuo, W. Lin, A. Pozdnyakov, S.S. Yu

National Taiwan University (NTU), Taipei, Taiwan

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

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

B. Asavapibhop, K. Kovitangoon, G. Singh, N. Srimanobhas

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

F. Boran, S. Cerci⁵¹, S. Damarseckin, Z.S. Demiroglu, C. Dozen, I. Dumanoglu, S. Girgis, G. Gokbulut, Y. Guler, I. Hos⁵², E.E. Kangal⁵³, O. Kara, A. Kayis Topaksu, U. Kiminsu, M. Oglakci, G. Onengut⁵⁴, K. Ozdemir⁵⁵, D. Sunar Cerci⁵¹, B. Tali⁵¹, S. Turkcapar, I.S. Zorbakir, C. Zorbilmez

Middle East Technical University, Physics Department, Ankara, Turkey

B. Bilin, G. Karapinar⁵⁶, K. Ocalan⁵⁷, M. Yalvac, M. Zeyrek

Bogazici University, Istanbul, Turkey

E. Gülmez, M. Kaya⁵⁸, O. Kaya⁵⁹, S. Tekten, E.A. Yetkin⁶⁰

Istanbul Technical University, Istanbul, Turkey

M.N. Agaras, S. Atay, A. Cakir, K. Cankocak

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

B. Grynyov

National Scientific Center, Kharkov Institute of Physics and Technology, Kharkov, Ukraine

L. Levchuk, P. Sorokin

University of Bristol, Bristol, United Kingdom

R. Aggleton, F. Ball, L. Beck, J.J. Brooke, D. Burns, E. Clement, D. Cussans, O. Davignon, H. Flacher, J. Goldstein, M. Grimes, G.P. Heath, H.F. Heath, J. Jacob, L. Kreczko, C. Lucas, D.M. Newbold⁶¹, S. Paramesvaran, A. Poll, T. Sakuma, S. Seif El Nasr-storey, D. Smith, V.J. Smith

Rutherford Appleton Laboratory, Didcot, United Kingdom

A. Belyaev⁶², C. Brew, R.M. Brown, L. Calligaris, D. Cieri, D.J.A. Cockerill, J.A. Coughlan, K. Harder, S. Harper, E. Olaiya, D. Petyt, C.H. Shepherd-Themistocleous, A. Thea, I.R. Tomalin, T. Williams

Imperial College, London, United Kingdom

G. Auzinger, R. Bainbridge, S. Breeze, O. Buchmuller, A. Bundock, S. Casasso, M. Citron, D. Colling, L. Corpe, P. Dauncey, G. Davies, A. De Wit, M. Della Negra, R. Di Maria,

A. Elwood, Y. Haddad, G. Hall, G. Iles, T. James, R. Lane, C. Laner, L. Lyons, A.-M. Magnan, S. Malik, L. Mastrolorenzo, T. Matsushita, J. Nash, A. Nikitenko⁶, V. Palladino, M. Pesaresi, D.M. Raymond, A. Richards, A. Rose, E. Scott, C. Seez, A. Shtipliyski, S. Summers, A. Tapper, K. Uchida, M. Vazquez Acosta⁶³, T. Virdee¹⁶, N. Wardle, D. Winterbottom, J. Wright, S.C. Zenz

Brunel University, Uxbridge, United Kingdom

J.E. Cole, P.R. Hobson, A. Khan, P. Kyberd, I.D. Reid, P. Symonds, L. Teodorescu, M. Turner

Baylor University, Waco, USA

A. Borzou, K. Call, J. Dittmann, K. Hatakeyama, H. Liu, N. Pastika, C. Smith

Catholic University of America, Washington DC, USA

R. Bartek, A. Dominguez

The University of Alabama, Tuscaloosa, USA

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

Boston University, Boston, USA

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

Brown University, Providence, USA

G. Benelli, D. Cutts, A. Garabedian, J. Hakala, U. Heintz, J.M. Hogan, K.H.M. Kwok, E. Laird, G. Landsberg, Z. Mao, M. Narain, J. Pazzini, S. Piperov, S. Sagir, R. Syarif, D. Yu

University of California, Davis, Davis, USA

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

University of California, Los Angeles, USA

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

University of California, Riverside, Riverside, USA

E. Bouvier, K. Burt, R. Clare, J. Ellison, J.W. Gary, S.M.A. Ghiasi Shirazi, G. Hanson, J. Heilman, P. Jandir, E. Kennedy, F. Lacroix, O.R. Long, M. Olmedo Negrete, M.I. Paneva, A. Shrinivas, W. Si, L. Wang, H. Wei, S. Wimpenny, B. R. Yates

University of California, San Diego, La Jolla, USA

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

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

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

California Institute of Technology, Pasadena, USA

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

Carnegie Mellon University, Pittsburgh, USA

M.B. Andrews, T. Ferguson, T. Mudholkar, M. Paulini, J. Russ, M. Sun, H. Vogel, I. Vorobiev, M. Weinberg

University of Colorado Boulder, Boulder, USA

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

Cornell University, Ithaca, USA

J. Alexander, J. Chaves, J. Chu, S. Dittmer, K. Mcdermott, N. Mirman, J.R. Patterson, A. Rinkevicius, A. Ryd, L. Skinnari, L. Soffi, S.M. Tan, Z. Tao, J. Thom, J. Tucker, P. Wittich, M. Zientek

Fermi National Accelerator Laboratory, Batavia, USA

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

University of Florida, Gainesville, USA

D. Acosta, P. Avery, P. Bortignon, D. Bourilkov, A. Brinkerhoff, A. Carnes, M. Carver, D. Curry, R.D. Field, I.K. Furic, J. Konigsberg, A. Korytov, K. Kotov, P. Ma, K. Matchev, H. Mei, G. Mitselmakher, D. Rank, D. Sperka, N. Terentyev, L. Thomas, J. Wang, S. Wang, J. Yelton

Florida International University, Miami, USA

Y.R. Joshi, S. Linn, P. Markowitz, J.L. Rodriguez

Florida State University, Tallahassee, USA

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

Florida Institute of Technology, Melbourne, USA

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

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

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

The University of Iowa, Iowa City, USA

B. Bilki⁶⁵, W. Clarida, K. Dilsiz⁶⁶, S. Durgut, R.P. Gandrajula, M. Haytmyradov, V. Khristenko, J.-P. Merlo, H. Mermerkaya⁶⁷, A. Mestvirishvili, A. Moeller, J. Nachtman, H. Ogul⁶⁸, Y. Onel, F. Ozok⁶⁹, A. Penzo, C. Snyder, E. Tiras, J. Wetzel, K. Yi

Johns Hopkins University, Baltimore, USA

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

The University of Kansas, Lawrence, USA

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

Kansas State University, Manhattan, USA

A. Ivanov, K. Kaadze, Y. Maravin, A. Mohammadi, L.K. Saini, N. Skhirtladze, S. Toda

Lawrence Livermore National Laboratory, Livermore, USA

F. Rebassoo, D. Wright

University of Maryland, College Park, USA

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

Massachusetts Institute of Technology, Cambridge, USA

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

University of Minnesota, Minneapolis, USA

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

University of Mississippi, Oxford, USA

J.G. Acosta, S. Oliveros

University of Nebraska-Lincoln, Lincoln, USA

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

State University of New York at Buffalo, Buffalo, USA

M. Alyari, J. Dolen, A. Godshalk, C. Harrington, I. Iashvili, D. Nguyen, A. Parker, S. Rappoccio, B. Roozbahani

Northeastern University, Boston, USA

G. Alverson, E. Barberis, A. Hortiangtham, A. Massironi, D.M. Morse, D. Nash, T. Orimoto, R. Teixeira De Lima, D. Trocino, D. Wood

Northwestern University, Evanston, USA

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

University of Notre Dame, Notre Dame, USA

N. Dev, M. Hildreth, K. Hurtado Anampa, C. Jessop, D.J. Karmgard, N. Kellams, K. Lannon, N. Loukas, N. Marinelli, F. Meng, C. Mueller, Y. Musienko³⁸, M. Planer, A. Reinsvold, R. Ruchti, G. Smith, S. Taroni, M. Wayne, M. Wolf, A. Woodard

The Ohio State University, Columbus, USA

J. Alimena, L. Antonelli, B. Bylsma, L.S. Durkin, S. Flowers, B. Francis, A. Hart, C. Hill, W. Ji, B. Liu, W. Luo, D. Puigh, B.L. Winer, H.W. Wulsin

Princeton University, Princeton, USA

S. Cooperstein, O. Driga, P. Elmer, J. Hardenbrook, P. Hebda, S. Higginbotham, D. Lange, J. Luo, D. Marlow, K. Mei, I. Ojalvo, J. Olsen, C. Palmer, P. Piroué, D. Stickland, C. Tully

University of Puerto Rico, Mayaguez, USA

S. Malik, S. Norberg

Purdue University, West Lafayette, USA

A. Barker, V.E. Barnes, S. Das, S. Folgueras, L. Gutay, M.K. Jha, M. Jones, A.W. Jung, A. Khatiwada, D.H. Miller, N. Neumeister, C.C. Peng, J.F. Schulte, J. Sun, F. Wang, W. Xie

Purdue University Northwest, Hammond, USA

T. Cheng, N. Parashar, J. Stupak

Rice University, Houston, USA

A. Adair, B. Akgun, Z. Chen, K.M. Ecklund, F.J.M. Geurts, M. Guilbaud, W. Li, B. Michlin, M. Northup, B.P. Padley, S.E. Park, J. Roberts, J. Rorie, Z. Tu, J. Zabel

University of Rochester, Rochester, USA

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

The Rockefeller University, New York, USA

R. Ciesielski, K. Goulianos, C. Mesropian

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

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

University of Tennessee, Knoxville, USA

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

Texas A&M University, College Station, USA

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

Texas Tech University, Lubbock, USA

N. Akchurin, J. Damgov, F. De Guio, P.R. Duderod, J. Faulkner, E. Gurpinar, S. Kunori, K. Lamichhane, S.W. Lee, T. Libeiro, T. Peltola, S. Undleeb, I. Volobouev, Z. Wang

Vanderbilt University, Nashville, USA

S. Greene, A. Gurrola, R. Janjam, W. Johns, C. Maguire, A. Melo, H. Ni, P. Sheldon, S. Tuo, J. Velkovska, Q. Xu

University of Virginia, Charlottesville, USA

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

Wayne State University, Detroit, USA

R. Harr, P.E. Karchin, J. Sturdy, S. Zaleski

University of Wisconsin - Madison, Madison, WI, USA

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

†: Deceased

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

d: Also at State Key Laboratory of Nuclear Physics and Technology; Peking University, Beijing, China

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

d: Also at Universidade Federal de Pelotas, Pelotas, Brazil

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

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

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

d: Also at Suez University, Suez, Egypt

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

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

d: Now at Helwan University, Cairo, Egypt

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

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

d: Also at Tbilisi State University, Tbilisi, Georgia

d: Also at Ilia State University, Tbilisi, Georgia

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

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

d: Also at University of Hamburg, Hamburg, Germany

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

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

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

d: Also at Institute of Physics; University of Debrecen, Debrecen, Hungary

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

d: Also at Institute of Physics, Bhubaneswar, India

d: Also at University of Visva-Bharati, Santiniketan, India

d: Also at University of Ruhuna, Matara, Sri Lanka

d: Also at Isfahan University of Technology, Isfahan, Iran

d: Also at Yazd University, Yazd, Iran

d: Also at Plasma Physics Research Center; Science and Research Branch; Islamic Azad University, Tehran, Iran

d: Also at Università degli Studi di Siena, Siena, Italy

d: Also at INFN Sezione di Milano-Bicocca; Università di Milano-Bicocca, Milano, Italy

d: Also at Laboratori Nazionali di Legnaro dell'INFN, Legnaro, Italy

d: Also at Purdue University, West Lafayette, USA

d: Also at International Islamic University of Malaysia, Kuala Lumpur, Malaysia

d: Also at Malaysian Nuclear Agency; MOSTI, Kajang, Malaysia

d: Also at Consejo Nacional de Ciencia y Tecnología, Mexico city, Mexico

d: Also at Warsaw University of Technology; Institute of Electronic Systems, Warsaw, Poland

- d: Also at Institute for Nuclear Research, Moscow, Russia
- d: Now at National Research Nuclear University 'Moscow Engineering Physics Institute' (MEPhI), Moscow, Russia
- d: Also at St. Petersburg State Polytechnical University, St. Petersburg, Russia
- d: Also at University of Florida, Gainesville, USA
- d: Also at P.N. Lebedev Physical Institute, Moscow, Russia
- d: Also at Budker Institute of Nuclear Physics, Novosibirsk, Russia
- d: Also at Faculty of Physics; University of Belgrade, Belgrade, Serbia
- d: Also at University of Belgrade; Faculty of Physics and Vinca Institute of Nuclear Sciences, Belgrade, Serbia
- d: Also at Scuola Normale e Sezione dell'INFN, Pisa, Italy
- d: Also at National and Kapodistrian University of Athens, Athens, Greece
- d: Also at Riga Technical University, Riga, Latvia
- d: Also at Universität Zürich, Zurich, Switzerland
- d: Also at Stefan Meyer Institute for Subatomic Physics (SMI), Vienna, Austria
- d: Also at Adiyaman University, Adiyaman, Turkey
- d: Also at Istanbul Aydin University, Istanbul, Turkey
- d: Also at Mersin University, Mersin, Turkey
- d: Also at Cag University, Mersin, Turkey
- d: Also at Piri Reis University, Istanbul, Turkey
- d: Also at Izmir Institute of Technology, Izmir, Turkey
- d: Also at Necmettin Erbakan University, Konya, Turkey
- d: Also at Marmara University, Istanbul, Turkey
- d: Also at Kafkas University, Kars, Turkey
- d: Also at Istanbul Bilgi University, Istanbul, Turkey
- d: Also at Rutherford Appleton Laboratory, Didcot, United Kingdom
- d: Also at School of Physics and Astronomy; University of Southampton, Southampton, United Kingdom
- d: Also at Instituto de Astrofísica de Canarias, La Laguna, Spain
- d: Also at Utah Valley University, Orem, USA
- d: Also at Beykent University, Istanbul, Turkey
- d: Also at Bingol University, Bingol, Turkey
- d: Also at Erzincan University, Erzincan, Turkey
- d: Also at Sinop University, Sinop, Turkey
- d: Also at Mimar Sinan University; Istanbul, Istanbul, Turkey
- d: Also at Texas A&M University at Qatar, Doha, Qatar
- d: Also at Kyungpook National University, Daegu, Korea