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Observation of Charge-Dependent Azimuthal Correlations in p -Pb Collisions and Its Implication for the Search for the Chiral Magnetic Effect

V. Khachatryan *et al.**
(CMS Collaboration)

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Charge-dependent azimuthal particle correlations with respect to the second-order event plane in p -Pb and PbPb collisions at a nucleon-nucleon center-of-mass energy of 5.02 TeV have been studied with the CMS experiment at the LHC. The measurement is performed with a three-particle correlation technique, using two particles with the same or opposite charge within the pseudorapidity range $|\eta| < 2.4$, and a third particle measured in the hadron forward calorimeters ($4.4 < |\eta| < 5$). The observed differences between the same and opposite sign correlations, as functions of multiplicity and η gap between the two charged particles, are of similar magnitude in p -Pb and PbPb collisions at the same multiplicities. These results pose a challenge for the interpretation of charge-dependent azimuthal correlations in heavy ion collisions in terms of the chiral magnetic effect.

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In relativistic heavy ion collisions, metastable domains of gluon fields may form with nontrivial topological configurations [1–4]. The interaction of quarks with these gluon fields will lead to an imbalance in left- and right-handed quarks, which violates local parity (P) symmetry [3,4]. In the presence of a strong magnetic field in a noncentral nucleus-nucleus (AA) collision, this chirality imbalance leads to an electric current perpendicular to the reaction plane, resulting in a final-state charge separation phenomenon, known as the chiral magnetic effect (CME) [5]. Attempts to measure this charge separation in heavy ion collisions were made by the STAR experiment at RHIC [6–10] and the ALICE experiment at the LHC [11]. In these measurements, a charge dependence of azimuthal correlations with respect to the reaction plane was observed, which is qualitatively consistent with the expectation of a charge separation from the CME.

The charge separation can be characterized by the P -odd sine term (a_1) in a Fourier decomposition of the particle azimuthal distribution [12]:

$$\frac{dN}{d\phi} \propto 1 + 2 \sum_n (v_n \cos[n(\phi - \Psi_{RP})] + a_n \sin[n(\phi - \Psi_{RP})]), \quad (1)$$

where $\phi - \Psi_{RP}$ represents the particle azimuthal angle with respect to the reaction plane angle Ψ_{RP} (determined by the impact parameter and beam axis), v_n and a_n denote the

coefficients of P -even and P -odd Fourier terms, respectively. Although the reaction plane is not an experimental observable, it can be approximated by the second-order event plane, Ψ_{EP} , determined by the direction of the beam and the maximal particle density in the elliptic azimuthal anisotropy. An azimuthal correlator proposed to explore the first coefficient, a_1 , of the P -odd Fourier terms characterizing the charge separation [12] is

$$\begin{aligned} \langle \cos(\phi_\alpha + \phi_\beta - 2\Psi_{EP}) \rangle &= \langle \cos(\phi_\alpha - \Psi_{EP}) \cos(\phi_\beta - \Psi_{EP}) \rangle \\ &\quad - \langle \sin(\phi_\alpha - \Psi_{EP}) \sin(\phi_\beta - \Psi_{EP}) \rangle. \end{aligned} \quad (2)$$

Here, α and β denote particles with the same or opposite charge sign and the brackets reflect an averaging over particles and events. Assuming particles α , β are uncorrelated except for their individual correlations with respect to the event plane, the first term on the right-hand side of Eq. (2) becomes $\langle v_{1,\alpha} v_{1,\beta} \rangle$, which is generally small and independent of charge [7], while the second term is sensitive to charge separation and can be expressed as $\langle a_{1,\alpha} a_{1,\beta} \rangle$, which can be measured.

The observation of the CME in heavy ion collisions remains inconclusive because of several identified sources of background correlations that can account for part or all of the observed charge-dependent azimuthal correlations [13–15]. For example, the effect of local charge conservation, coupled with the anisotropic emission of particles (v_2), can generate an effect resembling charge separation with respect to the reaction plane [15]. The charge-dependent azimuthal correlation signals observed in the data can be qualitatively described by models that do not include CME, such as the AMPT [16] and EPOS LHC [17] models. A significant amount of recent experimental and

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theoretical effort is directed toward quantifying possible mechanisms, including the CME, that can lead to charge-dependent azimuthal correlations [18].

This Letter presents the first application of charge-dependent azimuthal correlation analysis with respect to the event plane in proton-nucleus collisions, using p -Pb data collected with the CMS detector at the LHC at $\sqrt{s_{\text{NN}}} = 5.02$ TeV. High-multiplicity pp and p -Pb collisions have been shown to generate large final-state azimuthal anisotropies, comparable to those in AA collisions [19–32]. However, the CME contribution to any charge-dependent signal is expected to be small in a high-multiplicity p -Pb collision, as the proton likely intersects the Pb nucleus at a small impact parameter. Consequently, the magnetic field in the proton-nucleus overlap region is expected to be smaller than in peripheral PbPb collisions at similar multiplicities. Furthermore, based on Monte Carlo (MC) Glauber calculations [33], the angle between the magnetic field direction and the event plane of elliptic anisotropy is randomly distributed in p -Pb collisions, contrary to the situation for PbPb collisions. With a reduced magnetic field strength and a random field orientation, the CME contribution to any charge-dependent signal is expected to be small. The high-multiplicity events in p -Pb collisions exhibit collective effects and bulk properties similar to those found in AA collisions [29,31,34] but possess very different strengths and configurations of the initial magnetic field. Thus, they can provide a new way to explore the possible CME and local strong parity violation. With the implementation of a high-multiplicity trigger, the p -Pb data sample gives access to multiplicities comparable to those in peripheral PbPb collisions (e.g., $\sim 55\%$ centrality, where centrality is defined as the fraction of the total inelastic cross section, with 0% denoting the most central collisions), allowing for a direct comparison of the two systems with very different CME contributions in the overlap zone. The measurement is presented in different charge combinations as functions of event multiplicity and pseudorapidity (η) difference of correlated particles. In p -Pb collisions, the particle correlations with respect to the event planes that are obtained using particles with $4.4 < |\eta| < 5$ from the p - and Pb-going beam direction, are also explored.

The central feature of the CMS apparatus is a superconducting solenoid of 6 m internal diameter, providing a magnetic field of 3.8 T. Within the solenoid volume, there are four primary subdetectors including a silicon pixel and strip tracker detector, a lead tungstate crystal electromagnetic calorimeter (ECAL), and a brass and scintillator hadron calorimeter (HCAL), each composed of a barrel and two end cap sections. Muons are measured in gaseous ionization detectors embedded in the steel flux-return yoke outside the solenoid. The silicon tracker measures charged particles within the range $|\eta| < 2.5$. For charged particles with transverse momentum $1 < p_{\text{T}} < 10$ GeV

and $|\eta| < 1.4$, the track resolutions are typically 1.5% in p_{T} and 25–90 (45–150) μm in the transverse (longitudinal) impact parameter [35]. 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. [36].

The p -Pb data at $\sqrt{s_{\text{NN}}} = 5.02$ TeV, collected in 2013 at the LHC, correspond to an integrated luminosity of 35 nb^{-1} . The beam energies are 4 TeV for the protons and 1.58 TeV per nucleon for the lead nuclei. A subset of peripheral PbPb data at $\sqrt{s_{\text{NN}}} = 5.02$ TeV collected in 2015 (30%–80% centrality) is also used. The PbPb data were reprocessed using the same reconstruction algorithm as the p -Pb data, in order to directly compare the two systems at similar multiplicities. The event reconstruction, event selections, and the triggers, including the dedicated triggers to collect a large sample of high-multiplicity p -Pb events, are identical to those used in previous CMS particle correlation measurements [19,29]. In the offline analysis of p -Pb (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 p -Pb data sample, there is a 3% probability to have at least one additional interaction in the same bunch crossing (pileup). The procedure used to reject pileup events in p -Pb collisions yields a purity of 99.8% for single p -Pb collision events and is described in Ref. [29]. 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. [35], 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 track with respect to the primary vertex in the direction along the beam axis, $d_z/\sigma(d_z)$ is required to be less than 3, as is the corresponding impact parameter significance in the transverse plane, $d_T/\sigma(d_T)$. The relative uncertainty in p_{T} , $\sigma(p_{\text{T}})/p_{\text{T}}$, must be less than 10%. Each track is also required to leave at least one hit in one of the three layers of the pixel tracker. To ensure high tracking efficiency, only tracks with $|\eta| < 2.4$ and $p_{\text{T}} > 0.3$ GeV are used in this analysis.

The p -Pb and PbPb data are compared in classes of $N_{\text{trk}}^{\text{offline}}$, where primary tracks with $|\eta| < 2.4$ and $p_{\text{T}} > 0.4$ GeV are counted. To compare with results from other experiments, the PbPb data are also analyzed based on centrality classes for the 30%–80% centrality range. The average values of multiplicity, before and after correcting for detector and algorithm inefficiencies, in each multiplicity class of p -Pb and PbPb data, can be found in Ref. [29].

Without directly reconstructing the event plane, the expression shown in Eq. (2) can be alternatively evaluated using a three-particle correlator with respect to a third particle [6,7], $\langle \cos(\phi_\alpha + \phi_\beta - 2\phi_c) \rangle / v_{2,c}$, where $v_{2,c}$ corresponds to the elliptic flow of the particle c . The three-particle correlator is measured via the scalar product method of Q vectors [7,37]. The particles α and β are taken from the tracker with $|\eta| < 2.4$ and $0.3 < p_T < 3$ GeV, and are corrected for tracking efficiency to account for reconstruction effects. The particle c is measured by using the tower energies in the HF calorimeters with $4.4 < |\eta| < 5.0$. This choice of η range for HF towers imposes an η gap of at least 2 units with respect to particles α and β from the tracker, to minimize possible short-range correlations. To account for any occupancy effect of the HF detectors resulting from the large granularities in η and ϕ , each tower is weighted by its E_T value when calculating the Q vector. The $v_{2,c}$ is obtained following the standard scalar-product method [6,7], by correlating the Q vectors from the tracker region at midrapidity and the two HF detectors at forward rapidity. The three-particle correlator is evaluated for particles α and β carrying same sign (SS) and opposite sign (OS), as a function of pseudorapidity difference $|\Delta\eta|$ ($\equiv |\eta_\alpha - \eta_\beta|$). The SS combinations, (+, +) and (-, -), give consistent results within statistical uncertainty and are therefore combined. For p -Pb collisions, the three-particle correlator is also measured with particle c from HF+ and HF-, corresponding to the p - and Pb-going direction, respectively. For symmetric PbPb collisions, the results from HF+ and HF- are consistent with each other within statistical uncertainty and are therefore averaged. The effect of the nonuniform detector acceptance is found to be negligible by evaluating the cumulants of Q -vector products [38].

The absolute systematic uncertainty of the three-particle correlator has been studied. Varying the $d_z/\sigma(d_z)$ and $d_T/\sigma(d_T)$ from less than 3 (default) to less than 2 and 5, and the $\sigma(p_T)/p_T < 10\%$ (default) to $\sigma(p_T)/p_T < 5\%$, together yield a systematic uncertainty of $\pm 1.0 \times 10^{-5}$. The longitudinal primary vertex position (V_z) has been varied, using ranges $|V_z| < 3$ cm and $3 < |V_z| < 15$ cm, where the difference with respect to the default range $|V_z| < 15$ cm is $\pm 1.0 \times 10^{-5}$, taken as the systematic uncertainty. In p -Pb collisions only, using the lower threshold of the high-multiplicity trigger yields a systematic uncertainty of $\pm 3.0 \times 10^{-5}$, which accounts for the possible trigger bias from the inefficiency of the default trigger around the threshold. A final test of the analysis procedures is done by comparing “known” charge-dependent signals based on the EPOS event generator to those found after events are passed through a GEANT4 [39] simulation of the CMS detector response. Based on this test, a systematic uncertainty of $\pm 2.5 \times 10^{-5}$ is assigned. The tracking efficiency and acceptance of positively and negatively charged particles have been evaluated separately, and the difference has been

found to be negligible. All sources of systematic uncertainty are uncorrelated and added in quadrature to obtain the total absolute systematic uncertainty. No dependence of the systematic uncertainties on the sign combination, multiplicity, or $\Delta\eta$ is found. The systematic uncertainties in our results as a function of $|\Delta\eta|$ and multiplicity are point-to-point correlated. In p -Pb collisions, the systematic uncertainty is also observed to be independent of particle c pointing to the Pb- or p -going direction, and thus is quoted to be the same for these two situations.

Measurements of the charge-dependent three-particle correlator are shown in Fig. 1 as a function of the $|\Delta\eta|$ between charged particles α and β with the same and opposite signs, in the multiplicity range $185 \leq N_{\text{trk}}^{\text{offline}} < 220$ for p -Pb and PbPb collisions at $\sqrt{s_{\text{NN}}} = 5.02$ TeV. The p -Pb data are obtained with particle c in the Pb- and p -going sides separately. In both p -Pb and PbPb systems, a charge dependence of the three-particle correlator is observed for $|\Delta\eta|$ up to about 1.6. In this range, the SS correlators show significant negative values as $|\Delta\eta|$ decreases, while the OS correlators become positive towards $|\Delta\eta| \approx 0$. For $|\Delta\eta| > 1.6$, the SS and OS correlators converge to a common positive value, which is weakly dependent on $|\Delta\eta|$ up to about 4.8 units. Similar $|\Delta\eta|$ dependence of the three-particle correlator has been reported at $\sqrt{s_{\text{NN}}} = 0.2$ [6] and 2.76 TeV [11], measured up to $|\Delta\eta| \approx 1.6$. In p -Pb collisions, three-particle correlators obtained with particle c from the p -going side are shifted toward more positive values than those from the Pb-going side by approximately the same amount for both the SS and OS pairs. The Pb-going side results for the p -Pb collisions are of similar magnitude as the results for PbPb collisions. The common shift of SS and OS correlators between the p - and Pb-going side reference (c) particle, may be related to sources of correlations that are

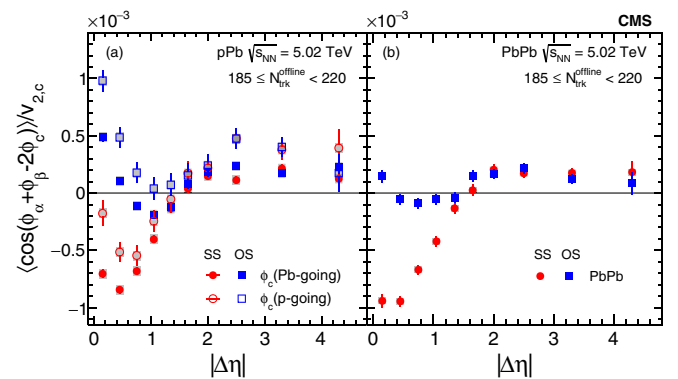


FIG. 1. The same and opposite sign three-particle correlator as a function of $|\Delta\eta| \equiv |\eta_\alpha - \eta_\beta|$ for $185 \leq N_{\text{trk}}^{\text{offline}} < 220$ in (a) p -Pb and (b) PbPb collisions at $\sqrt{s_{\text{NN}}} = 5.02$ TeV. The p -Pb results obtained with particle c in Pb-going (solid markers) and p -going (open markers) sides are shown separately. Statistical and systematic uncertainties are indicated by the error bars and shaded regions, respectively.

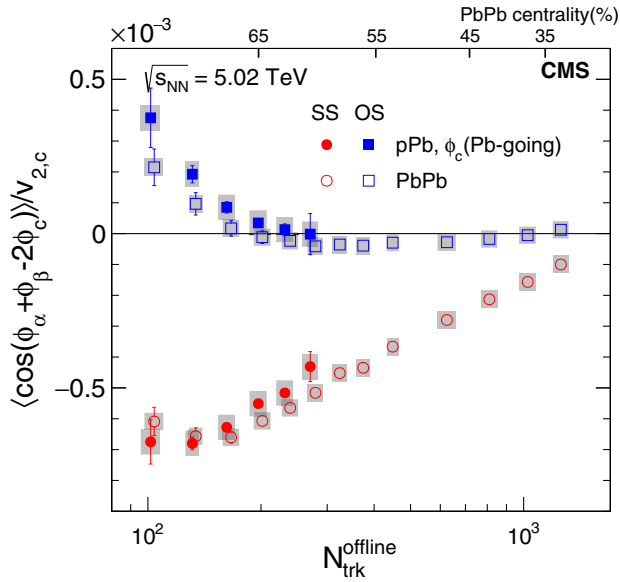


FIG. 2. The same sign and opposite sign three-particle correlator averaged over $|\eta_\alpha - \eta_\beta| < 1.6$ as a function of $N_{\text{trk}}^{\text{offline}}$ in p -Pb and PbPb collisions at $\sqrt{s_{\text{NN}}} = 5.02$ TeV are shown. Statistical and systematic uncertainties are indicated by the error bars and shaded regions, respectively.

charge-independent, such as directed flow and the momentum conservation effect, the latter being sensitive to the difference in multiplicity between p - and Pb-going directions.

To explore the multiplicity or centrality dependence of the three-particle correlator, an average of the results in Fig. 1 over $|\Delta\eta| < 1.6$ (charge-dependent region) is taken, where the average is weighted by the number of particle pairs in each $|\Delta\eta|$ range. The resulting $|\Delta\eta|$ -averaged three-particle correlators are shown in Fig. 2 as a function of $N_{\text{trk}}^{\text{offline}}$ for p -Pb (particle c from the Pb-going side) and PbPb collisions at $\sqrt{s_{\text{NN}}} = 5.02$ TeV. Up to $N_{\text{trk}}^{\text{offline}} = 300$, the p -Pb and PbPb results are measured in the same $N_{\text{trk}}^{\text{offline}}$ ranges. The centrality scale on the top of Fig. 2 relates to the PbPb experimental results. Within uncertainties, the SS and OS correlators in p -Pb and PbPb collisions exhibit the same magnitude and trend as a function of event multiplicity. The OS correlator reaches a value close to zero for $N_{\text{trk}}^{\text{offline}} > 200$, while the SS correlator remains negative, but the magnitude gradually decreases as $N_{\text{trk}}^{\text{offline}}$ increases. Part of the observed multiplicity (or centrality) dependence is understood as a dilution effect that falls with the inverse of event multiplicity [7]. The notably similar magnitude and multiplicity dependence of the three-particle correlator observed in p -Pb collisions relative to that in PbPb collisions again indicates that the dominant contribution of the signal is not related to the CME. The results of SS and OS three-particle correlators as functions of centrality in PbPb collisions at $\sqrt{s_{\text{NN}}} = 5.02$ TeV are also found to be consistent with the results from lower energy AA collisions [7,11].

To eliminate sources of correlations that are charge independent (e.g., directed flow, v_1) and to explore a possible charge separation effect generated by the CME, the difference of three-particle correlators between the OS and SS is shown as a function of $|\Delta\eta|$ in the multiplicity range $185 \leq N_{\text{trk}}^{\text{offline}} < 220$ [Fig. 3(a)] and as a function of $N_{\text{trk}}^{\text{offline}}$ averaged over $|\Delta\eta| < 1.6$ [Fig. 3(b)] for p -Pb and

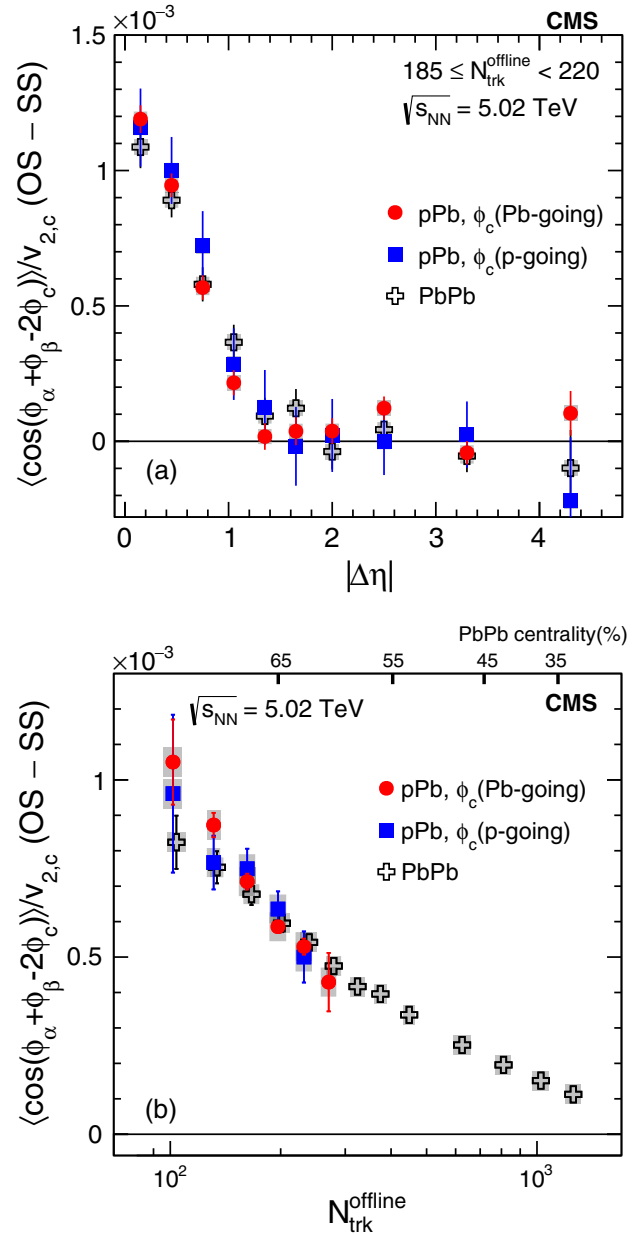


FIG. 3. The difference of the opposite sign and same sign three-particle correlators (a) as a function of $|\eta_\alpha - \eta_\beta|$ for $185 \leq N_{\text{trk}}^{\text{offline}} < 220$ and (b) as a function of $N_{\text{trk}}^{\text{offline}}$, averaged over $|\eta_\alpha - \eta_\beta| < 1.6$, in p -Pb and PbPb collisions at $\sqrt{s_{\text{NN}}} = 5.02$ TeV. The p -Pb results are obtained with particle c from Pb- and p -going sides separately. Statistical and systematic uncertainties are indicated by the error bars and shaded regions, respectively.

PbPb collisions at $\sqrt{s_{NN}} = 5.02$ TeV. After taking the difference, the p -Pb data with particle c from both the p - and Pb-going sides, and PbPb data, show nearly identical values. The charge-dependent difference is largest at $|\Delta\eta| \approx 0$ and drops to zero for $|\Delta\eta| > 1.6$, and also decreases as a function of $N_{\text{trk}}^{\text{offline}}$. The striking similarity in the observed charge-dependent azimuthal correlations strongly suggests a common physical origin. In PbPb collisions, it was suggested that the charge dependence of the three-particle correlator as well as its $|\Delta\eta|$ dependence are indications of the charge separation effect with respect to the event plane due to the CME [7,11]. However, as argued earlier, a strong charge separation signal from the CME is not expected in a very high-multiplicity p -Pb collision. The similarity seen between high-multiplicity p -Pb and peripheral PbPb collisions challenges the attribution of the observed charge-dependent correlations to the CME. Note that there is a hint of a slight difference between p -Pb and PbPb in the slopes of the $N_{\text{trk}}^{\text{offline}}$ dependence in Fig. 3(b), where the systematic uncertainties are point-to-point correlated. This difference is worth further investigation.

In summary, charge-dependent azimuthal correlations of same and opposite sign particles with respect to the second-order event plane have been measured in p -Pb and PbPb collisions at $\sqrt{s_{NN}} = 5.02$ TeV by the CMS experiment at the LHC. The correlation is extracted via a three-particle correlator as functions of particle $|\Delta\eta|$ and charged-particle multiplicity of the event. The difference between opposite and same sign particles as functions of $|\Delta\eta|$ and multiplicity is found to agree for p -Pb and PbPb collisions, possibly indicating a common underlying mechanism that generates the observed correlation. These results challenge the CME interpretation for the observed charge-dependent azimuthal correlations in nucleus-nucleus collisions at RHIC and the LHC.

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C. Beluffi,^{9,d} O. Bondu,⁹ S. Brochet,⁹ G. Bruno,⁹ A. Caudron,⁹ S. De Visscher,⁹ C. Delaere,⁹ M. Delcourt,⁹ B. Francois,⁹ A. Giammanco,⁹ A. Jafari,⁹ P. Jez,⁹ M. Komm,⁹ G. Krintiras,⁹ V. Lemaitre,⁹ A. Magitteri,⁹ A. Mertens,⁹ M. Musich,⁹ C. Nuttens,⁹ K. Piotrkowski,⁹ L. Quertenmont,⁹ M. Selvaggi,⁹ M. Vidal Marono,⁹ S. Wertz,⁹ N. Beliy,¹⁰ W. L. Aldá Júnior,¹¹ F. L. Alves,¹¹ G. A. Alves,¹¹ L. Brito,¹¹ C. Hensel,¹¹ A. Moraes,¹¹ M. E. Pol,¹¹ P. Rebello Teles,¹¹ E. Belchior Batista Das Chagas,¹² W. Carvalho,¹² J. Chinellato,^{12,e} A. Custódio,¹² E. M. Da Costa,¹² G. G. Da Silveira,^{12,f} D. De Jesus Damiao,¹² C. De Oliveira Martins,¹² S. Fonseca De Souza,¹² L. M. Huertas Guativa,¹² H. Malbousson,¹² D. Matos Figueiredo,¹² C. Mora Herrera,¹² L. Mundim,¹² H. Nogima,¹² W. L. Prado Da Silva,¹² A. Santoro,¹² A. Sznajder,¹² E. J. Tonelli Manganote,^{12,e} A. Vilela Pereira,¹² S. Ahuja,^{13a} C. A. Bernardes,^{13b} S. Dogra,^{13a} T. R. Fernandez Perez Tomei,^{13a} E. M. Gregores,^{13b} P. G. Mercadante,^{13b} C. S. Moon,^{13a} S. F. Novaes,^{13a} Sandra S. Padula,^{13a} D. Romero Abad,^{13b} J. C. Ruiz Vargas,^{13a} A. Aleksandrov,¹⁴ R. Hadjiiska,¹⁴ P. Iaydjiev,¹⁴ M. Rodozov,¹⁴ S. Stoykova,¹⁴ G. Sultanov,¹⁴ M. Vutova,¹⁴ A. Dimitrov,¹⁵ I. Glushkov,¹⁵ L. Litov,¹⁵ B. Pavlov,¹⁵ P. Petkov,¹⁵ W. Fang,^{16,g} M. Ahmad,¹⁷ J. G. Bian,¹⁷ G. M. Chen,¹⁷ H. S. Chen,¹⁷ M. Chen,¹⁷ Y. Chen,^{17,h} T. Cheng,¹⁷ C. H. Jiang,¹⁷ D. Leggat,¹⁷ Z. Liu,¹⁷ F. Romeo,¹⁷ S. M. Shaheen,¹⁷ A. Spiezia,¹⁷ J. Tao,¹⁷ C. Wang,¹⁷ Z. Wang,¹⁷ H. Zhang,¹⁷ J. Zhao,¹⁷ Y. Ban,¹⁸ G. Chen,¹⁸ Q. Li,¹⁸ S. Liu,¹⁸ Y. Mao,¹⁸ S. J. Qian,¹⁸ D. Wang,¹⁸ Z. Xu,¹⁸ C. Avila,¹⁹ A. Cabrera,¹⁹ L. F. Chaparro Sierra,¹⁹ C. Florez,¹⁹ J. P. Gomez,¹⁹ C. F. González Hernández,¹⁹ J. D. Ruiz Alvarez,¹⁹ J. C. Sanabria,¹⁹ N. Godinovic,²⁰ D. Lelas,²⁰ I. Puljak,²⁰ P. M. Ribeiro Cipriano,²⁰ T. Sculac,²⁰ Z. Antunovic,²¹ M. Kovac,²¹ V. Brigljevic,²² D. Ferencek,²² K. Kadija,²² B. Mesic,²² S. Micanovic,²² L. Sudic,²² T. Susa,²² A. Attikis,²³ G. Mavromanolakis,²³ J. Mousa,²³ C. Nicolaou,²³ F. Ptochos,²³ P. A. Razis,²³ H. Rykaczewski,²³ D. Tsiakkouri,²³ M. Finger,^{24,i} M. Finger Jr.,^{24,i} E. Carrera Jarrin,²⁵ A. A. Abdelalim,^{26,j,k} Y. Mohammed,^{26,l} E. Salama,^{26,m,n} M. Kadastik,²⁷ L. Perrini,²⁷ M. Raidal,²⁷ A. Tiko,²⁷ C. Veelken,²⁷ P. Eerola,²⁸ J. Pekkanen,²⁸ M. Voutilainen,²⁸ J. Härkönen,²⁹ T. Järvinen,²⁹ V. Karimäki,²⁹ R. Kinnunen,²⁹ T. Lampén,²⁹ K. Lassila-Perini,²⁹ S. Lehti,²⁹ T. Lindén,²⁹ P. Luukka,²⁹ J. Tuominiemi,²⁹ E. Tuovinen,²⁹ L. Wendland,²⁹ J. Talvitie,³⁰ T. Tuuva,³⁰ M. Besancon,³¹ F. Couderc,³¹ M. Dejardin,³¹ D. Denegri,³¹ B. Fabbro,³¹ J. L. Faure,³¹ C. Favaro,³¹ F. Ferri,³¹ S. Ganjour,³¹ S. Ghosh,³¹ A. Givernaud,³¹ P. Gras,³¹ G. Hamel de Monchenault,³¹ P. Jarry,³¹ I. Kucher,³¹ E. Locci,³¹ M. Machet,³¹ J. Malcles,³¹ J. Rander,³¹ A. Rosowsky,³¹ M. Titov,³¹ A. Zghiche,³¹ A. Abdulsalam,³² I. Antropov,³² S. Baffioni,³² F. Beaudette,³² P. Busson,³² L. Cadamuro,³² E. Chapon,³² C. Charlot,³² O. Davignon,³² R. Granier de Cassagnac,³² M. Jo,³² S. Lisniak,³² P. Miné,³² M. Nguyen,³² C. Ochando,³² G. Ortona,³² P. Paganini,³² P. Pigard,³² S. Regnard,³² R. Salerno,³² Y. Sirois,³² T. Strebler,³² Y. Yilmaz,³² A. Zabi,³² J.-L. Agram,^{33,o} J. Andrea,³³ A. Aubin,³³ D. Bloch,³³ J.-M. Brom,³³ M. Buttignol,³³ E. C. Chabert,³³ N. Chanon,³³ C. Collard,³³ E. Conte,^{33,o} X. Coubez,³³ J.-C. Fontaine,^{33,o} D. Gelé,³³ U. Goerlach,³³ A.-C. Le Bihan,³³ K. Skovpen,³³ P. Van Hove,³³ S. Gadrat,³⁴ S. Beauceron,³⁵ C. Bernet,³⁵ G. Boudoul,³⁵ E. Bouvier,³⁵ C. A. Carrillo Montoya,³⁵ R. Chierici,³⁵ D. Contardo,³⁵ B. Courbon,³⁵ P. Depasse,³⁵ H. El Mamouni,³⁵ J. Fan,³⁵ J. Fay,³⁵ S. Gascon,³⁵ M. Gouzevitch,³⁵ G. Grenier,³⁵ B. Ille,³⁵ F. Lagarde,³⁵ I. B. Laktineh,³⁵ M. Lethuillier,³⁵ L. Mirabito,³⁵ A. L. Pequegnot,³⁵ S. Perries,³⁵ A. Popov,^{35,p} D. Sabes,³⁵ V. Sordini,³⁵ M. Vander Donckt,³⁵ P. Verdier,³⁵ S. Viret,³⁵ T. Toriashvili,^{36,q} Z. Tsamalaidze,^{37,i} C. Autermann,³⁸ S. Beranek,³⁸ L. Feld,³⁸ A. Heister,³⁸ M. K. Kiesel,³⁸ K. Klein,³⁸ M. Lipinski,³⁸ A. Ostapchuk,³⁸ M. Preuten,³⁸ F. Raupach,³⁸ S. Schael,³⁸ C. Schomakers,³⁸ J. Schulz,³⁸ T. Verlage,³⁸ H. Weber,³⁸ V. Zhukov,^{38,p} A. Albert,³⁹ M. Brodski,³⁹ E. Dietz-Laursonn,³⁹ D. Duchardt,³⁹ M. Endres,³⁹ M. Erdmann,³⁹ S. Erdweg,³⁹ T. Esch,³⁹ R. Fischer,³⁹ A. Güth,³⁹ M. Hamer,³⁹ T. Hebbeker,³⁹ C. Heidemann,³⁹ K. Hoepfner,³⁹ S. Knutzen,³⁹ M. Merschmeyer,³⁹ A. Meyer,³⁹ P. Millet,³⁹ S. Mukherjee,³⁹ M. Olschewski,³⁹ K. Padeken,³⁹ T. Pook,³⁹ M. Radziej,³⁹ H. Reithler,³⁹ M. Rieger,³⁹ F. Scheuch,³⁹ L. Sonnenschein,³⁹ D. Teyssier,³⁹ S. Thüer,³⁹ V. Cherepanov,⁴⁰ G. Flügge,⁴⁰ B. Kargoll,⁴⁰ T. Kress,⁴⁰ A. Künsken,⁴⁰ J. Lingemann,⁴⁰ T. Müller,⁴⁰ A. Nehrke,⁴⁰ A. Nowack,⁴⁰ C. Pistone,⁴⁰ O. Pooth,⁴⁰ A. Stahl,^{40,r} M. Aldaya Martin,⁴¹ T. Arndt,⁴¹ C. Asawatangtrakuldee,⁴¹ K. Beernaert,⁴¹ O. Behnke,⁴¹ U. Behrens,⁴¹ A. A. Bin Anuar,⁴¹ K. Borras,^{41,s} A. Campbell,⁴¹ P. Connor,⁴¹ C. Contreras-Campana,⁴¹ F. Costanza,⁴¹ C. Diez Pardos,⁴¹ G. Dolinska,⁴¹ G. Eckerlin,⁴¹ D. Eckstein,⁴¹ T. Eichhorn,⁴¹ E. Eren,⁴¹ E. Gallo,^{41,t} J. Garay Garcia,⁴¹ A. Geiser,⁴¹ A. Gikhko,⁴¹ J. M. Grados Luyando,⁴¹ P. Gunnellini,⁴¹ A. Harb,⁴¹ J. Hauk,⁴¹ M. Hempel,^{41,u} H. Jung,⁴¹ A. Kalogeropoulos,⁴¹ O. Karacheban,^{41,u} M. Kasemann,⁴¹ J. Keaveney,⁴¹ C. Kleinwort,⁴¹ I. Korol,⁴¹ D. Krücker,⁴¹ W. Lange,⁴¹ A. Lelek,⁴¹ J. Leonard,⁴¹ K. Lipka,⁴¹ A. Lobanov,⁴¹ W. Lohmann,^{41,u} R. Mankel,⁴¹ I.-A. Melzer-Pellmann,⁴¹ A. B. Meyer,⁴¹ G. Mittag,⁴¹ J. Mnich,⁴¹ A. Mussgiller,⁴¹ E. Ntomari,⁴¹ D. Pitzl,⁴¹ R. Placakyte,⁴¹ A. Raspereza,⁴¹ B. Roland,⁴¹ M. Ö. Sahin,⁴¹ P. Saxena,⁴¹ T. Schoerner-Sadenius,⁴¹ C. Seitz,⁴¹ S. Spannagel,⁴¹ N. Stefaniuk,⁴¹ G. P. Van Onsem,⁴¹ R. Walsh,⁴¹ C. Wissing,⁴¹ V. Blobel,⁴² M. Centis Vignali,⁴² A. R. Draeger,⁴² T. Dreyer,⁴² E. Garutti,⁴² D. Gonzalez,⁴² J. Haller,⁴² M. Hoffmann,⁴² A. Junkes,⁴² R. Klanner,⁴² R. Kogler,⁴²

N. Kovalchuk,⁴² T. Lapsien,⁴² T. Lenz,⁴² I. Marchesini,⁴² D. Marconi,⁴² M. Meyer,⁴² M. Niedziela,⁴² D. Nowatschin,⁴² F. Pantaleo,^{42,r} T. Peiffer,⁴² A. Pericenu,⁴² J. Poehlsen,⁴² C. Sander,⁴² C. Scharf,⁴² P. Schleper,⁴² A. Schmidt,⁴² S. Schumann,⁴² J. Schwandt,⁴² H. Stadie,⁴² G. Steinbrück,⁴² F. M. Stober,⁴² M. Stöver,⁴² H. Tholen,⁴² D. Troendle,⁴² E. Usai,⁴² L. Vanelderen,⁴² A. Vanhoefer,⁴² B. Vormwald,⁴² M. Akbiyik,⁴³ C. Barth,⁴³ S. Baur,⁴³ C. Baus,⁴³ J. Berger,⁴³ E. Butz,⁴³ R. Caspart,⁴³ T. Chwalek,⁴³ F. Colombo,⁴³ W. De Boer,⁴³ A. Dierlamm,⁴³ S. Fink,⁴³ B. Freund,⁴³ R. Friese,⁴³ M. Giffels,⁴³ A. Gilbert,⁴³ P. Goldenzweig,⁴³ D. Haitz,⁴³ F. Hartmann,^{43,r} S. M. Heindl,⁴³ U. Husemann,⁴³ I. Katkov,^{43,p} S. Kudella,⁴³ P. Lobelle Pardo,⁴³ H. Mildner,⁴³ M. U. Mozer,⁴³ Th. Müller,⁴³ M. Plagge,⁴³ G. Quast,⁴³ K. Rabbertz,⁴³ S. Röcker,⁴³ F. Roscher,⁴³ M. Schröder,⁴³ I. Shvetsov,⁴³ G. Sieber,⁴³ H. J. Simonis,⁴³ R. Ulrich,⁴³ J. Wagner-Kuhr,⁴³ S. Wayand,⁴³ M. Weber,⁴³ T. Weiler,⁴³ S. Williamson,⁴³ C. Wöhrmann,⁴³ R. Wolf,⁴³ G. Anagnostou,⁴⁴ G. Daskalakis,⁴⁴ T. Gerasis,⁴⁴ V. A. Giakoumopoulou,⁴⁴ A. Kyriakis,⁴⁴ D. Loukas,⁴⁴ I. Topsis-Giotis,⁴⁴ S. Kesiosoglou,⁴⁵ A. Panagiotou,⁴⁵ N. Saoulidou,⁴⁵ E. Tziaferi,⁴⁵ I. Evangelou,⁴⁶ G. Flouris,⁴⁶ C. Foudas,⁴⁶ P. Kokkas,⁴⁶ N. Loukas,⁴⁶ N. Manthos,⁴⁶ I. Papadopoulos,⁴⁶ E. Paradas,⁴⁶ N. Filipovic,⁴⁷ G. Bencze,⁴⁸ C. Hajdu,⁴⁸ D. Horvath,^{48,v} F. Sikler,⁴⁸ V. Veszpremi,⁴⁸ G. Vesztergombi,^{48,w} A. J. Zsigmond,⁴⁸ N. Beni,⁴⁹ S. Czellar,⁴⁹ J. Karancsi,^{49,x} A. Makovec,⁴⁹ J. Molnar,⁴⁹ Z. Szillasi,⁴⁹ M. Bartók,^{50,w} P. Raics,⁵⁰ Z. L. Trocsanyi,⁵⁰ B. Ujvari,⁵⁰ S. Bahinipati,⁵¹ S. Choudhury,^{51,y} P. Mal,⁵¹ K. Mandal,⁵¹ A. Nayak,^{51,z} D. K. Sahoo,⁵¹ N. Sahoo,⁵¹ S. K. Swain,⁵¹ S. Bansal,⁵² S. B. Beri,⁵² V. Bhatnagar,⁵² R. Chawla,⁵² U. Bhawandeep,⁵² A. K. Kalsi,⁵² A. Kaur,⁵² M. Kaur,⁵² R. Kumar,⁵² P. Kumari,⁵² A. Mehta,⁵² M. Mittal,⁵² J. B. Singh,⁵² G. Walia,⁵² Ashok Kumar,⁵³ A. Bhardwaj,⁵³ B. C. Choudhary,⁵³ R. B. Garg,⁵³ S. Keshri,⁵³ S. Malhotra,⁵³ M. Naimuddin,⁵³ N. Nishu,⁵³ K. Ranjan,⁵³ R. Sharma,⁵³ V. Sharma,⁵³ R. Bhattacharya,⁵⁴ S. Bhattacharya,⁵⁴ K. Chatterjee,⁵⁴ S. Dey,⁵⁴ S. Dutt,⁵⁴ S. Dutta,⁵⁴ S. Ghosh,⁵⁴ N. Majumdar,⁵⁴ A. Modak,⁵⁴ K. Mondal,⁵⁴ S. Mukhopadhyay,⁵⁴ S. Nandan,⁵⁴ A. Purohit,⁵⁴ A. Roy,⁵⁴ D. Roy,⁵⁴ S. Roy Chowdhury,⁵⁴ S. Sarkar,⁵⁴ M. Sharan,⁵⁴ S. Thakur,⁵⁴ P. K. Behera,⁵⁵ R. Chudasama,⁵⁶ D. Dutta,⁵⁶ V. Jha,⁵⁶ V. Kumar,⁵⁶ A. K. Mohanty,^{56,r} P. K. Netrakanti,⁵⁶ L. M. Pant,⁵⁶ P. Shukla,⁵⁶ A. Topkar,⁵⁶ T. Aziz,⁵⁷ S. Dugad,⁵⁷ G. Kole,⁵⁷ B. Mahakud,⁵⁷ S. Mitra,⁵⁷ G. B. Mohanty,⁵⁷ B. Parida,⁵⁷ N. Sur,⁵⁷ B. Sutar,⁵⁷ S. Banerjee,⁵⁸ S. Bhowmik,^{58,aa} R. K. Dewanjee,⁵⁸ S. Ganguly,⁵⁸ M. Guchait,⁵⁸ Sa. Jain,⁵⁸ S. Kumar,⁵⁸ M. Maity,^{58,aa} G. Majumder,⁵⁸ K. Mazumdar,⁵⁸ T. Sarkar,^{58,aa} N. Wickramage,^{58,bb} S. Chauhan,⁵⁹ S. Dube,⁵⁹ V. Hegde,⁵⁹ A. Kapoor,⁵⁹ K. Kothekar,⁵⁹ S. Pandey,⁵⁹ A. Rane,⁵⁹ S. Sharma,⁵⁹ H. Behnamian,⁶⁰ S. Chenarani,^{60,cc} E. Eskandari Tadavani,⁶⁰ S. M. Etesami,^{60,cc} A. Fahim,^{60,dd} M. Khakzad,⁶⁰ M. Mohammadi Najafabadi,⁶⁰ M. Naseri,⁶⁰ S. Paktinat Mehdiabadi,^{60,ee} F. Rezaei Hosseinabadi,⁶⁰ B. Safarzadeh,^{60,ff} M. Zeinali,⁶⁰ M. Felcini,⁶¹ M. Grunewald,⁶¹ M. Abbrescia,^{62a,62b} C. Calabria,^{62a,62b} C. Caputo,^{62a,62b} A. Colaleo,^{62a} D. Creanza,^{62a,62c} L. Cristella,^{62a,62b} N. De Filippis,^{62a,62c} M. De Palma,^{62a,62b} L. Fiore,^{62a} G. Iaselli,^{62a,62c} G. Maggi,^{62a,62c} M. Maggi,^{62a} G. Miniello,^{62a,62b} S. My,^{62a,62b} S. Nuzzo,^{62a,62b} A. Pompili,^{62a,62b} G. Pugliese,^{62a,62c} R. Radogna,^{62a,62b} A. Ranieri,^{62a} G. Selvaggi,^{62a,62b} L. Silvestris,^{62a,r} R. Venditti,^{62a,62b} P. Verwilligen,^{62a} G. Abbiendi,^{63a} C. Battilana,^{63a} D. Bonacorsi,^{63a,63b} S. Braibant-Giacomelli,^{63a,63b} L. Brigliadori,^{63a,63b} R. Campanini,^{63a,63b} P. Capiluppi,^{63a,63b} A. Castro,^{63a,63b} F. R. Cavallo,^{63a} S. S. Chhibra,^{63a,63b} G. Codispoti,^{63a,63b} M. Cuffiani,^{63a,63b} G. M. Dallavalle,^{63a} F. Fabbri,^{63a} A. Fanfani,^{63a,63b} D. Fasanella,^{63a,63b} P. Giacomelli,^{63a} C. Grandi,^{63a} L. Guiducci,^{63a,63b} S. Marcellini,^{63a} G. Masetti,^{63a} A. Montanari,^{63a} F. L. Navarria,^{63a,63b} A. Perrotta,^{63a} A. M. Rossi,^{63a,63b} T. Rovelli,^{63a,63b} G. P. Siroli,^{63a,63b} N. Tosi,^{63a,63b,r} S. Albergo,^{64a,64b} S. Costa,^{64a,64b} A. Di Mattia,^{64a} F. Giordano,^{64a,64b} R. Potenza,^{64a,64b} A. Tricomi,^{64a,64b} C. Tuve,^{64a,64b} G. Barbagli,^{65a} V. Ciulli,^{65a,65b} C. Civinini,^{65a} R. D'Alessandro,^{65a,65b} E. Focardi,^{65a,65b} P. Lenzi,^{65a,65b} M. Meschini,^{65a} S. Paoletti,^{65a} G. Sguazzoni,^{65a} L. Viliani,^{65a,65b,r} L. Benussi,⁶⁶ S. Bianco,⁶⁶ F. Fabbri,⁶⁶ D. Piccolo,⁶⁶ F. Primavera,^{66,r} V. Calvelli,^{67a,67b} F. Ferro,^{67a} M. Lo Vetere,^{67a,67b} M. R. Monge,^{67a,67b} E. Robutti,^{67a} S. Tosi,^{67a,67b} L. Brianza,^{68a,r} M. E. Dinardo,^{68a,68b} S. Fiorendi,^{68a,68b,r} S. Gennai,^{68a} A. 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Jo,⁸¹ Y. Kim,⁸¹ B. Lee,⁸¹ K. Lee,⁸¹ K. S. Lee,⁸¹ S. Lee,⁸¹ J. Lim,⁸¹ S. K. Park,⁸¹ Y. Roh,⁸¹ J. Almond,⁸² J. Kim,⁸² H. Lee,⁸² S. B. Oh,⁸² B. C. Radburn-Smith,⁸² S. h. Seo,⁸² U. K. Yang,⁸² H. D. Yoo,⁸² G. B. Yu,⁸² M. Choi,⁸³ H. Kim,⁸³ J. H. Kim,⁸³ J. S. H. Lee,⁸³ I. C. Park,⁸³ G. Ryu,⁸³ M. S. Ryu,⁸³ Y. Choi,⁸⁴ J. Goh,⁸⁴ C. Hwang,⁸⁴ J. Lee,⁸⁴ I. Yu,⁸⁴ V. Dudenias,⁸⁵ A. Juodagalvis,⁸⁵ J. Vaitkus,⁸⁵ I. Ahmed,⁸⁶ Z. A. Ibrahim,⁸⁶ J. R. Komaragiri,⁸⁶ M. A. B. Md Ali,^{86,ii} F. Mohamad Idris,^{86,jj} W. A. T. Wan Abdullah,⁸⁶ M. N. Yusli,⁸⁶ Z. Zolkapli,⁸⁶ H. Castilla-Valdez,⁸⁷ E. De La Cruz-Burelo,⁸⁷ I. Heredia-De La Cruz,^{87,kk} A. Hernandez-Almada,⁸⁷ R. Lopez-Fernandez,⁸⁷ R. Magaña Villalba,⁸⁷ J. Mejia Guisao,⁸⁷ A. Sanchez-Hernandez,⁸⁷ S. Carrillo Moreno,⁸⁸ C. Oropeza Barrera,⁸⁸ F. Vazquez Valencia,⁸⁸ S. Carpitneyro,⁸⁹ I. Pedraza,⁸⁹ H. A. Salazar Ibarguen,⁸⁹ C. Uribe Estrada,⁸⁹ A. Morelos Pineda,⁹⁰ D. Krofcheck,⁹¹ P. H. Butler,⁹² A. Ahmad,⁹³ M. Ahmad,⁹³ Q. Hassan,⁹³ H. R. Hoorani,⁹³ W. A. Khan,⁹³ A. Saddique,⁹³ M. A. Shah,⁹³ M. Shoaib,⁹³ M. Waqas,⁹³ H. Bialkowska,⁹⁴ M. Bluj,⁹⁴ B. Boimska,⁹⁴ T. Frueboes,⁹⁴ M. Górski,⁹⁴ M. Kazana,⁹⁴ K. Nawrocki,⁹⁴ K. Romanowska-Rybinska,⁹⁴ M. Szeleper,⁹⁴ P. Zalewski,⁹⁴ K. Bunkowski,⁹⁵ A. Byszuk,^{95,ll} K. Doroba,⁹⁵ A. Kalinowski,⁹⁵ M. Konecki,⁹⁵ J. Krolikowski,⁹⁵ M. Misiura,⁹⁵ M. Olszewski,⁹⁵ M. Walczak,⁹⁵ P. Bargassa,⁹⁶ C. Beirão Da Cruz E Silva,⁹⁶ B. Calpas,⁹⁶ A. Di Francesco,⁹⁶ P. Faccioli,⁹⁶ P. G. Ferreira Parracho,⁹⁶ M. Gallinaro,⁹⁶ J. Hollar,⁹⁶ N. Leonardo,⁹⁶ L. Lloret Iglesias,⁹⁶ M. V. Nemallapudi,⁹⁶ J. Rodrigues Antunes,⁹⁶ J. Seixas,⁹⁶ O. Toldaiev,⁹⁶ D. Vadrucchio,⁹⁶ J. Varela,⁹⁶ P. Vischia,⁹⁶ S. Afanasiev,⁹⁷ P. Bunin,⁹⁷ M. Gavrilenko,⁹⁷ I. Golutvin,⁹⁷ I. Gorbunov,⁹⁷ A. Kamenev,⁹⁷ V. Karjavin,⁹⁷ A. Lanev,⁹⁷ A. Malakhov,⁹⁷ V. Matveev,^{97,mm,nn} V. Palichik,⁹⁷ V. Perelygin,⁹⁷ S. Shmatov,⁹⁷ S. Shulha,⁹⁷ N. Skatchkov,⁹⁷ V. Smirnov,⁹⁷ N. Voytishin,⁹⁷ A. Zarubin,⁹⁷ L. Chtchipounov,⁹⁸ V. Golovtsov,⁹⁸ Y. Ivanov,⁹⁸ V. Kim,^{98,oo} E. Kuznetsova,^{98,pp} V. Murzin,⁹⁸ V. Oreshkin,⁹⁸ V. Sulimov,⁹⁸ A. Vorobyev,⁹⁸ Yu. Andreev,⁹⁹ A. Dermenev,⁹⁹ S. Gninenko,⁹⁹ N. Golubev,⁹⁹ A. Karneyeu,⁹⁹ M. Kirsanov,⁹⁹ N. Krasnikov,⁹⁹ A. Pashenkov,⁹⁹ D. Tlisov,⁹⁹ A. Toropin,⁹⁹ V. Epshteyn,¹⁰⁰ V. Gavrilov,¹⁰⁰ N. Lychkovskaya,¹⁰⁰ V. Popov,¹⁰⁰ I. Pozdnyakov,¹⁰⁰ G. Safronov,¹⁰⁰ A. Spiridonov,¹⁰⁰ M. Toms,¹⁰⁰ E. Vlasov,¹⁰⁰ A. Zhokin,¹⁰⁰ A. Bylinkin,^{101,nn} O. Markin,¹⁰² E. Tarkovskii,¹⁰² V. Andreev,¹⁰³ M. Azarkin,^{103,nn} I. Dremin,^{103,nn} M. Kirakosyan,¹⁰³ A. Leonidov,^{103,nn} A. Terkulov,¹⁰³ A. Baskakov,¹⁰⁴ A. Belyaev,¹⁰⁴ E. Boos,¹⁰⁴ A. Ershov,¹⁰⁴ A. Gribushin,¹⁰⁴ A. Kaminskiy,^{104,qq} O. Kodolova,¹⁰⁴ V. Korotkikh,¹⁰⁴ I. Lokhtin,¹⁰⁴ I. Miagkov,¹⁰⁴ S. Obraztsov,¹⁰⁴ S. Petrushanko,¹⁰⁴ V. Savrin,¹⁰⁴ A. Snigirev,¹⁰⁴ I. Vardanyan,¹⁰⁴ V. Blinov,^{105,rr} Y. Skovpen,^{105,rr} D. Shtol,^{105,rr} I. Azhgirey,¹⁰⁶ I. Bayshev,¹⁰⁶ S. Bitioukov,¹⁰⁶ D. Elumakhov,¹⁰⁶ V. Kachanov,¹⁰⁶ A. Kalinin,¹⁰⁶ D. Konstantinov,¹⁰⁶ V. Krychkin,¹⁰⁶ V. Petrov,¹⁰⁶ R. Ryutin,¹⁰⁶ A. Sobol,¹⁰⁶ S. Troshin,¹⁰⁶ N. Tyurin,¹⁰⁶ A. Uzunian,¹⁰⁶ A. Volkov,¹⁰⁶ P. Adzic,^{107,ss} P. Cirkovic,¹⁰⁷ D. Devetak,¹⁰⁷ M. Dordevic,¹⁰⁷ J. Milosevic,¹⁰⁷ V. Rekovic,¹⁰⁷ J. Alcaraz Maestre,¹⁰⁸ M. Barrio Luna,¹⁰⁸ E. Calvo,¹⁰⁸ M. Cerrada,¹⁰⁸ M. Chamizo Llatas,¹⁰⁸ N. Colino,¹⁰⁸ B. De La Cruz,¹⁰⁸ A. Delgado Peris,¹⁰⁸ A. Escalante Del Valle,¹⁰⁸ C. Fernandez Bedoya,¹⁰⁸ J. P. Fernández Ramos,¹⁰⁸ J. Flix,¹⁰⁸ M. C. Fouz,¹⁰⁸ P. Garcia-Abia,¹⁰⁸ O. Gonzalez Lopez,¹⁰⁸ S. Goy Lopez,¹⁰⁸ J. M. Hernandez,¹⁰⁸ M. I. Josa,¹⁰⁸ E. Navarro De Martino,¹⁰⁸ A. Pérez-Calero Yzquierdo,¹⁰⁸ J. Puerta Pelayo,¹⁰⁸ A. Quintario Olmeda,¹⁰⁸ I. Redondo,¹⁰⁸ L. Romero,¹⁰⁸ M. S. Soares,¹⁰⁸ J. F. de Trocóniz,¹⁰⁹ M. Missiroli,¹⁰⁹ D. Moran,¹⁰⁹ J. Cuevas,¹¹⁰ J. Fernandez Menendez,¹¹⁰ I. Gonzalez Caballero,¹¹⁰ J. R. González Fernández,¹¹⁰ E. Palencia Cortezon,¹¹⁰ S. Sanchez Cruz,¹¹⁰ I. Suárez Andrés,¹¹⁰ J. M. Vizan Garcia,¹¹⁰ I. J. Cabrillo,¹¹¹ A. Calderon,¹¹¹ J. R. Castiñeiras De Saa,¹¹¹ E. Curras,¹¹¹ M. Fernandez,¹¹¹ J. Garcia-Ferrero,¹¹¹ G. Gomez,¹¹¹ A. Lopez Virto,¹¹¹ J. Marco,¹¹¹ C. Martinez Rivero,¹¹¹ F. Matorras,¹¹¹ J. Piedra Gomez,¹¹¹ T. Rodrigo,¹¹¹

A. Ruiz-Jimeno,¹¹¹ L. Scodellaro,¹¹¹ N. Trevisani,¹¹¹ I. Vila,¹¹¹ R. Vilar Cortabitarte,¹¹¹ D. Abbaneo,¹¹² E. Auffray,¹¹² G. Auzinger,¹¹² M. Bachtis,¹¹² P. Baillon,¹¹² A. H. Ball,¹¹² D. Barney,¹¹² P. Bloch,¹¹² A. Bocchi,¹¹² A. Bonato,¹¹² C. Botta,¹¹² T. Camporesi,¹¹² R. Castello,¹¹² M. Cepeda,¹¹² G. Cerminara,¹¹² M. D'Alfonso,¹¹² D. d'Enterria,¹¹² A. Dabrowski,¹¹² V. Daponte,¹¹² A. David,¹¹² M. De Gruttola,¹¹² A. De Roeck,¹¹² E. Di Marco,^{112,u} M. Dobson,¹¹² B. Dorney,¹¹² T. du Pree,¹¹² D. Duggan,¹¹² M. Dünser,¹¹² N. Dupont,¹¹² A. Elliott-Peisert,¹¹² S. Fartoukh,¹¹² G. Franzoni,¹¹² J. Fulcher,¹¹² W. Funk,¹¹² D. Gigi,¹¹² K. Gill,¹¹² M. Girone,¹¹² F. Glege,¹¹² D. Gulhan,¹¹² S. Gundacker,¹¹² M. Guthoff,¹¹² J. Hammer,¹¹² P. Harris,¹¹² J. Hegeman,¹¹² V. Innocente,¹¹² P. Janot,¹¹² J. Kieseler,¹¹² H. Kirschenmann,¹¹² V. Knünz,¹¹² A. Kornmayer,^{112,r} M. J. Kortelainen,¹¹² K. Kousouris,¹¹² M. Kramer,^{112,b} C. Lange,¹¹² P. Lecoq,¹¹² C. Lourenço,¹¹² M. T. Lucchini,¹¹² L. Malgeri,¹¹² M. Mannelli,¹¹² A. Martelli,¹¹² F. Meijers,¹¹² J. A. Merlin,¹¹² S. Mersi,¹¹² E. Meschi,¹¹² P. Milenovic,^{112,uu} F. Moortgat,¹¹² S. Morovic,¹¹² M. Mulders,¹¹² H. Neugebauer,¹¹² S. Orfanelli,¹¹² L. Orsini,¹¹² L. Pape,¹¹² E. Perez,¹¹² M. Peruzzi,¹¹² A. Petrilli,¹¹² G. Petrucciani,¹¹² A. Pfeiffer,¹¹² M. Pierini,¹¹² A. Racz,¹¹² T. Reis,¹¹² G. Rolandi,^{112,vv} M. Rovere,¹¹² M. Ruan,¹¹² H. Sakulin,¹¹² J. B. Sauvan,¹¹² C. Schäfer,¹¹² C. Schwick,¹¹² M. Seidel,¹¹² A. Sharma,¹¹² P. Silva,¹¹² P. Sphicas,^{112,ww} J. Steggemann,¹¹² M. Stoye,¹¹² Y. Takahashi,¹¹² M. Tosi,¹¹² D. Treille,¹¹² A. Triossi,¹¹² A. Tsiro,¹¹² V. Veckalns,^{112,xx} G. I. Veres,^{112,w} M. Verweij,¹¹² N. Wardle,¹¹² H. K. Wöhri,¹¹² A. Zagozdinska,^{112,ll} W. D. Zeuner,¹¹² W. Bertl,¹¹³ K. Deiters,¹¹³ W. Erdmann,¹¹³ R. Horisberger,¹¹³ Q. Ingram,¹¹³ H. C. Kaestli,¹¹³ D. Kotlinski,¹¹³ U. Langenegger,¹¹³ T. Rohe,¹¹³ F. Bachmair,¹¹⁴ L. Bäni,¹¹⁴ L. Bianchini,¹¹⁴ B. Casal,¹¹⁴ G. Dissertori,¹¹⁴ M. Dittmar,¹¹⁴ M. Donegà,¹¹⁴ C. Grab,¹¹⁴ C. Heidegger,¹¹⁴ D. Hits,¹¹⁴ J. Hoss,¹¹⁴ G. Kasieczka,¹¹⁴ P. Lecomte,^{114,a} W. Lustermann,¹¹⁴ B. Mangano,¹¹⁴ M. Marionneau,¹¹⁴ P. Martinez Ruiz del Arbol,¹¹⁴ M. Masciovecchio,¹¹⁴ M. T. Meinhard,¹¹⁴ D. Meister,¹¹⁴ F. Micheli,¹¹⁴ P. Musella,¹¹⁴ F. Nessi-Tedaldi,¹¹⁴ F. Pandolfi,¹¹⁴ J. Pata,¹¹⁴ F. Pauss,¹¹⁴ G. Perrin,¹¹⁴ L. Perrozzi,¹¹⁴ M. Quittnat,¹¹⁴ M. Rossini,¹¹⁴ M. Schönenberger,¹¹⁴ A. Starodumov,^{114,yy} V. R. Tavolaro,¹¹⁴ K. Theofilatos,¹¹⁴ R. Wallny,¹¹⁴ T. K. Aarrestad,¹¹⁵ C. Amsler,^{115,zz} L. Caminada,¹¹⁵ M. F. Canelli,¹¹⁵ A. De Cosa,¹¹⁵ C. Galloni,¹¹⁵ A. Hinzmann,¹¹⁵ T. Hreus,¹¹⁵ B. Kilminster,¹¹⁵ J. Ngadiuba,¹¹⁵ D. Pinna,¹¹⁵ G. Rauco,¹¹⁵ P. Robmann,¹¹⁵ D. Salerno,¹¹⁵ Y. Yang,¹¹⁵ A. Zucchetta,¹¹⁵ V. Candelise,¹¹⁶ T. H. Doan,¹¹⁶ Sh. Jain,¹¹⁶ R. Khurana,¹¹⁶ M. Konyushikhin,¹¹⁶ C. M. Kuo,¹¹⁶ W. Lin,¹¹⁶ Y. J. Lu,¹¹⁶ A. Pozdnyakov,¹¹⁶ S. S. Yu,¹¹⁶ Arun Kumar,¹¹⁷ P. Chang,¹¹⁷ Y. H. Chang,¹¹⁷ Y. W. Chang,¹¹⁷ Y. Chao,¹¹⁷ K. F. Chen,¹¹⁷ P. H. Chen,¹¹⁷ C. Dietz,¹¹⁷ F. Fiori,¹¹⁷ W.-S. Hou,¹¹⁷ Y. Hsiung,¹¹⁷ Y. F. Liu,¹¹⁷ R.-S. Lu,¹¹⁷ M. Miñano Moya,¹¹⁷ E. Paganis,¹¹⁷ A. Psallidas,¹¹⁷ J. f. Tsai,¹¹⁷ Y. M. Tzeng,¹¹⁷ B. Asavapibhop,¹¹⁸ G. Singh,¹¹⁸ N. Srimanobhas,¹¹⁸ N. Suwonjandee,¹¹⁸ A. Adiguzel,¹¹⁹ S. Cerci,^{119,aaa} S. Damarseckin,¹¹⁹ Z. S. Demiroglu,¹¹⁹ C. Dozen,¹¹⁹ I. Dumanoglu,¹¹⁹ S. Girgis,¹¹⁹ G. Gokbulut,¹¹⁹ Y. Guler,¹¹⁹ I. Hos,^{119,bbb} E. E. Kangal,^{119,ccc} O. Kara,¹¹⁹ A. Kayis Topaksu,¹¹⁹ U. Kiminsu,¹¹⁹ M. Oglakci,¹¹⁹ G. Onengut,^{119,ddd} K. Ozdemir,^{119,eee} D. Sunar Cerci,^{119,aaa} B. Tali,^{119,aaa} S. Turkcapar,¹¹⁹ I. S. Zorbakir,¹¹⁹ C. Zorbilmez,¹¹⁹ B. Bilin,¹²⁰ S. Bilmis,¹²⁰ B. Isildak,^{120,fff} G. Karapinar,^{120,ggg} M. Yalvac,¹²⁰ M. Zeyrek,¹²⁰ E. Gülmez,¹²¹ M. Kaya,^{121,hhh} O. Kaya,^{121,iii} E. A. Yetkin,^{121,jjj} T. Yetkin,^{121,kkk} A. Cakir,¹²² K. Cankocak,¹²² S. Sen,^{122,lll} B. Grynyov,¹²³ L. Levchuk,¹²⁴ P. Sorokin,¹²⁴ R. Aggleton,¹²⁵ F. Ball,¹²⁵ L. Beck,¹²⁵ J. J. Brooke,¹²⁵ D. Burns,¹²⁵ E. Clement,¹²⁵ D. 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R. Erbacher,¹³³ C. Flores,¹³³ G. Funk,¹³³ M. Gardner,¹³³ W. Ko,¹³³ R. Lander,¹³³ C. Mclean,¹³³ M. Mulhearn,¹³³ D. Pellett,¹³³ J. Pilot,¹³³ S. Shalhout,¹³³ J. Smith,¹³³ M. Squires,¹³³ D. Stolp,¹³³ M. Tripathi,¹³³ C. Bravo,¹³⁴ R. Cousins,¹³⁴ A. Dasgupta,¹³⁴ P. Everaerts,¹³⁴ A. Florent,¹³⁴ J. Hauser,¹³⁴ M. Ignatenko,¹³⁴ N. Mccoll,¹³⁴ D. Saltzberg,¹³⁴ C. Schnaible,¹³⁴ E. Takasugi,¹³⁴ V. Valuev,¹³⁴ M. Weber,¹³⁴ K. Burt,¹³⁵ R. Clare,¹³⁵ J. Ellison,¹³⁵ J. W. Gary,¹³⁵ S. M. A. Ghiasi Shirazi,¹³⁵ G. Hanson,¹³⁵ J. Heilman,¹³⁵ P. Jandir,¹³⁵ E. Kennedy,¹³⁵ F. Lacroix,¹³⁵ O. R. Long,¹³⁵ M. Olmedo Negrete,¹³⁵ M. I. Paneva,¹³⁵ A. Shrinivas,¹³⁵ W. Si,¹³⁵ H. Wei,¹³⁵ S. Wimpenny,¹³⁵ B. R. Yates,¹³⁵ J. G. Branson,¹³⁶ G. B. Cerati,¹³⁶ S. Cittolin,¹³⁶ M. Derdzinski,¹³⁶ A. Holzner,¹³⁶ D. Klein,¹³⁶ V. Krutelyov,¹³⁶ J. Letts,¹³⁶ I. Macneill,¹³⁶ D. Olivito,¹³⁶ S. Padhi,¹³⁶ M. Pieri,¹³⁶ M. Sani,¹³⁶ V. Sharma,¹³⁶ S. Simon,¹³⁶ M. Tadel,¹³⁶ A. Vartak,¹³⁶ S. Wasserbaech,^{136,ppp} C. Welke,¹³⁶ J. Wood,¹³⁶ F. 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Skinnari,¹⁴¹ L. Soffi,¹⁴¹ S. M. Tan,¹⁴¹ Z. Tao,¹⁴¹ J. Thom,¹⁴¹ J. Tucker,¹⁴¹ P. Wittich,¹⁴¹ M. Zientek,¹⁴¹ D. Winn,¹⁴² S. Abdullin,¹⁴³ M. Albrow,¹⁴³ G. Apollinari,¹⁴³ S. Banerjee,¹⁴³ L. A. T. Bauerdick,¹⁴³ A. Beretvas,¹⁴³ J. Berryhill,¹⁴³ P. C. Bhat,¹⁴³ G. Bolla,¹⁴³ K. Burkett,¹⁴³ J. N. Butler,¹⁴³ H. W. K. Cheung,¹⁴³ F. Chlebana,¹⁴³ S. Cihangir,^{143,a} M. Cremonesi,¹⁴³ V. D. Elvira,¹⁴³ I. Fisk,¹⁴³ J. Freeman,¹⁴³ E. Gottschalk,¹⁴³ L. Gray,¹⁴³ D. Green,¹⁴³ S. Grünendahl,¹⁴³ O. Gutsche,¹⁴³ D. Hare,¹⁴³ R. M. Harris,¹⁴³ S. Hasegawa,¹⁴³ J. Hirschauer,¹⁴³ Z. Hu,¹⁴³ B. Jayatilaka,¹⁴³ S. Jindariani,¹⁴³ M. Johnson,¹⁴³ U. Joshi,¹⁴³ B. Klima,¹⁴³ B. Kreis,¹⁴³ S. Lammel,¹⁴³ J. Linacre,¹⁴³ D. Lincoln,¹⁴³ R. Lipton,¹⁴³ T. Liu,¹⁴³ R. Lopes De Sá,¹⁴³ J. Lykken,¹⁴³ K. Maeshima,¹⁴³ N. Magini,¹⁴³ J. M. Marraffino,¹⁴³ S. Maruyama,¹⁴³ D. Mason,¹⁴³ P. McBride,¹⁴³ P. Merkel,¹⁴³ S. Mrenna,¹⁴³ S. Nahn,¹⁴³ C. Newman-Holmes,^{143,a} V. O'Dell,¹⁴³ K. Pedro,¹⁴³ O. Prokofyev,¹⁴³ G. Rakness,¹⁴³ L. Ristori,¹⁴³ E. 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Yumiceva,¹⁴⁷ M. R. Adams,¹⁴⁸ L. Apanasevich,¹⁴⁸ D. Berry,¹⁴⁸ R. R. Betts,¹⁴⁸ I. Bucinskaite,¹⁴⁸ R. Cavanaugh,¹⁴⁸ O. Evdokimov,¹⁴⁸ L. Gauthier,¹⁴⁸ C. E. Gerber,¹⁴⁸ D. J. Hofman,¹⁴⁸ K. Jung,¹⁴⁸ P. Kurt,¹⁴⁸ C. O'Brien,¹⁴⁸ I. D. Sandoval Gonzalez,¹⁴⁸ P. Turner,¹⁴⁸ N. Varelas,¹⁴⁸ H. Wang,¹⁴⁸ Z. Wu,¹⁴⁸ M. Zakaria,¹⁴⁸ J. Zhang,¹⁴⁸ B. Bilki,^{149,qqq} W. Clarida,¹⁴⁹ K. Dilsiz,¹⁴⁹ S. Durgut,¹⁴⁹ R. P. Gandrajula,¹⁴⁹ M. Haytmyradov,¹⁴⁹ V. Khristenko,¹⁴⁹ J.-P. Merlo,¹⁴⁹ H. Mermerkaya,^{149,rrr} A. Mestvirishvili,¹⁴⁹ A. Moeller,¹⁴⁹ J. Nachtman,¹⁴⁹ H. Ogul,¹⁴⁹ Y. Onel,¹⁴⁹ F. Ozok,^{149,sss} A. Penzo,¹⁴⁹ C. Snyder,¹⁴⁹ E. Tiras,¹⁴⁹ J. Wetzel,¹⁴⁹ K. Yi,¹⁴⁹ I. Anderson,¹⁵⁰ B. Blumenfeld,¹⁵⁰ A. Cocoros,¹⁵⁰ N. Eminizer,¹⁵⁰ D. Fehling,¹⁵⁰ L. Feng,¹⁵⁰ A. V. Gritsan,¹⁵⁰ P. Maksimovic,¹⁵⁰ C. Martin,¹⁵⁰ M. Osherson,¹⁵⁰ J. Roskes,¹⁵⁰ U. Sarica,¹⁵⁰ M. Swartz,¹⁵⁰ M. Xiao,¹⁵⁰ Y. Xin,¹⁵⁰ C. You,¹⁵⁰ A. Al-bataineh,¹⁵¹ P. Baringer,¹⁵¹ A. Bean,¹⁵¹ S. Boren,¹⁵¹ J. Bowen,¹⁵¹ C. Bruner,¹⁵¹ J. Castle,¹⁵¹ L. Forthomme,¹⁵¹ R. P. Kenny III,¹⁵¹ S. Khalil,¹⁵¹ A. Kropivnitskaya,¹⁵¹ D. Majumder,¹⁵¹ W. Mbrayer,¹⁵¹ M. Murray,¹⁵¹ S. Sanders,¹⁵¹ R. Stringer,¹⁵¹ J. D. Tapia Takaki,¹⁵¹ Q. Wang,¹⁵¹ A. Ivanov,¹⁵² K. Kaadze,¹⁵² Y. Maravin,¹⁵² A. Mohammadi,¹⁵² L. K. Saini,¹⁵² N. Skhirtladze,¹⁵² S. Toda,¹⁵² F. Rebassoo,¹⁵³ D. Wright,¹⁵³ C. Anelli,¹⁵⁴ A. Baden,¹⁵⁴ O. Baron,¹⁵⁴ A. Belloni,¹⁵⁴ B. Calvert,¹⁵⁴ S. C. Eno,¹⁵⁴ C. Ferraioli,¹⁵⁴ J. A. Gomez,¹⁵⁴ N. J. Hadley,¹⁵⁴ S. Jabeen,¹⁵⁴ R. G. Kellogg,¹⁵⁴ T. Kolberg,¹⁵⁴ J. Kunkle,¹⁵⁴ Y. Lu,¹⁵⁴ A. C. Mignerey,¹⁵⁴ F. Ricci-Tam,¹⁵⁴ Y. H. Shin,¹⁵⁴ A. Skuja,¹⁵⁴ M. B. Tonjes,¹⁵⁴ S. C. Tonwar,¹⁵⁴ D. Abercrombie,¹⁵⁵ B. Allen,¹⁵⁵ A. Apyan,¹⁵⁵ R. Barbieri,¹⁵⁵ A. Baty,¹⁵⁵ R. Bi,¹⁵⁵ K. Bierwagen,¹⁵⁵ S. Brandt,¹⁵⁵ W. Busza,¹⁵⁵ I. A. Cali,¹⁵⁵ Z. Demiragli,¹⁵⁵ L. Di Matteo,¹⁵⁵ G. Gomez Ceballos,¹⁵⁵ M. Goncharov,¹⁵⁵ D. Hsu,¹⁵⁵ Y. Iiyama,¹⁵⁵ G. M. Innocenti,¹⁵⁵ M. Klute,¹⁵⁵ D. Kovalskyi,¹⁵⁵ K. Krajczar,¹⁵⁵ Y. S. Lai,¹⁵⁵

Y.-J. Lee,¹⁵⁵ A. Levin,¹⁵⁵ P. D. Luckey,¹⁵⁵ B. Maier,¹⁵⁵ A. C. Marini,¹⁵⁵ C. McGinn,¹⁵⁵ C. Mironov,¹⁵⁵ S. Narayanan,¹⁵⁵ X. Niu,¹⁵⁵ C. Paus,¹⁵⁵ C. Roland,¹⁵⁵ G. Roland,¹⁵⁵ J. Salfeld-Nebgen,¹⁵⁵ G. S. F. Stephans,¹⁵⁵ K. Sumorok,¹⁵⁵ K. Tatar,¹⁵⁵ M. Varma,¹⁵⁵ D. Velicanu,¹⁵⁵ J. Veverka,¹⁵⁵ J. Wang,¹⁵⁵ T. W. Wang,¹⁵⁵ B. Wyslouch,¹⁵⁵ M. Yang,¹⁵⁵ V. Zhukova,¹⁵⁵ A. C. Benvenuti,¹⁵⁶ R. M. Chatterjee,¹⁵⁶ A. Evans,¹⁵⁶ A. Finkel,¹⁵⁶ A. Gude,¹⁵⁶ P. Hansen,¹⁵⁶ S. Kalafut,¹⁵⁶ S. C. Kao,¹⁵⁶ Y. Kubota,¹⁵⁶ Z. Lesko,¹⁵⁶ J. Mans,¹⁵⁶ S. Nourbakhsh,¹⁵⁶ N. Ruckstuhl,¹⁵⁶ R. Rusack,¹⁵⁶ N. Tambe,¹⁵⁶ J. Turkewitz,¹⁵⁶ J. G. Acosta,¹⁵⁷ S. Oliveros,¹⁵⁷ E. Avdeeva,¹⁵⁸ R. Bartek,^{158,tut} K. Bloom,¹⁵⁸ D. R. Claes,¹⁵⁸ A. Dominguez,^{158,tut} C. Fangmeier,¹⁵⁸ R. Gonzalez Suarez,¹⁵⁸ R. Kamalieddin,¹⁵⁸ I. Kravchenko,¹⁵⁸ A. Malta Rodrigues,¹⁵⁸ F. Meier,¹⁵⁸ J. Monroy,¹⁵⁸ J. E. Siado,¹⁵⁸ G. R. Snow,¹⁵⁸ B. Stieger,¹⁵⁸ M. Alyari,¹⁵⁹ J. Dolen,¹⁵⁹ J. George,¹⁵⁹ A. Godshalk,¹⁵⁹ C. Harrington,¹⁵⁹ I. Iashvili,¹⁵⁹ J. Kaisen,¹⁵⁹ A. Kharchilava,¹⁵⁹ A. Kumar,¹⁵⁹ A. Parker,¹⁵⁹ S. Rappoccio,¹⁵⁹ B. Roozbahani,¹⁵⁹ G. Alverson,¹⁶⁰ E. Barberis,¹⁶⁰ A. Hortiangtham,¹⁶⁰ A. Massironi,¹⁶⁰ D. M. Morse,¹⁶⁰ D. Nash,¹⁶⁰ T. Orimoto,¹⁶⁰ R. Teixeira De Lima,¹⁶⁰ D. Trocino,¹⁶⁰ R.-J. Wang,¹⁶⁰ D. Wood,¹⁶⁰ S. Bhattacharya,¹⁶¹ O. Charaf,¹⁶¹ K. A. Hahn,¹⁶¹ A. Kubik,¹⁶¹ A. Kumar,¹⁶¹ N. Mucia,¹⁶¹ N. Odell,¹⁶¹ B. Pollack,¹⁶¹ M. H. Schmitt,¹⁶¹ K. Sung,¹⁶¹ M. Trovato,¹⁶¹ M. Velasco,¹⁶¹ N. Dev,¹⁶² M. Hildreth,¹⁶² K. Hurtado Anampa,¹⁶² C. Jessop,¹⁶² D. J. Karmgard,¹⁶² N. Kellams,¹⁶² K. Lannon,¹⁶² N. Marinelli,¹⁶² F. Meng,¹⁶² C. Mueller,¹⁶² Y. Musienko,^{162,mm} M. Planer,¹⁶² A. Reinsvold,¹⁶² R. Ruchti,¹⁶² G. Smith,¹⁶² S. Taroni,¹⁶² M. Wayne,¹⁶² M. Wolf,¹⁶² A. Woodard,¹⁶² J. Alimena,¹⁶³ L. Antonelli,¹⁶³ B. Bylsma,¹⁶³ L. S. Durkin,¹⁶³ S. Flowers,¹⁶³ B. Francis,¹⁶³ A. Hart,¹⁶³ C. Hill,¹⁶³ R. Hughes,¹⁶³ W. Ji,¹⁶³ B. Liu,¹⁶³ W. Luo,¹⁶³ D. Puigh,¹⁶³ B. L. Winer,¹⁶³ H. W. Wulsin,¹⁶³ S. Cooperstein,¹⁶⁴ O. Driga,¹⁶⁴ P. Elmer,¹⁶⁴ J. Hardenbrook,¹⁶⁴ P. Hebda,¹⁶⁴ D. Lange,¹⁶⁴ J. Luo,¹⁶⁴ D. Marlow,¹⁶⁴ J. Mc Donald,¹⁶⁴ T. Medvedeva,¹⁶⁴ K. Mei,¹⁶⁴ M. Mooney,¹⁶⁴ J. Olsen,¹⁶⁴ C. Palmer,¹⁶⁴ P. Piroué,¹⁶⁴ D. Stickland,¹⁶⁴ A. Svyatkovskiy,¹⁶⁴ C. Tully,¹⁶⁴ A. Zuranski,¹⁶⁴ S. Malik,¹⁶⁵ A. Barker,¹⁶⁶ V. E. Barnes,¹⁶⁶ S. Folgueras,¹⁶⁶ L. Gutay,¹⁶⁶ M. K. Jha,¹⁶⁶ M. Jones,¹⁶⁶ A. W. Jung,¹⁶⁶ D. H. Miller,¹⁶⁶ N. Neumeister,¹⁶⁶ J. F. Schulte,¹⁶⁶ X. Shi,¹⁶⁶ J. Sun,¹⁶⁶ F. Wang,¹⁶⁶ W. Xie,¹⁶⁶ N. Parashar,¹⁶⁷ J. Stupak,¹⁶⁷ A. Adair,¹⁶⁸ B. Akgun,¹⁶⁸ Z. Chen,¹⁶⁸ K. M. Ecklund,¹⁶⁸ F. J. M. Geurts,¹⁶⁸ M. Guilbaud,¹⁶⁸ W. Li,¹⁶⁸ B. Michlin,¹⁶⁸ M. Northup,¹⁶⁸ B. P. Padley,¹⁶⁸ R. Redjimi,¹⁶⁸ J. Roberts,¹⁶⁸ J. Rorie,¹⁶⁸ Z. Tu,¹⁶⁸ J. Zabel,¹⁶⁸ B. Betchart,¹⁶⁹ A. Bodek,¹⁶⁹ P. de Barbaro,¹⁶⁹ R. Demina,¹⁶⁹ Y. t. Duh,¹⁶⁹ T. Ferbel,¹⁶⁹ M. Galanti,¹⁶⁹ A. Garcia-Bellido,¹⁶⁹ J. Han,¹⁶⁹ O. Hindrichs,¹⁶⁹ A. Khukhunaishvili,¹⁶⁹ K. H. Lo,¹⁶⁹ P. Tan,¹⁶⁹ M. Verzetti,¹⁶⁹ A. Agapitos,¹⁷⁰ J. P. Chou,¹⁷⁰ E. Contreras-Campana,¹⁷⁰ Y. Gershtein,¹⁷⁰ T. A. Gómez Espinosa,¹⁷⁰ E. Halkiadakis,¹⁷⁰ M. Heindl,¹⁷⁰ D. Hidas,¹⁷⁰ E. Hughes,¹⁷⁰ S. Kaplan,¹⁷⁰ R. Kunnawalkam Elayavalli,¹⁷⁰ S. Kyriacou,¹⁷⁰ A. Lath,¹⁷⁰ K. Nash,¹⁷⁰ H. Saka,¹⁷⁰ S. Salur,¹⁷⁰ S. Schnetzer,¹⁷⁰ D. Sheffield,¹⁷⁰ S. Somalwar,¹⁷⁰ R. Stone,¹⁷⁰ S. Thomas,¹⁷⁰ P. Thomassen,¹⁷⁰ M. Walker,¹⁷⁰ A. G. Delannoy,¹⁷¹ M. Foerster,¹⁷¹ J. Heideman,¹⁷¹ G. Riley,¹⁷¹ K. Rose,¹⁷¹ S. Spanier,¹⁷¹ K. Thapa,¹⁷¹ O. Bouhali,^{172,uuu} A. Celik,¹⁷² M. Dalchenko,¹⁷² M. De Mattia,¹⁷² A. Delgado,¹⁷² S. Dildick,¹⁷² R. Eusebi,¹⁷² J. Gilmore,¹⁷² T. Huang,¹⁷² E. Juska,¹⁷² T. Kamon,^{172,vvv} R. Mueller,¹⁷² Y. Pakhotin,¹⁷² R. Patel,¹⁷² A. Perloff,¹⁷² L. Perniè,¹⁷² D. Rathjens,¹⁷² A. Rose,¹⁷² A. Safonov,¹⁷² A. Tatarinov,¹⁷² K. A. Ulmer,¹⁷² N. Akchurin,¹⁷³ C. Cowden,¹⁷³ J. Damgov,¹⁷³ F. De Guio,¹⁷³ C. Dragoiu,¹⁷³ P. R. Duerdo,¹⁷³ J. Faulkner,¹⁷³ E. Gorpinar,¹⁷³ S. Kunori,¹⁷³ K. Lamichhane,¹⁷³ S. W. Lee,¹⁷³ T. Libeiro,¹⁷³ T. Peltola,¹⁷³ S. Undleeb,¹⁷³ I. Volobouev,¹⁷³ Z. Wang,¹⁷³ S. Greene,¹⁷⁴ A. Gurrola,¹⁷⁴ R. Janjam,¹⁷⁴ W. Johns,¹⁷⁴ C. Maguire,¹⁷⁴ A. Melo,¹⁷⁴ H. Ni,¹⁷⁴ P. Sheldon,¹⁷⁴ S. Tuo,¹⁷⁴ J. Velkovska,¹⁷⁴ Q. Xu,¹⁷⁴ M. W. Arenton,¹⁷⁵ P. Barria,¹⁷⁵ B. Cox,¹⁷⁵ J. Goodell,¹⁷⁵ R. Hirosky,¹⁷⁵ A. Ledovskoy,¹⁷⁵ H. Li,¹⁷⁵ C. Neu,¹⁷⁵ T. Sinthuprasith,¹⁷⁵ X. Sun,¹⁷⁵ Y. Wang,¹⁷⁵ E. Wolfe,¹⁷⁵ F. Xia,¹⁷⁵ C. Clarke,¹⁷⁶ R. Harr,¹⁷⁶ P. E. Karchin,¹⁷⁶ J. Sturdy,¹⁷⁶ D. A. Belknap,¹⁷⁷ J. Buchanan,¹⁷⁷ C. Caillol,¹⁷⁷ S. Dasu,¹⁷⁷ L. Dodd,¹⁷⁷ S. Duric,¹⁷⁷ B. Gomber,¹⁷⁷ M. Grothe,¹⁷⁷ M. Herndon,¹⁷⁷ A. Hervé,¹⁷⁷ P. Klabbers,¹⁷⁷ A. Lanaro,¹⁷⁷ A. Levine,¹⁷⁷ K. Long,¹⁷⁷ R. Loveless,¹⁷⁷ I. Ojalvo,¹⁷⁷ T. Perry,¹⁷⁷ G. A. Pierro,¹⁷⁷ G. Polese,¹⁷⁷ T. Ruggles,¹⁷⁷ A. Savin,¹⁷⁷ N. Smith,¹⁷⁷ W. H. Smith,¹⁷⁷ D. Taylor,¹⁷⁷ and N. Woods¹⁷⁷

(CMS Collaboration)

¹Yerevan Physics Institute, Yerevan, Armenia²Institut für Hochenergiephysik, Wien, Austria³Institute for Nuclear Problems, Minsk, Belarus⁴National Centre for Particle and High Energy Physics, Minsk, Belarus⁵Universiteit Antwerpen, Antwerpen, Belgium⁶Vrije Universiteit Brussel, Brussel, Belgium

- ⁷*Université Libre de Bruxelles, Bruxelles, Belgium*
⁸*Ghent University, Ghent, Belgium*
⁹*Université Catholique de Louvain, Louvain-la-Neuve, Belgium*
¹⁰*Université de Mons, Mons, Belgium*
¹¹*Centro Brasileiro de Pesquisas Físicas, Rio de Janeiro, Brazil*
¹²*Universidade do Estado do Rio de Janeiro, Rio de Janeiro, Brazil*
^{13a}*Universidade Estadual Paulista, São Paulo, Brazil*
^{13b}*Universidade Federal do ABC, São Paulo, Brazil*
¹⁴*Institute for Nuclear Research and Nuclear Energy, Sofia, Bulgaria*
¹⁵*University of Sofia, Sofia, Bulgaria*
¹⁶*Beihang University, Beijing, China*
¹⁷*Institute of High Energy Physics, Beijing, China*
¹⁸*State Key Laboratory of Nuclear Physics and Technology, Peking University, Beijing, China*
¹⁹*Universidad de Los Andes, Bogota, Colombia*
²⁰*University of Split, Faculty of Electrical Engineering, Mechanical Engineering and Naval Architecture, Split, Croatia*
²¹*University of Split, Faculty of Science, Split, Croatia*
²²*Institute Rudjer Boskovic, Zagreb, Croatia*
²³*University of Cyprus, Nicosia, Cyprus*
²⁴*Charles University, Prague, Czech Republic*
²⁵*Universidad San Francisco de Quito, Quito, Ecuador*
²⁶*Academy of Scientific Research and Technology of the Arab Republic of Egypt, Egyptian Network of High Energy Physics, Cairo, Egypt*
²⁷*National Institute of Chemical Physics and Biophysics, Tallinn, Estonia*
²⁸*Department of Physics, University of Helsinki, Helsinki, Finland*
²⁹*Helsinki Institute of Physics, Helsinki, Finland*
³⁰*Lappeenranta University of Technology, Lappeenranta, Finland*
³¹*IRFU, CEA, Université Paris-Saclay, Gif-sur-Yvette, France*
³²*Laboratoire Leprince-Ringuet, Ecole Polytechnique, IN2P3-CNRS, Palaiseau, France*
³³*Institut Pluridisciplinaire Hubert Curien, Université de Strasbourg, Université de Haute Alsace Mulhouse, CNRS/IN2P3, Strasbourg, France*
³⁴*Centre de Calcul de l'Institut National de Physique Nucléaire et de Physique des Particules, CNRS/IN2P3, Villeurbanne, France*
³⁵*Université de Lyon, Université Claude Bernard Lyon 1, CNRS-IN2P3, Institut de Physique Nucléaire de Lyon, Villeurbanne, France*
³⁶*Georgian Technical University, Tbilisi, Georgia*
³⁷*Tbilisi State University, Tbilisi, Georgia*
³⁸*RWTH Aachen University, I. Physikalisches Institut, Aachen, Germany*
³⁹*RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany*
⁴⁰*RWTH Aachen University, III. Physikalisches Institut B, Aachen, Germany*
⁴¹*Deutsches Elektronen-Synchrotron, Hamburg, Germany*
⁴²*University of Hamburg, Hamburg, Germany*
⁴³*Institut für Experimentelle Kernphysik, Karlsruhe, Germany*
⁴⁴*Institute of Nuclear and Particle Physics (INPP), NCSR Demokritos, Aghia Paraskevi, Greece*
⁴⁵*National and Kapodistrian University of Athens, Athens, Greece*
⁴⁶*University of Ioánnina, Ioánnina, Greece*
⁴⁷*MTA-ELTE Lendület CMS Particle and Nuclear Physics Group, Eötvös Loránd University, Budapest, Hungary*
⁴⁸*Wigner Research Centre for Physics, Budapest, Hungary*
⁴⁹*Institute of Nuclear Research ATOMKI, Debrecen, Hungary*
⁵⁰*University of Debrecen, Debrecen, Hungary*
⁵¹*National Institute of Science Education and Research, Bhubaneswar, India*
⁵²*Panjab University, Chandigarh, India*
⁵³*University of Delhi, Delhi, India*
⁵⁴*Saha Institute of Nuclear Physics, Kolkata, India*
⁵⁵*Indian Institute of Technology Madras, Madras, India*
⁵⁶*Bhabha Atomic Research Centre, Mumbai, India*
⁵⁷*Tata Institute of Fundamental Research-A, Mumbai, India*
⁵⁸*Tata Institute of Fundamental Research-B, Mumbai, India*
⁵⁹*Indian Institute of Science Education and Research (IISER), Pune, India*
⁶⁰*Institute for Research in Fundamental Sciences (IPM), Tehran, Iran*
⁶¹*University College Dublin, Dublin, Ireland*
^{62a}*INFN Sezione di Bari, Bari, Italy*
^{62b}*Università di Bari, Bari, Italy*

- ^{62c}Politecnico di Bari, Bari, Italy
- ^{63a}INFN Sezione di Bologna, Bologna, Italy
- ^{63b}Università di Bologna, Bologna, Italy
- ^{64a}INFN Sezione di Catania, Catania, Italy
- ^{64b}Università di Catania, Catania, Italy
- ^{65a}INFN Sezione di Firenze, Firenze, Italy
- ^{65b}Università di Firenze, Firenze, Italy
- ⁶⁶INFN Laboratori Nazionali di Frascati, Frascati, Italy
- ^{67a}INFN Sezione di Genova, Genova, Italy
- ^{67b}Università di Genova, Genova, Italy
- ^{68a}INFN Sezione di Milano-Bicocca, Milano, Italy
- ^{68b}Università di Milano-Bicocca, Milano, Italy
- ^{69a}INFN Sezione di Napoli, Roma, Italy
- ^{69b}Università di Napoli 'Federico II', Roma, Italy
- ^{69c}Università della Basilicata, Roma, Italy
- ^{69c}Università G. Marconi, Roma, Italy
- ^{70a}INFN Sezione di Padova, Padova, Italy
- ^{70b}Università di Padova, Padova, Italy
- ^{70c}Università di Trento, Trento, Italy
- ^{71a}INFN Sezione di Pavia, Pavia, Italy
- ^{71b}Università di Pavia, Pavia, Italy
- ^{72a}INFN Sezione di Perugia, Perugia, Italy
- ^{72b}Università di Perugia, Perugia, Italy
- ^{73a}INFN Sezione di Pisa, Pisa, Italy
- ^{73b}Università di Pisa, Pisa, Italy
- ^{73c}Scuola Normale Superiore di Pisa, Pisa, Italy
- ^{74a}INFN Sezione di Roma, Rome, Italy
- ^{74b}Università di Roma, Rome, Italy
- ^{75a}INFN Sezione di Torino, Novara, Italy
- ^{75b}Università di Torino, Novara, Italy
- ^{75c}Università del Piemonte Orientale, Novara, Italy
- ^{76a}INFN Sezione di Trieste, Trieste, Italy
- ^{76b}Università di Trieste, Trieste, Italy
- ⁷⁷Kyungpook National University, Daegu, Korea
- ⁷⁸Chonbuk National University, Jeonju, Korea
- ⁷⁹Chonnam National University, Institute for Universe and Elementary Particles, Kwangju, Korea
- ⁸⁰Hanyang University, Seoul, Korea
- ⁸¹Korea University, Seoul, Korea
- ⁸²Seoul National University, Seoul, Korea
- ⁸³University of Seoul, Seoul, Korea
- ⁸⁴Sungkyunkwan University, Suwon, Korea
- ⁸⁵Vilnius University, Vilnius, Lithuania
- ⁸⁶National Centre for Particle Physics, Universiti Malaya, Kuala Lumpur, Malaysia
- ⁸⁷Centro de Investigación y de Estudios Avanzados del IPN, Mexico City, Mexico
- ⁸⁸Universidad Iberoamericana, Mexico City, Mexico
- ⁸⁹Benemerita Universidad Autónoma de Puebla, Puebla, Mexico
- ⁹⁰Universidad Autónoma de San Luis Potosí, San Luis Potosí, Mexico
- ⁹¹University of Auckland, Auckland, New Zealand
- ⁹²University of Canterbury, Christchurch, New Zealand
- ⁹³National Centre for Physics, Quaid-I-Azam University, Islamabad, Pakistan
- ⁹⁴National Centre for Nuclear Research, Swierk, Poland
- ⁹⁵Institute of Experimental Physics, Faculty of Physics, University of Warsaw, Warsaw, Poland
- ⁹⁶Laboratório de Instrumentação e Física Experimental de Partículas, Lisboa, Portugal
- ⁹⁷Joint Institute for Nuclear Research, Dubna, Russia
- ⁹⁸Petersburg Nuclear Physics Institute, Gatchina (St. Petersburg), Russia
- ⁹⁹Institute for Nuclear Research, Moscow, Russia
- ¹⁰⁰Institute for Theoretical and Experimental Physics, Moscow, Russia
- ¹⁰¹Moscow Institute of Physics and Technology, Moscow, Russia
- ¹⁰²National Research Nuclear University 'Moscow Engineering Physics Institute' (MEPhI), Moscow, Russia
- ¹⁰³P.N. Lebedev Physical Institute, Moscow, Russia

- ¹⁰⁴*Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, Moscow, Russia*
¹⁰⁵*Novosibirsk State University (NSU), Novosibirsk, Russia*
¹⁰⁶*State Research Center of Russian Federation, Institute for High Energy Physics, Protvino, Russia*
¹⁰⁷*University of Belgrade, Faculty of Physics and Vinca Institute of Nuclear Sciences, Belgrade, Serbia*
¹⁰⁸*Centro de Investigaciones Energéticas Medioambientales y Tecnológicas (CIEMAT), Madrid, Spain*
¹⁰⁹*Universidad Autónoma de Madrid, Madrid, Spain*
¹¹⁰*Universidad de Oviedo, Oviedo, Spain*
¹¹¹*Instituto de Física de Cantabria (IFCA), CSIC-Universidad de Cantabria, Santander, Spain*
¹¹²*CERN, European Organization for Nuclear Research, Geneva, Switzerland*
¹¹³*Paul Scherrer Institut, Villigen, Switzerland*
¹¹⁴*Institute for Particle Physics, ETH Zurich, Zurich, Switzerland*
¹¹⁵*Universität Zürich, Zurich, Switzerland*
¹¹⁶*National Central University, Chung-Li, Taiwan*
¹¹⁷*National Taiwan University (NTU), Taipei, Taiwan*
¹¹⁸*Chulalongkorn University, Faculty of Science, Department of Physics, Bangkok, Thailand*
¹¹⁹*Cukurova University, Adana, Turkey*
¹²⁰*Middle East Technical University, Physics Department, Ankara, Turkey*
¹²¹*Bogazici University, Istanbul, Turkey*
¹²²*Istanbul Technical University, Istanbul, Turkey*
¹²³*Institute for Scintillation Materials of National Academy of Science of Ukraine, Kharkov, Ukraine*
¹²⁴*National Scientific Center, Kharkov Institute of Physics and Technology, Kharkov, Ukraine*
¹²⁵*University of Bristol, Bristol, United Kingdom*
¹²⁶*Rutherford Appleton Laboratory, Didcot, United Kingdom*
¹²⁷*Imperial College, London, United Kingdom*
¹²⁸*Brunel University, Uxbridge, United Kingdom*
¹²⁹*Baylor University, Waco, Texas, USA*
¹³⁰*The University of Alabama, Tuscaloosa, Alabama, USA*
¹³¹*Boston University, Boston, Massachusetts, USA*
¹³²*Brown University, Providence, Rhode Island, USA*
¹³³*University of California, Davis, California, USA*
¹³⁴*University of California, Los Angeles, California, USA*
¹³⁵*University of California, Riverside, California, USA*
¹³⁶*University of California, San Diego, La Jolla, USA*
¹³⁷*University of California, Santa Barbara - Department of Physics, Santa Barbara, California, USA*
¹³⁸*California Institute of Technology, Pasadena, California, USA*
¹³⁹*Carnegie Mellon University, Pittsburgh, Pennsylvania, USA*
¹⁴⁰*University of Colorado Boulder, Boulder, Colorado, USA*
¹⁴¹*Cornell University, Ithaca, New York, USA*
¹⁴²*Fairfield University, Fairfield, Connecticut, USA*
¹⁴³*Fermi National Accelerator Laboratory, Batavia, New York, USA*
¹⁴⁴*University of Florida, Gainesville, Florida, USA*
¹⁴⁵*Florida International University, Miami, Florida, USA*
¹⁴⁶*Florida State University, Tallahassee, Florida, USA*
¹⁴⁷*Florida Institute of Technology, Melbourne, Florida, USA*
¹⁴⁸*University of Illinois at Chicago (UIC), Chicago, Illinois, USA*
¹⁴⁹*The University of Iowa, Iowa City, Iowa, USA*
¹⁵⁰*Johns Hopkins University, Baltimore, Maryland, USA*
¹⁵¹*The University of Kansas, Lawrence, Kansas, USA*
¹⁵²*Kansas State University, Manhattan, Kansas, USA*
¹⁵³*Lawrence Livermore National Laboratory, Livermore, California, USA*
¹⁵⁴*University of Maryland, College Park, Maryland, USA*
¹⁵⁵*Massachusetts Institute of Technology, Cambridge, Massachusetts, USA*
¹⁵⁶*University of Minnesota, Minneapolis, Minnesota, USA*
¹⁵⁷*University of Mississippi, Oxford, Mississippi, USA*
¹⁵⁸*University of Nebraska-Lincoln, Lincoln, Nebraska, USA*
¹⁵⁹*State University of New York at Buffalo, Buffalo, New York, USA*
¹⁶⁰*Northeastern University, Boston, Massachusetts, USA*
¹⁶¹*Northwestern University, Evanston, Illinois, USA*
¹⁶²*University of Notre Dame, Notre Dame, Indiana, USA*
¹⁶³*The Ohio State University, Columbus, Ohio, USA*

- ¹⁶⁴Princeton University, Princeton, New Jersey, USA
¹⁶⁵University of Puerto Rico, Mayaguez, Puerto Rico, USA
¹⁶⁶Purdue University, West Lafayette, Indiana, USA
¹⁶⁷Purdue University Calumet, Hammond, Louisiana, USA
¹⁶⁸Rice University, Houston, Texas, USA
¹⁶⁹University of Rochester, Rochester, New York, USA
¹⁷⁰Rutgers, The State University of New Jersey, Piscataway, New Jersey, USA
¹⁷¹University of Tennessee, Knoxville, Tennessee, USA
¹⁷²Texas A&M University, College Station, Texas, USA
¹⁷³Texas Tech University, Lubbock, Texas, USA
¹⁷⁴Vanderbilt University, Nashville, Tennessee, USA
¹⁷⁵University of Virginia, Charlottesville, Virginia, USA
¹⁷⁶Wayne State University, Detroit, Michigan, USA
¹⁷⁷University of Wisconsin - Madison, Madison, Wisconsin, USA

^aDeceased.

^bAlso at Vienna University of Technology, Vienna, Austria.

^cAlso at State Key Laboratory of Nuclear Physics and Technology, Peking University, Beijing, China.

^dAlso at Institut Pluridisciplinaire Hubert Curien, Université de Strasbourg, Université de Haute Alsace Mulhouse, CNRS/IN2P3, Strasbourg, France.

^eAlso at Universidade Estadual de Campinas, Campinas, Brazil.

^fAlso at Universidade Federal de Pelotas, Pelotas, Brazil.

^gAlso at Université Libre de Bruxelles, Bruxelles, Belgium.

^hAlso at Deutsches Elektronen-Synchrotron, Hamburg, Germany.

ⁱAlso at Joint Institute for Nuclear Research, Dubna, Russia.

^jAlso at Helwan University, Cairo, Egypt.

^kAlso at Zewail City of Science and Technology, Zewail, Egypt.

^lAlso at Fayoum University, El-Fayoum, Egypt.

^mAlso at British University in Egypt, Cairo, Egypt.

ⁿAlso at Ain Shams University, Cairo, Egypt.

^oAlso at Université de Haute Alsace, Mulhouse, France.

^pAlso at Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, Moscow, Russia.

^qAlso at Tbilisi State University, Tbilisi, Georgia.

^rAlso at CERN, European Organization for Nuclear Research, Geneva, Switzerland.

^sAlso at RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany.

^tAlso at University of Hamburg, Hamburg, Germany.

^uAlso at Brandenburg University of Technology, Cottbus, Germany.

^vAlso at Institute of Nuclear Research ATOMKI, Debrecen, Hungary.

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

^xAlso at University of Debrecen, Debrecen, Hungary.

^yAlso at Indian Institute of Science Education and Research, Bhopal, India.

^zAlso at Institute of Physics, Bhubaneswar, India.

^{aa}Also at University of Visva-Bharati, Santiniketan, India.

^{bb}Also at University of Ruhuna, Matara, Sri Lanka.

^{cc}Also at Isfahan University of Technology, Isfahan, Iran.

^{dd}Also at University of Tehran, Department of Engineering Science, Tehran, Iran.

^{ee}Also at Yazd University, Yazd, Iran.

^{ff}Also at Plasma Physics Research Center, Science and Research Branch, Islamic Azad University, Tehran, Iran.

^{gg}Also at Università degli Studi di Siena, Siena, Italy.

^{hh}Also at Purdue University, West Lafayette, USA.

ⁱⁱAlso at International Islamic University of Malaysia, Kuala Lumpur, Malaysia.

^{jj}Also at Malaysian Nuclear Agency, MOSTI, Kajang, Malaysia.

^{kk}Also at Consejo Nacional de Ciencia y Tecnología, Mexico city, Mexico.

^{ll}Also at Warsaw University of Technology, Institute of Electronic Systems, Warsaw, Poland.

^{mm}Also at Institute for Nuclear Research, Moscow, Russia.

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

^{oo}Also at St. Petersburg State Polytechnical University, St. Petersburg, Russia.

^{pp}Also at University of Florida, Gainesville, USA.

^{qq}Also at INFN Sezione di Padova, Università di Padova, Padova, Italy, Università di Trento, Trento, Italy.

^{rr}Also at Budker Institute of Nuclear Physics, Novosibirsk, Russia.

- ^{ss} Also at Faculty of Physics, University of Belgrade, Belgrade, Serbia.
- ^{tt} Also at INFN Sezione di Roma, Università di Roma, Roma, Italy.
- ^{uu} Also at University of Belgrade, Faculty of Physics and Vinca Institute of Nuclear Sciences, Belgrade, Serbia.
- ^{vv} Also at Scuola Normale e Sezione dell'INFN, Pisa, Italy.
- ^{ww} Also at National and Kapodistrian University of Athens, Athens, Greece.
- ^{xx} Also at Riga Technical University, Riga, Latvia.
- ^{yy} Also at Institute for Theoretical and Experimental Physics, Moscow, Russia.
- ^{zz} Also at Albert Einstein Center for Fundamental Physics, Bern, Switzerland.
- ^{aaa} Also at Adiyaman University, Adiyaman, Turkey.
- ^{bbb} Also at Istanbul Aydin University, Istanbul, Turkey.
- ^{ccc} Also at Mersin University, Mersin, Turkey.
- ^{ddd} Also at Cag University, Mersin, Turkey.
- ^{eee} Also at Piri Reis University, Istanbul, Turkey.
- ^{fff} Also at Ozyegin University, Istanbul, Turkey.
- ^{ggg} Also at Izmir Institute of Technology, Izmir, Turkey.
- ^{hhh} Also at Marmara University, Istanbul, Turkey.
- ⁱⁱⁱ Also at Kafkas University, Kars, Turkey.
- ^{jjj} Also at Istanbul Bilgi University, Istanbul, Turkey.
- ^{kkk} Also at Yildiz Technical University, Istanbul, Turkey.
- ^{lll} Also at Hacettepe University, Ankara, Turkey.
- ^{mmm} Also at Rutherford Appleton Laboratory, Didcot, United Kingdom.
- ⁿⁿⁿ Also at School of Physics and Astronomy, University of Southampton, Southampton, United Kingdom.
- ^{ooo} Also at Instituto de Astrofísica de Canarias, La Laguna, Spain.
- ^{ppp} Also at Utah Valley University, Orem, USA.
- ^{qqq} Also at Argonne National Laboratory, Argonne, USA.
- ^{rrr} Also at Erzincan University, Erzincan, Turkey.
- ^{sss} Also at Mimar Sinan University, Istanbul, Istanbul, Turkey.
- ^{ttt} Also at Catholic University of America.
- ^{uuu} Also at Texas A&M University at Qatar, Doha, Qatar.
- ^{vvv} Also at Kyungpook National University, Daegu, Korea.