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CMS Collaboration, ; Canelli, Florencia ; Kilminster, Benjamin ; Aarestad, Thea ; Caminada, Lea ; De Cosa, Anna Paola ; Del Burgo, Riccardo ; Donato, Silvio ; Galloni, Camilla ; Hinzmann, Andreas ; Hreus, Tomas ; Ngadiuba, Jennifer ; Pinna, Deborah ; Rauco, Giorgia ; Robmann, Peter ; Salerno, Daniel ; Schweiger, Korbinian ; Seitz, Claudia ; Takahashi, Yuta ; Zucchetta, Alberto ; et al,

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Study of Jet Quenching with Z + jet Correlations in Pb-Pb and pp Collisions at $\sqrt{s_{NN}} = 5.02$ TeV

A. M. Sirunyan *et al.**

(CMS Collaboration)

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The production of jets in association with Z bosons, reconstructed via the $\mu^+\mu^-$ and e^+e^- decay channels, is studied in pp and, for the first time, in Pb-Pb collisions. Both data samples were collected by the CMS experiment at the LHC, at a nucleon-nucleon center-of-mass energy of 5.02 TeV. The Pb-Pb collisions were analyzed in the 0%–30% centrality range. The back-to-back azimuthal alignment was studied in both pp and Pb-Pb collisions for Z bosons with transverse momentum $p_T^Z > 60$ GeV/c and a recoiling jet with $p_T^{\text{jet}} > 30$ GeV/c. The p_T imbalance $x_{jZ} = p_T^{\text{jet}}/p_T^Z$, as well as the average number of jet partners per Z, R_{jZ} , was studied in intervals of p_T^Z . The R_{jZ} is found to be smaller in Pb-Pb than in pp collisions, which suggests that in Pb-Pb collisions a larger fraction of partons associated with the Z bosons fall below the 30 GeV/c p_T^{jet} threshold because they lose energy.

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The correlated production of vector bosons and jets in hard parton scatterings occurring in ultrarelativistic heavy ion collisions provides an ideal probe of the quark-gluon plasma (QGP), a deconfined state of quarks and gluons [1,2]. Final-state jets are created by the fragmentation of outgoing partons that interact strongly with the produced medium and lose energy [3–11], a phenomenon (“jet quenching”) observed at RHIC [12,13] and the LHC [14–18]. The transverse momentum (p_T) of the jet is highly correlated (through momentum conservation) with that of the associated Z boson, which is not affected by the medium [19–21] and reflects the initial energy of the parton. The lost energy can be related, via theoretical models, to the thermodynamical and transport properties of the medium [9–11,22–24]. At LHC energies, Z + jet production is dominated by quark jets for $p_T^{\text{jet}} \gtrsim 30$ GeV/c [21], the primary subprocess being $q(\bar{q}) + g \rightarrow Z + q(\bar{q})$ [19], hence providing information on the parton flavor (quark or gluon) and kinematics, and allowing detailed studies of the energy loss with a well-defined production process. The Z-jet correlations are particularly well suited to perform tomographic studies of the QGP, given the minimal contributions from background channels [20,25–27]. Correlations of jets with isolated photons are accessible at higher rates and carry similar information on parton energy loss [25–29] but suffer from an irreducible background of photons from jet fragmentation [17,30] as well as larger

uncertainties arising from the experimental selection of photon candidates.

This Letter describes the identification of Z + jet pairs in pp and Pb-Pb collisions, and the first characterization of parton energy loss through angular and p_T correlations between the jet and the Z, reconstructed in dimuon or dielectron decays. The back-to-back azimuthal alignment of the Z and jets is studied through the difference $\Delta\phi_{jZ} = |\phi^{\text{jet}} - \phi^Z|$. The Z + jet momentum imbalance is studied using the $x_{jZ} = p_T^{\text{jet}}/p_T^Z$ ratio and the p_T^Z dependence of its mean value, $\langle x_{jZ} \rangle$. The average number of jet partners per Z boson, R_{jZ} , is also reported. The analysis exploits Pb-Pb and pp data samples collected by CMS at a nucleon-nucleon center-of-mass energy of 5.02 TeV, corresponding to integrated luminosities of $404 \mu\text{b}^{-1}$ and 27.4 pb^{-1} , respectively.

The central feature of CMS is a superconducting solenoid of 6 m internal diameter, providing a magnetic field of 3.8 T. Within the solenoid volume are a silicon pixel and strip tracker, 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. Forward hadron calorimeters extend the pseudorapidity (η) coverage and are used for Pb-Pb event selection. Muons are measured in gas-ionization detectors located outside the solenoid. A more 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. [31].

The event samples are selected on-line with dedicated lepton triggers and cleaned off-line to remove noncollision events, such as beam-gas interactions or cosmic-ray muons [32]. In addition, events are required to have at least one reconstructed primary interaction vertex. The $Z \rightarrow e^+e^-$

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events are triggered if two ECAL clusters [33] have transverse energy greater than 15 GeV and $|\eta| < 2.5$, while the $Z \rightarrow \mu^+\mu^-$ triggers require one muon of $p_T > 15$ GeV/ c or two muons of $p_T > 10$ GeV/ c .

For the analysis of Pb-Pb collisions, the “centrality” (overlap of the two colliding nuclei) is determined by the sum of the total energy deposited in both forward hadron calorimeters [15]. The results refer to the 30% most central collisions, to focus on the region of highest physics interest. After all the other analysis selections, 78% of the Z boson events fall in this centrality range.

The PYTHIA 8.212 [34] Monte Carlo (MC) event generator, with tune CUETP8M1 [35], is used to simulate Z + jet signal events, with $p_T^Z > 30$ GeV/ c and rapidity $|y^Z| < 2.5$. A sample with a Z boson without any kinematic selection was produced using a next-to-leading order (NLO) generator, MADGRAPH5_AMC@NLO [36]. In the Pb-Pb case, a PYTHIA+HYDJET sample is created by embedding PYTHIA signal events in heavy ion events generated with HYDJET 1.9 [37] and tune HydroQJets. The generated events are propagated through the CMS apparatus using the GEANT4 [38] package. No unfolding is performed for the results presented. The recipe for applying a smearing of the jet p_T resolution is provided in Supplemental Material [39].

Electrons are identified as ECAL superclusters [40] matched in position and energy to tracks reconstructed in the tracker. They must have $p_T > 20$ GeV/ c , above the trigger threshold, and each supercluster must be within the acceptance of the tracker, $|\eta| < 2.5$. Electron candidates in the transition region between the barrel and end cap subdetectors ($1.44 < |\eta| < 1.57$) are excluded. In pp collisions, the electrons are selected via standard identification criteria [40]. A narrow transverse shape of showers in the ECAL and a low HCAL over ECAL energy ratio are required to reject misidentified electrons. Additional tracking information is used to distinguish electrons from charged hadrons [40]. For Pb-Pb collisions, the identification criteria have been optimized to compensate for the higher background levels in the calorimeters. With these selections, the pp and Pb-Pb electron reconstruction purities (efficiencies) are identical within 1% (10%).

Muons are selected by requiring segments in at least two muon detector planes and a good-quality fit when connecting them to tracker segments. This suppresses hadronic punchthrough and muons from in-flight decays of hadrons. A minimum number of hits in the pixel and strip layers is required, and the reconstructed muon tracks must point to the primary vertex in the transverse and longitudinal directions [41]. The same selections are applied for both pp and Pb-Pb data. In order to suppress the background continuum under the Z peak, mostly originating from uncorrelated simultaneous decays of heavy flavor mesons, the muons are required to have $p_T > 10$ GeV/ c . In addition, the muon tracks must fall in the acceptance of the muon detectors, $|\eta^\mu| < 2.4$.

Jet reconstruction uses the anti- k_T algorithm implemented in FASTJET [42], following the procedure of Ref. [16]. A small distance parameter, $R = 0.3$, minimizes the effects of fluctuations in the underlying event (UE), dominantly formed by soft processes in heavy ion collisions. The UE energy subtraction [43] is performed for Pb-Pb as described in Refs. [15–17]. Closure tests, done on MC samples without medium-induced jet energy loss, show no over subtraction of the UE in the Pb-Pb sample. No subtraction is applied in the pp sample, where the UE contribution is negligible. The jet energy is calibrated applying η^{jet} - and p_T^{jet} -dependent correction factors derived with the PYTHIA signal sample [44]. Then, dijet and photon + jet balance techniques [45] are used to correct for the residual detector response differences between measured and simulated samples. In addition, a centrality-dependent correction obtained from simulation studies is applied to remove the residual effects from the UE in Pb-Pb collisions. The UE from Pb-Pb data and MC samples are compared using the p_T density [44,46,47], defined as the median of the ratio of the jet transverse momentum to the jet area, for all jets in the event. Given the coarse centrality range used in the analysis, the difference between the measured and simulated Pb-Pb events has a negligible effect on jet reconstruction.

Except in Fig. 4, the resolutions of the measured jet energy and azimuthal angle in the pp samples are smeared to match those of the Pb-Pb sample. The jet energy resolution can be quantified using the Gaussian standard deviation σ of the $p_T^{\text{reco}}/p_T^{\text{gen}}$ ratio, where p_T^{reco} is the UE-subtracted, detector-level jet p_T and p_T^{gen} is the generator-level jet p_T without any contributions from the UE in Pb-Pb. It is determined using PYTHIA+HYDJET (for Pb-Pb) and PYTHIA (for pp) samples and parametrized as a function of p_T^{gen} using the expression $\sigma(p_T^{\text{gen}}) = C \oplus (S/\sqrt{p_T^{\text{gen}}}) \oplus (N/p_T^{\text{gen}})$, where \oplus stands for the sum in quadrature and the parameters C , S , and N are determined from simulation studies. The same parametrization is used to determine the jet azimuthal angle resolution, quantified by the Gaussian standard deviation σ_ϕ of the $|\phi^{\text{reco}} - \phi^{\text{gen}}|$ difference.

The Z candidates are defined as opposite-charge electron or muon pairs, with a reconstructed invariant mass ($M^{\ell\ell}$) in the interval 70–110 GeV/ c^2 and $p_T > 40$ GeV/ c . The invariant mass distributions of all the dileptons used in the Pb-Pb analysis are shown in Fig. 1. Each Z candidate is paired with all jets in the same event that pass the $p_T^{\text{jet}} > 30$ GeV/ c and $|\eta^{\text{jet}}| < 1.6$ selection. Simulation studies show that the jet selection efficiency and the energy resolution are well understood for this kinematic range. Additional energy corrections are applied to the jet p_T , to account for residual performance degradations observed in simulation studies. Jets reconstructed within $\Delta R < 0.4$ from a lepton are rejected, to eliminate jet energy contamination by leptons from Z decays.

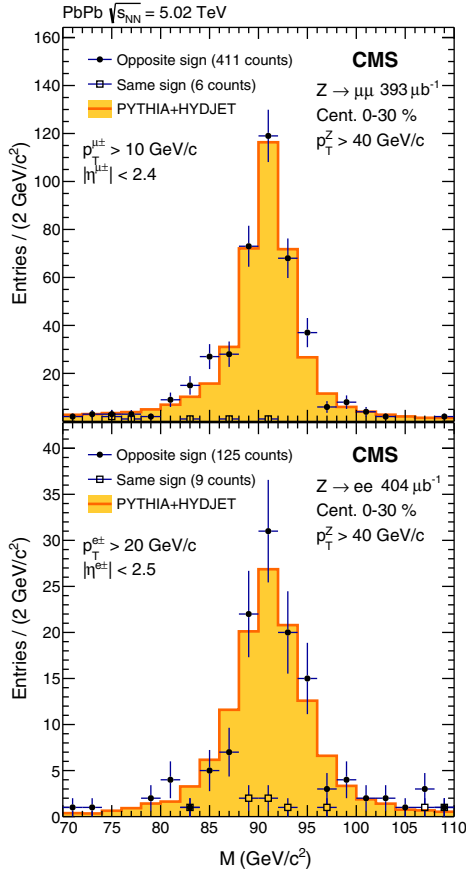


FIG. 1. Invariant mass distributions of the selected dimuons (top) and dielectrons (bottom), compared to PYTHIA+HYDJET $Z(\ell\ell) + \text{jet}$ events. The MC histogram is normalized to the number of events in the data.

For the analysis of Pb-Pb collisions, the background contribution from jets not produced in the same parton-parton interaction as the Z boson needs to be considered. This contribution arises from misidentified jets reconstructed from regional energy fluctuations in the high-multiplicity heavy ion UE or from additional initial hard interactions not related to the primary $Z + \text{jet}$ production. The background jet contributions are estimated constructing a mixed-event jet background by correlating the Z boson from each candidate $Z + \text{jet}$ event with jets reconstructed in subsets of 40 minimum bias events. All events must pass the off-line event selection and have the same centrality and interaction vertex as the $Z + \text{jet}$ candidate event. The resulting background jet spectrum is subtracted from the raw jet spectrum, eliminating coincidental $Z + \text{jet}$ pairs and ensuring that the final $Z + \text{jet}$ observables reflect the correlations of Z bosons and associated jets.

The systematic uncertainties related to Z boson reconstruction are sizable (negligible) in the dielectron (dimuon) channel. Comparing the measured and simulated dielectron invariant mass peaks shows that the average deviation between electron p_T^{reco} and p_T^{gen} is 0.5%. A systematic uncertainty is evaluated by shifting the

electron p_T by $\pm 0.5\%$, resulting in changes of $\langle x_{jZ} \rangle$ and R_{jZ} for Pb-Pb (pp) by 0.5% (0.3%) and 3% (0.8%), respectively. The simulated Z dielectrons reconstructed in central Pb-Pb collisions have a p_T resolution of 5% for $p_T^Z > 40 \text{ GeV}/c$. In Pb-Pb simulated events, p_T^Z is smeared by 5%, resulting in variations of $\langle x_{jZ} \rangle$ and R_{jZ} by 1.5% and 0.8%, respectively. When combining the two lepton results, a weighting is applied to the electron sample, to compensate for the different centrality dependencies of the Z boson reconstruction in the electron and muon channels. The difference between the corrected and uncorrected $\langle x_{jZ} \rangle$ and R_{jZ} values, 0.3% and 5.8%, respectively, is taken as systematic uncertainty.

Simulation studies show that the jet energy scale $\langle p_T^{\text{reco}}/p_T^{\text{gen}} \rangle$ can deviate from unity by up to 2%. Additional deviations can arise from differences between the fragmentation pattern of jets in measured and simulated events. To evaluate the corresponding systematic uncertainty, the jet energy scale is shifted for Pb-Pb (pp) upward by 6% (2%) and downward by 4% (2%). The higher upward variation reflects the relatively high energy scale of quark jets, which contribute more to the $Z + \text{jet}$ events than the gluon jets. The relative change in $\langle x_{jZ} \rangle$ and R_{jZ} for Pb-Pb (pp) is 5.4% (2.4%) and 4.6% (2.4%), respectively. Finally, differences between the measured and simulated samples suggest that the jet energy resolution is up to 15% worse in the data. The related systematic uncertainty is evaluated smearing p_T^{jet} by 15% in the Pb-Pb MC calculations. The pp data are smeared to simulate the poor resolution due to the UE fluctuations in Pb-Pb data. The smearing is performed with the relative resolution $\sigma_{\text{rel}} = \sqrt{\sigma_{\text{Pb-Pb}}^2 - \sigma_{pp}^2}$, where $\sigma_{\text{Pb-Pb}}$ and σ_{pp} correspond to the parametrizations described above. A systematic uncertainty is assigned by varying the relative resolution by $\pm 15\%$. The Pb-Pb (pp) relative change in $\langle x_{jZ} \rangle$ and R_{jZ} due to jet energy resolution is 2.5% and 3.7% (0.5% and 0.7%), respectively. The jet angular resolution correction implies an additional uncertainty on the pp sample, of 0.1% for $\langle x_{jZ} \rangle$ and 0.2% for R_{jZ} .

The total systematic uncertainties for Pb-Pb (pp) amount to 6.2% (2.5%) and 8.9% (2.6%) for the $\langle x_{jZ} \rangle$ and R_{jZ} results, respectively, of which 5.7% and 8.0% are uncorrelated between the pp and Pb-Pb results; the uncorrelated uncertainties do not reflect possible differences between p_T^{reco} and p_T^{gen} .

Figure 2, top, shows the $\Delta\phi_{jZ}$ distribution of $Z + \text{jet}$ pairs that pass all the selections; only $Z + \text{jet}$ pairs with $p_T^Z > 60 \text{ GeV}/c$ were included to reduce the fraction of events where energy loss effects cause the jet partner to fall below the $p_T^{\text{jet}} > 30 \text{ GeV}/c$ threshold. There are 678 and 232 events that pass the $p_T^Z > 60 \text{ GeV}/c$ selection in pp and in the 30% most central Pb-Pb collisions, respectively. To study if the angular distribution of jets with respect to

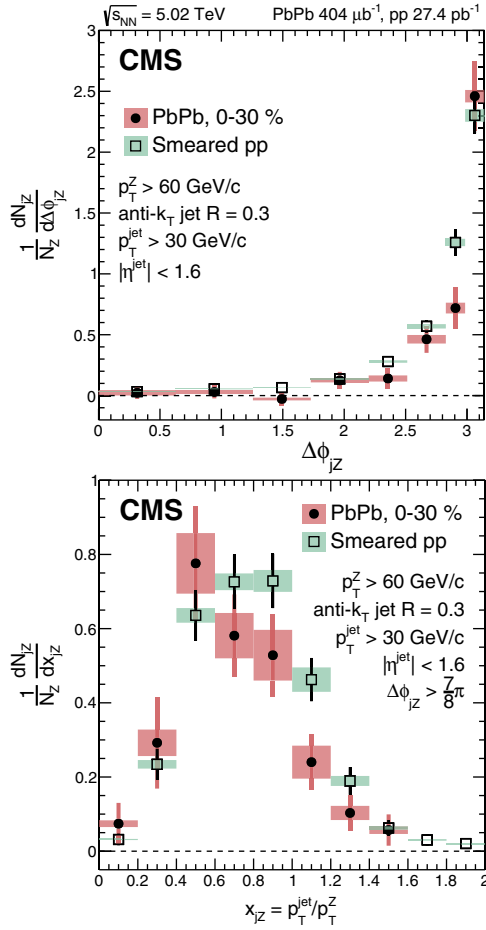


FIG. 2. Distributions of the azimuthal angle difference $\Delta\phi_{jZ}$ between the Z boson and the jet (top) and of the transverse momentum ratio x_{jZ} between the jet and the Z boson with $\Delta\phi_{jZ} > 7\pi/8$ (bottom). The distributions are normalized by the number of Z events, N_Z . Vertical lines (bands) indicate statistical (systematic) uncertainties.

the Z boson is affected by interactions of the parton with the medium, a Kolmogorov-Smirnov (KS) test was performed using pseudodata generated from identical underlying shapes. This test is useful to quantify shape differences, since it is sensitive to adjacent bins fluctuating in the same direction but not to the overall normalization. No significant difference is seen between the pp and Pb-Pb $\Delta\phi_{jZ}$ distributions; the probability to obtain a KS value larger than that observed in the data, the p value, is greater than 0.40, even if systematic uncertainties are excluded.

For the x_{jZ} and R_{jZ} results, shown in Figs. 2 and 3, only events with $\Delta\phi_{jZ} > 7\pi/8$ are used, to select mostly back-to-back Z + jet pairs; it keeps 63% and 73% of the pp and Pb-Pb events, respectively. Figure 2, bottom, shows the x_{jZ} distributions for Pb-Pb and pp collisions. Jet energy loss is expected to manifest itself both as a shift in the x_{jZ} distribution and an overall decrease in the number of Z + jet pairs as jets fall below the p_T^{jet} threshold. Therefore, the KS test was applied to the x_{jZ} distribution, and a

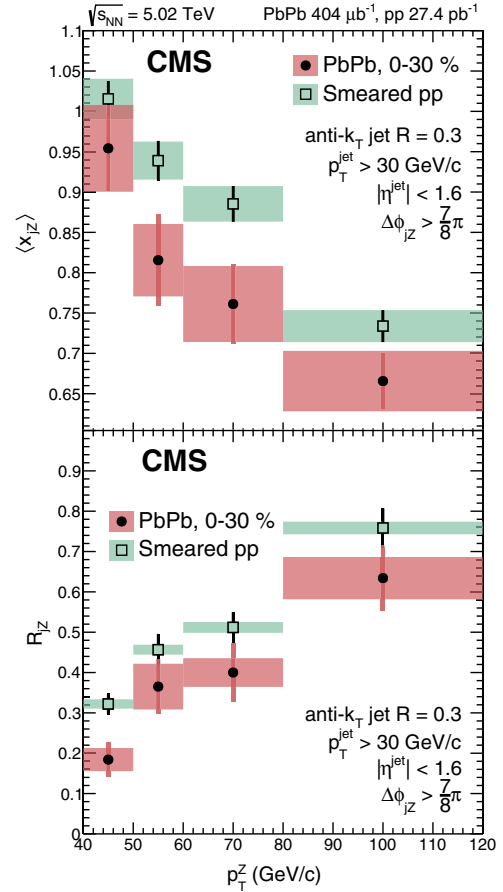


FIG. 3. The mean value of the x_{jZ} distribution (top) and the average number of jet partners per Z boson R_{jZ} (bottom), as a function of p_T^Z . Vertical lines (bands) indicate statistical (systematic) uncertainties.

separate overall normalization χ^2 test was applied to the total number of Z + jet pairs per Z leading to p values of $p_1 = 0.07$ and $p_2 = 0.01$, respectively. The systematic uncertainties and their correlations were included in these calculations. The combined p value [48] is $p_1 p_2 [1 - \ln(p_1 p_2)] = 0.0064$ when including Z + jet pairs with $p_T^{\text{jet}} > 40$ GeV/c, indicating that the two x_{jZ} distributions are significantly different.

The relative shift between the pp and Pb-Pb x_{jZ} distributions is studied using their means, $\langle x_{jZ} \rangle$, shown in Fig. 3, top, as a function of p_T^Z . The minimum p_T of the partner jet imposes a lower limit on the value of x_{jZ} . As p_T^Z increases relative to the p_T^{jet} cutoff, the kinematic phase space for lower x_{jZ} opens up, resulting in a shift towards lower x_{jZ} for higher p_T^Z . For all ranges, $\langle x_{jZ} \rangle$ is found to be lower in Pb-Pb collisions than in pp collisions, as expected from energy loss models of partons traversing the medium. Also R_{jZ} is expected to increase as a function of p_T^Z , as the $p_T^{\text{jet}} > 30$ GeV/c threshold restricts the phase space of jets counted for a given p_T^Z selection. Figure 3, bottom, shows the dependence of R_{jZ} on p_T^Z . The R_{jZ} values are

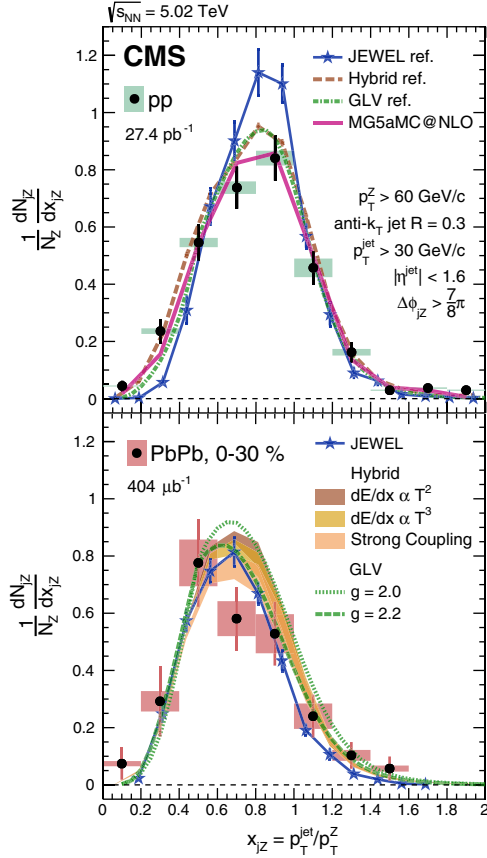


FIG. 4. Comparison of the measured pp (top) and Pb-Pb (bottom) x_{jZ} distributions with several theoretical models, smeared by the respective jet energy resolution: JEWEL [26], Hybrid [25], and GLV [27]. The JEWEL error bars represent statistical uncertainties, while the widths of the hybrid bands represent systematic variations. A MADGRAPH5_AMC@NLO calculation [36] is also shown.

found to be smaller in Pb-Pb than in pp . As their difference is approximately constant as a function of p_T^Z , a relatively smaller fraction of jets is lost in Pb-Pb collisions for larger initial (before traversing the medium) parton energies.

Figure 4 compares the x_{jZ} results to several theoretical calculations, using the same kinematic selections as the data. The Pb-Pb results are compared to three models that incorporate the phenomenon of jet quenching: Jet Evolution With Energy Loss (JEWEL) [26], Hybrid [25], and Guylassy-Levai-Vitev (GLV) [27]. The x_{jZ} pp measured results are compared to several nonquenching scenarios: the pp references used as inputs to the Pb-Pb models (different tunes of the PYTHIA LO event generator) and the MADGRAPH5_AMC@NLO generator [36], which includes matrix elements for Z plus 0, 1, and 2 jets at NLO and $Z + 3$ jets at LO. The pp calculations were smeared to reflect the detector resolution affecting the pp data. The JEWEL model is a dynamical, perturbative framework for jet quenching, which has been extended to simulate boson-jet events [26]. This Pb-Pb x_{jZ} calculation is consistent with the data within

the current precision, despite the poor agreement of its baseline with the pp measurement. The baseline PYTHIA8 tunes used by the Hybrid [25] and GLV [27] models, as well as MADGRAPH5_AMC@NLO, describe the pp data reasonably well. For Pb-Pb collisions, the hybrid model calculation labeled “Strong Coupling” combines a perturbative description of the weakly coupled physics of jet production and evolution, with a gauge-gravity duality description of the strongly coupled dynamics of the medium, and of the soft exchanges between the jet and the medium. Two weak coupling benchmark calculations are also shown, where the energy loss has a quadratic temperature dependence (collisional energy loss) or a cubic dependence (radiative energy loss). Given the large experimental and theoretical uncertainties, all three scenarios describe the Pb-Pb data reasonably well and cannot be distinguished. Nevertheless, the Strong Coupling curve appears closest to the data. The GLV model [27] generates the energy loss via out-of-cone radiation and collisional energy dissipation. Two curves are shown, for different coupling strengths between the jet and the medium, $g = 2.0$ and 2.2 , reflecting previous analyses of jet quenching measurements at 2.76 TeV [49,50]; the $g = 2.2$ curve seems favored by the data.

In summary, correlations of $p_T^Z > 40$ GeV/ c Z bosons with $p_T^{\text{jet}} > 30$ GeV/ c jets have been studied in pp and, for the first time, in Pb-Pb collisions. The data were collected with the CMS experiment during the 2015 data-taking period, at $\sqrt{s_{NN}} = 5.02$ TeV. No significant difference was found between the distributions of the azimuthal angle difference of the Z and the jet in pp and Pb-Pb collisions. The x_{jZ} distributions indicate that the Pb-Pb values tend to be lower than those measured in pp collisions. Correspondingly, the average value of the transverse momentum ratio $\langle x_{jZ} \rangle$ is smaller in Pb-Pb than in pp collisions, for all p_T^Z intervals. The average number of jet partners per Z , R_{jZ} , is lower in Pb-Pb than in pp collisions, for all p_T^Z intervals, which suggests that in Pb-Pb collisions a larger fraction of partons associated with Z bosons lose energy and fall below the 30 GeV/ c p_T^{jet} threshold. These measurements provide new input for the determination of jet quenching parameters using a selection of partons with well-defined flavor and initial kinematics.

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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,o} S. Kudella,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 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. Geralis,⁴⁴ V. A. Giakoumopoulou,⁴⁴ A. Kyriakis,⁴⁴ D. Loukas,⁴⁴ I. Topsis-Giotis,⁴⁴ S. Kesisoglou,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. Kotheekar,⁵⁹ S. Pandey,⁵⁹ A. Rane,⁵⁹ S. Sharma,⁵⁹ S. Chenarani,^{60,cc} E. Eskandari Tadavani,⁶⁰ S. M. Etesami,^{60,cc} M. Khakzad,⁶⁰ M. Mohammadi Najafabadi,⁶⁰ M. Naseri,⁶⁰ S. Paktinat Mehdiabadi,^{60,dd} F. Rezaei Hosseinabadi,⁶⁰ B. Safarzadeh,^{60,ee} 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. 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P. Traczyk,^{75a,75b} S. Belforte,^{76a} M. Casarsa,^{76a} F. Cossutti,^{76a} G. Della Ricca,^{76a,76b} A. Zanetti,^{76a} D. H. Kim,⁷⁷ G. N. Kim,⁷⁷ M. S. Kim,⁷⁷ S. Lee,⁷⁷ S. W. Lee,⁷⁷ Y. D. Oh,⁷⁷ S. Sekmen,⁷⁷ D. C. Son,⁷⁷ Y. C. Yang,⁷⁷ A. Lee,⁷⁸ H. Kim,⁷⁹ J. A. Brochero Cifuentes,⁸⁰ T. J. Kim,⁸⁰ S. Cho,⁸¹ S. Choi,⁸¹ Y. Go,⁸¹ D. Gyun,⁸¹ S. Ha,⁸¹ B. Hong,⁸¹ Y. Jo,⁸¹ Y. Kim,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,hh} F. Mohamad Idris,^{86,ii} 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,jj} 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. Carpinteyro,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. Szleper,⁹⁴ P. Zalewski,⁹⁴ K. Bunkowski,⁹⁵ A. Byszuk,^{95,kk} 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. Vadrucio,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,ll,mmm} 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,nn} E. Kuznetsova,^{98,oo} 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,mmm} M. Chadeeva,^{102,pp} M. Danilov,^{102,pp} V. Rusinov,¹⁰² V. Andreev,¹⁰³ M. Azarkin,^{103,mmm} I. Dremin,^{103,mmm} M. Kirakosyan,¹⁰³ A. Leonidov,^{103,mmm} A. Terkulov,¹⁰³ A. Baskakov,¹⁰⁴ A. Belyaev,¹⁰⁴ E. Boos,¹⁰⁴ A. Demiyarov,¹⁰⁴ A. Ershov,¹⁰⁴ A. Gribushin,¹⁰⁴ O. Kodolova,¹⁰⁴ V. Korotkiikh,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,qq} Y. Skovpen,^{105,qq} D. Shtol,^{105,qq} 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,rr} 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. Vizán García,¹¹⁰ I. J. Cabrillo,¹¹¹ A. Calderon,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. Bocci,¹¹² C. Botta,¹¹² T. Camporesi,¹¹² R. Castello,¹¹² M. Cepeda,¹¹² G. Cerminara,¹¹² Y. Chen,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,ss} M. Dobson,¹¹² B. 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Konigsberg,¹⁴⁵ A. Korytov,¹⁴⁵ J. F. Low,¹⁴⁵ P. Ma,¹⁴⁵ K. Matchev,¹⁴⁵ H. Mei,¹⁴⁵ G. Mitselmakher,¹⁴⁵ D. Rank,¹⁴⁵ L. Shchutka,¹⁴⁵ D. Sperka,¹⁴⁵ L. Thomas,¹⁴⁵ J. Wang,¹⁴⁵ S. Wang,¹⁴⁵ J. Yelton,¹⁴⁵ S. Linn,¹⁴⁶ P. Markowitz,¹⁴⁶ G. Martinez,¹⁴⁶ J. L. Rodriguez,¹⁴⁶ A. Ackert,¹⁴⁷ T. Adams,¹⁴⁷ A. Askew,¹⁴⁷ S. Bein,¹⁴⁷ S. Hagopian,¹⁴⁷ V. Hagopian,¹⁴⁷ K. F. Johnson,¹⁴⁷ H. Prosper,¹⁴⁷ A. Santra,¹⁴⁷ R. Yohay,¹⁴⁷ M. M. Baarmand,¹⁴⁸ V. Bhopatkar,¹⁴⁸ S. Colafranceschi,¹⁴⁸ M. Hohmann,¹⁴⁸ D. Noonan,¹⁴⁸ T. Roy,¹⁴⁸ F. Yumiceva,¹⁴⁸ M. R. Adams,¹⁴⁹ L. Apanasevich,¹⁴⁹ D. Berry,¹⁴⁹ R. R. Betts,¹⁴⁹ I. Bucinskaite,¹⁴⁹ R. Cavanaugh,¹⁴⁹ O. Evdokimov,¹⁴⁹ L. Gauthier,¹⁴⁹ C. E. Gerber,¹⁴⁹ D. J. Hofman,¹⁴⁹ K. Jung,¹⁴⁹ J. Kamin,¹⁴⁹ I. D. Sandoval Gonzalez,¹⁴⁹ N. Varelas,¹⁴⁹ H. Wang,¹⁴⁹ Z. Wu,¹⁴⁹ M. Zakaria,¹⁴⁹ J. Zhang,¹⁴⁹ B. Bilki,^{150,qqq} W. Clarida,¹⁵⁰ K. Dilsiz,¹⁵⁰ S. Durgut,¹⁵⁰ R. P. Gandrajula,¹⁵⁰ M. Haytmyradov,¹⁵⁰ V. Khristenko,¹⁵⁰ J.-P. Merlo,¹⁵⁰ H. Mermerkaya,^{150,rrr} A. Mestvirishvili,¹⁵⁰ A. Moeller,¹⁵⁰ J. Nachtman,¹⁵⁰ H. Ogul,¹⁵⁰ Y. Onel,¹⁵⁰ F. Ozok,^{150,sss} A. Penzo,¹⁵⁰ C. Snyder,¹⁵⁰ E. Tiras,¹⁵⁰ J. Wetzel,¹⁵⁰ K. Yi,¹⁵⁰ I. Anderson,¹⁵¹ B. Blumenfeld,¹⁵¹ A. Cocoros,¹⁵¹ N. Eminizer,¹⁵¹ D. Fehling,¹⁵¹ L. Feng,¹⁵¹ A. V. Gritsan,¹⁵¹ P. Maksimovic,¹⁵¹ M. Osherson,¹⁵¹ J. Roskes,¹⁵¹ U. Sarica,¹⁵¹ M. Swartz,¹⁵¹ M. Xiao,¹⁵¹ Y. Xin,¹⁵¹ C. You,¹⁵¹ A. Al-bataineh,¹⁵² P. Baringer,¹⁵² A. Bean,¹⁵² S. Boren,¹⁵² J. Bowen,¹⁵² J. Castle,¹⁵² L. Forthomme,¹⁵² R. P. Kenny III,¹⁵² S. Khalil,¹⁵² A. Kropivnitskaya,¹⁵² D. Majumder,¹⁵² W. Mcbrayer,¹⁵² M. Murray,¹⁵² S. Sanders,¹⁵² R. Stringer,¹⁵² J. D. Tapia Takaki,¹⁵² Q. Wang,¹⁵² A. Ivanov,¹⁵³ K. Kaadze,¹⁵³ Y. Maravin,¹⁵³ A. Mohammadi,¹⁵³ L. K. Saini,¹⁵³ N. Skhirtladze,¹⁵³ S. Toda,¹⁵³ F. Rebassoo,¹⁵⁴ D. Wright,¹⁵⁴ C. Anelli,¹⁵⁵ A. Baden,¹⁵⁵ O. Baron,¹⁵⁵ A. Belloni,¹⁵⁵ B. Calvert,¹⁵⁵ S. C. Eno,¹⁵⁵ C. Ferraioli,¹⁵⁵ J. A. Gomez,¹⁵⁵ N. J. Hadley,¹⁵⁵ S. Jabeen,¹⁵⁵ R. G. Kellogg,¹⁵⁵ T. Kolberg,¹⁵⁵ J. Kunkle,¹⁵⁵ Y. Lu,¹⁵⁵ A. C. Mignerey,¹⁵⁵ F. Ricci-Tam,¹⁵⁵ Y. H. Shin,¹⁵⁵ A. Skuja,¹⁵⁵ M. B. Tonjes,¹⁵⁵ S. C. Tonwar,¹⁵⁵ D. Abercrombie,¹⁵⁶ B. Allen,¹⁵⁶ A. Apyan,¹⁵⁶ V. Azzolini,¹⁵⁶ R. Barbieri,¹⁵⁶ A. Baty,¹⁵⁶ R. Bi,¹⁵⁶ K. Bierwagen,¹⁵⁶ S. Brandt,¹⁵⁶ W. Busza,¹⁵⁶ I. A. Cali,¹⁵⁶ M. D'Alfonso,¹⁵⁶ Z. Demiragli,¹⁵⁶ L. Di Matteo,¹⁵⁶ G. Gomez Ceballos,¹⁵⁶ M. Goncharov,¹⁵⁶ D. Hsu,¹⁵⁶ Y. Iiyama,¹⁵⁶ G. M. Innocenti,¹⁵⁶ M. Klute,¹⁵⁶ D. Kovalskyi,¹⁵⁶ K. Krajczar,¹⁵⁶ Y. S. Lai,¹⁵⁶ Y.-J. Lee,¹⁵⁶ A. Levin,¹⁵⁶ P. D. Luckey,¹⁵⁶ B. Maier,¹⁵⁶ A. C. Marini,¹⁵⁶ C. McGinn,¹⁵⁶ C. Mironov,¹⁵⁶ S. Narayanan,¹⁵⁶ X. Niu,¹⁵⁶ C. Paus,¹⁵⁶ C. Roland,¹⁵⁶ G. Roland,¹⁵⁶ J. Salfeld-Nebgen,¹⁵⁶ G. S. F. Stephans,¹⁵⁶ K. Tatar,¹⁵⁶ M. Varma,¹⁵⁶ D. Velicanu,¹⁵⁶ J. Veverka,¹⁵⁶ J. Wang,¹⁵⁶ T. W. Wang,¹⁵⁶ B. Wyslouch,¹⁵⁶ M. Yang,¹⁵⁶ A. C. Benvenuti,¹⁵⁷ R. M. Chatterjee,¹⁵⁷ A. Evans,¹⁵⁷ P. Hansen,¹⁵⁷ S. Kalafut,¹⁵⁷ S. C. Kao,¹⁵⁷ Y. Kubota,¹⁵⁷ Z. Lesko,¹⁵⁷ J. Mans,¹⁵⁷ S. Nourbakhsh,¹⁵⁷ N. Ruckstuhl,¹⁵⁷ R. Rusack,¹⁵⁷ N. Tambe,¹⁵⁷ J. Turkewitz,¹⁵⁷ J. G. Acosta,¹⁵⁸ S. Oliveros,¹⁵⁸ E. Avdeeva,¹⁵⁹ K. Bloom,¹⁵⁹ D. R. Claes,¹⁵⁹ C. Fangmeier,¹⁵⁹ R. Gonzalez Suarez,¹⁵⁹ R. Kamalieddin,¹⁵⁹ I. Kravchenko,¹⁵⁹ A. Malta Rodrigues,¹⁵⁹ F. Meier,¹⁵⁹ J. Monroy,¹⁵⁹ J. E. Siado,¹⁵⁹ G. R. Snow,¹⁵⁹ B. Stieger,¹⁵⁹ M. Alyari,¹⁶⁰ J. Dolen,¹⁶⁰ A. Godshalk,¹⁶⁰ C. Harrington,¹⁶⁰ I. Iashvili,¹⁶⁰ J. Kaisen,¹⁶⁰ A. Kharchilava,¹⁶⁰ A. Parker,¹⁶⁰ S. Rappoccio,¹⁶⁰ B. Roozbahani,¹⁶⁰ G. Alverson,¹⁶¹ E. Barberis,¹⁶¹ A. Hortiangtham,¹⁶¹ A. Massironi,¹⁶¹ D. M. Morse,¹⁶¹ D. Nash,¹⁶¹ T. Orimoto,¹⁶¹ R. Teixeira De Lima,¹⁶¹ D. Trocino,¹⁶¹ R.-J. Wang,¹⁶¹ D. Wood,¹⁶¹ S. Bhattacharya,¹⁶² O. Charaf,¹⁶² K. A. Hahn,¹⁶² A. Kumar,¹⁶² N. Mucia,¹⁶² N. Odell,¹⁶² B. Pollack,¹⁶² M. H. Schmitt,¹⁶² K. Sung,¹⁶² M. Trovato,¹⁶² M. Velasco,¹⁶² N. Dev,¹⁶³ M. Hildreth,¹⁶³ K. Hurtado Anampa,¹⁶³ C. Jessop,¹⁶³ D. J. Karmgard,¹⁶³ N. Kellams,¹⁶³

K. Lannon,¹⁶³ N. Marinelli,¹⁶³ F. Meng,¹⁶³ C. Mueller,¹⁶³ Y. Musienko,^{163,II} M. Planer,¹⁶³ A. Reinsvold,¹⁶³ R. Ruchti,¹⁶³ G. Smith,¹⁶³ S. Taroni,¹⁶³ M. Wayne,¹⁶³ M. Wolf,¹⁶³ A. Woodard,¹⁶³ J. Alimena,¹⁶⁴ L. Antonelli,¹⁶⁴ B. Bylsma,¹⁶⁴ L. S. Durkin,¹⁶⁴ S. Flowers,¹⁶⁴ B. Francis,¹⁶⁴ A. Hart,¹⁶⁴ C. Hill,¹⁶⁴ R. Hughes,¹⁶⁴ W. Ji,¹⁶⁴ B. Liu,¹⁶⁴ W. Luo,¹⁶⁴ D. Puigh,¹⁶⁴ B. L. Winer,¹⁶⁴ H. W. Wulsin,¹⁶⁴ S. Cooperstein,¹⁶⁵ O. Driga,¹⁶⁵ P. Elmer,¹⁶⁵ J. Hardenbrook,¹⁶⁵ P. Hebda,¹⁶⁵ D. Lange,¹⁶⁵ J. Luo,¹⁶⁵ D. Marlow,¹⁶⁵ T. Medvedeva,¹⁶⁵ K. Mei,¹⁶⁵ J. Olsen,¹⁶⁵ C. Palmer,¹⁶⁵ P. Piroué,¹⁶⁵ D. Stickland,¹⁶⁵ A. Svyatkovskiy,¹⁶⁵ C. Tully,¹⁶⁵ S. Malik,¹⁶⁶ A. Barker,¹⁶⁷ V. E. Barnes,¹⁶⁷ S. Folgueras,¹⁶⁷ L. Gutay,¹⁶⁷ M. K. Jha,¹⁶⁷ M. Jones,¹⁶⁷ A. W. Jung,¹⁶⁷ A. Khatiwada,¹⁶⁷ D. H. Miller,¹⁶⁷ N. Neumeister,¹⁶⁷ J. F. Schulte,¹⁶⁷ X. Shi,¹⁶⁷ J. Sun,¹⁶⁷ F. Wang,¹⁶⁷ W. Xie,¹⁶⁷ N. Parashar,¹⁶⁸ J. Stupak,¹⁶⁸ A. Adair,¹⁶⁹ B. Akgun,¹⁶⁹ Z. Chen,¹⁶⁹ K. M. Ecklund,¹⁶⁹ F. J. M. Geurts,¹⁶⁹ M. Guilbaud,¹⁶⁹ W. Li,¹⁶⁹ B. Michlin,¹⁶⁹ M. Northup,¹⁶⁹ B. P. Padley,¹⁶⁹ J. Roberts,¹⁶⁹ J. Rorie,¹⁶⁹ Z. Tu,¹⁶⁹ J. Zabel,¹⁶⁹ B. Betchart,¹⁷⁰ A. Bodek,¹⁷⁰ P. de Barbaro,¹⁷⁰ R. Demina,¹⁷⁰ Y. t. Duh,¹⁷⁰ T. Ferbel,¹⁷⁰ M. Galanti,¹⁷⁰ A. Garcia-Bellido,¹⁷⁰ J. Han,¹⁷⁰ O. Hindrichs,¹⁷⁰ A. Khukhunaishvili,¹⁷⁰ K. H. Lo,¹⁷⁰ P. Tan,¹⁷⁰ M. Verzetti,¹⁷⁰ A. Agapitos,¹⁷¹ J. P. Chou,¹⁷¹ Y. Gershtein,¹⁷¹ T. A. Gómez Espinosa,¹⁷¹ E. Halkiadakis,¹⁷¹ M. Heindl,¹⁷¹ E. Hughes,¹⁷¹ S. Kaplan,¹⁷¹ R. Kunnawalkam Elayavalli,¹⁷¹ S. Kyriacou,¹⁷¹ A. Lath,¹⁷¹ K. Nash,¹⁷¹ H. Saka,¹⁷¹ S. Salur,¹⁷¹ S. Schnetzer,¹⁷¹ D. Sheffield,¹⁷¹ S. Somalwar,¹⁷¹ R. Stone,¹⁷¹ S. Thomas,¹⁷¹ P. Thomassen,¹⁷¹ M. Walker,¹⁷¹ A. G. Delannoy,¹⁷² M. Foerster,¹⁷² J. Heideman,¹⁷² G. Riley,¹⁷² K. Rose,¹⁷² S. Spanier,¹⁷² K. Thapa,¹⁷² O. Bouhali,^{173,III} A. Celik,¹⁷³ M. Dalchenko,¹⁷³ M. De Mattia,¹⁷³ A. Delgado,¹⁷³ S. Dildick,¹⁷³ R. Eusebi,¹⁷³ J. Gilmore,¹⁷³ T. Huang,¹⁷³ E. Juska,¹⁷³ T. Kamon,^{173,IIII} R. Mueller,¹⁷³ Y. Pakhotin,¹⁷³ R. Patel,¹⁷³ A. Perloff,¹⁷³ L. Perniè,¹⁷³ D. Rathjens,¹⁷³ A. Safonov,¹⁷³ A. Tatarinov,¹⁷³ K. A. Ulmer,¹⁷³ N. Akchurin,¹⁷⁴ C. Cowden,¹⁷⁴ J. Damgov,¹⁷⁴ F. De Guio,¹⁷⁴ C. Dragoiu,¹⁷⁴ P. R. Duerdo,¹⁷⁴ J. Faulkner,¹⁷⁴ E. Gурpinar,¹⁷⁴ S. Kunori,¹⁷⁴ K. Lamichhane,¹⁷⁴ S. W. Lee,¹⁷⁴ T. Libeiro,¹⁷⁴ T. Peltola,¹⁷⁴ S. Undleeb,¹⁷⁴ I. Volobouev,¹⁷⁴ Z. Wang,¹⁷⁴ S. Greene,¹⁷⁵ A. Gurrola,¹⁷⁵ R. Janjam,¹⁷⁵ W. Johns,¹⁷⁵ C. Maguire,¹⁷⁵ A. Melo,¹⁷⁵ H. Ni,¹⁷⁵ P. Sheldon,¹⁷⁵ S. Tuo,¹⁷⁵ J. Velkovska,¹⁷⁵ Q. Xu,¹⁷⁵ M. W. Arenton,¹⁷⁶ P. Barria,¹⁷⁶ B. Cox,¹⁷⁶ J. Goodell,¹⁷⁶ R. Hirosky,¹⁷⁶ A. Ledovskoy,¹⁷⁶ H. Li,¹⁷⁶ C. Neu,¹⁷⁶ T. Sinthuprasith,¹⁷⁶ X. Sun,¹⁷⁶ Y. Wang,¹⁷⁶ E. Wolfe,¹⁷⁶ F. Xia,¹⁷⁶ C. Clarke,¹⁷⁷ R. Harr,¹⁷⁷ P. E. Karchin,¹⁷⁷ J. Sturdy,¹⁷⁷ D. A. Belknap,¹⁷⁸ J. Buchanan,¹⁷⁸ C. Caillol,¹⁷⁸ S. Dasu,¹⁷⁸ L. Dodd,¹⁷⁸ S. Duric,¹⁷⁸ B. Gomber,¹⁷⁸ M. Grothe,¹⁷⁸ M. Herndon,¹⁷⁸ A. Hervé,¹⁷⁸ P. Klabbers,¹⁷⁸ A. Lanaro,¹⁷⁸ A. Levine,¹⁷⁸ K. Long,¹⁷⁸ R. Loveless,¹⁷⁸ I. Ojalvo,¹⁷⁸ T. Perry,¹⁷⁸ G. A. Pierro,¹⁷⁸ G. Polese,¹⁷⁸ T. Ruggles,¹⁷⁸ A. Savin,¹⁷⁸ N. Smith,¹⁷⁸ W. H. Smith,¹⁷⁸ D. Taylor,¹⁷⁸ and N. Woods¹⁷⁸

(CMS Collaboration)

¹*Yerevan Physics Institute, Yerevan, Armenia*²*Institut für Hochenergiephysik, Wien, Austria*³*Institute for Nuclear Problems, Minsk, Belarus*⁴*National Centre for Particle and High Energy Physics, Minsk, Belarus*⁵*Universiteit Antwerpen, Antwerpen, Belgium*⁶*Vrije 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*

- ²⁴Charles University, Prague, Czech Republic
- ²⁵Universidad San Francisco de Quito, Quito, Ecuador
- ²⁶Academy of Scientific Research and Technology of the Arab Republic of Egypt,
Egyptian Network of High Energy Physics, Cairo, Egypt
- ²⁷National Institute of Chemical Physics and Biophysics, Tallinn, Estonia
- ²⁸Department of Physics, University of Helsinki, Helsinki, Finland
- ²⁹Helsinki Institute of Physics, Helsinki, Finland
- ³⁰Lappeenranta University of Technology, Lappeenranta, Finland
- ³¹IRFU, CEA, Université Paris-Saclay, Gif-sur-Yvette, France
- ³²Laboratoire Leprince-Ringuet, Ecole Polytechnique, IN2P3-CNRS, Palaiseau, France
- ³³Institut Pluridisciplinaire Hubert Curien (IPHC), Université de Strasbourg, CNRS-IN2P3, Strasbourg, France
- ³⁴Centre de Calcul de l'Institut National de Physique Nucléaire et de Physique des Particules, CNRS/IN2P3, Villeurbanne, France
- ³⁵Université de Lyon, Université Claude Bernard Lyon 1, CNRS-IN2P3, Institut de Physique Nucléaire de Lyon, Villeurbanne, France
- ³⁶Georgian Technical University, Tbilisi, Georgia
- ³⁷Tbilisi State University, Tbilisi, Georgia
- ³⁸RWTH Aachen University, I. Physikalisches Institut, Aachen, Germany
- ³⁹RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany
- ⁴⁰RWTH Aachen University, III. Physikalisches Institut B, Aachen, Germany
- ⁴¹Deutsches Elektronen-Synchrotron, Hamburg, Germany
- ⁴²University of Hamburg, Hamburg, Germany
- ⁴³Institut für Experimentelle Kernphysik, Karlsruhe, Germany
- ⁴⁴Institute of Nuclear and Particle Physics (INPP), NCSR Demokritos, Aghia Paraskevi, Greece
- ⁴⁵National and Kapodistrian University of Athens, Athens, Greece
- ⁴⁶University of Ioánnina, Ioánnina, Greece
- ⁴⁷MTA-ELTE Lendület CMS Particle and Nuclear Physics Group, Eötvös Loránd University, Budapest, Hungary
- ⁴⁸Wigner Research Centre for Physics, Budapest, Hungary
- ⁴⁹Institute of Nuclear Research ATOMKI, Debrecen, Hungary
- ⁵⁰Institute of Physics, University of Debrecen
- ⁵¹National Institute of Science Education and Research, Bhubaneswar, India
- ⁵²Panjab University, Chandigarh, India
- ⁵³University of Delhi, Delhi, India
- ⁵⁴Saha Institute of Nuclear Physics, Kolkata, India
- ⁵⁵Indian Institute of Technology Madras, Madras, India
- ⁵⁶Bhabha Atomic Research Centre, Mumbai, India
- ⁵⁷Tata Institute of Fundamental Research-A, Mumbai, India
- ⁵⁸Tata Institute of Fundamental Research-B, Mumbai, India
- ⁵⁹Indian Institute of Science Education and Research (IISER), Pune, India
- ⁶⁰Institute for Research in Fundamental Sciences (IPM), Tehran, Iran
- ⁶¹University 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
- ^{69d}Università G. Marconi, Roma, Italy
- ^{70a}INFN Sezione di Padova, Trento, Italy
- ^{70b}Università di Padova, Trento, 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*
^{74b}*Università di Roma*
^{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*
⁷⁷*Kyungpook National University, Daegu, Korea*
⁷⁸*Chonbuk National University, Jeonju, Korea*
⁷⁹*Chonnam National University, Institute for Universe and Elementary Particles, Kwangju, Korea*
⁸⁰*Hanyang University, Seoul, Korea*
⁸¹*Korea University, Seoul, Korea*
⁸²*Seoul National University, Seoul, Korea*
⁸³*University of Seoul, Seoul, Korea*
⁸⁴*Sungkyunkwan University, Suwon, Korea*
⁸⁵*Vilnius University, Vilnius, Lithuania*
⁸⁶*National Centre for Particle Physics, Universiti Malaya, Kuala Lumpur, Malaysia*
⁸⁷*Centro de Investigacion y de Estudios Avanzados del IPN, Mexico City, Mexico*
⁸⁸*Universidad Iberoamericana, Mexico City, Mexico*
⁸⁹*Benemerita Universidad Autonoma de Puebla, Puebla, Mexico*
⁹⁰*Universidad Autónoma de San Luis Potosí, San Luis Potosí, Mexico*
⁹¹*University of Auckland, Auckland, New Zealand*
⁹²*University of Canterbury, Christchurch, New Zealand*
⁹³*National Centre for Physics, Quaid-I-Azam University, Islamabad, Pakistan*
⁹⁴*National Centre for Nuclear Research, Swierk, Poland*
⁹⁵*Institute of Experimental Physics, Faculty of Physics, University of Warsaw, Warsaw, Poland*
⁹⁶*Laboratório de Instrumentação e Física Experimental de Partículas, Lisboa, Portugal*
⁹⁷*Joint Institute for Nuclear Research, Dubna, Russia*
⁹⁸*Petersburg Nuclear Physics Institute, Gatchina (St. Petersburg), Russia*
⁹⁹*Institute for Nuclear Research, Moscow, Russia*
¹⁰⁰*Institute for Theoretical and Experimental Physics, Moscow, Russia*
¹⁰¹*Moscow Institute of Physics and Technology, Moscow, Russia*
¹⁰²*National Research Nuclear University 'Moscow Engineering Physics Institute' (MEPhI), Moscow, Russia*
¹⁰³*P.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*Physics Department, Science and Art Faculty, Çukurova 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*Catholic University of America, Washington, DC, USA*
¹³¹*The University of Alabama, Tuscaloosa, Alabama, USA*
¹³²*Boston University, Boston, Massachusetts, USA*
¹³³*Brown University, Providence, Rhode Island, USA*
¹³⁴*University of California, Davis, Davis, California, USA*
¹³⁵*University of California, Los Angeles, California, USA*
¹³⁶*University of California, Riverside, Riverside, USA*
¹³⁷*University of California, San Diego, La Jolla, USA*
¹³⁸*University of California, Santa Barbara—Department of Physics, Santa Barbara, California, USA*
¹³⁹*California Institute of Technology, Pasadena, California, USA*
¹⁴⁰*Carnegie Mellon University, Pittsburgh, Pennsylvania, USA*
¹⁴¹*University of Colorado Boulder, Boulder, Colorado, USA*
¹⁴²*Cornell University, Ithaca, New York, USA*
¹⁴³*Fairfield University, Fairfield, Connecticut, USA*
¹⁴⁴*Fermi National Accelerator Laboratory, Batavia, Illinois, USA*
¹⁴⁵*University of Florida, Gainesville, Florida, USA*
¹⁴⁶*Florida International University, Miami, Florida, USA*
¹⁴⁷*Florida State University, Tallahassee, Florida, USA*
¹⁴⁸*Florida Institute of Technology, Melbourne, Florida, USA*
¹⁴⁹*University of Illinois at Chicago (UIC), Chicago, Illinois, USA*
¹⁵⁰*The University of Iowa, Iowa City, Iowa, USA*
¹⁵¹*Johns Hopkins University, Baltimore, Maryland, USA*
¹⁵²*The University of Kansas, Lawrence, Kansas, USA*
¹⁵³*Kansas State University, Manhattan, Kansas, USA*
¹⁵⁴*Lawrence Livermore National Laboratory, Livermore, California, USA*
¹⁵⁵*University of Maryland, College Park, Maryland, USA*
¹⁵⁶*Massachusetts Institute of Technology, Cambridge, Massachusetts, USA*
¹⁵⁷*University of Minnesota, Minneapolis, Minnesota, USA*
¹⁵⁸*University of Mississippi, Oxford, Mississippi, USA*
¹⁵⁹*University of Nebraska-Lincoln, Lincoln, Nebraska, USA*
¹⁶⁰*State University of New York at Buffalo, Buffalo, New York, USA*
¹⁶¹*Northeastern University, Boston, Massachusetts, USA*
¹⁶²*Northwestern University, Evanston, Illinois, USA*
¹⁶³*University of Notre Dame, Notre Dame, Indiana, USA*
¹⁶⁴*The Ohio State University, Columbus, Ohio, USA*
¹⁶⁵*Princeton University, Princeton, New Jersey, USA*
¹⁶⁶*University of Puerto Rico, Mayaguez, Puerto Rico, USA*
¹⁶⁷*Purdue University, West Lafayette, Indiana, USA*
¹⁶⁸*Purdue University Calumet, Hammond, Indiana, USA*
¹⁶⁹*Rice University, Houston, Texas, USA*
¹⁷⁰*University of Rochester, Rochester, New York, USA*
¹⁷¹*Rutgers, The State University of New Jersey, Piscataway, New Jersey, USA*
¹⁷²*University of Tennessee, Knoxville, Tennessee, USA*
¹⁷³*Texas A&M University, College Station, Texas, USA*
¹⁷⁴*Texas Tech University, Lubbock, Texas, USA*
¹⁷⁵*Vanderbilt University, Nashville, Tennessee, USA*
¹⁷⁶*University of Virginia, Charlottesville, Virginia, USA*
¹⁷⁷*Wayne State University, Detroit, Michigan, USA*
¹⁷⁸*University of Wisconsin—Madison, Madison, Wisconsin, USA*

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

- ^c Also at State Key Laboratory of Nuclear Physics and Technology, Peking University, Beijing, China.
- ^d Also at Institut Pluridisciplinaire Hubert Curien (IPHC), Université de Strasbourg, CNRS-IN2P3.
- ^e Also at Universidade Estadual de Campinas, Campinas, Brazil.
- ^f Also at Universidade Federal de Pelotas, Pelotas, Brazil.
- ^g Also at Université Libre de Bruxelles, Bruxelles, Belgium.
- ^h Also at Deutsches Elektronen-Synchrotron, Hamburg, Germany.
- ⁱ Also at Joint Institute for Nuclear Research, Dubna, Russia.
- ^j Also at Suez University, Suez, Egypt.
- ^k Also at British University in Egypt, Cairo, Egypt.
- ^l Also at Ain Shams University, Cairo, Egypt.
- ^m Also at Helwan University, Cairo, Egypt.
- ⁿ Also at Université de Haute Alsace, Mulhouse, France.
- ^o Also at Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, Moscow, Russia.
- ^p Also at Tbilisi State University, Tbilisi, Georgia.
- ^q Also at Ilia State University, Tbilisi, Georgia.
- ^r Also at CERN, European Organization for Nuclear Research, Geneva, Switzerland.
- ^s Also at RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany.
- ^t Also at University of Hamburg, Hamburg, Germany.
- ^u Also at Brandenburg University of Technology, Cottbus, Germany.
- ^v Also at Institute of Nuclear Research ATOMKI, Debrecen, Hungary.
- ^w Also at MTA-ELTE Lendület CMS Particle and Nuclear Physics Group, Eötvös Loránd University, Budapest, Hungary.
- ^x Also at Institute of Physics, University of Debrecen.
- ^y Also at Indian Institute of Science Education and Research, Bhopal, India.
- ^z Also 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 Yazd University, Yazd, Iran.
- ^{ee} Also at Plasma Physics Research Center, Science and Research Branch, Islamic Azad University, Tehran, Iran.
- ^{ff} Also at Università degli Studi di Siena, Siena, Italy.
- ^{gg} Also at Purdue University, West Lafayette, USA.
- ^{hh} Also at International Islamic University of Malaysia, Kuala Lumpur, Malaysia.
- ⁱⁱ Also at Malaysian Nuclear Agency, MOSTI, Kajang, Malaysia.
- ^{jj} Also at Consejo Nacional de Ciencia y Tecnología, Mexico city, Mexico.
- ^{kk} Also at Warsaw University of Technology, Institute of Electronic Systems, Warsaw, Poland.
- ^{ll} Also at Institute for Nuclear Research, Moscow, Russia.
- ^{mm} Also at National Research Nuclear University 'Moscow Engineering Physics Institute' (MEPhI), Moscow, Russia.
- ⁿⁿ Also at St. Petersburg State Polytechnical University, St. Petersburg, Russia.
- ^{oo} Also at University of Florida, Gainesville, USA.
- ^{pp} Also at P.N. Lebedev Physical Institute, Moscow, Russia.
- ^{qq} Also at Budker Institute of Nuclear Physics, Novosibirsk, Russia.
- ^{rr} Also at Faculty of Physics, University of Belgrade, Belgrade, Serbia.
- ^{ss} Also at INFN Sezione di Roma, Università di Roma, Roma, Italy.
- ^{tt} Also at University of Belgrade, Faculty of Physics and Vinca Institute of Nuclear Sciences, Belgrade, Serbia.
- ^{uu} Also at Scuola Normale e Sezione dell'INFN, Pisa, Italy.
- ^{vv} Also at National and Kapodistrian University of Athens, Athens, Greece.
- ^{ww} Also at Riga Technical University, Riga, Latvia.
- ^{xx} Also at Institute for Theoretical and Experimental Physics, Moscow, Russia.
- ^{yy} Also at Albert Einstein Center for Fundamental Physics, Bern, Switzerland.
- ^{zz} Also at Istanbul Aydin University, Istanbul, Turkey.
- ^{aaa} Also at Mersin University, Mersin, Turkey.
- ^{bbb} Also at Cag University, Mersin, Turkey.
- ^{ccc} Also at Piri Reis University, Istanbul, Turkey.
- ^{ddd} Also at Gaziosmanpasa University, Tokat, Turkey.
- ^{eee} Also at Adiyaman University, Adiyaman, 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 Texas A&M University at Qatar, Doha, Qatar.
- ^{uuu} Also at Kyungpook National University, Daegu, Korea.