Constraints on the initial state of PbPb collisions via measurements of Z boson yields and azimuthal anisotropy at $\sqrt{s_{NN}} = 5.02$ TeV

The CMS Collaboration

Abstract

The CMS experiment at the LHC has measured the differential cross sections of Z bosons decaying to pairs of leptons, as functions of transverse momentum and rapidity, in lead-lead collisions at a nucleon-nucleon center-of-mass energy of 5.02 TeV. The measured Z boson elliptic azimuthal anisotropy coefficient is compatible with zero, showing that Z bosons do not experience significant final-state interactions in the medium produced in the collision. Yields of Z bosons are compared to Glauber model predictions and are found to deviate from these expectations in peripheral collisions, indicating the presence of initial collision geometry and centrality selection effects. The precision of the measurement allows, for the first time, for a data-driven determination of the nucleon-nucleon integrated luminosity as a function of lead-lead centrality, thereby eliminating the need for its estimation based on a Glauber model.

“Published in Physical Review Letters as doi:10.1103/PhysRevLett.127.102002.”
Ultrarelativistic heavy ion collisions produce a hot partonic medium, known as the quark-gluon plasma (QGP) [1]. Energetic partons produced in the collision lose energy traversing the QGP, resulting in a phenomenon known as “jet quenching” [2, 3]. The magnitude of parton energy loss is frequently quantified with the nuclear modification factor ($R_{AA}$) defined as the ratio of a given particle’s yield in nucleus-nucleus collisions ($N_{AA}$) with the corresponding proton-proton cross section ($\sigma_{pp}$), scaled to account for the number of binary nucleon-nucleon interactions in the heavy ion collision [3]. For a collision impact parameter (or centrality) $b$, $R_{AA}(b) = N_{AA}(b)/[\sigma_{pp}T_{AA}(b)]$, where $T_{AA}$ is the transverse overlap function representing the collision’s effective integrated nucleon-nucleon luminosity. Head-on (central) collisions have larger $T_{AA}$ than glancing (peripheral) collisions. A Monte Carlo (MC) Glauber model is typically used to determine $T_{AA}(b)$ from transverse profiles of colliding nuclei [4]. If the nucleus-nucleus collision is a superposition of independent nucleon-nucleon collisions, $R_{AA}$ is unity. Deviations from unity typically indicate the presence of initial- and/or final-state effects. Since $Z$ bosons and their leptonic daughters carry no color charge, they are unaffected by final-state QGP effects and provide a clean test of both $T_{AA}$ Glauber scaling and modifications of the nuclear parton distribution functions (nPDFs) compared to the free proton case [5–8]. Because of their large mass and clean final state, $Z$ boson yields can be both precisely measured and accurately calculated using perturbative quantum chromodynamics (QCD). Previous measurements by the ALICE, ATLAS, and CMS Collaborations found $Z$ boson yields to be uniform in azimuth and consistent with pp cross sections scaled by Glauber model expectations [5–8]. Measurements involving $W$ bosons [9, 10] and photons [11–13] give similar results. However, the precision of these studies was statistically limited for peripheral collisions. Measurements of $R_{AA}$ for colored hard probes such as high transverse momentum ($p_T$) hadrons, jets, and quarkonia, showed a suppression, with respect to Glauber scaling expectations, in peripheral events where limited QGP production is expected, presenting a challenge to theoretical interpretations [14]. In this region, the Glauber model has large uncertainties from nucleon fluctuations and other sub-nucleon and nuclear structure effects [15]. Thus, understanding the onset of jet quenching as a function of centrality remains a key open question. Furthermore, the observation of QGP-like phenomena in the small systems produced in pp and proton-lead (pPb) collisions [16–20] indicates the possibility of final-state effects in such systems. A precision measurement of $Z$ bosons in peripheral nucleus-nucleus collisions can provide an experimental reference for the expected yields of hard probes in the absence of final-state effects, which may lead to an improved understanding of the onset of jet quenching in small systems.

In this Letter, the yields of $Z$ bosons decaying to pairs of muons or electrons are measured using the 2018 data set of PbPb collisions recorded by the CMS experiment at a nucleon-nucleon center-of-mass energy of $\sqrt{s_{NN}} = 5.02$ TeV. Contributions from virtual photons decaying to lepton pairs ($\gamma^* \rightarrow \ell^+\ell^-$, where $\ell = \mu, e$), over the invariant mass range $60 < m_{\ell\ell} < 120$ GeV, are included in the $Z$ boson signal. The results are compared with Glauber model predictions for $T_{AA}$ scaling of hard, colorless probes. A measurement of the $Z$ boson elliptic azimuthal anisotropy coefficient ($v_2$) is also presented. The observable $v_2$ is defined as the average of $\cos[2(\phi - \Psi_2)]$, where $\phi$ is the $Z$ boson azimuthal angle and $\Psi_2$ is the angle of maximum azimuthal particle density [21]. Finally, the $Z$ boson transverse momentum ($p_T^Z$) and rapidity ($y^Z$) distributions are measured.

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 are a silicon pixel and strip tracker, a lead tungstate crystal electromagnetic calorimeter (ECAL), and a brass and scintillator hadron calorimeter, each composed of a barrel and two endcap sections. Forward hadron (HF) calorimeters extend the pseudorapidity ($\eta$) coverage provided by the barrel and endcap detec-
tors. Muons are detected in gas-ionization chambers embedded in the steel flux-return yoke outside the solenoid. Events of interest are selected using a two-tiered trigger system [22, 23]. 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. [24].

The analyzed data corresponds to an integrated luminosity of $1.696 \pm 0.032 \text{nb}^{-1}$. Events containing at least one muon (electron) with $p_T > 12 (20) \text{GeV}$ are selected by the trigger. Collision centrality is determined from the total transverse energy deposited in both HF calorimeters. It is expressed as a percentage of the total hadronic cross section, with lower values corresponding to central collisions and larger values to peripheral collisions. The selected data correspond to $11.78 \pm 0.15$ billion sampled minimum-bias (MB) events in the 0–90% centrality range. The $T_{AA}$ values listed in Appendix A are used to normalize different centrality selections for comparison and are calculated with TGLAUBERMC v3.2 [26].

Detector acceptance and response effects are corrected using simulated MC events. The signal sample consists of $Z/\gamma^* \rightarrow \ell^+\ell^-$ production generated with MadGraph5_aMC@NLO (v2.4.2) [27] at next-to-leading order (NLO) in QCD. These events are interfaced with “tuned” [28] PYTHIA 8 (v2.3.0) [29] to simulate parton showering, hadronization, and underlying event production. Simulations account for the lead nucleus isospin content and use EPPS16 NLO nPDFs [30] combined with free-nucleon CT14 NLO PDFs [31]. This setup does not account for potential neutron skin effects, but such effects are expected to be small for neutral electroweak bosons [32]. The Z boson events are then overlaid onto PbPb events produced with HYDJET v1.9 [33]. Those events are then passed to GEANT4 [34] to emulate detector response.

Leptons are reconstructed using the CMS particle flow algorithm [35]. This algorithm applies loose isolation criteria to muons, but not for electrons. Muon (electron) candidates must have $|\eta^\ell| < 2.4 (2.1)$ and $p_T^\ell > 20 \text{GeV}$. Selection criteria are required to reject low-quality muons [36], resulting in $\approx 98\%$ identification efficiency. The effects of misreconstructed muons are negligible. A multivariate discriminant optimized using the TMVA package [37] selects electrons [38] with a working point corresponding to 90% identification efficiency and 80% rejection of misreconstructed electrons. Efficiencies of various stages of lepton reconstruction are measured using the “tag-and-probe” method [39] in data and simulation, as functions of $p_T^\ell$, $\eta^\ell$, and centrality. This includes lepton trigger efficiency, the efficiency of reconstructing a muon (electron) track that matches a muon detector plane (ECAL tower), and the probability that the lepton passes all selections. Discrepancies between data and simulation are corrected by weighting the simulation lepton efficiency by the ratio of the data and MC efficiencies.

The Z boson candidates are reconstructed from oppositely charged lepton pairs with $60 < m_{\ell\ell} < 120 \text{GeV}$ and $|y_Z| < 2.1$. This results in 19 104 (9863) candidates in the dimuon (dielectron) channel. The Z boson reconstruction efficiency ($\epsilon$) is calculated using the MC sample as functions of $p_T^Z$, $y_Z$, and centrality. The efficiency is around 70–95 (30–65)% from central to peripheral events in the dimuon (dielectron) channel. Candidates are weighted by $1/\epsilon$ to correct for lepton selection and detector inefficiencies. A similar correction for detector acceptance is applied to account for Z bosons produced within $|y_Z| < 2.1$ but having decays outside the $p_T^\ell$ or $\eta^\ell$ selections. The average acceptance is 0.68 in the dimuon channel, but only 0.58 in the dielectron channel because of the smaller $\eta^\ell$ range allowed.

Multiple background sources can create high-mass lepton pairs. The first is from QCD-initiated hard processes, such as the production of two leptons inside jets. Because this background arises largely from random lepton combinations, it is assumed that the production rates of
same-sign and opposite-sign lepton pairs are equal. A total of 44 (167) same-sign lepton pairs are observed in the dimuon (dielectron) channel. In the electron channel, misreconstruction of the electron charge slightly enhances the same-sign yield. After correcting for this effect, this background is 0.2 (1.0)% of the opposite-sign yield in the dimuon (dielectron) channel. A second background is generated by electromagnetic (EM) processes (e.g., $\gamma \gamma \rightarrow \ell^+ \ell^-$) [40]. Here, the photons are emitted by the incoming nuclei and tend to have very low $p_T$ [41]. Thus, the lepton pair $p_T$ strongly peaks near zero, and the daughter leptons are back-to-back in azimuth ($\phi$). Based on simulated STARLIGHT v2.2 [42] events, any dimuon (dielectron) candidates having $p_T < 1.25$ (2.50) GeV and acoplanarity, defined as $A_\phi = 1 - \Delta \phi / \pi$, less than 0.001 are identified as products of EM background. The $p_T$ threshold for the dielectron channel is larger because of the worse energy resolution of electrons compared to muons. In simulated events these selections correspond to 90% background rejection, and result in a small efficiency loss for Z bosons, which is taken care of with the applied corrections. Candidates resulting from this background account for 0.6 (0.7)% of the dimuon (dielectron) yield before subtraction. The other backgrounds considered are $Z \rightarrow \tau^+ \tau^-$, $tt$ production, and the production of W bosons decaying to a lepton that is combined with another lepton originating from a hadron decay. The expected yields are calculated as functions of centrality, $p_T^Z$, or $y_Z$ using appropriate MC samples. These backgrounds contribute less than 0.3% to the total yield in each channel.

The $p_T^Z$ resolution is around 6.5 (7.7)% in the dimuon (dielectron) channel. When measuring the $p_T^Z$ spectrum, this results in the migration of Z candidates between bins. This is corrected using an unregularized matrix inversion unfolding procedure implemented with the ROOFUNFOLD framework [43]. A cross-check using a regularized Bayesian method was found to give consistent results [44]. Systematic uncertainties related to mismodeling of the $p_T^Z$ distribution’s shape are negligible. However, the statistical uncertainty of the MC response matrix is propagated to the final spectrum as a systematic uncertainty. This uncertainty is up to 2 (4)% for the dimuon (dielectron) channel in the lowest $p_T^Z$ bin, but is $<1$ (2)% at higher $p_T^Z$.

To measure $v_2$, the 3-subevent scalar product method of Refs. [21, 45] is used. This technique compares $p_T^Z$ to the global event azimuthal shape measured using the HF calorimeters and midrapidity charged particles.

The centrality calibration is affected by the MB event selection efficiency of the HF calorimeters, which is $97.5^{+1.0}_{-0.5}$% for the 0–100% centrality range. The uncertainty in this efficiency is propagated to the final observables, resulting in a final uncertainty of 0.1 (8.4)% in central (peripheral) events. Uncertainties in the single-lepton trigger, reconstruction, and selection efficiencies are the dominant sources of uncertainty and are calculated with the tag-and-probe procedure. After accounting for each Z boson decay daughter, this effect propagates into a 3.0 (5.9)% uncertainty in the cross sections measured in the dimuon (dielectron) channel. An additional uncertainty of less than 1% accounts for the statistical uncertainty of the MC sample used to calculate the Z boson efficiency. The model dependence of the acceptance correction is calculated to be 0.6% by examining the impact of using different nPDF Hessian error sets [46]. The effect of electron charge misreconstruction is 0.5% in simulation. Differences between the electric charge sign-flip probability in data and simulation are estimated to be less than a factor of two, so an absolute uncertainty of 0.5% is assigned for this effect. The $A_\phi$ and $p_T$ selection criteria for removing EM backgrounds are varied between working points corresponding to 80 and 95% background rejection to gauge the sensitivity of the analysis to these selections. This results in an uncertainty of up to 1.5% in the 70–90% centrality range but is negligible elsewhere. When evaluated as a function of $p_T^Z$, this uncertainty is 4% in the lowest $p_T^Z$ bin, but decreases for higher $p_T^Z$ values. Uncertainties related to backgrounds estimated from simulation...
Figure 1: The $v_2$ of Z bosons in PbPb collisions for various centrality bins. The error bars represent statistical uncertainties. The boxes represent systematic uncertainties and may be smaller than the markers. A measurement from the ATLAS Collaboration at $\sqrt{s_{NN}} = 2.76$ TeV is also shown [5].

are negligible. Both decay channels are combined into a single measurement using the BLUE method [47]. Correlations between channels resulting from the centrality calibration, number of MB events, $T_{AA}$, and the acceptance correction are accounted for. For all observables, both channels are within 1.5 standard deviations ($\sigma$) of each other.

The Z boson $v_2$ as a function of centrality is shown in Fig. 1. A previous measurement from the ATLAS Collaboration at $\sqrt{s_{NN}} = 2.76$ TeV is also shown [5]. The new measurement in the 0–90% range is compatible with zero and is significantly more precise than the previous measurement. This confirms the expectation that Z bosons, being produced and decaying very early in the collision process, are largely unaffected by final-state effects such as hydrodynamic flow and energy loss.

The differential cross section of Z boson production as a function of $|y_Z|$ for 0–100% centrality events is shown in Fig. 2. Predictions from the MADGRAPH5_aMC@NLO MC generator interfaced with the CT14 free proton PDF [31], as well as the CT14+EPPS16 [30] and nCTEQ15 [48] nPDF sets are also shown. The models predictions are scaled up by the square of the atomic mass number $A^2$, where $A = 208$ for lead. The width of the model band indicates the PDF and QCD scale uncertainties added in quadrature. The data lie on the upper edge of the models. Inclusion of missing higher-order (next-to-NLO) corrections in the theoretical predictions would increase the total Z boson cross section by a few percent [49]. The predictions derived with the EPPS16 nPDF are closer to the data than those computed with the nCTEQ15 set. Differential cross sections as a function of $p_T^Z$ are shown in Fig. 3. The $p_T^Z$ distribution peaks around 5 GeV before falling sharply. The spectrum is compared to the MADGRAPH5_aMC@NLO calculations with different (n)PDF sets. Although the general trend of the data is correctly reproduced by the simulation, some discrepancies are apparent in different $p_T^Z$ regions. At low $p_T^Z$, this could be related to the lack of soft gluon resummation in the model, as discrepancies have also been observed in pp collisions [50]. The nPDF sets are around 10% lower than the free proton PDF at low $p_T^Z$, but this trend is reversed for $p_T^Z > 50$ GeV. However, the differences between the two nPDF sets are smaller than the deviation of the models from the data, indicating that modeling
Figure 2: The Z boson differential cross section as a function of $|y_Z|$. The error bars represent statistical uncertainties, while the boxes represent systematic uncertainties. Predictions using one PDF and two different nPDF sets are also shown.

Figure 3: The Z boson differential cross section as a function of $p_T^Z$. The error bars represent statistical uncertainties, while the boxes represent systematic uncertainties. Predictions using one PDF and two different nPDF sets are also shown. The lower panel shows the ratio of the predictions to data.
Figure 4: The $T_{AA}$-normalized yields of Z bosons as a function of centrality. The error bars, hollow boxes, and solid gray boxes represent the statistical, systematic, and $T_{AA}$ uncertainties, respectively. The value of the 0–90% data point, and the scaled HG-PYTHIA model are shown for comparison, with the width of the bands representing the contribution from the total 0–90% data point uncertainty.

improvements are needed to reproduce the measured $p_{T}^{Z}$ spectrum before considering nPDF modifications.

The $T_{AA}$-normalized Z boson yields are shown in Fig. 4 versus centrality. Previous analyses of Z boson production [5–7] have indicated that the $T_{AA}$-scaling assumption works well in central events and also for inclusive selections. Comparison of the data for centralities less than 40% with the inclusive 0–90% data point, shown by the dashed magenta line, confirms these previous results. However, a decreasing trend for the 40–90% centrality range can be seen, which was not observed with less precise measurements [5, 6]. The significance of this deviation from the 0–90% data point is 1.6σ (2.2σ) in the 40–90 (70–90)% range. This depletion is not expected to be caused by any final-state effect, because it would show up more prominently in central events.

One potential explanation for this trend is the presence of initial-state geometry and centrality selection effects in peripheral events [51]. Initial-state geometry effects can arise because bound nucleons have a spatial distribution that can shift the average nucleon-nucleon impact parameter away from that of pp collisions. Likewise, correlations between the hard process and the soft-particle production yield, which is used for estimating centrality, can shift the average $T_{AA}$ in a given centrality range away from the Glauber expectation. Such effects have been studied for high-$p_{T}$ charged-hadron production by the ALICE and CMS Collaborations [52, 53]. The HG-PYTHIA model [51] attempts to describe these geometric and selection effects by using the HIJING (v1.35) [54] event generator to simulate the initial geometry of a heavy ion event. In the HG-PYTHIA model, particle production is modeled by overlaying a PYTHIA 8 (v2.4.3) [29] event for each nucleon-nucleon scattering. These “heavy ion” events contain no QGP-related physics. To compare this model to the data, the $R_{AA}$ for hard scatterings was calculated using the model, before being scaled by the 0–90% data point to set the overall normalization. The HG-PYTHIA expectation is plotted as the hatched green boxes in Fig. 4, which are consistent with the data, indicating that the downward trend in peripheral events can be largely explained.
by a combination of geometric and selection effects. This result does not support the apparent increasing trend of the $T_{AA}$-scaled $Z$ boson yields measured in peripheral PbPb collisions by the ATLAS experiment [7], which was interpreted as an indication of a possible “shadowed” value of the nucleon-nucleon inelastic cross section in Ref. [55].

As the experimental uncertainties are comparable to the Glauber model uncertainties, the quantity $N_Z / (\sigma_{NN}^Z N_{evt})$ provides a new experimental proxy for $T_{AA}$. Here, $\sigma_{NN}^Z$ is the $Z$ boson production cross section in a nucleon-nucleon collision, which can be estimated using precise pp measurements [56]. This proxy would eliminate the need for Glauber modeling and related assumptions about nuclear structure. Furthermore, such a quantity would have centrality and selection effects incorporated, thereby allowing for the cancellation of these effects when measuring quantities such as $R_{AA}$. Such cancellations are crucial for studies of the onset of jet quenching in peripheral heavy ion collisions and other small systems, such as pp and pPb.

In summary, $Z$ boson yields and the elliptic flow coefficient ($v_2$) have been measured with high precision as functions of centrality in lead-lead collisions at a nucleon-nucleon center-of-mass energy of 5.02 TeV. The $Z$ boson $v_2$ is compatible with zero, consistent with the expectation of no significant final-state interactions in the quark-gluon plasma (QGP). The differential cross section of $Z$ boson production as a function of rapidity is found to lie on the upper edge of theoretical next-to-leading order (NLO) predictions derived with two different nuclear parton distribution functions. Discrepancies between data and NLO calculations are also observed in various regions of $Z$ boson transverse momentum, indicative of missing higher-order theoretical corrections. Appropriately scaled $Z$ boson yields are constant versus impact parameter for central and semi-central collisions, but a decreasing trend is seen for the first time for more peripheral events. This is compatible with the HG-PYTHIA model prediction, which accounts for initial collision geometry and centrality selection effects. These results provide a new experimental proxy for estimating the average nucleon-nucleon integrated luminosity as a function of centrality in heavy ion collisions. The ratio of $Z$ boson yields in PbPb over pp collisions can be used as an alternative to Glauber-model-based scaling for hard scattering processes, which also automatically accounts for potential effects related to event selection and centrality calibration. Such a method provides a useful tool for future searches for the onset of QGP effects on colored hard probes in the medium produced in peripheral heavy ion collisions and small colliding systems.

Acknowledgments

We congratulate our colleagues in the CERN accelerator departments for the excellent performance of the LHC and thank the technical and administrative staffs at CERN and at other CMS institutes for their contributions to the success of the CMS effort. In addition, we gratefully acknowledge the computing centers and personnel of the Worldwide LHC Computing Grid and other centers for delivering so effectively the computing infrastructure essential to our analyses. Finally, we acknowledge the enduring support for the construction and operation of the LHC, the CMS detector, and the supporting computing infrastructure provided by the following funding agencies: BMBWF and FWF (Austria); FNRS and FWO (Belgium); CNPq, CAPES, FAPERJ, FAPERGS, and FAPESP (Brazil); MES (Bulgaria); CERN; CAS, MoST, and NSFC (China); MINCIENCIAS (Colombia); MSES and CSF (Croatia); RIF (Cyprus); SENESCYT (Ecuador); MoER, ERC PUT and ERDF (Estonia); Academy of Finland, MEC, and HIP (Finland); CEA and CNRS/IN2P3 (France); BMBF, DFG, and HGF (Germany); GSRT (Greece); NKFI A (Hungary); DAE and DST (India); IPM (Iran); SFI (Ireland); INFN (Italy); MSIP and NRF (Republic of Korea); MES (Latvia); LAS (Lithuania); MOE and UM (Malaysia); BUAP, CIN-
References

[1] W. Busza, K. Rajagopal, and W. van der Schee, “Heavy ion collisions: The big picture and the big questions”, *Ann. Rev. Nucl. Part. Sci.* 68 (2018) 339, doi:10.1146/annurev-nucl-101917-020852, arXiv:1802.04801.

[2] J. D. Bjorken, “Energy loss of energetic partons in quark-gluon plasma: Possible extinction of high $p_T$ jets in hadron-hadron collisions”, Fermilab report FERMILAB-PUB-82-059-T, 1982.

[3] D. d’Enterria, “Jet quenching”, in *Relativistic Heavy Ion Physics*, R. Stock, ed., volume 23, p. 99. Springer-Verlag Berlin Heidelberg, 2010. arXiv:0902.2011.

[4] M. L. Miller, K. Reygers, S. J. Sanders, and P. Steinberg, “Glauber modeling in high energy nuclear collisions”, *Ann. Rev. Nucl. Part. Sci.* 57 (2007) 205, doi:10.1146/annurev.nucl.57.090506.123020, arXiv:nucl-ex/0701025.

[5] ATLAS Collaboration, “Measurement of $Z$ boson production in Pb+Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV with the ATLAS detector”, *Phys. Rev. Lett.* 110 (2013) 022301, doi:10.1103/PhysRevLett.110.022301, arXiv:1210.6486.

[6] CMS Collaboration, “Study of $Z$ production in PbPb and pp collisions at $\sqrt{s_{NN}} = 2.76$ TeV in the dimuon and dielectron decay channels”, *JHEP* 03 (2015) 022, doi:10.1007/JHEP03(2015)022, arXiv:1410.4825.

[7] ATLAS Collaboration, “$Z$ boson production in Pb+Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV measured by the ATLAS experiment”, *Phys. Lett. B* 802 (2020) 135262, doi:10.1016/j.physletb.2020.135262, arXiv:1910.13396.

[8] ALICE Collaboration, “$Z$-boson production in p-Pb collisions at $\sqrt{s_{NN}} = 8.16$ TeV and Pb-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV”, 2020. arXiv:2005.11126.

[9] ATLAS Collaboration, “Measurement of $W^\pm$ boson production in Pb+Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV with the ATLAS detector”, *Eur. Phys. J. C* 79 (2019) 935, doi:10.1140/epjc/s10052-019-7439-3, arXiv:1907.10414.

[10] CMS Collaboration, “Study of $W$ boson production in PbPb and pp collisions at $\sqrt{s_{NN}} = 2.76$ TeV”, *Phys. Lett. B* 715 (2012) 66, doi:10.1016/j.physletb.2012.07.025, arXiv:1205.6334.

[11] ALICE Collaboration, “Direct photon production in Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV”, *Phys. Lett. B* 754 (2016) 235, doi:10.1016/j.physletb.2016.01.020, arXiv:1509.07324.
[12] ATLAS Collaboration, “Centrality, rapidity and transverse momentum dependence of isolated prompt photon production in lead-lead collisions at $\sqrt{s_{NN}} = 2.76$ TeV measured with the ATLAS detector”, *Phys. Rev. C* **93** (2016) 034914, [doi:10.1103/PhysRevC.93.034914](https://doi.org/10.1103/PhysRevC.93.034914), [arXiv:1506.08552](https://arxiv.org/abs/1506.08552).

[13] CMS Collaboration, “Measurement of isolated photon production in pp and PbPb collisions at $\sqrt{s_{NN}} = 2.76$ TeV”, *Phys. Lett. B* **710** (2012) 256, [doi:10.1016/j.physletb.2012.02.077](https://doi.org/10.1016/j.physletb.2012.02.077), [arXiv:1201.3093](https://arxiv.org/abs/1201.3093).

[14] F. Arleo, “Quenching of hadron spectra in heavy ion collisions at the LHC”, *Phys. Rev. Lett.* **119** (2017) 062302, [doi:10.1103/PhysRevLett.119.062302](https://doi.org/10.1103/PhysRevLett.119.062302), [arXiv:1703.10852](https://arxiv.org/abs/1703.10852).

[15] D. d’Enterria and C. Loizides, “Progress in the Glauber model at collider energies”, 2020. [arXiv:2011.14909](https://arxiv.org/abs/2011.14909).

[16] ALICE Collaboration, “Long-range angular correlations on the near and away side in pPb collisions at $\sqrt{s_{NN}} = 5.02$ TeV”, *Phys. Lett. B* **719** (2013) 29, [doi:10.1016/j.physletb.2013.01.012](https://doi.org/10.1016/j.physletb.2013.01.012), [arXiv:1212.2001](https://arxiv.org/abs/1212.2001).

[17] ATLAS Collaboration, “Observation of associated near-side and away-side long-range correlations in $\sqrt{s_{NN}} = 5.02$ TeV proton-lead collisions with the ATLAS detector”, *Phys. Rev. Lett.* **110** (2013) 182302, [doi:10.1103/PhysRevLett.110.182302](https://doi.org/10.1103/PhysRevLett.110.182302), [arXiv:1212.5198](https://arxiv.org/abs/1212.5198).

[18] CMS Collaboration, “Evidence for collectivity in pp collisions at the LHC”, *Phys. Lett. B* **765** (2017) 193, [doi:10.1016/j.physletb.2016.12.009](https://doi.org/10.1016/j.physletb.2016.12.009), [arXiv:1606.06198](https://arxiv.org/abs/1606.06198).

[19] K. Dusling, W. Li, and B. Schenke, “Novel collective phenomena in high-energy proton-proton and proton-nucleus collisions”, *Int. J. Mod. Phys. E* **25** (2016) 1630002, [doi:10.1142/S0218301316300022](https://doi.org/10.1142/S0218301316300022), [arXiv:1509.07939](https://arxiv.org/abs/1509.07939).

[20] J. L. Nagle and W. A. Zajc, “Small system collectivity in relativistic hadronic and nuclear collisions”, *Ann. Rev. Nucl. Part. Sci.* **68** (2018) 211, [doi:10.1146/annurev-nucl-101916-123209](https://doi.org/10.1146/annurev-nucl-101916-123209), [arXiv:1801.03477](https://arxiv.org/abs/1801.03477).

[21] M. Luzum and J.-Y. Ollitrault, “Eliminating experimental bias in anisotropic-flow measurements of high-energy nuclear collisions”, *Phys. Rev. C* **87** (2013) 044907, [doi:10.1103/PhysRevC.87.044907](https://doi.org/10.1103/PhysRevC.87.044907), [arXiv:1209.2323](https://arxiv.org/abs/1209.2323).

[22] CMS Collaboration, “Performance of the CMS Level-1 trigger in proton-proton collisions at $\sqrt{s} = 13$ TeV”, *JINST* **15** (2020) P10017, [doi:10.1088/1748-0221/15/10/P10017](https://doi.org/10.1088/1748-0221/15/10/P10017), [arXiv:2006.10165](https://arxiv.org/abs/2006.10165).

[23] CMS Collaboration, “The CMS trigger system”, *JINST* **12** (2017) P01020, [doi:10.1088/1748-0221/12/01/P01020](https://doi.org/10.1088/1748-0221/12/01/P01020), [arXiv:1609.02366](https://arxiv.org/abs/1609.02366).

[24] CMS Collaboration, “The CMS experiment at the CERN LHC”, *JINST* **3** (2008) S08004, [doi:10.1088/1748-0221/3/08/S08004](https://doi.org/10.1088/1748-0221/3/08/S08004).

[25] See the Supplemental Material at [URL will be inserted by publisher] for values of $T_{AA}$ as a function of centrality.
[26] C. Loizides, J. Kamin, and D. d’Enterria, “Improved Monte Carlo Glauber predictions at present and future nuclear colliders”, Phys. Rev. C 97 (2018) 054910, doi:10.1103/PhysRevC.97.054910, arXiv:1710.07098.

[27] J. Alwall et al., “The automated computation of tree-level and next-to-leading order differential cross sections, and their matching to parton shower simulations”, JHEP 07 (2014) 079, doi:10.1007/JHEP07(2014)079, arXiv:1405.0301.

[28] CMS Collaboration, “Extraction and validation of a new set of CMS PYTHIA 8 tunes from underlying-event measurements”, Eur. Phys. J. C 80 (2020) 4, doi:10.1140/epjc/s10052-019-7499-4, arXiv:1903.12179.

[29] T. Sjöstrand et al., “An introduction to PYTHIA 8.2”, Comput. Phys. Commun. 191 (2015) 159, doi:10.1016/j.cpc.2015.01.024, arXiv:1410.3012.

[30] K. J. Eskola, P. Paakkinen, H. Paukkunen, and C. A. Salgado, “EPPS16: Nuclear parton distributions with LHC data”, Eur. Phys. J. C 77 (2017) 163, doi:10.1140/epjc/s10052-017-4725-9, arXiv:1612.05741.

[31] S. Dulat et al., “New parton distribution functions from a global analysis of quantum chromodynamics”, Phys. Rev. D 93 (2016) 033006, doi:10.1103/PhysRevD.93.033006, arXiv:1506.07443.

[32] I. Helenius, H. Paukkunen, and K. J. Eskola, “Neutron-skin effect in direct-photon and charged hadron-production in Pb+Pb collisions at the LHC”, Eur. Phys. J. C 77 (2017) 148, doi:10.1140/epjc/s10052-017-4709-9, arXiv:1606.06910.

[33] I. P. Lokhtin and A. M. Snigirev, “A model of jet quenching in ultrarelativistic heavy ion collisions and high-p_T hadron spectra at RHIC”, Eur. Phys. J. C 45 (2006) 211, doi:10.1140/epjc/s2005-02426-3, arXiv:hep-ph/0506189.

[34] GEANT4 Collaboration, “GEANT4—a simulation toolkit”, Nucl. Instrum. Meth. A 506 (2003) 250, doi:10.1016/S0168-9002(03)01368-8.

[35] CMS Collaboration, “Particle-flow reconstruction and global event description with the CMS detector”, JINST 12 (2017) P10003, doi:10.1088/1748-0221/12/10/P10003, arXiv:1706.04965.

[36] CMS Collaboration, “Performance of the CMS muon detector and muon reconstruction with proton-proton collisions at √s = 13 TeV”, JINST 13 (2018) P06015, doi:10.1088/1748-0221/13/06/P06015, arXiv:1804.04528.

[37] H. Voss, A. Höcker, J. Stelzer, and F. Tegenfeldt, “TMVA, the toolkit for multivariate data analysis with ROOT”, in XIth International Workshop on Advanced Computing and Analysis Techniques in Physics Research (ACAT), p. 40. 2007, arXiv:physics/0703039 [PoS(ACAT)040]. doi:10.22323/1.050.0040.

[38] CMS Collaboration, “Performance of electron reconstruction and selection with the CMS detector in proton-proton collisions at √s = 8 TeV”, JINST 10 (2015) P06005, doi:10.1088/1748-0221/10/06/P06005, arXiv:1502.02701.

[39] CMS Collaboration, “Measurements of inclusive W and Z cross sections in pp collisions at √s = 7 TeV”, JHEP 01 (2011) 080, doi:10.1007/JHEP01(2011)080, arXiv:1012.2466.
[40] CMS Collaboration, “Observation of forward neutron multiplicity dependence of dimuon acoplanarity in ultraperipheral PbPb collisions at $\sqrt{s_{NN}} = 5.02$ TeV”, 2020. arXiv:2011.05239.

[41] CMS Collaboration, “Evidence for light-by-light scattering and searches for axion-like particles in ultraperipheral PbPb collisions at $\sqrt{s_{NN}} = 5.02$ TeV”, Phys. Lett. B 797 (2019) 134826, doi:10.1016/j.physletb.2019.134826, arXiv:1810.04602.

[42] S. R. Klein et al., “STARlight: A Monte Carlo simulation program for ultra-peripheral collisions of relativistic ions”, Comput. Phys. Commun. 212 (2017) 258, doi:10.1016/j.cpc.2016.10.016, arXiv:1607.03838.

[43] T. Adye, “Unfolding algorithms and tests using RooUnfold”, in Proceedings, PHYSTAT 2011 Workshop on Statistical Issues Related to Discovery Claims in Search Experiments and Unfolding, CERN, Geneva, Switzerland 17-20 January 2011, p. 313. 2011. arXiv:1105.1160, doi:10.5170/CERN-2011-006.313.

[44] G. D’Agostini, “A multidimensional unfolding method based on Bayes’ theorem”, Nucl. Instrum. Meth. A 362 (1995) 487, doi:10.1016/0168-9002(95)00274-X.

[45] CMS Collaboration, “Measurement of prompt $D^0$ meson azimuthal anisotropy in Pb-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV”, Phys. Rev. Lett. 120 (2018) 202301, doi:10.1103/PhysRevLett.120.202301, arXiv:1708.03497.

[46] J. Butterworth et al., “PDF4LHC recommendations for LHC Run II”, J. Phys. G 43 (2016) 023001, doi:10.1088/0954-3899/43/2/023001, arXiv:1510.03865.

[47] A. Valassi, “Combining correlated measurements of several different physical quantities”, Nucl. Instrum. Meth. A 500 (2003) 391, doi:10.1016/S0168-9002(03)00329-2.

[48] K. Kovářík et al., “nCTEQ15 — Global analysis of nuclear parton distributions with uncertainties in the CTEQ framework”, Phys. Rev. D 93 (2016) 085037, doi:10.1103/PhysRevD.93.085037, arXiv:1509.00792.

[49] CMS Collaboration, “Determination of the strong coupling constant $\alpha_S(m_Z)$ from measurements of inclusive $W^\pm$ and $Z$ boson production cross sections in proton-proton collisions at $\sqrt{s} = 7$ and 8 TeV”, JHEP 06 (2020) 018, doi:10.1007/JHEP06(2020)018, arXiv:1912.04387.

[50] CMS Collaboration, “Measurements of differential $Z$ boson production cross sections in proton-proton collisions at $\sqrt{s} = 13$ TeV”, JHEP 12 (2019) doi:10.1007/JHEP12(2019)061, arXiv:1909.04133.

[51] C. Loizides and A. Morsch, “Absence of jet quenching in peripheral nucleus nucleus collisions”, Phys. Lett. B 773 (2017) 408, doi:10.1016/j.physletb.2017.09.002, arXiv:1705.08856.

[52] CMS Collaboration, “Charged-particle nuclear modification factors in XeXe collisions at $\sqrt{s_{NN}} = 5.44$ TeV”, JHEP 10 (2018) 138, doi:10.1007/JHEP10(2018)138, arXiv:1809.00201.

[53] ALICE Collaboration, “Analysis of the apparent nuclear modification in peripheral Pb-Pb collisions at 5.02 TeV”, Phys. Lett. B 793 (2019) 420, doi:10.1016/j.physletb.2019.04.047, arXiv:1805.05212.
[54] M. Gyulassy and X.-N. Wang, “HIJING 1.0: A Monte Carlo program for parton and particle production in high-energy hadronic and nuclear collisions”, *Comput. Phys. Commun.* **83** (1994) 307, doi:10.1016/0010-4655(94)90057-4, arXiv:nucl-th/9502021.

[55] K. J. Eskola, I. Helenius, M. Kuha, and H. Paukkunen, “Shadowing in inelastic nucleon-nucleon cross section?”, *Phys. Rev. Lett.* **125** (2020) 212301, doi:10.1103/PhysRevLett.125.212301, arXiv:2003.11856.

[56] ATLAS Collaboration, “Measurements of W and Z boson production in pp collisions at $\sqrt{s} = 5.02$ TeV with the ATLAS detector”, *Eur. Phys. J. C* **79** (2019) doi:10.1140/epjc/s10052-019-6622-x, arXiv:1810.08424, [Erratum: doi:10.1140/epjc/s10052-019-6870-9].
A Supplemental material

Table A.1: The average $T_{AA}$ values for $\sqrt{s_{NN}} = 5.02$ TeV PbPb collisions. The uncertainties result from the model parameters and the HF detector energy resolution.

| Centrality | $\langle T_{AA} \rangle$ (mb$^{-1}$) |
|------------|--------------------------------------|
| 0–5%       | 25.70 ± 0.47                        |
| 5–10%      | 20.40 ± 0.40                        |
| 10–20%     | 14.39 ± 0.30                        |
| 20–30%     | 8.80 ± 0.22                         |
| 30–40%     | 5.12 ± 0.16                         |
| 40–50%     | 2.78 ± 0.11                         |
| 50–70%     | 0.996 ± 0.050                       |
| 70–90%     | 0.1650 ± 0.0077                     |
| 0–90%      | 6.27 ± 0.14                         |
B  The CMS Collaboration

Yerevan Physics Institute, Yerevan, Armenia
A.M. Sirunyan\textsuperscript{5}, A. Tumasyan

Institut für Hochenergiephysik, Wien, Austria
W. Adam, F. Ambrogi, T. Bergauer, M. Dragicevic, J. Erö, A. Escalante Del Valle, R. Frühwirth\textsuperscript{1}, M. Jeitler\textsuperscript{1}, N. Krammer, L. Lechner, D. Liko, T. Madlener, I. Mikulec, F.M. Pitters, N. Rad, J. Schieck\textsuperscript{1}, R. Schöfbeck, M. Spanring, S. Templ, W. Waltenberger, C.-E. Wulz\textsuperscript{1}, M. Zarucki

Institute for Nuclear Problems, Minsk, Belarus
V. Chekhovsky, A. Litomin, V. Makarenko, J. Suarez Gonzalez

Universiteit Antwerpen, Antwerpen, Belgium
M.R. Darwish\textsuperscript{2}, E.A. De Wolf, D. Di Croce, X. Janssen, T. Kello\textsuperscript{3}, A. Lelek, M. Pieters, H. Rejeb Sfar, H. Van Haevermaet, P. Van Mechelen, S. Van Putte, N. Van Remortel

Vrije Universiteit Brussel, Brussel, Belgium
F. Blekman, E.S. Bol, S.S. Chhibra, J. D’Hondt, J. De Clercq, D. Lontkovskyi, S. Lowette, I. Marchesini, S. Moortgat, A. Morton, Q. Python, S. Tavernier, W. Van Doninck, P. Van Mulders

Université Libre de Bruxelles, Bruxelles, Belgium
D. Beghin, B. Bilin, B. Clerbaux, G. De Lentdecker, B. Dorney, L. Favart, A. Grebenyuk, A.K. Kalsi, I. Makarenko, L. Moureaux, L. Pétré, A. Popov, N. Postiau, E. Starling, L. Thomas, C. Vander Velde, F. Vanlaer, D. Vannerom, L. Wezenbeek

Ghent University, Ghent, Belgium
T. Cornelis, D. Dobur, M. Gruchala, I. Khvastunov\textsuperscript{4}, M. Niedziela, C. Roskas, K. Skovpen, M. Tytgat, W. Verbeke, B. Vermassen, M. Vit

Université Catholique de Louvain, Louvain-la-Neuve, Belgium
G. Bruno, F. Bury, C. Caputo, P. David, C. Delaere, M. Delcourt, I.S. Donertas, A. Giannmanco, V. Lemaitre, K. Mondal, J. Prisciandaro, A. Taliercio, M. Teklishyn, P. Vischia, S. Wuyckens, J. Zobec

Centro Brasileiro de Pesquisas Fisicas, Rio de Janeiro, Brazil
G.A. Alves, G. Correia Silva, C. Hensel, A. Moraes

Universidade do Estado do Rio de Janeiro, Rio de Janeiro, Brazil
W.L. Aldá Júnior, E. Belchior Batista Das Chagas, H. BRANDAO MALBOUISSON, W. Carvalho, J. Chinellato\textsuperscript{5}, E. Coelho, E.M. Da Costa, G.G. Da Silveira\textsuperscript{6}, D. De Jesus Damiao, S. Fonseca De Souza, J. Martins\textsuperscript{7}, D. Matos Figueiredo, M. Medina Jaime\textsuperscript{8}, M. Melo De Almeida, C. Mora Herrara, L. Mundim, H. Nogima, P. Rebello Teles, L.J. Sanchez Rosas, A. Santoro, S.M. Silva Do Amaral, A. Sznajder, M. Thiel, E.J. Tonelli Manganote\textsuperscript{5}, F. Torres Da Silva De Araujo, A. Vilela Pereira

Universidade Estadual Paulista \textsuperscript{a}, Universidade Federal do ABC \textsuperscript{b}, São Paulo, Brazil
C.A. Bernardes\textsuperscript{a,d}, L. Calligaris\textsuperscript{a}, T.R. Fernandez Perez Tomei\textsuperscript{a}, E.M. Gregores\textsuperscript{a,b}, D.S. Lemos\textsuperscript{a}, P.G. Mercadante\textsuperscript{a,b}, S.F. Novaes\textsuperscript{a}, Sandra S. Padula\textsuperscript{a}

Institute for Nuclear Research and Nuclear Energy, Bulgarian Academy of Sciences, Sofia, Bulgaria
A. Aleksandrov, G. Antchev, I. Atanasov, R. Hadjiiska, P. Iaydjiev, M. Misheva, M. Rodozov, M. Shopova, G. Sultanov
University of Sofia, Sofia, Bulgaria
M. Bonchev, A. Dimitrov, T. Ivanov, L. Litov, B. Pavlov, P. Petkov, A. Petrov

Beihang University, Beijing, China
W. Fang\textsuperscript{3}, Q. Guo, H. Wang, L. Yuan

Department of Physics, Tsinghua University, Beijing, China
M. Ahmad, Z. Hu, Y. Wang

Institute of High Energy Physics, Beijing, China
E. Chapon, G.M. Chen\textsuperscript{9}, H.S. Chen\textsuperscript{9}, M. Chen, A. Kapoor, D. Leggat, H. Liao, Z. Liu, R. Sharma, A. Spiezia, J. Tao, J. Thomas-wilsker, J. Wang, H. Zhang, S. Zhang\textsuperscript{9}, J. Zhao

State Key Laboratory of Nuclear Physics and Technology, Peking University, Beijing, China
A. Agapitos, Y. Ban, C. Chen, Q. Huang, A. Levin, Q. Li, M. Lu, X. Lyu, Y. Mao, S.J. Qian, D. Wang, Q. Wang, J. Xiao

Sun Yat-Sen University, Guangzhou, China
Z. You

Institute of Modern Physics and Key Laboratory of Nuclear Physics and Ion-beam Application (MOE) - Fudan University, Shanghai, China
X. Gao\textsuperscript{3}

Zhejiang University, Hangzhou, China
M. Xiao

Universidad de Los Andes, Bogota, Colombia
C. Avila, A. Cabrera, C. Florez, J. Fraga, A. Sarkar, M.A. Segura Delgado

Universidad de Antioquia, Medellin, Colombia
J. Jaramillo, J. Mejia Guisao, F. Ramirez, J.D. Ruiz Alvarez, C.A. Salazar Gonzalez, N. Vanegas Arbelaez

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

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

Institute Rudjer Boskovic, Zagreb, Croatia
V. Brigljevic, D. Ferenczek, D. Majumder, M. Roguljic, A. Starodumov\textsuperscript{10}, T. Susa

University of Cyprus, Nicosia, Cyprus
M.W. Ather, A. Attikis, E. Erodotou, A. Ioannou, G. Kole, M. Kolosova, S. Konstantinou, G. Mavromanolakis, J. Moussa, C. Nicolaou, F. Ptochos, P.A. Razis, H. Rykaczewski, H. Saka, D. Tsiakkouri

Charles University, Prague, Czech Republic
M. Finger\textsuperscript{11}, M. Finger Jr.\textsuperscript{11}, A. Kveton, J. Tomsa

Escuela Politecnica Nacional, Quito, Ecuador
E. Ayala

Universidad San Francisco de Quito, Quito, Ecuador
E. Carrera Jarrin
Academy of Scientific Research and Technology of the Arab Republic of Egypt, Egyptian Network of High Energy Physics, Cairo, Egypt
S. Abu Zeid, Y. Assran, A. Mohamed

Center for High Energy Physics (CHEP-FU), Fayoum University, El-Fayoum, Egypt
A. Lotfy, M.A. Mahmoud

National Institute of Chemical Physics and Biophysics, Tallinn, Estonia
S. Bhowmik, A. Carvalho Antunes De Oliveira, R.K. Dewanjee, K. Ehataht, M. Kadastik, M. Raidal, C. Veelken

Department of Physics, University of Helsinki, Helsinki, Finland
P. Eerola, L. Forthomme, H. Kirschenmann, K. Osterberg, M. Voutilainen

Helsinki Institute of Physics, Helsinki, Finland
E. Brücke, F. Garcia, J. Havukainen, V. Karimäki, M.S. Kim, R. Kinnunen, T. Lampén, K. Lassila-Perini, S. Laurila, S. Lehti, T. Lindén, H. Siikonen, E. Tuominen, J. Tuominiemi

Lappeenranta University of Technology, Lappeenranta, Finland
P. Luukka, T. Tuuva

IRFU, CEA, Université Paris-Saclay, Gif-sur-Yvette, France
C. Amendola, M. Besancon, F. Coudenc, M. Dejardin, D. Denegri, J.L. Faure, F. Ferri, S. Ganjour, A. Givernaud, P. Gras, G. Hamel de Monchenault, P. Jarry, B. Lenzi, E. Locci, J. Malcles, J. Rander, A. Rosowsky, M.Ö. Sahin, A. Savoy-Navarro, M. Titov, G.B. Yu

Université de Strasbourg, CNRS, IPHC UMR 7178, Strasbourg, France
J.-L. Agram, J. Andrea, D. Bloch, G. Bourgatte, J.-M. Brom, E.C. Chabert, C. Collard, J.-C. Fontaine, D. Gelé, U. Goerlach, C. Grimault, A.-C. Le Bihan, P. Van Hove

Institut de Physique des 2 Infinis de Lyon (IP2I), Villeurbanne, France
E. Asilar, S. Beauceron, C. Bernet, G. Boudoul, C. Camen, A. Carle, N. Chanon, D. Contardo, P. Depasse, H. El Mamouni, J. Fay, S. Gascon, M. Gouzevitch, B. Ille, Sa. Jain, I.B. Laktineh, H. Lattaud, A. Lesauvage, M. Lethuillier, L. Mirabito, L. Torterotot, G. Touquet, M. Vander Donckt, S. Viret

Georgian Technical University, Tbilisi, Georgia
A. Khvedelidze, Z. Tsamalaidze

RWTH Aachen University, I. Physikalisches Institut, Aachen, Germany
L. Feld, K. Klein, M. Lipinski, D. Meuser, A. Paulus, M. Preuten, M.P. Rauch, J. Schulz, M. Teroerde

RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany
D. Eliseev, M. Erdmann, P. Fackeldey, B. Fischer, S. Ghosh, T. Hebbeker, K. Hoepfner, H. Keller, L. Mastrolorenzo, M. Merschmeyer, A. Meyer, P. Millet, G. Mocellin, S. Mondal, S. Mukherjee, D. Noll, A. Novak, T. Pook, A. Pozdnyakov, T. Quast, M. Radziej, Y. Rath, H. Reithler, J. Roemer, A. Schmidt, S.C. Schuler, A. Sharma, S. Wiedenbeck, S. Zaleski
Budapest, Hungary
M. Bartók, R. Chudasama, M. Csanad, M.M.A. Gadallah, S. Lőkös, P. Major, K. Mandal, A. Mehta, G. Pasztor, O. Surányi, G.I. Veres

Wigner Research Centre for Physics, Budapest, Hungary
G. Bencze, C. Hajdu, D. Horvath, F. Sikler, V. Veszpremi, G. Vesztergombi

Institute of Nuclear Research ATOMKI, Debrecen, Hungary
S. Czellar, J. Karancsi, J. Molnar, Z. Szillasi, D. Teyssier

Institute of Physics, University of Debrecen, Debrecen, Hungary
P. Raics, Z.L. Trocsanyi, G. Zilizi

Eszterhazy Karoly University, Karoly Robert Campus, Gyongyos, Hungary
T. Csongor, F. Nemes, T. Novak

Indian Institute of Science (IISc), Bangalore, India
S. Choudhury, J.R. Komaragiri, D. Kumar, L. Panwar, P.C. Tiwari

National Institute of Science Education and Research, HBNI, Bhubaneswar, India
S. Bahinipati, D. Dash, C. Kar, P. Mal, T. Mishra, V.K. Muraleedharan Nair Bindhu, A. Nayak, D.K. Sahoo, N. Sur, S.K. Swain

Panjab University, Chandigarh, India
S. Bansal, S.B. Beri, V. Bhatnagar, S. Chauhan, N. Dhingra, R. Gupta, A. Kaur, S. Kaur, P. Kumari, M. Lohan, M. Meena, K. Sandeep, S. Sharma, J.B. Singh, A.K. Virdi

University of Delhi, Delhi, India
A. Ahmed, A. Bhardwaj, B.C. Choudhary, R.B. Garg, M. Gola, S. Keshri, A. Kumar, M. Naimuddin, P. Priyanka, K. Ranjan, A. Shah

Saha Institute of Nuclear Physics, HBNI, Kolkata, India
M. Bharti, R. Bhattacharya, S. Bhattacharya, D. Bhowmik, S. Dutta, S. Ghosh, B. Gomber, M. Maity, S. Nandan, P. Palit, A. Purohit, P.K. Rout, G. Saha, S. Sarkar, M. Sharan, B. Singh, S. Thakur

Indian Institute of Technology Madras, Madras, India
P.K. Behera, S.C. Behera, P. Kalbhor, A. Muhammad, R. Pradhan, P.R. Pujahari, A. Sharma, A.K. Sikdar

Bhabha Atomic Research Centre, Mumbai, India
D. Dutta, V. Kumar, K. Naskar, P.K. Netrakanti, L.M. Pant, P. Shukla

Tata Institute of Fundamental Research-A, Mumbai, India
T. Aziz, M.A. Bhat, S. Dugad, R. Kumar Verma, G.B. Mohanty, U. Sarkar

Tata Institute of Fundamental Research-B, Mumbai, India
S. Banerjee, S. Bhattacharya, S. Chatterjee, M. Guchait, S. Karmakar, S. Kumar, G. Majumder, K. Mazumdar, S. Mukherjee, D. Roy, N. Sahoo

Indian Institute of Science Education and Research (IISER), Pune, India
S. Dube, B. Kansal, K. Kothekar, S. Pandey, A. Rane, A. Rastogi, S. Sharma

Department of Physics, Isfahan University of Technology, Isfahan, Iran
H. Bakhshiansohi
INFIN Sezione di Pavia, Università di Pavia, Pavia, Italy
C. Aime, A. Braghieri, S. Calzaferri, D. Fiorina, P. Montagna, S.P. Ratti, V. Re, M. Ressegotti, C. Riccardi, P. Salvini, I. Vai, P. Vitulo

INFIN Sezione di Perugia, Università di Perugia, Perugia, Italy
M. Biasini, G.M. Bilei, D. Ciangottini, L. Fanò, P. Lariccia, G. Mantovani, V. Marianii, M. Menichelli, F. Moscatelli, A. Piccinelli, A. Rossii, A. Santocchia, D. Spiga, T. Tedeschi

INFIN Sezione di Pisa, Università di Pisa, Scuola Normale Superiore di Pisa, Pisa, Italy, Università di Siena, Siena, Italy
K. Androsov, P. Azzurri, G. Bagliesi, V. Bertacchi, L. Bianchini, T. Boccali, R. Castaldi, M.A. Ciocci, R. Dell’Orso, M.R. Di Domenico, S. Donato, L. Giannini, A. Giassi, M.T. Grippa, F. Ligabue, E. Manca, G. Mandorli, A. Messineo, F. Palla, G. Ramirez-Sanchez, A. Rizzi, G. Rolandi, S. Roy Chowdhury, A. Scribano, N. Shafiei, P. Spagnolo, R. Tenchina, G. Tonelli, A. Venturi, P.G. Verdini

INFIN Sezione di Roma, Sapienza Università di Roma, Rome, Italy
F. Cavallari, M. Cipriani, D. Del Re, E. Di Marco, M. Diemoz, E. Longo, P. Meridiani, G. Organtini, F. Pandolfi, R. Paramatti, C. Quaranta, S. Rahatliou, C. Rovella, F. Santanastasio, L. Soffi, R. Tramontano

INFIN Sezione di Torino, Università di Torino, Torino, Italy, Università del Piemonte Orientale, Novara, Italy
N. Amapane, R. Arcidiacono, S. Argiro, M. Arneodo, N. Bartosik, R. Bellan, A. Bellora, C. Biino, A. Cappati, N. Cartiglia, S. Cometti, M. Costa, R. Covarelli, N. Demaria, B. Kiani, F. Legger, C. Mariotti, S. Maselli, E. Migliore, V. Monaco, E. Monteil, M. Monteno, M.M. Obertino, G. Ortona, L. Pacher, N. Pastrovre, M. Pelliccioni, G.L. Pinna Angioni, M. Ruspà, R. Salvatico, F. Siviero, V. Sola, A. Solano, D. Soldi, A. Staiano, D. Trocino

INFIN Sezione di Trieste, Università di Trieste, Trieste, Italy
S. Belforte, V. Candelise, M. Casarsa, F. Cossutti, A. Da Rold, G. Della Ricca, F. Vazzoler

Kyungpook National University, Daegu, Korea
S. Dogra, C. Huh, B. Kim, D.H. Kim, G.N. Kim, J. Lee, S.W. Lee, C.S. Moon, Y.D. Oh, S.I. Pak, B.C. Radburn-Smith, S. Sekmen, Y.C. Yang

Chonnam National University, Institute for Universe and Elementary Particles, Kwangju, Korea
H. Kim, D.H. Moon

Hanyang University, Seoul, Korea
B. Francois, T.J. Kim, J. Park

Korea University, Seoul, Korea
S. Cho, S. Choi, Y. Go, S. Ha, B. Hong, K. Lee, K.S. Lee, J. Lim, J. Park, S.K. Park, J. Yoo

Kyung Hee University, Department of Physics, Seoul, Republic of Korea
J. Goh, A. Gurtu

Sejong University, Seoul, Korea
H.S. Kim, Y. Kim
Seoul National University, Seoul, Korea
J. Almond, J.H. Bhyun, J. Choi, S. Jeon, J. Kim, J.S. Kim, S. Ko, H. Kwon, H. Lee, K. Lee, S. Lee, K. Nam, B.H. Oh, M. Oh, S.B. Oh, H. Seo, U.K. Yang, I. Yoon

University of Seoul, Seoul, Korea
D. Jeon, J.H. Kim, B. Ko, J.S.H. Lee, I.C. Park, Y. Roh, D. Song, I.J. Watson

Yonsei University, Department of Physics, Seoul, Korea
H.D. Yoo

Sungkyunkwan University, Suwon, Korea
Y. Choi, C. Hwang, Y. Jeong, H. Lee, Y. Lee, I. Yu

College of Engineering and Technology, American University of the Middle East (AUM), Egaila, Kuwait
Y. Maghrbi

Riga Technical University, Riga, Latvia
V. Vleckalns

Vilnius University, Vilnius, Lithuania
A. Juodagalvis, A. Rinkevicius, G. Tamulaitys

National Centre for Particle Physics, Universiti Malaya, Kuala Lumpur, Malaysia
W.A.T. Wan Abdullah, M.N. Yusli, Z. Zolkapli

Universidad de Sonora (UNISON), Hermosillo, Mexico
J.F. Benitez, A. Castaneda Hernandez, J.A. Murillo Quijada, L. Valencia Palomo

Centro de Investigacion y de Estudios Avanzados del IPN, Mexico City, Mexico
G. Ayala, H. Castillo-Valdez, E. De La Cruz-Burelo, I. Heredia-De La Cruz, R. Lopez-Fernandez, D.A. Perez Navarro, A. Sanchez-Hernandez

Universidad Iberoamericana, Mexico City, Mexico
S. Carrillo Moreno, C. Oropeza Barrera, M. Ramirez-Garcia, F. Vazquez Valencia

Benemerita Universidad Autonoma de Puebla, Puebla, Mexico
J. Eysermans, I. Pedraza, H.A. Salazar Ibarguen, C. Uribe Estrada

Universidad Autonoma de San Luis Potosi, San Luis Potosi, Mexico
A. Morelos Pineda

University of Montenegro, Podgorica, Montenegro
J. Mijuskovic, N. Raicevic

University of Auckland, Auckland, New Zealand
D. Krofcheck

University of Canterbury, Christchurch, New Zealand
S. Bheesette, P.H. Butler

National Centre for Physics, Quaid-I-Azam University, Islamabad, Pakistan
A. Ahmad, M.I. Asghar, M.I.M. Awan, H.R. Hoorani, W.A. Khan, M.A. Shah, M. Shoaib, M. Waqas

AGH University of Science and Technology Faculty of Computer Science, Electronics and Telecommunications, Krakow, Poland
V. Avati, L. Grzanka, M. Malawski
National Centre for Nuclear Research, Swierk, Poland
H. Bialkowska, M. Bluj, B. Boimska, T. Frueboes, M. Górski, M. Kazana, M. Szleper, P. Traczyk, P. Zalewski

Institute of Experimental Physics, Faculty of Physics, University of Warsaw, Warsaw, Poland
K. Bunkowski, A. Byszuk, K. Doroba, A. Kalinowski, M. Konecki, J. Krolikowski, M. Olszewski, M. Walczak

Laboratório de Instrumentação e Física Experimental de Partículas, Lisboa, Portugal
M. Araújo, P. Bargassa, D. Bastos, P. Faccioli, M. Gallinaro, J. Hollar, N. Leonardo, T. Niknejad, J. Seixas, K. Shchelina, O. Toldaiev, J. Varela

Joint Institute for Nuclear Research, Dubna, Russia
S. Afanasiev, P. Bunin, M. Gavrilenko, I. Golutvin, I. Gorbunov, A. Kamenev, V. Karjavine, A. Lanev, A. Malakhov, V. Matveev, P. Moisenz, V. Palichik, V. Perelygin, M. Savina, V. Shalaev, S. Shmatov, S. Shulha, V. Smirnov, O. Teryaev, N. Voytishin, B.S. Yuldashev, A. Zarubin, I. Zhizhin

Petersburg Nuclear Physics Institute, Gatchina (St. Petersburg), Russia
G. Gavrilov, V. Golovtsov, Y. Ivanov, V. Kim, E. Kuznetsova, V. Murzin, V. Oreshkin, I. Smirnov, D. Sosnov, V. Sulimov, L. Uvarov, S. Volkov, A. Vorobyev

Institute for Nuclear Research, Moscow, Russia
Yu. Andreev, A. Dermenev, S. Gninenko, N. Golubev, A. Karneyeu, M. Kirsanov, N. Krasnikov, A. Pashenkov, G. Pivovarov, D. Tlisov, A. Toropin

Institute for Theoretical and Experimental Physics named by A.I. Alikhanov of NRC ‘Kurchatov Institute’, Moscow, Russia
V. Epshteyn, V. Gavrilov, N. Lychkovskaya, A. Nikitenko, V. Popov, G. Safronov, A. Spiridonov, A. Stepennov, M. Toms, E. Vlasov, A. Zhokin

Moscow Institute of Physics and Technology, Moscow, Russia
T. Aushev

National Research Nuclear University ‘Moscow Engineering Physics Institute’ (MEPhI), Moscow, Russia
R. Chistov, M. Danilov, A. Oskin, P. Parygin, S. Polikarpov

P.N. Lebedev Physical Institute, Moscow, Russia
V. Andreev, M. Azarkin, I. Dremin, M. Kirakosyan, A. Terkulov

Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, Moscow, Russia
A. Belyaev, E. Boos, A. Demiyanov, A. Ershov, A. Gribushin, O. Kodolova, V. Korotkikh, I. Lokhtin, S. Obraztsov, S. Petrushanko, V. Savrin, A. Snigirev, I. Vardanyan

Novosibirsk State University (NSU), Novosibirsk, Russia
V. Blinov, T. Dimova, L. Kardapoltsev, I. Ovtin, Y. Skovpen

Institute for High Energy Physics of National Research Centre ‘Kurchatov Institute’, Protvino, Russia
I. Azhgirey, I. Bayshev, V. Kachanov, A. Kalinin, D. Konstantinov, V. Petrov, R. Ryutin, A. Sobol, S. Troshin, N. Tyurin, A. Uzunian, A. Volkov

National Research Tomsk Polytechnic University, Tomsk, Russia
A. Babaev, A. Iuzhakov, V. Okhotnikov, L. Sukhikh
Tomsk State University, Tomsk, Russia
V. Borchsh, V. Ivanchenko, E. Tcherniaev

University of Belgrade: Faculty of Physics and VINCA Institute of Nuclear Sciences, Belgrade, Serbia
P. Adzic, P. Cirkovic, M. Dordevic, P. Milenovic, J. Milosevic

Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas (CIEMAT), Madrid, Spain
M. Aguilar-Benitez, J. Alcaraz Maestre, A. Álvarez Fernández, I. Bachiller, M. Barrio Luna, Cristina F. Bedoya, J.A. Brochero Cifuentes, C.A. Carrillo Montoya, M. Cepeda, M. Cerrada, N. Colino, B. De La Cruz, A. Delgado Peris, J.P. Fernández Ramos, J. Flix, M.C. Fouz, A. García Alonso, O. Gonzalez Lopez, S. Goy Lopez, J.M. Hernandez, M.I. Josa, J. León Holgado, D. Moran, A. Navarro Tobar, A. Pérez-Calero Yzquierdo, J. Puerta Pelayo, I. Redondo, L. Romero, S. Sánchez Navas, M.S. Soares, A. Triossi, L. Urda Gómez, C. Willmott

Universidad Autónoma de Madrid, Madrid, Spain
C. Albajar, J.F. de Trocóniz, R. Reyes-Almanza

Universidad de Oviedo, Instituto Universitario de Ciencias y Tecnologías Espaciales de Asturias (ICTEA), Oviedo, Spain
B. Alvarez Gonzalez, J. Cuevas, C. Erice, J. Fernandez Menendez, S. Folgueras, I. Gonzalez Caballero, E. Palencia Cortezon, C. Ramón Álvarez, J. Ripoll Sau, V. Rodríguez Bouza, S. Sanchez Cruz, A. Trapote

Instituto de Física de Cantabria (IFCA), CSIC-Universidad de Cantabria, Santander, Spain
I.J. Cabrillo, A. Calderon, B. Chazin Quero, J. Duarte Campderros, M. Fernandez, P.J. Fernandez Manteca, G. Gomez, C. Martinez Rivero, P. Martinez Ruiz del Arbol, F. Matorras, J. Piedra Gomez, C. Prieels, F. Ricci-Tam, T. Rodrigo, A. Ruiz-Jimeno, L. Scodellaro, I. Vila, J.M. Vizan Garcia

University of Colombo, Colombo, Sri Lanka
MK Jayananda, B. Kailasapathy, D.U.J. Sonnadara, DDC Wickramarathna

University of Ruhuna, Department of Physics, Matara, Sri Lanka
W.G.D. Dharmaratna, K. Liyanage, N. Perera, N. Wickramage

CERN, European Organization for Nuclear Research, Geneva, Switzerland
T.K. Aarrestad, D. Abbaneo, B. Akgun, E. Aufray, G. Auzinger, J. Baechler, P. Baillon, A.H. Ball, D. Barney, J. Bendavid, N. Beni, M. Bianco, A. Bocci, P. Bortignon, E. Bossini, E. Brondolin, T. Camporesi, G. Cerminara, L. Cristella, D. d’Enterria, A. Dabrowski, N. Daci, V. Daponte, A. David, A. De Roeck, M. Deile, R. Di Maria, M. Dobson, M. Dünser, N. Dupont, A. Elliott-Peisert, N. Emriskova, F. Fallavollita, D. Fasanella, S. Fiorendi, A. Florent, G. Franzoni, J. Fulcher, W. Funk, S. Giani, D. Gigi, K. Gill, F. Glege, L. Gouskos, M. Guibaud, D. Gulhan, M. Haranko, J. Hegeman, Y. Iiyama, V. Innocente, T. James, P. Janot, J. Kaspar, J. Kieseler, M. Komm, N. Kratochvil, C. Lange, P. Lecoq, K. Long, C. Lourenço, L. Malgeri, M. Mannelli, A. Massironi, F. Meijsers, S. Mersi, E. Meschi, F. Moortgat, M. Mulders, J. Ngadiuba, J. Niedziela, S. Orfanelli, L. Orsini, F. Pantaleoni, L. Pape, E. Perez, M. Peruzzi, A. Petrilli, G. Petrucchini, A. Pfeiffer, M. Pierini, D. Rabady, A. Racz, M. Rieger, M. Rovere, H. Sakulin, J. Salfeld-Nebgen, S. Scarfi, C. Schäfer, C. Schwick, M. Selvaggi, A. Sharma, P. Silva, W. Snoeys, P. Sphicas, J. Steggemann, S. Summers, V.R. Tavolaro, D. Treille, A. Tsirou, G.P. Van Onsem, A. Vartak, M. Verzetti, K.A. Wozniak, W.D. Zeuner
Paul Scherrer Institut, Villigen, Switzerland
L. Caminada, W. Erdmann, R. Horisberger, Q. Ingram, H.C. Kaestli, D. Kotlinski, U. Langenegger, T. Rohe

ETH Zurich - Institute for Particle Physics and Astrophysics (IPA), Zurich, Switzerland
M. Backhaus, P. Berger, A. Calandri, N. Chernyavskaya, A. De Cosa, G. Dissertori, M. Dittmar, M. Donegà, C. Dorfer, T. Gadek, T.A. Gómez Espinosa, C. Grab, D. Hits, W. Lustermann, A.-M. Lyon, R.A. Manzoni, M.T. Meinhard, F. Micheli, F. Nessi-Tedaldi, F. Pauss, V. Perovic, G. Perrin, L. Perrozzi, S. Pigazzini, M.G. Ratti, M. Reichmann, C. Reissel, T. Reitenspiess, B. Ristic, D. Ruini, D.A. Sanz Becerra, M. Schönenberger, V. Stampf, M.L. Vesterbacka Olsson, R. Walny, D.H. Zhu

Universität Zürich, Zurich, Switzerland
C. Amsler, C.M. Kuo, W. Lin, A. Roy, T. Sarkar, S.S. Yu

National Central University, Chung-Li, Taiwan
C. Adloff, C.M. Kuo, W. Lin, A. Roy, T. Sarkar

National Taiwan University (NTU), Taipei, Taiwan
L. Ceard, P. Chang, Y. Chao, K.F. Chen, P.H. Chen, W.-S. Hou, Y.Y. Li, R.-S. Lu, E. Paganis, A. Psallidas, A. Steen, E. Yazgan

Chulalongkorn University, Faculty of Science, Department of Physics, Bangkok, Thailand
B. Asavapibhop, C. Asawatangtrakuldee, N. Srimanobhas

Çukurova University, Physics Department, Science and Art Faculty, Adana, Turkey
M.N. Bakirci, F. Boran, S. Damarseckin, Z.S. Demiroglu, F. Dolek, C. Dozen, E. Eskut, G. Gokbulut, Y. Guler, E. Gurpınar Guler, C. Isik, E.E. Kangal, O. Kara, A. Kayis Topaksu, U. Kımısın, G. Onengut, K. Ozcılık, A.E. Simsek, B. Tali, U.G. Tok, H. Topakli, S. Yılmaz, M. Yalvac, U. Kocahmet, C. Zorbilmez

Middle East Technical University, Physics Department, Ankara, Turkey
B. Isildak, G. Karapinar, K. Ocalan, M. Yalvac

Bogazici University, Istanbul, Turkey
I.O. Atakisi, E. Gülmez, M. Kaya, O. Kaya, Ö. Özçelik, S. Tekten, E.A. Yetkin

Istanbul Technical University, Istanbul, Turkey
A. Cakir, K. Cankocak, Y. Komurcu, S. Sen

Istanbul University, Istanbul, Turkey
F. Aydogmus Sen, S. Cerci, B. Kaynak, S. Ozkorucuklu, D. Sunar Cerci

Institute for Scintillation Materials of National Academy of Science of Ukraine, Kharkov, Ukraine
B. Grynyov

National Scientific Center, Kharkov Institute of Physics and Technology, Kharkov, Ukraine
L. Levchuk

University of Bristol, Bristol, United Kingdom
E. Bhal, S. Bologna, J.J. Brooke, E. Clement, D. Cussans, H. Flacher, J. Goldstein, G.P. Heath, H.F. Heath, L. Kreczko, B. Krikler, S. Paramesvaran, T. Sakuma, S. Seif El Nasr-Storey, V.J. Smith, J. Taylor, A. Titterton
Rutherford Appleton Laboratory, Didcot, United Kingdom

K.W. Bell, A. Belyaev, C. Brew, R.M. Brown, D.J.A. Cockerill, K.V. Ellis, K. Harder, S. Harper, J. Linacre, K. Manolopoulos, D.M. Newbold, E. Olaiya, D. Petyt, T. Reis, T. Schuh, C.H. Shepherd-Themistocleous, A. Thea, I.R. Tomalin, T. Williams

Imperial College, London, United Kingdom

R. Bainbridge, P. Bloch, S. Bonomally, J. Borg, S. Breeze, O. Buchmuller, A. Bundock, V. Cepaitis, G.S. Chahal<sup>80</sup>, D. Colling, P. Dauncey, G. Davies, M. Della Negra, G. Fedi, G. Hall, G. Iles, J. Langford, L. Lyons, A.-M. Magnan, S. Malik, A. Martelli, V. Milosevic, J. Nash<sup>81</sup>, V. Palladino, M. Pesaresi, D.M. Raymond, A. Richards, A. Rose, E. Scott, C. Seez, A. Shtipliyski, M. Stoye, A. Tapper, K. Uchida, T. Virdee<sup>19</sup>, N. Wardle, S.N. Webb, D. Winterbottom, A.G. Zecchinelli

Brunel University, Uxbridge, United Kingdom

J.E. Cole, P.R. Hobson, A. Khan, P. Kyberd, C.K. Mackay, I.D. Reid, L. Teodorescu, S. Zahid

Baylor University, Waco, USA

A. Brinkerhoff, K. Call, B. Caraway, J. Dittmann, K. Hatakeyama, A.R. Kanuganti, C. Madrid, B. McMaster, N. Pastika, S. Sawant, C. Smith, J. Wilson

Catholic University of America, Washington, DC, USA

R. Bartek, A. Dominguez, R. Uniyal, A.M. Vargas Hernandez

The University of Alabama, Tuscaloosa, USA

A. Buccilli, O. Charaf, S.I. Cooper, S.V. Gleyzer, C. Henderson, P. Rumerio, C. West

Boston University, Boston, USA

A. Akpinar, A. Albert, D. Arcaro, C. Cosby, Z. Demiragli, D. Gastler, C. Richardson, J. Rohlf, K. Salyer, D. Sperka, D. Spitzbart, I. Suarez, S. Yuan, D. Zou

Brown University, Providence, USA

G. Benelli, B. Burkle, X. Coubez<sup>20</sup>, D. Cutts, Y.t. Duh, M. Hadley, U. Heintz, J.M. Hogan<sup>82</sup>, K.H.M. Kwok, E. Laird, G. Landsberg, K.T. Lau, J. Lee, M. Narain, S. Sagir<sup>83</sup>, R. Syarif, E. Usai, W.Y. Wong, D. Yu, W. Zhang

University of California, Davis, Davis, USA

R. Band, C. Brainerd, R. Breedon, M. Calderon De La Barca Sanchez, M. Chertok, J. Conway, R. Conway, P.T. Cox, R. Erbacher, C. Flores, G. Funk, F. Jensen, W. Ko<sup>†</sup>, O. Kukral, R. Lander, M. Mulhearn, D. Pellett, J. Pilot, M. Shi, D. Taylor, K. Tos, M. Tripathi, Y. Yao, F. Zhang

University of California, Los Angeles, USA

M. Bachtis, R. Cousins, A. Dasgupta, D. Hamilton, J. Hauser, M. Ignatenko, T. Lam, N. Mccoll, W.A. Nash, S. Regnard, D. Saltzberg, C. Schnaible, B. Stone, V. Valuev

University of California, Riverside, Riverside, USA

K. Burt, Y. Chen, R. Clare, J.W. Gary, S.M.A. Ghiasi Shirazi, G. Hanson, G. Karapostoli, O.R. Long, N. Manganelli, M. Olmedo Negrete, M.I. Paneva, W. Si, S. Wimpenny, Y. Zhang

University of California, San Diego, La Jolla, USA

J.G. Branson, P. Chang, S. Cittolin, S. Cooperstein, N. Deelen, M. Derdzinski, J. Duarte, R. Gerosa, D. Gilbert, B. Hashemi, V. Krutelyov, J. Letts, M. Masciovecchio, S. May, S. Padhi, M. Pieri, V. Sharma, M. Tadel, F. Würthwein, A. Yagil

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

N. Amin, C. Campagnari, M. Citron, A. Dorsett, V. Dutta, J. Incandela, B. Marsh, H. Mei, A. Ovcharova, H. Qu, M. Quinnan, J. Richman, U. Sarica, D. Stuart, S. Wang
California Institute of Technology, Pasadena, USA
D. Anderson, A. Bornheim, O. Cerri, I. Dutta, J.M. Lawhorn, N. Lu, J. Mao, H.B. Newman, T.Q. Nguyen, J. Pata, M. Spiropulu, J.R. Vlimant, S. Xie, Z. Zhang, R.Y. Zhu

Carnegie Mellon University, Pittsburgh, USA
J. Alison, M.B. Andrews, T. Ferguson, T. Mudholkar, M. Paulini, M. Sun, I. Vorobiev

University of Colorado Boulder, Boulder, USA
J.P. Cumalat, W.T. Ford, E. MacDonald, T. Mulholland, R. Patel, A. Perloff, K. Stenson, K.A. Ulmer, S.R. Wagner

Cornell University, Ithaca, USA
J. Alexander, Y. Cheng, J. Chu, D.J. Cranshaw, A. Datta, A. Frankenthal, K. Mcdermott, J. Monroy, J.R. Patterson, D. Quach, A. Ryd, W. Sun, S.M. Tan, Z. Tao, J. Thom, P. Wittich, M. Zientek

Fermi National Accelerator Laboratory, Batavia, USA
S. Abdullin, M. Albrow, M. Alyari, G. Apollinari, A. Apresyan, A. Apyan, S. Banerjee, L.A.T. Bauerdick, A. Beretvas, D. Berry, J. Berryhill, P.C. Bhat, K. Burkett, J.N. Butler, A. Canepa, G.B. Cerati, H.W.K. Cheung, F. Chlebana, M. Cremonesi, V.D. Elvira, J. Freeman, Z. Gecse, E. Gottschalk, L. Gray, D. Green, S. Grünendahl, O. Gutsche, R.M. Harris, S. Hasegawa, R. Heller, T.C. Herwig, J. Hirschauer, B. Jayatilaka, S. Jindariani, M. Johnson, U. Joshi, P. Klabbers, T. Klijnsma, B. Klima, M.J. Kortelainen, S. Lammel, D. Lincoln, R. Lipton, M. Liu, T. Liu, J. Lykken, K. Maeshima, D. Mason, P. McBride, P. Merkel, S. Mrenna, S. Nahn, V. O’Dell, V. Papadimitriou, K. Pedro, C. Pena, O. Prokofyev, F. Ravera, A. Reinsvold Hall, L. Ristori, B. Schneider, E. Sexton-Kennedy, N. Smith, A. Soha, W.J. Spalding, L. Spiegel, S. Stoynev, J. Strait, L. Taylor, S. Tkaczyk, N.V. Tran, L. Uplegger, E.W. Vaandering, H.A. Weber, A. Woodard

University of Florida, Gainesville, USA
D. Acosta, P. Avery, D. Bourilkov, L. Cadamuro, V. Cherepanov, F. Errico, R.D. Field, D. Guerrero, B.M. Joshi, M. Kim, J. Konigsberg, A. Korytov, K.H. Lo, K. Matchev, N. Menendez, G. Mitselmakher, D. Rosenzweig, K. Shi, J. Wang, S. Wang, X. Zuo

Florida State University, Tallahassee, USA
T. Adams, A. Askew, D. Diaz, R. Habibullah, S. Hagopian, V. Hagopian, K.F. Johnson, R. Khurana, T. Kolberg, G. Martinez, H. Prosper, C. Schiber, R. Yohay, J. Zhang

Florida Institute of Technology, Melbourne, USA
M.M. Baarmand, S. Butalla, T. Elkafrawy, M. Hohlmann, D. Noonan, M. Rahmani, M. Saunders, F. Yumiceva

University of Illinois at Chicago (UIC), Chicago, USA
M.R. Adams, L. Apanasevich, H. Becerril Gonzalez, R. Cavanaugh, X. Chen, S. Dittmer, O. Evdokimov, C.E. Gerber, D.A. Hangal, D.J. Hofman, C. Mills, G. Oh, T. Roy, M.B. Tonjes, N. Varelas, J. Viinikainen, X. Wang, Z. Wu

The University of Iowa, Iowa City, USA
M. Alhusseini, K. Dilsiz, S. Durgut, R.P. Gandrajula, M. Haytmyradov, V. Khristenko, O.K. Köseyan, J.-P. Merlo, A. Mestvirishvili, A. Moeller, J. Nachtman, H. Ogul, Y. Onel, F. Ozok, A. Penzo, C. Snyder, E. Tiras, J. Wetzel, K. Yi

Johns Hopkins University, Baltimore, USA
O. Amram, B. Blumenfeld, L. Corcodilos, M. Eminizer, A.V. Gritsan, S. Kyriacou, P. Maksimovic, C. Mantilla, J. Roskes, M. Swartz, T.Á. Vámi

The University of Kansas, Lawrence, USA
C. Baldenegro Barrera, P. Baringer, A. Bean, A. Bylinkin, T. Isidori, S. Khalil, J. King, G. Krintiras, A. Kropivnitskaya, C. Lindsey, N. Minafra, M. Murray, C. Rogan, C. Royon, S. Sanders, E. Schmitz, J.D. Tapia Takaki, Q. Wang, J. Williams, G. Wilson

Kansas State University, Manhattan, USA
S. Duric, A. Ivanov, K. Kaadze, D. Kim, Y. Maravin, T. Mitchell, A. Modak, A. Mohammadi

Lawrence Livermore National Laboratory, Livermore, USA
F. Rebassoo, D. Wright

University of Maryland, College Park, USA
E. Adams, A. Baden, O. Baron, A. Belloni, S.C. Eno, Y. Feng, N.J. Hadley, S. Jabeen, G.Y. Jeng, R.G. Kellogg, T. Koeth, A.C. Mignerey, S. Nabil, M. Seidel, A. Skuja, S.C. Tonwar, L. Wang, K. Wong

Massachusetts Institute of Technology, Cambridge, USA
D. Abercrombie, B. Allen, R. Bi, S. Brandt, W. Busza, I.A. Cali, Y. Chen, M. D’Alfonso, G. Gomez Ceballos, M. Goncharov, P. Harris, D. Hsu, M. Hu, M. Klute, D. Kovalskyi, J. Krupa, Y.-J. Lee, P.D. Luckey, B. Maier, A.C. Marini, C. McGinn, C. Mironov, S. Narayanan, X. Niu, C. Paus, D. Rankin, C. Roland, G. Roland, Z. Shi, G.S.F. Stephens, K. Sumorok, K. Tatar, D. Velicanu, J. Wang, T.W. Wang, Z. Wang, B. Wyslouch

University of Minnesota, Minneapolis, USA
R.M. Chatterjee, A. Evans, S. Guts†, P. Hansen, J. Hiltbrand, Sh. Jain, M. Krohn, Y. Kubota, Z. Lesko, J. Mans, M. Revering, R. Rusack, R. Saradhy, N. Schroeder, N. Strobbe, M.A. Wadud

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

University of Nebraska-Lincoln, Lincoln, USA
K. Bloom, S. Chauhan, D.R. Claes, C. Fangmeier, L. Finco, F. Golf, J.R. González Fernández, I. Kravchenko, J.E. Siado, G.R. Snow†, B. Stieger, W. Tabb, F. Yan

State University of New York at Buffalo, Buffalo, USA
G. Agarwal, H. Bandyopadhyay, C. Harrington, L. Hay, I. Iashvili, A. Kharchilava, C. McLean, D. Nguyen, J. Pekkanen, S. Rappoccio, B. Rozzbahani

Northeastern University, Boston, USA
G. Alverson, E. Barberis, C. Freer, Y. Haddad, A. Hortiangtham, J. Li, G. Madigan, B. Marzocchi, D.M. Morse, V. Nguyen, T. Orimoto, A. Parker, L. Skinnari, A. Tishelman-Charny, T. Wamorkar, B. Wang, A. Wisecarver, D. Wood

Northwestern University, Evanston, USA
S. Bhattacharya, J. Bueghly, Z. Chen, A. Gilbert, T. Gunter, K.A. Hahn, N. Odell, M.H. Schmitt, K. Sung, M. Velasco

University of Notre Dame, Notre Dame, USA
R. Bucci, N. Dev, R. Goldouzian, M. Hildreth, K. Hurtado Anampa, C. Jessop, D.J. Karmgard, K. Lannon, W. Li, N. Loukas, N. Marinelli, I. Mcalister, F. Meng, K. Mohrman, Y. Musienko†, R. Ruchti, P. Siddireddy, S. Taroni, M. Wayne, A. Wightman, M. Wolf, L. Zygala
The Ohio State University, Columbus, USA
J. Alimena, B. Bylsma, B. Cardwell, L.S. Durkin, B. Francis, C. Hill, A. Lefeld, B.L. Winer, B.R. Yates

Princeton University, Princeton, USA
P. Das, G. Dezoort, P. Elmer, B. Greenberg, N. Haubrich, S. Higginbotham, A. Kalogeropoulos, G. Kopp, S. Kwan, D. Lange, M.T. Lucchini, J. Luo, D. Marlow, K. Mei, I. Ojalvo, J. Olsen, C. Palmer, P. Piroué, D. Stickland, C. Tully

University of Puerto Rico, Mayaguez, USA
S. Malik, S. Norberg

Purdue University, West Lafayette, USA
V.E. Barnes, R. Chawla, S. Das, L. Gutay, M. Jones, A.W. Jung, B. Mahakud, G. Negro, N. Neumeister, C.C. Peng, S. Piperov, H. Qiu, J.F. Schulte, M. Stojanovic, N. Trevisani, F. Wang, R. Xiao, W. Xie

Purdue University Northwest, Hammond, USA
T. Cheng, J. Dolen, N. Parashar

Rice University, Houston, USA
A. Baty, S. Dildick, K.M. Ecklund, S. Freed, F.J.M. Geurts, M. Kilpatrick, A. Kumar, W. Li, B.P. Padley, R. Redjimi, J. Roberts, J. Rorie, W. Shi, A.G. Stahl Leiton

University of Rochester, Rochester, USA
A. Bodek, P. de Barbaro, R. Demina, J.L. Dulemba, C. Fallon, T. Ferbel, M. Galanti, A. Garcia-Bellido, O. Hindrichs, A. Khukhunaishvili, E. Ranken, R. Taus

Rutgers, The State University of New Jersey, Piscataway, USA
B. Chiarito, J.P. Chou, A. Gandrakota, Y. Gershtein, E. Halkiadakis, A. Hart, M. Heindl, E. Hughes, S. Kaplan, O. Karacheban, I. Laflotte, A. Lath, R. Montalvo, K. Nash, M. Osherson, S. Salur, S. Schnetzer, S. Somalwar, R. Stone, S.A. Thayil, S. Thomas, H. Wang

University of Tennessee, Knoxville, USA
H. Acharya, A.G. Delannoy, S. Spanier

Texas A&M University, College Station, USA
O. Bouhali, M. Dalchenko, A. Delgado, R. Eusebi, J. Gilmore, T. Huang, T. Kamon, H. Kim, S. Luo, S. Malhotra, R. Mueller, D. Överton, L. Perniè, D. Rathjens, A. Safonov, J. Sturdy

Texas Tech University, Lubbock, USA
N. Akchurin, J. Damgov, V. Hegde, S. Kunori, K. Lamichhane, S.W. Lee, T. Mengke, S. Muthumuni, T. Peltola, S. Undleeb, I. Volobouev, Z. Wang, A. Whitbeck

Vanderbilt University, Nashville, USA
E. Appelt, S. Greene, A. Gurrola, R. Janjam, W. Johns, C. Maguire, A. Melo, H. Ni, K. Padeken, F. Romeo, P. Sheldon, S. Tuo, J. Velkovska, M. Verweij

University of Virginia, Charlottesville, USA
M.W. Arenton, B. Cox, G. Cummings, J. Hakala, R. Hirosky, M. Joyce, A. Ledovskoy, A. Li, C. Neu, B. Tannenwald, Y. Wang, E. Wolfe, F. Xia

Wayne State University, Detroit, USA
P.E. Karchin, N. Poudyal, P. Thapa
University of Wisconsin - Madison, Madison, WI, USA
K. Black, T. Bose, J. Buchanan, C. Caillol, S. Dasu, I. De Bruyn, P. Everaerts, C. Galloni, H. He, M. Herndon, A. Hervé, U. Hussain, A. Lanaro, A. Loeliger, R. Loveless, J. Madhusudanan Sreekala, A. Mallampalli, D. Pinna, T. Ruggles, A. Savin, V. Shang, V. Sharma, W.H. Smith, D. Teague, S. Trembath-reichert, W. Vetens
†: Deceased
1: Also at Vienna University of Technology, Vienna, Austria
2: Also at Institute of Basic and Applied Sciences, Faculty of Engineering, Arab Academy for Science, Technology and Maritime Transport, Alexandria, Egypt
3: Also at Université Libre de Bruxelles, Bruxelles, Belgium
4: Also at IRFU, CEA, Université Paris-Saclay, Gif-sur-Yvette, France
5: Also at Universidade Estadual de Campinas, Campinas, Brazil
6: Also at Federal University of Rio Grande do Sul, Porto Alegre, Brazil
7: Also at UFMS, Nova Andradina, Brazil
8: Also at Universidade Federal de Pelotas, Pelotas, Brazil
9: Also at University of Chinese Academy of Sciences, Beijing, China
10: Also at Institute for Theoretical and Experimental Physics named by A.I. Alikhanov of NRC ‘Kurchatov Institute’, Moscow, Russia
11: Also at Joint Institute for Nuclear Research, Dubna, Russia
12: Also at Ain Shams University, Cairo, Egypt
13: Also at Suez University, Suez, Egypt
14: Also at British University in Egypt, Cairo, Egypt
15: Also at Zewail City of Science and Technology, Zewail, Egypt
16: Also at Purdue University, West Lafayette, USA
17: Also at Université de Haute Alsace, Mulhouse, France
18: Also at Erzincan Binali Yıldırım University, Erzincan, Turkey
19: Also at CERN, European Organization for Nuclear Research, Geneva, Switzerland
20: Also at RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany
21: Also at University of Hamburg, Hamburg, Germany
22: Also at Department of Physics, Isfahan University of Technology, Isfahan, Iran
23: Also at Brandenburg University of Technology, Cottbus, Germany
24: Also at Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, Moscow, Russia
25: Also at Institute of Physics, University of Debrecen, Debrecen, Hungary
26: Also at Physics Department, Faculty of Science, Assiut University, Assiut, Egypt
27: Also at MTA-ELTE Lendület CMS Particle and Nuclear Physics Group, Eötvös Loránd University, Budapest, Hungary
28: Also at Institute of Nuclear Research ATOMKI, Debrecen, Hungary
29: Also at IIT Bhubaneswar, Bhubaneswar, India
30: Also at Institute of Physics, Bhubaneswar, India
31: Also at G.H.G. Khalsa College, Punjab, India
32: Also at Shoolini University, Solan, India
33: Also at University of Hyderabad, Hyderabad, India
34: Also at Indian Institute of Technology (IIT), Mumbai, India
35: Also at Deutsches Elektronen-Synchrotron, Hamburg, Germany
36: Also at Department of Physics, University of Science and Technology of Mazandaran,
Behshahr, Iran
38: Now at INFN Sezione di Bari a, Università di Bari b, Politecnico di Bari c, Bari, Italy
39: Also at Italian National Agency for New Technologies, Energy and Sustainable Economic Development, Bologna, Italy
40: Also at Centro Siciliano di Fisica Nucleare e di Struttura Della Materia, Catania, Italy
41: Also at Università di Napoli ‘Federico II’, NAPOLI, Italy
42: Also at Riga Technical University, Riga, Latvia, Riga, Latvia
43: Also at Consejo Nacional de Ciencia y Tecnología, Mexico City, Mexico
44: Also at Warsaw University of Technology, Institute of Electronic Systems, Warsaw, Poland
45: Also at Institute for Nuclear Research, Moscow, Russia
46: Now at National Research Nuclear University ‘Moscow Engineering Physics Institute’ (MEPhI), Moscow, Russia
47: Also at Institute of Nuclear Physics of the Uzbekistan Academy of Sciences, Tashkent, Uzbekistan
48: Also at St. Petersburg State Polytechnical University, St. Petersburg, Russia
49: Also at University of Florida, Gainesville, USA
50: Also at Imperial College, London, United Kingdom
51: Also at P.N. Lebedev Physical Institute, Moscow, Russia
52: Also at Moscow Institute of Physics and Technology, Moscow, Russia, Moscow, Russia
53: Also at Budker Institute of Nuclear Physics, Novosibirsk, Russia
54: Also at Faculty of Physics, University of Belgrade, Belgrade, Serbia
55: Also at Trincomalee Campus, Eastern University, Sri Lanka, Nilaveli, Sri Lanka
56: Also at INFN Sezione di Pavia a, Università di Pavia b, Pavia, Italy, Pavia, Italy
57: Also at National and Kapodistrian University of Athens, Athens, Greece
58: Also at Universität Zürich, Zurich, Switzerland
59: Also at Stefan Meyer Institute for Subatomic Physics, Vienna, Austria, Vienna, Austria
60: Also at Laboratoire d’Annecy-le-Vieux de Physique des Particules, IN2P3-CNRS, Annecy-le-Vieux, France
61: Also at Gaziosmanpasa University, Tokat, Turkey
62: Also at Şırnak University, Şırnak, Turkey
63: Also at Department of Physics, Tsinghua University, Beijing, China, Beijing, China
64: Also at Beykent University, Istanbul, Turkey, Istanbul, Turkey
65: Also at Mersin University, Mersin, Turkey
66: Also at Piri Reis University, Istanbul, Turkey
67: Also at Adiyaman University, Adiyaman, Turkey
68: Also at Tarsus University, MERSIN, Turkey
69: Also at Ozyegin University, Istanbul, Turkey
70: Also at Izmir Institute of Technology, Izmir, Turkey
71: Also at Necmettin Erbakan University, Konya, Turkey
72: Also at Bozok Universitetesi Rektörlüğü, Yozgat, Turkey, Yozgat, Turkey
73: Also at Marmara University, Istanbul, Turkey
74: Also at Milli Savunma University, Istanbul, Turkey
75: Also at Kafkas University, Kars, Turkey
76: Also at Istanbul Bilgi University, Istanbul, Turkey
77: Also at Near East University, Research Center of Experimental Health Science, Nicosia, Turkey
78: Also at Hacettepe University, Ankara, Turkey
79: Also at School of Physics and Astronomy, University of Southampton, Southampton, United Kingdom
80: Also at IPPP Durham University, Durham, United Kingdom
81: Also at Monash University, Faculty of Science, Clayton, Australia
82: Also at Bethel University, St. Paul, Minneapolis, USA, St. Paul, USA
83: Also at Karamanoğlu Mehmetbey University, Karaman, Turkey
84: Also at California Institute of Technology, Pasadena, USA
85: Also at Bingol University, Bingol, Turkey
86: Also at Georgian Technical University, Tbilisi, Georgia
87: Also at Sinop University, Sinop, Turkey
88: Also at Mimar Sinan University, Istanbul, Istanbul, Turkey
89: Also at Nanjing Normal University Department of Physics, Nanjing, China
90: Also at Texas A&M University at Qatar, Doha, Qatar
91: Also at Kyungpook National University, Daegu, Korea, Daegu, Korea