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System-size dependence of charged-particle suppression in ultrarelativistic nucleus-nucleus collisions

The CMS Collaboration*

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Abstract

High-energy partons lose energy while propagating through the hot, strongly interacting medium produced in ultrarelativistic nucleus-nucleus collisions, leading to a suppression of particle production at high transverse momentum (p_{T}). The dependence of this energy loss on the size of the colliding nuclear system has yet to be firmly established experimentally. This Letter presents a systematic study of charged-particle suppression across four different nucleus-nucleus collision systems using nuclear modification factors (R_{AA}) measured by the CMS Collaboration at the CERN LHC. Previous CMS measurements of R_{AA} in oxygen-oxygen, xenon-xenon, and lead-lead collisions are recast with identical p_{T} intervals and are complemented by the first measurement of the charged-particle R_{AA} in neon-neon collisions at $\sqrt{s_{\mathrm{NN}}} = 5.36\,\mathrm{TeV}$. The neon-neon data correspond to an integrated luminosity of $0.76\,\mathrm{nb}^{-1}$. The R_{AA} in all collision systems examined show similar qualitative trends as a function of p_{T}, but have a magnitude which is ordered with the nucleon number A. The R_{AA} feature a downward slope at low p_{T}, a local minimum at around 5–7 GeV, and an upward slope with increasing p_{T}. The R_{AA} are also compared in terms of $A^{1/3}$, which is proportional to the nuclear radius. Models including only initial-state nuclear effects fail to reproduce the observed trends, whereas energy loss models reproduce the trends in the region $p_{\mathrm{T}} > 9.6\,\mathrm{GeV}$.

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*See Appendix G for the list of collaboration members

1 Introduction

In ultrarelativistic heavy ion collisions, a hot and deconfined state of strongly interacting matter, known as quark-gluon plasma (QGP), is formed [1, 2]. High-energy partons produced in initial hard scatterings traverse the QGP and probe its short-distance structure [3–5]. As a consequence of their interactions with the surrounding medium, partons lose energy while propagating through it [6, 7]. A characteristic experimental signature of parton energy loss in heavy ion collisions is the suppression of high transverse momentum (p_{T}) particle yields relative to those measured in a reference proton-proton (pp) collision system.

The magnitude of parton energy loss depends on the presence or absence of QGP formation and, if such a medium is formed, on its properties, including the temperature and transport properties characterizing parton-medium interactions. In the presence of the QGP, the amount of parton energy loss is expected to depend primarily on the in-medium path length traversed by the parton, which is strongly influenced by the size of the colliding nuclear system. In this context, the system size refers to the spatial extent of the nuclear overlap region, which is largely determined by the radii of the colliding nuclei. Energy loss proceeds via a combination of different mechanisms, e.g., collisional or radiative processes, which have different path-length dependences. Variations in the local temperature, the density, and the dynamic expansion of the medium also affect the path-length dependence of energy loss. Thus, the exact scaling of parton energy loss with system size is a theoretically challenging topic, and experimental input is needed to provide additional constraints. To date, studies of the system-size dependence have largely relied on centrality-selected observables in heavy ion collisions [8–14]. Centrality is used to quantify the geometric overlap of the two colliding nuclei and is based on the percentile of the total inelastic nucleus-nucleus (AA) cross section, with lower (higher) percentiles corresponding to more central (more peripheral) collisions. These measurements predominantly explore variations in collision geometry within a single nuclear system, rather than comparisons across different systems. They are affected by selection and geometry biases inherent to the centrality determination, particularly in peripheral events [9, 15, 16]. As a result, a quantitative and unbiased characterization of the system-size dependence of parton energy loss remains an open challenge, limiting the development of a unified theoretical description of nuclear suppression phenomena.

A characterization of nuclear suppression effects based instead on the nucleon number A provides a model-independent measure of the overall system size and a less biased approach to study the system-size dependence of parton energy loss. Recent light ion collision data, i.e., from oxygen-oxygen (OO) and neon-neon (NeNe) collisions [17–19], have provided a new avenue to probe the onset of parton energy loss effects in small nuclear collision systems. These data circumvent the aforementioned issues of event selection and geometric biases and complement the existing measurements in xenon-xenon (XeXe) and lead-lead (PbPb) collisions. In addition, high-p_{T} particle production preferentially selects more head-on central collisions, further reducing the range of collision geometries sampled by the measurement within a given collision system.

Nuclear suppression effects from parton energy loss can be quantified using the charged-particle nuclear modification factor, R_{AA}. For centrality-integrated (minimum bias) AA collisions, this factor can be defined as

$$R_{\mathrm{AA}} = \frac{1}{A^2}\left[\left(\frac{\mathrm{d}\sigma^{\mathrm{AA}}}{\mathrm{d}p_{\mathrm{T}}}\right) \Big/ \left(\frac{\mathrm{d}\sigma^{\mathrm{pp}}}{\mathrm{d}p_{\mathrm{T}}}\right)\right], \tag{1}$$

where σ^{AA} (σ^{pp}) denotes the charged-particle production cross section in nucleus-nucleus (pp)

collisions. The A^2 normalization originates from having A nucleons in each nucleus and therefore constitutes an exact quantity, avoiding model-dependent estimates of the nuclear overlap [20, 21]. Deviations of R_{AA} from unity indicate modifications of particle production arising from nuclear effects, including both initial- and final-state interactions. Owing to the steeply falling p_{T} spectrum, even modest amounts of energy loss can lead to a sizable suppression of the observed particle yields, making R_{AA} a particularly sensitive probe of medium-induced energy loss.

Recently, the CMS Collaboration reported the discovery of suppressed charged-particle production in inclusive OO collisions at a center-of-mass energy per nucleon pair $\sqrt{s_{\mathrm{NN}}} = 5.36\,\mathrm{TeV}$ by measuring the charged-particle R_{AA} [22]. When combined with existing centrality-integrated PbPb measurements at $\sqrt{s_{\mathrm{NN}}} = 5.02\,\mathrm{TeV}$ [12] and XeXe measurements at 5.44 TeV [9], these data provide a unique opportunity for an experimental constraint of parton energy loss effects versus the nuclear system size. The XeXe measurement uses the 80% most central collisions and is therefore expected to provide a close approximation to the inclusive R_{AA}.

Motivated by these developments, this Letter investigates the system-size dependence of high-p_{T} charged-particle production in AA collisions at the CERN LHC. In addition to existing charged-particle R_{AA} measurements, this analysis presents the first measurement of the charged-particle R_{AA} in NeNe collisions at $\sqrt{s_{\mathrm{NN}}} = 5.36\,\mathrm{TeV}$, adding an additional nuclear system having a size between that of OO and XeXe collisions. The four collision systems are presented in identical charged-particle p_{T} intervals to facilitate the systematic evaluation of the charged-particle R_{AA} as functions of p_{T} and A. Tabulated results are provided in the HEPData record for this analysis [23].

2 Detector description

The CMS apparatus [24, 25] is a multipurpose, nearly hermetic detector, designed to trigger on [26–28] and identify electrons, muons, photons, and hadrons [29–31]. A global "particle-flow" algorithm [32] aims to reconstruct all individual particles in an event, combining information provided by the all-silicon tracker and by the crystal electromagnetic and brass-scintillator hadron calorimeters, operating inside a 3.8 T superconducting solenoid, with data from the gas-ionization muon detectors embedded in the flux-return yoke outside the solenoid. The silicon tracker [33] measures charged particles up to pseudorapidity $|\eta| = 3.0$ with typical resolutions of 2.0% in p_{T} and 10–75 μm in the transverse impact parameter [34] for nonisolated particles of $1 < p_{\mathrm{T}} < 100\,\mathrm{GeV}$. The measurement is restricted to $|\eta| < 1$, in order to be able to compare with previous measurements. This is also a η interval where the p_{T} resolution and track reconstruction have optimal performance. The hadron forward (HF) calorimeter uses steel as an absorber and quartz fibers as the sensitive material. The two halves of the HF are located 11.2 m from the interaction region, one on each end from the interaction region, and together they provide coverage in the range $3.0 < |\eta| < 5.2$.

3 Charged-particle R_{AA} in NeNe collisions

In general, the NeNe measurement strategy follows the one devised for the charged-particle R_{AA} measurement in OO collisions in Ref. [22]. The same pp reference from Ref. [22] is used to evaluate the charged-particle R_{AA} in NeNe collisions.

The NeNe data were collected in 2025 using the same online selection as that employed in the OO analysis, based on energy deposits in the HF calorimeters in coincidence with col-

liding bunches. The average number of interactions per bunch crossing, typically referred to as pileup, was approximately 0.13. The total integrated luminosity used in this analysis is $0.76 \pm 0.04\,\mathrm{nb}^{-1}$. This value is obtained by combining two independent luminosity measurements. The first method is based on a preliminary analysis of van der Meer scan data [35, 36]. An independent luminosity determination was performed by comparing the observed Z boson yields to a well-calibrated reference data set [37]. The luminosities obtained with the two approaches are in good agreement; their central values differ by only 4.1%.

The NeNe R_{AA} analysis is reported for primary charged particles, defined as charged particles with a proper decay length $c\tau > 1\,\mathrm{cm}$. Particles that result from secondary decays are not considered primary if the parent particle is classified as primary. Charged particles are reconstructed in the silicon tracker. To reduce the contributions from secondary tracks, tracks are required to have a distance of closest approach (DCA) to any primary vertex smaller than three times the corresponding DCA uncertainty in both the transverse and longitudinal directions. Track reconstruction, selection criteria, and kinematic requirements ($|\eta| < 1$ and $3.0 < p_{\mathrm{T}} < 103.6\,\mathrm{GeV}$) are the same as those used in the OO measurement and in the corresponding pp reference analysis [22]. These selections ensure minimal bias from online and offline event requirements and maximize the cancellation of reconstruction-related uncertainties in the R_{AA} ratio. Restricting the measurement to $p_{\mathrm{T}} < 103.6\,\mathrm{GeV}$ improves control over contributions from misreconstructed tracks, which become increasingly challenging to constrain in the dense track environment of high-p_{T} jet showers.

Event selection requirements are chosen to efficiently select minimum bias NeNe collisions, while suppressing backgrounds from ultraperipheral [38] and beam-related interactions. Offline event selections follow exactly those of the OO analysis [22], and rely on coincidence signals that produce energy deposits above 13 GeV in one or more detector elements on each half of the HF. The presence of at least one reconstructed primary vertex [31] is also required. The resulting inefficiency arising from the event selection requirements for minimum bias events is below 1% for the fiducial region of the charged particles considered in this analysis. This inefficiency, particularly its impact on the charged particle p_{T} spectrum, is taken into account with the corrections to the primary charged-particle level p_{T} spectrum. Ion beam contamination, such as that from transmutation from the electromagnetic dissociation of ^{20}Ne [39], was found to be negligible based on the time dependence of distributions characterizing the event activity [40].

Simulated Monte Carlo events are employed to determine tracking efficiency and acceptance corrections, to assess the impact of momentum resolution and residual background contamination, and to validate the stability of the correction procedures. Minimum bias NeNe collisions are simulated using the HIJING v1.383 generator [41]. High-p_{T} charged-particle production is modeled by embedding PYTHIA v8.311 [42] events with the CP5 tune [43] into HIJING events, forming composite events that combine a hard scattering process with particle production from the underlying event [22]. Potential contamination from ultraperipheral collisions [38] is studied using the STARLIGHT v3.3.0 generator [44] and is found to be negligible for the phase-space region reported in this measurement. The detector response is simulated using GEANT4 [45]. After event generation, simulated events are weighted on an event-by-event basis such that the distribution of the position along the beam axis of reconstructed primary interaction vertices matches the one observed in data. Differences between data and simulation in the charged-particle species composition, such as the fractional composition of charged pions, kaons, protons, and strange hadrons, are corrected using the same procedure as in the OO analysis [22]. The procedure uses as input the p_{T}-dependent species fractions measured by the ALICE experiment in pp collisions [46, 47], which are further rescaled guided by the measured hadrochem-

istry evolution with the average charged-particle density ($\mathrm{d}N_{\mathrm{ch}}/\mathrm{d}\eta$) [48, 49] in order to match the expected composition for the NeNe collision system. The measurements in Refs. [48, 49] indicate that the particle species composition is governed by particle activity, independently of the collision system. For this correction, we assume a reference value of $\mathrm{d}N_{\mathrm{ch}}/\mathrm{d}\eta = 50$ for NeNe collisions, determined from the measured $\mathrm{d}N_{\mathrm{ch}}/\mathrm{d}\eta = 40$ in minimum bias OO collisions [50] scaled to the NeNe system using the Glauber calculations in Ref. [51] as input. The p_{T}-dependent correction factors are similar, to the per-mille level, to the ones from OO, as expected from the observed evolution of the particle species for those values of $\mathrm{d}N_{\mathrm{ch}}/\mathrm{d}\eta$ [48, 49].

Systematic uncertainties are evaluated through dedicated variations of the relevant correction inputs, following the same procedures as in the OO R_{AA} measurement [22]. The uncertainty on the particle species inputs from pp collisions is obtained by propagating the experimental uncertainties [46, 47] on the measured species fractions versus p_{T}; this effect cancels in the R_{AA} ratio but affects the charged-particle p_{T} spectrum. The particle species extrapolation uncertainty is determined by varying the assumed particle composition resulting from variations in the $\mathrm{d}N_{\mathrm{ch}}/\mathrm{d}\eta$-based extrapolation for central NeNe collisions. This uncertainty affects the spectrum and is propagated directly to the R_{AA}. The charged-particle p_{T} resolution uncertainty is propagated by applying an additional Gaussian smearing of 1% to the data; this uncertainty affects the charged-particle p_{T} spectrum but cancels in the R_{AA}. The luminosity uncertainty for NeNe collisions, 4.8%, is assumed to be uncorrelated from the luminosity uncertainty of 3.0% for pp collisions [22], amounting to a global normalization uncertainty of 5.7% in the R_{AA} observable. The tracking efficiency uncertainty is taken as a 2.1% p_{T}-independent uncertainty [52], fully correlated across p_{T} bins. This contribution cancels in the R_{AA} ratio but is present for the charged-particle p_{T} spectrum. Data-simulation differences in the rejection of secondary tracks are evaluated by varying the rejection selections, deriving new tracking efficiency tables for each variation, and taking the spread of the corrected yields as the corresponding systematic uncertainty. The DCA significance requirement is varied between two and five times its uncertainty. The resulting uncertainty on the spectrum cancels partially in the R_{AA}, and is under 3.5% because of partial cancellations. The systematic uncertainties are combined in quadrature. The corrected charged-particle p_{T} spectrum can be found in Appendix A. The resulting R_{AA} for NeNe collisions is presented in Fig. 1 together with other systems, following the p_{T} binning scheme discussed next.

4 Charged-particle R_{AA} dependence on p_{T} and A

To enable a consistent system-size comparison, the R_{AA} measurements in OO, NeNe, XeXe, and PbPb collisions ($A = 16$, 20, 129, and 208) are computed using a common p_{T} binning scheme corresponding to that of the published XeXe measurement [9], which has the coarsest binning. The study includes CMS results from minimum bias OO collisions at 5.36 TeV [22], minimum bias NeNe collisions at 5.36 TeV, XeXe collisions at 5.44 TeV in the 0–80% centrality range [9], and minimum bias PbPb collisions at 5.02 TeV [12]. The minor differences in collision energy are not expected to strongly affect the overall conclusions that can be drawn in the comparison of different systems, since comparisons of charged-particle R_{AA} measurements at 2.76 and 5.02 TeV show no strong dependence on collision energy at the TeV scale [12]. To recompute the PbPb R_{AA} from the published data, the PbPb and 5.02 TeV pp spectra are rebinned by merging adjacent p_{T} intervals using p_{T}-weighted averages to preserve the underlying spectral shapes, with statistical uncertainties combined in quadrature and systematic uncertainties combined linearly assuming full bin-to-bin correlation, while normalization uncertainties remain unchanged. The same procedure is applied consistently to the 5.02 TeV pp reference. The OO and NeNe R_{AA} measurements are repeated with the same binning scheme using the orig-

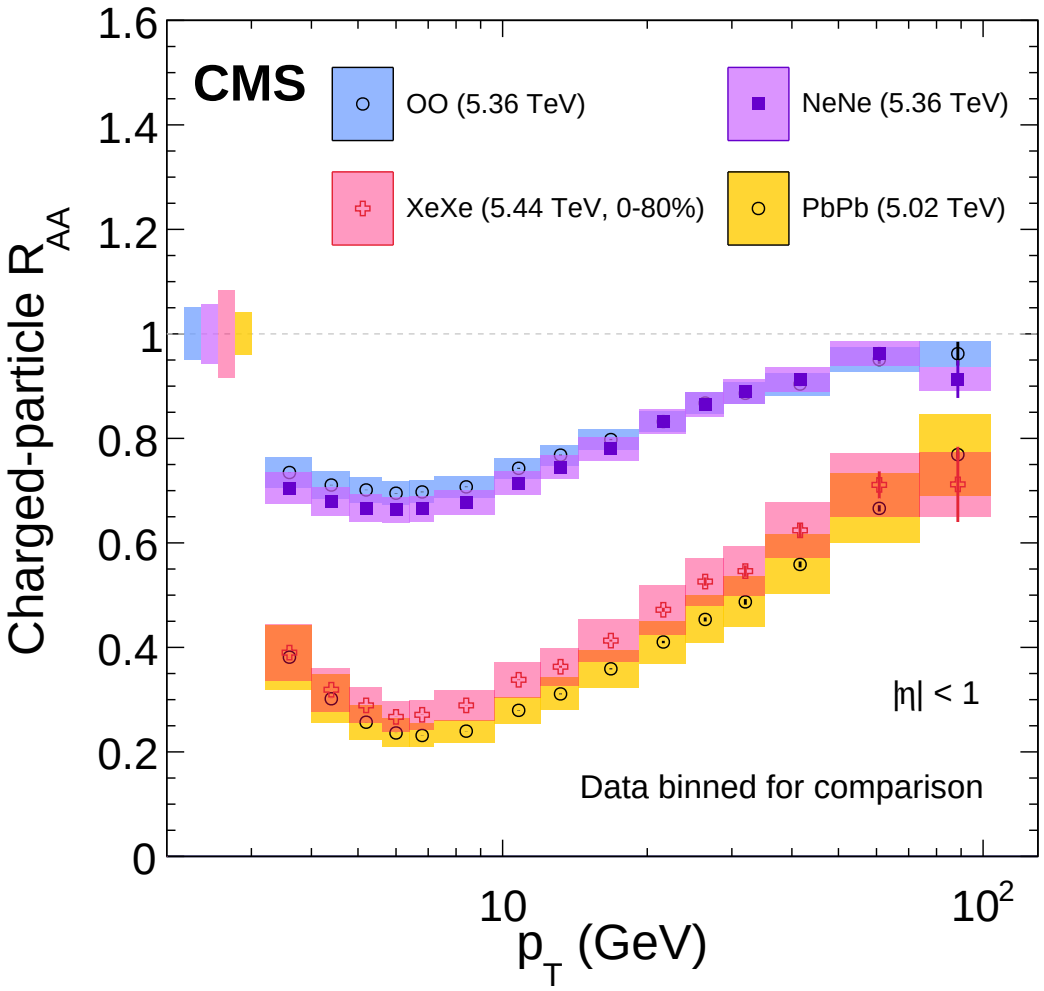

Figure 1: Charged-particle R_{AA} values versus p_T measured in NeNe collisions at 5.36 TeV compared to previous measurements in centrality-integrated OO collisions at 5.36 TeV [22], 0–80% centrality XeXe at 5.44 TeV [9], and minimum bias PbPb collisions at 5.02 TeV [12]. The vertical error bars represent statistical uncertainties and the boxes represent systematic uncertainties. Global normalization uncertainties are not included directly in the data markers error bands, but they are instead represented by the various boxes on the left around unity. For this compilation plot, a uniform p_T binning scheme is adopted to ensure a consistent comparison across collision systems, as described in the text. The same results with finer binning can be found in Appendix C.

inal data sets—no assumptions are needed regarding the combination of adjacent p_T intervals for these data. Further details of the binning procedure are provided in Appendix B, and the R_{AA} results with the high-granularity binning format can be found in Appendix C.

Figure 1 shows the measured charged-particle R_{AA} dependence on p_T for particles with $|\eta| < 1$. The NeNe results are compared to previous CMS measurements [9, 12, 22]. The NeNe and OO measurements display a similar p_T dependence, with NeNe exhibiting a stronger suppression below $p_T \approx 20$ GeV, while converging to comparable R_{AA} values at higher p_T. The NeNe measurement provides additional leverage to quantify how rapidly nuclear suppression effects change with the system size relative to OO. Different models initially predicted varying degrees of separation between these two systems [53]. The observed splitting between NeNe and

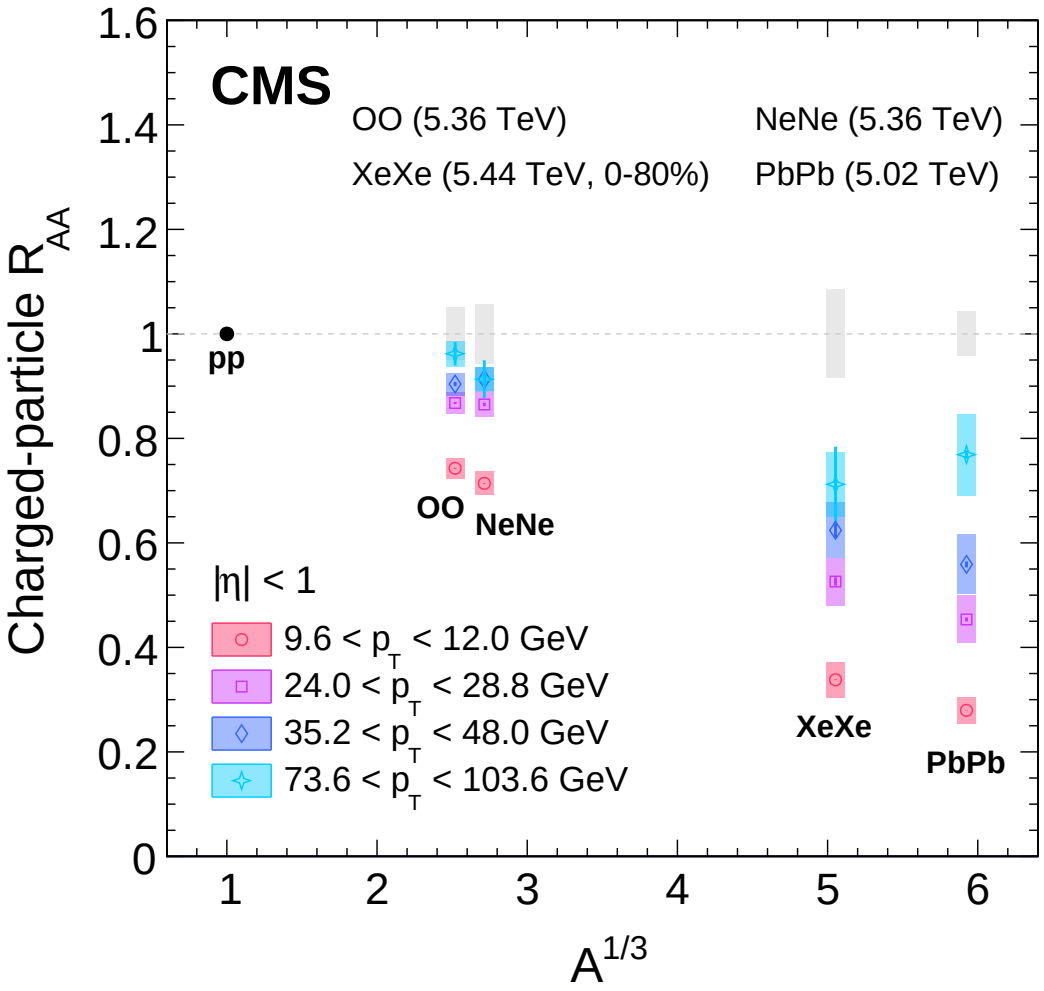

Figure 2: Charged-particle R_{AA} values, in intervals of p_{T}, versus $A^{1/3}$ of the AA colliding system. The open markers represent the measured R_{AA}, with the vertical bars representing the statistical uncertainty, and the vertical band representing the experimental uncertainty. Global normalization uncertainties for each data set are shown in the light-gray boxes around unity. For visualization purposes, a subset of four out of the fifteen p_{T} intervals is presented. A point for pp collisions at $A = 1$, in which the R_{AA} is unity by definition, is also included in the upper left.

OO hints at a smooth transition with system size. Owing to the current luminosity uncertainties affecting both light ion measurements, particularly the extent to which they are correlated, a definitive statement on their relative suppression magnitude is not yet possible. Data from the larger XeXe and PbPb systems show a substantially stronger suppression and a steeper increase of R_{AA} with p_{T}. Together with the light ion systems results, this highlights the systematic evolution of the p_{T}-dependent suppression pattern with collision system size. Overall, the shape of the R_{AA} as a function of p_{T} is similar across all systems, with a minimum around 5–7 GeV, a decreasing trend at low p_{T}, and a rising trend toward higher p_{T}. In heavy ion systems, the low-p_{T} behavior is typically attributed to the interplay of p_{T}-dependent effects such as Cronin enhancement [54] and radial flow [55, 56], while the magnitude and evolution of the suppression at high p_{T} are generally associated with parton energy loss in the medium.

Figure 2 presents the evolution of the charged-particle R_{AA} with $A^{1/3}$ for different AA collision

systems and for four representative p_T intervals spanning 9.6–103.6 GeV. Since the nuclear volume grows approximately with A, $A^{1/3}$ is proportional to the nuclear radius. Presenting the evolution of the R_{AA} with $A^{1/3}$ and in a fixed p_T interval enables a direct model-independent comparison of nuclear suppression effects with the system size. The level of suppression exhibits a monotonic dependence on the system size, with R_{AA} decreasing as A (or $A^{1/3}$) increases.

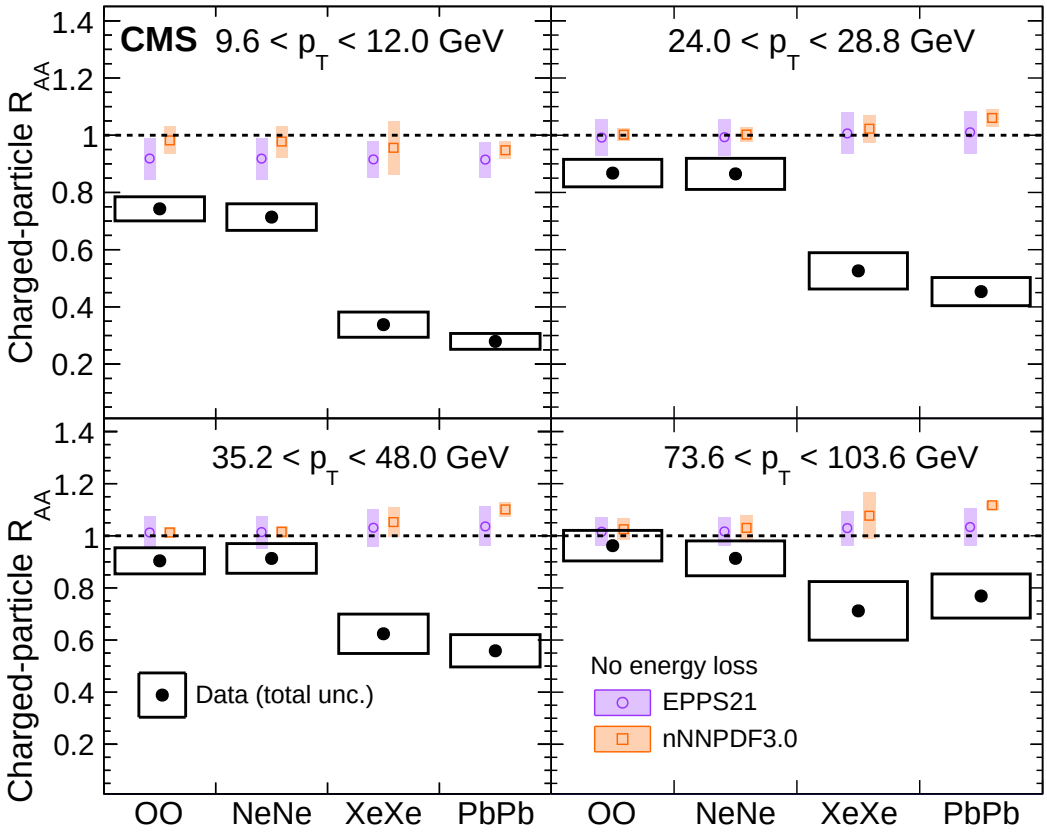

Figure 3: Comparison of the charged-particle R_{AA} measured in OO [22], NeNe, XeXe [9], and PbPb [12] collisions with NLO pQCD calculations that incorporate only initial-state effects through nPDFs and do not include parton energy loss [57, 58]. The open boxes with black circular markers represent the data. The box height represents the total experimental uncertainty obtained from the quadratic combination of statistical, systematic, and global normalization uncertainties. The purple markers correspond to calculations using the EPPS21 nPDF set [59], while the orange markers represent calculations based on the nNNPDF3.0 nPDF set [60]. The vertical uncertainty bands reflect the combined scale-variation and nPDF uncertainties, with the latter providing the dominant contribution.

The measured charged-particle R_{AA} across systems are compared to a set of theoretical calculations that span baseline nuclear initial-state effects and different implementations of parton energy loss in hot, strongly interacting matter. This cross-system comparison provides more stringent constraints than studies of R_{AA} versus p_T for individual collision systems, as it reduces the freedom for models to independently describe light and heavy ion collision systems. The calculations discussed here were provided following the first charged-particle R_{AA} measurement in OO collisions. A comparison is presented over four representative p_T intervals. A set of theoretical predictions for NeNe and OO collisions provided prior to the release of the

OO results is presented in Appendix F and, for the OO system, in Ref. [22], respectively. A comparison with the more recent calculations illustrates the difficulty in describing these data with the knowledge available before the OO experimental results.

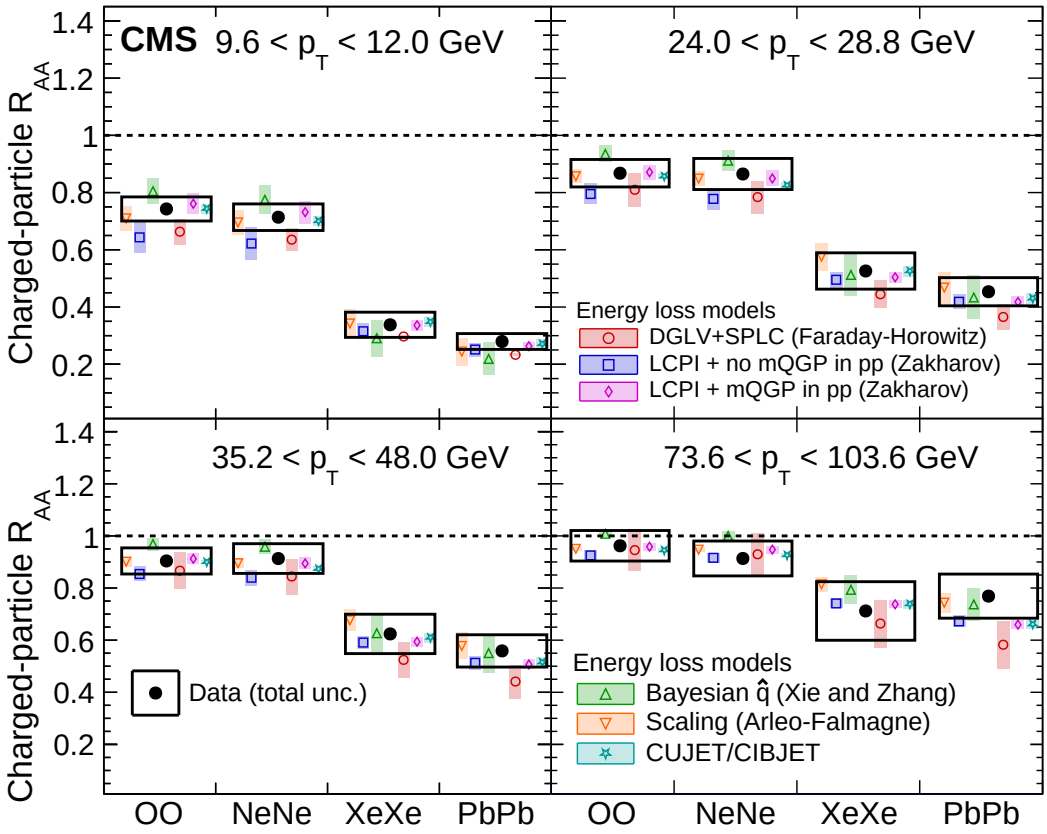

Figure 4: Comparison of the charged-particle R_{AA} measured in OO [22], NeNe, XeXe [9], and PbPb [12] collisions with calculations that incorporate parton energy loss effects [61–69]. The open boxes with black circular markers represent the data, with the box height indicating the total experimental uncertainty obtained from the quadratic combination of statistical, systematic, and global normalization uncertainties. The other colored markers represent theoretical predictions based on different approaches, as described in the text. The uncertainty band is smaller than the marker size for some of the calculations.

Figure 3 compares the measured R_{AA} to baseline calculations that include only initial-state nuclear effects and no final-state energy loss [57, 58]. These calculations are based on next-to-leading order (NLO) perturbative quantum chromodynamics (pQCD) calculations interfaced with modern nuclear parton distribution functions (nPDFs). Calculations using the EPPS21 [59] and nNNPDF3.0 [60] nPDF sets include the full propagation of nPDF uncertainties, as well as variations of the renormalization and factorization scales. These models predict a modest suppression at low p_T that is largely independent of A and arises from initial-state nuclear effects alone. As such, these baseline calculations establish a reference against which genuine final-state suppression effects can be isolated. Future analysis of recent pO data sets may further constrain the A dependence of nPDFs [70].

A comparison of theoretical calculations that include parton energy loss versus the data is presented in Fig. 4. The regime of validity of these begins at approximately $p_T > 10\,\text{GeV}$.

The Faraday–Horowitz calculation [61, 62] employs medium-induced radiative energy loss based on the Djordjevic–Gyulassy–Levai–Vitev (DGLV) formalism [63, 64], supplemented by collisional energy loss contributions and a short path-length correction (SPLC) designed for small collision systems. In this framework, the system-size dependence of R_{AA} emerges from the interplay between the in-medium path length traversed by hard partons and the evolving temperature profile of the medium. The predicted suppression increases smoothly with increasing A, and is compatible with the measurements within uncertainties for all collision systems, although some tension is present for the OO and NeNe data points. The calculations from DGLV+SPLC use the same parametrization as in the preliminary results, but they are presented according to the binning employed in this analysis. The measurements are also compared to predictions from the CUJET/CIBJET framework [67, 68], which is another DGLV-based description of parton energy loss coupled with viscous hydrodynamic modeling of the medium. These calculations incorporate an updated characterization of the medium properties based on a recent Bayesian analysis of the R_{AA} versus the high-p_{T} elliptic flow coefficient v_2 of heavy ion collisions at RHIC and the LHC [69]. This Bayesian analysis constrained the temperature-dependent chromoelectric and chromomagnetic composition of the QGP, particularly the abundance of chromomagnetic monopoles. The Bayesian analysis does not include light ion collision data. These theoretical calculations are compatible with the data within the uncertainties for these p_{T} intervals.

Calculations based on the light-cone path integral (LCPI) formalism [65] include medium-induced radiative energy loss applied to a pQCD baseline with nPDFs. The calculation shown in Fig. 4 corresponds to model scenarios with or without the formation of a "mini QGP" (mQGP) droplet in pp collisions, leading to different extrapolations toward small A. The resulting R_{AA} calculation without QGP formation in pp exhibits some tension at low p_{T} with respect to the measured R_{AA} in light ion collisions, but is compatible for all p_{T}. The prediction with a QGP formation in pp is in agreement with the data within the uncertainties.

A complementary approach is provided by calculations that determine the jet transport coefficient $\hat{q}$ using Bayesian inference constrained by heavy ion data [71]. The variable $\hat{q}$ characterizes the average p_{T} broadening per unit path length experienced by a high-energy parton traversing the deconfined nuclear medium. In this framework, the space–time evolution of the medium is described using 3+1 dimensional relativistic hydrodynamics [72], and energy loss is implemented consistently across collision systems by scaling the temperature and path length distributions experienced by propagating partons. The resulting calculations reproduce the rise of R_{AA} toward smaller A, and are compatible with the measurement within the uncertainties.

The results are compared to a model that provides an empirical description of high-p_{T} hadron suppression in heavy ion collisions [66] based on scaling properties. In this approach, the magnitude and system-size dependence of R_{AA} are governed by an effective parton energy loss scale inferred from the observed scaling of suppression with collision geometry and particle multiplicity. The scaling parametrization is inspired by the expected relationship between parton energy loss and in-medium path length at leading order in pQCD. Fits of this scaling model to RHIC and LHC data yield an average parton energy loss with an approximately linear dependence of the in-medium path length; light ion collision data are not included in this fit. These scaling-based calculations are in agreement with the data within the uncertainties.

The LCPI and CUJET/CIBJET calculations use charged-particle p_{T} spectra from pp collisions calculated at leading order in perturbation theory, whereas DGLV+SPLC and Bayesian use NLO pQCD calculations. Differences in the fragmentation function parametrizations do not substantially change the slope of the predicted charged-particle p_{T} spectrum in pp collisions,

as summarized in Refs. [73, 74]. The R_{AA} observable benefits from substantial cancellations of the renormalization and factorization scale uncertainties and fragmentation function fit uncertainties in the ratio, while remaining sensitive to modifications of particle production arising from nuclear effects.

Overall, models that include parton energy loss naturally generate a monotonic decrease of R_{AA} with increasing A, qualitatively consistent with the data. The magnitude and detailed A dependence vary among models, reflecting differences in the assumptions about medium formation in small and large systems, the path-length dependence of energy loss, and the temperature scaling of the jet transport coefficient $\hat{q}$. Although still compatible within the combined experimental and theoretical uncertainties, a subset of the models tend to slightly underestimate the central value of the data, as seen in Fig. 4. Therefore, the CMS R_{AA} measurements offer enhanced sensitivity to key aspects of energy loss modeling when considered in aggregate as opposed to individually. This is further supported by the comparison to the theoretical predictions presented prior to the release of the preliminary results, which is described in Appendix F. A comparison of the theoretical calculations of R_{AA} as a function of p_{T} can be found in Appendix E.

5 Summary

This Letter presents a systematic study of the system-size dependence of the charged-particle nuclear modification factor (R_{AA}) versus transverse momentum (p_{T}). The study is based on a cross-system comparison that minimizes centrality selection biases. For this purpose, the analysis reports the first measurement of the charged-particle R_{AA} in minimum bias neon-neon (NeNe) collisions at a center-of-mass energy per nucleon pair of 5.36 TeV, based on data collected in 2025 and corresponding to an integrated luminosity of $0.76\,\mathrm{nb}^{-1}$. By comparing existing CMS measurements in oxygen-oxygen, xenon-xenon, and lead-lead collisions with the new NeNe results, this analysis samples nuclear systems across a broad range of nucleon number values (A). This enables an evaluation of the role that the system size has on energy loss. The R_{AA} is measured for charged particles with pseudorapidity $|\eta| < 1$ using identical p_{T} intervals across all collision systems, which allows for a direct comparison of nuclear suppression effects with A, which characterizes the system size.

The R_{AA} at a given p_{T} value is found to monotonically decrease as a function of the cubic root of the nucleon number $A^{1/3}$, a quantity that is related to the nuclear radius. The p_{T} dependences of R_{AA} in all collision systems have similar qualitative shapes, with a local minimum at about 5–7 GeV. The inclusion of the NeNe system extends the coverage in system size and enables a more complete mapping of the evolution of suppression effects across collision systems.

Comparisons with theoretical calculations show that baseline perturbative quantum chromodynamics predictions incorporating nuclear parton distribution functions predict only modest modifications relative to $R_{\mathrm{AA}} = 1$, with a weak dependence on A. In contrast, models that also include parton energy loss reproduce the observed monotonic evolution of R_{AA} with increasing A. Differences among these calculations in the predicted R_{AA} value and its detailed system-size dependence reflect variations in the modeling of medium effects. Overall, models incorporating parton energy loss describe the measurements within experimental and theoretical uncertainties. This study constrains the existence and characteristics of any transition towards a deconfined, hot medium as the system size increases. Hence, this measurement offers guidance for the selection of ion species in future nuclear physics programs at the LHC.

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Data availability

Release and preservation of data used by the CMS Collaboration as the basis for publications is guided by the CMS data preservation, re-use and open access policy.

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A Charged-particle spectrum of the NeNe system

Figure A.1 shows the p_{T} spectrum of primary charged particles measured in NeNe collisions at $\sqrt{s_{\mathrm{NN}}} = 5.36\,\mathrm{TeV}$. The pp spectrum is the one used in Ref. [22]. The spectra are used as an input for the construction of the nuclear modification factor presented in the main text.

B Bin merging procedure for PbPb R_{AA}

The p_{T}-binning of the PbPb R_{AA} measurement is finer than the XeXe binning at high p_{T}. The PbPb R_{AA} bins are merged according to the binning scheme of the XeXe R_{AA} measurement [9]. The bin edges from the XeXe measurement are shared with the PbPb measurement bins. To match the p_{T} binning constraints of the XeXe analysis, the two bins of the PbPb R_{AA} having ranges 35.2–41.6 and 41.6–48.0 GeV were merged into a single 35.2–48.0 GeV bin, and the two bins having ranges 48.0–60.8 and 60.8–73.6 GeV were merged into 48.0–73.6 GeV. Bin merging was performed at the level of the PbPb and pp spectra to account for the in-bin p_{T} shape of the individual PbPb and pp distributions used to compute R_{AA}.

Bins within the PbPb and pp spectra were merged separately using the HEPData entry associated with Ref. [12]. In this procedure, central values were combined as a p_{T}-weighted average. This is because the spectra were reported as invariant cross sections with a prefactor of $1/p_{\mathrm{T}}$, which must be removed before the combination of yields in the bin merging procedure. Statistical uncertainties of the bins were added in quadrature while the systematic uncertainties were combined linearly and averaged for each merged bin, assuming fully correlated bin-to-bin uncertainties. Both uncertainties were weighted by the p_{T} and bin widths of the constituent bins. The formulas below summarize the bin-merging procedure for the cross section (σ) corresponding to a merged bin in the numerator of the charged-particle R_{AA} in PbPb collisions.

Consider the set of original p_{T} bins indexed by i, which are combined into a single merged bin. For each original bin i, $\sigma^{\mathrm{PbPb}}_{\mathrm{bin},i}$ denotes the measured cross section, $\Delta p_{\mathrm{T},i}$ denotes the bin width, and $p_{\mathrm{T},i}$ denotes the bin center. The quantities $\sigma^{\mathrm{PbPb}}_{\mathrm{bin,\,stat},i}$ and $\sigma^{\mathrm{PbPb}}_{\mathrm{bin,\,syst},i}$ denote the statistical and systematic uncertainties, respectively. The merged bin is characterized by a total width $\Delta p_{\mathrm{T}}^{\mathrm{merged}}$ and a representative center $p_{\mathrm{T}}^{\mathrm{merged}}$. The central value of the merged cross section is obtained as

$$\sigma^{\mathrm{PbPb}}_{\mathrm{merged}} = \frac{\sum_i \sigma^{\mathrm{PbPb}}_{\mathrm{bin},i} \Delta p_{\mathrm{T},i} p_{\mathrm{T},i}}{\Delta p_{\mathrm{T}}^{\mathrm{merged}} p_{\mathrm{T}}^{\mathrm{merged}}}. \tag{2}$$

The statistical uncertainty of the merged bin, assuming the statistical uncertainties of the origi-

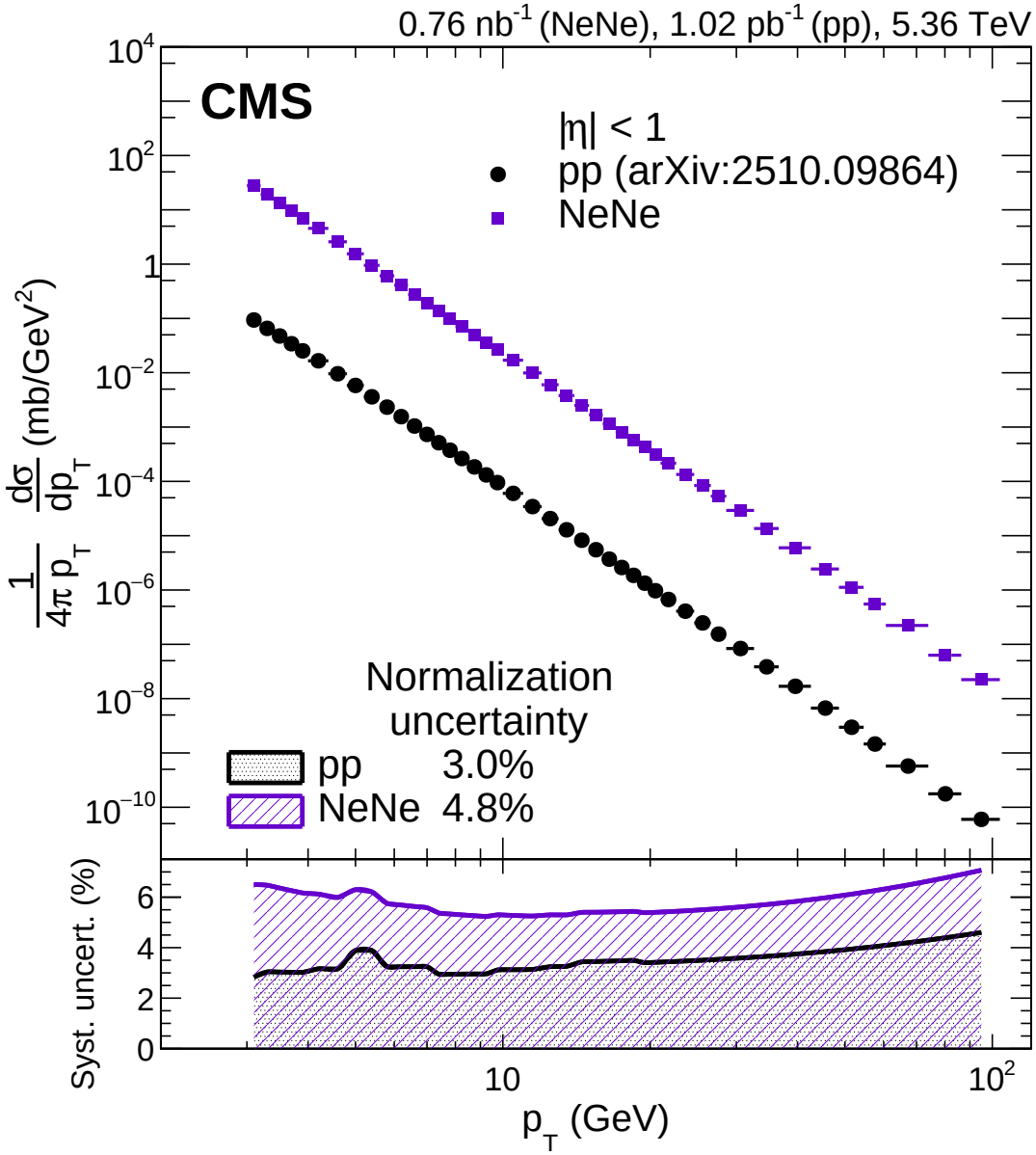

Figure A.1: Differential invariant cross section spectrum as function of p_{T} of primary charged particles measured in NeNe collisions at $\sqrt{s_{\mathrm{NN}}} = 5.36\,\mathrm{TeV}$ at midrapidity. The pp spectrum is from Ref. [22]. The markers show the average cross section across the entire bin width, not the cross section value at the center of each bin. Statistical uncertainties are smaller than the markers.

nal bins are uncorrelated, is computed as

$$\sigma^{\mathrm{PbPb}}_{\mathrm{stat,\,merged}} = \frac{\left[\sum_i \left(\sigma^{\mathrm{PbPb}}_{\mathrm{bin,\,stat},i}\Delta p_{\mathrm{T},i} p_{\mathrm{T},i}\right)^2\right]^{1/2}}{\Delta p_{\mathrm{T}}^{\mathrm{merged}} p_{\mathrm{T}}^{\mathrm{merged}}}. \tag{3}$$

The systematic uncertainty, treated as fully correlated across the merged bins, is evaluated as

$$\sigma^{\mathrm{PbPb}}_{\mathrm{syst,\,merged}} = \frac{\sum_i \sigma^{\mathrm{PbPb}}_{\mathrm{bin,\,syst},i}\Delta p_{\mathrm{T},i} p_{\mathrm{T},i}}{\Delta p_{\mathrm{T}}^{\mathrm{merged}} p_{\mathrm{T}}^{\mathrm{merged}}}. \tag{4}$$

The normalization uncertainty remains unaffected by the bin-merging procedure. The same bin merging procedure was employed for the denominator of the pp reference system. Although the main focus of this analysis is on symmetric AA collisions, for completeness, we also repeated the procedure for the pPb system using the inputs presented in the same HEPData record.

C Charged-particle R_{AA} with nominal p_{T} binning

Figure C.1 shows the charged-particle nuclear modification factor R_{AA} measured with the nominal p_{T} binning used for each collision system. For OO, NeNe, and PbPb, the binning is finer than the coarser binning used for the common system comparison presented in Fig. 4.

D Charged-particle R_{AA} with coarser p_{T} binning, including the pPb system

Figure D.1 shows the charged-particle nuclear modification factor R_{AA} measured with a coarser p_{T} binning. The pPb system is included for comparison. The results are fully corrected and correspond to those used in the main analysis.

E Theoretical calculations for R_{AA} as functions of p_{T} for all systems

Figures E.1 and E.2 present theoretical calculations of the charged-particle R_{AA} versus p_{T} for minimum bias OO and NeNe collisions, XeXe collisions in the 0–80% centrality interval, and minimum bias PbPb collisions, compared to the data in the same intervals. These are the same theoretical calculations presented in the main body of the Letter. Figure E.1 shows calculations that include only initial-state nuclear effects and no final-state energy loss, whereas Fig. E.2 presents calculations that incorporate parton energy loss in the hot and dense medium produced in AA collisions. The comparison highlights the substantial additional suppression observed in the data when final-state interactions are present, particularly at high p_{T}, and illustrates the limited system-size dependence expected from initial-state effects alone over the range of collision systems and p_{T} considered.

F Theoretical predictions for NeNe R_{AA} versus p_{T} provided prior to preliminary results

Figure F.1 presents theoretical predictions provided prior to the release of the preliminary results of the charged-particle R_{AA} measurements in NeNe and OO collisions.

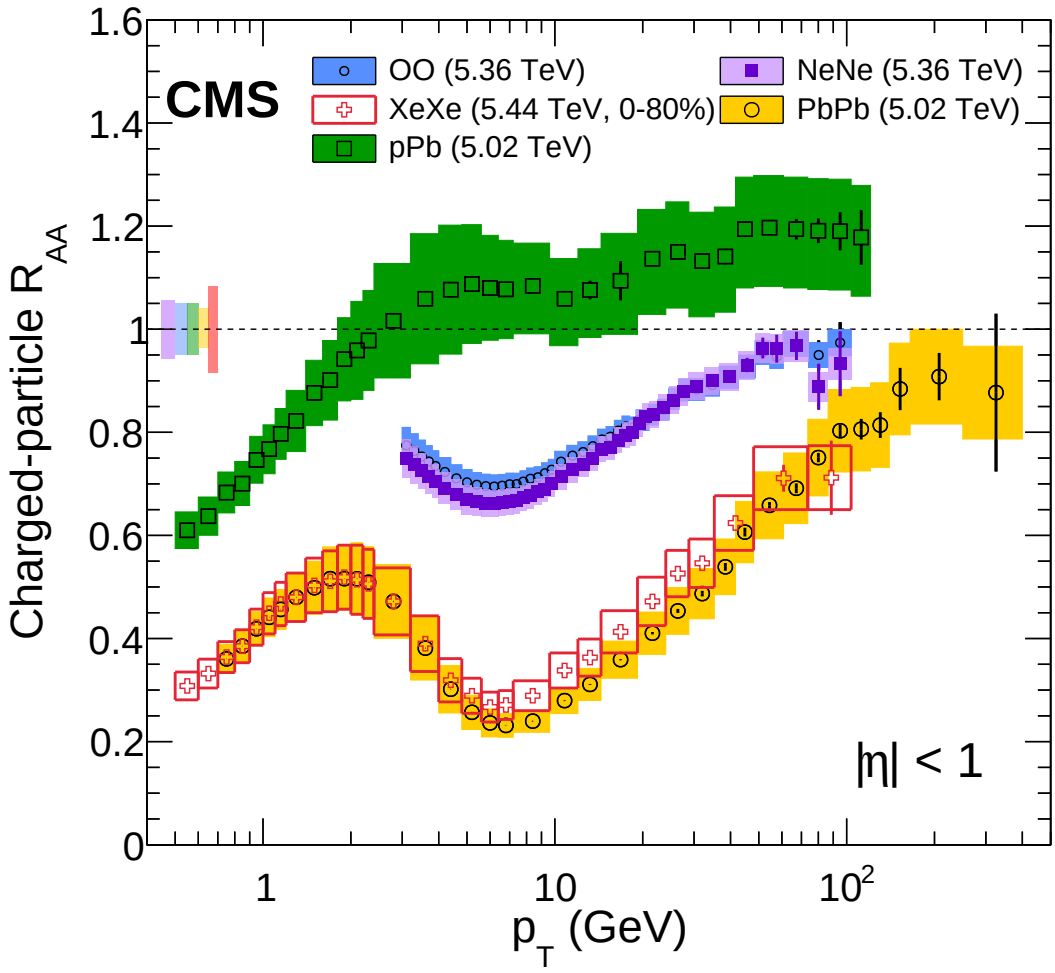

Figure C.1: Charged-particle nuclear modification factor R_{AA} measured using the nominal p_{T} binning for OO, NeNe, XeXe, PbPb, and pPb collisions. The vertical bands around the markers indicate the total experimental uncertainties, while the vertical error bars show the statistical uncertainties. The boxes on the left, centered at unity, represent the relative normalization uncertainty for each collision system.

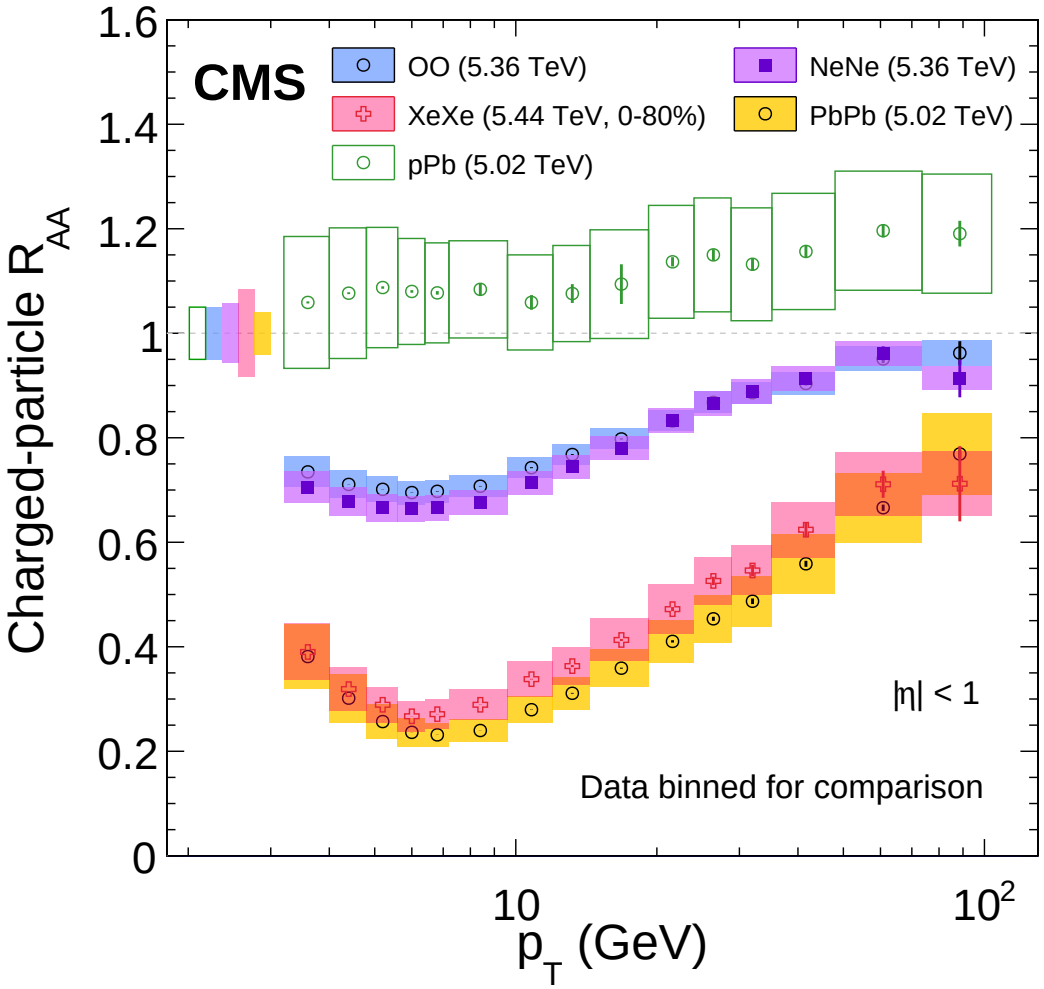

Figure D.1: Charged-particle nuclear modification factor R_{AA} measured using the common p_{T} binning scheme for OO, NeNe, XeXe, PbPb, and pPb collisions. The vertical bands around the markers indicate the total experimental uncertainties, while the vertical error bars show the statistical uncertainties. The boxes on the left, centered at unity, represent the relative normalization uncertainty for each collision system.

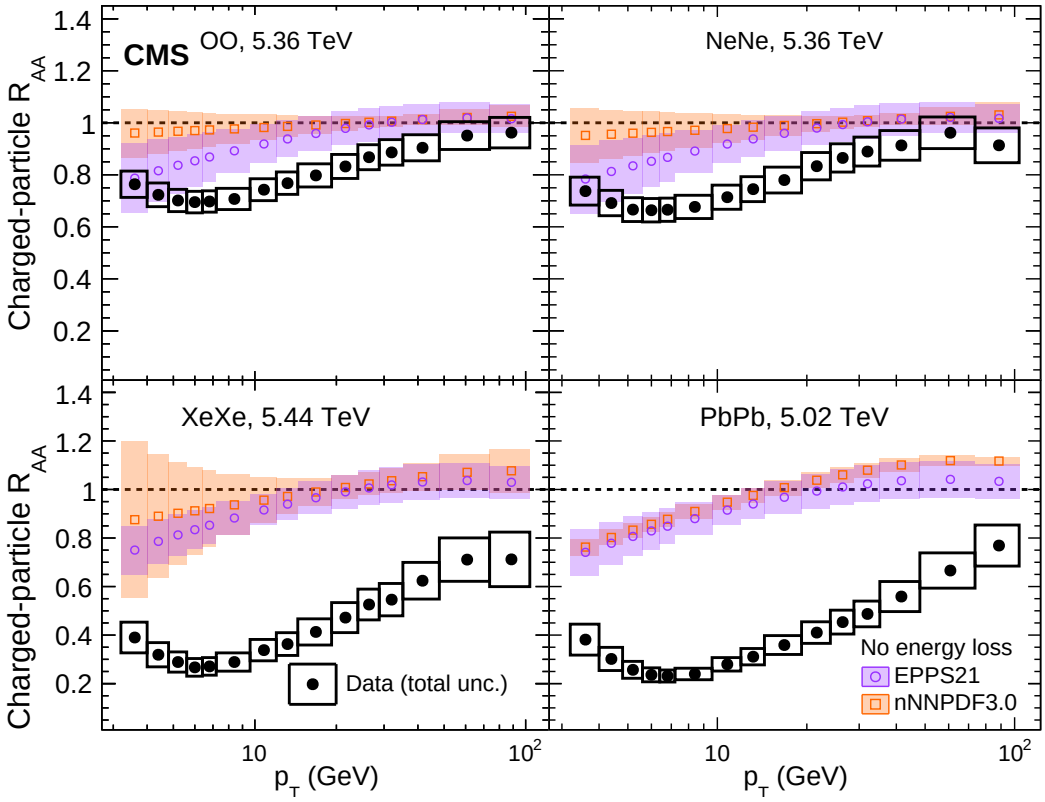

Figure E.1: Charged-particle R_{AA} as a function of p_{T} in minimum bias OO ($\sqrt{s_{\mathrm{NN}}} = 5.36\,\mathrm{TeV}$), minimum bias NeNe (5.36 TeV), XeXe (0–80%, 5.44 TeV), and minimum bias PbPb (5.02 TeV) collisions. The measurements are compared with theoretical calculations without final-state energy loss [57, 58], illustrating the expected size of initial-state nuclear effects. The purple markers correspond to calculations using the EPPS21 nPDF set [59], while the orange markers represent calculations based on the nNNPDF3.0 nPDF set [60]. Details of the calculations are discussed in the main body of the text.

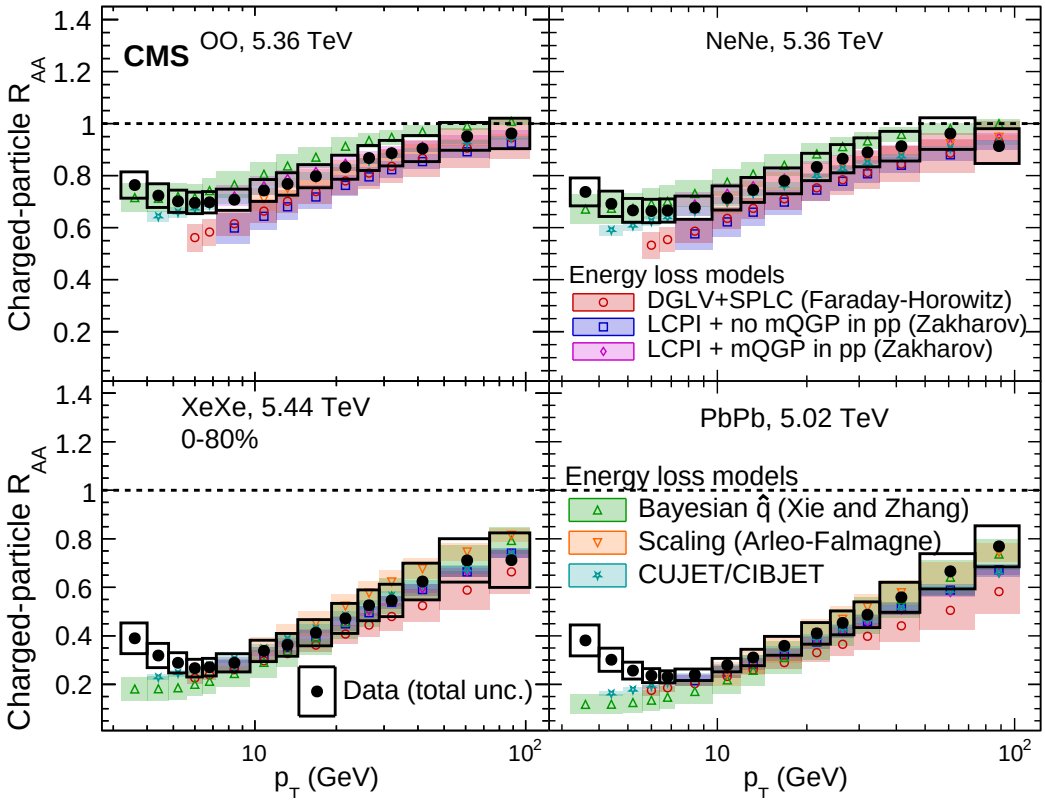

Figure E.2: Charged-particle R_{AA} as a function of p_{T} in minimum bias OO ($\sqrt{s_{\mathrm{NN}}} = 5.36\,\mathrm{TeV}$), minimum bias NeNe (5.36 TeV), XeXe (0–80%, 5.44 TeV), and minimum bias PbPb (5.02 TeV) collisions. The measurements are compared with theoretical calculations that include parton energy loss in the medium [61–69]. Details of the calculations are discussed in the main body of the text.

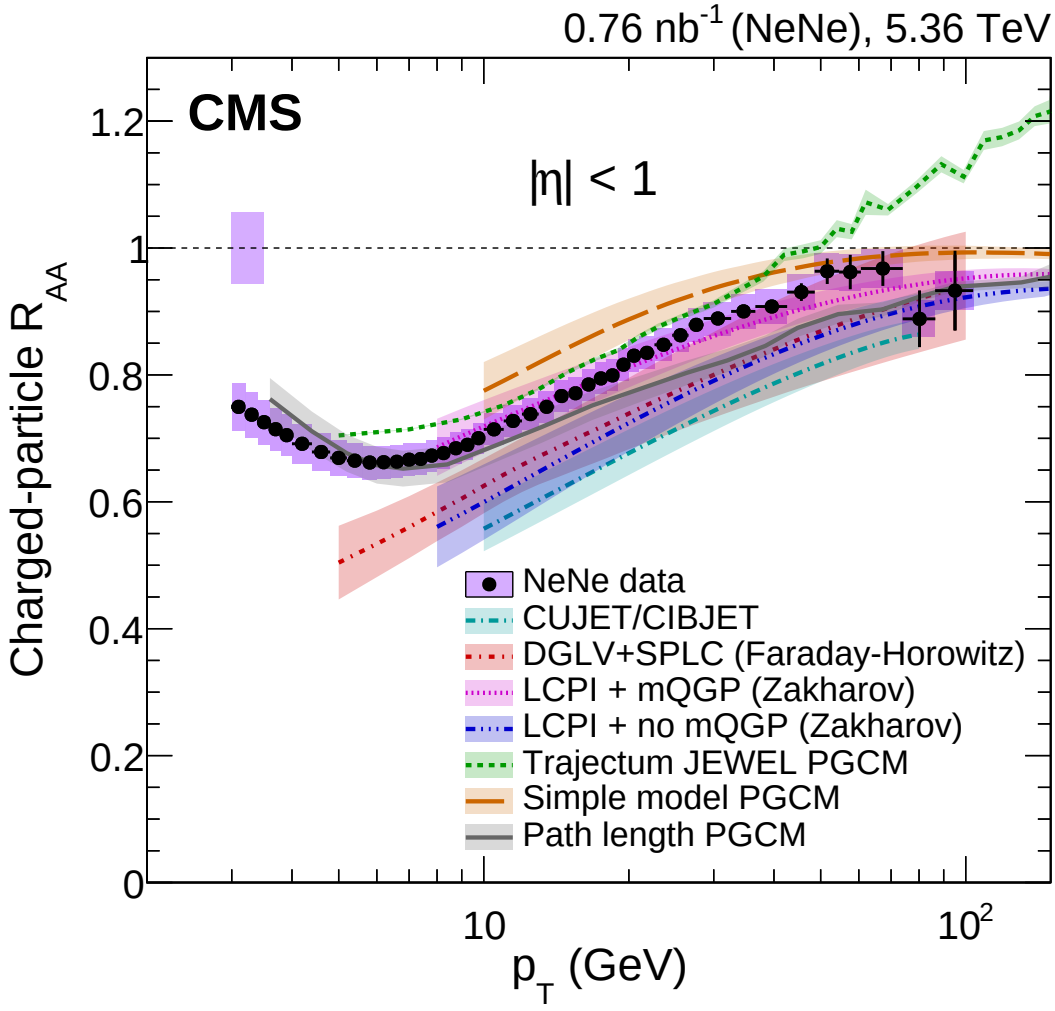

Figure F.1: Theoretical predictions for the charged-particle R_{AA} in NeNe collisions compared to the measured NeNe R_{AA} [59, 62–65, 67, 68, 75–90], provided prior to the release of the preliminary NeNe and OO results.

Leading-order pQCD calculations based on the LCPI formalism that include nuclear modifications of the parton distribution functions via the EPS09 set [75], both assuming and neglecting the formation of a QGP droplet in the pp reference system (with or without a "mini QGP", mQGP) [65], reproduce the measured p_{T} dependence and overall suppression magnitude within experimental uncertainties. A pQCD-based calculation implementing the DGLV opacity expansion with small-system corrections (DGLV+SLPC) [62] provides a similarly good description of the data across the measured p_{T} range.

Predictions from the CUJET/CIBJET framework [67, 68], which couples viscous hydrodynamics to a DGLV energy loss formalism [63, 64] but does not include nPDF effects, yield systematically lower R_{AA} values than observed in the data. The theoretical uncertainties in this calculation arise primarily from variations in the strong coupling constant.

The data are further compared to models described in Ref. [76], which incorporate nuclear structure inputs from the projected generator coordinate method (PGCM) [77–82]. Theoretical predictions using an alternative set of nuclear structure inputs from nuclear lattice effective field theory [91–93] were also provided and yield very similar R_{AA} values as PGCM-based predictions [76]. An implementation based on the Baier-Dokshitzer-Mueller-Peigné-Schiff–Zakharov formalism [94–97], referred to as the "Simple model" [76, 83], tends to overestimate the measured R_{AA}, with the discrepancy decreasing toward higher p_{T}. Predictions obtained by coupling the JEWEL event generator [84–87] to the TRAJECTUM hydrodynamic framework [88, 89], including nPDF effects via the EPPS21 set [59], overestimate the measured R_{AA} and predict values exceeding unity at p_{T} of approximately 50 GeV. An alternative energy loss model that parametrizes the suppression through a path-length- and p_{T}-dependent energy loss [90], combined with the hydrodynamic description of TRAJECTUM, qualitatively reproduces key features of the NeNe measurement, including the presence of a local minimum in R_{AA}, although the minimum occurs at a slightly higher p_{T} than observed in the data.

G The CMS Collaboration

Yerevan Physics Institute, Yerevan, Armenia
A. Belyaev, A. Gevorgyan, A. Hayrapetyan, A. Tumasyan[1]

Marietta Blau Institute for Particle Physics, Vienna, Austria
W. Adam, L. Benato, T. Bergauer, M. Dragicevic, S. Gundacker, A.K. Guven, P.S. Hussain, M. Jeitler[2], N. Krammer, A. Li, D. Liko, M. Matthewman, J. Schieck[2], R. Schöfbeck[2], M. Shooshtari, M. Sonawane, N. Van Den Bossche, W. Waltenberger, C.-E. Wulz[2]

Universiteit Antwerpen, Antwerpen, Belgium
T. Janssen, H. Kwon, D. Ocampo Henao, T. Van Laer, P. Van Mechelen

Vrije Universiteit Brussel, Brussel, Belgium
D. Ahmadi, J. Bierkens, N. Breugelmans, S. Dansana, A. De Moor, M. Delcourt, C. Gupta, F. Heyen, Y. Hong, K. Kang, P. Kashko, S. Lowette, I. Makarenko, S. Nandakumar, S. Tavernier, M. Tytgat[3], G.P. Van Onsem, S. Van Putte, D. Vannerom, T. Wybouw

Université Libre de Bruxelles, Bruxelles, Belgium
A. Beshr, B. Bilin, F. Caviglia Roman, B. Clerbaux, A.K. Das, I. De Bruyn, G. De Lentdecker, E. Ducarme, H. Evard, L. Favart, I. Kalaitzidou, A. Khalilzadeh, A. Malara, M.A. Shahzad, L. Thomas, M. Vanden Bemden, C. Vander Velde, P. Vanlaer, C. Yuan, F. Zhang

Ghent University, Ghent, Belgium
A. Cauwels, M. De Coen, D. Dobur, C. Giordano, G. Gokbulut, K. Kaspar, D. Kavtaradze, D. Marckx, A. Mehta, K. Skovpen, A.M. Tomaru, J. van der Linden, J. Vandenbroeck

Université Catholique de Louvain, Louvain-la-Neuve, Belgium
H. Aarup Petersen, A. Benecke, A. Bethani, A. Cappati, J. De Favereau De Jeneret, C. Delaere, F. Gameiro Casalinho, A. Giammanco, A.O. Guzel, M. Hussain, Z. Lawrence, V. Lemaitre, J. Lidrych, P. Malek, S. Turkcapar

Centro Brasileiro de Pesquisas Fisicas, Rio de Janeiro, Brazil
G.A. Alves, M. Barroso Ferreira Filho, E. Coelho, M.V. Gonçalves Sales, C. Hensel, D. Matos Figueiredo, T. Menezes De Oliveira, C. Mora Herrera, P. Rebello Teles, M. Soeiro, E.J. Tonelli Manganote[4], A. Vilela Pereira

Universidade do Estado do Rio de Janeiro, Rio de Janeiro, Brazil
W.L. Aldá Júnior, H. Brandao Malbouisson, W. Carvalho, J. Chinellato[5], G. Correia Silva, M. Costa Reis, E.M. Da Costa, D. Da Silva Dalto, G.G. Da Silveira[6], D. De Jesus Damiao, S. Fonseca De Souza, R. Gomes De Souza, S. S. Jesus, T. Laux Kuhn[6], K. Maslova, K. Mota Amarilo, L. Mundim, H. Nogima, J.P. Pinheiro, A. Santoro, A. Sznajder, M. Thiel, F. Torres Da Silva De Araujo[7], D. Torres Machado

Universidade Estadual Paulista, Universidade Federal do ABC, São Paulo, Brazil
C.A. Bernardes, L. Calligaris, J. Carvalho Leite, M. P. Coelho, F. Damas, T.R. Fernandez Perez Tomei, E.M. Gregores, B. Lopes Da Costa, I. Maietto Silverio, P.G. Mercadante, S.F. Novaes, Sandra S. Padula, V. Scheurer

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

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

University of Sofia, Sofia, Bulgaria
A. Dimitrov, L. Litov, B. Pavlov, P. Petkov, A. Petrov

Instituto De Alta Investigación, Universidad de Tarapacá, Casilla 7 D, Arica, Chile
S. Keshri, D. Laroze, M. Meena, S. Thakur

Universidad Tecnica Federico Santa Maria, Valparaiso, Chile
W. Brooks

Beihang University, Beijing, China
T. Cheng, L. Wang, L. Yuan

Department of Physics, Tsinghua University, Beijing, China
J. Gu, Z. Hu, Z. Liang, J. Liu, X. Wang, Y. Wang, H. Yang, S. Zhang, Y. Zhao

Institute of High Energy Physics, Beijing, China
N. Bi, G.M. Chen[8], H.S. Chen[8], M. Chen[8], Y. Chen, B. Hou[8], Q. Hou, F. Iemmi, C.H. Jiang, H. Liao, G. Liu, Z.-A. Liu[9], S. Song, J. Tao, C. Wang[8], J. Wang, A. Zada, H. Zhang, J. Zhao

State Key Laboratory of Nuclear Physics and Technology, Peking University, Beijing, China
Y. Ban, A. Carvalho Antunes De Oliveira, S. Deng, X. Geng, B. Guo, Q. Guo, Z. He, C. Jiang, A. Levin, C. Li, Q. Li, Y. Mao, S. Qian, S.J. Qian, X. Qin, C. Quaranta, X. Sun, D. Wang, J. Wang, T. Yang, M. Zhang, Y. Zhao, C. Zhou

State Key Laboratory of Nuclear Physics and Technology, Institute of Quantum Matter, South China Normal University, Guangzhou, China
X. Hua, S. Yang

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

University of Science and Technology of China, Hefei, China
N. Lu

Nanjing Normal University, Nanjing, China
G. Bauer[10,11], L. Chen, Z. Cui[11], B. Li[12], H. Wang, K. Yi[13], J. Zhang, F. Zhu

Institute of Frontier and Interdisciplinary Science, Shandong University, Qingdao, China
C. Li

Institute of Modern Physics and Key Laboratory of Nuclear Physics and Ion-beam Application (MOE) - Fudan University, Shanghai, China
Y. Li, Y. Zhou[14]

Zhejiang University, Hangzhou, Zhejiang, China
Z. Lin, C. Lu, M. Xiao[15]

Universidad de Los Andes, Bogota, Colombia
C. Avila, A. Cabrera, C. Florez, J.A. Reyes Vega

Universidad de Antioquia, Medellin, Colombia
C. Rendón, M. Rodriguez, A.A. Ruales Barbosa, J.D. Ruiz Alvarez

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

University of Split, Faculty of Science, Split, Croatia
M. Kovac, A. Petkovic, T. Sculac

Institute Rudjer Boskovic, Zagreb, Croatia
P. Bargassa, V. Brigljevic, D. Ferencek, K. Jakovcic, A. Starodumov, T. Susa

University of Cyprus, Nicosia, Cyprus
A. Attikis, S. Konstantinou, C. Leonidou, L. Paizanos, F. Ptochos, P.A. Razis, H. Rykaczewski, H. Saka, A. Stepennov

Charles University, Prague, Czech Republic
M. Finger[†], M. Finger Jr.

Escuela Politecnica Nacional, Quito, Ecuador
E. Acurio

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
A.A. Abdelalim[16,17], B. El-mahdy[18]

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

National Institute of Chemical Physics and Biophysics, Tallinn, Estonia
K. Jaffel, M. Kadastik, T. Lange, C. Nielsen, J. Pata, M. Raidal, N. Seeba, L. Tani

Department of Physics, University of Helsinki, Helsinki, Finland
E. Brücken, A. Milieva, K. Osterberg, M. Voutilainen

Helsinki Institute of Physics, Helsinki, Finland
F. Garcia, T. Hilden, P. Inkaew, K.T.S. Kallonen, R. Kumar Verma, T. Lampén, K. Lassila-Perini, B. Lehtela, S. Lehti, T. Lindén, N.R. Mancilla Xinto, M. Myllymäki, M.m. Rantanen, S. Saariokari, N.T. Toikka, J. Tuominiemi

Lappeenranta-Lahti University of Technology, Lappeenranta, Finland
N. Bin Norjoharuddeen, H. Kirschenmann, P. Luukka, H. Petrow

IRFU, CEA, Université Paris-Saclay, Gif-sur-Yvette, France
M. Besancon, F. Couderc, M. Dejardin, D. Denegri, P. Devouge, J.L. Faure, F. Ferri, P. Gaigne, S. Ganjour, P. Gras, F. Guilloux, G. Hamel de Monchenault, M. Kumar, V. Lohezic, Y. Maidannyk, J. Malcles, F. Orlandi, L. Portales, S. Ronchi, M.Ö. Sahin, P. Simkina, M. Titov, M. Tornago

Laboratoire Leprince-Ringuet, CNRS/IN2P3, Ecole Polytechnique, Institut Polytechnique de Paris, Palaiseau, France
R. Amella Ranz, F. Beaudette, K. Biriukov, G. Boldrini, P. Busson, C. Charlot, M. Chiusi, T.D. Cuisset, O. Davignon, A. De Wit, T. Debnath, I.T. Ehle, S. Ghosh, A. Gilbert, R. Granier de Cassagnac, M. Manoni, M. Nguyen, S. Obraztsov, C. Ochando, R. Salerno, J.B. Sauvan, Y. Sirois, G. Sokmen, Y. Song,

L. Urda Gómez, B. Voirin, A. Zabi, A. Zghiche

Université de Strasbourg, CNRS, IPHC UMR 7178, Strasbourg, France
J.-L. Agram[19], J. Andrea, D. Bloch, J.-M. Brom, E.C. Chabert, C. Collard, G. Coulon, C. Eschenlauer, S. Falke, U. Goerlach, A.-C. Le Bihan, G. Saha, A. Savoy-Navarro[20], P. Vaucelle

Centre de Calcul de l'Institut National de Physique Nucleaire et de Physique des Particules, CNRS/IN2P3, Villeurbanne, France
A. Di Florio, B. Orzari

Institut de Physique des 2 Infinis de Lyon (IP2I), Villeurbanne, France
D. Amram, S. Beauceron, B. Blancon, G. Boudoul, N. Chanon, D. Contardo, P. Depasse, H. El Mamouni, J. Fay, E. Fillaudeau, S. Gascon, M. Gouzevitch, C. Greenberg, B. Ille, E. Jourd'Huy, M. Lethuillier, K. Long, B. Massoteau, L. Mirabito, A. Purohit, M. Vander Donckt, C. Verollet

Georgian Technical University, Tbilisi, Georgia
G. Adamov, I. Lomidze, Z. Tsamalaidze[21]

RWTH Aachen University, I. Physikalisches Institut, Aachen, Germany
K.F. Adamowicz, V. Botta, S. Consuegra Rodríguez, L. Feld, K. Klein, M. Lipinski, P. Nattland, V. Oppenländer, A. Pauls, D. Pérez Adán

RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany
C. Daumann, S. Diekmann, N. Eich, D. Eliseev, F. Engelke, J. Erdmann, M. Erdmann, M.Z. Farkas, B. Fischer, T. Hebbeker, K. Hoepfner, A. Jung, N. Kumar, M.y. Lee, F. Mausolf, M. Merschmeyer, A. Meyer, A. Pozdnyakov, W. Redjeb, H. Reithler, U. Sarkar, V. Sarkisovi, A. Schmidt, J.G. Schulz, C. Seth, A. Sharma, J.L. Spah, V. Vaulin, U. Willemsen, S. Zaleski, F.P. Zinn

RWTH Aachen University, III. Physikalisches Institut B, Aachen, Germany
M.R. Beckers, G. Flügge, N. Hoeflich, T. Kress, A. Nowack, O. Pooth, A. Stahl

Deutsches Elektronen-Synchrotron, Hamburg, Germany
A. Abel, M. Aldaya Martin, J. Alimena, Y. An, I. Andreev, J. Bach, S. Baxter, H. Becerril Gonzalez, O. Behnke, F. Blekman[22], K. Borras[23], A. Campbell, S. Chatterjee, L.X. Coll Saravia, G. Eckerlin, D. Eckstein, E. Gallo[22], A. Geiser, M. Guthoff, A. Hinzmann, M. Kasemann, C. Kleinwort, R. Kogler, M. Komm, D. Krücker, F. Labe, W. Lange, D. Leyva Pernia, J.h. Li, K.-Y. Lin, K. Lipka[24], W. Lohmann[25], J. Malvaso, R. Mankel, I.-A. Melzer-Pellmann, M. Mendizabal Morentin, A.B. Meyer, G. Milella, K. Moral Figueroa, A. Mussgiller, L.P. Nair, J. Niedziela, A. Nürnberg, J. Park, E. Ranken, A. Raspereza, D. Rastorguev, L. Rygaard, M. Scham[26,23], S. Schnake[23], P. Schütze, C. Schwanenberger[22], D. Schwarz, D. Selivanova, K. Sharko, M. Shchedrolosiev, A. Sritharan, D. Stafford, M. Torkian, S. Vashishtha, A. Ventura Barroso, R. Walsh, D. Wang, Q. Wang, K. Wichmann, L. Wiens[23], C. Wissing, Y. Yang, S. Zakharov, A. Zimermmane Castro Santos

University of Hamburg, Hamburg, Germany
A.R. Alves Andrade, M. Antonello, S. Bollweg, M. Bonanomi, L. Ebeling, K. El Morabit, Y. Fischer, M. Frahm, P.P. Gadow, E. Garutti, A. Grohsjean, A.A. Guvenli, J. Haller, D. Hundhausen, M. Jalalvandi, G. Kasieczka, P. Keicher, R. Klanner, W. Korcari, T. Kramer, C.c. Kuo, J. Lange, A. Lobanov, J. Matthiesen, L. Moureaux,

K. Nikolopoulos, K.J. Pena Rodriguez, N. Prouvost, B. Raciti, M. Rieger, D. Savoiu, P. Schleper, M. Schröder, J. Schwandt, T. Tore von Schwartz, M. Sommerhalder, H. Stadie, G. Steinbrück, R. Ward, B. Wiederspan, M. Wolf, C. Yede

Karlsruher Institut fuer Technologie, Karlsruhe, Germany
A. Brusamolino, E. Butz, Y.M. Chen, T. Chwalek, A. Dierlamm, G.G. Dincer, U. Elicabuk, N. Faltermann, M. Giffels, A. Gottmann, F. Hartmann[27], F. Hummer, U. Husemann, J. Kieseler, M. Klute, J. Knolle, R. Kunnilan Muhammed Rafeek, O. Lavoryk, J.M. Lawhorn, S. Maier, N. Meenamthuruthil Radhakrishnan, T. Mehner, M. Molch, A.A. Monsch, M. Mormile, Th. Müller, E. Pfeffer, M. Presilla, G. Quast, K. Rabbertz, B. Regnery, R. Schmieder, T. Selezneva, N. Shadskiy, I. Shvetsov, L. Sowa, L. Stockmeier, K. Tauqeer, M. Toms, B. Topko, N. Trevisani, C. Verstege, T. Voigtländer, R.F. Von Cube, J. Von Den Driesch, C. Winter, R. Wolf, W.D. Zeuner, X. Zuo

Institute of Nuclear and Particle Physics (INPP), NCSR Demokritos, Aghia Paraskevi, Greece
G. Anagnostou, G. Daskalakis, A. Kyriakis

National and Kapodistrian University of Athens, Athens, Greece
P. Iosifidou, P. Katris, M. Kotsarini, G. Melachroinos, Z. Painesis, N. Plastiras, N. Saoulidou, K. Theofilatos, E. Tziaferi, E. Tzovara, K. Vellidis, I. Zisopoulos

National Technical University of Athens, Athens, Greece
T. Chatzistavrou, G. Karapostoli, K. Kousouris, K. Paschos, E. Siamarkou, G. Tsipolitis

University of Ioánnina, Ioánnina, Greece
I. Evangelou, C. Foudas, P. Katsoulis, P. Kokkas, P.G. Kosmoglou Kioseoglou, N. Manthos, I. Papadopoulos, J. Strologas

HUN-REN Wigner Research Centre for Physics, Budapest, Hungary
C. Hajdu, D. Horvath[28,29], Á. Kadlecsik, C. Lee, K. Márton, A.J. Rádl[30], F. Sikler, V. Veszpremi

MTA-ELTE Lendület CMS Particle and Nuclear Physics Group, Eötvös Loránd University, Budapest, Hungary
G. Balint, M. Csanád, D. Cynolter, K. Farkas, A. Fehérkuti[31], M.M.A. Gadallah[32], M. León Coello, G. Pásztor, G.I. Veres

Faculty of Informatics, University of Debrecen, Debrecen, Hungary
B. Ujvari, G. Zilizi

HUN-REN ATOMKI - Institute of Nuclear Research, Debrecen, Hungary
G. Bencze, S. Czellar, J. Molnar, Z. Szillasi

Karoly Robert Campus, MATE Institute of Technology, Gyongyos, Hungary
T. Csorgo[31], F. Nemes[31], T. Novak, I. Szanyi[33]

IIT Bhubaneswar, Bhubaneswar, India
S. Bahinipati, R. Raturi

Panjab University, Chandigarh, India
S. Bansal, S.B. Beri, V. Bhatnagar, B. Chauhan, S. Chauhan, N. Dhingra[34], A. Kaur, H. Kaur, M. Kaur, S. Kumar, T. Sheokand, J.B. Singh, A. Singla, K. Verma

University of Delhi, Delhi, India
A. Bhardwaj, A. Chhetri, B.C. Choudhary, A. Kumar, A. Kumar, M. Naimuddin, S. Phor, C. Prakash, K. Ranjan, M.K. Saini

Indian Institute of Technology Mandi (IIT-Mandi), Himachal Pradesh, India
M. Kumari, P. Palni, S. Rana, A. Rathore

University of Hyderabad, Hyderabad, India
S. Acharya[35], B. Gomber

Saha Institute of Nuclear Physics, HBNI, Kolkata, India
S. Bhattacharya, S. Das Gupta, S. Dutta, S. Dutta, S. Sarkar

Indian Institute of Technology Madras, Madras, India
M.M. Ameen, P.K. Behera, S. Chatterjee, G. Dash, A. Dattamunsi, P. Jana, P. Kalbhor, S. Kamble, J.R. Komaragiri[36], P.R. Pujahari, A.K. Sikdar, R.K. Singh, P. Verma, S. Verma, A. Vijay

IISER Mohali, India, Mohali, India
S. Nayak, H. Rajpoot, B.K. Sirasva

Tata Institute of Fundamental Research-A, Mumbai, India
L. Bhatt, S. Dugad, T. Mishra, G.B. Mohanty, M. Shelake, P. Suryadevara

Tata Institute of Fundamental Research-B, Mumbai, India
A. Bala, S. Banerjee, S. Barman[37], R.M. Chatterjee, J. Chhikara, M. Guchait, Sh. Jain, A. Jaiswal, S. Kumar, M. Maity[37], G. Majumder, K. Mazumdar, R. Pramanik, R. Saxena, P. Sharma, A. Thachayath

National Institute of Science Education and Research, An OCC of Homi Bhabha National Institute, Bhubaneswar, Odisha, India
D. Maity[38], P. Mal, K. Naskar[38], A. Nayak[38], K. Pal, P. Sadangi, S. Shuchi, S.K. Swain, S. Varghese[38], D. Vats[38]

Indian Institute of Science Education and Research (IISER), Pune, India
S. Dube, P. Hazarika, B. Kansal, A. Laha, R. Sharma, S. Sharma, K.Y. Vaish

Indian Institute of Technology Hyderabad, Telangana, India
C. Agrawal, B. Babu

Isfahan University of Technology, Isfahan, Iran
H. Bakhshiansohi[39], A. Jafari[40], V. Sedighzadeh Dalavi, M. Zeinali[41]

Institute for Research in Fundamental Sciences (IPM), Tehran, Iran
S. Bashiri, S. Chenarani[42], S.M. Etesami, Y. Hosseini, M. Khakzad, E. Khazaie, M. Mohammadi Najafabadi, M. Nourbakhsh, S. Tizchang[43]

University College Dublin, Dublin, Ireland
M. Felcini, M. Grunewald

INFN Sezione di Bari[a], Università di Bari[b], Politecnico di Bari[c], Bari, Italy
M. Abbrescia[a,b], M. Barbieri[a,b], M. Buonsante[a,b], A. Colaleo[a,b], D. Creanza[a,c], N. De Filippis[a,c], M. De Palma[a,b], W. Elmetenawee[a,b,16], N. Ferrara[a,c], L. Fiore[a], L. Generoso[a,b], L. Longo[a], M. Louka[a,b], G. Maggi[a,c], M. Maggi[a], S. My[a,b], F. Nenna[a,b], S. Nuzzo[a,b], A. Pellecchia[a,b], A. Pompili[a,b], F.M. Procacci[a,b], G. Pugliese[a,c], R. Radogna[a,b], D. Ramos[a], A. Ranieri[a], L. Silvestris[a],

F.M. Simone[a,c], Ü. Sözbilir[a], A. Stamerra[a,b], D. Troiano[a,b], R. Venditti[a,b], P. Verwilligen[a], A. Zaza[a,b]

INFN Sezione di Bologna[a], Università di Bologna[b], Bologna, Italy
G. Abbiendi[a], S. Balducci[a,b], C. Battilana[a,b], D. Bonacorsi[a,b], P. Capiluppi[a,b], F.R. Cavallo[a], M. Cruciani[a,b], M. Cuffiani[a,b], G.M. Dallavalle[a], T. Diotalevi[a,b], F. Fabbri[a], R. Farinelli[a], D. Fasanella[a], L. Ferragina[a,b], P. Giacomelli[a], C. Grandi[a], L. Guiducci[a,b], M. Lorusso[a,b], L. Lunerti[a], S. Marcellini[a], G. Masetti[a], F.L. Navarria[a,b], G. Paggi[a,b], A.M. Rossi[a,b], S. Rossi Tisbeni[a,b], T. Rovelli[a,b], G.P. Siroli[a,b]

INFN Sezione di Catania[a], Università di Catania[b], Catania, Italy
S. Costa[a,b,44], A. Di Mattia[a], A. Lapertosa[a], R. Potenza[a,b], A. Tricomi[a,b,44]

INFN Sezione di Firenze[a], Università di Firenze[b], Firenze, Italy
J. Altork[a,b], G. Barbagli[a], G. Bardelli[a], A. Calandri[a,b], B. Camaiani[a,b], A. Cassese[a], R. Ceccarelli[a], V. Ciulli[a,b], C. Civinini[a], R. D'Alessandro[a,b], L. Damenti[a,b], E. Focardi[a,b], T. Kello[a], G. Latino[a,b], P. Lenzi[a,b], M. Lizzo[a], M. Meschini[a], S. Paoletti[a], A. Papanastassiou[a,b], G. Sguazzoni[a], L. Viliani[a]

INFN Laboratori Nazionali di Frascati, Frascati, Italy
L. Benussi, S. Colafranceschi[45], S. Meola[46], D. Piccolo

INFN Sezione di Genova[a], Università di Genova[b], Genova, Italy
M. Alves Gallo Pereira[a], F. Ferro[a], E. Robutti[a], S. Tosi[a,b]

INFN Sezione di Milano-Bicocca[a], Università di Milano-Bicocca[b], Milano, Italy
A. Benaglia[a], F. Brivio[a], V. Camagni[a,b], F. Cetorelli[a,b], F. De Guio[a,b], M.E. Dinardo[a,b], P. Dini[a], S. Gennai[a], R. Gerosa[a,b], A. Ghezzi[a,b], P. Govoni[a,b], L. Guzzi[a], G. Lavizzari[a,b], M.T. Lucchini[a,b], M. Malberti[a], S. Malvezzi[a], A. Massironi[a], D. Menasce[a], L. Moroni[a], M. Paganoni[a,b], S. Palluotto[a,b], D. Pedrini[a], A. Perego[a,b], T. Tabarelli de Fatis[a,b]

INFN Sezione di Napoli[a], Università di Napoli 'Federico II'[b], Napoli, Italy; Università della Basilicata[c], Potenza, Italy; Scuola Superiore Meridionale (SSM)[d], Napoli, Italy
S. Buontempo[a], F. Confortini[a,b], C. Di Fraia[a,b], F. Fabozzi[a,c], L. Favilla[a,d], A.O.M. Iorio[a,b], L. Lista[a,b,47], P. Paolucci[a,27], B. Rossi[a]

INFN Sezione di Padova[a], Università di Padova[b], Padova, Italy; Universita degli Studi di Cagliari[c], Cagliari, Italy
P. Azzi[a], N. Bacchetta[a,48], D. Bisello[a,b], L. Borella[a], P. Bortignon[a,c], G. Bortolato[a,b], A.C.M. Bulla[a,c], R. Carlin[a,b], P. Checchia[a], T. Dorigo[a,49], F. Gasparini[a,b], U. Gasparini[a,b], S. Giorgetti[a], P. Grutta[a], M. Gulmini[a,50], N. Lai[a], E. Lusiani[a], M. Margoni[a,b], A.T. Meneguzzo[a,b], M. Missiroli[a], J. Pazzini[a,b], F. Primavera[a,b], P. Ronchese[a,b], R. Rossin[a,b], F. Simonetto[a,b], M. Toffano[a], M. Tosi[a,b], A. Triossi[a,b], S. Ventura[a], P. Zotto[a,b], A. Zucchetta[a,b]

INFN Sezione di Pavia[a], Università di Pavia[b], Pavia, Italy
S. Abu Zeid[a,51], C. Aimè[a], A. Braghieri[a], M. Brunoldi[a,b], S. Calzaferri[a,b], P. Montagna[a,b], M. Pelliccioni[a,b], V. Re[a], C. Riccardi[a,b], P. Salvini[a], I. Vai[a,b], P. Vitulo[a,b]

INFN Sezione di Perugia[a], Università di Perugia[b], Perugia, Italy
S. Ajmal[a,b], M.E. Ascioti[a,b], G.M. Bilei[†a], W.D. Buitrago Ceballos[a], C. Carrivale[a,b],

D. Ciangottini[a,b], L. Della Penna[a,b], L. Fanò[a,b], V. Mariani[a,b], M. Menichelli[a], F. Moscatelli[a,52], A. Rossi[a,b], A. Santocchia[a,b], D. Spiga[a], T. Tedeschi[a,b]

INFN Sezione di Pisa[a], Università di Pisa[b], Scuola Normale Superiore di Pisa[c], Pisa, Italy; Università di Siena[d], Siena, Italy
C.A. Alexe[a,c], P. Asenov[a,b], P. Azzurri[a], G. Bagliesi[a], L. Bianchini[a,b], T. Boccali[a], E. Bossini[a], D. Bruschini[a,c], R. Castaldi[a], F. Cattafesta[a,c], M.A. Ciocci[a,d], M. Cipriani[a,b], R. Dell'Orso[a], S. Donato[a,b], A. Feliziani[a,d], R. Forti[a,b], A. Giassi[a], F. Ligabue[a,c], A.C. Marini[a,b], A. Messineo[a,b], S. Mishra[a], V.K. Muraleedharan Nair Bindhu[a,b], S. Nandan[a], F. Palla[a], M. Riggirello[a,c], A. Rizzi[a,b], G. Rolandi[a,c], A. Scribano[a], P. Solanki[a,b], P. Spagnolo[a], F. Tenchini[a,b], R. Tenchini[a], G. Tonelli[a,b], N. Turini[a,d], F. Vaselli[a,c], A. Venturi[a], P.G. Verdini[a]

INFN Sezione di Roma[a], Sapienza Università di Roma[b], Roma, Italy
P. Akrap[a,b], C. Basile[a,b], S.C. Behera[a], F. Cavallari[a], L. Cunqueiro Mendez[a,b], F. De Riggi[a,b], D. Del Re[a,b], M. Del Vecchio[a,b], E. Di Marco[a], M. Diemoz[a], F. Errico[a], L. Frosina[a,b], R. Gargiulo[a,b], B. Harikrishnan[a,b], F. Lombardi[a,b], L. Martikainen[a,b], G. Organtini[a,b], N. Palmeri[a,b], R. Paramatti[a,b], T. Pauletto[a,b], S. Rahatlou[a,b], C. Rovelli[a], F. Santanastasio[a,b], L. Soffi[a], V. Vladimirov[a,b]

INFN Sezione di Torino[a], Università di Torino[b], Torino, Italy; Università del Piemonte Orientale[c], Novara, Italy
N. Amapane[a,b], R. Arcidiacono[a,c], S. Argiro[a,b], M. Arneodo[†a,c], N. Bartosik[a,c], F. Bashir[a,b], R. Bellan[a,b], A. Bellora[a,b], C. Biino[a], C. Borca[a,b], N. Cartiglia[a], M. Costa[a,b], R. Covarelli[a,b], N. Demaria[a], E. Ferrando[a,b], L. Finco[a], M. Grippo[a,b], B. Kiani[a,b], L. Lanteri[a,b], F. Luongo[a,b], M. Marchisio Caprioglio[a,b], C. Mariotti[a], S. Maselli[a], A. Mecca[a,b], L. Menzio[a,b], P. Meridiani[a], E. Migliore[a,b], M. Monteno[a], M.M. Obertino[a,b], G. Ortona[a], L. Pacher[a,b], N. Pastrone[a], M. Ruspa[a,c], F. Siviero[a,b], V. Sola[a,b], A. Solano[a,b], A. Staiano[a], C. Tarricone[a,b], D. Trocino[a], G. Umoret[a,b], E. Vlasov[a,b], R. White[a,b]

INFN Sezione di Trieste[a], Università di Trieste[b], Trieste, Italy
J. Babbar[a,b,53], S. Belforte[a], V. Candelise[a,b], M. Casarsa[a], F. Cossutti[a], K. De Leo[a], G. Della Ricca[a,b], R. Delli Gatti[a,b], C. Giraldin[a,b]

Kyungpook National University, Daegu, Korea
S. Dogra, J. Hong, J. Kim, T. Kim, D. Lee, H. Lee, J. Lee, S.W. Lee, C.S. Moon, Y.D. Oh, S. Sekmen, B. Tae, Y.C. Yang

Department of Mathematics and Physics - GWNU, Gangneung, Korea
M.S. Kim

Chonnam National University, Institute for Universe and Elementary Particles, Kwangju, Korea
G. Bak, P. Gwak, H. Kim, H. Lee, S. Lee, D.H. Moon, J. Seo

Department of Physics, Chung-Ang University, Seoul, Korea
K. Lee, Y. Lee

Hanyang University, Seoul, Korea
E. Asilar, F. Carnevali, J. Choi[54], T.J. Kim, Y. Ryou, J. Song, T. Yang

Korea University, Seoul, Korea
S. Ha, B. Hong, J. Kim, K. Lee, S. Lee, J. Padmanaban, B.A.N. Putra, J. Yoo

Kyung Hee University, Department of Physics, Seoul, Korea
J. Goh, J. Shin, S. Yang

Sejong University, Seoul, Korea
L. Kalipoliti, Y. Kang, H. S. Kim, Y. Kim, B. Ko, S. Lee

Seoul National University, Seoul, Korea
J.H. Bhyun, J. Choi, J. Choi, W. Jun, H. Kim, J. Kim, J. Kim, T. Kim, Y. Kim, Y.W. Kim, S. Ko, H. Lee, J. Lee, J. Lee, B.H. Oh, J. Shin, U.K. Yang, I. Yoon

University of Seoul, Seoul, Korea
W. Heo, W. Jang, D. Kim, S. Kim, J.S.H. Lee, Y. Roh, I.J. Watson

Yonsei University, Department of Physics, Seoul, Korea
G. Cho, Y. Eo, K. Hwang, H. Jang, B. Kim, D. Kim, S. Kim, H.D. Yoo

Sungkyunkwan University, Suwon, Korea
Y. Lee, I. Yu

College of Engineering and Technology, American University of the Middle East (AUM), Dasman, Kuwait
T. Beyrouthy, Y. Gharbia

Kuwait University - College of Science - Department of Physics, Safat, Kuwait
F. Alazemi

Riga Technical University, Riga, Latvia
K. Dreimanis, O.M. Eberlins, A. Gaile, M. Klevs, C. Munoz Diaz, D. Osite, G. Pikurs, R. Plese, A. Potrebko, M. Seidel, D. Sidiropoulos Kontos

University of Latvia (LU), Riga, Latvia
N.R. Strautnieks

Vilnius University, Vilnius, Lithuania
M. Ambrozas, A. Juodagalvis, S. Nargelas, S. Nayak, G. Tamulaitis

National Centre for Particle Physics, Universiti Malaya, Kuala Lumpur, Malaysia
I. Yusuff[55], Z. Zolkapli

Universidad de Sonora (UNISON), Hermosillo, Mexico
J.F. Benitez, A. Castaneda Hernandez, A. Cota Rodriguez, L.E. Cuevas Picos, H.A. Encinas Acosta, L.G. Gallegos Maríñez, J.A. Murillo Quijada, L. Valencia Palomo

Centro de Investigacion y de Estudios Avanzados del IPN, Mexico City, Mexico
G. Ayala, H. Castilla-Valdez, H. Crotte Ledesma, R. Lopez-Fernandez, J. Mejia Guisao, R. Reyes-Almanza, A. Sánchez Hernández

Universidad Iberoamericana, Mexico City, Mexico
C. Oropeza Barrera, D.L. Ramirez Guadarrama, M. Ramírez García

Benemerita Universidad Autonoma de Puebla, Puebla, Mexico
I. Bautista, F.E. Neri Huerta, I. Pedraza, H.A. Salazar Ibarguen, C. Uribe Estrada

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

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

National Centre for Physics, Quaid-I-Azam University, Islamabad, Pakistan
A. Ahmad, M.I. Asghar, A. Awais, M.I.M. Awan, W.A. Khan

AGH University of Krakow, Krakow, Poland
V. Avati, L. Forthomme, L. Grzanka, M. Malawski, K. Piotrzkowski

National Centre for Nuclear Research, Swierk, Poland
H. Awedikian, M. Bluj, M. Ghimiray, M. Górski, M. Kazana, M. Szleper, P. Zalewski

Institute of Experimental Physics, Faculty of Physics, University of Warsaw, Warsaw, Poland
K. Bunkowski, K. Doroba, A. Kalinowski, M. Konecki, J. Krolikowski, W. Matyszkiewicz, A. Muhammad, S. Slawinski

Warsaw University of Technology, Warsaw, Poland
P. Fokow, K. Pozniak, W. Zabolotny

Laboratório de Instrumentação e Física Experimental de Partículas, Lisboa, Portugal
M. Araujo, C. Beirão Da Cruz E Silva, A. Boletti, M. Bozzo, T. Camporesi, G. Da Molin, M. Gallinaro, R. Guitton, J. Hollar, H. Legoinha, N. Leonardo, G.B. Marozzo, A. Petrilli, M. Pisano, J. Seixas, J. Varela, J.W. Wulff

Faculty of Physics, University of Belgrade, Belgrade, Serbia
P. Adzic, L. Markovic, P. Milenovic, V. Milosevic

VINCA Institute of Nuclear Sciences, University of Belgrade, Belgrade, Serbia
D. Devetak, M. Dordevic, J. Milosevic, L. Nadderd, V. Rekovic, M. Stojanovic

Centro de Investigaciones Energéticas Medioambientales y Tecnológicas (CIEMAT), Madrid, Spain
M. Alcalde Martinez, J. Alcaraz Maestre, Cristina F. Bedoya, J.A. Brochero Cifuentes, Oliver M. Carretero, M. Cepeda, M. Cerrada, N. Colino, B. De La Cruz, A. Delgado Peris, A. Escalante Del Valle, D. Fernández Del Val, J.P. Fernández Ramos, J. Flix, M.C. Fouz, M. Gonzalez Hernandez, O. Gonzalez Lopez, S. Goy Lopez, J.M. Hernandez, M.I. Josa, J. Llorente Merino, C. Martin Perez, E. Martin Viscasillas, D. Moran, C. M. Morcillo Perez, Á. Navarro Tobar, A. Pérez-Calero Yzquierdo, J. Puerta Pelayo, I. Redondo, D.D. Redondo Ferrero, J. Vazquez Escobar

Universidad Autónoma de Madrid, Madrid, Spain
J.F. de Trocóniz

Universidad de Oviedo, Instituto Universitario de Ciencias y Tecnologías Espaciales de Asturias (ICTEA), Oviedo, Spain
E. Aller Gutierrez, B. Alvarez Gonzalez, J. Ayllon Torresano, A. Cardini, J. Cuevas, J. Del Riego Badas, D. Estrada Acevedo, J. Fernandez Menendez, S. Folgueras, I. Gonzalez Caballero, P. Leguina, M. Obeso Menendez, E. Palencia Cortezon, J. Prado Pico, S. Sanchez Cruz, A. Soto Rodríguez, P. Vischia

Instituto de Física de Cantabria (IFCA), CSIC-Universidad de Cantabria, Santander, Spain
S. Blanco Fernández, I.J. Cabrillo, A. Calderon, M. Caserta, J. Duarte Campderros, M. Fernandez, G. Gomez, C. Lasaosa García, R. Lopez Ruiz, C. Martinez Rivero, P. Martinez Ruiz del Arbol, F. Matorras, P. Matorras Cuevas, E. Navarrete Ramos, J. Piedra Gomez, C. Quintana San Emeterio, V. Rodriguez, L. Scodellaro, I. Vila, R. Vilar Cortabitarte, J.M. Vizan Garcia

University of Colombo, Colombo, Sri Lanka
B. Kailasapathy[56]

University of Ruhuna, Department of Physics, Matara, Sri Lanka
W.G.D. Dharmaratna[57], N. Perera

CERN, European Organization for Nuclear Research, Geneva, Switzerland
D. Abbaneo, C. Amendola, R. Ardino, E. Auffray, J. Baechler, D. Barney, J. Bendavid, I. Bestintzanos, M. Bianco, A. Bocci, L. Borgonovi, C. Botta, A. Bragagnolo, C.E. Brown, C. Caillol, G. Cerminara, P. Connor, K. Cormier, D. d'Enterria, A. Dabrowski, P. Das, A. David, M.M. Defranchis, M. Deile, M. Dobson, P.J. Fernández Manteca, B.A. Fontana Santos Alves, E. Fontanesi, W. Funk, A. Gaddi, S. Giani, D. Gigi, K. Gill, F. Glege, M. Glowacki, A. Gruber, J. Hegeman, J.K. Heikkilä, R. Hofsaess, B. Huber, T. James, P. Janot, L. Jeppe, O. Kaluzinska, O. Karacheban[25], G. Karathanasis, S. Laurila, P. Lecoq, J. León Holgado, E. Leutgeb, C. Lourenço, A.-M. Lyon, M. Magherini, L. Malgeri, F. Meijers, J.A. Merlin, S. Mersi, E. Meschi, M. Migliorini, F. Monti, F. Moortgat, M. Mulders, M. Musich, I. Neutelings, S. Orfanelli, F. Pantaleo, M. Pari, F. Pereira Carneiro, G. Petrucciani, A. Pfeiffer, M. Pierini, M. Pitt, H. Qu, A. Reimers, B. Ribeiro Lopes, F. Riti, P. Rosado, M. Rovere, H. Sakulin, R. Salvatico, S. Scarfi, S.F. Schaefer, M. Selvaggi, P. Silva, P. Sphicas[58], A.G. Stahl Leiton, A. Steen, S. Summers, G. Terragni, D. Treille, P. Tropea, E. Vernazza, M. Vojinovic, J. Wanczyk[59], S. Wuchterl, M. Zarucki, P. Zehetner, P. Zejdl, G. Zevi Della Porta

PSI Center for Neutron and Muon Sciences, Villigen, Switzerland
L. Caminada[60], W. Erdmann, R. Horisberger, Q. Ingram, H.C. Kaestli, D. Kotlinski, C. Lange, U. Langenegger, A. Nigamova, L. Noehte[60], L. Redard-Jacot[60], T. Rohe, A. Samalan

ETH Zurich - Institute for Particle Physics and Astrophysics (IPA), Zurich, Switzerland
T.K. Aarrestad, M. Backhaus, T. Bevilacqua[60], G. Bonomelli, C. Cazzaniga, K. Datta, P. De Bryas Dexmiers D'Archiacchiac[59], A. De Cosa, G. Dissertori, M. Dittmar, M. Donegà, F. Glessgen, C. Grab, N. Härringer, T.G. Harte, M.Köppel, W. Lustermann, M. Malucchi, R.A. Manzoni, L. Marchese, F. Nessi-Tedaldi, F. Pauss, A.A. Petre, J. Prendi, B. Ristic, S. Rohletter, P.M. Sander, R. Seidita, J. Steggemann[59], A. Tarabini, C.Z. Tee, D. Valsecchi, P.H. Wagner, R. Wallny

Universität Zürich, Zurich, Switzerland
C. Amsler[61], P. Bärtschi, F. Bilandzija, M.F. Canelli, G. Celotto, Z. Ghafoor, T.A. Goldschmidt, V. Guglielmi, A. Jofrehei, B. Kilminster, T.H. Kwok, S. Leontsinis, V. Lukashenko, A. Macchiolo, F. Meng, J. Motta, P. Robmann, E. Shokr, F. Stäger, R. Tramontano, P. Viscone

National Central University, Chung-Li, Taiwan
D. Bhowmik, C.M. Kuo, P.K. Rout, S. Taj, P.C. Tiwari[36]

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

High Energy Physics Research Unit, Department of Physics, Faculty of Science, Chulalongkorn University, Bangkok, Thailand
C. Asawatangtrakuldee, N. Srimanobhas

Tunis El Manar University, Tunis, Tunisia
Y. Maghrbi

Çukurova University, Physics Department, Science and Art Faculty, Adana, Turkey
D. Agyel, F. Dolek, I. Dumanoglu[62], Y. Guler[63], E. Gurpinar Guler[63], A. Kayis Topaksu, G. Onengut, K. Ozdemir[64], B. Tali[65], U.G. Tok, E. Uslan

Hacettepe University, Ankara, Turkey
S. Sen

Bogazici University, Istanbul, Turkey
B. Akgun, I.O. Atakisi[66], E. Gülmez, M. Kaya[67], O. Kaya[68], M.A. Sarkisla[69], S. Tekten[70]

Istanbul Technical University, Istanbul, Turkey
D. Boncukcu, A. Cakir, K. Cankocak[62,71], A.D. Gungordu

Istanbul University, Istanbul, Turkey
B. Hacisahinoglu, I. Hos[72], B. Kaynak, S. Ozkorucuklu, O. Potok, H. Sert, C. Simsek, C. Zorbilmez

Yildiz Technical University, Istanbul, Turkey
S. Cerci, B. Isildak, E. Simsek, D. Sunar Cerci, T. Yetkin[73]

National Science Centre, Kharkiv Institute of Physics and Technology, Kharkiv, Ukraine
L. Levchuk

University of Bristol, Bristol, United Kingdom
J.J. Brooke, A. Bundock, F. Bury, E. Clement, D. Cussans, D. Dharmender, H. Flacher, J. Goldstein, H.F. Heath, M.-L. Holmberg, A. Karakoulaki, L. Kreczko, S. Paramesvaran, L. Robertshaw, M.S. Sanjrani[39], J. Segal, V.J. Smith

Rutherford Appleton Laboratory, Didcot, United Kingdom
A.H. Ball, K.W. Bell, A. Belyaev[74], C. Brew, R.M. Brown, D.J.A. Cockerill, A. Elliot, K.V. Ellis, J. Gajownik, K. Harder, S. Harper, J. Linacre, K. Manolopoulos, M. Moallemi, D.M. Newbold, E. Olaiya, D. Petyt, T. Reis, A.R. Sahasransu, G. Salvi, T. Schuh, C.H. Shepherd-Themistocleous, I.R. Tomalin, K.C. Whalen, T. Williams

Imperial College, London, United Kingdom
I. Andreou, S. Awan, R. Bainbridge, P. Bloch, O. Buchmuller, C.A. Carrillo Montoya, D. Colling, A. Cox, I. Das, P. Dauncey, G. Davies, M. Della Negra, S. Fayer, G. Fedi, G. Hall, H.R. Hoorani, A. Howard, G. Iles, C.R. Knight, P. Krueper, J. Langford, K.H. Law, L. Lyons, A.-M. Magnan, B. Maier, S. Mallios, A. Mastronikolis, J. Nash[75], M. Pesaresi, P.B. Pradeep, E.V. Protopapa, B.C. Radburn-Smith, A. Richards, A. Rose, T.B. Runting, L. Russell, K. Savva, R. Schmitz, C. Seez, R. Shukla, A. Tapper, T. Travis, K. Uchida, G.P. Uttley, T. Virdee[27], N. Wardle, D. Winterbottom, J. Xiao

Brunel University, Uxbridge, United Kingdom
J.E. Cole, L. Juckett, A. Khan, P. Kyberd, I.D. Reid

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

Bethel University, St. Paul, Minnesota, USA
J.M. Hogan

Catholic University of America, Washington, DC, USA
R. Bartek, A. Dominguez, S. Raj, B. Sahu, A.E. Simsek, B. Singhal, S.S. Yu

The University of Alabama, Tuscaloosa, Alabama, USA
B. Bam, A. Buchot Perraguin, S. Campbell, R. Chudasama, S.I. Cooper, C. Crovella, G. Fidalgo, S.V. Gleyzer, R. Kaur, A. Khukhunaishvili, K. Matchev, E. Pearson, P. Rumerio[76], E. Usai, R. Yi

Boston University, Boston, Massachusetts, USA
S. Cholak, Z. Demiragli, C. Erice, C. Fangmeier, C. Fernandez Madrazo, J. Fulcher, J. Garcia De Castro, F. Golf, S. Jeon, J. O'Cain, I. Reed, J. Rohlf, D. Sperka, I. Suarez, A. Tsatsos, E. Wurtz, A.G. Zecchinelli

Brown University, Providence, Rhode Island, USA
G. Barone, G. Benelli, D. Cutts, S. Ellis, S. Gottlieb, L. Gouskos, M. Hadley, L. Hay, U. Heintz, K.W. Ho, R. Jain, T. Kwon, L. Lambrecht, G. Landsberg, K.T. Lau, M. LeBlanc, J. Luo, S. Mondal, J. Roloff, T. Russell, S. Sagir[77], X. Shen, M. Stamenkovic, S. Sunnarborg, J. Tang, N. Venkatasubramanian

University of California, Davis, Davis, California, USA
S. Abbott, S. Baradia, B. Barton, R. Breedon, H. Cai, M. Calderon De La Barca Sanchez, E. Cannaert, M. Chertok, M. Citron, J. Conway, P.T. Cox, F. Eble, R. Erbacher, C. Fairchild, O. Kukral, S. Ostrom, I. Salazar Segovia, J.H. Steenis, J.S. Tafoya Vargas, W. Wei, S. Yoo

University of California, Los Angeles, California, USA
K. Adamidis, H. Ancelin, M. Bachtis, D. Campos, R. Cousins, S. Crossley, G. Flores Avila, J. Hauser, M. Ignatenko, M.A. Iqbal, T. Lam, Y.f. Lo, E. Manca, A. Nunez Del Prado, D. Saltzberg, V. Valuev

University of California, Riverside, Riverside, California, USA
R. Clare, J.W. Gary, G. Hanson

University of California, San Diego, La Jolla, California, USA
A. Aportela, A. Arora, J.G. Branson, S. Cittolin, B. D'Anzi, D. Diaz, J. Duarte, L. Giannini, Y. Gu, J. Guiang, V. Krutelyov, R. Lee, J. Letts, H. Li, R. Marroquin Solares, M. Masciovecchio, F. Mokhtar, S. Morovic, S. Mukherjee, M. Pieri, D. Primosch, M. Quinnan, V. Sharma, M. Tadel, E. Vourliotis, F. Würthwein, A. Yagil, Z. Zhao

University of California, Santa Barbara - Department of Physics, Santa Barbara, California, USA
A. Barzdukas, L. Brennan, C. Campagnari, S. Carron Montero[78], K. Downham, C. Grieco, J.S. Guo, M.M. Hussain, J. Incandela, M.W.K. Lai, A.J. Li, P. Masterson, J. Richman, S.N. Santpur, D. Stuart, T.Á. Vámi, X. Yan, D. Zhang

California Institute of Technology, Pasadena, California, USA

A. Albert, S. Bhattacharya, A. Bornheim, O. Cerri, Z. Hao, L. Mori, H.B. Newman, T. Sievert, P. Simmerling, E. Sledge, M. Spiropulu, C. Sun, J.R. Vlimant, R.A. Wynne, S. Xie, R.Y. Zhu

Carnegie Mellon University, Pittsburgh, Pennsylvania, USA
J. Alison, S. An, M. Cremonesi, V. Dutta, E.Y. Ertorer, T. Ferguson, T.A. Gómez Espinosa, A. Harilal, A. Kallil Tharayil, M. Kanemura, A. Khanal, C. Liu, M. Marchegiani, P. Meiring, S. Murthy, P. Palit, K. Park, M. Paulini, A. Roberts, A. Sanchez, Y. Zhou

University of Colorado Boulder, Boulder, Colorado, USA
J.P. Cumalat, W.T. Ford, J. Fraticelli, A. Hart, M. Herrmann, S. Kwan, J. Pearkes, N. Schonbeck, K. Stenson, K.A. Ulmer, S.R. Wagner, N. Zipper, D. Zuolo

Cornell University, Ithaca, New York, USA
J. Alexander, X. Chen, G. De Castro, J. Dickinson, A. Duquette, J. Fan, X. Fan, J. Grassi, P. Kotamnives, K. Krzyzanska, J. Monroy, G. Niendorf, M. Oshiro, J.R. Patterson, A. Ryd, J. Thom, H.A. Weber, B. Weiss, P. Wittich, Y. Wu, R. Zou, L. Zygala

Fermi National Accelerator Laboratory, Batavia, Illinois, USA
M. Albrow, M. Alyari, O. Amram, G. Apollinari, A. Apresyan, L.A.T. Bauerdick, D. Berry, J. Berryhill, P.C. Bhat, K. Burkett, J.N. Butler, A. Canepa, G.B. Cerati, H.W.K. Cheung, F. Chlebana, C. Cosby, G. Cummings, I. Dutta, V.D. Elvira, J. Freeman, A. Gandrakota, Z. Gecse, L. Gray, D. Green, A. Grummer, S. Grünendahl, D. Guerrero, O. Gutsche, R.M. Harris, J. Hirschauer, V. Innocente, B. Jayatilaka, S. Jindariani, M. Johnson, U. Joshi, R.S. Kim, B. Klima, S. Lammel, D. Lincoln, R. Lipton, T. Liu, K. Maeshima, D. Mason, P. McBride, P. Merkel, S. Mrenna, S. Nahn, J. Ngadiuba, D. Noonan, S. Norberg, V. Papadimitriou, N. Pastika, K. Pedro, C. Pena[79], C.E. Perez Lara, V. Perovic, F. Ravera, A. Reinsvold Hall[80], L. Ristori, M. Safdari, E. Sexton-Kennedy, E. Smith, N. Smith, A. Soha, L. Spiegel, S. Stoynev, J. Strait, L. Taylor, S. Tkaczyk, N.V. Tran, L. Uplegger, E.W. Vaandering, C. Wang, I. Zoi

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

Florida State University, Tallahassee, Florida, USA
T. Adams, A. Al Kadhim, D. Alam, A. Askew, S. Bower, R. Goff, R. Hashmi, A. Hassani, T. Kolberg, G. Martinez, M. Mazza, H. Prosper, P.R. Prova, R. Yohay

Florida Institute of Technology, Melbourne, Florida, USA
B. Alsufyani, S. Das, S. Demarest, L. Hasa, M. Hohlmann, M. Lavinsky, E. Yanes

University of Illinois Chicago, Chicago, Illinois, USA
M.R. Adams, N. Barnett, A. Baty, C. Bennett, N. Brandman-hughes, R. Cavanaugh, S.J. Das, R. Escobar Franco, O. Evdokimov, C.E. Gerber, H. Gupta, M. Hawksworth, A. Hingrajiya, D.J. Hofman, Z. Huang, J.h. Lee, C. Mills, S. Nanda, G. Nigmatkulov, B. Ozek, V. Pant, T. Phan, D. Pilipovic, R. Pradhan, E. Prifti, T. Roy, D. Shekar, N. Singh, F. Strug, A. Thielen, M.B. Tonjes, N. Varelas,

M.A. Wadud, A. Wang, J. Yoo

The University of Iowa, Iowa City, Iowa, USA
M. Alhusseini, D. Blend, K. Dilsiz[81], O.K. Köseyan, A. Mestvirishvili[82], O. Neogi, H. Ogul[83], Y. Onel, A. Penzo, C. Snyder

Johns Hopkins University, Baltimore, Maryland, USA
B. Blumenfeld, J. Davis, A.V. Gritsan, Z. Huang, L. Kang, S. Kyriacou, P. Maksimovic, N. Pinto, M. Roguljic, S. Sekhar, M.V. Srivastav, M. Swartz

The University of Kansas, Lawrence, Kansas, USA
A. Abreu, L.F. Alcerro Alcerro, J. Anguiano, S. Arteaga Escatel, P. Baringer, A. Bean, R. Bhattacharya, M. Chukwuka, Z. Flowers, D. Grove, J. King, G. Krintiras, M. Lazarovits, C. Le Mahieu, J. Marquez, M. Murray, M. Nickel, S. Popescu[84], E. Reynolds, C. Rogan, C. Royon, S. Rudrabhatla, S. Sanders, G. Wilson

Kansas State University, Manhattan, Kansas, USA
A. Ahmad, B. Allmond, N. Islam, A. Ivanov, K. Kaadze, Y. Maravin, J. Natoli, G.G. Reddy, D. Roy, G. Sorrentino

University of Maryland, College Park, Maryland, USA
Z. Alton, A. Baden, A. Belloni, J. Bistany-riebman, S.C. Eno, N.J. Hadley, S. Jabeen, R.G. Kellogg, T. Koeth, B. Kronheim, S. Lascio, J. Lee, P. Major, A.C. Mignerey, C. Palmer, C. Papageorgakis, M.M. Paranjpe, E. Popova[85], A. Shevelev, M. Wrotny, L. Zhang

Massachusetts Institute of Technology, Cambridge, Massachusetts, USA
C. Baldenegro Barrera, H. Bossi, S. Bright-Thonney, I.A. Cali, Y.c. Chen, P.c. Chou, M. D'Alfonso, K. Devereaux, J. Eysermans, C. Freer, G. Gomez-Ceballos, M. Goncharov, G. Grosso, P. Harris, D. Hoang, A. Holtermann, G.M. Innocenti, K. Ivanov, G. Kopp, B. Cs. Kovács, D. Kovalskyi, J. Lang, L. Lavezzo, Y.-J. Lee, P. Lugato, C. Mcginn, E. Moreno, A. Novak, M.I. Park, C. Paus, C. Reissel, C. Roland, G. Roland, X. Rong, S. Rothman, T.a. Sheng, G.S.F. Stephans, D. Walter, J. Wang, Z. Wang, B. Wyslouch, T. J. Yang

University of Minnesota, Minneapolis, Minnesota, USA
A. Alpana, B. Crossman, W.J. Jackson, C. Kapsiak, M. Krohn, D. Mahon, J. Mans, B. Marzocchi, R. Rusack, O. Sancar, R. Saradhy, N. Strobbe

University of Nebraska-Lincoln, Lincoln, Nebraska, USA
K. Bloom, D.R. Claes, S.V. Dixit, G. Haza, J. Hossain, C. Joo, I. Kravchenko, K.H.M. Kwok, Y. Mehra, J. Morris, A. Rohilla, J.E. Siado, A. Vagnerini, A. Wightman

State University of New York at Buffalo, Buffalo, New York, USA
H. Bandyopadhyay, H.w. Hsia, I. Iashvili, A. Kalogeropoulos, A. Kharchilava, A. Mandal, C. McLean, M. Morris, D. Nguyen, O. Poncet, S. Rappoccio, H. Rejeb Sfar, W. Terrill, A. Williams, D. Yu

Northeastern University, Boston, Massachusetts, USA
A. Aarif, G. Alverson, E. Barberis, S. Bein, J. Bonilla, B. Bylsma, M. Campana, R. Clark, J. Dervan, Y. Haddad, Y. Han, I. Israr, A. Krishna, M. Lu, N. Manganelli, R. Mccarthy, D.M. Morse, T. Orimoto, L. Skinnari, C.S. Thoreson,

E. Tsai, D. Wood

Northwestern University, Evanston, Illinois, USA
S. Dittmer, K.A. Hahn, S. King, D. Li, M. Mcginnis, Y. Miao, D.G. Monk, M.H. Schmitt, A. Taliercio, M. Velasco, J. Wang, D. Wilbern

University of Notre Dame, Notre Dame, Indiana, USA
G. Agarwal, R. Band, R. Bucci, S. Castells, A. Das, A. Datta, A. Ehnis, R. Goldouzian, M. Hildreth, T. Ivanov, C. Jessop, K. Lannon, J. Lawrence, L. Lutton, J. Mariano, N. Marinelli, P. Mastrapasqua, A. Masud, T. McCauley, C. Mcgrady, C. Moore, Y. Musienko[21], H. Nelson, M. Osherson, A. Piccinelli, R. Ruchti, A. Townsend, Y. Wan, M. Wayne, H. Yockey

The Ohio State University, Columbus, Ohio, USA
M. Carrigan, R. De Los Santos, L.S. Durkin, C. Hill, M. Joyce, L. Nestor, D.A. Wenzl, B.L. Winer, B. R. Yates

Princeton University, Princeton, New Jersey, USA
H. Bouchamaoui, G. Dezoort, P. Elmer, A. Frankenthal, M. Galli, B. Greenberg, K. Kennedy, Y. Lai, D. Lange, A. Loeliger, D. Marlow, I. Ojalvo, J. Olsen, F. Simpson, D. Stickland, C. Tully, S. Yoon

University of Puerto Rico, Mayaguez, Puerto Rico, USA
S. Malik, R. Sharma

Purdue University, West Lafayette, Indiana, USA
S. Chandra, A. Gu, L. Gutay, M. Huwiler, M. Jones, A.W. Jung, I.G. Karslioglu, D. Kondratyev, J. Li, M. Liu, M. Macedo, G. Negro, N. Neumeister, G. Paspalaki, S. Piperov, N.R. Saha, J.F. Schulte, R. Sharma, F. Wang, A.L. Wesolek, A. Wildridge, W. Xie, Y. Yao, Y. Zhong

Purdue University Northwest, Hammond, Indiana, USA
N. Parashar, A. Pathak, E. Shumka

Rice University, Houston, Texas, USA
D. Acosta, A. Agrawal, C. Arbour, T. Carnahan, K.M. Ecklund, F.J.M. Geurts, I. Krommydas, N. Lewis, W. Li, J. Lin, X. Liu, C. Loizides, O. Miguel Colin, B.P. Padley, R. Redjimi, J. Rotter, C. Vico Villalba, M. Wulansatiti, E. Yigitbasi, Y. Zhang

University of Rochester, Rochester, New York, USA
O. Bessidskaia Bylund, A. Bodek, P. de Barbaro[†], R. Demina, A. Garcia-Bellido, H.S. Hare, O. Hindrichs, N. Parmar, P. Parygin[85], H. Seo, R. Taus, Y.h. Yu

Rutgers, The State University of New Jersey, Piscataway, New Jersey, USA
B. Chiarito, J.P. Chou, S.V. Clark, S. Donnelly, D. Gadkari, Y. Gershtein, E. Halkiadakis, C. Houghton, D. Jaroslawski, A. Kobert, I. Laflotte, A. Lath, J. Martins, P. Meltzer, M. Perez Prada, K. Ramdin, B. Rand, J. Reichert, P. Saha, S. Salur, S. Somalwar, R. Stone, S.A. Thayil, S. Thomas, A. K. Virdi, J. Vora

University of Tennessee, Knoxville, Tennessee, USA
A. Abdelhamid, D. Ally, A.G. Delannoy, S. Fiorendi, J. Harris, T. Holmes, A.R. Kanuganti, N. Karunarathna, J. Lawless, L. Lee, E. Nibigira, B. Skipworth, S. Spanier, A. Vendrasco

Texas A&M University, College Station, Texas, USA
D. Aebi, M. Ahmad, T. Akhter, K. Androsov, A. Basnet, A. Bolshov, O. Bouhali[86], A. Cagnotta, S. Cooperstein, V. D'Amante, R. Eusebi, P. Flanagan, J. Gilmore, Y. Guo, T. Kamon, S. Luo, R. Mueller, G. Pizzati, A. Safonov

Texas Tech University, Lubbock, Texas, USA
N. Akchurin, J. Damgov, Y. Feng, N. Gogate, W. Jin, S.W. Lee, C. Madrid, A. Mankel, T. Peltola, I. Volobouev

Vanderbilt University, Nashville, Tennessee, USA
E. Appelt, Y. Chen, S. Greene, A. Gurrola, W. Johns, R. Kunnawalkam Elayavalli, A. Melo, D. Rathjens, F. Romeo, S. Tuo, J. Velkovska, J. Zhang

University of Virginia, Charlottesville, Virginia, USA
B. Cardwell, H. Chung, B. Cox, J. Hakala, G. Hamilton Ilha Machado, R. Hirosky, M. Jose, A. Ledovskoy, C. Mantilla, C. Neu, C. Ramón Álvarez, Z. Wu

Wayne State University, Detroit, Michigan, USA
P.E. Karchin

University of Wisconsin - Madison, Madison, Wisconsin, USA
A. Aravind, S. Banerjee, K. Black, T. Bose, E. Chavez, R. Cruz, S. Dasu, P. Everaerts, C. Galloni, H. He, M. Herndon, A. Herve, C.K. Koraka, S. Lomte, R. Loveless, J. Marquez, A. Mohammadi, S. Mondal, T. Nelson, G. Parida, D. Pinna, A. Savin, V. Shang, V. Sharma, R. Simeon, W.H. Smith, D. Teague, M. Thakore, A. Thete, A. Warden

Authors affiliated with an international laboratory covered by a cooperation agreement with CERN
S. Afanasiev, V. Alexakhin, Yu. Andreev, D. Budkouski, R. Chistov, M. Danilov, T. Dimova, I. Gorbunov, A. Kamenev, V. Karjavine, O. Kodolova[87], V. Korenkov, I. Korsakov, A. Kozyrev, A. Lanev, A. Malakhov, V. Matveev, A. Nikitenko[88,87], V. Palichik, V. Perelygin, O. Radchenko, M. Savina, V. Shalaev, S. Shmatov, S. Shulha, Y. Skovpen, K. Slizhevskiy, V. Smirnov, O. Teryaev, A. Toropin, N. Voytishin, A. Zarubin, I. Zhizhin

Authors affiliated with an institute formerly covered by a cooperation agreement with CERN
L. Dudko, V. Kim[21], V. Murzin, V. Oreshkin, D. Sosnov

†: Deceased
[1]Also at Yerevan State University, Yerevan, Armenia
[2]Also at TU Wien, Vienna, Austria
[3]Also at Ghent University, Ghent, Belgium
[4]Also at FACAMP - Faculdades de Campinas, Sao Paulo, Brazil
[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 The University of the State of Amazonas, Manaus, Brazil
[8]Also at University of Chinese Academy of Sciences, Beijing, China
[9]Also at University of Chinese Academy of Sciences, Beijing, China
[10]Also at School of Physics, Zhengzhou University, Zhengzhou, China
[11]Now at Henan Normal University, Xinxiang, China
[12]Also at University of Shanghai for Science and Technology, Shanghai, China
[13]Also at The University of Iowa, Iowa City, Iowa, USA

[14]Also at Nanjing Normal University, Nanjing, China
[15]Also at Center for High Energy Physics, Peking University, Beijing, China
[16]Also at Helwan University, Cairo, Egypt
[17]Now at Zewail City of Science and Technology, Zewail, Egypt
[18]Also at Cairo University, Cairo, Egypt
[19]Also at Université de Haute Alsace, Mulhouse, France
[20]Also at Purdue University, West Lafayette, Indiana, USA
[21]Also at an institute formerly covered by a cooperation agreement with CERN
[22]Also at University of Hamburg, Hamburg, Germany
[23]Also at RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany
[24]Also at Bergische University Wuppertal (BUW), Wuppertal, Germany
[25]Also at Brandenburg University of Technology, Cottbus, Germany
[26]Also at Forschungszentrum Jülich, Juelich, Germany
[27]Also at CERN, European Organization for Nuclear Research, Geneva, Switzerland
[28]Also at HUN-REN ATOMKI - Institute of Nuclear Research, Debrecen, Hungary
[29]Now at Universitatea Babes-Bolyai - Facultatea de Fizica, Cluj-Napoca, Romania
[30]Also at MTA-ELTE Lendület CMS Particle and Nuclear Physics Group, Eötvös Loránd University, Budapest, Hungary
[31]Also at HUN-REN Wigner Research Centre for Physics, Budapest, Hungary
[32]Also at Physics Department, Faculty of Science, Assiut University, Assiut, Egypt
[33]Also at The University of Kansas, Lawrence, Kansas, USA
[34]Also at Punjab Agricultural University, Ludhiana, India
[35]Also at University of Hyderabad, Hyderabad, India
[36]Also at Indian Institute of Science (IISc), Bangalore, India
[37]Also at University of Visva-Bharati, Santiniketan, India
[38]Also at Institute of Physics, Bhubaneswar, India
[39]Also at Deutsches Elektronen-Synchrotron, Hamburg, Germany
[40]Also at Isfahan University of Technology, Isfahan, Iran
[41]Also at Sharif University of Technology, Tehran, Iran
[42]Also at Department of Physics, University of Science and Technology of Mazandaran, Behshahr, Iran
[43]Also at Department of Physics, Faculty of Science, Arak University, ARAK, Iran
[44]Also at Centro Siciliano di Fisica Nucleare e di Struttura Della Materia, Catania, Italy
[45]Also at James Madison University, Harrisonburg, Maryland, USA
[46]Also at Università degli Studi Guglielmo Marconi, Roma, Italy
[47]Also at Scuola Superiore Meridionale, Università di Napoli 'Federico II', Napoli, Italy
[48]Also at Fermi National Accelerator Laboratory, Batavia, Illinois, USA
[49]Also at Lulea University of Technology, Lulea, Sweden
[50]Also at Laboratori Nazionali di Legnaro dell'INFN, Legnaro, Italy
[51]Also at Ain Shams University, Cairo, Egypt
[52]Also at Consiglio Nazionale delle Ricerche - Istituto Officina dei Materiali, Perugia, Italy
[53]Also at UPES - University of Petroleum and Energy Studies, Dehradun, India
[54]Also at Institut de Physique des 2 Infinis de Lyon (IP2I), Villeurbanne, France
[55]Also at Department of Applied Physics, Faculty of Science and Technology, Universiti Kebangsaan Malaysia, Bangi, Malaysia
[56]Also at Trincomalee Campus, Eastern University, Sri Lanka, Nilaveli, Sri Lanka
[57]Also at Saegis Campus, Nugegoda, Sri Lanka
[58]Also at National and Kapodistrian University of Athens, Athens, Greece
[59]Also at Ecole Polytechnique Fédérale Lausanne, Lausanne, Switzerland

[60]Also at Universität Zürich, Zurich, Switzerland
[61]Also at Stefan Meyer Institute for Subatomic Physics, Vienna, Austria
[62]Also at Near East University, Research Center of Experimental Health Science, Mersin, Turkey
[63]Also at Konya Technical University, Konya, Turkey
[64]Also at Izmir Bakircay University, Izmir, Turkey
[65]Also at Adiyaman University, Adiyaman, Turkey
[66]Also at Istanbul Sabahattin Zaim University, Istanbul, Turkey
[67]Also at Marmara University, Istanbul, Turkey
[68]Also at Milli Savunma University, Istanbul, Turkey
[69]Also at Informatics and Information Security Research Center, Gebze/Kocaeli, Turkey
[70]Also at Kafkas University, Kars, Turkey
[71]Now at Istanbul Okan University, Istanbul, Turkey
[72]Also at Istanbul University - Cerrahpasa, Faculty of Engineering, Istanbul, Turkey
[73]Also at Istinye University, Istanbul, Turkey
[74]Also at School of Physics and Astronomy, University of Southampton, Southampton, United Kingdom
[75]Also at Monash University, Faculty of Science, Clayton, Australia
[76]Also at Università di Torino, Torino, Italy
[77]Also at Karamanoğlu Mehmetbey University, Karaman, Turkey
[78]Also at California Lutheran University, Thousand Oaks, California, USA
[79]Also at California Institute of Technology, Pasadena, California, USA
[80]Also at United States Naval Academy, Annapolis, Maryland, USA
[81]Also at Bingol University, Bingol, Turkey
[82]Also at Georgian Technical University, Tbilisi, Georgia
[83]Also at Sinop University, Sinop, Turkey
[84]Also at Horia Hulubei National Institute of Physics and Nuclear Engineering (IFIN-HH), Bucharest, Romania
[85]Now at another institute formerly covered by a cooperation agreement with CERN
[86]Also at Hamad Bin Khalifa University (HBKU), Doha, Qatar
[87]Also at Yerevan Physics Institute, Yerevan, Armenia
[88]Also at Imperial College, London, United Kingdom