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Letter

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

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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 $\sqrt{s_{_{NN}}}$ = 5.36 TeV. The neon-neon data correspond to an integrated luminosity of 0.76 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 $p_T > 9.6$ GeV.

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.,

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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

$$R_{AA} = \frac{1}{A^2}\left[\left(\frac{d\sigma^{AA}}{dp_T}\right)\bigg/\left(\frac{d\sigma^{pp}}{dp_T}\right)\right], \quad (1)$$

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 $\sqrt{s_{NN}} = 5.36$ TeV by measuring the charged-particle R_{AA} [22]. When combined with existing centrality-integrated PbPb measurements at $\sqrt{s_{NN}} = 5.02$ 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 $\sqrt{s_{NN}} = 5.36$ 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 $1 < p_T < 100$ 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 colliding 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 $c\tau > 1$ 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 $3.0 < p_T < 103.6$ 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 $p_T < 103.6$ 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 ultra-peripheral [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 ultra-peripheral 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 hadrochemistry 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 supplementary material Section 1. 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

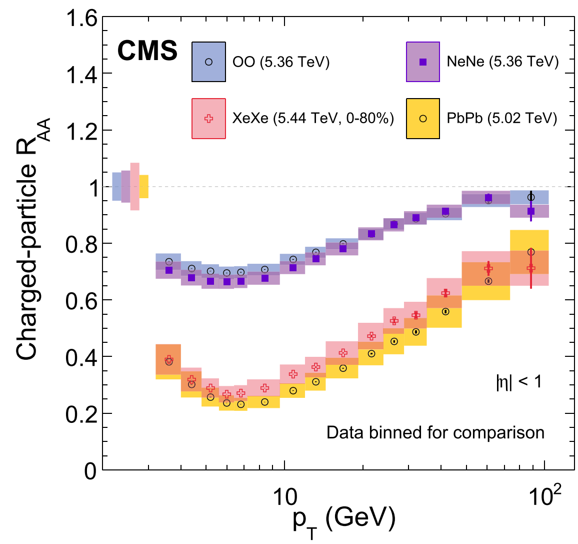

Fig. 1. Charged-particle R_{AA} values versus p_{T} measured in NeNe collisions at 5.36 TeV compared to previous measurements in centrality-integrated OO collisions at 5.36 TeV [22], 0–80% centrality XeXe at 5.44 TeV [9], and minimum bias PbPb collisions at 5.02 TeV [12]. The vertical error bars represent 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 supplementary material Section 3.

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 original 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 supplementary material Section 2, and the R_{AA} results with the high-granularity binning format can be found in supplementary material Section 3.

Fig. 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 $p_{\mathrm{T}} \approx 20$ 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 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

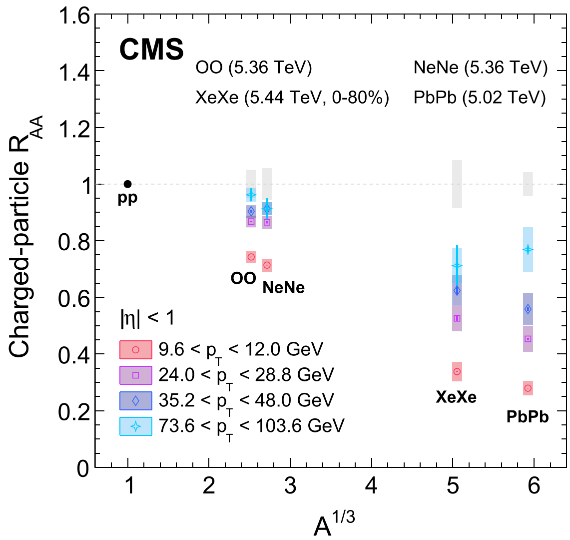

Fig. 2. Charged-particle R_{AA} values, in intervals of p_T, versus $A^{1/3}$ of the AA colliding system. The open markers represent the measured R_{AA}, with the vertical bars representing the statistical uncertainty, and the vertical band representing the experimental uncertainty. Global normalization 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.

magnitude and evolution of the suppression at high p_T are generally associated with parton energy loss in the medium.

Fig. 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.

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 supplementary material Section 6 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.

Fig. 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 $p_T > 10$ 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

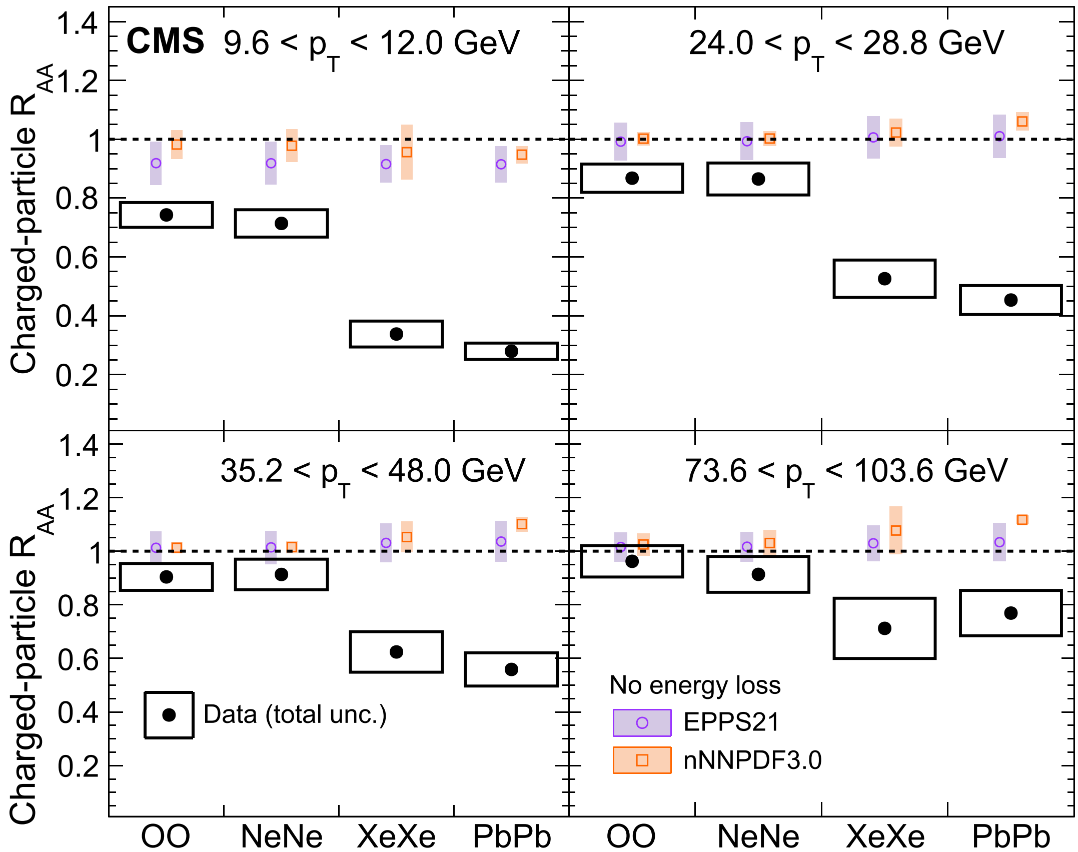

Fig. 3. Comparison of the charged-particle R_{AA} measured in OO [22], NeNe, XeXe [9], and PbPb [12] collisions with NLO pQCD calculations that incorporate only initial-state effects through nPDFs and do not include parton energy loss [57,58]. The open boxes with black circular markers represent the 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.

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 supplementary material Section 6. A comparison of the theoretical calculations of R_{AA} as a function of p_T can be found in supplementary material Section 5.

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 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.

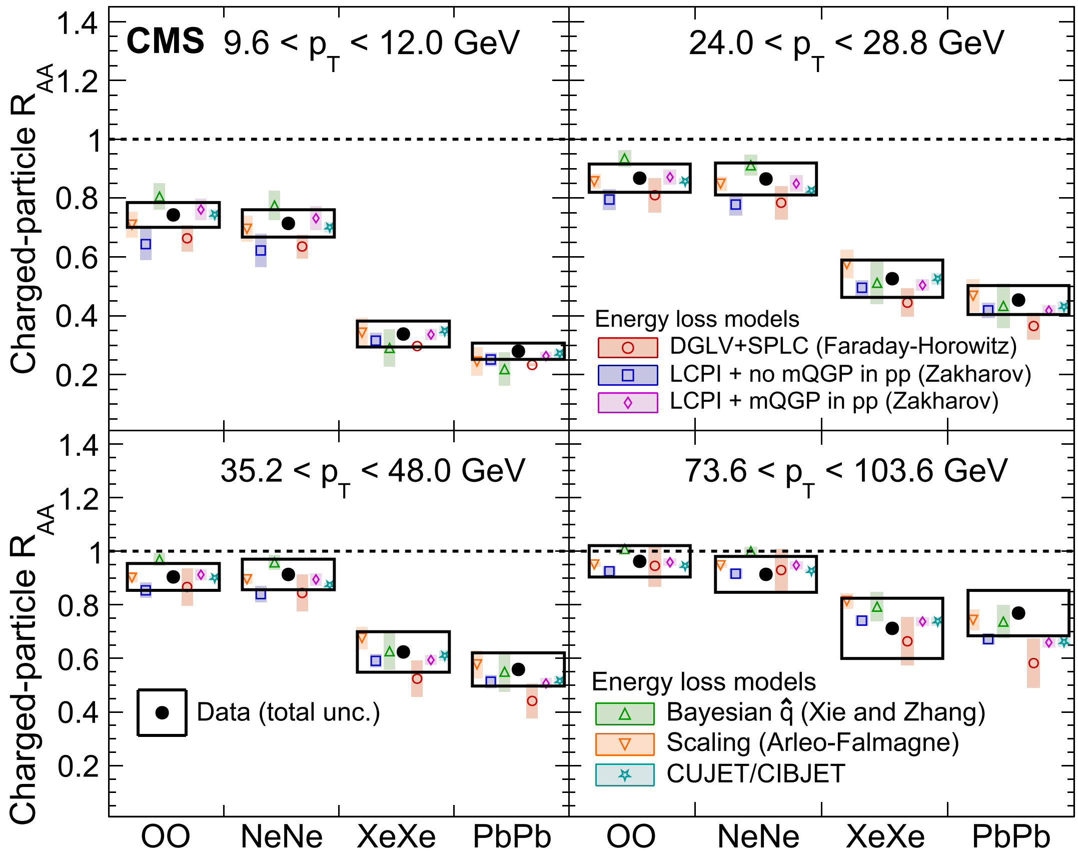

Fig. 4. Comparison of the charged-particle R_{AA} measured in OO [22], NeNe, XeXe [9], and PbPb [12] collisions with calculations that incorporate parton energy loss effects [61–69]. The open boxes with black circular markers represent the data, with the box height indicating the total experimental uncertainty 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.

Comparisons with theoretical calculations show that baseline perturbative quantum chromodynamics predictions incorporating nuclear parton distribution functions predict only modest modifications relative to $R_{AA} = 1$, 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.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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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.

Supplementary material

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