EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH (CERN)

CERN-EP-2025-226
2025/10/10

CMS-HIN-25-008

arXiv:submit/6878155 [nucl-ex] 10 Oct 2025

Discovery of suppressed charged-particle production in ultrarelativistic oxygen-oxygen collisions

The CMS Collaboration*

Abstract

A hot and dense state of nuclear matter, known as the quark-gluon plasma, is created in collisions of ultrarelativistic heavy nuclei. Highly energetic quarks and gluons, collectively referred to as partons, lose energy as they travel through this matter, leading to suppressed production of particles with large transverse momenta (p_{T}). Conversely, high-p_{T} particle suppression has not been seen in proton-lead collisions, raising questions regarding the minimum system size required to observe parton energy loss. Oxygen-oxygen (OO) collisions examine a region of effective system size that lies between these two extreme cases. The CMS detector at the CERN LHC has been used to quantify charged-particle production in inclusive OO collisions for the first time via measurements of the nuclear modification factor (R_{AA}). The R_{AA} is derived by comparing particle production to expectations based on proton-proton (pp) data and has a value of unity in the absence of nuclear effects. The data for OO and pp collisions at a nucleon-nucleon center-of-mass energy $\sqrt{s_{_{\mathrm{NN}}}} = 5.36\,\mathrm{TeV}$ correspond to integrated luminosities of $6.1\,\mathrm{nb}^{-1}$ and $1.02\,\mathrm{pb}^{-1}$, respectively. The R_{AA} is below unity with a minimum of 0.69 ± 0.04 around $p_{\mathrm{T}} = 6\,\mathrm{GeV}$. The data exhibit better agreement with theoretical models incorporating parton energy loss as compared to baseline models without energy loss.

Submitted to Physical Review Letters

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In high-energy collisions of heavy nuclei, a medium consisting of a hot and dense state of nuclear matter with deconfined quarks and gluons, known as the quark-gluon plasma (QGP), is created [1, 2]. The QGP exhibits many striking properties, including fluid-like collective behavior as well as mass- and flavor-dependent modification of particle production when compared to expectations based on proton-proton (pp) data [3–8]. Understanding the dynamics of these phenomena and how they emerge from the underlying theory of the strong force, quantum chromodynamics (QCD) [9, 10], is a key goal of modern high-energy nuclear physics.

The microscopic structure of the QGP at short length scales, where individual quark and gluon degrees of freedom are most salient, is experimentally accessible through the examination of high-momentum scattering processes that can happen concurrently with QGP production [11]. The scattered quarks and gluons, collectively known as partons, can interact with the QGP and lose energy via collisional and radiative processes [12]. This parton energy loss causes "jet quenching", a term used to describe the resulting modification of yields, energies, and spatial distributions of particles originating from the initial scattered parton [13].

In hadron collider experiments, particles having transverse momentum (p_{T}) greater than a few GeV are almost entirely produced via the fragmentation and hadronization of high-energy partons. Thus, high-p_{T} particle spectra are sensitive to parton energy loss effects. Modifications of these spectra are typically quantified using a ratio between the spectra of interest and a baseline found using pp collisions at the same center-of-mass energy per nucleon pair ($\sqrt{s_{_{\mathrm{NN}}}}$). Specifically, the relevant pp spectrum is scaled to account for the larger number of nucleon-nucleon interactions in a nucleus-nucleus collision. Early measurements of this ratio, known as the nuclear modification factor (R_{AA}), at the CERN SPS [14, 15], the BNL RHIC [5–8], and the CERN LHC [16–18] were among the first indications of jet quenching at their respective collision energy scales. More recent charged-particle R_{AA} measurements at the LHC using lead (^{208}Pb) collisions at $\sqrt{s_{_{\mathrm{NN}}}} = 5.02\,\mathrm{TeV}$ [19–21] and xenon (^{129}Xe) collisions at 5.44 TeV [21–23] found R_{AA} to be in the range of 0.2–0.3 for particles with p_{T} around 8 GeV, indicating significant jet quenching effects in collisions of heavy nuclei.

In small collision systems, e.g., pp and pPb, observations of QGP-like effects including collectivity [24] and the enhanced production of strange hadrons [25, 26], have prompted questions of whether a small droplet of QGP can be produced in such collisions [27]. However, jet quenching has not been observed in these systems [28–31], and the pPb R_{AA} is close to unity at particle $p_{\mathrm{T}} > 2\,\mathrm{GeV}$ [19, 21, 32]. The absence of a jet quenching signal could be attributable to a lack of QGP production, or alternatively, the very short path length a parton would have to traverse to exit a QGP droplet. It has been proposed to experimentally test the latter hypothesis using collisions of light nuclei having low nuclear mass number (A). Such collisions will potentially create a QGP volume in between those of pPb and heavier ion collisions [33]. These intermediate systems are also less sensitive to initial-state energy density fluctuations that hinder theoretical descriptions of smaller systems [34, 35]. Theoretical models incorporating jet quenching have predicted charged-particle R_{AA} suppression that should be experimentally accessible, of the order of 25% for $\mathrm{A} = 16$ at LHC energies [33, 36–38].

In 2025, the LHC delivered TeV-scale collisions of ^{16}O nuclei for the first time. This Letter presents the first measurement of the p_{T}-differential cross section of charged-particle production in oxygen-oxygen (OO) collisions at $\sqrt{s_{_{\mathrm{NN}}}} = 5.36\,\mathrm{TeV}$ using data collected by the CMS experiment. A reference spectrum measured using pp data from 2024 at the same collision energy is also reported. The charged-particle R_{AA} for inclusive OO collisions is then constructed using the following definition:

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

where σ^{AA} (σ^{pp}) is the cross section for charged-particle production in nucleus-nucleus (pp) collisions. Notably, because the prefactor accounting for the number of nucleons in ^{16}O is exact, this formulation does not contain any model-dependent uncertainties, e.g., from Glauber modeling [39, 40]. The OO data are compared to other collision systems at similar $\sqrt{s_{_{NN}}}$, as well as predictions from theoretical models. Tabulated results are provided in the HEPData record for this analysis [41].

A description of the CMS detector and the Monte Carlo (MC) simulations used to evaluate its performance can be found in Appendix A.1. The pp data were collected using a trigger that only required two coincident colliding bunches in the detector, while the OO data were collected using a trigger that searched for one or more energy deposits of at least 7 GeV in either of the forward hadron (HF) calorimeters. The total integrated luminosity utilized was $1.02 \pm 0.03\,\mathrm{pb}^{-1}$ for the pp sample and $6.1 \pm 0.2\,\mathrm{nb}^{-1}$ for the OO sample. These values are determined by combining two independent measurements. The first is a preliminary analysis of van der Meer scan [42, 43] data. A second luminosity determination was conducted using a method that compares observed Z boson yields to a well-calibrated reference dataset [44]. The luminosities extracted from both methods are in good agreement with each other.

The average number of interactions per bunch crossing (μ), typically referred to as pileup, was 4.7 and 0.14 for the pp and OO datasets, respectively. While pileup effects are negligible for OO collisions, the pp data are corrected for pileup effects by repeating the measurement using subsets taken at different times. These subsets sample μ ranging from 1.0 to 7.6 and are used to extrapolate to $\mu \approx 0$. This is a 1.2% correction to the pp and R_{AA} results.

Collision events are required to have at least one primary vertex [45] formed from two tracks within 15 cm of the detector center in the z direction. Additionally, OO events are required to produce energy deposits above 13 GeV in one or more detector elements on each side of the HF. These requirements result in a selection inefficiency below 1% for events producing a charged particle having $p_T > 3$ GeV and pseudorapidity $|\eta| < 1$, and a correction for the remaining inefficiency is applied. Similarly, residual contamination from ultraperipheral events [46] is found to be negligible for this measurement. Ion beam contamination resulting from electromagnetic dissociation processes [47] of ^{16}O was found to be negligible for this analysis by studying the time-dependence of event activity distributions [48].

The measurements reported here are for charged primary particles, which are defined as all charged particles having an average proper lifetime $c\tau > 1$ cm. Particles that result from secondary decays are not considered primary if the parent particle is classified as primary. Charged particles are examined using the hits they leave in the silicon tracker. Tracks and the vertices from which they originate are reconstructed using algorithms discussed in Ref. [45]. Tracks must satisfy the "high purity" selection described therein to reduce contamination resulting from spurious tracks not associated with a charged particle, also known as misreconstruction. Only tracks in the ranges $|\eta| < 1$ and $3.0 < p_T < 103.6$ GeV are used. If a track has $p_T > 10$ GeV, the relative uncertainty in its p_T is required to be less than 10%, as determined by the track fit. The misreconstruction rate of tracks is found to be below 1% in simulation. To enhance the fraction of tracks that correspond to primary particles, the analysis only considers tracks having a distance of closest approach (DCA) to any primary vertex less than three times the associated DCA uncertainty in both the x-y plane and z direction. In simulation, contamination effects from secondary particles are around 0.5% after these selections. To facilitate cancellation of reconstruction effects and uncertainties when formulating the R_{AA} observable, identical track reconstruction procedures and selections are applied to both pp and OO datasets.

The resulting tracking efficiency is evaluated using the PYTHIA [49] generator for pp collisions and using PYTHIA overlaid with HIJING [50] for OO collisions. For a majority of particles considered ($\pi^{\pm}$, $\mathrm{K}^{\pm}$, p, and $\overline{\mathrm{p}}$), the efficiency is approximately constant at 90% in both collision systems. Charged strange baryons ($\Sigma^{\pm}$, Ξ^{-}, Ω^{-}, and their antiparticles) have lifetimes long enough to be considered primary particles, but mostly decay before traversing enough of the tracker to be reconstructed. PYTHIA underestimates the production rates of strange particles in pp [20] and pPb [26] collisions, resulting in a slight overestimation of the tracking efficiency. To account for this effect, the relative production rates of different particle types in simulation are weighted to match those in 7 TeV pp data [51, 52] using a procedure similar to the one outlined in Ref. [20]. In pp collisions, this reduces the overall charged-particle reconstruction efficiency calculated using PYTHIA by around 6% at $p_{\mathrm{T}} = 3\,\mathrm{GeV}$ but results in a less than 1% difference for $p_{\mathrm{T}} > 8\,\mathrm{GeV}$. For OO collisions, a similar procedure is used with an additional extrapolation factor, based on control samples in data, that accounts for expected differences between the OO and pp data. Motivated by measurements [26, 53] indicating that the hadron composition of an event scales in a universal way with charged-particle density, $\mathrm{d}N_{\mathrm{ch}}/\mathrm{d}\eta$, this factor estimates the change of light-hadron production rates with event activity. Specifically, the particle abundances used to weight the simulation are scaled in a p_{T}-independent manner from a pp-like working point of $\mathrm{d}N_{\mathrm{ch}}/\mathrm{d}\eta = 8$ to the measured value for inclusive OO collisions of $\mathrm{d}N_{\mathrm{ch}}/\mathrm{d}\eta \approx 40$ [54]. This amounts to an additional 3% correction at $p_{\mathrm{T}} = 3\,\mathrm{GeV}$ which decreases to below 1% for $p_{\mathrm{T}} > 10\,\mathrm{GeV}$. To compensate for track reconstruction inefficiencies, residual track misreconstruction effects, and secondary-track contamination, correction factors are applied on a track-by-track basis as functions of p_{T} and η.

The uncertainty in the tracking efficiency due to the particle composition weighting procedure has two components. The first is calculated by propagating the experimental uncertainties in the input pp data through the entire procedure. This uncertainty is less than 2.0% for $p_{\mathrm{T}} > 10\,\mathrm{GeV}$ in the pp and OO cross sections but fully cancels in R_{AA}. The second component results from the extrapolation procedure used to account for differences between OO and pp data. This component is calculated by examining two variations: one with no extrapolation and one where the extrapolation goes to $\mathrm{d}N_{\mathrm{ch}}/\mathrm{d}\eta = 100$, corresponding to the density expected in the most head-on OO collisions. This uncertainty, which is only applicable to the OO spectra and R_{AA} measurements, is 3% at $p_{\mathrm{T}} = 3\,\mathrm{GeV}$ and less than 1% at $p_{\mathrm{T}} > 10\,\mathrm{GeV}$. The uncertainty caused by potential mismodeling of the tracking efficiency in simulation (other than the previously discussed differences in the types of particles produced) is evaluated by comparing the relative reconstruction efficiencies of pions coming from different D^0 meson decays [55] in 13 TeV pp data. This uncertainty is 2.1% for both pp and OO collisions and cancels fully when calculating R_{AA}. To study the sensitivity of the measurement to secondary-track backgrounds, the analysis is repeated after changing the DCA selection to require tracks to have less than two or five times their DCA uncertainty. The maximum of the two variations is taken as a systematic uncertainty and is up to 3.5% in pp and 5.6% in OO collisions. This uncertainty is under 3.5% for R_{AA} because of partial cancellations. The pp pileup correction factor of 1.2% is taken as an uncertainty for the pp spectrum and R_{AA} measurements. The uncertainty attributed to bin migration effects caused by finite track p_{T} resolution is less than 1% for the spectra measurements and fully cancels in the R_{AA} measurement. Uncertainties resulting from the luminosity calibrations are not included in the total systematic uncertainty but are reported as a separate normalization uncertainty that is fully correlated across all p_T values probed. Summaries of the systematic uncertainties as functions of p_T are provided in Appendix A.2.

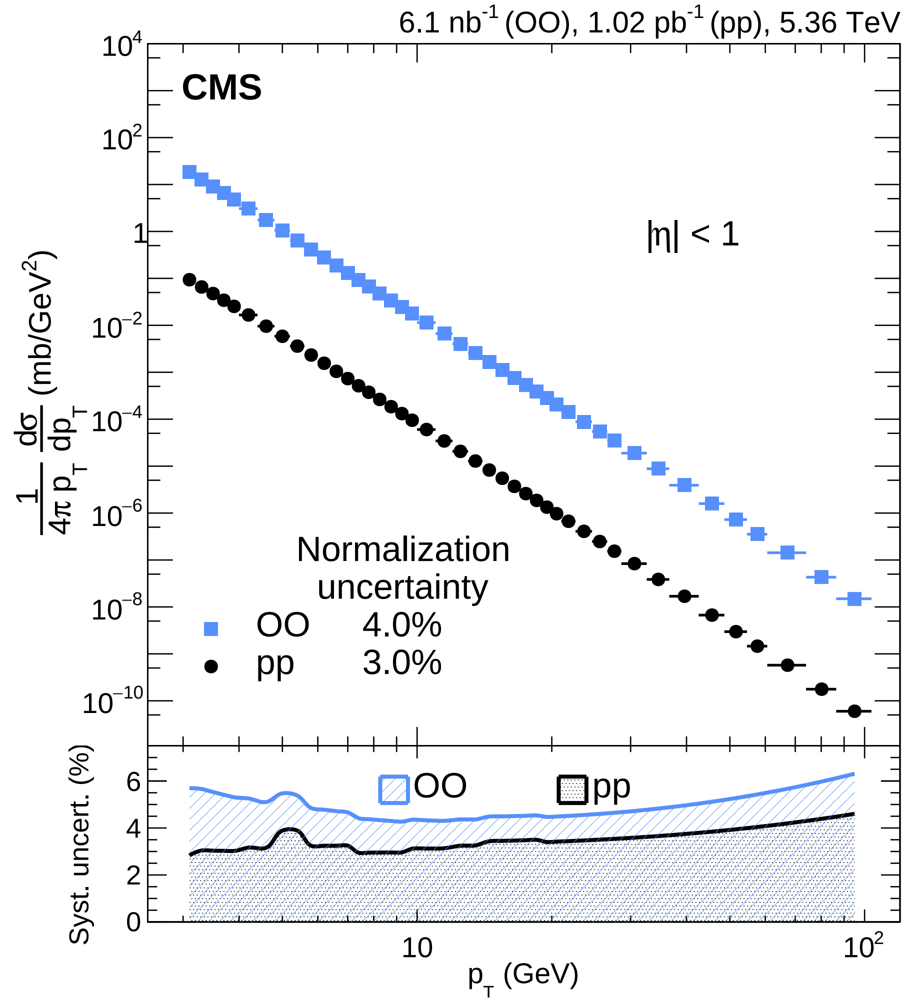

Figure 1: The charged-particle p_T-differential invariant cross sections for pp (black circles) and OO (blue squares) collisions. The markers show the average cross section across the entire bin width, not the cross section value at the center of each bin. Statistical uncertainties are smaller than the markers.

The charged-particle p_T-differential cross sections are reported in Fig. 1. The cross sections are scaled by $1/(4\pi p_T)$ so that they are reported within a Lorentz-invariant phase space. Systematic uncertainties, excluding the luminosity uncertainties, are shown in the lower panel. Both spectra exhibit roughly power law behavior, which is consistent with previous measurements of charged-particle spectra at these energies [19, 22, 29, 56, 57].

The solid markers in Fig. 2 display the measured charged-particle R_{AA} for inclusive OO collisions. The R_{AA} shows significant p_T dependence, with the lowest p_T data having R_{AA} around 0.77. As the probed p_T increases, the R_{AA} exhibits a local minimum at around $p_T = 6\,\text{GeV}$ before increasing to a value consistent with unity at p_T values approaching 100 GeV. The R_{AA} value of 0.69 ± 0.04 (systematic, with negligible statistical uncertainty) at the local minimum is more than five standard deviations from unity, making this the first definitive observation of particle suppression in OO collisions. The measurement uncertainty is dominated by uncertainties in the overall normalization of the OO and pp cross sections arising from the luminosity determination. For comparison, previous CMS measurements of the inclusive charged-particle

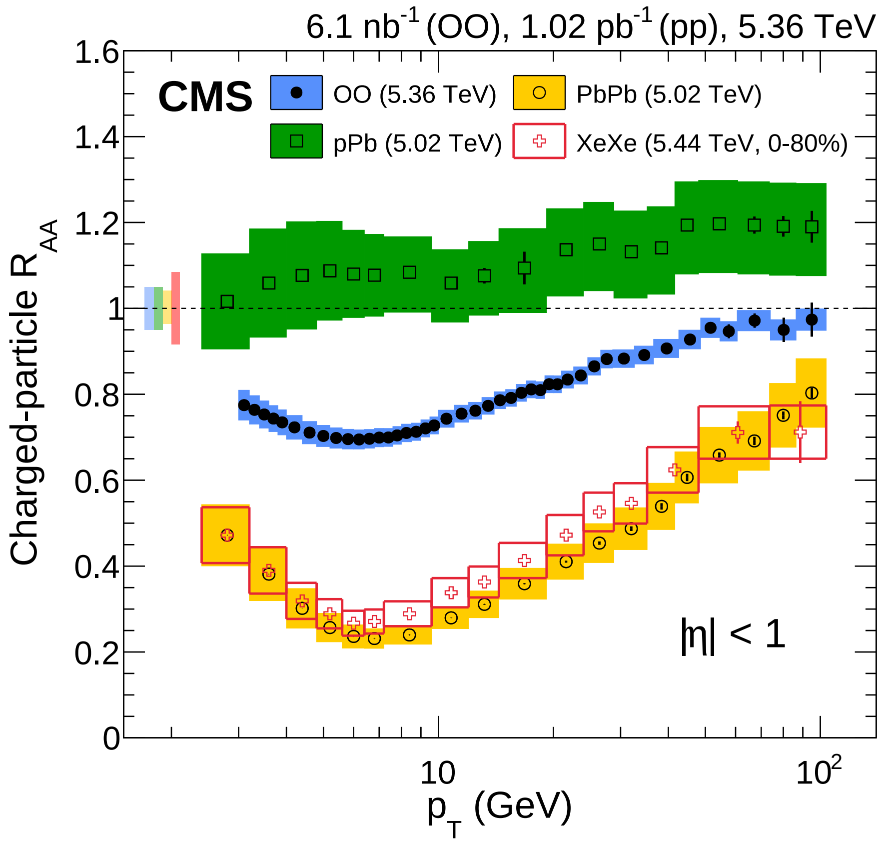

Figure 2: The charged-particle R_{AA} for inclusive 5.36 TeV OO collisions (solid markers) as a function of particle p_T. Error bars represent statistical uncertainties and boxes represent systematic uncertainties not related to the luminosity calibration. The R_{AA} for pPb [19, 29], XeXe [22], and PbPb [19] collisions (open markers) are also shown. Normalization uncertainties are shown by the bands around unity.

R_{AA} are shown for pPb and PbPb collisions at $\sqrt{s_{NN}} = 5.02$ TeV [19, 29], as well as the R_{AA} for XeXe data at $\sqrt{s_{NN}} = 5.44$ TeV [22]. The XeXe sample corresponds to the top 80% most head-on collisions, which is expected to be close to the R_{AA} values for an inclusive event selection. The behavior of the OO R_{AA}, i.e., a downward slope until around 6 GeV followed by an upward trend approaching unity, is qualitatively similar to that observed in larger collision systems such as XeXe and PbPb. In those systems, the downward slope at lower p_T is typically attributed to the p_T-dependence of effects such as Cronin enhancement [58] and radial flow [59, 60], whereas the magnitude and trend of suppression at higher p_T is associated with the strength of parton energy loss. An ordering with collision system size is apparent, with the R_{AA} for pPb collisions being above, and for XeXe and PbPb collisions being below the OO data.

Figure 3 shows a comparison of the OO R_{AA} measurement to theoretical predictions. Models in the upper row of panels will be discussed first. The green line in the upper left panel shows a baseline model that contains no parton energy loss effects: a next-to-leading order (NLO) perturbative QCD (pQCD) calculation [33, 69] that has been interfaced with the EPPS21 nuclear parton distribution functions (nPDFs) [70]. The outer green band represents the 68% confidence level of the nPDF uncertainties, while the inner green band shows scale uncertainties of the calculation. Comparisons to this model with other nPDF choices are shown in Appendix A.3. The green line in the upper right panel shows the same baseline model interfaced with a parton en-

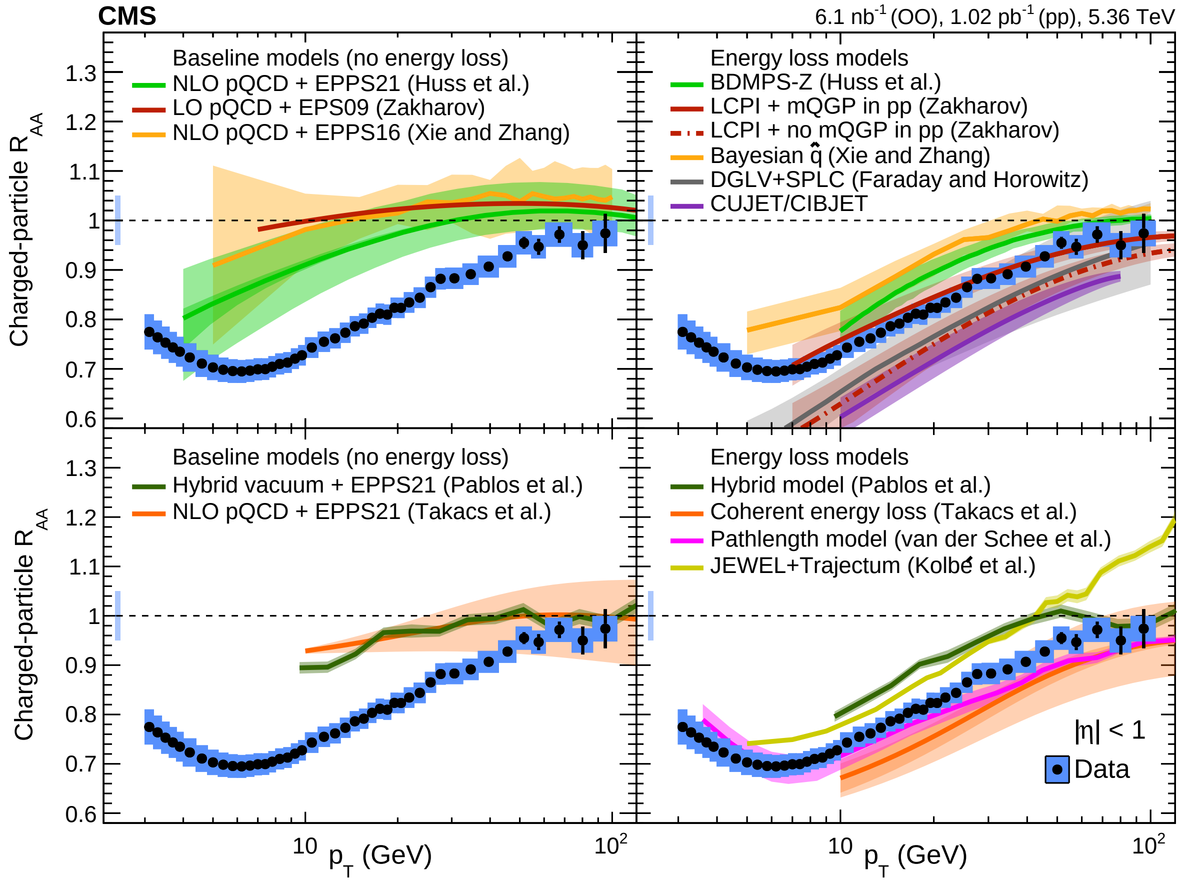

Figure 3: Comparison of the OO R_{AA} measurement to various theoretical predictions [33, 36, 37, 61–69]. Models in the left panels are baselines that do not include parton energy loss, while models on the right include energy loss. The normalization uncertainty of the measurement is shown by the band around unity.

ergy loss model using the BDMPS-Z framework [36]. Some suppression of the R_{AA}, particularly in the range of $p_T < 20$ GeV, can clearly be attributed to the baseline model, but the inclusion of energy loss effects brings the model closer to the data. The red line in the upper left panel shows a leading order calculation [37] interfaced with the EPS09 [71] nPDF set. This model predicts a similar high-p_T baseline but is less suppressed at lower p_T values as compared to the one using EPPS21. The red lines in the upper right panel shows the same model combined with the LCPI energy loss framework [37]. The solid and dashed lines show scenarios where a QGP droplet, denoted as “mQGP”, is or is not created in pp collisions, respectively. The inclusion of energy loss effects clearly improves the agreement with the data, with the measurement favoring the scenario where a QGP droplet is formed in pp collisions. The yellow band in the upper left panel shows a NLO pQCD model using the EPPS16 [72] nPDF set. Here, the band represents a 90% confidence interval. Similar high p_T behavior is seen as in the other baseline models, and less suppression is predicted at low p_T, as compared to EPPS21. In the upper right panel, this model is combined with the CLVisc (3+1)D hydrodynamics model [73], and energy loss is included via the incorporation of a jet transport coefficient $\hat{q}$ that is determined using Bayesian inference techniques [61]. The uncertainty band illustrates the 90% confidence interval resulting from variations in $\hat{q}$. This model seems to qualitatively capture the shape of the data but predicts a smaller suppression magnitude. The purple and gray bands show models that do not include nPDF effects, i.e., the baseline without energy loss is equal to unity. The purple band illustrates a prediction from the CUJET/CIBJET model [62, 63], which combines viscous hydrodynamics with a DGLV theory of energy loss [74, 75]. The uncertainty band reflects variations in the strong coupling constant used. This model predicts a stronger suppression than what is observed. A similar model utilizing DGLV radiative energy loss combined with collisional energy loss and an additional short path length correction (SPLC) for small systems is shown by the gray band [68]. The uncertainty reflects variations induced by the choice of the cutoff momentum scales used. The central values give smaller R_{AA} compared to data, but the two are largely consistent within uncertainties for $p_T > 20\,\mathrm{GeV}$.

The lower row of panels in Fig. 3 shows additional comparisons. The dark-green band in the lower left panel shows a baseline calculation without energy loss effects that uses EPPS21. In the lower right panel, the Hybrid model [64] has been used to add energy loss effects. In this implementation, the Hybrid model is run using event-by-event hydrodynamics profiles [76]. Although the presence of energy loss effects causes a suppression of the R_{AA}, the predicted values are still above the data for most of the p_T range examined. The orange band in the lower left panel illustrates a NLO pQCD baseline model [65] interfaced with EPPS21. In the lower right panel, this model has energy loss effects added by coupling the model to event-by-event hydrodynamics simulations and including coherent energy loss [66, 77–79]. The model is consistent with the data within the uncertainties, although its central values illustrate a slightly more pronounced p_T-dependence. The dark-yellow band in the lower right panel shows the JEWEL [67] MC generator which has been interfaced with the TRAJECTUM code [67, 80–82]. The model predicts a larger R_{AA} value as compared to the data, with the values exceeding unity at high p_T. The JEWEL generator is expected to perform better when examining jets rather than individual hadrons, which could explain this behavior. The pink band in the lower right panel shows a model that extrapolates from PbPb R_{AA} values using a path length integral and the temperature profile experienced by partons as they travel through the medium, as calculated using TRAJECTUM [67, 81–83]. This last model describes the data well.

The comparisons with models reveal conclusions that appear to be independent of the exact details of the model examined. Firstly, the role of nPDFs is clearly important—the oxygen nPDF alone can potentially cause an R_{AA} suppression up to half of that seen in data. Further nPDF constraints coming from the recently-collected LHC OO and pO datasets may improve this in the future. Secondly, models including energy loss effects describe R_{AA} better than baseline models. Most models capture the p_T-dependent shape of R_{AA} for $p_T > 10\,\mathrm{GeV}$, but a sizable spread exists in the predicted scale of R_{AA}. Overall, the data are consistent with the presence of parton energy loss effects in OO collisions, and this measurement places quantitative constraints on models incorporating energy loss in small collision systems.

In summary, we report the first measurement of the charged-particle nuclear modification factor (R_{AA}) as a function of transverse momentum (p_T) in oxygen-oxygen collisions at a center of mass energy per nucleon pair of 5.36 TeV. The R_{AA} is significantly suppressed and reaches a minimum of 0.69 ± 0.04 around $p_T = 6\,\mathrm{GeV}$. However, R_{AA} rises to become consistent with unity for p_T values approaching 100 GeV. Comparisons with previous measurements of other collision systems reveal a system-size dependence of R_{AA} suppression in nuclear collisions. The data are more consistent with theoretical models that incorporate parton energy loss effects as compared to baseline models without energy loss, supporting the hypothesis that a medium of sufficient size to give rise to observable parton energy loss is created. This measurement constrains models attempting to predict jet quenching in small systems and represents an important first step towards the realization of a physics program examining collisions of light nuclei at TeV-scale energies.

Acknowledgments

We congratulate our colleagues in the CERN accelerator departments for the excellent performance of the LHC and thank the technical and administrative staffs at CERN and at other CMS institutes for their contributions to the success of the CMS effort. In addition, we gratefully acknowledge the computing centers and personnel of the Worldwide LHC Computing Grid and other centers for delivering so effectively the computing infrastructure essential to our analyses. Finally, we acknowledge the enduring support for the construction and operation of the LHC, the CMS detector, and the supporting computing infrastructure provided by the following funding agencies: SC (Armenia), BMBWF and FWF (Austria); FNRS and FWO (Belgium); CNPq, CAPES, FAPERJ, FAPERGS, and FAPESP (Brazil); MES and BNSF (Bulgaria); CERN; CAS, MoST, and NSFC (China); MINCIENCIAS (Colombia); MSES and CSF (Croatia); RIF (Cyprus); SENESCYT (Ecuador); ERC PRG, TARISTU24-TK10 and MoER TK202 (Estonia); Academy of Finland, MEC, and HIP (Finland); CEA and CNRS/IN2P3 (France); SRNSF (Georgia); BMFTR, DFG, and HGF (Germany); GSRI (Greece); NKFIH (Hungary); DAE and DST (India); IPM (Iran); SFI (Ireland); INFN (Italy); MSIT and NRF (Republic of Korea); MES (Latvia); LMTLT (Lithuania); MOE and UM (Malaysia); BUAP, CINVESTAV, CONACYT, LNS, SEP, and UASLP-FAI (Mexico); MOS (Montenegro); MBIE (New Zealand); PAEC (Pakistan); MES, NSC, and NAWA (Poland); FCT (Portugal); MESTD (Serbia); MICIU/AEI and PCTI (Spain); MOSTR (Sri Lanka); Swiss Funding Agencies (Switzerland); MST (Taipei); MHESI (Thailand); TUBITAK and TENMAK (Türkiye); NASU (Ukraine); STFC (United Kingdom); DOE and NSF (USA).

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A Additional material

A.1 Description of the CMS detector

The CMS apparatus [84, 85] is a multipurpose, nearly hermetic detector, designed to trigger on [86–88] and identify electrons, muons, photons, and hadrons [45, 89, 90]. A global "particle-flow" algorithm [91] aims to reconstruct all individual particles in an event, combining information provided by the all-silicon inner 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 [92] measures charged particles up to $|\eta| = 3.0$ with typical resolutions of 2.0% in p_{T} and 10–75 μm in the transverse impact parameter [93] for nonisolated particles of $1 < p_{\mathrm{T}} < 100\,\mathrm{GeV}$. The hadron forward 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, and together they provide coverage in the range $3.0 < |\eta| < 5.2$.

Simulated MC samples are used to evaluate detector performance and calculate correction factors. For pp collisions, the PYTHIA 8.311 event generator [49] with the CP5 tune [94] is employed. To study OO collisions, a PYTHIA event is overlaid with an OO HIJING v1.383 [50] event to form a composite event containing both a hard scattering process as well as particle production from the underlying event. Potential contamination from ultraperipheral collisions [46] is studied using STARLIGHT v3.3.0 [95]. The GEANT4 [96] program is used to simulate the CMS detector response. After event generation, an event-by-event weight is used to ensure that the distribution of the z position of reconstructed primary interaction points in simulation matches that in data.

A.2 Summaries of the uncertainties

A visual summary of the systematic uncertainties relevant for the spectra measured in this analysis is shown in Fig. A.1. The integrated luminosity uncertainty is reported as a separate uncertainty and is not included in the total coming from other sources. The non-monotonic behavior at lower p_T values results from propagating the experimental uncertainties of the input ALICE data used for the particle species correction. Figure A.2 shows a similar summary for the R_{AA} measurement after correlations between the OO and pp measurements are taken into account.

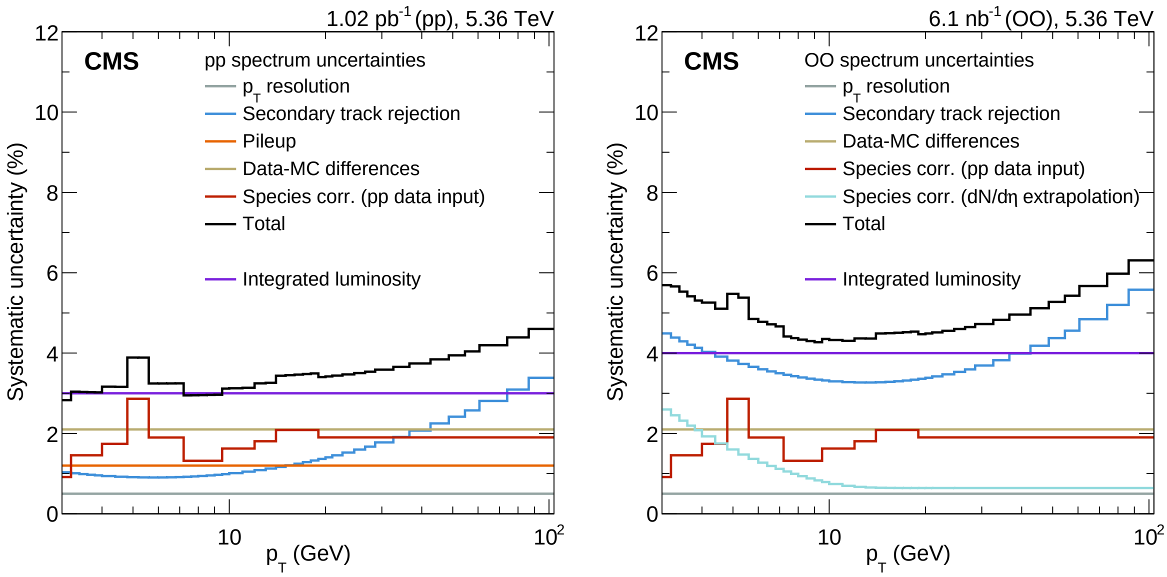

Figure A.1: Systematic uncertainties related to the 5.36 TeV pp (left) and OO (right) cross section measurements, presented as a function of p_T.

A.3 Comparison to different nPDF models

Figure A.3 shows the baseline model described in Refs. [33, 69] with three different nPDF hypotheses. The data lie under all three nPDF choices. The EPPS21 model predicts the strongest nPDF modification of R_{AA}, whereas the nNNPDF3.0 [97] and TUJU21 [98] nPDF sets predict a rather modest suppression effect. TUJU21 currently does not include LHC data having hadronic final states. These data tend to favor a stronger shadowing of the gluon nPDF, so this difference could potentially explain why TUJU21 and EPPS21 predict different behavior [99]. EPPS21 and nNNPDF3.0 include similar data in their global fits, but the models predict different A-dependence of nPDF modifications. In particular, nuclear effects tend to be smaller for low-A nuclei in nNNPDF3.0 as compared to EPPS21 [100].

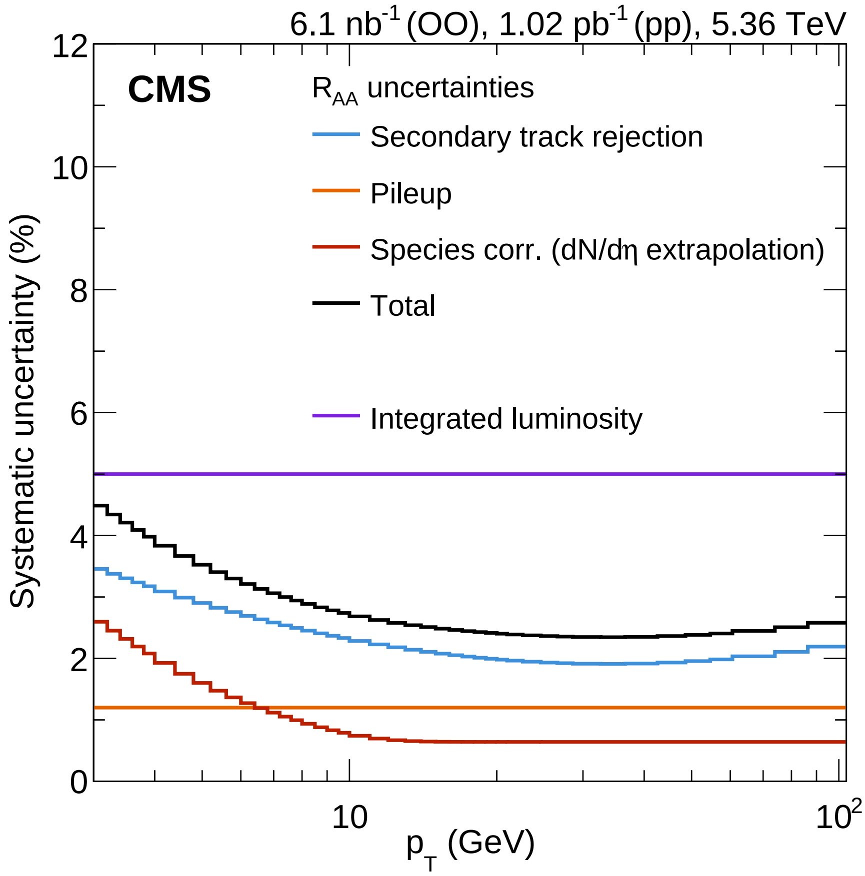

Figure A.2: Systematic uncertainties related to the measurement of R_{AA} for 5.36 TeV OO collisions, presented as a function of p_{T}.

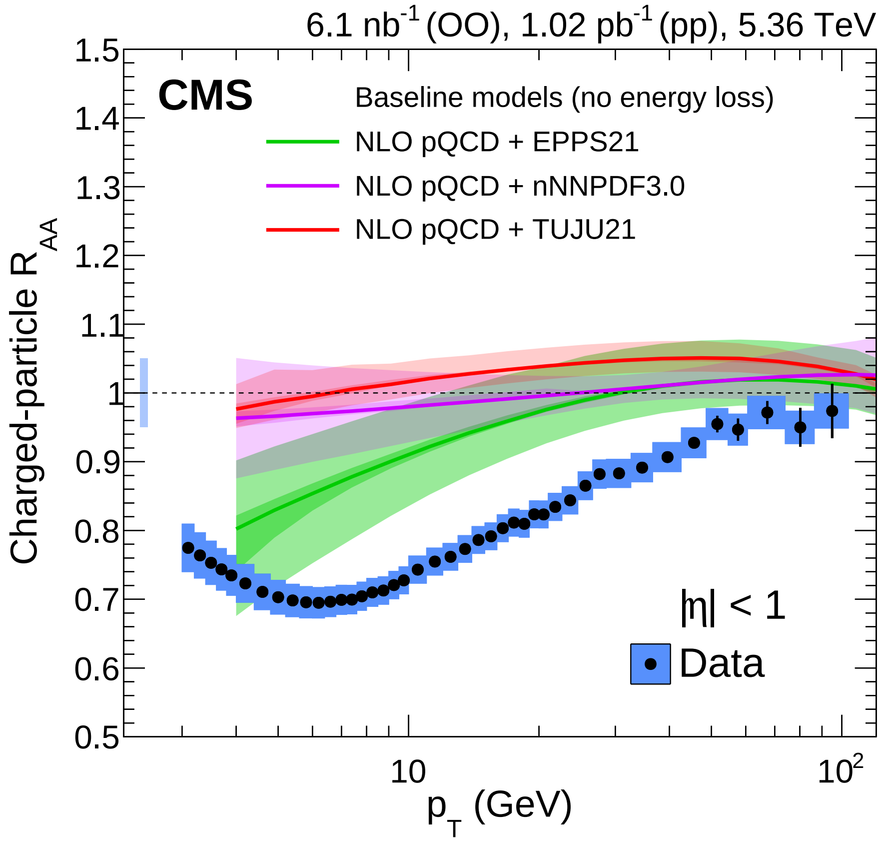

Figure A.3: Comparison of the OO R_{AA} to a theoretical model [33] without energy loss effects that uses three different nPDF choices [70, 97, 98].

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