


## Observation of Suppressed Charged-Particle Production in Ultrarelativistic Oxygen-Oxygen Collisions

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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  $\sqrt{s_{NN}} = 5.36$  TeV correspond to integrated luminosities of  $6.1 \text{ nb}^{-1}$  and  $1.02 \text{ pb}^{-1}$ , respectively. The  $R_{AA}$  is below unity with a minimum of  $0.69 \pm 0.04$  around  $p_T = 6$  GeV. The data exhibit better agreement with theoretical models incorporating parton energy loss as compared to baseline models without energy loss.

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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 ( $\sqrt{s_{NN}}$ ). 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 super proton synchrotron [14,15], the relativistic heavy ion collider (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 ( $^{208}\text{Pb}$ ) collisions at  $\sqrt{s_{NN}} = 5.02$  TeV [19–21] and xenon ( $^{129}\text{Xe}$ ) 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  $p\text{Pb}$ , observations of QGP-like effects, including collectivity [24] and the enhanced production of strange hadrons [25,26], have

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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  $p\text{Pb}$   $R_{\text{AA}}$  is close to unity at particle  $p_{\text{T}} > 2$  GeV [19,21,32]. A 20% suppression of the  $\pi^0$   $R_{\text{AA}}$  in deuterium-gold collisions was seen at RHIC when selecting events producing large particle multiplicities [33], but questions remain regarding the degree to which these event selections may cause measurement biases [34]. In all of these systems, the absence of a clear 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  $p\text{Pb}$  and heavier ion collisions [35]. These intermediate systems are also less sensitive to initial-state energy density fluctuations that hinder theoretical descriptions of smaller systems [36,37]. Theoretical models incorporating jet quenching have predicted charged-particle  $R_{\text{AA}}$  suppression that should be experimentally accessible, of the order of 25% for  $A = 16$  at LHC energies [35,38–40].

In 2025, the LHC delivered TeV-scale collisions of  $^{16}\text{O}$  nuclei for the first time. This Letter presents the first measurement of the  $p_{\text{T}}$ -differential cross section of charged-particle production in oxygen-oxygen (OO) collisions at  $\sqrt{s_{\text{NN}}} = 5.36$  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  $R_{\text{AA}}$  for inclusive OO collisions is then constructed using the following definition:

$$R_{\text{AA}} = \frac{1}{A^2} \left[ \frac{\left( \frac{d\sigma^{\text{AA}}}{dp_{\text{T}}} \right)}{\left( \frac{d\sigma^{pp}}{dp_{\text{T}}} \right)} \right], \quad (1)$$

where  $\sigma^{\text{AA}}$  ( $\sigma^{pp}$ ) is the cross section for charged-particle production in nucleus-nucleus ( $pp$ ) collisions. Notably, because the prefactor accounting for the number of nucleons in  $^{16}\text{O}$  is exact, this formulation does not contain any model-dependent uncertainties, e.g., from Glauber modeling [41,42]. The OO data are compared to other collision systems at similar  $\sqrt{s_{\text{NN}}}$ , as well as predictions from theoretical models. Tabulated results are provided in the HEPData record for this analysis [43].

A complete description of the CMS apparatus is reported in Refs. [44,45]. A description of the Monte Carlo (MC) simulations used to evaluate detector performance can be found in End Matter (Description of event simulations).

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  $1.02 \pm 0.03$  pb $^{-1}$  for the  $pp$  sample and  $6.1 \pm 0.2$  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 [46,47] data. A second luminosity determination was conducted using a method that compares observed  $Z$  boson yields to a well-calibrated reference dataset [48]. The luminosities extracted from both methods are in good agreement with each other.

The average number of interactions per bunch crossing ( $\mu$ ), 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  $\mu$  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  $R_{\text{AA}}$  results.

Collision events are required to have at least one primary vertex [49] 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  $p_{\text{T}} > 3$  GeV and pseudorapidity  $|\eta| < 1$ , and a correction for the remaining inefficiency is applied. Similarly, residual contamination from ultraperipheral events [50] is found to be negligible for this measurement. Ion beam contamination resulting from electromagnetic dissociation processes [51] of  $^{16}\text{O}$  was found to be negligible for this analysis by studying the time dependence of event activity distributions [52].

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. [49]. 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  $3.0 < p_{\text{T}} < 103.6$  GeV are used. If a track has  $p_{\text{T}} > 10$  GeV, the relative uncertainty in its  $p_{\text{T}}$  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 [53] generator for  $pp$  collisions and using PYTHIA overlaid with HIJING [54] for OO collisions. For a majority of particles considered ( $\pi^\pm$ ,  $K^\pm$ ,  $p$ , and  $\bar{p}$ ), the efficiency is between 89% and 91% in both collision systems. Charged strange baryons ( $\Sigma^\pm$ ,  $\Xi^-$ ,  $\Omega^-$ , 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 [55,56] 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  $p_T = 3$  GeV but results in a less than 1% difference for  $p_T > 8$  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 [26,57] indicating that the hadron composition of an event scales in a universal way with charged-particle density,  $dN_{ch}/d\eta$ , 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  $dN_{ch}/d\eta = 8$  to the measured value for inclusive OO collisions of  $dN_{ch}/d\eta \approx 40$  [58]. This amounts to an additional 3% correction at  $p_T = 3$  GeV, which decreases to below 1% for  $p_T > 10$  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  $\eta$ .

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  $p_T > 10$  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  $dN_{ch}/d\eta = 100$ , 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

$p_T = 3$  GeV and less than 1% at  $p_T > 10$  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 [59] 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. When compared to the  $pp$  spectrum measured at 5.02 TeV by CMS in Ref. [19], the precision achieved for the 5.36 TeV  $pp$  measurement improved from around 7% to about 4% because of a better understanding of the tracking efficiency, a more sophisticated treatment of pileup effects, and new constraints on the particle composition weighting procedure. Summaries of the systematic uncertainties are provided in End Matter (Summaries of the uncertainties).

The  $p_T$ -differential invariant cross sections of charged hadrons are reported in Fig. 1. Both spectra exhibit roughly power law behavior, which is consistent with previous measurements of charged-particle spectra at these energies [19,22,29,60,61].

The measured  $R_{AA}$ , shown in Fig. 2, exhibits 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  $p_T = 6$  GeV before increasing to a value consistent with unity at  $p_T$  values approaching 100 GeV. The  $R_{AA}$  value of  $0.69 \pm 0.04$  (systematic + normalization, 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. For comparison, previous CMS measurements of the inclusive charged-particle  $R_{AA}$  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

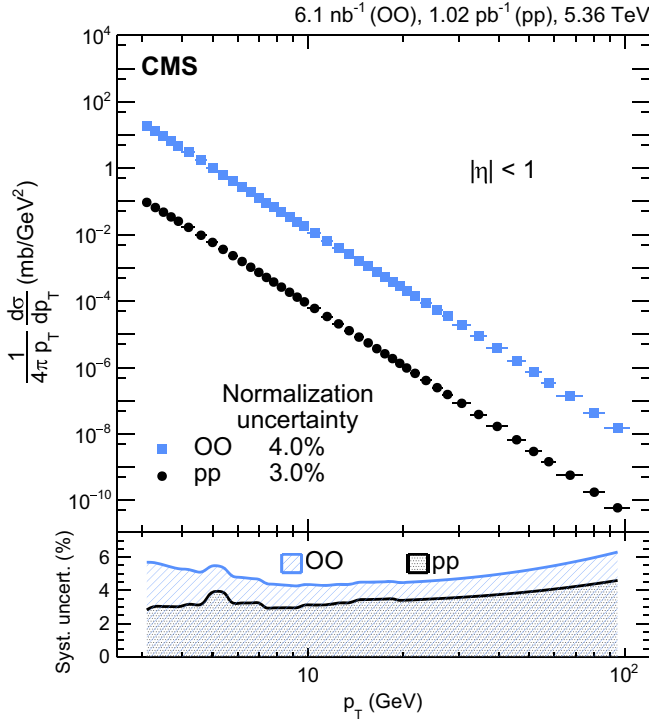


FIG. 1. The charged-particle  $p_T$ -differential invariant cross sections for  $pp$  (black circles) and OO (blue squares) collisions. The markers show the average cross section across the entire bin width, not the cross section value at the center of each bin. Statistical uncertainties are smaller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

$R_{AA}$  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 [62] and radial flow [63,64], 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 compares the OO  $R_{AA}$  to theoretical predictions. Predictions in the left panels do not include parton energy loss, while those in the right panels include energy loss. Model [a] is a next-to-leading order (NLO) perturbative QCD (pQCD) calculation [35,65] interfaced with the EPPS21 nuclear parton distribution functions (nPDFs) [66]. The outer band represents nPDF uncertainties, while the inner band shows scale uncertainties of the calculation. Comparisons to this model with other nPDF choices are shown in Supplemental Material [67], which contains Refs. [68–71]. The model in the left panel does not include parton energy loss effects, but it is interfaced with a parton energy loss model using the BDMPS-Z framework [38] in the right panel. 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

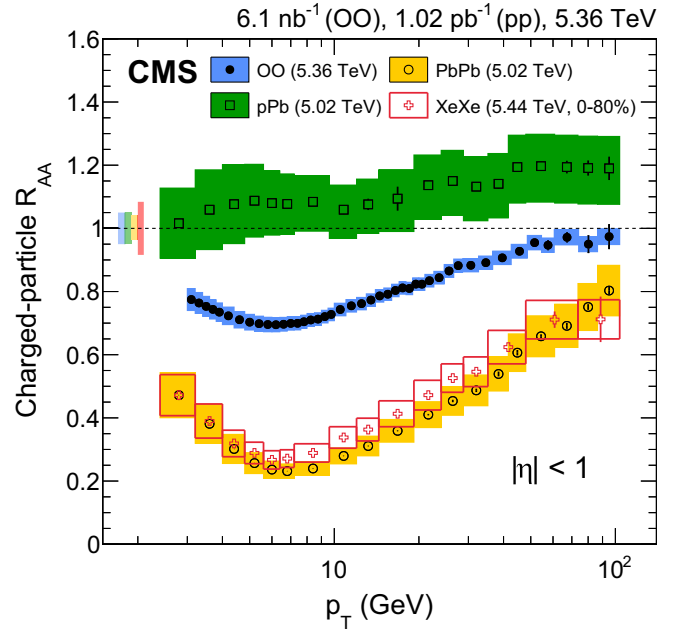


FIG. 2. The charged-particle  $R_{AA}$  for inclusive 5.36 TeV OO collisions (solid markers). Error bars represent statistical uncertainties, and boxes represent systematic uncertainties. The  $R_{AA}$  for  $pPb$  [19,29], XeXe [22], and PbPb [19] collisions (open markers) are also shown. Normalization uncertainties are shown by the bands around unity.

brings the prediction closer to the data. Model [b] is a leading order calculation [39] interfaced with the EPS09 [72] nPDF set. In the right panel, it is combined with the LCPI energy loss framework [39] in two scenarios where a QGP droplet, denoted as “mQGP,” is or is not created in  $pp$  collisions. 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. Model [c] represents an NLO pQCD model using the EPPS16 [73] nPDF set. In the right panel, it is combined with the CLVisc (3 + 1)D hydrodynamics model [74], with energy loss included by incorporating a jet transport coefficient  $\hat{q}$  determined using Bayesian inference techniques [75]. The uncertainty band results from variations in  $\hat{q}$ . This model seems to qualitatively capture the shape of the data but predicts a smaller suppression magnitude. Models [d] and [e] do not include nPDF effects, i.e., the baseline equals unity. Model [d] illustrates the CUJET/CIBJET model [76,77], which combines viscous hydrodynamics with a DGLV theory of energy loss [78,79]. The uncertainty band reflects variations in the strong coupling constant used. Model [e] is similar and utilizes DGLV radiative energy loss combined with collisional energy loss and an additional short path length correction for small systems [80]. The uncertainty reflects variations induced by the choice of the cutoff momentum scales used. Both [d] and [e] predict smaller  $R_{AA}$  compared to data, and [e] is consistent within data within uncertainties for  $p_T > 20$  GeV. Model [f] is an

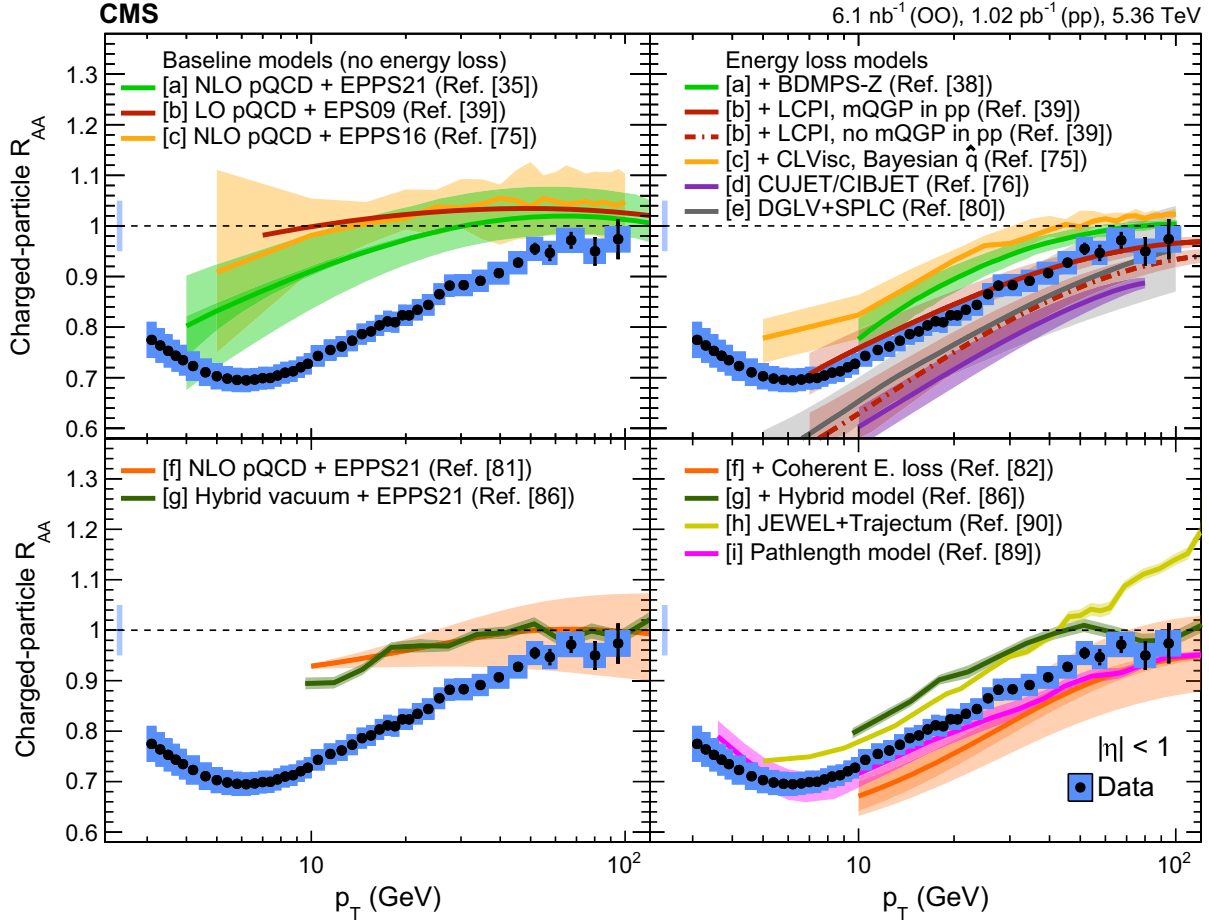


FIG. 3. Comparison of the OO  $R_{AA}$  measurement to various theoretical predictions [35,38,39,65,75–77,80–82,86,89]. The normalization uncertainty of the measurement is shown by the band around unity on the left side of each panel. The uncertainty bands around the predictions indicate 68% confidence limit intervals, except for model [c], where they indicate a 90% interval.

NLO pQCD baseline model [81] interfaced with EPPS21, and the width of the corresponding band shows nPDF and scale uncertainties. Energy loss effects are added in the right panel by coupling the model to event-by-event hydrodynamics simulations and including coherent energy loss [82–85]. The darker band represents an additional uncertainty obtained by varying the model parameters after they were constrained using a Bayesian fit to previously measured hadron spectra. The prediction is consistent with the data within the uncertainties, although its central values illustrate a slightly more pronounced  $p_T$  dependence. Model [g] represents a baseline calculation that uses EPPS21. On the right, the Hybrid model [86] has been used to add energy loss effects using event-by-event hydrodynamics profiles [87]. 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. Model [h] is the JEWEL [88] MC generator, which has been interfaced with the TRAJECTUM code [89–92]. It 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. Note that only statistical uncertainties are shown for the Hybrid model, its baseline, and JEWEL + TRAJECTUM, while other uncertainties were neglected. Model [i] 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 [89,91–93]. It 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  $p_T > 10$  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  $0.69 \pm 0.04$  around  $p_T = 6$  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 toward the realization of a physics program examining collisions of light nuclei at TeV-scale energies.

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*Data availability*—Release and preservation of data used by CMS Collaboration as the basis for publications is guided by the CMS data preservation, reuse, and open access policy [94].

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## End Matter

*Description of event simulations*—Simulated MC samples are used to evaluate detector performance and calculate correction factors. For  $pp$  collisions, the PYTHIA 8.311 event generator [53] with the CP5 tune [95] is employed. To study OO collisions, a PYTHIA event is overlaid with an OO HIJING v1.383 [54] 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 [50] is studied using STARlight v3.3.0 [96]. The GEANT4 [97] 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.

*Summaries of the uncertainties*—A visual summary of the systematic uncertainties relevant for the spectra measured in this analysis is shown in Fig. 4. The integrated luminosity uncertainty is reported as a separate uncertainty and is not included in the total coming from other sources. The nonmonotonic behavior at lower  $p_T$  values results from propagating the experimental uncertainties of the input ALICE data used for the particle species correction. Figure 5 shows a similar summary for the  $R_{AA}$  measurement after correlations between the OO and  $pp$  measurements are taken into account.

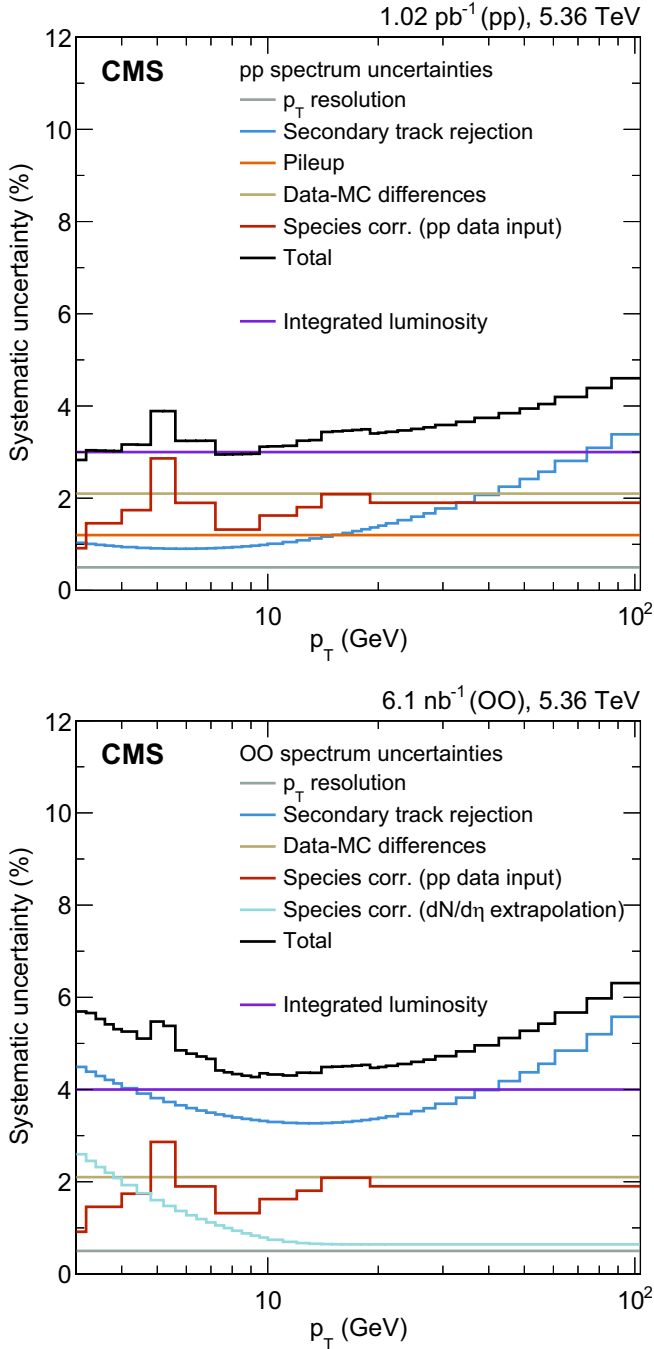


FIG. 4. Systematic uncertainties related to the 5.36 TeV  $pp$  (left) and OO (right) cross section measurements, presented as a function of  $p_T$ .

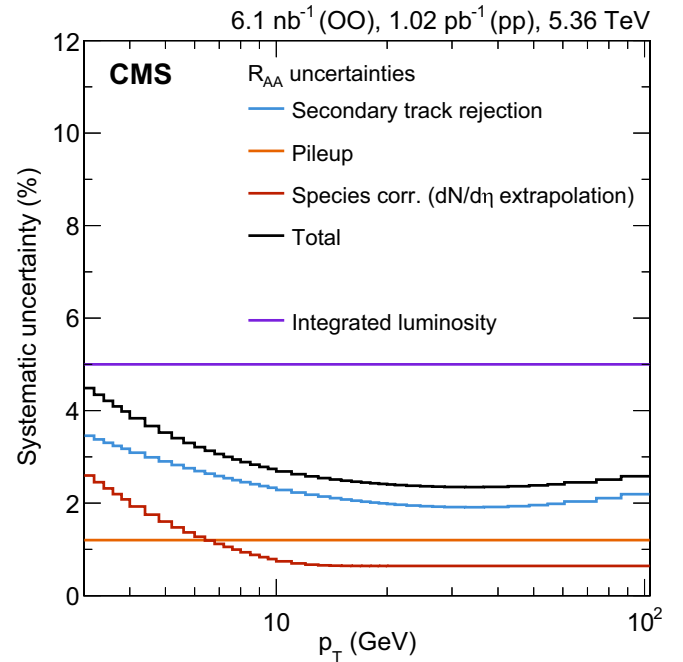


FIG. 5. Systematic uncertainties related to the measurement of  $R_{AA}$  for 5.36 TeV OO collisions, presented as a function of  $p_T$ .

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 C. Zhou<sup>18</sup> , S. Yang<sup>19</sup> , Z. You<sup>20</sup> , K. Jaffel<sup>21</sup> , N. Lu<sup>21</sup> , G. Bauer,<sup>22,j,k</sup> Z. Cui,<sup>22,k</sup> B. Li,<sup>22,l</sup> H. Wang<sup>22</sup> , K. Yi<sup>22,m</sup> ,  
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