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Measurement of inclusive jet production and nuclear modifications in pPb collisions at $\sqrt{s_{\mathrm{NN}}} = 5.02\,\mathrm{TeV}$

The CMS Collaboration*

Abstract

Inclusive jet production in pPb collisions at a nucleon-nucleon (NN) center-of-mass energy of $\sqrt{s_{\mathrm{NN}}} = 5.02\,\mathrm{TeV}$ is studied with the CMS detector at the LHC. A data sample corresponding to an integrated luminosity of $30.1\,\mathrm{nb}^{-1}$ is analyzed. The jet transverse momentum spectra are studied in seven pseudorapidity intervals covering the range $-2.0 < \eta_{\mathrm{CM}} < 1.5$ in the NN center-of-mass frame. The jet production yields at forward and backward pseudorapidity are compared and no significant asymmetry about $\eta_{\mathrm{CM}} = 0$ is observed in the measured kinematic range. The measurements in the pPb system are compared to reference jet spectra obtained by extrapolation from previous measurements in pp collisions at $\sqrt{s} = 7\,\mathrm{TeV}$. In all pseudorapidity ranges, nuclear modifications in inclusive jet production are found to be small, as predicted by next-to-leading order perturbative QCD calculations that incorporate nuclear effects in the parton distribution functions.

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*See Appendix A for the list of collaboration members

1 Introduction

Jet measurements play an important role in the study of the quark gluon plasma (QGP) produced in relativistic heavy ion collisions. A key observable in these studies is the phenomenon of jet quenching [1–6], in which the partons produced in hard scattering lose energy through gluon radiation and elastic scattering in the hot and dense partonic medium. Jet quenching was first observed at RHIC through measurements of high transverse momentum (p_{T}) hadrons [7] and dihadron correlations [8]. At the LHC, this phenomenon was observed more directly as dijet momentum imbalance [9, 10] and photon-jet energy imbalance [11] in PbPb collisions. An important ingredient in understanding how the presence of a hot QCD medium affects the jets is the comparison to reference measurements from collision systems that are not expected to produce the QGP. Most often, pp collisions at the same center-of-mass energy are used as a reference. Modifications in jet yields [12, 13], shapes [14], and fragmentation patterns [15, 16] in PbPb collisions have been found in comparison to expectations based on pp measurements. These modifications are found to depend on the overlap between the colliding nuclei, and are largest in the most central (i.e., largest overlap) PbPb collisions.

The interpretation of the jet modification results in nucleus-nucleus collisions and the understanding of their relation to the properties of the QGP requires detailed knowledge of all nuclear effects that could influence the comparisons with the pp system. Nuclear modifications may already be present at the initial state of the collisions, independently of QGP formation. Such modifications are collectively referred to as cold nuclear matter (CNM) effects and include parton energy loss and multiple scattering before the hard scattering, and modifications of the parton distribution functions in the nucleus (nPDFs) with respect to those of a free nucleon (PDFs). Some nPDF modifications have been previously deduced from measurements of lepton-nucleus deep inelastic scattering and Drell–Yan production of lepton pairs from $\mathrm{q\overline{q}}$ annihilation in proton-nucleus collisions [17]. In addition, measurements of π^0 production in deuteron-gold collisions at RHIC [18] are also included in recent nPDF fits to better constrain the nuclear gluon distributions [19]. There are several ranges in the parton fractional momenta x in which the data show suppression or enhancement in the nPDFs relative to the proton PDFs. At small x ($\lesssim$0.01), the nPDFs are found to be suppressed, a phenomenon commonly referred to as "shadowing" [20]. In the range $0.02 \lesssim x \lesssim 0.2$, the nPDFs are enhanced ("antishadowing" [17]), and for $x \gtrsim 0.2$ a suppression has been seen ("EMC effect" [21]).

Proton-lead (pPb) collisions at the LHC provide an opportunity to evaluate the CNM effects and establish an additional reference for the interpretation of measurements performed in PbPb collisions. The results of several pPb studies involving jets or dijets [22–24], electroweak bosons [25, 26], and high p_{T} charged particles [27, 28] are already available. No significant indication of jet quenching was found so far in the pPb studies of inclusive jet production [22, 29], dijet momentum balance [23], dijet acoplanarity [23, 24], or charged-hadron measurements [27, 28]. The shapes of the dijet [23] and Z boson [25] pseudorapidity distributions are found to be in better agreement with EPS09 nPDF predictions [19] than with the free-proton PDFs for measurements inclusive in the impact parameter. Hints of modifications larger than those presently included in the EPS09 nPDFs have also been seen [25–27]. In particular, the charged hadron spectra [27] are found to be enhanced at high p_{T} beyond the anti-shadowing included in EPS09. Significant modifications with respect to those included in EPS09 have also been found for impact-parameter-dependent measurements [22, 23]. The interpretation of the latter results is more difficult because of the kinematic biases introduced through the event selections [22, 23, 30–32].

In this paper we present the CMS measurements of inclusive jet production in pPb collisions at a nucleon-nucleon (NN) center-of-mass energy of $\sqrt{s_{\mathrm{NN}}} = 5.02\,\mathrm{TeV}$ as a function of p_{T} in several pseudorapidity regions in the range $-2.0 < \eta_{\mathrm{CM}} < 1.5$ in the NN center-of-mass system. No additional event activity selections have been made to avoid the associated kinematic biases. The measurements extend in p_{T} up to $500\,\mathrm{GeV}/c$ and are sensitive to nPDF modifications in the anti-shadowing and EMC effect regions. Since presently there are no experimental results available from pp collisions at $\sqrt{s} = 5.02\,\mathrm{TeV}$, pp reference jet spectra in pseudorapidity ranges corresponding to the present measurements are obtained by extrapolating jet measurements at $\sqrt{s} = 7\,\mathrm{TeV}$ [33]. The paper is organized as follows: Section 2 provides the experimental details, Section 3 gives an account of the systematic uncertainties in the measurements, Section 4 presents the results, and Section 5 summarizes our findings.

2 Data analysis

This measurement is based on a data sample of pPb collisions corresponding to an integrated luminosity of $30.1\,\mathrm{nb}^{-1}$ collected by the CMS experiment in 2013. The beam energies were 4 TeV for protons and 1.58 TeV per nucleon for lead nuclei, resulting in a center-of-mass energy per nucleon pair of 5.02 TeV. The direction of the higher-energy proton beam was initially set up to be clockwise within CMS conventions, and was reversed after a data set corresponding to an integrated luminosity of $21\,\mathrm{nb}^{-1}$ was recorded. As a result of the energy difference of the colliding beams, the nucleon-nucleon center-of-mass in the pPb collisions is shifted with respect to zero rapidity in the laboratory frame. Both portions of the data set are analyzed independently and the results are found to be compatible within their uncertainties. In order to reduce the statistical uncertainties, the two data sets are then combined. Results from the first data taking period are reflected along the z-axis so that in the combined analysis the proton travels in the positive z and pseudorapidity η direction. In the laboratory frame $\eta = -\ln[\tan(\theta/2)]$, where θ is the polar angle defined with respect to the proton beam direction. The results are presented in this convention, after transformation to the NN center-of-mass frame, which for massless particles is equivalent to a shift in pseudorapidity: $\eta_{\mathrm{CM}} = \eta - 0.465$.

2.1 Experimental setup

A detailed description of the CMS detector and of its coordinate system can be found in Ref. [34]. It features nearly hermetic calorimetric coverage and high-resolution tracking for the reconstruction of energetic jets and charged particles. The calorimeters consist of a lead tungstate crystal electromagnetic calorimeter (ECAL), and a brass and scintillator hadron calorimeter (HCAL) with coverage up to $|\eta| = 3$. The quartz/steel hadron forward (HF) calorimeters extend the calorimetry coverage in the region $3.0 < |\eta| < 5.2$, and are used in offline event selection. The calorimeter cells are grouped in projective towers of granularity $\Delta\eta\times\Delta\phi = 0.087\times0.087$ (where ϕ is the azimuthal angle in radians) for the central pseudorapidity region used in the present jet measurement, and have coarser segmentation (about twice as large) at forward pseudorapidity. The central calorimeters are enclosed in a superconducting solenoid with 3.8 T magnetic field. Charged particles are reconstructed by the tracking system, located inside the calorimeters and the superconducting coil. It consists of silicon pixel and strip layers covering the range $|\eta| < 2.5$, and provides track reconstruction with momentum resolution of about 1.5% for high-p_{T} particles. Muons are measured in gas-ionization detectors embedded in the steel flux-return yoke outside the solenoid.

2.2 Event selection

The CMS online event selection employs a hardware-based level-1 (L1) trigger and a software-based high-level trigger (HLT). A minimum bias sample is selected by the L1 requirement of a pPb bunch crossing at the interaction point and an HLT requirement of at least one reconstructed track with $p_T > 0.4\,\text{GeV}/c$ in the pixel tracker. This minimum bias trigger was prescaled by a large factor for most of the 5.02 TeV data collection, because of the high instantaneous luminosity of the LHC. In order to increase the p_T range of the measurement, additional HLT triggers were used to select events based on the presence of a jet with $p_T > 20$, 40, 60, 80, or $100\,\text{GeV}/c$ reconstructed in the calorimeters.

For the offline analysis, an additional selection of hadronic collisions is applied by requiring a coincidence of at least one HF calorimeter tower with more than 3 GeV of total energy on the positive and negative sides of the interaction point. Events are further required to have at least one reconstructed primary vertex with at least two associated tracks [35]. A maximum distance of 15 cm between the primary vertex and the nominal interaction point along the beam line is required to ensure maximum tracking acceptance. Additionally, track-based selection cuts are applied to suppress of beam-related background events [36]. The instantaneous luminosity of the pPb run in 2013 resulted in a 3% probability of at least one additional interaction occurring in the same bunch crossing. Events with more than one interaction ("pileup" events) are removed using a rejection algorithm developed in Ref. [27]. The pileup-rejection efficiency of this filter is found to be $90 \pm 2\%$ in minimum bias events and it removes a very small fraction (0.01%) of the events without pileup. In order to combine the spectra measured from the various jet-triggered data samples, the events included in the analysis are weighted according to the individual HLT prescale factors corresponding to the trigger object with maximum p_T in the event. The left panel of Fig. 1 shows the prescale-weighted jet spectra that are reconstructed with the anti-k_T [37] algorithm from each HLT trigger path and the combined inclusive jet spectrum. The ratios of each HLT-triggered spectrum to the combined jet spectrum are shown in the right panel of Fig. 1. In the range of p_T where the triggers are fully efficient, this ratio is unity and independent of jet p_T.

2.3 Jet reconstruction and corrections

The CMS particle-flow (PF) algorithm [38, 39] identifies stable particles in an event by combining information from all sub-detector systems, classifying them as electrons, muons, photons, and charged and neutral hadrons. The PF candidates are then clustered into jets using the anti-k_T sequential recombination algorithm [37] provided in the FASTJET framework [40]. The results in this analysis are obtained using a distance parameter $R = 0.3$. The underlying event (UE) contribution to the jet energy is subtracted using an iterative procedure described in Refs. [10, 41]. The jet energies are then corrected to contain the energy of all final-state jet constituents as described in Ref. [42]. The jet energy corrections are derived using simulated PYTHIA (6.462, Z2 tune) [43, 44] events and measurements of the energy balance of dijet and photon+jet pPb collision events are used to correct differences between data and Monte Carlo (MC) distributions [23, 42]. In the jet reconstruction process, there is a possibility that the jet energy is estimated incorrectly, or a jet is found in a region where the UE has an upward fluctuation, but no hard scattering has occurred (a "fake" jet). In MC the "real" and "fake" jets can be distinguished by requiring that the reconstructed jet is matched to a generator-level jet. In data, this cannot be done directly, but the contribution of fake jets could be estimated from MC, provided that it is tuned to describe the data, and specific jet selections are developed to identify and remove the misreconstructed jets. We estimate that about 10% of the jets reconstructed at $p_T = 50\,\text{GeV}/c$ in pPb collisions are fake, and this fraction quickly drops to a level of 10^{-4}

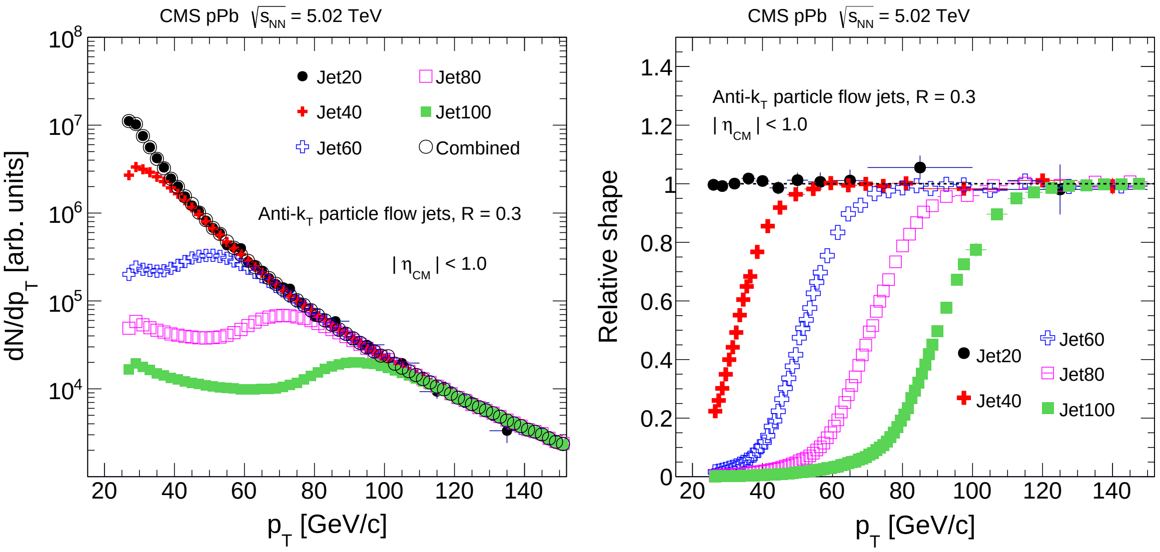

Figure 1: Left: The weighted jet spectra using prescale factors from each HLT-triggered event sample and the combined jet spectrum. A subset of the data is plotted to illustrate the procedure. Right: The ratios of each individual HLT-triggered jet spectrum to the combined jet spectrum. Statistical uncertainties are shown as vertical bars, and p_{T} bin widths as horizontal bars.

at $p_{\mathrm{T}} \approx$ 100 GeV/c. After the jet-identification cuts are applied, we estimate that less than 1% fake jets remain in the sample.

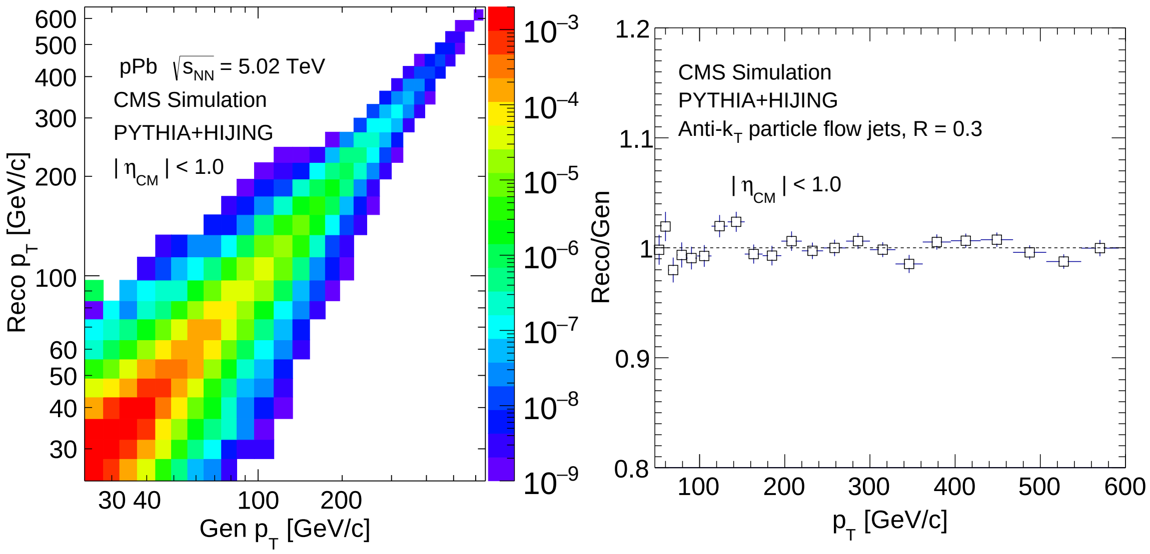

Figure 2: Left: Response matrix built from PYTHIA+HIJING simulation. Right: The ratios of the Bayesian unfolded jet p_{T} spectrum reconstructed in the simulation and the generator-level spectrum.

Because of the finite detector resolution and the steeply falling p_{T} distributions, the measured jet p_{T} spectra are smeared with respect to the true distributions, although the mean value of the reconstructed jet energy is corrected as described above. The jet energy resolution is estimated to be 13% (8%) for jet $p_{\mathrm{T}} = 60\,(300)\,\mathrm{GeV}/c$. A Bayesian unfolding technique [45] is employed to account for such resolution effects, as implemented in the RooUnfold package [46]. The migration of jets in pseudorapidity is not explicitly corrected for; it is instead included as an uncertainty, as discussed in Section 3.1. In the unfolding method, a response matrix is built based on MC simulations and is used to obtain the "true" jet p_T distribution from the measured one. Jets are first generated with the PYTHIA event generator and then embedded into pPb collisions simulated with the HIJING event generator (version 1.383) [47], which have particle multiplicity distributions comparable to the pPb data and can account for additional resolution effects associated with the higher detector occupancy. These embedded MC samples are denoted hereafter by PYTHIA+HIJING. The unfolding technique is tested by building the response matrix with detector jets (Reco) and generated jets (Gen) from half of the MC sample and applying it to unfold the other half of the sample. The left panel of Fig. 2 shows the response matrix obtained using the PYTHIA+HIJING simulation, while the right panel shows the ratio of the jet spectrum reconstructed from the simulation after unfolding to the generator-level jet spectrum. The unfolded MC jet spectrum is compatible with the generator-level jet spectrum within the statistical uncertainties. The results reported in this paper are based on the Bayesian unfolding technique that uses four iteration steps. Up to eight iteration steps are used in evaluating the systematic uncertainties as discussed in Section 3.1. The generator level PYTHIA jet spectrum is used as a prior in the unfolding. The data points are reported in the center of each p_T bin without corrections for binning effects.

The pPb jet cross sections are obtained in several pseudorapidity intervals. To study the evolution of the jet cross section with pseudorapidity, ratios of jet spectra are computed either using symmetric positive and negative pseudorapidity intervals around mid-rapidity, or normalizing the distributions by the mid-rapidity jet spectrum. These ratios are taken in the same p_T bin and the values are reported at the center of the bin. To study nuclear effects on jet production, the jet spectra in pPb collisions are compared to pp reference spectra obtained by extrapolation from previous jet cross section measurements in pp collisions at higher center-of-mass energy. The nuclear modification factor, R_{pPb}, evaluated in several pseudorapidity intervals, is defined as

$$R_{\mathrm{pPb}} = \frac{1}{A}\frac{\mathrm{d}^2\sigma_{\mathrm{jet}}^{\mathrm{pPb}}/\mathrm{d}p_{\mathrm{T}}\,\mathrm{d}\eta}{\mathrm{d}^2\sigma_{\mathrm{jet}}^{\mathrm{pp}}/\mathrm{d}p_{\mathrm{T}}\,\mathrm{d}\eta} = \frac{1}{A}\frac{1}{L}\frac{\mathrm{d}^2N_{\mathrm{jet}}^{\mathrm{pPb}}/\mathrm{d}p_{\mathrm{T}}\,\mathrm{d}\eta}{\mathrm{d}^2\sigma_{\mathrm{jet}}^{\mathrm{pp}}/\mathrm{d}p_{\mathrm{T}}\,\mathrm{d}\eta}, \tag{1}$$

where $L = 30.1\,\mathrm{nb}^{-1}$ is the effective integrated luminosity in the pPb analysis, corrected for event-selection efficiency and trigger prescales, and A is the mass number of the lead nucleus. Since presently there are no available experimental results from pp collisions at $\sqrt{s} = 5.02\,\mathrm{TeV}$, for this paper we use extrapolated, rather than measured, pp reference spectra. Hence we denote the nuclear modification factors as R^*_{pPb}.

2.4 Proton-proton reference jet spectra

The reference pp spectra are constructed extrapolating previously published inclusive jet spectra measured in pp collisions at $\sqrt{s} = 7\,\mathrm{TeV}$. Measurements performed with the anti-k_T jet algorithm with two distance parameters, $R = 0.5$ and 0.7 [33], are used in the extrapolation. The extrapolation is based on the PYTHIA generator (6.462, Z2 tune) and is performed in two steps. First, the $\sqrt{s} = 7\,\mathrm{TeV}$ jet cross section measurements are extrapolated to $\sqrt{s} = 5.02\,\mathrm{TeV}$ and then scaled to $R = 0.3$, since a smaller distance parameter is used in the pPb analysis to minimize the UE background fluctuations. The PYTHIA generator is used to estimate p_T-dependent scaling factors. While this scaling is model dependent, the ratio of the jet cross sections measured with $R = 0.5$ and 0.7 appears to be well reproduced in PYTHIA within 3% [33]. Several alternative methods are used to derive cross section scaling factors in $\sqrt{s}$ and in distance parameter in order to evaluate the systematic uncertainties discussed in Section 3.2. The extrapolated jet spectra are shown in Fig. 3. Scaling factors are applied, as noted in the legend, to enhance the visibility.

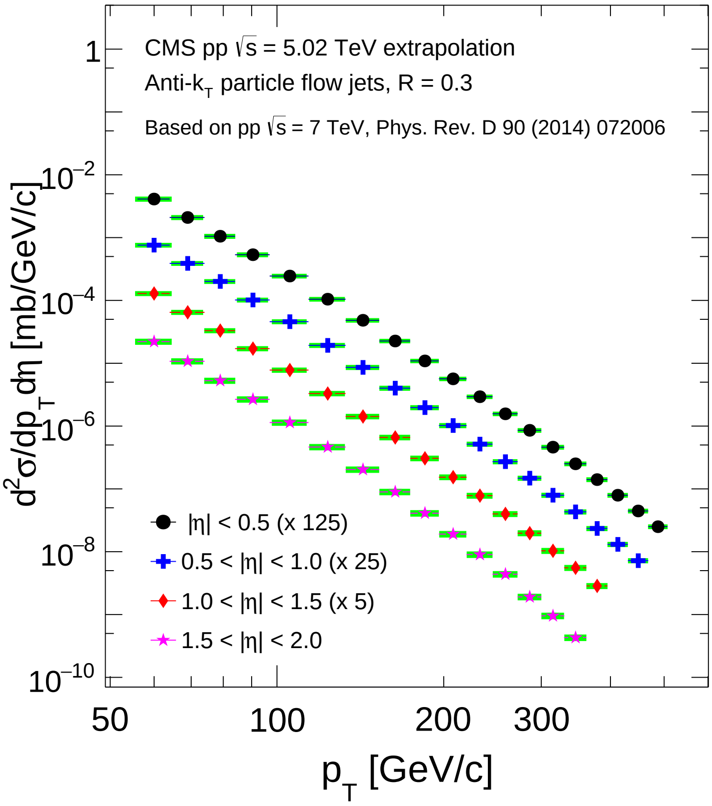

Figure 3: Jet spectra at $\sqrt{s} = 5.02\,\text{TeV}$ extrapolated from previous pp measurements at $\sqrt{s} = 7\,\text{TeV}$ [33]. Additional scaling factors listed in the legend are applied to enhance the visibility. The horizontal bars represent the bin size, and the points are plotted in the center of the bin. The shaded boxes denote the systematic uncertainties in the extrapolation procedure. The statistical uncertainties are smaller than the symbol size.

3 Systematic uncertainties

3.1 Systematic uncertainties in the pPb measurement

There are several sources of systematic uncertainty in the measurements of the jet spectra, the jet yield asymmetry, and the nuclear modification factors R^*_{pPb}. The dominant uncertainties in the spectra measured in pPb collisions come from the unfolding of the spectra and from the jet energy scale (JES) corrections, which are partially correlated since they both aim to correct for the difference between the reconstructed and the true jet energy. The stability of the unfolding procedure and its ability to recover the generator-level jet spectrum have been verified with simulation studies, which included the use of different numbers of iterations ($n = 2, 3, 4, 5, 6, 7, 8$). In the data, the unfolded spectra for $n = 4$ are compared to the spectra obtained with different values of n and the difference is included in the systematic uncertainty. In addition, since the true jet spectrum may differ in shape from the spectrum in the MC generator, the slope of the prior guess distribution is varied such that the yield at low p_T increases or decreases by a factor of 3, while at high p_{T} the yield is changed by about 10–20%. After this variation the spectra are unfolded and then are compared to the nominal unfolded spectra to estimate the uncertainty due to the nominal input distribution. The uncertainties from unfolding are largest (up to 5%) in the low p_{T} region and at large absolute pseudorapidity. Uncertainties that arise from the different jet energy resolution in the data and MC simulation are evaluated by smearing the unfolding matrix to account for these differences and then redoing the unfolding. The resulting differences in the final jet spectra are found to be less than 1%. The JES uncertainty is about 1% and induces up to 7% changes at high p_{T} because of the steeply falling jet spectra.

Additional cross checks are performed comparing the spectra obtained with different jet reconstruction algorithms (such as subtracting the UE in the jet algorithm or correcting for it in the transfer matrix), and comparing the unfolded results when the unfolding matrix uses the reconstructed jet p_{T} with or without jet energy corrections. The total uncertainty in the jet spectra due to the JES and unfolding varies from about 5% at low jet p_{T} at mid-rapidity to about 10% for high p_{T} and forward rapidity.

The fake jet contribution is estimated on the basis of a MC study of various jet quality variables that are used to identify genuine and misreconstructed jet contributions. In the PYTHIA+HIJING embedded samples these variables are optimized to remove misreconstructed jets, while preserving the largest fraction of genuine jets. The uncertainty in the misreconstructed jet contribution in the jet spectra is estimated by varying the jet quality requirements and comparing the resulting spectra in data and in simulation. It is about 1% for all pseudorapidity ranges.

The unfolding procedure does not correct for possible misreconstruction of the jet axis, and therefore jets may migrate from one pseudorapidity interval to another thus altering the jet spectra measured in different η ranges. The uncertainty associated with the jet pointing resolution is estimated by building the unfolding matrix using either the generated or the reconstructed jet axis, and comparing the resulting unfolded jet spectra. This uncertainty is found to be of the order of 1% in the central pseudorapidity region and 2% at large absolute pseudorapidity.

The jet spectra in pPb collisions are also subject to an overall scale uncertainty, due to the uncertainties in the integrated luminosity measurement. The scale uncertainty is estimated to be 3.5%, as described in Ref. [48].

The systematic uncertainty in the inclusive jet production asymmetry only includes those factors that depend on the jet pseudorapidity, such as the JES, unfolding, and misreconstructed jet contribution uncertainties. The overall scale uncertainty due to the luminosity normalization cancels out. As a cross check, the jet yield asymmetry uncertainties are evaluated using a combination of the two data sets with different beam directions. In that case, the jet yield asymmetry can be measured using detector elements that are only in the positive η or in the negative η ranges in the laboratory frame. Since the detector is symmetric, these regions have similar acceptance and performance and we expect that systematic effects are also similar. Alternatively, the jet yield asymmetry is measured from each portion of the data independently, and the results of this comparison confirm the systematic uncertainty estimate obtained by evaluating each source of uncertainty separately.

3.2 Systematic uncertainties in the pp reference

The uncertainties in the extrapolated pp reference spectra take into account the uncertainties in the distance parameter dependence of the cross sections at $\sqrt{s} = 7\,\mathrm{TeV}$ and the scaling to the smaller $R = 0.3$ value, the uncertainty in the $\sqrt{s}$ dependent scaling, as well as the uncertainties of the input spectra used in the extrapolation. The uncertainties in the inclusive jet measurements from pp collisions at $\sqrt{s} = 7\,\text{TeV}$ reported in Ref. [33] are taken as the upper and lower limits of the cross sections used in the extrapolation, and are reflected in the uncertainties of the resulting reference spectra. The following alternative approaches are used to derive scaling factors and evaluate their uncertainties.

1. PYTHIA 8, CUETP8M1 tune [49, 50]

   In the kinematic range studied, this tune has a different quark-to-gluon jet ratio and different jet shapes than the PYTHIA 6, Z2 tune used for the nominal result.

2. POWHEG+PYTHIA event generator [51, 52]

   The POWHEG generator is used to compute the cross section at next-to-leading order (NLO) accuracy, and PYTHIA (6.462, Z2 tune) is used to describe the parton showering and hadronization.

3. NLO calculations [53, 54] with several different parametrizations of the parton distribution functions [55] and non-perturbative corrections based on PYTHIA (6.462, Z2 tune).

4. Jet cross section measurements with $R = 0.7$ at $\sqrt{s} = 7\,\text{TeV}$ [33] and $\sqrt{s} = 2.76\,\text{TeV}$ [56] are used to evaluate $\sqrt{s}$ dependent scaling factors using x_T-based interpolation ($x_\text{T} \equiv 2p_\text{T}c/\sqrt{s}$).

The jet cross sections for $R = 0.3$ and $R = 0.5$ at $\sqrt{s} = 5.02$ TeV are evaluated using (1), (2), and (3). Then the ratios between the cross sections obtained with these two distance parameters, in the default PYTHIA calculation (6.462, Z2 tune) and in the alternative methods, are compared to each other, leading to an uncertainty in the distance parameter scaling of around 5%. The $\sqrt{s}$ scaling factors are evaluated with (2) and (3) for $R = 0.5$, and with (2), (3), and (4) for $R = 0.7$. These scaling factors are compared to the results from PYTHIA (6.462, Z2 tune). The uncertainties in the $\sqrt{s}$ scaling factors range from 4% at low jet p_T in the mid-rapidity region to 7% at high p_T and at forward rapidity. The total uncertainty in the pp reference extrapolation is found to range between 9% at mid-rapidity and 11% at forward rapidity. These uncertainties include a 2.4% scale uncertainty from the integrated luminosity measurement [33].

3.3 Summary of systematic uncertainties

A summary of the systematic uncertainties in the jet spectra in pPb collisions, the jet yield asymmetry measurements in pPb collisions, the reference pp spectra, and the nuclear modification factors R^*_pPb are listed in Table 1. The uncertainties depend on the jet p_T and pseudorapidity, and the table shows representative values in two jet p_T and η_CM ranges. The uncertainties vary smoothly between these ranges. The total systematic uncertainties listed for the nuclear modification factors R^*_pPb do not include the scale uncertainty of 4.3% from the integrated luminosity measurements in pPb (3.5%) and pp (2.4%) collisions. The luminosity uncertainties cancel in the measurements of the jet yield asymmetry. The remaining uncertainties are partially correlated in jet p_T, with the unfolding uncertainty dominating at low jet p_T and the JES uncertainty dominating at high jet p_T.

4 Results and discussion

The inclusive jet differential cross sections in pPb collisions at $\sqrt{s_\text{NN}} = 5.02\,\text{TeV}$ are shown in Fig. 4 for six consecutive η intervals in the range $-2.0 < \eta_\text{CM} < 1.5$ and the range $|\eta_\text{CM}| <$

Table 1: Systematic uncertainties in the measurement of the jet spectra in pPb collisions are shown in the first four lines. The sources and corresponding systematic uncertainties in the extrapolated pp reference are presented in the next four lines. The total uncertainties in the jet spectra in pPb collisions, the reference pp spectra, the jet yield asymmetry in pPb collisions, and R^{*}_{pPb} are shown in the bottom four lines. The uncertainties depend on the jet p_{T} and pseudorapidity, and the table shows representative values in two jet p_{T} and η_{CM} ranges. The uncertainties vary smoothly between these two ranges. Total systematic uncertainties listed for the nuclear modification factors R^{*}_{pPb} do not include the scale uncertainty of 4.3% due to the uncertainty in the integrated luminosity measurements in pPb (3.5%) and pp (2.4%) collisions.

	Source	Jet $p_{\mathrm{T}} < 80\,\mathrm{GeV}/c$		Jet $p_{\mathrm{T}} > 150\,\mathrm{GeV}/c$	
		$\lvert\eta_{\mathrm{CM}}\rvert < 1$	$\lvert\eta_{\mathrm{CM}}\rvert > 1.5$	$\lvert\eta_{\mathrm{CM}}\rvert < 1$	$\lvert\eta_{\mathrm{CM}}\rvert > 1.5$
pPb:	JES & unfolding	5%	8%	7%	10%
	Misreconstructed jet contribution	1%	1%	1%	1%
	Jet pointing resolution	1%	2%	1%	2%
	Integrated luminosity	3.5%	3.5%	3.5%	3.5%
pp:	Input data	6%	8%	5%	7%
	Cone-size dependence	5%	5%	5%	5%
	Collision-energy dependence	4%	5%	6%	7%
	Integrated luminosity	2.4%	2.4%	2.4%	2.4%
Total:	pPb spectra	6%	9%	8%	11%
	pPb asymmetry	7%	11%	10%	14%
	pp reference	9%	11%	10%	11%
	R^{*}_{pPb}	10%	14%	12%	15%

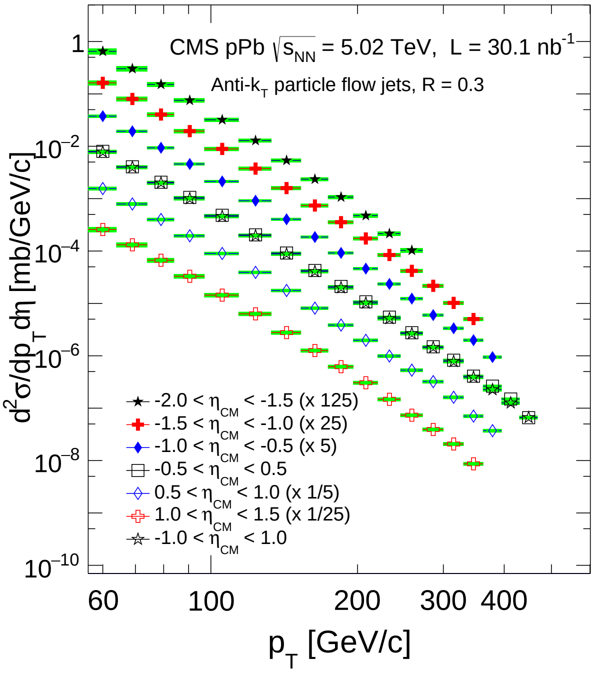

Figure 4: Inclusive jet differential cross section in pPb collisions at $\sqrt{s_{\mathrm{NN}}} = 5.02\,\mathrm{TeV}$ in six consecutive eta bins plus the range $\lvert\eta_{\mathrm{CM}}\rvert < 1.0$. The spectra are scaled by arbitrary factors for better visibility. The horizontal bars represent the bin width, and the filled boxes indicate the systematic uncertainties. The statistical uncertainties are smaller than the symbol size.

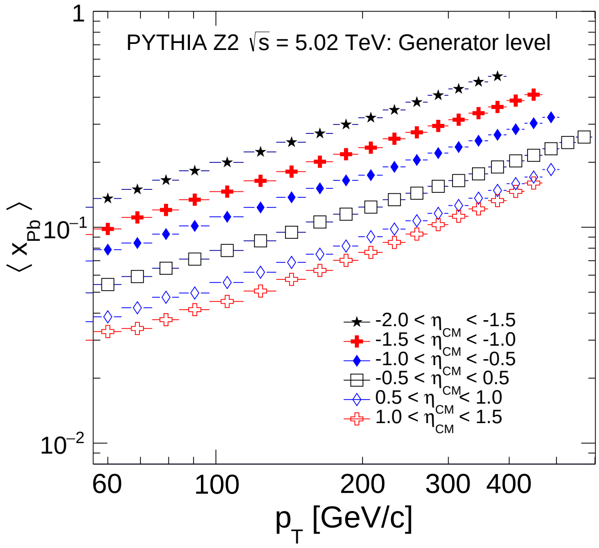

Figure 5: Mean x values of partons in the Pb nucleus, $\langle x_{\mathrm{Pb}} \rangle$, corresponding to the jet p_{T} and pseudorapidity ranges covered in the measurements. The $\langle x_{\mathrm{Pb}} \rangle$ values are determined using the PYTHIA event generator [43].

1.0 for reference purposes. The distributions are scaled by arbitrary factors described in the legend to enhance visibility. These spectra are used to study the pseudorapidity dependence of inclusive jet production in pPb collisions and possible nuclear effects. In symmetric collisions, such as in the pp system, the kinematic range in the fractional momentum x probed with the jets in forward and backward pseudorapidity is the same and the production is symmetric about $\eta_{\mathrm{CM}} = 0$. In the pPb system, the jets produced at forward pseudorapidity (proton beam direction) correlate with smaller x values from the Pb nucleus than those produced at backward pseudorapidity. Based on a generator-level study made with PYTHIA, the average x values from the Pb nucleus (Fig. 5) that are probed in the kinematic range covered by the present measurement are estimated to be in the range $0.03 \lesssim \langle x_{\mathrm{Pb}} \rangle \lesssim 0.5$. Values of p_{T} that correspond to $\langle x_{\mathrm{Pb}} \rangle \lesssim 0.2$ are associated with anti-shadowing in the nPDFs. The region $\langle x_{\mathrm{Pb}} \rangle \gtrsim 0.2$ is associated with a suppression in the nPDFs with respect to the free-nucleon PDFs (EMC effect), and can be reached at high jet p_{T} in the backward pseudorapidity region ($\eta < -1$).

The forward-backward asymmetry of the jet production is evaluated by taking the ratio between the jet yields in the Pb-going and the proton-going directions for two pseudorapidity intervals: $0.5 < |\eta_{\mathrm{CM}}| < 1.0$ and $1.0 < |\eta_{\mathrm{CM}}| < 1.5$. The results are shown in Fig. 6 as a function of jet p_{T}. There is no significant asymmetry observed in the jet production within the covered pseudorapidity range, although a small effect at high p_{T} cannot be excluded with the present systematic uncertainties. The modifications in the nPDFs, if present, are of similar magnitude in the x ranges covered by the measurements in the forward and backward directions. This result is similar to the findings from the CMS charged-hadron measurements at high p_{T} [27].

The evolution of the jet spectra with pseudorapidity can also be studied by normalizing each spectrum to the one obtained in the mid-rapidity range ($|\eta_{\mathrm{CM}}| < 1$). The normalized jet cross section distributions are shown in the left panel of Fig. 7. In the right panel of Fig. 7 we examine the pseudorapidity dependence in the normalized jet cross sections in three fixed p_{T} bins. The data points are offset for visibility. No significant pseudorapidity asymmetry is observed as can also be seen by comparing the open and closed stars or open and closed crosses in the left panel. The jet spectra become softer away from the mid-rapidity region, and the pseudo-

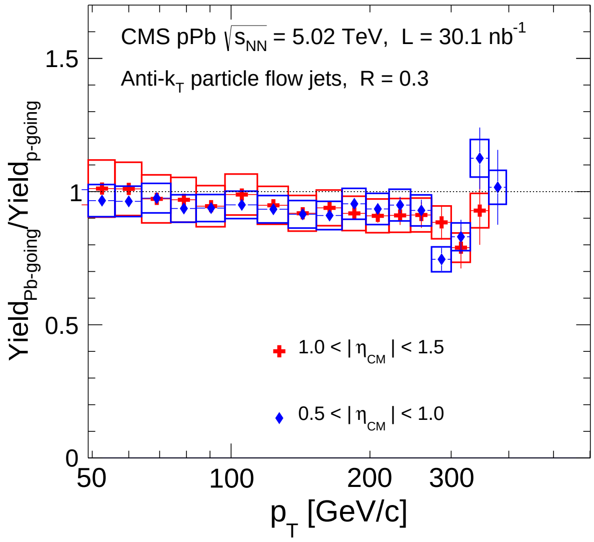

Figure 6: Inclusive jet asymmetry as a function of jet p_T for $0.5 < |\eta_{CM}| < 1.0$ and $1.0 < |\eta_{CM}| < 1.5$. The asymmetry is calculated as the ratio between the jet yields at negative pseudorapidity (Pb beam direction) and positive pseudorapidity (proton-going side). The vertical bars represent the statistical uncertainties and the open boxes represent the systematic ones.

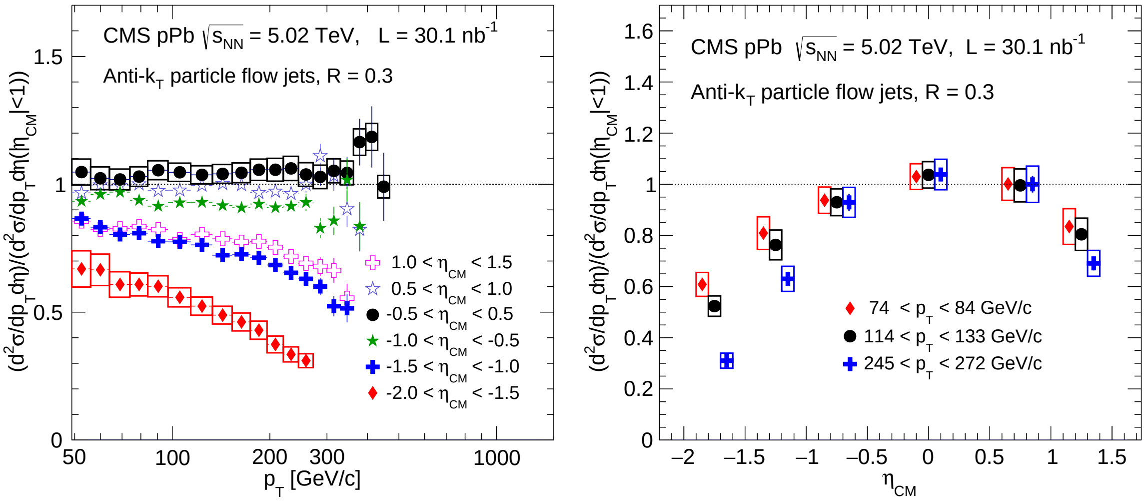

Figure 7: Left: Inclusive jet cross section in pPb collisions as a function of jet p_T normalized to the production at mid-rapidity ($|\eta_{CM}| < 1$) for six η_{CM} intervals. The vertical bars represent the statistical uncertainties. The systematic uncertainties at mid-rapidity and in the most backward pseudorapidity are shown with open boxes. The uncertainties in the other pseudorapidity ranges have similar magnitude. Right: Inclusive jet cross section in pPb collisions as a function of η_{CM} normalized to the cross section at $|\eta_{CM}| < 1$, for three jet p_T ranges. The open boxes represent the systematic uncertainties. The data points are shifted in pseudorapidity to enhance the visibility. The η_{CM} bin boundaries are as specified in the left panel. The statistical uncertainties are smaller than the symbols.

rapidity distributions become narrower with increasing jet p_{T} as a result of the softening of the distributions at forward and backward pseudorapidity.

The inclusive jet nuclear modification factors R^{*}_{pPb} as a function of jet p_{T} are shown in Fig. 8 for six center-of-mass pseudorapidity bins, along with an NLO perturbative QCD (pQCD) calculation [57] using the EPS09 nPDFs [19]. For most of the measured p_{T} and η_{CM} ranges, the experimental R^{*}_{pPb} values are systematically above the theoretical prediction. However, this difference is not significant, given the size of the systematic uncertainties and the fact that they are strongly correlated in p_{T}. The R^{*}_{pPb} values are approximately independent of p_{T}. In the theoretical prediction there is a decrease in R_{pPb} with p_{T} in the backward pseudorapidity region, which is associated with the onset of the EMC effect at high values of x in the Pb nucleus. In the range of p_{T} where the measurements probe the anti-shadowing region, the R^{*}_{pPb} values show a hint of an enhancement with respect to the pp reference, e.g. for $|\eta_{\mathrm{CM}}| < 0.5$ and $56 < p_{\mathrm{T}} < 300\,\mathrm{GeV}/c$, $R^{*}_{\mathrm{pPb}} = 1.17 \pm 0.01\,(\mathrm{stat}) \pm 0.12\,(\mathrm{syst})$. This enhancement is smaller than the one observed in the charged-hadron measurement [27] and closer to the theoretical prediction. Direct measurements of the jet and charged-hadron reference spectra in pp collisions at $\sqrt{s} = 5\,\mathrm{TeV}$ are needed to reduce the systematic uncertainties in the measurements of the nuclear modification factors and provide better constraints to the theory.

The results of the jet R^{*}_{pPb} measurements presented here are consistent with those reported by the ATLAS collaboration [22]. In Fig. 9 we compare our results to the ATLAS measurement at mid-rapidity, $|y_{\mathrm{CM}}| < 0.3$, for the 0–90% most central collisions, performed using a distance parameter $R = 0.4$. Although the event selections and the jet reconstruction are not exactly the same in the two measurements, the results are in good agreement.

5 Summary

The inclusive jet spectra and nuclear modification factors in pPb collisions at $\sqrt{s_{_{\mathrm{NN}}}} = 5.02\,\mathrm{TeV}$ have been measured. The data, corresponding to an integrated luminosity of $30.1\,\mathrm{nb}^{-1}$, were collected by the CMS experiment in 2013. The jet transverse momentum spectra were measured for $p_{\mathrm{T}} > 56\,\mathrm{GeV}/c$ in six pseudorapidity intervals covering the range $-2 < \eta_{\mathrm{CM}} < 1.5$ in the NN center-of-mass system. The jet spectra were found to be softer away from mid-rapidity. The jet production at forward and backward pseudorapidity were compared, and no significant asymmetry about $\eta_{\mathrm{CM}} = 0$ was observed in the measured kinematic range.

The differential jet cross section results were compared with extrapolated pp reference spectra based on jet measurements in pp collisions at $\sqrt{s} = 7\,\mathrm{TeV}$. The inclusive jet nuclear modification factors R^{*}_{pPb} were observed to have small enhancements compared to the reference pp jet spectra at low jet p_{T} in all η_{CM} ranges. In the anti-shadowing region, for $|\eta_{\mathrm{CM}}| < 0.5$ and $56 < p_{\mathrm{T}} < 300\,\mathrm{GeV}/c$, the value $R^{*}_{\mathrm{pPb}} = 1.17 \pm 0.01\,(\mathrm{stat}) \pm 0.12\,(\mathrm{syst})$ was found. The R^{*}_{pPb} appears to be approximately independent of p_{T}, except in the most backward pseudorapidity range. The R^{*}_{pPb} measurements were found to be compatible with theoretical predictions from NLO pQCD calculations that use EPS09 nPDFs.

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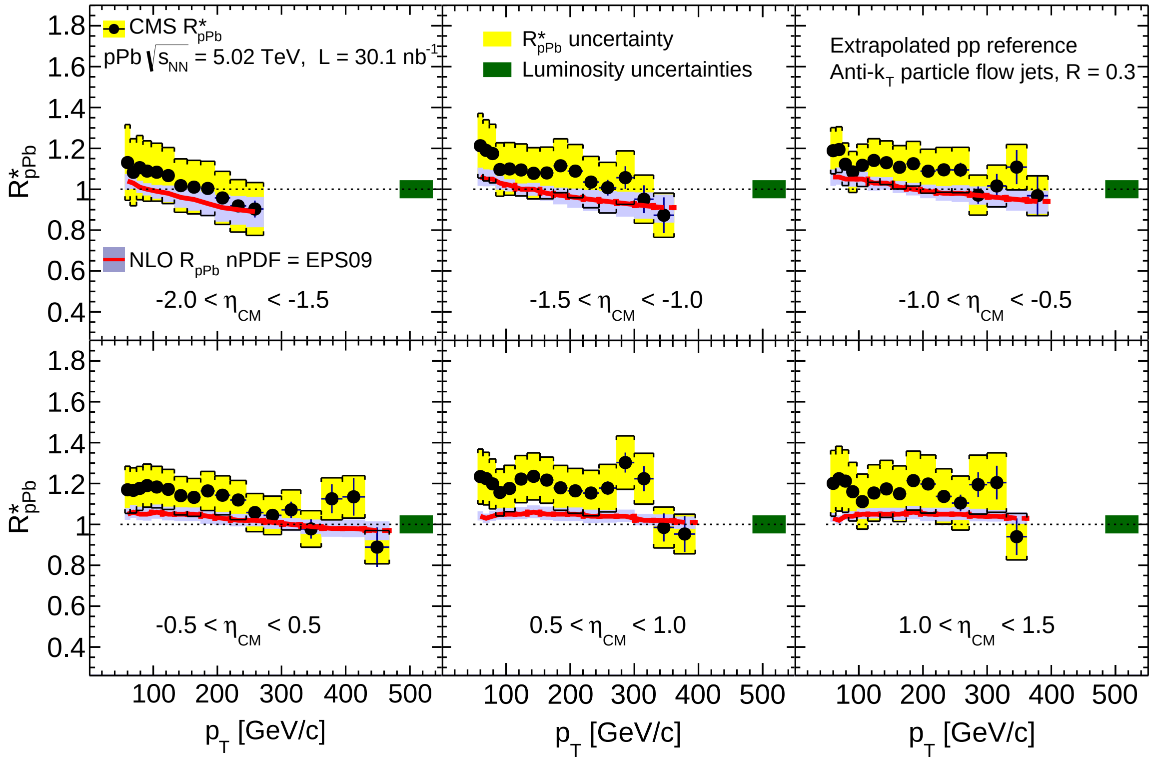

Figure 8: Inclusive jet nuclear modification factor R^*_{pPb} as a function of jet p_{T} in $\sqrt{s_{\text{NN}}} = 5.02\,\text{TeV}$ pPb collisions, using a pp reference extrapolated from previous measurements [33] at $\sqrt{s} = 7\,\text{TeV}$. The vertical bars represent the statistical uncertainties, and the open boxes represent the systematic ones. The filled rectangular boxes around $R^*_{\text{pPb}} = 1$ represent the luminosity uncertainties in the pPb and pp measurements. The CMS measurements are compared to a NLO pQCD calculation [57] that is based on the EPS09 nPDFs [19]. The theoretical calculations are shown with solid lines, and the shaded bands around them represent the theoretical uncertainties.

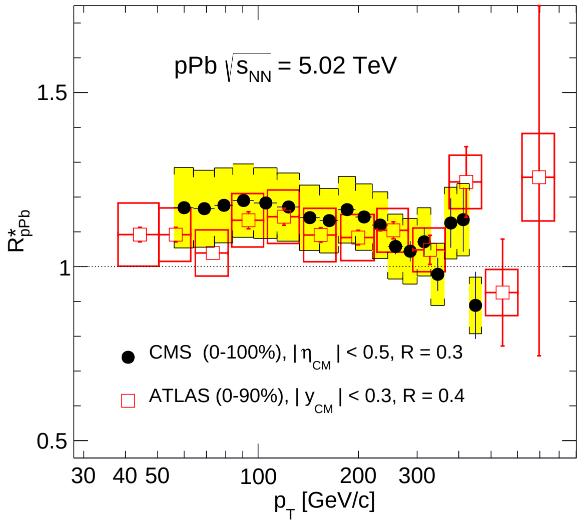

Figure 9: Inclusive jet R^*_{pPb} integrated over centrality and in the $|\eta_{CM}| < 0.5$ range for anti-k_T jets with distance parameter $R = 0.3$ from this work, compared to ATLAS results [22] at $|y_{CM}| < 0.3$ for the 0–90% most central collisions with distance parameter $R = 0.4$. The vertical bars show the statistical uncertainties, and the open boxes represent the systematic uncertainties.

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