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Study of high-p_{T} charged particle suppression in PbPb compared to pp collisions at $\sqrt{s_{\mathrm{NN}}} = 2.76$ TeV

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Abstract The transverse momentum spectra of charged particles have been measured in pp and PbPb collisions at $\sqrt{s_{NN}} = 2.76$ TeV by the CMS experiment at the LHC. In the transverse momentum range $p_{\mathrm{T}} = 5$–10 GeV$/c$, the charged particle yield in the most central PbPb collisions is suppressed by up to a factor of 7 compared to the pp yield scaled by the number of incoherent nucleon–nucleon collisions. At higher p_{T}, this suppression is significantly reduced, approaching roughly a factor of 2 for particles with p_{T} in the range $p_{\mathrm{T}} = 40$–100 GeV$/c$.

1 Introduction

The charged particle spectrum at large transverse momentum (p_{T}), dominated by hadrons originating from parton fragmentation, is an important observable for studying the properties of the hot, dense medium produced in high-energy heavy-ion collisions. The study of the modifications of the p_{T} spectrum in PbPb compared to pp collisions at the same collision energy can shed light on the detailed mechanism by which hard partons lose energy traversing the medium [1, 2], complementing recent studies of jet quenching and fragmentation properties using fully reconstructed jets [3, 4].

Using data collected by the Compact Muon Solenoid (CMS) experiment at the LHC, this paper presents measurements of charged particle yields as a function of p_{T} and event centrality in PbPb collisions at a center-of-mass energy per nucleon pair $\sqrt{s_{NN}} = 2.76$ TeV. The PbPb charged particle spectra are compared to the corresponding p_{T}-differential cross sections measured in pp collisions at the same center-of-mass energy, a measurement that follows closely the analysis described in Ref. [5]. Charged tracks are measured in the pseudorapidity range $|\eta| < 1$, where $\eta = -\ln[\tan(\theta/2)]$, with θ the polar angle of the track with respect to the counterclockwise beam direction.

The measurements are motivated by lower-energy results [6–9] from the Relativistic Heavy Ion Collider (RHIC), where high-p_{T} particle production was found to be strongly suppressed relative to expectations from an independent superposition of nucleon–nucleon collisions. This observation is typically expressed in terms of the nuclear modification factor,

$$R_{\mathrm{AA}}(p_{\mathrm{T}}) = \frac{\mathrm{d}^2 N_{\mathrm{ch}}^{\mathrm{AA}}/\mathrm{d}p_{\mathrm{T}}\,\mathrm{d}\eta}{\langle T_{\mathrm{AA}}\rangle \mathrm{d}^2\sigma_{\mathrm{ch}}^{\mathrm{pp}}/\mathrm{d}p_{\mathrm{T}}\,\mathrm{d}\eta}, \tag{1}$$

where $N_{\mathrm{ch}}^{\mathrm{AA}}$ and $\sigma_{\mathrm{ch}}^{\mathrm{pp}}$ represent the charged particle yield per event in nucleus–nucleus (AA) collisions and the charged particle cross section in pp collisions, respectively. In order to compare the yield of high-p_{T} charged particles produced in PbPb and pp collisions, a scaling factor, the nuclear overlap function T_{AA}, is needed to provide a proper normalization at a given PbPb centrality. This factor is computed as the ratio between the number of binary nucleon–nucleon collisions N_{coll}, calculated from the Glauber model of the nuclear collision geometry [10], and the inelastic nucleon–nucleon (NN) cross section $\sigma_{\mathrm{inel}}^{\mathrm{NN}} = 64 \pm 5$ mb at $\sqrt{s} = 2.76$ TeV [11]. It can be interpreted as the NN-equivalent integrated luminosity per collision at any given PbPb centrality. The mean of the nuclear overlap function $\langle T_{\mathrm{AA}}\rangle$, averaged over a given centrality bin, is used to determine the nuclear modification factor at that PbPb centrality.

In addition, the centrality dependence of the PbPb spectrum can also be examined through the T_{AA}-scaled ratio of spectra in central and peripheral bins,

$$R_{\mathrm{CP}}(p_{\mathrm{T}}) = \frac{(\mathrm{d}^2 N_{\mathrm{ch}}^{\mathrm{AA}}/\mathrm{d}p_{\mathrm{T}}\,\mathrm{d}\eta)/\langle T_{\mathrm{AA}}\rangle\ [\text{central}]}{(\mathrm{d}^2 N_{\mathrm{ch}}^{\mathrm{AA}}/\mathrm{d}p_{\mathrm{T}}\,\mathrm{d}\eta)/\langle T_{\mathrm{AA}}\rangle\ [\text{peripheral}]}. \tag{2}$$

In the absence of initial- and/or final-state effects on the PbPb p_{T} spectrum, the factors R_{AA} and R_{CP} at high p_{T} are

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unity by construction. However, as observed first at RHIC in 200 GeV AuAu collisions [6–9] and later by ALICE in 2.76 TeV PbPb collisions [12], the yield of $p_T \sim 5$–10 GeV/c charged particles is suppressed in the most central heavy-ion collisions by up to a factor of five compared to that in pp collisions. The CMS measurement presented in this paper confirms these results with improved experimental uncertainties and extends the measured transverse momentum range to 100 GeV/c.

2 Data sample and analysis procedures

This measurement is based on $\sqrt{s_{NN}} = 2.76$ TeV PbPb data samples corresponding to integrated luminosities of 7 μb^{-1} and 150 μb^{-1}, collected by the CMS experiment in 2010 and 2011, respectively. The pp reference measurement uses a data sample collected in $\sqrt{s} = 2.76$ TeV collisions in the 2011 LHC run, corresponding to an integrated luminosity of 230 nb^{-1}.

A detailed description of the CMS detector can be found in Ref. [13]. The central feature of the CMS apparatus is a superconducting solenoid of 6 m internal diameter, providing an axial magnetic field of 3.8 T. Immersed in the magnetic field are the pixel tracker, the silicon strip tracker, the lead-tungstate crystal electromagnetic calorimeter (ECAL), and the brass/scintillator hadron calorimeter (HCAL). Muons are measured in gas ionization detectors embedded in the steel return yoke. The tracker consists of 1440 silicon pixel and 15 148 silicon strip detector modules and measures charged particle trajectories within the nominal pseudorapidity range $|\eta| < 2.4$. The pixel tracker consists of three 53.3 cm long barrel layers and two endcap disks on each side of the barrel section. The innermost barrel layer has a radius of 4.4 cm, while for the second and third layers the radii are 7.3 cm and 10.2 cm, respectively. The tracker is designed to provide a track impact parameter resolution of about 100 μm and a transverse momentum resolution of about 0.7 (2.0) % for 1 (100) GeV/c charged particles at normal incidence ($\eta = 0$) [14]. The beam scintillator counters (BSCs) are located at a distance of 10.86 m from the nominal interaction point (IP), one on each side, and cover the $|\eta|$ range from 3.23 to 4.65. Each BSC is a set of 16 scintillator tiles. The BSC elements provide hit and coincidence rates with a time resolution of 3 ns and an average minimum ionising particle detection efficiency of 95.7 %. The two steel/quartz-fibre hadron forward calorimeters (HF), which extend the calorimetric coverage beyond the barrel and endcap detectors to the $|\eta|$ region between 2.9 and 5.2, are used for further offline selection of collision events. For online event selection, CMS uses a two-level trigger system: a hardware level (L1) and a software-based higher level (HLT).

A sample of minimum bias events from PbPb collisions was collected, based on a trigger requiring a coincidence between signals in the opposite sides of either the HF or the BSCs. To ensure a pure sample of inelastic hadronic collision events, additional offline selections were performed. These include a beam-halo veto, based on the BSC timing, an offline requirement of at least 3 towers on each HF with an energy deposit of more than 3 GeV per tower, a reconstructed vertex, based on at least two pixel tracks with $p_T > 75$ MeV/c, and a rejection of beam-scraping events, based on the compatibility of pixel cluster shapes with the reconstructed primary vertex. Further details can be found in Ref. [4].

The collision event centrality is determined from the event-by-event total energy deposition in both HF calorimeters. The distribution of this observable in minimum bias events from the 2010 data sample, shown in Fig. 1(a), is used to divide the event sample into 40 centrality bins, each corresponding to 2.5 % of the total inelastic cross section. Figure 1(b) shows the distribution of events according to centrality bin, which is flat by construction for the minimum bias selection, except in the most peripheral events where the trigger and offline event selection are no longer fully efficient. Figure 1 also shows the distributions of the total HF energy and of the cross-section fraction for the events selected by single-jet triggers with calibrated transverse energy thresholds of $E_T = 65$ GeV (Jet65) and 80 GeV (Jet80) from the 2011 data samples. The reconstruction of calorimeter-based jets in heavy-ion collisions in the online trigger as well as in the offline analysis is performed with an iterative cone algorithm modified to subtract the soft underlying event on an event-by-event basis [15]. The overall selection efficiency is estimated to be (97 ± 3) % based on Monte Carlo (MC) simulations [4]. For the pp analysis, there is an uncertainty from the estimated number of additional collision interactions in a given beam crossing (i.e. “event pile-up”) in addition to the uncertainties from the event selection efficiency. For the PbPb analysis, the uncertainty due to the event pile-up fraction is negligible (<0.1 %).

For this analysis, the events are analyzed in six centrality bins: 0–5 % (most central), 5–10 %, 10–30 %, 30–50 %, 50–70 %, and 70–90 % (most peripheral). Details of the centrality determination are described in Ref. [4].

The event centrality, specified as a fraction of the total inelastic cross section, can be related to properties of the PbPb collisions such as the number of nucleons undergoing at least one inelastic collision (N_{part}) and the total number of binary nucleon–nucleon collisions (N_{coll}). The calculation of these properties is based on a Glauber model of the incoming nuclei [10] and studies of bin-to-bin smearing, caused by finite resolution effects and evaluated using fully simulated and reconstructed MC events [4]. The

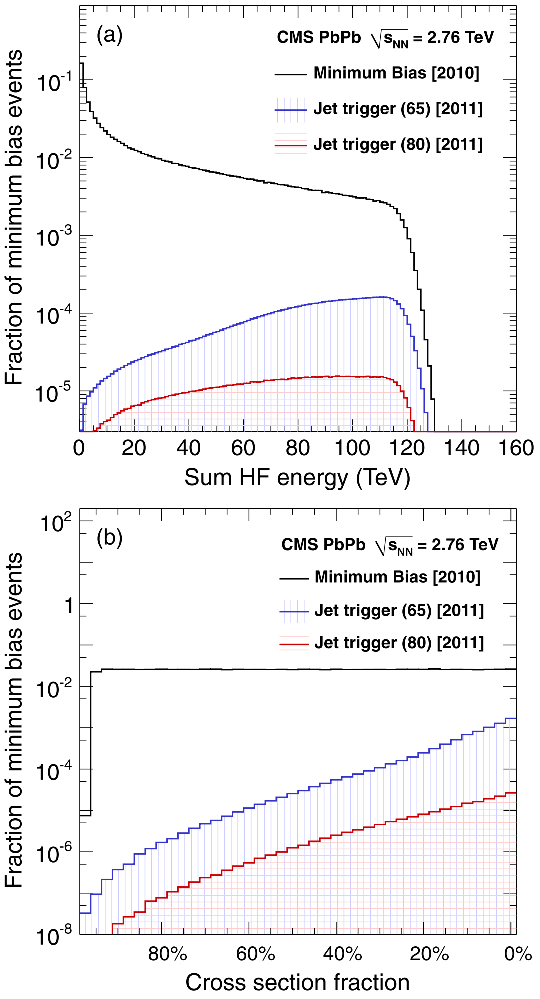


Fig. 1 (**a**) Probability distribution of the total HF energy for minimum bias events (*black line*), Jet65-triggered (*blue-shaded region*), and Jet80-triggered (*red-shaded region*) events. (**b**) Distribution of the events in bins of fractional cross section for minimum bias (*black line*), Jet65-triggered (*blue-shaded region*), and Jet80-triggered (*red-shaded region*) events. By convention, 0 % denotes the most central events and 100 % the most peripheral

mean and r.m.s. of the N_{part}, N_{coll}, and T_{AA} distributions, along with their corresponding systematic uncertainties, are listed in Table 1 for the six centrality bins used in this analysis. The uncertainties on the centrality variables are derived from propagating the uncertainties on the event selection efficiency and on the parameters of the Glauber model.

In order to extend the statistical reach of the p_{T} spectra in the highly prescaled minimum bias sample, data recorded in 2011 by unprescaled single-jet triggers, Jet65 and Jet80, are included in the analysis. The jet E_{T} thresholds in the trigger are applied after subtracting the contribution from the underlying event and correcting for the calorimeter response. Transverse energy distributions of the most energetic reconstructed jet with $|\eta| < 2$, referred to as the leading jet, are shown in the upper panel of Fig. 2(a) for the three samples (minimum bias, Jet65, and Jet80) as a function of corrected E_{T}, and normalized per minimum bias event. The distribution for the Jet80 trigger has a peak in the low-E_{T} region as a consequence of stricter ECAL and HCAL noise elimination, as well as a tighter pseudorapidity requirement in the offline leading-jet selection than in the trigger. This feature is less prominent in the lower threshold Jet65 jet trigger because the rate of noise triggers relative to the rate of true jet triggers is smaller at lower jet E_{T}. The lower panel in Fig. 2(a) shows the trigger efficiency given by the ratio of each jet-triggered distribution to that from the immediately looser selection. The Jet65 (Jet80) trigger becomes fully efficient above $E_{\mathrm{T}} = 80$ (100) GeV. Following the procedure introduced in the analogous measurement of the charged particle spectra in 0.9 and 7 TeV pp collisions [5], the spectra for $|\eta| < 1.0$ are calculated separately in three ranges of leading-jet E_{T}, below 80 GeV, between 80 and 100 GeV, and above 100 GeV, each corresponding to a fully efficient trigger path, and then combined to obtain the final result. Figure 2(b) shows the contributions from the three ranges to the combined spectrum. The lower panel of the figure compares the combined spectrum to the minimum bias spectrum alone, which is in good agreement within statistical uncertainties. As in the previous analysis [5], a p_{T}-dependent

Table 1 The average number of participating nucleons (N_{part}), number of binary nucleon–nucleon collisions (N_{coll}), and nuclear overlap function (T_{AA}) for the centrality bins used in this analysis. The r.m.s. values give the spread over the centrality bins, which are expressed as fractions of the total inelastic PbPb cross section

Centrality bin	$\langle N_{\mathrm{part}}\rangle$	r.m.s.	$\langle N_{\mathrm{coll}}\rangle$	r.m.s.	$\langle T_{\mathrm{AA}}\rangle$ (mb^{-1})	r.m.s.
0–5 %	381 ± 2	19.2	1660 ± 130	166	25.9 ± 1.06	2.60
5–10 %	329 ± 3	22.5	1310 ± 110	168	20.5 ± 0.94	2.62
10–30 %	224 ± 4	45.9	745 ± 67	240	11.6 ± 0.67	3.75
30–50 %	108 ± 4	27.1	251 ± 28	101	3.92 ± 0.37	1.58
50–70 %	42.0 ± 3.5	14.4	62.8 ± 9.4	33.4	0.98 ± 0.14	0.52
70–90 %	11.4 ± 1.5	5.73	10.8 ± 2.0	7.29	0.17 ± 0.03	0.11
50–90 %	26.7 ± 2.5	18.84	36.9 ± 5.7	35.5	0.58 ± 0.09	0.56

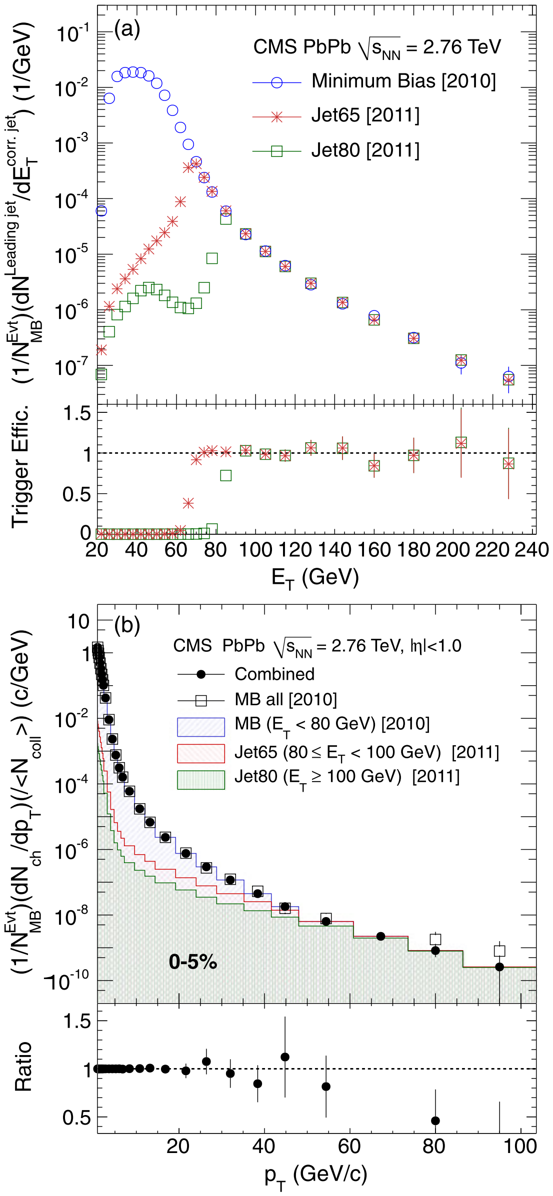


Fig. 2 (**a**) *Upper panel*: Corrected transverse energy E_{T} of leading jets with $|\eta| < 2$ for a minimum bias trigger and two jet triggers normalized to the number of selected minimum bias events $N_{\mathrm{MB}}^{\mathrm{Evt}}$. *Lower panel*: efficiency curves for the jet triggers with corrected energy thresholds of 65 and 80 GeV. (**b**) *Upper panel*: The three trigger contributions to the charged particle transverse momentum spectrum and their sum (*filled circles*) for the 0–5 % most central events. *Open squares* show the minimum bias spectrum for all values of leading-jet E_{T}. *Lower panel*: the ratio of the combined spectrum to the minimum bias spectrum

normalization uncertainty of 0–4 % is assigned to this procedure of matching the spectra from the different triggered samples.

The reconstruction of charged particles in PbPb collisions, based on hits in the silicon pixel and strip detectors, is performed similarly to what is done in pp collisions [5, 16]. However, some criteria have been fine-tuned to cope with the challenges presented by the much higher hit density in central PbPb collisions. First, prior to track reconstruction, the three-dimensional primary vertex position is fitted from a collection of pixel-only tracks reconstructed with three hits in the pixel detector and extrapolating back to a region around the beam spot. Next, to reduce the random combinatorial background, track candidates are built from triplet seeds alone, consisting of hits in three layers of the pixel barrel and endcap detectors. The seeds from a restricted region within 2 mm of the primary vertex are constructed with a minimum p_{T} of 0.9 GeV/c. Further selections are made on the normalized goodness-of-fit (i.e. χ^2) of the track fit and on the compatibility of the fitted triplet seeds with the primary vertex, before propagating the seed trajectories through the strip tracker to build fully reconstructed tracks.

To improve the track reconstruction efficiency, two more iterations of the tracking are performed after removing hits unambiguously belonging to the tracks found in the first iteration. This procedure is based on the standard pp iterative tracking [16]. More efficient pp-based pixel-pair and triplet-track seedings are used in the second and third iterations, respectively. The tracks found in the later iterations are merged with the first-iteration tracks after removing any duplicate tracks, based on the fraction of shared hits. Lastly, the calorimeter (ECAL and HCAL) information is used to improve tracking efficiency at high p_{T} ($\gtrsim$30 GeV/c) by requiring looser quality criteria for tracks that are determined to be calorimeter compatible. This is possible because genuine charged hadron tracks with high p_{T} are expected to leave large energy deposits in the calorimeter. Tracks are matched to the closest calorimeter cell in (η, ϕ), where ϕ is the azimuthal angle of the track. A track is determined to be compatible with the matched calorimeter cell if the sum of the transverse energy measured by the ECAL and HCAL cells is above a minimum fraction (30 %) of the track transverse momentum. Finally, tight quality criteria are imposed for tracks that are incompatible with their matched calorimeter cell energy. These include requirements of at least 13 hits on the track (counting stereo strip layers separately), a relative momentum resolution of less than 5 %, a normalized χ^2 of less than 0.15 times the number of hits, and transverse and longitudinal impact parameters of less than three times the sum in quadrature of the uncertainties on the impact parameter and the corresponding vertex position.

Each track is weighted by a factor that accounts for the geometrical acceptance of the detector, the efficiency of the reconstruction algorithm, the fraction of the tracks for which a single charged particle is reconstructed as more than one track, the fraction of tracks corresponding to non-primary charged particles, and the fraction of misidentified tracks that do not correspond to any charged particle. These correction factors are applied differentially as functions of pseudorapidity, transverse momentum, transverse energy of the leading jet, and event centrality. The various correction terms are estimated based on simulated minimum bias PbPb events from the HYDJET [17] generator. To improve the statistical precision of the correction factors at high p_T, HYDJET MC samples are also mixed at the level of simulated hits with dijet events generated with different settings of the hard-scattering scale ($\hat{p}_T = 30, 50, 80, 110$, and 170 GeV/$c$) from PYQUEN [17], a generator for the simulation of rescattering as well as radiative and collisional energy loss of hard partons in heavy-ion collisions.

Before applying the tight quality selections on the reconstructed tracks, the charged particle reconstruction efficiency is studied by inserting simulated pion tracks or PYQUEN dijet events into two different background samples: (i) simulated minimum bias HYDJET events by mixing GEANT4 [18] detector hits, and (ii) PbPb data events by combining the raw digitized detector signals. The efficiencies estimated by these two methods agree within 3.0–5.7 % in the range $1 < p_T < 100$ GeV/c. Due to limitations in the data-mixing technique, the two cannot be compared on an equal footing after applying all of the quality cuts, in particular those involving the consistency of a track with the primary vertex. However, it is possible to ensure that the distributions on which the selections are made (i.e. the χ^2 of the track fit, the distance of closest approach between track and vertex, the number of hits in the silicon pixel and strip detectors) are consistent between the data and the MC simulations, both as a function of p_T and event centrality. To this end, an additional series of checks is performed by varying the requirements imposed during the track selection and in the determination of the corresponding MC-based corrections. The resulting variations in the corrected results are within the quoted systematic uncertainties.

The fraction of misidentified tracks estimated from simulated events for each leading-jet E_T sample as a function of track p_T is checked against an estimate from data that uses the sidebands of the impact parameter distributions. Studies of simulated events reveal that, at low p_T and in peripheral events (e.g. 50–90 %), the sidebands are dominated by secondaries and products of weak decays because of their displaced vertex positions. However, in central events (e.g. 0–5 %) and at high p_T they are mostly misidentified tracks. Based on varying the functional form of the sideband extrapolation under the peak from correctly reconstructed primary tracks, a 2.5–4.0 % systematic uncertainty is quoted for the fraction of misidentified tracks remaining after all selection cuts. An additional check is performed for tracks with p_T above 10 GeV/c to correlate the reconstructed track momentum with the energy deposited in the ECAL and HCAL. The fraction of high-p_T tracks with an atypically small amount of energy deposited in the calorimeters is consistent with the quoted uncertainty on the misidentification rate.

The tendency for finite bin widths and finite transverse-momentum resolution to deform a steeply falling p_T spectrum is corrected for in the analysis of the pp spectrum [5]. The higher occupancy in PbPb events than in pp events has negligible effect on the momentum resolution. The resulting 3.0 % systematic uncertainty is dominated by the uncertain shape of the momentum spectrum at high p_T. For the R_{AA} and R_{CP} measurements, a 2.0 % systematic uncertainty is quoted after subtracting the correlated uncertainty between the PbPb and pp p_T spectra, or between the central and peripheral PbPb p_T spectra. A summary of all the contributions to the systematic uncertainty affecting the PbPb and pp p_T spectra, and the resulting R_{AA} and R_{CP} values, is given in Table 2.

Table 2 Summary of the various contributions to the systematic uncertainties affecting the PbPb and pp p_T spectra, and the nuclear modification factors R_{AA} and R_{CP}

Source	Uncertainty [%]	
	PbPb	pp
Track reconstruction efficiency	3.0–5.7	2.2–3.6
Non-primary and misidentified tracks	2.5–4.0	1.0–3.2
Momentum resolution and binning	3.0	0.3–2.7
Normalization of jet-triggered spectra	0.0–4.0	0.0–6.0
Event selection	3.0	3.5
Pile-up estimation	<0.1	1.2
Total for p_T spectra	5.8–9.1	4.4–9.0
Luminosity	–	6.0
T_{AA} determination	4.1–18.0	–
Total for R_{CP}	6.7–20.0	–
Total for R_{AA}	9.9–23.0	–

3 Results

The charged particle invariant differential yield ($E\,\mathrm{d}^3N_{ch}/\mathrm{d}p^3$) averaged over the pseudorapidity $|\eta| < 1.0$ in pp collisions is shown in Fig. 3(a). The invariant and p_T-differential pp cross section is obtained by normalizing the corresponding yield by the integrated luminosities described in Refs. [19, 20]. Also shown in Fig. 3(a) are various generator-level predictions from the PYTHIA MC [21] for different tunes [22–25], and the ratios of the data to the various MC predictions. The pp measurement is also compared to the empirical global power-law scaling prediction [26] with an exponent $n = 4.9$ determined from the previous CMS measurements [5] by plotting $(\sqrt{s})^{n=4.9} E\,\mathrm{d}^3\sigma/\mathrm{d}p^3$ versus the scaling variable $x_T = 2p_T/\sqrt{s}$, as shown in Fig. 3(b).

The pp measurement at $\sqrt{s} = 2.76$ TeV is consistent with the global power-law fit established in Ref. [5]. The next-to-leading-order (NLO) prediction [26] for $\sqrt{s} = 2.75$ TeV

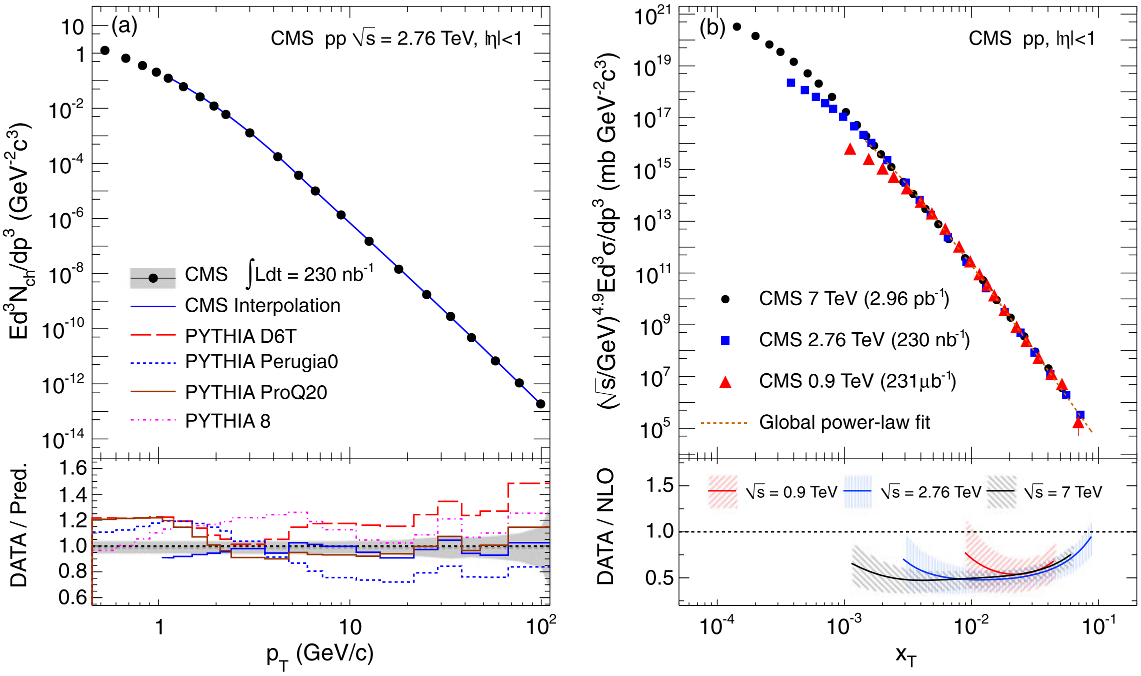


Fig. 3 (**a**) *Upper panel*: Invariant charged particle differential yield for $|\eta| < 1.0$ in pp collisions at $\sqrt{s} = 2.76$ TeV compared with the predictions of four tunes [22–25] of the PYTHIA MC generator and with the CMS interpolated spectrum using data at 0.9 and 7 TeV [5]. *Lower panel*: the ratio of the measured spectrum to the predictions of the four PYTHIA tunes and to the interpolated spectrum. The *grey band* corresponds to the statistical and systematic uncertainties of the measurement added in quadrature. (**b**) *Upper panel*: Inclusive charged particle invariant differential cross sections, scaled by $(\sqrt{s})^{4.9}$, for $|\eta| < 1.0$ as a function of the scaling parameter x_T for CMS data at 0.9 and 7 TeV [5] and this analysis at 2.76 TeV. The result is the average of the positive and negative charged particles. *Lower panel*: ratios of the differential cross sections measured at 0.9, 2.76, and 7 TeV to those predicted by NLO calculations [26]. The *bands* show the variations in the predictions when changing the factorization scales from 0.5 to 2.0 p_T

overestimates the measured cross section by almost a factor of two, as shown in Fig. 3(b).

The PbPb spectrum is shown for six centrality bins and compared to the measured pp reference spectrum, scaled by the nuclear overlap function, in Fig. 4. For easier viewing, several sets of points have been scaled by the arbitrary factors given in the figure. By comparing the PbPb measurements to the dashed lines representing the scaled pp reference spectrum, it is clear that the charged particle spectrum is strongly suppressed in central PbPb events compared to pp, with the most pronounced suppression at around 5–10 GeV/c.

The nuclear modification factor R_{AA} is constructed according to Eq. (1) by dividing the PbPb p_T spectrum for each centrality range by the scaled pp reference spectrum (i.e. the filled points by the dashed lines in Fig. 4). It is presented as a function of p_T in Fig. 5 for each of the six centrality bins. The yellow boxes around the points show the systematic uncertainties, including those from the pp reference spectrum, listed in Table 2. An additional systematic uncertainty from the T_{AA} normalization, common to all points and also listed in Table 2, is displayed as the shaded band around unity in each plot. The statistical uncertainties do not increase monotonically as a function of p_T, as seen most prominently in the peripheral bins, as a consequence of combining the highly prescaled minimum bias sample with the two unprescaled jet triggers, as discussed in Sect. 2. In the most peripheral events (70–90 %), a moderate suppression of about a factor of 2 ($R_{AA} \approx 0.6$) is observed at low p_T, with R_{AA} rising slightly with increasing transverse momentum. The suppression becomes more pronounced in the more central collisions, as expected from the increasingly dense final-state system and longer average path-lengths traversed by hard-scattered partons before fragmenting into final hadrons. In the 0–5 % centrality bin, R_{AA} reaches a minimum value of about 0.13 at $p_T = 6$–7 GeV/c. At higher p_T, the value of R_{AA} rises and levels off above 40 GeV/c at approximately 0.5. A rising R_{AA} may simply reflect the flattening of the unquenched nucleon–nucleon spectrum at high p_T if one assumes a constant fractional energy loss, although the magnitude of the rise varies among the different theoretical models.

The T_{AA}-scaled ratio of spectra in central and peripheral bins, R_{CP}, is constructed according to Eq. (2). The peripheral interval used for the normalization is chosen as the combined 50–90 % centrality bin to improve the statistical precision at high p_T. This approach removes the 4.4–9.0 % systematic uncertainty from the pp reference. Also part of the

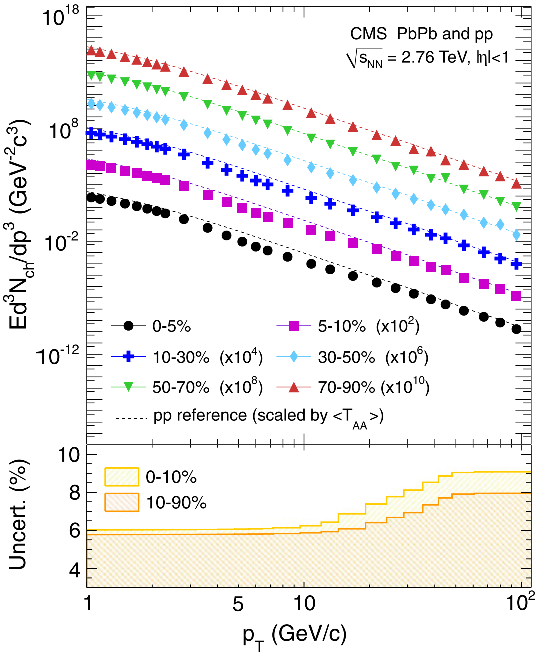


Fig. 4 *Upper panel*: Invariant charged particle differential yield in PbPb collisions at 2.76 TeV in bins of collision centrality (*symbols*), compared to that of pp at 2.76 TeV, normalized by the corresponding pp invariant cross sections scaled by the nuclear overlap function (*dashed lines*). The spectra for different centrality bins have been scaled by the arbitrary factors shown in the figure, for easier viewing. The statistical uncertainty is smaller than the marker size for most of the points. *Lower panel*: The average relative systematic uncertainties of the PbPb differential yields for the 0–10 % and 10–90 % centrality intervals, as a function of p_T

T_{AA} uncertainties is correlated between centrality bins and cancels out in the R_{CP} ratio. The resulting values of R_{CP} for the four most central bins are shown in Fig. 6. The statistical uncertainty of R_{CP} does not increase monotonically with p_T for the same reasons as mentioned for R_{AA}. As in the measurement of R_{AA}, the R_{CP} results show that the p_T spectra in central PbPb collisions are significantly suppressed compared to peripheral collisions.

The evolution of the nuclear modification factor with center-of-mass energy, from the SPS [27, 28] to RHIC [29, 30] and then to the LHC [12], is presented in Fig. 7. Note that RHIC results are shown for both neutral pions and charged hadrons, the latter being less suppressed below $p_T \approx 8$ GeV/c [29, 30] possibly due to parton recombination processes that enhance proton production and thus the overall yield of charged hadrons [31]. Below $p_T \approx 10$ GeV/c, charged hadron production at the LHC is found to be about 50 % more suppressed than at RHIC, and has a similar suppression value as for neutral pions measured by PHENIX [29].

The CMS measurement of R_{AA} presented in this paper for the 0–5 % centrality interval is compared to the ALICE result [12] in Fig. 7. Note that the pp spectrum measured by CMS at $\sqrt{s} = 2.76$ TeV is roughly 5–15 % higher than the ALICE spectrum obtained by interpolating their 0.9 and 7 TeV spectra [12]. The two R_{AA} results are in agreement within their respective statistical and systematic uncertainties.

The high-p_T measurement of R_{AA} from this analysis, up to $p_T = 100$ GeV/c, is also compared to a number of theoretical predictions, for the LHC design energy of $\sqrt{s_{NN}} = 5.5$ TeV (PQM [32] with medium transport-coefficient $\langle\hat{q}\rangle = 30$–$80$ GeV^2/fm and GLV [33, 34] for various values of the medium gluon pseudorapidity density dN_g/dy) and for the actual collision energy of $\sqrt{s_{NN}} = 2.76$ TeV (ASW [35, 36] and YaJEM [37] including a model for elastic energy loss parameterized with the P_{esc} variable). While most models predict the generally rising behavior of R_{AA} that is observed in the data at high p_T, the magnitude of the predicted slope varies greatly between models, depending on the assumptions for the jet-quenching mechanism. The new CMS measurement presented here should help in constraining the quenching parameters used in these models and improve the understanding of parton energy loss in a hot and dense medium.

4 Summary

Measurements of the charged particle transverse momentum spectra have been presented for $\sqrt{s_{NN}} = 2.76$ TeV pp and PbPb collisions. The results for the PbPb collisions have been compared to the measured pp p_T spectrum scaled by the corresponding number of incoherent nucleon–nucleon collisions. The high-p_T yields in central PbPb collisions are significantly suppressed when compared to peripheral PbPb and pp collisions. In the range $p_T = 5$–10 GeV/c, the suppression is stronger than that seen at RHIC. Beyond 10 GeV/c, both R_{AA} and R_{CP} show a rising trend, as already suggested by data from the ALICE experiment, limited to $p_T = 20$ GeV/c. The CMS measurement, with improved statistical precision, clearly shows that this rise continues at higher p_T, approaching a suppression factor $R_{AA} \approx 0.5$–0.6 in the range 40–100 GeV/c. The overall p_T dependence of the suppression can be described by a number of phenomenological predictions. The detailed evolution of the R_{AA} rise from 6 to 100 GeV/c depends on the details of the models. Together with measurements of high-p_T charged hadron azimuthal anisotropies, inclusive jet spectra, fragmentation functions, and dijet transverse energy balance, this measurement of the nuclear modification factors as a function of p_T and collision centrality should help elucidate the mechanism of jet quenching and the properties of the medium produced in heavy-ion collisions at collider energies.

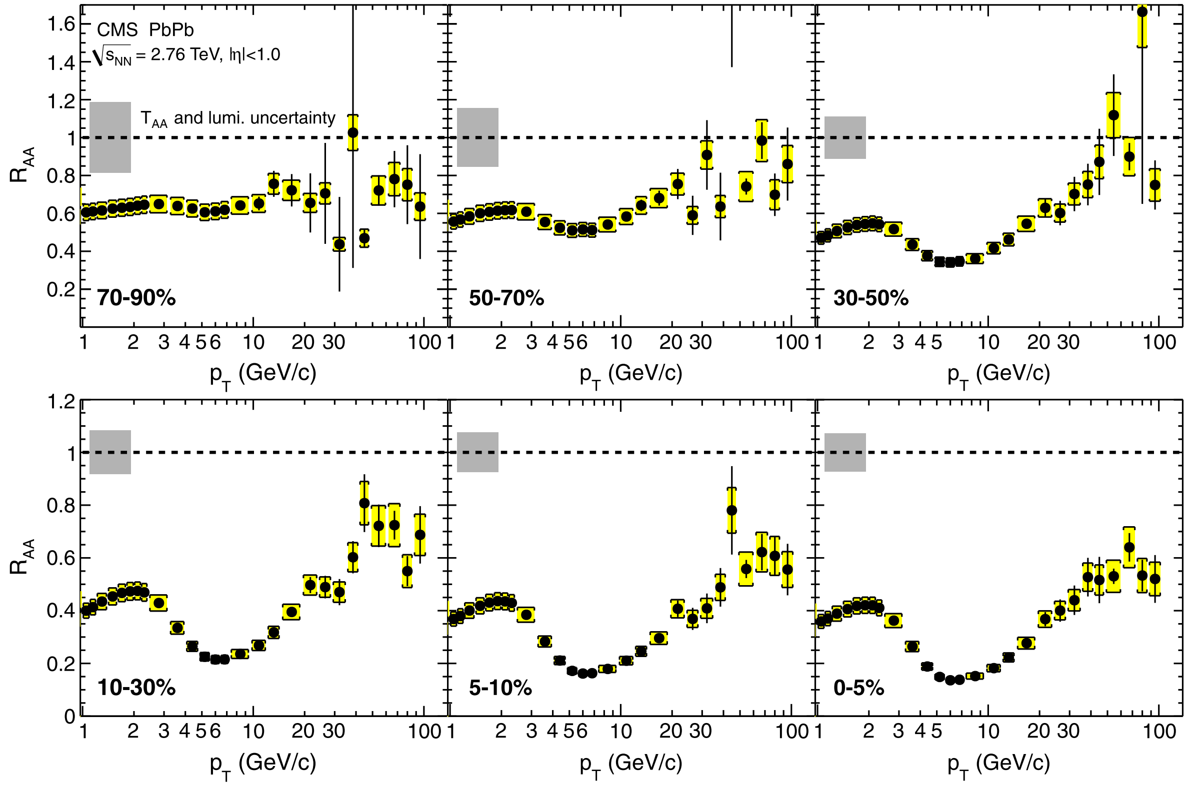
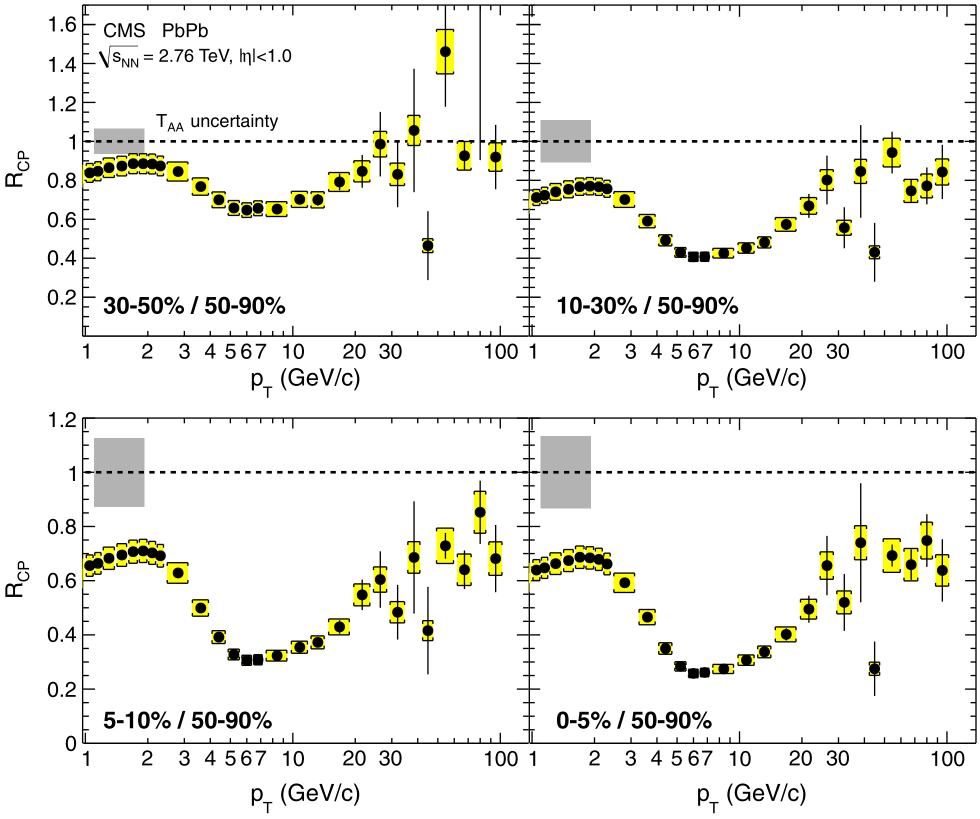


Fig. 5 Nuclear modification factor R_{AA} (*filled circles*) as a function of p_{T} for six PbPb centralities. The *error bars* represent the statistical uncertainties and the *yellow boxes* represent the p_{T}-dependent systematic uncertainties. An additional systematic uncertainty from the normalization of T_{AA} and the pp integrated luminosity, common to all points, is shown as the *shaded band* around unity in each plot

Fig. 6 T_{AA}-scaled ratio of p_{T} spectra in central and peripheral bins, R_{CP}, as a function of p_{T} for four PbPb centralities. The *error bars* represent the statistical uncertainties and the *yellow boxes* the p_{T}-dependent systematic uncertainties. An additional systematic uncertainty from the normalization of T_{AA}, common to all points, is shown as the *shaded band* around unity in each plot



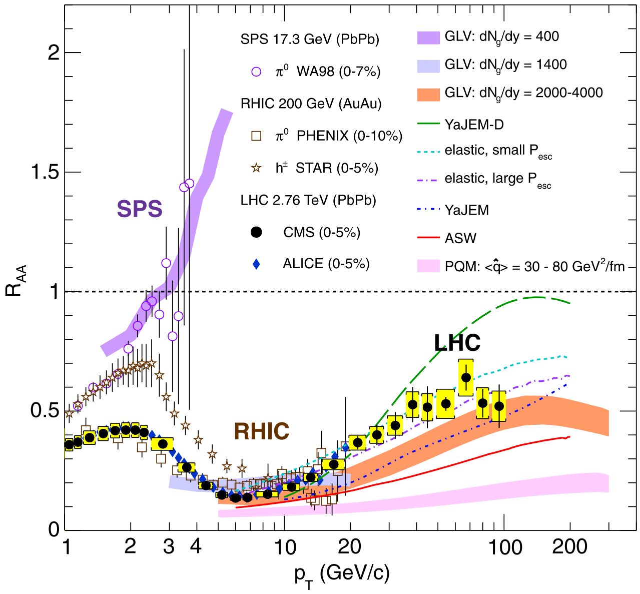


Fig. 7 Measurements of the nuclear modification factor R_{AA} in central heavy-ion collisions at three different center-of-mass energies, as a function of p_{T}, for neutral pions (π^0), charged hadrons ($h^\pm$), and charged particles [12, 27–30], compared to several theoretical predictions [32–37] (see text). The *error bars* on the points are the statistical uncertainties, and the *yellow boxes* around the CMS points are the systematic uncertainties. Additional absolute T_{AA} uncertainties of order ±5 % are not plotted. The *bands* for several of the theoretical calculations represent their uncertainties

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