PHYSICS LETTERS B

Centrality dependence of charged particle production at large transverse momentum in Pb–Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV

ALICE Collaboration

ABSTRACT

The inclusive transverse momentum (p_T) distributions of primary charged particles are measured in the pseudo-rapidity range $|\eta| < 0.8$ as a function of event centrality in Pb–Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV with ALICE at the LHC. The data are presented in the p_T range $0.15 < p_T < 50$ GeV/c for nine centrality intervals from 70–80% to 0–5%. The results in Pb–Pb are presented in terms of the nuclear modification factor R_{AA} using a pp reference spectrum measured at the same collision energy. We observe that the suppression of high-p_T particles strongly depends on event centrality. The yield is most suppressed in central collisions (0–5%) with $R_{AA} \approx 0.13$ at $p_T = 6$–7 GeV/c. Above $p_T = 7$ GeV/c, there is a significant rise in the nuclear modification factor, which reaches $R_{AA} \approx 0.4$ for $p_T > 30$ GeV/c. In peripheral collisions (70–80%), only moderate suppression ($R_{AA} = 0.6$–0.7) and a weak p_T dependence is observed. The measured nuclear modification factors are compared to other measurements and model calculations.

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1. Introduction

High-energy collisions of heavy-ions enable the study of hot and dense strongly interacting matter [1–5]. At sufficiently high temperature, it is expected that partons (quarks and gluons) are the dominant degrees of freedom. During the very early stage of the collision, some of the incoming partons experience scatterings with large momentum transfers. These partons lose energy when they traverse the hot and dense medium that is formed. One of the major goals of the heavy-ion physics programme at the LHC is to understand the underlying mechanisms for parton energy loss and use this as a tool to probe the properties of the medium.

Parton energy loss in heavy-ion collisions was first observed at RHIC as the suppression of high-p_T particle production in Au–Au collisions compared to expectations from an independent super-position of nucleon–nucleon collisions [6–9]. At RHIC, the particle production in central (0–5%) Au–Au collisions at $\sqrt{s_{NN}} = 200$ GeV is suppressed by a factor of 5 at $p_T = 5$–6 GeV/c [8,9], and is consistent with being independent of p_T over the measured range $5 < p_T < 20$ GeV/c [10].

The increase of the charged particle density ($dN_{ch}/d\eta$) at mid-rapidity from RHIC energies to actual LHC energies by a factor of around 2.2 [11] implies a similar increase in energy density. However, the observed suppression of high-p_T particle production also depends on the ratio of quarks to gluons due to their different color factors, and on the steepness of the p_T spectra of the scattered partons. At the LHC the initial parton p_T spectra are less

steep than at RHIC and the ratio of gluons to quarks at a given p_T is higher [12]. The measurement of high-p_T hadron production at the LHC helps to disentangle the effects which cause the suppression and provides a critical test of existing energy loss calculations [13]. In particular, the large p_T reach provides a means to study the dependence of the energy loss on the initial parton energy.

We present a measurement of the p_T distributions of charged particles in $0.15 < p_T < 50$ GeV/c with pseudo-rapidity $|\eta| < 0.8$, where $\eta = -\ln[\tan(\theta/2)]$, with θ the polar angle between the charged particle direction and the beam axis. Results are presented for different centrality intervals in Pb–Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV. They are compared with measurements in pp collisions, by calculating the nuclear modification factor

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

where N_{ch}^{AA} and σ_{ch}^{pp} represent the charged particle yield in nucleus–nucleus (AA) collisions and the cross section in pp collisions, respectively. The nuclear overlap function T_{AA} is calculated from the Glauber model [14] and averaged over each centrality interval, $\langle T_{AA}\rangle = \langle N_{coll}\rangle/\sigma_{inel}^{NN}$, where $\langle N_{coll}\rangle$ is the average number of binary nucleon–nucleon collisions and σ_{inel}^{NN} is the inelastic nucleon–nucleon cross section.

Early results from ALICE [15] showed that the production of charged particles in central (0–5%) Pb–Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV is suppressed by more than a factor of 6 at $p_T = 6$–7 GeV/c compared to an independent superposition of nucleon–nucleon collisions, and that the suppression is stronger than that observed at RHIC. The present data extend the study of high-p_T

Table 1
Average values of the number of participating nucleons $\langle N_{part} \rangle$ and the nuclear overlap function $\langle T_{AA} \rangle$ [14] for the centrality intervals used in the analysis.

Centrality	$\langle N_{part} \rangle$	$\langle T_{AA} \rangle$ (mb^{-1})
0–5%	383 ± 3	26.4 ± 1.1
5–10%	330 ± 5	20.6 ± 0.9
10–20%	261 ± 4	14.4 ± 0.6
20–30%	186 ± 4	8.7 ± 0.4
30–40%	129 ± 3	5.0 ± 0.2
40–50%	85 ± 3	2.68 ± 0.14
50–60%	53 ± 2	1.32 ± 0.09
60–70%	30.0 ± 1.3	0.59 ± 0.04
70–80%	15.8 ± 0.6	0.24 ± 0.03

particle suppression in Pb–Pb out to $p_T = 50$ GeV/c with a systematic study of the centrality dependence.

Moreover, the systematic uncertainties related to the pp reference were significantly reduced with respect to the previous measurement by using the p_T distribution measured in pp collisions at $\sqrt{s} = 2.76$ TeV [16].

2. Experiment and data analysis

The ALICE detector is described in [17]. The Inner Tracking System (ITS) and the Time Projection Chamber (TPC) are used for vertex finding and tracking. The minimum-bias interaction trigger was derived from signals from the forward scintillators (VZERO), and the two innermost layers of the ITS (Silicon Pixel Detector − SPD). The collision centrality is determined using the VZERO. In addition, the information from two neutron Zero Degree Calorimeters (ZDCs) positioned at ± 114 m from the interaction point was used to remove contributions from beam-gas and electromagnetic interactions. The trigger and centrality selection are described in more detail in [11]. 事件被分为9个中心度，以占总强子散射截面的百分比表示。

The following analysis is based on $1.6 \cdot 10^7$ minimum-bias Pb–Pb events recorded by ALICE in 2010. For this study, the events are divided into nine centrality intervals from the 70–80% to the 0–5% most central Pb–Pb collisions, expressed in percentage of the total hadronic cross section. The event centrality can be related to the number of participating nucleons N_{part} and the nuclear overlap function T_{AA} by using simulations based on the Glauber model [14]. The average values of N_{part} and T_{AA} for each centrality interval, $\langle N_{part} \rangle$ and $\langle T_{AA} \rangle$, along with their corresponding systematic uncertainties, are listed in Table 1. The errors include the experimental uncertainties on the inelastic nucleon–nucleon cross section $\sigma_{inel}^{NN} = 64 \pm 5$ mb at $\sqrt{s_{NN}} = 2.76$ TeV [18] and on the parameters of the nuclear density profile used in the Glauber simulations (more details in [11]).

The primary vertex position was determined from the tracks reconstructed in the ITS and the TPC by using an analytic χ^2 minimization method, applied after approximating each of the tracks by a straight line in the vicinity of their common origin. The event is accepted if the coordinate of the reconstructed vertex measured along the beam direction (z-axis) is within ± 10 cm around the nominal interaction point. The event vertex reconstruction is fully efficient for the event centralities covered.

Primary charged particles are defined as all prompt particles produced in the collision, including decay products, except those from weak decays of strange hadrons. A set of standard cuts based on the number of space points and the quality of the momentum fit in the TPC and ITS is applied to the reconstructed tracks. Track candidates in the TPC are required to have hits in at least 120 (out of a maximum of 159) pad-rows and χ^2 per point of the momentum fit smaller than 4. Such tracks are projected to the ITS and used for further analysis if at least 2 matching hits (out

of a maximum of 6) in the ITS, including at least one in the SPD, are found. In addition, the χ^2 per point of the momentum fit in the ITS must be smaller than 36. In order to improve the purity of primary track reconstruction at high p_T we developed a procedure where we compare tracking information from the combined ITS and TPC track reconstruction algorithm to that derived only from the TPC and constrained by the interaction vertex point. We calculated the $\chi^2_{TPC\text{-}ITS}$ between these tracks using the following formula

$$\chi^2_{TPC\text{-}ITS} = (\mathbf{v_{TPC}} - \mathbf{v_{TPC\text{-}ITS}})^{\mathbf{T}} \cdot (\mathbf{C_{TPC}} + \mathbf{C_{TPC\text{-}ITS}})^{-1}$$
$$\cdot (\mathbf{v_{TPC}} - \mathbf{v_{TPC\text{-}ITS}}) \qquad (2)$$

where $\mathbf{v_{TPC}}$, $\mathbf{v_{TPC\text{-}ITS}}$ and $\mathbf{C_{TPC}}$, $\mathbf{C_{TPC\text{-}ITS}}$ represent the measured track parameter vectors $\mathbf{v} = (x, y, z, \theta, \phi, 1/p_T)$ and their covariance matrices, respectively. If the $\chi^2_{TPC\text{-}ITS}$ is larger than 36 the track candidate is rejected. At $p_T = 0.15$–50 GeV/c, this procedure removes about 2–7% (1–3%) of the reconstructed tracks in the most central (peripheral) collisions. This procedure in fact removes high-p_T fake tracks, which originate from spurious matches of low p_T particles in the TPC to hits in the ITS, and would result in an incorrect momentum assignment.

Finally, tracks are rejected from the sample if their distance of closest approach to the reconstructed vertex in the longitudinal direction d_z is larger than 2 cm or $d_{xy} > 0.018$ cm $+ 0.035$ cm $\cdot p_T^{-1}$ in the transverse direction with p_T in GeV/c, which corresponds to 7 standard deviations of the resolution in d_{xy} (see [19] for details). The upper limit on the d_z ($d_z < 2$ cm) was set to minimize the contribution of tracks coming from pileup and beam-gas background events. These cuts reject less than 0.5% of the reconstructed tracks independently of p_T and collision centrality.

The efficiency and purity of the primary charged particle selection are estimated using a Monte Carlo simulation with HIJING [20] events and a GEANT3 [21] model of the detector response. We used a HIJING tune which reproduces approximately the measured charged particle density in central collisions [11]. In the most central events, the overall primary charged particle reconstruction efficiency (tracking efficiency and acceptance) in $|\eta| < 0.8$ is 36% at $p_T = 0.15$ GeV/c and increases to 65% for $p_T > 0.6$ GeV/c. In the most peripheral events the efficiency is larger than that for the central events by about 1–3%. The contribution from secondary particles was estimated using the d_{xy} distributions of data and HIJING and is consistent with the measured strangeness to charged particle ratio from the reconstruction of K_s^0, Λ and $\overline{\Lambda}$ invariant mass peaks in Pb–Pb [22]. The total contribution from secondary tracks at $p_T = 0.15$ GeV/c is 13 (7)% for central (peripheral) events and decreases to about 0.6% above $p_T = 4$ GeV/c for both central and peripheral events. From a systematic variation of the $\chi^2_{TPC\text{-}ITS}$ cut and comparison of track properties in MC to data we conclude that the number of properly reconstructed tracks rejected as high-p_T fake tracks is around 1–2% (0.5–1%) in the most central (peripheral) collisions. We also conclude that the contribution from the high-p_T fake tracks to the p_T spectra is negligible independently of the collision centrality and p_T.

The transverse momentum of charged particles is reconstructed from the track curvature measured in the magnetic field $B = 0.5$ T using the ITS and TPC detectors. The p_T resolution is estimated from the track residuals to the momentum fit and verified by cosmic muon events, and the width of the invariant mass peaks of Λ, $\overline{\Lambda}$ and K_s^0 reconstructed from their decays to two charged particles. For the selected tracks the relative p_T resolution ($\sigma(p_T)/p_T$) amounts to 3.5% at $p_T = 0.15$ GeV/c, has a minimum of 1% at $p_T = 1$ GeV/c, and increases linearly to 10% at $p_T = 50$ GeV/c. It is independent of the centrality of the selected events. From the study of the invariant mass distributions of Λ and K_s^0 as a

Table 2

Contribution to the systematic uncertainties on the p_T spectra (0.15–50 GeV/c) for the most central and peripheral Pb–Pb collisions. Also listed are the systematic uncertainties on the pp reference (0.15–50 GeV/c) [16].

Centrality class	0–5%	70–80%
Centrality selection	0.4%	6.7%
Event selection	3.2%	3.4%
Track selection	4.1–7.3%	3.6–6.0%
Tracking efficiency	5%	5%
p_T resolution correction	< 1.8%	< 3%
Material budget	0.9–1.2%	0.5–1.7%
Particle composition	0.6–10%	0.5–7.7%
MC generator	2.5%	1.5%
Secondary particle rejection	< 1%	< 1%
Total for p_T spectra	8.2–13.5%	10.3–13.4%
Total for pp reference	6.3–18.8%	
pp reference normalization	1.9%	

function of p_T we estimate that the relative uncertainty on the p_T resolution is around 20%. From the mass difference between Λ and $\overline{\Lambda}$ and the ratio of positively to negatively charged tracks, assuming charge symmetry at high p_T, the upper limit of the systematic uncertainty of the momentum scale is estimated to be $|\Delta(p_T)/p_T| < 0.005$ at $p_T = 50$ GeV/c. This has an effect of around 1.5% on the yield of the measured spectra at the highest p_T. To account for the finite p_T resolution, correction factors for the reconstructed p_T spectra at $p_T > 10$ GeV/c are derived using a folding procedure. The corrections depend on collision centrality due to the change of the spectral shape and reach 4 (8)% at $p_T = 50$ GeV/c in the most central (peripheral) collisions.

The systematic uncertainties on the p_T spectra are summarized in Table 2. The systematic uncertainties related to centrality selection were estimated by a comparison of the p_T spectra when the limits of the centrality classes are shifted by $\pm 1\%$ (e.g. for the 70–80% centrality class, 70.7–80.8% and 69.3–79.2%), which is a relative uncertainty on the fraction of the hadronic cross section used in the Glauber fit [11] to determine the centrality classes. We also varied the event and track quality selection criteria and the Monte Carlo assumptions to estimate systematic uncertainties on the p_T spectra. In particular, we studied a variation of the most abundant charged particle species (pions, kaons, protons) by $\pm 30\%$ to match the measured ratios and their uncertainties [22]. The material budget was varied by $\pm 7\%$ [23], and the secondary yield from strangeness decays in the Monte Carlo by $\pm 30\%$ to match the measured d_{xy} distributions. Moreover, we used a different event generator, DPMJET [24], to calculate MC correction maps. The systematic uncertainties on the p_T spectra, related to the high-p_T fake track rejection procedure, were estimated by varying the track matching criteria in the range $25 < \chi^2_{\text{TPC-ITS}} < 49$, and amount to 1–4% (1–2%) in the most central (peripheral) collisions. The total systematic uncertainties on the corrected p_T spectra depend on p_T and event centrality and amount to 8.2–13.5% (10.3–13.4%) in the most central (peripheral) collisions.

A dedicated run of the LHC to collect pp reference data at $\sqrt{s} = 2.76$ TeV took place in March 2011. Data taken in this run were used to measure the charged particle p_T spectrum that forms the basis of the pp reference spectrum for R_{AA}. Using these data the systematic uncertainties in R_{AA} related to the pp reference could be significantly improved (Table 2) compared to the previous publication [15], allowing for an exploration of high-p_T particle suppression in Pb–Pb out to 50 GeV/c. More details about the pp reference determination can be found in [16].
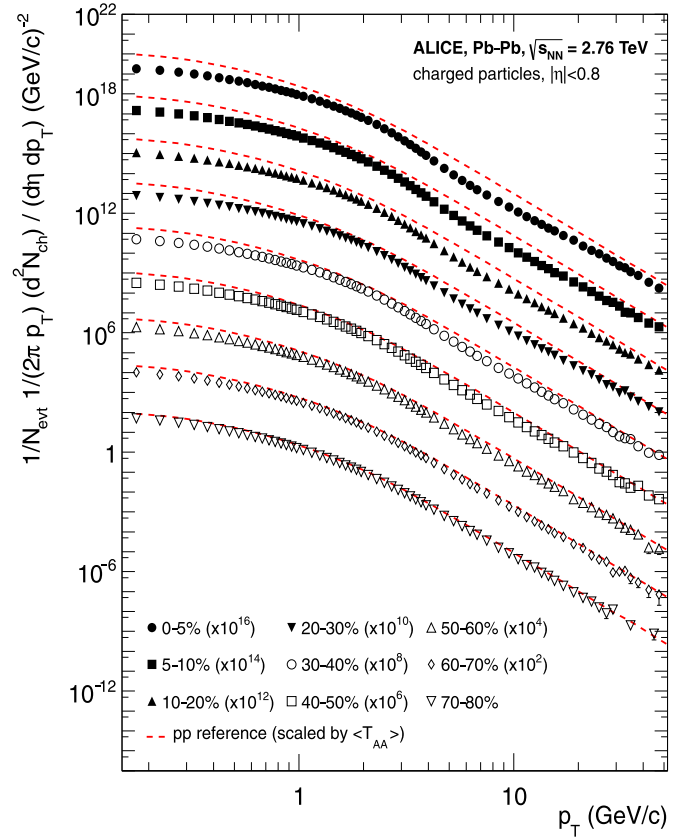

Fig. 1. Charged particle p_T distribution measured in Pb–Pb collisions in different centrality intervals. The spectra are scaled for better visibility. The dashed lines show the pp reference [16] spectra scaled by the nuclear overlap function determined for each centrality interval (Table 1) and by the Pb–Pb spectra scaling factors. The systematic and statistical uncertainties for Pb–Pb are added quadratically. The uncertainties on the pp reference are not shown.

3. Results

The fully corrected p_T spectra of inclusive charged particles measured in Pb–Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV in nine different centrality intervals, and the scaled pp reference spectra are shown in Fig. 1. At low p_T, the transverse momentum spectra differ from the pp reference. This is in agreement with the previously observed scaling behavior of the total charged particle production as a function of centrality [11]. A marked depletion of the spectra at high transverse momentum ($p_T > 5$ GeV/c) develops gradually as centrality increases, indicating strong suppression of high-p_T particle production in central collisions.

The nuclear modification factors for nine centrality intervals are shown in Fig. 2. In peripheral collisions (70–80%), only moderate suppression ($R_{AA} = 0.6$–0.7) and a weak p_T dependence is observed. Towards more central collisions, a pronounced minimum at about $p_T = 6$–7 GeV/c develops while for $p_T > 7$ GeV/c there is a significant rise of the nuclear modification factor. This rise becomes gradually less steep with increasing p_T. In the most central collisions (0–5%), the yield is most suppressed, $R_{AA} \approx 0.13$ at $p_T = 6$–7 GeV/c, and R_{AA} reaches ≈ 0.4 with no significant p_T dependence for $p_T > 30$ GeV/c.

The dependence of R_{AA} on the collision centrality, expressed in terms of N_{part} and the charged particle multiplicity density ($dN_{\text{ch}}/d\eta$), are shown in Fig. 3 for different intervals of p_T. Also shown are results from PHENIX at RHIC in Au–Au collisions at $\sqrt{s_{NN}} = 200$ GeV [9]. The strongest centrality dependence is observed for particles with $5 < p_T < 7$ GeV/c. At higher p_T, the
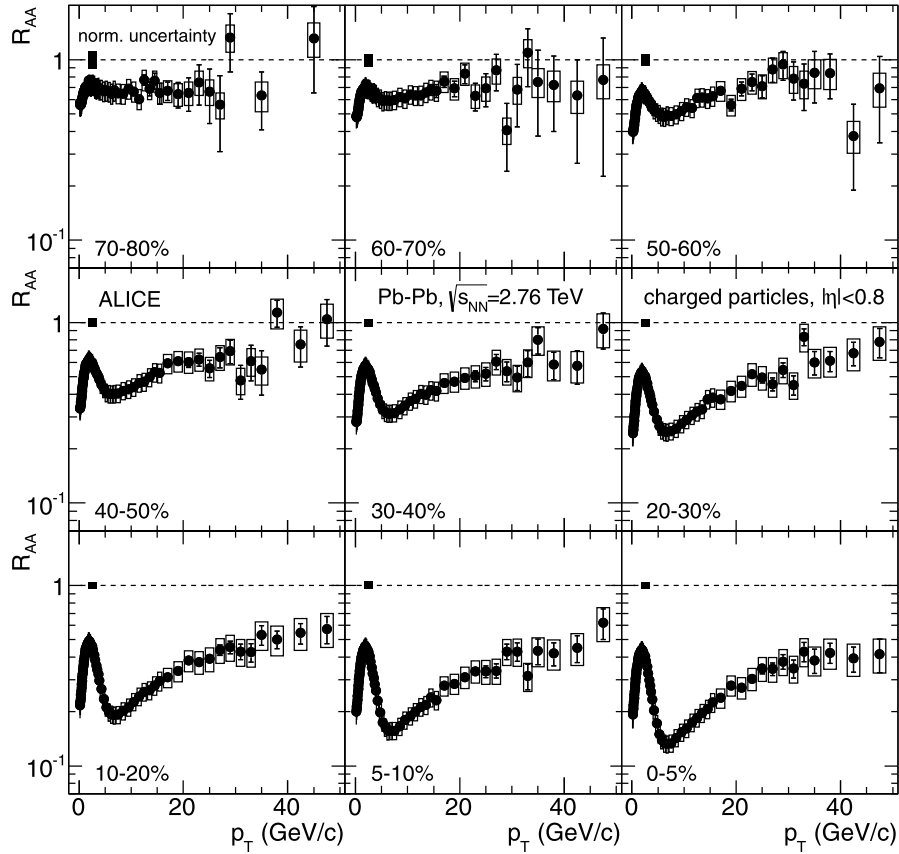
Fig. 2. Nuclear modification factor R_{AA} of charged particles measured in Pb–Pb collisions in nine centrality intervals. The boxes around data points denote p_T-dependent systematic uncertainties. The systematic uncertainties on the normalization which are related to $\langle T_{AA} \rangle$ and the normalization of the pp data are added in quadrature and shown as boxes at $R_{AA} = 1$.

centrality dependence weakens gradually. In comparison to results from RHIC, the LHC data in the same p_T window show a suppression which is larger by a factor of about 1.2 at all $\langle N_{part} \rangle$ (Fig. 3, top panel). This implies that the shape of the N_{part} dependence at RHIC and the LHC is very similar when the same p_T is compared, indicating a strong relation between collision geometry and energy loss. The overall increase of suppression at the LHC as compared to RHIC may be expected from the larger density and longer lifetime of the fireball. The suppression reaches similar values when results from RHIC are compared to results from the LHC in terms of $dN_{ch}/d\eta$, as shown in Fig. 3 (bottom panel). Larger values of suppression than at RHIC are observed in central collisions at the LHC, where the charged particle multiplicity exceeds that of the most central collisions at RHIC. It should be noted that the suppression at a given centrality results from a subtle interplay between the parton p_T spectrum, the quark-to-gluon ratio, and the medium density, all of which exhibit a significant energy dependence. Further model studies are needed to evaluate their relative contributions.

The ALICE measurement of R_{AA} in the most central Pb–Pb collisions (0–5%) is compared to the CMS result [25] in Fig. 4. Both measurements agree within their respective statistical and systematic uncertainties.

In Fig. 4, the measured R_{AA} for 0–5% central collisions is also compared to model calculations. All selected models use RHIC data to calibrate the medium density and were available before the preliminary version of the data reported in this Letter. All model calculations except WHDG [26] use a hydrodynamical description of the medium, but different extrapolation assumptions from RHIC to LHC. A variety of energy loss formalisms is used. An increase of

R_{AA} due to a decrease of the relative energy loss with increasing p_T is seen for all the models.

The curves labeled WHDG, ASW, and Higher Twist (HT) are based on analytical radiative energy loss formulations that include interference effects. Of those curves, the multiple soft gluon approximation (ASW [27]) and the opacity expansion (WHDG [26]) show a larger suppression than seen in the measurement, while one of the HT curves (Chen [28]) with lower density provides a good description. The other HT (Majumder [29]) curve shows a stronger rise with p_T than measured. The elastic energy loss model by Renk (elastic) [30] does not rise steeply enough with p_T and overshoots the data at low p_T. The YaJEM-D model [31], which is based on medium-induced virtuality increases in a parton shower, shows too strong a p_T-dependence of R_{AA} due to a formation time cut-off.

A more systematic study of the energy loss formalisms, preferably with the same model(s) for the medium density is needed to rule out or confirm the various effects. Deviations of the nuclear parton distribution functions (PDFs) from a simple scaling of the nucleon PDF with mass number A (e.g. shadowing) are also expected to affect the nuclear modification factor. These effects are predicted to be small for $p_T > 10$ GeV/c at the LHC [26] and will be quantified in future p–Pb measurements.

4. Summary

We have reported the measurements of charged particle p_T spectra and nuclear modification factors R_{AA} as a function of event centrality in Pb–Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV. The results indicate a strong suppression of charged particle production in Pb–Pb
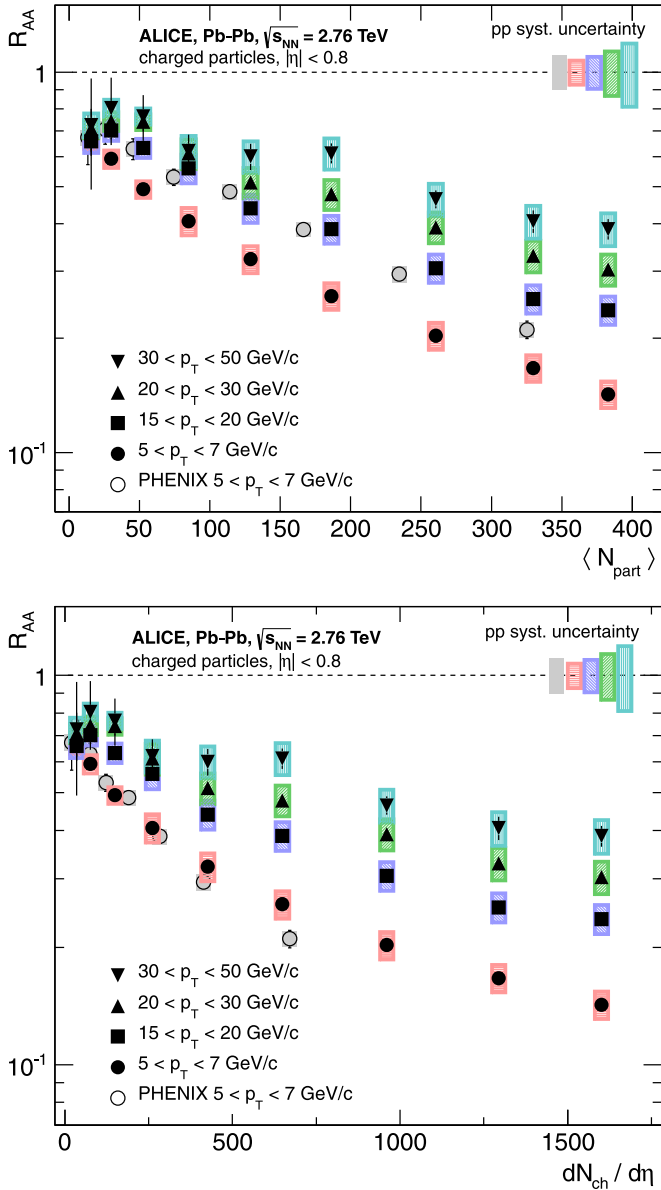
Fig. 3. Nuclear modification factor R_{AA} of charged particles as a function of $\langle N_{part} \rangle$ (top panel) and $dN_{ch}/d\eta$ (bottom panel) measured by ALICE in Pb–Pb collisions in different p_T-intervals, compared to PHENIX results in $5 < p_T < 7$ GeV/c [9]. The boxes around the data represent the p_T-dependent uncertainties on the Pb–Pb p_T spectra. The boxes at $R_{AA} = 1$ represent the systematic uncertainties on the pp reference in different p_T-intervals (p_T-interval increases from left to right, the leftmost is for PHENIX). The systematic uncertainties on the overall normalization for ALICE and PHENIX are not shown.

collisions and a characteristic centrality and p_T dependence of the nuclear modification factors. In central collisions (0–5%) the yield is most strongly suppressed ($R_{AA} \approx 0.13$) at $p_T = 6$–7 GeV/c. Above $p_T = 7$ GeV/c, there is a significant rise in the nuclear modification factor, which reaches $R_{AA} \approx 0.4$ for $p_T > 30$ GeV/c. This result is in agreement with the CMS measurement within statistical and systematic uncertainties. The suppression is weaker in peripheral collisions (70–80%) with $R_{AA} = 0.6$–0.7 and no strong p_T dependence. The observed suppression of high-p_T particles in central Pb–Pb collisions provides evidence for strong parton energy loss and a large medium density at the LHC. We observe that the suppression of charged particles with $5 < p_T < 7$ GeV/c reaches similar values when results from RHIC are compared to results from LHC in terms of the $dN_{ch}/d\eta$. The measured R_{AA} in 0–5%
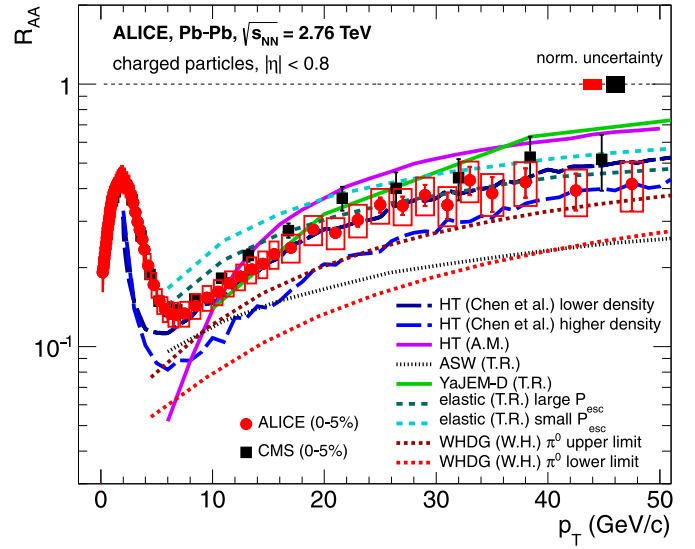
Fig. 4. Nuclear modification factor R_{AA} of charged particles measured by ALICE in the most central Pb–Pb collisions (0–5%) in comparison to results from CMS [25] and model calculations [26–31]. The boxes around the data denote p_T-dependent systematic uncertainties. For CMS statistical and systematic uncertainties on R_{AA} are added in quadrature. The systematic uncertainties on the normalization which are related to $\langle T_{AA} \rangle$ and the normalization of the pp data are added in quadrature and shown as boxes at $R_{AA} = 1$ (the right-most is for CMS).

central collisions is compared to model calculations. An increase of R_{AA} due to a decrease of the relative energy loss with increasing p_T is seen for all the models. The measurement presented here, together with measurements of particle correlations [32] and measurements using jet reconstruction [33], will help in understanding the mechanism of jet quenching and the properties of the medium produced in heavy-ion collisions.

Acknowledgements

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Šándor [47], A. Sandoval [56], S. Sano [113], M. Sano [114], R. Santo [54], R. Santoro [98,30,10], J. Sarkamo [38], E. Scapparone [97], F. Scarlassara [20], R.P. Scharenberg [83], C. Schiaua [70], R. Schicker [82], C. Schmidt [85], H.R. Schmidt [115], S. Schreiner [30], S. Schuchmann [52], J. Schukraft [30], Y. Schutz [30,102], K. Schwarz [85], K. Schweda [85,82], G. Scioli [19], E. Scomparin [94], R. Scott [112], G. Segato [20], I. Selyuzhenkov [85], S. Senyukov [58], J. Seo [84], S. Serci [22], E. Serradilla [8,56], A. Sevcenco [50], A. Shabetai [102], G. Shabratova [59], R. Shahoyan [30], S. Sharma [80], N. Sharma [77], S. Rohni [80], K. Shigaki [39], M. Shimomura [114], K. Shtejer [7], Y. Sibiriak [88], M. Siciliano [23], E. Sicking [30], S. Siddhanta [96], T. Siemiarczuk [100], D. Silvermyr [74], C. Silvestre [64], G. Simatovic [55,86], G. Simonetti [30], R. Singaraju [116], R. Singh [80], S. Singha [116], V. Singhal [116], B.C. Sinha [116], T. Sinha [89], B. Sitar [33], M. Sitta [27], T.B. Skaali [18], K. Skjerdal [15], R. Smakal [34], N. Smirnov [120], R.J.M. Snellings [45], C. Søgaard [71], R. Soltz [68], H. Son [17], J. Song [84], M. Song [123], C. Soos [30], F. Soramel [20],

I. Sputowska [104], M. Spyropoulou-Stassinaki [78], B.K. Srivastava [83], J. Stachel [82], I. Stan [50], I. Stan [50], G. Stefanek [100], M. Steinpreis [16], E. Stenlund [29], G. Steyn [79], J.H. Stiller [82], D. Stocco [102], M. Stolpovskiy [43], K. Strabykin [87], P. Strmen [33], A.A.P. Suaide [107], M.A. Subieta Vásquez [23], T. Sugitate [39], C. Suire [42], M. Sukhorukov [87], R. Sultanov [46], M. Šumbera [73], T. Susa [86], T.J.M. Symons [67], A. Szanto de Toledo [107], I. Szarka [33], A. Szczepankiewicz [104,30], A. Szostak [15], M. Szymański [118], J. Takahashi [108], J.D. Tapia Takaki [42], A. Tauro [30], G. Tejeda Muñoz [1], A. Telesca [30], C. Terrevoli [28], J. Thäder [85], D. Thomas [45], R. Tieulent [109], A.R. Timmins [110], D. Tlusty [34], A. Toia [36,20,93], H. Torii [113], L. Toscano [94], V. Trubnikov [2], D. Truesdale [16], W.H. Trzaska [38], T. Tsuji [113], A. Tumkin [87], R. Turrisi [93], T.S. Tveter [18], J. Ulery [52], K. Ullaland [15], J. Ulrich [61,51], A. Uras [109], J. Urbán [35], G.M. Urciuoli [95], G.L. Usai [22], M. Vajzer [34,73], M. Vala [59,47], L. Valencia Palomo [42], S. Vallero [82], P. Vande Vyvre [30], M. van Leeuwen [45], L. Vannucci [66], A. Vargas [1], R. Varma [40], M. Vasileiou [78], A. Vasiliev [88], V. Vechernin [117], M. Veldhoen [45], M. Venaruzzo [21], E. Vercellin [23], S. Vergara [1], R. Vernet [6], M. Verweij [45], L. Vickovic [103], G. Viesti [20], O. Vikhlyantsev [87], Z. Vilakazi [79], O. Villalobos Baillie [90], Y. Vinogradov [87], L. Vinogradov [117], A. Vinogradov [88], T. Virgili [26], Y.P. Viyogi [116], A. Vodopyanov [59], K. Voloshin [46], S. Voloshin [119], G. Volpe [28,30], B. von Haller [30], D. Vranic [85], G. Øvrebekk [15], J. Vrláková [35], B. Vulpescu [63], A. Vyushin [87], V. Wagner [34], B. Wagner [15], R. Wan [5], D. Wang [5], M. Wang [5], Y. Wang [5], Y. Wang [82], K. Watanabe [114], M. Weber [110], J.P. Wessels [30,54], U. Westerhoff [54], J. Wiechula [115], J. Wikne [18], M. Wilde [54], A. Wilk [54], G. Wilk [100], M.C.S. Williams [97], B. Windelband [82], L. Xaplanteris Karampatsos [105], C.G. Yaldo [119], Y. Yamaguchi [113], S. Yang [15], H. Yang [12], S. Yasnopolskiy [88], J. Yi [84], Z. Yin [5], I.-K. Yoo [84], J. Yoon [123], W. Yu [52], X. Yuan [5], I. Yushmanov [88], V. Zaccolo [71], C. Zach [34], C. Zampolli [97], S. Zaporozhets [59], A. Zarochentsev [117], P. Závada [49], N. Zaviyalov [87], H. Zbroszczyk [118], P. Zelnicek [51], I.S. Zgura [50], M. Zhalov [75], X. Zhang [63,5], H. Zhang [5], F. Zhou [5], Y. Zhou [45], D. Zhou [5], J. Zhu [5], X. Zhu [5], J. Zhu [5], A. Zichichi [19,10], A. Zimmermann [82], G. Zinovjev [2], Y. Zoccarato [109], M. Zynovyev [2], M. Zyzak [52]

[1] *Benemérita Universidad Autónoma de Puebla, Puebla, Mexico*
[2] *Bogolyubov Institute for Theoretical Physics, Kiev, Ukraine*
[3] *Budker Institute for Nuclear Physics, Novosibirsk, Russia*
[4] *California Polytechnic State University, San Luis Obispo, CA, United States*
[5] *Central China Normal University, Wuhan, China*
[6] *Centre de Calcul de l'IN2P3, Villeurbanne, France*
[7] *Centro de Aplicaciones Tecnológicas y Desarrollo Nuclear (CEADEN), Havana, Cuba*
[8] *Centro de Investigaciones Energéticas Medioambientales y Tecnológicas (CIEMAT), Madrid, Spain*
[9] *Centro de Investigación y de Estudios Avanzados (CINVESTAV), Mexico City and Mérida, Mexico*
[10] *Centro Fermi – Centro Studi e Ricerche e Museo Storico della Fisica "Enrico Fermi", Rome, Italy*
[11] *Chicago State University, Chicago, United States*
[12] *Commissariat à l'Energie Atomique, IRFU, Saclay, France*
[13] *Departamento de Física de Partículas and IGFAE, Universidad de Santiago de Compostela, Santiago de Compostela, Spain*
[14] *Department of Physics Aligarh Muslim University, Aligarh, India*
[15] *Department of Physics and Technology, University of Bergen, Bergen, Norway*
[16] *Department of Physics, Ohio State University, Columbus, OH, United States*
[17] *Department of Physics, Sejong University, Seoul, South Korea*
[18] *Department of Physics, University of Oslo, Oslo, Norway*
[19] *Dipartimento di Fisica dell'Università and Sezione INFN, Bologna, Italy*
[20] *Dipartimento di Fisica dell'Università and Sezione INFN, Padova, Italy*
[21] *Dipartimento di Fisica dell'Università and Sezione INFN, Trieste, Italy*
[22] *Dipartimento di Fisica dell'Università and Sezione INFN, Cagliari, Italy*
[23] *Dipartimento di Fisica dell'Università and Sezione INFN, Turin, Italy*
[24] *Dipartimento di Fisica dell'Università 'La Sapienza' and Sezione INFN, Rome, Italy*
[25] *Dipartimento di Fisica e Astronomia dell'Università and Sezione INFN, Catania, Italy*
[26] *Dipartimento di Fisica 'E.R. Caianiello' dell'Università and Gruppo Collegato INFN, Salerno, Italy*
[27] *Dipartimento di Scienze e Innovazione Tecnologica dell'Università del Piemonte Orientale and Gruppo Collegato INFN, Alessandria, Italy*
[28] *Dipartimento Interateneo di Fisica 'M. Merlin' and Sezione INFN, Bari, Italy*
[29] *Division of Experimental High Energy Physics, University of Lund, Lund, Sweden*
[30] *European Organization for Nuclear Research (CERN), Geneva, Switzerland*
[31] *Fachhochschule Köln, Köln, Germany*
[32] *Faculty of Engineering, Bergen University College, Bergen, Norway*
[33] *Faculty of Mathematics, Physics and Informatics, Comenius University, Bratislava, Slovakia*
[34] *Faculty of Nuclear Sciences and Physical Engineering, Czech Technical University in Prague, Prague, Czech Republic*
[35] *Faculty of Science, P.J. Šafárik University, Košice, Slovakia*
[36] *Frankfurt Institute for Advanced Studies, Johann Wolfgang Goethe-Universität Frankfurt, Frankfurt, Germany*
[37] *Gangneung-Wonju National University, Gangneung, South Korea*
[38] *Helsinki Institute of Physics (HIP) and University of Jyväskylä, Jyväskylä, Finland*
[39] *Hiroshima University, Hiroshima, Japan*
[40] *Indian Institute of Technology Bombay (IIT), Mumbai, India*
[41] *Indian Institute of Technology Indore (IIT), Indore, India*
[42] *Institut de Physique Nucléaire d'Orsay (IPNO), Université Paris-Sud, CNRS-IN2P3, Orsay, France*
[43] *Institute for High Energy Physics, Protvino, Russia*

[44] *Institute for Nuclear Research, Academy of Sciences, Moscow, Russia*
[45] *Nikhef, National Institute for Subatomic Physics and Institute for Subatomic Physics of Utrecht University, Utrecht, Netherlands*
[46] *Institute for Theoretical and Experimental Physics, Moscow, Russia*
[47] *Institute of Experimental Physics, Slovak Academy of Sciences, Košice, Slovakia*
[48] *Institute of Physics, Bhubaneswar, India*
[49] *Institute of Physics, Academy of Sciences of the Czech Republic, Prague, Czech Republic*
[50] *Institute of Space Sciences (ISS), Bucharest, Romania*
[51] *Institut für Informatik, Johann Wolfgang Goethe-Universität Frankfurt, Frankfurt, Germany*
[52] *Institut für Kernphysik, Johann Wolfgang Goethe-Universität Frankfurt, Frankfurt, Germany*
[53] *Institut für Kernphysik, Technische Universität Darmstadt, Darmstadt, Germany*
[54] *Institut für Kernphysik, Westfälische Wilhelms-Universität Münster, Münster, Germany*
[55] *Instituto de Ciencias Nucleares, Universidad Nacional Autónoma de México, Mexico City, Mexico*
[56] *Instituto de Física, Universidad Nacional Autónoma de México, Mexico City, Mexico*
[57] *Institut of Theoretical Physics, University of Wroclaw, Poland*
[58] *Institut Pluridisciplinaire Hubert Curien (IPHC), Université de Strasbourg, CNRS-IN2P3, Strasbourg, France*
[59] *Joint Institute for Nuclear Research (JINR), Dubna, Russia*
[60] *KFKI Research Institute for Particle and Nuclear Physics, Hungarian Academy of Sciences, Budapest, Hungary*
[61] *Kirchhoff-Institut für Physik, Ruprecht-Karls-Universität Heidelberg, Heidelberg, Germany*
[62] *Korea Institute of Science and Technology Information, Daejeon, South Korea*
[63] *Laboratoire de Physique Corpusculaire (LPC), Clermont Université, Université Blaise Pascal, CNRS–IN2P3, Clermont-Ferrand, France*
[64] *Laboratoire de Physique Subatomique et de Cosmologie (LPSC), Université Joseph Fourier, CNRS-IN2P3, Institut Polytechnique de Grenoble, Grenoble, France*
[65] *Laboratori Nazionali di Frascati, INFN, Frascati, Italy*
[66] *Laboratori Nazionali di Legnaro, INFN, Legnaro, Italy*
[67] *Lawrence Berkeley National Laboratory, Berkeley, CA, United States*
[68] *Lawrence Livermore National Laboratory, Livermore, CA, United States*
[69] *Moscow Engineering Physics Institute, Moscow, Russia*
[70] *National Institute for Physics and Nuclear Engineering, Bucharest, Romania*
[71] *Niels Bohr Institute, University of Copenhagen, Copenhagen, Denmark*
[72] *Nikhef, National Institute for Subatomic Physics, Amsterdam, Netherlands*
[73] *Nuclear Physics Institute, Academy of Sciences of the Czech Republic, Řež u Prahy, Czech Republic*
[74] *Oak Ridge National Laboratory, Oak Ridge, TN, United States*
[75] *Petersburg Nuclear Physics Institute, Gatchina, Russia*
[76] *Physics Department, Creighton University, Omaha, NE, United States*
[77] *Physics Department, Panjab University, Chandigarh, India*
[78] *Physics Department, University of Athens, Athens, Greece*
[79] *Physics Department, University of Cape Town, iThemba LABS, Cape Town, South Africa*
[80] *Physics Department, University of Jammu, Jammu, India*
[81] *Physics Department, University of Rajasthan, Jaipur, India*
[82] *Physikalisches Institut, Ruprecht-Karls-Universität Heidelberg, Heidelberg, Germany*
[83] *Purdue University, West Lafayette, IN, United States*
[84] *Pusan National University, Pusan, South Korea*
[85] *Research Division and ExtreMe Matter Institute EMMI, GSI Helmholtzzentrum für Schwerionenforschung, Darmstadt, Germany*
[86] *Rudjer Bošković Institute, Zagreb, Croatia*
[87] *Russian Federal Nuclear Center (VNIIEF), Sarov, Russia*
[88] *Russian Research Centre Kurchatov Institute, Moscow, Russia*
[89] *Saha Institute of Nuclear Physics, Kolkata, India*
[90] *School of Physics and Astronomy, University of Birmingham, Birmingham, United Kingdom*
[91] *Sección Física, Departamento de Ciencias, Pontificia Universidad Católica del Perú, Lima, Peru*
[92] *Sezione INFN, Trieste, Italy*
[93] *Sezione INFN, Padova, Italy*
[94] *Sezione INFN, Turin, Italy*
[95] *Sezione INFN, Rome, Italy*
[96] *Sezione INFN, Cagliari, Italy*
[97] *Sezione INFN, Bologna, Italy*
[98] *Sezione INFN, Bari, Italy*
[99] *Sezione INFN, Catania, Italy*
[100] *Soltan Institute for Nuclear Studies, Warsaw, Poland*
[101] *Nuclear Physics Group, STFC Daresbury Laboratory, Daresbury, United Kingdom*
[102] *SUBATECH, Ecole des Mines de Nantes, Université de Nantes, CNRS-IN2P3, Nantes, France*
[103] *Technical University of Split FESB, Split, Croatia*
[104] *The Henryk Niewodniczanski Institute of Nuclear Physics, Polish Academy of Sciences, Cracow, Poland*
[105] *The University of Texas at Austin, Physics Department, Austin, TX, United States*
[106] *Universidad Autónoma de Sinaloa, Culiacán, Mexico*
[107] *Universidade de São Paulo (USP), São Paulo, Brazil*
[108] *Universidade Estadual de Campinas (UNICAMP), Campinas, Brazil*
[109] *Université de Lyon, Université Lyon 1, CNRS/IN2P3, IPN-Lyon, Villeurbanne, France*
[110] *University of Houston, Houston, TX, United States*
[111] *University of Technology and Austrian Academy of Sciences, Vienna, Austria*
[112] *University of Tennessee, Knoxville, TN, United States*
[113] *University of Tokyo, Tokyo, Japan*
[114] *University of Tsukuba, Tsukuba, Japan*
[115] *Eberhard Karls Universität Tübingen, Tübingen, Germany*
[116] *Variable Energy Cyclotron Centre, Kolkata, India*
[117] *V. Fock Institute for Physics, St. Petersburg State University, St. Petersburg, Russia*
[118] *Warsaw University of Technology, Warsaw, Poland*
[119] *Wayne State University, Detroit, MI, United States*
[120] *Yale University, New Haven, CT, United States*
[121] *Yerevan Physics Institute, Yerevan, Armenia*
[122] *Yildiz Technical University, Istanbul, Turkey*

[123] *Yonsei University, Seoul, South Korea*
[124] *Zentrum für Technologietransfer und Telekommunikation (ZTT), Fachhochschule Worms, Worms, Germany*

[*] Corresponding author.
   E-mail address: j.otwinowski@gsi.de (J. Otwinowski).
[i] Also at: M.V. Lomonosov Moscow State University, D.V. Skobeltsyn Institute of Nuclear Physics, Moscow, Russia.
[ii] Also at: University of Belgrade, Faculty of Physics and "Vinča" Institute of Nuclear Sciences, Belgrade, Serbia.