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Transverse momentum dependence of inclusive primary charged-particle production in p–Pb collisions at $\sqrt{s_{\rm NN}}$ = 5.02 TeV

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Abstract The transverse momentum ($p_{\rm T}$) distribution of primary charged particles is measured at midrapidity in minimum-bias p–Pb collisions at $\sqrt{s_{\rm NN}} = 5.02$ TeV with the ALICE detector at the LHC in the range $0.15 < p_{\rm T} < 50$ GeV/c. The spectra are compared to the expectation based on binary collision scaling of particle production in pp collisions, leading to a nuclear modification factor consistent with unity for $p_{\rm T}$ larger than 2 GeV/c, with a weak indication of a Cronin-like enhancement for $p_{\rm T}$ around 4 GeV/c. The measurement is compared to theoretical calculations and to data in Pb–Pb collisions at $\sqrt{s_{\rm NN}} = 2.76$ TeV.

Measurements of particle production in proton-nucleus collisions at high energies enable the study of fundamental properties of Quantum Chromodynamics (QCD) over a broad range of parton fractional momentum x and parton densities (see [1] for a review). They also provide reference measurements for the studies of deconfined matter created in nucleus–nucleus collisions [2].

The first measurements of charged-particle production in minimum-bias p–Pb collisions at the LHC at a centre-of-mass energy per nucleon-nucleon pair of $\sqrt{s_{\rm NN}}$ = 5.02 TeV [3,4] showed that: (i) the charged particle multiplicity density at midrapidity scales approximately with the number of participating nucleons ($\langle N_{\rm part}\rangle = 7.9 \pm 0.6$ for minimum-bias collisions) calculated in a Glauber model [5] and (ii) the transverse momentum ($p_{\rm T}$) spectrum, measured in the range 0.5–20 GeV/c [4], exhibits binary collision scaling above a few GeV/c, as expected in the absence of any significant nuclear modification effect. The latter is quantified by the nuclear modification factor, $R_{\rm pPb}$, the ratio of the $p_{\rm T}$ spectrum in p–Pb collisions and a reference obtained by scaling the measurement in pp collisions with the number of binary nucleon-nucleon collisions in p–Pb. The preliminary result by the CMS collaboration [6] hints at an enhancement of particle production in p–Pb collisions above binary collision scaling, leading to $R_{\rm pPb} > 1$, for $p_{\rm T}$ exceeding about 30 GeV/c. The preliminary result by the ATLAS collaboration [7] exhibits also, for collisions corresponding to 0–90 % centrality, $R_{\rm pPb}$ values above unity for $p_{\rm T}$ in the range 20–100 GeV/c.

In this letter we present an update of our previously published $p_{\rm T}$ spectra of primary charged particles [4] based on the 60 times larger sample size collected with the ALICE detector [8] in 2013 in minimum-bias collisions. These data allow a significant extension of the transverse momentum range. The present analysis is essentially identical to the previous and therefore we update only the information related to the enlarged data set; the reader is referred to the earlier publications [4,9–11] for a more detailed and complete description.

The ALICE minimum-bias trigger is defined by a coincidence of signals in detectors covering in pseudorapidity[1] $2.8 < \eta < 5.1$ (VZERO-A) and $-3.7 < \eta < -1.7$ (VZERO-C). In the 2013 data sample, 106 million events (corresponding to an integrated luminosity of $50.7 \pm 1.6\ \mu{\rm b}^{-1}$) satisfy the trigger and offline event-selection criteria, which select essentially non-single-diffractive (NSD) minimum-bias collisions. The centre-of-mass pseudorapidity is defined as $\eta_{\rm cms} = -\eta - |y_{\rm NN}|$, with the proton beam at positive rapidity; $|y_{\rm NN}| = 0.465$ is the rapidity of the centre-of-mass for nucleon-nucleon collisions. This equation is exact only for massless or very high $p_{\rm T}$ particles. The spectra are corrected on a statistical basis using the measurements by ALICE in p–Pb collisions of the η distribution of inclusive charged particle production [3] and of the pion, kaon, and proton yields [12]; this correction depends on the $\eta_{\rm cms}$ range and on $p_{\rm T}$, reaching about 20 % for the lowest $p_{\rm T}$ bin.

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[1] In the laboratory frame $\eta = -\ln[\tan(\vartheta/2)]$, with ϑ the polar angle between the charged particle and the beam axis; the proton beam has negative η.

Table 1 Systematic uncertainties on the p_{T}-differential yields in p–Pb and pp collisions. The quoted ranges span the p_{T} dependence of the uncertainties in the measured range, 0.15–50 GeV/c. Normalization uncertainties are also quoted

Uncertainty	Value (%)
Event selection	0.6
Track selection	1.0–5.5
Tracking efficiency	3.0
p_{T} resolution	0–1.3
p_{T} scale	0–1.5
Particle composition	0.1–0.4
MC generator used for correction	1.0
Secondary particle rejection	0.5–4.0
Material budget	0.2–1.5
Total for p–Pb, p_{T}-dependent	3.4–6.7
Normalization p–Pb	3.1
Total for pp, p_{T}-dependent	6.8–8.2
Normalization pp	3.6
Nuclear overlap $\langle T_{\mathrm{pPb}}\rangle$	3.6

The systematic uncertainty of the particle composition [12] leads to a systematic uncertainty in our spectra of up to 0.4 %.

The systematic uncertainties on the spectra are evaluated as in previous analyses of pp [10], Pb–Pb [9], and p–Pb [4] data. The uncertainty due to the p_{T} scale is negligible below 20 GeV/c and reaches 1.5 % at 50 GeV/c. The main contributions and the total uncertainties are listed in Table 1.

The p_{T} spectra of charged particles measured in minimum-bias (NSD) p–Pb collisions at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV are shown in Fig. 1 for the ranges $|\eta_{\mathrm{cms}}| < 0.3$, $-0.8 < \eta_{\mathrm{cms}} < -0.3$, and $-1.3 < \eta_{\mathrm{cms}} < -0.8$. The pp reference spectrum, $\langle T_{\mathrm{pPb}}\rangle(1/2\pi p_{\mathrm{T}})\mathrm{d}^2\sigma^{\mathrm{pp}}/\mathrm{d}\eta\mathrm{d}p_{\mathrm{T}}$, is also included. $\langle T_{\mathrm{pPb}}\rangle$ is the average nuclear overlap function, calculated using the Glauber model [13], which gives $\langle T_{\mathrm{pPb}}\rangle = \langle N_{\mathrm{coll}}\rangle/\sigma_{\mathrm{NN}} = 0.0983 \pm 0.0035$ mb^{-1}, with $\langle N_{\mathrm{coll}}\rangle = 6.9 \pm 0.6$ and $\sigma_{\mathrm{NN}} = 70 \pm 5$ mb. Since the data in pp collisions [10] indicate only a very small η dependence of the p_{T} spectrum in the range measured by ALICE ($|\eta| < 0.8$), our current reference spectrum is, differently than in [4,10], for $|\eta| < 0.8$. It was obtained by data interpolation at low p_{T} and by scaling the measurement at $\sqrt{s} = 7$ TeV with the ratio of spectra calculated with NLO pQCD at $\sqrt{s} = 5.02$ and 7 TeV [10].

In the lower panel of Fig. 1 the ratios of the spectra for backward ($-0.8 < \eta_{\mathrm{cms}} < -0.3$ and $-1.3 < \eta_{\mathrm{cms}} < -0.8$) pseudorapidity ranges to that at $|\eta_{\mathrm{cms}}| < 0.3$ are shown. The indication of a slight softening of the p_{T} spectrum when going from central to backward (Pb-side) pseudorapidity, observed already in the pilot-run data of 2012 [4] (note opposite η_{cms} sign convention in [4]) is confirmed with better significance and extended in p_{T} down to 0.15 GeV/c.

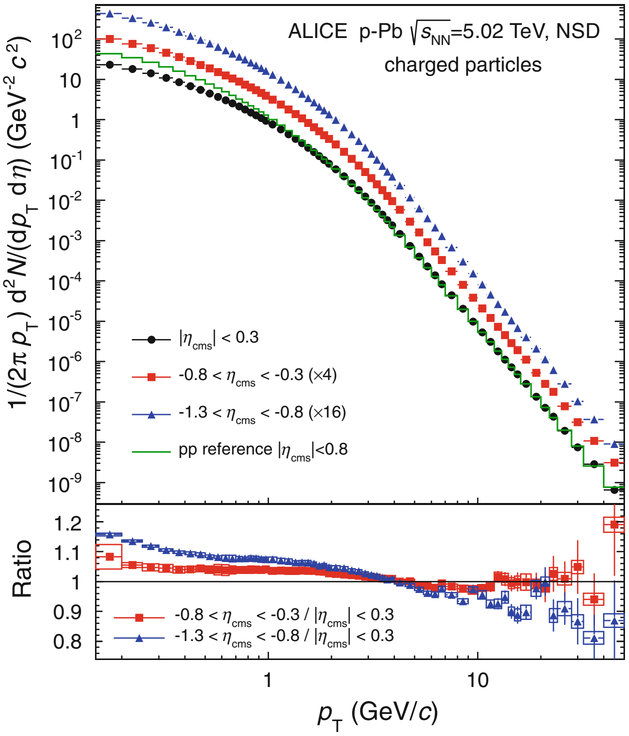

Fig. 1 Transverse momentum distributions of charged particles in minimum-bias (NSD) p–Pb collisions for different pseudorapidity ranges (*upper panel*). The spectra are scaled by the factors indicated. The *histogram* represents the reference spectrum (cross section scaled by the nuclear overlap function, T_{pPb}) in inelastic pp collisions, determined in $|\eta| < 0.8$. The *lower panel* shows the ratio of spectra in p–Pb at backward pseudorapidities to that at $|\eta_{\mathrm{cms}}| < 0.3$. The *vertical bars* (*boxes*) represent the statistical (systematic) uncertainties

A good description of our earlier measurement of spectra in p–Pb collisions [4] was achieved in the EPOS3 model [14] including a hydrodynamical description of the collision, while the PHSD model [15] significantly underestimated the spectra for p_{T} values of several GeV/c.

In order to quantify nuclear effects in p–Pb collisions, the p_{T}-differential yield relative to the pp reference, the nuclear modification factor, is calculated as:

$$R_{\mathrm{pPb}}(p_{\mathrm{T}}) = \frac{\mathrm{d}^2N^{\mathrm{pPb}}/\mathrm{d}\eta\mathrm{d}p_{\mathrm{T}}}{\langle T_{\mathrm{pPb}}\rangle \mathrm{d}^2\sigma^{\mathrm{pp}}/\mathrm{d}\eta\mathrm{d}p_{\mathrm{T}}}, \tag{1}$$

where N^{pPb} is the charged particle yield in p–Pb collisions.

The measurement of the nuclear modification factor R_{pPb} for charged particle production in $|\eta_{\mathrm{cms}}| < 0.3$ and $-1.3 < \eta_{\mathrm{cms}} < 0.3$ is shown in Fig. 2. The uncertainties of the p–Pb and pp spectra are added in quadrature, separately for the statistical and systematic uncertainties. The systematic uncertainties are largely correlated between adjacent p_{T} bins. The total systematic uncertainty on the normalization, the quadratic sum of the uncertainty on $\langle T_{\mathrm{pPb}}\rangle$, the normalization of the pp reference spectrum and the normalization of

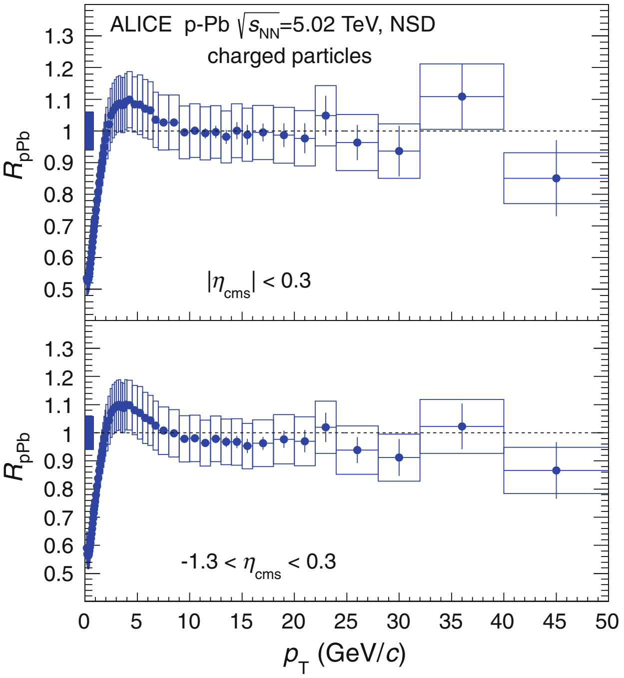

Fig. 2 The nuclear modification factor of charged particles as a function of transverse momentum, measured in minimum-bias (NSD) p–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV in two pseudorapidity ranges, $|\eta_{cms}| < 0.3$ and $-1.3 < \eta_{cms} < 0.3$. The statistical errors are represented by *vertical bars*, the systematic errors by *boxes* around data points. The relative systematic uncertainties on the normalization are shown as *boxes* around unity near $p_T = 0$

the p–Pb data, amounts to 6.0 %. The R_{pPb} factor is consistent with unity up to $p_T = 50$ GeV/c. The average values of R_{pPb} in $|\eta_{cms}| < 0.3$ are 0.995±0.007 (stat.) ±0.084 (syst.) for the p_T range 10–20 GeV/c, 0.990 ± 0.031 (stat.)±0.090 (syst.) in the range 20–28 GeV/c and 0.969 ± 0.056 (stat.)±0.090 (syst.) in the range 28–50 GeV/c. The systematic uncertainties are weighted averages of the values in p_T bins, with statistical uncertainties as inverse square weights; all values carry in addition the common overall normalization uncertainty of 6 %.

The data indicate a small enhancement, R_{pPb} above unity, barely significant within systematic errors, around 4 GeV/c, i.e. in the p_T region where the much stronger Cronin enhancement is seen at lower energies [16,17].

The p–Pb data provide important constraints to models of nuclear modification effects. As an illustration, in Fig. 3 the measurement of R_{pPb} at $|\eta_{cms}| < 0.3$ is compared to theoretical model predictions. The predictions for shadowing [18], calculated at next-to-leading order (NLO) with the EPS09s nuclear modification of parton distribution functions, describe the data for $p_T \gtrsim 6$ GeV/c. The calculations are for π^0, which may explain the differences with respect to data at low p_T; for high p_T, the ALICE data on identified pions, kaons, and protons [21] give support that the comparison of our data on inclusive charged particles to EPS09s calculations for π^0 is meaningful. The LO pQCD model including cold nuclear matter effects [19] exhibits a distinct trend of decreasing R_{pPb}, which is not supported by the data. The prediction with the HIJING 2.1 model, shown for two fragmentation schemes [20], exhibits a more pronounced trend of decreasing R_{pPb} at high p_T. It is interesting to note that calculations with the EPOS LHC model [22], not included here, show a similar trend. Several predictions based on the saturation (Color Glass Condensate) model are available [23–25]; they were shown previously [4] to describe, in their range of validity, namely up to several GeV/c, the R_{pPb} data.

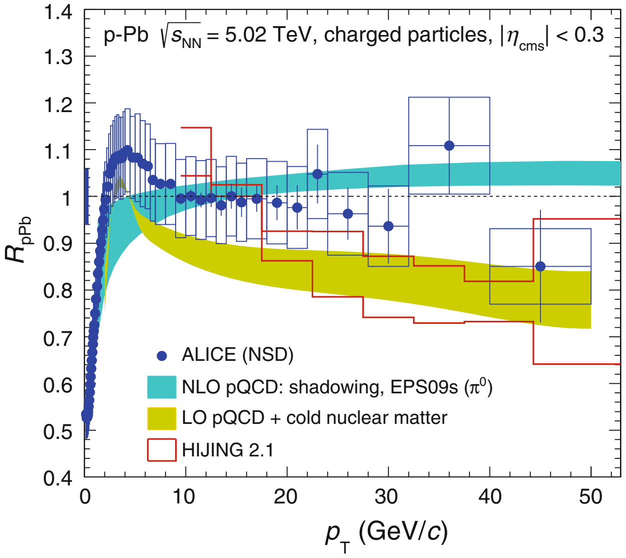

Fig. 3 Transverse momentum dependence of the nuclear modification factor R_{pPb} of charged particles measured in minimum-bias (NSD) p–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV. The ALICE data in $|\eta_{cms}| < 0.3$ (*symbols*) are compared to model calculations [18–20] (bands, see text for details). The *vertical bars* (*boxes*) show the statistical (systematic) uncertainties. The relative systematic uncertainty on the normalization is shown as a box around unity near $p_T = 0$

In Fig. 4 we compare the measurement of the nuclear modification factor for inclusive primary charged-particle ($h^{\pm}$) production in p–Pb collisions to that in central (0–5 % centrality) Pb–Pb collisions [9,26]. The p–Pb data demonstrate that the suppression of hadron production at high p_T in Pb–Pb collisions, understood in theoretical models as a consequence of parton energy loss in (deconfined) QCD matter (see [9] and references therein), has no contribution from initial state effects. The ALICE p–Pb data show no sign of nuclear matter modification of hadron production at high p_T and are therefore fully consistent with the observation of binary collision scaling in Pb–Pb of observables which are not affected by hot QCD matter (direct photons [27] and vector bosons [28,29]).

In summary, we have extended our measurements of the charged-particle p_T spectra and nuclear modification factor in minimum-bias (NSD) p–Pb collisions at $\sqrt{s_{NN}} =$ 5.02 TeV. The results, covering a substantially-extended p_T

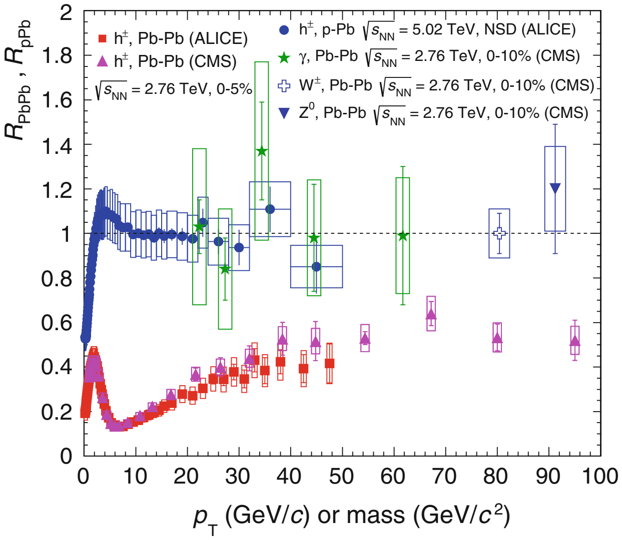

Fig. 4 Transverse momentum dependence of the nuclear modification factor R_{pPb} of charged particles ($h^{\pm}$) measured in minimum-bias (NSD) p–Pb collisions at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV in comparison to data on the nuclear modification factor R_{PbPb} in central Pb–Pb collisions at $\sqrt{s_{\mathrm{NN}}} = 2.76$ TeV. The Pb–Pb data are for charged particle [9,26], direct photon [27], Z^0 [28] and $W^{\pm}$ [29] production. All data are for midrapidity

range, $0.15 < p_{\mathrm{T}} < 50$ GeV/c, exhibit, within uncertainties, no deviation from binary collision scaling at high p_{T}; the nuclear modification factor remains consistent with unity for $p_{\mathrm{T}} \gtrsim 2$ GeV/c. The data at high p_{T} are described by a prediction based on NLO pQCD calculations with PDF shadowing and further underline our earlier observation [4] that initial state effects do not contribute to the strong suppression of hadron production at high p_{T} observed at the LHC in Pb–Pb collisions.

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