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

The ALICE Collaboration[*]

Abstract

The transverse momentum (p_{T}) distribution of primary charged particles is measured at midrapidity in minimum-bias p–Pb collisions at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV with the ALICE detector at the LHC in the range $0.15 < p_{\mathrm{T}} < 50$ 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_{T} larger than 2 GeV/c. The measurement is compared to theoretical calculations and to data in Pb–Pb collisions at $\sqrt{s_{\mathrm{NN}}} = 2.76$ TeV.

[*]See Appendix A for the list of collaboration members

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 $\sqrt{s_{\mathrm{NN}}}$ = 5.02 TeV [3, 4] showed that: i) the charged particle multiplicity density at midrapidity scales approximately with the number of participating nucleons ($\langle N_{\mathrm{part}}\rangle = 7.9 \pm 0.6$ for minimum-bias collisions) calculated in a Glauber model [5] and ii) the transverse momentum (p_{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_{pPb}, the ratio of the p_{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 $R_{\mathrm{pPb}} > 1$, for p_{T} exceeding about 30 GeV/c. The preliminary result by the ATLAS collaboration [7] exhibits, for collisions corresponding to 0–90% centrality, R_{pPb} values slightly above unity and independent of p_{T} in the range 4–22 GeV/c.

In this letter we present an update of our previously published p_{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.

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 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±1.6 μb^{-1}) satisfy the trigger and offline event-selection criteria, which select essentially non-single-diffractive (NSD) minimum-bias col-

[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.

lisions. 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. 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 $p_{\rm T}$ scale uncertainty 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.

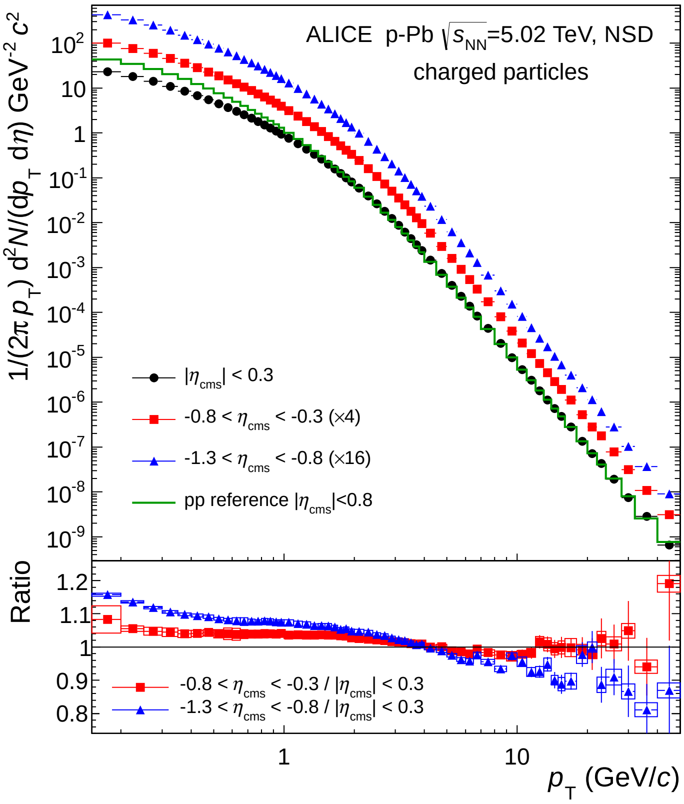

Fig. 1: Transverse momentum distributions of charged particles in minimum-bias (NSD) p–Pb collisions for different pseudorapidity ranges (upper panel). The spectra are scaled by the factors indicated. The histogram represents the reference spectrum (cross section scaled by the nuclear overlap function, $T_{\rm pPb}$) 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 $|\eta_{\rm cms}| < 0.3$. The vertical bars (boxes) represent the statistical (systematic) uncertainties.

The $p_{\rm T}$ spectra of charged particles measured in minimum-bias (NSD) p–Pb collisions at $\sqrt{s_{\rm NN}} = 5.02$ TeV are shown in Fig. 1 for the ranges $|\eta_{\rm cms}| < 0.3$, $-0.8 < \eta_{\rm cms} < -0.3$, and $-1.3 < \eta_{\rm cms} < -0.8$. The pp reference spectrum, $\langle T_{\rm pPb}\rangle {\rm d}^2\sigma^{\rm pp}/{\rm d}\eta {\rm d}p_{\rm T}$, is also included. $\langle T_{\rm pPb}\rangle$ is the average nuclear overlap function, calculated using the Glauber model [13], which gives $\langle T_{\rm pPb}\rangle = \langle N_{\rm coll}\rangle/\sigma_{\rm NN} = 0.0983 \pm 0.0035$ mb^{-1}, with $\langle N_{\rm coll}\rangle = 6.9 \pm 0.6$ and $\sigma_{\rm NN} = 70 \pm 5$ mb. Since the data in pp collisions [10] do not indicate any η dependence of the $p_{\rm T}$ 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 $p_{\rm T}$ 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 ($-0.8 < \eta_{\rm cms} < -0.3$ and $-1.3 < \eta_{\rm cms} < -0.8$) pseudorapidity ranges to that at $|\eta_{\rm cms}| < 0.3$ are shown. The indication of a slight softening of the $p_{\rm T}$ spectrum when going from central to backward (Pb-side) pseudorapidity, observed already in the pilot-run data of 2012 [4] (note opposite $\eta_{\rm cms}$ sign convention in [4]) is confirmed with better significance and extended in $p_{\rm T}$ down to 0.15 GeV/c.

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 $p_{\rm T}$ values of several GeV/c.

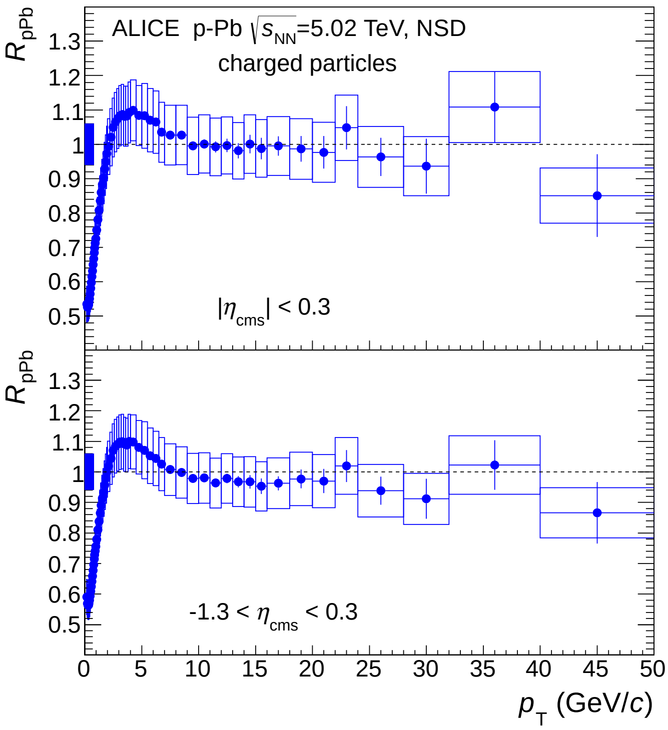

Fig. 2: The nuclear modification factor of charged particles as a function of transverse momentum, measured in minimum-bias (NSD) p–Pb collisions at $\sqrt{s_{\rm NN}} = 5.02$ TeV in two pseudorapidity ranges, $|\eta_{\rm cms}| < 0.3$ and $-1.3 < \eta_{\rm cms} < 0.3$. The statistical errors are represented 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 $p_{\rm T} = 0$.

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

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

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

The measurement of the nuclear modification factor $R_{\rm pPb}$ for charged particle production in $|\eta_{\rm cms}| < 0.3$ and $-0.3 < \eta_{\rm cms} < 1.3$ 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 $p_{\rm T}$ bins. The total systematic uncertainty on the normalization, the quadratic sum of the uncertainty on $\langle T_{\rm pPb}\rangle$, the normalization of the pp reference spectrum and

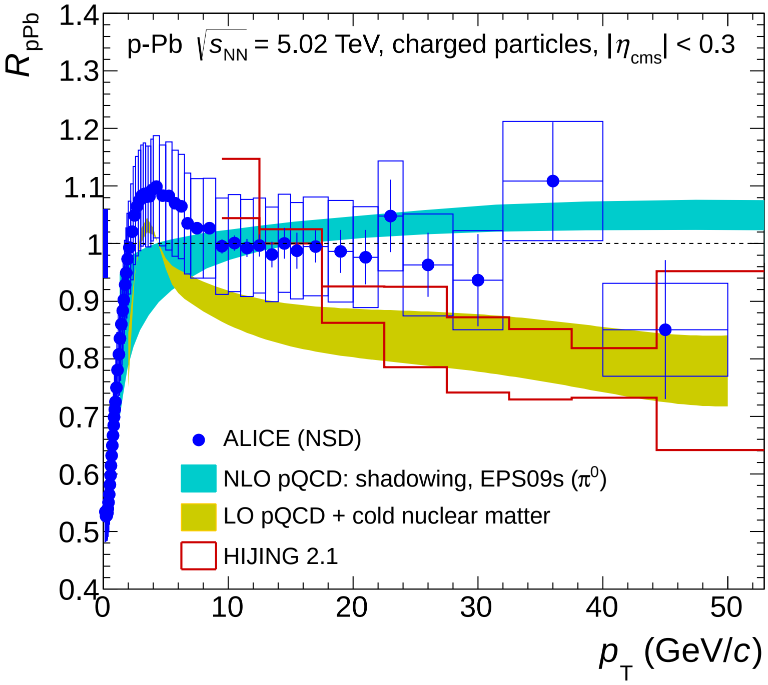

Fig. 3: Transverse momentum dependence of the nuclear modification factor $R_{\rm pPb}$ of charged particles measured in minimum-bias (NSD) p–Pb collisions at $\sqrt{s_{\rm NN}} = 5.02$ TeV. The ALICE data in $|\eta_{\rm cms}| < 0.3$ (symbols) are compared to model calculations [18–20] (bands, see text 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 $p_{\rm T} = 0$.

the normalization of the p–Pb data, amounts to 6.0%. The $R_{\rm pPb}$ factor is consistent with unity up to $p_{\rm T}$ =50 GeV/c. The average values of $R_{\rm pPb}$ in $|\eta_{\rm cms}| < 0.3$ are 0.995±0.007 (stat.)±0.084 (syst.) for the $p_{\rm T}$ 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 $p_{\rm T}$ 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, $R_{\rm pPb}$ above unity, barely significant within systematic errors, around 4 GeV/c, i.e. in the $p_{\rm T}$ 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 $R_{\rm pPb}$ at $|\eta_{\rm cms}| < 0.3$ is compared to theoretical model predictions. The predictions for shadowing [18], calculated at next-to-leading order (NLO) with the EPS09s nuclear modication of parton distribution functions describe the data well for $p_{\rm T} \gtrsim 6$ GeV/c (the calculations are for π^0). The LO pQCD model including cold nuclear matter effects [19] exhibits a distinct trend of decreasing $R_{\rm pPb}$, 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 $R_{\rm pPb}$ at high $p_{\rm T}$. It is interesting to note that calculations with the EPOS LHC model [21], not included here, show a similar trend. Several predictions based on the saturation (Color Glass Condensate) model are available [22–24]; they were shown previously [4] to describe the $R_{\rm pPb}$ data for $p_{\rm T}$ of a few GeV/c.

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, 25]. The p–Pb data demonstrate that the suppression of hadron production at high $p_{\rm T}$ in Pb–Pb collisions,

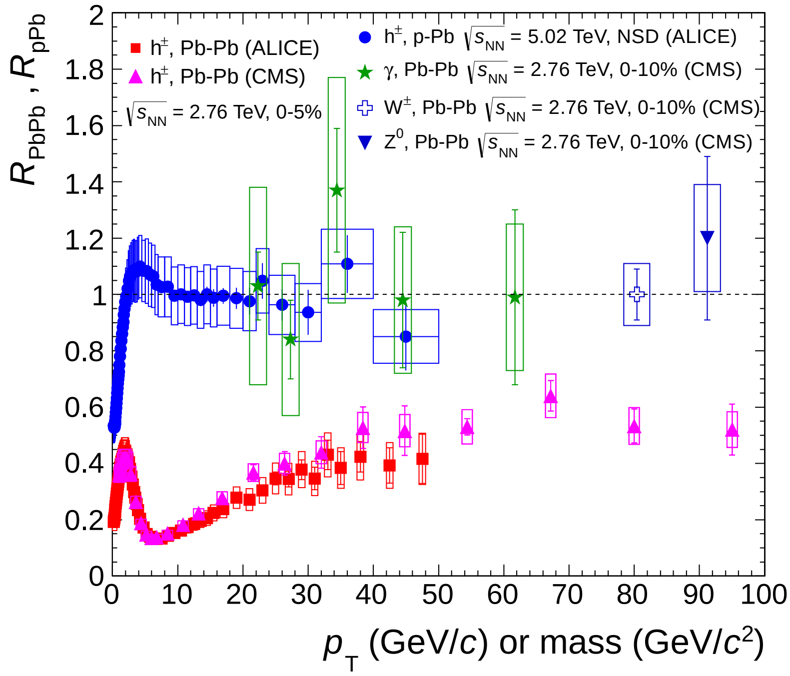

Fig. 4: Transverse momentum dependence of the nuclear modification factor $R_{\rm pPb}$ of charged particles ($h^{\pm}$) measured in minimum-bias (NSD) p–Pb collisions at $\sqrt{s_{\rm NN}} = 5.02$ TeV in comparison to data on the nuclear modification factor $R_{\rm PbPb}$ in central Pb–Pb collisions. The Pb–Pb data are for charged particle [9, 25], direct photon [26], Z^0 [27] and $W^{\pm}$ [28] production. All data are for midrapidity.

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 $p_{\rm T}$ 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 [26] and vector bosons [27, 28])

In summary, we have extended our measurements of the charged-particle $p_{\rm T}$ spectra and nuclear modification factor in minimum-bias (NSD) p–Pb collisions at $\sqrt{s_{\rm NN}} = 5.02$ TeV. The results, covering a substantially-extended $p_{\rm T}$ range, $0.15 < p_{\rm T} < 50$ GeV/c, exhibit, within uncertainties, no deviation from binary collision scaling at high $p_{\rm T}$; the nuclear modification factor remains consistent with unity for $p_{\rm T} \gtrsim 2$ GeV/c. The data 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 $p_{\rm T}$ observed at the LHC in Pb–Pb collisions.

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References

[1] C. Salgado *et al.*, *Proton-Nucleus Collisions at the LHC: Scientific Opportunities and Requirements*, J. Phys. **G39**, 015010 (2012), `arXiv:1105.3919`, `doi:10.1088/0954-3899/39/1/015010`.

[2] B. Muller, J. Schukraft and B. Wyslouch, *First results from Pb+Pb collisions at the LHC*, Ann. Rev. Nucl. Part. Sci. **62**, 361 (2012), `arXiv:1202.3233`, `doi:10.1146/annurev-nucl-102711-094910`.

[3] ALICE Collaboration, B. Abelev *et al.*, *Pseudorapidity density of charged particles p–Pb*

collisions at $\sqrt{s_{\rm NN}} = 5.02$ *TeV*, Phys. Rev. Lett. **110**, 032301 (2013), arXiv:1210.3615, doi:10.1103/PhysRevLett.110.032301.

[4] ALICE Collaboration, B. Abelev *et al.*, *Transverse momentum distribution and nuclear modification factor of charged particles in p–Pb collisions at* $\sqrt{s_{\rm NN}} = 5.02$ *TeV*, Phys. Rev. Lett. **110**, 082302 (2013), arXiv:1210.4520, doi:10.1103/PhysRevLett.110.082302.

[5] M. L. Miller, K. Reygers, S. J. Sanders and P. Steinberg, *Glauber modeling in high energy nuclear collisions*, Ann. Rev. Nucl. Part. Sci. **57**, 205 (2007), arXiv:nucl-ex/0701025, doi:10.1146/annurev.nucl.57.090506.123020.

[6] CMS Collaboration, CERN Report No. CMS-PAS-HIN-12-017, 2013 (unpublished).

[7] ATLAS Collaboration, CERN Report No. ATLAS-CONF-2013-107, 2013 (unpublished).

[8] ALICE Collaboration, B. B. Abelev *et al.*, *Performance of the ALICE Experiment at the CERN LHC*, submitted (2014), arXiv:1402.4476.

[9] ALICE Collaboration, B. Abelev *et al.*, *Centrality dependence of charged particle production at large transverse momentum in Pb–Pb collisions at* $\sqrt{s_{\rm NN}} = 2.76$ *TeV*, Phys. Lett. B **720**, 52 (2013), arXiv:1208.2711.

[10] ALICE Collaboration, B. B. Abelev *et al.*, *Energy Dependence of the Transverse Momentum Distributions of Charged Particles in pp Collisions Measured by ALICE*, Eur. Phys. J. **C73**, 2662 (2013), arXiv:1307.1093, doi:10.1140/epjc/s10052-013-2662-9.

[11] ALICE Collaboration, B. B. Abelev *et al.*, *Multiplicity dependence of the average transverse momentum in pp, p-Pb, and Pb-Pb collisions at the LHC*, Phys. Lett. **B727**, 371 (2013), arXiv:1307.1094, doi:10.1016/j.physletb.2013.10.054.

[12] ALICE Collaboration, B. B. Abelev *et al.*, *Multiplicity Dependence of Pion, Kaon, Proton and Lambda Production in p–Pb Collisions at* $\sqrt{s_{NN}}$ *= 5.02 TeV*, Phys. Lett. **B728**, 25 (2014), arXiv:1307.6796, doi:10.1016/j.physletb.2013.11.020.

[13] B. Alver, M. Baker, C. Loizides and P. Steinberg, *The PHOBOS Glauber Monte Carlo*, 0805.4411, arXiv:0805.4411.

[14] K. Werner, B. Guiot, I. Karpenko and T. Pierog, *Analysing radial flow features in p-Pb and p-p collisions at several TeV by studying identified particle production in EPOS3*, 1312.1233, arXiv:1312.1233.

[15] V. Konchakovski, W. Cassing and V. Toneev, *p+Pb collisions at 5.02 TeV in the Parton-Hadron-String-Dynamics transport approach*, 1401.4409, arXiv:1401.4409.

[16] J. W. Cronin *et al.*, *Production of hadrons at large transverse momentum at 200, 300, and 400 GeV*, Phys. Rev. D **11**, 3105 (1975), doi:10.1103/PhysRevD.11.3105.

[17] B. Kopeliovich, J. Nemchik, A. Schafer and A. Tarasov, *Cronin effect in hadron production off nuclei*, Phys. Rev. Lett. **88**, 232303 (2002), arXiv:hep-ph/0201010, doi:10.1103/PhysRevLett.88.232303.

[18] I. Helenius, K. J. Eskola, H. Honkanen and C. A. Salgado, *Impact-parameter dependent nuclear parton distribution functions: EPS09s and EKS98s and their applications in nuclear hard processes*, JHEP **1207**, 073 (2012), arXiv:1205.5359, doi:10.1007/JHEP07(2012)073.

[19] Z.-B. Kang, I. Vitev and H. Xing, *Nuclear modification of high transverse momentum particle production in p+A collisions at RHIC and LHC*, Phys. Lett. **B718**, 482 (2012), arXiv:1209.6030, doi:10.1016/j.physletb.2012.10.046.

[20] R. Xu, W.-T. Deng and X.-N. Wang, *Nuclear modification of high-*$p_{\rm T}$ *hadron spectra in p+A collisions at LHC*, Phys. Rev. **C86**, 051901 (2012), arXiv:1204.1998, doi:10.1103/PhysRevC.86.051901.

[21] T. Pierog, I. Karpenko, J. Katzy, E. Yatsenko and K. Werner, *EPOS LHC : test of collective hadronization with LHC data*, 1306.0121, arXiv:1306.0121.

[22] P. Tribedy and R. Venugopalan, *QCD saturation at the LHC: comparisons of models to p+p and A+A data and predictions for p+Pb collisions*, Phys. Lett. **B710**, 125 (2012), arXiv:1112.2445, doi:10.1016/j.physletb.2012.02.047.

[23] J. L. Albacete, A. Dumitru, H. Fujii and Y. Nara, *CGC predictions for p+Pb collisions at the LHC*, Nucl. Phys. **A897**, 1 (2013), arXiv:1209.2001, doi:10.1016/j.nuclphysa.2012.09.012.

[24] A. H. Rezaeian, *CGC predictions for p+A collisions at the LHC and signature of QCD saturation*, Phys. Lett. **B718**, 1058 (2013), arXiv:1210.2385, doi:10.1016/j.physletb.2012.11.066.

[25] CMS Collaboration, S. Chatrchyan *et al.*, *Study of high-p_{T} charged particle suppression in PbPb compared to pp collisions at $\sqrt{s_{\mathrm{NN}}} = 2.76$ TeV*, Eur. Phys. J. **C72**, 1945 (2012), arXiv:1202.2554, doi:10.1140/epjc/s10052-012-1945-x.

[26] CMS Collaboration, S. Chatrchyan *et al.*, *Measurement of isolated photon production in pp and PbPb collisions at $\sqrt{s_{\mathrm{NN}}} = 2.76$ TeV*, Phys. Lett. **B710**, 256 (2012), arXiv:1201.3093, doi:10.1016/j.physletb.2012.02.077.

[27] CMS Collaboration, S. Chatrchyan *et al.*, *Study of Z boson production in PbPb collisions at nucleon-nucleon centre of mass energy = 2.76 TeV*, Phys. Rev. Lett. **106**, 212301 (2011), arXiv:1102.5435, doi:10.1103/PhysRevLett.106.212301.

[28] CMS Collaboration, S. Chatrchyan *et al.*, *Study of W boson production in PbPb and pp collisions at $\sqrt{s_{\mathrm{NN}}} = 2.76$ TeV*, Phys. Lett. **B715**, 66 (2012), arXiv:1205.6334, doi:10.1016/j.physletb.2012.07.025.

A The ALICE Collaboration

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Filchagin[93] , D. Finogeev[51] , F.M. Fionda[31] , E.M. Fiore[31] , E. Floratos[82] , M. Floris[34] , S. Foertsch[60] , P. Foka[91] , S. Fokin[94] , E. Fragiacomo[104] , A. Francescon[34,28] , U. Frankenfeld[91] , U. Fuchs[34] , C. Furget[65] , M. Fusco Girard[29] , J.J. Gaardhøje[74] , M. Gagliardi[25] , A.M. Gago[97] , M. Gallio[25] , D.R. Gangadharan[19] , P. Ganoti[78] , C. Garabatos[91] , E. Garcia-Solis[13] , C. Gargiulo[34] , I. Garishvili[69] , J. Gerhard[39] , M. Germain[107] , A. Gheata[34] , M. Gheata[34,57] , B. Ghidini[31] , P. Ghosh[124] , S.K. Ghosh[4] , P. Gianotti[66] , P. Giubellino[34] , E. Gladysz-Dziadus[110] , P. Glässel[87] , A. Gomez Ramirez[47] , P. González-Zamora[10] , S. Gorbunov[39] , L. Görlich[110] , S. Gotovac[109] , L.K. Graczykowski[126] , A. Grelli[52] , A. Grigoras[34] , C. Grigoras[34] , V. Grigoriev[70] , A. Grigoryan[1] , S. Grigoryan[61] , J.M. Gronefeld[91] , B. Grinyov[3] , N. Grion[104] , J.F. Grosse-Oetringhaus[34] , J.-Y. Grossiord[122] , R. Grosso[34] , F. Guber[51] , R. Guernane[65] , B. Guerzoni[26] , M. Guilbaud[122] , K. Gulbrandsen[74] , H. Gulkanyan[1] , M. Gumbo[83] , T. Gunji[119] , A. Gupta[84] , R. Gupta[84] , K. H. Khan[15] , R. Haake[49] , Ø. Haaland[17] , C. Hadjidakis[46] , M. Haiduc[57] , H. Hamagaki[119] , G. Hamar[128] , L.D. Hanratty[96] , A. Hansen[74] , J.W. Harris[129] , H. Hartmann[39] , A. Harton[13] , D. Hatzifotiadou[99] , S. Hayashi[119] , S.T. Heckel[48] , M. Heide[49] , H. Helstrup[35] , A. Herghelegiu[72] , G. Herrera Corral[11] , B.A. Hess[33] , K.F. Hetland[35] , B. Hippolyte[50] , J. Hladky[55] , P. Hristov[34] , M. Huang[17] , T.J. Humanic[19] , N. Hussain[41] , D. Hutter[39] , D.S. Hwang[20] , R. Ilkaev[93] , I. Ilkiv[71] , M. Inaba[120] , G.M. Innocenti[25] , C. Ionita[34] , M. Ippolitov[94] , M. Irfan[18] , M. Ivanov[91] , V. Ivanov[79] , A. Jachołkowski[27] , P.M. Jacobs[68] , C. Jahnke[113] , H.J. Jang[62] , M.A. Janik[126] , P.H.S.Y. Jayarathna[115] , C. Jena[28] , S. Jena[115] , R.T. Jimenez Bustamante[58] , P.G. Jones[96] , H. Jung[40] , A. Jusko[96] , V. Kadyshevskiy[61] , S. Kalcher[39] , P. Kalinak[54] , A. Kalweit[34] , J. Kamin[48] , J.H. Kang[130] , V. Kaplin[70] , S. Kar[124] , A. Karasu Uysal[63] , O. Karavichev[51] , T. Karavicheva[51] , E. Karpechev[51] , U. Kebschull[47] , R. Keidel[131] , D.L.D. Keijdener[52] , M.M. Khan[iii,18] , P. Khan[95] , S.A. Khan[124] , A. Khanzadeev[79] , Y. Kharlov[106] , B. Kileng[35] , B. Kim[130] , D.W. Kim[62,40] , D.J. Kim[116] , J.S. Kim[40] , M. Kim[40] , M. Kim[130] , S. Kim[20] , T. Kim[130] , S. Kirsch[39] , I. Kisel[39] , S. Kiselev[53] , A. Kisiel[126] , G. Kiss[128] , J.L. Klay[6] , J. Klein[87] , C. Klein-Bösing[49] , A. Kluge[34] , M.L. Knichel[91] , A.G. Knospe[111] , C. Kobdaj[34,108] , M. Kofarago[34] , M.K. Köhler[91] , T. Kollegger[39] , A. Kolojvari[123] , V. Kondratiev[123] , N. Kondratyeva[70] , A. Konevskikh[51] , V. Kovalenko[123] , M. Kowalski[110] , S. Kox[65] , G. Koyithatta Meethaleveedu[44] , J. Kral[116] , I. Králik[54] , F. Kramer[48] , A. Kravčáková[38] , M. Krelina[37] , M. Kretz[39] , M. Krivda[96,54] , F. Krizek[77] , E. Kryshen[34] , M. Krzewicki[91] , V. Kučera[77] , Y. Kucheriaev[94,i] , T. Kugathasan[34] , C. Kuhn[50] , P.G. Kuijer[75] , I. Kulakov[48] , J. Kumar[44] , P. Kurashvili[71] , A. Kurepin[51] , A.B. Kurepin[51] , A. Kuryakin[93] , S. Kushpil[77] , M.J. Kweon[87] , Y. Kwon[130] , P. Ladron de Guevara[58] , C. Lagana Fernandes[113] , I. Lakomov[46] , R. Langoy[125] , C. Lara[47] , A. Lardeux[107] , A. Lattuca[25] , S.L. La Pointe[52] , P. La Rocca[27] , R. Lea[24] , G.R. Lee[96] , I. Legrand[34] , J. Lehnert[48] , R.C. Lemmon[76] , V. Lenti[98] , E. Leogrande[52] , M. Leoncino[25] , I. León Monzón[112] , P. Lévai[128] , S. Li[7,64] , J. Lien[125] , R. Lietava[96] , S. Lindal[21] , V. Lindenstruth[39] , C. Lippmann[91] , M.A. Lisa[19] , H.M. Ljunggren[32] , D.F. Lodato[52] , P.I. Loenne[17] , V.R. Loggins[127] , V. Loginov[70] , D. Lohner[87] , C. Loizides[68] , X. Lopez[64] , E. López Torres[9] , X.-G. Lu[87] , P. Luettig[48] , M. Lunardon[28] , G. Luparello[52] , R. Ma[129] , A. Maevskaya[51] , M. Mager[34] , D.P. Mahapatra[56] , S.M. Mahmood[21] , A. Maire[87] , R.D. Majka[129] , M. Malaev[79] , I. Maldonado Cervantes[58] , L. Malinina[iv,61] , D. Mal'Kevich[53] , P. Malzacher[91] , A. Mamonov[93] , L. Manceau[105] , V. Manko[94] , F. Manso[64] , V. Manzari[98] , M. Marchisone[64,25] , J. Mareš[55] , G.V. Margagliotti[24] , A. Margotti[99] , A. Marín[91] , C. Markert[111] , M. Marquard[48] , I. Martashvili[118] , N.A. Martin[91] , P. Martinengo[34] , M.I. Martínez[2] , G. Martínez García[107] , J. Martin Blanco[107] , Y. Martynov[3] , A. Mas[107] , S. Masciocchi[91] , M. Masera[25] , A. Masoni[100] , L. Massacrier[107] , A. Mastroserio[31] , A. Matyja[110] , C. Mayer[110] , J. Mazer[118] , M.A. Mazzoni[103] , F. Meddi[22] , A. Menchaca-Rocha[59] , J. Mercado Pérez[87] , M. Meres[36] , Y. Miake[120] , K. Mikhaylov[61,53] , L. Milano[34] , J. Milosevic[v,21] , A. Mischke[52] , A.N. Mishra[45] , D. Miśkowiec[91] , J. Mitra[124] , C.M. Mitu[57] , J. Mlynarz[127] , N. Mohammadi[52] , B. Mohanty[73,124] , L. Molnar[50] , L. Montaño Zetina[11] , E. Montes[10] , M. Morando[28] , D.A. Moreira De Godoy[113] , S. Moretto[28] , A. Morsch[34] , V. Muccifora[66] , E. Mudnic[109] , D. Mühlheim[49] , S. Muhuri[124] , M. Mukherjee[124] , H. Müller[34] , M.G. Munhoz[113] , S. Murray[83] , L. Musa[34] , J. Musinsky[54] , B.K. Nandi[44] , R. Nania[99] , E. Nappi[98] , C. Nattrass[118] , K. Nayak[73] , T.K. Nayak[124] , S. Nazarenko[93] , A. Nedosekin[53] , M. Nicassio[91] , M. Niculescu[34,57] , B.S. Nielsen[74] , S. Nikolaev[94] , S. Nikulin[94] , V. Nikulin[79] , B.S. Nilsen[80] , F. Noferini[12,99] , P. Nomokonov[61] , G. Nooren[52] , J. Norman[117] ,

A. Nyanin[94] , J. Nystrand[17] , H. Oeschler[87] , S. Oh[129] , S.K. Oh[vi,40] , A. Okatan[63] , L. Olah[128] , J. Oleniacz[126] , A.C. Oliveira Da Silva[113] , J. Onderwaater[91] , C. Oppedisano[105] , A. Ortiz Velasquez[32] , A. Oskarsson[32] , J. Otwinowski[91] , K. Oyama[87] , P. Sahoo[45] , Y. Pachmayer[87] , M. Pachr[37] , P. Pagano[29] , G. Paić[58] , F. Painke[39] , C. Pajares[16] , S.K. Pal[124] , A. Palmeri[101] , D. Pant[44] , V. Papikyan[1] , G.S. Pappalardo[101] , P. Pareek[45] , W.J. Park[91] , S. Parmar[81] , A. Passfeld[49] , D.I. Patalakha[106] , V. Paticchio[98] , B. Paul[95] , T. Pawlak[126] , T. Peitzmann[52] , H. Pereira Da Costa[14] , E. Pereira De Oliveira Filho[113] , D. Peresunko[94] , C.E. Pérez Lara[75] , A. Pesci[99] , V. Peskov[48] , Y. Pestov[5] , V. Petráček[37] , M. Petran[37] , M. Petris[72] , M. Petrovici[72] , C. Petta[27] , S. Piano[104] , M. Pikna[36] , P. Pillot[107] , O. Pinazza[99,34] , L. Pinsky[115] , D.B. Piyarathna[115] , M. Płoskoń[68] , M. Planinic[121,92] , J. Pluta[126] , S. Pochybova[128] , P.L.M. Podesta-Lerma[112] , M.G. Poghosyan[34] , E.H.O. Pohjoisaho[42] , B. Polichtchouk[106] , N. Poljak[92] , A. Pop[72] , S. Porteboeuf-Houssais[64] , J. Porter[68] , B. Potukuchi[84] , S.K. Prasad[127] , R. Preghenella[99,12] , F. Prino[105] , C.A. Pruneau[127] , I. Pshenichnov[51] , G. Puddu[23] , P. Pujahari[127] , V. Punin[93] , J. Putschke[127] , H. Qvigstad[21] , A. Rachevski[104] , S. Raha[4] , J. Rak[116] , A. Rakotozafindrabe[14] , L. Ramello[30] , R. Raniwala[85] , S. Raniwala[85] , S.S. Räsänen[42] , B.T. Rascanu[48] , D. Rathee[81] , A.W. Rauf[15] , V. Razazi[23] , K.F. Read[118] , J.S. Real[65] , K. Redlich[vii,71] , R.J. Reed[129] , A. Rehman[17] , P. Reichelt[48] , M. Reicher[52] , F. Reidt[34] , R. Renfordt[48] , A.R. Reolon[66] , A. Reshetin[51] , F. Rettig[39] , J.-P. Revol[34] , K. Reygers[87] , V. Riabov[79] , R.A. Ricci[67] , T. Richert[32] , M. Richter[21] , P. Riedler[34] , W. Riegler[34] , F. Riggi[27] , A. Rivetti[105] , E. Rocco[52] , M. Rodríguez Cahuantzi[2] , A. Rodriguez Manso[75] , K. Røed[21] , E. Rogochaya[61] , S. Rohni[84] , D. Rohr[39] , D. Röhrich[17] , R. Romita[76] , F. Ronchetti[66] , L. Ronflette[107] , P. Rosnet[64] , A. Rossi[34] , F. Roukoutakis[82] , A. Roy[45] , C. Roy[50] , P. Roy[95] , A.J. Rubio Montero[10] , R. Rui[24] , R. Russo[25] , E. Ryabinkin[94] , Y. Ryabov[79] , A. Rybicki[110] , S. Sadovsky[106] , K. Šafařík[34] , B. Sahlmuller[48] , R. Sahoo[45] , P.K. Sahu[56] , J. Saini[124] , S. Sakai[68] , C.A. Salgado[16] , J. Salzwedel[19] , S. Sambyal[84] , V. Samsonov[79] , X. Sanchez Castro[50] , F.J. Sánchez Rodríguez[112] , L. Šándor[54] , A. Sandoval[59] , M. Sano[120] , G. Santagati[27] , D. Sarkar[124] , E. Scapparone[99] , F. Scarlassara[28] , R.P. Scharenberg[89] , C. Schiaua[72] , R. Schicker[87] , C. Schmidt[91] , H.R. Schmidt[33] , S. Schuchmann[48] , J. Schukraft[34] , M. Schulc[37] , T. Schuster[129] , Y. 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