Production of light flavour hadrons at intermediate and high p_T in pp, p–Pb and Pb–Pb collisions measured with ALICE

Michael Linus Knichel for the ALICE Collaboration [1]

Physikalisches Institut, Ruprecht-Karls-Universität Heidelberg, Im Neuenheimer Feld 226, 69120 Heidelberg, Germany

Abstract

Light flavour transverse momentum spectra at intermediate and high p_T provide an important baseline for the measurement of perturbative QCD processes in pp, for the evaluation of initial state effects in p–Pb, and for investigating the suppression from parton energy loss in Pb–Pb collisions. The measurement of the nuclear modification factor R_{pPb} for inclusive charged particles is extended up to 50 GeV/c in p_T compared to our previous measurement and remains consistent with unity up the largest momenta. Results on R_{pPb} of charged pions, kaons and protons that cover up to 14 GeV/c in p_T are presented and compared to R_{pPb} of inclusive charged particles. On the production of charged pions, kaons, and protons up to $p_T = 20$ GeV/c in Pb–Pb collisions final results for R_{AA} are presented.

© 2014 CERN. Published by Elsevier B.V. All rights reserved.

1. Introduction

In proton–proton collisions particles at intermediate and high p_T are produced in hard scattering processes with large virtuality. The cross section for these processes can be calculated with perturbative QCD (pQCD) approaches. Measurements of transverse momentum spectra provide

---

a test of pQCD calculations which include non-perturbative effects in the parton distribution functions and fragmentation functions. Phenomenological approaches used in Monte Carlo event generators need to be tuned bases on measured data. Moreover, pp collisions provide a reference (QCD vacuum) to study the effects induced by the QCD medium formed in nucleus–nucleus collisions and by the nuclear initial-state in proton–nucleus collisions.

Initial and final state nuclear effects in p–Pb and Pb–Pb collisions result in particle production that differs from an incoherent superposition of nucleon–nucleon collisions. The difference is quantified by the nuclear modification factor

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

where $\langle N_{\mathrm{coll}}\rangle$ is the average number of binary nucleon–nucleon collisions in one Pb–Pb or p–Pb collision and $\langle T\rangle$ is the average nuclear overlap function. For unidentified charged particles the rapidity y is approximated by the pseudorapidity η.

Proton–lead collisions allow the study of so-called cold nuclear matter (CNM) effects, for instance nuclear shadowing (nuclear modification of the parton distribution functions) and k_{T} broadening (due to multiple scattering of the partons prior to the hard scattering). Collective effects might also be present in p–Pb collisions and are a possible explanation for the double-ridge recently observed in di-hadron correlations [1–3]. Preliminary results from CMS [4] and ATLAS [5] show an enhancement of particle production above 30 GeV/c in p_{T} compared to expectations from binary collision scaling. Since CNM effects are present also in nucleus–nucleus collisions they have to be taken into account in the interpretation of Pb–Pb results.

In collisions of heavy nuclei a hot QCD medium, the Quark–Gluon Plasma (QGP), is created leading to strong collective effects at low and intermediate p_{T} (most prominently radial flow). In addition, parton energy loss in the QGP induces a suppression of the high p_{T} particle yields.

For charged π, K, p we present preliminary results on R_{pPb} ($p_{\mathrm{T}} < 14$ GeV/c) and final results on R_{AA} ($p_{\mathrm{T}} < 20$ GeV/c). The analysis of charged particles in p–Pb is extended up to $p_{\mathrm{T}} = 50$ GeV/c (the first analysis [6] was statistically limited to $p_{\mathrm{T}} < 20$ GeV/c).

2. Analysis

The ALICE experiment [7] is focused on the study of the hot and dense QCD medium created in heavy-ion collisions. Among the LHC experiments ALICE has unique particle identification (PID) capabilities at mid-rapidity ($|\eta| < 0.9$). The data presented here were collected with minimum bias triggers from the Silicon Pixel Detector (SPD) and the VZERO scintillators. Charged tracks and the interaction vertex are reconstructed using the Inner Tracking System (ITS), a six-layer silicon detector, and the Time Projection Chamber (TPC). Pions with transverse momenta up to 2 GeV/c (kaons up to 2.8 GeV/c and protons up to 3 GeV/c) are identified on a track-by-track basis with different detectors providing PID over different momentum ranges (see e.g. [8] for details). The differential energy loss $\mathrm{d}E/\mathrm{d}x$ is measured in the ITS and the TPC and combined with time-of-flight measurements in the TOF detector and the Cherenkov angle from the High Momentum Particle Identification Detector (HMPID). For transverse momenta above 2–3 GeV/c (currently up to $p_{\mathrm{T}} = 20$ GeV/c) identified particle spectra are obtained from a statistical analysis of the energy loss in the TPC in the relativistic rise region. The inclusive $\mathrm{d}E/\mathrm{d}x$ distribution is fitted – in intervals of p_{T} and η – by the sum of four Gaussians (π, K, p, e) with their mean and width fixed from clean samples of identified particles. The p_{T} distributions are finally ob-

tained as the product of the charged particle spectra and the fractions of π, K, p from the dE/dx analysis and corrected for the variations in acceptance and efficiency.

For the 2013 p–Pb data, with recent improvements in the reconstruction procedure, the transverse momentum resolution achieved by combined ITS-TPC tracking ranges from $\sigma(p_T)/p_T \approx$ 1% at $p_T = 1$ GeV/c to $\sigma(p_T)/p_T \approx 3\%$ at $p_T = 50$ GeV/c. In the previously reconstructed pp and Pb–Pb data the resolution is $\sigma(p_T)/p_T \approx 10\%$ at $p_T = 50$ GeV/c. Tracking and PID performance of the ALICE detector are described in detail in [9].

3. Results

Transverse momentum spectra of primary charged particles have been measured in pp collisions at $\sqrt{s} = 0.9, 2.76$ and 7 TeV [10]. Next-to-leading order (NLO) pQCD calculations [11] over-predict the measured cross-sections by about a factor 2. A similar discrepancy has been observed for neutral pions [12] and by CMS [13,14]. Measured jet spectra [15] are in much better agreement with NLO calculations pointing to the fragmentation functions as main source of the discrepancy. However, NLO calculations give a reasonable description of the $\sqrt{s}$ dependence of p_T distributions and are therefore used to scale the measured charged particle p_T spectrum from $\sqrt{s} = 7$ TeV to $\sqrt{s} = 5.02$ TeV, the centre-of-mass energy of p–Pb collisions. At low transverse momenta ($p_T < 5$ GeV/c) the reference spectrum is constructed as a bin-by-bin interpolation between the measurements at $\sqrt{s} = 2.76$ TeV and $\sqrt{s} = 7$ TeV, assuming a power law behavior of the cross section with $\sqrt{s}$ for fixed p_T. For identified hadrons (π, K, p) the power law interpolation method is used for the full p_T range (up to 14 GeV/c).

In p–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV the nucleon–nucleon (NN) centre-of-mass (CM) system is moving with $\Delta y_{cm} = 0.465$ in the direction of the proton; y and η_{cms} are in the CM frame. As a sign convention we take y and η_{cms} to be positive along the direction of the proton.[2] The average nuclear overlap of $\langle T_{pPb} \rangle = \langle N_{coll} \rangle / \sigma_{pp}^{INEL} = 0.0983 \pm 0.0035$ mb^{-1} is obtained from a Monte Carlo Glauber simulation with $\sigma_{pp}^{INEL} = (70 \pm 5)$ mb.

Fig. 1 shows R_{pPb} for charged particles at mid-rapidity $|\eta_{cms}| < 0.3$ in p–Pb collisions [16], compared to three model calculations. The next-to-leading order (NLO) pQCD calculation with EPS09s nuclear PDFs [17] describes the charged particle data for $p_T > 6$ GeV/c. The calculation is for π^0 and describes well the R_{pPb} of charged π over the full range ($p_T < 1.3$ GeV/c). The leading order (LO) pQCD calculation with isospin effect, Cronin effect, cold nuclear matter energy loss and dynamical shadowing separately implemented [18] shows a decrease of R_{pPb} with p_T not seen in the data. In HIJING 2.1 [19] (shown with different factorization schemes) this decreasing trend is even more pronounced.

At low p_T an approximate scaling with the number of participants is observed, corresponding to $R_{pPb} \approx 0.57$. A hint of an enhancement in the Cronin region around $p_T = 2$–4 GeV/c is visible. Note that systematic uncertainties are correlated between neighbouring p_T bins. Up to the largest p_T of 50 GeV/c no deviation from binary collision scaling is observed for charged particles, with an average $\langle R_{pPb} \rangle = 0.969 \pm 0.056$(stat.)$\pm 0.090$(syst.)$\pm 0.06$(norm.) for $28 < p_T < 50$ GeV/c. For charged jets R_{pPb} is consistent with unity up to 90 GeV/c in p_T [20]. Data presented by CMS [4] and ATLAS [5] show a rising trend in R_{pPb} at large $p_T > 30$ GeV/c but given the current systematic uncertainties the difference is barely significant. As part of the difference comes from the reference spectrum, pp data $\sqrt{s} = 5$ TeV would be very useful.

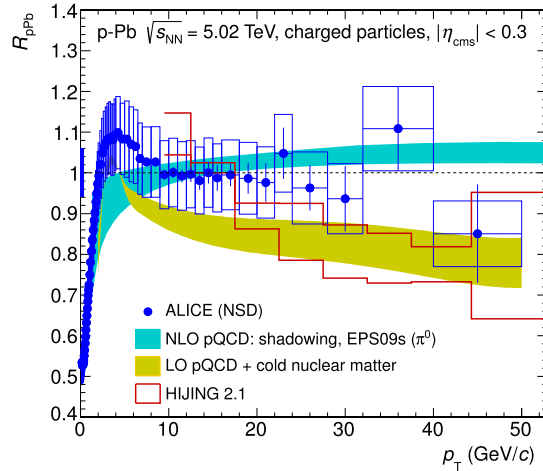
[2] This is opposite to the convention used in [6].

Fig. 1. Nuclear modification factor R_{pPb} of primary charged particles at mid-rapidity $|\eta_{cms}| < 0.3$ measured in non-single-diffractive (NSD) p–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV [16] compared to model calculations using NLO pQCD with EPS09s nuclear PDFs [17], LO pQCD with additional implementation of cold nuclear matter effects [18] and HI-JING 2.1 [19].
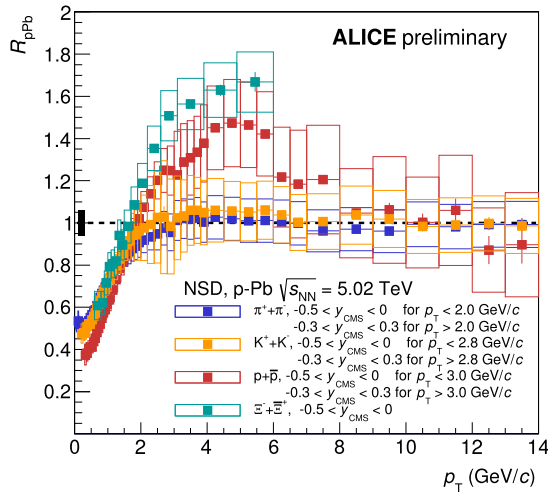

Fig. 2. Nuclear modification factor R_{pPb} of primary charged π, K, p and Ξ at mid-rapidity measured in NSD p–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV.

Fig. 2 shows the R_{pPb} for charged π, K, p up to $p_T = 14$ GeV/c and for Ξ up to 6 GeV/c. Ξ baryons are measured in their decay $\Xi^- \to \Lambda\pi^-$, with the subsequent decay $\Lambda \to p\pi^-$. The nuclear modification factor of π and K does not differ from the charged particle result within the systematic uncertainties. At intermediate momenta of $2 < p_T < 6$ GeV/c a mass ordering with $R_{pPb}^\pi \approx R_{pPb}^K < R_{pPb}^p < R_{pPb}^\Xi$ is observed. In Pb–Pb collisions a similar mass ordering is observed and attributed to radial flow. A notable Cronin peak is only observed for p and Ξ implying that the small enhancement of R_{pPb} for charged particles is driven by the protons. At larger transverse
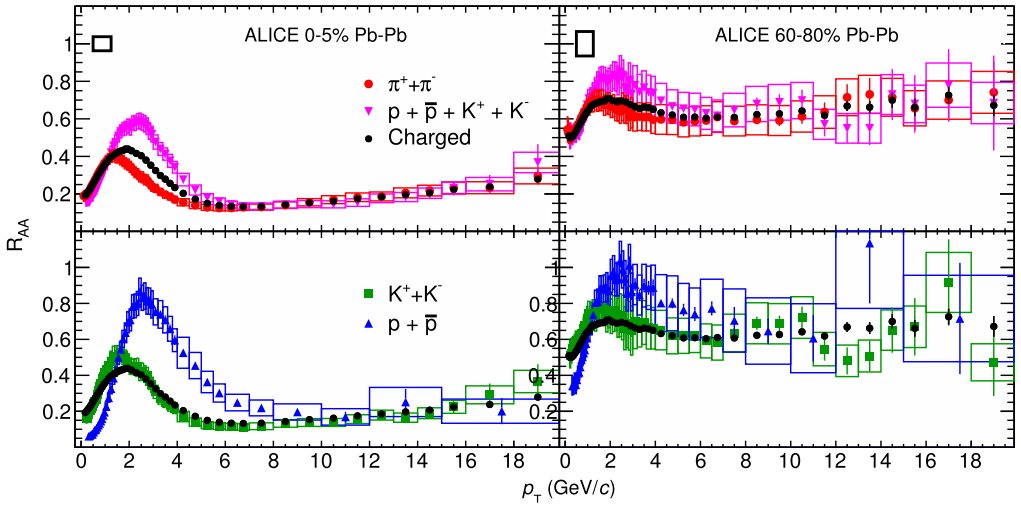
Fig. 3. The nuclear modification factor R_{AA} of π, K, p in central (0–5%) and peripheral (60–80%) Pb–Pb collisions [8] compared to the R_{AA} of inclusive charged particles [21].

momenta of $p_T > 8$ GeV/c the nuclear modification factors of π, K, p are all consistent with unity.

The nuclear modification factor R_{AA} for π, K, p up to 20 GeV/c [8] is shown in Fig. 3 for central (0–5%) and peripheral (60–80%) Pb–Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV with comparison to the charged particle R_{AA} [21]. For large transverse momenta ($p_T > 10$ GeV/c) the strong suppression observed for inclusive charged particles does not depend on the particle type.

4. Conclusions

In p–Pb collisions soft particle production at low p_T scales approximately with the number of participating nucleons and hard particle production at large p_T scales with the number of binary nucleon–nucleon collisions, with a smooth transition in between. This indicates that there are no strong initial or final state nuclear effects at large p_T. At intermediate p_T the small enhancement (Cronin peak) is caused by protons. Identified light hadrons exhibit a mass ordering of R_{pPb} at intermediate p_T which is qualitatively similar to that in Pb–Pb collisions. At $p_T > 8$ GeV/c π, K and p R_{pPb} is consistent with unity. In Pb–Pb collisions large suppression is observed for all particle species, with differences from radial flow visible in the R_{AA} at low and intermediate p_T, while above 10 GeV/c the suppression is common for all species with the p/π and K/π ratios not differing from those in pp collisions.

References

[1] S. Chatrchyan, et al., CMS Collaboration, Phys. Lett. B 718 (2013) 795–814.
[2] B. Abelev, et al., ALICE Collaboration, Phys. Lett. B 719 (2013) 29–41.
[3] G. Aad, et al., ATLAS Collaboration, Phys. Rev. Lett. 110 (2013) 182302.
[4] CMS Collaboration, CERN Report No. CMS-PAS-HIN-12-017, 2013.
[5] ATLAS Collaboration, CERN Report No. ATLAS-CONF-2014-029, 2014.
[6] B. Abelev, et al., ALICE Collaboration, Phys. Rev. Lett. 110 (2013) 082302.
[7] K. Aamodt, et al., ALICE Collaboration, J. Instrum. 3 (2008) S08002.

[8] B.B. Abelev, et al., ALICE Collaboration, arXiv:1401.1250.
[9] B.B. Abelev, et al., ALICE Collaboration, arXiv:1402.4476.
[10] B.B. Abelev, et al., ALICE Collaboration, Eur. Phys. J. C 73 (2013) 2662.
[11] R. Sassot, P. Zurita, M. Stratmann, Phys. Rev. D 82 (2010) 074011.
[12] B. Abelev, et al., ALICE Collaboration, Phys. Lett. B 717 (2012) 162–172.
[13] S. Chatrchyan, et al., CMS Collaboration, J. High Energy Phys. 1108 (2011) 086.
[14] S. Chatrchyan, et al., CMS Collaboration, Eur. Phys. J. C 72 (2012) 1945.
[15] B. Abelev, et al., ALICE Collaboration, Phys. Lett. B 722 (2013) 262–272.
[16] B.B. Abelev, et al., ALICE Collaboration, arXiv:1405.2737.
[17] I. Helenius, K.J. Eskola, H. Honkanen, C.A. Salgado, J. High Energy Phys. 1207 (2012) 073.
[18] Z.-B. Kang, I. Vitev, H. Xing, Phys. Lett. B 718 (2012) 482–487.
[19] R. Xu, W.-T. Deng, X.-N. Wang, Phys. Rev. C 86 (2012) 051901.
[20] R. Haake (for the ALICE Collaboration), PoS EPS-HEP2013 (2013) 176.
[21] B. Abelev, et al., ALICE Collaboration, Phys. Lett. B 720 (2013) 52–62.