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Abelev, B.; Adam, J.; Adamová, D.; Bearden, Ian; Bilandzic, Ante; Bøggild, Hans; Chojnacki, Marek; Christensen, Christian Holm; Dalsgaard, Hans Hjersing; Gaardhøje, Jens Jørgen; Gulbrandsen, Kristjan Herlache; Hansen, Alexander Colliander; Nielsen, Børge Svane; Nygaard, Casper; Søgaard, Carsten; Zaccolo, Valentina

Published in:
arXiv.org: Physics

Publication date:
2012

Document Version
Publisher's PDF, also known as Version of record

Citation for published version (APA):
Abelev, B., Adam, J., Adamová, D., Bearden, I., Bilandzic, A., Bøggild, H., ... Zaccolo, V. (2012). Transverse momentum distribution and nuclear modification factor of charged particles in p–Pb collisions at sNN=5.02TeV. arXiv.org: Physics, (arXiv:1210.4520).

EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

CERN-PH-EP-2012-306
October 17, 2012

Transverse Momentum Distribution and Nuclear Modification Factor of Charged Particles in p–Pb Collisions at $\sqrt{s_{\rm NN}} = 5.02$ TeV

The ALICE Collaboration*

Abstract

The transverse momentum ($p_{\rm T}$) distribution of primary charged particles is measured in non-single-diffractive p–Pb collisions at $\sqrt{s_{\rm NN}} = 5.02$ TeV with the ALICE detector at the LHC. The $p_{\rm T}$ spectra measured near central rapidity in the range $0.5 < p_{\rm T} < 20$ GeV/c exhibit a weak pseudorapidity dependence. The nuclear modification factor $R_{\rm pPb}$ is consistent with unity for $p_{\rm T}$ above 2 GeV/c. This measurement indicates that the strong suppression of hadron production at high $p_{\rm T}$ observed in Pb–Pb collisions at the LHC is not due to an initial-state effect. The measurement is compared to theoretical calculations.

*See Appendix A for the list of collaboration members

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

Parton energy loss in hot QCD matter is expected to lead to a modification of energetic jets in this medium (jet quenching) [3]. Originating from energetic partons produced in initial hard collisions, hadrons at high transverse momentum p_T are an important observable for the study of deconfined matter. Experiments at RHIC have shown [4, 5] that the production of charged hadrons at high p_T in Au–Au collisions is suppressed compared to the expectation from an independent superposition of nucleon–nucleon collisions (binary collision scaling).

By colliding Pb nuclei at the LHC it was shown [6–8] that the production of charged hadrons in central collisions at a center-of-mass (cms) collision energy per nucleon pair $\sqrt{s_{NN}} = 2.76$ TeV shows a stronger suppression than at RHIC, indicating a state of QCD matter with an even higher energy density. At the LHC, the suppression remains substantial up to 100 GeV/c [7,8] and is also seen in reconstructed jets [9]. A p–Pb control experiment is needed to establish whether the initial state of the colliding nuclei plays a role in the observed suppression of hadron production at high-p_T in Pb–Pb collisions. In addition, p–Pb data should also provide tests of models that describe QCD matter at high gluon density, giving insight into phenomena such as parton shadowing or gluon saturation [1].

In this letter, we present a measurement of the p_T distributions of charged particles in p–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV. The data were recorded with the ALICE detector [10] during a short LHC p–Pb run performed in September 2012 in preparation for the main run scheduled at the beginning of 2013. Each beam contained 13 bunches; 8 pairs of bunches were colliding in the ALICE interaction region, providing a luminosity of about 8×10^{25} cm^{-2}s^{-1}. The interaction region had an r.m.s. width of 6.3 cm in the longitudinal direction and of about 60 μm in the transverse directions.

The trigger required a signal in either of two arrays of 32 scintillator tiles each, covering full azimuth and $2.8 < \eta_{lab} < 5.1$ (VZERO-A) and $-3.7 < \eta_{lab} < -1.7$ (VZERO-C), respectively. The pseudorapidity in the detector reference frame, $\eta_{lab} = -\ln[\tan(\theta/2)]$, with θ the polar angle between the charged particle and the beam axis, is defined such that the proton beam has negative η_{lab}. This configuration led to a trigger rate of about 200 Hz, with a hadronic collision rate of about 150 Hz. The efficiency of the VZERO trigger was estimated from a control sample of events triggered by signals from two Zero Degree Calorimeters (ZDC) positioned symmetrically at 112.5 m from the interaction point, with an energy resolution of about 20% for single neutrons of a few TeV.

The offline event selection is identical to that used for the analysis of charged-particle pseudorapidity density ($dN_{ch}/d\eta_{lab}$) reported in [11]. A signal is required in both VZERO-A and VZERO-C. Beam–gas and other machine-induced background events with deposited energy above the thresholds in the VZERO or ZDC detectors are suppressed by requiring the signal timing to be compatible with that of a nominal p–Pb interaction. The remaining background after these requirements is estimated from triggers on non-colliding bunches, and found to be negligible. The resulting sample of events consists of non-single-diffractive (NSD) collisions as well as single-diffractive and electromagnetic interactions. The efficiency of the trigger and offline event selection for the different interactions is estimated using a combination of event generators, see [11] for details. An efficiency of 99.2% for NSD collisions is estimated, with a negligible contamination from single-diffractive and electromagnetic interactions. The number of events used for the analysis is 1.7×10^6.

The primary vertex position is determined with tracks reconstructed in the Inner Tracking System (ITS) and the Time Projection Chamber (TPC) by using a χ^2 minimization procedure described in [8]. The event vertex reconstruction algorithm is fully efficient for events with at least one track in the acceptance, $|\eta_{lab}| < 1.4$ (when the center of the interaction region is included as an additional constraint). An event is accepted if the coordinate of the reconstructed vertex measured along the beam direction is within ± 10 cm around the center of the interaction region.

Primary charged particles are defined as all prompt particles produced in the collision, including decay products, except those from weak decays of strange hadrons. Selections based on the number of space points and the quality of the track fit, as well as on the distance of closest approach to the reconstructed vertex, are applied to the reconstructed tracks (see [8] for details). The efficiency and purity of the primary charged particle selection are estimated from a Monte Carlo simulation using the DPMJET event generator [12] with particle transport through the detector using GEANT3 [13]. The systematic uncertainties on corrections are estimated via a comparison to a Monte Carlo simulation using the HIJING event generator [14]. The overall primary charged particle reconstruction efficiency (the product of tracking efficiency and acceptance) for $|\eta_{\rm lab}| < 0.8$ is 79% at $p_{\rm T} = 0.5$ GeV/c, reaches 81% at 0.8 GeV/c and decreases to 72% for $p_{\rm T} > 2$ GeV/c. From Monte Carlo simulations it is estimated that the residual contamination from secondary particles is 1.6% at $p_{\rm T} = 0.5$ GeV/c and decreases to about 0.6% for $p_{\rm T} > 2$ GeV/c.

The transverse momentum of charged particles is determined from the track curvature in the magnetic field of 0.5 T. The $p_{\rm T}$ resolution is estimated from the space-point residuals to the track fit and verified by the width of the invariant mass of $\mathrm{K^0_S}$ mesons reconstructed in their decay to two charged pions. For the selected tracks the relative $p_{\rm T}$ resolution is 1.3% at $p_{\rm T} = 0.5$ GeV/c, has a minimum of 1.0% at $p_{\rm T} = 1$ GeV/c, and increases linearly to 2.2% at $p_{\rm T} = 20$ GeV/c. The uncertainty on the $p_{\rm T}$ resolution is ± 0.7% at $p_{\rm T} = 20$ GeV/c, leading to a systematic uncertainty on the differential yield of up to 3% at this $p_{\rm T}$ value.

Table 1: Systematic uncertainties on the $p_{\rm T}$-differential yields in p–Pb and pp collisions for $|\eta_{\rm cms}| < 0.3$. The quoted ranges span the $p_{\rm T}$ dependence of the uncertainties.

Uncertainty	Value
Event selection	1.0–2.0%
Track selection	0.9–2.7%
Tracking efficiency	3.0%
$p_{\rm T}$ resolution	0–3.0%
Particle composition	2.2–3.1%
MC generator used for correction	1.0%
Secondary particle rejection	0.4–1.1%
Material budget	0–0.5%
Acceptance (conversion to $\eta_{\rm cms}$)	0–0.6%
Total for p–Pb, $p_{\rm T}$-dependent	5.2–5.5%
Normalization p–Pb	3.1%
Total for pp, $p_{\rm T}$-dependent	7.7–8.2%
Normalization pp	3.6%
Nuclear overlap $\langle T_{\rm pPb} \rangle$	3.6%

Due to the different energy per nucleon of the two colliding beams, imposed by the two-in-one magnet design of the LHC, the nucleon-nucleon cms moves with a rapidity $y_{\rm NN} = 0.465$ in the direction of the proton beam. As a consequence, the detector coverage, $|\eta_{\rm lab}| < 0.8$, implies, for the nucleon-nucleon cms, roughly $-0.3 < \eta_{\rm cms} < 1.3$. The calculation of $\eta_{\rm cms} = \eta_{\rm lab} + y_{\rm NN}$ is accurate only for massless particles or at high $p_{\rm T}$. Consequently, the differential yield at low $p_{\rm T}$ suffers from a distortion, which is estimated and corrected for based on the particle composition in the HIJING event generator. For $p_{\rm T} = 0.5$ GeV/c, the correction is 1% for $|\eta_{\rm cms}| < 0.3$ and reaches 3% for $0.8 < \eta_{\rm cms} < 1.3$. The systematic uncertainties were estimated by varying the relative particle abundances by factors of 2 around the nominal values. The uncertainty is sizable only at low $p_{\rm T}$ and is dependent on $\eta_{\rm cms}$. It is 0.6% for

$|\eta_{\rm cms}| < 0.3$, 4.3% for $0.3 < \eta_{\rm cms} < 0.8$, and 5.1% for $0.8 < \eta_{\rm cms} < 1.3$.

The systematic uncertainties on the $p_{\rm T}$ spectrum are summarized in Table 1 for $|\eta_{\rm cms}| < 0.3$. The total uncertainties exhibit a weak $p_{\rm T}$ and $\eta_{\rm cms}$ dependence. The total systematic uncertainties range between 5.2% and 5.5% for $|\eta_{\rm cms}| < 0.3$ and reach between 5.6% and 7.1% for $0.8 < \eta_{\rm cms} < 1.3$.

In order to quantify nuclear effects in p–Pb collisions, a comparison to a reference $p_{\rm T}$ spectrum in pp collisions is needed. In the absence of a measurement at $\sqrt{s}$ =5.02 TeV, the reference spectrum is obtained by interpolating or scaling data measured at $\sqrt{s}$ =2.76 and 7 TeV. For $p_{\rm T} < 5$ GeV/c, the measured invariant cross section for charged particle production in pp collisions, $\mathrm{d}^2\sigma^{\rm pp}_{\rm ch}/\mathrm{d}\eta\,\mathrm{d}p_{\rm T}$, is interpolated bin-by-bin, assuming a power law dependence as a function of $\sqrt{s}$. For $p_{\rm T} > 5$ GeV/c, the measured data at $\sqrt{s} = 7$ TeV is scaled by a factor obtained from NLO pQCD calculations [15]. For $p_{\rm T} < 5$ GeV/c, the largest of the relative systematic uncertainties of the spectrum at 2.76 or 7 TeV is assigned as the systematic uncertainty at the interpolated energy. For $p_{\rm T} > 5$ GeV/c, the relative difference between the NLO-scaled spectrum for different choices of the renormalization μ_R and factorization μ_F scales ($\mu_R = \mu_F = p_{\rm T}$, $p_{\rm T}/2$, $2p_{\rm T}$) is added to the systematic uncertainties on the spectrum at 7 TeV. In addition, an uncertainty of 2.2% is estimated comparing the interpolated and the NLO-scaled data. The total systematic uncertainty range from 7.7% to 8.2% for $0.5 < p_{\rm T} < 20$ GeV/c. The NLO-based scaling of the data at $\sqrt{s} = 2.76$ TeV gives a result well within these uncertainties. More details can be found in [16].

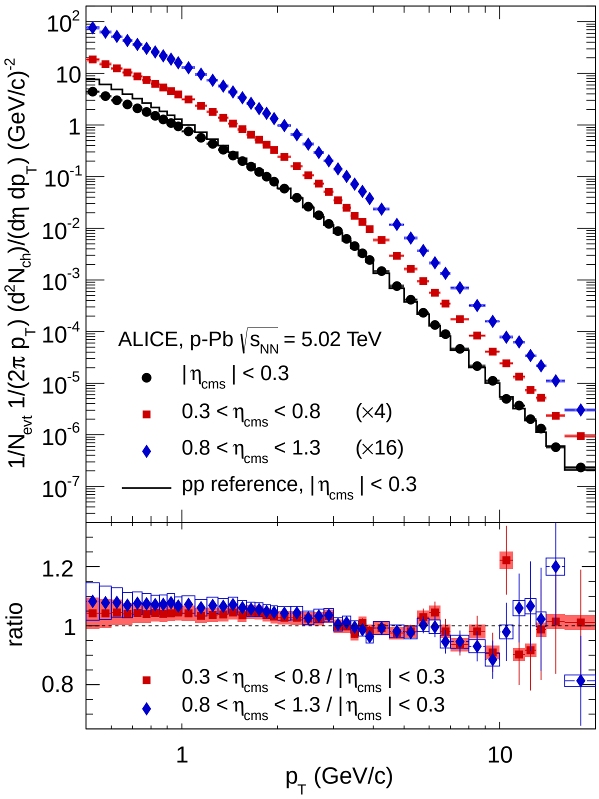

Fig. 1: Transverse momentum distributions of charged particles in NSD p–Pb collisions for different pseudorapidity ranges (upper panel). The spectra are scaled by the factors indicated. The histogram represents the reference spectrum in pp collisions (see text). The lower panel shows the ratio of the spectra at forward pseudorapidities to that at $|\eta_{\rm cms}| < 0.3$. The vertical bars (boxes) represent the statistical (systematic) errors.

The final pp reference spectrum is the product of the interpolated invariant cross section and the average nuclear overlap $\langle T_{\rm pPb}\rangle$, calculated employing the Glauber model [17], which gives $\langle T_{\rm pPb}\rangle = 0.0983 \pm$

0.0035 mb^{-1}. The uncertainty is obtained by varying the parameters in the Glauber model calculation, see [11].

The p_{T} spectra of charged particles measured in NSD p–Pb collisions at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV are shown in Fig. 1 together with the interpolated pp reference spectrum. At high p_{T}, the p_{T} distributions in p–Pb collisions are similar to that in pp collisions, as expected in the absence of nuclear effects. There is an indication of a softening of the p_{T} spectrum when going from central to forward pseudorapidity. This is a small effect, as seen in the ratios of the spectra for forward pseudorapidities to that at $|\eta_{\mathrm{cms}}| < 0.3$, shown in Fig. 1 (lower panel). Calculations with the DPMJET event generator [12], which predict well the measured $\mathrm{d}N_{\mathrm{ch}}/\mathrm{d}\eta_{\mathrm{lab}}$ [11], overpredict the spectra by up to 33% for $p_{\mathrm{T}} < 0.7$ GeV/c and underpredict them by up to 50% for $p_{\mathrm{T}} > 0.7$ 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:

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

where $N_{\mathrm{ch}}^{\mathrm{pPb}}$ is the charged particle yield in p–Pb collisions. The nuclear modification factor is unity for hard processes which are expected to exhibit binary collision scaling. For the region of several tens of GeV, binary collision scaling was experimentally confirmed in Pb–Pb collisions at the LHC by the recent measurements of observables which are not affected by hot QCD matter, direct photon [18], Z^0 [19], and $W^{\pm}$ [20] production. The present measurement in p–Pb collisions extends this important experimental verification down to the GeV scale and to hadronic observables.

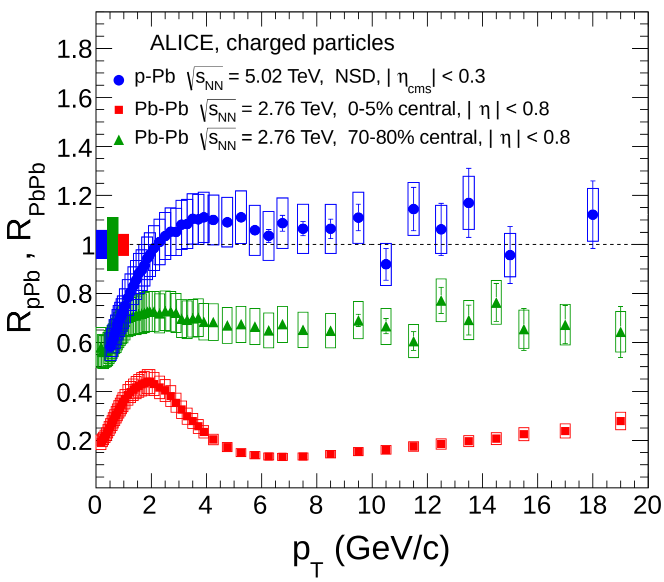

Fig. 2: The nuclear modification factor of charged particles as a function of transverse momentum in NSD p–Pb collisions at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV. The data for $|\eta_{\mathrm{cms}}| < 0.3$ are compared to measurements [8] in central (0–5% centrality) and peripheral (70–80%) Pb–Pb collisions at $\sqrt{s_{\mathrm{NN}}} = 2.76$ TeV. The statistical errors are represented by vertical bars, the systematic errors by (filled) boxes around data points. The relative systematic uncertainties on the normalization are shown as boxes around unity near $p_{\mathrm{T}} = 0$ for p–Pb (left box), peripheral Pb–Pb (middle box) and central Pb-Pb (right box).

The measurement of the nuclear modification factor R_{pPb} for charged particles at $|\eta_{\mathrm{cms}}| < 0.3$, is shown in Fig. 2. The uncertainties of the p–Pb and pp spectra are added in quadrature, separately for the statistical

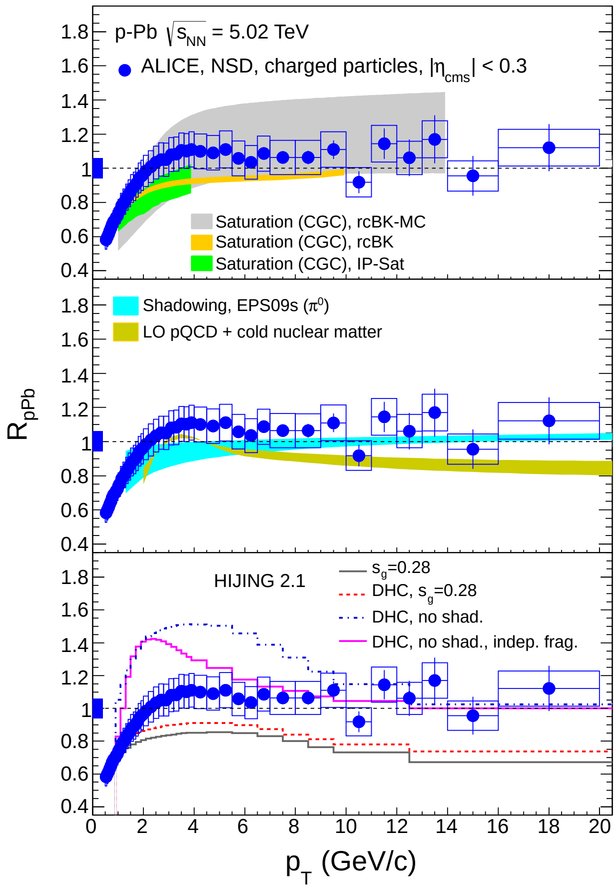

Fig. 3: Transverse momentum dependence of the nuclear modification factor R_{pPb} of charged particles measured in p–Pb collisions at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV. The ALICE data in $|\eta_{\mathrm{cms}}| < 0.3$ (symbols) are compared to model calculations (bands or lines, see text for details; for HIJING, DHC stands for decoherent hard collisions). The vertical bars (boxes) show the statistical (systematic) errors. The relative systematic uncertainty on the normalization is shown as a box around unity near $p_{\mathrm{T}} = 0$.

and systematic uncertainties. The total systematic uncertainty on the normalization, quadratic sum of the uncertainty on $\langle T_{\mathrm{pPb}} \rangle$, the normalization of the pp data and the normalization of the p–Pb data, amounts to 6.0%.

In Fig. 2 we compare the measurement of the nuclear modification factor in p–Pb to that in central (0–5% centrality) and peripheral (70–80% centrality) Pb–Pb collisions at $\sqrt{s_{\mathrm{NN}}} = 2.76$ TeV [8]. R_{pPb} is consistent with unity for $p_{\mathrm{T}} \gtrsim 2$ GeV/c, demonstrating that the strong suppression observed in central Pb–Pb collisions at the LHC [6–8] is not due to an initial-state effect, but rather a fingerprint of the hot matter created in collisions of heavy ions.

The so-called Cronin effect [21] (see [22] for a review), namely a nuclear modification factor above unity at intermediate p_{T}, was observed at lower energies in proton–nucleus collisions. In d–Au collisions at $\sqrt{s_{\mathrm{NN}}} = 200$ GeV, R_{dAu} reached values of about 1.4 for charged hadrons in the p_{T} range 3 to 5 GeV/c [23–26]. The present measurement clearly indicates a smaller magnitude of the Cronin effect at the LHC; the data are even consistent with no enhancement within systematic uncertainties.

Data in p–Pb are important also to provide constraints to models. For illustration, in Fig. 3 the measurement of R_{pPb} at $|\eta_{\mathrm{cms}}| < 0.3$ is compared to theoretical predictions. Note that the measurement is performed for NSD collisions. With the HIJING [14] and DPMJET [12] event generators, it is estimated that the inclusion of single-diffractive events would lead to a decrease of R_{pPb} by 3–4%. Several predictions based on the Colour Glass Condensate (CGC) model are available [27–29]. The calculations of Tribedy and Venugopalan [27] are shown for two implementations (rcBK and IP-Sat, see [27] for details). The calculations within IP-Sat are consistent with the data, while those within rcBK slightly underpredict the measurement. The prediction of Albacete et al. [28], for the rcBK Monte Carlo model, is consistent with the measurement within the rather large uncertainties of the model. The CGC calculations of Rezaeian [29], not included in Fig. 3, are consistent with those of [27, 28]. The shadowing calculations of Helenius et al. [30], performed at NLO with the EPS09s Parton Distribution Functions and DSS fragmentation functions describe the data well (the calculations are for π^0). The predictions by Kang et al. [31], performed within a framework combining leading order pQCD and cold nuclear matter effects, show R_{pPb} values below unity for $p_{\mathrm{T}} \gtrsim 6$ GeV/c, which is not supported by the data. The prediction from the HIJING 2.1 model [32] describes, with shadowing, the trend seen in the data, although it seems that, with the present shadowing parameter s_g, the model underpredicts the data. The comparisons in Fig. 3 clearly illustrate that the data are crucial for the theoretical understanding of cold nuclear matter as probed in p–Pb collisions at the LHC.

In summary, we have reported measurements of the charged-particle p_{T} spectra and nuclear modification factor in p–Pb collisions at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV. The data, covering $0.5 < p_{\mathrm{T}} < 20$ GeV/c, show a nuclear modification factor consistent with unity for $p_{\mathrm{T}} \gtrsim 2$ GeV/c. This measurement indicates that the strong suppression of hadron production at high p_{T} observed at the LHC in Pb–Pb collisions is not due to an initial-state effect, but is the fingerprint of jet quenching in hot QCD matter.

Acknowledgements

Thanks are due to J. Albacete, A. Dumitru, I. Helenius, P. Tribedy, R. Venugopalan, I. Vitev, X.-N. Wang, and their collaborators for useful input concerning their models.

The ALICE collaboration would like to thank all its engineers and technicians for their invaluable contributions to the construction of the experiment and the CERN accelerator teams for the outstanding performance of the LHC complex.
The ALICE collaboration acknowledges the following funding agencies for their support in building and running the ALICE detector:
State Committee of Science, Calouste Gulbenkian Foundation from Lisbon and Swiss Fonds Kidagan, Armenia;
Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq), Financiadora de Estudos e Projetos (FINEP), Fundação de Amparo à Pesquisa do Estado de São Paulo (FAPESP);
National Natural Science Foundation of China (NSFC), the Chinese Ministry of Education (CMOE) and the Ministry of Science and Technology of China (MSTC);
Ministry of Education and Youth of the Czech Republic;
Danish Natural Science Research Council, the Carlsberg Foundation and the Danish National Research Foundation;
The European Research Council under the European Community’s Seventh Framework Programme;
Helsinki Institute of Physics and the Academy of Finland;
French CNRS-IN2P3, the ‘Region Pays de Loire’, ‘Region Alsace’, ‘Region Auvergne’ and CEA, France;
German BMBF and the Helmholtz Association;
General Secretariat for Research and Technology, Ministry of Development, Greece;
Hungarian OTKA and National Office for Research and Technology (NKTH);
Department of Atomic Energy and Department of Science and Technology of the Government of India;
Istituto Nazionale di Fisica Nucleare (INFN) of Italy;
MEXT Grant-in-Aid for Specially Promoted Research, Japan;

Joint Institute for Nuclear Research, Dubna;
National Research Foundation of Korea (NRF);
CONACYT, DGAPA, México, ALFA-EC and the HELEN Program (High-Energy physics Latin-American–European Network);
Stichting voor Fundamenteel Onderzoek der Materie (FOM) and the Nederlandse Organisatie voor Wetenschappelijk Onderzoek (NWO), Netherlands;
Research Council of Norway (NFR);
Polish Ministry of Science and Higher Education;
National Authority for Scientific Research - NASR (Autoritatea Naţională pentru Cercetare Ştiinţifică - ANCS);
Ministry of Education and Science of Russian Federation, International Science and Technology Center, Russian Academy of Sciences, Russian Federal Agency of Atomic Energy, Russian Federal Agency for Science and Innovations and CERN-INTAS;
Ministry of Education of Slovakia;
Department of Science and Technology, South Africa;
CIEMAT, EELA, Ministerio de Educación y Ciencia of Spain, Xunta de Galicia (Consellería de Educación), CEADEN, Cubaenergía, Cuba, and IAEA (International Atomic Energy Agency);
Swedish Research Council (VR) and Knut & Alice Wallenberg Foundation (KAW);
Ukraine Ministry of Education and Science;
United Kingdom Science and Technology Facilities Council (STFC);
The United States Department of Energy, the United States National Science Foundation, the State of Texas, and the State of Ohio.

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