Physics Letters B 763 (2016) 313–336

Contents lists available at ScienceDirect

Physics Letters B

www.elsevier.com/locate/physletb

Transverse momentum, rapidity, and centrality dependence of inclusive charged-particle production in $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV $p+\mathrm{Pb}$ collisions measured by the ATLAS experiment

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ARTICLE INFO

Article history:
Received 23 May 2016
Received in revised form 14 August 2016
Accepted 24 October 2016
Available online 29 October 2016
Editor: D.F. Geesaman

ABSTRACT

Measurements of the per-event charged-particle yield as a function of the charged-particle transverse momentum and rapidity are performed using $p+\mathrm{Pb}$ collision data collected by the ATLAS experiment at the LHC at a centre-of-mass energy of $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV. Charged particles are reconstructed over pseudorapidity $|\eta| < 2.3$ and transverse momentum between 0.1 GeV and 22 GeV in a dataset corresponding to an integrated luminosity of 1 $\mu\mathrm{b}^{-1}$. The results are presented in the form of charged-particle nuclear modification factors, where the $p+\mathrm{Pb}$ charged-particle multiplicities are compared between central and peripheral $p+\mathrm{Pb}$ collisions as well as to charged-particle cross sections measured in pp collisions. The $p+\mathrm{Pb}$ collision centrality is characterized by the total transverse energy measured in $-4.9 < \eta < -3.1$, which is in the direction of the outgoing lead beam. Three different estimations of the number of nucleons participating in the $p+\mathrm{Pb}$ collision are carried out using the Glauber model and two Glauber–Gribov colour-fluctuation extensions to the Glauber model. The values of the nuclear modification factors are found to vary significantly as a function of rapidity and transverse momentum. A broad peak is observed for all centralities and rapidities in the nuclear modification factors for charged-particle transverse momentum values around 3 GeV. The magnitude of the peak increases for more central collisions as well as rapidity ranges closer to the direction of the outgoing lead nucleus.

1. Introduction

Proton–nucleus collisions at ultrarelativistic energies provide an opportunity to understand the role of the nuclear environment in modifying hard scattering rates. Several physics effects are expected to induce deviations from a simple proportionality between the scattering rate and the number of binary nucleon–nucleon collisions [1]. First, nuclear shadowing effects have long been observed in deep-inelastic scattering on nuclei, as well as in proton–nucleus collisions, indicating that nucleons embedded in a nucleus have a modified structure. This modification tends to suppress hadron production at low to moderate momentum, and is addressed by a variety of theoretical approaches [2,3]. Some of these approaches describe hadron production cross sections in terms of a universal set of nuclear parton distribution functions (nPDF), which are parameterized as modifications to the free nucleon PDFs [4–12]. Second, energy loss in "cold nuclear matter" is expected to modify hadron production rates at high transverse momentum (p_{T}) [13–16]. Third, a relative enhancement of hadron production rates at moderate momenta is observed in proton–nucleus collisions [17], which can be attributed to initial-state scattering of the incoming nucleon [18,19] or radial flow effects [20]. Finally, the appearance of "ridge-like" structures in high-multiplicity pp and $p+\mathrm{Pb}$ events [21–25] suggests that small collision systems have the same hydrodynamic origin as $\mathrm{Pb}+\mathrm{Pb}$ events [26], or that there are already strong correlations in the initial state from gluon saturation [27]. All these effects can be explored experimentally by the measurement of charged-hadron production as a function of transverse momentum.

For proton-lead ($p+\mathrm{Pb}$) collisions, assuming that the initial parton densities are the incoherent superposition of the nucleonic parton densities, the per-event particle production yield can be estimated by the product $\sigma_{\mathrm{NN}} \times \langle T_{\mathrm{Pb}} \rangle$. Here σ_{NN} is the cross section for the analogous nucleon–nucleon collision process and $\langle T_{\mathrm{Pb}} \rangle$ is the average value of the nuclear thickness function over a distribution of the impact parameters of protons incident on the nuclear target. It can be thought of as a per-collision luminosity. The nuclear modification factor, $R_{p\mathrm{Pb}}$, is defined as the ratio of the measured charged-particle production yield in $p+\mathrm{Pb}$ collisions, normalized by $\langle T_{\mathrm{Pb}} \rangle$, to the cross section of the charged-particle production yield in pp collisions:

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http://dx.doi.org/10.1016/j.physletb.2016.10.053
0370-2693/

$$R_{p\mathrm{Pb}}(p_\mathrm{T}, y^*) = \frac{1}{\langle T_\mathrm{Pb}\rangle} \frac{1/N_\mathrm{evt}\, \mathrm{d}^2 N_{p\mathrm{Pb}}/\mathrm{d}y^* \mathrm{d}p_\mathrm{T}}{\mathrm{d}^2\sigma_{pp}/\mathrm{d}y^*\mathrm{d}p_\mathrm{T}}, \tag{1}$$

where N_evt is the number of $p+\mathrm{Pb}$ events, $\mathrm{d}^2N_{p\mathrm{Pb}}/\mathrm{d}y^*\mathrm{d}p_\mathrm{T}$ is the differential yield of charged particles in $p+\mathrm{Pb}$ collisions and $\mathrm{d}^2\sigma_{pp}/\mathrm{d}y^*\mathrm{d}p_\mathrm{T}$ is the differential charged-particle production cross section in pp collisions. Both numerator and denominator are presented in terms of y^*, the rapidity in the nucleon–nucleon centre-of-mass frame. In the absence of initial-state and nuclear effects, the ratio $R_{p\mathrm{Pb}}$ is expected to be unity at high p_T [28]. Another measure of nuclear modification is the quantity R_CP, which is defined to be:

$$R_\mathrm{CP}(p_\mathrm{T}, \eta) = \frac{\langle T_\mathrm{Pb,P}\rangle}{\langle T_\mathrm{Pb,C}\rangle} \frac{(1/N_\mathrm{evt,C})\mathrm{d}^2N_{p\mathrm{Pb,C}}/\mathrm{d}\eta\mathrm{d}p_\mathrm{T}}{(1/N_\mathrm{evt,P})\mathrm{d}^2N_{p\mathrm{Pb,P}}/\mathrm{d}\eta\mathrm{d}p_\mathrm{T}}, \tag{2}$$

and can be constructed without the need for a pp reference spectrum. The indices “P” and “C” label peripheral (large impact parameter) and central (small impact parameter) centrality intervals, respectively. The R_CP is presented as a function of pseudorapidity (η) rather than y^* since both numerator and denominator are from the same colliding systems. Measurements of $R_{p\mathrm{Pb}}$ and R_CP provide useful input for constraining models of shadowing, energy loss and radial flow effects. They should also provide useful input for the determination of nuclear parton distribution functions, in particular as a function of proton impact parameter [6]. The absolute values of the nuclear modification depend on the $\langle T_\mathrm{Pb}\rangle$ values and should be interpreted with respect to the assumptions underlying the particular model used to calculate the normalization.

A recent ATLAS publication [29] has reported measurements of the mean charged-particle multiplicity as a function of pseudorapidity and collision centrality and explored the relationship between the centrality dependence of the particle production and models of the initial nuclear geometry. The results presented here utilize the same centrality definition and geometric models, but build upon that work by exploring the p_T, η and y^* dependence of per-event charged-particle yields in $p+\mathrm{Pb}$ collisions at a centre-of-mass energy $\sqrt{s_\mathrm{NN}} = 5.02\,\mathrm{TeV}$ and comparing that dependence to the expectations from pp collisions through the quantities $R_{p\mathrm{Pb}}$ and R_CP.

These measurements are an extension of a similar programme carried out at the Relativistic Heavy Ion Collider, where all experiments reported the absence of charged-particle suppression at $2 < p_\mathrm{T} < 10\,\mathrm{GeV}$ in $d+\mathrm{Au}$ collisions [30–35], in contrast to the strong suppression found in $\mathrm{Au}+\mathrm{Au}$ collisions [31,33]. Measurements of nuclear modification factors as a function of transverse momentum in a narrow pseudorapidity window relative to the centre-of-mass frame $|\eta_\mathrm{CM}| < 0.3$ have been reported by ALICE integrated over centrality [36,37] and differentially for several centrality classes [38,39]. Similarly, CMS results have been reported integrated over centrality and in a broader pseudorapidity window, $|\eta_\mathrm{CM}| < 1$ [40].

2. The ATLAS detector

The ATLAS detector [41] at the Large Hadron Collider (LHC) covers almost the entire solid angle[1] around the collision point. It consists of an inner tracking detector surrounded by a thin superconducting solenoid, electromagnetic and hadronic calorimeters, and a muon spectrometer incorporating three large superconducting toroidal magnets.

The inner detector (ID) system is immersed in a 2 T axial magnetic field and provides charged-particle tracking in the pseudorapidity range $|\eta| < 2.5$. The ID tracker is composed of three detector subsystems. Closest to the interaction point is a high-granularity silicon pixel detector covering $|\eta| < 2.7$, which typically provides three measurements per track. Next is a silicon microstrip tracker (SCT), which typically yields four pairs of hits per track, each providing a two-dimensional measurement point. The silicon detectors are complemented by the straw-tube transition radiation tracker, which enables radially extended track reconstruction up to $|\eta| = 2.0$.

The calorimeter system covers the pseudorapidity range $|\eta| < 4.9$. Within the region $|\eta| < 3.2$, electromagnetic calorimetry is provided by high-granularity lead/liquid-argon (LAr) electromagnetic calorimeters, with an additional thin LAr presampler covering $|\eta| < 1.8$, to measure the contribution of showers initiated in the material upstream of the calorimeters. Hadronic calorimetry is provided by a steel/scintillator-tile calorimeter, segmented into three barrel structures within $|\eta| < 1.7$, and two copper/LAr hadronic endcap calorimeters covering $1.5 < |\eta| < 3.2$. The calorimeter coverage is completed with forward copper/LAr and tungsten/LAr calorimeter modules optimized for electromagnetic and hadronic measurements, respectively, covering $3.1 < |\eta| < 4.9$. The minimum-bias trigger scintillators (MBTS) detect charged particles over $2.1 < |\eta| < 3.9$ using two hodoscopes, each of which is subdivided into 16 counters positioned at $z = \pm 3.6$ m.

A three-level trigger system is used to select events [42]. The Level-1 trigger is implemented in hardware and uses a subset of detector information to reduce the event rate to 100 kHz. This is followed by two software-based trigger levels which together reduce the event rate to about 1000 Hz, which is recorded for data analysis.

3. Datasets and event selection

3.1. Event selection in $p+\mathrm{Pb}$ collisions

The $p+\mathrm{Pb}$ collisions were recorded by the ATLAS detector in September 2012 using a trigger that selected events with at least one hit in each side of the MBTS, with the resulting dataset corresponding to an integrated luminosity of 1 $\mu\mathrm{b}^{-1}$. During that run the LHC was configured with a clockwise 4 TeV proton beam and an anti-clockwise 1.57 TeV per-nucleon $^{208}\mathrm{Pb}$ beam that together produced collisions with a nucleon–nucleon centre-of-mass energy of $\sqrt{s} = 5.02$ TeV and a longitudinal rapidity boost of $y_\mathrm{lab} = 0.465$ units with respect to the ATLAS laboratory frame. Following a common convention used for $p+\mathrm{A}$ measurements, the rapidity is taken to be positive in the direction of the proton beam, i.e. opposite to the usual ATLAS convention for pp collisions. With this convention, the ATLAS laboratory frame rapidity, y, and the $p+\mathrm{Pb}$ centre-of-mass system rapidity, y^*, are related by $y^* = y - 0.465$.

Charged-particle tracks and collision vertices are reconstructed from clusters in the pixel detector and the SCT using an algorithm optimized for minimum-bias pp measurements [43]. The $p+\mathrm{Pb}$ events are required to have a collision vertex satisfying $|z_\mathrm{vtx}| < 150$ mm, at least one hit in each side of the MBTS, and a difference between the time measurements in the two MBTS hodoscopes of less than 10 ns. Events containing multiple $p+\mathrm{Pb}$ collisions (pile-up) are suppressed by rejecting events that contain a second reconstructed vertex with a scalar transverse momentum

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[1] ATLAS uses a right-handed coordinate system with its origin at the nominal interaction point (IP) in the centre of the detector and the z-axis along the beam pipe. The x-axis points from the IP to the centre of the LHC ring, and the y-axis points upwards. Cylindrical coordinates (r, ϕ) are used in the transverse plane, ϕ being the azimuthal angle around the z-axis. The pseudorapidity is defined in terms of the polar angle θ as $\eta = -\ln\tan(\theta/2)$. Angular distance is measured in units of $\Delta R \equiv \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$.