Centrality dependence of low- p_T and high- p_T particle production in proton–lead collisions with ATLAS

Evgeny Shulga,
on behalf of the ATLAS Collaboration

National Research Nuclear University (NRNU MEPhI), Kashirskoe shosse 31, Moscow, Russian Federation

Abstract

Measurements of the centrality dependence of low- p_T and high- p_T particle production in proton–lead collisions at the LHC can provide unique insight into the dynamics of soft and hard scattering processes and the initial state of ultra-relativistic nuclear collisions. Recent results have shown that both soft and hard processes may be significantly influenced by event-to-event fluctuations (variations) in the structure of the proton. In this proceedings, the latest measurements of the centrality dependence of charged particle, and Z boson production with the ATLAS detector at the LHC are used to explore these questions. In particular, the sensitivity of the charged particle pseudorapidity distribution in proton–lead collisions to the choice of centrality variable is discussed. Separately, to address recent measurements of the correlation between the initial-state hard scattering kinematics in dijet events and forward transverse energy in proton–proton collisions will be presented.

Keywords: particle production, Z boson, transverse energy, proton structure

1. Introduction

This proceedings will summarise several most recent ATLAS measurements related to the low- p_T and high- p_T particle production in proton–lead (p +Pb) and proton–proton (pp) collisions. Recent particle production measurements from p +Pb collisions at LHC provide important insight on soft particle production, which allow tests for various models of soft particle production dynamics [1]. The strong centrality dependence of high- p_T hadron [2] and jet production [3, 4] in proton–lead collisions have raised questions about energy production at large rapidities in collisions involving a large proton-x. To address this, measurements of the correlation between the initial-state hard scattering kinematics in dijet events and forward transverse energy in pp collisions will be presented [5].

2. Analysis

The LHC provided proton–lead collisions at a nucleon–nucleon centre-of-mass energy of $\sqrt{s_{NN}} = 5.02$ TeV. The centrality determination of ATLAS uses the total transverse energy, $\sum E_T^{Pb}$, measured in the negative pseudorapidity sections of the forward calorimeter in the range $-4.9 < \eta < -3.2$ (in the direction of the Pb beam). Three different models are used for centrality definition: the Glauber model [6] and two Glauber-Gribov Color Fluctuation (GGCF) models [7, 8] with the magnitude of the fluctuations, characterized by the parameter ω_σ , with $\omega_\sigma = 0.11$ and $\omega_\sigma = 0.2$, which is identical to that used in Ref. [9].

Charge particle multiplicity [9] and Z-boson [10] analyses use 2012 and 2013 ATLAS p +Pb collision data at $\sqrt{s_{\text{NN}}} = 5.02$ TeV, respectively. A minimum bias (MB) event sample was obtained by requiring signal in the Minimum Bias Trigger Scintillator and used for multiplicity analysis [9]. Following stringent data-quality requirements [10], the $Z \rightarrow ee$ and $Z \rightarrow \mu\mu$ analyses use samples corresponding to integrated luminosity values of $29.4 \pm 0.8 \text{ nb}^{-1}$ and $28.1 \pm 0.8 \text{ nb}^{-1}$, respectively. The Z-boson analyses use high-level electron and muon triggers [10]. The relationship between jet production in the central region and the underlying event activity in a pseudorapidity-separated region is studied in 4.0 pb^{-1} of $\sqrt{s} = 2.76 \text{ TeV } pp$ events [5]. The jet reconstruction and associated background determination procedures closely follow those developed within ATLAS for jet measurements in heavy ion and pp collisions [3, 11]. This procedure is summarised and described in more detail in Ref. [10].

The multiplicity measurement was performed using only the pixel detector to maximize the efficiency for reconstructing charged particles with low transverse momenta. Two approaches are used in this analysis. The first is the two-point tracklet method used in heavy ion collision experiments [12]. The second is the use of pixel tracks, which has a smaller acceptance but provides a measurement of the particle p_T . The $dN_{\text{ch}}/d\eta$ measured using pixel tracks is used as a cross-check to that measured using the two-point tracklets, for detailed description see Ref. [9]. The left panel of Figure 1 shows the $dN_{\text{ch}}/d\eta$ divided by the number of participating pairs of nucleons ($\langle N_{\text{part}} \rangle/2$) as a function of $\langle N_{\text{part}} \rangle$, in five η intervals, including the full pseudorapidity interval, $-2.7 < \eta < 2.7$, and the three Glauber model variants. The $dN_{\text{ch}}/d\eta/(\langle N_{\text{part}} \rangle/2)$

Fig. 1. (left) The $dN_{\text{ch}}/d\eta/(\langle N_{\text{part}} \rangle/2)$ as a function of $\langle N_{\text{part}} \rangle$ in several η -regions (taken from Ref. [9]) and (right) the yield of Z bosons per event scaled by the mean number of nucleon-nucleon collisions $\langle N_{\text{coll}} \rangle$ (taken from Ref. [10]) as a function of the mean number of participating nucleons $\langle N_{\text{part}} \rangle$. Each panel uses a different Glauber variant configuration in calculating $\langle N_{\text{part}} \rangle$ (and $\langle N_{\text{coll}} \rangle$); displayed from top to bottom are: the standard Glauber model with no Glauber-Gribov color fluctuations, GGCF with $\omega_{\sigma} = 0.11$, and GGCF $\omega_{\sigma} = 0.2$. Z boson results are compared to the CT10 model prediction plotted at $\langle N_{\text{part}} \rangle = 2$. The bars indicate statistical uncertainty and the shaded boxes systematic uncertainty. The systematic uncertainties are correlated bin-by-bin.

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51 values from the standard Glauber model are approximately constant up to $\langle N_{\text{part}} \rangle \approx 10$ and then increase
 52 for larger $\langle N_{\text{part}} \rangle$. This trend is absent in the Glauber-Gribov model with $\omega_{\sigma} = 0.11$, which shows a rel-
 53 atively constant behaviour for the integrated yield divided by the number of participant pairs. Finally,

the $dN_{\text{ch}}/d\eta/(\langle N_{\text{part}} \rangle/2)$ values from the Glauber-Gribov model with $\omega_{\sigma} = 0.2$ show a slight decrease with $\langle N_{\text{part}} \rangle$ in all η intervals.

In contrast to the $dN_{\text{ch}}/d\eta/(\langle N_{\text{part}} \rangle/2)$ measurement, the Z boson yield divided by $\langle N_{\text{coll}} \rangle$ should be independent of centrality. To investigate this, the per-event yield of Z bosons within $-3 < y_Z^* < 2$, divided by $\langle N_{\text{coll}} \rangle$, is displayed as a function of $\langle N_{\text{part}} \rangle$ in the right panel of Figure 1. For reference, the data are plotted as they would be with no centrality bias correction in the open points, for more details see [10]. The yield is independent of centrality defined using the standard Glauber model. Using the GGCF centrality models increases $\langle N_{\text{coll}} \rangle$ in central events and reduces it in peripheral events, consequently the yield divided by $\langle N_{\text{coll}} \rangle$ is reduced in central events and increased in peripheral events. Finally, the ratio of the Z yield to the charged-particle multiplicity was evaluated for each centrality interval and found to scale as $\langle N_{\text{coll}} \rangle / \langle N_{\text{part}} \rangle = (\langle N_{\text{part}} \rangle - 1) / \langle N_{\text{part}} \rangle$ as expected, demonstrating the consistency of the centrality dependence of hard and soft particle production (for more details, see Ref. [13]).

Measurements of transverse energy production at large rapidity are needed to constrain particle production models, which systematically underpredict the total transverse energy at forward rapidities in hard scattering events [14]. The dependence of single and dijet production in the proton-going direction [3, 4] on the underlying event activity in the Pb-going direction was observed to contradict geometric models of how jet and underlying event production should correlate, giving rise to novel interpretations [15]. More generally, the modification of soft particle production in NN collisions in the presence of a hard process is expected to affect estimates of the collision geometry of p +Pb collisions with a hard scatter [16, 17, 18]. Thus a control experiment in pp collisions which determines how soft particle production at negative pseudorapidities varies with the x in the projectile (target) designated beam-proton headed towards positive (negative) rapidity can provide insight into the relevance of these various scenarios.

The sum of the transverse energy at large pseudorapidity, ΣE_T , is measured in the forward calorimeter $-4.9 < \eta < -3.2$ and corrected for the detector response. In pp collisions the asymmetric choice of the ΣE_T -measuring region means that the target proton plays the role of one of the nucleons in the Pb. The average value, $\langle \Sigma E_T \rangle$, is reported as a function of the average dijet transverse momentum, $p_T^{\text{avg}} = (p_{T,1} + p_{T,2})/2$, and pseudorapidity, $\eta^{\text{dijet}} = (\eta_1 + \eta_2)/2$, where $p_{T,1}$ and η_1 are the transverse momentum and pseudorapidity of the leading (highest- p_T) jet in the event, while $p_{T,2}$ and η_2 are those for the subleading (second highest- p_T) jet. Results are also reported as a function of two kinematic quantities $x_{\text{proj}} = p_T^{\text{avg}}(e^{+\eta_1} + e^{+\eta_2})/\sqrt{s}$ and $x_{\text{targ}} = p_T^{\text{avg}}(e^{-\eta_1} + e^{-\eta_2})/\sqrt{s}$, which in a leading order picture correspond to the Bjorken- x in each proton. Events with two jets were selected, where the transverse momenta of the jets were $p_{T,1} > 50$ GeV, $p_{T,2} > 20$ GeV, and $p_T^{\text{avg}} > 50$ GeV. Both jets were required to have $\eta_{1,2} > -2.8$ to separate them by 0.4 units in pseudorapidity from the ΣE_T -measuring region. Furthermore, the leading jet was also required to have $\eta_1 < 3.2$ to match the acceptance of the central-jet trigger. Fig. 2 shows that $\langle \Sigma E_T \rangle$ decreases in a linear fashion with x_{targ} , but is mostly insensitive to x_{proj} . Since x_{proj} and x_{targ} are generally anti-correlated in dijet events, the data were also analysed by fixing each variable in a narrow range and testing the dependence of $\langle \Sigma E_T \rangle$ on the other, and this gave results quantitatively similar to those in Fig. 2. The MC event generators described in details in Ref. [5] have qualitatively similar behaviour. They describe the x_{proj} dependence well, but PYTHIA 6 and PYTHIA 8 show a slightly stronger dependence on x_{targ} , while HERWIG ++ shows a moderately weaker one. The observed dependence admits a simple interpretation: when the hard scattering involves a parton with large x_{targ} , the beam remnant has less longitudinal energy and transverse energy production at large pseudorapidity downstream of the target nucleon is substantially reduced.

3. Conclusions

This proceedings presents recent ATLAS measurements of the centrality dependence of the charged particle and Z boson production, in p +Pb collisions at a nucleon-nucleon centre-of-mass energy of $\sqrt{s_{NN}} = 5.02$ TeV and the dependence of transverse energy production at large pseudorapidity in pp collisions on hard scattering kinematics.

The $dN_{\text{ch}}/d\eta/(\langle N_{\text{part}} \rangle/2)$ was found to scale with N_{part} . Similarly, the centrality-dependent Z boson yield is found to scale with N_{coll} . Both measurements are sensitive to the Glauber modeling, showing different performance switching from standard Glauber modeling to the Glauber-Gribov approach.

Fig. 2. Measured ratio $E_T / \langle \Sigma E_T \rangle^{\text{ref}}$ in hard-scatter pp collisions, shown as a function of x_{targ} (left) and x_{proj} (right). The shaded bands represent total systematic and statistical uncertainties in the data in quadrature while the vertical bars represent statistical uncertainties only. The bottom panel shows the ratio of the predictions of three MC event generators to the data. Taken from Ref. [5].

Transverse energy production at large pseudorapidity on the hard-scattering kinematics of proton–proton collisions results provide counter-evidence to claims that the observed centrality-dependence of the jet rate in p +Pb collisions simply arises from the suppression of transverse energy production at negative rapidity in the hard-scattered NN sub-collision. In the p +Pb data, the deviations from the expected centrality dependence are observed to depend only on, and increase with, x in the proton. Therefore, for this effect to be consistent with arising from a feature of NN collisions, transverse energy production at small angles should decrease strongly and continuously with increasing x in the proton headed in the opposite direction. The results presented in Ref. [5] do not obviously support such a scenario.

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