Charged particle production in $p$+$Pb$ collisions measured by the ATLAS detector

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Abstract. Per-event charged particle spectra and nuclear modification factors are measured with the ATLAS detector at the LHC in $p$+$Pb$ interactions at $\sqrt{s_{NN}} = 5.02$ TeV. Results are presented as a function of transverse momentum, rapidity, and in different intervals of collision centrality, which is characterised in $p$+$Pb$ collisions by the total transverse energy measured over the pseudorapidity interval $-3.2 < \eta < -4.9$ in the direction of the lead beam. Three different calculations of the number of nucleons participating in $p$+$Pb$ collisions have been performed, assuming the Glauber model and its Glauber-Gribov Colour Fluctuation extensions. The results using different models are compared with each other, as well as with other measurements made under the same conditions and also with centrality definition based on different rapidity intervals.

1. Introduction

Proton-nucleus ($p$+$Pb$) collisions probe the physics of the initial state of ultra-relativistic heavy ion collisions without the effects of thermalization, playing an important role in $Pb$+$Pb$ collisions evolution [1]. $p$+$Pb$ charged hadron spectra of high transverse momentum ($p_T$) can provide insight on the effect of an extended nuclear target on the dynamics of soft and hard scattering processes and subsequent particle production. For an extensive review of predictions see [2].

2. Analysis

For $p$+$Pb$ collisions the expected particle production rate can be quantified using the “nuclear modification factor” which is calculated as the ratio of differential yield of charged particles in $p$+$Pb$ collisions divided by the average value of the nuclear thickness function $\langle T_{Pb} \rangle$ (in units of inverse barns) [3] and differential charged-particle production cross section measured in $pp$ collisions. Differential yield of charged particles can be measured as a function of centrality, $\eta$ and $y^*$, which due to different beam energies has its centre-of-mass system boosted by $-0.465$ [4].

This proceedings presents a measurement of charged-hadron spectra, $R_{pPb}$, as a function of $p_T$ and intervals of collision centrality for $0.5 < p_T < 150$ GeV. The collision centrality is estimated using the sum of transverse energy measured in the ATLAS [5] forward calorimeter, $3.1 < |\eta| < 4.9$, only in the outgoing Pb beam direction for $p$+$Pb$ [3]. The dependence of $p$+$Pb$ collisions on the number of participating nucleons ($N_{part}$) is estimated using two models: the Glauber model [6] and the Glauber-Gribov colour-fluctuation approach [7], with the relative fluctuations determined by the parameter $\Omega$. $pp$ data is recorded by the ATLAS experiment in the 2011 and 2013 physics runs of the LHC at $\sqrt{s} = 2.76$ TeV and $\sqrt{s} = 5.02$ TeV respectively.
The proton-proton data sets used to obtain the reference measurement for \( p+\text{Pb} \) low \( p_T \) results at \( \sqrt{s} = 7 \text{ TeV} \) with total integrated luminosity 130 \( \mu \text{b}^{-1} \) were obtained in April 2010. \( pp \) data at \( \sqrt{s} = 5.02 \text{ TeV} \) recorded in 2015 with an integrated luminosity of 25 \( \text{pb}^{-1} \) is used to obtain the reference with the highest available \( p_T \) values. The events were preselected within the vertex range \( |z_{\text{vtx}}| < 150 \text{ mm} \), and at least one hit in each of the MBTS detectors. In addition, a time difference of less than 10 ns was required between the two MBTS sides.

The events used in this analysis are selected from several triggered samples. Minimum bias (MB) samples were obtained requiring signal in the Minimum Bias Trigger Scintillator. For jet triggered samples, jets were reconstructed in events that passed the MB requirement using the anti-\( \text{kt} \) algorithm [8] with the distance parameter \( R=0.4 \). Events were selected by the jet trigger if they contained jets with \( E_T \) above a certain threshold. Multiple thresholds were defined. Only a fraction of all events which fired a trigger was randomly selected to be recorded for further analysis. This fraction was set differently for each trigger. Total spectra were obtained by merging spectra from MB and jet triggers, all of them scaled by reciprocal of the fraction to obtain MB spectra up to high \( p_T \) [9, 10].

Charge particle tracks are reconstructed in the ATLAS Inner Detector [5]. Tracks are measured using a combination of silicon pixel detector (Pixel), silicon microstrip detector (SCT), and a straw tube transition radiation tracker (TRT), all immersed in a 2 T axial magnetic field. Charged particles typically traverse 3 layers of silicon pixel detectors, 4 layers of double sided microstrip detector, and 36 straws. Each track is required to have at least 1 hit in the Pixel detector, a hit in the innermost layer if such hit is expected by the tracking model, and at least 6 hits in the SCT. Additionally, tracks with \( p_T > 10 \text{ GeV} \) are required to produce at least 8 hits in the TRT. These requirements select tracks with good \( p_T \) resolution and suppress the contribution of poorly reconstructed tracks. Yet they limit the analysis to the coverage of the TRT detector, thus all tracks are selected with \( |\eta| < 2 \). To ensure that the tracks originate from the event vertex of \( \text{Pb}+\text{Pb} \) \( (p+A) \) collisions, the transverse impact parameter, \( d_0 \), and \( z_0 \sin \theta\) (\( z_0 \) is the longitudinal impact parameter) are required to be less than 3 (1.5) mm. Tracks selected for the analysis are also required to satisfy the conditions on the impact parameters significances: \( |d_0/\sigma_{d_0}| < 3 \) and \( |z_0 \sin \theta/\sigma_{z_0 \sin \theta}| < 3 \). The \( d_0 \) and \( z_0 \sin \theta \) parameters and their uncertainties are estimated by a vertex finding algorithm. The jet is reconstructed with a radius parameter of \( \Delta R = 0.4 \) in \( p+\text{Pb} \) and \( pp \) collisions. The track-to-jet matching requirement is applied to all tracks with \( p_T > 15 \text{ GeV} \) in \( p+\text{Pb} \) and \( p_T \leq 1.3 \times p_T^{jet} \) in \( pp \) collisions both in the MB and jet-triggered samples, to reduce the amount of mis-measured tracks at high \( p_T \) and accounting for energy conservation and possible jet energy mismeasurement. The jet trigger with the lowest threshold becomes fully efficient in \( \sqrt{s} = 5.02 \text{ TeV} \) at \( p_T^{jet} = 26 \text{ GeV} \) [10]. Tracks associated with electrons and muons with \( p_T > 10 \text{ GeV} \) coming predominately from electroweak decays are subtracted from the measured spectra. Reconstructed charged particle spectra in different collision systems are corrected for mis-measured tracks and secondary particles, for limited momentum resolution, and for tracking inefficiency. The resulting spectra are unfolded using the iterative Bayesian unfolding [11] to correct for the finite detector \( p_T \) resolution.

In case of low \( p_T \), once the differential \( pp \) cross section at \( \sqrt{s} = 2.76 \text{ and } 7 \text{ TeV} \) have been measured, the differential \( pp \) cross section at \( \sqrt{s_{\text{NN}}} = 5.02 \text{ TeV} \) obtained by interpolation. The interpolation is proportional to \( \ln(\sqrt{s}) \) and it is performed for every \( p_T \) bin in each rapidity interval used in the \( p+\text{Pb} \) analysis [4].

3. Results

The cross sections of charged particle production at \( \sqrt{s} = 5.02 \text{ TeV} \) in \( p+\text{Pb} \) and \( pp \) collisions are presented in figure 1. The \( p+\text{Pb} \) spectra are scaled by \( \langle T_{p\text{Pb}} \rangle \) using the standard Glauber model. The \( pp \) spectra are presented in the same \( p_T \) and \( y \) ranges as were the \( p+\text{Pb} \) results in [9].
Figure 1. Invariant charged particle yields measured in three centrality intervals 0-10%, 20-30% and 60-90% as a function of $p_T$ integrated over $-1.5 < y^* < 2$ [10]. Statistical errors are indicated with vertical lines and the systematic uncertainties on the invariant yields are indicated by boxes of the same colour.

Figure 2 shows $R_{pPb}$ in three different centrality intervals and for the rapidity interval $-2 < y^* < 1.5$. The nuclear modification factors increase with momentum in the region $0.1 < p_T < 2$ GeV, then reach a maximum and decrease up to $p_T \approx 8$ GeV. Above that momentum the nuclear modification factor is constant within the experimental uncertainties. While the central interval $0 - 10\%$ shows an increase toward lower $p_T$, the peripheral interval shows a decrease. The low $p_T$ behavior is consistent with previous ATLAS measurements [4]. The magnitude of the peak strongly depends both on rapidity and centrality. It increases from peripheral to the central collisions and from the proton beam direction to the Pb beam direction [4]. The choice of the different geometrical model strongly affects the level of the plateau in the central events and its magnitude with respect to peripheral. Higher $p_T$ ranges have been also measured, showing a clear trend of increasing enhancement towards higher $p_T$. This trend does not have a strong rapidity dependence but is more marked in peripheral events [9]. The results for high $p_T$ measurement do not show the same trend at high $p_T$ as was observed by the CMS collaboration [12] and support the results of the the ALICE collaboration [13].

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Figure 2. Nuclear modification factor $R_{pPb}$ measured in three centrality intervals 0-10%, 20-30% and 60-90%. Statistical uncertainties are shown with vertical lines and brackets represent systematic uncertainties, with an exception of the fully correlated systematic uncertainties that are shown with the gray bands around unity. Statistical errors are indicated with vertical lines and the systematic uncertainties on the invariant yields are indicated by boxes of the same colour. The result of this analysis is compared to that of the previous analysis [4] with used an interpolation method for deriving the pp spectra at $\sqrt{s} = 5.02$ TeV.
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