

MEASUREMENT OF HARD PROBES IN p +Pb AND Pb+Pb COLLISIONS WITH THE ATLAS DETECTOR*

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Recent measurements from the ATLAS experiment of high- p_T processes in relativistic proton–lead and lead–lead interactions at the Large Hadron Collider (LHC) are presented. In particular, the inclusive jet production results are reviewed including the centrality dependence of the jet nuclear modification factors (NMF) for p +Pb and Pb+Pb collisions at energies of $\sqrt{s_{NN}} = 5.02$ TeV and 2.76 TeV, respectively. Additionally, recent results on the electroweak boson rates in Pb+Pb collisions are presented and compared to the theoretical model predictions. The hard probe measurements provide important information on the initial conditions as well as on the properties of the dense medium created in heavy ion collisions.

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1. Introduction

The high- p_T observables have become one of the main probes of the quark–gluon plasma (QGP) since the first measurements at the Relativistic Heavy Ion Collider (RHIC) [1] and continue to play a crucial role in studies of nuclear interactions at the LHC [2]. Particularly important is the production of jets originating from hard scattered partons which is strongly suppressed in the dense medium created in heavy ion collisions. The jet suppression phenomenon, called also jet quenching, is expected to be sensitive to in-medium partonic energy losses during the early parton shower development, thus providing access into the properties of QGP. On the other hand, the

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QGP is expected to be transparent to the electromagnetic and weakly interacting particles. Thus, the high- p_T electroweak observables (like photons, Z and W boson yields) can probe the initial state effects in nuclear interactions, such as parton shadowing, as well as they can be used to calibrate hard scattering rates involving jets.

ATLAS [3] has an excellent capability to measure hard probes in heavy ion collisions. In the innermost part of ATLAS, the tracking system of charged particles is located, consisting of the silicon pixel detector, semiconductor microstrip tracker (SCT) and transition radiation tracker (TRT), covering wide pseudorapidity range ($|\eta| < 2.5$ for the silicon detectors and $|\eta| < 2$ for TRT) and equipped with a 2 T axial magnetic field. The inner detectors are surrounded by electromagnetic and hadronic calorimeters also covering large pseudorapidity range of $|\eta| < 4.9$, which can trigger on and precisely measure jets, photons and electrons. The outer layer of the ATLAS detector comprises the muon spectrometer which serves both as a trigger system and as an excellent detector to measure muons within pseudorapidity range $|\eta| < 2.7$. The muon spectrometer is immersed in a toroidal magnetic field generated by three superconducting magnet systems. In heavy ion collisions, the total transverse energy detected by the forward calorimeters (FCal), located in the pseudorapidity range of $3.1 < |\eta| < 4.9$ is also used to estimate the collision centrality, both in p +Pb and Pb+Pb interactions.

For the hard probe measurements presented in this paper, the Pb+Pb data of integrated luminosity $L_{\text{int}} \approx 0.17 \text{ nb}^{-1}$ was used, from the LHC 2011 physics run during which lead ions were collided at energy of $\sqrt{s_{NN}} = 2.76 \text{ TeV}$ and additionally, for the study of jets the p +Pb data was also analysed of $L_{\text{int}} \approx 31 \text{ nb}^{-1}$ from the 2013 LHC run when protons and lead ions were collided at energy of $\sqrt{s_{NN}} = 5.02 \text{ TeV}$.

2. Electroweak probes in Pb+Pb collisions

Recently, the W boson rates were measured in the muon channel in Pb+Pb collisions [4]. The muon candidates are reconstructed as a combined inner detector and muon spectrometer tracks using the χ^2 minimization procedure. The W boson candidates are reconstructed from muon and neutrino of transverse momenta above 25 GeV. The neutrino transverse momentum is estimated by the missing transverse momentum obtained from all charged tracks reconstructed in the inner tracking detector for each event. A sample of W boson candidates with $m_T^W > 40 \text{ GeV}$ was obtained with the estimated background level of about 7%. Figure 1 shows the background-, acceptance- and efficiency-corrected rates scaled by the mean number of binary nucleon-nucleon collisions, $\langle N_{\text{coll}} \rangle$, of positively and negatively charged W bosons as

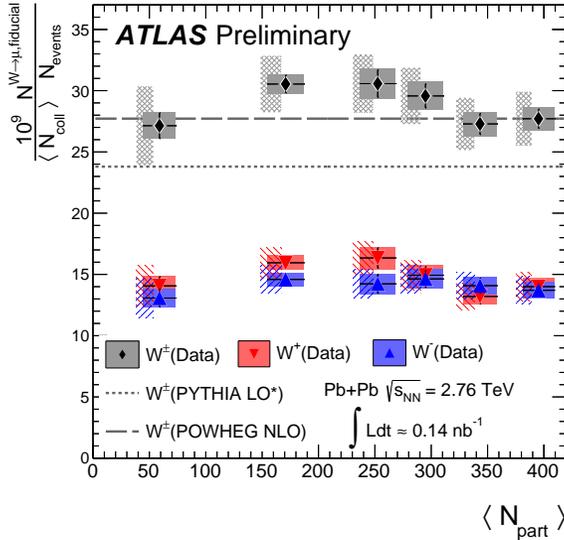


Fig. 1. W boson production yield per binary collision as a function of the mean number of participants $\langle N_{\text{part}} \rangle$ for W^+ , W^- , and W^\pm in $\sqrt{s_{NN}} = 2.76$ TeV $Pb+Pb$ collisions [4]. Also shown are LO* [5] and NLO [6] predictions.

well as their sum, as a function of centrality expressed by the mean number of participating nucleons, $\langle N_{\text{part}} \rangle$. It can be seen that there is no centrality dependence of the scaled rates and the W rates are in agreement with predictions based on the modified leading-order and next-to-leading-order calculations using the MRSTLO* [5] and MSTW2008NLO [6] parton distribution functions, respectively. Another electroweak probe not expected to be modified in the dense and hot medium is the yield of Z bosons. In the ATLAS detector, the Z boson rate has been measured using the 2011 $Pb+Pb$ sample [7] and adopting reconstructed Z candidates for the $Z \rightarrow e^+e^-$ and $Z \rightarrow \mu^+\mu^-$ channels. The level of background events was estimated to be 5% and 1% for the di-electron and di-muon channels, respectively. The corrected p_T spectra of Z bosons, combined from the two decay channels, are shown in five centrality classes in Fig. 2 (left panel). The spectra are compared to Pythia yields normalized to the NNLO $p+p$ cross section [8] and scaled by the average nuclear thickness function $\langle T_{AA} \rangle$. As one can see, the Z boson p_T spectra are in agreement with Pythia predictions.

The ATLAS detector has also excellent capability to measure high- p_T , isolated prompt photons, an electromagnetic probe also expected not to be modified via the dense medium. Photons are reconstructed in ATLAS [9] using the large-acceptance, longitudinally segmented ATLAS electromagnetic calorimeter, after subtracting the contribution from underlying background, done on an event-by-event basis. Figure 2 shows the measured yield

of prompt photons in lead–lead collisions in a kinematic range of photon $p_T = 45\text{--}200$ GeV and $|\eta| < 1.3$, in four ranges of collision centrality. It is observed in Fig. 2 that after scaling by the mean nuclear thickness $\langle T_{AA} \rangle$ the measured photon yields are in a good agreement with the next-to-leading order pQCD calculations, as implemented in JETPHOX [10], implying a simple linear scaling of the high- p_T photon production in Pb+Pb collisions with the number of binary nucleon–nucleon collisions.

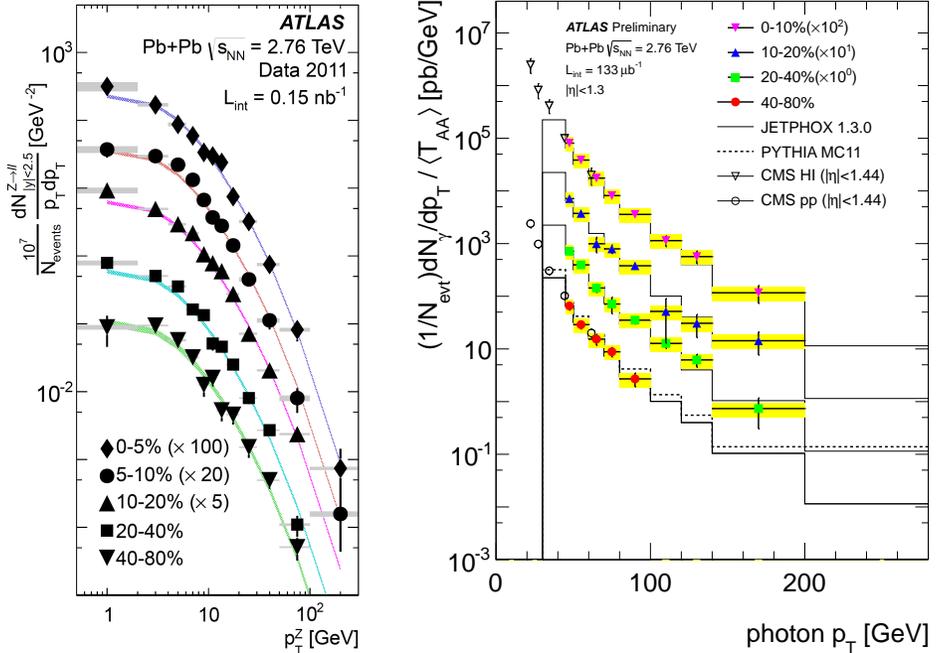


Fig. 2. Left: The p_T^Z spectra of measured Z bosons in five centrality classes in $\sqrt{s_{NN}} = 2.76$ TeV Pb+Pb collisions [7]. The data are compared to Pythia simulation normalized to the NNLO $p + p$ cross section, scaled by $\langle T_{AA} \rangle$ [8]. Right: Efficiency corrected yields of prompt photons in $|\eta| < 1.3$ using isolation cone radius $R_{\text{iso}} = 0.3$ and isolation energy of 6 GeV [9]. For comparison, also included are CMS Pb+Pb and $p + p$ data [10].

3. Jets in Pb+Pb collisions

In contrary to the electroweak probes, it is expected that interactions of hard-scattered partons with the hot and dense medium can lead to a strong suppression of high- p_T jet yields in nuclear collisions when compared to the yields in $p+p$ collisions scaled by the number of binary nucleon–nucleon interactions. Observations of the strong high- p_T suppression of charged hadrons

in nuclear collisions at the RHIC and LHC energies is a direct signature of a new state of matter with partonic energy losses much larger than those in the cold hadronic matter. At the LHC, lead ions collide at energy 2.76 TeV, which is 14 times higher than the energy of Au+Au interactions at RHIC. Due to the extended kinematic reach and excellent calorimetry jets are clearly visible in heavy ion collisions at the LHC and their properties have been extensively studied since the first ATLAS publication [2]. In the presented analysis, jets are reconstructed using anti- k_t algorithm with jet size parameter $R = 0.4$. A special procedure to subtract the heavy-ion underlying event was applied on an event-by-event basis [11]. The jet quenching phenomenon in Pb+Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV is studied via the measurement of the nuclear modification factor

$$R_{CP} = \frac{N_{\text{coll}}^{\text{peripheral}}}{N_{\text{coll}}^{\text{central}}} \frac{dN_{\text{Pb+Pb}}^{\text{central}}/dp_T}{dN_{\text{Pb+Pb}}^{\text{peripheral}}/dp_T}, \quad (1)$$

where the reference spectrum $dN_{\text{Pb+Pb}}^{\text{peripheral}}/dp_T$ is the jet p_T spectrum for the 60–80% peripheral Pb+Pb collisions, while $dN_{\text{Pb+Pb}}^{\text{central}}/dp_T$ represents spectra for more central bins (see Fig. 3). It can be seen in Fig. 3 that for each

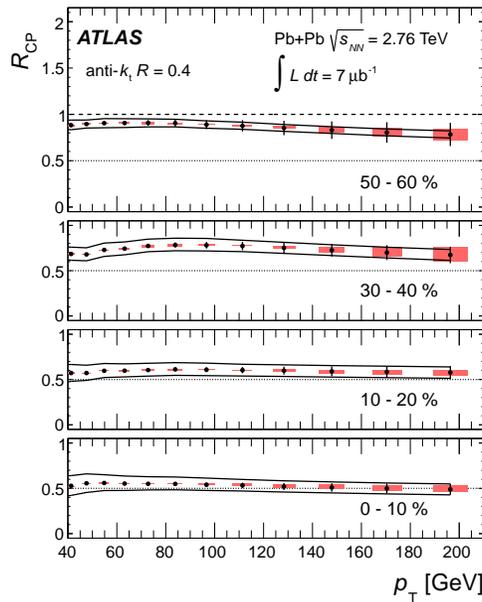


Fig. 3. The nuclear modification factor R_{CP} as a function of jet p_T for $R = 0.4$ anti- k_t jets in four centrality bins of $\sqrt{s_{NN}} = 2.76$ TeV Pb+Pb collisions [11]. Dotted lines indicate $R_{CP} = 0.5$, and the dashed line at the top panel indicates $R_{CP} = 1$.

centrality bin R_{CP} weakly depends on the jet transverse momentum being close to 1 in the most peripheral collisions (approximate N_{coll} scaling) and ≈ 0.5 for the most central collisions. This strong suppression of jet yields in central collisions is also illustrated in Fig. 4 where the nuclear modification factor R_{CP} is shown as a function of centrality expressed via the number of participating nucleons $\langle N_{part} \rangle$ in six jet transverse momentum intervals covering the p_T range from 38 GeV to 182 GeV. It is observed in this figure that in each p_T range, R_{CP} drops from about 0.9 to 0.5 for $\langle N_{part} \rangle$ increasing from peripheral to the most central collisions.

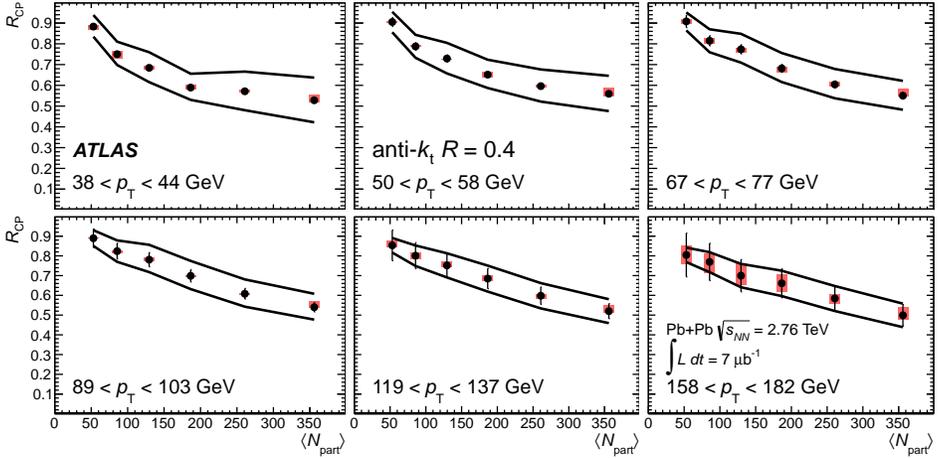


Fig. 4. The nuclear modification factor R_{CP} in $\sqrt{s_{NN}} = 2.76$ TeV Pb+Pb collisions as a function of $\langle N_{part} \rangle$ for $R = 0.4$ anti- k_t jets in six p_T bins [11].

4. Jets in p +Pb collisions

The recent LHC data on proton–lead collisions provide a unique opportunity to study cold nuclear matter effects, thus serving as a control experiment to the Pb+Pb measurements. With the new data, ATLAS has obtained results on jet yields using the same jet reconstruction algorithm as for Pb+Pb collisions [12]. It turned out that particularly interesting is the jet production in the proton-going direction, *i.e.* in the kinematic range of low Bjorken x of partons from lead ions where effects such as saturation of the partonic distributions might be present [13]. To study the jet production, first the nuclear modification factor was measured inclusively for p +Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV. The result is shown in Fig. 5 as a function of p_T in four different y^* rapidity ranges, where y^* is the jet centre-of-mass

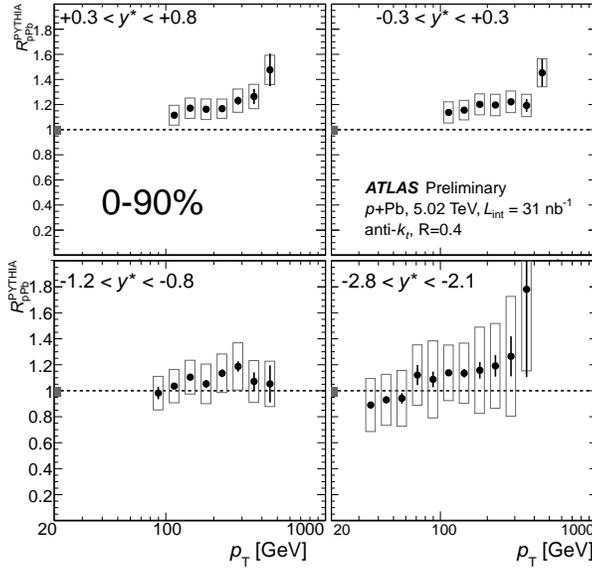


Fig. 5. R_{pPb}^{Pythia} for $R = 0.4$ jets in $\sqrt{s_{NN}} = 5.02$ TeV $p+Pb$ collisions for 0–90% centrality bin. Each panel shows the R_{pPb}^{Pythia} in a different centre-of-mass jet rapidity bin.

rapidity¹. For the NMF measurement as a reference the Pythia truth jet spectrum was used. It can be seen that in each rapidity range $R_{pPb}^{\text{Pythia}} \approx 1$ indicating an approximate N_{coll} scaling. The nuclear modification factor R_{CP} was also obtained in different centrality bins taking as a reference the jet yield for peripheral $p+Pb$ collisions with centrality 60–90%. In Fig. 6 R_{CP} is shown as a function of p_T for the 10% most central $p+Pb$ collisions (top-left panel) as well as for less central one, 30–40%, (bottom-left panel). For each centrality, R_{CP} is presented in six jet rapidity ranges, covering the proton-going direction, $-4.4 < y^* < -0.3$. Figure 6 also shows that in the most central collisions significant jet suppression is observed at high p_T and the suppression increases with p_T and towards forward rapidity regions. It is interesting to re-plot the nuclear modification factor R_{CP} as a function of the total jet momentum, $p_T \cosh(y^*)$. The corresponding NMF is shown in Fig. 6 (right panels). It can be observed that the same jet yields are measured for a given total jet momentum in different rapidity ranges.

¹ At the LHC in $p+Pb$ interaction at energies of $\sqrt{s_{NN}} = 5.02$ TeV, protons of energy 4 TeV were collided with lead ions of energy 1.57 TeV. This energy asymmetry results in a relative rapidity shift between the centre-of-mass and rest frames of $\Delta y = \pm 0.47$. In this analysis, proton-going direction is defined at $y^* < 0$.

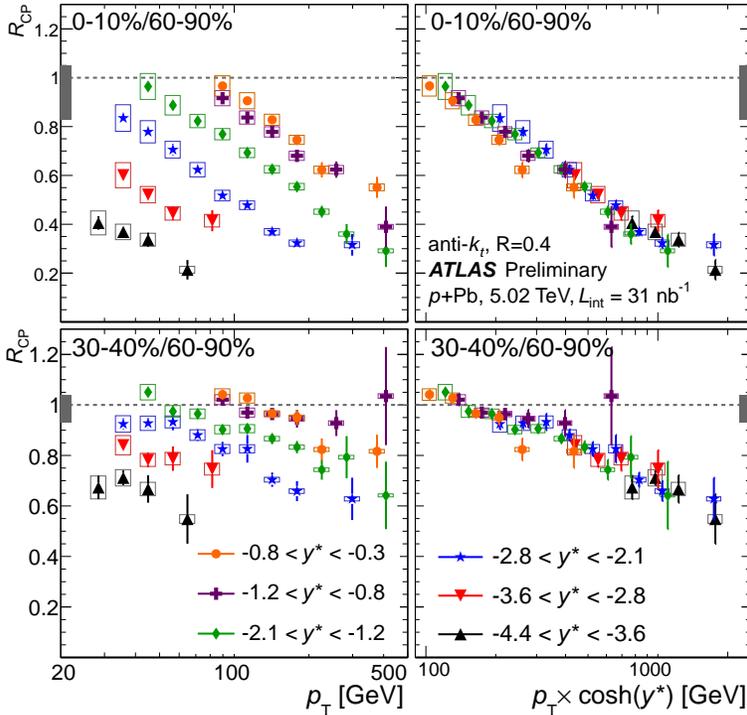


Fig. 6. R_{CP} for $R = 0.4$ jets in $\sqrt{s_{NN}} = 5.02$ TeV $p+Pb$ collisions [12]. The top row shows the R_{CP} for 0–10%/60–90% and the bottom row shows the R_{CP} for 30–40%/60–90%. In the left column, the R_{CP} is plotted as a function of jet p_T . In the right column, the R_{CP} is plotted against the jet momentum, $p_T \cosh(y^*)$.

5. Summary

The outstanding performance of the ATLAS detector during the LHC 2.76 TeV Pb+Pb and 5.02 TeV $p+Pb$ runs allowed for determination of several high- p_T probes providing insight into the hot and dense medium created in heavy ion collisions. The results on the electroweak probes are found to be consistent with the expectations that the medium is transparent to the high- p_T photons, W and Z bosons created in the early stage of nuclear collisions. The boson yields in different Pb+Pb centrality classes are consistent with the pQCD predictions for proton–proton production scaled by the mean number of binary nucleon–nucleon interactions, $\langle N_{coll} \rangle$. On the other hand, colour sensitive probes such as jets are strongly suppressed in central Pb+Pb collisions, providing direct insight on the properties of the quark–gluon plasma.

Results on the jet nuclear modification factor R_{CP} in $p+Pb$ collisions indicate a strong, centrality-dependent reduction in the yield of jets in central collisions relative to that in peripheral collisions. In addition, when the data are re-plotted as a function of $p_T \cosh(y^*)$, the results from different rapidity bins fall into roughly a single trend suggesting that the mechanism responsible for the observed effects depends on the total jet momentum.

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