Recent results on hard processes in $p+$Pb, Pb+Pb, and $pp$ collisions from the ATLAS Experiment at the LHC

Laura Havener on behalf of the ATLAS collaboration
Physics Department, Columbia University, New York, NY 10027 USA
E-mail: lbh3133@columbia.edu

Abstract. In relativistic heavy–ion collisions, a hot medium with a high density of unscreened colour charges is produced. Hard processes from parton–parton scattering in the early stages of the collision can be used as probes of the medium since the initial state is mostly understood such that differences from $pp$ collisions in the final state can be attributed to interactions with the medium. The initial and final state effects are separated by comparing $p+$Pb and $pp$ collisions. Recent results from the ATLAS experiment at the LHC on the production of electroweak bosons, jets, and quarkonia are discussed in $p+$Pb and Pb+Pb collisions, compared to $pp$. Recent results on ultra–peripheral collisions are also shown.

1. Introduction
In relativistic heavy–ion (HI) collisions, a hot dense medium with a high density of unscreened colour charges is produced, called quark–gluon plasma (QGP) [1]. Hard processes from parton–parton scattering are produced in the early stages of the collision. The initial state of these processes are mostly understood when considering cold nuclear matter (CNM) effects. Thus products from hard interactions can be used as probes of the medium since differences from $pp$ collisions in the final state can be attributed to interactions with the medium. The initial state effects, like CNM, can be separated out by using $p+$Pb collisions and comparing to $pp$ collisions. Recent hard probes results using the ATLAS detector [2] at the LHC, including electroweak bosons, quarkonia, jets, and charged hadrons, in Pb+Pb, $p+$Pb, and $pp$ at $\sqrt{s_{NN}} = 2.76$ TeV and 5.02 TeV are presented in this proceeding.

2. Electroweak bosons
Electroweak bosons, like photons, Z, and W bosons, are treated as controls in HI collisions. As they are colorless and do not interact with the medium, there should be no modification to their production rates. They are useful for verifying that we understand the nuclear geometry of the collision. The production of Z bosons in the di-muon decay channel is measured in 5.02 TeV Pb+Pb and $pp$ data. Z boson candidates from pairs of oppositely charged muons are used to calculate the Z boson rate in Pb+Pb and $pp$. The rates are compared through the nuclear modification factor, $R_{AA}$, defined below:
where $T_{AA}$ is the nuclear thickness function which accounts for the geometric enhancement of per-collision nucleon-nucleon luminosity to allow for a proper assessment of the quenching effects [3] and $N_{\text{evt}}$ is the total number of Pb+Pb collisions within a chosen centrality interval.

The Z boson $R_{AA}$ as a function of $N_{\text{part}}$ is shown in the bottom panel of figure 1. It is consistent with unity and has no dependence on $N_{\text{part}}$ which indicates that the $T_{AA}$ factor is under control since no modification is expected in the medium [6]. The same analysis is performed in $p$+Pb collisions and the $R_{p\text{Pb}}$, defined in equation 2, is evaluated as a function of the Z boson rapidity, $y$, in the right-hand side of figure 1. This shows a slight forward-backward asymmetry that is consistent with nPDF (nuclear parton distribution function) effects [7].

$$R_{p\text{Pb}} = \frac{1}{A_{\text{Pb}}} \frac{d\sigma_{p\text{Pb}}/dy}{d\sigma_{pp}/dy}$$ (2)

![Figure 1](image1.png)

**Figure 1.** The left top panel shows the Z-boson yield in Pb+Pb collisions divided by $T_{AA}$ (circles) as a function of $N_{\text{part}}$ and the cross section for $pp$ collisions at $N_{\text{part}} = 2$ (diamond). The bottom panel shows the $R_{AA}$ as a function of $N_{\text{part}}$ [6]. The right panel shows the $R_{p\text{Pb}}$ as a function of Z boson rapidity. The blue line is simulation (see reference) [7].

The production of W bosons in the $W \rightarrow \mu \nu$ channel is measured in 5.02 TeV Pb+Pb data. The yields of positively and negatively charged muons are shown in the left panel in figure 2 as a function of $N_{\text{part}}$ and scaled by $T_{AA}$. Both are independent of $N_{\text{part}}$ which is excepted since W bosons should not interact with the medium. The $W^+$ yield is 10% higher than the $W^-$ yield which is consistent with the MC simulation. The right panel shows the muon asymmetry as a function of $|\eta_{\mu}|$, which is described well by the MC simulation [8].

3. Jets

Jets originate from partons that are expected to lose energy in interactions with the medium through a phenomena called ‘jet quenching’ [9, 10]. Recent results from ATLAS are more precise with better control over the systematic and the background subtraction due to the underlying event. They are unfolded for detector effects which enables direct theory comparisons. They have better statistics that allow for measurements at high jet $p_T$ and differentially in rapidity and jet $p_T$, as well as measurements of boson+jet systems.
Figure 2. The left panel shows the W boson yields divided by $T_{AA}$ as a function of $N_{\text{part}}$ for $W^+$ (circles) and $W$ (squares). The MC simulation (see reference) is in the dashed lines. The right panel shows the muon charge asymmetry in 0–80% centrality range as a function of $\eta$. Theory predictions (see reference) are indicated with the markers shifted along the x-axis [8].

Figure 3. The left panel shows the $R_{AA}$ as a function of jet $p_T$ for jets for three centrality intervals. The right panel shows the ratio of the $R_{AA}(|y|)$ to the $R_{AA}(|y| < 0.3)$ for jets in 0-10% centrality in different $p_T$ intervals [11].

3.1. Jet suppression

The jet yield is expected to be suppressed in central collisions relative to $pp$ collisions at fixed $p_T$ in HI collisions due to in-medium energy loss. This section describes new measurements of jet yields in Pb+Pb and $pp$ data collected at 5.02 TeV. The individual jet spectra and cross sections are unfolded to correct for bin migration due to experimental effects [4, 5]. The $R_{AA}$, defined in a similar way as in equation 1, as function of $p_T$ is shown in figure 3 in different centrality intervals. The $R_{AA}$ is less than 1 for all centralities, but it is lower in more central collision, where it is around 0.5, than in peripheral collisions. The rapidity dependence of the $R_{AA}$ is shown in Figure 3 by evaluating the ratio of the $R_{AA}(|y|)$ to the $R_{AA}$ at $|y| < 0.3$ in intervals of $p_T$. The ratio is flat at lower $p_T$, but as the $p_T$ is increased the $R_{AA}$ starts to decrease with rapidity. This decrease is the most significant in the highest $p_T$ interval [11].
3.2. Jet imbalance
Dijets are an effective probe of jet quenching because jets originating from the same hard scattering can lose different amounts of energy as they traverse the medium whereas in \( pp \) collisions the jets are expected to be balanced. This section presents a new measurement of the dijet asymmetry in Pb+Pb and \( pp \) collisions at 2.76 TeV using the observable \( x_3 = p_{T1}/p_{T2} \) that has been fully corrected for detector effects by unfolding in 2D in the two jet’s \( p_T \) [4, 5].

The left panels in figure 4 show the centrality dependence of \( x_3 \), which demonstrates that as more central collisions are probed the dijets become more asymmetric. The most probable configuration for \( pp \) is 1, whereas for central Pb+Pb it is 0.5. The right panels show the leading jet \( p_{T1} \) dependence in 0–10% centrality, where a drastic \( p_{T1} \) dependence is observed in which the Pb+Pb become like the \( pp \) at higher \( p_{T1} \) [12].

![Figure 4. Distributions of \( \frac{1}{N} \frac{dN}{dx_3} \) in Pb+Pb and \( pp \) collisions for 100 < \( p_{T1} \) < 126 GeV for different centralities (left six panels) and for 0-10% centrality for different \( p_{T1} \) intervals (right four panels) [12].](image)

Photons are not strongly interacting so are unmodified by the medium produced in HI collisions. Thus measuring \( \gamma+ \)jets in HI collisions allow for an estimate of the energy of the original parton before it loses energy in the medium. Also, \( \gamma+ \)jets are more likely to originate from quarks than dijets so can help constrain the flavor dependence of energy loss. This section presents a measurement of \( \gamma+ \)jet correlations in Pb+Pb and \( pp \) collisions at 5.02 TeV using the observable \( x_3 = p_{T1}^{\text{jet}}/p_{T1}^{\gamma} \). The distributions for 0-10% Pb+Pb, \( pp \), and MC simulations are shown in figure 5. The Pb+Pb has more asymmetric pairs than in MC and \( pp \) [13].

3.3. Jet fragmentation
The internal structure of jets is expected to be modified in Pb+Pb collisions compared to \( pp \) collisions. This section describes a new measurement of the jet fragmentation functions (FF) in Pb+Pb, \( p+ \)Pb, and \( pp \) collisions at 5.02 TeV. The \( p+ \)Pb results help determine if there are modifications in the jet FF due to the presence of a large nucleus. The FF are defined as:

\[
D(z) = \frac{1}{N_{\text{jet}}} \frac{dN_{\text{ch}}}{dz},
\]  

(3)
Figure 5. Distributions of $\frac{1}{N_{\text{ch}}} \frac{dN_{\gamma}}{dx_{\gamma}}$ for 0-10% Pb+Pb data (black circles), $pp$ (white boxes), and MC (shaded yellow) in different $p_T$ intervals [13].

where $N_{\text{ch}}$ is the number of charged particles associated with the jet, $N_{\text{jet}}$ is the number of jets, and $z = p_T^{\text{jet}} \cos \Delta R/p_T^{\text{jet}}$, where $\Delta R = \sqrt{\Delta \eta^2 + \Delta \phi^2}$. The FF are then compared between Pb+Pb or p+Pb and $pp$ collisions using the ratio $R_{D(z)} = D(z)_{\text{PbPb}} / D(z)_{pp}$.

The FF in Pb+Pb data are measured for a jet $p_T$ range of 126-501 GeV and are corrected for detector effects using 2D unfolding in jet $p_T$ and track $z$ [4, 5]. The left panel of figure 6 shows that the $R_{D(z)}$ is consistent for three jet $p_T$ intervals for $z \gtrsim 0.3$ which indicates that the enhancement of hard fragments is nearly independent of jet $p_T$. The right panel shows the $R_{D(z)}$ for a jet $p_T$ range 126-158 GeV for this measurement and a previous measurement at 2.76 TeV. An enhancement at low $z$ and high $z$, with a suppression in between is shown. The low and mid $z$ behavior are indicative of jet internal structure modification where the energy loss is transferred into soft particles inside and near the jet. The high $z$ enhancement could be explained by differences in expected energy loss for quark and gluon jets since there are more quark jets at higher $z$ and quark jets are expected to lose less energy than gluon jets [14]. The modification of the jet internal structure is shown to be similar between the two center-of-mass energies [16].

Figure 6. The left-most panel shows the $R_{D(z)}$ for different $p_T^{\text{jet}}$ intervals in 0–10% centrality. The left center panel shows the $R_{D(z)}$ for 126 < $p_T^{\text{jet}}$ < 158 GeV at 5.02 TeV (black circles) compared to 2.76 TeV (open squares) [16]. The right center panel shows the $R_{D(z)}$ ratios for 0–30% $\gamma$-tagged (red circles) and 0–10% inclusive jets (black squares). The right-most panel shows the $R_{D(z)}$ ratios for 30–80% $\gamma$-tagged (red circles) and 30–40% inclusive jets (black squares) [18].

The FF are also measured for $p+\text{Pb}$ collisions for a jet $p_T$ range is 45-260 GeV. The $R_{D(z)}$ are shown in figure 7 in six different jet $p_T$ intervals. The ratios are consistent with unity which indicates no evidence for modification of the jet internal structure in $p+\text{Pb}$ collisions [15].

The internal structure of $\gamma$-tagged jets should also be modified by the medium but in a potentially different way than inclusive jets for the reasons mentioned in section 3.2. Also, inclusive jets have already been quenched making them an indirect comparison to jets in $pp$.
collisions. They also preferentially select jets that have been less quenched [14, 17]. The photon is not expected to be quenched so comparing $\gamma$-tagged jets in $pp$ and Pb+Pb collisions is a more direct comparison of the same jets. This section describes a measurement of $\gamma$-tagged jet FF in Pb+Pb collisions at 5.02 TeV. They are measured by selecting a photon with $E_T^\gamma$ between 79.6-126 GeV that is azimuthally balanced to a jet with $p_T$ between 63.1-144 GeV. The $R_{D(z)}$ are shown in the right panels of figure 6 compared between the $\gamma$-tagged and inclusive jets in central and peripheral collisions. The $\gamma$-tagged jets have a stronger modification than the inclusive jets in central collisions and become in better agreement in more peripheral collisions [18].

4. Quarkonia

Color charge screening is where bound quarkonia states screen themselves from the medium produced in HI collisions [19]. Eventually they will break apart, leading to a suppression of bound states. The more loosely bound the state, the easier it is to break up (melt) and the stronger the suppression at a fixed temperature. This is called sequential melting which can probe the temperature of the medium since different states will melt at different temperatures.

$J/\psi \rightarrow \mu^+\mu^-$ and $\psi(2S) \rightarrow \mu^+\mu^-$ charmonia production are measured in Pb+Pb and $pp$ at 5.02 TeV. Both the “prompt $J/\psi$”, from the immediate formation of the composite $c\bar{c}$ bound state, and the “non-prompt $J/\psi$”, from the decay of b-quarks, are measured. The prompt can study sequential melting and the non-prompt can study b-quark suppression [20]. The left panels of figure 8 shows the $R_{AA}$ as a function of $p_T$ for prompt $J/\psi$ on the left and non-prompt $J/\psi$ on the right. The ratio of the $R_{AA}$ for $\psi(2S)$ to $J/\psi (\psi(2S)/J/\psi)$ is evaluated in the right panels of figure 8. For prompt the ratio is less than unity indicating that the $\psi(2S)$ are more suppressed than the $J/\psi$. For non-prompt the ratio is consistent with unity, which is expected since b-quark quenching should be the same regardless of which charmonia state forms [21].

$J/\psi \rightarrow \mu^+\mu^-$ and $\psi(2S) \rightarrow \mu^+\mu^-$ charmonia production are also measured in the $p+Pb$ data at 5.02 TeV to look for CNM effects. The $R_{pPb}$ as a function of $p_T$ for prompt $J/\psi$, shown is the left panel of figure 9, is consistent with unity indicating no CNM effects. The right hand panel of figure 9 shows the ratio of the $R_{pPb}$ for $\psi(2S)$ and $J/\psi (\psi(2S)/J/\psi)$ as function of $y^*$ which decrease slightly with rapidity [22].

5. Ultra-peripheral collisions

HI collisions are an intense source of photons in ultra-peripheral collisions (UPC) allowing both photo-nuclear dijet production and light-by-light (LbyL) scattering. In HI UPC events, where strong interactions do not play a role, the large electromagnetic field strengths, which scale with $Z^2$, allows for LbyL scattering ($\gamma\gamma \rightarrow \gamma\gamma$) [23, 24, 25]. A measurement of the cross section for LbyL scattering in UPC events in Pb+Pb data at 5.02 TeV is shown in the left panel of figure 10.
The excess in the data is consistent with MC predictions of LbyL scattering. The cross section is measured to be 70±24 (stat.)±17 (syst.) nb, which is consistent with predicted values [26].

Photo-nuclear dijets in UPC events can study the nPDF at low x [27]. These events are found by looking for a rapidity gap in the main detector since no significant particle production in the rapidity region between the dijet system and the nucleus is expected. Also, zero neutrons in the ATLAS zero degree calorimeters (ZDC) on one side and one or more neutrons on the other side is required because the photon breaks up one nucleus while the other stays intact. A measurement of the cross section for photo-nuclear jet production in UPC events in Pb+Pb data at 5.02 TeV is shown in the right panel of figure 10 as a function of $x_A = (m_{jets}/\sqrt{s})e^{-y_{jets}}$, where $m_{jets}$ and $y_{jets}$ are the combined mass and rapidity of all the jets in the event. It is shown in $H_T = \Sigma_i p_{Ti}$ intervals, where $i$ runs over all the measured jets in an event. It is compared to PYTHIA+STARLIGHT [28] and is shown to be mostly consistent [29].

6. Conclusion
A variety of new measurements from ATLAS at the LHC in Pb+Pb, p+Pb, and pp collisions have been shown. Measurements of EW bosons show no effect from the medium in Pb+Pb collisions thus indicating an understanding of the nuclear geometry. Measurements of jets show jet suppression up to a TeV in energy, jet imbalance in both photon+jet and dijet systems, and modifications of the jet internal structure in both photon+jets and inclusive jets. $J/\psi$ and $\psi(2S)$ production show evidence of sequential melting. Finally, new data from UPC collisions allow for direct photon and photo-nuclear production measurements.
Figure 10. The left panel shows the diphoton invariant mass distribution for the data (points) and MC predictions (histograms, see reference) [26]. The right panel shows the photo-nuclear jet double–differential cross-section for as a function of $x_A$ for different intervals of $H_T$ compared to Pythia+STARlight [28] (dashed lines) [29].

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