Hard Probes at ATLAS

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The ATLAS collaboration has measured several hard probe observables in Pb+Pb and p+Pb collisions at the LHC. These measurements include jets which show modification in the hot dense medium of heavy ion collisions as well as color neutral electro-weak bosons. Together, they elucidate the nature of heavy ion collisions.

1 Introduction

The ATLAS collaboration has measured a wide range of hard probes in Pb+Pb collisions at √sNN = 2.76 TeV, as well as in p+Pb collisions at √sNN = 5.02 TeV. Using 0.15 nb⁻¹ of Pb+Pb collisions from the 2011 LHC run, ATLAS has measured inclusive charged hadrons, jets, photons, W bosons, and Z bosons. From a short pilot p+Pb run in 2012, inclusive charged particles have been measured, as well as jets from approximately 30 nb⁻¹ of p+Pb collisions in the 2013 LHC run. Taken together these observables provide significant insight into the physics of heavy-ion collisions. In particular, the detailed measurement of jet properties in Pb+Pb collisions elucidates the phenomena of energy loss in the strongly-coupled quark gluon plasma (QGP). This is complemented by the measurement of electro-weak bosons which do not interact with the QGP and thus may function as 'standard candles' with regards to energy loss. Measurements in p+Pb collisions allow an investigation of initial state effects in a system not expected to produce a hot dense QCD medium.

2 The ATLAS Detector

The ATLAS detector covers nearly the entire solid angle around the collision point. It consists of an inner tracking detector system surrounded by a thin superconducting solenoid, electromagnetic and hadronic calorimeters, and a muon spectrometer incorporating three superconducting toroid magnet systems.

The inner-detector system is immersed in a 2 T axial magnetic field and provides charged particle tracking in the range |η| < 2.5. The high-granularity silicon pixel detector covers the vertex region and is surrounded by the silicon microstrip tracker and the transition radiation tracker.

The calorimeters cover the range |η| < 4.9. Within the region |η| < 3.2, electromagnetic calorimetry is provided by barrel and end-cap high-granularity lead liquid-argon calorimeters, with an additional thin liquid-argon presampler covering |η| < 1.8. The electromagnetic calorimeter is complemented by a hadronic calorimeter. Forward calorimeters (FCal) are located in the range 3.1 < |η| < 4.9.
The muon spectrometer comprises separate trigger and high-precision tracking chambers that measure the deflection of muons in the magnetic field. The precision chambers cover the region $|\eta| < 2.7$ with three layers of monitored drift tubes, complemented by cathode strip chambers in the innermost layer of the forward region. The muon trigger system covers the range $|\eta| < 2.4$ with resistive plate chambers in the barrel, and thin gap chambers in the end-cap regions.

3 Electro-weak Bosons

Electro-weak boson in Pb+Pb collisions are not expected to be affected by interactions with the QGP. To confirm this the production of photons, $W$ bosons, and $Z$ bosons is measured and the production rates compared to an expectation of “binary scaling”. In a binary scaling scenario, the yield of the observable is directly proportional to the mean number of binary nucleon-nucleon collisions, $\langle N_{\text{coll}} \rangle$. Each Pb+Pb collision is assigned a centrality class based on the magnitude of the underlying event transverse energy measured in the FCal, and associated with a value of $\langle N_{\text{coll}} \rangle$. $W$ bosons are measured in the $W \rightarrow \mu \nu$ channel, where the neutrino is identified via missing $p_T$ in the event. $Z$ bosons are fully reconstructed via the di-electron and di-muon channels. The yield of $W$ bosons, and $Z$ bosons divided by $\langle N_{\text{coll}} \rangle$ in different centrality classes is shown in Figure 1. The figure shows that across centrality classes the yield of $W$ and $Z$ bosons consistently scales with $\langle N_{\text{coll}} \rangle$. Photons display the same scaling behavior.

In addition to the integrated yields shown in Figure 1, the rapidity differential production rates may be studied in order to search for modifications of the nuclear parton distribution function (PDF). The data are compared to models which do not incorporate any PDF modification and are found to be in good agreement with the data, although the precision of the experimental results does not allow us to exclude nuclear PDF modification.

4 Jet Properites

4.1 Jets in Pb+Pb Collisions

The reconstruction of jets allows us to probe the properties of the dense medium created in heavy ion collisions, and how color sensitive objects interact with it. The jets are reconstructed using an anti-$k_t$ algorithm with distance parameters $R=0.4$, and are fully corrected for detector effects. The suppression of jet production may be quantified using the nuclear modification...
factor, $R_{CP}$:

$$R_{CP} = \frac{\langle N_{coll,P} \rangle (1/N_{coll,C}) d^2 N_C/d\eta d\pt}{\langle N_{coll,C} \rangle (1/N_{coll,P}) d^2 N_P/d\eta d\pt}$$

where C and P refer to central and peripheral event classes, respectively. Figure 2 shows the $R_{CP}$ of jets as a function of $\langle N_{part} \rangle$, demonstrating the suppression of the jet yield in stark contrast to the electro-weak boson yield discussed above. The suppression observed is independent of the jet $p_T$ within the experimental uncertainties.

Figure 2 – Unfolded $R_{CP}$ values as a function of $\langle N_{part} \rangle$ for several $p_T$ bins. The error bars indicate statistical errors from the unfolding; the shaded boxes indicate point-to-point systematic errors that are only partially correlated. The solid lines indicate systematic errors that are fully correlated between all points. The horizontal errors indicate systematic uncertainties on $\langle N_{part} \rangle$.

To further understand the structure of the jets and possible mechanisms of quenching, we may consider the fragmentation function of the jets:

$$z = \frac{p_T^\text{particle}}{p_T^\text{jet}} \cos(\sqrt{\Delta \eta^2 + \Delta \phi^2}), D(z) = \frac{1}{N_{jet}} \frac{dN_{\text{particle}}}{dz}$$

where particle refers to reconstructed tracks inside the reconstructed jet cone, and $D(z)$ is fully corrected for detector effects. The ratio $R_{D(z)} = \frac{D(z)_{\text{central}}}{D(z)_{\text{peripheral}}}$ reflects the modification of the fragmentation function in central events. Figure 3 shows $R_{D(z)}$ for several centralities, and indicates that within the experimental uncertainties the leading particle at high $D(z)$ is unmodified but rather that only lower momentum particles at mid $D(z)$ are.

4.2 Jets in $p+Pb$ Collisions

In addition to the Pb+Pb measurements, the jet nuclear modification factor has been studied in $p+Pb$ collisions as shown in Figure 4. A strong suppression is observed increasing in centrality, $p_T$, and rapidity in the center of mass frame ($y^*$). Interestingly, when plotted against the quantity $p_T \cosh(y^*)$ the $R_{CP}$ in all rapidity bins lie on top of each other; the reason for this remains somewhat obscure. To complement the jet $R_{CP}$, the jet yield has also been compared to a Pythia prediction, shown on the right side of Figure 4. This comparison indicates that the suppression seen in the $R_{CP}$ is composed both of suppression of jets in central events as well as enhancement of jets in peripheral events. The origin of this effect is not yet clear.

5 Summary

The ATLAS heavy-ion program has made many measurements of hard probes only a sampling of which is presented here. From these measurements a clear picture has emerged in which color neutral electro-weak bosons are unmodified in the hot dense QCD medium and serve as
Figure 3 – $R_{D^{*}}$, for $R = 0.4$ jets. The error bars on the data points indicate statistical uncertainties while the shaded bands indicate systematic uncertainties that are uncorrelated or partially correlated between points. The solid lines indicate systematic uncertainties that are 100% correlated between points.

Figure 4 – Far left: $R_{CP}$ is plotted against jet $p_{T}$. Second from left: $R_{CP}$ is plotted against the quantity $p_{T}\cosh(y^*)$. Right columns: The ratio of the data jet yield to the PYTHIA modeled yield. Each panel shows the ratio for jets in multiple centrality intervals at a fixed rapidity bin. Error bars on data points represent statistical uncertainties, boxes represent systematic uncertainties, and the shaded boxes plotted at unity indicate the systematic uncertainty resulting from the calculation of $\langle N_{coll} \rangle$.

a baseline for color sensitive probes as well as providing an opportunity to search for nuclear modification of PDFs. On the other hand, color sensitive jets are strongly modified and allow a direct investigation of the nature of in-medium processes. The $p+Pb$ collision system has opened another front of inquiry some of the results of which are not yet well understood.

References