Heavy Ion Physics with ATLAS

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Abstract. An overview of the ATLAS results from Pb+Pb collisions at \( \sqrt{s_{NN}} = 2.76 \) TeV is presented. ATLAS has measured properties of the bulk particle production including extensive and systematic measurements of the azimuthal particle distributions and correlations. The results for hard probes include both single jet and di-jet measurements, Z bosons, photons, and high \( p_T \) inclusive charged tracks as well as particles identified as coming from heavy flavor decays. Taken together these results provide a compelling picture of the interaction of hard particles in the dense QCD medium. Results shown are from the \( \sim 10 \mu b^{-1} \) of minimum bias data recorded in the 2010 LHC heavy ion run, as well as from \( \sim 0.15 \) nb\(^{-1}\) sampled in the 2011 LHC heavy ion run.

1. Introduction
Lead-lead collisions at \( \sqrt{s_{NN}} = 2.76 \) TeV in the Large Hadron Collider (LHC) provide the opportunity to study strongly interacting matter at the highest temperatures achieved in the laboratory. The ATLAS experiment has a robust heavy-ion program to take advantage of this opportunity. In the 2010 and 2011 LHC runs, yielding approximately 10 \( \mu b^{-1} \) and 0.15 nb\(^{-1}\), respectively, the ATLAS experiment has made a set of measurements that form an emerging picture of the hot dense matter created in a heavy ion collision. These measurements include bulk properties of the system - charged particle multiplicity [1] and extensive measurements of the azimuthal particle distributions and correlations [2, 3] - as well as hard probes such as photons [4, 5], W [6] and Z bosons[7, 8], high transverse momentum, \( p_T \), charged tracks [9], single and di-jet measurements [10, 11, 12, 13], and muons from heavy flavor decays [14].

The ATLAS detector [15] at the LHC covers nearly the entire solid angle around the collision point. It consists of an inner tracking detector surrounded by a thin superconducting solenoid, electromagnetic and hadronic calorimeters, and a muon spectrometer incorporating three superconducting toroid magnet systems. The inner-detector system (ID) is immersed in a 2 T axial magnetic field and provides charged particle tracking in the pseudorapidity range \( |\eta| < 2.5 \). The high-granularity silicon pixel detector covers the vertex region and is surrounded by the silicon microstrip tracker and transition radiation tracker. The calorimeter system covers the range \( |\eta| < 4.9 \). Within the region \( |\eta| < 3.2 \), electromagnetic calorimetry is provided by barrel and endcap high-granularity lead-liquid-argon (LAr) calorimeters, with an additional thin LAr presampler covering \( |\eta| < 1.8 \). Forward calorimeters (FCal) are located in the range \( 3.1 < |\eta| < 4.9 \). The muon spectrometer comprises separate trigger and high-precision tracking chambers that measure the deflection of muons in a magnetic field generated by superconducting air-core toroids. The precision tracking chamber system covers the region \( |\eta| < 2.7 \) with trigger coverage in the range \( |\eta| < 2.4 \).
2. Particle Flow

An important observable used to understand the hot dense medium is the azimuthal anisotropy of hadron emission. At low $p_T$ (less than approximately 4 GeV), this anisotropy is believed to result from a pressure-driven anisotropic expansion of the created matter, with more hadrons emitted in the direction of the largest pressure gradients. The observed azimuthal anisotropy is customarily expressed as a Fourier series in azimuthal angle $\phi$:

$$dN/d\phi = N \left( 1 + 2 \sum_{n} v_n \cos \left( n(\phi - \Phi_n) \right) \right)$$  (1)

where $\Phi_n$ is the $n$-th order reaction plane and $v_n$ are the amplitudes of the Fourier expansion. In typical non-central heavy ion collisions where the nuclear overlap region has an “elliptic” shape (or quadrupole asymmetry) on average, the azimuthal anisotropy is expected to be dominated by the $v_2$ component. However, in addition to this the positions of the nucleons in the overlap region can fluctuate to create matter distributions with additional shape components, such as dipole ($n = 1$), triangular ($n = 3$), and higher asymmetries. Figure 1 shows the azimuthal distribution of particles in three events. The sizable fluctuations seen in the figure are consistent with a hydrodynamic description of the evolution of the medium.

For a more thorough understanding of the bulk properties of the system, we may measure directly the event-by-event $v_2$, $v_3$, and $v_4$ components of the system as shown in Figure 2. Beyond the $v_n$ distributions themselves in several $p_T$ bins, the lower panels of the figure shows the distributions scaled such that each $p_T$ bin’s mean matches the mean of the $p_T > 0.5$ GeV bin. Following this scaling, there is strikingly good agreement in the distributions at different $p_T$. This suggests that the medium’s hydrodynamic response to the initial geometry is largely independent of particle $p_T$.

As shown in Figure 3 the flow components may also be measured using two particle correlations. The analysis employs a large $\Delta \eta$ requirement of $2 < |\Delta \eta| < 5$, to prevent contamination from non-flow physics. Considering all the Fourier components up to $n=6$ allows a precise reconstruction of the two particle $\Delta \phi$ correlations. This implies that the shape observed in two particle correlations at low $p_T$ can be largely attributed to geometric and collective phenomena without invoking jet quenching mechanisms.
Figure 2. Top panels: The unfolded distributions for $v_n$ in the 20-25% centrality interval for charged particles in $p_T > 0.5$ GeV, $1.0 > p_T > 0.5$ GeV and $p_T > 1$ GeV. Bottom panels: same distributions but rescaled horizontally so the $v_n$ values match that for $p_T > 0.5$ GeV. The shaded bands represent the systematic uncertainties on the $v_n$-shape. Figure is from reference [3].

Figure 3. The steps involved in the extraction of $v_n$ values for 2-3 GeV fixed-$p_T$ correlations in the 0-5% centrality interval: (a) two-dimensional correlation function, (b) the one-dimensional $\Delta \phi$ correlation function for $2 < |\Delta \eta| < 5$. Figure is from reference [2].

Taken together these and other measurements allow us to begin to form a coherent picture of the medium geometry and evolution.
3. Penetrating Probes

High momentum particles allow us to probe the properties of the dense medium created in heavy ion collisions, and how color sensitive objects interact with it. Inclusive single particle measurements as well as two particle correlations have suggested that jets are being “quenched” in the medium, and much effort has been made to understand the mechanisms of this quenching. The suppression of particle production may be quantified using the nuclear modification factor, \( R_{CP} \):

\[
R_{CP} = \frac{\langle N_{coll}\rangle(P) \langle 1/N_{c tratt.} \rangle_\text{d}^2 N_{C}/\text{d}p_T}{\langle N_{coll}\rangle(C) \langle 1/N_{c tratt.} \rangle_\text{d}^2 N_{P}/\text{d}p_T} \tag{2}
\]

where \( C \) and \( P \) refer to central and peripheral event classes, respectively, and \( \langle N_{coll} \rangle \) is the mean number of binary collisions in a given centrality class. The left panel of Figure 4 shows the \( R_{CP} \) of inclusive charged particles measured by ATLAS [9], and as expected from previous results it displays a clear suppression of particles in central Pb+Pb events. The right panel shows the nuclear modification factor of muons from heavy flavor decay. The figure shows that although the heavy flavor yield is suppressed in central events compared to peripheral events just as for charged particles, the shape of the modification in \( p_T \) and the magnitude of the suppression may hint at some differences.

![Figure 4](image)

**Figure 4.** Left: \( R_{CP} \) measured in \(|\eta| < 2.5\) in three centrality combinations: with 0-5\%, 30-40\% and 50-60\% as numerators and a common peripheral sample 60-80\% as denominator. The statistical uncertainties are shown with vertical lines and the overall systematic uncertainty at each point is shown with gray boxes. Figure is from reference [9]. Right: Muons from heavy flavor decays \( R_{CP} \) as a function of \( p_T \) for different centrality bins. The bars represent both statistical and systematic uncertainties. The contribution of the systematic uncertainties for \( \langle N_{coll} \rangle \) and efficiency, which are fully correlated between \( p_T \) bins, are indicated by the shaded boxes. Figure is from reference [14].

To go beyond the single particle measurement and look more closely at the jets themselves, ATLAS has made the first direct observation of jet quenching by measuring the imbalance of di-jet energies [13]. The imbalance is expressed in terms of the asymmetry, \( A_J \), of two jets:

\[
A_J = \frac{E_{T1} - E_{T2}}{E_{T1} + E_{T2}}, \quad \Delta \phi > \frac{\pi}{2} \tag{3}
\]

where the jets are reconstructed by an anti-\( k_T \) algorithm [16] with distance parameters \( R=0.4 \). Figure 5 shows the asymmetry and \( \Delta \phi \) distributions for Pb+Pb, p+p, and simulated events. In the more peripheral Pb+Pb events as in p+p and simulation, \( A_J \) is peaked at zero implying no relative modification of the jet energy, i.e. no quenching. However in more central Pb+Pb events...
this is no longer the case, showing that there is a relative quenching of one of the two jets due to the presence of the dense medium. Despite this quenching of the jet energy, $\Delta \phi$ distributions remain consistent even in the most central collisions. The energy imbalance is limited in that it reflects only the relative modification a two jet event, but does not reflect any modification of the leading jet’s energy nor the overall jet production rate. To learn more about jet quenching, in addition to the jet energy imbalance one may measure the nuclear modification factor, $R_{CP}$, of the fully reconstructed jets rather than inclusive single particles [10]. Figure 6 shows the $R_{CP}$ of jets as a function of $N_{part}$, clearly demonstrating the suppression of the overall jet yield in addition to the imbalance seen in Figure 5. The suppression observed is independent of the jet $p_T$ within the experimental uncertainties.

Further understanding of how jets interact with the medium is provided by considering the azimuthal distribution of jets. The di-jet energy asymmetry and jet $R_{CP}$ show that there is significant quenching, however this is averaged over all medium lengths the jets may be probing. In order to directly examine the path length dependence of jet modification we may measure the distribution of jets relative to the reaction plane of the collision, which as discussed in the previous section reflects the anisotropy of the medium. Similarly defined to the $v_2$ used to measure the flow, $v_{jet}^2$ measures anisotropy of jets relative to the amount of medium they traverse. Figure 7 shows $v_{jet}^2$ as a function of $p_T$.

Figures 5 - 7 clearly indicate jet quenching due to the medium; to study the mechanisms of the quenching we may measure the structure of the reconstructed jets themselves. A possible mechanism of jet suppression may involve radiated gluons from the leading parton being shunted out of the jet cone due to multiple scattering with the medium, which would lead to a dependence on the jet cone size of the jet $R_{CP}$. Figure 8 plots the relative $R_{CP}$ of jets with different distance parameters, $R$, relative to $R=0.2$ jets. Although the uncertainties are sizable there is a significant
Figure 6. Unfolded $R_{\text{CP}}$ values as a function of $N_{\text{part}}$ for $R = 0.4$ anti-$k_t$ jets in six $p_T$ 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 $N_{\text{part}}$. Figure is from reference [10].

Figure 7. $v_{j}^{2}$ as a function of $p_T$ for several centrality bins. The error bars on the points indicate statistical uncertainties while the shaded bands represent systematic uncertainties. Figure is from reference [12].

increase with greater $R$, consistent with a scenario in which some suppression in a smaller jet radius due to multiple scattering of radiated gluons is mitigated by looking in a larger jet radius.
To further understand the structure of the jets and possible mechanisms of quenching, we may consider the fragmentation function of the jets (following background and unfolding):

$$D(z) = \frac{p_{T,\text{particle}}}{p_{T,\text{jet}}} \cos(\sqrt{\Delta \eta^2 + \Delta \phi^2})$$  \hspace{1cm} (4)

and the ratio:

$$R_{D(z)} = \frac{D(z)_{\text{central}}}{D(z)_{\text{peripheral}}}$$  \hspace{1cm} (5)

where particle refers to reconstructed tracks inside the reconstructed jet cone. The ratio $R_{D(z)}$ reflects the modification of the jet substructure with centrality where there is suppression. Figure 9 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.

In contrast to the modification of color sensitive objects discussed above, color neutral bosons are expected to be unmodified in the medium. To confirm this as well as the $\langle N_{\text{coll}} \rangle$ scaling assumptions as in Equation 2, we measure photons and $Z$ bosons as shown in Figures 10 and 11. The boson yields are compared to pQCD models of production that include no modification due to the presence of the medium or to the nuclear parton distribution functions, and show good agreement.

The color neutral bosons provide an unbiased baseline from which to measure jet modification in the medium. In a boson+jet event the boson allows direct access to the initial hard scattering which produced both the boson and the jet, and is thus a useful baseline from which to evaluate the jet modification. We may consider the azimuthal distribution of boson+ jet pairs and the momentum fraction $p_{T,\text{jet}}/p_{T,\text{boson}}$ (analogous to the di-jet quantities shown in Figure 5). As in the di-jet case the azimuthal distribution is consistent between central Pb+Pb events and an unmodified pQCD model, however selecting azimuthally correlated events there is a reduction.
Figure 9. Ratios of $D(z)$ for six bins in collision centrality to those in peripheral (60-80%) collisions, $R_{D(z)}$, 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 is from reference [11].

in the mean $p_T$ of the jet compared to the boson $p_T$. The means of the $p_T^{jet}/p_T^{boson}$ and the boson + jet yield normalized per the number of bosons are shown in Figures 12 and 13 for both the data and simulation. Although the uncertainties are large (especially in the $Z$ boson case) these measurements show a qualitative result consistent with jet quenching and hold promise for future precision studies.

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Figure 10. Efficiency corrected yields of isolated photons in $|\eta| < 1.3$ (left), divided by JETPHOX 1.3 predictions with the same isolation requirement (right). Statistical uncertainties are shown by the bars. Systematic uncertainties on the photon yields are combined and shown by the yellow bands. Figure is from reference [5].

Figure 11. Left: corrected per-event $p_T^Z$ spectra of measured $Z$ bosons in five centrality classes. The data are compared to a PYTHIA simulation normalized to the NNLO p+p cross section and scaled by $\langle T_{AA} \rangle$, shown as bands. Right: ratios of the data to the model in each centrality class. Bars represent statistical uncertainties, boxes represent systematic uncertainties, and bands represent the normalization uncertainty. Figure is from reference [7].

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Figure 12. Left: The mean energy fraction $\langle x_J \rangle = \langle p_{T,jet}/p_{T,photon} \rangle$ from fully corrected and unfolded distributions calculated as a function of jet radius ($R = 0.2$ and $R = 0.3$), and for each radius as a function of $N_{part}$. Right: The integrated yield of jets per photon $R_J$. The kinematic cuts are photon $60 < p_T < 90$ GeV, $p_T^{jet} > 25$ GeV and $\Delta \phi_{j,\gamma} > 7\pi/8$. The error bars represent statistical errors, while the grey bands indicate the systematic uncertainties. The data are compared to PYTHIA+Data events, calculated for true jets and photons, for simulated events (with data overlay) with a reconstructed photon passing analysis selections. The figures are from reference [5].

Figure 13. Left: The extracted means from the $p_T^{jet}/p_T^Z$ distributions of the fully corrected data plotted as a function of $\langle N_{part} \rangle$, for each of the three considered jet cone sizes. Right: The fraction of events with a $Z$ boson ($p_T^Z > 60$ GeV) that also have a jet reconstructed ($p_T^{jet} > 25$ GeV, $p_T^{jet}/p_T^Z > 25/60$) as a function of $\langle N_{part} \rangle$. The data are compared to a baseline of PYTHIA, which does not contain any jet energy loss mechanisms. Bars represent statistical uncertainties, and shaded boxes systematic uncertainties. The systematic uncertainties are largely correlated across the $N_{part}$ bins. The width of the PYTHIA band represents its uncertainty. The points at $N_{part} = 140$ refer to 0-80% centrality, and therefore are not independent relative to the points at $N_{part} = 83, 309$. The figures are from reference [8].