Jet Measurements in Heavy Ion Collisions with ATLAS

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first stable beams heavy-ion collisions

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what happens to jets as they pass through the quark-gluon plasma? what does that tell us about the properties of the QGP?
The performance of the jet reconstruction is evaluated by calculating the jet energy response and bias in the jet reconstruction software in a comparison of data and simulation. The cross calibration verified in a preliminary study suggests that data and simulation agree within the uncertainties of the cross calibration procedure. The jet reconstruction is further validated through its application in various centrality ranges, as shown in the figure. The jet energy resolution uncertainties are estimated for 2015 data with 25 ns bunch spacing as a function of jet pseudorapidity (η), with the results presented in Table 4. The jet energy scale and its uncertainties are also included.

**Figure 12:** Event fraction as a function of jet energy (ET) for different centrality ranges.

**Figure 13:** Flow modulation and punch-through predictions for Pb+Pb collisions at 5.02 TeV, compared with 2015 data (25 ns bunch spacing).

**Figure 14:** Preliminary, Run 287044, ATLAS-Preliminary, Pb+Pb 5.02 TeV, 0.49 nb⁻¹, and ATLAS-CONF-2016-110, Pb+Pb |Δr_NN|= 5.02 TeV, 28 mb⁻¹.

The idea is that the forward calorimeter (FCal) sum of transverse energies (ΣET) is correlated with collision impact parameter.
jet reconstruction in heavy ion collisions in ATLAS

jet constituents: 0.1 x 0.1 calorimeter towers in $\eta \times \varphi$

large UE: $R = 0.4$ jet $\rightarrow A_{\text{jet}} = 0.5$

subtract up to 150 GeV from jet energy
Jet Energy Scale: ~1% centrality dependence above 100 GeV

Jet Energy Resolution: degraded in central collisions wrt pp due to underlying event fluctuations
$R_{AA} = \text{number of jets in PbPb collisions/ pp collisions scaled by nuclear thickness function}$

$R_{AA} = 1 \rightarrow \text{jets in PbPb collisions like pp collisions}$

**ATLAS**  
anti-$k_t$ $R = 0.4$ jets, $\sqrt{s_{\text{NN}}} = 5.02$ TeV

2015 data: Pb+Pb 0.49 nb$^{-1}$, pp 25 pb$^{-1}$

$\langle T_{AA} \rangle$ and luminosity uncer.

significant quenching over entire kinematic range of the measurement out to $\sim$1 TeV
rapidity dependence of $R_{AA}$

- why rapidity?
  - fraction of quark jets increases with $|y|$ at fixed jet $p_T$
  - quarks jets should lose less energy than gluon jets
    - **increase RAA with $|y|$**
    - jet $p_T$ spectra become steeper with increasing $|y|$
      - **decrease RAA with $|y|$**
rapidity dependence of $R_{AA}$

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$p_{T_{\text{jet}}} > 316$ GeV: the effects of the steeper spectra dominate the measurement
charged hadrons

XeXe collisions provide a first look at the collision system dependence at the LHC

first results show that the jet modifications are consistent in XeXe & PbPb at the same system size large uncertainties for Npart < ~50
what about the structure of the jets in PbPb collisions?
calorimeter response to light jets

different calorimeter response to quark and gluon jets,
also different between PYTHIA & HERWIG
jet fragmentation

how do the particles in the jet carry its momentum?

\[ D(z) \equiv \frac{1}{N_{\text{jet}}} \frac{dN_{\text{ch}}}{dz} \]
\[ D(p_T) \equiv \frac{1}{N_{\text{jet}}} \frac{dN_{\text{ch}}}{dp_T} \]

\[ z \equiv \frac{p_T \cos \Delta R}{p_T^{\text{jet}}} \]
unfolding for fragmentation functions

measured

\( p_T \) jet

track \( z \)

response matrix in \( p_T, \text{meas}, p_T, \text{true}, z, \text{meas}, z, \text{true} \)

unfolded

\( p_T \) jet

particle \( z \)
unfolding for fragmentation functions

response matrix in $p_{T,\text{meas}}, p_{T,\text{true}}, z_{\text{meas}}, z_{\text{true}}$

measured

$\begin{array}{c}
\text{track } z \\
p_{T,\text{jet}}
\end{array}$

unfolded

$\begin{array}{c}
\text{particle } z \\
p_{T,\text{jet}}
\end{array}$

$D(z)_{\text{sub}} / D(z)$

$\begin{array}{c}
p_T^{\text{jet}}: 251-316 \text{ GeV}
\end{array}$

small UE effect

similar unfolding change in pp & PbPb

1805.05424
unfolding for fragmentation functions

**Response matrix in** $p_T^{meas}$, $p_T^{true}$, $z^{meas}$, $z^{true}$

**measured**

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**Unfolded**

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**$p_T^{jet}$**

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**Track z**

---

**$p_T^{jet}$**

---

**Particle z**

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**$p_T^{jet}$**: 126 - 158 GeV

- ATLAS
  - Pb+Pb, $\sqrt{s_{NN}} = 5.02$ TeV, 0.49 nb$^{-1}$, 0-10%
  - $pp$, $\sqrt{s} = 5.02$ TeV, 25 pb$^{-1}$
  - anti-$k$, $R=0.4$ jets, $|y|<2.1$

** measured / unfolded $D(z)_{sub} / D(z)$**

**$126 < p_T^{jet} < 158$ GeV**

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**$p_T^{jet}$**: 251 - 316 GeV

- ATLAS
  - Pb+Pb, $\sqrt{s_{NN}} = 5.02$ TeV, 0.49 nb$^{-1}$, 0-10%
  - $pp$, $\sqrt{s} = 5.02$ TeV, 25 pb$^{-1}$
  - anti-$k$, $R=0.4$ jets, $|y|^{jet}<2.1$

**measured / unfolded $D(z)_{sub} / D(z)$**

**$251 < p_T^{jet} < 316$ GeV**

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- Large centrality dependence to JER due to UE fluctuations
- Biggest effect at high z due to steepness of the fragmentation functions at $z\sim 1$
- Small UE effect similar unfolding change in $pp$ & PbPb
functions at quarks and gluons with the QGP. Previous measurements of the rapidity dependence of jet fragmentation observables in Pb+Pb collisions is of great interest, in part because at initial- and final-state e+e− collisions, it was found in Ref. \cite{13} that jets in Pb+Pb collisions show no evidence of modification when compared with those in pp collisions. The pseudorapidity is defined in terms of the polar angle \( \theta \) between the jet axis and the charged-particle direction in pseudorapidity and azimuth, \( \eta \) = \( \ln \tan(\theta/2) \).

Relative to jets in pp collisions, there is a suppression of the charged-particle yield. At the same time, an excess of low-\( p_T \) particles is observed for particles in a wide region around the jet cone. Different ratios are measured in Pb+Pb and pp collisions at the same collision energy, the ratios of charged-particle densities being the azimuthal angle around the jet \( \phi \). There is a suppression of the charged-particle density for particles in a wide region around the jet cone. Different ratios are measured in Pb+Pb and pp collisions at the same collision energy, the ratios of charged-particle densities being the azimuthal angle around the jet \( \phi \).

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\[ R_{D(z)} \equiv \frac{D(z)_{\text{PbPb}}}{D(z)_{\text{pp}}} \]

Observe centrality and jet \( p_T \) dependent modifications to fragmentation functions in PbPb collisions.
fragmentation functions in $z$ & $p_T$

**$R_D(z)$**

- **ATLAS**
  - $|y^{\text{jet}}| < 2.1$ anti-$k_T$, $R=0.4$ jets

- Points denote:
  - $126 < p_T^{\text{jet}} < 158$ GeV
  - $200 < p_T^{\text{jet}} < 251$ GeV
  - $316 < p_T^{\text{jet}} < 398$ GeV

**$R_D(p_T)$**

- **ATLAS**
  - $|y^{\text{jet}}| < 2.1$ anti-$k_T$, $R=0.4$ jets

- Points denote:
  - $126 < p_T^{\text{jet}} < 158$ GeV
  - $200 < p_T^{\text{jet}} < 251$ GeV
  - $316 < p_T^{\text{jet}} < 398$ GeV

**Experimental Conditions**

- Pb+Pb, $\sqrt{s_{NN}} = 5.02$ TeV, 0.49 nb$^{-1}$, 0-10%
- $pp$, $\sqrt{s} = 5.02$ TeV, 25 pb$^{-1}$
high z scaling: related to fragmentation?

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high $z$ scaling: related to fragmentation?

low $p_T$ scaling: QGP scale?
consistent $R_D(z)$ for unfolded results due to unfolding changing as a function of $p_T^{jet}$
larger energy loss for gluons than quarks followed by pythia fragmentation
jet fragmentation (II)

where are the particles in and around the jet?

\[
D(p_T, r) = \frac{1}{N_{\text{jet}}} \frac{1}{2\pi r} \frac{d^2 n_{\text{ch}}(r)}{dr dp_T}
\]

\[N_{\text{jet}} = 2 \pi \int_0^{R_{\text{jet}}} dR D(p_T, R)\]

\[\int_0^{R_{\text{jet}}} dR D(p_T, R) = 1\]
radial dependence of low $p_T$ particles

$126 < p_{T \text{jet}} < 158$ GeV

$0 - 10\%$

$\text{Pb+Pb} \ \sqrt{s_{NN}} = 5.02$ TeV, $0.49 \text{ nb}^{-1}$

$\text{pp} \ \sqrt{s} = 5.02$ TeV, $25 \text{ pb}^{-1}$ anti-$k_T$, $R=0.4$

- $1.6 < p_T < 2.5$ GeV
- $2.5 < p_T < 4.0$ GeV
- $4.0 < p_T < 6.3$ GeV
- $6.3 < p_T < 10.0$ GeV
- $10.0 < p_T < 25.1$ GeV
- $25.1 < p_T < 63.1$ GeV

$p_T < 4$ GeV: broader angular distribution in PbPb

$p_T > 4$ GeV: narrower angular distribution in PbPb

modifications grow with radius within the jet cone
why jet mass in PbPb collisions?

$m/p_T$ related to the angular width of the jet

**physics question**: how are the parton showers resolved by the QGP?

**experimental question**: how does $R_{AA}$ depend on $m/p_T$?
**m/\(p_T\) distributions: PbPb & pp collisions**

R = 0.4 anti-\(k_T\) jets

Measurement over wide kinematic and centrality range

Jet constituents 0.1x0.1 towers no soft drop
Figure 8: \( R_{AA} \) as a function of \( m/p_T \)

- over a wide kinematic & centrality range, no significant modification to \( m/p_T \) observed

- experimental goals:
  - reducing the systematic uncertainties
  - also: rapidity dependence to change the quark/gluon fractions
some theory comparisons
some theory comparisons

ATLAS

anti-\(k\), \(R=0.4\) jets, \(\sqrt{s_{NN}}=5.02\) TeV

0-10%, \(|y| < 2.1\)

2015 pp data, 25 pb\(^{-1}\)

2015 Pb+Pb data, 0.49 nb\(^{-1}\)
some theory comparisons
jet $R_{AA}$ not well described by any model which provided calculations, but FF, $\gamma$-jet and charged particles can be described—what do we learn from this?
summary

• ATLAS has many complementary results designed to constrain the physics of jet quenching
• focus on unfolded results which allow comparisons across observables and to models
  • many model calculations available already
• focus on systematic measurements as a function of jet $p_T$ and rapidity
• I’ve only flashed the photon-jet results (see Dennis Perepelitsa’s talk) but they are a key part of the ATLAS program
• what are the most important measurements to move make with the 2018 data to constraint the physics of jet quenching?
  • full results: https://twiki.cern.ch/twiki/bin/view/AtlasPublic/HeavylonsPublicResults

looking forward to extending these measurements with the 2018 data!
backup
flow effects on JES & fake jet rejection

$R_{AA}$

$ATLAS$

anti-$k_t$, $R = 0.4$ jets, $\sqrt{s_{NN}} = 5.02$ TeV

0-10%, $|y| < 2.8$

2015 $pp$ data, 25 pb$^{-1}$

2015 Pb+Pb data, 0.49 nb$^{-1}$

$ATLAS$ Simulation

Powheg + Pythia 8 inclusive jets

Pb+Pb data overlay

anti-$k_t$, $R = 0.4$ jets, $\sqrt{s_{NN}} = 5.02$ TeV

$|\eta| < 1.0$

$100 < p_T^{\text{truth}} < 200$ GeV

$\langle p_T^{\text{rec}}/p_T^{\text{truth}} \rangle$

$0-10\%$ no flow correction

$0-10\%$

$20-30\%$

$40-50\%$

$60-70\%$
jet mass performance

- Jet mass scale (JMS): approximately independent of centrality
- Jet mass resolution (JMR): increases in central collisions and at low jet $p_T$
- Expected from worse JER/UE in this region

**Figure 1:** The mean (top) and the resolution (bottom) of $m^2/p^2$ for $pp$ collisions (left) and 0–10% Pb+Pb collisions (right).
unfolding

two dimensional Bayesian unfolding in $m/p_T$ and $p_T$ to correct for JMS and resolution effects
Figure 6: Ratios of $D(p_T, r)$ distributions for $p_T$ of 126 to 158 GeV (left) and of 200 to 251 GeV (right) in Pb+Pb collisions to pp collisions as a function of angular distance $r$ for two $p_T$ selections and six centrality intervals ($p_T$ selections are shown by closed and open symbols). The vertical bars on the data points indicate statistical uncertainties while the shaded boxes indicate systematic uncertainties. There are no uncertainties on the $r$ values, the finite widths of the shaded boxes are purely aesthetic.

Figure 7: $R_D(p_T, r)$ as a function of $r$ for 0–10% collisions for charged particles with 1.6 $< p_T < 2.5$ GeV (closed symbols) and 6.3 $< p_T < 10.0$ GeV (open symbols) for four $p_T$ selections: 126–158 GeV, 158–200 GeV, 200–251 GeV, and 251–316 GeV. There are no uncertainties on the $r$ values, the finite widths of the shaded boxes are purely aesthetic.