Jet measurements with the ATLAS detector in Pb+Pb and $p$+Pb collisions

Aaron Angerami
Hard Probes 2013
Tuesday, November 5, 2013
What We Know from RHIC

- Indirect observation of quenching established by two key measurements
  - Suppression in rate of inclusive hadron production at high $p_T$ — nuclear modification factor $R_{AA}$
  - Modification of di-hadron azimuthal correlations

- QCD factorization is explicitly broken in nucleus—nucleus collisions

- "Phase 0" of an LHC jet quenching program is to extend these exact measurements to the LHC

- "Phase I" is to perform analogous measurements with fully reconstructed jets with high precision
Add LHC measurements to the picture

Gradual rise in $R_{AA}$ manifest feature of suppression
Ushering in the LHC Era: Dijet Asymmetry

A_J = \frac{E_T^1 - E_T^2}{E_T^1 + E_T^2}

E_T^1 > 100 \text{ GeV}
E_T^2 > 25 \text{ GeV}

First direct observation of jet quenching

Significant fraction of events with enhanced dijet asymmetry while simultaneously preserving the back-to-back angular correlation
Jet properties
Fragmentation function, jet shape

Inclusive energy loss
Hard scattering rates, jet suppression

Correlations and differential energy loss
asymmetry and $\Delta\phi$ distributions:
dijet, $\gamma$-jet and $Z$-jet
jet-hadron correlations
Inclusive Jet Suppression

- What about centrality-dependent modification of jet spectra?
  - Jet kinematics more sensitive to parton suffering energy loss
  - Access dynamics of full parton shower

- Medium effects may cause jet energy to be transported outside the nominal jet cone

- Can lost energy be recovered by expanding size of jet definition (radius)?

⇒ Measure single jet suppression with multiple jet sizes
Results: $R_{CP}$ vs $p_T$ in Centrality Bins

$R_{CP}$ vs $p_T$ in Centrality Bins

$R = 0.2$

$R = 0.4$

Use 60–80 % as peripheral reference
Results: $R_{CP}$ vs $R$

**0—10% centrality**

- **ATLAS**
- Pb+Pb $\sqrt{s_{NN}} = 2.76$ TeV
- $\int L dt = 7 \mu$b$^{-1}$

**89 < $p_T$ <103 GeV**

- **ATLAS**
- Pb+Pb $\sqrt{s_{NN}} = 2.76$ TeV
- $\int L dt = 7 \mu$b$^{-1}$

---

Monday, October 28, 13
Quantitative statement of $R$ dependence

\[ \frac{R_{CP}}{R_{CP}}^{0.2} \]

\[ \int L \, dt = 7 \, \mu b^{-1} \]

\[ Pb+Pb \sqrt{s_{NN}} = 2.76 \text{ TeV} \]

0 - 10%

Ratios of $R_{CP}$ to $R_{CP}$ with $R=0.2$

Measure *relative* suppression with respect to most suppressed $R$ value ($R=0.2$)

Variation with $R$ is significant

Note switch log scale to focus on low $p_T$ behavior

\[ p_T \, [\text{GeV}] \]

- Many systematics cancel, correlated between different $R$
- Statistical correlation between different $R$ values included and propagated through unfolding
Jet Suppression and Collision Geometry

- Jets produced with different angles with respect to event plane ($\Delta \phi$) will see different path lengths and density profiles in the medium.

$$\Delta \phi = \phi^{\text{jet}} - \Psi_2$$

→ Measure single jet suppression as a function of $\Delta \phi$ : $v_2^{\text{jet}}$
Jet Suppression and Collision Geometry

- 1-5% modulation of yield

- Centrality dependence consistent with naive expectation from geometric considerations
Jet Suppression and Collision Geometry

- Compare ratio of yields at $\Delta \phi=0$ and $\pi/2$ to expectation from pure second harmonic modulation
- Almost no room for different modulation modulation (e.g. $\cos^2 2\Delta \phi$) which may be expected from non-linear path length dependence
- Need calculation with full realistic geometry
Asymmetry: Differential Energy Loss

- $\gamma/Z$— jet correlations provide clean probe since $\gamma$ and $Z$ (or leptonic decay products) do not suffer energy loss
  - Do NOT expect jets recoiling against $\gamma/Z$ to have same $p_T$ as $\gamma/Z$
  - Effects like initial state parton shower cause broadening of distribution
    - Focus on $x_J = p_T^{\text{jet}} / p_T^{\gamma/Z}$

- Unmodified $x_J$ and $A_J$ distributions in are different $\gamma$— and $Z$—jet events
  - Large virtuality required to produce $Z$
  - Potentially provide different handles on energy loss since intrinsic are different
Slight differences in kinematic selection and analysis details but same general trend—large systematic shift to lower x values in central collisions.
**Z–jet Correlations**

### 0–20% centrality

- ATLAS Preliminary
- Pb+Pb $\sqrt{s_{NN}}=2.76$ TeV, $L_{int}=0.15$ nb
- Anti-$k_T$ Jet $R=0.2$, $p_T^{jet}>25$, $p_T^{Z}>60$ GeV, $p_T^{jet}/p_T^{Z}>25/60$
- PYTHIA: Mean=0.79±0.01
- Pb+Pb: Mean=0.62±0.04±0.03
- 0-20% Centrality

### 20–80% centrality

- ATLAS Preliminary
- Pb+Pb $\sqrt{s_{NN}}=2.76$ TeV, $L_{int}=0.15$ nb
- Anti-$k_T$ Jet $R=0.2$, $p_T^{jet}>25$, $p_T^{Z}>60$ GeV, $p_T^{jet}/p_T^{Z}>25/60$
- PYTHIA: Mean=0.79±0.01
- Pb+Pb: Mean=0.70±0.07±0.05
- 20-80% Centrality

> Mostly proof of principle due to low statistics but hints at potential of the measurement when more data comes

> General trend compatible with photon-jet results
Jet Structure: Fragmentation Function

- Use tracks inside of jets
- Subtract UE contribution to correlation
- $z$ is longitudinal momentum fraction
Jet Structure: Centrality Dependence

- Enhancement at low $z$/large $\xi$
- Suppression at moderate $z$/\$\xi$
- Hard component behavior may exhibit additional enhancement

**ATLAS Preliminary**
Pb+Pb$\sqrt{s_{NN}}=2.76$ TeV
$L_{\text{int}}=0.14$ nb$^{-1}$

- anti-$k_T$ $R=0.4$
- $p_T^{\text{jet}}>100$ GeV
- 0-10%/60-80%

**Ratio** = $D_{0-10\%}/D_{60-80\%}$
Jet Structure: Centrality Dependence

Ratio = \( D_{0-10\%} / D_{60-80\%} \)

- Similar trends in \( D(z) \) and \( D(p_T) \) distributions
- \( D(p_T) \) does not have quenching effect in denominator
  - Slightly cleaner interpretation
Jet Transverse Structure

- Consistent with small but significant centrality-dependent change in structure
- Measurement needs to be repeated using 2011 data

- Similar conclusion to jet shape
- Room for gradual broadening
- Needs precision measurement and quantitative prediction
The “Average Jet”

- In HI we have event-by-event fluctuations in both the parton shower and the jet interactions with the medium

➡ Key question: Is quenching driven by average energy loss effects or by significant event-by-event variation not well represented by the average?

- Use suppression measurement with simple quenching models to give estimate of average energy loss

- Contrast with asymmetry observation: jets frequently lose more than 50% of their energy
Typical- vs fluctuation- driven quenching paradigm

- How can measurements and calculations be more discriminating?
- Large quenching effects still preserve dijet $\Delta \phi$ correlations
  - Rigorous approach considering full parton shower needed to describe LHC data

- $R$ dependence of single jet suppression suggests some medium induced radiation recovered by going using larger jet definition
- Supported by preliminary jet shape measurements
- Conversely, asymmetry measurements show imbalance recovered in soft particles at large $R$
- Need to be precise about energy being radiated away at “large angles”
  - Can such calculations also describe excess at low $z$/high $\xi$ in fragmentation functions?
- Path length dependence needs serious investigation
- How does $L$ dependence survive integration over realistic geometry?
Inclusive jet production in $p+$Pb collisions

- Jet $p_T$ spectra measured as a function of centrality and rapidity in CM frame, $y^*$
- Measurement performed with bin-by-bin unfolding in $p_T$ range where correction factors are centrality independent
- Centrality determined from total $E_T$ in FCal (3.2 < |$\eta$| < 4.9) in Pb-going direction (backwards)
  - Following convention established from pilot run, proton going in (-) direction
- Energy within jets in FCal is excluded from centrality determination
- Measurement uses 2013 $p+$Pb data from both beam orientations 31 nb$^{-1}$
Jet $R_{CP} : 60-90\%$ used as peripheral reference

Jets suppressed by up to a factor of three

Suppression increases with $p_T$ and $y^*$

Could this be an initial state energy loss effect?

Colored bands are $N_{coll}$ uncertainties

More forward
**R_{pPb}^{PYTHIA}: minimum bias averaged**

- No pp data available at this energy
- Rescaling of existing pp jet cross sections possible
- For now use PYTHIA as reference for absolute suppression

\[
R_{pPb}^{PYTHIA} = \frac{1}{N_{\text{evt}}} \left( \frac{1}{\langle T_A \rangle} \frac{dN_{\text{jet}}}{dp_T dy^*} \right)_{\text{cent}} \left( \frac{d\sigma_{\text{jet}}}{dp_T dy^*} \right)_{\text{PYTHIA}}
\]

Shaded bands are \(N_{\text{coll}}\) uncertainties
**$R_{\text{pPb}}^{\text{PYTHIA}}$: minimum bias averaged**

Total number of jets observed in data consistent with what you would expect from PYTHIA

If there is “simple” energy loss, would see fewer total jets

May even see slight enhancement at mid-rapidity

But no significant suppression especially at forward rapidities
$R_{pPb}^{\text{PYTHIA}}$: centrality dependence

Slight suppression in central collisions but enhancement in peripheral

Reminiscent of PHENIX result in dAu

Effect never explained

Could this be an initial state energy loss effect?

Not obvious how to reconcile this with lack of suppression in total number of jets...
Jet $R_{CP}$

Each $y^*$ bin shows similar suppression when plotted as a function of $p_T \cosh(y^*)$

- Looks as if effect depends on (parton) energy
- Also looks “kinematic”
- More central collisions lead to lower effective $\sqrt{s}$