Measurements of Jets and Jet Quenching in $\sqrt{s_{NN}}=2.76$ TeV Pb+Pb Collisions with the ATLAS Detector at the LHC

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Jets in Heavy Ion Collisions

- Jets provide a powerful tool for determining the degrees of freedom and their effective scales in heavy ion collisions.

- Results from the RHIC program show that high $p_T$ particle production is suppressed and that usual factorization of hard processes is broken in nuclear collisions.
  - $q^2$ not dominant scale
  - new relevant scales: intensive (T) extensive (L) ?

- Single particle suppression doesn’t tell us:
  - Does energy remain in jet but redistributed among fragments?
  - Or is the jet energy being transferred to the medium?

- Need to go beyond single particles, look at **full jets**
Radiative Energy Loss

Medium interactions induce additional radiation modifying usual vacuum fragmentation

high z region of fragmentation function sensitive to medium induced radiation

Radiative Energy Loss

Broadening of radiation may cause energy deposition outside jet cone

Predictions of radiative energy loss suggest energy can be recovered by expanding jet cone

First indication of suppression of full jets
Momentum balance from hard process not contained in jets

\[ A_J = \frac{E_T^1 - E_T^2}{E_T^1 + E_T^2} \quad \Delta\phi \quad E_{T1} > 100 \text{ GeV} \quad E_{T2} > 25 \text{ GeV} \]

Understanding Asymmetry

• Asymmetry results are startling, does this constrain energy loss picture?

• Difficult with a two-jet observable by itself. Supplement with single jet observables:
  • Jet spectra/R_{CP}
  • Longitudinal and transverse fragment distributions (z and j_T)

• Known to be sensitive to quantitative details of energy loss

• Less sensitive to global event features, hopefully can disentangle potentially complicated medium effects
**ATLAS Detector: Calorimeter**

- **E_T** in barrel strongly correlated with FCal
- FCal **E_T** used to determine centrality
  \[3.2 < |\eta| < 4.9\]
- Jets in barrel used in analysis \[|\eta| < 2.8\]
- Both EM and hadronic calorimetry
Jet Reconstruction

• Jets reconstructed using anti-k_{t} algorithm with two choices of R parameter (R=0.4 and R=0.2)

• Inputs are 0.1x0.1 (\Delta \eta \times \Delta \phi) calorimeter towers

• Average background computed per calorimeter sampling layer per 0.1 \eta strip for each event

• Potential jets excluded from averaging to prevent bias

R=0.4 jets

• utilize an iterative procedure to determine background

• background modulated by elliptic flow before subtraction
Jet Spectra $R=0.4$

Raw spectra with bin-by-bin unfolding, additional 22% systematic uncertainty from jet energy scale

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$R_{CP}$ $R=0.4$ Jets

Gradual turn on of medium effects with increasing centrality

Clear factor of $\sim 2$ suppression indicated in most central collisions
Entire jet, not just leading fragment
**$R_{CP} \ R=0.2 \ Jets$**

Slightly more suppression observed
Not much energy recovered by larger cone size

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Jet Fragments: Transverse Structure

All charged particles with $p_T > 2$ GeV and within jet radius

Lack of broadening consistent with Rcp measurement
Some change in shape with centrality, not enough to indicate a strong effect

$\Delta R = \sqrt{(\eta - \eta_{jet})^2 + (\phi - \phi_{jet})^2}$
Jet Fragments: Longitudinal Structure

\[ z = \frac{p_T}{E_{jet} \cos \Delta R} \]

**R=0.4**

- \( E_{T,jet} > 100 \text{ GeV} \)
  - \( R = 0.4, 0-10\%, p_T > 2 \text{ GeV} \)
  - \( R = 0.4, 40-80\%, p_T > 2 \text{ GeV} \)

**R=0.2**

- \( E_{T,jet} = 75-100 \text{ GeV} \)
  - \( R = 0.2, 0-10\%, p_T > 2 \text{ GeV} \)
  - \( R = 0.2, 40-80\%, p_T > 2 \text{ GeV} \)

Large modification at high z not indicated
Slight redistribution of jet’s energy among fragments seen at mid-low z (0.2)

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Jet Fragments: Longitudinal Structure

Modest modification at mid-low $z$

But high $z$ behavior unlike prediction
Two-Jet Observables: Di-jet Asymmetry

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

\[ E_{T1} > 100 \text{ GeV} \]
\[ E_{T2} > 25 \text{ GeV} \]

Contributions to second peak mostly from events where second jet consistent with background level.
Di-jet Asymmetry: $R=0.2$

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

$E_T^1 > 100 \text{ GeV}$

$E_T^2 > 25 \text{ GeV}$

Distribution flatter, peak smeared out
Asymmetry: Energy Dependence, R=0.2

Increasing jet energy stretches peak out

More peripheral restores peaking at low values of $A_J$
Summary

• Di-jet asymmetry indicates significant distortion in momentum balance contained in jets that increases with centrality, nearly flat away from peak

• $R_{CP}$ measurements support the interpretation that asymmetry is caused by significant suppression of high energy jets

• Small variation between results of different cone sizes shows little room for suppression coming from out-of-cone energy loss

• $j_T$ and $z$ distributions provide complementary result indicating that the suppression mechanism does not modify longitudinal or transverse distributions of charged particle jet fragments as would be expected with radiation-dominated energy loss scenario

• Convincing picture that energy loss is not radiation-dominated and mechanism involves complicated interplay with collisional effects
Supporting Slides
Jet Spectra R=0.2

ATLAS Preliminary

Centrality
- 0-10 %
- 10-20 %
- 20-30 %
- 30-40 %
- 40-50 %
- 50-60 %
- 60-80 %

Pb+Pb $\sqrt{s_{NN}} = 2.76$ TeV

$\int L = 7 \mu$ b$^{-1}$

R = 0.2
Jet Fragments: Longitudinal Structure

\[ R = 0.2 \]
Yields vs Centrality

ATLAS Preliminary

$R = 0.4$

$100 < E_T < 125 \text{ GeV}$

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

$L_{int} = 7 \mu \text{ b}^{-1}$

$125 < E_T < 150 \text{ GeV}$

$75 < E_T < 100 \text{ GeV}$

$150 < E_T < 200 \text{ GeV}$

$100 < E_T < 125 \text{ GeV}$

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Jet Performance: Resolution from MC

\[ \sigma \left( \frac{\Delta E_T}{E_T} \right) = \sqrt{\left\langle \left( \frac{E_{T,\text{truth}} - E_{T,\text{reco}}}{E_{T,\text{truth}}} \right)^2 \right\rangle} - \left\langle \frac{E_{T,\text{truth}} - E_{T,\text{reco}}}{E_{T,\text{truth}}} \right\rangle^2 \]

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ATLAS Detector: Inner Detector

Jets in heavy ion collisions