ATLAS Measurements of Jets in Heavy-Ion Collisions

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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: temperature, system size?

• 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


Pb+Pb@5500 GeV

\[ R_{AA}(E_T) \]

\[ E_T (GeV) \]
Di-jet Asymmetry: Original Result

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

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

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

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

From Nov. PRL ~ 2μb⁻¹


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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/central to peripheral ratio ($R_{CP}$)
  
  • 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

Analysis uses jets in barrel: |\eta| < 2.8

2010 Pb Ion run:
7 \mu b^{-1}, 50 M events
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

Clear **factor of ~2 suppression** indicated in most central collisions
Entire jet, not just leading fragment

Gradual turn on of medium effects with increasing centrality

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**R_{CP} R=0.2 Jets**

Slightly more suppression observed
Not much energy recovered by larger cone size: 0.2 ⇒ 0.4
Jet Fragments: Transverse Structure

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

Lack of broadening consistent with $R_{CP}$ measurement
Some change in shape with centrality, not enough to indicate a strong effect
Jet Fragments: Longitudinal Structure

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

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

**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

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

Updated from published result

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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
Less sensitive to background fluctuations

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Asymmetry: Energy Dependence, R=0.2

Increasing jet energy stretches peak out

Peak at low values of $A_J$ restored in peripheral collisions

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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

• Results not obviously consistent with radiation-dominated energy loss except possibly at large angles
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

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

$R = 0.2$

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Jet Fragments: Longitudinal Structure

R=0.2

ATLAS Preliminary
Pb+Pb $s_{NN} = 2.76$ TeV
$L_{int} = 7 \mu$b

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Yields vs Centrality

ATLAS Preliminary
R = 0.4

100 < $E_T$ < 125 GeV

Pb+Pb $\sqrt{s_{NN}}$ = 2.76 TeV
$L_{int} = 7 \mu$ b$^{-1}$

125 < $E_T$ < 150 GeV

ATLAS Preliminary
R = 0.2

50 < $E_T$ < 75 GeV

Pb+Pb $\sqrt{s_{NN}}$ = 2.76 TeV
$L_{int} = 7 \mu$ b$^{-1}$

75 < $E_T$ < 100 GeV

ATLAS Preliminary
R = 0.4

150 < $E_T$ < 200 GeV

100 < $E_T$ < 125 GeV

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Jet Performance: Resolution from MC

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

ATLAS Preliminary

Data: $|\eta|<2.8$

7x7 towers

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

Pb+Pb

Standard deviation of 7x7 towers $E_T$ [MeV] vs. FCal $\Sigma E_T$ [TeV]
ATLAS Detector: Inner Detector

Jets in heavy ion collisions

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