Measurements of Hard Probes in Heavy Ion Collisions with ATLAS

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Thursday, February 7, 2013
Jets in Heavy Ion Collisions

- Jets provide a powerful tool for determining medium properties via jet quenching
  - Energy loss of a parton or modification of its parton shower through interactions with medium

- Fully reconstructed jets are directly sensitive to energy loss
  - Jet kinematics closely related to those of parton suffering energy loss

- Functional definition of a jet in HI collisions
  - Energy clustered in a jet reconstruction algorithm above the uncorrelated underlying event
  - May include medium response (correlated)

- New measurements provide quantitative constraints on quenching mechanism and medium transport coefficients
Hard scattering rates and inclusive energy loss

\(\gamma/Z/W\) : sensitive to CNM effects
Jets : both CNM and quenching

Correlations and differential energy loss
asymmetry and \(\Delta\phi\) distributions
dijet, \(\gamma\)-jet and \(Z\)-jet

Jet properties
Fragmentation function
The ATLAS Detector

Detector characteristics
- Width: 44m
- Diameter: 22m
- Weight: 7000t

ZDC@ ±140 m
EM barrel and end cap use "accordion" design for uniform radiation length

- Liquid argon end-caps
  - $1.7 \mid \eta \mid < 3.2$

- Hadronic end-cap (HEC)

- EM end-cap (EMEC)

Steel-scintillator hadronic calorimeters

- Tile barrel
  - $\mid \eta \mid < 1.0$
  - $0.8 < \mid \eta \mid < 1.7$

- Extended tile barrel

- Liquid argon end-cap

- Liquid argon barrel
  - $\mid \eta \mid < 1.5$

  - High granularity precision calorimeter
  - Fine $\eta$ segmentation in first layer for $\gamma$—$\pi^0$ separation
  - Presampler layer to measure early showers

- Liquid argon Forward calorimeter (FCal)

- Combined EM and hadronic
  - $3.2 < \mid \eta \mid < 4.9$

- Strip cells in Layer 1

- Square cells in Layer 2

- Cells in Layer 3
  - $\Delta \phi \Delta \eta = 0.0245 \pm 0.05$

-Trigger Tower
  - $\Delta \eta = 0.1$

- Trigger Tower
  - $\Delta \phi = 0.0982$

- Hadronic end-cap

- EM end-cap

-/Columbia University IN THE CITY OF NEW YORK/
Heavy Ions in ATLAS

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

\[
\int \mathcal{L} \, dt = 140 \, \mu b^{-1}
\]
Results from the LHC indicate asymmetric dijet events are a manifest feature of heavy ion collisions.
**Dijet Asymmetry: Original Result**

Significant fraction of events with enhanced dijet asymmetry while simultaneously preserving the back-to-back angular correlation

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

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

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

First direct observation of jet quenching

**ATLAS**

**Columbia University in the City of New York**

**Thursday, February 7, 13**

[hep-ex/1210.6182]
Beyond Asymmetry

- Dijet asymmetry is striking signature of jet quenching but it is also difficult to understand quantitatively
  - Dependent on energy loss of two jets with path-length correlation
- Supplement the picture by studying inclusive quenching
  - Hard scattering rates in HI \( R_{AA}, R_{CP} \)
- Must decouple quenching from CNM effects
  - Check rates of color neutral processes:
    - \( \gamma, W^\pm \rightarrow \ell^\pm \nu_\ell, Z^0 \rightarrow \ell^+ \ell^- \)
    - Directly sensitive to NPDF
- Systematically map out dependence of energy loss
Clean measurement: Di-lepton mass distribution shows background near Z peak

Measurements in both e⁺e⁻ and μ⁺μ⁻ channels provide consistency check

\[ \langle N_{\text{coll}} \rangle \] – scaled yields show no significant centrality dependence for both channels and independent of \( p_T \)
Production rate consistent with $T_{AA}$-scaling both as a function of $p_T$, centrality and rapidity

"Model" is PYTHIA with cross section scaled by NNLO calculation and $\langle T_{AA} \rangle$
Measurement of isolated photons using double sideband technique

- Simultaneously apply isolation and “tight” shower requirements
- Correct for inefficiency and contamination

\[
\frac{(1/N_{\text{evt}}) dN/dp_T}{\langle T_{\text{AA}} \rangle} \text{ [pb/GeV]} = 10^7, 10^5, 10^3, 10, 10^{-1}, 10^{-3}, 10^{-5}, 10^{-7}
\]

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

\[
E_T(R_{\text{iso}}=0.3) \text{ [GeV]}
\]

\[
\text{Non-tight}
\]

\[
\text{HI Tight}
\]

\[
A \quad B
\]

\[
C \quad D
\]
Direct Photon Production Rates

\[ \langle T_{AA} \rangle \text{--scaled yield is consistent with NLO calculation (JETPHOX)} \]

No significant centrality or \( p_T \) dependence observed

\[ \langle T_{AA} \rangle \]

\( p_T \) dependence

\[ \text{Data/JETPHOX} \]

\( 0-10\% (+6) \)

\( 10-20\% (+4) \)

\( 20-40\% (+2) \)

\( 40-80\% \)

\( \text{ATLAS Preliminary} \)

\( \text{Pb+Pb} \sqrt{s_{NN}} = 2.76 \, \text{TeV} \)

\( L_{\text{int}} = 133 \, \mu\text{b}^{-1} \quad |\eta| < 1.3 \)
Jet Suppression

- 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

- Jets produced with different angles wrt to event plane (Δφ) will see different path lengths and density profiles in the medium
  ➡️ Measure single jet suppression as a function of Δφ: \( v_2^{\text{jet}} \)
Perform event-by-event subtraction per calorimeter cell in jet

\[ E_{Tj}^{\text{sub}} = E_{Tj} - A_j \rho_i(\eta_j) (1 + 2v_{2i} \cos [2(\phi_j - \Psi_2)]) \]

- Average, \( \eta \)-dependent background \( E_T \) density: \( \rho \)
- Elliptic flow modulation: \( \eta \) and \( \rho_T \) averaged \( v_2 \)
  \( \Rightarrow \) Jet energy unaffected by global elliptic flow

Two-step procedure to prevent jets from biasing subtraction

- Define jet “seeds” and exclude from \( \rho \) and \( v_2 \) determination
  - e.g. only blue cells included in \( \rho(\eta) \)
Results: $R_{CP}$ vs $\rho_T$ in Centrality Bins

$R = 0.2$  

$R = 0.4$

Result fully unfolded (SVD method) for finite jet energy resolution

Use 60–80 % as peripheral reference
Results: $R_{CP}$ vs $N_{part}$ in $p_T$ bins

- Centrality dependence as represented by $N_{part}$
- Suppression turns on differently for high and low $p_T$ jets
Results: $R_{CP}$ vs $R$

0–10% centrality

<table>
<thead>
<tr>
<th>$R_{CP}$</th>
<th>$p_T$</th>
</tr>
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<tbody>
<tr>
<td>0.2</td>
<td>38 p_T &lt; 44 GeV</td>
</tr>
<tr>
<td>0.3</td>
<td>50 p_T &lt; 58 GeV</td>
</tr>
<tr>
<td>0.4</td>
<td>89 &lt; p_T &lt; 103 GeV</td>
</tr>
<tr>
<td>0.5</td>
<td>158 &lt; p_T &lt; 182 GeV</td>
</tr>
</tbody>
</table>

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

89 < $p_T$ <103 GeV

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<tbody>
<tr>
<td>0.2</td>
<td>0–10% centrality</td>
</tr>
<tr>
<td>0.3</td>
<td>10–20%</td>
</tr>
<tr>
<td>0.4</td>
<td>30–40%</td>
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<tr>
<td>0.5</td>
<td>50–60%</td>
</tr>
</tbody>
</table>

$\text{ATLAS}$  
$\text{Pb+Pb} \sqrt{s_{NN}} = 2.76 \text{ TeV}$  
$\int L dt = 7 \mu b^{-1}$
Quantitative statement of $R$ dependence

\[
\frac{R_{CP}}{R_{CP}} = 0.2 \quad 0 - 10 \%
\]

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

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

ATLAS

- $R = 0.3$
- $R = 0.4$
- $R = 0.5$

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

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

- Many systematics cancel, correlated between different $R$
- Statistical correlation between different $R$ values included and propagated through unfolding
Results: $v_2$ vs $p_T$

\[ \int L \, dt = 0.14 \, \text{nb}^{-1} \quad 5 - 10\% \]

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

\[ \text{anti-}k_t \, R = 0.2 \quad 10 - 20\% \]

\[ \text{ATLAS preliminary} \]

\[ \text{Jet energy resolution (unfolded)} \]

\[ \text{EP resolution} \]

5% modulation in jet yield at low $p_T$, decreases with $p_T$ to ~1.5%
Results: $v_2$ vs $N_{\text{part}}$

Modulation is smallest in most central collisions where initial collision geometry is most symmetric
Conclusions: Hard Scattering Rates

- Production of color-neutral probes consistent with binary scaling, **three independent checks**: $Z \rightarrow e^+e^-$, $Z \rightarrow \mu^+\mu^-$ and $\gamma$
- Jets are **suppressed by factor of two** in central collisions and show no $p_T$ dependence for $38 < p_T < 210$ GeV
  - Roughly same as single particle $R_{AA}$ for $p_T > 30$ GeV
- Jets with larger $R$ show less suppression more so at low $p_T$
- Centrality dependence of suppression turns on differently for high and low $p_T$ jets
- **Significant modulation of jet yield** with respect to event plane
  - 5% at low $p_T$ decreasing to ~1.5% at 200 GeV
  - Modulation is smallest in most central collisions where initial collision geometry is most symmetric
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
\(\gamma\)-jet: \(x_J\) Distributions

\[ R = 0.2 \]

\[ R = 0.3 \]
γ-jet: Per photon yield

- Integrated yield of recoiling jets normalized per photon
- Suppression is caused by increased fraction of jets that do not fall in the $p_T$ range considered

$R_{Jγ}$ vs. $N_{part}$ for $R=0.2$ and $R=0.3$ at $\sqrt{s_{NN}}=2.76$ TeV.

- $R=0.2$ Data
- $R=0.2$ PYTHIA + Data
- $R=0.3$ Data
- $R=0.3$ PYTHIA + Data

ATLAS Preliminary

Pb+Pb $L_{int}=0.13$ nb$^{-1}$

$\sqrt{s_{NN}}=2.76$ TeV
**Z–jet Correlations**

**0–20% centrality**

ATLAS Preliminary
Pb+Pb $\sqrt{s_{NN}}=2.76$ TeV, $L_{int}=0.15$ nb$^{-1}$

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$^{-1}$

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
Jet Structure: Fragmentation Function

\[ D(z) = p_T \cos(\Delta R)/p_T^{\text{jet}} \]

\[ \text{ATLAS Preliminary} \]

\[ \text{Pb+Pb} \sqrt{s_{\text{NN}}} = 2.76 \text{ TeV} \]
\[ L_{\text{int}} = 0.14 \text{ nb}^{-1} \]

\[ \text{D}(z) \]

\[ \text{D}(p_T) \]

\[ p_T^{\text{jet}} > 100 \text{ GeV} \]
\[ p_T > 2 \text{ GeV} \]

\[ \text{ATLAS} \]

\[ \text{CONF-2012-115} \]

\[ \text{ATLAS Experiment} \]

\[ \text{IN THE CITY OF NEW YORK} \]
Similar trends in $D(z)$ and $D(p_T)$ distributions

- Enhancement at low $z/p_T$
- Suppression at moderate $z/p_T$
- High $p_T$ behavior may exhibit additional enhancement
Jet Structure: $R$ Dependence

$R = 0.2$

$R = 0.3$

$D(z)$

Behavior persists for smaller radii

$D(\rho_T)$

Robust against UE effects which increase with $R$
Looking forward

- ATLAS HI jet program just getting started

Roadmap
1) Qualitative understanding of quenching mechanism
2) Quantitative values of medium parameters
3) Study temperature evolution of parameters, especially near phase transition — RHIC is crucial for this!

Papers
- Dijet asymmetry
- Rates of color neutral probes (Z)
- Inclusive jet suppression and jet size dependence

Preliminary Results
- Rates of color neutral probes (γ/W)
- γ — and Z— jet correlations
- Azimuthal dependence of suppression (v_2 for jets)
- Fragmentation function
- Suppression of heavy flavor tagged jets
- Charged hadron R_{CP}

For complete ATLAS HI results see: https://twiki.cern.ch/twiki/bin/view/AtlasPublic/HeavyIonsPublicResults
Additional Slides
The dashed tracks are invisible to the detector.
Single hadron $R_{CP}$

**ATLAS** Preliminary
Pb+Pb $\sqrt{s_{NN}}=2.76$TeV
Data 2010 + 2011
$L_{\text{int}} = 0.15\text{nb}^{-1}$
Single hadron $R_{CP}$ : $\eta$ dependence

ATLAS Preliminary
Pb+Pb $\sqrt{s_{NN}}$=2.76TeV
Data 2010 + 2011
$L_{\text{int}} = 0.15\text{nb}^{-1}$
Invariant Yield: Prompt Muons

Pb+Pb \( \sqrt{s_{NN}} = 2.76 \) TeV
\(|\eta| < 1.05\)
\[ \int L \, dt = 7 \mu b^{-1} \]

- Use signal fraction to extract spectrum
- Muon reco efficiency correction applied

Error bars: uncorrelated combined statistical+systematic
• Generally flat with $p_T$ however statistical fluctuation in peripheral bin makes trend difficult to evaluate
Muon $R_{PC}$ vs $p_T$

- Can evaluate $R_{PC}$ instead
- Easier to see very flat $p_T$ dependence

\[ R_{PC} = \frac{\frac{1}{N_{coll}} \frac{1}{N_{evt}} \frac{dN}{dp_T}}{\frac{1}{N_{coll}} \frac{1}{N_{evt}} \frac{dN}{dp_T}} \bigg|_{0-10} - \bigg|_{\text{periph}} \]

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

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<th>$p_T$ [GeV]</th>
<th>$0.0$</th>
<th>$0.5$</th>
<th>$1.0$</th>
<th>$1.5$</th>
<th>$2.0$</th>
<th>$2.5$</th>
<th>$3.0$</th>
<th>$3.5$</th>
<th>$4.0$</th>
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<td>10-20% / 0-10%</td>
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<td>60-80% / 0-10%</td>
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Pb+Pb $\sqrt{s_{NN}} = 2.76$ TeV

$|\eta| < 1.05$

$\int L \, dt = 7 \, \mu b^{-1}$
Muon $R_{CP}$ vs $N_{part}$

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

**ATLAS** Preliminary

Pb+Pb

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

$|\eta| < 1.05$

- $4 < p_T < 5$ GeV
- $6 < p_T < 7$ GeV
- $8 < p_T < 9$ GeV
- $10 < p_T < 14$ GeV

$\langle N_{part} \rangle$
W Yields

\[ \int L \approx 5 \, \text{nb}^{-1} \quad \sqrt{s_{NN}} = 2.76 \, \text{TeV} \]

\[ R_{PC} \]

ATLAS Preliminary

Data 2010

Total uncertainty
Centrality

- Determined from FCal $E_T$ distribution, which is well correlated with total event activity

- Standard centrality definitions:
  - “central”: 0-60% divided into 6 10%
  - “peripheral” 60-80%

- $N_{\text{coll}}, N_{\text{part}}$ and uncertainties from Glauber

- $R_{CP}$ uses ratio: $R_{\text{coll}}^\text{cent} = \frac{\langle N_{\text{coll}}^{\text{cent}} \rangle}{\langle N_{\text{coll}}^{60-80} \rangle}$
• Apply IRC safe jet definition to measured $E_T$ distribution in calorimeter

• In addition to jet signal, also have contribution from underlying event (UE)

• **Define** jet measurement as energy **correlated** with single QCD hard scattering, need to separate from **uncorrelated** UE contribution

\[
\frac{dE_{T\text{total}}}{d\eta d\phi} = \frac{dE_{T\text{UE}}}{d\eta d\phi} + \frac{dE_{T\text{jet}}}{d\eta d\phi}
\]

• Construct estimate of UE background, subtract and run jet finding
  
  • Average depends strongly on centrality, must determine event-by-event
  
  • Must be modulated to include flow effects \[1 + 2v_2 \cos[2 (\phi - \Psi_2)]\]

• Jets must be excluded from the estimate of the background
Jet Reconstruction

- Define average background excluding cells $\Delta R < 0.4$ from jet

- Calculate event plane angle from FCal

$$\Psi_2 = \frac{1}{2} \tan^{-1}\left( \frac{\sum_k w_k E_{T,k} \sin(2\phi_k)}{\sum_k w_k E_{T,k} \cos(2\phi_k)} \right)$$

- Calculate $v_2$ per sampling layer:

$$v_{2i} = \frac{\sum_{j \in i} E_{T,j} \cos[2(\phi_j - \Psi_2)]}{\sum_{j \in i} E_{T,j}}$$

- Average over $\eta$ excluding bins within 0.4 of seeds

- Also reconstruct track jets, run anti-$k_t$ $R=0.4$ on particles $p_T > 4$ GeV
Jet Reconstruction: First Step

- Calculate $v_2$
- Run anti-$k_t$ with $R=0.4$ on tracks $p_T > 4$ GeV
- Run anti-$k_t$ with $R=0.2$ on unsubtracted $E_T$ distribution
- Define initial seeds as all jets with:
  - $D = \frac{\text{max(tower } E_T)}{\text{mean(tower } E_T)} > 4$
  - At least one tower $E_T > 3$ GeV
- Exclude from average background all cells within jet seeds
- Define a background, modulate by $v_2$, to build subtracted jets
- Apply jet energy scale calibration to subtracted jets
Jet Reconstruction: Second Step

- Use output of previous step to define new seeds:
  - Jets with $E_T > 25$ GeV
  - Track jets $p_T > 10$ GeV
  - Define new background excluding cells $\Delta R < 0.4$ from jets
  - Define new $v_2$:
    - Calculate $v_2$ in each $\eta$ bin (0.1)
    - Average over $\eta$ excluding bins within 0.4 of seeds
  - Run anti-$k_t$ $R=0.2$, 0.3, 0.4 and 0.5 on subtracted background
  - Calibrate jet energy scale
Reconstruction capabilities evaluated using MC
- Use PYTHIA dijets embedded into HIJING events
- Validated using data, extract systematics
• Matching between track jets and calo jets to study calorimetric response in MC and data
• Limits effects of possible medium-modified fragmentation on JES
• All values not shown 0.5%

<table>
<thead>
<tr>
<th>$R$</th>
<th>0 - 10 %</th>
<th>10 - 20 %</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.2</td>
<td>0.5 %</td>
<td>0.5 %</td>
</tr>
<tr>
<td>0.3</td>
<td>1.0 %</td>
<td>0.5 %</td>
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<tr>
<td>0.4</td>
<td>1.5 %</td>
<td>1.0 %</td>
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<tr>
<td>0.5</td>
<td>2.5 %</td>
<td>1.5 %</td>
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• JES uncertainty constant above 70 GeV (table)
• Grows linearly, doubling from its nominal value at 30 GeV
Performance: Jet Energy Resolution

- Extract “σ” through statistical RMS or Gaussian fit
- Low $E_T$: dominated by UE fluctuations
- High $E_T$: limited by intrinsic detector resolution
- Described by functional form:

$$\frac{\sigma(\Delta E_T)}{E_T} = \frac{1}{E_T} \left( a \sqrt{E_T} \oplus b \oplus c E_T \right)$$

- $a$: sampling fluctuations
- $c$: proportional to energy e.g. holes
- $b$: UE fluctuations

ATLAS simulation

anti-$k_t$ $R = 0.4$

$\sigma [\Delta E_T/E_T^{\text{truth}}]$ fit, 0-10%
$\sigma [\Delta E_T/E_T^{\text{truth}}]$ fit, 60-80%
$\langle \Delta E_T/E_T^{\text{truth}} \rangle$, 0-10%
$\langle \Delta E_T/E_T^{\text{truth}} \rangle$, 60-80%

Efficiency

$\langle \Delta E_T/E_T^{\text{truth}} \rangle$ or $\sigma [\Delta E_T/E_T^{\text{truth}}]$
Fluctuations Analysis

- Uncorrelated UE fluctuations underneath jet not subtracted
- Effect on jet spectrum corrected by unfolding
  - MC must provide accurate description of UE fluctuations
- Study distributions of $E_T$ sum in groups of rectangular groups of towers approximately same size as jets (e.g. 7x7 $\leftrightarrow$ R=0.4)
**Performance: Jet Energy Resolution**

- **Fixed by fluctuation analysis**

\[
\frac{\sigma(\Delta E_T)}{E_T} = \frac{1}{E_T} \left( a\sqrt{E_T} \oplus b \oplus cE_T \right)
\]

- **Free parameters in fit**
  - Fit results give a and c values in agreement for all centralities
  - Establishes quantitative relationship between UE fluctuations and \( \Delta E_T \) fluctuations (JER)

ATLAS simulation
- \( \sigma [\Delta E_T/ E_T^{\text{truth}} + \text{fit, 0-10\%}] \)
- \( \sigma [\Delta E_T/ E_T^{\text{truth}} + \text{fit, 60-80\%}] \)
- \( \langle \Delta E_T \rangle / E_T^{\text{truth}}, 0-10\% \)
- \( \langle \Delta E_T \rangle / E_T^{\text{truth}}, 60-80\% \)

Pb+Pb \( \sqrt{s_{NN}} = 2.76 \text{ TeV} \int L dt = 240 \text{ mb}^{-1} \)
Jet Reconstruction : Corrections

- Jet energy scale calibration factors obtained specifically for HI reconstruction
  - Cell energies are at “EM” scale
  - Response calibrated to EM deposition only
  - Apply multiplicative ($p_T$, $\eta$, $R$ dependent) JES factor
  - Derive using “Numerical Inversion” procedure, MC based
- Energy bias
  - If cells in final jets were not excluded by seeds, some (or all) of the jet’s energy will have biased the background
  - After selecting “good” jets (fake rejection) apply correction removing any biases these jets may have on background
Unfolding

- UE and detector effects result in finite JER
  - Jet spectrum is steeply falling
  - Result is significant bin migration
- Use MC to generate response matrix
  - Contains information about bin migration
- SVD unfolding
  - Invert response using curvature constraint on result to regularize unfolding
- Unfolding checks
  - Apply to MC, look for bias
  - “Refold” data, check refolded looks like input

Hocker and Kartvelishvili: hep-ph/9509307
Error Analysis: Statistical Errors

- Since unfolding involves bin migration there is non-trivial covariance matrix
- Use toy method to estimate statistical uncertainty
- Construct fluctuation of data using measured covariance
- Unfold “pseudo experiment”
- Repeat many times, calculate statistical covariance
- Apply same method to include statistical uncertainty in response matrix from MC
- Combine two covariance matrices as independent sources

\[
\rho_{ij} = \frac{\text{Cov}(Y_i, Y_j)}{\sqrt{\text{Var}(Y_i)} \sqrt{\text{Var}(Y_j)}}
\]

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

ATLAS

0 - 10 % Centrality

Thursday, February 7, 13
Overview of Systematic Uncertainties

- **JES**: Relative energy scale differences central and peripheral
- **JER**: Possible disagreement between data and MC in UE fluctuations

**Efficiency**: cover possible MC/data differences, 5% for $p_T < 100$ GeV

**$X_{ini}$**: Sensitivity to power in power law: $+0.5$, $-0.5$

**$R_{coll}$**: sensitive to centrality determination, $\sigma_{NN}$

**Regularization**: Sensitivity to choice of $k$: +/-1
Measured Yield Before Corrections

Red curve: fit to $1 + 2 v_2^\text{jet} \cos 2\Delta\phi$

5 - 10 % $\text{anti-}\kappa_t R = 0.2$
$60 < p_T < 80 \text{ GeV}$

10 - 20 %
$\int L \, dt = 0.14 \text{ nb}^{-1}$
$\sqrt{s_{NN}} = 2.76 \text{ TeV}$
$v_2^\text{jet} \bigg|_{\text{meas}} = 0.032 \pm 0.002$

20 - 30 %
$v_2^\text{jet} \bigg|_{\text{meas}} = 0.042 \pm 0.002$

30 - 40 %
$v_2^\text{jet} \bigg|_{\text{meas}} = 0.041 \pm 0.002$

40 - 50 %
$v_2^\text{jet} \bigg|_{\text{meas}} = 0.034 \pm 0.003$

50 - 60 %
$v_2^\text{jet} \bigg|_{\text{meas}} = 0.027 \pm 0.004$
Event Plane Resolution

ATLAS preliminary

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

2010 MB, $\int L \, dt = 8 \, \mu b^{-1}$

2011 jets, $\int L \, dt = 0.14 \, nb^{-1}$
Azimuthal Dependence of Jet Performance

\[ \langle \Delta p_T / p_T \rangle \]

- \( 45 < p_T < 60 \text{ GeV} \)
  - ATLAS preliminary simulation

- \( 60 < p_T < 80 \text{ GeV} \)
  - anti-\( k_t \), \( R = 0.2 \)
  - 10 - 20 \%

- \( 80 < p_T < 110 \text{ GeV} \)

\[ \sigma [ \Delta p_T / p_T ] \]

- \( 45 < p_T < 60 \text{ GeV} \)
  - ATLAS preliminary simulation

- \( 60 < p_T < 80 \text{ GeV} \)
  - anti-\( k_t \), \( R = 0.2 \)
  - 10 - 20 \%

- \( 80 < p_T < 110 \text{ GeV} \)
Overview of Systematic Uncertainties

ATLAS preliminary

anti-$k_t$ $R = 0.2$

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

$\int L \, dt = 0.14$ nb$^{-1}$

Jet energy resolution
Event plane resolution
Spectral shape

Error on $v_{2}^{jet}$ x 100

$50 - 100\%$

$30 - 40\%$

$10 - 20\%$

$40 - 50\%$

$20 - 30\%$

$50 - 60\%$

$p_T$ [GeV]
Systematic Uncertainties

• Both JER and JES uncertainties, fill response matrix with modified \((p_T^{\text{reco}}, p_T^{\text{truth}})\)

• Unfold with new response matrix, use difference from nominal result as error

\[
p_T^{\text{reco}} \rightarrow p_T^{\text{reco}}(1 + f(p_T^{\text{true}})) \quad f(p_T = 40) = 2f(p_T = 70)
\]

• **JES**: used MC closure, overlay and in-situ study

• **JER**: use fluctuation analysis, vary \(b \rightarrow b' = b(1 + g)\) to cover data/MC difference

  • \(g = 2.5\%, 2.5\%, 5\%, 7.5\%\) for \(R = 0.2, 0.3, 0.4\) and \(0.5\)

  • Use \(b'\) to calculate a new JER \(\sigma(b')\), rescale \(\Delta p_T = (p_T^{\text{truth}} - p_T^{\text{reco}})\)

\[
p_T^{\text{reco}} \rightarrow p_T^{\text{truth}} + (p_T^{\text{truth}} - p_T^{\text{reco}}) \frac{\sigma(b')}{\sigma(b)}
\]
Two-Jet Observables: Dijet Asymmetry

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

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

Contributions to second peak mostly from events where second jet consistent with background level

Updated from published result
**Dijet Asymmetry: \( R=0.2 \)**

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

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

Smaller \( R \) is less sensitive to background fluctuations.

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

Increasing jet energy stretches peak out

Peak at low values of $A_J$ restored in peripheral collisions
Dijet Angular Correlation

- $\Delta \phi$ distributions show (almost) no modification
- Contribution in tail likely due to combinatoric match with uncorrelated or fake low energy jet
- Rate is reduced for smaller $R$ value, consistent with lower fake rate for these jets

$\Delta \phi$ vs. $E_{T1}$, $E_{T2}$ for different centralities.

- Centrality 0-10%
  - $E_{T1} > 100$ GeV
  - $E_{T2} > 25$ GeV
  - $R = 0.4$

- Centrality 10-20%
  - $E_{T1} > 100$ GeV
  - $E_{T2} > 25$ GeV
  - $R = 0.2$

- Centrality 20-30%
  - $E_{T1} > 100$ GeV
  - $E_{T2} > 25$ GeV
  - $R = 0.4$

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

Pb+Pb Data

p+p Data
Photon Reconstruction

Non-tight

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HI Tight

| A | B |

Normalized counts

$E_T(R_{iso}=0.3)$ [GeV]

$0-10\%$

$E_T(R_{iso}=0.3)$ [GeV]

ATLAS Preliminary

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

$L_{int} = 133 \ \mu$b$^{-1}$

• Data

• PYTHIA+HIJING

Thursday, February 7, 13
Photon Performance

Efficiency

1-Purity

ATLAS Preliminary

Photon ID \( \in \) 40-80%
Photon ID \( \in \) 20-40%
Photon ID \( \in \) 10-20%
Photon ID \( \in \) 0-10%
Total \( \in \) 40-80%
Total \( \in \) 20-40%
Total \( \in \) 10-20%
Total \( \in \) 0-10%

\( p_T [\text{GeV}] \)

\( p_T [\text{GeV}] \)

\( \sqrt{s_{\text{NN}}} = 2.76 \text{ TeV} \)

\( L_{\text{int}} = 133 \mu b^{-1} \)

40-80%
20-40%
10-20%
0-10%