Measurements of Jet Suppression with ATLAS

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Parallel Session 2B
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Jets in Heavy Ion Collisions

- Jets provide a powerful tool for determining medium properties via jet quenching
- 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

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

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

From Nov. 2010 PRL ~ 2\(\mu\)b\(^{-1}\)

First direct observation of jet quenching

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Beyond Asymmetry

- Asymmetry sensitive to **differential** energy loss
- Can gain additional insight by considering **inclusive** energy loss
  - Single inclusive jet spectra and central to peripheral ratio $R_{CP}$
Beyond Asymmetry

- Asymmetry sensitive to **differential** energy loss
- Can gain additional insight by considering **inclusive** energy loss
  - Single inclusive jet spectra and central to peripheral ratio $R_{CP}$
- Medium-induced radiation can distribute jet’s energy outside cone

- Can lost energy be recovered by expanding jet size?

**Measure single jet suppression with multiple jet sizes**

He, Vitev, and Zhang hep-ph/1105.2566
Path Length Dependence

• Look at single inclusive jet production as a function of angle with respect to event plane

\[ \Delta \phi = \phi^{\text{jet}} - \Psi_2 \]

• Longer path length for jets with larger \( \Delta \phi \)

Measure single jet suppression as a function of \( \Delta \phi \)
The ATLAS Detector

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

- Perform **event-by-event subtraction** per calorimeter cell in jet

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

  - Average, \( \eta \)-dependent background \( E_T \) density: \( \rho \)
  - Elliptic flow modulation: \( \eta \) and \( \rho_T \) averaged \( v_2 \)

- **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
Jet Suppression: Single Inclusive Jets

- Performed with 2010 Pb+Pb data
  - Integrated luminosity of 7 \( \mu b^{-1} \), \( \sim 50 \) million events
- Use anti-\( k_t \) algorithm with \( R=0.2, 0.3, 0.4 \) and 0.5
  - \( | \eta | < 2.1, \ 38 < p_T < 210 \) GeV
  - Reject “fake” jets from UE by requiring a match to either
    - Track jets (reconstructed from charged particles) or
      electron/photon with \( p_T > 7 \) GeV
- Fully unfolded for experimental effects
  - SVD unfolding procedure

\[
R_{CP} = \frac{1}{N_{coll}} \frac{1}{N_{evt}} \frac{dN\ cent}{dp_T} \left| \begin{array}{c}
\frac{1}{N_{coll}} \frac{1}{N_{evt}} \frac{dN\ 60-80}{dp_T}
\end{array} \right|
\]

Submitted to PLB
arXiv:1208.1967
Unfolding

- $R_{CP}$

**ATLAS**

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

- $0 - 10 \%$

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

- $R = 0.2$, measured
- $R = 0.2$, corrected
- $R = 0.4$, measured
- $R = 0.4$, corrected

- 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

$\text{Columbia University IN THE CITY OF NEW YORK}$
Results: $R_{CP}$ vs $p_T$ in Centrality Bins

ATLAS

$R_{CP}$ vs $p_T$ for $0 - 10\%$, $10 - 20\%$, $30 - 40\%$, and $50 - 60\%$ centrality bins.

ATLAS

$R_{CP}$ vs $p_T$ for $0 - 10\%$, $10 - 20\%$, $30 - 40\%$, and $50 - 60\%$ centrality bins.

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

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

$\text{anti-}k_t R = 0.2$

$\text{anti-}k_t R = 0.4$
Results: $R_{CP}$ vs $N_{part}$ in $p_T$ Bins

- **Correlated:** JES, efficiency, $x_{ini}$, $R_{coll}$
- **Partially correlated:** regularization, JER
- Error bars: sqrt of diagonal elements of covariance matrix
- Horizontal width of boxes, $N_{part}$ uncertainty

\[ \text{ATLAS} \]
- $38 < p_T < 44 \text{ GeV}$
- $50 < p_T < 58 \text{ GeV}$
- $67 < p_T < 77 \text{ GeV}$

\[ \text{89} < p_T < 103 \text{ GeV} \]
- $119 < p_T < 137 \text{ GeV}$
- $158 < p_T < 182 \text{ GeV}$

\[ \int_L dt = 7 \text{ } \mu \text{b}^{-1} \] \[ \sqrt{s_{NN}} = 2.76 \text{ TeV} \]
Results: $R_{CP}$ vs $R$

**ATLAS**

- **0-10 % Centrality**
  - $158 < p_T < 182$ GeV
  - $89 < p_T < 103$ GeV
  - $50 < p_T < 58$ GeV
  - $38 < p_T < 44$ GeV

- Fixed centrality, 0-10%.
- Different $p_T$ bins

- Fixed $p_T$, 89 -103 GeV.
- Different centrality bins

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

$\int L \, dt = 7 \mu$b$^{-1}$
Quantitative Statement of $R$ Dependence

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

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

ATLAS

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

$R_{\text{CP}}^R / R_{\text{CP}}$ vs. $p_T$ [GeV]

0 - 10 %
Conclusions: Inclusive Jet Measurements

- In central collisions, jets suppressed by factor of two relative to peripheral
  - Flat in $p_T$, $R_{CP} \sim 0.5$ for $38 < p_T < 210$ GeV
  - Roughly same as single particle $R_{AA}$ for $p_T > 30$ GeV
- $R$ dependence
  - Jets with larger $R$ show less suppression
  - More $R$ dependence at lower $p_T$
    - Qualitatively consistent w/ existing calculation (Vitev et al.)
- Centrality/$N_{\text{part}}$ dependence
  - Suppression turns on differently for high and low $p_T$ jets
Jet Suppression: Azimuthal Dependence

- Extend 2010 measurement by measuring
  - Suppression as a function of angle wrt EP:
  - Amplitude of modulation: \( \nu_2^{jet} \)
- Performed with 2011 Pb+Pb data
  - Integrated luminosity of 0.14 nb\(^{-1} \)
- Use anti-\( k_t \) algorithm with \( R=0.2 \)
  - \( |\eta| < 2.1, 45 < p_T < 210 \) GeV
  - Apply fake rejection
- Correct experimental effects
  - JER: bin-by-bin unfolding, appropriate for smaller jet radii
  - EP resolution

\[
R_{\Delta \phi} = \frac{\frac{d^2 N_{jet}}{dp_T d\phi} \mid_{\Delta \phi = \Delta \phi_i}}{\frac{d^2 N_{jet}}{dp_T d\phi} \mid_{\Delta \phi = \Delta \phi_j}}
\]
Measured Yield Before Corrections

**Red curve:** fit to $1 + 2 v_2^{\text{jet}} \bigg|_{\text{meas}} \cos 2\Delta\phi$

**ATLAS preliminary**

$N_{\text{jet}} \frac{d^2 p_T}{d\phi_{\text{jet}}} \frac{d\phi}{d\phi_{\text{jet}}}$

$5 - 10\%$  
$\Delta\phi$  
$60 < p_T < 80 \text{ GeV}$

$0.016 \pm 0.002$

$10 - 20\%$

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

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

$0.032 \pm 0.002$

$20 - 30\%$

$0.042 \pm 0.002$

$30 - 40\%$

$0.041 \pm 0.002$

$40 - 50\%$

$0.034 \pm 0.003$

$50 - 60\%$

$0.027 \pm 0.004$

**ATLAS EXPERIMENT**

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In the City of New York
Results: $R_{\Delta \phi}$ vs $p_T$

\[ R_{\Delta \phi} = \frac{\frac{d^2 N_{\text{jet}}}{dp_T d\phi} |_{\Delta \phi = \Delta \phi_i}}{\frac{d^2 N_{\text{jet}}}{dp_T d\phi} |_{\Delta \phi = \Delta \phi_j}} \]

Suppression relative to “in-plane” : $0 \leq \Delta \phi < \frac{\pi}{8}$

*ATLAS preliminary*

a

anti-$k_t$ $R = 0.2$

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

$\int L \, dt = 0.14 \, \text{nb}^{-1}$
Results: $v_2$ vs $p_T$

\[ \int L \, dt = 0.14 \, \text{nb}^{-1} \quad \text{5 - 10 \%} \]
\[ \text{Pb+Pb} \, \sqrt{s_{NN}} = 2.76 \, \text{TeV} \]

ATLAS preliminary

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

\[ \text{20 - 30 \%} \]

\[ \text{50 - 60 \%} \]
**Results: $v_2$ vs $N_{\text{part}}$**

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

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

\[ \text{anti-}k_t \, R = 0.2 \]

**ATLAS preliminary**

- $45 < p_T < 60 \, \text{GeV}$
- $60 < p_T < 80 \, \text{GeV}$
- $80 < p_T < 110 \, \text{GeV}$
- $110 < p_T < 160 \, \text{GeV}$
Conclusions: Azimuthal Dependence

- Jets are suppressed by up to 15% out-of-plane relative in-plane
- Relative suppression decreases with $p_T$
- 5% modulation in jet yield at low $p_T$, decreases with $p_T$ to ~1.5%
- Modulation is smallest in most central collisions where initial collision geometry is most symmetric
Additional Slides
Detecting Particles
ATLAS Calorimeter

$|\eta| < 1.0$

- Tile barrel
- Tile extended barrel

$0.8 < |\eta| < 1.7$

$1.5 < |\eta| < 3.2$

- LAr hadronic end-cap (HEC)
- LAr electromagnetic end-cap (EMEC)

$3.2 < |\eta| < 4.9$

- LAr forward (FCAL)
- LAr electromagnetic barrel
  $|\eta| < 1.5$
Perceived Problems with Jet Measurements

- Uncorrelated UE fluctuations present under jet even after subtraction
- UE fluctuations from soft particles can be reconstructed as jets (fakes)
- Quenched jets may have different particle composition and fragmentation than unquenched jets in MC
Uncorrelated UE fluctuations present under jet even after subtraction

Need accurate MC description (HIJING) to:

- Provide asymmetry baseline
- Correct for JER/unfolding in jet spectrum

Check with fluctuations study

- Use groups of towers approximately the same size as jets (e.g. Area $R=0.4$ jet ~ Area 7x7 tower group)
- Sum $E_T$ in each window and look at distribution
Uncorrelated UE fluctuations present under jet even after subtraction

- Check with fluctuations study
- Use groups of towers approximately the same size as jets (e.g. Area $R=0.4$ jet ~ Area 7x7 tower group)
- Sum $E_T$ in each window and look at distribution

See ATLAS-CONF-2012-045
http://cdsweb.cern.ch/record/1440894
UE fluctuations from soft particles can be reconstructed as jets (fakes)

- Worse for larger $R$, contribute up to $\sim 80$ GeV
- Require additional signal of hard particle production
  - Reject fakes by requiring jet to match:
    - Track jets or EM clusters with $p_T > 7$ GeV
  - Residual fake rate estimated to be $\sim 3\%$ at 50 GeV
Quenched jets may have different particle composition and fragmentation than unquenched jets in MC

- Jet energy scale calibrations expect “normal” jets (vacuum fragmentation)
- Quenching effects could introduce centrality dependence in jet energy scale
- Track jet energy scale independent of centrality
- Use track jet/calo jet matching to provide data-driven check by comparing relative energy scale
  
  \[ \langle E_{T^{\text{calo}}} \rangle \text{ as function of } E_{T^{\text{trackjet}}} \]

- Differences in JES < 3%, included in systematic uncertainties
Event Selection

- 2010 Pb Pb 2.76 TeV data
- All good runs/lumi blocks with solenoidal field on
- Minimum bias event selection:
  - ZDC coincidence trigger
    - L1_ZDC_AND or L1_ZCD_A_C
  - MBTS timing: $\Delta t_{\text{MBTS}} < 3\,\text{ns}$
  - Good reconstructed vertex
- After selection: 51 million events, $\int L\,dt = 7\mu b^{-1}$
- Event selection cuts estimated to be 2% inefficient
  - Included in centrality determination
- Solenoidal field off data not used $\sim 1\mu b^{-1}$
**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%

- $N_{coll}$, $N_{part}$ and uncertainties from Glauber
  - $R_{CP}$ uses ratio: $R_{coll}^{cent} = \frac{\langle N_{coll}^{cent} \rangle}{\langle N_{coll}^{60-80} \rangle}$
Jets In Heavy Ion Collisions

- 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: 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:
  • $D = \max(\text{tower } E_T)/\text{mean(\text{tower } E_T}) > 4$
  • 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

- 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: 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
Monte Carlo Sample

- **Truth jets**: run anti-$k_t$ on particles from MC event generators

- **Reconstructed jets**: apply GEANT detector simulation, reconstruct as in data

- Jet performance studies and corrections derived from three samples
  - **HIJING only**: used in estimates of fake rate
  - **HIJING+PYTHIA**: Jet performance, response matrices
    - HIJING events with a PYTHIA jet event embedded per event
    - For each truth jet, find nearest reconstructed jet within $\Delta R < 0.2$
Analysis Details: Single Inclusive Jets

- UE fluctuations of soft particles can be reconstructed as jets
  - Worse for larger $R$, contribute up to $p_T \sim 80$ GeV
  - Remove by requiring additional signal consistent with hard particles
  - **Reject fakes** by requiring jet match ($\Delta R < 0.2$):
    - track jet or an EM cluster with $p_T > 7$ GeV
  - Rate for fake jets after rejection estimated to be ~2% at 50 GeV
- For the spectrum analysis require jets to have $|\eta| < 2.1$
  - Measurement performed on range $38 < p_T < 210$ GeV
  - Total number of jets in sample:
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>
</tr>
<tr>
<td>0.4</td>
<td>1.5 %</td>
<td>1.0 %</td>
</tr>
<tr>
<td>0.5</td>
<td>2.5 %</td>
<td>1.5 %</td>
</tr>
</tbody>
</table>

JES uncertainty constant above 70 GeV (table)

Grows linearly, doubling from its nominal value at 30 GeV
## JES Uncertainty

<table>
<thead>
<tr>
<th>$R$</th>
<th>0.2</th>
<th>0.3</th>
<th>0.4</th>
<th>0.5</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-10</td>
<td>0.5%</td>
<td>0.5%</td>
<td>0.5%</td>
<td>0.5%</td>
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<td>10-20</td>
<td>0.5%</td>
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<td>20-30</td>
<td>0.5%</td>
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<td>30-40</td>
<td>0.5%</td>
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<td>40-50</td>
<td>0.5%</td>
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<tr>
<td>50-60</td>
<td>0.5%</td>
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</tbody>
</table>
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:

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

$\Rightarrow$ **a**: sampling fluctuations $\Rightarrow$ centrumy independent
$\Rightarrow$ **b**: UE fluctuations $\Rightarrow$ centrumy dependent
$\Rightarrow$ **c**: proportional to energy e.g. holes
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. $7\times7 \leftrightarrow R=0.4$)
Performance: Jet Energy Resolution

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

- Fit results give a and c values in agreement for all centralities
- Establishes quantitative relationship between UE fluctuations and \(\Delta E_T\) fluctuations (JER)
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 ($\rho_T$, $\eta$, $R$ 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
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

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

ATLAS

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

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

0 - 10 % Centrality

\[ \text{anti-} k_t, R = 0.2 \]

\[ \text{anti-} k_t, R = 0.3 \]

\[ \text{anti-} k_t, R = 0.4 \]

\[ \text{anti-} k_t, R = 0.5 \]
Overview of Systematic Uncertainties

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

- **Efficiency**: cover possible MC/data differences, 5% for $p_T < 100$ GeV.
- **$X_{\text{ini}}$**: Sensitivity to power in power law: $+0.5$, $-0.5$.
- **$R_{\text{coll}}$**: sensitive to centrality determination, $\sigma_{NN}$.
- **Regularization**: Sensitivity to choice of $k$:+/-1.

**Graph Details**:
- $\delta R_{\text{CP}}$ [%]
- $p_T$ [GeV]
- $\int L \, dt = 7 \, \mu b^{-1}$
- $\sqrt{s_{NN}} = 2.76$ TeV
- ATLAS
- Pb+Pb
- $R = 0.4$
- 0-10%
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$^{-1}$
Dependence of Jet Performance

\[ \langle \frac{\Delta p_T}{p_T} \rangle \]

\[ 45 < p_T < 60 \text{ GeV} \]

\[ \sigma[\frac{\Delta p_T}{p_T}] \]

\[ 45 < p_T < 60 \text{ GeV} \]

\[ \text{ATLAS preliminary simulation} \]

\[ 60 < p_T < 80 \text{ GeV} \]

\[ \text{ATLAS preliminary simulation} \]

\[ \text{anti-}k_t, R = 0.2 \]

\[ 10 - 20 \% \]

\[ 80 < p_T < 110 \text{ GeV} \]

\[ \text{anti-}k_t, R = 0.2 \]

\[ 10 - 20 \% \]
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
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

- **JES**: used MC closure, overlay and in-situ study
  \[
  p_T^{\text{reco}} \rightarrow p_T^{\text{reco}} (1 + f(p_T^{\text{true}})) \quad f(p_T = 40) = 2f(p_T = 70)
  \]
  - Includes background subtraction effects and differences in fragmentation

- **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: \( R=0.2 \)

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

\( E_{T1} > 100 \text{ GeV} \)
\( E_{T2} > 25 \text{ GeV} \)

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

**ATLAS Preliminary**

<table>
<thead>
<tr>
<th>Centrality</th>
<th>$E_T^1 &gt; 100$ GeV</th>
<th>$E_T^2 &gt; 25$ GeV</th>
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</thead>
<tbody>
<tr>
<td>0-10%</td>
<td>$R=0.4$</td>
<td>$R=0.2$</td>
</tr>
<tr>
<td>10-20%</td>
<td>$R=0.2$</td>
<td>$R=0.4$</td>
</tr>
<tr>
<td>20-30%</td>
<td>$R=0.4$</td>
<td>$R=0.2$</td>
</tr>
<tr>
<td>30-40%</td>
<td>$R=0.2$</td>
<td>$R=0.4$</td>
</tr>
<tr>
<td>40-60%</td>
<td>$R=0.4$</td>
<td>$R=0.2$</td>
</tr>
<tr>
<td>50-60%</td>
<td>$R=0.2$</td>
<td>$R=0.4$</td>
</tr>
<tr>
<td>60-70%</td>
<td>$R=0.4$</td>
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</tr>
<tr>
<td>70-80%</td>
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<td>$R=0.4$</td>
</tr>
</tbody>
</table>

**Parameters**

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

**Data Sources**

- HIJING + PYTHIA
- Pb+Pb Data
- p+p Data