Angular correlations of jets in lead-lead collisions at 2.76 TeV using the ATLAS detector

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Quark Matter 2014, May 21, 2014
Jets in Heavy Ion Collisions

- Jets provide a powerful tool to probe the hot and dense medium created in HI collisions.
- RHIC's measurements of single high $p_T$ particles: the first evidence for jet quenching.
- A significant modification of di-jet and photon-jet $p_T$-balance and suppression of inclusive jet spectra with increasing collision centrality is observed at the LHC.
  - The single jet measurements are sensitive to the average energy loss.
  - The dijet measurements probe differences in the quenching between the two parton showers.
Jets in Heavy Ion Collisions

- The purpose of this analysis is to study properties of final state with neighbouring jets.
- It may help to disentangle the contributions of path length and fluctuations to the quenching.
- It may provide more detailed insight on the modification of the parton shower in the quark gluon plasma.
The ATLAS Detector
Jet Reconstruction at ATLAS

- Reconstruction algorithm: anti-$k_t$ with $R=0.2$, 0.3 and 0.4.
- Input: calorimeter towers $0.1 \times 0.1$ ($\Delta \eta \times \Delta \phi$).
- Event-by-event background subtraction:
  \[ E_{Tj}^{\text{sub}} = E_{Tj} - A_j \rho_i(\eta_j) (1 + 2v_{2i} \cos[2(\phi_j - \Psi_2)]) \]
- Jets corrected for flow contribution.
- Anti-$k_t$ reconstruction prior to the background subtraction.
- Underlying event estimated for each longitudinal layer and $\eta$ slice separately.
- Jet candidates are excluded with requirement $D = \frac{E_{T\text{max}}}{\langle E_{T\text{max}} \rangle} > 4$ to avoid bias of the UE determination.
- Additional iteration step to remove residual effect of the jets on the background estimation.
Two data samples were used:

- Pb+Pb data recorded in 2011 using jet triggers with integrated luminosity of 0.14 nb\(^{-1}\).
- Pb+Pb data recorded in 2011 using Minimum Bias (MB) with integrated luminosity of 7 \(\mu\)b\(^{-1}\).

Jet trigger algorithm required a \(R = 0.2\) jet with \(E_T > 20\) GeV.

All events were required to satisfy MB events selection: good timing and vertex.

Data are compared to MC, where MC Pythia di-jet events were embedded into real MB Pb+Pb events.
Neighbouring jet production

- Measured variable is defined as

\[ R_{\Delta R} = \frac{1}{dN_{\text{jet}}^\text{test} / dE_T^\text{test}} \sum_{i=1}^{N_{\text{jet}}^\text{test}} \frac{dN_{\text{jet},i}^\text{nbr}}{dE_T^\text{test}}(E_T^\text{test}, E_T^{\text{nbr}, \Delta R}) \]

- The rate of the neighbouring jets that accompany a test jet with given \( E_T^\text{test} \).

- Two different binning logics are used:
  - Minimum \( E_{T,\text{min}}^{\text{nbr}} \)
  - Minimum \( E_{T,\text{min}}^{\text{test}} \)

\[ \frac{dR_{\Delta R}}{dE_T^{\text{nbr}}} = \frac{\Delta R_{\Delta R}}{\Delta E_T^{\text{nbr}}}(E_T^{\text{test}}, E_T^{\text{nbr}}, \Delta R) \]

- The centrality dependence is studied by evaluation central to peripheral ratios \( \rho_{R_{\Delta R}} \).
Neighbouring jet production

Analysis bins:

- **3 jet sizes**: \( R = 0.2, 0.3 \) and 0.4 jets
- **5 bins** in the test jet transverse energy \( (E_{t}^{\text{test}}) \)
- **4 bins** in the neighbouring jet transverse energy \( (E_{T}^{\text{nbr}}) \).
- Four centrality bins: 0 - 10% - 20% - 40% - 80%
- The size of the annulus: \( \Delta R_{\text{min}} < \Delta R < 1.6 \), where
  - \( \Delta R_{\text{min}} = 0.8 \) (\( R = 0.4 \) jet)
  - \( \Delta R_{\text{min}} = 0.6 \) (\( R = 0.3 \) jets)
  - \( \Delta R_{\text{min}} = 0.5 \) (\( R = 0.2 \) jets)
Standard HI event selection criteria

“fake” jets (from UE fluctuations) were identified and rejected by requirement of matching calorimeter jet to a track jet or electro-magnetic cluster with $E_T > 7$ GeV.

Measurement is restricted to $|\eta| < 2.8$.

The annulus size restricts the position of test jets to $|\eta| < 1.2$.

Jet $E_T$ was corrected to reduce the effect of the jet up-feeding due to JER.
Two independent hard scatterings may result in an additional contribution to the yield of neighbouring jets. (Significant cross-section in Pb+Pb collisions).

A subtraction of such combinatoric contribution is needed:

\[ R_{\Delta R} = R_{\Delta R}^{raw} - R_{\Delta R}^{combi} \]

We benefit from Pythia to overlay data here.
Two independent hard scatterings may result in an additional contribution to the yield of neighbouring jets. (Significant cross-section in Pb+Pb collisions).

A subtraction of such combinatoric contribution is needed:

$$R_{\Delta R} = R_{\Delta R}^{raw} - R_{\Delta R}^{combi}$$

Minimum Bias events are used to estimate yield of combinatoric neighbouring jets in the annulus. (Correction for the effect when two neighbouring jets overlap is applied.)
Analysis flow

- Bin-by-bin unfolding is used to correct for bin migration due to the finite JER.
- It also corrects for efficiency and for the migration inside and outside the annulus.

Efficiency and bin-by-bin correction factors

**ATLAS simulation** Preliminary
Pb+Pb MC
$\sqrt{s_{NN}} = 2.76$ TeV

<table>
<thead>
<tr>
<th>$E_T^{\text{test}}$</th>
<th>0.8&lt;(\Delta R)&lt;1.6</th>
<th>anti-(k_T)</th>
<th>d=0.4</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-10%</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>10-20%</td>
<td></td>
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<td></td>
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<tr>
<td>20-40%</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>40-80%</td>
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</tr>
</tbody>
</table>

Subtracted \(R_{\Delta R}\)

Unfolded \(R_{\Delta R}\)
**Systematic Uncertainties**

- The measurement is dominated by the statistical uncertainty.

- Systematic uncertainties due to:
  - Jet Energy Scale
  - Jet Energy Resolution
  - Jet Angular Resolution
  - Unfolding
  - Trigger
  - MC non-closure

### Maximal systematic uncertainties

<table>
<thead>
<tr>
<th>Source</th>
<th>$\delta R_{AR}$ 0–10%</th>
<th>$\delta R_{AR}$ 40–80%</th>
<th>$\delta R_{SR}$ 0–10%</th>
</tr>
</thead>
<tbody>
<tr>
<td>JES</td>
<td>12%</td>
<td>6%</td>
<td>5%</td>
</tr>
<tr>
<td>JER</td>
<td>4%</td>
<td>2%</td>
<td>2%</td>
</tr>
<tr>
<td>Angular resolution</td>
<td>2%</td>
<td>0.5%</td>
<td>2%</td>
</tr>
<tr>
<td>Unfolding</td>
<td>6%</td>
<td>2%</td>
<td>5%</td>
</tr>
<tr>
<td>MC</td>
<td>5%</td>
<td>5%</td>
<td>5%</td>
</tr>
<tr>
<td>Trigger</td>
<td>5%</td>
<td>–</td>
<td>5%</td>
</tr>
</tbody>
</table>

ATLAS Preliminary

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

Pb+Pb 2011

anti-$k_T$, $d=0.4$

$0.8 < \Delta R < 1.6$

$E_T^{\text{test}} > 70$ GeV

Centrality: 0–10%
The distribution exhibits a monotonic increase with increasing $E_T^{\text{test}}$. This is consistent in shape with the previous measurement by D0 (arXiv:1207.4957). Suppression from peripheral to central collisions is observed.
The central to peripheral ratio does not exhibit any strong dependence on the test jet $E_T$.

The suppression factor in the most central collisions is at the level of 0.5-0.7 for all three thresholds on $E_T^{nbr}$.

The suppression becomes less pronounced with decreasing centrality.

This is qualitatively consistent with the observation of the centrality dependent suppression of inclusive jet yields.
Yields of neighbouring jets

The similar trends of the suppression can be seen. But less pronounced than for the ratio evaluated as a function of test jet $E_T$. 

- [Image of graphs showing the yields of neighbouring jets for different values of $R$.]
Yields of neighbouring jets were fitted by a power-law fit. The spectral index was extracted and summarized as a function of the centrality for different jet collections.

<table>
<thead>
<tr>
<th></th>
<th>0-10%</th>
<th>10-20%</th>
<th>20-40%</th>
<th>40-80%</th>
</tr>
</thead>
<tbody>
<tr>
<td>$R = 0.4$</td>
<td>$2.66 \pm 0.23$</td>
<td>$2.72 \pm 0.22$</td>
<td>$2.93 \pm 0.15$</td>
<td>$3.29 \pm 0.21$</td>
</tr>
<tr>
<td>$R = 0.3$</td>
<td>$2.75 \pm 0.21$</td>
<td>$2.45 \pm 0.20$</td>
<td>$2.95 \pm 0.16$</td>
<td>$3.23 \pm 0.19$</td>
</tr>
<tr>
<td>$R = 0.2$</td>
<td>$2.76 \pm 0.19$</td>
<td>$2.58 \pm 0.19$</td>
<td>$2.67 \pm 0.17$</td>
<td>$3.00 \pm 0.20$</td>
</tr>
</tbody>
</table>

Indication of a change in the $E_T^{\text{nbr}}$ spectral shape from peripheral to central collisions.

The significance is limited due to limited statistics of available data sample.
The central to peripheral ratio evaluated as a function of $E_T^{nbr}$ suggests a decrease of suppression with increasing $E_T^{nbr}$.

Such a decrease of suppression may in fact be expected:
- Two partons have similar energy and similar in-medium path-length.
- In the configuration of $E_T^{nbr} \sim E_T^{test}$ the per test jet normalization effectively removes the impact of the suppression.
Conclusions

- We have studied the production of neighbouring jets in HI collisions.
- Centrality dependence is observed in data:
  - $R_{\Delta R}$ is the lowest for central collisions.
  - Significant suppression from peripheral to central collisions when test jet $E_T$ is different from the neighbouring jet $E_{nbr}$.
  - The central to peripheral ratio evaluated as a function of $E_T^{nbr}$ suggests a decrease of suppression with increasing $E_T^{nbr}$.
  - Indication of a change in the $E_T^{nbr}$ spectral shape from peripheral to central collisions.
- The suppression does not exhibit any strong dependence on the test jet $E_t^{test}$. (qualitatively consistent with the measurement of the inclusive jet suppression)
Impact of various corrections

\[ \frac{dR_{\Delta R}}{dE_T^{\text{nbr}}} \text{ [GeV}^{-1}] \]

- **ATLAS** Preliminary
- Pb+Pb 2011
- \( \sqrt{s_{\text{NN}}} = 2.76 \text{ TeV} \)
- \( L_{\text{int}} = 0.14 \text{ nb}^{-1} \)
- \( E_T^{\text{test}} > 80 \text{ GeV} \)
- \( 30 < E_T^{\text{nbr}} < 45 \text{ GeV} \)
- \( 0.8 < \Delta R < 1.6 \)
Yields of neighbouring $R=0.4$ jets in the MC

- Very good agreement in different centrality bins.
Performance of the Jet Reconstruction

**ATLAS simulation** Preliminary
Pb+Pb MC
\[ s_{NN} = 2.76 \text{ TeV} \]

- \( E_T^{\text{test}} > 90 \text{ GeV} \)
- \( 0.5 < \Delta R < 1.6 \)
- anti-\( k_T \) \( d=0.2 \)

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

**ATLAS simulation** Preliminary
\( E_T^{\text{test}} > 90 \text{ GeV} \)
\( 0.5 < \Delta R < 1.6 \)
anti-\( k_T \) \( d=0.2 \)
Centrality

- Characterize centrality by percentile of total cross-section using total $E_T$ measured in Forward Calorimeter ($3.2<|\eta|<4.9$).

- Centrality → number of participants $N_{\text{part}}$ and binary collisions $N_{\text{coll}}$ determined with the default Glauber analysis.
Performance of the Jet Reconstruction

- Performance is evaluated using pp hard scattering events from Pythia overlying on top of MB Pb+PB events.