Measurement of momentum flow relative to the dijet system in PbPb and pp collisions

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Motivation

- Increase in asymmetry of dijet pairs in central events
  - Translates into 10% decrease of $<p_{T,2}/p_{T,1}>$
  - $\Delta p_{T} \approx 10\text{ GeV}/c$ more compared to leading jet

- Balance is not recovered inside a cone of $\Delta R<0.8$.
- $\text{PbPb}$ Dijet imbalance is balanced by out-of-cone low $p_T$ particles

NEW

- Measurement of missing $p_T$ differential in $\Delta R$
- What is the angular shape, $p_T$ composition and multiplicity of the balancing spectrum?
Datasets and event selection

DATA

**pp**
- 2.76 TeV
- 5.3 pb$^{-1}$
- High $p_T$ trigger
  - A jet with $p_T > 80$ GeV/c
- Track reconstruction:
  - 7 iterations,
    $p_T > 0.2$ GeV/c
- Jet reconstruction
  - Anti-$k_T$ Calo $R=0.3$

**PbPb**
- 2.76 TeV
- 150 μb$^{-1}$
- High $p_T$ trigger
  - A jet with $p_T > 80$ GeV/c
- Track reconstruction:
  - 3 iterations,
    $p_T > 0.4$ GeV/c
- Jet reconstruction
  - Anti-$k_T$ Calo $R=0.3$
  - HF/Voronoi subtraction

MC

- PYTHIA simulation with same reconstruction as pp data.
- PYTHIA sample embedded into a HYDJET background with heavy ion reconstruction as in PbPb data.

• **Dijet selection:**
  - $p_{T,1} > 120$ GeV/c
  - $p_{T,2} > 50$ GeV/c
  - $|\eta_1|, |\eta_2| < 1.6$ (0.5)
  - $\Delta\phi > 5\pi/6$

• **Charged particles:**
  - $p_T > 0.5$ GeV/c
  - $|\eta| < 2.4$

Yue Shi Lai
Poster Session
Yesterday
Performance of HF/Voronoï UE subtraction

Sum of $E_T$ of UE subtracted calo towers that fall in $R=0.3$ in random directions in MB events:

Mean random cone $E_T$ as a function of $\eta$:

Good agreement between data and MC

Deviation from zero $<0.5$-1 GeV

CMS-PAS-HIN-14-010
Track corrections

• Tracks are corrected for reconstruction efficiency, fake rate (both in pp and PbPb) and secondary particles (in pp).

• After the corrections reconstructed track distributions agree with generator-level charged particle distributions in:
  – $\eta$
  – $\phi$
  – $p_T$
  – Distance to a jet axis
  – centrality
Multiplicty difference

Direction of the dijet is defined as:

\[ \phi_{\text{dijet}} = \frac{1}{2}(\phi_1 + (\pi - \phi_2)) \]

Different than in PRC 84 (2011) 024906 where the axis of projection is the leading jet direction.

This change provides UE cancellation differential in \( \Delta R \).

What is the **multiplicity** of particles that balance the “extra” lost \( p_T \)?

\[ \Delta_{\text{mult}} = \begin{array}{c}
\text{Number of charged particles in hemisphere 2} \\
\text{Subleading jet}
\end{array} - \begin{array}{c}
\text{Number of charged particles in hemisphere 1} \\
\text{Leading jet}
\end{array} \]
Results - Multiplicity difference vs. $A_J$

Multiplicity difference (in acceptance) increases as a function of $A_J$.

- The increase is larger in PbPb.
- The enhancement in PbPb compared to pp increases with centrality.
  - Large $A_J$, 0-10% → 15 extra particles.

$A_J = (p_{T,1} - p_{T,2})/(p_{T,1} + p_{T,2})$
What is the multiplicity and spectrum of particles that balance the “extra” lost $p_T$?

Calculate the missing $p_T$ for charged particles in different $p_T$ ranges

$$\nu_T^\parallel = \sum_i -p_T^i \cos (\phi_i - \phi_{Dijet})$$
Results - Missing $p_T$ vs. $A_J$

- Access to high $p_T$ particles increases as a function of $A_J$
- In pp $\rightarrow$ Balanced by 2-8 GeV/c particles
- In PbPb $\rightarrow$ Balanced by particles with $p_T < 2$ GeV/c
What is the **angular distribution** of these particles with respect to the dijet system?

Calculate the missing $p_T$ for charged particles that fall in slices of $\Delta R$:

$$p_T^\parallel = \left( \sum_i -p_T^i \cos (\phi_i - \phi_{\text{dijet}}) \right) |R_{\text{down}} < \Delta R < R_{\text{up}}$$

$$\Delta R = \sqrt{\Delta \phi_{\text{Trk,jet}}^2 + \Delta \eta_{\text{Trk,jet}}^2}$$
Results - Missing $p_T$ vs. $\Delta R$

Inclusive $A_J$

High $p_T$ imbalance at small $\Delta R$

Balanced by low $p_T$ particles in subleading jet direction

Extends up to large $\Delta R$
Results - Missing $p_T$ vs. $\Delta R$

CMS-PAS-HIN-14-010

Already small enhancement of low $p_T$ charged particles
Results - Missing $p_T$ vs. $\Delta R$

Enhancement of low $p_T$ particles

PbPb 0-30%

PbPb –pp

Larger imbalance in PbPb

$A_J > 0.22$
Results - Missing $p_T$ vs. $\Delta R$

Difference in missing $p_T$ in pp and PbPb above $\Delta R=0.4$ is $<1$ GeV.

$|\eta_1,|\eta_2|<0.50, A_J > 0.22$

$|\eta_{\text{tr}}|<2.4, \Delta \phi_{1,2}>5\pi/6$

$p_{T,1}>120, p_{T,2}>50$ GeV/c
Results - Missing $p_T$ vs. $\Delta R$

Shape of the balancing distribution in pp and PbPb is very similar

$A_J > 0.22$
Results - Missing $p_T$ vs. $\Delta R$

Shape of the balancing distribution in pp and PbPb is very similar.

After matching the missing $p_T$ at $\Delta R<0.2$
Summary

• The dijet in-cone momentum imbalance is compensated by:
  – PbPb: Low $p_T$ charged particles (0.5-2 GeV/c)
  – pp: Particles in the $p_T = 2$-8 GeV/c range

• A larger multiplicity of associated particles is seen in PbPb compared to pp.

• Small $\Delta R$ imbalance is balanced by low $p_T$ particles in large $\Delta R$. The excess of low $p_T$ particles goes up to $\Delta R=1.8$.

• The angular shape of the balancing distribution agrees in PbPb and pp within systematic uncertainties, but the composition in $p_T$ is different.
Projection axis choice

**Leading jet axis**

- $\Delta\phi_{1,2} \neq \pi$ → Projection of $p_T$ of charged particles in small $\Delta R$ near subleading jet is smaller than those near leading jet

**Dijet axis**

- Restores the symmetry of particles near leading and subleading jet → UE cancels by azimuthal symmetry
Track corrections

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Arbitrary units

PYTHIA+HYDJET
HI Tracking

PYTHIA
pp Tracking

Ratio

CMS Preliminary
Simulation

\[ \text{gen. particle} \]
\[ \text{reco. trk} \]
\[ \text{corrected trk} \]

\( p_T \) (GeV/c)
Jet $p_T$ scale and resolution comparison

Earlier subtraction algorithm

HF/Voronoi subtraction

CMS-PAS-HIN-14-010

CMS-HIN-12-004
• One can observe non-zero total missing $p_T$ in generator level PYTHIA.
The reconstruction effects are slightly different for PYTHIA and PYTHIA+HYDJET, because of the different jet and track reconstruction used.
Generator-level overall missing $p_T$

CMS-PAS-HIN-14-010

- Missing $p_T$ in truth level

**PYTHIA:**
- for all charged particles with $p_T > 0.5$ GeV/c within $|\eta|<2.4$
- for all charged particles with $p_T > 0.5$ GeV/c without $|\eta|<2.4$ selection
- for all charged particles without $p_T > 0.5$ GeV/c selection within $|\eta|<2.4$ selection
- For all charged particles
Summary of systematics (1)

Multiplicity difference \( v. A_J \)

<table>
<thead>
<tr>
<th>Jet reco and selection</th>
<th>pp</th>
<th>PbPb 50 - 100%</th>
<th>PbPb 30 - 50%</th>
<th>PbPb 10 - 30%</th>
<th>PbPb 0 - 10%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Track reco.</td>
<td>0.8</td>
<td>0.5 - 1.0</td>
<td>0.5 - 1.0</td>
<td>1.0</td>
<td>1.0</td>
</tr>
<tr>
<td>Residual JES</td>
<td>0.5</td>
<td>0.5</td>
<td>0.5</td>
<td>0.8</td>
<td>1.0</td>
</tr>
<tr>
<td>Residual track corr.</td>
<td>0.2 - 0.7</td>
<td>0.1 - 0.7</td>
<td>0.1 - 1.0</td>
<td>0.1 - 1.2</td>
<td>0.1 - 1.5</td>
</tr>
<tr>
<td>Event selection</td>
<td>&lt; 0.1</td>
<td>&lt; 0.1</td>
<td>&lt; 0.1</td>
<td>&lt; 0.1</td>
<td>&lt; 0.1</td>
</tr>
<tr>
<td>HCAL noise</td>
<td>&lt; 0.1</td>
<td>&lt; 0.1</td>
<td>&lt; 0.1</td>
<td>&lt; 0.1</td>
<td>&lt; 0.1</td>
</tr>
<tr>
<td>Pile-up</td>
<td>&lt; 0.2</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

Total Systematics: 1.1 - 1.5, 1.1 - 1.3, 1.2 - 1.7, 2.8 - 3.0, 3.3 - 3.5

JES, JER, fake jets, swapping of lead sublead jet

Missing p_T \( v. A_J \)

<table>
<thead>
<tr>
<th>Jet reco.</th>
<th>pp (GeV/c)</th>
<th>PbPb 50 - 100% (GeV/c)</th>
<th>PbPb 30 - 50% (GeV/c)</th>
<th>PbPb 10 - 30% (GeV/c)</th>
<th>PbPb 0 - 10% (GeV/c)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2 - 5</td>
<td>3 - 4</td>
<td>3 - 5</td>
<td>2 - 3</td>
<td>2 - 4</td>
<td></td>
</tr>
<tr>
<td>0.5 - 2</td>
<td>1 - 4</td>
<td>2 - 4</td>
<td>1 - 3</td>
<td>1 - 3</td>
<td></td>
</tr>
<tr>
<td>2.1 - 5.4</td>
<td>4.1 - 5.7</td>
<td>3.6 - 6.4</td>
<td>2.2 - 4.2</td>
<td>2.2 - 5.0</td>
<td></td>
</tr>
<tr>
<td>0.5</td>
<td>1.0</td>
<td>0.5</td>
<td>0.5</td>
<td>0.5</td>
<td></td>
</tr>
<tr>
<td>0.2</td>
<td>0.5</td>
<td>0.4</td>
<td>0.6</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Total Systematics: 2.2 - 5.5, 4.3 - 5.8, 3.7 - 6.5, 2.4 - 4.3, 2.4 - 5.1

Nonclosure in track correction
### Summary of systematics (2)

#### Missing $p_T$ v. $\Delta R$ for pp

<table>
<thead>
<tr>
<th>$\Delta R$</th>
<th>$&lt; 0.2$</th>
<th>$0.2 - 0.8(1.2)$</th>
<th>$&gt; 0.8(1.2)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$A_j$ All</td>
<td>4</td>
<td>5</td>
<td>10</td>
</tr>
<tr>
<td>Jet reco.</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Track reco.</td>
<td>0.5</td>
<td>1.25</td>
<td>0.1</td>
</tr>
<tr>
<td>Residual JES</td>
<td>0.5</td>
<td>0.5</td>
<td>0.2</td>
</tr>
<tr>
<td>Residual track corr.</td>
<td>0.1</td>
<td>0.2</td>
<td>0.5</td>
</tr>
<tr>
<td>Pile-up</td>
<td>0.1</td>
<td>0.2</td>
<td>0.5</td>
</tr>
<tr>
<td>Total</td>
<td>4.1</td>
<td>5.2</td>
<td>10.4</td>
</tr>
</tbody>
</table>

#### Missing $p_T$ v. $\Delta R$ for PbPb

<table>
<thead>
<tr>
<th>$\Delta R$</th>
<th>$&lt; 0.8(1.2)$</th>
<th>$0.2 - 0.8(1.2)$</th>
<th>$&gt; 0.8(1.2)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$A_j$ All</td>
<td>5</td>
<td>5</td>
<td>10</td>
</tr>
<tr>
<td>Jet reco.</td>
<td>1.5</td>
<td>1</td>
<td>3</td>
</tr>
<tr>
<td>Track reco.</td>
<td>0.5</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>Residual JES</td>
<td>0.8</td>
<td>0.5</td>
<td>1.5</td>
</tr>
<tr>
<td>Residual track corr.</td>
<td>0.8</td>
<td>0.5</td>
<td>1.5</td>
</tr>
<tr>
<td>Total</td>
<td>5.3</td>
<td>5.2</td>
<td>10.8</td>
</tr>
</tbody>
</table>

#### Missing $p_T$ v. $\Delta R$ for PbPb-pp

<table>
<thead>
<tr>
<th>$\Delta R$</th>
<th>$&lt; 0.2$</th>
<th>$0.2 - 0.8(1.2)$</th>
<th>$&gt; 0.8(1.2)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$A_j$ All</td>
<td>2</td>
<td>1.5</td>
<td>2</td>
</tr>
<tr>
<td>Jet reco.</td>
<td>1.5</td>
<td>1</td>
<td>1.5</td>
</tr>
<tr>
<td>Track reco.</td>
<td>2.2</td>
<td>1.8</td>
<td>2.5</td>
</tr>
<tr>
<td>Total reco.</td>
<td>0.2</td>
<td>0.3</td>
<td>0.3</td>
</tr>
<tr>
<td>Residual JES</td>
<td>0.4</td>
<td>0.2</td>
<td>0.4</td>
</tr>
<tr>
<td>Residual track corr.</td>
<td>0.4</td>
<td>0.2</td>
<td>0.4</td>
</tr>
<tr>
<td>Pile-up</td>
<td>0.1</td>
<td>0.2</td>
<td>0.5</td>
</tr>
<tr>
<td>Total</td>
<td>2.2</td>
<td>1.8</td>
<td>2.5</td>
</tr>
</tbody>
</table>

*Uncorrelated combination*
Motivation

**pp collisions**

Compare pp and PbPb to constrain the energy loss mechanisms responsible of the enhancement of fraction of large $A_J$ events in PbPb.

**PbPb collisions**

What is the angular distribution of these particles with respect to the dijet system?

What is the spectrum and multiplicity of particles that balance the “extra” lost $p_T$ by subleading jet compared to leading jet?
What is the **multiplicity** and spectrum of particles that balance the “extra” lost $p_T$?

$$\phi_{\text{dijet}} = \frac{1}{2}(\phi_1 + (\pi - \phi_2))$$

$$\Delta_{\text{mult}} = N_{\text{trk}}^{\text{corr}} [\Delta \phi_{\text{dijet,trk}} > \pi/2] - N_{\text{trk}}^{\text{corr}} [\Delta \phi_{\text{dijet,trk}} < \pi/2]$$

$\Delta_{\text{mult}}$ = Number of charged particles in hemisphere 2 - Number of charged particles in hemisphere 1

Near Subleading jet  
Near Leading jet
Results - Multiplicity difference vs. $\Delta p_{T,1,2}$

- Similar trend as a function of leading and subleading jet $p_T$ difference
Large $A_J$ selection enhances the fraction of subleading jets with significant energy loss.
Results - Missing $p_T$ vs. $\Delta R$

Larger imbalance in PbPb

Enhancement of low $p_T$ particles

$|\eta_1, \eta_2|<0.50, A_J > 0.22$

$|\eta_{uk}|<2.4, \Delta \phi_{1,2} > 5\pi/6$

$p_{T,1}>120, p_{T,2}>50$ GeV/c

$A_J > 0.22$
Results - Missing $p_T$ vs. $\Delta R$

- $|\eta_1,|\eta_2|<0.50, A_J > 0.22$
- $|\eta_{tk}|<2.4, \Delta \phi_{1,2}>5\pi/6$
- $p_{T,1}>120, p_{T,2}>50$ GeV/c

$\phi_{dijet}$, $\phi_1$, $\phi_2$
In-cone missing $p_T$
Out-of-cone missing $p_T$

- pp 5.3 pb$^{-1}$
- PbPb 150 μb$^{-1}$
- PbPb 0-30%

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

- Out-of-Cone, $0.8 < \Delta R$
- PbPb - pp 30-100%
- PbPb - pp 0-30%

- $p_T^{\text{trk}} (|\eta|<2.4)$
  - 0.5 - 1.0
  - 1.0 - 2.0
  - 2.0 - 4.0
  - 4.0 - 8.0
  - 8.0 - 300.0
  - $> 0.5$

- $p_{T,1} > 120$ GeV/c
- $|\eta_1|,|\eta_2|<1.6$

- $p_{T,2} > 50$ GeV/c
- $\Delta\phi_{1,2} > 5\pi/6$