Angular distributions of the quenched energy flow from dijets with different radius parameters in CMS

Quark Matter 2015
Kobe, Japan
On behalf of the CMS experiment at the LHC
Observation of Dijet Asymmetry in PbPb

\[ A_J = \frac{p_{T,1} - p_{T,2}}{p_{T,1} + p_{T,2}} \]

- Modification observed of \( A_J \) in central PbPb
- Where does the momentum go? (Far from the cone)
- To study: characterize missing \( p_T \) incrementally in \( \eta-\phi \)
Samples and Selection

- **pp**: 5.3 pb\(^{-1}\) at 2.76 TeV
- Single Jet 80 GeV Trigger
  - Fully efficient at 120 GeV

- **PbPb**: 166 µb\(^{-1}\) at 2.76 TeV
- Single Jet 80 GeV Trigger
  - Fully efficient at 120 GeV

**Dijet selection:**
- \(p_T^{1} > 120\) GeV
- \(p_T^{2} > 50\) GeV
- \(|\eta^{1}|, |\eta^{2}| < 1.6 (0.6)\)
- \(\Delta\phi^{1,2} > 5\pi/6\)

**Track Selection:**
- \(p_T > 0.5\) GeV
- \(|\eta| < 2.4\)

anti-\(k_t\) calorimeter jets (See backup slide 21)

Corrected for efficiency/fake rate (See backup slides 20,22)
Analysis: The Dijet Axis

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

Flip subleading jet and bisect axes

\[ \Delta = \sqrt{(\eta_{\text{trk}} - \eta_{\text{jet}})^2 + (\phi_{\text{trk}} - \phi_{\text{jet}})^2} \]
Analysis: Binning Tracks by $\Delta$

![Graph showing binning tracks by $\Delta$](image)

- **Leading** Hemisphere
- **Subleading** Hemisphere

$\langle p_T^\parallel \rangle = -c_{\text{trk}} \times p_{T,\text{trk}} \times \cos(\phi_{\text{trk}} - \phi_{\text{dijet}})$

- Leading side
- Track here contributes to Leading side

CMS (2.76 TeV)

- $5.3 \text{ pb}$
- $< 0.22$
Analysis: Binning Tracks by $\Delta$

First bin $\Delta$

$$\Delta = \sqrt{(\eta_{trk} - \eta_{jet})^2 + (\phi_{trk} - \phi_{jet})^2}$$
Analysis: Binning Tracks by $\Delta$

$\Delta = \sqrt{(\eta_{trk} - \eta_{jet})^2 + (\phi_{trk} - \phi_{jet})^2}$

Increasing $\Delta \rightarrow$ Move away from leading and subleading jets

Second bin $\Delta$

Subleading

Leading
Analysis: Binning Tracks by $\Delta$

\[ \Delta = \sqrt{(\eta_{\text{trk}} - \eta_{\text{jet}})^2 + (\phi_{\text{trk}} - \phi_{\text{jet}})^2} \]

Third bin $\Delta$

Subleading

Leading

Annuli eventually cover entire event
**Missing $P_T$ vs. $\Delta$ with $R = 0.3$ (All $A_J$)**

- Asymmetry is balanced in central PbPb by low $p_T$ particles through large angles
- Characterized finely in $\Delta$ increments of 0.2
Missing $P_T$ and Jet Radius

- Jet shape differences in Gen. PYTHIA for different $R$

- Shifting third jet position in Gen. PYTHIA relative to subleading jet
Multiple R Missing $P_T$ vs. $\Delta$

**CMS**

**$A_J$ Inclusive**

- **$\langle P_T^{\parallel} \rangle$**
- **$\langle P_T^{\perp} \rangle$**

**pp**

$R = 0.2$

$5.3 \text{ pb}^{-1} (2.76 \text{ TeV})$

$PbPb$ (0-30%)

$R = 0.2$

$166 \mu\text{b}^{-1} (2.76 \text{ TeV})$

$PbPb - pp$

$R = 0.2$

**CMS-HIN-14-010-PUB**

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### A_{J} Inclusive

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<td>PbPb R = 0.5</td>
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#### Zoom of Top Panels

- **pp (0-30%)**
- **PbPb - pp**

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**Zoom on pp and PbPb Distributions (I)**

CMS Inclusive $A_J$ Jet; 0-30% $p_{T,1} > 120; p_{T,2} > 50$ GeV $l_1 l_2 < 0.6; \Delta \phi_{1,2} > \pi/6$

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<th>pp R = 0.4</th>
<th>pp R = 0.5</th>
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<td>PbPb R = 0.5</td>
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</tbody>
</table>

**CMS-HIN-14-010-PUB**

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Zoom on pp and PbPb Distributions (II)

**AJ Inclusive**

- Subleading side peak shifts outward in $\Delta$ from 0.2->0.5
- Third jet possible position pushed out with R increase
pp and PbPb Cumulative Curves (I)

**A_J Inclusive**

**pp**

**PbPb (0-30%)**

**PbPb - pp**

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**Compare Curves**

- **CMS**
- **A_J Inclusive**
- **anti-k_t Jet; 0-30%**
- **p_{T,1} > 120; p_{T,2} > 50 GeV**
- **ln|t_1|, ln|t_2| < 0.6; Δφ_{1,2} > 5π/6**

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**CMS-HIN-14-010-PUB**

**pp R = 0.2**

**pp R = 0.3**

**pp R = 0.4**

**pp R = 0.5**

**PbPb R = 0.2**

**PbPb R = 0.3**

**PbPb R = 0.4**

**PbPb R = 0.5**

**PbPb - pp R = 0.2**

**PbPb - pp R = 0.3**

**PbPb - pp R = 0.4**

**PbPb - pp R = 0.5**

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pp and PbPb Cumulative Curves (II)

- Curve difference between PbPb and pp primarily in first bin $\Delta$
- For all $R$, curves very similar between PbPb and pp with $\Delta > 0.2$
  - Total missing $p_T$ variation with $R$ parameter in pp matched by PbPb
- Constituent composition of missing $p_T$ differs between systems
Difference of PbPb and pp (I)

**A\_J Inclusive**

**pp**

**PbPb (0-30%)**

**PbPb - pp**

**Zoom —— of Difference**

CMS-HIN-14-010-PUB
• High $p_T$ change in first bin $\Delta$ from $R=0.2 \rightarrow 0.5$ within systematic
• Low $p_T$ excess increases in both magnitude and angle with $R=0.2 \rightarrow 0.5$
  • Final “catch-all” bin increase suggests longer tail
Summary and the Future

- Missing $p_T$ finely characterized through large angles $\Delta$
  - Different dijet configurations were sampled by R variation
- Cumulative curves similar to first order for all jet R
  - Modification primarily of constituents carrying momentum
- Increased statistics of Run2 -> precise mapping for models
Backup
Impact of Tracking Cuts on Missing $P_T$

 CMS Preliminary

Simulation

no $p_T$ or $\eta$ cut

$|\eta|<2.4$

$p_T>0.5$ GeV/c

$|\eta|<2.5$, $p_T>0.5$ GeV/c

$\Delta\phi>5\pi/6$, $|\eta_1|,|\eta_2|<1.6$

CMS-HIN-14-010-PAS

$\langle p_T^\parallel\rangle$ (GeV/c)

$A_J$

PYTHIA

Generator-level $R = 0.3$

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Jet Reconstruction with HF/Voronoi Algorithm

- **UE at mid-\(\eta\) mapped by energy deposition at forward-\(\eta\)**
- **Equalization removes negative energy towers**
  - Shifted from surrounding positive energy towers
- **An energy correction based on fragmentation is applied to minimize bias from non-linear calorimeter response**
  - Applied to pp and PbPb
• Define tracking correction on track-by-track basis as:

\[ c_{\text{trk}} = \frac{(1 - \text{misreconstruction}) \times (1 - \text{secondary-particle})}{(\text{efficiency}) \times (1 + \text{multiple-reconstruction})} \]

• Correct for efficiency/fake rate (+ secondary/multiple reco. in pp)
• Iterative tracking corrections in \( p_T \), \( \phi \), \( \eta \), centrality, and minimum jet distance
## Summary of Systematics

\( R = 0.2/0.4/0.5 \)

<table>
<thead>
<tr>
<th>( \Delta )</th>
<th>( R = 0.2 )</th>
<th>( R = 0.4 )</th>
<th>( R = 0.5 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jet reconstruction</td>
<td>&lt; 0.2 0.2–2.0</td>
<td>&lt; 0.2 0.2–2.0</td>
<td>&lt; 0.2 0.2–2.0</td>
</tr>
<tr>
<td>Data/MC differences for JES</td>
<td>1 0.1–0.4</td>
<td>1 0.1–0.5</td>
<td>1 0.1–0.7</td>
</tr>
<tr>
<td>Fragmentation dependent JES</td>
<td>2 0.1–0.5</td>
<td>2 0.1–0.4</td>
<td>2 0.1–0.3</td>
</tr>
<tr>
<td>Track corrections</td>
<td>1 0.1–0.4</td>
<td>1 0.1–0.3</td>
<td>1 0.1–0.3</td>
</tr>
<tr>
<td>Data/MC differences for tracking</td>
<td>2 0.2–0.7</td>
<td>2 0.1–1.1</td>
<td>2 0.1–1.1</td>
</tr>
<tr>
<td>Total</td>
<td>3 0.2–0.9</td>
<td>3 0.3–1.1</td>
<td>3 0.2–1.1</td>
</tr>
</tbody>
</table>
3rd Jet Position in Gen. PYTHIA

Gen. PYTHIA

$p_{T,3} > 30 \text{GeV/c}$

$\Delta_{2,3}$

Event Fraction

$R=0.2$

$R=0.3$

$R=0.4$

$R=0.5$
Gen. PYTHIA Jet Shapes

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

$|\eta_1|,|\eta_2|<1.6$

$\Delta\phi>5\pi/6, p_T^{\text{particle}}>0.5$ GeV/c

leading jet
Missing \( P_T \) vs. \( \Delta \) with \( R = 0.3 \) (\( A_J < 0.22 \))

**Scale Change**

(Decrease)

\[ \Delta \]

\[ T \]

\[ \Delta \]

\[ 0.5 - 1.0 \]

\[ 1.0 - 2.0 \]

\[ 2.0 - 4.0 \]

\[ 4.0 - 8.0 \]

\[ 8.0 - 300.0 \]

\[ h_{\text{trk}} | < 2.4 \]

\[ h_{l,1}, h_{l,2} | < 0.6; \Delta \phi_{l,2} > 5\pi/6 \]

\[ P_T,1 > 120; P_T,2 > 50 \text{ GeV} \]

**CMS**

\[ \text{pp} \]

\[ \text{PbPb 30-100\%} \]

\[ \text{PbPb 0-30\%} \]

\[ \text{CMS-HIN-14-010-PUB} \]
Missing $p_T$ vs. $\Delta$ with $R = 0.3$ ($A_J > 0.22$)

- Low $p_T$ particles enhanced by cut on $A_J > 0.22$
- Cumulative curves track despite scale change
Missing $P_T$ vs. $A_J$ with $R = 0.3$
• Multiplicity excess towards subleading side shows centrality and A_J dependence
Multiple $R$ Missing $P_T$ vs. $\Delta$ ($A_J > 0.22$)

$A_J > 0.22$

CMS

$\langle |p_T^{||} - p_T^\Delta| \rangle$ [$\text{GeV}$]

- $0.5-1.0$
- $1.0-2.0$
- $2.0-4.0$
- $4.0-8.0$
- $8.0-300.0$

$|\ln|l_1l_2| < 2.4; \Delta \phi > 5\pi/6$

Anti-$k_t$, Jet; 0-30%

$P_{T,1} > 120; P_{T,2} > 50$ GeV

CMS-HIN-14-010-PUB

CMS
Multiple $R$ Missing $P_T$ vs. $\Delta$ ($A_J > 0.22$)

$A_J > 0.22$

$pp$ →

PbPb (0-30%)

PbPb - pp →

CMS-HIN-14-010-PUB
Multiple R Missing P_T vs. A_J

CMS

anti-k, Jet; 0-10% \[ p_{T,1} > 120; p_{T,2} > 50 \text{ GeV} \]
\[ \eta_{1,2} < 1.6; \Delta \phi_{1,2} > 5\pi/6 \]

\[ \langle p_T^{\perp} \rangle_{\text{trk}} \text{ [GeV]} \]

\[ \langle p_T^{\perp} \rangle_{\text{trk}} \text{ [GeV]} \]

\[ \eta \mid \eta < 2.4 \]

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dN/dp_T for all R

- Potential R dependence in low p_T contribution (0.5-1.0 GeV)
- R = 0.2 -> R = 0.5 difference slightly greater than summed statistical and systematic error