Heavy Flavor Jet with CMS

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for the CMS Collaboration

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Motivation for heavy flavor jets

• In PbPb collisions:
  – Energy loss via jet quenching phenomenon.
  – Different interactions in quark-gluon-plasma depend on mass of quark
  – A measurement of heavy flavor jet could provide the info of flavor-dependent energy loss and probe the content of jet quenching

• In pPb collisions:
  – Quantification of cold nuclear matter effects for heavy-flavor jet in PbPb.
Heavy flavor jet identification

- **b** quark has long life time and decay length
- The flight distance ($L_{xyz}$) is used as discriminating variable
- The displacement of jet tracks used as a cross-check
- **c** jets identification is similar but with additional selection to enhance the **c** jets purity
Calculating the heavy flavor jet fraction

\[ E_b = \frac{C_b f_{b}^{btag} N_{jets}^{btag}}{f_{b}^{untagged} N_{jets}^{untagged}} \]  \[1\]

\[ N_{jets}^{b} = N_{jets}^{total} f_{b}^{btag} \]  \[2\]

- Purity calculated via template fits to secondary vertex mass
- Efficiency calculated using template fit before and after flavor tagging

PRL 113:132301(2014)
b jet and c jet in 5 TeV pPb collisions

- No enhancement for jets in pPb with respect to pp for heavy flavor jet
- No significant CNM effects in heavy flavor jet jet production is observed
b jet suppression in 2.76 TeV PbPb collisions

- Larger suppression in more central collisions
- Suppression at the level of inclusive jet
- b dijet measurement dominant by flavor creation process might provide more info for energy loss flavor dependence

PRL 113:132301(2014) ; CMS PAS HIN-12-004
Dijet momentum imbalance measurement

- anti-$k_T$ Particle Flow $R=0.4$ jets

- UE subtraction with iterative noise/pedestal subtraction

- Dijet selection:
  - $|\eta|<1.5$
  - $p_{T,1}>100$ GeV/c
  - $p_{T,2}>40$ GeV/c
  - $\Delta\phi_{1,2}>2\pi/3$

- Dijet momentum imbalance
  - $X_J=p_{T,2}/p_{T,1}$
b-tagging in PbPb collisions at 5 TeV

• Combined Secondary Vertex discriminator is constructed by vertex and track information to identify b dijets

• The working point is selected to obtain 90% pure sample

• Tagging efficiency corrections are applied in : $p_T$, $\eta$, Centrality

• ~10% contamination is taken into account as a systematic uncertainty

CMS PAS HIN-16-005, CDS:2202805
Data/PYTHIA discrepancy is found in b dijet momentum imbalance.

After reweighting, Data/PYTHIA in agreement

FCR in analysis selection 53% → 70%

Similar conclusion in CDF PRD71 (2005) 092001
• Combinatorial background removed with sideband method
Inclusive and b dijet imbalance in 5 TeV PbPb collisions

**pp**

PbPb 30-100%

PbPb 10-30%

PbPb 0-10%

**Inclusive dijets**

**b dijets**

CMS PAS HIN-16-005

Cheng-Chieh Peng

Hard Probe 2016
The imbalance of b dijets has been observed for the first time.

The increase of imbalance of inclusive dijets from pp to central PbPb collisions has been confirmed at 5TeV.

Inclusive dijet and b dijet imbalance are within uncertainty.
Summary

• Both b jets and b dijets measurement in PbPb collisions are on the same level as inclusive jet
  – No significant flavor-dependent energy loss is observed

• b jets and c jets $R_{pA}^{PYTHIA}$ measurement in pPb collision are consistent with unity
  – No significant CNM effects is observed
• C-Tagging uses 3-prong secondary vertex to lower the misidentification rate wrt to light Jets.

• Use Corrected Secondary Vertex Mass:

\[ M_{\text{corr}} = \sqrt{M^2 + p^2 \sin^2 \theta_1 + p \sin \theta_1} \]

• Attempts to restore Mass from missing energy.
Comparison to Inclusive-Jets

CMS

Nuclear Modification Factor

CMS Preliminary

PLB 754:59; PRL 113:132301

arXiv: 1601.02001, CDS: 1472722
Parton mass-dependent effects are small at high-$p_T$ – consistent with pQCD prediction.

No significant Flavor-dependent energy loss has been found.

Rpa Result consistent with pQCD predictions of small CNM effects.
The following set of variables with high discriminating power and low correlations is used:

- the vertex category (real, “pseudo,” or “no vertex”);
- the 2D flight distance significance;
- the vertex mass;
- the number of tracks at the vertex;
- the ratio of the energy carried by tracks at the vertex with respect to all tracks in the jet;
- the pseudo-rapidity of the tracks at the vertex with respect to the jet axis;
- the 2D IP significance of the first track that raises the invariant mass above the charm threshold of 1.5 GeV when subsequently summing up tracks ordered by decreasing IP significance;
- the number of tracks in the jet;
- the 3D signed IP significances for each track in the jet
b jet Production Mechanism

Flavor Creation (FCR)
- Gluon fusion or $qq$ annihilation
- Heavy quarks are back-to-back

Flavor Excitation (FEX)
- Sea $bb$ pair is excited by gluon or light quark
- Heavy quark is back-to-back with light parton

Gluon Splitting (GSP)
- Gluon splits into $bb$
- Small angle between heavy quarks
Flavor process reweighting

• Reweight the flavor process based on the difference of MC and Data in three Categories:
  • $|\Delta\phi_{1,2}|>2\pi/3$ : The two highest $p_T$ jets are b-tagged and back-to-back
  • $|\Delta\phi_{1,3}|>2\pi/3$ : The first and third highest $p_T$ jets are b-tagged and back-to-back
  • $|\Delta\phi_{1,3}|<\pi/3$ : The first and third highest $p_T$ jets are b-tagged and nearby

<table>
<thead>
<tr>
<th>Category</th>
<th>FCR</th>
<th>FEX</th>
<th>GSP</th>
</tr>
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<tbody>
<tr>
<td>$</td>
<td>\Delta\phi_{1,2}</td>
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<td>57%</td>
</tr>
<tr>
<td>$</td>
<td>\Delta\phi_{1,3}</td>
<td>&gt;2\pi/3$</td>
<td>11%</td>
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<td>\Delta\phi_{1,3}</td>
<td>&lt;\pi/3$</td>
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<table>
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<tr>
<th>Category</th>
<th>MC</th>
<th>Data</th>
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<td>$</td>
<td>\Delta\phi_{1,3}</td>
<td>&lt;\pi/3$</td>
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</table>
Dijet $\Delta \phi$ after reweighting

CMS Preliminary

25.8 pb$^{-1}$ (5.02 TeV pp)

anti-$k_T$ PF Jets, R=0.4

$p_{T,1}>100$ GeV, $p_{T,2}>40$ GeV

b-tagged

\[ \sigma(|\Delta \phi|)_{\text{data}} = 0.244 \pm 0.005 \]
\[ \sigma(|\Delta \phi|)_{\text{MC}} = 0.314 \pm 0.008 \]

Data - MC

| $|\Delta \phi|$ | 0 | 0.5 | 1 | 1.5 | 2 | 2.5 | 3 |
|----------------|---|----|---|----|---|----|---|
| Data - MC      | -0.06 | -0.04 | 0 | 0.02 | 0.04 | 0.06 | 0 |

Hard Probe 2016
Dijet systematic uncertainties:

<table>
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<tr>
<th>Source</th>
<th>pp</th>
<th>30-100%</th>
<th>10-30%</th>
<th>0-10%</th>
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<td>Combinatorial subtraction</td>
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<td>0.001</td>
<td>0.006</td>
<td>0.014</td>
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<tr>
<td>Subleading jet finding</td>
<td>-</td>
<td>0.002</td>
<td>0.004</td>
<td>0.004</td>
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<tr>
<td>Energy scale</td>
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<td>0.013</td>
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<tr>
<td>Jet resolution</td>
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<td>0.008</td>
<td>0.010</td>
<td>0.012</td>
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<tr>
<td>total</td>
<td>0.007</td>
<td>0.010</td>
<td>0.016</td>
<td>0.023</td>
</tr>
</tbody>
</table>

Table 4: Absolute systematic uncertainties on $\langle x_j \rangle$ for inclusive dijets.

<table>
<thead>
<tr>
<th>Source</th>
<th>pp</th>
<th>30-100%</th>
<th>10-30%</th>
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<tbody>
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<tr>
<td>Subleading jet finding</td>
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<td>0.002</td>
<td>0.004</td>
<td>0.004</td>
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<tr>
<td>Tagging efficiency</td>
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<tr>
<td>Jet energy scale</td>
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<td>0.006</td>
<td>0.010</td>
<td>0.013</td>
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<tr>
<td>Jet resolution</td>
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<td>0.008</td>
<td>0.010</td>
<td>0.012</td>
</tr>
<tr>
<td>total</td>
<td>0.008</td>
<td>0.014</td>
<td>0.018</td>
<td>0.023</td>
</tr>
</tbody>
</table>

Table 5: Absolute systematic uncertainties on $\langle x_j \rangle$ for $b$ dijets.

- pp results have been smeared according to the jet resolution in PbPb in order to make data-based reference