Studies of Jet-Track Correlations in PbPb collisions with CMS

Hard Probes 2015
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Questions this talk will address

• How are charged particles distributed around jets?
• What happens to these distributions when we compare leading and subleading jets?
• How many particles are there around these jets as a function of $p_T$ and centrality?
• What are effects of the QGP medium created in PbPb collisions that doesn’t appear in pp?
Compact Muon Solenoid

- EM Calorimeter (ECAL)
- Hadron Calorimeter (HCAL)
- Beam Scintillator Counters (BSC)
- Forward Calorimeter (HF)
- Tracker (Pixels and Strips)
- Muon System
Jets and tracks

Standard CMS HI track selection
- $|\eta| < 2.4$
- $1.0 > p_T > 2.0 \text{ GeV/c}$
- $2.0 > p_T > 3.0 \text{ GeV/c}$
- $3.0 > p_T > 4.0 \text{ GeV/c}$
- $4.0 > p_T > 8.0 \text{ GeV/c}$

Standard CMS HI jet selection
- Anti $k_T$ jets with $R = 0.3$
- $|\eta| < 1.6$
- Jet $p_T > 120 \text{ GeV/c}$
- Fully efficient from a triggered dataset corresponding to 166 $\text{ub}^{-1}$
Jet-track correlations

Signal pair distribution:

same event pairs

\[ S(\Delta \eta, \Delta \phi) = \frac{1}{N_{\text{trig}}} \frac{d^2 N_{\text{same}}}{d \Delta \eta d \Delta \phi} \]
Jet-track correlations

$\eta = \ln(\tan(\theta/2))$

$\Delta \eta$

$\Delta \phi$

$\eta = 2 (\theta=15°)$

$\eta = 1 (\theta=45°)$

$\eta = 0 (\theta=90°)$

Signal pair distribution:

**CMS Preliminary**
PbPb 166 $\mu b^{-1}$ (2.76 TeV) Centrality 0-10%

$p_{T,jet} > 120$ GeV/c

$1 < p_{T}^{assoc} < 2$ GeV/c

Mixed event pair distribution:

**CMS Preliminary**
PbPb 166 $\mu b^{-1}$ (2.76 TeV) Centrality 0-10%

$p_{T,jet} > 120$ GeV/c

$1 < p_{T}^{assoc} < 2$ GeV/c

\[
S(\Delta \eta, \Delta \phi) = \frac{1}{N_{trig}} \frac{d^2 N^{same}}{d \Delta \eta d \Delta \phi}
\]

\[
ME(\Delta \eta, \Delta \phi) = \frac{1}{N_{trig}} \frac{d^2 N^{mix}}{d \Delta \eta d \Delta \phi}
\]
Jet-track correlations

Divide Signal by Mixed Event

Signal pair distribution:
same event pairs

Mixed event pair distribution:
mixed event pairs

Associated hadron yield per trigger:
\[
\frac{1}{N_{\text{trig}}} \frac{d^2 N_{\text{pair}}}{d\Delta\eta d\Delta\phi} = ME(0, 0) \times \frac{S(\Delta\eta, \Delta\phi)}{ME(\Delta\eta, \Delta\phi)}
\]

\[
S(\Delta\eta, \Delta\phi) = \frac{1}{N_{\text{trig}}} \frac{d^2 N_{\text{same}}}{d\Delta\eta d\Delta\phi}
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\[
ME(\Delta\eta, \Delta\phi) = \frac{1}{N_{\text{trig}}} \frac{d^2 N_{\text{mix}}}{d\Delta\eta d\Delta\phi}
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Jet-track correlations

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\frac{1}{N_{trig}} \frac{d^2 N_{pair}}{d\Delta\eta d\Delta\phi} = ME(0, 0) \times \frac{S(\Delta\eta, \Delta\phi)}{ME(\Delta\eta, \Delta\phi)}
\]

Signal pair distribution:

Mixed event pair distribution:

\[S(\Delta\eta, \Delta\phi) = \frac{1}{N_{trig}} \frac{d^2 N_{same}}{d\Delta\eta d\Delta\phi}\]

\[ME(\Delta\eta, \Delta\phi) = \frac{1}{N_{trig}} \frac{d^2 N_{mix}}{d\Delta\eta d\Delta\phi}\]
Jet track correlation topology
Jet track correlation topology

“Near-side” ($\Delta \phi, \Delta \eta \sim 0$) correlations from particles around a jet
Jet track correlation topology

“Near-side” ($\Delta \phi, \Delta \eta \sim 0$) correlations from particles around a jet

“Away-side” ($\Delta \phi \sim \pi$) correlations from particles around the other jet
Long range nearside jet correlations (weak in this example)

“Away-side” ($\Delta \phi \sim \pi$) correlations from particles around the other jet

“Near-side” ($\Delta \phi$, $\Delta \eta \sim 0$) correlations from particles around a jet
Study the jet peak

Long range nearside jet correlations (weak in this example)

“Away-side” ($\Delta \phi \sim \pi$)
back-to-back jet correlations

“Near-side” ($\Delta \phi, \Delta \eta \sim 0$)
correlations from particles around a jet
Subtract combinatorial and long range bkg

Construct the $|\Delta \phi|$ projection from the correlation region
$1.5 < |\Delta \eta| < 3.0$
Subtract combinatorial and long range bkg

Fit a constant + the first 2 Fourier cosine terms and a Gaussian for the away side

\[ B(\Delta \phi) = B_0 \left( 1 + 2V_1 \cos(\Delta \phi) + 2V_2 \cos(2\Delta \phi) + A_{AS} \exp\left( -\left(\frac{|\Delta \phi - \pi|}{\alpha}\right)^\beta\right) \right) \]
Subtract combinatorial and long range bkg
Zoom in on the jet peak after subtracting
Project into $\Delta \eta$
Repeat for pp
Δη versus Centrality

CMS Preliminary

Centrality 50-100%
1<p_T^{assoc}<2GeV/c
p_{T,jet}>120 GeV/c
PbPb Inclusive Jets
pp Inclusive Jets

Centrality 30-50%
anti-k_T jets, R=0.3
|η_{jet}|<1.6

Centrality 0-10%
Projected |Δφ|<1.0
Subtract pp from PbPb
Leading vs Subleading

• Look at leading and subleading in dijet events

• Standard CMS HI dijet selection
  – Reconstruct all jets with $|\eta| < 2.0$
  – Leading and subleading reside $|\eta| < 1.6$
  – $|\text{dijet } \Delta\phi| > 5\pi/6$
  – Leading jet $p_T > 120$ GeV/c
  – Subleading jet $p_T > 50$ GeV/c
Vary centrality for Leading Jet
Vary centrality for Leading & Subl Jet

Leading

Subleading
Subtract pp from PbPb for Lead and Subleading.
Yield in Leading vs Subleading Jets

Integrate to find excess yield

PbPb – pp
Yield in Leading vs Subleading Jets

CMS Preliminary

PbPb 166 µb⁻¹ (2.76 TeV)

pp 5.3 pb⁻¹ (2.76 TeV)

Integrate to find excess yield

Centrality 50-100%
- Leading Jets
- Subleading Jets

Centrality 30-50%
- \( p_{T,jet1} > 120 \text{ GeV/c} \)
- \( p_{T,jet2} > 50 \text{ GeV/c} \)
- \( \Delta \phi_{1,2} > 5\pi/6 \)

Centrality 10-30%
- anti-\( k_T \) jets, \( R=0.3 \)
- \( |\eta_{jet}| < 1.6 \)

Centrality 0-10%
- Projected \( |\Delta \eta| < 1.0, |\Delta \phi| < 1.0 \)

PbPb – pp
Yield in Leading vs Subleading Jets

**CMS Preliminary**

**PbPb** 166 μb\(^{-1}\) (2.76 TeV)

**pp** 5.3 pb\(^{-1}\) (2.76 TeV)

Centrality 50-100%

- Leading Jets
- Subleading Jets

Centrality 30-50%

- \(p_T, \text{jet}_1 > 120 \text{ GeV/c}\)
- \(p_T, \text{jet}_2 > 50 \text{ GeV/c}\)
- \(\Delta \phi_{1,2} > 5\pi/6\)

Centrality 10-30%

- anti-\(k_T\) jets, \(R=0.3\)
- \(|\eta_\text{jet}| < 1.6\)

Centrality 0-10%

- Projected \(|\Delta \eta| < 1.0, |\Delta \phi| < 1.0\)

Vary associate track \(p_T\):

- \(1.0 > p_T > 2.0 \text{ GeV/c}\)
- \(2.0 > p_T > 3.0 \text{ GeV/c}\)
- \(3.0 > p_T > 4.0 \text{ GeV/c}\)
- \(4.0 > p_T > 8.0 \text{ GeV/c}\)

Less excess particles at higher \(p_T\)
Width of the Leading vs Subleading Jet

Fit the distribution with the sum of two Gaussians centered at zero

\[ f(\Delta \eta) = a_1 \exp \left( \frac{-\Delta \eta^2}{2\sigma_1^2} \right) + a_2 \exp \left( \frac{-\Delta \eta^2}{2\sigma_2^2} \right) \]

Width $\equiv |\Delta \eta|$ range that contains 67% of the total correlated yield
|Δη| Width Leading vs Subleading Jet

CMS Preliminary

PbPb 166 μb⁻¹ (2.76 TeV)

Centrality 50-100%
- PbPb Leading Jets
- pp Leading Jets

Centrality 30-50%
- $p_{T, \text{jet}_1} > 120 \text{ GeV/c}$
- $p_{T, \text{jet}_2} > 50 \text{ GeV/c}$
- $\Delta \phi_{1,2} > 5\pi/6$

Centrality 10-30%
- anti-$k_T$ jets, $R=0.3$
- $|\eta_{\text{jet}}|<1.6$

Centrality 0-10%
- Projected $|\Delta \phi|<1.0$

PbPb Subleading Jets
- pp Subleading Jets

|Δη| Width Leading vs Subleading Jet

pp 5.3 pb⁻¹ (2.76 TeV)

Centrality 10-30%
- anti-$k_T$ jets, $R=0.3$
- $|\eta_{\text{jet}}|<1.6$

Centrality 0-10%
- Projected $|\Delta \phi|<1.0$

Track $p_T$ (GeV/c)
Summary

• Jet track correlations were measured for leading and subleading jets
• Inclusive jets are pp-like in peripheral collisions but have an excess yield in central collisions at low $p_T$
• Subleading jets have greater excess yield compared to pp than leading jets
• Leading and subleading jets in PbPb are broader for low track $p_T$ compared to pp, effect goes away at high $p_T$, no strong centrality dependence
Vary Centrality $|\Delta \phi|$
Vary Centrality Leading & Subleading |Δφ|
Leading $|\Delta \phi|$ width

CMS Preliminary

- **PbPb 166 $\mu$b$^{-1}$ (2.76 TeV)**
  - Centrality 50-100%
  - **PbPb Leading Jets**
  - pp Leading Jets

- **PbPb 166 $\mu$b$^{-1}$ (2.76 TeV)**
  - Centrality 30-50%
  - $p_T_{jet1} > 120$ GeV/c
  - $p_T_{jet2} > 50$ GeV/c
  - $\Delta \phi_{1,2} > 5\pi/6$

- **pp 5.3 $pb^{-1}$ (2.76 TeV)**
  - Centrality 10-30%
  - anti-$k_T$ jets, R=0.3
  - $|\eta_{jet}| < 1.6$

- **Centrality 0-10%**
  - Projected $|\Delta \eta| < 1.0$

- Graphs show $\Delta \phi$ width as a function of $p_T$ for different centrality classes.

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Subleading $|\Delta \phi|$ width

CMS Preliminary

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

- Centrality 50-100%
- $p_T, jet_1 > 120$ GeV/c
- $p_T, jet_2 > 50$ GeV/c
- $\Delta \phi_{1,2} > 5\pi/6$

- pp Subleading Jets

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

- Centrality 30-50%
- anti-$k_T$ jets, R=0.3
- $|\eta|_{jet}<1.6$

- Centrality 0-10%
- Projected $|\Delta \eta|<1.0$

- PpPb Subleading Jets

- $p_T, jet > 80$ GeV/c

- Centrality 0-10%
- Projected $|\Delta \eta|<1.0$

- Projected $|\Delta \eta|<1.0$
Missing $p_T$ comparison

- Missing-$p_T$ analysis: projects all tracks onto average dijet axis, takes subleading minus leading hemispheres
- Jet-track analysis: could do the same from correlation—just weight by $p_T^{\text{assoc}} \cos(\Delta \phi)$
- Cross-check shown perfect consistency between the two studies
- Missing-$p_T$ phase space:
  - $\Delta \eta$-$\Delta \phi$ area integrated into each $\Delta r$ bin (cartoon for illustration)
  - Last $\Delta r$ bin shown is catch-all for $\Delta r > 1.8$
ALICE Jet Broadening Statement

arXiv: 1506.03984

\[ \Phi(\Delta \phi) \]

ALICE

0-10% Pb-Pb \( \sqrt{s_{NN}} \):

Anti-\( k_T \) charged jets

40 < \( p_{T,jet}^{\text{reco,ch}} \) < 60 GeV/c

TT(20,50) - TT(8,9)

\[ \sigma = 0.173 \pm 0.031 \text{(stat)} \pm 0.005 \text{(sys)} \]

\[ \sigma = 0.164 \pm 0.015 \text{(stat)} \]

Statistical errors only

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Event Fraction

\[ \int \Delta \phi = 150 \mu b^{-1} \]

Centrality 0-20%

120 < \( p_{t_1} < 150 \text{ GeV/c} \)

150 < \( p_{t_1} < 180 \text{ GeV/c} \)

180 < \( p_{t_1} < 220 \text{ GeV/c} \)

220 < \( p_{t_1} < 260 \text{ GeV/c} \)

260 < \( p_{t_1} < 300 \text{ GeV/c} \)

300 < \( p_{t_1} < 500 \text{ GeV/c} \)

Anti-\( k_T \) (PFlow), \( R = 0.3 \)

\( p_{t_2} > 30 \text{ GeV/c} \)