Missing $p_T$ measurements in CMS

3rd Workshop on Jet Modification in the RHIC and LHC Era
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On Behalf of CMS Collaboration
Overview

• Motivation and Previous Results
• Samples and Event Selection
• Jet Reconstruction with New HF/Voronoï Method
• Track Reconstruction and Corrections
• Observables and Results
  • Hemisphere Multiplicity Difference
  • Missing $p_T$ v. $A_J$
  • Missing $p_T$ v. $\Delta R$
• Summary and Plans
Motivation (I)

- Dijet imbalance observed in PbPb collisions as part of first LHC heavy ions run
  - Enhanced relative to pp, marked centrality dependance

- Can ask:
  - Where does the missing momentum go? (Outside the jet cone?)
  - How is the total momentum distributed amongst particles in different $p_T$ ranges?
Motivation (II)

\[ \mathbf{p}_T = \sum_{\text{Tracks}} -p_T^{\text{Track}} \cos (\phi_{\text{Track}} - \phi_{\text{Leading Jet}}) \]

Enhancement of low momentum contribution by centrality

Momentum towards subleading recovered out of cone

Motivation (III)

- Dijet imbalance observed in cone ($A_J$) is not fully recovered until large $\Delta R$
  - Lower momentum contribution preferentially towards the subleading jet axis
  - Large $\Delta R$ momentum contribution also preferentially towards the subleading jet axis

- Can still ask (and to be presented):
  - What is the distribution of this momentum imbalance as a function of $\Delta R$?
  - How does this compare to pp?
  - In contrast with previous comparisons to PYTHIA+HYDJET
Samples and Selection

- PbPb data at 2.76 TeV with integrated luminosity of 150 μb⁻¹
  - Tracks reconstructed over 3 iterations
  - Calo jets, reconstructed with anti-k_T R = 0.3, Voronoi subtraction
- pp data at 2.76 TeV with integrated luminosity of 5.3 pb⁻¹
  - Tracks reconstructed over 7 iterations
  - Calo jets, reconstructed with anti-k_T R = 0.3
- High p_T trigger in PbPb and pp, require jet with p_T > 80 GeV/c
- 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
- Track Selection
  - p_T > 0.5 GeV/c
  - |\eta| < 2.4

Impact of cuts

CMS-PAS-HIN-14-010
Jet Reco. w/ Voronoi Algorithm (I)

- New CMS underlying event subtraction algorithm

- Model the underlying event at mid-rapidities by the transverse energy eta dependence and Fourier harmonics at forward rapidity

- Subtraction of the underlying event performed on constituent basis
  - energy subtracted from individual towers
  - results in negative towers

- Equalization to remove negative towers
  - Energy is redistributed
  - Smear jets by transferring energy locally to negative towers
Random cone study in minimum bias data shows result consistent with zero through centrality and deviation of less than 1 GeV/c as function of $\eta$. 
• Correct for efficiency and fake rate in both pp and PbPb
  • Additional secondary rate correction applied to pp
• Correction parameters are:
  • Centrality (event density)
  • $p_T$
  • $\phi$
  • $\eta$
  • Minimum $\Delta R_{jet}$ (local density)
• Good agreement with truth after correction in all parameters
  • Left: example in $p_T$
Observables: A Cartoon Picture

Project onto diet axis

Define cones w.r.t. individual jet axes
Observables: Dijet Axis

Define new axis for projection of track $p_T$: **Dijet Axis**

- $\phi_{dijet} = (\phi_1 + (\pi - \phi_2))/2$
- CMS-HIN-10-004 used leading jet axis
  - Leading axis results in non-cancellation of background in $\Delta R$
  - Dijet axis makes $p_T$ sum symmetric w.r.t. dijet system, background cancels
Observables: Multiplicity Difference

- CMS-HIN-10-004, observed tracks in subleading hemisphere of lower $p_T$ than leading

- Can revisit observation with a multiplicity difference measurement

Define:

$$\Delta_{mult} = N_{Trk}^{\text{Corrected}} |\Delta \phi_{Trk, \text{average}} > \pi/2 | - N_{Trk}^{\text{Corrected}} |\Delta \phi_{Trk, \text{average}} < \pi/2|,$$

Hemisphere 2 Hemisphere 1
Observables: Missing $p_T$ v. $A_J$

- Revisit to missing $p_T$ measurement
- More differential in centrality
- Examine relative to pp
- Define sum of track momentum projected onto dijet axis:

$$p_T^\parallel = \sum_i -p_T^i \cos (\phi_i - \phi_{\text{Dijet}}).$$


What do we expect after subtracting pp?
Observables: Missing $p_T$ v. $\Delta R$ (I)

- What is the missing $p_T$ distribution through large $\Delta R$?
- Do we recover full imbalance?
- How does this compare to pp?
- Define binning:

$$\Delta R = \sqrt{\Delta \phi_{\text{Trk, jet}}^2 + \Delta \eta_{\text{Trk, jet}}^2}$$


What is the full distribution this samples?
Observables: Missing $p_T$ v. $\Delta R$ (II)

- Limited here in $\Delta R$ due to statistics and acceptance
- Need mid-rapidity jets


$$\Delta R = \sqrt{\Delta \phi_{\text{Trk,jet}}^2 + \Delta \eta_{\text{Trk,jet}}^2}$$
• As function of \( A_J = (p_{T,1} - p_{T,2})/(p_{T,1} + p_{T,2}) \), increasing multiplicity towards subleading hemisphere

• excess approaches 15 particles in most central PbPb relative to pp
• As function of $\Delta p_{T,12} = (p_{T,1} - p_{T,2})$, similar picture
  • excess approaches same rough numbers in PbPb central collisions towards subleading hemisphere
• Compared to pp, see a centrality dependent excess of 0.5 - 2.0 $p_T$ particles towards subleading hemisphere
• Replace 2.0 - 8.0 $p_T$ particles in pp
Results: Missing $p_T$ v. $\Delta R$ (I)

- Inclusive $A_J$ selection
- See a centrality dependent enhancement of low $p_T$ particles in PbPb relative to pp

Excess through large $\Delta R$
Results: Missing $p_T$ v. $\Delta R$ (II)

• $A_J < 0.22$ selection
• Some enhancement of $0.5$-$1.0$ GeV/c particles in PbPb relative to the same selection in pp

0.5 - 1.0 $p_T$ excess through large $\Delta R$
Results: Missing $p_T$ v. $\Delta R$ (III)

- $A_J > 0.22$ selection
- See a greater enhancement of low $p_T$ particles in PbPb relative to the same selection in pp, particularly $1.0$-$2.0$ GeV/c
Results: Missing $p_T$ v. $\Delta R$ (IV)

In pp, out-of-cone radiation for $A_J > 0.22$ selection carried by third jets

0.5 - 2.0 GeV/c $p_T$ balances in PbPb

2.0 - 8.0 GeV/c $p_T$ balances in pp
Results: Missing $p_T$ v. $\Delta R$ (V)

Totals within 1 GeV/c of zero outside of cone of $R = 0.4$.

Difference between PbPb and pp in momentum of particles making up imbalance.

Curves of integrated missing $p_T$ similar shape, adjust starting point?
Results: Missing $p_T$ v. $\Delta R$ (VI)

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Adjusting for starting point, curves in PbPb and pp approximately the same
Summary and Plans

- Dijet momentum imbalance can be recovered by summing over large angles
  - Subleading jet particles are characterized by higher multiplicities at a lower momentum
  - Relative to pp, observe lower momenta and higher multiplicities
    - 2.0 - 8.0 GeV in pp -> 0.5 - 2.0 in PbPb
    - Integrated curve very similar after adjusting first bin

- Currently pursuing generator comparisons:
  - Particularly for $\Delta R$ distribution, look for low $p_T$ enhancement through large angles and integrated curves
  - Working with generator authors to integrate into framework useable by CMS collaboration in spirit of Lisbon Accord (I believe our next topic?)
Backup
Backup: Gen. Pythia w/ Cuts

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

PYTHIA

Generator-level $R = 0.3$
Backup: Jet $p_T$ scale and resolution

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CMS Preliminary Simulation

$|\eta|<2$

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

anti-$k_T$ Calo R=0.3

$\mu(p_T^{\text{Reco}}/p_T^{\text{Gen}})$

$\sigma(p_T^{\text{Reco}}/p_T^{\text{Gen}})$

PYTHIA
PYTHIA+HYDJET

50-100 %
30-50 %
10-30 %
0-10 %

$p_T^{\text{Gen}}$ (GeV/c)
Define dijet axis as bisecting axis between leading and flipped subleading hemispheres defined w.r.t. axis perpendicular to dijet.
Backup: Out-Cone


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pp 5.3 pb\(^{-1}\)

PbPb 150 \(\mu\)b\(^{-1}\)

PbPb 0-30%

\(\sqrt{s_{NN}} = 2.76\) TeV

Out-of-Cone, 0.8 < \(\Delta R\)

PbPb - pp

PbPb - pp

\(p_T > 120\) GeV/c

\(p_T > 50\) GeV/c

|\(\eta\),|\(\phi|<1.6\)

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