Dijet Measurements in pPb Collisions

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INTRODUCTION

Data and MC

Centrality in pPb and event classes

Overview of the analysis:

Major systematics

Results

DIJET PSEUDORAPIDITY, $\eta_{\text{dijet}} = \frac{\eta_1 + \eta_2}{2}$

Comparison to EPS09 nPDF

Dependence on total forward activity

Dependence on Pb (p) side forward activity

SUMMARY
Data and MC

DATA

• High-p_T jet trigger (a jet with p_T > 100 GeV/c)
• Pb ion is going in the positive z direction
• p beam energy 4 TeV, Pb beam energy 1.58 TeV
• Pseudorapidity shift NN center of mass to -0.465

MC

• Boosted PYTHIA pp jets with η_{CoM} = -0.465
• Embedded PYTHIA sample into a HIJING pPb background

Dijet selection:

| \eta | <3, p_{T,1} > 120 \text{ GeV/c}, p_{T,2} > 30 \text{ GeV/c}, \Delta\phi_{1,2} > 2\pi/3 |
Centrality in PbPb and pPb

Compared to Minimum bias:
- Dijet $N_{trk}$ and $E_T^{HF}$ biased towards larger values
- Slope is also different: $N_{trk} \approx 100$, $E_T^{HF} \approx 20$ dijet, 30 GeV MB

Slicing direction doesn’t vary the chosen events significantly.
Centrality classes in pPb

Let us choose one vertical and one horizontal slice which will have same $\langle HF E_T \rangle$ and same $\langle N_{trk} \rangle$

Event activity on Pb side vs event activity on p side
- Correlation is very loose.
- Different trends:
  Proton side $E_T$ energy rise as a function of Pb side energy rise flattens out.

What about peripheral PbPb?
CASE 1
Correlation between centrality variable and dijet observable due to the overlapping range of measurement.

CASE 2
Correlation between centrality variable and dijet observable due to energy momentum conservation.

CASE 3,4...
Chance determination of biases is limited by how well MC describes data.
Minimum bias selection:
At least one particle with $E > 3$ GeV in the pseudorapidity range $-5 < \eta < -3$ and one in the range $3 < \eta < 5$
Jet energy scale corrections (JEC):

- JEC from MC + Data Driven JEC
- Tag & Probe:
  - at HCAL barrel
  - at HCAL end cap
- Described in JINST 6 (2011) 11002
- Corrects for the calorimeter response difference in data and MC
- Important for this analysis to go forward pseudorapidities.

Forward activity binning:

- We quote the change in PYTHIA+HIJING sample with respect to inclusive centrality bin.

Pile-up filter:

- Important only for highest activity events. It removes:
  - $\approx 2\%$ of minimum bias events
  - $\approx 5\%$ of high multiplicity events
  - $\approx 4\%$ of dijet events
Overview of the results

RESULTS

• **No sign of jet quenching (yet?):** We do not observe significant modification in pT ratios of leading and subleading jet. (Any modification <\%2)

• **Compared to nPDFs:** Dijet pseudorapidity distribution is modified with respect to MC in a way that is compatible with nPDF predictions

• **Dijet pseudorapidity shift:** Dijet pseudorapidity distribution shifts significantly towards Pb going side as one goes to higher forward activity events
**RESULTS**

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- **Dijet pseudorapidity shift:** Dijet pseudorapidity distribution shifts significantly towards Pb going side as one goes to higher forward activity events
Comparison to EPS09 predictions

Agreement between data with EPS09 within systematics.
Data has slightly larger modification in anti-shadowing and EMC regions compared to CT10+EPS09. (DSSZ agreement would be worse)

Large uncertainties in forward region.

Escola, Paukkunen, Salgado. arxiv:1308.6733

CMS PAS HIN-13-001
Forward activity dependence of $\eta_{\text{dijet}}$

- Going to large HF $E_T$ $N_{\text{part}}$ only increases very little.

- Large variation in dijet pseudorapidity distribution.

CMS PAS HIN-13-001
• Shift slightly less compared to the mean dijet eta vs forward activity on both sides.
  (shift ≈0.2 instead of 0.27)
• Remember from slide 7 that the shift in PYTHIA is in opposite direction, cancellation occurs reducing the effect.
\[ \eta_{\text{dijet}} \text{ at fixed proton side forward activity} \]

- When energy on proton size is small \( < \eta_{\text{dijet}} \) almost flat as a function of forward activity on Pb side.
\( \eta_{\text{dijet}} \) at fixed proton side forward activity

CMS Preliminary

- \( p_{T,1} > 120 \), \( p_{T,2} > 30 \text{ GeV/c} \), \( \Delta \phi_{1,2} > \frac{2\pi}{3} \)

Still flat..
$\eta_{\text{dijet}}$ at fixed proton side forward activity

Slope starts to increase..
$\eta_{\text{dijet}}$ at fixed proton side forward activity

Slope increases even more..
\[ \eta_{dijet} \] at fixed proton side forward activity

And even more..
When proton side energy is fixed the slope of the mean dijet $\eta$ vs $E_{T}^{HF,Pb}$ gets smaller (compare any set of colored points with black curve, black curve shows larger shift)

Does this mean that the shift in dijet $\eta$ is because of the indirect requirement of large $E_{T}^{HF,p}$ in the large $E_{T}^{HF,p} + E_{T}^{HF,Pb}$ bin? **But** we observe the shift event when the proton side activity is fixed (e.g. Red and orange points)
Summary

Centrality in pPb

• Different analyses are sensitive to different (physics) biases
• Biases that show up with jet observables can teach us good lessons about the nature of pPb collisions with high (low) event activity.

Dijet pseudorapidity distributions

• Compared to nPDFs:
  – Dijet results can be used to constrain nPDF’s.
  – NLO+EPS09 and data comparison has improved agreement with respect to NLO and data comparison in EMC and anti-shadowing regions.
    • Discrepancy in anti-shadowing region < 2.5%, EMC region < 5%.

• Dijet pseudorapidity as a function of activity:
  – Large systematic shift which cannot be explained with impact parameter dependence of nPDFs.
  – The effect that causes the shift gets smaller when proton side forward activity is fixed and Pb side forward activity is varied. Is this energy momentum conservation again or something more (related to initial state radiation/fluctuations in proton size or jet quenching)?
BACK-UP
Going to large HF energy

\[ E_{JJ} = p_{T,1} \cosh(\eta_2) + p_{T,1} \cosh(\eta_2) \]

Pb side HF energy ISR \[
\text{Cheap } N_{\text{nuc}} \gg 1
\]

Proton side HF energy ISR \[
\text{Expensive } N_{\text{nuc}} = 1
\]

Shifts PDF of proton to lower x values

\[ \eta<0 \quad \text{"}x_{Pb}\text{"} \rightarrow \text{Pb} \rightarrow \text{p} \quad \text{"}x_p\text{"} \quad \eta>0 \]

Squeezes the dijet \( \eta \) distribution

Shifts dijet \( \eta \) distribution in Pb going direction
Fluctuating initial state

Coleman-Smith, Müller. arXiv:1307.5911

| $N_\pi$ | $P(N_\pi)$ | $\int dx \, P_\eta(x,Q|N_\pi)$ |
|-------|-----------|-----------------|
| 0     | 0.889     | 2.292           |
| 1     | 0.104     | 0.747           |
| 2     | 0.00618   | 0.068           |
| 3     | 0.00024   | 0.0027          |
| 4     | $7.17 \times 10^{-6}$ |                |

(Over) Simplified calculation

\[ \eta_{dijet} \approx \log(x_{Pb}/x_p) \]
\[ x_p \rightarrow 0.8 \cdot x_p : \eta_{dijet} \rightarrow \log(x_{Pb}/0.8 \cdot x_p) = \log(x_{Pb}/x_p) + 0.01 \]
\[ x_p \rightarrow 0.2 \cdot x_p : \eta_{dijet} \rightarrow \log(x_{Pb}/0.2 \cdot x_p) = \log(x_{Pb}/x_p) + 0.7 \]

Averaging these (Of course in reality the weights are not equal)

\[ \eta_{dijet} \rightarrow \eta_{dijet} + 0.36 \]

Largest contribution to the shift comes from hard scattering of parton’s of pions rather than proton’s.
Tywoniuk, Casalderrey. IS2013, Illa da Toxa, Spain

- Hard scattering CoM and plasma CoM are not the same.
  - Plasma CoM is moving towards Pb going direction, because of multiple collisions.
- Plasma is much larger in longitudinal direction than in transverse direction, so jets get quenched least if they go transverse in plasma rest frame.

![Plasma rest frame](image)

Reduces jets symmetrically around plasma rest frame
Shifts dijet $\eta$ distribution
Impact parameter dependent nPDFs

At high $p_T$ and $y=3$ small modification as a function of centrality. Change by going from 0-20% to 60-80% is <5%.
We should keep in mind investigations to explain ridge observed in high multiplicity pPb events, since nPDF can be modified with these processes.
Centrality bias with $N_{ch}$

Each jet means additional $N_{ch} \sim 20$

Event more likely to have 3 (or more) jets

Compare to flat PYTHIA+HIJING points
With and mean vs dijet energy

Boosted PYTHIA Z2 Tune

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Final state interactions

CMS Preliminary
pPb ∫ L dt=18.48 nb⁻¹

\[
\sigma(\Delta \phi_{1,2})
\]

\[
E_T^{HF[|\eta|>4]} \text{ (GeV)}
\]

\[
\frac{1}{N_{dijet}} \frac{dN_{dijet}}{d\Delta \phi_{1,2}} = \frac{e^{(\Delta \phi - \pi)/\sigma}}{(1 - e^{-\pi/\sigma}) \sigma}.
\]

anti-\( k_T \) (PFlow) R=0.3
\[
\Delta \phi_{1,2} > 2\pi/3, |\eta|<3
\]

\[
< p_{T,2} / p_{T,1} >
\]

\[
E_T^{HF[|\eta|>4]} \text{ (GeV)}
\]
Kinematic reach for CMS, pPb @ $\sqrt{s} = 8.8$ TeV (0.1 pb$^{-1}$)

Jets cover high $Q^2$ and $10^{-4} < x < 1$.

With the dijet selection of the analysis:

- $p_{T,1} > 120$ GeV/c,
- $p_{T,2} > 30$ GeV/c,
- $\Delta \phi_{12} > 2\pi/3$
Centrality classes in pPb

Let us choose one vertical and one horizontal slice which will have same \(<\text{HF } E_T>\) and same \(<N_{\text{trk}}>\).

Event activity on Pb side vs event activity on p side:

- Correlation is very loose.
- Different trends:
  - Proton side \(E_T\) energy rise as a function of Pb side energy rise flattens out.

What about peripheral PbPb?

Each centrality variable can give us a different piece of information. We should look at and show as many as possible.
The shift we observe of magnitude \( \approx 0.27 \) in \( \langle \eta_{\text{dijet}} \rangle \).  
Remaining centrality biases:  
- Looking at PYTHIA+HIJING:  
  - Slight shift in dijet eta towards smaller \( \eta_{\text{dijet}} \)  
    (in the opposite direction of the shift in data)  
  - Narrowing of dijet eta  

- Not included in PYTHIA+HIJING: Interaction of signal and background event, initial state fluctuations...