Modifications to Jet Spectra and Substructure in PbPb Collisions with CMS

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Physics of Jets in Medium

- Modified in medium compared to MonteCarlo and pp reference
  - Energy is redistributed in and out-of-cone
  - Substructure observables are a tool to study this redistribution
Rehearsals Next Week:

Wednesday: Jet RAA 10:00, Jet Substructure 10:40, Gamma+jet

Tuesday: Dijet-eta 16:00

Monday: Gluon splitting 14:00, D+jets 14:40

Meaning: next two weeks will be virtual

Full Agenda

Hard Probes Approval freeze: September 7

BOOST/ICHEP Approval freeze: June 22

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Good performance just with CHS at typical levels of pileup

Typical level of pileup here -> peripheral-most in PbPb

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For more details see JINST 12 (2017) P10003 and morning talk from Anna Benecke

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Jet Reconstruction with CMS in PbPb

- Fluctuations in $\rho$ contribute to jet resolution as N term:

$$\sigma\left(\frac{p_T^{\text{RECO}}}{p_T^{\text{GEN}}}\right) = \sqrt{C^2 + \frac{S^2}{p_T^{\text{GEN}}} + \frac{N^2}{(p_T^{\text{GEN}})^2}}$$

- Typically HI chooses small cone and low-$p_T$
- Alternatively, scale away UE by $p_T$
  - $N/p_T$ in quadratic sum, and go to large cone

- **pp**: 27.4 pb\(^{-1}\) at 5.02 TeV
- **PbPb**: 404 µb\(^{-1}\) at 5.02 TeV

Fig. From: CMS-DP-2018-024
Additional Complications in PbPb

- Hard and soft components from single vertex $O(10 \text{ fm})$
- Background is modulated in $\phi$ (flow of medium)
- Jet-medium interaction gives ambiguous correlated background

Subtracting Underlying Event in HI at CMS

- Considering subtraction as \textbf{two} separate problems
  1. What amount of UE to subtract
  2. How to subtract
- Then for CMS substructure measurements:

  Constituent Subtraction (CS)
  
  1: Estimated by median unsubtracted $k_t$ jet
  
  2: Add “ghost” particles randomly with fixed area and $p_T$ according to rho, subtracting from real particles iteratively until gone

For more details see JHEP06 (2014) 092 and morning talk from Peter Berta
Measurement of $z_g$ in pp with Open Data

**Successful application in open data with tracks in 7 TeV pp**

**Good description by theory and generators**
Measurement of $z_g$ in pp

- PYTHIA6, PYTHIA8, and HERWIG++ all describe distribution shape to $\sim 15\%$
- Given reasonable baseline, how does it look in PbPb?
Measurement of $z_g$ in PbPb

$\sqrt{s_{NN}} = 5.02$ TeV, pp 27.4 $\mu$b$^{-1}$, PbPb 404 $\mu$b$^{-1}$

- $z_{cut}$ and $\beta$ here are “Flat” grooming setting
- Increasing shape modification with centrality
Measurement of $z_g$ in PbPb

Centrality: 0-10%

$140 < p_{T,\text{jet}} < 160 \text{ GeV}$

Soft Drop $\beta = 0$, $z_{\text{cut}} = 0.1$, $\Delta R_{12} > 0.1$

$300 < p_{T,\text{jet}} < 500 \text{ GeV}$

- Persistent effect thru large $p_T$ range
- Consistent at highest $p_T$, but statistically limited
Measurement of Groomed Mass in pp collisions

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- Left: Grooming does not consider radial distance (β=0)
- Right: Grooming preferentially selects jet core
- PYTHIA6, HERWIG++ show good agreement with data

See also CMS-PAS-SMP-16-010 and ATLAS (Sub. PRL) pp groomed jet mass

Identify subjets satisfying condition:

\[
\frac{\min(p_{T,i}, p_{T,j})}{p_{T,i} + p_{T,j}} > z_{cut} \left( \frac{\Delta R_{ij}}{R_0} \right)^\beta
\]

Calculate:

\[
M_g = (p_{1\mu} p_{2\mu})^{0.5}
\]

Normalize by jet \(p_T\)
Measurement of Groomed Mass in PbPb

- Core shows no modification
- “Flat” grooming shows shape modified at large $M_g/p_T$
No simultaneous MC description of $M_g/p_T$

- Models that describe enhancement in “Flat” grooming also show large $M_g/p_T$ in core grooming
Measuring Jet Shapes with a Boson Tag

Both jets interact with medium

Energy is redistributed

Dijet

Photon propagates unmodified

• Photon gives a clean tag of the starting momentum
• Also probes a different q/g fraction (see backup)
• At statistical cost - measurements at much lower p_T than corresponding inclusive measurements
Measuring Jet Shapes with a Boson Tag

1 Introduction

1. Introduction

\[ \sqrt{s_{NN}} = 5.02 \text{ TeV}, \text{PbPb} 404 \mu \text{b}^{-1}, \text{pp} 27.4 \text{ pb}^{-1} \]

**CMS Preliminary**

\[ p_T^\gamma > 60 \text{ GeV/c}, |\eta^\gamma| < 1.44, \Delta \phi_{\gamma} > \frac{7\pi}{8} \]

anti-\( k_T \) jet \( R = 0.3, p_T^{\text{jet}} > 30 \text{ GeV/c} \)

\[ |\eta^\text{jet}| < 1.6, p_T^{\text{trk}} > 1 \text{ GeV/c} \]

\[ \rho(r) = \frac{1}{\delta r} \sum_{\text{jets}} \sum_{\text{trk} \in [r_a, r_b]} \left( \frac{p_T^{\text{trk}}}{p_T^{\text{jet}}} \right) \]

\[ \sum_{\text{trk} \in [0, r_f]} \left( \frac{p_T^{\text{trk}}}{p_T^{\text{jet}}} \right) \]

**CMS-PAS-HIN-18-006**

- Look at track sums in rings around the jet axis, normalized to the full jet charged energy

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Measuring Jet Shapes with a Boson Tag

- In central PbPb, observe enhancement of periphery particles
- Comparable to results of groomed jet mass with $\beta=0$

$\sqrt{s_{NN}} = 5.02$ TeV, PbPb 404 $\mu$b$^{-1}$, pp 27.4 pb$^{-1}$

$\rho > 60$ GeV/c, $|\eta| < 1.44$, $\Delta\phi > \frac{7\pi}{8}$

anti-$k_T$ jet $R = 0.3$, $p_T^{\text{jet}} > 30$ GeV/c

$|\eta^{\text{jet}}| < 1.6$, $p_T^{\text{trk}} > 1$ GeV/c

- Take Ratio w/ pp

$\text{CMS-PAS-HIN-18-006}$
Updating Constituent Subtraction at CMS

- Substitute iterative pedestal estimation of underlying event in $\eta$-strips into CS (see backup)
- Expanding CS jets to forward region, $|\eta| > 1.3$
- Add modulation to underlying event in $\varphi$ to account for flow

Constituent Subtraction (CS)

1: Estimated by median unsubtracted $k_T$ jet

2: Add "ghost" particles randomly with fixed area and $p_T$ according to rho, subtracting from real particles iteratively until gone

1a: $\rho$ estimated in $\eta$-strips defined by detector geometry

1b: Add event-by-event $\varphi$ modulation
- Extract an event-by-event $v_2$ and $v_3$ by fitting particle flow candidates
- Extracted $v_2(v_3)$ are used to modulate CS $\rho$ to add ghost particles
Jet Energy Scale at $R=0.4$ and $R=0.8$

- Scale closure of $R=0.4$ (Left) and $R=0.8$ (Right) jets over all centrality
- Identical corrections applied to all centrality, derived from unsubtracted jets in PYTHIA events

Fig. From: CMS-DP-2018-024
Jet Energy Resolution at $R=0.4$ and $R=0.8$

- Energy resolution of $R=0.4$ (Left) and $R=0.8$ (Right) jets over all centrality.
- In large cone, UE drives high resolution at low-$p_T$.
  - JER $\sim 18\%$ at 200 GeV ($R=0.8$).

Fig. From: CMS-DP-2018-024
Jet energy scale closure as function of event plane for R=0.8 w/o flow correction (Left) and with flow correction (Right).

- Significant flattening of scale translates directly to resolution reduction.
Conclusions

- Inclusive jet substructure measurements show no modification to jet core
- Modification observed with flat grooming in $z_g, M_g/p_T$
- Boson tagged jets at lower $p_T$ show energy redistributed out of cone
- HI jets are being commissioned for large-$R$ spectra/substructure
Backup
Jet energy scale closure as function of event plane for $R=0.4$ w/o flow correction (Left) and with flow correction (Right).

- Some flattening of scale less than corresponding $R=0.8$ case.
Illustration of CS Subtraction Iterations
Constituent Subtraction

**SIGNAL:** Hard-scattering in PbPb collision producing jets

**UNDERLYING EVENT:** Uncorrelated particles from other nucleon-nucleon interactions

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GHOST PARTICLES: Artificial particles added to the event with fixed area. Ghosts are given a $p_T$ according to $\rho$ times the area they inhabit, $A_g$.
• Add “ghost” particles with fixed area according to:

\[ p^g_T = A_g \cdot \rho_i \]

\[ m^g_0 = A_g \cdot \rho_{m_0} \]
Constituent Subtraction

- Combine iteratively with real particles by minimizing metric:

\[ \Delta R_{i,k} = p_{T_i} \cdot \sqrt{(y_i - y_k^g)^2 + (\phi_i - \phi_k^g)^2}. \]
Constituent Subtraction

- Particle $p_T >$ Ghost $p_T$
- Ghost $p_T = 0$
- Particle $p_T = -$ Ghost $p_T$

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“CMS”
Constituent Subtraction

- Note: Some signal will occasionally be subtracted by probability. Relatedly, some UE will remain.
Constituent Subtraction

- Particle $p_T < \text{Ghost } p_T$
- Ghost $p_T = \text{Particle } p_T$
- Particle $p_T = 0$

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SIGNAL
UNDERLYING EVENT
GHOST PARTICLES
Constituent Subtraction

- Particle $p_T <$ Ghost $p_T$
- Ghost $p_T = $ Particle $p_T$
- Particle $p_T = 0$

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Constituent Subtraction

- Continue until ghost or real particles are exhausted
- Cluster remaining event into jets

\[ JHEP06 \text{(2014) 092} \]

\[ \eta \]

\[ \phi \]

"CMS"

SIGNAL

UNDERLYING EVENT

GHOST PARTICLES
Illustration of PU Subtraction Iterations
Iterative Pedestal Algorithm

1. $<E_T>$ calculated in strips of $\eta$.
   Subtract $<E_T> + \sigma$

- $\rho$ or $<E_T>$ is calculated in strips of rapidity
  - Follows HCal tower geometry ($\Delta \eta=0.087$ at mid-rapidity)
- Constituents are combined into pseudotowers
- Pseudotower energy is reduced by $<E_T>$ plus a compensating $\sigma(E_T)$
- Negative towers are zeroed

For details see:
- CMS, arXiv:1102.1957
- Kodolova et al., EPJC 50 (2007) 117
Iterative Pedestal Algorithm

1. $<E_T>$ calculated in strips of $\eta$. Subtract $<E_T> + \sigma$

2. Run anti-$k_T$ algorithm on background-subtracted towers

- Subtracted towers are clustered into anti-$k_T$ jets
- On first iteration, jets are necessarily oversubtracted
  - Included in estimation of underlying event

For details see:

- CMS, *arXiv:1102.1957*
- Kodolova et al., *EPJC 50 (2007) 117*
- Subtracting towers are clustered into anti-$k_T$ jets
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Iterative Pedestal Algorithm

1. $<E_T>$ calculated in strips of $\eta$. Subtract $<E_T> + \sigma$

2. Run anti-$k_T$ algorithm on background-subtracted towers

3. Exclude reconstructed jets and re-estimate background

- A second iteration is run excluding “jetty” regions of the detector from each $\eta$-strip extraction

- Reduced jet bias to estimation of underlying event

For details see:

- CMS, arXiv:1102.1957
- Kodolova et al., EPJC 50 (2007) 117
- Reduced jet bias to estimation of underlying event

Iterative Pedestal Algorithm

1. \(<E_T>\) calculated in strips of \(\eta\). Subtract \(<E_T> + \sigma\)
2. Run anti-\(k_T\) algorithm on background-subtracted towers
3. Exclude reconstructed jets and re-estimate background
4. Re-run anti-\(k_T\) algorithm to get final jets

- Subtract towers according to new estimate in same manner as first iteration
- Cluster newly subtracted towers into final set of anti-\(k_T\) jets

For details see:
- CMS, arXiv:1102.1957
- Kodolova et al., EPJC 50 (2007) 117
Dijet has greater fraction of gluon relative to both boson+jets

Z and γ + jets fraction comparable above 100 GeV

Below 100, γ has greater fraction quark than Z
Experimental Results: Measured jet production in R-scans
- Some effect at low-$p_T$, converges at high-$p_T$
- Restricted to low-$p_T$ by sample size
- Limited systematically by pp reference being taken during different data-taking periods
- Limited in R by underlying-event (UE) at low-$p_T$