STUDIES OF JET SUBSTRUCTURE IN HEAVY ION COLLISIONS WITH CMS

Ran Bi
for the CMS Collaboration

11th International Workshop on Boosted Object Phenomenology, Reconstruction and Searches in HEP (BOOST 2019)
22 July 2019
Cambridge, MA
PHOTON-TAGGED

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HEAVY ION COLLISIONS

- Heavy ion collisions provide a glimpse of the early universe
  - hot, dense matter known as the quark-gluon plasma (QGP)
  - strongly interacting, deconfined medium of free quarks/gluons
  - large underlying event for the most head-on collisions - $O(10^4)$ particles

- QGP exhibits interesting phenomena
  - jet quenching - medium-induced jet energy loss

- Study and extract properties of QGP

Dijet: 200 GeV / 70 GeV

Jet 0, pt: 205.1 GeV
Jet 1, pt: 70.0 GeV
ENERGY LOSS IN DIJET EVENTS

- Jet quenching is a characteristic feature of the QGP
  - observed through measurements of jet energy loss in dijet systems

- Question: where does the jet energy go, how is it redistributed?
- Caveat: both jets can be modified when traversing the medium

![Jet quenching diagram](image-url)
Electroweak bosons are good probes of the medium
- colourless - not subject to medium-induced energy loss through the strong interaction
- good proxy of the initial energy of the partons produced in the hard scattering
- production processes constrain quark/gluon fraction of recoil parton
- statistics: photons > Z bosons; background: photons > Z bosons

Photons (isolated photons)
- background mostly from boosted neutral meson decays
- subtracted using a template fit method
  - signal template is extracted from simulated events
  - background is modelled using sideband region of data

Z bosons
- reconstructed through dilepton channels
- 2015: ~400 µb⁻¹; 2018: 1.5 nb⁻¹
MOMENTUM IMBALANCE IN PbPb COLLISIONS

• Isolated-photon/Z-boson + jet correlations in PbPb @ 5.02 TeV
  • clear evidence for in-medium jet energy loss

• Models with different descriptions of the energy loss mechanisms are able to predict the results within the experimental uncertainties

• Results give a crude picture of jet quenching
  • more detailed measurements required for a complete description
JET SUBSTRUCTURE IN PbPb COLLISIONS (INCLUSIVE JETS)

- Differentiate between different mechanisms by measurements of jet substructure
  - previous measurements with inclusive jets show some modification

Jet fragmentation function

\[ \xi_{\text{jet}} = \ln \frac{|p_{\text{jet}}|^2}{p_{\text{trk}} \cdot p_{\text{jet}}} \]

CMS PbPb $\sqrt{s_{\text{NN}}} = 2.76$ TeV

- PbPb
- pp reference data

$100 < p_{T\text{jet}} < 300$ GeV/c, $0.3 < |\eta_{\text{jet}}| < 2$

$|p_{\text{trk}}| > 1$ GeV/c, $R < 0.3$

Jet fragmentation function

- $0-10\%$
- $10-30\%$
- $30-50\%$
- $50-70\%$
- $70-100\%$
JET SUBSTRUCTURE IN PBPB COLLISIONS (INCLUSIVE JETS)

- Differentiate between different mechanisms by measurements of jet substructure
  - previous measurements with inclusive jets show some modification

- Jet shape

\[
\rho(r) = \frac{1}{\delta r} \frac{\sum_{\text{jets}} \sum_{\text{trk} \in [r_a, r_b]} (p_{T,\text{trk}} / p_{T,\text{jet}})}{\sum_{\text{jets}} \sum_{\text{trk} \in [0, r_j]} (p_{T,\text{trk}} / p_{T,\text{jet}})}
\]

- Modifications to jet shape are interesting
  - may be because of kinematics and/or quark/gluon fractions
**BACKGROUND SUBTRACTION (EVENT MIXING)**

- Jets and tracks from the underlying event are uncorrelated with the photon
  - Estimate contribution of underlying event by embedding the photon into minimum bias (MB) events
  - Select MB events with similar event characteristics
    - Event activity (centrality), primary vertex position, event plane angle

- Subtraction for jet-based observables is straightforward

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**isolated-photon+jet event**

**MB event**
BACKGROUND SUBTRACTION (EVENT MIXING . . . )

- Contributions from background tracks (UE) and background jets (fake jets) must be subtracted.
BACKGROUND SUBTRACTION (EVENT MIXING . . . . . .)

• Contributions from background tracks (UE) and background jets (fake jets) must be subtracted
PHOTON-TAGGED JET FRAGMENTATION FUNCTION

- Enhancement of low-pT particles, depletion of high-pT particles
PHOTON-TAGGED JET FRAGMENTATION FUNCTION

- Enhancement of low-pT particles, depletion of high-pT particles

\[ \frac{1}{N_{\text{jet}}} \frac{dN_{\text{trk}}}{d\xi_{\text{jet}}} \]

CMS Cent. 30 - 100%

CMS Cent. 0 - 30%

\[ p_T^{\text{jet}} > 1 \text{ GeV/c}, \text{anti-} k_T \text{ jet } R = 0.3 \]

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

\[ \xi_{\text{jet}} = \ln \frac{|p_T^{\text{jet}}|^2}{p_T^{\text{trk}} \cdot p_T^{\text{jet}}} \]

\[ \xi_{\gamma} = \ln \frac{-|p_T^{\gamma}|^2}{p_T^{\text{trk}} \cdot p_T^{\gamma}} \]
PHOTON-TAGGED JET FRAGMENTATION FUNCTION

- Enhancement of low-pT particles, depletion of high-pT particles

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

\[ p_T^{\gamma} > 1 \text{ GeV/c}, \text{ anti-}k_T \text{ jet } R = 0.3 \]
\[ p_T^{\text{jet}} > 30 \text{ GeV/c}, |\eta^{\text{jet}}| < 1.6 \]
\[ p_T^{\gamma} > 60 \text{ GeV/c}, |\eta^{\gamma}| < 1.44, \Delta\phi_{\gamma\text{jet}} > \frac{7\pi}{8} \]
• Stronger modification for $\zeta^\gamma_T$ than for $\zeta^{\text{jet}}$
  • jet energy quenched

• Models describe data to different extents
  • both SCET$_G$ and CoLBT-hydro models describe trend of both observables
  • hybrid model does not do well, but the addition of back reaction improves agreement with data
  • enhancement at large $\xi$ (low-$p_T$ particles) underestimated by all models
PHOTON-TAGGED JET SHAPE

- Distribution of jet energy in transverse direction with respect to jet axis
  - complementary information to jet fragmentation function

$\sqrt{s_{\text{NN}}} = 5.02$ TeV

$\text{PbPb}$ 404 $\mu$b$^{-1}$, pp 27.4 pb$^{-1}$

CMS Supplementary

$\rho(r)$

PbPb / pp

- $p_T^\gamma > 60$ GeV/c, $|\eta^\gamma| < 1.44$, $p_T^{\text{jet}} > 1$ GeV/c
- anti-$k_T$ jet $R = 0.3$, $p_T^{\text{jet}} > 30$ GeV/c, $|\eta^{\text{jet}}| < 1.6$, $\Delta\eta^{\text{jet}} > \frac{7\pi}{8}$
PHOTON-TAGGED JET SHAPE

- Comparison to inclusive jet shapes
  - no depletion at intermediate $r$
    - increased quark/gluon ratio
    - lower jet $p_T$ threshold - jets lose more energy

PbPb / pp

$\rho(r)$

PbPb / pp

Cent. 0 - 10%

$p_T^{jet} > 60$ GeV/c

$p_T^{jet} > 30$ GeV/c

$\eta < 1.44$, $p_T^{jet} < 1.6$

$\phi$-jet

Threshold - jets lose more energy

$\eta$-jet

$\Delta T_{trk}$

$\Delta \phi$

$\gamma$-jet

$\pi$-jet

$\rho(r)/p_T^{pp}$

$\rho(r)/p_T^{PbPb}$

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PbPb 404 NN = 5.02 TeV

Cent. 50 - 100%

Cent. 30 - 50%

Cent. 10 - 30%

Cent. 0 - 10%

22 July 2019

BOOST 2019
PHOTON-TAGGED JET SHAPE

- Comparison to inclusive jet shapes
  - no depletion at intermediate $r$
  - increased quark/gluon ratio
  - lower jet $p_T$ threshold - jets lose more energy

- Comparison to models
  - both SCET$^G$/LBT both describe trend
  - different mechanisms, interpretations
SUMMARY

- Jet substructure is a key probe of medium properties and interactions
  - boson-tagged jet measurements constrain recoil parton momentum and quark/gluon fractions
- In-medium jet energy loss and modification of jet fragmentation functions and jet shape
  - relatively unmodified jet core
  - suppression of intermediate $p_T$ particles
  - enhancement of low $p_T$ particles away from the jet axis

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BACKUP
ANALYSIS TECHNIQUE

• Reconstruct photons, tracks, jets

• Correlate selected photons with all jets (back-to-back with the photon) within the event (inclusive jet measurement)

• Subtract backgrounds
  • Underlying event
  • Neutral meson decays

• Smear jet resolutions/correct for resolution effects
  • Necessary for proper comparison between PbPb and pp data
Photons produced from neutral meson decays mimic direct photons
- Generally have wider shower shapes
- Estimated and subtracted using a template fitting method
  - Signal template from simulation
  - Background template from data

Subtract distributions based on the relative fractions present

Final result
\[ \frac{1}{\text{purity}} \times \text{Observable from all photon candidates} - \frac{1 - \text{purity}}{\text{purity}} \times \text{Observable from sideband photons} \]
QUARK/GLUON FRACTIONS

- dijets
- γ-jets
- Z-jets
ENERGY LOSS MECHANISMS

- Various models exist with different approaches to modelling the energy loss.
HADRON PT AND XI

\[
\xi_{\text{jet}} = \ln \left( \frac{P_{\text{trk}}}{P_{\text{jet}}} \right) \]

Jet, trk, and $R_{(\text{jet}, \text{trk})} = 0$

- $p_{\text{jet}}^{T} = 30 \text{ GeV/c}$
- $p_{\text{jet}}^{T} = 60 \text{ GeV/c}$
- $p_{\text{jet}}^{T} = 90 \text{ GeV/c}$
ATLAS PHOTON-JET COMPARISON TO MODELS

**ATLAS**

5.02 TeV, 25 pb$^{-1}$

$p_T^\gamma = 63.1$-$79.6$ GeV

- pp
- JEWEL+PYTHIA
- Hybrid
- BDMPS-Z
- SCET$_G$

**ATLAS**

5.02 TeV, 0.49 nb$^{-1}$

$p_T^\gamma = 63.1$-$79.6$ GeV

- Pb+Pb 0-10%
- Hybrid
- BDMPS-Z
- SCET$_G$

$(\bar{q}=2$-$8$ GeV$^2$/fm)

- $g = 2.0$-$2.2$

**ATLAS**

5.02 TeV, 25 pb$^{-1}$

$p_T^\gamma = 100$-$158$ GeV

- pp
- JEWEL+PYTHIA
- Hybrid
- BDMPS-Z

**ATLAS**

5.02 TeV, 0.49 nb$^{-1}$

$p_T^\gamma = 100$-$158$ GeV

- Pb+Pb 0-10%
- Hybrid
- BDMPS-Z

$(\bar{q}=2$-$8$ GeV$^2$/fm)
$\sqrt{s_{NN}} = 5.02$ TeV, PbPb 404 $\mu$b$^{-1}$, pp 27.4 pb$^{-1}$

CMS

$p_T^> > 60$ GeV/c, $h_T^< < 1.44$, $\Delta \phi^< > \frac{7\pi}{8}$

anti-$k_T$ jet $R = 0.3$, $p_T^{\text{jet}} > 30$ GeV/c, $h_T^{\text{jet}} < 1.6$

$p_T^{\text{trk}} > 1$ GeV/c

$1/N^{\text{jet}} dN^{\text{jet}}/d\xi^{\text{jet}}$

50-100% (+6)

30-50% (+4)

10-30% (+2)

0-10% (PbPb)

 pp (smeared)

PbPb / pp

0.5 1.0 1.5 2.0 2.5 3.0 3.5 4.0 4.5

$\xi^{\text{jet}}$

50-100% (+3)

30-50% (+2)

10-30% (+1)

0-10%
$\sqrt{s_{NN}} = 5.02$ TeV

PbPb 404 \( \mu b^{-1} \), pp 27.4 pb\(^{-1}\)

$P_{T}^{\text{trk}} > 1$ GeV/c, anti-$k_T$ jet $R = 0.3$, \( p_{T}^{\text{jet}} > 30\) GeV/c, $|\eta_{\text{jet}}| < 1.6$

$p_{T}^{\text{trk}} > 60$ GeV/c, $h_{\gamma} l < 1.44$, $\Delta \phi_{l\gamma} > \frac{7\pi}{8}$

CMS Supplementary Cent. 50 - 100%

CMS Supplementary Cent. 30 - 50%

CMS Supplementary Cent. 10 - 30%

CMS Supplementary Cent. 0 - 10%
$\sqrt{s_{NN}} = 5.02$ TeV

$\text{PbPb } 404 \mu b^{-1}, \text{ pp } 27.4 \text{ pb}^{-1}$

$P_{T}^{\text{jet}} > 1 \text{ GeV/c}, \text{ anti-}k_{T} \text{ jet } R = 0.3, P_{T}^{\text{jet}} > 30 \text{ GeV/c}, |\eta^{\text{jet}}| < 1.6$

$P_{T}^{\gamma} > 60 \text{ GeV/c}, |\eta^{\gamma}| < 1.44, \Delta \phi^{\gamma} > \frac{\pi}{6}$

$\frac{1}{N^{\text{jet}}} \frac{dN^{\mu}}{d\xi_{T}}$

CMS

Cent. 50 - 100%

Cent. 30 - 50%

Cent. 10 - 30%

Cent. 0 - 10%

$\frac{\text{PbPb} / \text{ pp}}{\text{PbPb} / \text{ pp}}$

$0.5$ $1$ $1.5$ $2$ $2.5$ $3$ $3.5$ $4$

$1$ $2$ $3$ $4$ $5$ $6$ $7$ $8$

$\xi_{T}$
CMS Supplementary

- $p_T^\gamma > 60$ GeV/c, $|\eta^\gamma| < 1.44$
- $p_T^{\text{trk}} > 1$ GeV/c
- anti-$k_T$ jet $R = 0.3$
- $p_T^{\text{jet}} > 30$ GeV/c
- $|\eta^{\text{jet}}| < 1.6$
- $\Delta\phi_J > \frac{7\pi}{8}$

CMS $\sqrt{s} = 5.02$ TeV, pp 27.4 pb$^{-1}$

MC / Data

\[ \rho(r) \]