Jet energy loss in boson-jet events in PbPb collisions at 5.02 TeV with CMS

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Energy loss in PbPb dijet events

- High energy quarks and gluons are used to study the properties of the quark-gluon plasma
- Dijet asymmetry measured in PbPb collisions
- Both jets are modified when passing through the medium

\[ A_J = \frac{(p_{T,1} - p_{T,2})}{(p_{T,1} + p_{T,2})} \]
Energy loss in PbPb boson-jet events

- Bosons in boson-jet events do not interact with the medium
- Clean tag of the initial parton energy

- Photons:
  - Higher statistics
  - Background processes have to be subtracted:
    - Neutral meson decay
    - Fragmentation photons

- Z bosons:
  - No contamination
  - Low statistics
Analysis

- Reconstruct bosons, jets
- Pair selected bosons with every jet in event (boson-inclusive jet measurement)
- Smear the pp jet spectra
- Subtract contributions from background processes (underlying event, neutral meson decays)

- Observables:
  - Azimuthal correlation ($\Delta \phi_{JV}$)
  - Transverse momentum imbalance ($x_{JV} = p_{TJ}/p_{TV}$)
    - $R_{JV}$: Average number of jets per boson
  - Jet spectra ratio ($I_{AA}$)

$V$ is $\gamma$ (photon) or Z boson

 CMS
 Z $\rightarrow \mu \mu$
 Cent. 0-30 %
 $p_T^\mu > 40$ GeV/c

Mixed-event background subtraction

Background jets from the underlying event

- Jets from the underlying event are not correlated with the boson
- Estimate this contribution by embedding the boson into minimum bias events

\[
\text{Background jets from the underlying event} = \text{boson} - \text{boson+jet event}
\]
Photon purity (photon-jet only)

Photons produced by neutral meson decays

- Generally have wider shower shapes
- Estimate this contribution by using a template fit on the width of the shower shape:
  - Signal template from Monte-Carlo
  - Background template from non-isolated sideband in data
Azimuthal correlation $\Delta\phi_{JZ}$ (Z-jet events)

- No broadening of the $\Delta\phi_{JZ}$ distribution within uncertainties

- **Not** statistically significant, p-value of 0.14

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

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

CMS

- PbPb, 0-30 %
- Smeared pp

$p^{Z} > 60$ GeV/c

anti-$k_T$ jet $R = 0.3$

$p^{jet}_{T} > 30$ GeV/c

$|\eta^{jet}| < 1.6$

HIN-15-013

arXiv: 1702.01060
Theory comparisons - $\Delta \phi_{JZ}$

- Consistent with both pQCD (JEWEL + PYTHIA) and hybrid strong/weak coupling (Hybrid) models within uncertainties

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

PbPb 404 $\mu$b$^{-1}$

CMS

- PbPb, 0-30 %
- Hybrid Strong Coupling
- Hybrid $dE/dx \propto T^3$
- Hybrid $dE/dx \propto T^2$
- JEWEL+PYTHIA

$p_T^Z > 60$ GeV/c

anti-$k_T$ jet $R = 0.3$

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

$|\eta|^{jet} < 1.6$
Azimuthal correlation $\Delta \phi_{J\gamma}$ (photon-jet)

- No broadening observed in photon-jet events in PbPb collisions relative to pp collisions
Theory comparison - $\Delta\phi_{jy}$

- LBT – pQCD model which keeps track of recoil thermal partons
- All models are in good agreement with data
Transverse momentum imbalance ($x_{jZ}$)

- Select only back-to-back jets ($\Delta \phi_{jZ} > 7\pi/8$)
- $x_{jZ}$ distribution in central PbPb collisions is shifted towards lower values, compared to pp collisions

$$x_{jZ} = \frac{p_{T}^{\text{jet}}}{p_{T}^{Z}}$$

CMS

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

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

HIN-15-013
arXiv: 1702.01060
Theory comparisons - $x_{JZ}$

- Predictions for the pp reference can be found in the backup slides

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

$PbPb 404$ $\mu$b$^{-1}$

CMS

- PbPb, 0-30 %

$\frac{1}{N_{JZ}} \frac{dN_{JZ}}{dx_{JZ}}$

- $p_T^Z > 60$ GeV/c
- anti-$k_T$ jet $R = 0.3$
- $p_{T\text{jet}} > 30$ GeV/c
- $|\eta_{\text{jet}}| < 1.6$
- $\Delta\phi_{JZ} > \frac{7}{8}\pi$

$HIN-15-013$

$x_{JZ} = p_T^{\text{jet}}/p_T^Z$
Transverse momentum imbalance ($x_{J\gamma}$)

- $x_{J\gamma}$ distribution is suppressed at low photon $p_T$ but shifted to lower values at high photon $p_T$. 

**Figure:**

- CMS Preliminary:
  - PbPb
  - pp (smeared)

- Conditions:
  - $\delta_{NN} = 5.02$ TeV
  - anti-$k_T$ Jet $R = 0.3$, $p_{T,\text{jet}} > 30$ GeV/c, $|\eta_{\text{jet}}| < 1.6$, $\Delta \phi_{\gamma,\text{jet}} > \frac{7\pi}{8}$

- Data:
  - PbPb 404 $\mu$b$^{-1}$, pp 25.8 $\mu$b$^{-1}$

- Graphs showing $dN_{J\gamma}/dx_{J\gamma}$ for different $p_{T,\gamma}$ ranges:
  - 0 - 30%
  - 40 < $p_{T,\gamma}$ < 50 GeV/c
  - 50 < $p_{T,\gamma}$ < 60 GeV/c
  - 60 < $p_{T,\gamma}$ < 80 GeV/c
  - 60 < $p_{T,\gamma}$ < 100 GeV/c
  - 80 < $p_{T,\gamma}$ < 100 GeV/c
  - $p_{T,\gamma} > 100$ GeV/c

**Legend:**

- $N_{J\gamma}$
- $dN_{J\gamma}/dx_{J\gamma}$
- $p_{T,\gamma}$
- $x_{J\gamma}$
Theory comparison - $x_{J\gamma}$

Main features of $x_{J\gamma}$ distributions are reproduced by all models.
Transverse momentum imbalance ($x_{J\gamma}$)

- $x_{J\gamma}$ distributions with more differential centrality binning

- Greater suppression and shifting of the $x_{J\gamma}$ distribution as the centrality increases
Mean $x_{J\gamma}/x_{JZ}$

• Lower mean $x_{J\gamma}/x_{JZ}$ in central PbPb collisions than in pp collisions
• Results consistent between photon-jet and Z-jet analyses
Average number of jets per boson ($R_{J\gamma}/R_{JZ}$)

- Mean $x_{J\gamma}/x_{JZ}$ characterizes the energy loss of jets.

- $R_{J\gamma}/R_{JZ}$ is defined as the integral of the $x_{J\gamma}/x_{JZ}$ distributions, and represents the average number of jets per boson.

- Jets that lose energy and fall below the jet $p_T$ threshold of 30 GeV/c result in a lower $R_{J\gamma}/R_{JZ}$.
Average number of jets per boson ($R_{Jγ}/R_{JZ}$)

- Lower $R_{Jγ}/R_{JZ}$ in central PbPb collisions than in pp collisions
- Results consistent between photon-jet and Z-jet analyses
$R_{J\gamma}$ (as function of centrality)

- Clear dependence of $R_{J\gamma}$ on both centrality and photon $p_T$

CMS Preliminary

\[ \sqrt{s_{NN}} = 5.02 \text{ TeV} \]

$40 < p_T^\gamma < 50 \text{ GeV/c}$

$\Delta\phi_{J\gamma} > \frac{7\pi}{8}$

$50 < p_T^\gamma < 60 \text{ GeV/c}$

$60 < p_T^\gamma < 80 \text{ GeV/c}$

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

increasing photon $p_T$

- $\gamma + \text{Jet}$ and $\gamma + \text{hadrons}$
Jet $I_{AA}$ (photon-jet events)

- $I_{AA}$ (ratio of jet spectra in PbPb to pp) adds information about jet energy loss over the kinematic range.

Increasing photon $p_T$
Summary

- Photon-jet and Z-jet correlations were studied with PbPb and pp data at 5.02 TeV
- No evidence of broadening of the $\Delta\phi$ distributions
- $x_{J\gamma}/x_{JZ}$ distributions are suppressed and shifted to lower $p_T$ in PbPb collisions versus pp collisions
Backup
Z mass peaks

HIN-15-013
arXiv: 1702.01060
Q Scale

- Z+jet events have higher Q scale than photon+jet
Signal Photon

Identify signal photons by:
Isolation requirement based on calorimeter energy deposits
Extract fraction of signal photons based on shower shape

Leading order

- Compton
- Annihilation

Higher orders

- Bremsstrahlung
- Fragmentation

Final state not differentiable

ISOLATED

ISOLATED

NON-ISOLATED
Jet smearing for jets in pp collisions

- Different jet energy and angular resolutions for PbPb and pp collisions
  - Smear the pp jet spectra to match that of PbPb

- Parametrize the jet energy resolution with the C, S and N parameters:
  \[
  \sigma \left( \frac{p_T^{RECO}}{p_T^{GEN}} \right) = \sqrt{C^2 + \frac{S^2_{GEN}}{p_T^{GEN}} + \frac{N^2}{(p_T^{GEN})^2}}
  \]

- Smear the jet spectra by the relative resolutions:
  \[
  \sigma_{rel} = \sqrt{(C_{PbPb}^2 - C_{pp}^2) + \frac{(S_{PbPb}^2 - S_{pp}^2)}{p_T^{GEN}} + \frac{(N_{PbPb}^2 - N_{pp}^2)}{(p_T^{GEN})^2}}
  \]

- Similar procedure is applied for the angular resolution
Theory comparisons – $\Delta \phi_{jZ}$ (pp)

CMS

- Smeared pp
- Hybrid
- JEWEL+PYTHIA

$\sqrt{s} = 5.02$ TeV

pp 27.4 pb$^{-1}$

- $p_T^Z > 60$ GeV/c
- anti-$k_T$ jet $R = 0.3$
- $p_T^{jet} > 30$ GeV/c
- $|\eta^{jet}| < 1.6$
Theory comparisons – $\Delta \phi_{J\gamma}$ (pp)
Theory comparison – $x_{JZ}$ (pp reference)
Theory comparison – $x_{J\gamma}$ (pp reference)
Theory comparison – $x_{J\gamma}$
Theory comparison – $x_{J\gamma}$ (pp reference)
Theory comparison - $R_{JZ}$

CMS

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

PbPb 404 $\mu$b$^{-1}$

- Hybrid Strong Coupling
- Hybrid $dE/dx \propto T^3$
- Hybrid $dE/dx \propto T^2$
- JEWEL+PYTHIA

- PbPb, 0-30 %

$R_{JZ}$ vs $p_T^Z (\text{GeV/c})$

$\Delta \phi_{jZ} > \frac{7}{8}\pi$

anti-$k_T$ jet $R = 0.3$

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

$|\eta^{\text{jet}}| < 1.6$
Theory comparison – $R_{JZ}$ (pp reference)

CMS

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

- Hybrid
- JEWEL+PYTHIA

Smeared pp

anti-$k_T$ jet R = 0.3
$p_T^{\text{jet}} > 30$ GeV/c
$|\eta^{\text{jet}}| < 1.6$
$\Delta\phi_{JZ} > \frac{7\pi}{8}$

$p_T^Z$ (GeV/c)
Theory comparison – $\langle x_{j\gamma} \rangle$ (pp reference)

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

$\Delta \phi_{j\gamma} > \frac{7\pi}{8}$

PbPb 404 $\mu$b$^{-1}$, pp 25.8 pb$^{-1}$

CMS Preliminary

- pp (smeared)
- pp (Hybrid Model)
- pp (JEWEL + PYTHIA)

0 - 30%
anti-$k_T$ Jet $R = 0.3$
$p_T^{\text{jet}} > 30$ GeV/c
$|\eta^{\text{jet}}| < 1.6$
Theory comparison – $R_{J\gamma}$ (pp reference)
Previous results - $\Delta \phi_{J\gamma}$
Previous results - $x_{J\gamma}$
Previous results - $x_{J\gamma}$
Previous results – $<x_{JY}>/R_{JY}$
Previous results – Jet $I_{AA}$

The figure shows the CMS Preliminary results for jet $I_{AA}$ in PbPb collisions at various $p_T$ ranges: 40 GeV < $p_T$ < 50 GeV, 50 GeV < $p_T$ < 60 GeV, 60 GeV < $p_T$ < 80 GeV, and $p_T$ > 80 GeV. The data is presented for the 30-100% and 0-30% centrality bins.

- PbPb 30-100%:
  - $p_T$ range: 20 GeV to 140 GeV
  - CMS Preliminary
  - $\sqrt{s_{NN}}$ = 2.76 TeV
  - PbPb 150 $\mu$b$^{-1}$
  - pp 5.3 pb$^{-1}$

- PbPb 0-30%:
  - $p_T$ range: 20 GeV to 140 GeV
  - CMS Preliminary
  - $\sqrt{s_{NN}}$ = 2.76 TeV
  - PbPb 150 $\mu$b$^{-1}$
  - pp 5.3 pb$^{-1}$
Other results – ATLAS $x_{J\gamma}$

\[ (1/N_{J\gamma})(dN/dx_{J\gamma}) \]

- $60 < p_T^{J\gamma} < 80$ GeV
  - 0-10% Pb+Pb, 0.49 nb$^{-1}$
  - $pp$, 26 pb$^{-1}$
  - PYTHIA 8 + Data Overlay

- $80 < p_T^{J\gamma} < 100$ GeV
  - ATLAS Preliminary
  - 5.02 TeV

- $100 < p_T^{J\gamma} < 150$ GeV

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