ENERGY LOSS IN DIJET EVENTS

- Jet quenching is a characteristic feature of the QGP
  - Observed through measurements of jet energy loss in dijet systems
- Caveat: both jets can be modified when passing through the medium

![CMS Experiment at LHC, CERN](image)

Data recorded: 11 Nov 16 18:39 2010 CEST
Run/Event: 161079 / 332928
Luminosity: 249

![Graph](image)

- \[ A_J = \frac{(p_{T,1} - p_{T,2})}{(p_{T,1} + p_{T,2})} \]

PLB 712 (2012) 176
ENERGY LOSS IN PHOTON-JET EVENTS

- Photons, being colourless, do not interact with the medium
  - Clean tag of the initial energy
  - Better handle on the quark/gluon jet ratio
- Measurements with photon-jet and Z-jet events show clear evidence for in-medium energy loss

CMS

anti-k_T jet R = 0.3, p_T^{jet} > 30 GeV/c, |Δφ^{jet}| < 1.6, |η_{jet}| < 1.44, p_T^{γ} > 60 GeV/c, Δφ^{γ} > \frac{7π}{8}, \sqrt{s_{NN}} = 5.02 TeV, PbPb 404 \mu b^{-1}, pp 27.4 pb^{-1}

PLB 785 (2018) 14B
PHOTON-TAGGED JET SUBSTRUCTURE

- What is happening to the quenched jet?
  - Jet substructure measurements can help answer this

\[
\frac{1}{N_{\text{jet}}} \frac{dN_{\text{track}}}{d\xi}
\]

CMS PbPb $\sqrt{s_{NN}} = 2.76$ TeV
150 $\mu$b$^{-1}$

\[
\xi = \ln\left(\frac{1}{z}\right)
\]

PbPb
- pp reference data

$100 < p_T^{\text{jet}} < 300$ GeV/c
$0.3 < |\eta| < 2$
$R < 0.3$

$R_T > 1$ GeV/c

PRC 90 (2014) 024908

20 March 2019
High-pT physics in the RHIC and LHC era
PHOTON-TAGGED JET SUBSTRUCTURE

- What is happening to the quenched jet?
  - Jet substructure measurements can help answer this.
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
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
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.
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

\[
\text{Final result} = \frac{1}{\text{purity}} \times \text{Observable from all photon candidates} \quad - \quad \frac{1 - \text{purity}}{\text{purity}} \times \text{Observable from sideband photons}
\]
OBSERVABLES (JET FRAGMENTATION FUNCTION)

- Jet fragmentation function
  \[ \xi_{\text{jet}} = \ln \frac{|p_{\text{jet}}^2|}{p_{\text{trk}}^2 \cdot p_{\text{jet}}^2} \]
  - Distribution of jet momentum parallel to the jet axis
    - Sensitive to hadronisation

- Can also be calculated with respect to photon momentum
  \[ \xi_{T} = \ln \frac{-|p_{\gamma}^2|}{p_{\text{trk}}^2 \cdot p_{T}^2} \]
  - Momentum conservation is valid only in transverse direction
  - Takes advantage of better energy resolution of photons
RESULTS (JET FRAGMENTATION FUNCTION)

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

\[ \sqrt{s_{NN}} = 5.02 \text{ TeV} \]
\[ p_T^{\text{jet}} > 1 \text{ GeV/c}, \text{ anti}-k_T \text{ jet } R = 0.3 \]
\[ p_T^{\text{jet}} > 30 \text{ GeV/c}, |\eta^{\text{jet}}| < 1.6 \]
\[ p_T^{\text{jet}} > 60 \text{ GeV/c}, |\eta^{\text{jet}}| < 1.44, \Delta\phi_{\text{tr}} > \frac{7\pi}{8} \]
RESULTS (JET FRAGMENTATION FUNCTION)

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

![Graphs showing JET FRAGMENTATION FUNCTION results]
MODEL COMPARISONS (JET FRAGMENTATION FUNCTION)

- Stronger modification for $\xi^\gamma_T$ than for $\xi^{\text{jet}}$
  - Jet energy quenched
- Both SCET$_G$ and CoLBT-hydro models describe trend of both observables
- Hybrid does not do well, but addition of back reaction improves agreement with data
- Enhancement at large $\xi$ (low-p$_T$ particles) is underestimated in all models
OBSERVABLES (JET SHAPE)

- Distribution of jet energy in transverse direction with respect to jet axis
  - Complementary information to jet fragmentation function
  $$\rho(r) = \frac{1}{\delta r} \frac{\sum_{\text{jets}} \sum_{\text{trk} \in [0,r_f]} \left( \frac{p_{T}^{\text{trk}}}{p_{T}^{\text{jet}}} \right)}{\sum_{\text{jets}} \sum_{\text{trk} \in [r_a,r_b]} \left( \frac{p_{T}^{\text{trk}}}{p_{T}^{\text{jet}}} \right)}$$

- CMS: Supplementary
  - Cent. 50 - 100%
  - Cent. 30 - 50%
  - Cent. 10 - 30%
  - Cent. 0 - 10%

- PbPb 404 µb⁻¹, pp 27.4 pb⁻¹
- $\sqrt{s_{NN}} = 5.02$ TeV

- $p_{T}^{j} > 60$ GeV/c, $|\eta^{j}| < 1.44$, $p_{T}^{\text{trk}} > 1$ GeV/c
- anti-$k_{t}$ jet $R = 0.3$, $p_{T}^{\text{jet}} > 30$ GeV/c, $|\eta^{\text{jet}}| < 1.6$, $\Delta_{\phi} > \frac{7\pi}{8}$

- ARXIV:1809.08602

- 20 March 2019

High-pT physics in the RHIC and LHC era
RESULTS (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
RESULTS (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
    - SCET$_G$/LBT both describe trend
RESULTS (JET SHAPE)

- Comparison to heavy flavour jets
  - Measure radial distribution of D⁰ mesons in jets
  - Probe the origin of the modification of inclusive hadrons at large r

- Similar modification observed for low-pₜ D⁰ mesons
  - Low-pₜ D⁰ mesons tend to be further away from jet axis

\[ \text{CMS-PAS-HIN-18-007} \]
SUMMARY

• Photon-tagged measurements constrain initial parton kinematics and flavour

• Photon-tagged jet asymmetry:
  • Rough measure of absolute energy loss

• Photon-tagged jet fragmentation functions:
  • Depletion of high-\(p_T\) particles and excess of low-\(p_T\) particles within the jet

• Photon-tagged jet shapes:
  • Larger amount of jet energy found at larger radial distances from the jet axis
  • Measurements of heavy flavour particles in jets may help with understanding the mechanism
BACKUP
HADRON PT AND XI

\begin{align*}
\xi_{\text{jet}} &= \ln \left( \frac{p_{T}^{\text{jet}}}{p_{T}^{\text{trk}}} \right) \\
p_{T}^{\text{trk}} \text{ (GeV/c)} &\quad \begin{cases} 
0.5 & 1 \\
1.5 & 2 \\
2.5 & 3 \\
3.5 & 4 \\
4.5 & 5
\end{cases}
\end{align*}

\Delta R (\text{jet, trk}) = 0

\text{jet} \quad \text{trk} 

\begin{align*}
p_{T}^{\text{jet}} &= 30 \text{ GeV/c} \\
p_{T}^{\text{jet}} &= 60 \text{ GeV/c} \\
p_{T}^{\text{jet}} &= 90 \text{ GeV/c}
\end{align*}
QUARK/GLUON FRACTIONS

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

- Various models exist with different approaches to modelling the energy loss
ATLAS PHOTON-JET CENTRALITY DEPENDENCE

**ATLAS**

- **pp** 5.02 TeV, 25 pb\(^{-1}\)
- **Pb+Pb** 5.02 TeV, 0.49 nb\(^{-1}\)

- \(p_T^\gamma = 63.1-79.6\) GeV
- \(p_T^\gamma = 79.6-100\) GeV

\(p_T^\gamma\) (same each panel)

- **pp** (same each panel)
- **Pb+Pb**
ATLAS PHOTON-JET CENTRALITY DEPENDENCE

\[ \frac{1}{N} \frac{dN}{dx_{\gamma}} \]

**ATLAS**

*pp* 5.02 TeV, 25 pb\(^{-1}\)

Pb+Pb 5.02 TeV, 0.49 nb\(^{-1}\)

\( p_{T}^{\gamma} = 100-158 \text{ GeV} \)

\( p_{T}^{\gamma} = 158-200 \text{ GeV} \)

- \( pp \) (same each panel)
- Pb+Pb
ATLAS PHOTON-JET COMPARISON TO MODELS

\( \frac{1}{N_J} \langle dN/dx_J \rangle \)

**ATLAS**
- 5.02 TeV, 25 pb\(^{-1}\)
- \( p_T^\gamma = 63.1-79.6 \text{ GeV} \)

- **pp**
- JEWEL+PYTHIA
- Hybrid
- BDMPS-Z
- SCET\(_G\)

\( \frac{1}{N_J} \langle dN/dx_J \rangle \)

**ATLAS**
- 5.02 TeV, 0.49 nb\(^{-1}\)
- \( p_T^\gamma = 63.1-79.6 \text{ GeV} \)

- **Pb+Pb 0-10%**
- JEWEL+PYTHIA
- Hybrid
- BDMPS-Z
- SCET\(_G\)

\( \frac{1}{N_J} \langle dN/dx_J \rangle \)

**ATLAS**
- 5.02 TeV, 25 pb\(^{-1}\)
- \( p_T^\gamma = 100-158 \text{ GeV} \)

**ATLAS**
- 5.02 TeV, 0.49 nb\(^{-1}\)
- \( p_T^\gamma = 100-158 \text{ GeV} \)

- **Pb+Pb 0-10%**
- JEWEL+PYTHIA
- Hybrid
- BDMPS-Z

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

\( g = 2.0-2.2 \)
\( \sqrt{s_{\text{NN}}} = 5.02 \, \text{TeV} \)

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

CMS

Supplementary Cent. 50 - 100%

Supplementary Cent. 30 - 50%

Supplementary Cent. 10 - 30%

Supplementary Cent. 0 - 10%

\[ p_T^{\text{jet}} > 1 \, \text{GeV/c}, \text{anti-} k_T \text{ jet } R = 0.3, p_T^{\text{jet}} > 30 \, \text{GeV/c}, |\eta^{\text{jet}}| < 1.6 \]

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

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

\[ \frac{\text{PbPb}}{\text{pp}} \]

\( 1 \rightarrow 4 \)
\( \sqrt{s_{NN}} = 5.02 \text{ TeV} \)

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

\( p_T^{\text{jett}} > 1 \text{ GeV/c}, \text{ anti-}k_T \text{ jet } R = 0.3, p_T^{\text{jett}} > 30 \text{ GeV/c}, |\eta^{\text{jett}}| < 1.6 \)

\( p_T^{\gamma} > 60 \text{ GeV/c}, \eta^{\gamma} < 1.44, \Delta \phi^{\gamma} > \frac{7\pi}{8} \)
\[ r_0 \in [0.05, 0.15, 0.2, 0.25, 0.3] \]

MC / Data

CMS
Supplementary

\[ \sqrt{s} = 5.02 \text{ TeV}, \text{ pp } 27.4 \text{ pb}^{-1} \]

- \[ p_T^{\gamma} > 60 \text{ GeV/c}, |\eta| < 1.44 \]
- \[ p_T^{\pi} > 1 \text{ GeV/c} \]
- \[ |\eta| < 1.6 \]
- \[ |\Delta \phi| > \frac{7\pi}{8} \]

- \[ \text{anti-}\kappa_T \text{ jet } R = 0.3 \]
- \[ p_T^{\text{jet}} > 30 \text{ GeV/c} \]
ATLAS PHOTON-TAGGED JET FRAGMENTATION FUNCTIONS

\[ \text{Ratio of } D(p_T) \]

\[ \text{Ratio of } D(z) \]