Jet Quenching with CMS

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Specific measurements from the CMS experiment based on PbPb and pp collisions at 2.76 TeV

- Dijet and photon+jet asymmetry
- Nuclear modification factor $R_{AA}$
- Flavor dependence of jet quenching
- Jet shapes and fragmentation functions
Direct observation of jet quenching was done with dijet events!

CMS Experiment at LHC, CERN
Data recorded: Sun Nov 14 19:31:39 2010 CEST
Run/Event: 151076 / 1328520
Lumi section: 249
Dijet asymmetry (Aj) observable was used for initial observation:

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

**Jet Quenching**: Direct Observation of Jet Quenching at LHC

Small Aj (balanced dijet)  
Large Aj (un-balanced dijet)

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**References**

- PRC 84 (2011) 024906
- PLB 712 (2012) 176
Jet Quenching: Direct Observation of Jet Quenching at LHC

Dijet asymmetry (Aj) observable was used for initial observation:

$$A_J = \frac{p_{T1} - p_{T2}}{p_{T1} + p_{T2}}$$

**Small Aj** (balanced dijet) vs **Large Aj** (un-balanced dijet)

**PP-like simulation**

**PbPb data**

Difference observed in central collisions is due to quenching!
Jet Quenching: Direct Observation of Jet Quenching at LHC

Dijet asymmetry (A_J) observable was used for initial observation:

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

Parton energy loss is observed as a pronounced energy imbalance in central PbPb collisions!

Small Aj (balanced dijet)

Large Aj (un-balanced dijet)

PP-like simulation

PbPb data
Difference observed in central collisions is due to quenching!
Energy loss is observed for all $p_T$ bins. MC-Data difference has no significant dependence on jet $p_T$. 
Jet Quenching: with Photon+Jet Correlations

γ+jet events are a direct probe for the parton energy loss in QGP!

1. Jets are quenched but photons are not
2. When there is no quenching, photon has the energy of the jet
3. When there is quenching, it is a direct probe for quark energy loss
4. No surface bias as in dijet events
Jet Quenching : $\gamma$-Jet Correlation

Momentum imbalance in photon-jet events?

\[ X_{J\gamma} = \frac{p_{T,jet}}{p_{T,\gamma}} \]

Centrality dependent large momentum imbalance is observed photon-jet events as well!
Jet Quenching: Is the angular correlation modified?

Given the large energy (momentum) imbalance seen in dijet (photon-jet) events:

*Interesting question: is the angular correlation modified between “dijet” and “photon and jet” events?*
Jet Quenching: Is the dijet angular correlation modified?

ΔΦ is an important variable to select a clean dijet (photon-jet) sample!

ΔΦ_{12} = Φ_{1, jet} - Φ_{2, jet}  
ΔΦ_{Jγ} = Φ_{γ} - Φ_{jet}

ΔΦ_{12} → peripheral "pp-like"  
ΔΦ_{Jγ} → central

No apparent modification of ΔΦ distributions.
Jet Quenching: Where does this energy go?

Observed a large dijet (photon-jet) energy (momentum) imbalance!

*Where does this energy go?*
Jet Quenching: Where does this energy go?

\[ \langle p_{T}^{\parallel} \rangle = \sum_{\text{Tracks}} -p_{T}^{\text{Track}} \cos (\phi_{\text{Track}} - \phi_{\text{Leading Jet}}) \]

All tracks “inside” the jet cone \( \Delta R < 0.8 \)

All tracks “outside” the jet cone \( \Delta R > 0.8 \)

All tracks

The momentum difference in the dijet is balanced by low \( p_{T} \) particles outside the jet cone!

The total summed projected momentum is close to zero.

Sum over all the tracks in the event

CMS 0-30% Pb+Pb \( \sqrt{s_{NN}} = 2.76 \) TeV

Integration time: 6.7 \( \mu \)b

In-Cone \( \Delta R < 0.8 \)

Out-of-Cone \( \Delta R > 0.8 \)

0-30%

Inside the jet cone: Excess towards leading jet

Outside of the jet cone: Excess towards sub-leading jet

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Dijet energy or photon+jet momentum asymmetry can not provide all the information about the parton energy loss. We would like to know more!

- How are the inclusive jet yields suppressed?
- How does the suppression depend on jet energy and collision centrality?
- Does suppression depend on the size of the jet?
- Does the suppression depend on the flavor of the initial parton?
- Is the jet structure modified?

Such measurements can provide quantitative constraints on the quenching mechanism!
Suppression of inclusive jet rates ($R_{AA}$) from CMS

$$R_{AA} = \frac{dN_{AA}^{jets}/d\mathbf{p}_T}{\langle T_{AA} \rangle d\sigma_{pp}^{jets}/d\mathbf{p}_T}$$

$R_{AA}$: Compare PbPb (central) to pp (vacuum)

No clear dependence of suppression on jet $p_T$ and cone size!
Are inclusive jets suppressed in same manner as charged hadrons?

Suppression for charged particles:

Suppression for jets:

Looking the same parton $p_T$ range!

Like for charged particles, high $p_T$ jet $R_{AA}$ is flat at $\approx 0.5$
Flavor dependence?

- **First b-jet identification in HI collisions!**
  => Identify b-jets using displaced tracks

- **Validation:** measured fraction of jets that have b’s in PbPb (pp) is consistent with expectations within uncertainties!

- **Result:** b-jet quenching is comparable to light flavor quenching within uncertainties!

- First observation of b-jet suppression at high-$p_T$. 

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Validation

Result
Are “jet shapes” also modified?

Jet shapes measure the energy flow inside the jet!

Jet shapes in heavy-ion collisions expected to be distorted by energy loss in medium

- Centrality dependent broadening
- But this has never been measured before!

Differential Jet Shape

Differential jet shape is the transverse momentum fraction inside a given radial annulus in \( \eta-\phi \) space

\[
\rho(r) = \frac{1}{\delta r} \frac{1}{N_{\text{jet}}} \sum_{\text{jets}} \frac{p_T(r - \delta r/2, r + \delta r/2)}{p_T^{\text{jet}}}
\]
In presence of a medium expect:
(a) PbPb/pp ratio to deviate from 1
(b) Effect to be stronger in central collisions

~40% rise
ratio=1.0 means no medium effect

Peripheral "pp-like"

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In presence of a medium expect:
(a) PbPb/pp ratio to deviate from 1
(b) Effect to be stronger in central collisions

CMS PAS HIN-12-013

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How is the transverse momentum distributed inside the jet cone?

Historically, jet fragmentation functions (\(\xi\)) defined as \(\log(1/z)\), where \(z\) is the momentum fraction of the jet carried by an individual particle:
A clear centrality dependent modification of the inclusive jet fragmentation functions in PbPb collisions!
CMS have presented very interesting results in heavy ion collisions

- Many of these observables have low correlation to one-another. They serve as useful independent confirmations of the quenching properties.

Our measurements indicate consistent view of the hot and dense medium

- Large energy (momentum) imbalance in dijet (photon+jet) events
- No clear jet $p_T$ and cone size dependence is observed for inclusive jet $R_{AA}$
- $b$-jets are quenched similarly to the light quark jets
- Centrality dependent modest broadening and modification of jet shapes/fragmentation functions

All CMS public results can be found here:

https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsHIN
Jet Reconstruction in CMS

A popular anti-kT algorithm is used for jet reconstruction used in CMS analyses!

Several different cone sizes are used depending on the purpose of the analyses: \( \Delta R = 0.3, 0.5, 0.7 \)

**CMS heavy-ion jet analyses prefer to use:**
1- small cone size \( R = 0.3 \) as default
2- Particle-Flow event reconstruction

A typical high pT jet composition

Underlying Event Subtraction
Iterative pile-up subtraction


[2] CMS-PAS-PFT-09-001

Underlying Event Subtraction

For details see:
- Kodolova et al., [EPJC 50 (2007) 117](http://link.springer.com/article/10.1140/epjc/s10052-007-0286-1)
UE Background Subtraction

1- Eta Reflection

\[ \eta(bkg\_jet) = -\eta(jet) \]

\[ \Delta \eta < 0.3 \] region is not used in order to avoid overlay between the signal jet and background jet.

2- Event Mixing

Jet Event

MinBias Event

Same technique used in FF and jet shape (Cross-checks)

Same as HIN-11-004
PbPb and pp comparison:
- Jet $p_T$ resolutions different
- Jet $p_T$ spectra are different

- **Smearing**
  Smear $p_T$ of jets in pp data to compensate for difference in jet resolutions

- **Re-weighting**
  Re-weight pp data to match jet $p_T$ distribution in PbPb
More than 95% of the jet energy deposited in $r < 0.2$
How is the track $p_T$ distributed inside the jet cone?

1. High $p_T$ particles are located close to the jet axis
2. Low $p_T$ particles are mostly located at large angles from the jet axis.
Long lifetime of b (~1.5 ps) leads to measurable (mm or cm) displaced secondary vertices (SV)

Subsequent charm decay may lead to a tertiary vertex

B-jets are tagged using reconstructed SV’s, using the flight distance of the SV as a discriminating variable

We then extract the b-jet fraction by a fit to the SV mass

An alternative tagger based only the impact parameter of the tracks in the jet is used to corroborate the SV performance

b-jet Identification in CMS: CMS-PAS-BTV-11-004
Tagging and counting b-quarks

Secondary vertex tagged using flight distance significance

Tagging efficiency estimated in a data-driven way

Purity from template fits to (tagged) secondary vtx mass distributions

CMS PAS HIN-12-003

CMS Preliminary

\( \sqrt{s_{NN}} = 2.76 \text{ TeV} \)

\( 80 < p_T < 100 \text{ GeV/c} \)

\( \chi^2/NDF = 10.1 / 11 \)