Jets and high-$p_T$ probes of the QGP

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Specific measurements from the CMS experiment based on PbPb and pp collisions at 2.76 TeV, and pPb collisions at 5.02 TeV that address the questions below:

- What does happen to the quenched jet?
- Is the jet energy modified in pPb?
- Does jet quenching have any flavor dependence?
**Introduction: Jet Quenching**

Heavy-ion collisions create a Quark Gluon Plasma (QGP). This “medium” suppresses strongly-interacting high-$p_T$ particles!

- Quarks and gluons will lose energy from interacting with the medium
  - “Quenching”: Energy loss of a parton or modification of its parton shower through interactions with the medium

- Typical approach to study quenching:
  1. Make measurement in heavy ion collisions where medium is present
  2. Make same measurement in pp (or pp-like) collisions and compare
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\[
R_{AA} = \frac{1}{N_{\text{evnts}}} \frac{d^2N_{\text{PbPb}}}{dydp_T} \frac{d^2\sigma_{pp}}{dydp_T} \frac{1}{<T_{AB}>} 
\]

In the absence of the medium \( R_{AA} = 1 \)
In the case of suppression \( R_{AA} < 1 \)
In the case of enhancement \( R_{AA} > 1 \)
Introduction: Large Hadron Collider (LHC)

Designed to collide @ 5.5 TeV

14 times higher collision energy with respect to Relativistic Heavy Ion Collider (RHIC)!

<table>
<thead>
<tr>
<th>Period</th>
<th>Species</th>
<th>Energy</th>
<th>Lumi</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dec. 2010</td>
<td>Pb+Pb</td>
<td>2.76 TeV</td>
<td>7 µb⁻¹</td>
</tr>
<tr>
<td>Dec. 2011</td>
<td>Pb+Pb</td>
<td>2.76 TeV</td>
<td>150 µb⁻¹</td>
</tr>
<tr>
<td>Mar. 2011</td>
<td>p+p</td>
<td>2.76 TeV</td>
<td>230 nb⁻¹</td>
</tr>
<tr>
<td>Jan. 2013</td>
<td>p+Pb</td>
<td>5.02 TeV</td>
<td>35 nb⁻¹</td>
</tr>
<tr>
<td>Fev. 2013</td>
<td>p+p</td>
<td>2.76 TeV</td>
<td>5.4 pb⁻¹</td>
</tr>
</tbody>
</table>

ALICE ATLAS LHCb

Switzerland

27 km circumference

France

Leman Lake

CMS

Data included from 2013-01-20 14:08 to 2013-02-10 05:05 UTC

LHC Delivered: 36.14 nb⁻¹
CMS Recorded: 35.50 nb⁻¹

pPb luminosity 98% DAQ eff.
Excellent tracking resolution and jet reconstruction even in the high-multiplicity events!
Direct observation of jet quenching was done with dijet events!
Jet Quenching: Direct Observation of Jet Quenching at LHC

- Strong jet-quenching in PbPb collisions
- Observed as a pronounced dijet $p_T$ imbalance

**PP-like simulation**

**PbPb data**
Difference observed in central collisions is due to quenching!

**Peripheral (pp like)**

**Central**

- $A_j = \frac{(p_{T1} - p_{T2})}{(p_{T1} + p_{T2})}$

**CMS**

- $\sqrt{s_{NN}} = 2.76$ TeV
- $\int L dt = 150 \mu$b$^{-1}$
- $\int L dt = 231 \text{ nb}^{-1}$

**PYTHIA+HYDJET**

- $p_{T1} > 120$ GeV/c
- $p_{T2} > 30$ GeV/c
- $\Delta \phi_{12} > \frac{2}{3} \pi$

**PbPb**

- 70-100%
- 0-10%
Jet Quenching: Direct Observation of Jet Quenching at LHC

Small Aj (balanced dijet)

Large Aj (un-balanced dijet)

Event centrality determination

Events are classified according to the percentile of the PbPb inelastic cross section based on total deposited energy in the forward calorimeters.

PbPb data

Difference observed in central collisions is due to quenching!

- Strong jet-quenching in PbPb collisions
- Observed as a pronounced dijet $p_T$ imbalance
- 10% decrease of $<p_{T,2}/p_{T,1}>$ for central collisions

$=>$ Subleading jets get quenched (~10GeV) more compared to leading jets

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Jet Quenching: Where does this energy go?

Since early 2011 we know that the momentum difference in the dijet is balanced by low $p_T$ particles outside the jet cone!

$$p_T^\parallel = \sum_{\text{Tracks}} -p_T^{\text{Track}} \cos (\phi_{\text{Track}} - \phi_{\text{Leading Jet}})$$

CMS 0-30%

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PRC 84 (2011) 024906
Jet Quenching: Where does this energy go?

Since early 2011 we know that the momentum difference in the dijet is balanced by low $p_T$ particles outside the jet cone!

- 35 GeV missing at $\Delta R < 0.2$ for $A_j > 0.22$ in 0-30%
- High $p_T$ imbalance at small $\Delta R$ is balanced by low $p_T$ particles in subleading jet direction
- Extends up to large $\Delta R$
- Shape of the balancing distribution in pp and PbPb is very similar
Jet Quenching: **First Experimental Jet Shapes in “HI collisions”**

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

Measuring fractional radial energy distribution (inclusive jets)

In presence of a medium expect:

(a) PbPb/pp ratio to deviate from 1
(b) Centrality dependent broadening and effect to be stronger in central collisions

\[ \rho(r) = \frac{1}{f_{\text{ch}} \delta r N_{\text{jet}}} \sum_{ \text{jets} } \frac{p_{\text{T}}(r - \delta r/2, r + \delta r/2)}{p_{\text{T}}^{\text{jet}}} \]

- **Peripheral (“pp-like”)**
- **Central**

Broader jet shapes in PbPb: Enhancement of low \( p_T \) particles

PbPb/pp ratio = 1.0 means no medium effect

~40% rise

PbPb/pp ratio = 1.0 means no medium effect
Jet Quenching: Jet Fragmentation Functions

Measuring in-cone track moment distribution projected onto jet axis (inclusive jets)

A clear centrality dependent modification of the inclusive jet fragmentation functions in PbPb collisions!

\[ z = \frac{p_{\text{track}}}{p_{\text{jet}}}, \quad \xi = \ln \frac{1}{z} \]

\[ \text{PbPb/pp ratio=1.0 means no medium effect} \]

\[ \text{Enhancement of low } p_T \text{ particle} \]

\[ \text{No modification at high } p_T \]

\[ \text{Suppression of intermediate particle } p_T \text{ in the cone} \]
Jet energy is essentially unmodified in pPb:

- As seen for instance in gamma-jet correlations
- \( R_{J\gamma} \) = fraction of photons with a jet of \( p_T > 30 \text{ GeV} \)
- PbPb results updated with new pp reference
Jet Quenching: $R_{pA}$ and $R_{AA}$ for jets and b-jets

Jet $R_{pA}$ is $\approx 1$ while high $p_T$ jet $R_{AA}$ is flat at $\approx 0.5$
Jet Quenching: $R_{pA}$ and $R_{AA}$ for jets and b-jets

- Jet $R_{pA}$ is $\approx 1$ while high $p_T$ jet $R_{AA}$ is flat at $\approx 0.5$
- Jets coming from $b$ are suppressed as inclusive jets ($R_{AA} \approx 0.5$) in PbPb
- Not suppressed in pPb ($R_{AA} \approx 1$)
Jet Quenching: $R_{pA}$ and $R_{AA}$ for jets and tracks

Inclusive Jets

- CMS preliminary
- Inclusive jet $R_{pA}$ (0-100%) $|\eta_{CM}| < 0.5$
- Inclusive jet $R_{AA}$ (0-5%) $|\eta| < 2$

Charged Particles

- CMS Preliminary
- Charged particles $R_{pA}$ $|\eta_{CM}| < 1$
- Charged particles $R_{AA}$ (0-5%) $|\eta| < 1$

• Enhancement observed at high-$p_T$
• Too large to be due to anti-shadowing?
• Other nuclear effect?
• Urgently need pp reference at 5.02 TeV
Jet Quenching: Modified dijet rapidity in pPb

The mean of dijet $\eta$ shifts monotonically vs forward energy.

Dijet $\eta$ widths become smaller vs forward energy.

Strong modification of the dijet pseudorapidity vs forward activity.

- The mean of dijet $\eta$ shifts monotonically vs forward energy.
- Dijet $\eta$ widths become smaller vs forward energy.
Summary

- CMS has 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
  - Jets are heavily quenched in PbPb
    - Extensive studies on where the energy goes
      - to large angles and lower $p_T$
  - Jets are not strongly quenched on pPb ($R_{pA} \sim 1$)
  - No strong flavour dependence at high-$p_T$ ($R_{AA} \sim 0.5$ for b-jet and inclusive jet)

- All CMS public results can be found here:
  
  [https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsHIN](https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsHIN)
Extra Slides
\( \eta_{CM} \) in \( pPb \)

- \( pPb \) collisions are natively asymmetric
  - \( E(\text{proton}) = 4 \text{ TeV}, E(Pb) = 1.58 \text{ TeV/N} \)
  - Distributions of jets are centered around \( \pm 0.465 \) units in \( \eta \)
- \( \eta \) distributions are corrected to the center-of-mass eta
- \( \text{Pbp} \) \( \eta \) distribution is “mirrored” (\( \eta \rightarrow -\eta \))
  - This ensures consistency when \( pPb \) and \( \text{Pbp} \) results are used together
Identifying b-jets

- Primary identification method is using a **Secondary Vertex**
  - Long lifetime of $b = \text{mm or cm vertex displacement}$
- Flight distance ($L_{xy}$) of the secondary vertex used as a discriminating variable
- Tagging methods independent of secondary vertex reconstruction used as cross-check

B-quark decays are heavily CKM-suppressed -> Long lifetimes

Algorithms described in:
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