Measurement of Quenched Energy Flow for Dijets in PbPb collisions with CMS

Yen-Jie Lee (MIT)
For the CMS Collaboration

NPA Seminar
Yale, USA
15 October, 2015
Trying to answer two important questions in the high density QCD:

- Where is the critical point of the QCD phase diagram?
- What is the property of Quark Gluon Plasma?
Ideal World

Quark Gluon Plasma Brick

High Energy Quark

Medium
Parton Cascade in Vacuum

Parton shower

Hadronization

High Energy Jet
Large Virtuality Q

Hadrons
Medium Changes vs. Time
Space-time information is also important in heavy ion environment
Parton Energy Loss Models

Two theoretical approaches:

**Perturbative QCD**
- Weak coupling limit
  - Collisional energy loss
  - Radiative energy loss

**Holographic calculation**
- Strong coupling limit
  - AdS/CFT “drag force”

Diagram showing energy loss processes in parton interactions.
The High Energy Frontier

Large Hadron Collider

Pb+Pb collisions
2.76 TeV (2010-13)
14x jump with respect to RHIC!
2015: 5.1 TeV

27 km circumference

Lake Geneva

CMS
France
ALICE
ATLAS
Switzerland

RHIC

LHC

Yen-Jie Lee (MIT)
19 institutes, 110 members
Work in the Heavy Ion Physics Group
Heavy Ion data analysis and run preparation
CMS Detector

EM and Hadron calorimeters
- photons, isolation, jet reconstruction

Inner tracker:
- charged particles
- vertex, isolation

Muon
- $|\eta| < 2.4$

HCAL
- $|\eta| < 5.2$

ECAL
- $|\eta| < 3.0$

Tracker
- $|\eta| < 2.5$
Particle Reconstruction with CMS

Key:
- Blue: Muon
- Red: Electron
- Green: Charged Hadron (e.g. Pion)
- Grey: Neutral Hadron (e.g. Neutron)
- Dashed Grey: Photon

Neutral Hadron

Charged Hadron

Transverse slice through CMS

Silicon Tracker

Electromagnetic Calorimeter

Hadron Calorimeter

Superconducting Solenoid

Iron return yoke interspersed with Muon chambers

Yen-Jie Lee (MIT)
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Heavy Ion Collision Recorded by the CMS Detector

CMS Experiment at the LHC, CERN

Data recorded: 2010-Nov-14 18:37:44.420271 GMT (19:37:44 CEST)
Run / Event: 151076 / 1405388
Underlying Event Background

Goal: To study high $p_T$ jets event-by-event

How do we subtract the background from soft scatterings?

Take advantage of the large acceptance CMS detector:
**Predict the background** with the measured energy in the forward calorimeter
Training done with **minimum-bias events** (optimized by SVD method)
**Anti-k_T algorithm** is used in the most CMS publications

On average, charged hadrons carry ~65% of the jet momentum

**Measure the known part**

**Correct the rest by MC simulation**

Optimize the use of calorimeter and tracker

Example: “Particle Flow” in CMS
CMS Jet Reconstruction Strategy

Remove underlying events contribution

MC Simulation PYTHIA
Validated with dijet, photon(Z)-jet data
Jet Transverse Momentum Spectra

Nuclear Modification Factor ($R_{AA}$):

Ratio of the jet cross-section in PbPb and pp scaled by the number of nucleon-nucleon collisions

- **pPb Collisions**: No significant modification
- **Head-on PbPb Collisions**: Large suppression of high $p_T$ jet

Large final state effect observed in PbPb collisions

Is the jet structure modified in PbPb collisions?
Inclusive Jet Shape and “Fragmentation Function”

Jet shape \( \text{PbPb} / \text{pp} \)

- **Jet shape:**
  - “the jet energy distribution” as a function of \( R \)

Charged particle in cone \( \text{PbPb} - \text{pp} \)

- **Jet Fragmentation function:**
  - how transverse momentum is distributed inside the jet cone
Inclusive Jet Shape and “Fragmentation Function”

Jet shape PbPb / pp

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

anti-$k_T$ jets: $R = 0.3$

$|p_T^{\text{jet}}| > 100 \text{ GeV/c}$

$0.3 < |\eta^{\text{jet}}| < 2$

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

Energy

0-10% PbPb

Charged particle in cone PbPb - pp

0-10% PbPb

$120 < \text{Jet } p_T < 300 \text{ GeV/c}$

One more low $p_T$ particle in the jet cone $R=0.3$

Observation of energy redistribution inside the jet cone

(Some modification at large $R$; ~ one more low track $p_T$)

The bulk of the Jet structure is actually pretty similar to that in pp
Probe the QGP with High Energy Quarks and Gluons

Increased rate of asymmetric dijets in central PbPb collisions
Probe the QGP with High Energy Quarks and Gluons

Small $A_J$

Large $A_J$ ($A_J \sim 0.5$)

Where does the energy go?

Increased rate of asymmetric dijets in central PbPb collisions

$A_J = \frac{p_{T,1} - p_{T,2}}{p_{T,1} + p_{T,2}}$
Significant Energy Flow Out of the Jet Cone

Tracks in the jet cone
ΔR<0.8

Tracks out of the jet cone
ΔR>0.8

CMS

CMS 0-30%
Pb+Pb √s_{NN}=2.76 TeV
\int \text{d}t = 6.7 \mu b^{-1}

PRC 84 (2011) 024906
Significant Energy Flow Out of the Jet Cone

Tracks in the jet cone \( \Delta R < 0.8 \)
Tracks out of the jet cone \( \Delta R > 0.8 \)

Jet collimation

• Partons undergo Brownian motion
• Medium "trims away" soft component to large angle

Casalderrey-Solana, Milhano, Wiedemann
Significant Energy Flow Out of the Jet Cone

- Tracks in the jet cone $\Delta R < 0.8$
- Tracks out of the jet cone $\Delta R > 0.8$

Jet collimation

Decoherence

CMS

- **Color coherence** (angular ordered radiation) is destroyed in the strongly interacting medium
- Open up the **phase space for wide angle radiation**

**PRC 84 (2011) 024906**

Mehtar-Tani, Salgado
PLB 707 (2012) 156-159
Tracks in the jet cone \(\Delta R < 0.8\)

Tracks out of the jet cone \(\Delta R > 0.8\)

**Jet collimation**

**Decoherence**

**Turbulence cascade**

- Effect of multiple branchings in medium: "Quasidemocratic branching"
- Effective mechanism which brings soft partons to large angle

PRC 84 (2011) 024906

Blaizot, Iancu, Mehtar-Tani
PRL 111 052001 (2013)
Significant Energy Flow Out of the Jet Cone

Tracks in the jet cone $\Delta R < 0.8$

Tracks out of the jet cone $\Delta R > 0.8$

Jet collimation

Decoherence

Turbulence cascade

Third jet quenching

- Vacuum-like parton shower also extend to large angle \textbf{as large as} $R \sim 1.0$
- The third jet may be quenched and produce soft particles out of the small jet cone $R = 0.3$
Significant Energy Flow Out of the Jet Cone

Tracks in the jet cone $\Delta R<0.8$

Tracks out of the jet cone $\Delta R>0.8$

Jet collimation

Decoherence

Turbulence cascade

Third jet quenching

• The medium takes energy away from the high energy parton and turns that energy into heat / collective motion of the medium.
• Produce **extra soft particles** in the final state

Casalderrey-Solana, Gulhan, Mihano, Pablos, Rajagopal, ...

PRC 84 (2011) 024906

Strongly coupling approach, hydro
Significant Energy Flow Out of the Jet Cone

Jet collimation

Decoherence

Turbulence cascade

Third jet quenching

(1) How many particles are carrying the missing energy?

(2) What is the angular distribution of the quenched energy flow with respect to the dijet axis?

Strongly coupling approach, hydro
Measurement of the Quenched Energy Flow

Idea: Use all charged particles ($p_T > 0.5$ GeV/c)
Study the transverse momentum balance (uncorrelated UE cancels)

Difficulty: Large PbPb underlying event (UE)
Datasets and Event Selection

\[ \sqrt{s_{NN}} = 2.76 \text{ TeV} \]

**pp**
- 5.3 pb\(^{-1}\)
- Jet trigger with \(p_T > 80\) GeV/c
- Track reconstruction:
  - \(p_T > 0.2\) GeV/c
- Anti-\(k_T\) Calorimeter jet
  - With \(R=0.3\)

**PbPb**
- 150 \(\mu\)b\(^{-1}\)
- Jet trigger with \(p_T > 80\) GeV/c
- Track reconstruction:
  - \(p_T > 0.4\) GeV/c
- Anti-\(k_T\) Calorimeter jet
  - With \(R=0.3\)
  - HF/Voronoi UE subtraction

**Dijet selection:**
- \(p_{T,1} > 120\) GeV/c
- \(p_{T,2} > 50\) GeV/c
- \(|\eta_1|, |\eta_2| < 1.6\) (0.5)
- \(\Delta \phi > 5\pi/6\)

**Charged particles:**
- \(p_T > 0.5\) GeV/c
- \(|\eta| < 2.4\)
What is the **multiplicity** of the particles that balance the “extra” lost $p_T$?
What is the **multiplicity** of the particles that balance the “extra” lost $p_T$?

Compare the multiplicities in the **leading** and **subleading jet** hemispheres.

**Direction of the dijet** is defined as:

$$\phi_{\text{dijet}} = \frac{1}{2}(\phi_1 + (\pi - \phi_2))$$

(In contrast to PRC 84 (2011) 024906, where the leading jet direction was used.)

Provide UE cancellation differential in $\Delta R$
What is the multiplicity of the particles that balance the “extra” lost $p_T$?

Compare the multiplicities in the leading and subleading jet hemispheres.

Direction of the dijet is defined as:

$$\varphi_{\text{dijet}} = \frac{1}{2} (\varphi_1 + (\pi - \varphi_2))$$

(In contrast to PRC 84 (2011) 024906, where the leading jet direction was used)

Provide UE cancellation differential in $\Delta R$:

$$\Delta_{\text{mult}} = N_{\text{ch in subleading jet hemisphere}} - N_{\text{ch in leading jet hemisphere}}$$
Multiplicity difference between the subleading and leading hemisphere is increasing vs. dijet asymmetry in pp and peripheral PbPb. There are more charged particles in the subleading hemisphere.
Multiplicity Difference (subleading – leading jet)

- This increase is larger in central PbPb
- The enhancement in PbPb compared to pp increases with centrality
  - Large $A_J$, 0-10%: ~16 extra particles ($p_T > 0.5$ GeV) in the subleading jet hemisphere
What is the multiplicity and $p_T$ spectra of the particles that balance the lost $p_T$?

$$p_T^\parallel = \sum_i -p_T^i \cos (\phi_i - \phi_{Dijet})$$

Charged particle azimuthal angle

Dijet axis

Projection to dijet axis
Missing $p_T^\parallel$ vs. $A_J$

More energy flow in the **subleading** jet direction

More energy flow in the **leading** jet direction

The momentum imbalance inside the jet cone is restored if we consider all particles in the event (in both pp and PbPb collisions)
Missing $p_T^\| \text{ vs. } A_J$

More energy flow in the **subleading** jet direction

More energy flow in the **leading** jet direction

- Missing $p_T$ from high $p_T$ particles increases as a function of $A_J$
- In pp \[\rightarrow\] Balanced by 2-8 GeV/c particles
- In 0-10% PbPb \[\rightarrow\] Balanced by particles with $p_T < 4$ GeV/c

 CMS pp

- Gen. PYTHIA

PbPb 0-10%

\[\sqrt{s_{NN}} = 2.76 \text{ TeV}\]
What is the **angular distribution** of these particles with respect to the dijet system?

Calculate the missing $p_T$ for charged particles that fall in slices of $\Delta$

\[
p_T^\parallel = \left( \sum_i -p_T^i \cos (\phi_i - \phi_{dijet}) \right) |_{R_{\text{down}} < \Delta < R_{\text{up}}}
\]

\[
\Delta = \sqrt{\Delta \phi^2_{\text{Trk,Jet}} + \Delta \eta^2_{\text{Trk,Jet}}}
\]
What is the **angular distribution** of these particles with respect to the dijet system?

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\]

\[
\Delta = \sqrt{\Delta \phi^2_{\text{Trk,jet}} + \Delta \eta^2_{\text{Trk,jet}}}
\]
Missing $p_T^{\parallel}$ vs. $\Delta$ in pp

- Subleading jet direction
- Leading jet direction
- Asymmetry inside the jet cone
- Contribution from third jet

Integrated curve from 0-ΔR

Equation:

$$\Delta = \sqrt{\Delta \phi_{Trk, jet}^2 + \Delta \eta_{Trk, jet}^2}$$

Datasets:
- CMS
- pp
- pp $\langle p_T^{\parallel} \rangle_{\Delta}$
- pp $\langle p_T \rangle_{[0,\Delta]}$

Conditions:
- $p_{T,1} > 120$, $p_{T,2} > 50$ GeV/c
- $|\eta_1,|\eta_2| < 0.50$, $\Delta \phi_{1,2} > 5 \pi/6$
- anti-$k_T$ Calo R=0.3
- $|\eta_{\text{trk}}| < 2.4$
- $p_T^{\text{trk}}$ (GeV/c):
  - 0.5-300 GeV/c

References:
- arXiv 1509.09029
Missing $p_T \parallel$ vs. $\Delta$ in pp

Subleading jet direction

Leading jet direction

Asymmetry inside the jet cone

Contribution from third jet

Integrated curve from 0 to $\Delta$

$p_{T,1} > 120$, $p_{T,2} > 50$ GeV/c

$|\eta_1|, |\eta_2| < 0.50$, $\Delta \phi_{1,2} > 5\pi/6$

anti-$k_T$ Calo $R = 0.3$

$|\eta_{trk}| < 2.4$

$p_{T, trk}$ (GeV/c):

- 0.5 - 1.0
- 1.0 - 2.0
- 2.0 - 4.0
- 4.0 - 8.0
- $> 8.0$
- $> 300.0$

$\Delta = \sqrt{\Delta \phi_{Trk, jet}^2 + \Delta \eta_{Trk, jet}^2}$

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NPA Seminar @ Yale
Missing $p_T^{\parallel}$ vs. $\Delta$

Subleading jet direction

Leading jet direction

$p_{T,1}>120$, $p_{T,2}>50$ GeV/c
$|\eta_1,|\eta_2|<0.50, \Delta \phi_{1,2} > 5\pi/6$
anti-$k_T$ Calo $R=0.3$

Inclusive $A_J$

arXiv 1509.09029

NPA Seminar @ Yale
Missing $p_T^{\parallel}$ vs. $\Delta$

Subleading jet direction

Leading jet direction

$p_{T,1} > 120$, $p_{T,2} > 50$ GeV/c

$|\eta_1|, |\eta_2| < 0.50, \Delta\phi_{1,2} > 5\pi/6$

anti-$k_T$ Calo $R=0.3$

Inclusive $A_J$

Open circles: Integrated over particle $p_T$

Slight modification of the cumulative energy flow

CMS pp

PbPb 0-30%

$(\text{PbPb 0-30\%}) - \text{pp}$

$\langle p_T^{\parallel} \rangle_{p_{T,\Delta}}$ [GeV]

0.5-1.0

1.0-2.0

2.0-4.0

4.0-8.0

8.0-300.0

$|\eta_{\text{trk}}| < 2.4$

$\Delta = \sqrt{\Delta\phi_{\text{Trk,}\gamma}^2 + \Delta\eta_{\text{Trk,}\gamma}^2}$

arXiv 1509.09029
Missing $p_T^{\|}$ vs. $\Delta$

Subleading jet direction

Leading jet direction

$p_{T,1}>120$, $p_{T,2}>50$ GeV/c

$|\eta_1,|\eta_2|<0.50, \Delta\phi_{1,2}>5\pi/6$

anti-$k_T$ Calo $R=0.3$

Inclusive $A_J$

Slight modification of the cumulative energy flow

High $p_T$ imbalance at small $\Delta$

$\langle p_T^{\|} \rangle_{p_{T,\Delta}}$ [GeV]

$|\eta_{\text{trk}}| < 2.4$

$\Delta = \sqrt{\Delta\phi_{\text{Trk,jet}}^2 + \Delta\eta_{\text{Trk,jet}}^2}$
Missing $p_T^{||}$ vs. $\Delta$

Subleading jet direction

Leading jet direction

$\langle p_T^{||} \rangle_{p_T^{trk,\Delta}}$ [GeV]

- $0.5-1.0$
- $1.0-2.0$
- $2.0-4.0$
- $4.0-8.0$
- $8.0-300.0$

$|\eta_{trk}| < 2.4$

CMS pp PbPb 0-30%

Slight modification of the cumulative energy flow

High $p_T$ imbalance at small $\Delta$

Balanced by low $p_T$ particles in subleading jet direction

Extends up to large $\Delta$

Inclusive $A_J$

$p_{T,1} > 120$, $p_{T,2} > 50$ GeV/c
$|\eta_1|, |\eta_2| < 0.50$, $\Delta\phi_{1,2} > 5\pi/6$
anti-$k_T$ Calo $R=0.3$

arXiv 1509.09029
Anti-$k_T$ Jets with Different R Parameters

Jets reconstructed with $R=0.5$ gives "wider" jet

Jets reconstructed with $R=0.2$ gives "narrower" jet

- Jets are only meaningful if the algorithm is defined
- Different parameter R select different sets of dijet events!!
- Jet width dependent studies
“Shooting Jets with Different Width” through the Medium

CMS $A_\perp$ Inclusive

-anti-$k_t$ Jet; 0-30%
- $p_{T,1} > 120$; $p_{T,2} > 50$ GeV
- $|\eta_{1,2}| < 0.6$; $\Delta \phi_{1,2} > 5\pi/6$

$|\eta_{trk}| < 2.4$

- pp
- PbPb
- PbPb - pp

5.3 pb$^{-1}$ (2.76 TeV)
166 x b$^{-1}$ (2.76 TeV)
“Shooting Jets with Different Width” through the Medium

Narrower jets

Wider jets

- Quenched energy distribution depends on the R parameter used in the Anti-\(k_T\) algorithm

\[ \Delta = \sqrt{\Delta \phi_{\text{Trk.jet}}^2 + \Delta \eta_{\text{Trk.jet}}^2} \]
“Shooting Jets with Different Width” through the Medium

Narrower jets

Wider jets

- Quenched energy distribution depends on the R parameter used in the Anti-$k_T$ algorithm
- Hint of narrower leading jet (or wider subleading jet) in PbPb collisions?

$$\Delta = \sqrt{\Delta \phi_{Trk,jet}^2 + \Delta \eta_{Trk,jet}^2}$$
"Shooting Jets with Different Width" through the Medium

- Quenched energy distribution depends on the R parameter used in the Anti-\(k_T\) algorithm
- Hint of narrower leading jet (or wider subleading jet) in PbPb collisions?
- Soft particles extends to larger \(\Delta\) in dijet events reconstructed with larger R parameter
Comparison to Theory and Outlook

LHC Run II (2015)
Significant Energy Flow Out of the Jet Cone

Jet collimation

Decoherence

Turbulence cascade

Third jet quenching

Strongly coupling approach, hydro

0-10% PbPb collision

~16 extra particles ($p_T > 0.5$ GeV) in the subleading jet hemisphere
Significant Energy Flow Out of the Jet Cone

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Jet Data vs. JEWEL event generator

A Jet Quenching Monte Carlo based on weak coupling approach:

Reasonable description of jet FF, jet $R_{AA}$ and charged hadron $R_{AA}$
Motivate high $p_T$ **flavor tagged jet analysis**: (heavy) quark vs. gluon jets
Very high $p_T$ heavy flavor meson (from quark jets): complementary to the high $p_T$ heavy flavor jets
Excellent capability of (decay) particle identification with CMS
Flavor Dependence of Jet Quenching

Fully reconstructed $D^0 \rightarrow K\pi^+$ over a wide kinematic range

Charged Hadrons

Yen-Jie Lee (MIT)  NPA Seminar @ Yale
Outlook: Identified Heavy Flavor Jet and Mesons

2011 2.76 TeV PbPb data (0.15/nb)
- b-jet
- D(*) meson

2013 5.02 TeV pPb data (35/nb)
- B meson
- b-jet
- c-jet

2015-17 5.1 TeV PbPb data (~1.5/nb)
- D(*) meson
- B meson
- c-jet
- b-jet

HL-LHC (10/nb): (b)-jet quenching at O(TeV)
• **An iterative feedback cycle** between theory and experiment **has started!**
  • Quenched jet event generator
  • A systematical comparison between models and data

• **LHC Run II:**
  • High statistics Photon-Jet and the first Z-Jet measurements
  • High statistics (di-)jet measurement up to $p_T \sim 1$ TeV
  • Multi-jet correlation
  • Flavor dependence of the parton energy loss from low to high $p_T$ with jets and mesons

... **Stay tuned!!!**
Backup slides