Jet results in heavy ion collisions from CMS

Yen-Jie Lee (MIT)
For the CMS collaboration

2nd Conference on Heavy Ion Collisions in the LHC era and beyond
Quy Nhon, Vietnam
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Probing the properties of the medium

Collisional energy loss

Radiative energy loss

Strong coupling: “AdS drag force”

Goal: understand the properties of the produced medium

Status: validating the theoretical understanding of jet quenching
Jet quenching without jets

SPS 17.3 GeV (PbPb)  
- π° WA98 (0-7%)  
- RHIC 200 GeV (AuAu)  
- π° PHENIX (0-10%)  
- h± STAR (0-5%)  
- LHC 2.76 TeV (PbPb)  
- CMS (0-5%)  
- ALICE (0-5%)  
- GLV: dN/dy = 400  
- GLV: dN/dy = 1400  
- GLV: dN/dy = 2000-4000  
- YaJEM-D  
- elastic, small $P_{esc}$  
- elastic, large $P_{esc}$  
- YaJEM  
- ASW  
- PQM: $\langle \phi \rangle = 30 - 80$ GeV$^2$/fm

$R_{AA}$ vs $p_T$ (GeV/c)
Why do we study jet quenching with jets?

![Graph showing jet quenching](image)

\[ z = \frac{p_{\text{jet}} \cdot p_{\text{ch}}}{|p_{\text{jet}}|^2} \]

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Yen-Jie Lee (MIT)  
2nd Conference on HI Collisions  
EPJC 71 (2011) 1795
Jet as a versatile probe

Probe the Initial State Effects:
Extraction of nPDF

Probe the Final State
Modification of Jets

Search for medium response
Where does the quenched energy go?
Jet as a versatile probe

Probe the Initial State Effects: Extraction of nPDF

→ $p(d)A$ collisions
(Di-)Jet production in pPb collisions at 5.02 TeV

Inclusive (charged) jet $R_{pPb}$

- CMS full jet, $-0.5 < \eta_{cm} < 0.5$
- ALICE charged jet, $-0.5 < \eta_{cm} < 0.5$
- ATLAS full jet, $-0.3 < \eta_{cm} < 0.3$

Jet $R_{pPb} \approx 1.1 \pm 0.2$, Consistent with pQCD calculation with EPS09 nPDF

Subleading Jet $p_T$ / leading jet $p_T$

- $p_{T,1} > 120$, $p_{T,2} > 30$ GeV/c
- $|\eta| < 3$, $\Delta\phi_{1,2} > 2\pi/3$

CMS pPb 35 nb$^{-1}$

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

EPJC 74 (2014) 2951
Jet quenching from dijet analysis in pPb:
- Dijet asymmetry <2%
- No sizable deviation from unity found in jet $R_{pPb}$

→ Jets for nPDF studies!

CMS pPb 35 nb$^{-1}$
$\sqrt{s_{NN}} = 5.02$ TeV
$p_{T,1} > 120$ GeV/c
$p_{T,2} > 30$ GeV/c
$\Delta \phi_{1,2} > 2\pi/3$
All $E_T^{j} > 4$

Boosted PYTHIA6 Z2
@ 5.02 TeV

EMC

Anti-shadowing

Shadowing

In the lab frame

EPJC 74 (2014) 2951
Compare to CT10 and CT10+EPS09

CMS pPb 35 nb^{-1}

- $\sqrt{s_{NN}} = 5.02$ TeV
- $p_{T,1} > 120$ GeV/c
- $p_{T,2} > 30$ GeV/c
- $\Delta \phi_{1,2} > 2\pi/3$
- All $E_T$ \(4 < |\eta| < 5.2\)

Hannu’s QM14 talk
Dijet $dN/d\eta$ vs. event activity

(Too) large modification vs. event activity.
Can not be explained by centrality dependent nPDF
Jet fragmentation pattern in pPb

- Track $p_T$ spectra inside the jet cone is measured in pPb collisions
- Ratio of pPb and the interpolated pp reference is consistent with unity
Jet as a versatile probe

Probe the Initial State Effects: Extraction of nPDF

Probe the Final State Modification of Jets
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 $A_J$ ($A_J \sim 0.5$)

Increased rate of asymmetric dijets in central PbPb collisions

$A_J = \frac{p_{T,1} - p_{T,2}}{p_{T,1} + p_{T,2}}$

Yen-Jie Lee (MIT)
Jet Fragmentation at LHC

Using **Jet Energy** as a reference

CMS FF $R_{AA}$ compared to ATLAS FF $R_{CP}$

$$Z = \frac{p_{||}^{\text{Trk}}}{p^{\text{Jet}}}$$

Qualitative consistent results between CMS and ATLAS

ATLAS: indication of enhancement of low $\xi$ (high $z$) particles in the jet cone

![Graph showing CMS and ATLAS results](image)

- **CMS-HIN-12-013**
  - 0-10%/pp
  - $100 < p_{T}^{\text{jet}} < 300$ GeV/c

- **ATLAS QM2014**
  - 0-10%/60-80%
  - $p_{T}^{\text{jet}} > 100$ GeV/c

CMS: PRC 90 (2014) 024908
ATLAS: PLB 739 (2014) 320-342

High $p_{T}$ particles
Low $p_{T}$ particles
Photon-Jet correlation

\[ x_{J\gamma} = \frac{p_{T\text{jet}}}{p_{T\gamma}} \]

- \( p_{T\gamma} > 60 \text{ GeV/c} \)
- \( p_{T\text{jet}} > 30 \text{ GeV/c} \)
- \( \Delta\phi_{J\gamma} > \frac{7}{8}\pi \)
- \( |\eta\gamma| < 1.44 \)
- \( |\eta\text{Jet}| < 1.61 \)

CMS-PAS-HIN-13-006
PLB 718 (2013) 773

- ~10% of the jet energy goes out of the jet cone
- Where does the quenched energy go?

PbPb Data
Smeared pp reference
PbPb PYTHIA + HYDJET

0% - 10%
Jet as a versatile probe

Probe the Initial State Effects: Extraction of nPDF

Probe the Final State Modification of Jets

Search for medium response Where does the quenched energy go?
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

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

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

Decoherence

CMS

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Turbulence cascade

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Strongly coupling approach, hydro

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(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?
Measurement of quenched energy flow

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

Leading jet
Subleading jet

Difficulty: Large PbPb underlying event (UE)
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 $\Delta R$
Multiplicity difference (subleading – leading jet)

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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 (subleading – leading jet)

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

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%: $\sim 14$ 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 $p_T$?

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

Projection to dijet axis

Charged particle azimuthal angle

Dijet axis

\[ \frac{1}{2}(\phi_1 + (\pi - \phi_2)) \]

\[ \phi_{\text{dijet}} \]
Missing $p_T^{\parallel}$ 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**  → Balanced by 2-8 GeV/c particles

In 0-10% **PbPb**  → Balanced by particles with $p_T < 2$ GeV/c

CMS PAS-HIN-14-010

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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 $\Delta R$

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

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

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

$$\Delta R = \sqrt{\Delta \phi^2_{\text{Trk,jet}} + \Delta \eta^2_{\text{Trk,jet}}}$$
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$$\Delta R = \sqrt{\Delta \phi_{\text{Trk,jet}}^2 + \Delta \eta_{\text{Trk,jet}}^2}$$

What is the angular distribution of these particles with respect to the dijet system?
Missing $p_T^\parallel$ vs. $\Delta R$ in pp

Subleading jet direction

Contribution from third jet

Leading jet direction

Asymmetry inside the jet cone

CMS Preliminary

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

anti-$k_T$ Calo $R=0.3$

$|\eta_{trk}| < 2.4$

$p_{trk}^\parallel$ (GeV/c):
- 0.5 - 1.0
- 2.0 - 4.0
- 1.0 - 2.0
- 4.0 - 8.0
- $> 0.5$
- 8.0 - 300.0

CMS-PAS-HIN-14-010
Missing $p_T^\parallel$ vs. $\Delta R$

Subleading jet direction

Leading jet direction

CMS PAS-HIN-14-010

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Missing $p_T^\parallel$ vs. $\Delta R$

Subleading jet direction

Leading jet direction

Cumulative energy flow are similar

Open circles: Integrated over particle $p_T$

Inclusive $A_J$
Missing $p_T^\parallel$ vs. $\Delta R$

Cumulative energy flow are similar

High $p_T$ imbalance at small $\Delta R$

Inclusive $A_J$

CMS-PAS-HIN-14-010
Missing $p_T^\parallel$ vs. $\Delta R$

High $p_T$ imbalance at small $\Delta R$

Balanced by low $p_T$ particles in subleading jet direction

Extends up to large $\Delta R$

Cumulative energy flow are similar

Inclusive $A_J$

CMS-PAS-HIN-14-010

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Significant energy flow out of the jet cone

Jet collimation

Decoherence

Turbulence cascade

Third jet quenching

Strongly coupling approach, hydro

(1) How many particles are carrying the missing energy?
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Jet data vs. JEWEL

Jet Quenching Monte Carlo based on weak coupling approach:

Reasonable description of jet FF, jet $R_{AA}$ and charged hadron $R_{AA}$
Description of the jet data with strong coupling approach

Jet $R_{AA}$

Jet FF

Quark/Gluon Ratio $A_J$

Dijet Asymm.
Outlook

• LHC Run II: PbPb @ 5 TeV in 2015
  • High statistics photon-jet sample
  • Z-jet correlation
  • Multi-jet correlation
  • Flavor tagged jet

• Need an iterative feedback cycle between theory and experiment
  • Quenched jet event generator
  • Tell us your favorite analysis with Run II data!
Backup slides
Consistent picture: excess of low $p_T$ particle in the jet cone

PHENIX
Photon-tagged Hadron $I_{AA}$

$5 < p_T^\gamma < 9 \text{ GeV/c} \times 0.5 < p_T^h < 7 \text{ GeV/c}$

- $|\Delta \phi - \pi| < \pi/2$
- $|\Delta \phi - \pi| < \pi/3$
- $|\Delta \phi - \pi| < \pi/6$

- global sys = ± 6%

(a)

$PbPb - pp$

CMS Preliminary

$Z = p_{||}^{\text{Trk}} / p_{\text{Jet}}$

STAR
Jet-Hadron

$\Delta D(z)$

$ATLAS Preliminary$

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

0.14 nb$^{-1}$

anti-$k_t$, $R=0.3$

$92 < p_T^{\text{jet}} < 92$ GeV/c

0-10% - 60-80%

Data

Systematic Uncertainty

$Z = p_{||}^{\text{Trk}} / p_{\text{Jet}}$