Jets at the LHC: Where does the lost energy go?

Yen-Jie Lee (MIT)

3rd Workshop on Jet Modification in the RHIC and LHC Era
Wayne State University, Detroit, USA
18 August, 2014
High $p_T$ charged particles

Suppression of high $p_T$ particles in AA collisions
Why do we study jet quenching with jets?

- Theoretically calculable, infra-red/collinear safe

- Allow the use of a well defined object (by algorithm) to study “the final parton energy” and how the energy is distributed with respect to the direction of the out-going parton

- Allow us to select quenched jets (i.e., jets from partons which have lost a lot of energy when passing through the medium)
Charged particle spectra in pp and PYTHIA agree within 20-60%
Jet spectra in pp

![Graphs showing jet spectra in pp](image)
Where does the lost energy go?

• Reconstructed jet analysis
  – Jet spectra / $R_{AA}$
  – Dijet / photon-jet asymmetry

• Energy redistribution inside the jet cone:
  – Jet FF and jet shape

• Energy distribution out of the jet cone
  – Missing $p_T$ measurements
Charged particle and jet $R_{pPb}$ (QM2014)

**Charged particle $R_{pPb}$**

- CMS, $|\eta|<1$
- ATLAS, $|\eta|<1$
- ALICE, $|\eta|<0.3$

$pPb \sqrt{s_{NN}} = 5.02$ TeV, charged particles

Need to check jet fragmentation function

**Jet spectra seem to be under control**

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

ATLAS Preliminary

2011 Pb+Pb data, $L_{int} = 0.14$ nb$^{-1}$
2013 pp data, $L_{int} = 4.0$ pb$^{-1}$
$\sqrt{s_{NN}} = 2.76$ TeV

anti-$k_T$, $R = 0.4$ jets

Jet $R_{AA}$

$80 < p_T < 100$ GeV

CMS Preliminary

Anti-$k_T$ Particle Flow Jets $R = 0.3$

$\langle N_{part} \rangle$

$R_{AA}$

$\int L dt = 129 \mu b^{-1} |\eta| < 2$

Bayesian

Uncorr statistical

- 100 < $p_T$ (GeV/c) < 110
- 100 < $p_T$ (GeV/c) < 300

Total systematics
Preliminary ATLAS and CMS $R_{AA}$

![Graph showing jet modification in the RHIC and LHC Era](image)

- **PbPb $\sqrt{s_{NN}} = 2.76$ TeV, $|\eta| < 2$**
- **Bayesian**
  - Uncorr statistical
  - Total systematics

**ATLAS Preliminary**
- $80 < p_T < 100$ GeV

**CMS Preliminary**
- Anti-$k_T$ $R=0.4$

- **Uncorr statistical**
- **Total systematics**
Weak dependence on jet rapidity
Quark/gluon fraction (as well as the slope of the jet pT spectra) changes v.s. y
Preliminary Jet $R_{AA}$ at LHC

ALICE new result 10-30%

ATLAS new results on jet $R_{AA}$

$R_{AA}$ raises as a function of jet $p_T$
Jet $R_{AA}$ in PbPb collisions at LHC

Establish a rising trend from low to high jet $p_T$
Jet $R_{AA}$ in PbPb collisions at LHC

![Graph showing jet $R_{AA}$ vs. jet $p_T$](image)

- Pb+Pb $\sqrt{s_{NN}}=2.76$ TeV
- CMS anti-$k_T$ jet $R=0.2$ 0-5%
- ALICE anti-$k_T$ $R=0.2$ jet 0-10%
- ATLAS anti-$k_T$ $R=0.4$ jet 0-10%

~ Agreement between CMS and ATLAS at high jet $p_T$

Agree with charged particle $R_{AA}$ at high $p_T$

Different at low $p_T$

It would be nice to have low $p_T$ CMS data / ATLAS $R_{AA}$ with $R=0.2$ / ALICE high $p_T$ data
Jet $R_{AA}$ in PbPb collisions at LHC

It would be nice to have low $p_T$ CMS data / ATLAS

Different $a$

ATLAS $R_{CP}$ ratio
PLB 719 (2013) 220-241

Yen-Jie Lee (MIT)  3rd Workshop on Jet Modification in the RHIC and LHC Era
Dijet asymmetry $A_J$ in RHIC and LHC

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

Anti-$k_T$ $R=0.2$, $p_{T,1}>16$ GeV & $p_{T,2}>8$ GeV with $p_T^{cut}>2$ GeV/c

Balanced dijet

Imbalanced dijet

Yen-Jie Lee (MIT) 3rd Workshop on Jet Modification in the RHIC and LHC Era
Dijet energy ratio (imbalance)

- Energy imbalance increases with centrality
- Very high $p_T$ jets are also quenched

Anti-$k_T$ jet $R = 0.3$

$\langle p_{T,2}/p_{T,1} \rangle$

$\sqrt{s_{\text{in}}} = 2.76$ TeV, $\int L dt = 150 \mu b^{-1}$

$\sqrt{s} = 2.76$ TeV, $\int L dt = 231$ nb$^{-1}$

PYTHIA+HYDJET

$50-100\%$

$p_{T,2} > 30$ GeV/c

$\Delta \phi_{12} > \frac{2}{3} \pi$

$20-50\%$

$0-20\%$

PLB 712 (2012) 176
Fraction of jets with an away side jet

• Given a leading jet with $p_T > 150$ GeV/c, >90% of them has an away side partner

• Fake away side jet rate is < 4%
\(\gamma\)-”inclusive jet” correlations

- Photons serve as an **unmodified** energy tag for the jet partner.
- Ratio of the \(p_T\) of jets to photons (\(x_{J\gamma} = p_{T\text{jet}}/p_{T\gamma}\)) is a **direct measure** of the jet energy loss.
- Gradual **centrality-dependence** of the \(x_{J\gamma}\) distribution.

Anti-\(k_T\) jet \(R = 0.3\)

---

PLB 718 (2013) 773

CMS-PAS-HIN-13-006
$X_{j_g}$ spectra vs photon $p_T$
Updated pp reference for photon-jet analysis

Photon pT > 60 GeV/c, Jet pT > 30 GeV/c

Away size jet lose ~10% of the energy or ~ O(10 GeV) in 0-10% PbPb collisions

14% of the photons lose their away-side partner

CMS Preliminary \( \sqrt{s_{NN}} = 2.76\text{TeV}, \) PbPb 150 \( \mu \text{b}^{-1} \), pp 5.3 pb\(^{-1} \)

\( \Delta \phi_{JY} > \frac{7}{8} \pi \)

Plotted values:
- PbPb Data
- pp Data
- Smeared pp reference
- PYTHIA + HYDJET

\( \langle X_{JY} \rangle \)

\( N_{\text{part}} \)

PLB 718 (2013) 773
CMS-PAS-HIN-13-006
CMS published result photon+inclusive jet
Photon $p_T > 60$ GeV/c, Jet $p_T > 30$ GeV/c

ATLAS preliminary photon+leading jet
$60 < \text{Photon } p_T < 90$ GeV/c, Jet $p_T/\text{Photon } p_T > 0.4$

Qualitative consistent result between ATLAS and CMS
Lose constant fraction of energy

What will happen if we take the amount of lost energy (O(10%)) from photon-jet / dijet measurement and use that to modify PYTHIA jet $p_T$ spectra?

- **5% energy**: $p_T \rightarrow 0.95 p_T$
- **10% energy**: $p_T \rightarrow 0.90 p_T$
- **20% energy**: $p_T \rightarrow 0.80 p_T
What will happen if we take the amount of lost energy ($O(10\text{GeV})$) from photon-jet / dijet measurement and use that to shift PYTHIA jet $p_T$ spectra?

$p_T \rightarrow p_T - 10$ GeV

$p_T \rightarrow p_T - 15$ GeV

$p_T \rightarrow p_T - 20$ GeV
Compared to LHC data

Constant fractional energy loss doesn’t describe the trend established by ALICE+CMS data

The resulting jet $R_{AA}$ could be reproduced by shifting the jet spectra by -15 GeV.
Jet quenching with jets

O(10 GeV) energy goes out of the jet cone
Jet quenching with jets

O(10 GeV) energy goes out of the jet cone

Inside the jet cone?
Using **Jet Energy** as a reference

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

$$Z = p_T^{Trk} / p_T^{Jet}$$

Qualitative consistent results between CMS and ATLAS

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

CMS-HIN-12-013
0-10%/pp
100 < $p_T^{jet} < 300$ GeV/c

ATLAS QM2014
0-10%/60-80%
$p_T^{jet} > 100$ GeV/c

CMS: Arxiv 1406.0932
ATLAS: Arxiv: 1406.2979
Using **Photon Energy** as a reference

The FF shape can not be explained by simple shift of pp fragmentation function

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

\[ |\Delta \phi_{\gamma\pi}| < \pi/2 \]

\[ |y| < 0.35 \]

\[ p+p/Au+Au \rightarrow \gamma + h + X \]

- PHENIX Au+Au 0-40% @ 200 GeV
  - global sys = ± 8.8%

- PHENIX p+p
  - global sys = ± 8%

\[ 1/N_{\text{trig}} \frac{dN}{d\xi} \]

\[ I_{AA} \]

**Enhancement of low \( p_T \) particles**

\[ \xi = \ln(1/z_T) \]

\[ \xi=\ln(1/z_T) \]

**Associated yield**

\[ \text{Track } p_T \sim 2 \text{ GeV} \]

**Photon-hadron correlation**

- PHENIX I_{AA}
- FF(50% energy loss) / FF(pp)

PRL 111,032301 (2013)
Consistent picture: excess of low $p_T$ particle in the jet cone

**PHENIX**

- $5 < p_T^\gamma < 9$ GeV/$c \times 0.5 < p_T^h < 7$ GeV/$c$
- $|\Delta\phi-\pi|<\pi/2$
- $|\Delta\phi-\pi|<\pi/3$
- $|\Delta\phi-\pi|<\pi/6$

- global sys $= \pm 6\%$

**CMS**

CMS: ArXiv 1406.0932

**ATLAS**

ATLAS: Arxiv: 1406.2979
Jet quenching with jets

O(10 GeV) energy goes out of the jet cone

O(1 GeV) “radiated energy” or “medium recoil” carried by low $p_T$ particles inside the jet cone

How about the region close to the jet axis?
Inclusive jet spectra: jet $R_{AA}$

Anti-$k_T$ jets with $R = 0.2, 0.3, 0.4$

Strong suppression of inclusive high $p_T$ jets
A cone of $R=0.2, 0.3, 0.4$ doesn’t catch all the radiated energy

CMS PAS HIN-12-004

If PbPb = superposition of pp
Do we collect the radiated energy with large cone size?

Anti-\( k_T \) jets with
\[ R = 0.2, 0.3, 0.4, 0.5 \]

\[
\frac{R_{CP}^{(R=0.5)}}{R_{CP}^{(R=0.2)}} > 1
\]
→ recovery of lost energy, change in jet shape with respect to the pp reference

ATLAS Jet \( R_{CP}^{(R=0.3)} / R_{CP}^{(R=0.2)} \sim 1.0 \pm 0.2 \)
Allows to recover up to 0-4% more jet energy when moving from \( R=0.2 \) → \( R=0.3 \) in PbPb collisions than pp reference
Jet shape vs. $R_{AA}$ ratio

Ratio of jet shapes in PbPb and pp collisions

ATLAS Jet $R_{CP}$ (R=0.3) / $R_{AA}$ (R=0.2) $\sim 1.0 \pm 0.2$
Allows to recover up to 0-4% more jet energy than pp reference
Jet shape vs. $R_{AA}$ ratio

Changing the R from 0.2 to 0.3 $\rightarrow$ recover more radiated energy

CMS observed this change in R recover $\sim$1% more energy in PbPb than pp

CMS and ATLAS results are roughly compatible

ATLAS Jet $R_{CP}$ (R=0.3) / $R_{AA}$ (R=0.2) $\sim$ 1.0 $\pm$ 0.2
Allows to recover up to 4% more jet energy than pp reference
\[ \Delta_{\text{recoil}} = \left( \frac{1}{N_{\text{trig}}} \frac{dN}{dp_{T,jet}} \right)_{20-50} - \left( \frac{1}{N_{\text{trig}}} \frac{dN}{dp_{T,jet}} \right)_{8-9} \]

\[ \Delta_{\text{Recoil}}(R=0.2)/\Delta_{\text{Recoil}}(R=0.4) \]

\[ \Delta_{\text{Recoil}}(R=0.2)/\Delta_{\text{Recoil}}(R=0.5) \]

Indication of recovery of the lost parton energy with larger cone size
(also consistent with no energy redistribution)

Consistent picture between CMS, ATLAS and ALICE
Caveat: jet shape depends on jet distance parameter

- Important to perform analyses with different cone sizes
- Comparison between jets reconstructed with different cone size is tricky
  - At the same jet $p_T$: Essentially comparing a different set of jets
  - Small distance parameter + cut on jet $p_T \rightarrow$ selecting on narrow jets
Jet quenching with jets

O(1 GeV) “radiated energy” or “medium recoil” carried by low $p_T$ particles inside the jet cone

O(10 GeV) energy goes out of the jet cone

Hint of less quenching with larger $R$

R=0.5 can’t capture all the radiated energy

How far does the lost energy go?
The momentum difference in the dijet is balanced by low p_T particles outside the jet cone. 

\[ \mathbf{p}_T^\parallel = \sum_{\text{Tracks}} -p_T^{\text{Track}} \cos (\phi_{\text{Track}} - \phi_{\text{Leading Jet}}) \]

0-30% Central PbPb

Out of the jet cones
Excess towards sub-leading jet

Inside the jet cones
Excess towards leading jet

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

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

balanced jets
unbalanced jets
All tracks
Lost energy at RHIC and LHC

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

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

Lost energy: found in large \( \Delta \phi(\Delta R) \) with respect to the away-side jet axis, converted to low \( p_T \) particles.

PRL 111,032301 (2013)
2014: Multiplicity difference vs. $A_J$

Multiplicity difference (in acceptance) increases as a function of $A_J$.

The increase is larger in PbPb.

The enhancement in PbPb compared to pp increases with centrality.

$A_J = (p_{T,1} - p_{T,2})/(p_{T,1} + p_{T,2})$

Large $A_J$, 0-10% $\rightarrow$ 15 extra particles

Yen-Jie Lee (MIT) 3rd Workshop on Jet Modification in the RHIC and LHC Era
What is the multiplicity and spectrum of particles that balance the “extra” lost $p_T$?

Calculate the missing $p_T$ for charged particles in different $p_T$ ranges

$$p_T^\parallel = \sum_i -p_T^i \cos (\phi_i - \phi_{dijet})$$
Results - Missing $p_T$ vs. $A_J$

Access to high $p_T$ particles increases as a function of $A_J$

In pp  \(\rightarrow\) Balanced by 2-8 GeV/c particles

In PbPb  \(\rightarrow\) Balanced by particles with $p_T < 2$ GeV/c
Results - Missing $p_T$ vs. $\Delta R$

**PbPb 0-30%**

$A_J > 0.22$

Enhancement of low $p_T$ particles in PbPb

Out of cone radiation is carried by a third jet in pp

---

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

PbPb 0-30%

PbPb –pp

$A_J > 0.22$

Similar shape of the balancing distribution in pp and PbPb

Enhancement of low $p_T$ particles in PbPb

Out of cone radiation is carried by a third jet in pp

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

- **PbPb 0-30%**
  - $A_J > 0.22$
  - After matching the missing $p_T$ at $\Delta R < 0.2$

- **PbPb –pp**
  - Similar shape of the balancing distribution in PbPb vs. pp

**Equations and Figures:**
- $\frac{1}{2} (\Delta R<0.2) p_{T,1} > 120, p_{T,2} > 50$ GeV/c
- $|\eta_1|, |\eta_2| < 0.5$
- $|\eta_{3k}| < 2.4, \Delta \phi_{1,2} > 5\pi/6$
- $\frac{1}{2} (\Delta R<0.2) p_{T,1} > 120, p_{T,2} > 50$ GeV/c

**Graphs:**
- Cumulative $<p_T^*>$ (GeV/c) vs. $\Delta R$
- Comparison of PbPb and pp distributions after matching missing $p_T$.
Lost energy at RHIC

R=0.2 cone ——> R=0.4 cone

Dijet transverse momentum balance is recovered with anti-\( k_T \) \( R=0.4 \) jet reconstruction!!

Selection on the hard fragmenting jet may bias the production vertex of the jets toward the surface of the medium

→ interesting to see what we get when implementing similar bias at the LHC
Jet quenching at LHC

Artist’s view of a di-bullet event
What’s the fraction energy radiated out of the jet cone?

From jet $R_{AA}$ and photon-jet: $\sim 10\%$ of the jet energy go out of the jet cone at high $p_T$, $O(10 \text{ GeV})$

To figure out the $\Delta E(p_T)$ directly from data:

$\rightarrow$ Important to measure triggered jet differential cross-section using different trigger objects (using ideally isolated photons for CMS+ATLAS / leading hadron in ALICE)

$\rightarrow$ Measurements with different distance parameters

$\rightarrow$ Measure jets from gluon, quark and heavy quark separately using $W$+jet, $Z$+jet, photon+jet and dijet events

Can we recover the lost energy by jet reconstruction with large $R$?

Lost energy is recovered slowly, $R=0.2-0.5$ doesn’t recover all the lost energy

Different behavior observed (in STAR) if biased jet fragmentation selection is used
Summary and outlook (2/2)

Jet structure modified?

Excess of low $p_T$ particles inside the jet cone.

Modified jet FF and/or jet shapes can be explained by different classes of models.

Which part of it is coming from the changing q/g fraction?

How does parton energy loss depend on the fragmentation pattern?

Can we learn more using sub-jet reconstruction?

Fluctuation of jet fragmentation modification?

Where does the lost energy go?

The lost energy is carried by low $p_T$ particles far away from the jet cone.

Distribution of lost energy: Initial configuration (2/3/multi-jet) + medium effects?

Can we kill the effect by biasing the jet fragmentation?

Can we kill / enhance the effect by requiring / rejecting a third jet in the event?

What are the alternative way to select quenched jets?
Backup slides