Jet shower evolution in medium and dijet asymmetry in Pb+Pb collisions at the LHC

Guang-You Qin
Duke University

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Outline

- Jet study in HIC
- Jet shower evolution in medium
- Dijet asymmetry at the LHC
- Summary and outlook
Jet study in HIC

ATLAS

CMS
Jet study in HIC

1. How are jet showers modified in the medium?

2. How does the medium respond to the jet shower propagation?
Jet shower = leading parton $E_L$ + radiated gluons $f_g(w,k_t^2)$
A partonic jet shower in medium

**Leading parton:**
Transfers energy to medium by elastic collisions
Radiates gluons due to scatterings in the medium (*inside* and *outside* jet cone)

**Radiated gluons (**vacuum & medium-induced**):**
Transfer energy to medium by elastic collisions
Be kicked out of the jet cone by multiple scatterings after emission
Jet shower evolution is governed by:

\[ E_L(t) = E_L(t_i) - \int \hat{e}_L dt - \int \omega d\omega dk^2_{\perp} dt \frac{dN^\text{med}}{d\omega dk^2_{\perp} dt} \]

\[ df_g(\omega, k^2_{\perp}, t) \frac{dt}{dt} = \hat{e} \frac{\partial f_g}{\partial \omega} + \frac{1}{4} \hat{q} \nabla^2_{k_{\perp}} f_g + \frac{dN^\text{med}}{d\omega dk^2_{\perp} dt} \]

Energy loss from the jet cone is obtained as:

\[ \Delta E_J(R) = \int_{R} \omega d\omega dk^2_{\perp} \left[ f_g(\omega, k^2_{\perp}, t_i) - f_g(\omega, k^2_{\perp}, t_f) \right] + \int \omega d\omega dk^2_{\perp} dt \frac{dN^\text{med}}{d\omega dk^2_{\perp} dt} + \int \hat{e}_L dt \]
Inputs

• Obtain jet vacuum radiation spectrum from PYTHIA
  – Only gluons with the formation time $t_{\text{form}}$ smaller than $t_i$ are radiated

$$ f_g(\omega, k^2, t_i) = f_g^{\text{PYTHIA}}(\omega, k^2) \theta(t_i - t_{\text{form}}) $$

• Medium-induced radiation from higher twist formalism

$$ \frac{dN_{g}^{\text{med}}}{d\omega dk^2 dt} = \frac{2\alpha_s xP(x)\hat{q}(t)}{\pi\omega k^4} \sin^2 \left( \frac{t - t_i}{2t_{\text{form}}} \right) $$

  Wang, Guo, 2001
  Majumder, 2009

• Transport coefficients scaled with the temperature/entropy of the medium

$$ \hat{q} = 4T\hat{e} \propto T^3 $$
Jet cone energy loss in a brick of QGP

Medium effect on vacuum radiation dominates earlier times
Medium-induced radiation effects catch up later
Leading parton collisional E-loss is small

A quark jet
E=100GeV

Jet cone R=0.4
T=250MeV
\( \hat{Q} = 0.7\text{GeV}^2/\text{fm} \)
\( t_i=0.6\text{fm/c} \)
\( \omega_{min}=2\text{GeV} \)
Dijet asymmetry measurements

Di-jet asymmetry increases with centrality
Di-jet angular distribution is largely unchanged

\[ A_J = \frac{E_{T,1} - E_{T,2}}{E_{T,1} + E_{T,2}} \]

Background fluctuations: Cacciari, Salam and Soyez, arXiv:1011.2878

R=0.4, anti-\( k_T \), \( E_1 > 100 \text{GeV}, \ E_2 > 25 \text{GeV}, \ \Delta \phi > \pi, \ |\eta| < 2.8 \]
Initialization for the LHC

- Scale $\hat{q}$ with entropy density $s \propto T^3 \rho_{\text{part}}$

- Wood-Saxon for nuclear density function

- Medium thermalized at $t_0=0.6\text{fm/c}$, $T_0=520\text{MeV}$

- 1-D Bjorken expansion for the medium

- No jet-medium interaction below $T=160\text{MeV}$
Calculate dijet asymmetry for the LHC

**Proton + Proton**
- Generate p+p events from PYTHIA including ISR and FSR
- Reconstruct jets using anti-kt
- Select di-jets according to EXP
- Calculate p+p di-jet asymmetry

**Lead + Lead**
- Sample di-jets production points according binary collision distr.
- Apply jet cone cone energy loss in medium to p+p di-jets
- Calculate Pb+Pb di-jet asymmetry

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

**No trigger bias:**
Jet 1 and Jet 2 treated with equal footing

**Extreme trigger bias:**
Jet 1 along shorter path
Jet 2 along longer path
Here a Gaussian smearing with $\sigma \propto \sqrt{E_{\text{jet}}}$ is applied for the energy resolution of the calorimeter.

\begin{align*}
R &= 0.4, \text{ anti-}k_T \\
E_1 &> 100\text{GeV} \\
E_2 &> 25\text{GeV} \\
\Delta \phi &> \pi, |\eta| < 2.8 \\
<\hat{q}> &= 0.77\text{GeV}^2/\text{fm} \\
\hat{q} &= 1.9\text{GeV}^2/\text{fm} \\
&\text{for } T = 400\text{MeV}
\end{align*}
CMS result

$R=0.5$, anti-$k_T$
$E_1>120\text{GeV}$
$E_2>50\text{GeV}$
$\Delta\phi>2\pi/3$, $|\eta|<2$

$\langle \hat{q} \rangle = 0.93\text{GeV}^2/\text{fm}$
$\hat{q} = 2.3\text{GeV}^2/\text{fm}$ for $T=400\text{MeV}$

20% difference for $\hat{q}$ between CMS and ATLAS
Summary and outlook

- A simplified but realistic framework for studying jet shower evolution in medium
  - Includes collisional energy loss and momentum broadening
  - Includes vacuum radiation and medium-induced radiation

- Compare to dijet asymmetry in Pb+Pb collisions at the LHC
  - 20% difference in $\hat{q}$ for CMS and ATLAS
  - The extracted $\hat{q}$ values consistent with RHIC results

- Other observables (jet $R_{AA}$, jet structure, reaction plane dependence, gamma-jets ...)
- Complete Monte-Carlo simulation
- Realistic simulation of background fluctuations
- Medium response to jet shower propagation
Je vous remercie de votre attention!