Full jet evolution in quark-gluon plasma and nuclear modification of jet structure in Pb+Pb collisions at the LHC

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Outline

- Motivation and Framework
  - Nuclear modification on jet energy
    - Inclusive jet spectra
    - Di-jet and photon-jet asymmetry
  - Nuclear modification on jet structure
- Summary and Outlook
Motivation: Full jet

- Energy loss of the leading parton due to medium induced radiation may be not the energy loss of the full jet.
- Collisional energy loss may be more important for full jets than single hadrons.
- Jet structure and its modification can reveal more detailed information.
**Framework: Boltzmann transport equation**

\[
\frac{d}{dt} f_j(\omega_j, k^2_{j\perp}, t) = \hat{e}_j \frac{\partial}{\partial \omega_j} f_j(\omega_j, k^2_{j\perp}, t) + \frac{1}{4} \hat{q}_j \nabla_{k\perp}^2 f_j(\omega_j, k^2_{j\perp}, t)
\]

- **Collisional energy loss**

\[
\begin{align*}
\text{gain} & \quad + \sum_i \int d\omega_i dk^2_{i\perp} \tilde{\Gamma}_{i \rightarrow j} (\omega_j, k^2_{j\perp} | \omega_i, k^2_{i\perp}) f_i(\omega_i, k^2_{i\perp}, t) \\
\text{loss} & \quad - \sum_i \int d\omega_i dk^2_{i\perp} \tilde{\Gamma}_{j \rightarrow i} (\omega_i, k^2_{i\perp} | \omega_j, k^2_{j\perp}) f_j(\omega_j, k^2_{j\perp}, t)
\end{align*}
\]

**Radiation**

\[
f_j(\omega_j, k^2_{j\perp}, t) = \frac{dN_j(\omega_j, k^2_{j\perp}, t)}{d\omega_j dk^2_{j\perp}}
\]

\[
\hat{e} = \frac{dE}{dt} \quad \hat{q} = \frac{d(\Delta p\perp)^2}{dt} \quad \hat{q} = 4T\hat{e}
\]

**Interaction Cross Sections**

\[
\Gamma(\omega, k^2_\perp | E, 0) = \frac{2\alpha_s}{\pi} \frac{x P(x) \hat{q}(t)}{\omega k^4_\perp} \sin^2 \frac{t - t_i}{2\tau_f}
\]

- \(t_i = \frac{2E x_i (1-x_i)}{k^2_{i\perp}}\)

- \(\tau_f = \frac{2\omega_i x_{ij} (1-x_{ij})}{k^2_{ij\perp}}\)

\(\omega_{cut} = 2 GeV\)
Hydrodynamic Simulation using VISH2+1

Initial condition from PYTHIA
Quark distribution

Gluon distribution

quark jet
Observables on full jets energy loss

$$R_{AA} = \frac{1}{\langle N_{coll} \rangle} \frac{d^2 N_{AA}/d\eta dp_T}{d^2 N_{pp}/d\eta dp_T}$$
Centrality dependence

\[ \hat{q}_{0}^{30-40\%} = \hat{q}_{0}^{0-10\%} \frac{T^{3}(\tau_{0}, 0)^{30-40\%}}{T^{3}(\tau_{0}, 0)^{0-10\%}} \]
Effects of different interaction mechanisms on Jet Energy Loss

R=0.3

Collisional energy loss contribute the most, medium induced radiation contribute least but can enhance other mechanism.
Modification of Jet shape

Jet shape function is normalized and deep-falling, exact fit on each data point is difficult.
Modification of Jet shape: mid-centrality

\[ R = 0.3, E_{\text{jet}} > 100 \text{GeV} \]

- CMS, 10-30%
- CMS, 30-50%

- \( \hat{q}_0 = 1.6 \text{ GeV}^2/\text{fm}, 30-40\% \)
- \( \hat{q}_0 = 1.8 \text{ GeV}^2/\text{fm}, 30-40\% \)
Modification of jet shape: Energy and flavor dependence
Jet shape: gamma-jet

Same energy dependence in gamma-jet
Effects of different mechanisms on Modification of Jet shape

Rad. and Broad. transport energy from center to periphery
Coll. lead inner core lose less fraction of energy than outer part
Effects of different mechanisms on Modification of Jet shape: lower energy jet

Rad. and Broad. become stronger, the inner core can be affected more easily.
Sensitivity to the value of qhat

Every mechanism has sensitivity to qhat, but the sensitivity become modest when all of them exist.
Jet shape modification

- Jet shape function

\[ \rho(r) = \frac{\sum \frac{p_T^i}{p_T^\text{jet}} \left( r - \frac{1}{2} \delta r \right) \theta \left[ (r + \frac{1}{2} \delta r) - r_i \right]}{\delta r} \]

- Inclusive, \( E_{\text{jet}} \geq 100 \text{ GeV} \ (\Delta R = 0.3) \)
Summary

- Coupled differential transport equations are constructed to study the evolution of the partonic jet shower in the QGP medium, can describe the nuclear modification of the full jet energy and jet structure at LHC simultaneously.

- The special effects of different jet-medium interaction mechanisms are analyzed, showing us that different mechanisms must be considered together to explain all the experimental data.

Outlook

Energy *et al* dependent transport coefficients, hadronization, jet FF...
Thanks for your attention!
Small angle approximation:

\[ \langle \left( \frac{k_{j\perp}}{\omega_j} \right)^2 \rangle \approx \theta_i^2 + \theta_{ij}^2 \approx \left( \frac{k_{i\perp}}{\omega_i} \right)^2 + \left( \frac{k_{ij\perp}}{\omega_j} \right)^2 \]

\[ t_i = \frac{2 E x_i (1 - x_i)}{k_{i\perp}^2} \]

\[ \tau_f = \frac{2 \omega_i x_{ij} (1 - x_{ij})}{k_{ij\perp}^2} \]

\[ \omega_{cut} = 2 GeV \]
Framework: Coupled differential Equations

Quark in the jet

\[
\frac{d}{dt} f_q(\omega_j, k_{j\perp}^2, t) = \hat{e} \frac{\partial f_q}{\partial \omega_j} + \frac{1}{4} \hat{q} \nabla_{k\perp}^2 f_q \\
+ \int d\omega_i dk_{i\perp}^2 \tilde{\Gamma}_{q\to qg}(\omega_j, k_{j\perp}^2 | \omega_i, k_{i\perp}^2) f_q(\omega_i, k_{i\perp}^2, t) + 2n_f \int d\omega_i dk_{i\perp}^2 \tilde{\Gamma}_{g\to qg}(\omega_j, k_{j\perp}^2 | \omega_i, k_{i\perp}^2) f_g(\omega_i, k_{i\perp}^2, t) \\
- \int d\omega_i dk_{i\perp}^2 \tilde{\Gamma}_{q\to qg}(\omega_i, k_{i\perp}^2 | \omega_j, k_{j\perp}^2) f_q(\omega_j, k_{j\perp}^2, t)
\]

Gluon in the jet

\[
\frac{d}{dt} f_g(\omega_j, k_{j\perp}^2, t) = \hat{e} \frac{\partial f_g}{\partial \omega_j} + \frac{1}{4} \hat{q} \nabla_{k\perp}^2 f_g \\
+ 2 \int d\omega_i dk_{i\perp}^2 \tilde{\Gamma}_{g\to gg}(\omega_j, k_{j\perp}^2 | \omega_i, k_{i\perp}^2) f_g(\omega_i, k_{i\perp}^2, t) + \int d\omega_i dk_{i\perp}^2 \tilde{\Gamma}_{q\to qg}(\omega_j, k_{j\perp}^2 | \omega_i, k_{i\perp}^2) f_q(\omega_i, k_{i\perp}^2, t) \\
- \int d\omega_i dk_{i\perp}^2 \tilde{\Gamma}_{g\to qg}(\omega_i, k_{i\perp}^2 | \omega_j, k_{j\perp}^2) f_g(\omega_j, k_{j\perp}^2, t) - n_f \int d\omega_i dk_{i\perp}^2 \tilde{\Gamma}_{g\to g\bar{q}}(\omega_i, k_{i\perp}^2 | \omega_j, k_{j\perp}^2) f_g(\omega_j, k_{j\perp}^2, t)
\]
Final distribution without $g \rightarrow q\bar{q}$
Framework

Guang-You Qin and Berndt Muller, PRL,106,162302

\[ f_g(\omega, k_\perp^2, t) = \frac{dN_g(\omega, k_\perp^2, t)}{d\omega dk_\perp^2} \]

\[
\frac{d}{dt} f_g(\omega, k_\perp^2, t) = \hat{e} \frac{\partial f_g}{\partial \omega} + \frac{1}{4} \hat{q} \nabla_{k_\perp}^2 f_g + \frac{dN_{g}^{\text{med}}}{d\omega dk_\perp^2 dt}
\]

\[
\hat{e} = \frac{dE}{dt}
\]

\[
\hat{q} = \frac{d(\Delta p_\perp)^2}{dt}
\]

\[
\hat{q} = 4T \hat{e}
\]

Only leading parton radiate

HT formula
\[ \rho_{g}^{\text{ini}}(r=0.05) = 9, \quad \rho_{q}^{\text{ini}}(r=0.05) = 10 \]

\[ R_{AA}^{\rho}(r=0.05) = \frac{\rho_{g} R_{AA}^{\rho} (1-x) + \rho_{q} R_{AA}^{\rho} x}{0.5(\rho_{g} + \rho_{q})} \]
Leading parton Energy Loss

\[ \Delta E_{\text{Rad}} = \int \omega d\omega dk^2 d\tau \frac{dN_g(\omega, k^2, \tau)}{d\omega dk^2 d\tau} \]

\[ \hat{\epsilon} = \frac{\hat{q}}{4T} \]

\[ \Delta E_{\text{Coll}} = \int \hat{\epsilon}(t) dt \]
Leading parton Energy Loss

Fig. 5. Comparison of the average radiative and elastic energy losses of light-quarks (left) and light- and heavy-quarks (right) passing through the medium produced in central \( AuAu \) collisions at RHIC energies as obtained by the AMY [24] and DGLV [25] models (see later).
Cone size dependence

\[ E_{\text{jet}}(R) = \sum_i \int_R \omega_i f_i(\omega_i, k_{i \perp}^2) d\omega_i dk_{i \perp}^2 \]
$w_{\text{cut}}$ dependence

[Graphs showing $R_{AA}$ and $\rho(r)$ vs. $p_T$ and $r$ for different $w_{\text{cut}}$ and $q_0$.]