Heavy and light flavor jet quenching

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Outline

• A Linearized Boltzmann Transport (LBT) approach to heavy/light flavor jet quenching (with elastic & inelastic contributions)

• Full jet energy loss and modification (collisional, radiative, broadening)

• Use jet-like angular de-correlation to probe medium-induced broadening ($q^{\hat{\text{a}}}t$)
Jet quenching

- The study of jet quenching/modification can provide valuable information about hot and dense QGP produced in heavy-ion collisions
Radiative & collisional processes

In the limit of soft scatterings, the effect of elastic collisions can be described by FP equation (longitudinal drag, longitudinal diffusion & transverse diffusion)

\[
\frac{\partial f}{\partial z^-} = \left[ D_{L1} \frac{\partial}{\partial l_q^-} + \frac{1}{2} D_{L2} \frac{\partial^2}{\partial^2 l_q^-} + \frac{1}{2} D_{T2} \nabla_{l_q \perp}^2 \right] f(z^-, l_q^-, \vec{l}_q \perp)
\]

The medium-induced gluon radiation spectrum from higher-twist formalism:

\[
\frac{dN_g}{dx d\vec{l}_\perp^2 dz^-} \approx \frac{4\alpha_s}{\pi} P(x) \frac{D_{T,2}}{l_\perp^4} \sin^2\left(\frac{z^- - z_i^-}{2\tau_f^-}\right)
\]

Jet transport coefficients control both collisional and radiative contributions

GYQ, Majumder, PRC 2013
Guo, Wang, PRL, 2000
Majumder, PRD, 2012
Radiative & collisional contributions

McGill-AMY rad.+coll.

Duke Langevin coll.+rad.

GYQ, Ruppert, Gale, Jeon, Moore, Mustafa, PRL 2008; Cao, GYQ, Bass, PRC 2013
A Linearized Boltzmann Transport (LBT) approach for heavy & light flavor jet quenching

- **Boltzmann equation:**
  \[ p_1 \cdot \partial f_1(x_1, p_1) = E_1 C[f_1] \]

- **Elastic collisions:**
  \[
  \Gamma_{12\rightarrow34} = \frac{\gamma_2}{2E_1} \int \frac{d^3p_2}{(2\pi)^32E_2} \int \frac{d^3p_3}{(2\pi)^32E_3} \int \frac{d^3p_4}{(2\pi)^32E_4} \\
  \times f_2(\vec{p}_2) \left[ 1 \pm f_3(\vec{p}_1 - \vec{k}) \right] \left[ 1 \pm f_4(\vec{p}_2 + \vec{k}) \right] S_2(s, t, u) \\
  \times (2\pi)^4 \delta^{(4)}(p_1 + p_2 - p_3 - p_4) |\mathcal{M}_{12\rightarrow34}|^2
  \]
  \[ P_{\text{el}} = \Gamma \Delta t \]

- **Inelastic collisions:**
  \[ \langle N_g \rangle(E, T, t, \Delta t) = \Delta t \int dx dk_{\perp}^2 \frac{dN_g}{dx dk_{\perp}^2} dt \]
  \[ P(n) = \frac{\langle N_g \rangle^n}{n!} e^{-\langle N_g \rangle} \]
  \[ P_{\text{inel}} = 1 - e^{-\langle N_g \rangle} \]

- **Elastic + Inelastic:**
  \[ P_{\text{tot}} = P_{\text{el}}(1 - P_{\text{inel}}) + P_{\text{inel}} \]

Elastic & inelastic energy loss from LBT

\[ \langle \Delta E \rangle \text{ (GeV)} \]

- c: elastic
- q: elastic
- g: elastic
- c: inelastic
- q: inelastic
- g: inelastic

\[ E_{\text{init}} = 30 \text{ GeV} \]
\[ T = 300 \text{ MeV} \]

Quenching hierarchy

$R_{AA}$ from LBT (heavy & light flavor hadrons)
Not only the interaction of the leading hard parton with the medium constituents, but also the fate of radiated shower partons

\[ E_{\text{jet}} = E_{\text{in}} + E_{\text{lost}} \]
\[ = E_{\text{in}} + E_{\text{out}}^{(\text{radiation})} + E_{\text{out}}^{(\text{broadening})} + E_{\text{th}}^{(\text{collision})} \]

GYQ, Muller, PRL, 2011; Casalderrey-Solana, Milhano, Wiedemann, JPG 2011; Young, Schenke, Jeon, Gale, PRC, 2011; Dai, Vitev, Zhang, PRL 2013; Wang, Zhu, PRL 2013; Blaizot, Iancu, Mehtar-Tani, PRL 2013; etc.
Full jet evolution in medium

- Solve the 3D (energy & transverse momentum) evolution for shower partons inside the full jet
- Include both collisional (the longitudinal drag and transverse diffusion) and all radiative/splitting processes

\[
\frac{d}{dt} f_j(\omega_j, k_{j\perp}^2, t) = \left( \hat{e}_j \frac{\partial}{\partial \omega_j} + \frac{1}{4} \hat{q}_j \nabla_{k_{\perp}}^2 \right) f_j(\omega_j, k_{j\perp}^2, t) \\
+ \sum_i \int d\omega_i dk_{i\perp}^2 \frac{d\Gamma_{i\rightarrow j}(\omega_j, k_{j\perp}^2 | \omega_i, k_{i\perp}^2)}{d\omega_j d^2 k_{j\perp} dt} f_i(\omega_i, k_{i\perp}^2, t) \\
- \sum_i \int d\omega_i dk_{i\perp}^2 \frac{d\Gamma_{j\rightarrow i}(\omega_i, k_{i\perp}^2 | \omega_j, k_{j\perp}^2)}{d\omega_i d^2 k_{i\perp} dt} f_j(\omega_j, k_{j\perp}^2, t)
\]

\[E_{jet}(R) = \sum_i \int_{R} \omega_i f_i(\omega_i, k_{i\perp}^2) d\omega_i dk_{i\perp}^2\]

Ningbo Chang, GYQ, arXiv:1603.01920
Full jet energy loss (radiative, collisional, broadening)

From center, $\tilde{q}_0 = 1.8 \text{ GeV}^2/\text{fm}$

(a) Quark jet

Ningbo Chang, GYQ, arXiv:1603.01920
The soft outer part of jets is easier to be modified (some absorbed by medium), while the modification of the inner hard cone is more difficult.

The enhancement at large $r$ is consistent with the broadening.

The final modification of jet shape comes from the interplay of different contributions.

Ningbo Chang, GYQ, arXiv:1603.01920
Various full jet observables

Ningbo Chang, GYQ, arXiv:1603.01920
Jet-like correlations
Most of (theoretical) studies on jet-like correlations in AA collisions mainly focus on the nuclear modification of the (per-trigger) yield. We will use the angular correlations to probe the transverse momentum broadening.
Dijet angular correlations in pp & AA

Resum all order soft gluon radiation in vacuum at NLL for dijet angular correlation by Sun, Yuan, Yuan, PRL 2014; PRD 2015
Extend the formalism to include the broadening effect induced by the QCD medium for dijet angular correlation by Mueller, Wu, Xiao, Yuan, arXiv:1604.04250
Probing $q^\text{hat}$ via dihadron & hadron-jet angular correlations

Lin Chen, GYQ, Shu-Yi Wei, Bo-Wen Xiao, Han-Zhong Zhang, in preparation
Momentum imbalance $q_T$ distribution (in pp)

\[ \bar{q}_\perp = \bar{p}_{T,1} + \bar{p}_{T,2} \]

\[ \langle q^2 \rangle_{AA} \approx \langle q^2 \rangle_{pp} + \langle \bar{q} L \rangle_{AA} \]

Lin Chen, GYQ, Shu-Yi Wei, Bo-Wen Xiao, Han-Zhong Zhang, in preparation
Summary

• *Radiative & collisional* processes play different roles in different probes and observables
  – Light & heavy flavor jet quenching, full jet energy loss, nuclear modification of jet shape

• Jet transport coefficients control both *collisional* and *radiative* contributions

• Probe medium-induced *broadening* \( (q^{\text{hat}}) \) via jet-like angular correlations
backup
Test for collisional & radiative energy loss from LBT

Sensitivity to jet transport parameter

Ningbo Chang, GYQ, arXiv:1603.01920
Full jet energy loss
(jet size dependence of different contributions)

![Graph showing jet energy loss in different conditions](image-url)
Uncertainty from $\omega_{\text{cut}}$
Nuclear modification of jet shape

Ningbo Chang, GYQ, arXiv:1603.01920
Extraction of jet transport parameter

Jet transport coefficients control both collisional and radiative contributions

 RHIC energy scan

10GeV quark jet


McGill-AMY:
GYQ, Ruppert, Gale, Jeon, Moore, Mustafa, PRL 2008

HT-BW:

HT-M:
Majumder, Chun, PRL 2012

GLV-CUJET:
Xu, Buzzatti, Gyulassy, arXiv: 1402.2956

MARTINI-AMY:
Schenke, Gale, Jeon, PRC 2009

NLO SYM:
Zhang, Hou, Ren, JHEP 2013

Jet transport coefficients control both collisional and radiative contributions

\[
\hat{q} \approx \begin{cases} 
1.2 \pm 0.3 \\
1.9 \pm 0.7 
\end{cases} \text{ GeV}^2/\text{fm} \text{ at } \begin{cases} 
T=370 \text{ MeV} \\
T=470 \text{ MeV} 
\end{cases}
\]

\[
\hat{q} = \frac{d\langle \Delta p_{\perp}^2 \rangle}{dt} = \int d^2 k_{\perp} k_{\perp}^2 \frac{d \Gamma(k_{\perp})}{d^2 k_{\perp} dt} \approx \frac{8 \pi^2 \alpha_s C_R}{N_c^2 - 1} \int dy^{-} \langle F^{\mu+}(0) F^{\mu+}(y^{-}) \rangle
\]
Dihadron correlation

\[
\frac{d\sigma}{d\Delta\phi} = \sum_{a,b,c,d} \int p_T^{h_1} dp_T^{h_1} \int p_T^{h_2} dp_T^{h_2} \int \frac{dz_c}{z_c^2} \int \frac{dz_d}{z_d^2} \\
\times \int b \ db \ J_0(q_{\perp} b) e^{-S(Q,b)} x_a f_a(x_a, \mu_b) x_b f_b(x_b, \mu_b) \\
\times \frac{1}{\pi} \frac{d\sigma_{ab\rightarrow cd}}{d\hat{t}} D_c(z_c, \mu_b) D_d(z_d, \mu_b)
\]

\[
S(Q, b) = S_p^i(Q, b) + S_p^f(Q, b) + S_{np}(Q, b) \\
+ \frac{b^2}{4} (\langle \hat{q}_c L \rangle + \langle \hat{q}_d L \rangle)
\]