Jets & Heavy Flavors in HIC from a Partonic Transport Approach and a Multistage Approach

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Weiyao Ke, Los Alamos National Laboratory
Characterizing quark-gluon plasma from jets and heavy flavors

- Jet transport parameter $\hat{q}$.
- Heavy quark momentum diffusion parameters $\kappa$.

Intermediate to high-$p_T$ HF modifications

- Energy loss from soft rad. & collisions, $\omega \sim T$.
- Medium-modified fragmentation and mass effects.
- Non-perturbative input and models: fragmentation, recombination, etc.
Characterizing quark-gluon plasma from jets and heavy flavors

- Jet transport parameter \( \hat{q} \).
- Heavy quark momentum diffusion parameters \( \kappa \).

From jet modifications to \( \hat{q} \)

- Angular-dependent energy transport by parton shower in the medium.
- Medium excitations induced by energy loss.
• Study of HF & jet in the LIDO partonic transport approach.

• Progresses in JETSCAPE multistage jet evolution: modified DGLAP + transport.

• Jets: inferring QGP $\hat{q}$ from jet & hadron suppression at both RHIC and LHC.

• Heavy flavors: towards a consistent description of light and heavy quenching new information from HF-tagged jets.

• Impact of future high precision data at RHIC.
Transport equations of hard partons \( f_H = f(t, x, p)\Theta(p \cdot u > E_{\text{min}}), \)

\[
(\partial_t - v \cdot \partial_x)f_H(t, x, p) = \Theta(p \cdot u > E_{\text{min}})\{C_{nn}f_H + C_{n(n+1)}f_H\}
\]

- Collisional processes: number of hard partons does not change \( n \rightarrow n \).
- Medium-induced radiative & semi-hard recoil processes: \( n \rightarrow n + 1 \).
- (In most studies) medium is assumed to be a locally thermal gas of massless partons:
  \( f_{q,g}(p) = [e^{p \cdot u/T} + 1]^{-1} \). QGP flow and temperature obtained in bulk medium simulations.
LIDO: Linearized Boltzmann + Diffusion Partonic Transport Model

\[ \frac{df_H}{dt} = Df_H + D_{12}f_H + C_{22}f_H + C_{23}f_H \]

Large-angle collisions with thermal partons \( f_s(p') = e^{-p' \cdot u / T} \)

\[ \frac{d\sigma}{d^2q} \propto \frac{\alpha_s^2}{q^4} \Theta(q_{\perp}^2 - Q_c^2), \quad C_{22}f_H(p) = \int_{q,p'} f_s(p') \left\{ \frac{d\sigma}{d^2q} f_H(p-q) - \frac{d\sigma}{d^2q} f_H(p) \right\} \]

Small-angle collisions absorbed in a diffusion component\(^1\): \( Df_H(p) = -\left\{ \eta \nabla_p + \frac{\kappa_{s,ij}}{2} \nabla_{p^i} \right\} f_H(p). \)

The jet transport parameter combines both small & large-angle contribution

\[ \hat{q}_F(T, p) \equiv \frac{d\langle \Delta k_T^2 \rangle}{dt} = \alpha_s C_F T m_D^2 \ln \frac{Q_c^2}{m_D^2} + \int_{p'} f_s(p') \left\{ 2(N_c^2 - 1) \frac{d\sigma_{qg}}{d^2q} + 4N_f N_c \frac{d\sigma_{qq}}{d^2q} \right\} \Theta(q_{\perp}^2 - Q_c^2) q_{\perp}^2 d^2q_{\perp} \]

\(^1\)In J. Ghiglieri, G. D. Moore, D. Teaney JHEP 03, 095(2016), separation requires \( m_D \ll Q_c \ll T \). we take \( Q_c = 2m_D \)
\[
\frac{df_H}{dt} = \mathcal{D} f_H + \mathcal{D}_{12} f_H + C_{22} f_H + C_{23} f_H
\]

Diffusion-induced 1 to 2 radiation:
\[
\mathcal{D}_{12} f_H(x, p) = \int_k \frac{\alpha_s P_{ij}(z)}{2\pi^2 k^2} \hat{g}_s \frac{f_H(x/z, p + k)}{z} \frac{dz}{z} + \ldots
\]

Large-\(q\) collision-induced 2 to 3 radiation:
\[
C_{23} f_H(x, p) = \int_{k, q, p'} \frac{d\sigma_{23}}{dzd^2k d^2q} f_s(p') f_H(x/z, p + k - q) \frac{dz}{z} + \ldots
\]
LIDO: Linearized Boltzmann + Diffusion Partonic Transport Model

\[ \frac{df_H}{dt} = Df_H + D_{12}f_H + C_{22}f_H + C_{23}f_H \]

Diffusion-induced 1 to 2 radiation:

\[ D_{12}f_H(x,p) = \int_k \frac{\alpha_s P_{ij}(z)}{2\pi^2 k^2} \hat{q}_s f_H \left( \frac{x}{z}, p + k \right) \frac{dz}{z} + \ldots \]

Large-\( q \) collision-induced 2 to 3 radiation:

\[ C_{23}f_H(x,p) = \int_{k,q,p'} d\sigma_{23} f_s(p') f_H \left( \frac{x}{z}, p + k - q \right) \frac{dz}{z} + \ldots \]

2 → 3 cross-sections in the limit \( \sqrt{z(1-z)\hat{s}_{ij}} \gg q, k \)
\[
\frac{df_H}{dt} = Df_H + D_{12}f_H + C_{22}f_H + C_{23}f_H
\]

Diffusion-induced 1 to 2 radiation:
\[
D_{12}f_H(x, p) = \int_k \frac{\alpha_s P_{ij}(z)}{2\pi^2 k^2} \hat{q}_s f_H(\frac{x}{z}, p + k) \frac{dz}{z} + ...
\]

Large-\(q\) collision-induced 2 to 3 radiation:
\[
C_{23}f_H(x, p) = \int_{k, q, p'} \frac{d\sigma_{23}}{dzdk^2dq} f_s(p') f_H(\frac{x}{z}, p + k - q) \frac{dz}{z} + ...
\]

(Deep) Landau-Pomeranchuk-Midgal effect: suppressing radiation with \(\#\lambda_{\text{mfp}}/\tau_f\). Energy loss: \(\Delta E_{\text{rad}}\) only dominates \(\Delta E_{\text{el}}\) by \(\alpha_s \ln E\).
For jet study: a simple model for medium excitation

- Energy-momentum deposition to soft sector:
  \[
  \frac{d\delta p^\mu}{dt}(t, x) = \int_p \Theta(p \cdot u < E_{\text{min}}) p^\mu \frac{d}{dt} f_H(t, x, p)
  \]

- An ideal-hydro response:
  \[
  \frac{de}{d\Omega_{k'}} = \frac{\delta p^0 + \hat{k}' \cdot \delta \vec{p}/c_s}{4\pi}, \quad \frac{d\vec{p}}{d\Omega_{k'}} = \frac{3(c_s\delta p^0 + \hat{k}' \cdot \delta \vec{p})\hat{k}'}{4\pi}
  \]

- Freeze-out to massless particles with radial flow \( v_\perp \) ⇒ corrections to momentum density in the cone:
  \[
  \frac{d\Delta p_T}{d\phi d\eta} = \int \frac{3}{4\pi} \frac{4}{4\pi} \frac{\sigma u_\mu - \hat{\rho}_\mu}{\sigma^4} \delta p^\mu(\hat{k}) \frac{d\Omega_{\hat{k}}}{4\pi}
  \]

\[
\sigma = \gamma_\perp \left[ \cosh(\eta - \eta_s - \eta_{\hat{k}}) - v_\perp \cos(\phi - \phi_{\hat{k}}) \right]
\]

Other methods: recoiled partons (JEWEL), recoiled parton + rescatterings (LBT), coupled jet-hydro evolution (CoLBT, JETSCAPE), Hybrid model (next talk).
In LIDO simulations:

- Pythia generates vacuum shower down to transition scale $Q_0$.
- LIDO for time-evolution of shower in QGP in regions $T > T_c$.
- Pythia8 handles vacuum shower and fragmentation when $T < T_c$.

Results depend on $Q_0$.

- $Q_0$ can be tuned to data. Note that jet and HF $R_{AA}$ are less sensitive to $Q_0$.
- Physical expectation: $Q_0 \approx$ momentum broadening.

- For example: in Björken medium with $\hat{q} = 5T^3$

<table>
<thead>
<tr>
<th>Systems</th>
<th>Pb-Pb 5 TeV</th>
<th>Au-Au 0.2 TeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-5%</td>
<td>40-50%</td>
<td>0-5%</td>
</tr>
</tbody>
</table>

$5t_0 T_0^3$ [GeV$^2$]:

- ATLAS, jets
- ALICE, jets
- STAR, chg. jets
- CMS, hadron

$Q_0$ can be a function of beam energy and centrality.
JETSCAPE framework: the multistage in-medium jet evolution approach

A program envelop coupling jet shower and medium evolution + statistical inference package.

Philosophy for the jet sector:
applying different models to different phase space regions of parton energy $E$, virtuality $Q$ and $T$.

The multistage method [PRC96(2017)024909, 1903.07706]

At high-virtuality $Q^2 = \frac{k_\perp^2}{x(1-x)} > Q_0^2$: medium-modified DGLAP evolution (MATTER [PRC88(2013)014909])

$$P(Q'; Q) = \exp \left\{ - \int_{Q/2}^{Q^2} \int dx \frac{dN_{ij}}{dx dQ^2} dQ^2 \right\}$$

At low-virtuality $Q < Q_0$, the time-ordered transport equation (e.g. LBT [PRC91(2015)054908])

$$P(t_2; t_1) = \exp \left\{ - \int_{t_1}^{t_2} \int dx \frac{dN_{ij}(t)}{dx d^2k_\perp} dx d^2k_\perp dt \right\}$$
In this approach, $\hat{q}$ depends on $E$, $T$, and $Q$.

\[
\begin{align*}
\frac{\hat{q}}{T^3}_{\text{LBT}} &= \# \left\{ a \frac{\ln(E/\Lambda) - \ln b}{\ln^2(E/\Lambda)} + c \frac{\ln(E/T) - \ln d}{\ln^2(ET/\Lambda^2)} \right\} \\
\frac{\hat{q}}{T^3}_{\text{Matter}} &= \# \left\{ \Theta(Q - Q_0) a \frac{\ln(Q/\Lambda) - \ln(Q_0/\lambda)}{\ln^2(Q/\Lambda)} + c \frac{\ln(E/T) - \ln d}{\ln^2(ET/\Lambda^2)} \right\}
\end{align*}
\]

A Bayesian analysis is performed with inclusive hadron $R_{AA}$ at both RHIC and LHC.

Model choices: MATTER (modified DGLAP) + LBT (transport), both use the higher-twist formula for induced parton radiation.
Recent hadron & jet studies within the JETSCAPE framework [2204.01163]

△ Weaker $Q_0$ dependence in the multi-stage approach.

△ Simultaneous description of hadron and jet $R_{AA}$ at RHIC energy
Objective: determine “jet-medium coupling $\alpha_s(\mu_{\text{med}}) = g_s^2(\mu_{\text{med}})/4\pi$”, then the $\hat{q}$

$$\hat{q}_F(T, p) = \alpha_s(\mu_{\text{med}}) C_F T m_D^2 \ln \frac{Q_c^2}{m_D^2} + \int_{p'} f_s(p') \left\{ 2(N_c^2 - 1) \frac{d\sigma_{qg}}{d^2q_{\perp}} + 4N_f N_c \frac{d\sigma_{qq}}{d^2q_{\perp}} \right\} \Theta(q_{\perp}^2 - Q_c^2) q_{\perp}^2 d^2q_{\perp}$$

- $0.7\pi T < \mu_{\text{med}} < 4\pi T$: controls in-medium $g_s$:
  $$\frac{g_s^2(k_{\perp})}{4\pi} = \frac{4\pi}{\beta_0} \ln^{-1} \left[ \frac{\max\{k_{\perp}, \mu_{\text{med}}^2\}}{\Lambda^2} \right]$$

- $0.5 < Q_0 < 2.0$ GeV: separates vacuum-like and transport evolution.

- $0.15 < T_f < 0.17$ GeV, sudden transition to confinement below $T < T_f$. 

$\hat{q}$ from hadron+jet data in central Au-Au & Pb-Pb [JHEP05(2021)041]
LIDO Bayesian analysis of $\hat{q}$ from hadron and jet

- $Q_0^{LHC}$ varies independently from $Q_0^{RHIC}$.
- Favors higher $T_f$ than the pseudo-critical $T_c$.
- Running of $g_s$ in medium saturates around $k_\perp > \mu_{med} \approx 4.2 T$ (or $1.3\pi T$).

Results: jet-medium coupling $g$ and jet transport parameter $\hat{q}$

Left: maximum coupling at different temperature $g_s(\mu_{\text{med}})$
Right: $\hat{q}$ at $p = 10$ and 100 GeV for a quark. [JHEP05(2021)041]


- Results consistent with JET collaboration. (using inclusive hadron suppression).
- Higher than the recent JETSCAPE Collaboration analysis (using inclusive hadron suppression).
  A possible explanation could be the use of medium-modified DGLAP evolution for $Q > Q_0$. 

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The cone-size dependence of jet $R_{AA}$ from LIDO

[Image 19x112 to 197x237]
[Image 236x142 to 435x221]

△ Unbiased region (red) are in sensitive to the high-$p_T$ hadron trigger. [STAR: PRC 102, 054913(2020)]

• LHC: LIDO predicts $R_{AA}$ increased by 10% from $R = 0.2$ to $R = 1.0$ at $p_T^{jet} = 500$ GeV.

• RHIC: Weak $R$-dependence in the unbiased region. Trigger bias understood from simulation.

[CMS: JHEP 05, 284(2021)]
Heavy-flavor meson suppression at large $p_T$

**LIDO: $R_{AA}^{\pi,D,B}$ in 0-10% Au-Au@0.2 TeV**

- **Same $\hat{q}$ (median) as calibrated to $R_{AA}^{\text{jet}}$ and $R_{AA}^{h}$.** *Previous works [PRC98(2018)06490] only used heavy-flavor data.*

- **Consistent $\hat{q}$ for $q, c, b$ overestimates the flavor separation.**

- **Similar problem in a recent QCD-evolution based calculation [2204.00634].** *Need interactions in the hadronic stage? A large NP contribution from $g \rightarrow D, B?$*

**Recent progress from the JETSCAPE multi-stage evolution**

*Figure 1: Comparison of $D^0$ meson nuclear modification factor $R_{AA}$ and azimuthal anisotropy $v_2(2)$ using the multi-stage energy loss approach (MATTER + LBT) with CMS data for central Pb + Pb collisions at 5.02 TeV. (Left) $D^0$ meson $R_{AA}$ (Right) $D^0$ meson $v_2(2)$. Computed with two switching virtuality $Q_0 = 2$ GeV and $Q_0 = 2\sqrt{2}$ GeV.*


- **A consistent study of both charm and light flavor to appear soon.**

- **Check if similar problem exists for the multi-stage approach with $h, D & B$.**
What can be learned from heavy-flavor jets?

HF-jet suppression in LIDO (in preparation)

- A clear mass dependence recently suggested by ATLAS measurements at 5.02 TeV.
- LIDO seem to result in too large a mass separation of $R_{AA}^{b\text{-jet}}$ and $R_{AA}^{\text{jet}}$
- Heavy jet continued to be highly suppressed at high $p_T$. 


[ATLAS 2204.13530]
More information contained in the fragmentation / HF-jet correlation

Suppression of inclusive HF spectra is only probing the HF modification near \( z \approx 1 \) (energy loss limit).

\[
\frac{d\sigma_{AA\rightarrow Q}}{dq_T} \propto \frac{1}{q_T^n}
\]

\[
\frac{d\sigma_{AA\rightarrow HF}}{dp_T} = \frac{d\sigma_{AA\rightarrow Q}}{dq_T} \otimes D_{AA}(z) \propto \int z^{N-1} D_{AA}(z) dz
\]

Heavy-flavor in jet fragmentation tests the full-\( z \) dependence.

- The shape is a mixture of \( Q \rightarrow HF \), \( g \rightarrow HF \), \( q \rightarrow HF \)
- Study the NP contribution from \( g \rightarrow HF \) meson, e.g., \( D \)-meson fragmentation function from hadron-in-jet analysis in \( p+p \) [PRD96(2017)034028].
(Perturbative) Medium-induced charm flavor production

- LO collisional processes and induced $g \to c + \bar{c}$.
- $\hat{q} \Delta \tau \lesssim m_c^2 \ll m_b^2$. 
(Perturbative) Medium-induced charm flavor production

- LO collisional processes and induced $g \rightarrow c + \bar{c}$.
- $\hat{q} \Delta \tau \lesssim m_c^2 \ll m_b^2$.
- Can be important for $R_{AA}^{c\text{-jets}}$ at high $p_T$. 
Impact of future high-precision jet & HF measurement at RHIC

- High precision HF, jet measurements with much higher reach of jet $p_T$.
- However, the dominant uncertainty in current Bayesian analysis is theory/interpolation uncertainty ($\sim 10\%$).
- The gain of information will be limited by theory / model...

[sPHENIX Beam Use Proposal]
Impact of future sPHENIX heavy-flavor data

Pseudodata: $R_{AA}^{D}$, $\nu_2^D$ from simulations w/ "true" parameters + current uncertainties.

Current level of uncertainties in the charm diffusion constant using STAR uncertainty level.

Charm, $\nu = 0.6$

$4\pi T^2/\sqrt{s}$

$T/T_c$

1.00 1.25 1.50 1.75 2.00 2.25 2.50 2.75 3.00
Impact of future sPHENIX heavy-flavor data

Pseudodata: $R_{AA}^D$, $v_2^D$ from simulations w/ “true” parameters + projected uncertainties.

Uncertainties in the charm diffusion constant using the projected sPHENIX data.

Note that the residue uncertainty band comes from theory and interpolation uncertainty.
Summary and outlook for HF and jet in HIC

- The pure LIDO transport approach:
  - Vacuum shower + LIDO (collisional + radiative)
  - $\hat{q}$ determined from hadron and jet $R_{AA}$ at RHIC and LHC.

- The JETSCAPE multistage approach:
  - Medium-modified high-virtuality shower + time-evolution of low-virtuality partons in QGP.
  - Expected to further reduce model uncertainties in the future.

- Heavy flavor: using same $\hat{q}$ in LIDO overestimate the flavor suppression between $R_{AA}^{h,D,B}$.

- Heavy-flavor jets can provide more information:
  - The full-$z$ dependence of modified HF fragmentation
  - Perturbative & NP contributions of $g \rightarrow HF$.

- With future high-precision sPHENIX data on HF:
  - One expects the uncertainty on $\hat{q}, \kappa$ to decrease.
  - But currently limited by theory / interpolation uncertainties in statistical analysis.
Questions?
Uncertainties of $Q_0$: advantage of using jet $R_{AA}$ to calibrate $\hat{q}$

Experimental data:

[STAR charged jet: PRC 102, 054913(2020)]
[ALICE jet: PRC 101 034911(2020)]
[ATLAS jet: PLB 790 108-128(2019)]
[CMS D: PLB 287 474-496(2018)]
[CMS h: JHEP 04, 039(2017)]
[PHENIX $\pi$: PRC 87, 034911(2013)]

Test the variation of $Q_0 = 0.5, 1.0, 2.0$ GeV.

- Light hadron $R_{AA}$ are very sensitive to $Q_0$.
- Jet and heavy-flavor $R_{AA}$ at the LHC energy are the least sensitive.
Uncertainties: the QGP termination temperature \( T_f \)

Experimental data:

- [STAR charged jet: PRC 102, 054913(2020)]
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- [CMS h: JHEP 04, 039(2017)]
- [PHENIX \( \pi \): PRC 87, 034911(2013)]

Change \( T_f = 0.15, 0.16, 0.17 \) GeV. ⇔ effectly change color density near \( T_c \).
Uncertainties: $\mu_{\text{med}}$ or $g_s(\max\{k_T, \mu_{\text{med}}\})$

Experimental data:

[STAR charged jet: PRC 102, 054913(2020)]

[ALICE jet: PRC 101 034911(2020)]

[ATLAS jet: PLB 790 108-128(2019)]

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[CMS h: JHEP 04, 039(2017)]

[PHENIX π: PRC 87, 034911(2013)]

Changing the coupling strength by varying $\mu_{\text{med}} = 2T, 4T, 8T$ GeV
Test the transport of energy: fragmentation function

- Calculations that treats everything with partonic dynamics well describes the fragmentation at $z p_T^{jet} > 2$ GeV (red bands).
- Use collective excitations to redistribution soft particles improves at $p_T \lesssim 2$ GeV.
Test the transport of energy: a detailed look at low-$p_T$ particles

Jet shape with different minimum hadron $p_T$

- Energy is shifted to particles at lower $p_T$ and larger $r$.
- Discrepancy appears within the cone for $p_{T,\text{cut}} = 4$ GeV
  - Can this be fixed by fine-tuning of parameters?
  - Suggest missing physics? Such as coalescence shifting intermediate-$p_T$ hadrons to higher $p_T$.
Dynamics of HF & jet from intermediate to high $p_T$

**Intermediate to high-$p_T$ HF production**

- Probe modification/loss of large-$z$ partons
  - Energy loss from soft rad. & collisions, $\omega \sim T$.
  - Medium-modified fragmentation and mass effects.
  - Non-perturbative input and models: fragmentation, recombination, etc.

**Jet modifications**

- Also sensitive to energy redistribution
  - Collisions, induced radiations.
  - Collective excitations.

Useful for studying the modified HF fragmentation.