Heavy-flavor Jet in QGP from Partonic Transport

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Experiments at the LHC and sPHENIX make possible the study of HF-tagged jets in \(AA\) hadrons & decay products

Projected high-accuracy nuclear modification of \(h^\pm/D/B\) and jets/b-jets.
What can we achieve with both HF-hadron & HF-jet quenching?

Charm & bottom at not too large $p_T$

- Collisional processes.
- Suppressed radiations from not only dead-cone effects, but also kinematics.
- Hadronization via fragmentation and coalescence.

*Need all ingredients to study the modifications.*

Modifications of heavy-quark jets:

- The same partonic interactions.
- *Less sensitive to hadronization model.*
- *More sensitive to $Q$ vs $g \rightarrow HF.*
- Medium excitations of a non-relativistic moving particle.
What do we want to calculate?

- Hadrons: $R_{AA}$, $v_n$ of $h^\pm$, $D$, $B$ (✓).

- Light and heavy-jets:
  - $R_{AA}$ (✓) and $v_n$ ⇒ use w/ hadron obs to study partonic transport & hadronization.
  - Radius dependence ⇒ how energy is recovered around massless/massive jet parton.

- Hadron-in-jet fragmentation / HF-jet correlation
  - $D_{h,\text{HF}}(z, p_T)$ to probe the medium-modified fragmentation.
  - HQ diffusion with jet reference.
Our model: parton shower + LIDO in-medium transport equations

- Pythia8 hard processes + shower down to scale $Q_0$.


- Vacuum shower + fragmentation (Pythia8) for partons escaping the QGP.
HQ jets from event generation in the vacuum

In Pythia8 simulation:

- HQ from LO hard collisions.
- HQ from Showers.

- $b$-jets at sPHENIX will be ideal to test $b \to b$-jets.
• **LO** $gg, q\bar{q} \rightarrow Q\bar{Q}$ and $Q$ from initial-state space-like evolution: almost instantaneously visible in the medium $\tau = 0^+$.  

• **Final-state** $g \rightarrow Q\bar{Q}$,  
  • Splitting happens with $Q > Q_0$ are initialized as $Q$ and $\bar{Q}$ in the medium at $\tau = \tau_{g \rightarrow Q\bar{Q}} \rightarrow independent heavy-quark transport in QGP (needs improvements at the LHC jet energy).  
  • Heavy flavor production from fragmentation outside the medium $\rightarrow gluon transport in the medium.
LIDO linearized partonic transport in a background QGP medium, assuming parton densities
\[ f_s(t, x, p) = e^{-p \cdot u(t, x)/T(t, x)} \]

\[ p \cdot \partial f_H(t, x, p) = p^0 \left\{ \underbrace{C_{nn} f_H}_{\text{collisional}} + \underbrace{C_{n(n+1)} f_H}_{\text{inelastic}} \right\} \]

- Medium-induced jet parton branching.
  - Including approximate implementation of medium-induced \( Q \rightarrow Qg, g \rightarrow Q\bar{Q} \)
- Jet induced splitting of medium partons & semi-hard recoil.
Inelastic processes in the LIDO transport model

In the CoM frame of the jet & medium partons \((E_J = E_M \sim \sqrt{E_T})\)

\[
\int_{k,q,p'} \frac{d\sigma_{23}}{dzd^2k^2d^2q} f_s(p') \left[ f_H\left(\frac{x}{z}, p + k - q\right) - f_H(x, p) \right] \frac{dz}{z} \Theta(y_{cm}) + \frac{d\sigma_{23}}{dzd^2k^2d^2q} f_H(p) f_s(x/z, p' + k + q) \frac{dz}{z} \Theta(-y_{cm})
\]

\[\nabla\] 17 incoherent \(2 \rightarrow 3\) cross-sections with \(t\)-channel gluon exchange.

jet parton \((y_{cm} > 0)\) splittings

medium parton \((y_{cm} < 0)\) splittings

Back to QGP frame

- \(E_J \gg 3T\), LPM suppression by dynamically suppressing the rate with \(\frac{\lambda_{mfp}}{\tau_f(t)}\), \(\tau_f(t) = \frac{2x(1-x)E}{k_{\perp}(t) + m_{\text{eff}}^2}\)
- \(E_M \sim 3T\), medium splitting is still treated as incoherent processes.
LIDO simulated induced $g \rightarrow gg$ spectra in a brick

Theory references from the method introduced in [S. Caron-Huot, C. Gale PRC82(2010)064902 modified collinear splitting, resumming multiple collisions.]

\[
\frac{d\Gamma_{bc}^{a}(t)}{dk} = \frac{P_{bc}^{a(0)}(x)}{\pi p} \times \text{Re} \int_{0}^{t} dt_1 \int_{q,p} \frac{iq \cdot p}{\delta E(q)} C(t) K(t, q; t_1, p). 
\]

In an expanding medium $T \propto 1/\tau^{1/3}$

Theory points from same method but with $T = T(\tau)$. 
Mass effects in parton splittings

In the vacuum\(^1\)

\[
\frac{dN_{QQ}}{dxdk_\perp^2} = \frac{\alpha_s C_F}{2\pi} \frac{1}{k_\perp^2 + x^2 M^2} \left[ \frac{1 + (1 - x)^2}{x} - \frac{2x(1 - x)M^2}{k_\perp^2 + x^2 M^2} \right], \quad \frac{dN_{gQ}}{dxdk_\perp^2} = \frac{\alpha_s T_R}{2\pi} \frac{1}{k_\perp^2 + M^2} \left[ x^2 + (1 - x)^2 + \frac{2x(1 - x)M^2}{k_\perp^2 + M^2} \right]
\]

In the medium, e.g.,

\[
\frac{dN_{QQ}}{dxdk_\perp^2} = \frac{\alpha_s}{k_\perp^2} P(x) F(k_\perp^2, x^2 M^2) + \alpha_s M^2 G(k_\perp^2, x^2 M^2).
\]

- Massive kinematics and propagator (e.g., dead-cone of $Q \rightarrow Qg$). Approximately implemented in the transport equation \(\left( \frac{k_\perp^2(t)}{k_\perp^2(t)^2 + x^2 M^2} \right)^2\).
- New terms \(\langle \uparrow \downarrow \rangle \propto M^2\) (harder to implement in LIDO).

\(^1\)Pythia implements different forms NPB603(2001)297–34, e.g., matrix-element approach for $Q \rightarrow Qg$. 
Heavy-flavor channels in LIDO: $Q \rightarrow Qg$, $g \rightarrow Q\bar{Q}$

- Energy loss from $Q \rightarrow Qg$ channel.
- Term $\propto x^3 M^2$ is not included. But they are less important for energy loss.

- Simulation of medium-induced jet $g \rightarrow Q\bar{Q}$ in LIDO \n
- Theory reference (dashed lines)

\[ d\Gamma_{bc}^{q}(t) = \frac{P_{bc}^{q}(t)}{\pi p} \times \text{Re} \int_{0}^{t} dt_{1} \int_{E^{-}}^{E^{+}} \frac{iq \cdot p}{\delta E(q)} C(t) K(t, q; t_{1}, p). \]

\[ \text{e.g., } \frac{(x^2 + (1-x)^2) q \cdot p}{\delta E(q, m)} + \frac{m^2}{\delta E(q, m)}. \]
Charm quarks from medium excitations?

Another possibility of modifying charm production associated to jets propagating in the QGP:

The splitting of a medium gluon to $c + \bar{c}$ under a “hard kick” from the jet parton.

- Produce low-$p_T$/large-angle HF associate to jets.
- A new type of medium excitation that produces charm!
Consistent description of jet & (HF)hadron quenching?

Apply same set of $g_s(k_\perp, \mu_{\text{med}})$ and other parameters to calculate $R_{AA}^{h,\text{jet}}$ and $R_{AA}^{D,B}$

- With the same jet-medium coupling, LIDO overestimates flavor separations of $R_{AA}$ (coupling fit for hadron/jet suppression is smaller than previously fitted with open HF).
- Low-$p_T$ open HF, sensitivity to the precise hadronization processes.
- Intermediate $p_T$, how much HF come from $g \rightarrow$HF?
HF-jet quenching (preliminary) vs latest measurements

LIDO over-predicts the separation of $R_{A_A}^{b-jet}$ vs $R_{A_A}^{jet}$ (ATLAS [2204.13530], $p_T > 80$ GeV).

LIDO under-estimates the separation of $R_{A_A}^{D-jet}$ vs $R_{A_A}^{jet}$ ($p_T < 50$ GeV). [ALICE: ALI-PREL-506530, JHEP01(2022)174]

- Probe energy loss with less impact from hadronization models.
- Need more precise control of $g \rightarrow$ HF contribution as function of $p_T$. 
Flavor hierarchy of jet quenching at RHIC & LHC

- A clear flavor dependent jet quenching, but not all addressed by dead cone effects.
- Again, need to simultaneously fix $Q, g \rightarrow$ HF contribution.

[PoS(HardProbes2020)060 / 2008.07622, no $p_T$ cuts on $D, B$ in this calculation]
This is sensitive to HF fragmentation function.

Fairly hard HF-in-jet FF At "low" $p_T^{\text{jet}}$ jet. Would be interesting to push to lower $p_T^{\text{jet}}$ at sPHENIX.
HF-in-jet fragmentation function (central Pb-Pb@5.02 TeV)

- This is sensitive to HF fragmentation function.
- Fairly hard HF-in-jet FF At "low" $p_T^{jet}$ jet. Would be interesting to push to lower $p_T^{jet}$ at sPHENIX.
- At high-$p_T^{jet}$, $g \rightarrow$HF leads to a softened FF.
- Induced charm production impacts low-$z$.

Difference of induced charm production (from both jet and medium splittings).
Jet cone size dependence at sPHENIX

- Inclusive-jet $R_{AA}$: weak $R$ dependence.
- $b$-jet $R_{AA}$ ($b \rightarrow b$ jets are shown), almost independent of $0.2 < R < 0.6$ from simulations.
- Looking forward to precise $R$-dependence of inclusive vs $b$-jets from sPHENIX.
Summary

- Heavy-flavor jets have already become accessible in heavy-ion collision experiments.
  - Probing flavor dependent parton energy loss with less impact from hadronization.
  - Opportunity to constrain $g, Q \rightarrow$ HF contributions in AA.
- HF jets from Pythia8 + LIDO simulations for sPHENIX
  - Expect huge difference between inclusive and $b$-jet quenching.
  - Weak $R$ dependence of $b$-jet $R_{AA}$.
- From sPHENIX & LHC experiments:
  - sPHENIX $b$-jet samples are ideal to constrain $b \rightarrow b$ jets.
  - At higher jet $p_T$, $g$ HF jets and search for $c\bar{c}$ from medium excitation.
Associated charm production around the jet

Jet-HF radial correlation profile [CMS: JHEP05, 006(2018)]

- High $p_T^D$: energy loss of heavy quarks relative to jet momentum.
- Low $p_T^D$ around high-$p_T$ jets, HQ diffusion & extra charm production from jet-induced medium excitation?
The jet transport parameter in LIDO contains contributions from both small & large-\(q\) contribution

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

\(\hat{q}_s = \kappa_{s,xx} + \kappa_{s,yy}\)

\(\alpha_s = \alpha_s(\max\{q_\perp^2, \mu_{\text{med}}^2\})\)

The running coupling in the medium is assumed to be

\[
\alpha_s(q) = \frac{4\pi}{\beta_0} \ln \frac{1}{\max\{\mu_{\text{med}}^2, q^2\}}, \quad \mu_{\text{med}} \propto T \text{ is a tunable parameter.}
\]
• 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 (no transverse flow)
  \[
  \frac{de}{d\Omega_{k'}} = \frac{\delta p^0 + \hat{k}' \cdot \delta \vec{p}/c_s}{4\pi}, \quad \frac{d\vec{p}}{d\Omega_{k'}} = \frac{3(c_s \delta p^0 + \hat{k}' \cdot \delta \vec{p})\hat{k}'}{4\pi}.
  \]
  Requires \( R_{\text{response}} \gg r_{\text{energy loss}}. \)

• Freeze-out to massless particles under a radial transverse flow \( v_\perp \Rightarrow \) corrects the momentum density in \( \eta-\phi \) plane.
  \[
  \frac{d\Delta p_T}{d\phi d\eta} = \int \frac{3}{4\pi} \frac{\sigma u^\mu - \hat{p}^\mu}{\sigma^4} \delta p^\mu(\hat{k}) \frac{d\Omega_{\hat{k}}}{4\pi}
  \]
  \[
  \sigma = \gamma_\perp \left[ \cosh(\eta - \eta_s - \eta_{\hat{k}}) - v_\perp \cos(\phi - \phi_{\hat{k}}) \right]
  \]
Model calibration w/ hadron & jet $R_{AA}$ in central Au-Au & Pb-Pb [JHEP05(2021)041]

- $0.7\pi T < \mu_{\text{med}} < 4\pi T$: goes into the coupling in $m_D$, $d\sigma_{qg}$, $d\sigma_{qq}$, and radiation.

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

- $0.5 < Q_0 < 2.0$ GeV: initialization scales, vary **independently** at RHIC and LHC.

- $0.15 < T_f < 0.17$ GeV: “confinement” temperature for jet quenching.

Individual parameters, note $Q_{0, \text{LHC}} > Q_{0, \text{RHIC}}$. Consistent with $\Delta p_T^2$ in fast-expanding medium.

<table>
<thead>
<tr>
<th>Systems</th>
<th>AA 5 TeV</th>
<th>AA 0.2 TeV</th>
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<tr>
<td>$0-5%$</td>
<td>0.46</td>
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$5t_0 T_0^3 [\text{GeV}^2]$
Experimental data used in the model calibration

- $\pi^0$ in 0-10% Au-Au@200 GeV [PHENIX PRC 87(2013)034911].
- $h^{\pm}$ in 0-10% Pb-Pb@5.02 TeV [CMS JHEP04(2017)039].
- $D$ in 0-10% Pb-Pb@5.02 TeV [CMS PLB287(2018)474-496].
- $R = 0.4$ charged jets in 0-10% Au-Au@200 GeV [STAR PRC102(2020)054913].
- $R = 0.4$ jets in 0-10% Pb-Pb@5.02 TeV [ALICE PRC101(2020)034911; ATLAS PLB 790(2019)108-128].
Knowledge in the hadron(HF)-in-jet fragmentation function

- The HF-in-jet FF is a mixture of $Q \to HF$, $g \to HF$, $q \to HF$, weighted by the partonic cross-section.

One can extract $c, b, g, q \to D$ FF in the vacuum, using the hadron-in-jet data [DP Anderle et al PRD96(2017)034028].

- Can we use similar information $AA$ to extract in-medium $Q, g, q \to D, B$ fragmentation functions?
For example, for the channel $g \rightarrow Q + \bar{Q}$

\[
\frac{dN_{\text{coll}}}{d\Delta z} = \int d^{2}q_{1} d^{2}q_{2} \left\{ q^{2} + (1 - s)^{2} \right\} \frac{1}{\lambda_{1}(z)} \frac{1}{\lambda_{2}(z)} \int d^{2}q_{3} \frac{1}{\sigma_{dd}} \frac{1}{d^{2}q_{L}} \left[ \delta_{3-L}^{\text{min}} - \frac{a_{N}}{2\pi^{2}} \int d^{2}q_{4} \right] + \ldots \right\}.
\]

$[\text{Opacity } N = 1 \text{ from } SCET_{G}, \text{ Kang, Ringer, Vitev JHEP1703(2017)146}]$ $[\text{Multiple-soft region from the BDMPS-Z formula, Attems et al, 2203.11241}]$