Heavy-flavor Jet in QGP from Partonic Transport

RBRC Workshop: Predictions for sPHENIX
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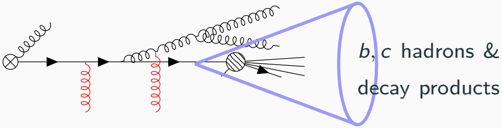
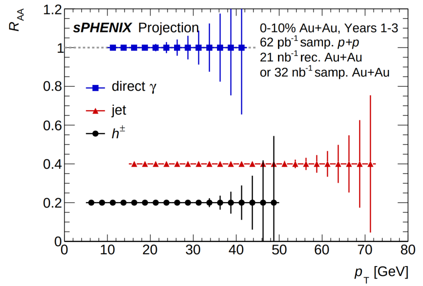
Heavy flavor and HF-jets capability at sPHENIX

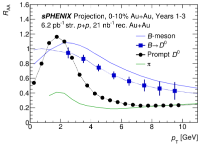
Experiments at the LHC and sPHENIX make possible the study of HF-tagged jets in *AA*

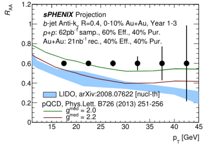


b, *c* hadrons & decay products

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:

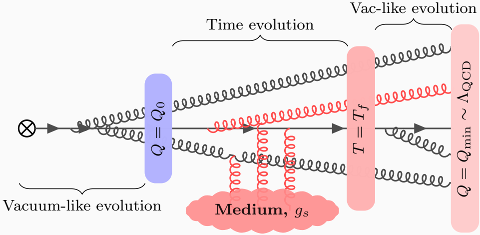
- The same partonic interactions.
- *Less sensitive to hadronization model.*
- *More sensitive to Q vs $g \to$ HF.*
- Medium excitations of a non-relativistic moving particle.

What do we want to calculate?

- Hadrons: R_{AA}, v_n of $h^{\pm}, D, B$ (✓).
- Light and heavy-jets:
  - R_{AA} (✓) and $v_n \Rightarrow$ use w/ hadron obs to study partonic transport & hadronization.
  - Radius dependence $\Rightarrow$ how energy is recovered around massless/massive jet parton.
- Hadron-in-jet fragmentation / HF-jet correlation
  - $D_{h,\mathrm{HF}}(z, p_T)$ to probe the medium-modified fragmentation.
  - HQ diffusion with jet reference.

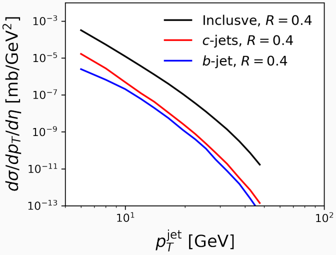
Our model: parton shower + LIDO in-medium transport equations

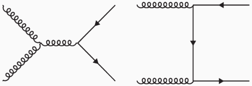
- Pythia8 hard processes + shower down to scale Q_0.



- Partonic transport [LIDO: PRC100(2019)064911, JHEP05(2021)041] for $Q < Q_0$ & $T > T_f$.
- Vacuum shower + fragmentation (Pythia8) for partons escaping the QGP.

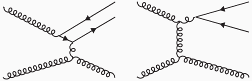
HQ jets from event generation in the vacuum





(a) s-channel Flavor Creation

(b) t-channel Flavor Creation



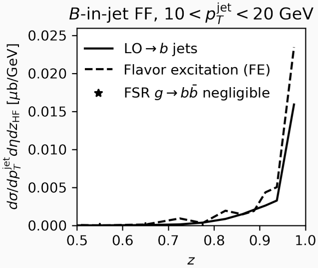
(c) Flavor Excitation

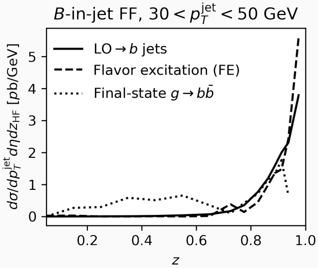
(d) Gluon Splitting

[PRD 99(2019)072003]

In Pythia8 simulation:

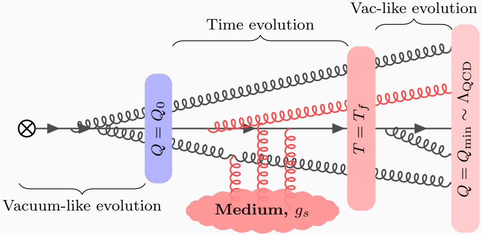
- ◁ HQ from LO hard collisions.
- ◁ HQ from Showers.





- b-jets at sPHENIX will be ideal to test $b \to b$-jets.

Timescales of HQ production in the Pythia8+LIDO simulation



- LO $gg, q\bar{q} \to Q\bar{Q}$ and Q from initial-state space-like evolution: almost instantaneously visuable in the medium $\tau = 0^+$.
- Final-state $g \to Q\bar{Q}$,
  - Splitting happens with $Q > Q_0$ are initialized as Q and $\bar{Q}$ in the medium at $\tau = \tau_f^{g\to Q\bar{Q}}$ → independent heavy-quark transport in QGP (needs improvements at the LHC jet energy).
  - Heavy flavor production from fragmentation outside the medium → gluon transport in the medium.

HF & jets in the LIDO partonic transport description

LIDO linearized partonic transport in a background QGP medium, assuming parton densities $f_s(t,x,p) = e^{-p\cdot u(t,x)/T(t,x)}$.

$$p \cdot \partial f_H(t,x,p) = p^0 \left\{ \underbrace{\mathcal{C}_{nn} f_H}_{\textit{collisional}} + \underbrace{\mathcal{C}_{n(n+1)} f_H}_{\textit{inelastic}} \right\}$$

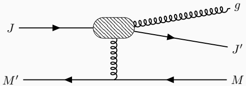
- Medium-induced jet parton branching.
  - $\star$ Including approximate implementation of medium-induced $Q \to Qg, g \to Q\bar{Q}$
- Jet induced splitting of medium partons & semi-hard recoil.

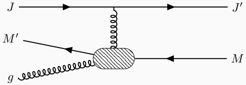
Inelastic processes in the LIDO transport model

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

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

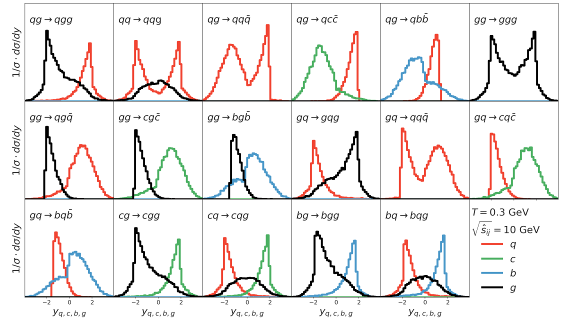
jet parton ($y_{\rm cm}>0$) splittings





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

▽ 17 incoherent $2 \to 3$ cross-sections with t-channel gluon exchange.

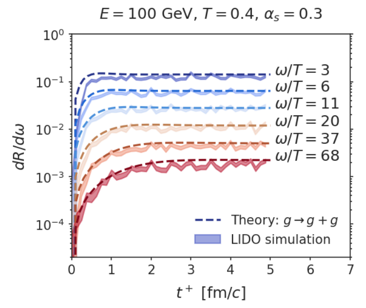


Back to QGP frame

- $E_J \gg 3T$, LPM suppression by dynamically suppressing the rate with $\frac{\lambda_{\rm mfp}}{\tau_f(t)}$, $\tau_f(t) = \frac{2x(1-x)E}{\mathbf{k}_\perp^2(t)+m_{\rm eff}^2}$
- $E_M \sim 3T$, medium splitting is still treated as incoherent processes.

Medium-induced light-flavor splitting tested in brick & expanding media.

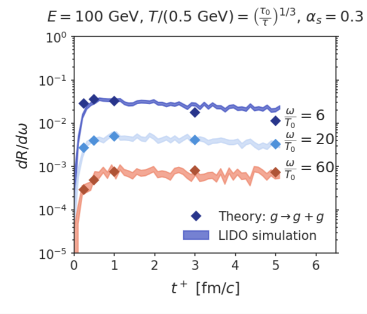
LIDO simulated induced $g \to gg$ spectra in a brick



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

$$\frac{d\Gamma^a_{bc}(t)}{dk} \equiv \frac{P^{a(0)}_{bc}(x)}{\pi p} \times \mathrm{Re}\int_0^t dt_1 \int_{\mathbf{q},\mathbf{p}} \frac{i\mathbf{q}\cdot\mathbf{p}}{\delta E(\mathbf{q})}\mathcal{C}(t)K(t,\mathbf{q};t_1,\mathbf{p}).$$

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]

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

In the medium, e.g., $\frac{dN_{QQ}}{dxd\mathbf{k}_\perp^2} = \frac{\alpha_s}{\mathbf{k}_\perp^2}P(x)F(\mathbf{k}_\perp^2, x^2M^2) + \alpha_s M^2 G(\mathbf{k}_\perp^2, x^2M^2)$.

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

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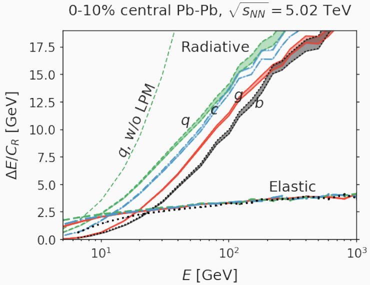
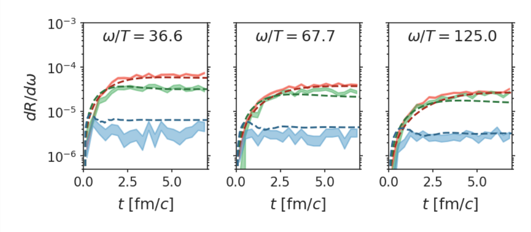
[1] Pythia implements different forms NPB603(2001)297–34, e.g., matrix-element approach for $Q \to Qg$.

Heavy-flavor channels in LIDO: $Q \to Qg$ $g \to Q\bar{Q}$



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



$g \to q\bar{q}$, $g \to c\bar{c}$, $g \to b\bar{b}$

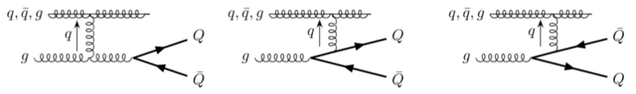
- Simulation of medium-induced jet $g \to Q\bar{Q}$ in LIDO ▽
- Theory reference (dashed lines)

$$\frac{d\Gamma^a_{bc}(t)}{dk} \equiv \frac{P^{a(0)}_{bc}(x)}{\pi p} \times \mathrm{Re} \int_0^t dt_1 \int_{\mathbf{q},\mathbf{p}} \frac{i\mathbf{q}\cdot\mathbf{p}}{\delta E(\mathbf{q})} \mathcal{C}(t) K(t, \mathbf{q}; t_1, \mathbf{p}).$$

e.g., $\frac{(x^2+(1-x)^2)\mathbf{q}\cdot\mathbf{p}}{\delta E(\mathbf{q},m)} + \frac{m^2}{\delta E(\mathbf{q},m)}$

Charm quarks from medium excitations?

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

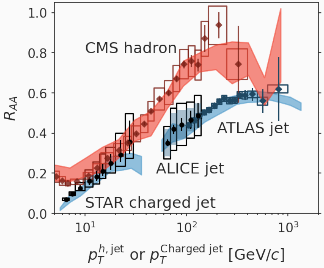


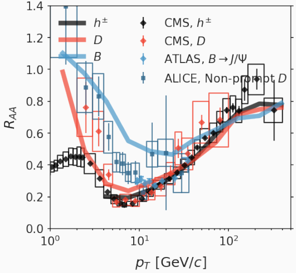
The splitting of a medium gluon to $c + \bar{c}$ under a "hard kick" from the jet parton.

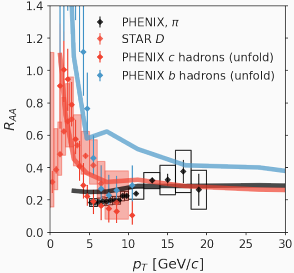
- Produce low-p_T/large-angle HF associate to jets.
- A new type of medium excitation that produces charm!

Consistent description of jet & (HF)hadron quenching?

▽ Apply same set of $g_s(\mathbf{k}_\perp, \mu_{\mathrm{med}})$ and other parameters to calculate $R_{AA}^{\mathrm{h,jet}}$ and $R_{AA}^{D,B}$





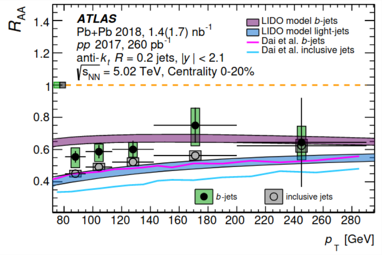


[ATLAS EPJC78(2018)9 762; CMS PLB782(2018)474, JHEP04(2017)039; ALICE 2202.00815; PHENIX 2203.17058, PRC93(2016)034904 ; STAR PRC99(2019)034908.]

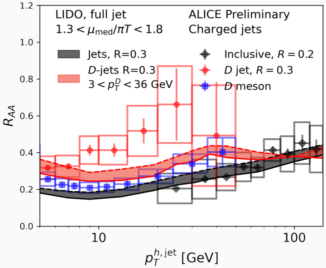
- With the same jet-medium coupling, LIDO overestimates flavor separations of R_{AA} (coupling fit for hadron/jet suppression is smaller than previously fitted with open HF).
- Low-p_T open HF, sensitivity to the precise hadronization processes.
- Intermediate p_T, how much HF come from $g \to$HF?

HF-jet quenching (preliminary) vs latest measurements

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

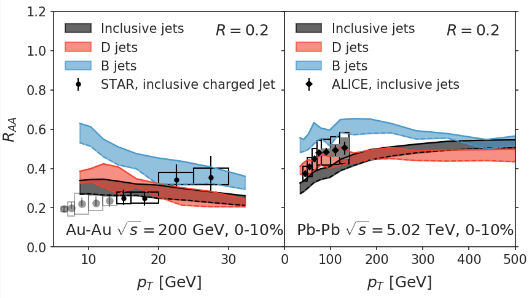


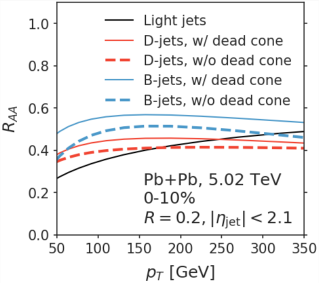
LIDO under-estimates the separation of $R_{AA}^{D\text{-jet}}$ vs R_{AA}^{jet} ($p_T < 50$ GeV). [ALICE: ALI-PREL-506530, JHEP01(2022)174]



- Probe energy loss with less impact from hadronization models.
- Need more precise control of $g \to$ HF contribution as function of p_T.

Flavor hierarchy of jet quenching at RHIC & LHC

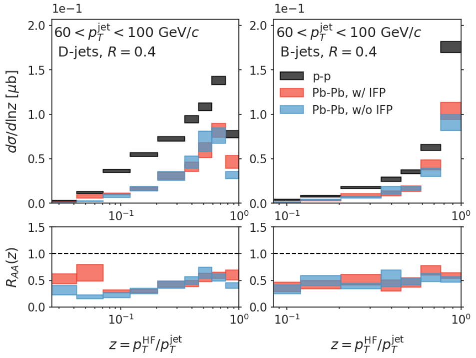




[PoS(HardProbes2020)060 / 2008.07622, no p_T cuts on D, B in this calculation]

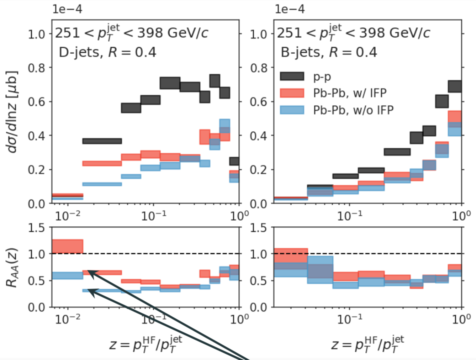
- A clear flavor dependent jet quenching, but not all addressed by dead cone effects.
- Again, need to simultaneously fix $Q, g \to$ HF contribution.

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" $p_T^{\rm jet}$ jet. Would be interesting to push to lower $p_T^{\rm jet}$ at sPHENIX.

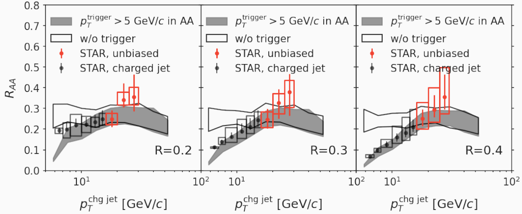
HF-in-jet fragmentation function (central Pb-Pb@5.02 TeV)



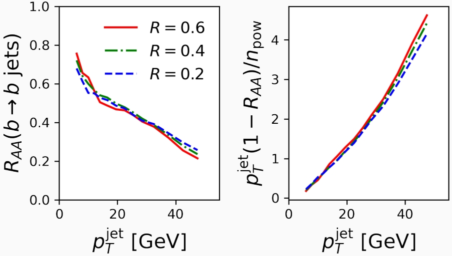
Difference of induced charm production (from both jet and medium splittings).

- 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}, $g \to$HF leads to a softened FF.
- Induced charm production impacts low-z.

Jet cone size dependence at sPHENIX



- Inclusive-jet R_{AA}: weak R dependence.



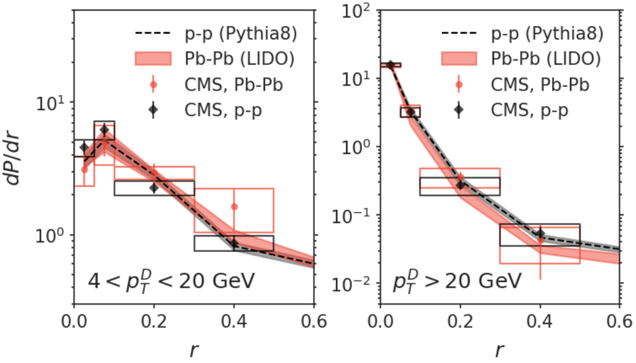
- b-jet R_{AA} ($b \to b$ jets are shown), almost independent of $0.2 < R < 0.6$ from simulations.
- Looking forward to precise R-dependence of inclusive vs b-jets from sPHENIX.

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.

Questions?

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?

Jet-medium coupling and the jet transport parameter in LIDO

The jet transport parameter in LIDO contains contributions from both small & large-q contribution

$$\hat{q}_F(T,p) = \underbrace{m_D^2 C_F T \alpha_s(\mu_{\mathrm{med}}) \ln \frac{Q_c^2}{m_D^2}}_{\hat{q}_s=\kappa_{s,xx}+\kappa_{s,yy}} + \underbrace{\int_{p'} f_s(p') \left\{ 2(N_c^2-1)\frac{d\sigma_{qg}}{d^2\mathbf{q}_\perp} + 4N_f N_c \frac{d\sigma_{qq}}{d^2\mathbf{q}_\perp} \right\} \Theta(\mathbf{q}_\perp^2 - Q_\mathrm{c}^2)\mathbf{q}_\perp^2 d^2\mathbf{q}_\perp}_{\alpha_s=\alpha_s(\max\{\mathbf{q}_\perp^2, \mu_{\mathrm{med}^2}\})}$$

The running coupling in the medium is assumed to be

$$\alpha_s(q) = \frac{4\pi}{\beta_0} \frac{1}{\ln \frac{\max\{\mu_{\mathrm{med}}^2, q^2\}}{\Lambda^2}}, \quad \mu_{\mathrm{med}} \propto T \text{ is a tunable parameter.}$$

For jet study: a simple model for medium excitation

- Energy-momentum deposition to soft sector:

$$\frac{d\delta p^\mu}{dt}(t,x) = \int_{\mathbf{p}} \Theta(p\cdot u < E_{\min})\, p^\mu \frac{d}{dt} f_H(t,x,p)$$

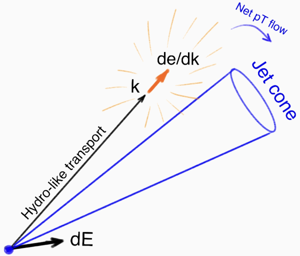
- An ideal-hydro response (no transverse flow)

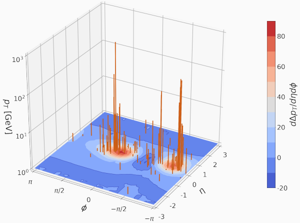
$$\frac{de}{d\Omega_{k'}} = \frac{\delta p^0 + \hat{k}'\cdot\delta\vec{p}/c_s}{4\pi}, \qquad \frac{d\vec{p}}{d\Omega_{k'}} = \frac{3(c_s\delta p^0 + \hat{k}'\cdot\delta\vec{p})\hat{k}'}{4\pi}.$$

  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 η-ϕ plane.

$$\begin{aligned}\frac{d\Delta p_T}{d\phi d\eta} &= \int \frac{3}{4\pi}\frac{\frac{4}{3}\sigma u_\mu - \hat{p}_\mu}{\sigma^4}\delta p^\mu(\hat{k})\frac{d\Omega_{\hat{k}}}{4\pi} \\ \sigma &= \gamma_\perp\left[\cosh(\eta-\eta_s-\eta_{\hat{k}}) - v_\perp\cos(\phi-\phi_{\hat{k}})\right]\end{aligned}$$



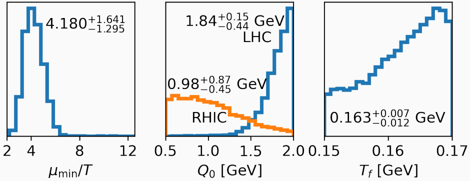


Model calibration w/ hadron & jet R_{AA} in central Au-Au & Pb-Pb [JHEP05(2021)041]

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

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

- $0.5 < Q_0 < 2.0$ GeV: initialization scales, vary **independently** at RHIC and LHC.
- $0.15 < T_f < 0.17$ GeV: “confinement” temperature for jet quenching.



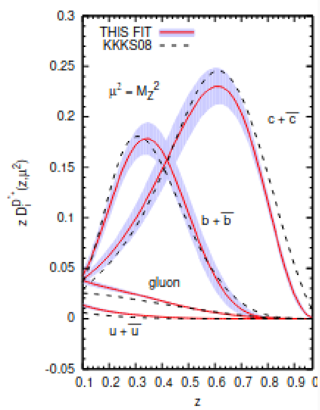
Individual parameters, note $Q_0^{\rm LHC} > Q_0^{\rm RHIC}$.
Consistent with Δp_T^2 in fast-expanding medium

Systems	*AA* 5 TeV		*AA* 0.2 TeV
	0-5%	40-50%	0-5%
$5 t_0 T_0^3$ [GeV^2]	1.1	0.55	0.46

Experimental data used in the model calibration

- π^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



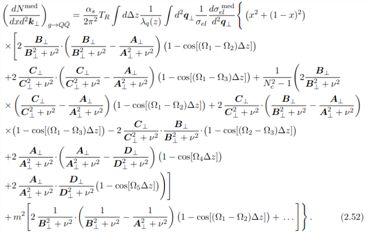
- The HF-in-jet FF is a mixture of $Q \to$ HF, $g \to$ HF, $q \to$ HF, weighted by the partonic cross-section.

◁ 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?

Frame Title

- For example, for the channel $g \to Q + \bar{Q}$



$$\begin{aligned}
\left(\frac{dN^{\text{med}}}{dxd^2\boldsymbol{k}_\perp}\right)_{g\to Q\bar{Q}} &= \frac{\alpha_s}{2\pi^2}T_R\int d\Delta z\frac{1}{\lambda_q(z)}\int d^2\boldsymbol{q}_\perp\frac{1}{\sigma_{el}}\frac{d\sigma_{el}^{\text{med}}}{d^2\boldsymbol{q}_\perp}\Bigg\{\left(x^2+(1-x)^2\right)\\
&\times\Bigg[2\,\frac{\boldsymbol{B}_\perp}{\boldsymbol{B}_\perp^2+\nu^2}\cdot\left(\frac{\boldsymbol{B}_\perp}{\boldsymbol{B}_\perp^2+\nu^2}-\frac{\boldsymbol{A}_\perp}{\boldsymbol{A}_\perp^2+\nu^2}\right)\left(1-\cos[(\Omega_1-\Omega_2)\Delta z]\right)\\
&+2\,\frac{\boldsymbol{C}_\perp}{\boldsymbol{C}_\perp^2+\nu^2}\cdot\left(\frac{\boldsymbol{C}_\perp}{\boldsymbol{C}_\perp^2+\nu^2}-\frac{\boldsymbol{A}_\perp}{\boldsymbol{A}_\perp^2+\nu^2}\right)\left(1-\cos[(\Omega_1-\Omega_3)\Delta z]\right)+\frac{1}{N_c^2-1}\Bigg(2\frac{\boldsymbol{B}_\perp}{\boldsymbol{B}_\perp^2+\nu^2}\\
&\times\left(\frac{\boldsymbol{C}_\perp}{\boldsymbol{C}_\perp^2+\nu^2}-\frac{\boldsymbol{A}_\perp}{\boldsymbol{A}_\perp^2+\nu^2}\right)\left(1-\cos[(\Omega_1-\Omega_2)\Delta z]\right)+2\,\frac{\boldsymbol{C}_\perp}{\boldsymbol{C}_\perp^2+\nu^2}\cdot\left(\frac{\boldsymbol{B}_\perp}{\boldsymbol{B}_\perp^2+\nu^2}-\frac{\boldsymbol{A}_\perp}{\boldsymbol{A}_\perp^2+\nu^2}\right)\\
&\times\left(1-\cos[(\Omega_1-\Omega_3)\Delta z]\right)-2\,\frac{\boldsymbol{C}_\perp}{\boldsymbol{C}_\perp^2+\nu^2}\cdot\frac{\boldsymbol{B}_\perp}{\boldsymbol{B}_\perp^2+\nu^2}\cdot\left(1-\cos[(\Omega_2-\Omega_3)\Delta z]\right)\\
&+2\,\frac{\boldsymbol{A}_\perp}{\boldsymbol{A}_\perp^2+\nu^2}\cdot\left(\frac{\boldsymbol{A}_\perp}{\boldsymbol{A}_\perp^2+\nu^2}-\frac{\boldsymbol{D}_\perp}{\boldsymbol{D}_\perp^2+\nu^2}\right)\left(1-\cos[\Omega_4\Delta z]\right)\\
&+2\,\frac{\boldsymbol{A}_\perp}{\boldsymbol{A}_\perp^2+\nu^2}\cdot\frac{\boldsymbol{D}_\perp}{\boldsymbol{D}_\perp^2+\nu^2}\left(1-\cos[\Omega_5\Delta z]\right)\Bigg)\Bigg]\\
&+m^2\left[2\,\frac{1}{\boldsymbol{B}_\perp^2+\nu^2}\cdot\left(\frac{1}{\boldsymbol{B}_\perp^2+\nu^2}-\frac{1}{\boldsymbol{A}_\perp^2+\nu^2}\right)\left(1-\cos[(\Omega_1-\Omega_2)\Delta z]\right)+\ \ldots\right]\Bigg\}. \qquad (2.52)
\end{aligned}$$

[Opacity $N = 1$ from $SCET_{\mathrm{G}}$, Kang, Ringer, Vitev JHEP1703(2017)146]

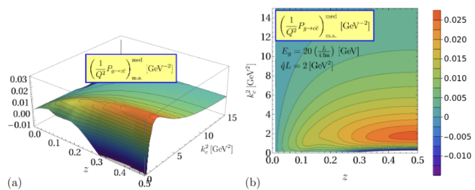


Figure 6. The medium-modified $g \to c\bar{c}$ splitting function evaluated in the saddle point approximation (4.9)-(4.12). The two panels show different representations of the same calculation.

[Multiple-soft region from the BDMPS-Z formula, Attems et al, 2203.11241]