Heavy-flavor production in dense QCD matter

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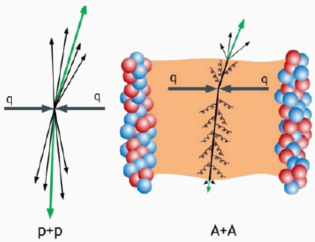
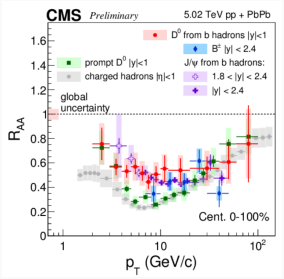
Heavy flavor production in p-p and A-A





$$R_{AA} = \frac{dN_{AA\to h}/dp_T}{\langle T_{AA}\rangle d\sigma_{pp\to h}/dp_T}$$

- Factorized formula for charm & bottom meson production

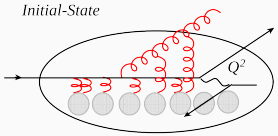
$$d\sigma_{pp\to h} = f_{i/p}(x_i, Q) f_{j/p}(x_j, Q) \otimes d\hat{\sigma}_{ij\to k} \otimes D_{h/k}(z, \mu_F)$$

- In A-A, QCD medium introduces additional scales
  - Cold nuclear matter (CNM): $\Delta k_T^2 \sim \Lambda^2(A^{1/3} - 1)$.
  - Quark-gluon plasma (QGP): $T, \mu_D \sim g_s T$.
- Modified heavy-flavor production in A-A
  - Initial states: $f_{i/p} f_{j/p} \longrightarrow f_{i/A} f_{j/B}(x; \Delta k_T^2, \cdots)$.
  - Final states: $D(z) \longrightarrow D_{\mathrm{med}}(z; T \cdots)$.
- Mass is additional handle to probe medium properties.

A study of light & heavy with both IS and FS effects.

Initial-state effects I: multiple collisions

In p-A collisions ▽

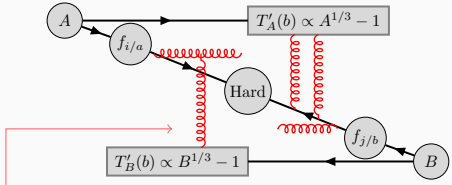


- Multiple collisions lead to transverse momentum broadening (Cronin effect)

$$\langle \mathrm{k}_\perp^2 \rangle = 2\mu^2 \xi \frac{L}{\lambda_{q,g}}$$

$$\mu^2 = 0.12\ \mathrm{GeV}^2,\ 1.0 < \lambda_g < 1.5\ \mathrm{fm}.$$

Generalization to A-A collisions ▽



Multiple collision broadening and power corrections

- Power corrections from coherent multiple collisions (dynamical shadowing) [J.-W. Qiu, I. Vitev, PLB632 507-511], effectively shift parton momentum fractions by

$$\frac{\delta x_a}{x_a} \propto \frac{\langle \mathrm{k}_\perp^2 \rangle_B}{-u}, \qquad \frac{\delta x_b}{x_b} \propto \frac{\langle \mathrm{k}_\perp^2 \rangle_A}{-t}$$

$$f(x,\mu) \to f(x+\delta x,\mu)\frac{1}{\pi} e^{-\mathrm{k}_\perp^2/\langle \mathrm{k}_\perp^2 \rangle}$$

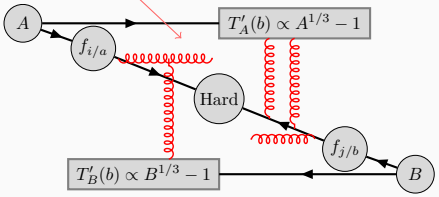
Initial-state effects II: radiative energy loss in the CNM

Energy loss from medium-induced initial-state soft gluon emissions [I. Vitev, PRC75(2007)064906]

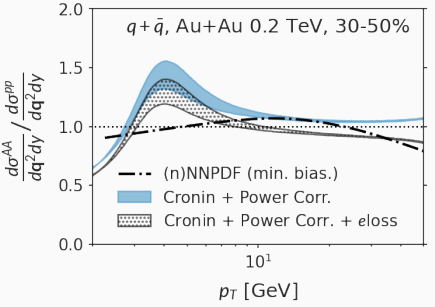
$$\frac{\Delta x_a}{x_a} \approx \frac{L_B}{\lambda_g}\int_{m_N/p^+}^{1} dx \int_{(xm_N)^2}^{(xp^+)^2} d\mathrm{k}_\perp^2 \frac{\alpha_s C_R}{\pi} \int_0^{\frac{\mu p^+}{4}} d^2\mathrm{q}_\perp \frac{\mu^2}{\pi(\mathrm{q}_\perp^2+\mu^2)^2}\left[\frac{\mathrm{q}_\perp^2}{\mathrm{k}_\perp^2(\mathrm{k}_\perp-\mathrm{q}_\perp)^2} - \frac{2(\mathrm{q}_\perp^2-\mathrm{q}_\perp\cdot\mathrm{k}_\perp)}{\mathrm{k}_\perp^2(\mathrm{k}_\perp-\mathrm{q}_\perp)^2}\frac{\sin\frac{\mathrm{k}_\perp^2 L_B}{xp^+}}{\frac{\mathrm{k}_\perp^2 L_B}{xp^+}}\right]$$

Broadening + power corr.+ eloss: $f(x,\mu) \to f(x+\delta x+\Delta x,\mu)\frac{1}{\pi}e^{-\mathrm{k}_\perp^2/\langle \mathrm{k}_\perp^2\rangle}$

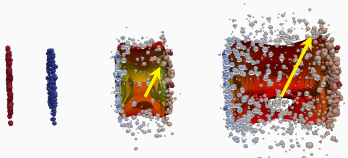
Induced radiation



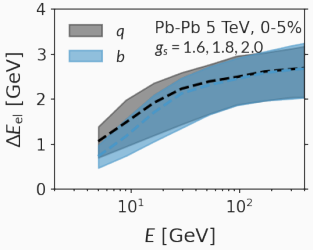
▽ Dynamical approach [Z.-B. Kang et al. PLB718(2012)482-487]
v.s. nNNPDF [R. A. Khalek et al. (nNNPDF3.0) 2201.12363.]



Final-state effects I: elastic energy loss in the quark-gluon plasma



Hydrodynamic-based simulation of QGP provides temperature profiles $T(\tau, x, y)$ [H. Song, U. Heinz, PRC77(2008)064901; J. E. Bernhard, 1804.06469;]



- HTL collisional energy loss of hard parton [E. Braaten, M. H. Thoma PRD44(1991)R2625(R).] :

$$\Delta E_{\rm el} = \int_{x_0}^{x_0+\hat{n}\Delta z} d\Delta z \frac{C_R}{4}\mu_D^2\alpha_s(ET)\ln\left(\frac{ET}{\mu_D^2}\right)\left(\frac{1}{v} - \frac{1-v^2}{2v^2}\ln\frac{1+v}{1-v}\right)$$

Screening (Debye) mass in the QGP: $\mu_D = \sqrt{1+\frac{N_f}{6}}g_s T$.

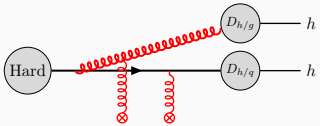
- As an approximation, we use an event-averaged $\langle \Delta E_{\rm el}\rangle$ to shift the final-state parton momentum in the perturbative cross-section (NLO)

$$d\sigma_{AA\to h} = f_{i/p}f_{j/p} \otimes d\hat{\sigma}_{ij\to k}(E + \langle \Delta E_{\rm el}\rangle) \otimes D_{h/k}(z, \mu_F)$$

Medium-modified splitting functions from SCET$_G$

- SCET$_G$: SCET Lagrangian coupled to background Glauber gluon of the medium[G. Ovanesyan, I. Vitev, JHEP06(2011)080]

$$\mathcal{L}_{\rm SCET}(\xi_n, A_n) + \mathcal{L}_G(\xi_n, A_n, A_G)$$
$$\mathcal{L}_G = e^{-i(p-p')x}\left[\bar{\xi}_n \Gamma^{\mu,c}_{qqG}\xi_n - i\Gamma^{\mu\alpha\beta,cab}_{ggG} A^a_{n,\alpha} A^b_{n,\beta}\right] A^c_{G,\mu}(x)$$



- Background A_G is a superposition of the color field generate by medium sources,

$$A^{\mu,a}(x) \quad = \quad \sum_i g_s \int e^{-iq(x-y)} \frac{g^{\mu\nu} + \cdots}{q^2 - \mu_D^2} J^a_{\nu,i}(y) dy^4, \quad q \sim (\lambda^2, \lambda^2, \vec{\lambda})$$

- Here source is assumed to be static ($J^i = 0, J^0 \neq 0$), with the local densities $\langle J^0(x)\rangle = \frac{d_{q,g}}{e^{p\cdot u(x)/T(x)} \pm 1}$ for quarks and gluons

Medium-modified splitting functions from SCET$_G$

- Medium-modified splitting functions for heavy quark [Kang, Ringer, Vitev, JHEP03(2017)146] :

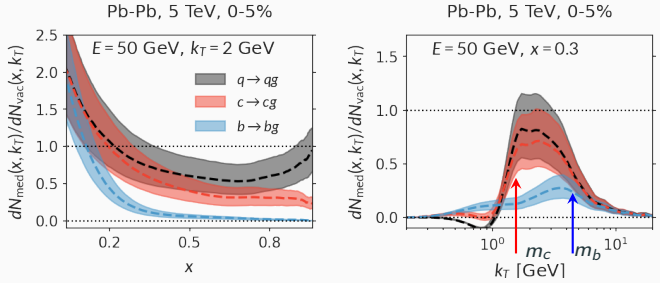
▽ ΔP_{QQ} ΔP_{Qg} ▷

$$\left(\frac{dN^{\rm med}}{dxd^2\boldsymbol{k}_\perp}\right)_{Q\to Qg} = \frac{\alpha_s}{2\pi^2}C_F\int\frac{d\Delta z}{\lambda_g(z)}\int d^2\boldsymbol{q}_\perp\frac{1}{\sigma_{el}}\frac{d\sigma_{el}^{\rm med}}{d^2\boldsymbol{q}_\perp}\left\{\left(\frac{1+(1-x)^2}{x}\right)\left[\frac{\boldsymbol{B}_\perp}{\boldsymbol{B}_\perp^2+\nu^2}\right.\right.$$
$$\times\left(\frac{\boldsymbol{B}_\perp}{\boldsymbol{B}_\perp^2+\nu^2}-\frac{\boldsymbol{C}_\perp}{\boldsymbol{C}_\perp^2+\nu^2}\right)(1-\cos[(\Omega_1-\Omega_2)\Delta z])+\frac{\boldsymbol{C}_\perp}{\boldsymbol{C}_\perp^2+\nu^2}\cdot\left(2\frac{\boldsymbol{C}_\perp}{\boldsymbol{C}_\perp^2+\nu^2}-\frac{\boldsymbol{A}_\perp}{\boldsymbol{A}_\perp^2+\nu^2}\right.$$
$$\left.-\frac{\boldsymbol{B}_\perp}{\boldsymbol{B}_\perp^2+\nu^2}\right)(1-\cos[(\Omega_1-\Omega_3)\Delta z])+\frac{\boldsymbol{B}_\perp}{\boldsymbol{B}_\perp^2+\nu^2}\cdot\frac{\boldsymbol{C}_\perp}{\boldsymbol{C}_\perp^2+\nu^2}(1-\cos[(\Omega_2-\Omega_3)\Delta z])$$
$$+\frac{\boldsymbol{A}_\perp}{\boldsymbol{A}_\perp^2+\nu^2}\cdot\left(\frac{\boldsymbol{D}_\perp}{\boldsymbol{D}_\perp^2+\nu^2}-\frac{\boldsymbol{A}_\perp}{\boldsymbol{A}_\perp^2+\nu^2}\right)(1-\cos[\Omega_4\Delta z])-\frac{\boldsymbol{A}_\perp}{\boldsymbol{A}_\perp^2+\nu^2}\cdot\frac{\boldsymbol{D}_\perp}{\boldsymbol{D}_\perp^2+\nu^2}(1-\cos[\Omega_5\Delta z])$$
$$\left.+\frac{1}{N_c^2}\frac{\boldsymbol{B}_\perp}{\boldsymbol{B}_\perp^2+\nu^2}\cdot\left(\frac{\boldsymbol{A}_\perp}{\boldsymbol{A}_\perp^2+\nu^2}-\frac{\boldsymbol{B}_\perp}{\boldsymbol{B}_\perp^2+\nu^2}\right)(1-\cos[(\Omega_1-\Omega_2)\Delta z])\right]$$
$$\left.+x^3m^2\left[\frac{1}{\boldsymbol{B}_\perp^2+\nu^2}\cdot\left(\frac{1}{\boldsymbol{B}_\perp^2+\nu^2}-\frac{1}{\boldsymbol{C}_\perp^2+\nu^2}\right)(1-\cos[(\Omega_1-\Omega_2)\Delta z])+\ldots\right]\right\}\qquad(2.51)$$

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

- Event-averaged $\frac{dN_{\rm med}/dx/dk_\perp}{dN_{\rm vac}/dx/dk_\perp}$ ▷
  Bands: $g_s = 1.8 \pm 0.2$.

- Mass effects modify radiation at finite x and $k_T \lesssim M$.



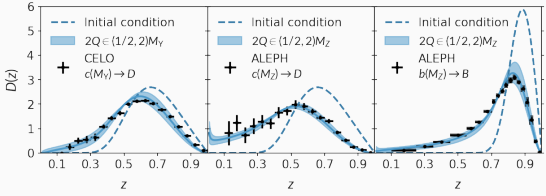
Fragmentation functions from the modified DGLAP evolution

$$\frac{\partial D_{h/i}(z,Q^2)}{\partial \ln Q^2} = [P_{ji}^{\rm vac} + \Delta P_{ji}^{\rm med}] \otimes D_{h/j}(z,Q^2), \qquad Q^2 = \frac{k_\perp^2 + x m_3^2 + (1-x)m_2^2 - x(1-x)m_1^2}{x(1-x)}$$

- Lund-Bowler initial condition ($Q_0 = 0.4$ GeV) [Bowler ZPC11(1981)169] : $D_{D/c} = d(z, m_c)$, $D_{B/b} = d(z, m_b)$

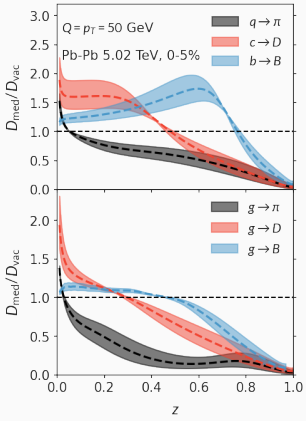
$$d(z,m) = \frac{(1-z)^a}{z^{1+bm_T^2}} e^{-bm_T^2/z}, \; a = 0.89, \; b = 3.3 \; \mathrm{GeV}^2.$$

Evolution in the vacuum ▽



- $D_{D/g} = D_{B/g} = 0$ at $Q = Q_0$; *non-zero but small* at $Q > Q_0$ due to evolution. Non-perturbative input can be important for inclusive spectra [D. Anderle et al. PRD96(2017)034028] though not included.

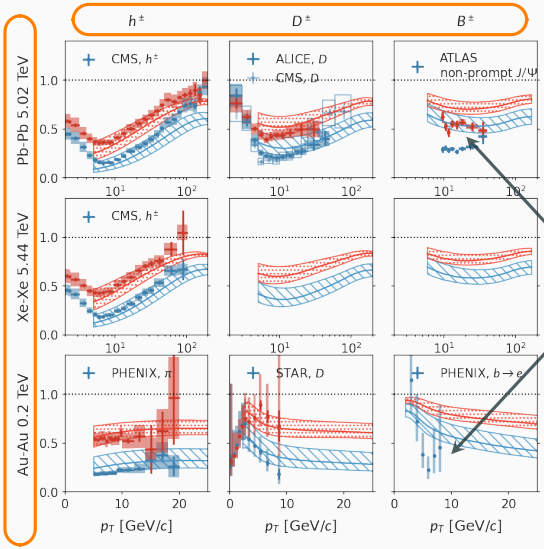
Medium modifications ▽



Inclusive spectra $d\sigma^i \sim q_T^{-N}, N \gg 1$

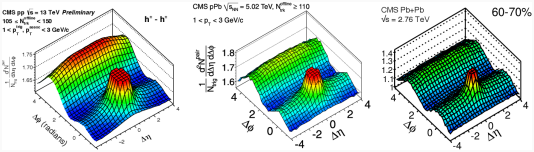
$d\sigma^i \otimes D_{h/i}(z) \sim \int_{p_T/q_T}^1 z^{N-1} D(z) dz$

Nuclear modification factors in large colliding systems



- Jet-medium coupling constant $g_s = 1.8 \pm 0.2$ $(0.20 < \alpha_s < 0.32)$.
- Reasonable description of R_{AA} for light and D (prefer slightly different g_s).
- Systematic deviations are more pronounced for B ($B \to J/\Psi, e$) mesons.
  $\Rightarrow$ possible missing physics:
  - Non-perturbative $g \to D, B$ input.
  - Interactions and break-up of heavy mesons in hadronic matter.

Identify QGP signals in small colliding system



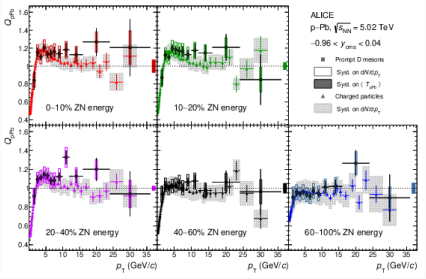
[CMS measured 2-particle correlations in p-p, p-Pb, Pb-Pb]

- Similarity between p-Pb and Pb-Pb can suggests final-state interactions in small systems.

$T_{\max}$ [GeV] achieved in hydro simulation

p-Pb 5 TeV		O-O 7 TeV	
0-1%	60-90%	0-10%	30-50%
0.315	0.174	0.325	0.263

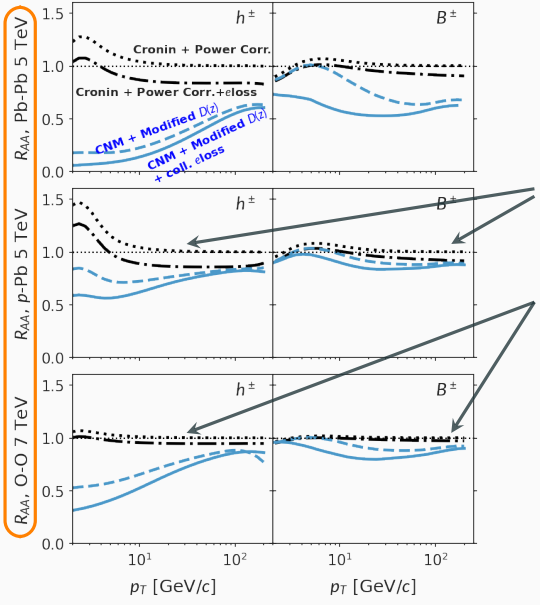
- *But quenching of high-p_T hadrons and heavy flavors is not yet unambiguously observed.*



△ D-meson $Q_{p\text{-Pb}}$, ALICE JHEP12(2019)092. Use neutrons in ZDC for centrality selection.

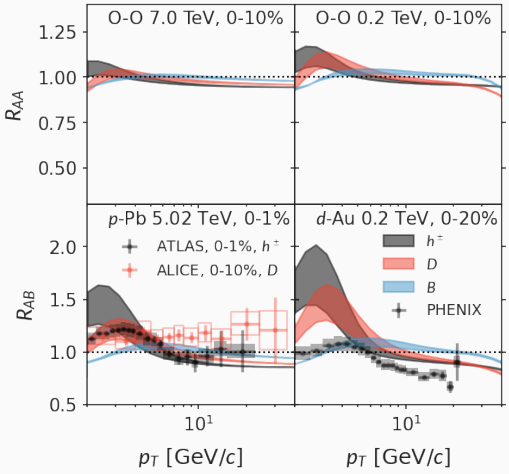
Need a better understanding of the baseline (no-QGP).

CNM and QGP effects small colliding systems



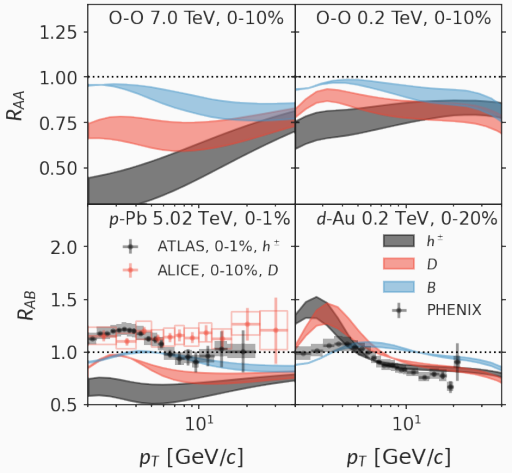
- Large A-A collisions: notable CNM effects but overwhelmed by energy loss in the QGP.
- Asymmetric p/d-A collisions: comparable CNM and QGP effects.
- Light A-A collisions: small CNM effects, good indicator of QGP effects in small systems.
- Relatively, collisional energy loss becomes important in small systems

Scenario I: no QGP formation, only cold nuclear matter effects



- d-Au data: [PHENIX, PRC96(2017)064905] ; p-Pb data: [ATLAS, PLB763(2016)313-336 (with $\langle T_{pA} \rangle$ calculated from the Glauber-Gribov model)] .
- CNM effects alone qualitatively describes $h^{\pm}$ modifications in p-Pb, d-Au for $p_T > 5$ GeV.
- Cannot explain $R_{pA}^{D} > 1$ at high p_T.

Scenario II: with "QGP" formation



QGP in small systems created near T_c can be very different from large & high-T QGP.

In this special context, QGP color density is still assumed to be *locally thermal* $\propto T^3$ from hydro simulations.

- QGP effects in d-Au at $\sqrt{s} = 0.2$ TeV are small.
- For p-Pb at $\sqrt{s} = 5.02$ TeV, calculations with local-thermal QGP color density are inconsistent with data.
- To be tested by light-ion program at RHIC and LHC.

Conclusion

Medium-modified factorized calculation for HF with both IS and FS effects

- Initial-state broadening + dynamical shadowing + CNM energy loss.
- HTL collisional energy loss.
- Modified fragmentation evolved with $\mathrm{SCET_G}$ in-medium splitting functions.
- Ongoing efforts:
  - NP input to $g \to$HF mesons.
  - HF interactions in the hadronic phase.
  - Beyond CNM-*e*loss calculation, more sophisticated initial-state k_T-broadening.

Predictions of R_{AA} in small-system w/ and w/o QGP:

- CNM effects are strong in asymmetric small-large collisions (p-Pb and d-Au), weaker in O-O collisions.
- QGP corrections assuming local-thermal color density are inconsistent with R_{AA} in p-Pb.

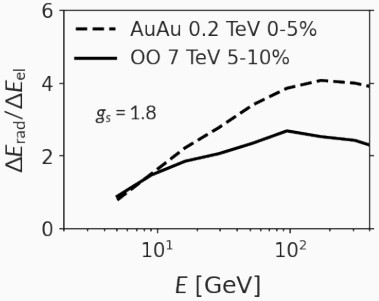
Questions?

Collisional energy loss in small systems

- Collisional and radiative energy loss scales different with medium geometry. For example $T^3 \propto \tau^{-\alpha}$, neglecting logs in $\alpha_s, \ln(E/T), \cdots$

$$\Delta E_{\rm rad} \propto L^{2-\alpha} \quad \text{v.s.} \quad \Delta E_{\rm el} \propto L^{1-\frac{2}{3}\alpha}$$

- From realistic hydro simulations of Au-Au 0.2 TeV 0-5% and O-O 7 TeV 5-10%
  - Similar initial temperature $T \approx 0.32$ GeV.
  - QGP size differ by a factor of 2.3.



- Define a "radiative energy loss"

$$\Delta E_{\rm rad} = \int d\mathrm{k}_\perp^2 \int_{1/2}^{1} \frac{d\Delta P_{qq}^{\rm med}}{dx d\mathrm{k}_\perp^2}(1-x)dx$$

- Left: the relative importance of $\Delta E_{\rm rad}$ (charm) is reduced relative to $\Delta E_{\rm el}$ in the smaller system.