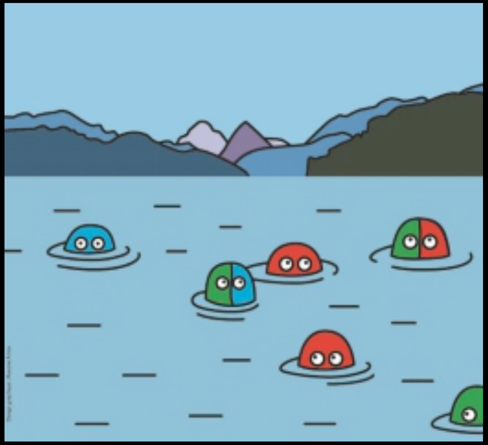
Ivan Vitev

Searching for QGP droplets with high p_T and heavy flavor



FH2022 Programme "Heavy Flavours from small to large systems "
Institut Pascal, Orsay, France
October 3-21, 2022

Los Alamos
NATIONAL LABORATORY
EST. 1943

Outline of the talk

- QGP formation puzzles in small systems
- Overview of CNM effects
- In-medium evolution for heavy flavor
- Phenomenological results for light and heavy flavor
- Conclusions and future directions

Bottom line up front: Heavy Flavor is an underexplored area at the intersections of hadronic, heavy ion, and EIC science. It provides tremendous theory advancement opportunities.

Acknowledgment of support

and Horizons 2020

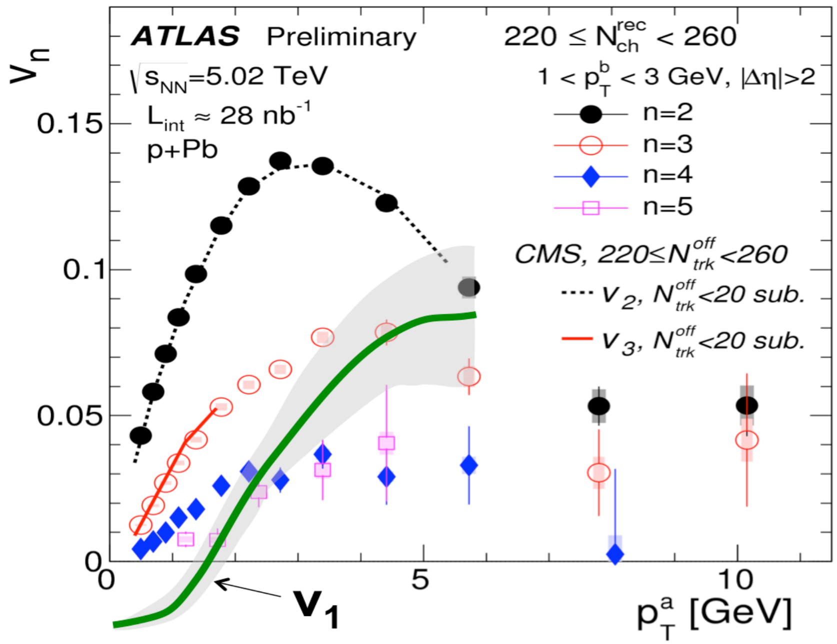
U.S. DEPARTMENT OF ENERGY
Office of Science

TMD Collaboration

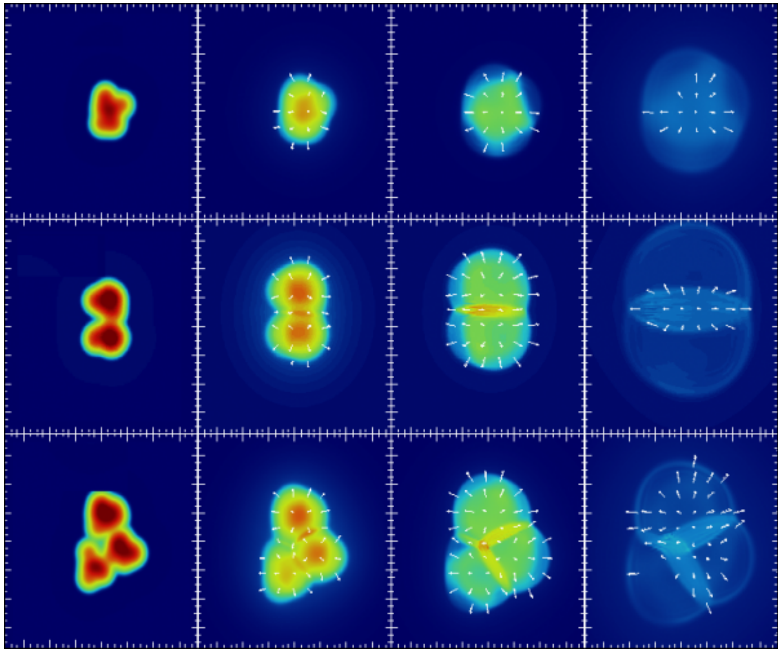
LDRD
LABORATORY DIRECTED RESEARCH & DEVELOPMENT

Universality of the anisotropy distributions

- Very similar behavior in p(d)+A and A+A systems at C.M. energies from 8 GeV to 5 TeV



ATLAS collab. (2014)

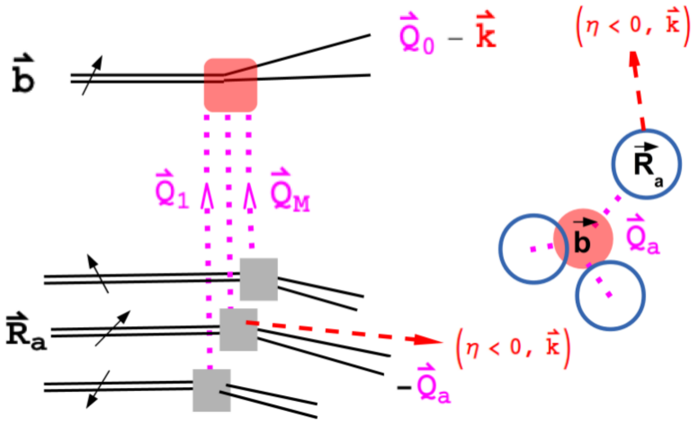


PHENIX collab. (2017)

- At the same time jet quenching has not been observed in them

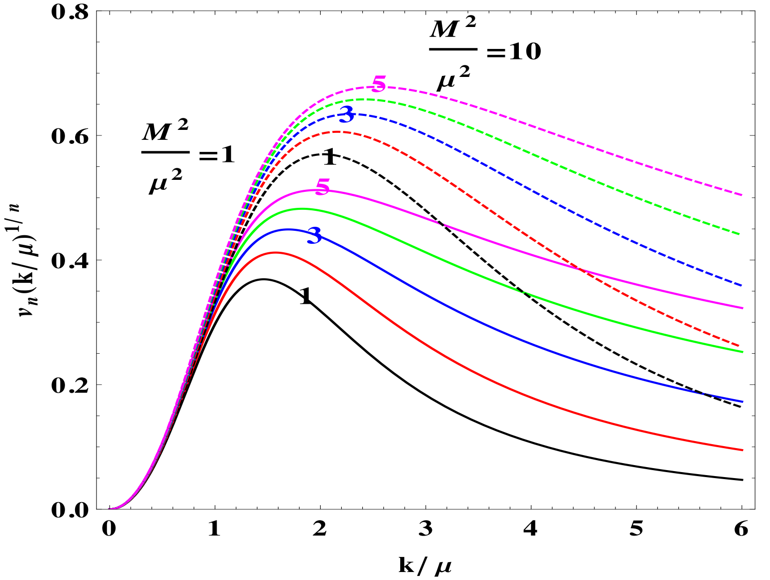
Alternatives and open questions

- Even with hydro's success, alternative mechanism can contribute. There can be CGC/saturation effects



M. Gyulassy et al . (2014)

B. Schenke et al . (2014)

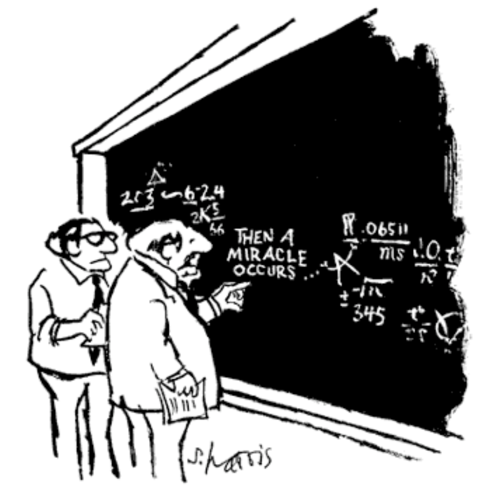


- Scaling relation for the azimuthal harmonics

$$[v_n^{GB}(k,q,0)]^{1/n} = [v_m^{GB}(k,q,0)]^{1/m}$$

What are reliable jet quenching predictions in small systems? How do they differ between light and heavy flavor? How do we improve the description of heavy flavor theoretically? What are the prediction from Cold nuclear matter effects?

Nuclear matter effects



"I think you should be more explicit here in step two."

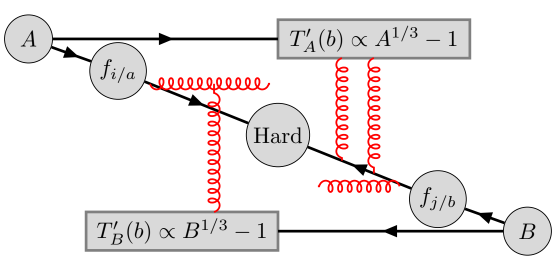
Production of light and heavy hadrons

QCD factorization approach is well established. Still large uncertainties remain related to non-perturbative physics / hadronization (fragmentation functions). This is especially true for heavy flavor

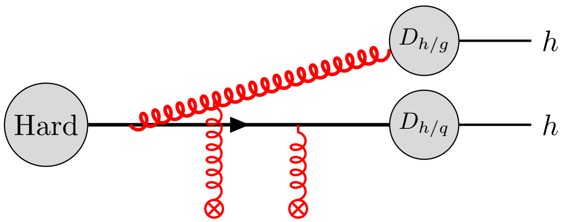
$$\frac{d\sigma^{H_1 H_2 \to hX}}{dp_T d\eta} = \frac{2p_T}{S} \sum_{abc} f_a^{H_1} \otimes f_b^{H_2} \otimes d\hat{\sigma}_{ab}^c \otimes D_c^h$$

Specific applications include LO, NLO, + resummation and parton showers. Also PYTHIA baseline (LO+PS)

In the presence of nuclear matter – initial-state (CNM) and final-state (QGP effects)

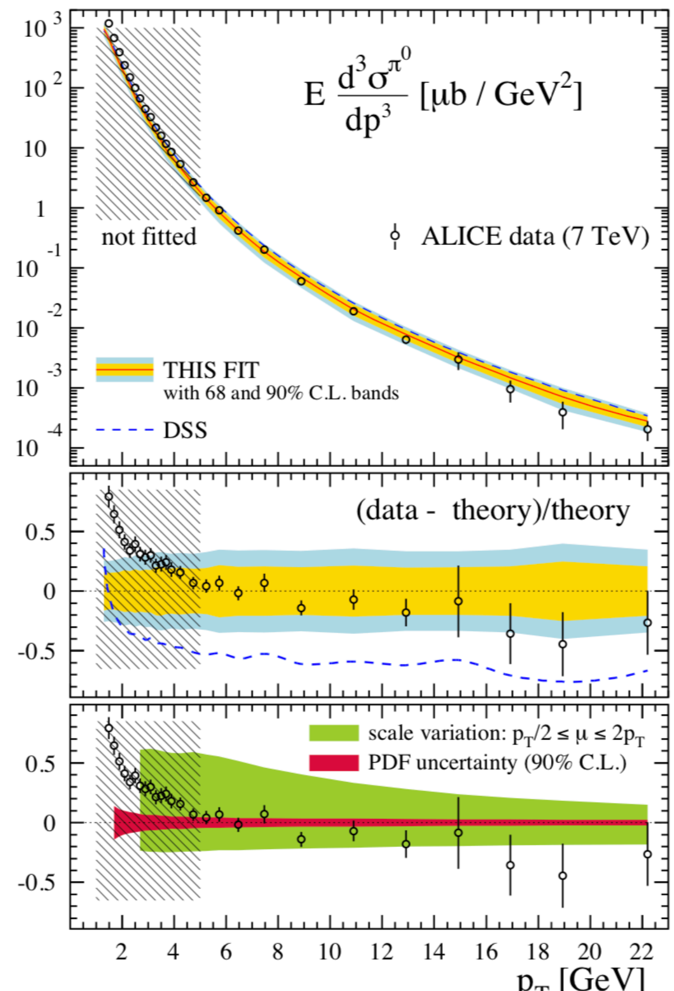


Initial-state (IS)



Final-state (FS)

Calculate those effects dynamically (with very few parameters)



D. De Florian et al. (2015)

Cold nuclear matter effects I

Process dependent corrections to QCD factorization

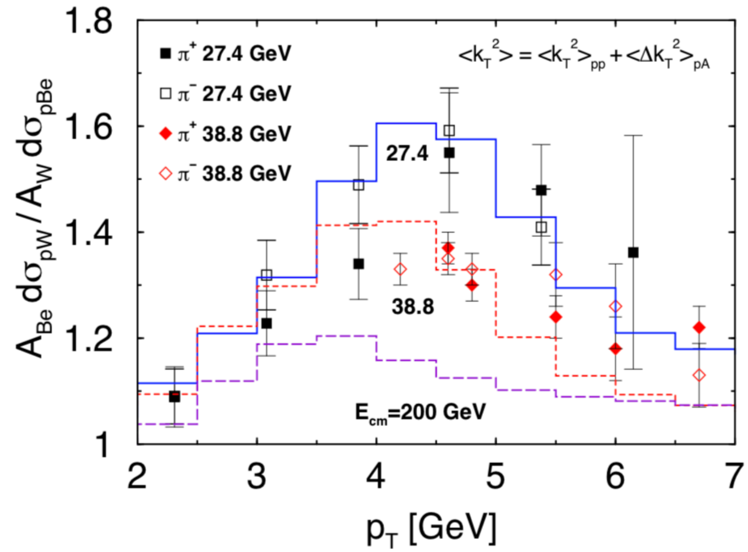
W. Kei et al. (2022)

$$\frac{d\sigma_k}{d\mathbf{q}^2 dy} = \frac{4}{s}\sum_{ij}\int d\eta_{\rm c.m.} \int d^2\mathbf{k}_i f_{i/A}(x_i+\Delta x_i,\mathbf{k}_i;\mu_F)\int d^2\mathbf{k}_j f_{j/B}(x_j+\Delta x_j,\mathbf{k}_j;\mu_F) \times \frac{d\sigma_{ij\to k}}{d\cos\theta_{\rm c.m.}}(x_i x_j s,\cos\theta_{\rm c.m.};\mu_R).$$

$$y = \frac{1}{2}\ln\frac{x_i}{x_j} + \eta_{\rm c.m.}$$

$$\left[\mathbf{q}_T - \frac{\mathbf{k}_i+\mathbf{k}_j}{2}\right]^2 = \frac{x_i x_j s \sin^2\theta_{\rm c.m.}}{4}.$$

Calculated corrections appear as kinematic modifications



- **Cronin effect (and of course isospin)**

M. Gyulassy et al. (2002)

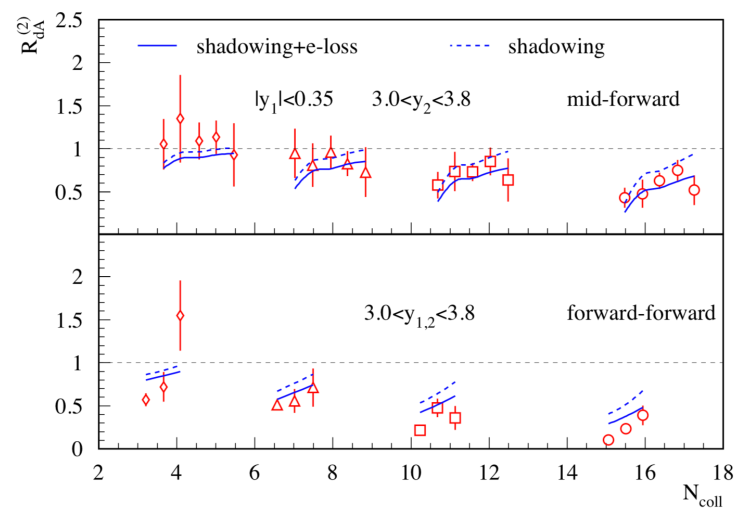
$$g(\mathbf{k}) = \exp(-\mathbf{k}_T^2/\langle\mathbf{k}_T^2\rangle_{pp})/\pi\langle\mathbf{k}_T^2\rangle_{pp},$$

$$\langle k_T^2\rangle_{pA} \approx \langle k_T^2\rangle_{pp} + L_A\frac{\mu^2}{\lambda}\ln(1+c\,p_T^2/\mu^2)$$

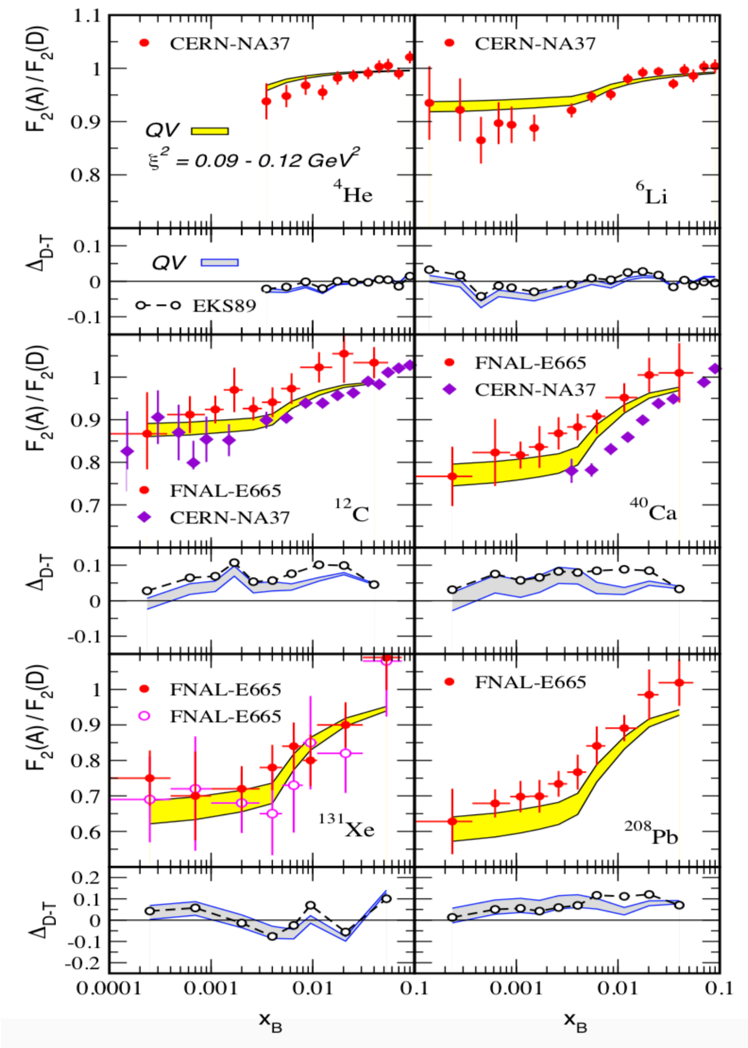
- **CNM energy loss**

I.V. (2007)

$$\Delta x/x = \epsilon_{\rm fl}\int_{m_N/p^+}^{1} dx \int_{xm_N\le|\mathbf{k}|\le xp^+} d^2\mathbf{k}\, x\frac{dN_{\rm IS}}{dx d^2\mathbf{k}}.$$



Cold nuclear matter effects II

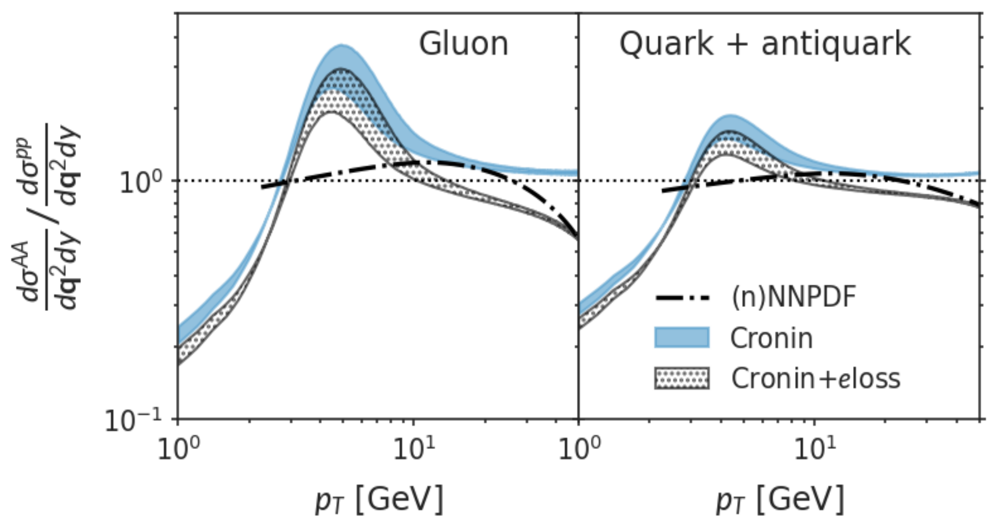


- **Coherent power corrections**

J. Qiu et al. (2005)

$$\Delta x_i/x_i \sim \mu^2 A^{1/3}/(-u) \qquad \Delta x_j/x_j \sim \mu^2 B^{1/3}/(-t)$$

Clear understanding of the centrality dependence of CNM effects. Much more "structure" than in nPDF parameterizations



Parton level results at RHIC compared to nPDF parameterization

W. Kei et al. (2022)

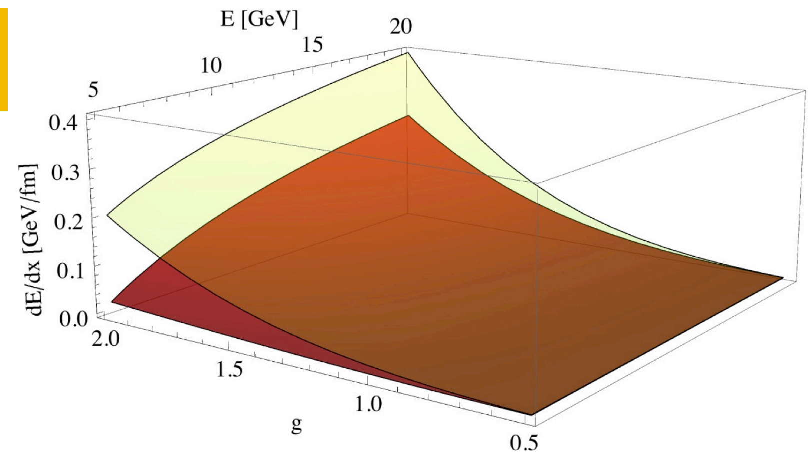
QGP effects I

Final-state collisional and radiative processes

- **Collisional energy loss (QGP specific)**

$$\frac{dE_{\rm el}}{d\Delta z} = \frac{C_F}{4}\left(1+\frac{N_f}{6}\right)\alpha_s(ET)\, g_s^2 T^2 \ln\left(\frac{ET}{m_D^2}\right)\left(\frac{1}{v} - \frac{1-v^2}{2v^2}\ln\frac{1+v}{1-v}\right)$$

Can be done many different waves. Used a source term formalism. (Allows also to understand the collisional e-loss in parton showers)



B. Neufeld. et al. (2014)

- **In-medium splitting functions / radiative energy loss**

M. Sievert et al. (2019)

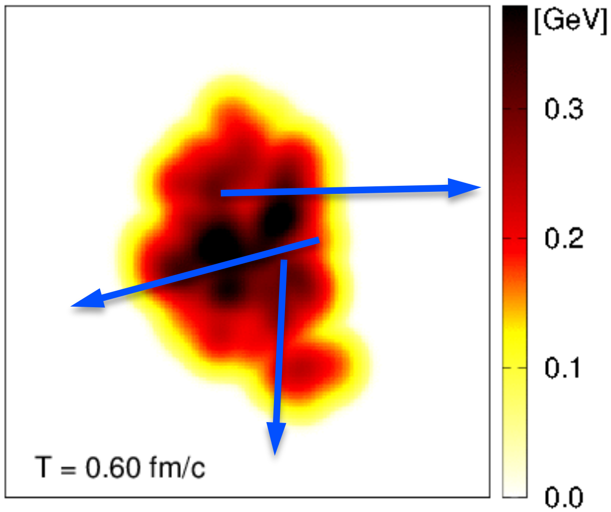
$$\mathbf{A} = \mathbf{k},\ \mathbf{B} = \mathbf{k} + x\mathbf{q},\ \mathbf{C} = \mathbf{k} - (1-x)\mathbf{q},\ \mathbf{D} = \mathbf{k} - \mathbf{q},$$

$$\omega_1 = \frac{\mathbf{B}^2}{x(1-x)p^+},\quad \omega_2 = \frac{\mathbf{C}^2}{x(1-x)p^+},$$
$$\omega_3 = \frac{\mathbf{C}^2-\mathbf{B}^2}{x(1-x)p^+},\quad \omega_4 = \frac{\mathbf{A}^2}{x(1-x)p^+},\quad \omega_5 = \frac{\mathbf{A}^2-\mathbf{D}^2}{x(1-x)p^+}.$$

$$\begin{aligned}
\left(\frac{dN^{\rm med}}{dx\,d^2k_\perp}\right)_{Q\to Qg} &= \frac{\alpha_s}{2\pi^2}C_F\int\frac{d\Delta z}{\lambda_g(z)}\int d^2q_\perp \frac{1}{\sigma_{el}}\frac{d\sigma_{el}^{\rm med}}{d^2q_\perp}\Bigg\{\left(\frac{1+(1-x)^2}{x}\right)\Bigg[\frac{B_\perp}{B_\perp^2+\nu^2}\\
&\times\left(\frac{B_\perp}{B_\perp^2+\nu^2}-\frac{C_\perp}{C_\perp^2+\nu^2}\right)(1-\cos[(\Omega_1-\Omega_2)\Delta z]) + \frac{C_\perp}{C_\perp^2+\nu^2}\cdot\bigg(2\frac{C_\perp}{C_\perp^2+\nu^2}-\frac{A_\perp}{A_\perp^2+\nu^2}\\
&-\frac{B_\perp}{B_\perp^2+\nu^2}\bigg)(1-\cos[(\Omega_1-\Omega_3)\Delta z]) + \frac{B_\perp}{B_\perp^2+\nu^2}\cdot\frac{C_\perp}{C_\perp^2+\nu^2}(1-\cos[(\Omega_2-\Omega_3)\Delta z])\\
&+\frac{A_\perp}{A_\perp^2+\nu^2}\cdot\left(\frac{D_\perp}{D_\perp^2+\nu^2}-\frac{A_\perp}{A_\perp^2+\nu^2}\right)(1-\cos[\Omega_4\Delta z]) - \frac{A_\perp}{A_\perp^2+\nu^2}\cdot\frac{D_\perp}{D_\perp^2+\nu^2}(1-\cos[\Omega_5\Delta z])\\
&+\frac{1}{N_c^2}\frac{B_\perp}{B_\perp^2+\nu^2}\cdot\left(\frac{A_\perp}{A_\perp^2+\nu^2}-\frac{B_\perp}{B_\perp^2+\nu^2}\right)(1-\cos[(\Omega_1-\Omega_2)\Delta z])\Bigg]\\
&+x^3m^2\left[\frac{1}{B_\perp^2+\nu^2}\cdot\left(\frac{1}{B_\perp^2+\nu^2}-\frac{1}{C_\perp^2+\nu^2}\right)(1-\cos[(\Omega_1-\Omega_2)\Delta z])+\ldots\right]\Bigg\}
\end{aligned}$$

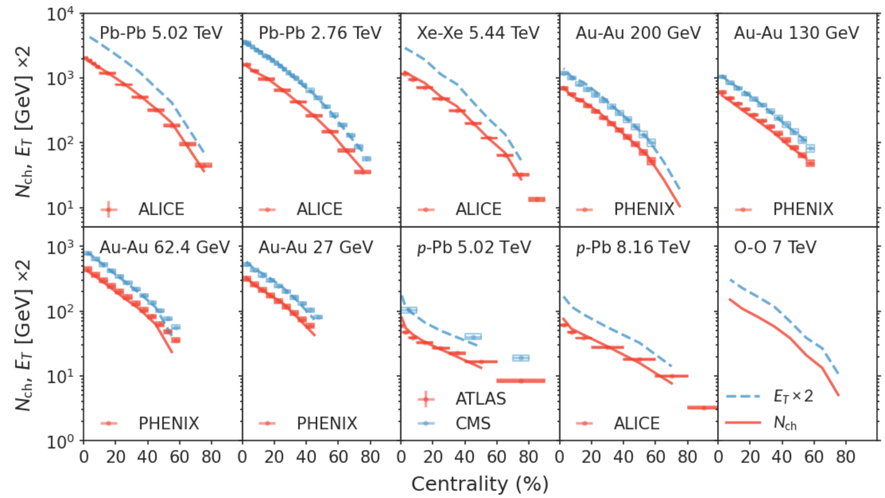
We valuated branching for light and heavy flavor and the energy loss limit. Also full understanding of the dead cone effect

QGP effects II



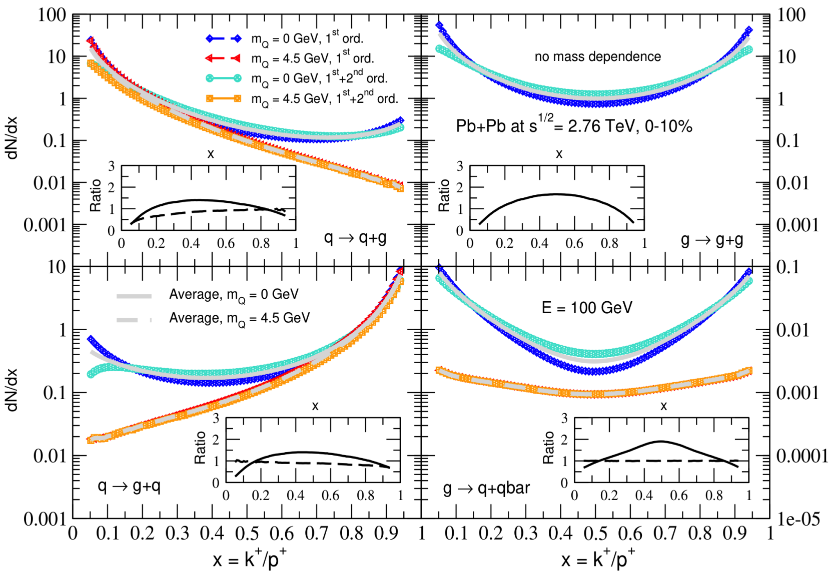
- **Simulation**

C. Shen et al. (2014)



Hydro medium and TRENTO initial conditions

J. Bernhard (2018)



System size dependence (expanding QGP)

$$\frac{\Delta E_{\rm el}}{E} \propto \int_{\tau_0}^{\tau_0+L} \mu^2 d\Delta z \propto L^{1/3} \qquad \frac{\Delta E_{\rm rad}}{E} \propto \int_{\tau_0}^{\tau_0+L} \frac{\mu^2}{\lambda_g} \Delta z d\Delta z \propto L$$

Much weaker path length dependence of collisional vs radiative E-loss. Implies increased importance in small systems

W. Ke et al. (2022)

Light and heavy flavor fragmentation and evolution

The following choices are made :
Light – DSS, heavy - Lund-Bowers

$$D(z) = z^{-1-bM_\perp^2}(1-z)^a e^{-\frac{bM_\perp^2}{z}}$$

M. Bowers (1981)

Other parameterizations, Peterson, HQET calculations, etc …

Direct extraction give much larger gluon frag. component

$$\frac{\partial D^0_{h/i}(z,Q^2)}{\partial \ln Q^2} = \sum_j \int_z^1 \frac{dx}{x}\left[P'_{ji}(x\to 1-x, Q^2) + d_{ji}(Q^2)\delta(1-x)\right] D_{h/j}\left(\frac{z}{x}, Q^2\right)$$

D. Anderle et al.2017)

Various HQ parameterizations understood as initial conditions. Evolution generates a gluon fragmentation component through RG evolution

$$d_{qq}(Q^2) = \frac{\alpha_s(Q^2)}{2\pi} C_F \frac{3}{2},$$

$$d_{HH}(Q^2,r) = \frac{\alpha_s(Q^2)}{2\pi} C_F c_{HH}(r),$$

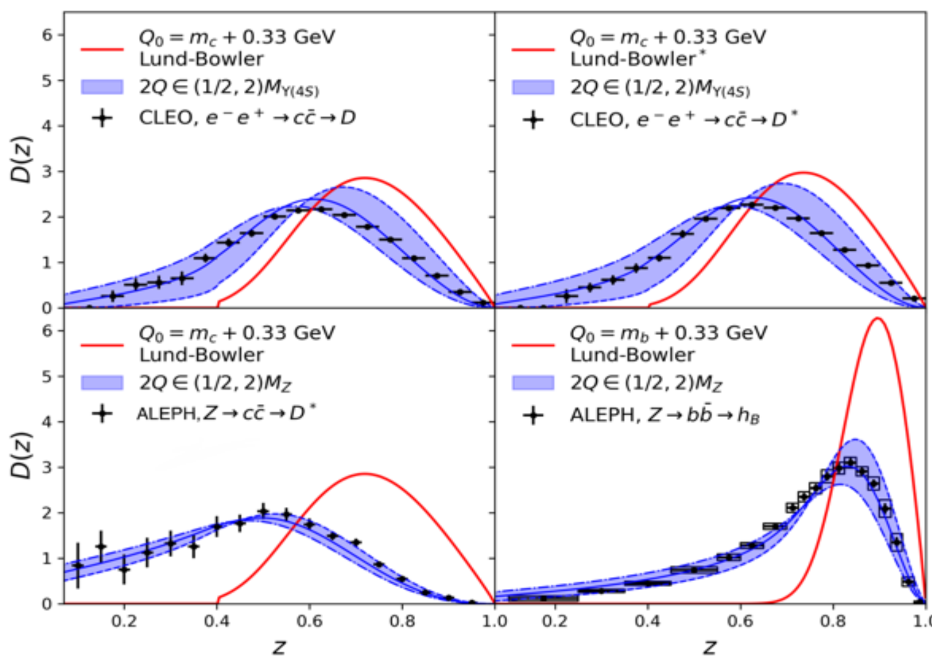
$$d_{gg}(Q^2,r) = \frac{\alpha_s(Q^2)}{2\pi}\left[\frac{11}{6}N_c - N_f T_F \frac{2}{3} + \sum_{H=c,b} T_F c_{gH}(r)\right]$$

Heavy flavor specific $r = M/Q$

$$c_{gH}(r) = F\left(\frac{1+\sqrt{1-4r^2}}{2}\right) - F\left(\frac{1-\sqrt{1-4r^2}}{2}\right) - 2r^2\sqrt{1-4r^2},$$

$$F(x) = -x^4 + \frac{4}{3}x^3 - x^2,$$

$$c_{HH}(r) = \frac{1}{1+r^2} + \frac{2r^2+1}{2(1+r^2)^2} + \frac{2r^2}{1+r^2} - 2\ln\frac{1}{1+r^2}.$$

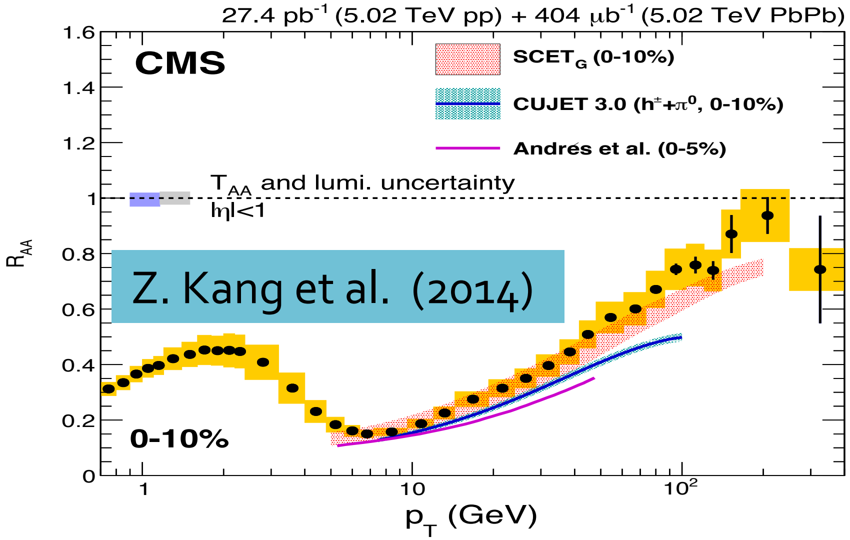


Light and heavy flavor fragmentation and evolution

In-medium evolution – full form, not hybrid between E-loss and RG

$$P'_{ji} \to P'_{ji} + \mathbf{k}^2 \frac{dN_{ji}^{\mathrm{med}\prime}}{dx d\mathbf{k}^2} \quad \text{with } x \to 1 - x,$$

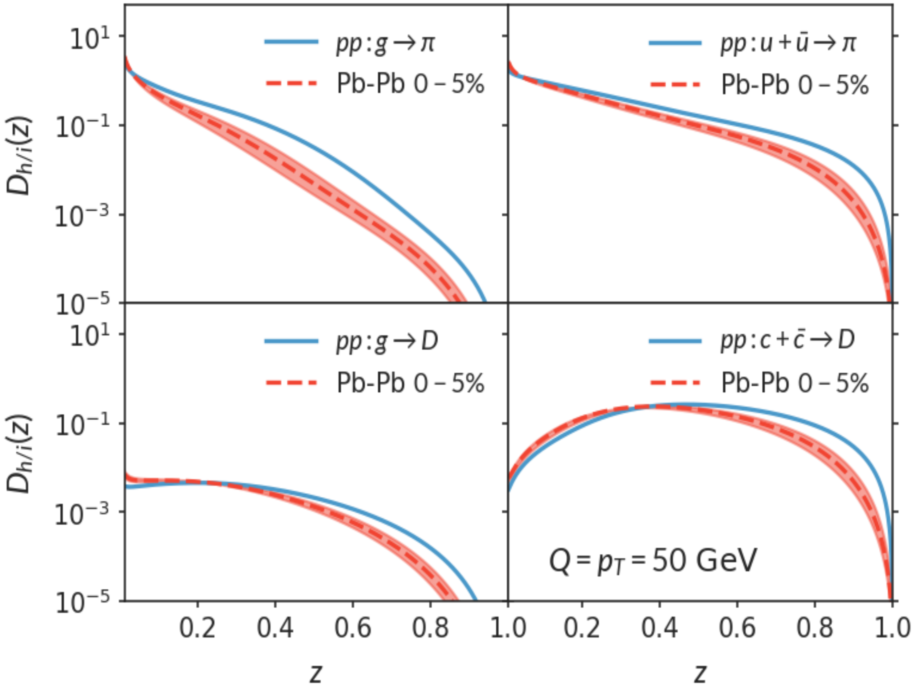
$$d_{ji}(Q^2) \to d_{ji}(Q^2) + d_{ji}^{\mathrm{med}}(Q^2)$$



There is clear understanding of connection to radiative E-loss

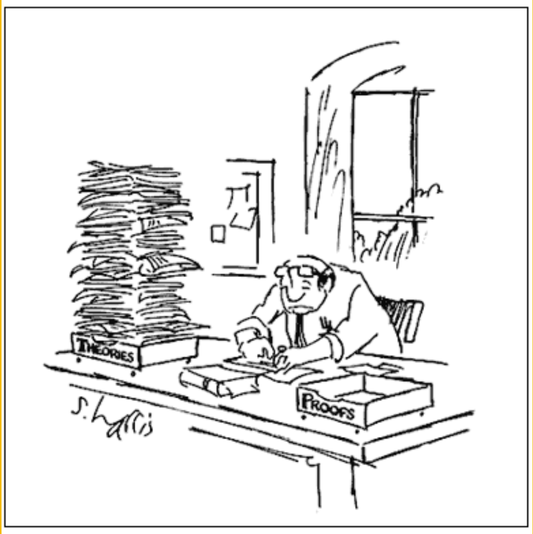
$$D_{h/c}^{\mathrm{med.}}(z,Q) = D_{h/c}(z,Q) e^{-[n(z)-1]\left\langle \frac{\Delta E}{E} \right\rangle_z - \langle \tilde{N^g} \rangle_z}.$$

First in-medium scaling violations done here for heavy flavor in the QGP. It is also combined with collisional energy losses

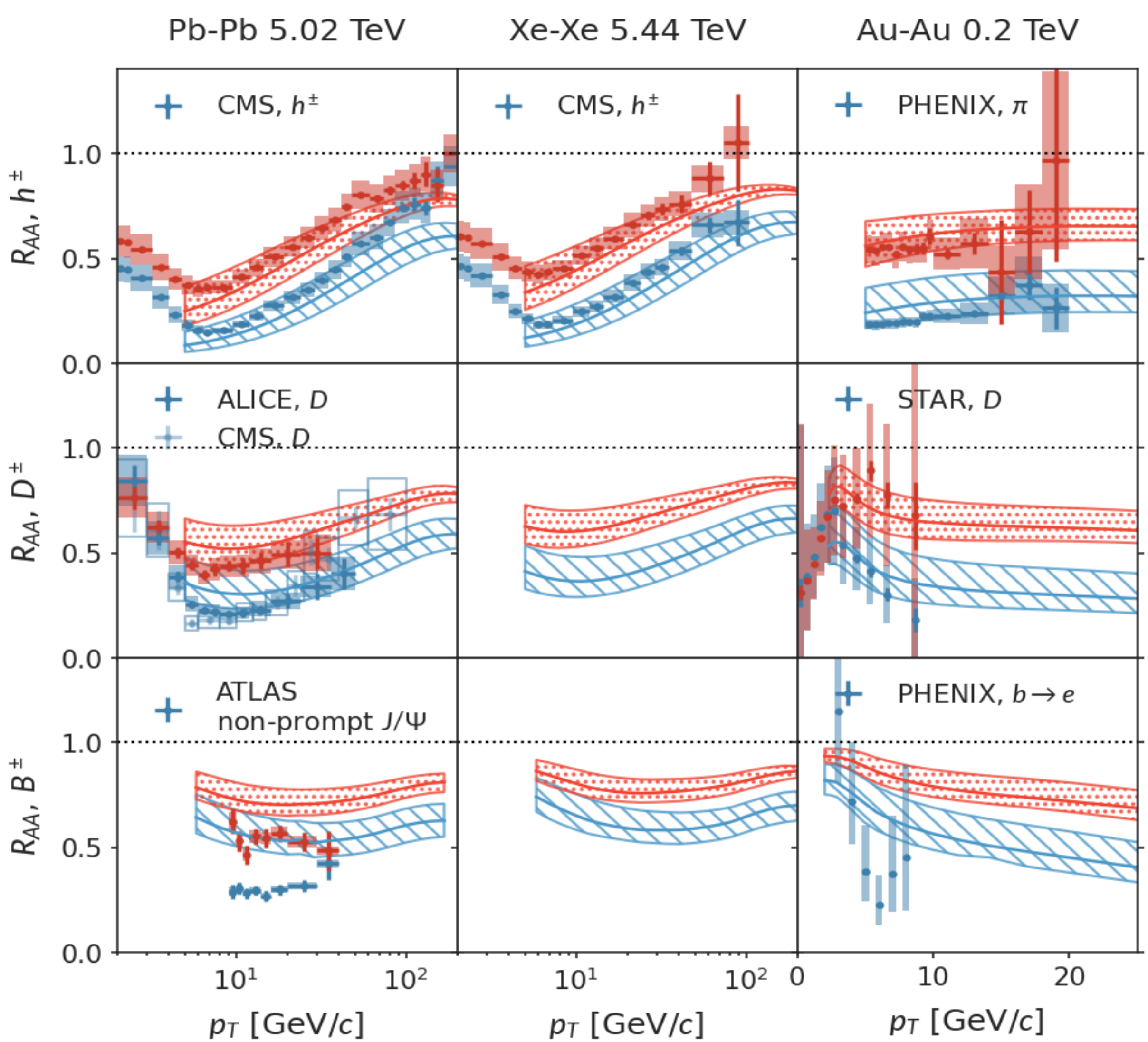


W. Ke et al (2022)

Phenomenology



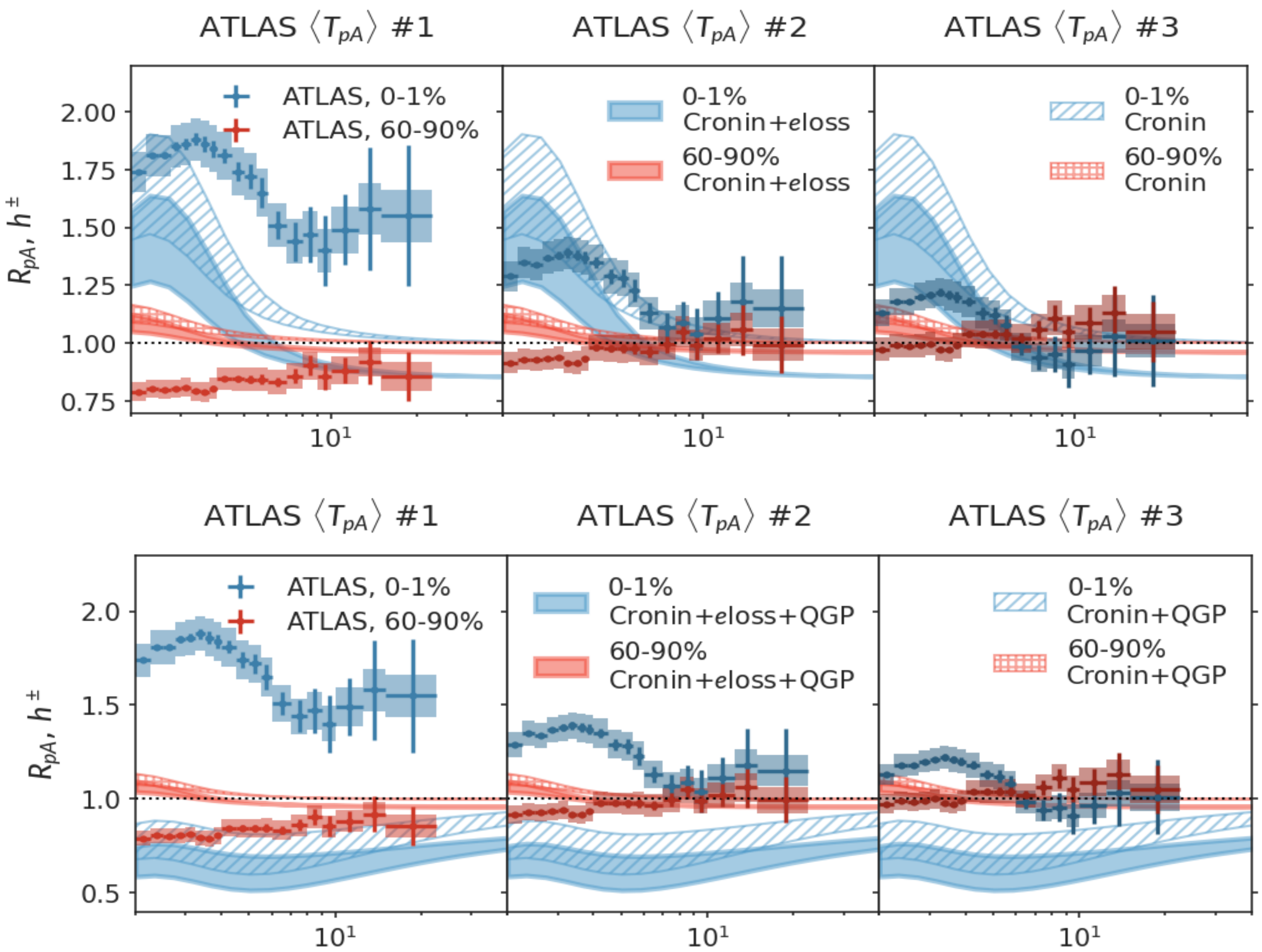
Phenomenology – large systems



- Theoretical results agree with existing light hadron and D meson measurements at RHIC and LHC. True for both central and peripheral collisions
- Can further identify trends from the comparison with data – slightly larger coupling is favored at RHIC than LHC. In addition, heavy flavor prefers slightly larger coupling.
- There is tension with the B meson production (or non-prompt J/psi). May be dissociation?

Coming back to discussion of radiative vs collisional processes – radiative dominate except for B mesons at low p_T

Phenomenology – small systems

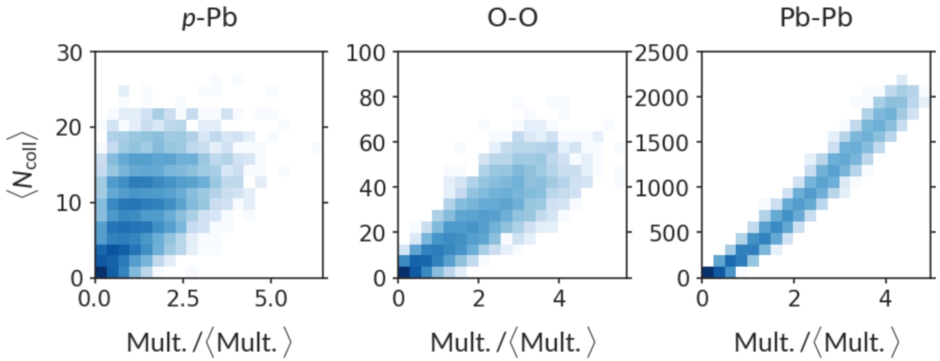


- It is difficult to establish a correlation between particle multiplicities and centrality is asymmetric systems (as in p+A)
- Cold nuclear matter effects need to be better constrained. Scenario #1 oe not seem compatible with any combination. Scenarios #2 and #3 differ by the amount of room they leave for CNM energy loss. Cronin effect also smaller
- If we include QGP assumption (as given by hydro) there is significant suppression regardless of CNM effects. Incomatible

W. Ke et al. (2022)

Centrality determination in p/d+A challenging. No room for quenching effects in p+Pb

QGP in small systems I?



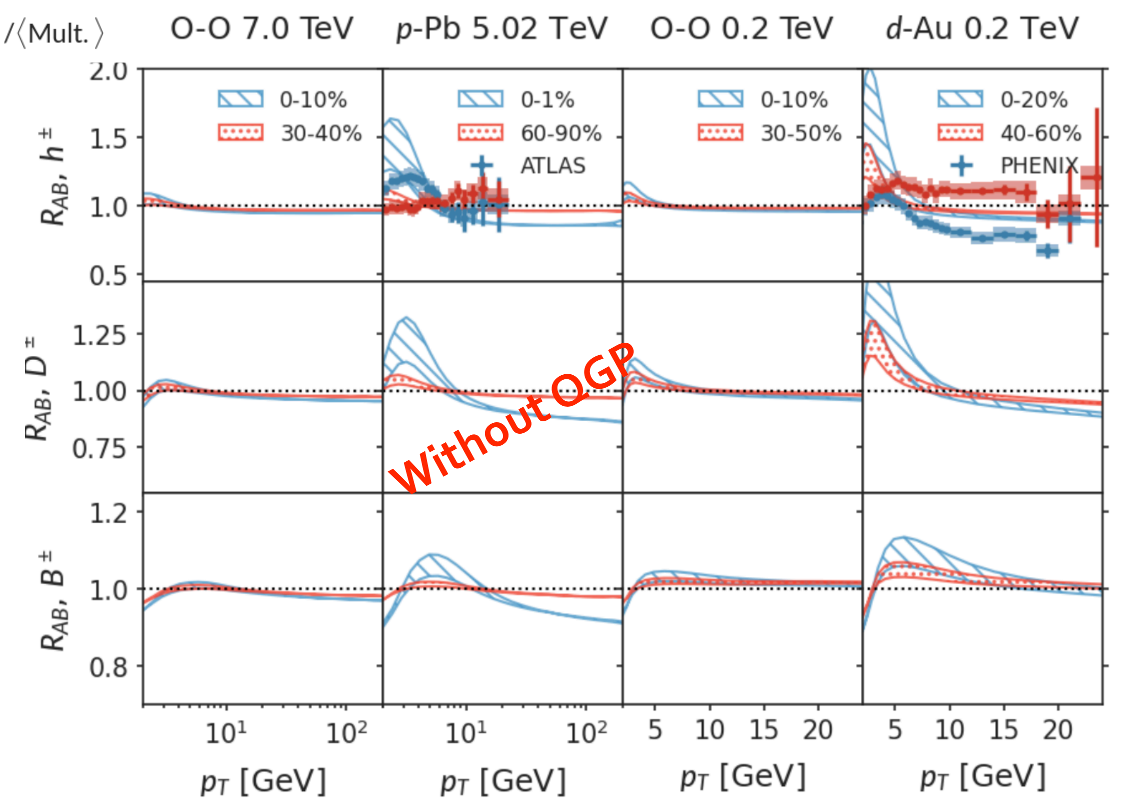
Correlation between multiplicity and number of collisions can be vastly improved in collisions of small nuclei (such as O+O).

Certain interesting observations

CNM effects are quite sensitive to the C.M. energy. They are reduced at LHC and enhanced at RHIC.

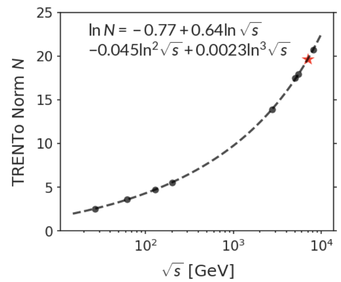
CNM effects are more pronounced in small but very asymmetric systems as opposed to small but symmetric systems

CNM effects are very small for O+O, so it is an excellent baseline for QGP searches in small systems

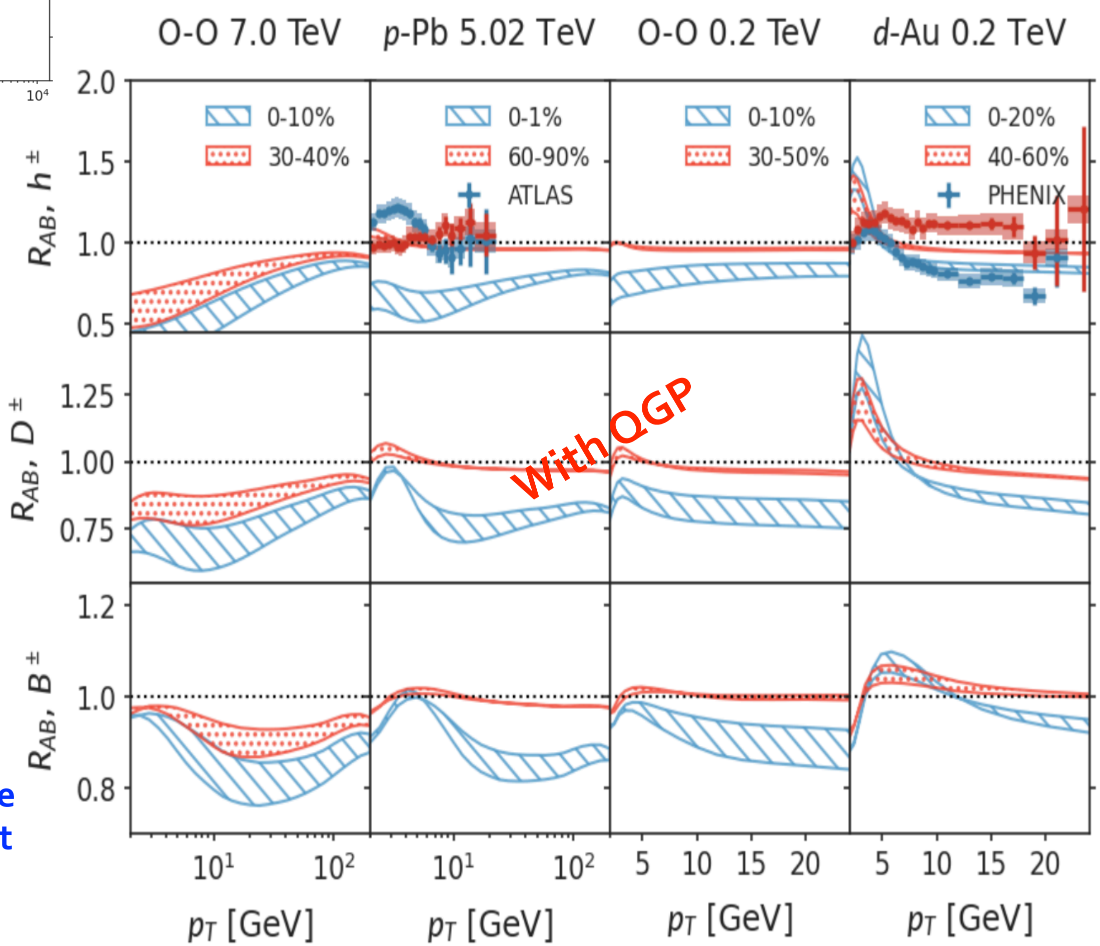


QGP in small systems II?

Systems		$T_{\max}$ [GeV]
Pb-Pb 5.02 TeV	0-10%	0.415
	30-50%	0.362
Xe-Xe 5.44 TeV	0-10%	0.401
	30-50%	0.340
Au-Au 0.2 TeV	0-10%	0.312
	30-50%	0.278
p-Pb 5.02 TeV	0-1%	0.315
	60-90%	0.174
O-O 7 TeV	0-10%	0.331
	30-50%	0.272
d-Au 0.2 TeV	0-5%	0.225
	40-60%	0.167
O-O 0.2 TeV	0-10%	0.237
	30-50%	0.192



To perform hydrodynamic simulations we extrapolate the TRENTo multipliciy parameter



QGP effects are clearly identifiable in O+O. They are more than a actor of two. Can also be seen in heavy flavor at 10 GeV and above.

Interestingly d+Au behaves differently (more compatible with QGP effects)

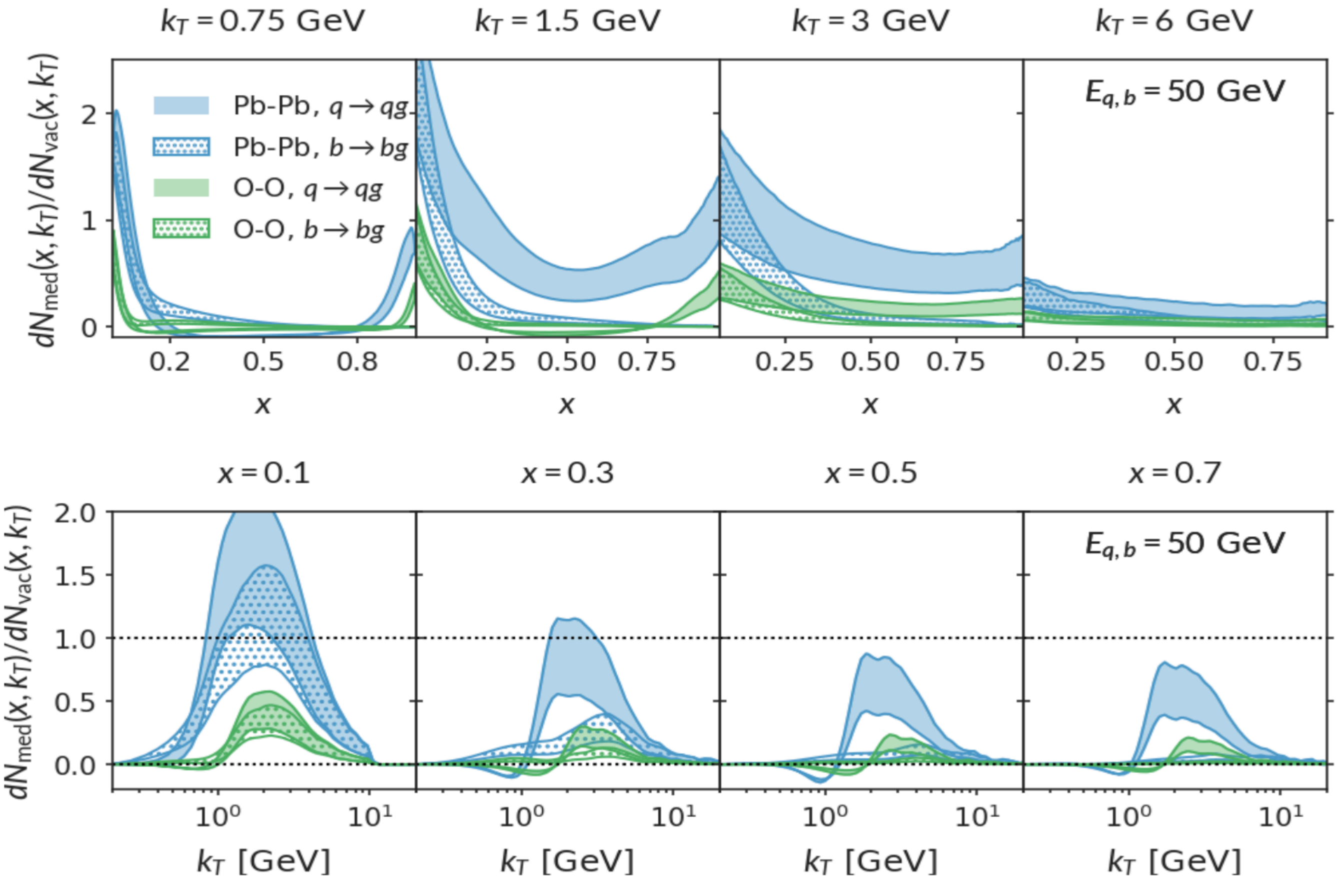
If strong quenching is established, then one can try to identity it in inclusive jets and jet substructure. For discovery purposes, hadrons are ideal probes.

Conclusions

- We investigated systematically the modification of light and heavy-flavor hadron production in small and large colliding systems at moderate and high p_T. Our goal was to differentiate the impact of cold nuclear matter and hot QGP effects.
- In small colliding systems we found that the CNM effects alone can already explain the basic patterns observed in p-Pb collisions scaled by the improved Glauber-Gribov model. In spite of the remaining uncertainties, we established that the current model of QGP formation in p-A, as described by hydrodynamics, leads to quenching of hadron spectra that is inconsistent with the p-Pb data
- In O-O collisions at RHIC and LHC, we found that CNM effects alone only lead to very small corrections, while the formation of a QGP can suppress charged particle spectra by more than a factor of two at the LHC and by 20% at RHIC energy. Unlike the suppression in large systems that is dominated by induced radiation, collisional energy loss in O-O reactions results in modifications comparable to the effects of in-medium evolution.
- The predicted suppression in small systems at LHC energies with and without QGP formation is very distinct and can be easily tested with future measurements. We finally observed that if QGP quenching effects are identified in O-O, the enhanced contribution from collisional processes can be tested by simultaneously looking at the flavor dependence of R_{AA}.

The exploration of the extreme phases of matter has also fascinated the general public. The HI program should make the most out of QGP searches (including exotic small systems)

Differential branching spectra



- Production of hadrons and jets can be understood from the broader and softer splitting functions
- Holds to higher orders in opacity

Most importantly – additional medium-induced contribution to factorization formulas (final-state) – Additional scaling violation due to the medium-induced shower. Additional component to jet functions

Comparison to other CNM effects

- Differences not large in regions of interest
- Except for B mesons in small systems (OO) below 10 GeV