Initial-state and final-state effects on hadron production in small collision systems

Ivan Vitev

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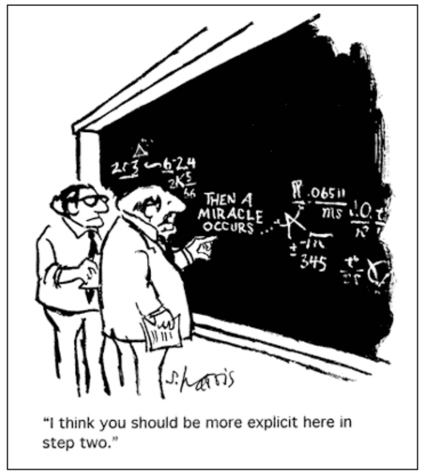
HEFTY COLLABORATION

Los Alamos NATIONAL LABORATORY

Outline



1. Hadron production in perturbative QCD, uncertainties
2. Heavy flavor fragmentation
3. Calculation of cold nuclear matter effects
4. QGP model for final state interactions and in-medium DGLAP evolution
5. Novel insights into parton showers from renormalization group analysis
6. Phenomenological results
7. Conclusions

Based on work with Weiyao Ke 2204.00634 [hep-ph], 2301.11940 [hep-ph]
Input from earlier work on in-medium DGLAP, SCET splitting functions, CNM effects, …

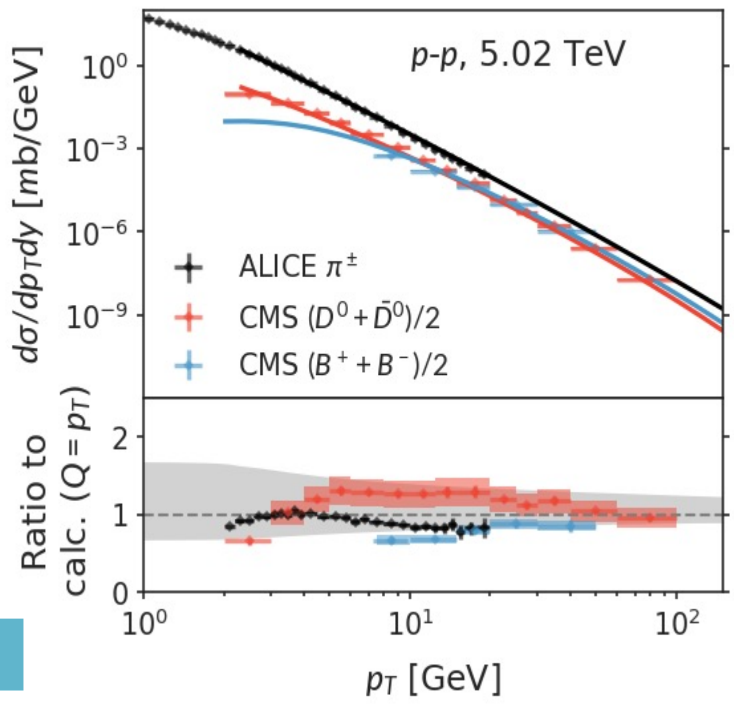
We acknowledge DOE, LANL LDRD, and HEFTY NT Topical Collaboration support

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

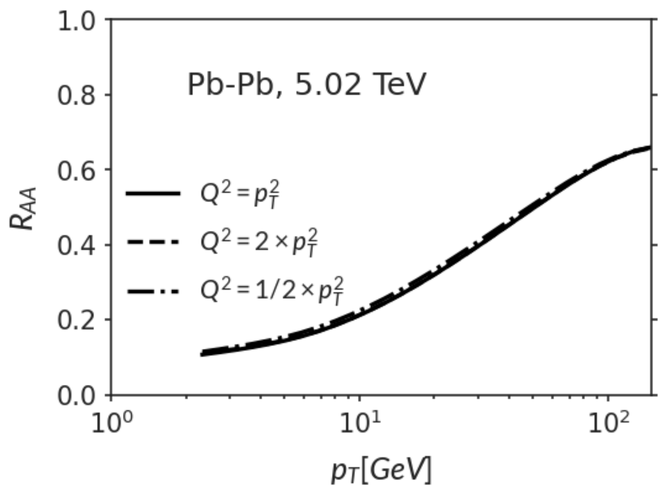
$$\frac{d\sigma^{H_1 H_2 \to hX}}{dp_T d\eta} = \frac{2p_T}{S} \sum_{abc} f_a^{H_1} \otimes f_b^{H_2} \otimes d\hat{\sigma}_{ab}^c \otimes D_c^h$$

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



W. Ke et al. (2022)

Description of data in p+p at the 10-30% level, comparable with the sale dependence of cross sections



Inherent uncertainties, scheme, scale, PDF and FF choice

Perturbative uncertainties cancel in the R_{AB} ratios

Light and heavy flavor fragmentation and evolution

Light – DSS, heavy - Lund-Bowers

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

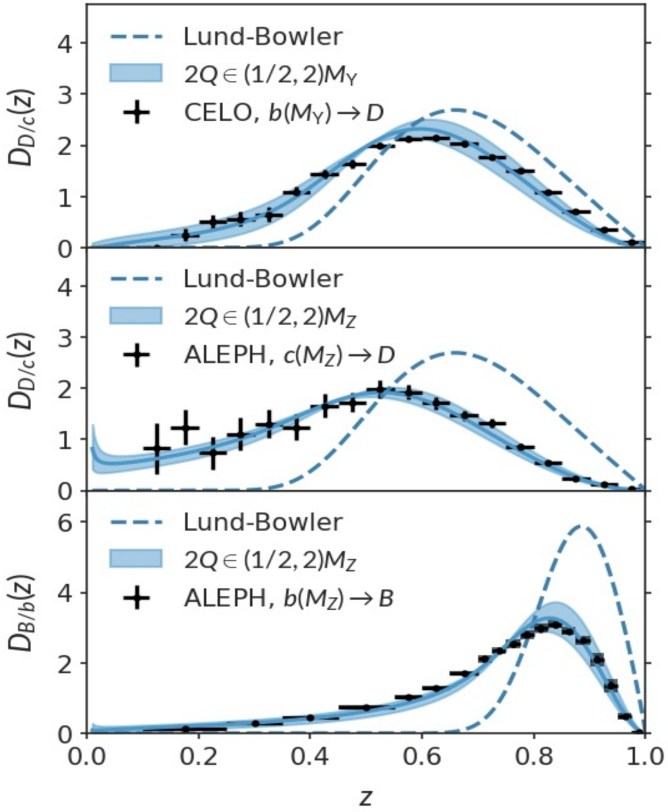
M. Bowers (1981)

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

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

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

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



Heavy flavor specific $r = M/Q$

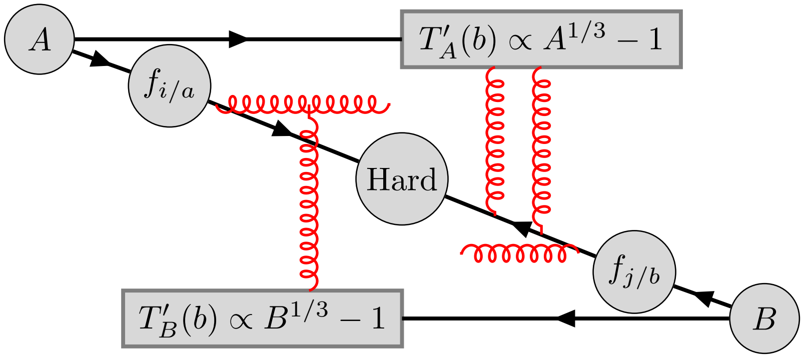
$$c_{gH}(r) = F\left(\frac{1+\sqrt{1-4r^2}}{2}\right) - F\left(\frac{1-\sqrt{1-4r^2}}{2}\right) - 2r^2\sqrt{1-4r^2},$$

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

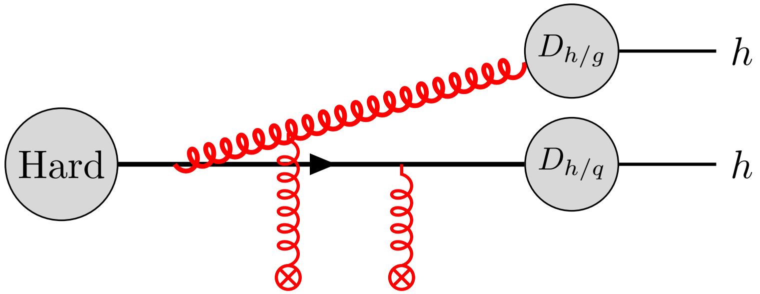
$$c_{HH}(r) = \frac{1}{1+r^2} + \frac{2r^2+1}{2(1+r^2)^2} + \frac{2r^2}{1+r^2} - 2\ln\frac{1}{1+r^2}.$$

Cold nuclear matter effects

Nuclear matter – initial-state (CNM) and final-state (QGP effects)



Initial-state (IS)



Final-state (FS)

Cold nuclear matter effects can be related to nuclear structure – leading twist effects parametrized in nPDFs
CNM effects can also arise form the collisional and radiative processes in large nuclei (just like in the QGP)

Process dependent corrections to QCD factorization

Calculated corrections appear as kinematic modifications

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

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

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

CNM implementation and results

Specific CNM effects we consider arise from the elastic, inelastic, and coherent re-scattering of partons in nuclei

M. Gyulassy et al. (2002)

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

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

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

- **Coherent power corrections**

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

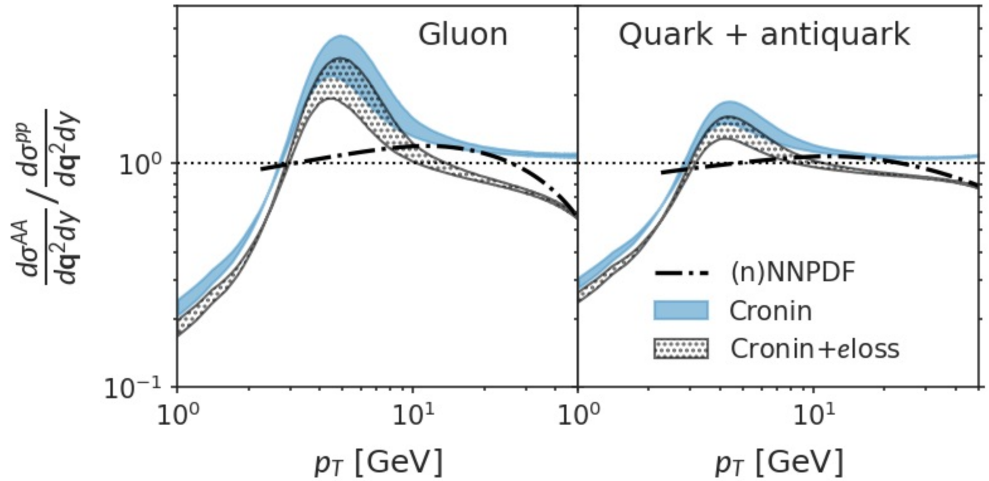
J. Qiu et al. (2005)

- **CNM energy loss**

I.V. (2007)

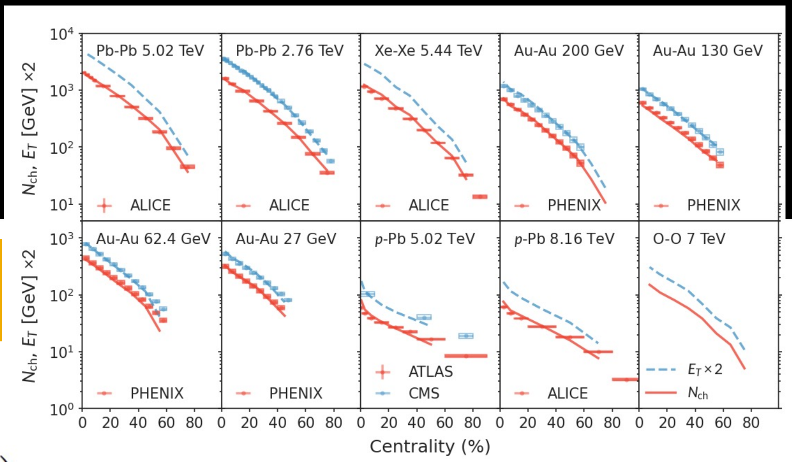
$$\Delta x / x = \epsilon_{\mathrm{fl}} \int_{m_N/p^+}^{1} dx \int_{x m_N \le |\mathbf{k}| \le x p^+} d^2\mathbf{k}\; x \frac{dN_{\mathrm{IS}}}{dx d^2\mathbf{k}}$$

Parton level results at RHIC compared to nPDF parameterization



For prospects for better (TMD based) description of the low p_T region Cronin effect, etc – see talk by Weiyao Ke

QGP effects



Hydro medium and TRENTO initial conditions

J. Bernhard (2018)

Final-state collisional and radiative processes

- **Collisional energy loss**

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

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

M. Sievert et al. (2019)

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

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

$$\frac{dN_{qq}^{\rm med}}{dxd\mathbf{k}^2} \equiv P_{qq}(x,\mathbf{k}^2)\int_0^\infty d\Delta z\int d^2\mathbf{q}\frac{dR_g(\Delta z)}{d^2\mathbf{q}} \left\{\left[\frac{\mathbf{B}}{\mathbf{B}^2}\cdot\left(\frac{\mathbf{B}}{\mathbf{B}^2}-\frac{\mathbf{C}}{\mathbf{C}^2}\right)+\frac{1}{N_c^2}\frac{\mathbf{B}}{\mathbf{B}^2}\cdot\left(\frac{\mathbf{A}}{\mathbf{A}^2}-\frac{\mathbf{B}}{\mathbf{B}^2}\right)\right][1-\cos(\omega_1\Delta z)] + \frac{\mathbf{C}}{\mathbf{C}^2}\cdot\left(2\frac{\mathbf{C}}{\mathbf{C}^2}-\frac{\mathbf{A}}{\mathbf{A}^2}-\frac{\mathbf{B}}{\mathbf{B}^2}\right)[1-\cos(\omega_2\Delta z)]+\frac{\mathbf{B}}{\mathbf{B}^2}\cdot\frac{\mathbf{C}}{\mathbf{C}^2}[1-\cos(\omega_3\Delta z)] - \frac{\mathbf{A}}{\mathbf{A}^2}\cdot\left(\frac{\mathbf{A}}{\mathbf{A}^2}-\frac{\mathbf{D}}{\mathbf{D}^2}\right)[1-\cos(\omega_4\Delta z)]-\frac{\mathbf{A}}{\mathbf{A}^2}\cdot\frac{\mathbf{D}}{\mathbf{D}^2}[1-\cos(\omega_5\Delta z)]\right\},$$

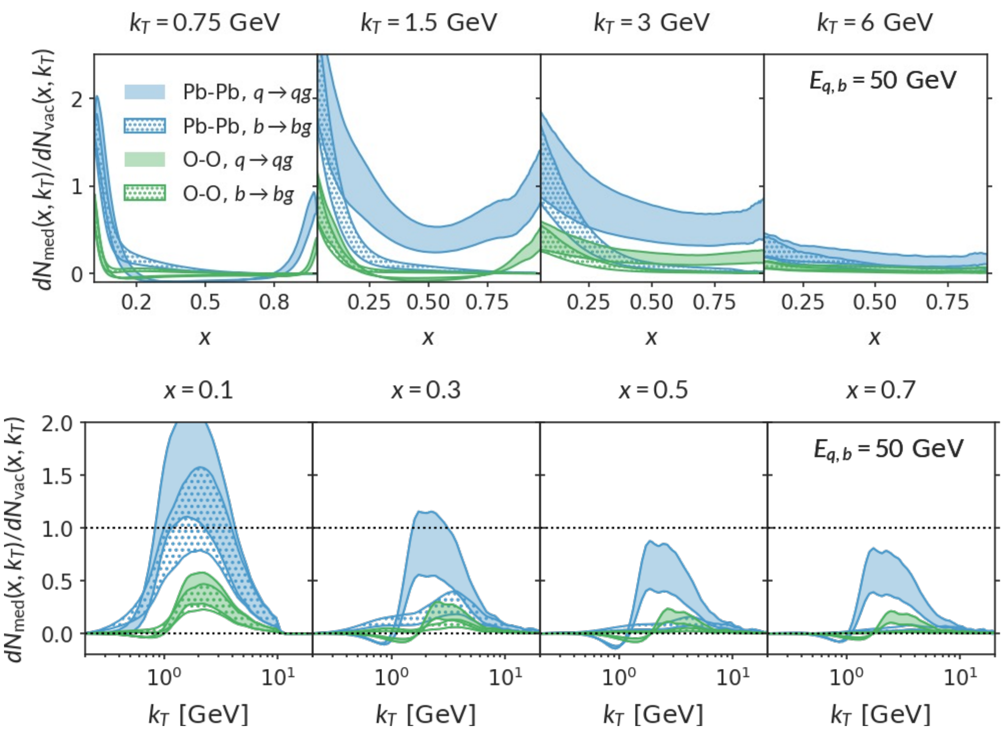
Also evaluated branching for heavy flavor and the energy loss limit

System size dependence (expanding QGP)

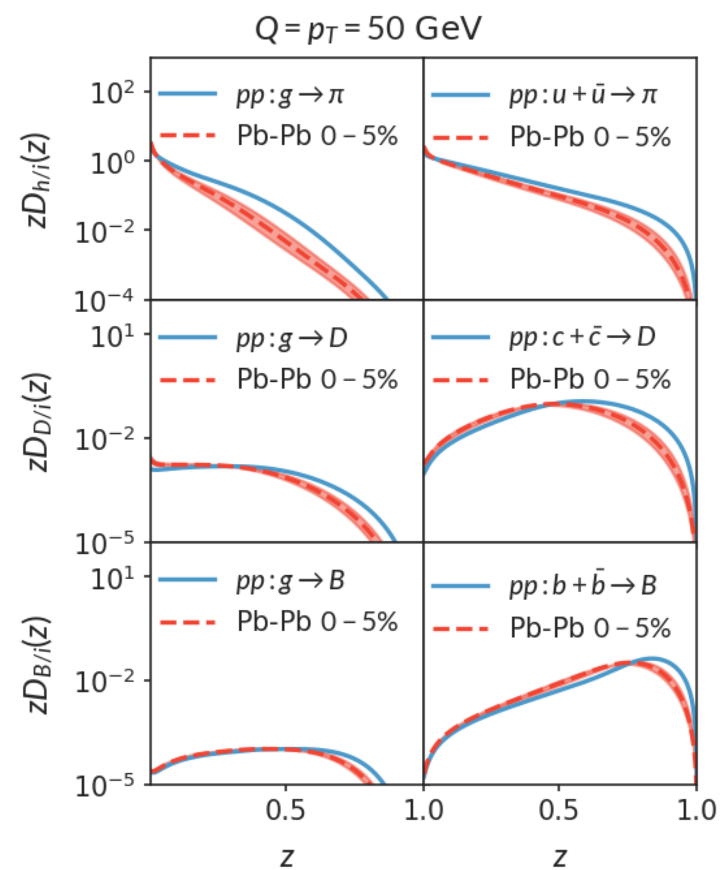
$$\frac{\Delta E_{\rm el}}{E}\propto\int_{\tau_0}^{\tau_0+L}\mu^2 d\Delta z\propto L^{1/3}\qquad \frac{\Delta E_{\rm rad}}{E}\propto\int_{\tau_0}^{\tau_0+L}\frac{\mu^2}{\lambda_g}\Delta z d\Delta z\propto L$$

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

Light and heavy flavor fragmentation and evolution



Enhancement of soft branching and larger angle radiation



In-medium DGLAP evolution

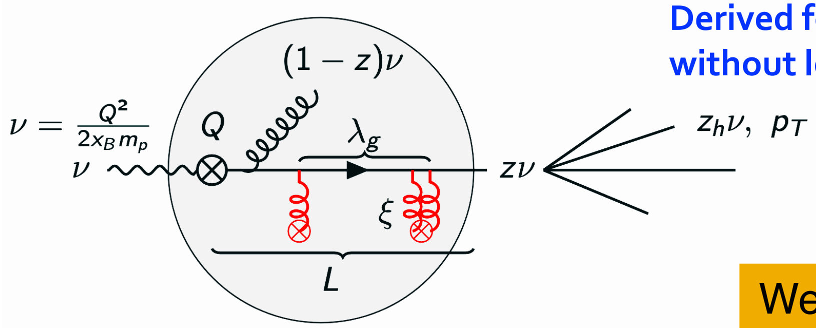
Z. Kang et al. (2014)

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

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

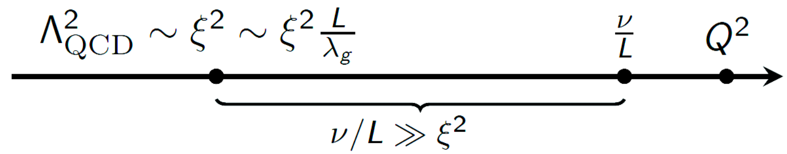
Additional medium-induced scaling violations

RG analysis of parton showers in nuclear matter



W. Ke et al. (2023)

Derived for DIS for simplicity (non-evolving medium, fixed scales) but without loss of generality



We encounter many ratios of scales in reactions with nuclei
Will resum large logarithms of Q/Qo and E/ξ²L

- We were able to identify a simple analytic limit of the splitting functions integrate the transverse degrees of freedom using dim. reg. and isolate the endpoint divergences

$$\Delta F_{\rm NS}^{\rm med}(z) = \int_z^1 \frac{dx}{x} F_{\rm NS}\left(\frac{z}{x}\right) P_{qq}^{\rm med(1)}(x) \quad + \quad \text{virtual term.}$$

Color non-singlet distribution as an example

$$P_{qq}^{\rm med(1)}(x) = A(\alpha_s, \cdots) \cdot \frac{P_{qq}^{vac(0)}(x)}{[x(1-x)]^{1+2\epsilon}} \cdot \left[\frac{\mu^2 L}{\chi z \nu}\right]^{2\epsilon} \cdot C_n \Delta_n(x)$$

$$\Delta F_{\rm NS}(z) = A(\alpha_s, \cdots)\left(\frac{1}{2\epsilon} + \ln\frac{\mu^2 L}{\chi z \nu}\right) 2C_F[\underbrace{2C_A\left(-\frac{d}{dz} + \frac{1}{z}\right)}_{\text{from } x\to 1} + \underbrace{\frac{C_F}{z}}_{x\to 0}]F_{\rm NS}(z) + \text{F.O.}$$

- Divergences are cancelled by the soft-collinear sector

A new set of evolution equations

- Derived a full set of RG evolution equations. The NS distribution has a very elegant traveling wave solution

- **Color non-singlet**

$$\frac{\partial F_{\rm NS}(\tau,z)}{\partial\tau} = 2C_F\left(2C_A\frac{\partial}{\partial z} - \frac{2C_A+C_F}{z}\right)F_{\rm NS}$$

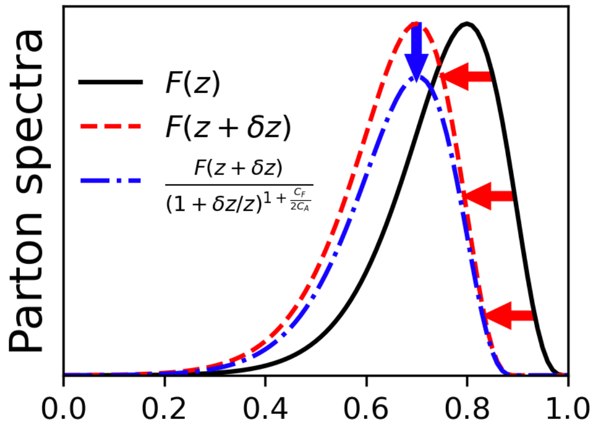
- **Color singlet**

$$\frac{\partial F_f}{\partial\tau} = \left(4C_FC_A\frac{\partial}{\partial z} - \frac{4C_FC_A+2C_F^2}{z}\right)F_f + 2C_FT_F\frac{F_g}{z},$$

$$\frac{\partial F_g}{\partial\tau} = \left(4C_A^2\frac{\partial}{\partial z} - \frac{2N_fC_F}{z}\right)F_g + 2C_F^2\sum_f\frac{F_f}{z}.$$

$$F_{\rm NS}(\tau,z) = \frac{F_{\rm NS}\left(0, z+4C_FC_A\tau\right)}{(1+4C_FC_A\tau/z)^{1+C_F/(2C_A)}}$$

$$\tau(\mu^2) = \frac{\rho_G L^2}{\nu}\frac{\pi B}{2\beta_0}\left[\alpha_s(\mu^2) - \alpha_s\left(\chi\frac{z\nu}{L}\right)\right]$$



Can directly identify parton energy loss, the nuclear size dependence of the modification, etc

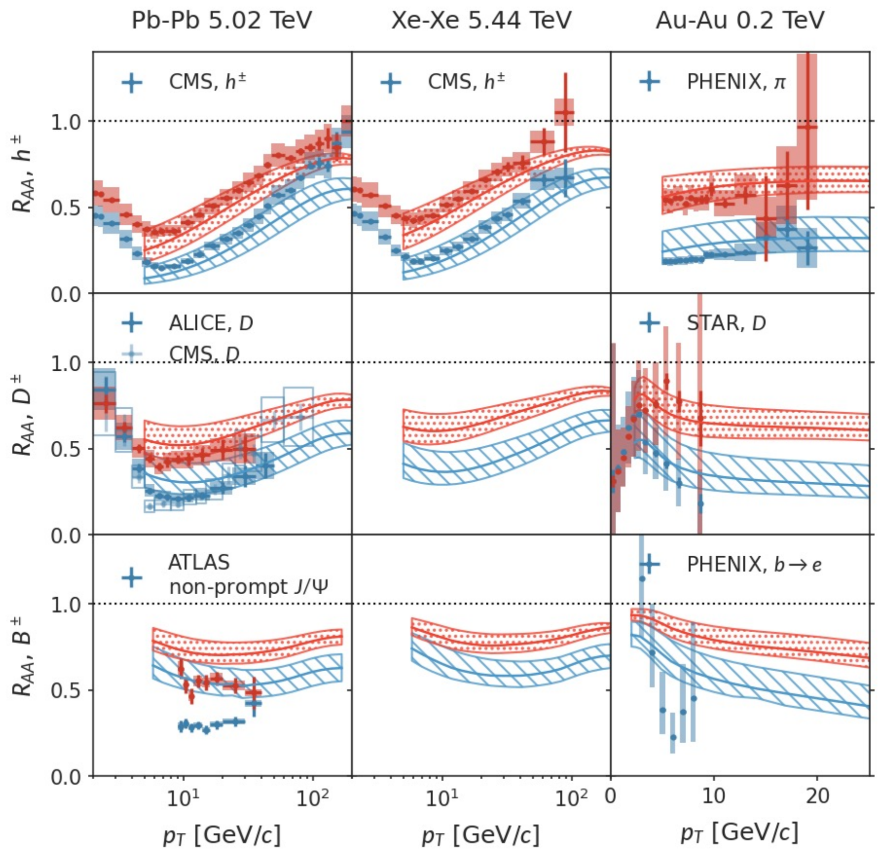
W. Ke et al. (2023)

With this knowledge, we were able to show that in-medium DGLAP evolution resumes the same enhanced logs of $E/\xi^2 L$

Phenomenological results

Large systems

Radiative processes dominate

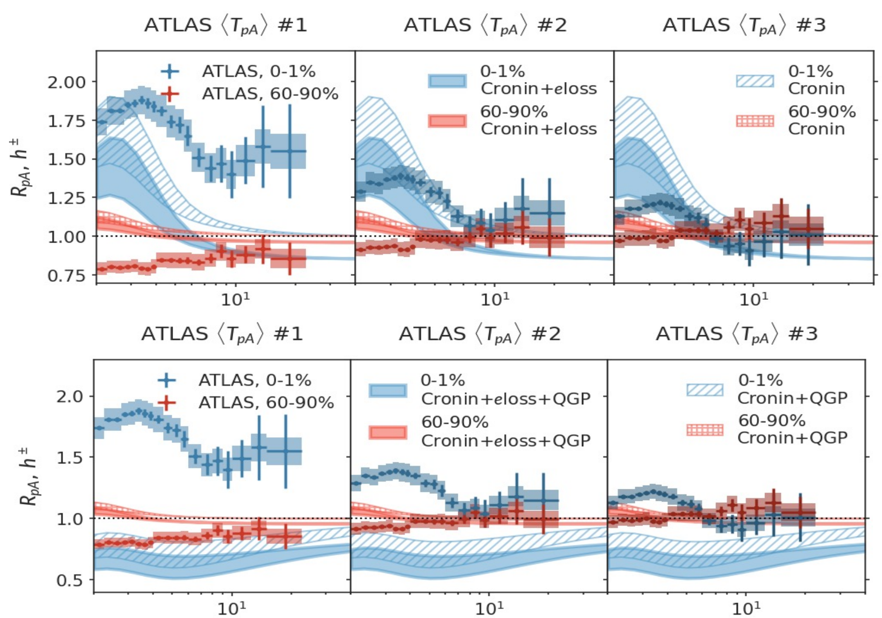


W. Ke et al. (2022)

Theoretical results agree with existing light hadron and D meson measurements at RHIC and LHC. True for both central and peripheral collisions

There is tension with the B meson production (or non-prompt J/psi). May be dissociation?

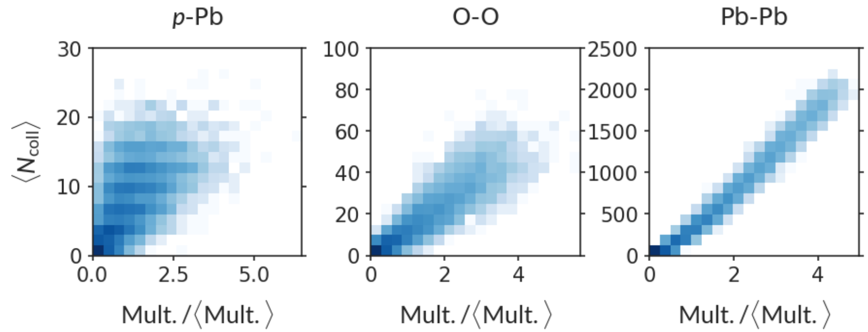
Small systems



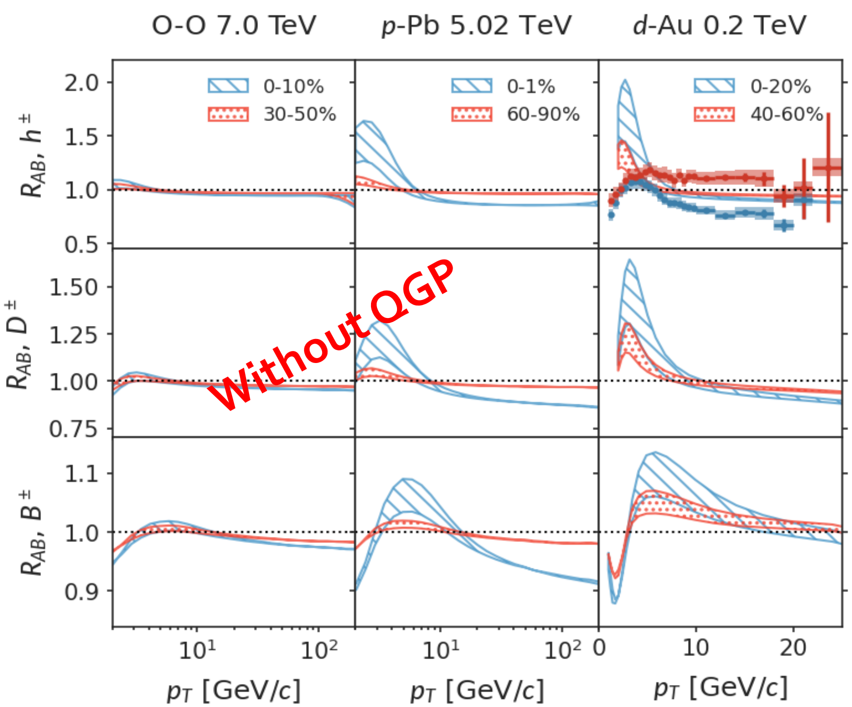
Centrality determination in p/d+A challenging. No room for quenching effects in p+Pb

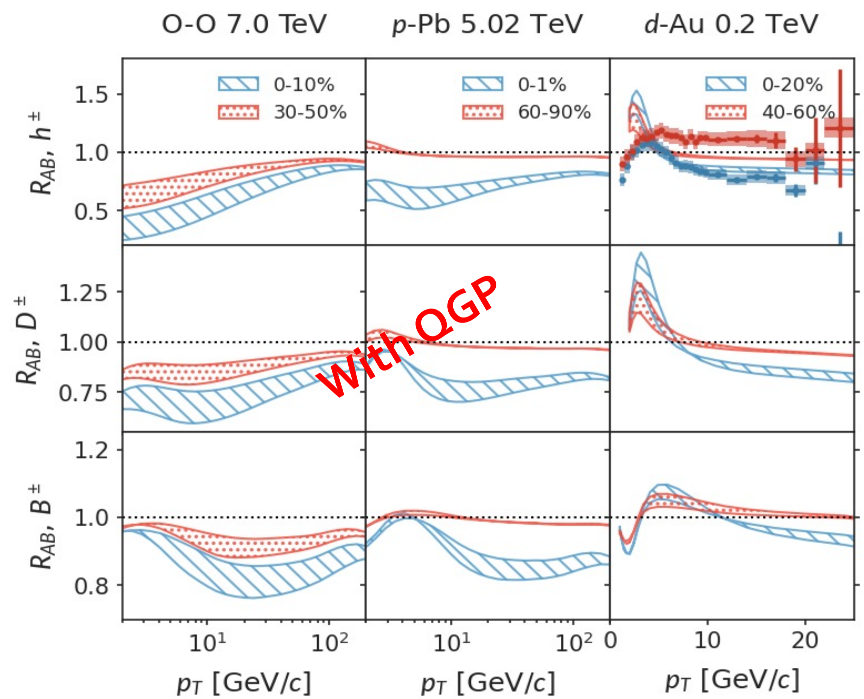
QGP in small systems?

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



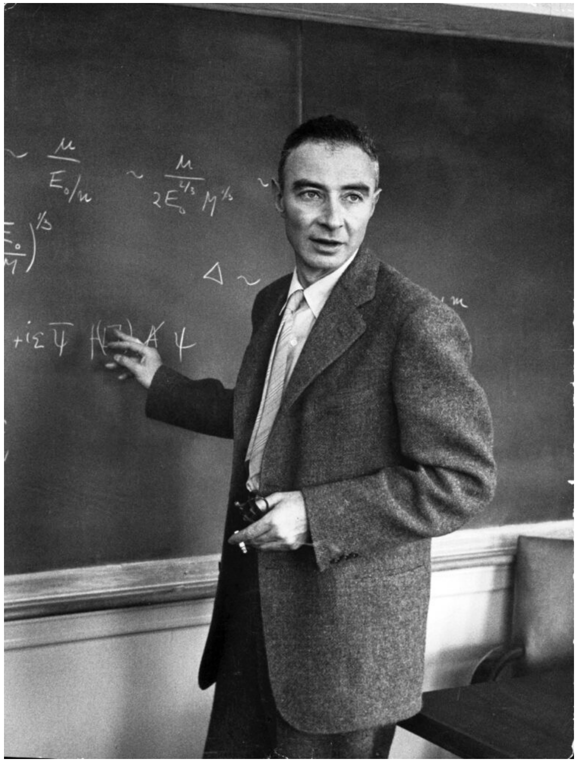
From jet quenching perspective whether QGP is produced or not can be easily distinguished in small systems (assuming good determination of centrality)





Fellowship opportunities at LANL

The T-2 group (Nuclear and Particle Physics, Astrophysics and Cosmology) in the Theoretical Division at Los Alamos National Laboratory invites applications for postdoctoral positions in Nuclear Theory to begin in Fall 2024.



We conduct research on a broad set of topics, including effective theories of strong and weak interactions, heavy-ion physics and physics of the quark-gluon plasma, low-energy phenomenology within and beyond the Standard Model, neutrino physics and astrophysics, nuclear astrophysics, nuclear structure, perturbative QCD, and quantum few- and many-body systems, and quantum computing. Candidates in all these areas are strongly encouraged to apply. Scientists in the group working in these areas include Carlson, Gandolfi, Fuyuto, Lee, Mereghetti, Neill, Tews and Vitev. We collaborate actively with our colleagues in high-energy theory and applied nuclear theory in T-2 and have close ties with our colleagues in astrophysics, cosmology, condensed matter/quantum information and experimental physics.

Exceptionally well qualified candidates may be considered for a Director's Postdoctoral Fellowship or Distinguished (Feynman/Oppenheimer) Postdoctoral Fellowship. Candidates wishing to be considered for these Fellowships must have all application materials submitted by **Monday, October 16, 2023**. Apply at https://academicjobsonline.org/ajo/jobs/25491

For eligibility and salary information, please see https://www.lanl.gov/careers/career-options/postdoctoral-research/index.php.

Conclusions

- Hadron production has been instrumental in the discovery of jet quenching and jet tomography at RHIC. First to benefit from modern QCD / SCET techniques in nuclear matter. Non-perturbative uncertainties remain but largely cancel in modification ratios
- We reported the first application of in-medium DGLAP evolution to heavy flavor hadrons in the QGP. Good description of light hadrons and D mesons in large systems. Small/intermediate p_T tension for B mesons (non-prompt J/Ψ)
- We performed a new renormalization group analysis of parton shower in nuclear matter. Derived and solved a new set of RG equations – faster and more efficient than mDGLAP, providing unique analytic insights
- An important question is whether QGP can be produced in small (p-sized) systems, jet quenching does not support that hypothesis at present at the LHC.
- At RHIC current results are not incompatible with the QGP assumption in d+Au, but uncertainties on centrality determination remain (now seem improved with direct photons)
- My personal opinion is that multiple observables have to be correlated and O+O is necessary - has to be compared/contrasted to p/dA - before we can draw firm conclusions about small systems

Nowadays we tend to see QGP everywhere