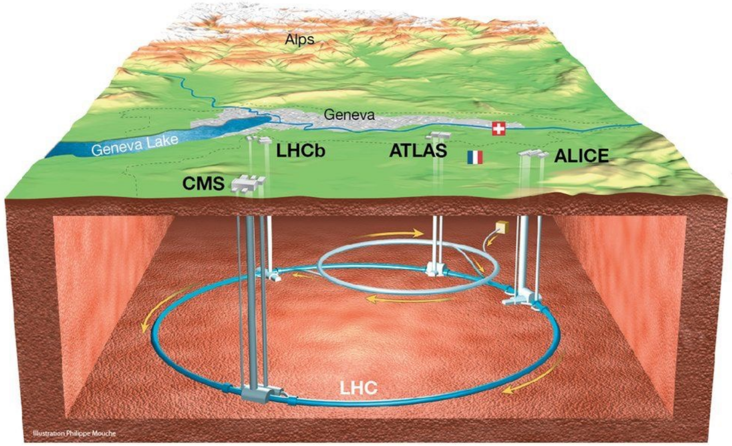
Ivan Vitev

# Jets & Heavy flavors: From HICs to EIC

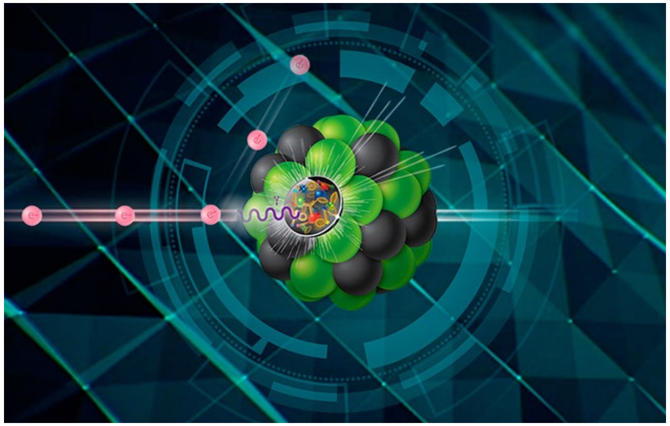
2022 QCD Town Hall Meeting on Hot and Cold QCD
MIT, Boston, MA
September 23-25, 2022

Los Alamos
NATIONAL LABORATORY
EST. 1943

# Outline of the talk



- Jets
- Open heavy flavor
- Quarkonia
- Conclusions



For complementary discussion for jets and heavy flavor … , see other talks in the townhall

Acknowledgment of support

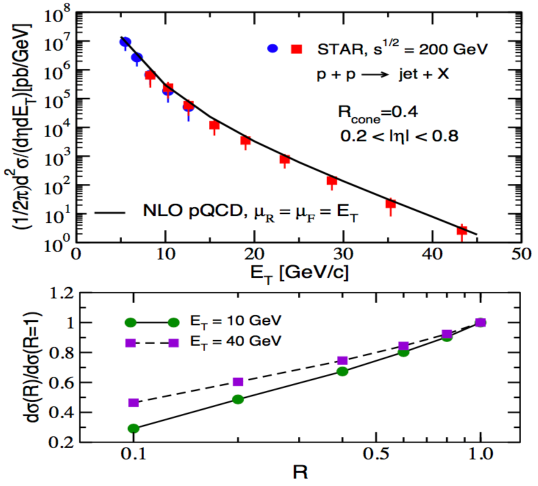
U.S. DEPARTMENT OF ENERGY
Office of Science

TMD Collaboration

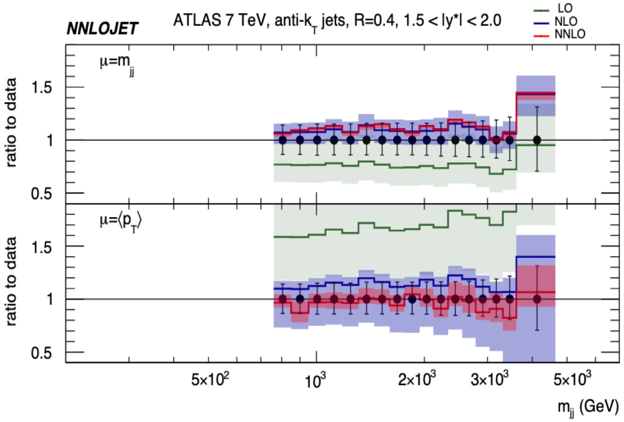
LDRD
LABORATORY DIRECTED RESEARCH & DEVELOPMENT

# Production of hard probes

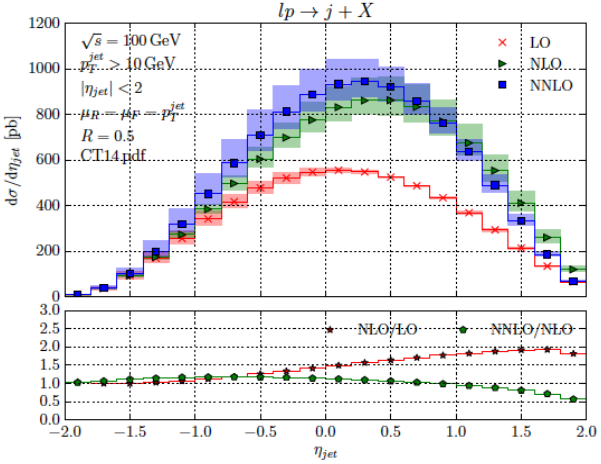
Based on QCD / SCET factorization. Calculations at next-to-leading order (and resummation where applicable) are standard. Calculations at NNLO also exist but still time consuming



I. Vitev et al. (2009)



A. Gehrmann-De Ridder et al. (2018)



G. Abelof et al. (2016)

**Hadrons**

$$E_h \frac{d^3\sigma^{\ell N\to hX}}{d^3P_h} = \frac{1}{S}\sum_{i,f}\int_0^1 \frac{dx}{x}\int_0^1 \frac{dz}{z^2}\, f^{i/N}(x,\mu)$$

$$\times\, D^{h/f}(z,\mu)\left[\hat{\sigma}^{i\to f} + f_{\rm ren}^{\gamma/\ell}\left(\frac{-t}{s+u},\mu\right)\hat{\sigma}^{\gamma i\to f}\right].$$

**Factorization Examples (ep)**

**Similarly pp**

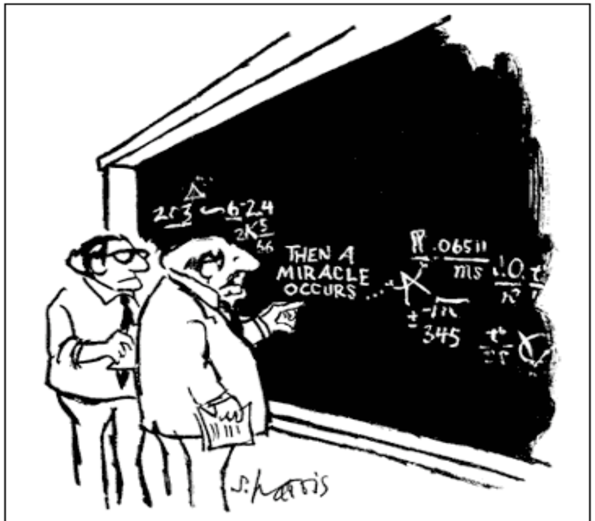
**Jets**

$$E_J \frac{d^3\sigma^{lN\to jX}}{d^3P_J} = \frac{1}{S}\sum_{i,f}\int_0^1 \frac{dx}{x}\int_0^1 \frac{dz}{z^2}\, f_{i/N}(x,\mu)$$

$$\times\, \hat{\sigma}^{i\to f}(s,t,u,\mu)\, J_f(z, p_T R, \mu)\,,$$

For more discussion see EIC theory workshop: https://indico.bnl.gov/event/16740/

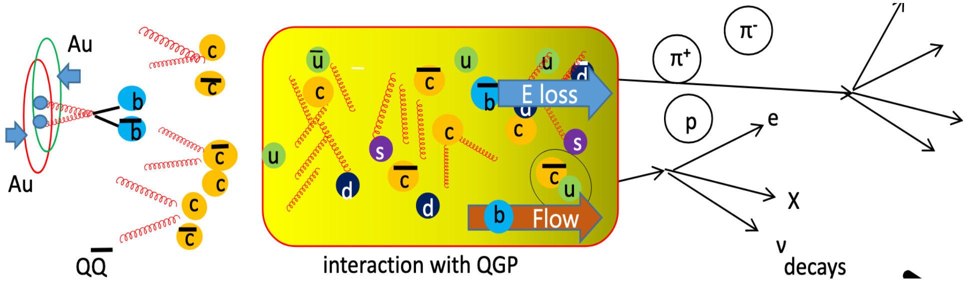
# Jets



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

# Energy loss in QCD matter

## For light partons radiative energy loss dominates



| | |
|---|---|
| BDMPS-Z | R. Baier et al . (1997) |
| GLV | M. Gyulassy et al . (2000) |
| HT | X. Guo et al . (2000) |
| AMY | P. Arnold et al. (2002) |

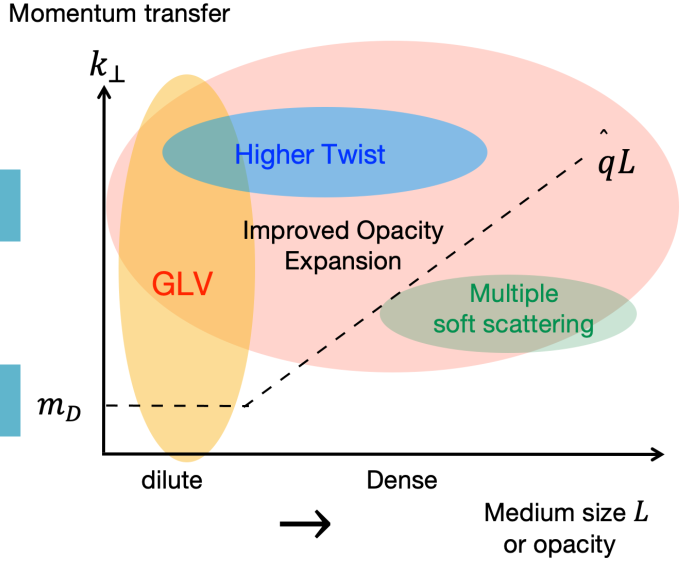
## Connecting different regimes and formalisms

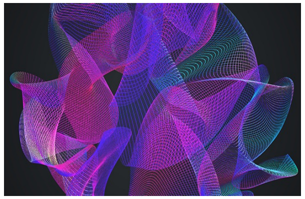
- Numerical approaches

S. Caron-Huot et al . (2016) | C. Andres et al . (2020)

- Analytic approaches, e.g. improved opacity expansion (IOE)

Y. Mehtar-Tani (2019) | J. Barata et al. (2021)





$$\frac{dp_1}{dt} = -\frac{\pi\sqrt{g_{YM}^2 N}}{2}T^2\frac{v}{\sqrt{1-v^2}}$$

## Strong coupling / hybrid approaches

C. Herzog et al. (2006) | S. Gubser (2006)

J. Casalderey-Solana et al. (2006)

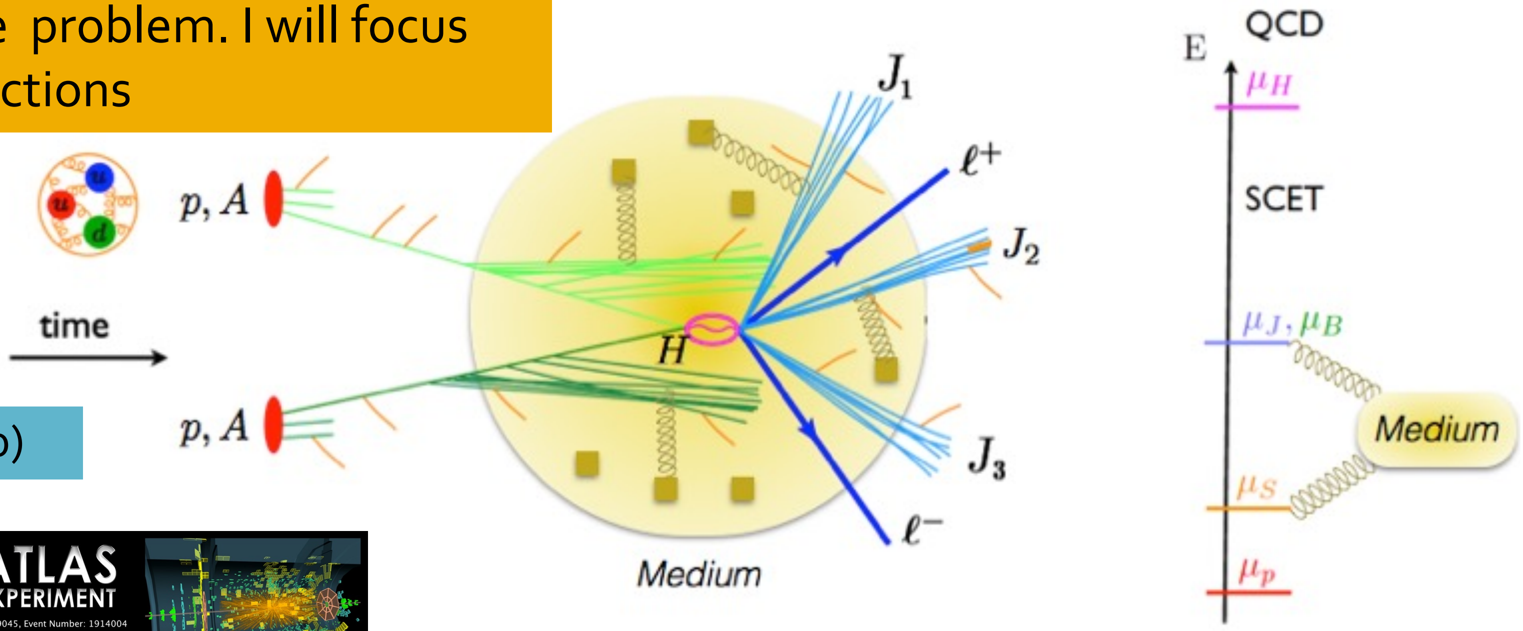
# EFTs for hard probes in matter

A. Idilbi et al. (2008)

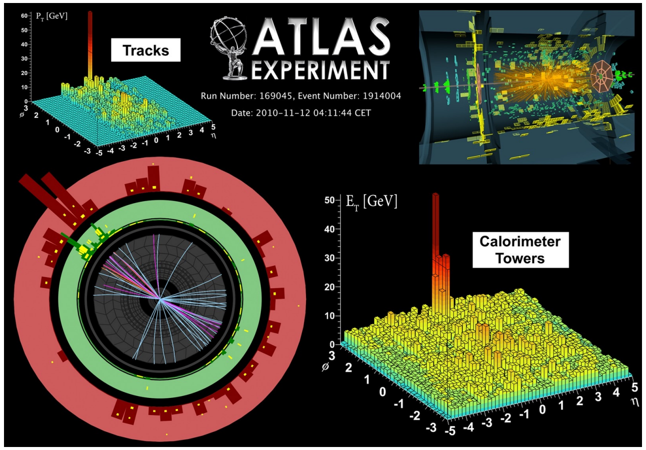
Ovanesyan et al. (2011)

V. Vaidya et al. (2021)

- QCD in the medium remains a multi-scale problem. I will focus on x+A reactions



Aad et al. (2010)



- Factorization, with modified J (jet), B (beam), S (soft) functions

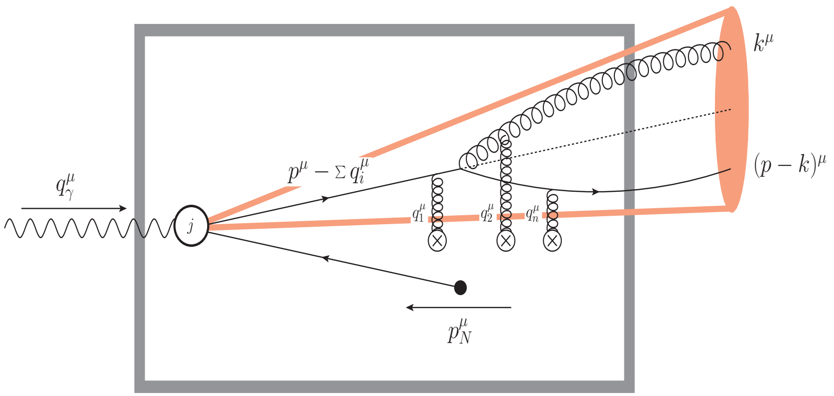
$$\sigma = \mathrm{Tr}(HS) \otimes \prod_{i=1}^{n_B} B_i \otimes \prod_{j=1}^{N} J_j + \text{power corrections}$$

# In-medium splitting functions

G. Ovanesyan et al . (2012)

Z. Kang et al . (2016)

M. Sievert et al . (2018)



**In-medium splitting functions necessary for higher order and resumed calculations**

**Develop specific EFTs for particle propagation in matter**

$$\frac{dN(tot.)}{dxd^2k_\perp} = \frac{dN(vac.)}{dxd^2k_\perp} + \frac{dN(med.)}{dxd^2k_\perp}$$

- Factorize form the hard part
- Gauge-invariant
- Depend on the properties of the medium
- Can be expressed as proportional to Altarelli-Parisi

**Representative example**

$$\left(\frac{dN}{dxd^2\boldsymbol{k}_\perp}\right)_{q\to qg} = \frac{\alpha_s}{2\pi^2}C_F\frac{1+(1-x)^2}{x}\int\frac{d\Delta z}{\lambda_g(z)}\int d^2\mathbf{q}_\perp\frac{1}{\sigma_{el}}\frac{d\sigma_{el}^{\text{medium}}}{d^2\mathbf{q}_\perp}\left[-\left(\frac{\boldsymbol{A}_\perp}{\boldsymbol{A}_\perp^2}\right)^2+\frac{\boldsymbol{B}_\perp}{\boldsymbol{B}_\perp^2}\cdot\left(\frac{\boldsymbol{B}_\perp}{\boldsymbol{B}_\perp^2}-\frac{\boldsymbol{C}_\perp}{\boldsymbol{C}_\perp^2}\right)\right.$$
$$\times\left(1-\cos[(\Omega_1-\Omega_2)\Delta z]\right)+\frac{\boldsymbol{C}_\perp}{\boldsymbol{C}_\perp^2}\cdot\left(2\frac{\boldsymbol{C}_\perp}{\boldsymbol{C}_\perp^2}-\frac{\boldsymbol{A}_\perp}{\boldsymbol{A}_\perp^2}-\frac{\boldsymbol{B}_\perp}{\boldsymbol{B}_\perp^2}\right)\left(1-\cos[(\Omega_1-\Omega_3)\Delta z]\right)$$
$$+\frac{\boldsymbol{B}_\perp}{\boldsymbol{B}_\perp^2}\cdot\frac{\boldsymbol{C}_\perp}{\boldsymbol{C}_\perp^2}\left(1-\cos[(\Omega_2-\Omega_3)\Delta z]\right)+\frac{\boldsymbol{A}_\perp}{\boldsymbol{A}_\perp^2}\cdot\left(\frac{\boldsymbol{A}_\perp}{\boldsymbol{A}_\perp^2}-\frac{\boldsymbol{D}_\perp}{\boldsymbol{D}_\perp^2}\right)\cos[\Omega_4\Delta z]$$
$$\left.+\frac{\boldsymbol{A}_\perp}{\boldsymbol{A}_\perp^2}\cdot\frac{\boldsymbol{D}_\perp}{\boldsymbol{D}_\perp^2}\cos[\Omega_5\Delta z]+\frac{1}{N_c^2}\frac{\boldsymbol{B}_\perp}{\boldsymbol{B}_\perp^2}\cdot\left(\frac{\boldsymbol{A}_\perp}{\boldsymbol{A}_\perp^2}-\frac{\boldsymbol{B}_\perp}{\boldsymbol{B}_\perp^2}\right)\left(1-\cos[(\Omega_1-\Omega_2)\Delta z]\right)\right].$$

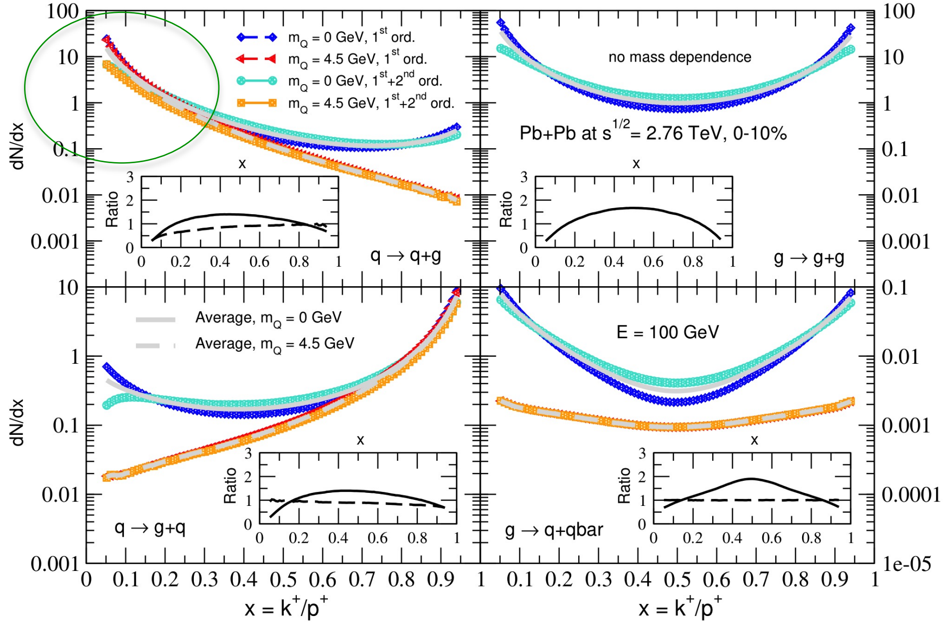
**Large number of scatterings limit**

J. Blaizot et al . (2013)

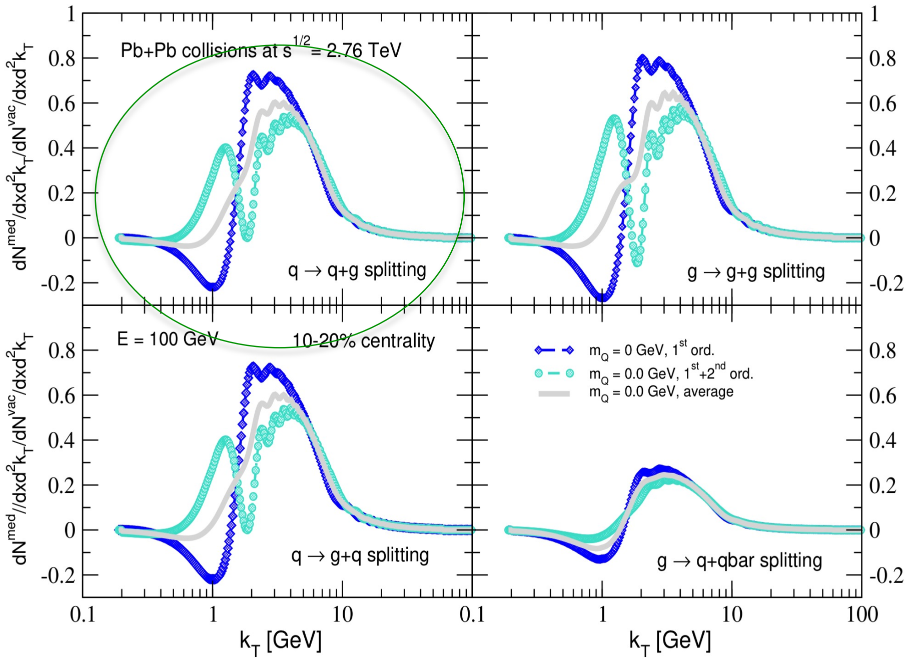
L. Apolinario et al . (2014)

# Differential branching spectra

M. Sievert et al . (2019)



- Production of hadrons and jets can be understood from the broader and softer splitting functions
- Holds to higher orders in opacity
- Numerical evaluation using modern ML techniques

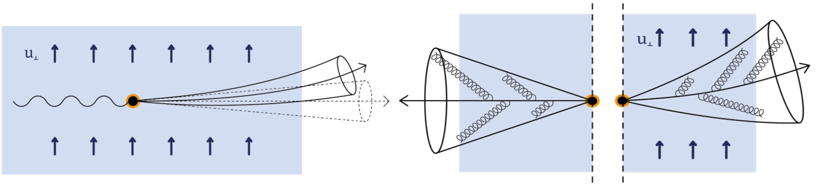


**Most importantly – additional medium-induced contribution to factorization formulas (final-state) – Additional scaling violation due to the medium-induced shower. Additional component to jet functions**

Novel phenomenology - higher order and resumed calculations that bridge the gap between HEP and HP

# Effect of medium motion and inhomogeneities

- In the QGP - transverse and longitudinal expansion, rotation at non-zero impact parameter, fluctuations
- Cold nuclear matter – orbital motion of nucleons, breakup of the nucleus, color charge fluctuations



A. Sadofyev et al . (2021)

**Effects on broadening and radiation**

- Several selected results

**Scattering**

$$\langle \boldsymbol{p}_\perp \rangle = 3 \frac{\boldsymbol{u}_\perp}{(1-u_z)} \frac{L}{\lambda} \frac{\mu^2}{E} \ln \frac{E}{\mu}$$

**Radiation**

$$\left\langle \frac{\boldsymbol{k}_\perp}{k_\perp^2} \right\rangle = \frac{N_c}{C_F} \frac{L}{\lambda} \frac{\boldsymbol{u}_\perp}{8(1-u_z)xE}$$

$$E \frac{dN^{(1)}}{d^2k_\perp \, dx \, d^2p_\perp \, dE} = \frac{\alpha_s \, N_c}{\pi^2 x} \left( E \frac{dN^{(0)}}{d^2p_\perp \, dE} \right) \int_0^L dz \, \rho \int d^2q_\perp \bar{\sigma}(q_\perp^2)$$
$$\times \left\{ \frac{2\boldsymbol{k}_\perp \cdot \boldsymbol{q}_\perp}{k_\perp^2 (k-q)_\perp^2} \left( 1 - \cos \left( \frac{(k-q)_\perp^2}{2xE} z \right) \right) + \frac{q_\perp^2}{k_\perp^2 (q_\perp^2 + \mu^2)} \frac{\boldsymbol{u}_\perp \cdot \boldsymbol{k}_\perp}{2(1-u_z)xE} \right\}$$

**MC by boosting to local rest frame**

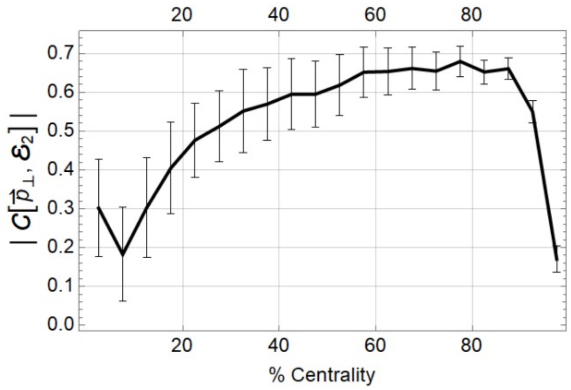
Y. He et al . (2020)

- Jet drift and its characterization via Pearson coefficients

L. Antiporda et al . (2022)

$$\langle \vec{p}_\perp \cdot \boldsymbol{\mathcal{V}}_2 \rangle = \left\langle (\vec{p}_\perp \cdot \hat{e}_\perp) \, v_2 \, e^{2i(\theta - \psi_2)} \right\rangle$$

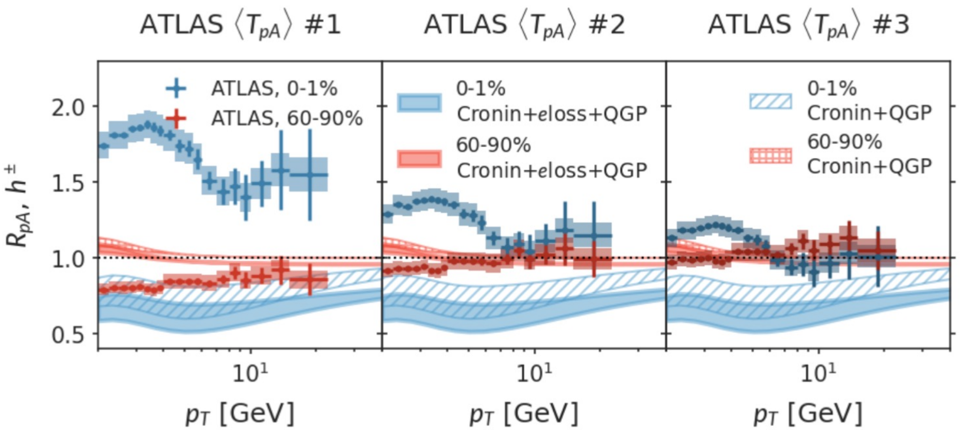
$$\mathcal{C}[\vec{p}_\perp, \boldsymbol{\mathcal{V}}_2] \equiv \frac{\left\langle (\vec{p}_\perp \cdot \hat{e}_\perp) \, v_2 \, e^{2i(\theta - \psi_2)} \right\rangle}{\mathcal{J}_2\{2\} \, v_2\{2\}} \approx \frac{\left\langle (\vec{p}_\perp \cdot \hat{e}_\perp) \, \varepsilon_2 \, e^{2i(\theta - \psi_2)} \right\rangle}{\mathcal{J}_2\{2\} \, \varepsilon_2\{2\}} = \mathcal{C}[\vec{p}_\perp, \boldsymbol{\mathcal{E}}_2]$$



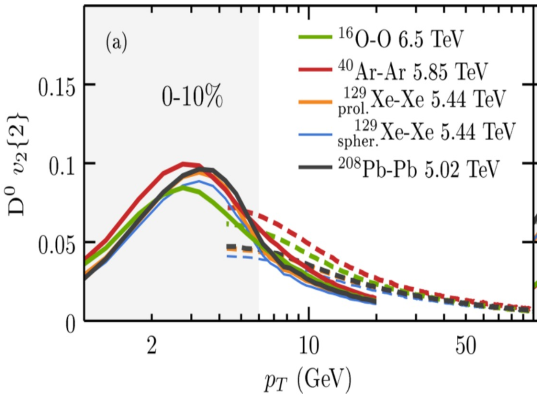
# Quenching in small systems

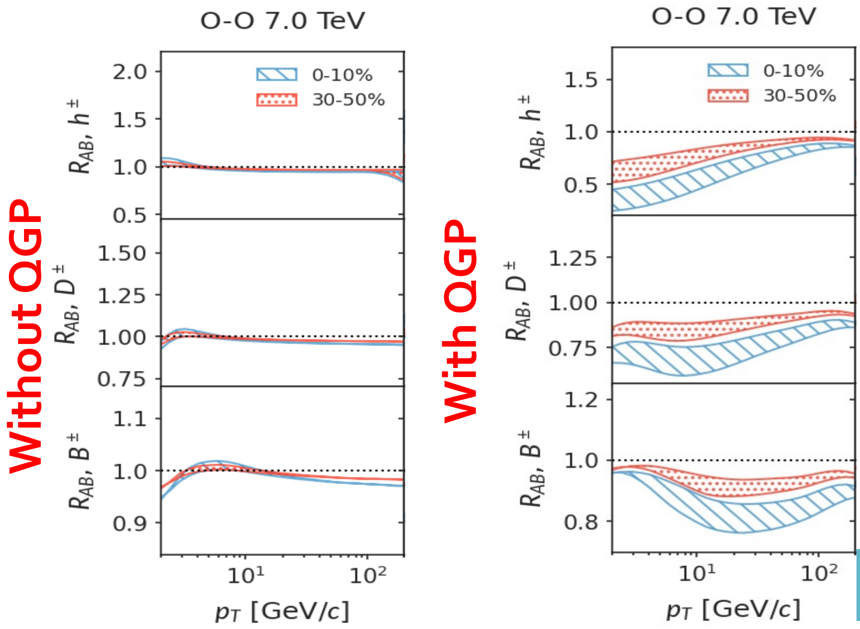
- In small systems (e.g. pPb, dAu) azimuthal asymmetries have been measured, interpreted as possible signatures of QGP formation
- No evidence for jet quenching measurements. In fact, incompatible with jet quenching phenomenology

W. Ke et al. (2022)



R. Katz et al . (2020)





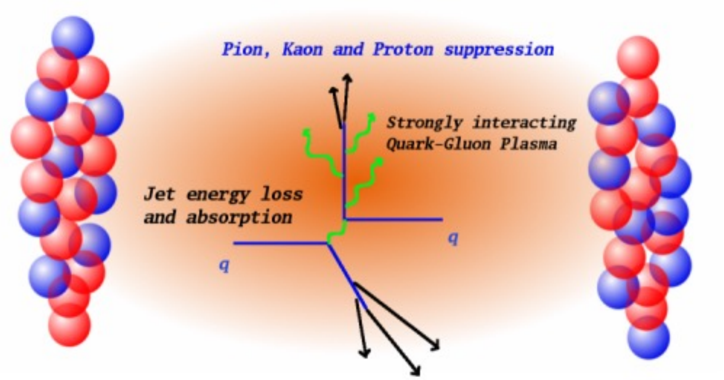
Significant interest in small symmetric systems, such as OO, to better constrain centrality and put limits on the smallest QGP droplets in nature

A. Huss et al . (2021)

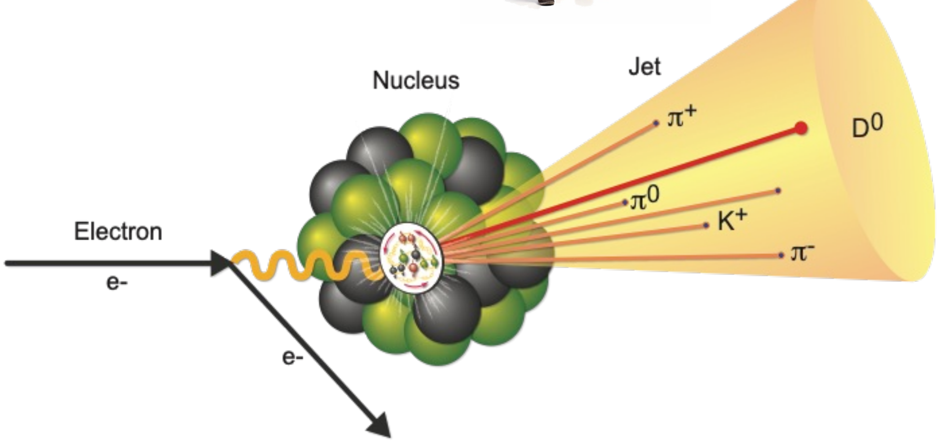
# Understanding the AA and eA connection

- AA and eA collisions share a lot of similar physics. Due to the LPM effect the "energy loss" decreases rapidly with energy. The kinematics to look for in-medium interactions / effects on hadronization is very different

Imagine sitting on the nucleus



- Jets at any rapidity roughly in the co-moving plasma frame (Only~ transverse motion at any rapidity)
- Largest effects at midrapidity
- Higher C.M. energies correspond to larger plasma densities



- Jets are on the nuclear rest frame Longitudinal momentum matters
- Largest effects are at forward rapidities
- Smaller C.M. energies (larger only increase the rapidity gap)

# Jet results at the EIC

- The physics of reconstructed jet modification

H. Li et al. (2020)

$$R_{eA}(R) = \frac{1}{A}\frac{\int_{\eta 1}^{\eta 2} d\sigma/d\eta dp_T\big|_{e+A}}{\int_{\eta 1}^{\eta 2} d\sigma/d\eta dp_T\big|_{e+p}}$$

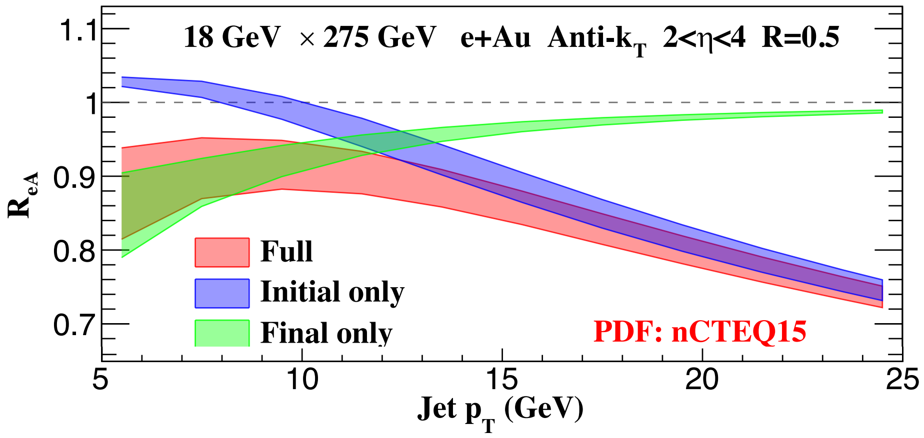
**Physics very similar to HIC**

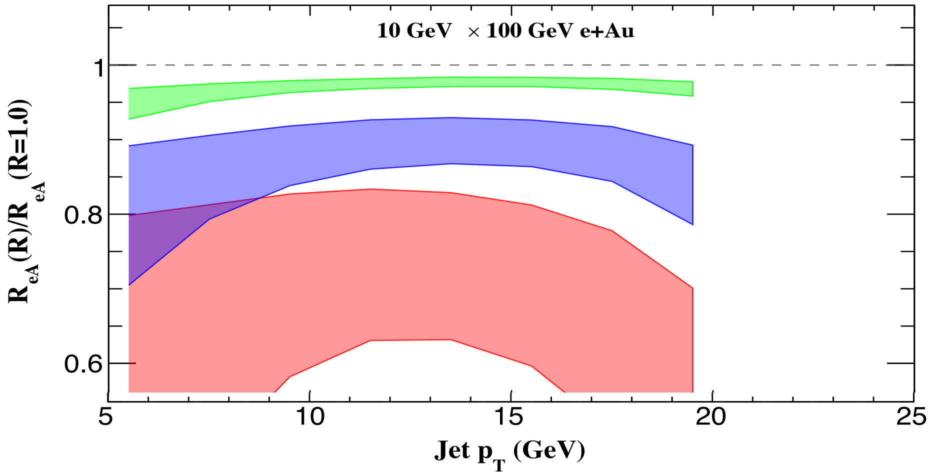
- Initial-state effects parametrized in nuclear parton distribution functions or nPDFs
- Final-state effects from the interaction of the jet and the nuclear medium – in-medium parton showers

$$J_q^{\mathrm{med},(1)}(z,\omega R,\mu) = \left[\int_{z(1-z)\omega\tan(R/2)}^{\mu} dq_\perp P_{qq}(z,q_\perp)\right]_+ + \int_{z(1-z)\omega\tan(R/2)}^{\mu} dq_\perp P_{gq}(z,q_\perp)\,. \quad (15)$$

**Similar strategy, new results**

$$R_R = R_{eA}(R) / R_{eA}(R=1)$$



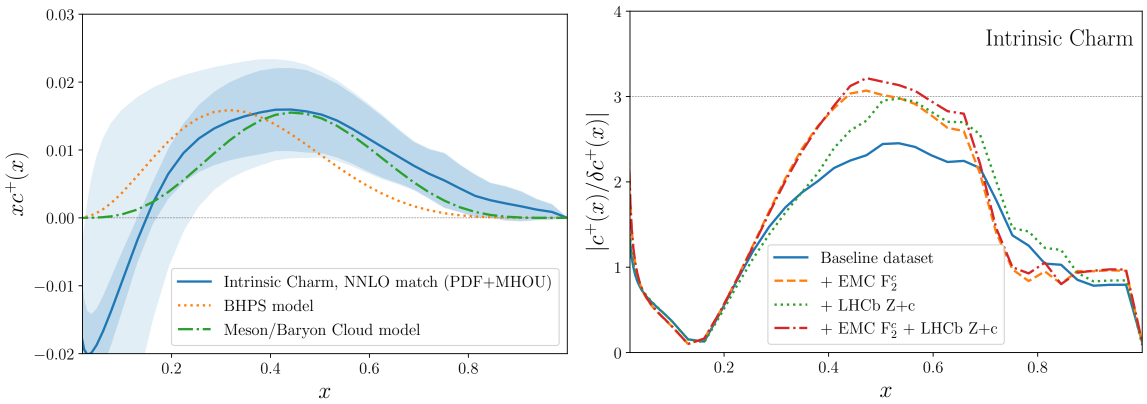


Jets at EIC will shed light on the long-standing question of initial vs final state effects in cold nuclear matter, CNM transport properties

# Open heavy flavor

# New developments in intrinsic charm

- Machine learning applications for subtle signals in hadron structure now exist. New analysis adds to hints from baseline dataset

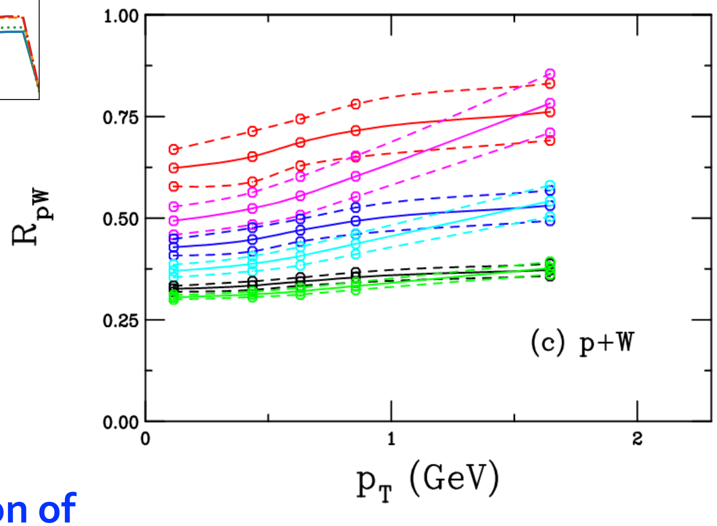


**NNPDF Collab. (2022)**

- Extraction of intrinsic charm compared to models
- Effect of EMC and LHCb Z+c jet data on IC statistical significance (3σ)

**Can be tested by $F_2^{charm}$ at the EIC**

**T. Hobbs et al . (2017)**



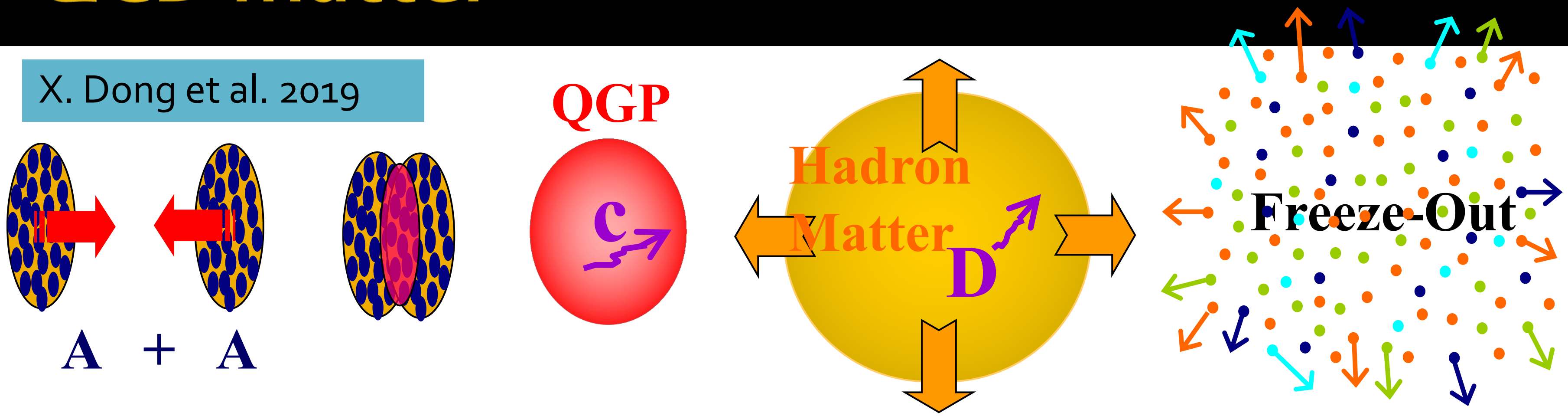
- Opportunity to develop new phenomenology / strategies to search for intrinsic charm in p+A and at the the EIC

**Intrinsic charm can be reflected in the nuclear modification of J/Ψ at forward rapidity/$x_F$/x. Example of p+A reactions with 0.1%, 0.3%, and 1% intrinsic charm**

**R. Vogt. (2021)**

# Heavy quarks as Brownian markers of QCD matter

X. Dong et al. 2019



- Produced early, diffuse through QCD medium
- Large mass ($m_Q/T >> 1$) → thermalization delayed → memory of interaction

$\Rightarrow$ direct access to transport coefficient:

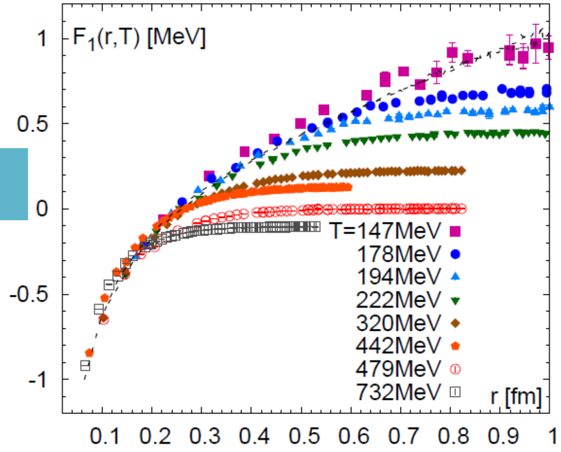
$$\langle x^2\rangle - \langle x\rangle^2 = 6\, \mathcal{D}_s\, t$$

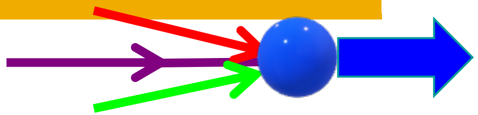
## Strongly Coupled Approach

- Hydrodynamics for bulk medium
- In-medium heavy-quark interactions ↔ lattice QCD
- Probe of hadronization mechanisms:

$$c \longrightarrow D,\ D_s,\ \Lambda_c,\ \ldots,$$

S. Liu et al. 2017



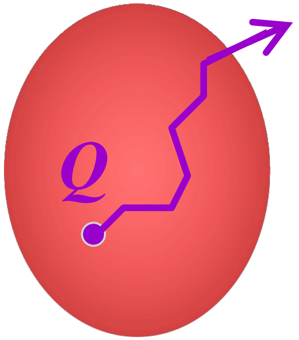


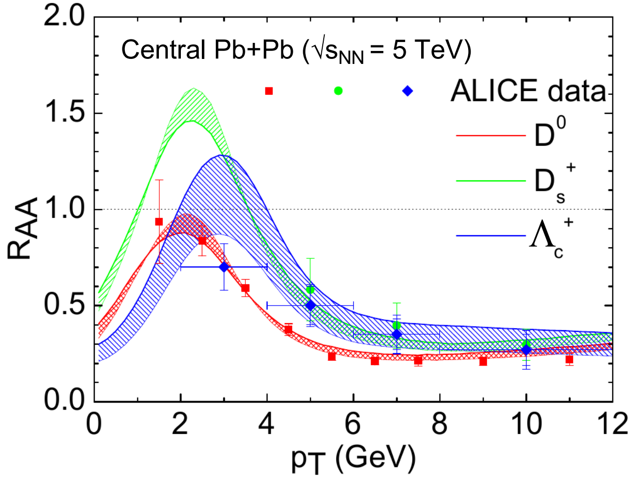
# Heavy quarks as Brownian markers of QCD matter

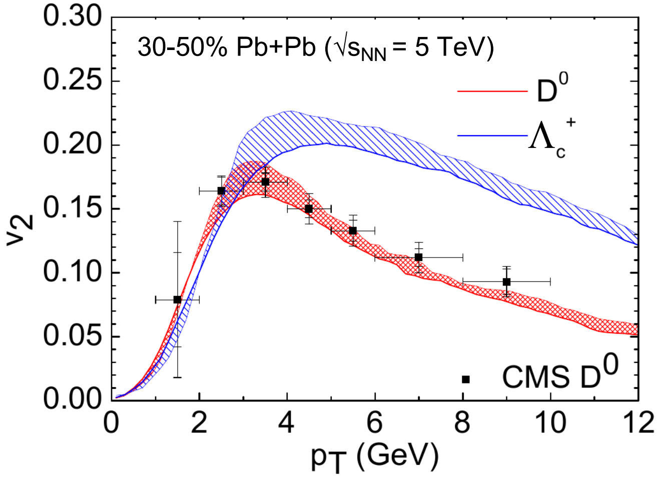
**Fokker-Planck:**

$$\frac{\partial}{\partial t} f_Q(t,\boldsymbol{p}) = \gamma \frac{\partial}{\partial p_i}\left[p_i f_Q(t,\boldsymbol{p})\right] + D\Delta_{\boldsymbol{p}} f_Q(t,\boldsymbol{p})$$

M. He et al. 2019

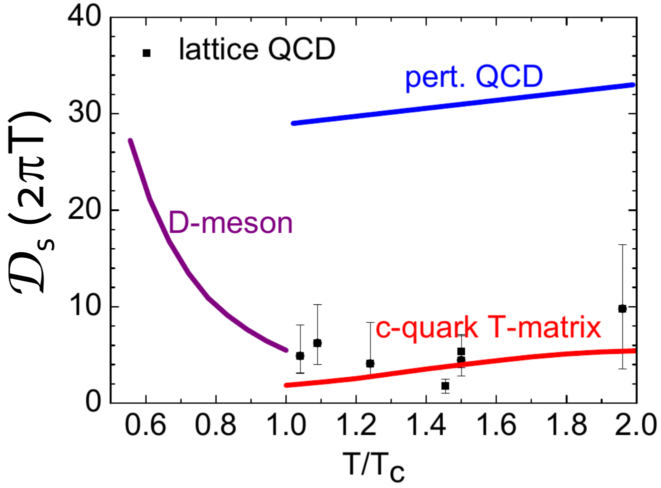






- Hierarchy of hadronic species ⟶ signature of quark recombination

- Large elliptic flow
  ⟶ heavy quarks "dragged" along by QCD fireball
  ⇒ $(2\pi T)\mathcal{D}_s$ near lower quantum bound (~1)
- sPHENIX: much improved sensitivity with bottom!
- EIC: cold matter + hadronization

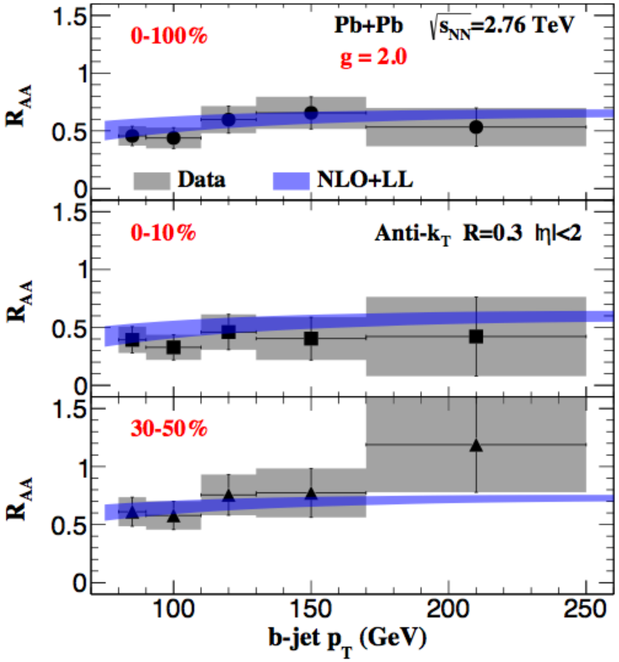


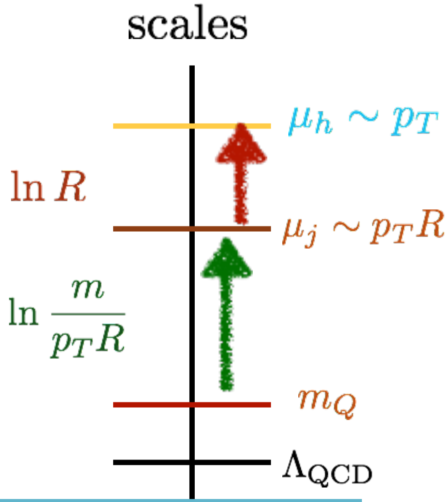
# Charm and beauty jet production

The semi-inclusive jet function formalism can be extended to HF jets. Good description of exp. data in hadronic collisions

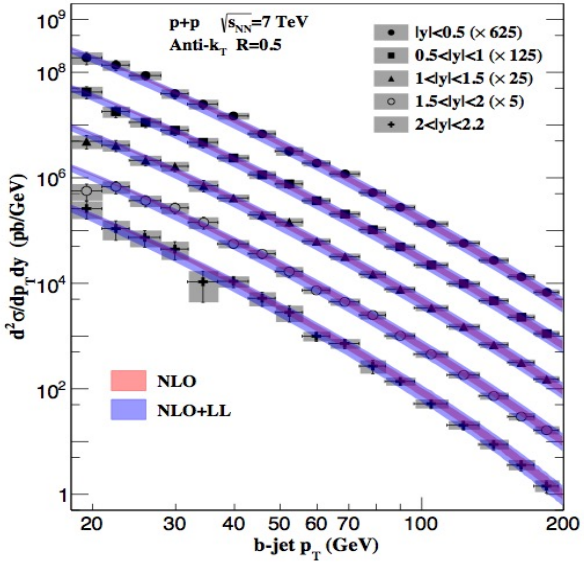
C. Bauer et al. (2013)

L. Dai et al. (2016) (2018)





H. Li et al. (2019)



- In addressing heavy flavor quenching, care should be taken in accounting for the significant gluon contribution to the charm and beauty production
- Control over the relative contribution of CNM effects, radiative and collisional energy losses is important
- Significant effort is needed to understand the transition form the low $p_T$ diffusive regime

M. Djordjevic et al. (2017)

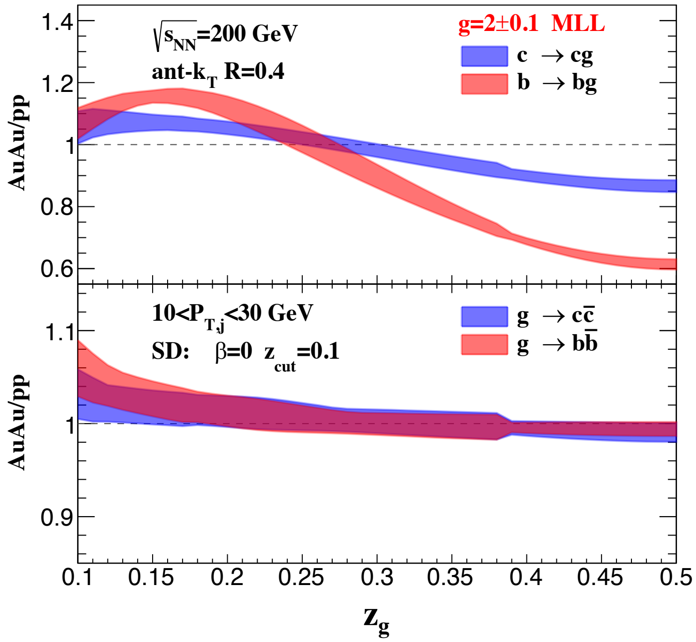
# Heavy flavor jet substructure

At RHIC jet energies, and at lower jet energies at the LHC there is a unique reversal of the mass hierarchy of jet quenching effects on jet substructure

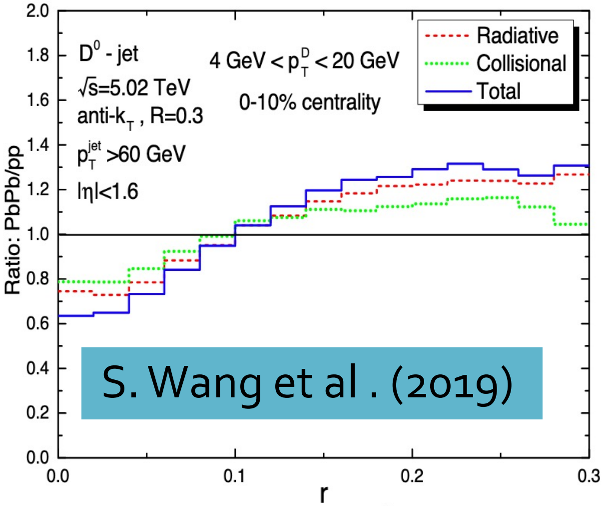
$$\frac{p_{med}^{Q\to Qg}(z_g)}{p_{pp}^{Q\to Qg}(z_g)} \sim \frac{1}{z_g^2}, \quad \frac{p_{med}^{j\to i\bar{i}}(z_g)}{p_{pp}^{j\to i\bar{i}}(z_g)} \sim \frac{1}{z_g}, \quad \frac{p_{med}^{g\to Q\bar{Q}}(z_g)}{p_{pp}^{g\to Q\bar{Q}}(z_g)} \sim \text{const.}$$

**Groomed, soft dropped momentum sharing distributions**

H. Li et al . (2018)

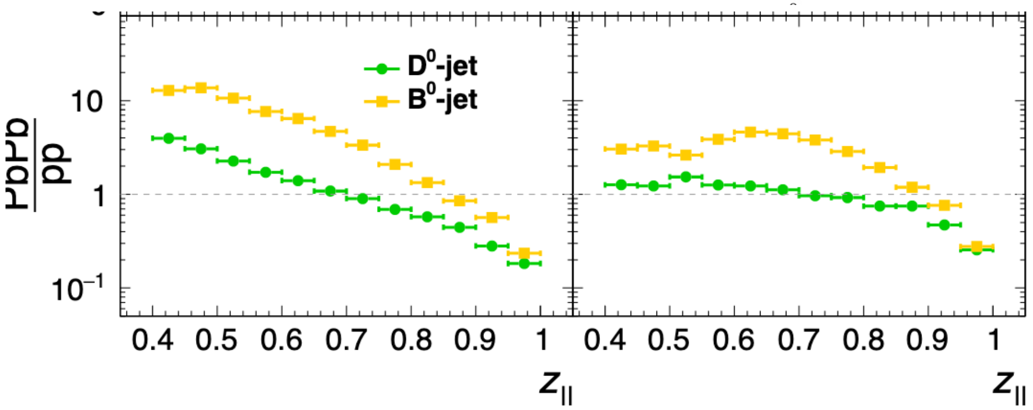


**On can extend the studies to D and B meson transverse and longitudinal profile modification in jets and look for signatures of the dead cone effect in A+A**



S. Wang et al . (2019)

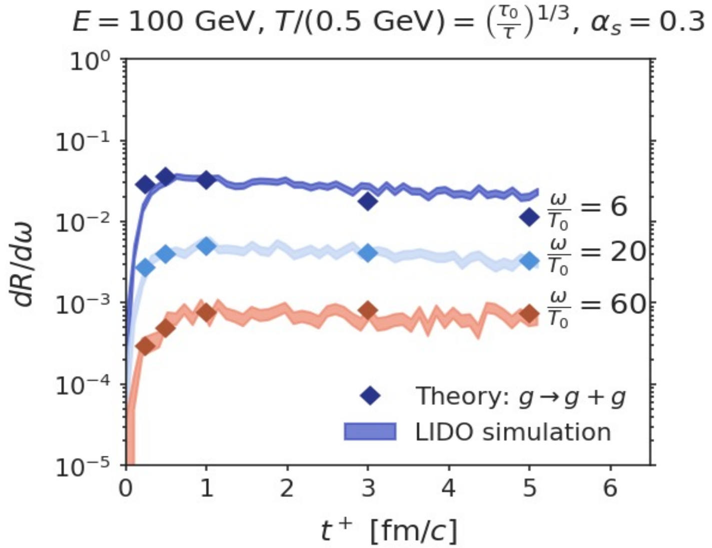
Y. Li et al. (2022)



# Heavy flavor in transport simulations - LIDO

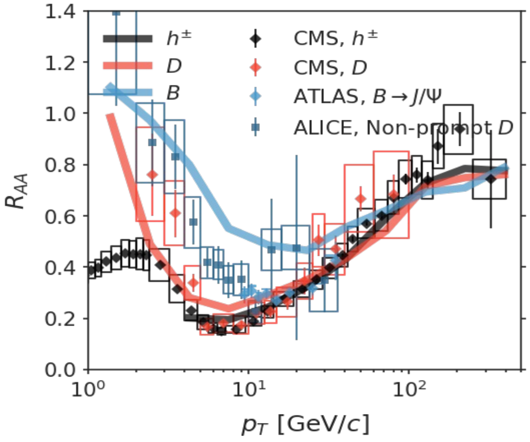
LIDO: partonic transport simulation of light & heavy-flavor dynamics in dense QGP

- $C_{nn}[f]$: diffusion + large-$q$ collisions.
- $C_{n(n+1)}[f]$: induced radiation, with dynamical implementation of LPM effect.

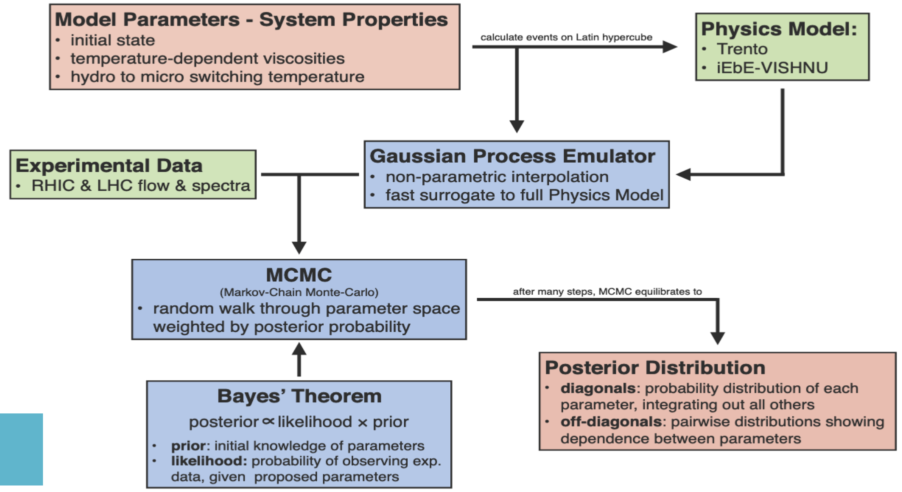


W. Ke et al. (2019)

**Recent progress made in the description of heavy flavor mesons and heavy flavor jets**



Toward constraining heavy flavor dynamics with Bayesian analysis



**Model Parameters - System Properties**
- initial state
- temperature-dependent viscosities
- hydro to micro switching temperature

calculate events on Latin hypercube

**Physics Model:**
- Trento
- iEbE-VISHNU

**Experimental Data**
- RHIC & LHC flow & spectra

**Gaussian Process Emulator**
- non-parametric interpolation
- fast surrogate to full Physics Model

**MCMC**
(Markov-Chain Monte-Carlo)
- random walk through parameter space weighted by posterior probability

after many steps, MCMC equilibrates to

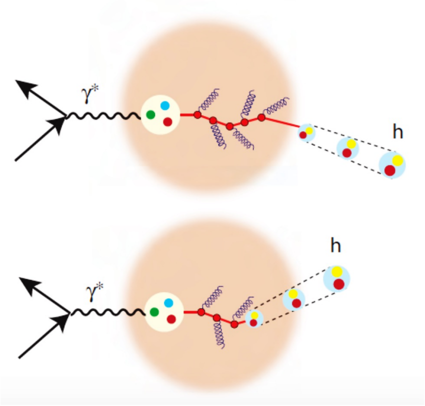
**Posterior Distribution**
- **diagonals**: probability distribution of each parameter, integrating out all others
- **off-diagonals**: pairwise distributions showing dependence between parameters

**Bayes' Theorem**
posterior ∝ likelihood × prior
- **prior**: initial knowledge of parameters
- **likelihood**: probability of observing exp. data, given proposed parameters

S. Bass et al. (2017)

# Heavy flavor at the EIC and the physics of hadronization

A. Accardi et al . (2009)

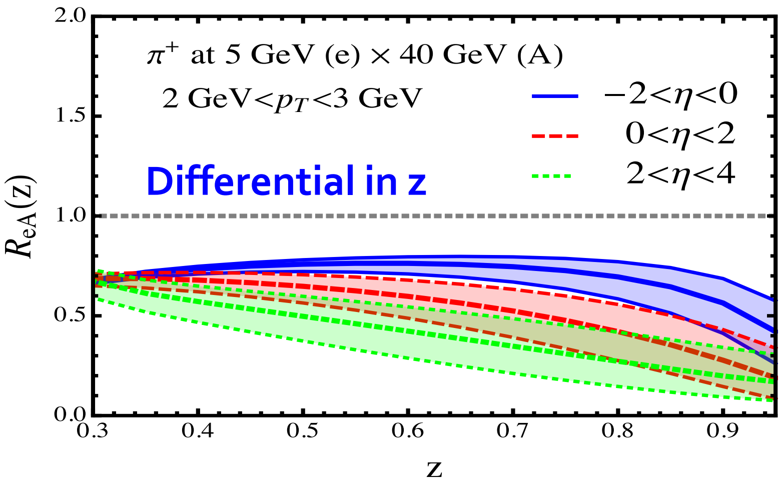


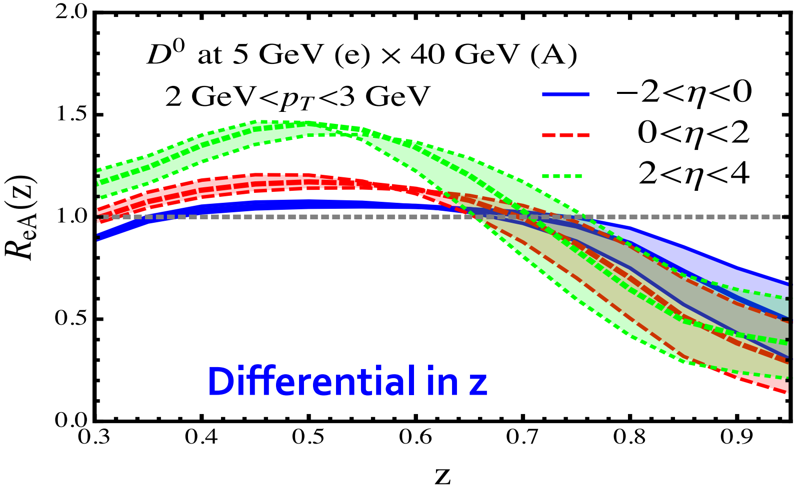
The space-time picture of hadronization is unknown. Competing explanations of hadron attenuation in large nuclei (HERMES), cannot be resolved with light hadrons

$$R^h_{eA}(p_T,\eta,z) = \frac{\left.\frac{N^h(p_T,\eta,z)}{N^{\rm inc}(p_T,\eta)}\right|_{\rm e+Au}}{\left.\frac{N^h(p_T,\eta,z)}{N^{\rm inc}(p_T,\eta)}\right|_{\rm e+p}}$$

**Effects are the largest at forward rapidities (p/A going) at the EIC**

**Light pions show the largest nuclear suppression at the EIC. However, to differentiate models of hadronization heavy flavor mesons are necessary**

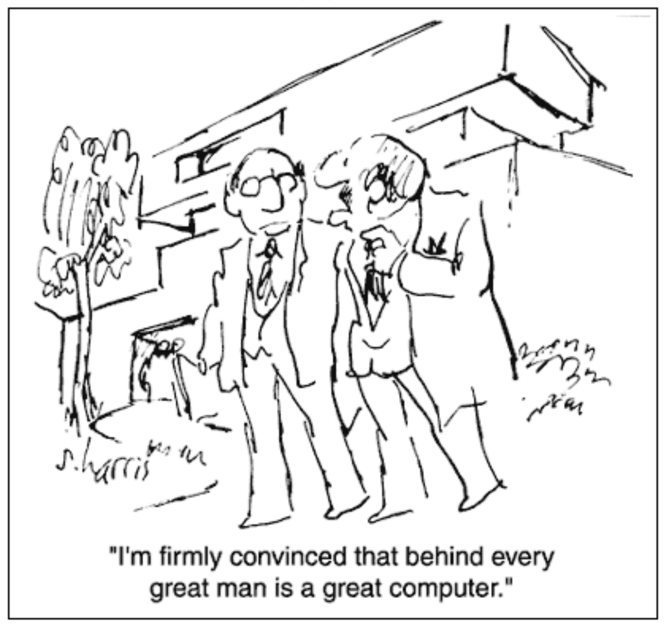




EIC theory will provide clear new insights into hadronization from light + heavy flavor

Z. Liu et al . (2020)

# Quarkonia



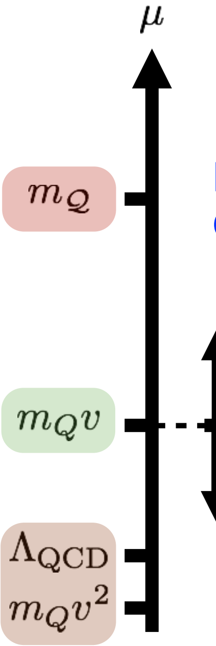
"I'm firmly convinced that behind every great man is a great computer."

# Production of quarkonia and NRQCD

- Non-Relativistic QCD (NRQCD) -a particular type of effective theory (EFT)

Bodwin *et al.* (1995)

Cho *et al.* (1996)



Perturbative

Non-Perturbative

Explores all regimes of QCD

$$|\mathbf{p}_Q| \sim m_Q v \quad K_Q \sim m_Q v^2$$

$$b\bar{b}: \quad v^2 \sim 0.1$$
$$c\bar{c}: \quad v^2 \sim 0.3$$

$$\mathcal{L}_{\mathrm{NRQCD}} = \mathcal{L}_{\mathrm{light}} + \psi^\dagger\Big(iD_0 + \frac{\mathbf{D}^2}{2M}\Big)\psi + \chi^\dagger\Big(iD_0 - \frac{\mathbf{D}^2}{2M}\Big)\chi$$

QCD without the heavy flavor

ultra-soft

+ heavy - soft interactions at NLO

pNRQCD N. Brambilla *et al. (2000)*

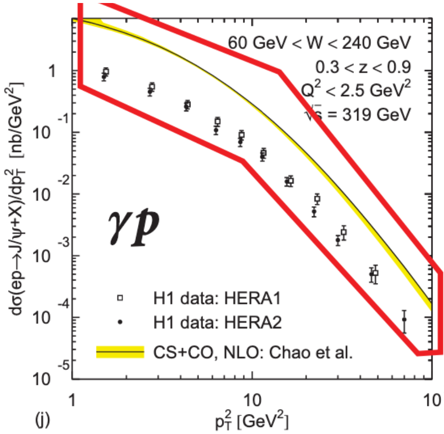
vNRQCD M. Luke *et al. (2000)*

M. Butenschon *(2012)*

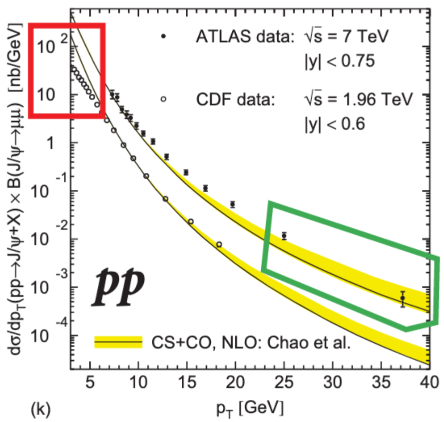
J. Lansberg (2020)

- NRQCD factorization formula. Short distance cross sections (perturbatively calculable) and long distance matrix elements (fit to data, scaling relations)

$$d\sigma(a+b \to \mathcal{Q}+X) = \sum_n d\sigma(a+b \to Q\overline{Q}(n)+X)\langle \mathcal{O}_n^{\mathcal{Q}} \rangle$$



(j)

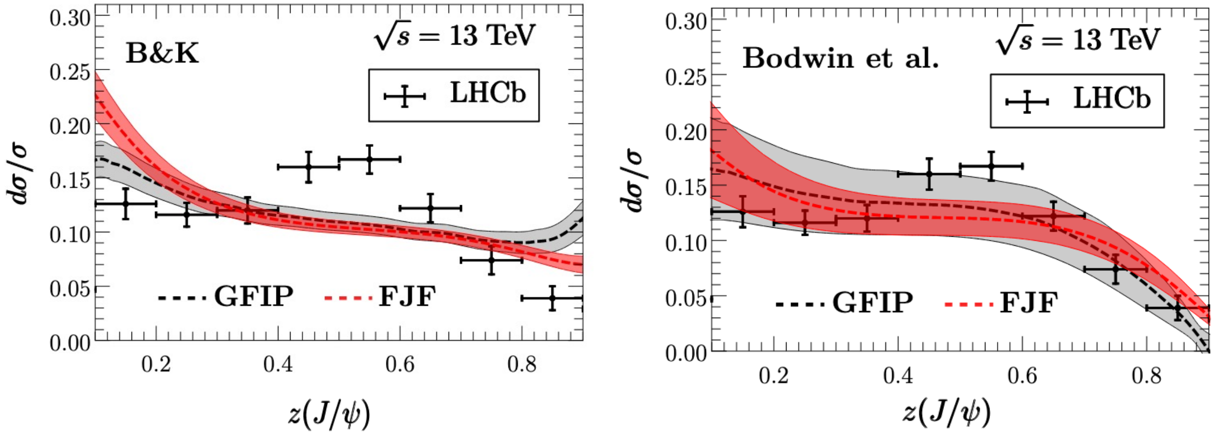


(k)

Strong tensions remain in the EIC relevant small to moderate $p_T$ region

# Opportunities in p+p and at the EIC

- Universality of long distance matrix elements is not established. Differences between extractions
- Use quarkonium production in jets to constrain LDMEs



R. Bain *et al. (2017)*

New TMD formalism at small and intermediate $p_T$ for both production and decay of quarkonium states

$$\frac{d\sigma}{dy\, d^2q_\perp} = \frac{4M^4\, H(M^2,\mu^2)}{2sM^2(N_c^2-1)}\,\Gamma^*_{\rho\sigma}\Gamma_{\mu\nu}(2\pi)\int d^2\boldsymbol{k}_{n\perp}\, d^2\boldsymbol{k}_{\bar{n}\perp}\, d^2\boldsymbol{k}_{s\perp}\,\delta^{(2)}\left(\boldsymbol{q}_\perp - \boldsymbol{k}_{n\perp} - \boldsymbol{k}_{\bar{n}\perp} - \boldsymbol{k}_{s\perp}\right)$$
$$\times\, G^{\sigma\nu}_{g/A}(x_A, \boldsymbol{k}_{n\perp}, S_A; \zeta_A, \mu)\, G^{\rho\mu}_{g/B}(x_B, \boldsymbol{k}_{\bar{n}\perp}, S_B; \zeta_B, \mu)\, S_{\eta_Q}\left[{}^1S_0^{[1]}\right](\boldsymbol{k}_{s\perp};\mu)$$

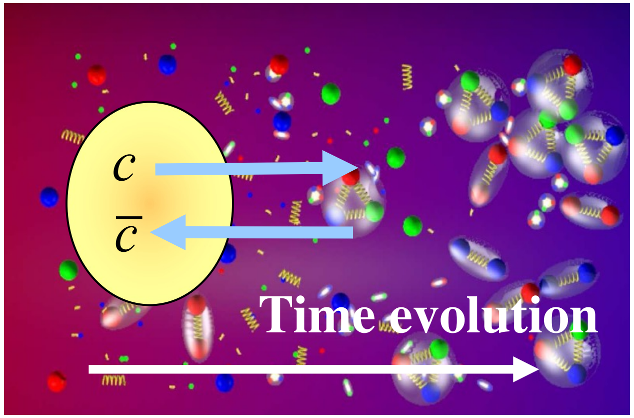
Non-perturbative physics of hadronization captured in shape functions

$$\tilde{S}_{\eta_Q}\left[{}^1S_0^{[1]}\right](\xi_T;\mu) = \frac{\tilde{S}^{(0)}_{\eta_Q}\left[{}^1S_0^{[1]}\right](\xi_T;\mu)}{\tilde{S}(\xi_T;\mu)}$$

M. Echevarria (2019)

S. Fleming *et al.* (2019)

# NRQCD in the nuclear medium



**At the Lagrangian level**

Y. Makris et al. (2019)

$$\mathcal{L}_{\mathrm{NRQCD}_G} = \mathcal{L}_{\mathrm{NRQCD}} + \mathcal{L}_{Q-G/C}(\psi, A^{\mu,a}_{G/C}) + \mathcal{L}_{g-G/C}(A^{\mu,b}_{s}, A^{\mu,a}_{G/C})$$

- Glauber gluons - transverse to the direction of propagation contribution
- Coulomb gluons - isotropic momentum distribution

$$\mathcal{L}^{(0)}_{Q-G/C}(\psi, A^{\mu,a}_{G/C}) = \sum_{\mathbf{p},\mathbf{q}_T} \psi^\dagger_{\mathbf{p}+\mathbf{q}_T}\Big(-gA^0_{G/C}\Big)\psi_{\mathbf{p}} \ \ \underline{(collinear/static/soft)}.$$

$$\mathcal{L}^{(1)}_{Q-G}(\psi, A^{\mu,a}_{G}) = g\sum_{\mathbf{p},\mathbf{q}_T} \psi^\dagger_{\mathbf{p}+\mathbf{q}_T}\Big(\frac{2A^{\mathbf{n}}_G(\mathbf{n}\cdot\boldsymbol{\mathcal{P}}) - i\Big[(\boldsymbol{\mathcal{P}}_\perp\times\mathbf{n})A^{\mathbf{n}}_G\Big]\cdot\boldsymbol{\sigma}}{2m}\Big)\psi_{\mathbf{p}} \ \ (collinear)$$

$$\mathcal{L}^{(1)}_{Q-C}(\psi, A^{\mu,a}_{C}) = 0 \ \ (static)$$

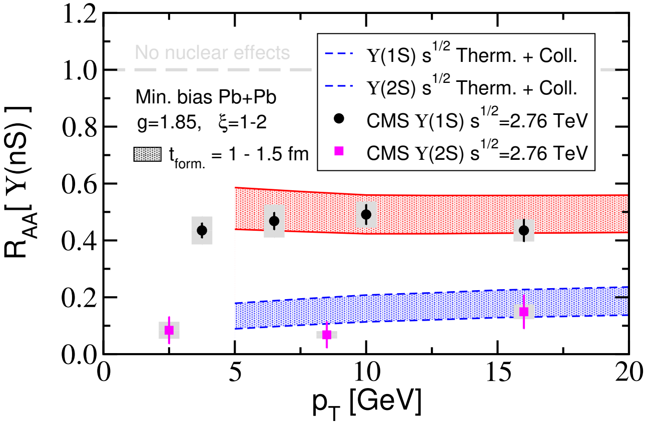
$$\mathcal{L}^{(1)}_{Q-C}(\psi, A^{\mu,a}_{C}) = g\sum_{\mathbf{p},\mathbf{q}_T} \psi^\dagger_{\mathbf{p}+\mathbf{q}_T}\Big(\frac{2\mathbf{A}_C\cdot\boldsymbol{\mathcal{P}} + [\boldsymbol{\mathcal{P}}\cdot\mathbf{A}_C] - i\Big[\boldsymbol{\mathcal{P}}\times\mathbf{A}_C\Big]\cdot\boldsymbol{\sigma}}{2m}\Big)\psi_{\mathbf{p}} \ \ (soft)$$

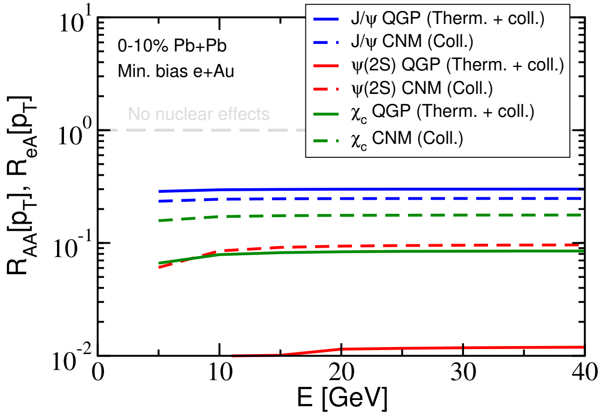
Dissociation rates will depend on the type of the source of scattering in the medium, but only at higher orders

Quarkonium transport in the QGP vs cold nuclear matter at the EIC

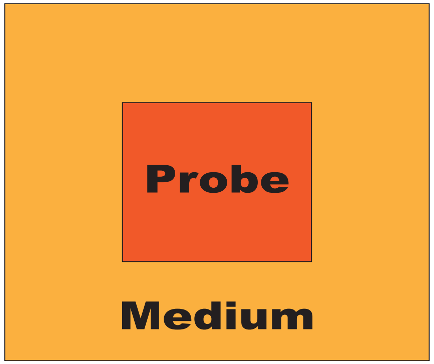
S. Aronson *et al.* (2017)

I. Olivant et al. (2021)

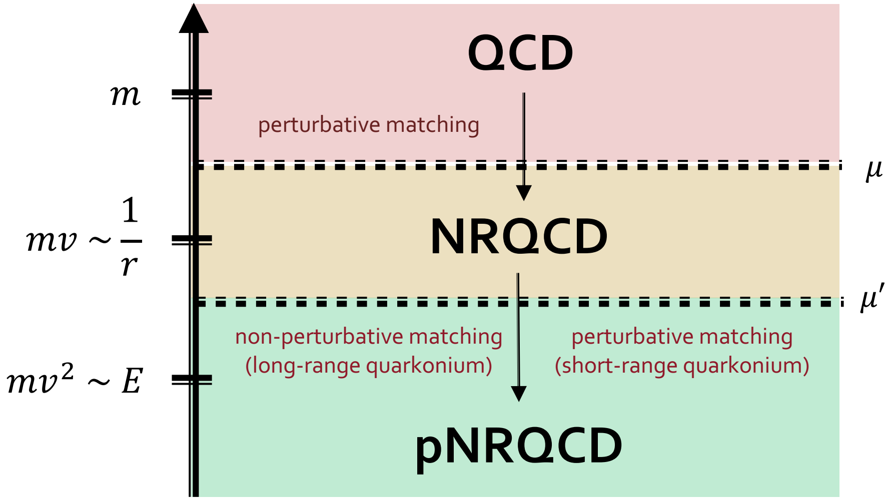


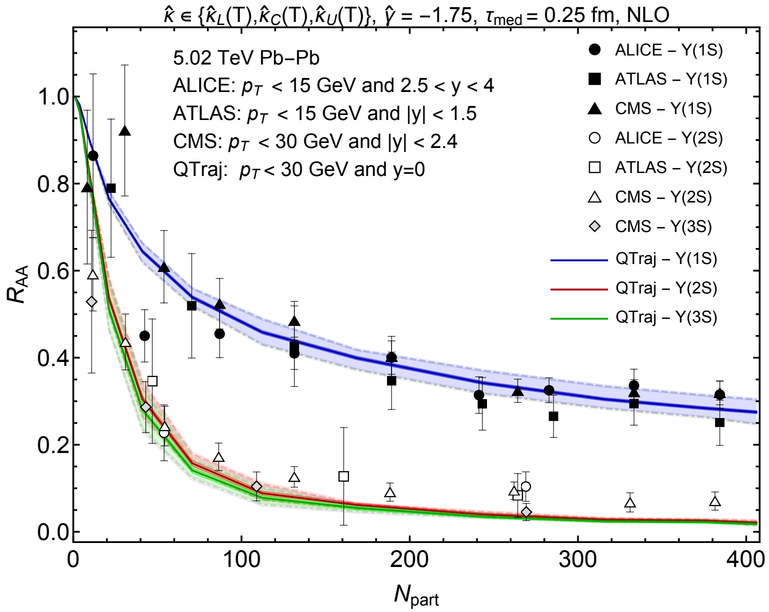


# In-medium heavy quarkonium propagation – open quantum systems



**Probe** = heavy-quarkonium state
**Medium** = light quarks and gluons that comprise the medium





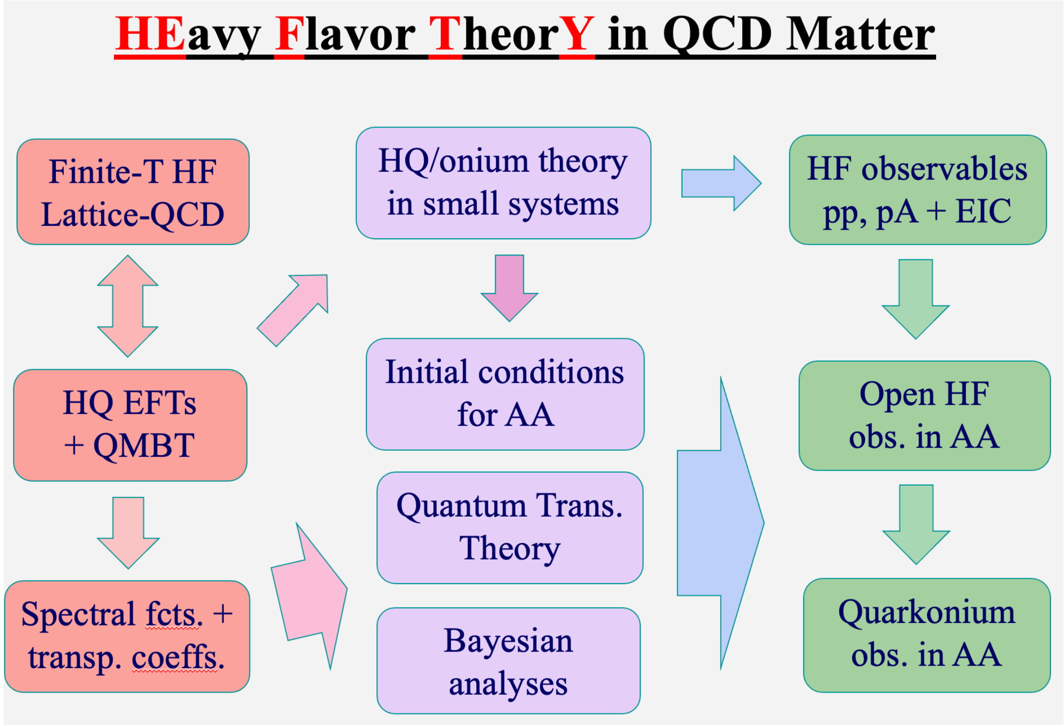
N. Brambilla et al. (2022)

- Can use **open quantum systems methods** and **effective field theory** methods to obtain ***quantum master equations*** for the evolution heavy quarkonium reduced density matrix.

- Current applications target **bottomonium propagation in the QGP,** however, similar methods **can be applied to non-thermal media** such as the matter through which heavy quarkonium states propagate at the EIC.

# Opportunities and initiatives

Near to intermediate term – proposal for a NT topical collaboration **HEFTY in QCD matter**. Resolve the outstanding HF puzzles. Provide immediate much needed support for RIHC and LHC experiment. Pave the way a for vibrant HF program at the EIC.



## HEavy Flavor TheorY in QCD Matter

Finite-T HF Lattice-QCD

HQ EFTs + QMBT

Spectral fcts. + transp. coeffs.

HQ/onium theory in small systems

Initial conditions for AA

Quantum Trans. Theory

Bayesian analyses

HF observables pp, pA + EIC

Open HF obs. in AA

Quarkonium obs. in AA

## Theory for EIC

"We recommend the establishment of a national EIC theory alliance to enhance and broaden the theory community needed to advance EIC physics goals and the experimental program. This theory alliance will develop a diverse workforce through a competitive national EIC theory fellow program and tenure-track bridge positions, including appointments at minority serving institutions."

# Conclusions

- Jets and heavy flavor production are important drivers of QCD in nuclear matter. Still, many open theoretical questions remain – from relevant EFTs in multi-scale problems, propagation of partons in different types of nuclear matter, to the non-perturbative hadronization into light and heavy mesons, and quarkonia. These must be resolved to fully utilize the RHIC, LHC, and EIC capabilities
- The precise analysis of more traditional observables - suppression of hadrons, jets, and quarkonia; correlations; vector boson tagging; and substructure remain a priority using advanced theory that bridges the gap between high energy and nuclear physics
- There are new opportunities for hard probes physics to place a limit on the smallest QGP droplets in nature, improve the simulations using ML techniques, develop new observables, apply Bayesian statistical analysis to extract properties of cold and hot QCD matter. In order to achieve this we must place emphasis on analytic theory. Without rigorous, systematically improvable first-principles theory the results of our numerical analyses will not be conclusive
- There are tremendous intellectual communalities in jet and heavy flavor physics applied to hadronic, heavy ion, and DIS reactions. It is a natural point of convergence for the broad QCD community. It is important to realize and advance those connections. Now is the right time for a focused theory effort and investment to answer the most pressing HF and jet puzzles and lay the groundwork for the EIC