Ivan Vitev

Heavy flavor theory overview

HEFTY COLLABORATION

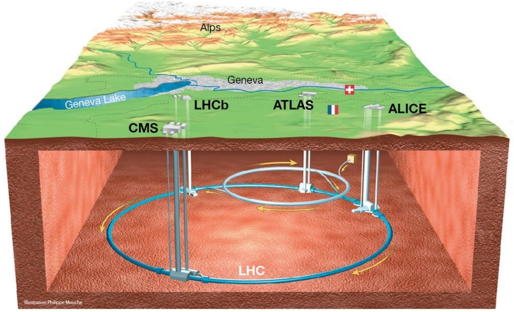
Second workshop on advancing the understanding of non-perturbative QCD using energy flow
CFNS, Stony Brook, NY / Online
November 6-9, 2023

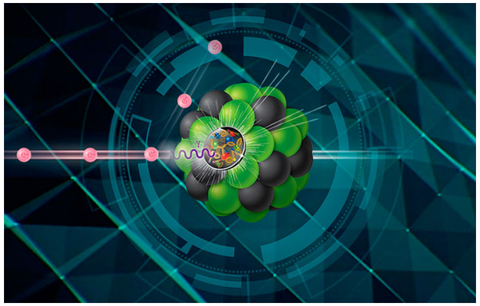
Los Alamos NATIONAL LABORATORY EST. 1943

Outline of the talk

- Heavy flavor in elementary collisions
- Heavy flavor in reactions with nuclei
- Conclusions

For complementary discussion of heavy flavor, see other talks in the workshop





Acknowledgment of support:

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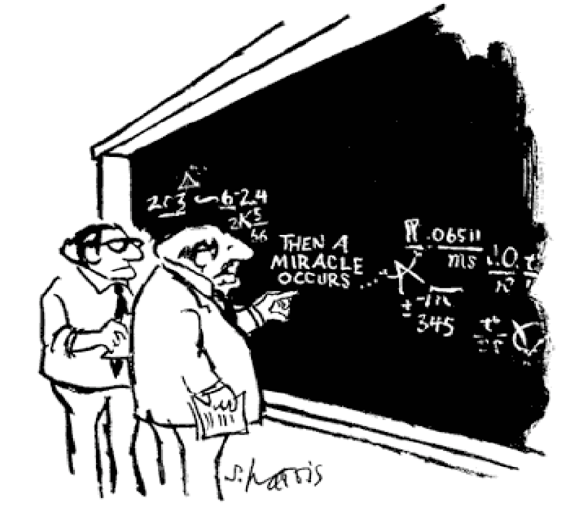
Heavy flavor in elementary collisions



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

Heavy flavor schemes and effects on PDF extraction

Treatment of charm, beauty, and top in perturbative QCD

$$F_{2,h}^{FFN} = \sum_{k=1}^{\infty} a_s^k(n_f) \sum_{i=q,g} H_{2,i}^{(k)}(n_f) \otimes f_i(n_f),$$

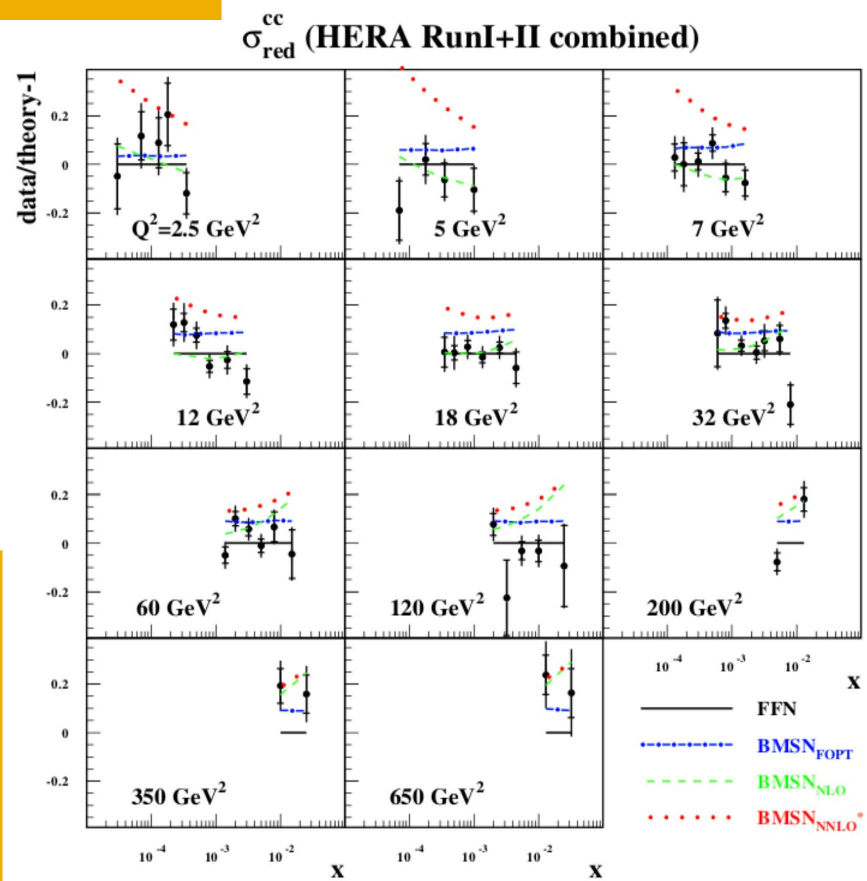
$$F_{2,h}^{ZMVFN} = \sum_{k=0}^{\infty} a_s^k(n_f+1) \sum_{i=q,g,h} C_{2,i}^{(k)}(n_f+1) \otimes f_i(n_f+1)$$

Fixed flavor schemes – typically at low virtualities

Variable flavor schemes – as one goes to higher energies, effectively resum Q^2/m_c^2 (or Q^2/m_b^2)

- Different schemes and different prescriptions in the variable flavor number scheme
  ACOT, S-ACOT, RT, FONLL, …
- Critical assessment and comparisons will be necessary for the EIC

S. Alekhin et al . (2020)



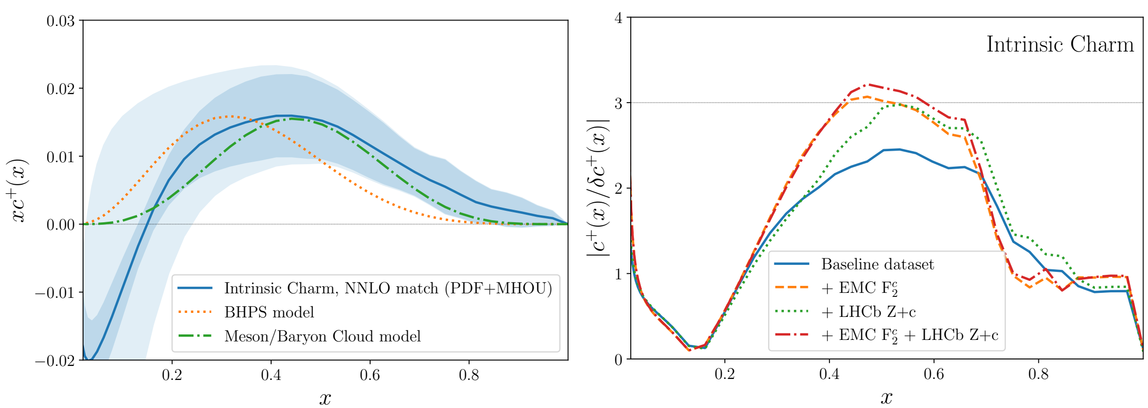
Confronting HF schemes with HERA data - FF and a particular VFF

New developments in intrinsic charm

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

NNPDF Collab. (2022)

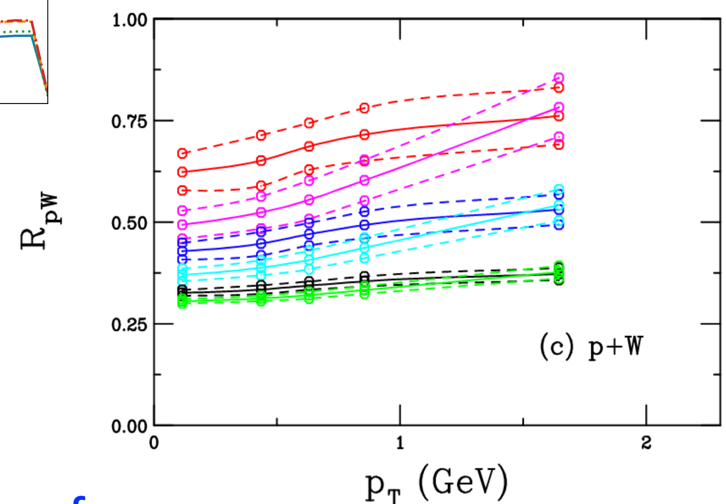
- **Extraction of intrinsic charm compared to models**
- **Effect of EMC and LHCb Z+c jet data on IC statistical significance (3σ)**



T. Hobbs et al . (2017)

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

- Opportunity to develop phenomenology / strategies to search for intrinsic charm 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 meson production

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

Fragmentation functions

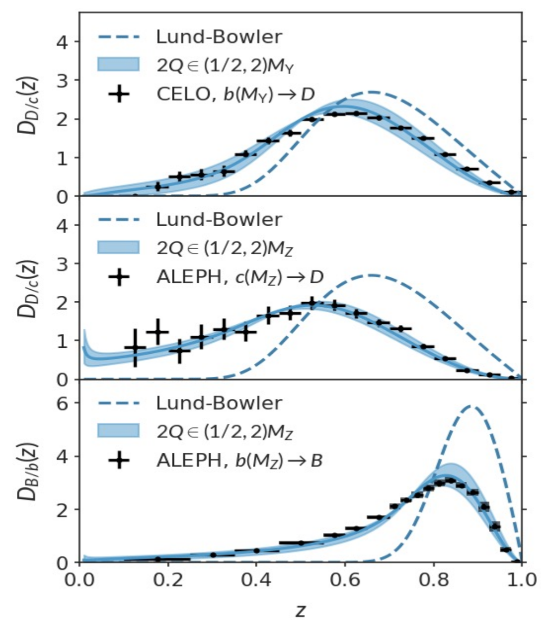
$$D(z) = z^{-1-bM_\perp^2}(1-z)^a e^{-\frac{bM_\perp^2}{z}}$$

Boundary condition

M. Bowlers *(1981)*

Evolution

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



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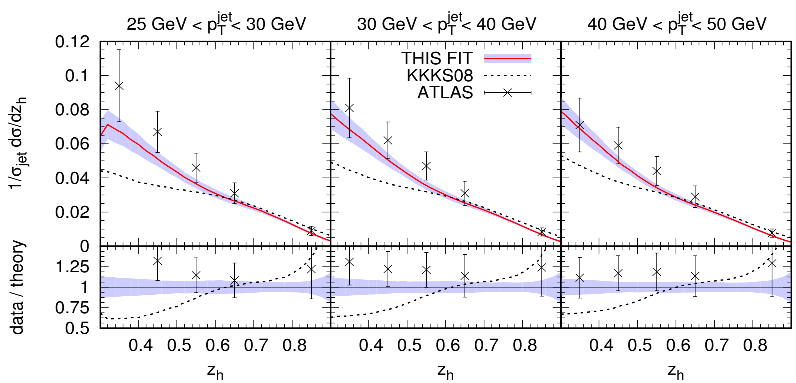
W. Ke et al. (2023)

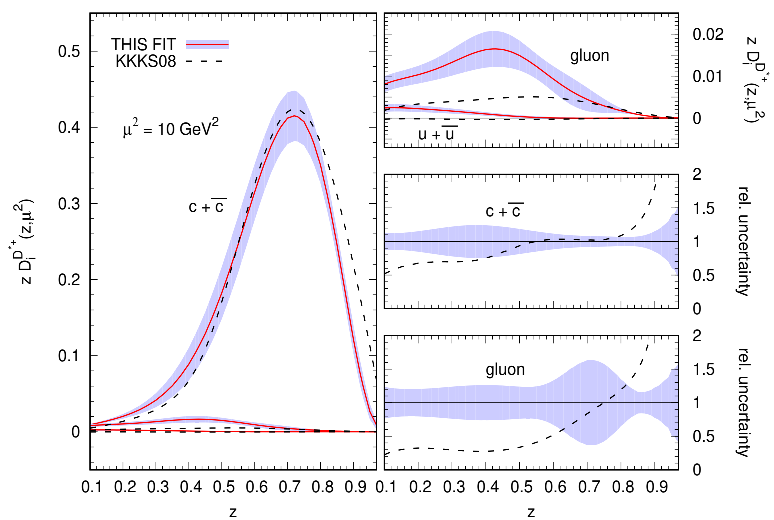
Larger gluon frag. contribution from HF in jets

D. Anderle et al (2017)

Gluon FF contribution

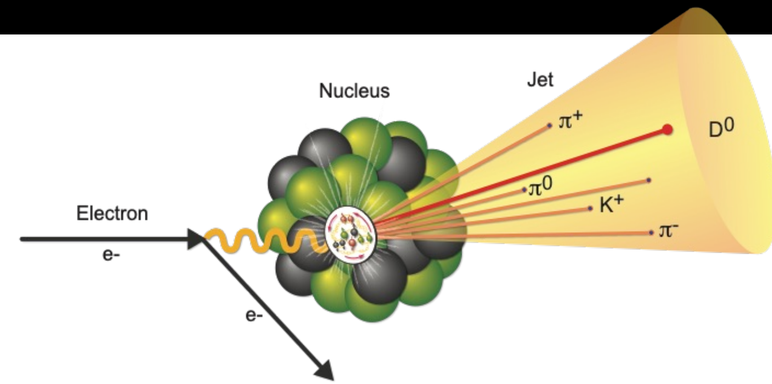
Especially important at LHC energies





Charm and beauty jet production

- Recent advances are based in SCET – precision theory for small radius jets and heavy flavor jets based on semi-inclusive jet functions



$$E_J \frac{d^3\sigma}{d^3P_J} = \frac{1}{S}\sum_{i,f}\int_0^1 \frac{dx}{x}\int_0^1 \frac{dz}{z^2} f^{i/N}(x,\mu)\, J_{J_Q/f}(z, p_T R, m, \mu)\left[\hat{\sigma}_{i\to f} + f_{\rm ren}^{\gamma/\ell}\left(\frac{-t}{s+u},\mu\right)\hat{\sigma}^{\gamma i\to f}\right]$$

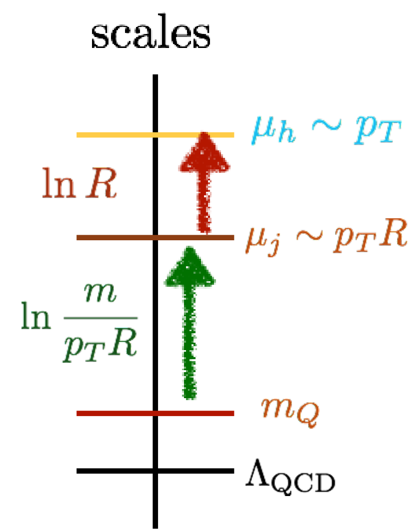
The SiJFs Evolve according to DGLAP-like equations

$$\frac{d}{d\ln\mu^2}\begin{pmatrix} J_{J_Q/s}(x,\mu) \\ J_{J_s/g}(x,\mu)\end{pmatrix} = \frac{\alpha_s}{2\pi}\int_x^1 \frac{dz}{z}\begin{pmatrix} P_{qq}(z) & 2P_{gq(z)} \\ P_{qg}(z) & P_{gg}(z)\end{pmatrix}\begin{pmatrix} J_{J_Q/s}(x/z,\mu) \\ J_{J_s/g}(x/z,\mu)\end{pmatrix}$$

Resums
ln μ/p_TR

$$\mathcal{M}^{\rm in-jet}_{g\to Q\bar{Q}}(p_T R, m) = 2\sum_{l=g,Q}\bar{K}_{l/g}(p_T R, m, \mu_F)\bar{D}_{Q/l}(m,\mu_F)$$

Resums
ln p_TR/m



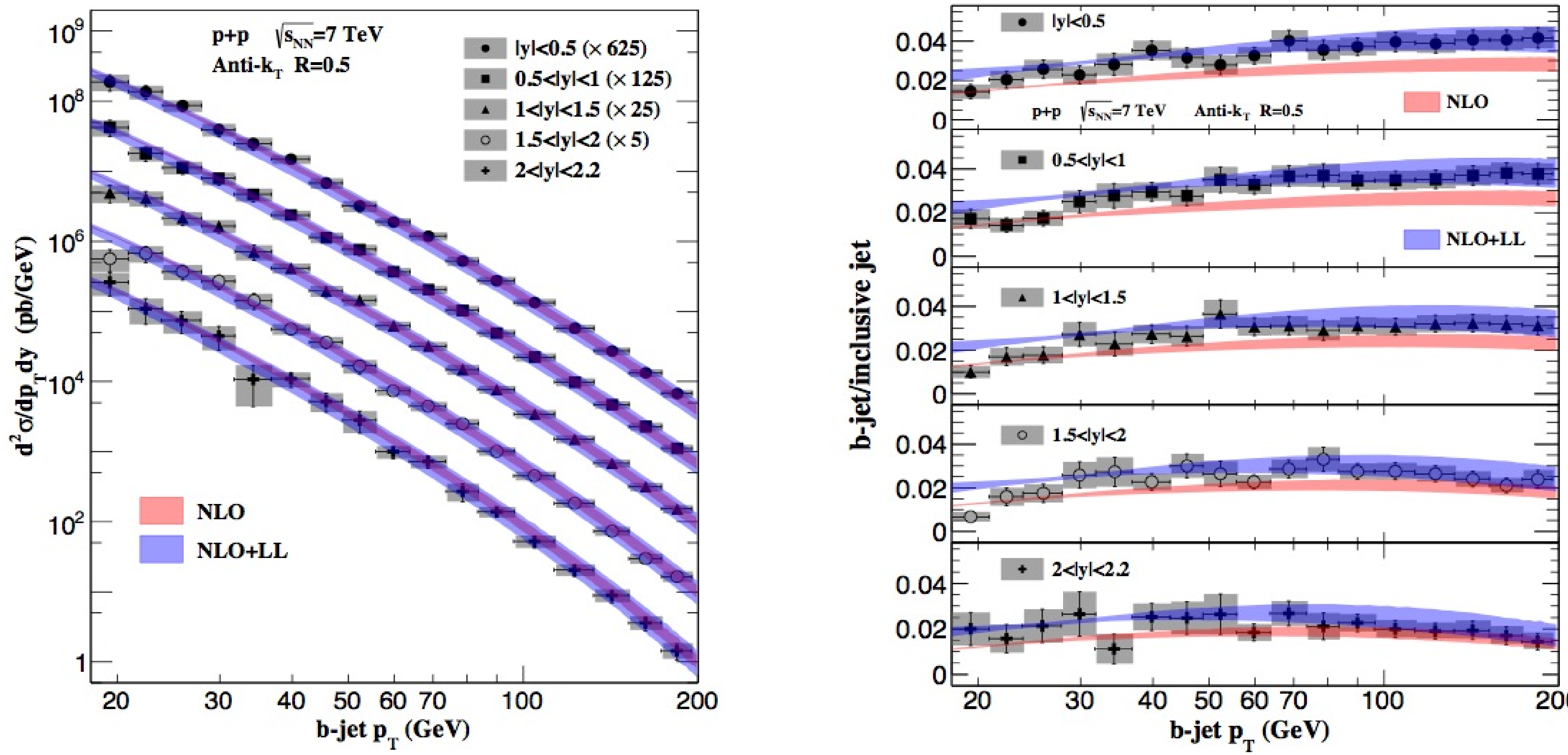
The integrated perturbative kernel at the jet typical scale

The integrated parton fragmentation function from parton *l* to parton *Q*

C. Bauer et al. (2013)

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

B-jet production – example from pp collisions



- So far tested in pp. Data are consistent with the theoretical predictions
- For the ratio b-jets to inclusive jets the difference between NLO+LL and NLO can be traced also to the differences in the inclusive jet cross section

H. Li et al. (2018)

Heavy flavor jet substructure

- Heavy quarks (large mass) provide the opportunity to develop tailored EFTs for ultimate precision in substructure calculations

C. Lee *et al.* (2019)

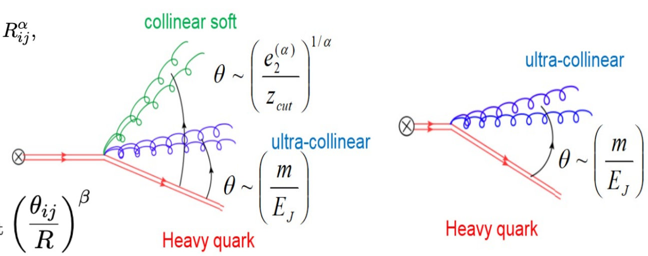
Two point energy energy correlator

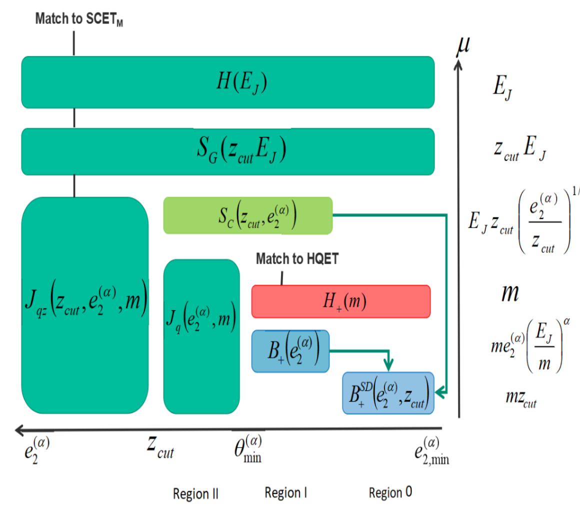
A. Larkoski *et al.* (2013)

$$e_2^{(\alpha)}|_{e^+e^-} = \sum_{i<j\in J} z_i z_j (\theta_{ij})^\alpha \qquad e_2^{(\alpha)}|_{pp} = \frac{1}{p_{T_J}^2} \sum_{i<j\in J} p_{T_i} p_{T_j} R_{ij}^\alpha,$$

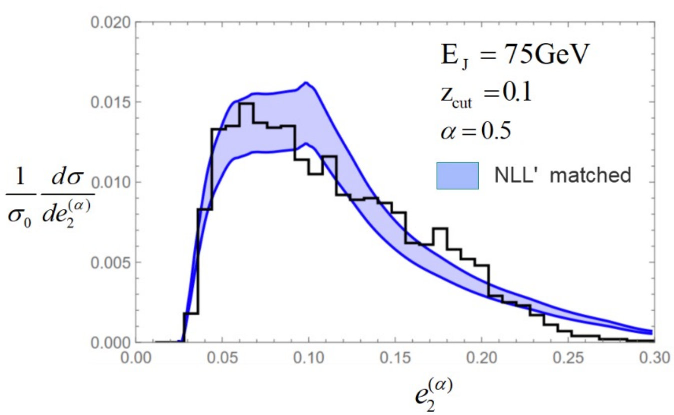
Subject to soft drop grooming

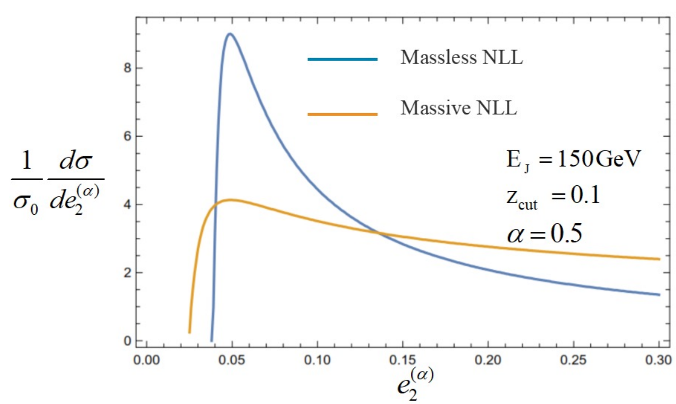
$$\frac{\min\{E_i, E_j\}}{E_i + E_j} > z_{\rm cut} \left(\frac{\theta_{ij}}{R}\right)^\beta \qquad \frac{\min\{p_{Ti}, p_{Tj}\}}{p_{Ti} + p_{Tj}} > z_{\rm cut} \left(\frac{\theta_{ij}}{R}\right)^\beta$$





The HQ mass, definition of observable and grooming introduce multiple scales that must be treated in a new EFT





EEC exhibit non-trivial structure. Can be used to discriminate light and heavy flavor jets

Production of quarkonia and NRQCD

μ

m_Q

$m_Q v$

Λ_{QCD}

$m_Q v^2$

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

Bodwin *et al.* (1995)

Cho *et al.* (1996)

Explores all regimes of QCD $|\mathbf{p}_Q| \sim m_Q v \quad K_Q \sim m_Q v^2$

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

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

Perturbative

Non-Perturbative

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

QCD without the heavy flavor

ultra-soft

+ heavy - soft interactions at NLO

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

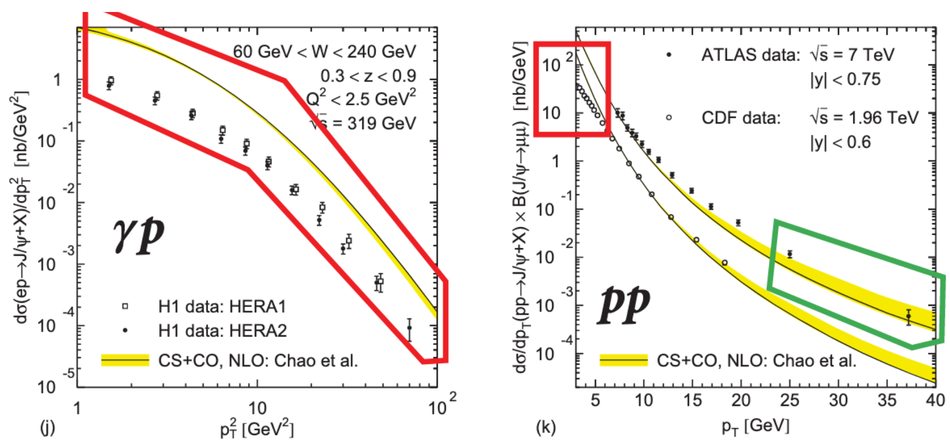
vNRQCD M. Luke *et al. (2000)*

M. Butenschon *(2012)*

J. Lansberg (2020)

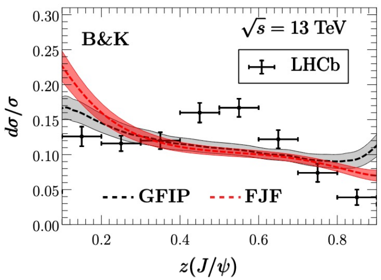
- NRQCD factorization formula. Short distance cross sections (perturbatively calculable) and long distance matrix elements (fit to data, scaling relations)

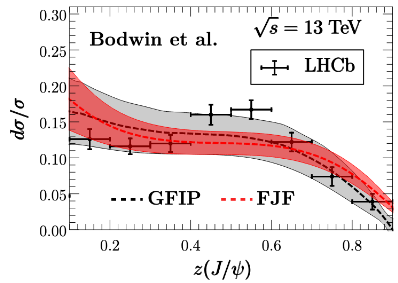
$$d\sigma(a+b \to \mathcal{Q}+X) = \sum_n d\sigma(a+b \to Q\overline{Q}(n)+X)\langle\mathcal{O}_n^{\mathcal{Q}}\rangle$$



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

Opportunities in p+p and e+p





Use quarkonium production in jets to constrain LDMEs. Around mid-rapidity

R. Bain *et al. (2017)*

Fragmentation mechanism, and TMD formalism at small and intermediate p_T

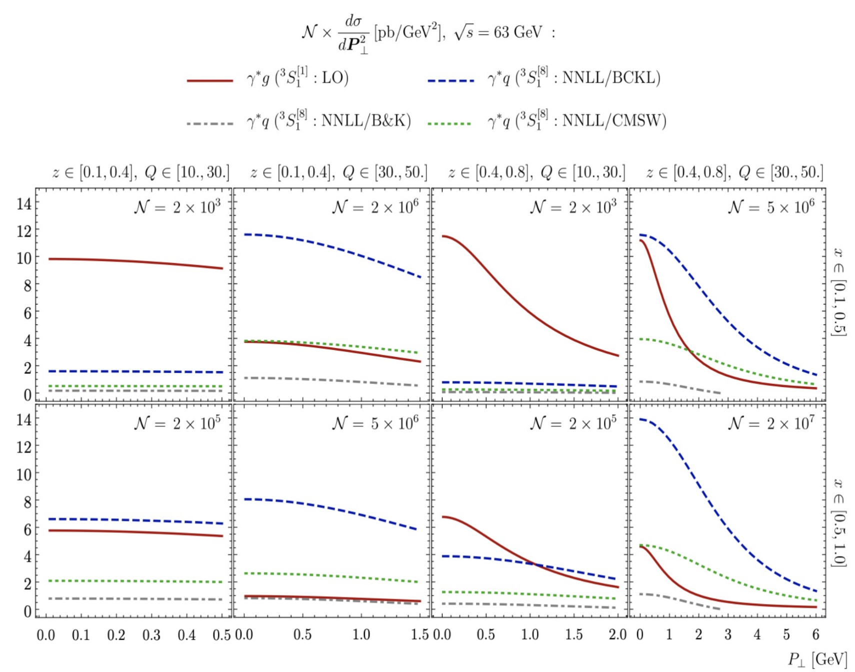
$$\frac{d\sigma}{dy\,d^2q_\perp} = \frac{4M^4\,H(M^2,\mu^2)}{2sM^2(N_c^2-1)}\,\Gamma^*_{\rho\sigma}\Gamma_{\mu\nu}(2\pi)\int d^2\boldsymbol{k}_{n\perp}d^2\boldsymbol{k}_{\bar{n}\perp}d^2\boldsymbol{k}_{s\perp}\,\delta^{(2)}\left(\boldsymbol{q}_\perp - \boldsymbol{k}_{n\perp} - \boldsymbol{k}_{\bar{n}\perp} - \boldsymbol{k}_{s\perp}\right)$$
$$\times\, G^{\sigma\nu}_{g/A}(x_A,\boldsymbol{k}_{n\perp},S_A;\zeta_A,\mu)\,G^{\rho\mu}_{g/B}(x_B,\boldsymbol{k}_{\bar{n}\perp},S_B;\zeta_B,\mu)\,S_{\eta_Q}\left[{}^1S_0^{[1]}\right](\boldsymbol{k}_{s\perp};\mu)\,, \quad (16)$$

Non-perturbative physics 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)



More in TMDs:

There are other approaches at small-x to combine NRQD + CGC

M. Echevarria et al. (2007)

Quarkonium polarization

Describing data on polarization has been challenging – "polarization puzzle"

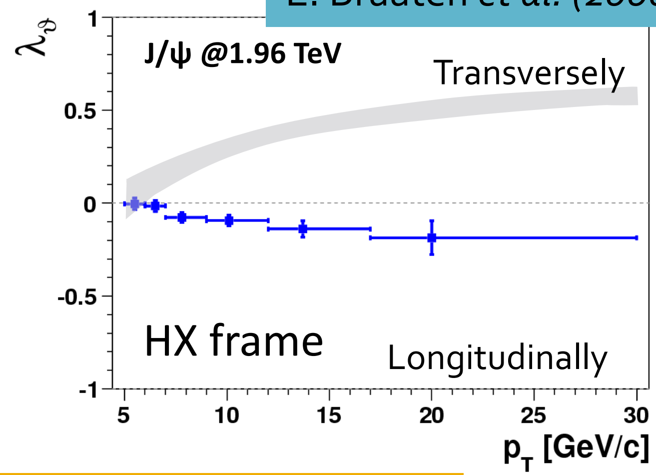
$$\frac{dN}{d\Omega} \propto 1 + \lambda_\theta \cos^2\theta + \lambda_\varphi \sin^2\theta \cos 2\varphi + \lambda_{\theta\varphi} \sin 2\theta \cos\varphi$$

$\lambda_\vartheta = +1$: "transverse" (= photon-like) pol.

$\lambda_\vartheta = -1$: "longitudinal" pol.

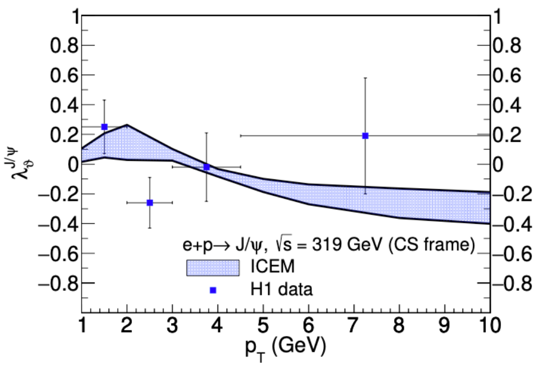
Improvement based on fine tuning of LDMEs in NRQCD

E. Braaten *et al. (2000)*



Alternative models - ICEM

$$\frac{d^2\sigma}{dp_T^2 dW^2 dz} = F_Q \sum_{j=\{q,\bar{q},g\}} \int_{M_Q}^{2m_H} dM_\psi \int dy dx_2 f_{\gamma/e}(y, Q^2) f_{j/p}(x_2, \mu^2) d\hat{\sigma}_{\gamma j \to c\bar{c}+X}$$



V. Cheung et al. (2023)

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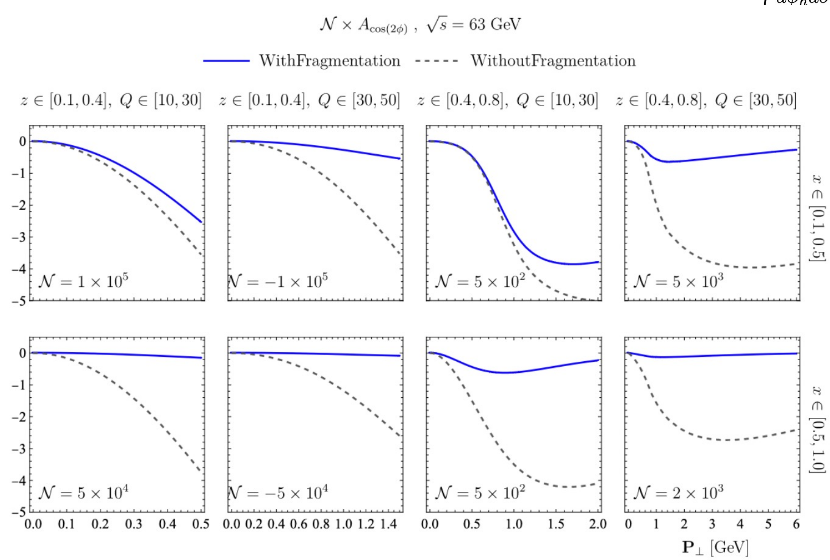
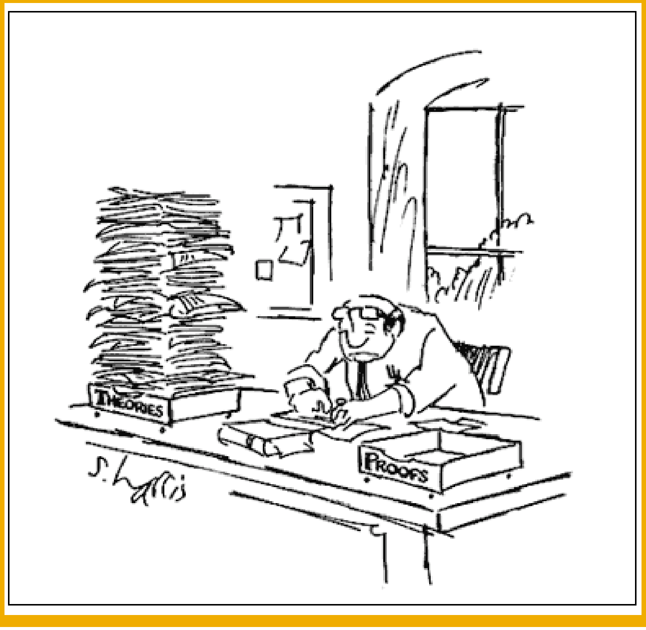
M. Copeland et al. (2023)

Calculation of fragmentation functions

$$A_W(\mathbf{P}_\perp) = \frac{\int d\phi_h W(\phi_h) d\sigma}{\int d\phi_h d\sigma}$$

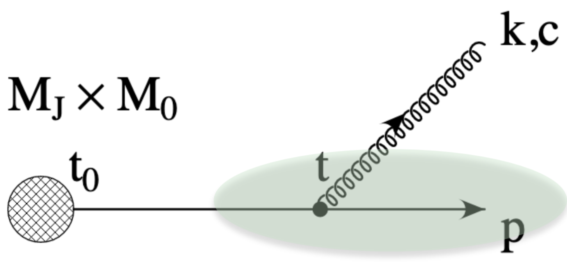


Heavy flavor in reactions with nuclei



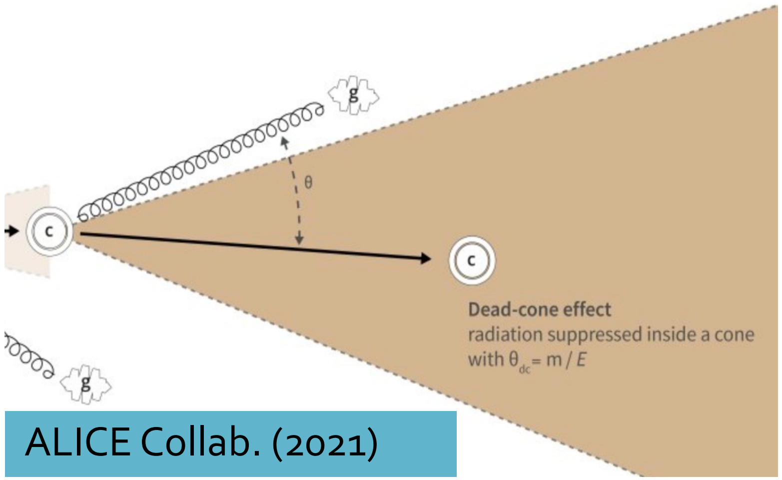
Heavy flavor propagation in matter

Vacuum



Y. Dokshitzer. *et al.* (2001)

$$\left(\frac{dN^{\rm vac}}{dx d^2\boldsymbol{k}_\perp}\right)_{Q\to Qg} = C_F \frac{\alpha_s}{\pi^2}\frac{1}{\boldsymbol{k}_\perp^2 + x^2 m^2}\left[\frac{1-x+x^2/2}{x} - \frac{x(1-x)m^2}{\boldsymbol{k}_\perp^2 + x^2m^2}\right]$$

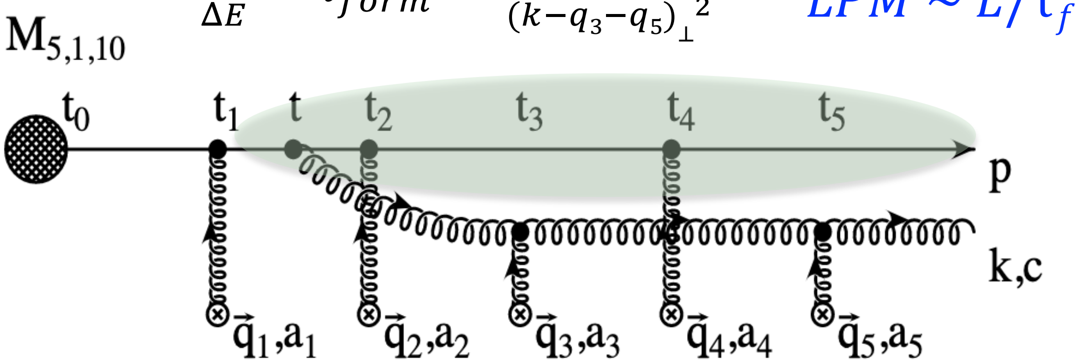


ALICE Collab. (2021)

Medium

Formation time of the (soft) gluon at t

$$\frac{1}{\Delta E} = \tau_{form} = \frac{2\omega}{(k-q_3-q_5)_\perp{}^2} \qquad LPM \sim L/\tau_f$$



- In this case future interactions can affect this formation time (This is a quantum coherent effect.)
- Energy loss formalisms developed and connections explored

M. Djordjevic et al. (2003)

B. Zhang et al. (2003)

N. Armesto et al. (2003)

Y. Mehtar-Tani et al. (2019)

E-loss is the soft gluon emission limit of medium-induced radiative corrections

Collisional and radiative processes for heavy quarks

Collisional energy losses

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

E. Braaten et al. (1991) | B. Neufeld et al. (2014)

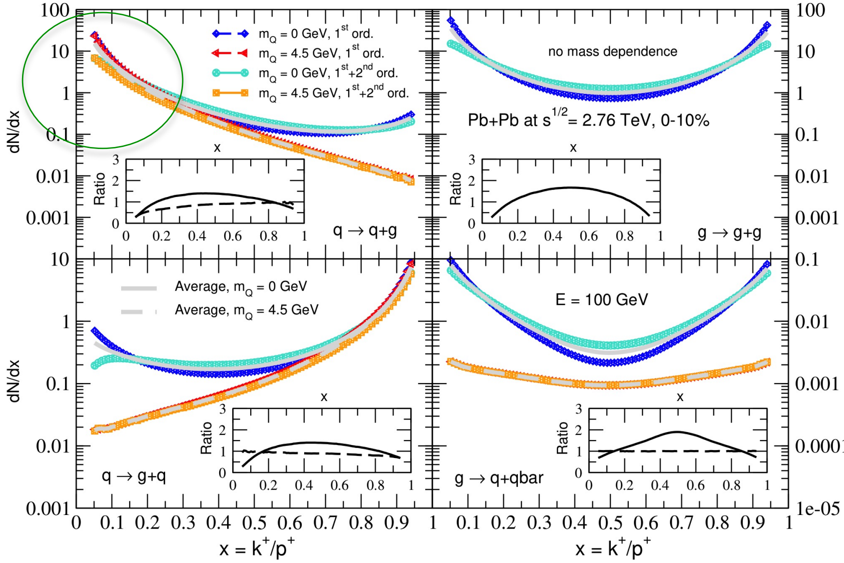
- Factorize form the hard part
- Gauge-invariant
- Depend on the properties of the medium
- Can be expressed as proportional to Altarelli-Parisi

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

Develop specific EFTs for particle propagation in matter

Z. Kang et al . (2016) | M. Sievert et al . (2018)

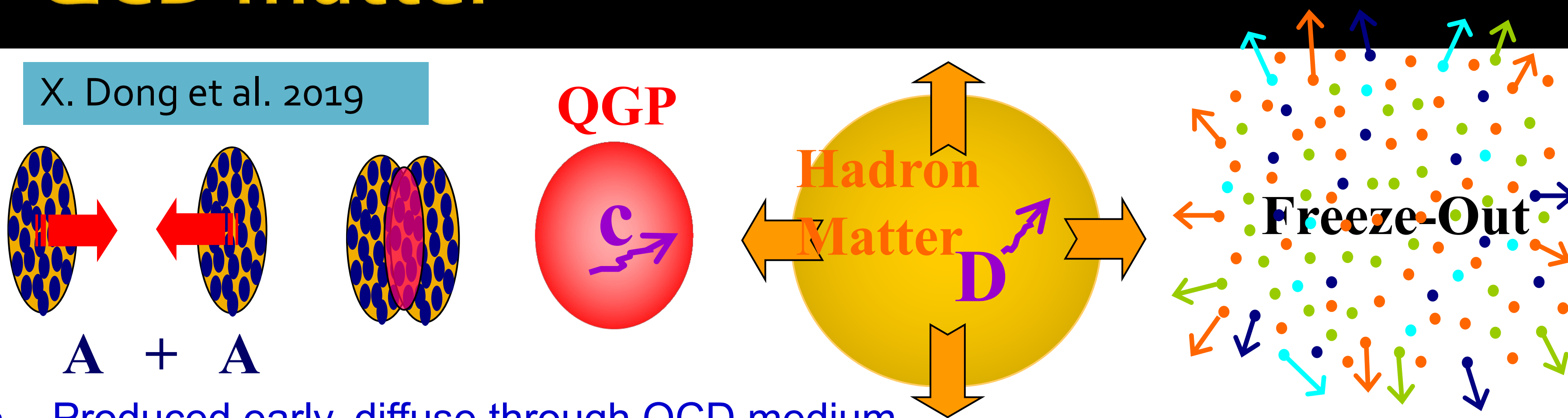
$$\left(\frac{dN^{\rm med}}{dxd^2\boldsymbol{k}_\perp}\right)_{Q\to Qg} = \frac{\alpha_s}{2\pi^2}C_F\int\frac{d\Delta z}{\lambda_g(z)}\int d^2\boldsymbol{q}_\perp\frac{1}{\sigma_{el}}\frac{d\sigma_{el}^{\rm med}}{d^2\boldsymbol{q}_\perp}\left\{\left(\frac{1+(1-x)^2}{x}\right)\left[\frac{\boldsymbol{B}_\perp}{\boldsymbol{B}_\perp^2+\nu^2}\right.\right.$$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



Parton showers in matter are softer and broader than the ones in the vacuum

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
  ⇒ direct access to transport coefficient:

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

Connection to LQCD - Diffusion coefficients

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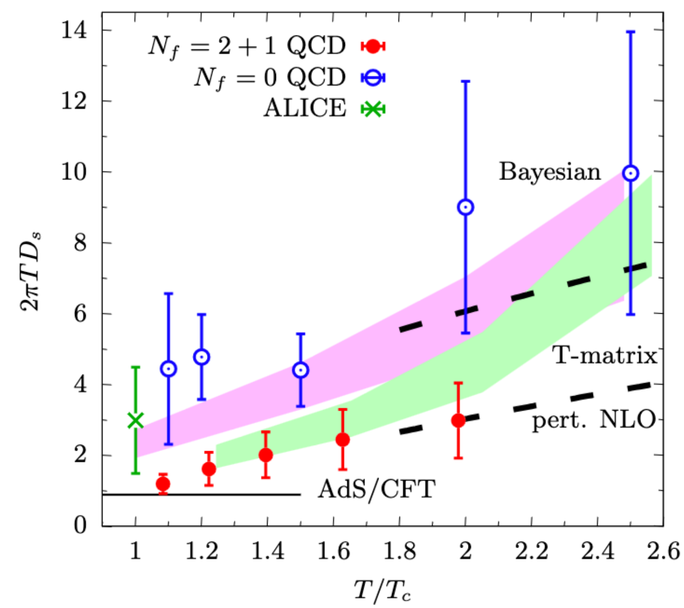
L. Altenkort et al. (2023)

Calculation with light dynamical quarks

$$\kappa(T) = 2T \lim_{\omega\to 0} \left[\rho_E(\omega, T)/\omega\right]$$

$$D_s = 2T^2/\kappa$$



Low p_T diffusion and recombination

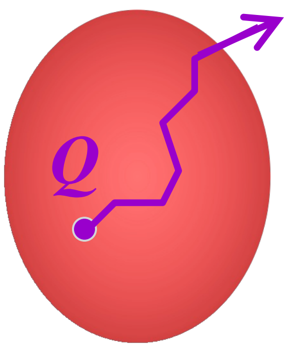
Langevin:

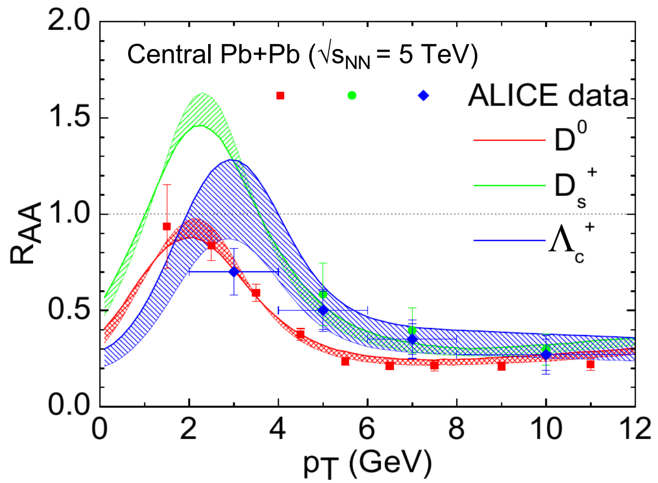
$$dp^i = -\eta_D p^i dt + C^{ik} \rho^k \sqrt{dt}.$$

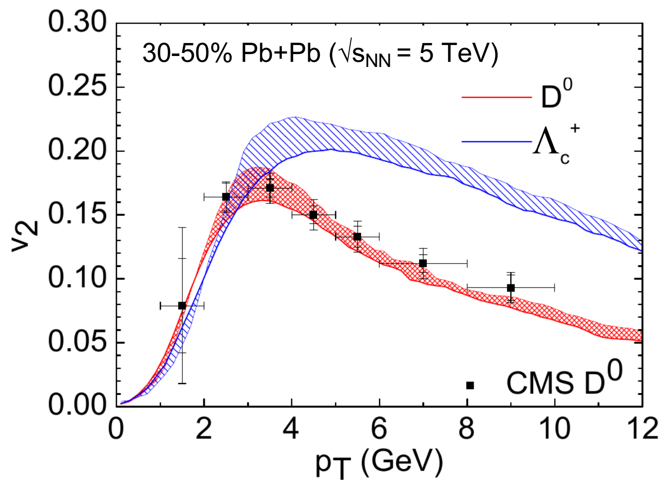
Fokker-Planck:

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

M. He et al. 2019







- Hierarchy of hadronic species → signature of quark recombination
- Large elliptic flow
  → heavy quarks “dragged” along by QCD fireball

Hadronization is very important in this region – recombination vs fragmentation. Significant differences reman that are being studied

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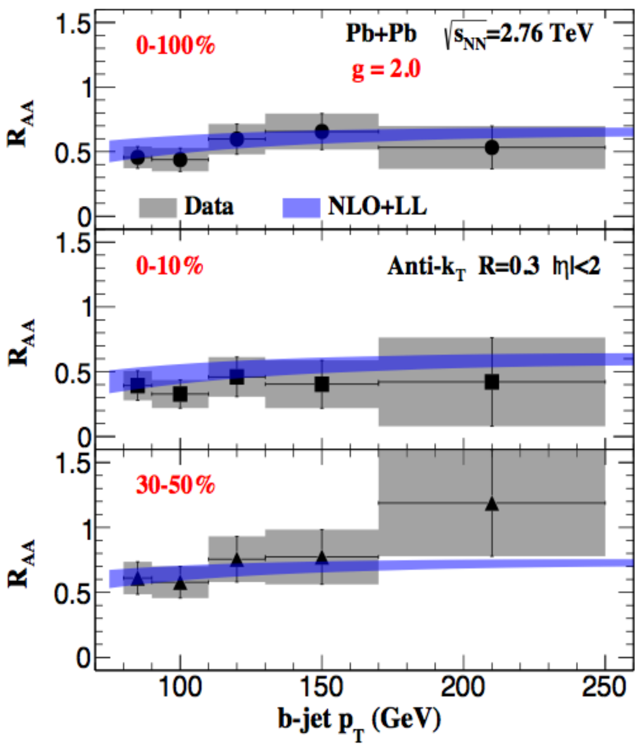
Charm and beauty jet production in HI collisions

The semi-inclusive jet function formalism for HF jets can be extended to heavy ion collisions

H. Li et al. (2019)



Collisional E-losses

$$J_{J_Q/i}^{\mathrm{med},(0)}(z, p_T, \delta p_T^i) = z\delta_{iQ}\left[\delta\left(1 - z - \frac{\delta p_T^i}{p_T + \delta p_T^i}\right) - \delta(1-z)\right]$$

Radiation: after summing over all diagrams

$$J_{J_Q/Q}^{\mathrm{med},(1)}(z, p_T R, m, \mu) = \left[\int_{z(1-z)p_T R}^{\mu} dq_\perp P_{QQ}^{\mathrm{med}}(z, m, q_\perp)\right]_+$$

$$J_{J_s/g}^{\mathrm{med},(1)}(z, p_T R, m, \mu) = \left[\int_{z(1-z)p_T R}^{\mu} dq_\perp P_{Qg}^{\mathrm{med}}(z, m, q_\perp)\right]_+ + \int_{z(1-z)p_T R}^{\mu} dq_\perp P_{Qg}^{\mathrm{med}}(z, m, q_\perp)$$

- 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

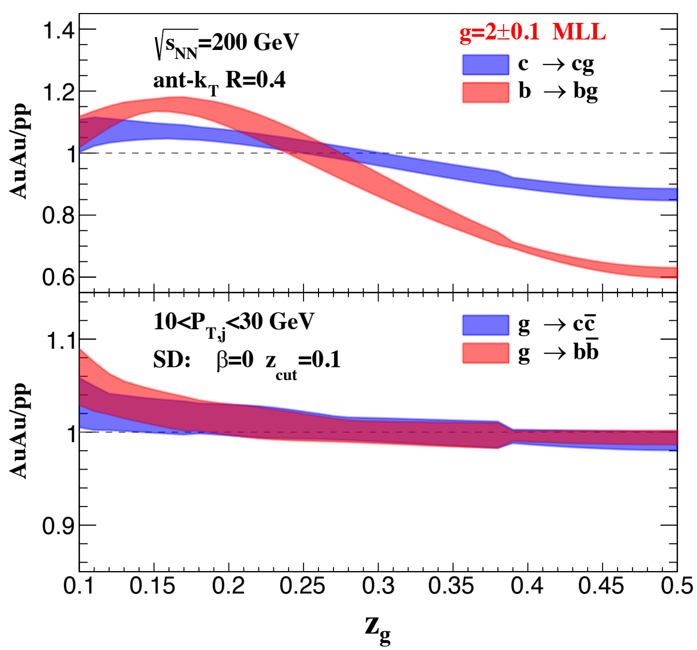
Heavy flavor jet substructure

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

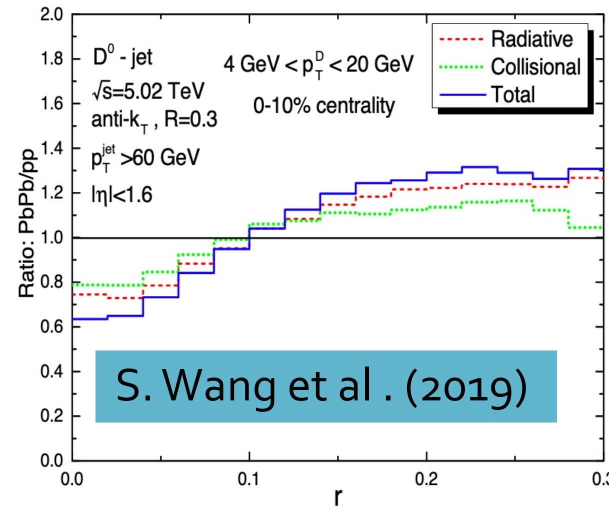
$$\frac{p_{med}^{Q\to Qg}(z_g)}{p_{pp}^{Q\to Qg}(z_g)} \sim \frac{1}{z_g^2}, \quad \frac{p_{med}^{j\to i\bar{i}}(z_g)}{p_{pp}^{j\to i\bar{i}}(z_g)} \sim \frac{1}{z_g}, \quad \frac{p_{med}^{g\to Q\bar{Q}}(z_g)}{p_{pp}^{g\to Q\bar{Q}}(z_g)} \sim \text{const.}$$

Groomed, soft dropped momentum sharing distributions

H. Li et al . (2018)

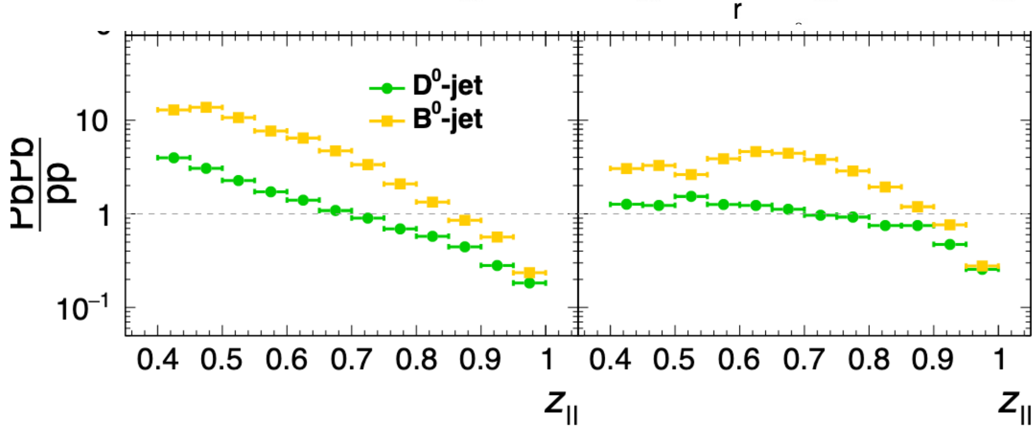


On can extend the studies to D and B meson transverse and longitudinal profile modification in jets and look for signatures of the dead cone effect in A+A



S. Wang et al . (2019)

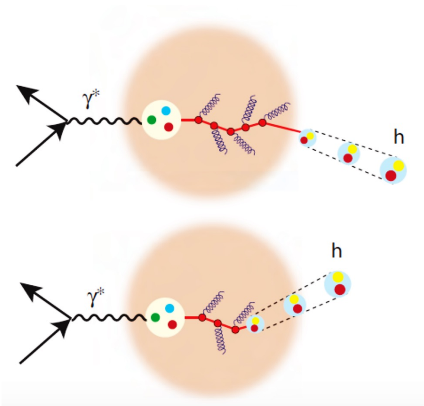
Y. Li et al. (2022)



Heavy flavor 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

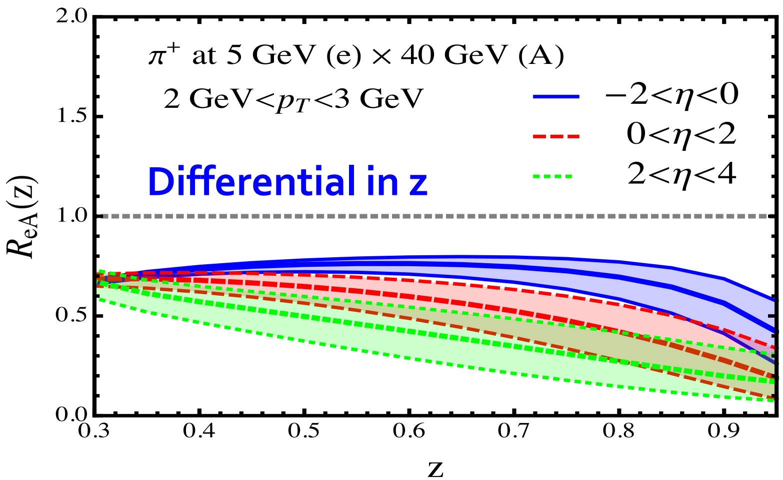


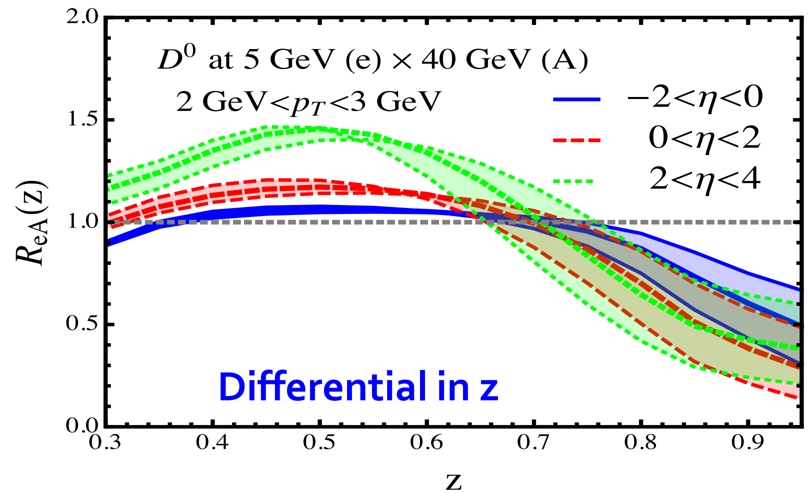
$$R^h_{eA}(p_T,\eta,z) = \frac{\left.\frac{N^h(p_T,\eta,z)}{N^{\mathrm{inc}}(p_T,\eta)}\right|_{e+\mathrm{Au}}}{\left.\frac{N^h(p_T,\eta,z)}{N^{\mathrm{inc}}(p_T,\eta)}\right|_{e+p}}$$

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

Z. Liu et al . (2020)

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





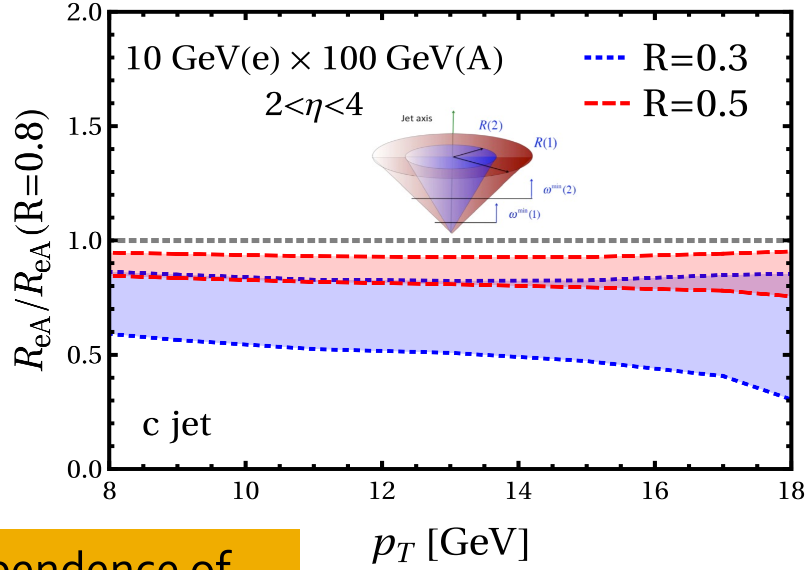
EIC theory will provide clear new insights into hadronization from light + heavy flavor

Highlighted in the 2023 LRP

Heavy flavor jets at EIC and centrality dependence

Jet measurements can benefit both nPDF extraction and understanding hadronization / nuclear matter transport properties - separate initial-state and final-state effects

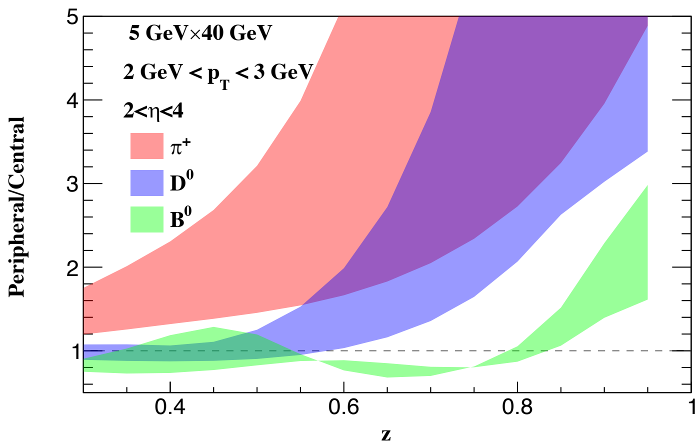
H. Li et al. (2021)



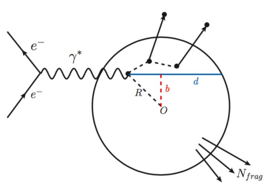
Vacuum and in-medium shower differences - define the ratio of modifications for 2 radii (it is a double ratio) $R_R = R_{eA}(R)/\, R_{eA}(R=0.8)$

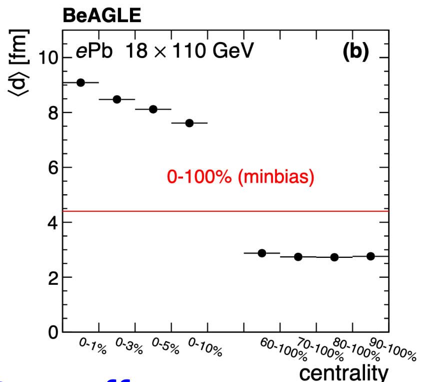
Effectively eliminates initial-state effects Final-state suppression can be almost a factor of 2 for small radii.

H. Li et al. (2023)



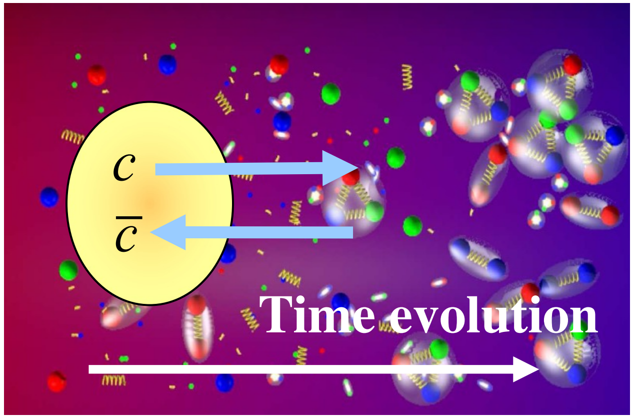
Centrality dependence of light and heavy flavor production at the EIC





Test the path length dependence of CNM effects

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

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

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

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

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

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)

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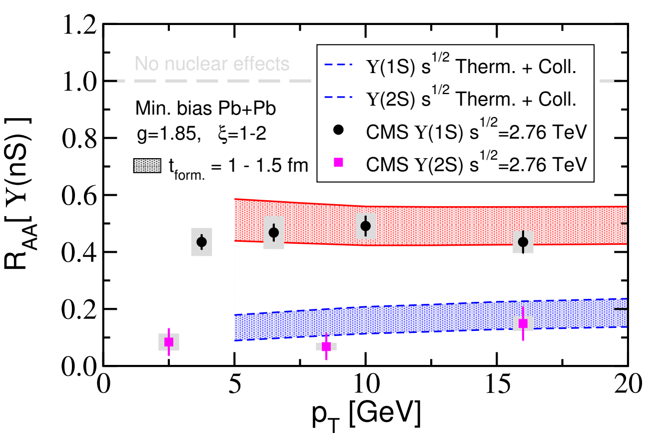
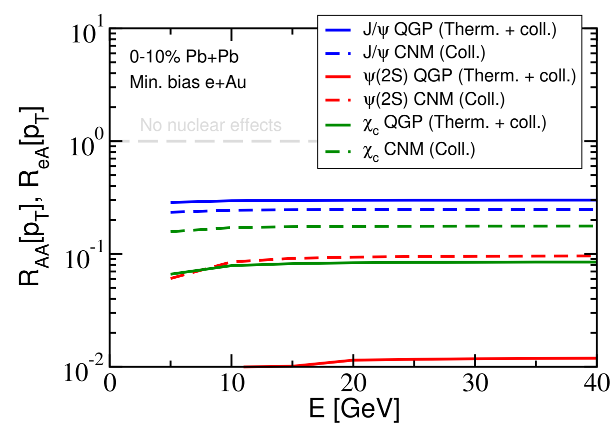
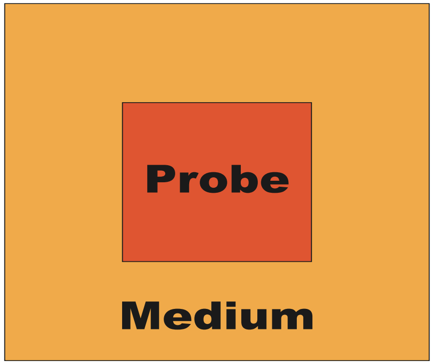




In-medium heavy quarkonium propagation – open quantum systems



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

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

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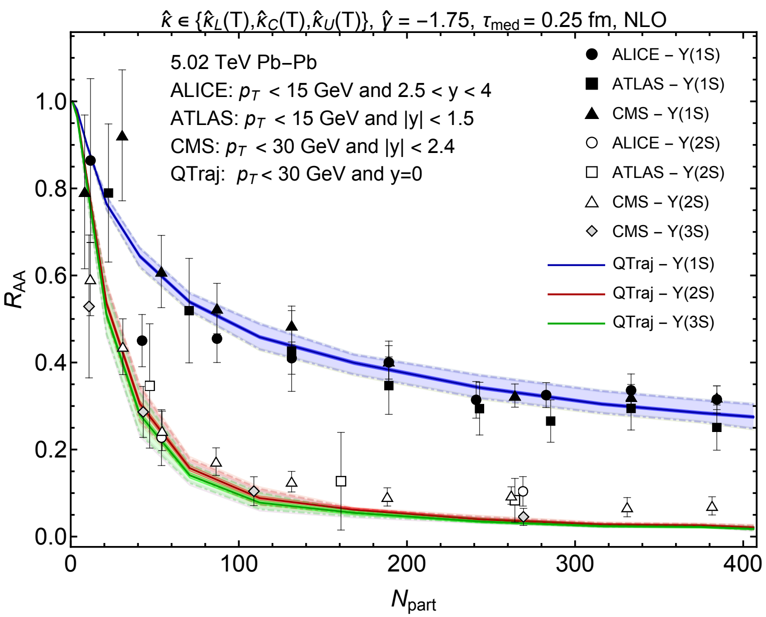
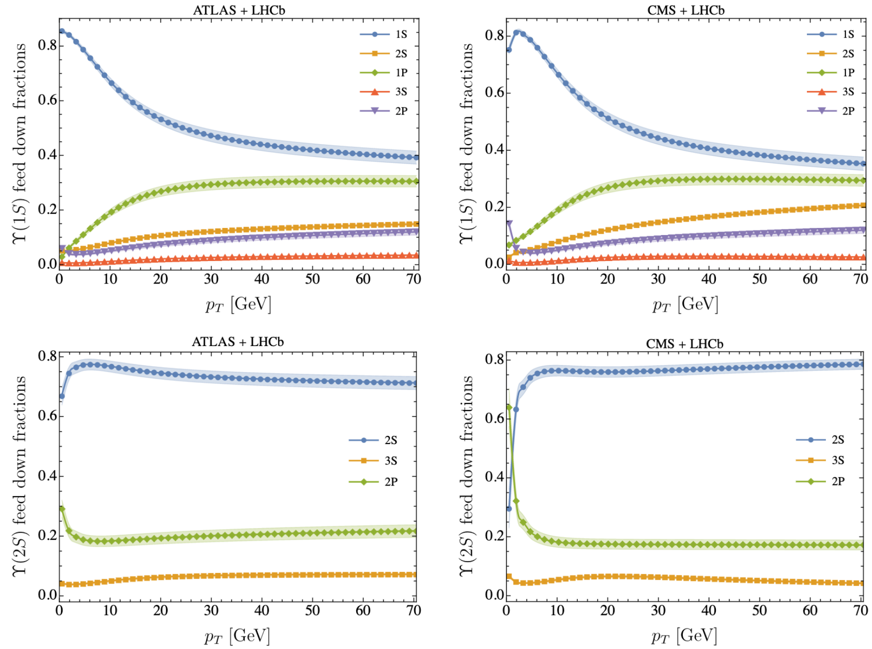


N. Brambilla et al. (2022)

Transverse-momentum dependent feed down

J. Boyd et al. (2023)



HF programs

INT Program

July 29 - August 23, 2024
Heavy Ion Physics in the EIC era (24-2b)
Y. T. Chien, M. Djordjevic, I. Vitev
Embedded Workshop: August 19 - 23

HEFTY COLLABORATION Summer School

Expect to be in the Santa Fe area
Summer school on heavy flavor physics
J. Terry, I. Vitev
Dates: TBD – we will keep you posted

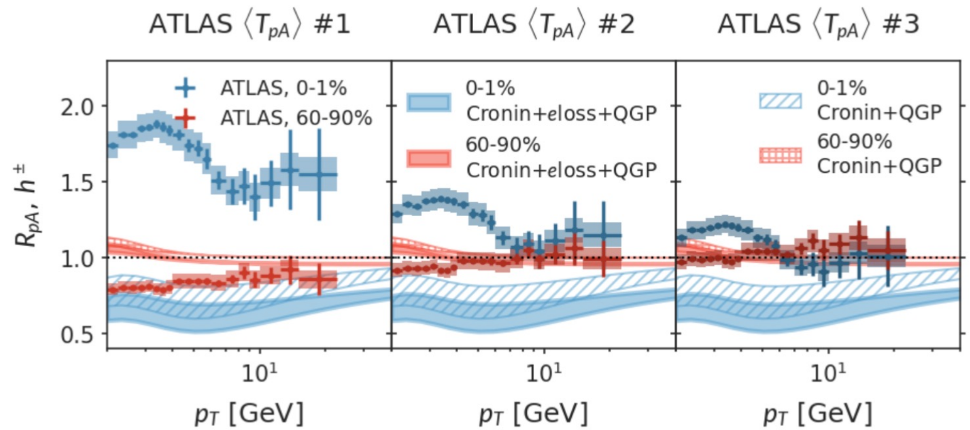
Conclusions

- Heavy flavor production is an important driver of QCD theory. Still, many open theoretical questions remain – from relevant EFTs in multi-scale problems, to the non-perturbative HF content of nucleons and nuclei, hadronization into heavy mesons, and quarkonia. These must be resolved to fully utilize the RHIC, LHC, and EIC capabilities
- The precise analysis of HF observables - suppression of D, B mesons, c,b-jets, and quarkonia; correlations; and HF jet substructure remain a priority using advanced theory that bridges the gap between high energy and nuclear physics. There are a number of dedicated efforts in the HF arena (much more so than in the light flavor and inclusive jets), including the new HEFTY NT topical collaboration
- There are new opportunities for HF physics to improve our understanding of non-perturbative aspects of QCD, develop new observables, understand the role of HQ mass on parton transport, QCD radiation, apply Bayesian statistical analysis to extract properties of cold and hot QCD matter, interface LQCD with PQCD and transport models. 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 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 to capitalize on theory effort and investments to answer the most pressing HF questions with an eye on RHIC, LHC and the EIC

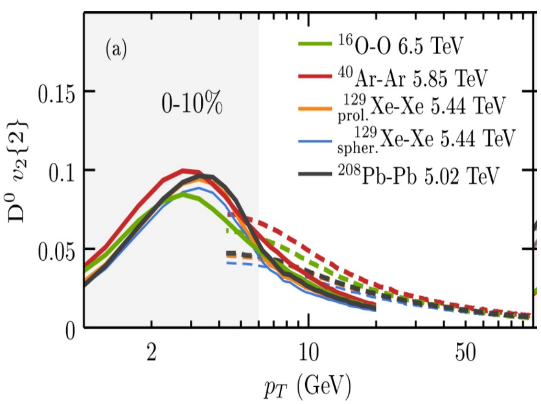
Quenching in small systems

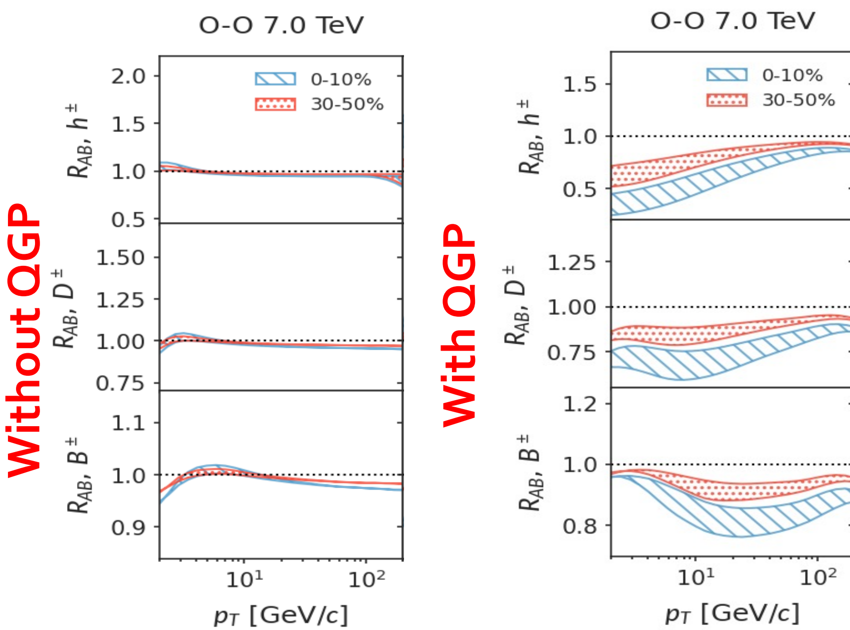
- In small systems (e.g. pPb, dAu) azimuthal asymmetries have been measured, interpreted as possible signatures of QGP formation
- No evidence for jet quenching measurements. In fact, incompatible with jet quenching phenomenology

W. Ke et al. (2022)



R. Katz et al . (2020)





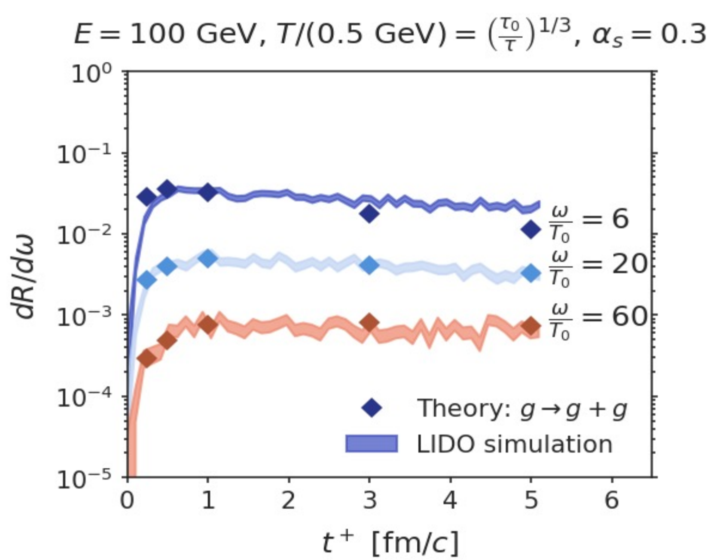
Significant interest in small symmetric systems, such as OO, to better constrain centrality and put limits on the smallest QGP droplets in nature

A. Huss et al . (2021)

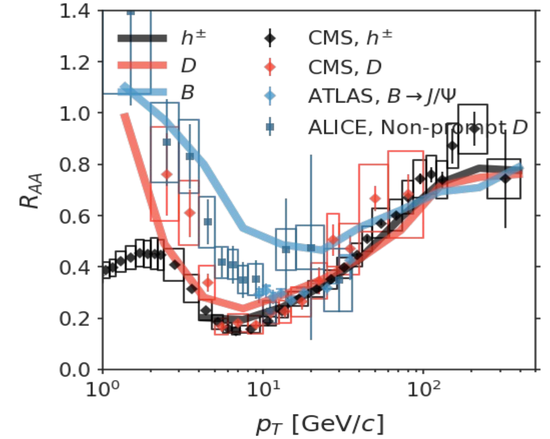
Heavy flavor in transport simulations - LIDO

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

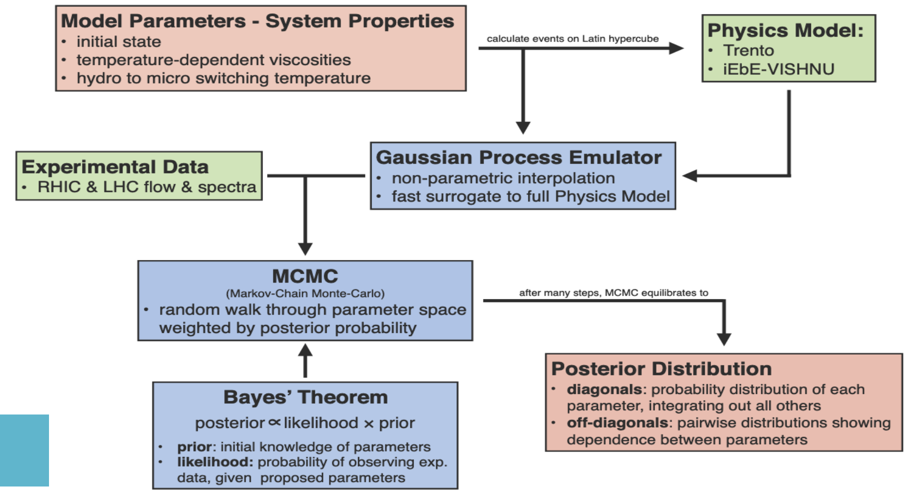
- $C_{nn}[f]$: diffusion + large-q collisions.
- $C_{n(n+1)}[f]$: induced radiation, with dynamical implementation of LPM effect.



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



Toward constraining heavy flavor dynamics with Bayesian analysis



W. Ke et al. (2019)

S. Bass et al. (2017)