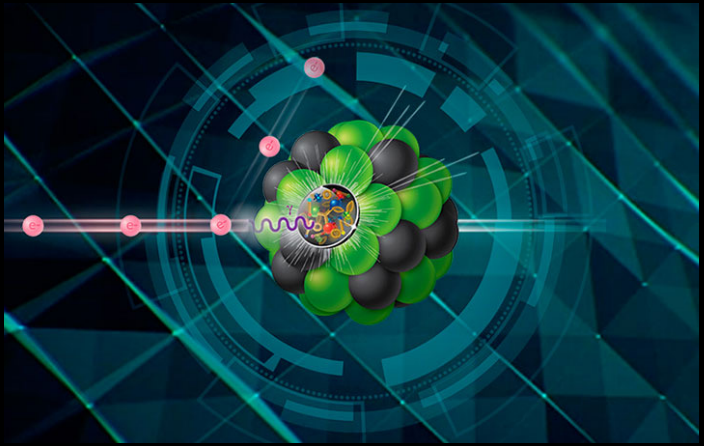
Ivan Vitev

Heavy flavor production, energy loss, and study of hadronization at EIC



CFNS Workshop "Theory for EIC in the next decade"
MIT, Boston, MA
September 20-22, 2022

Los Alamos NATIONAL LABORATORY EST. 1943

Outline of the talk

- Open heavy flavor and quarkonia production in elementary collisions
- Heavy flavor in nuclei – Glauber gluons, energy loss and in-medium showers
- The physics of hadronization and current status
- Heavy flavor observables at the EIC and connection to hadronization
- 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. Investment in heavy flavor physics is urgently needed**

Open HF at the EIC: https://indico.bnl.gov/event/9273/
Quarkonia at the EIC: https://indico.bnl.gov/event/12899/

For complementary discussion for jets and heavy flavor in relation to TMDs, non-perturbative analysis, nuclear PDFs, exotics, precision physics, small-x … see other talks in the workshop

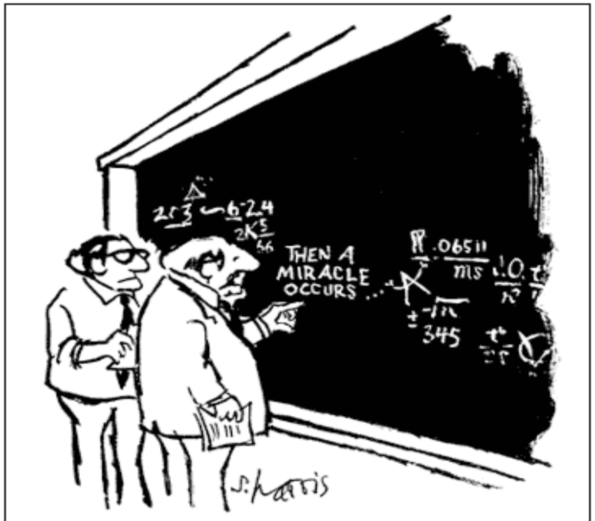
Acknowledgment of support

U.S. DEPARTMENT OF ENERGY Office of Science

TMD Collaboration

LDRD LABORATORY DIRECTED RESEARCH & DEVELOPMENT

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

S. Alekhin et al . (2020)

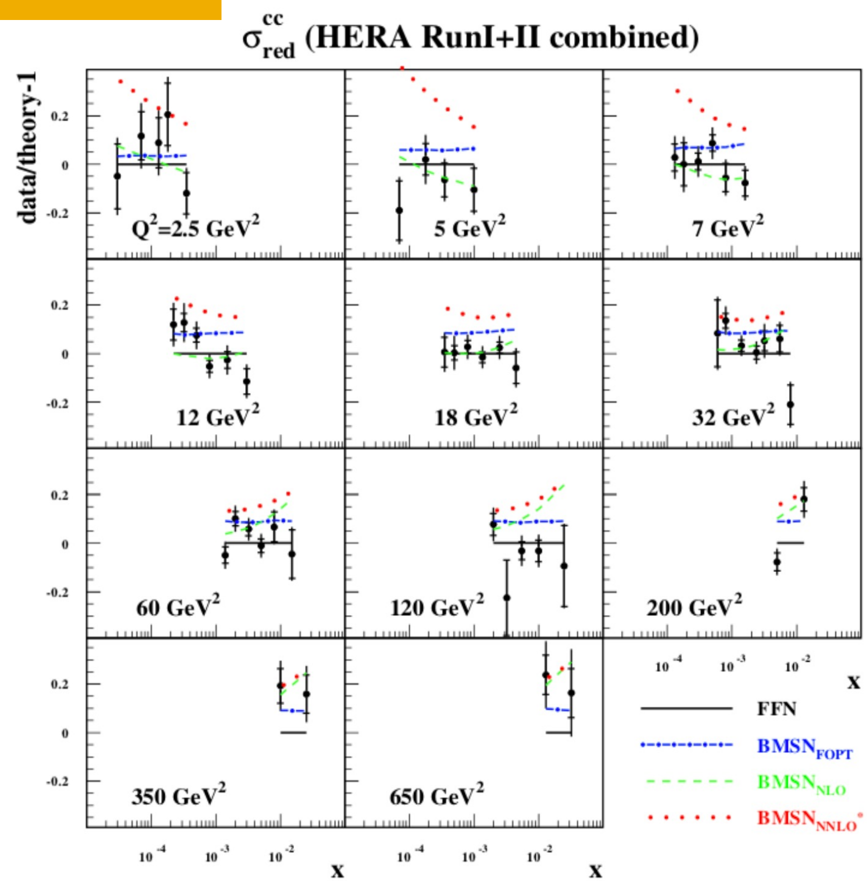
$$F_{2,h}^{FFN} = \sum_{k=1}^{\infty} a_s^k(n_f) \sum_{i=q,g} H_{2,i}^{(k)}(n_f) \otimes f_i(n_f),$$

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

Fixed flavor schemes – typically at low virtualities

Variable flavor schemes – as one goes to higher energies, effectively resums 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 useful for the EIC

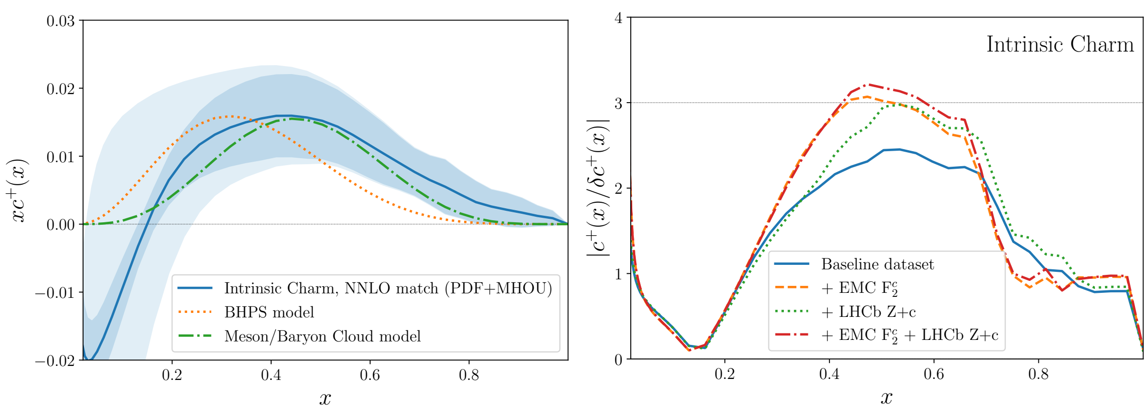


Confronting HF schemes with HERA data - FF and a particular VFF

S. Talk by F. Olness

New developments in intrinsic charm

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



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

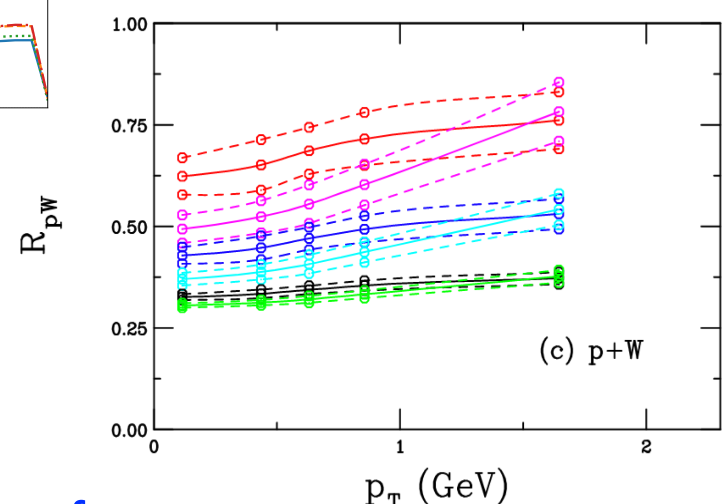
- Opportunity to develop phenomenology / strategies to search for intrinsic charm at the the EIC

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

NNPDF Collab. (2022)

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

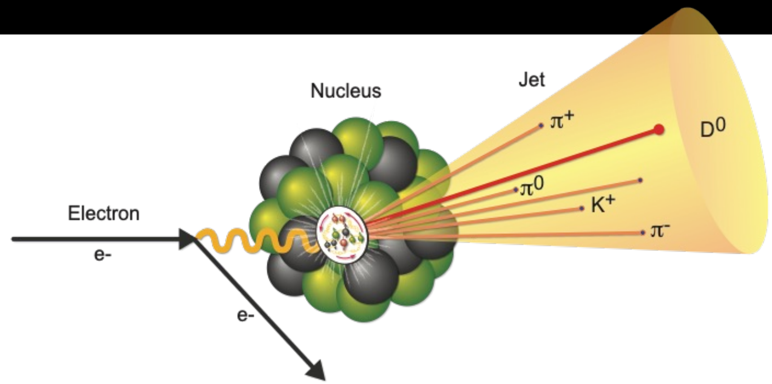
T. Hobbs et al . (2017)



R. Vogt. (2021)

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

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

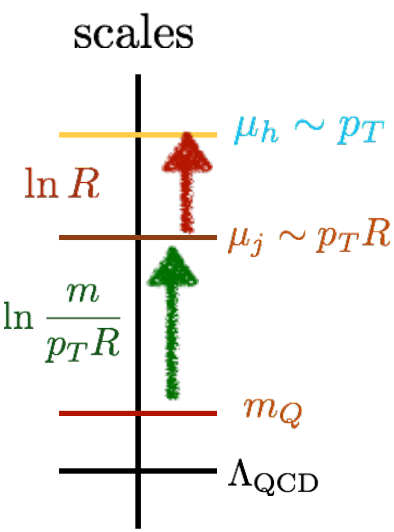
Resums ln $\mu/p_T R$

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

Resums ln $p_T R/m$

The integrated perturbative kernel at the jet typical scale

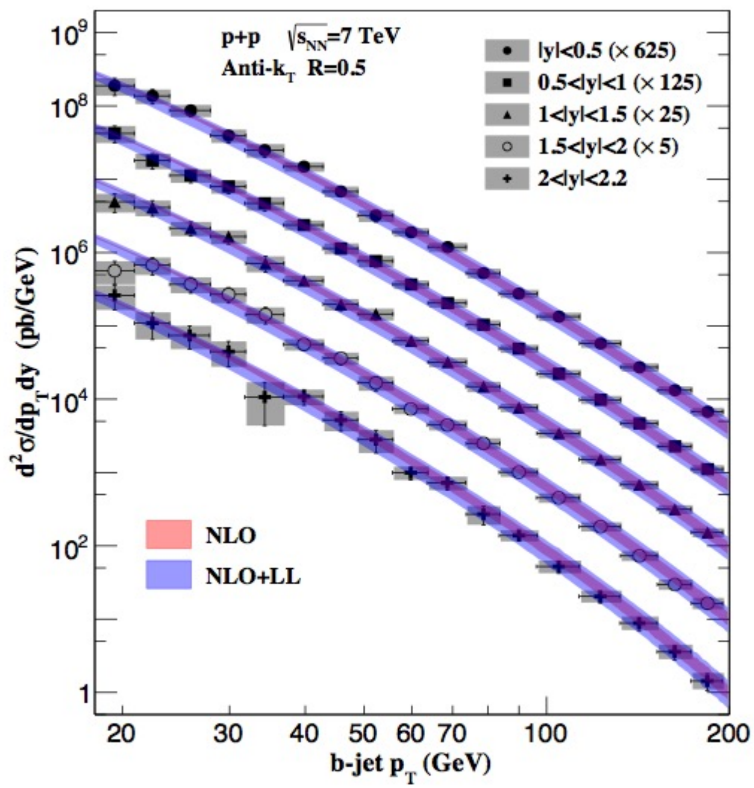
The integrated parton fragmentation function from parton *l* to parton *Q*

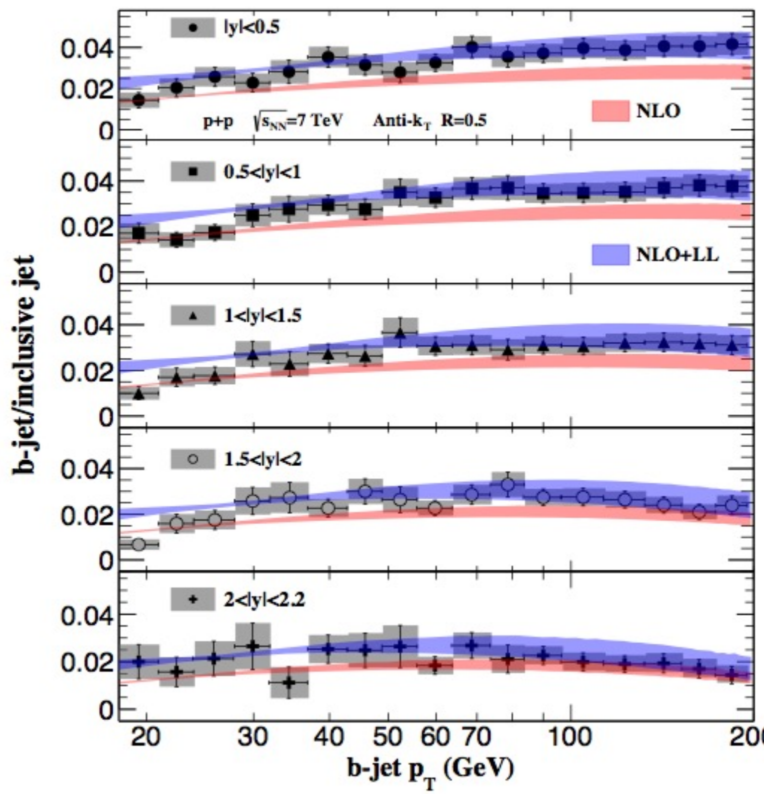


C. Bauer et al. (2013)

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)

For spin see talk by Z. Kang

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)

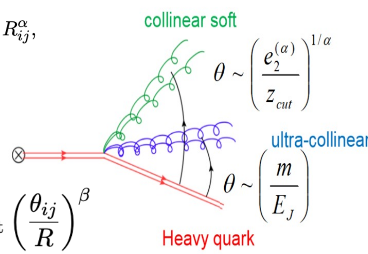
Two point energy energy correlator

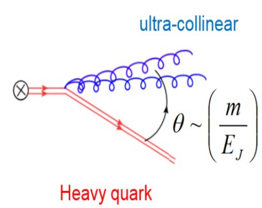
A. Larkoski *et al.* (2013)

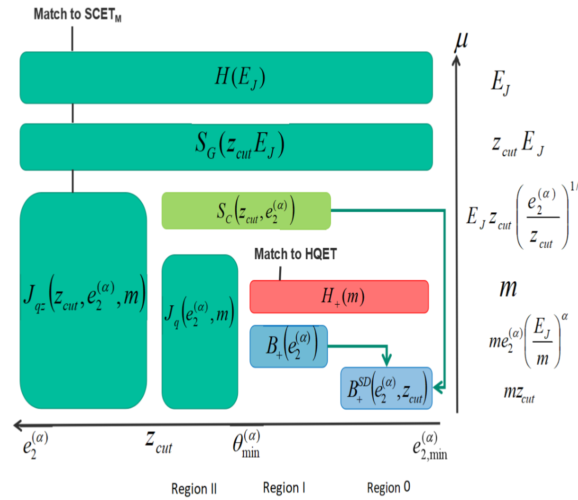
$$e_2^{(\alpha)}|_{e^+e^-} = \sum_{i<j\in J} z_i z_j (\theta_{ij})^\alpha \qquad e_2^{(\alpha)}|_{pp} = \frac{1}{p_{T_J}^2} \sum_{i<j\in J} p_{T_i} p_{T_j} R_{ij}^\alpha,$$

Subject to soft drop grooming

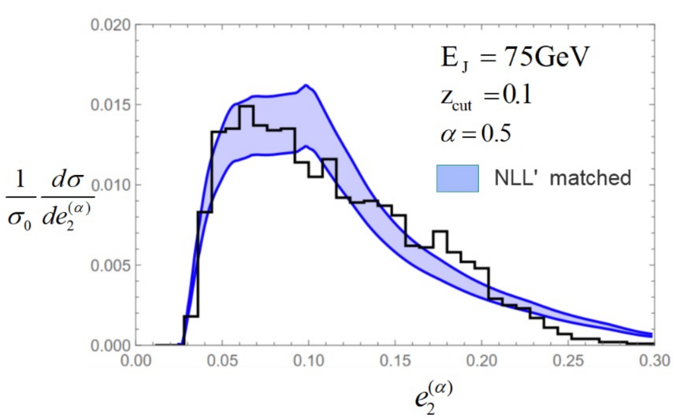
$$\frac{\min\{E_i, E_j\}}{E_i + E_j} > z_{\rm cut} \left(\frac{\theta_{ij}}{R}\right)^\beta \qquad \frac{\min\{p_{Ti}, p_{Tj}\}}{p_{Ti} + p_{Tj}} > z_{\rm cut} \left(\frac{\theta_{ij}}{R}\right)^\beta$$

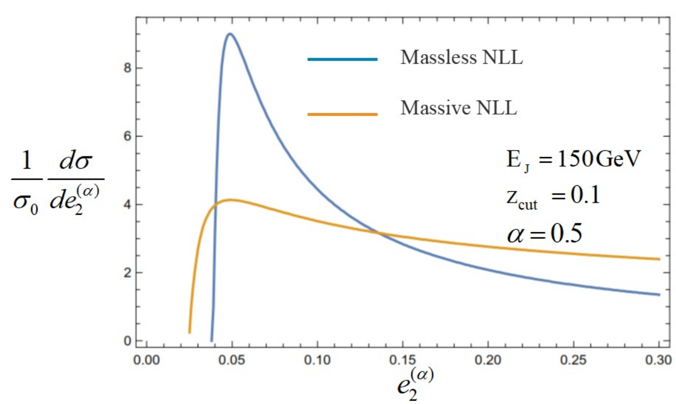






The HQ mass, definition of observable and grooming introduce multiple scales that must be treated in a new EFT





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

Production of quarkonia and NRQCD

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

Bodwin *et al.* (1995)

Cho *et al.* (1996)

μ

m_Q

$m_Q v$

Λ_{QCD}

$m_Q v^2$

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

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

QCD without the heavy flavor

ultra-soft

+ heavy - soft interactions at NLO

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

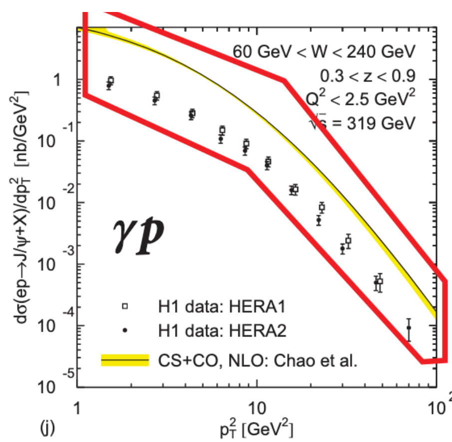
vNRQCD M. Luke *et al. (2000)*

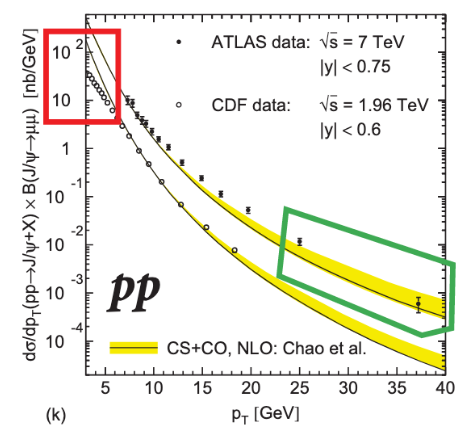
M. Butenschon *(2012)*

J. Lansberg (2020)

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

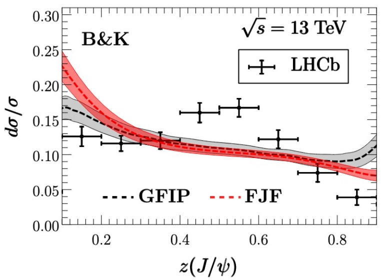
$$d\sigma(a+b \to \mathcal{Q}+X) = \sum_n d\sigma(a+b \to Q\overline{Q}(n)+X) \langle \mathcal{O}_n^{\mathcal{Q}} \rangle$$

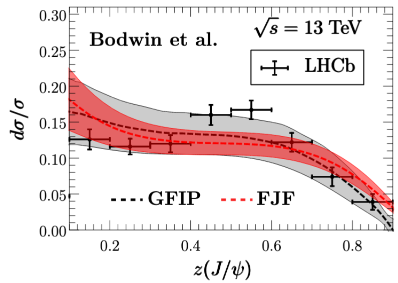




Strong tensions remain in the EIC relevant small to moderate p_T region

Opportunities in e+p at the EIC





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

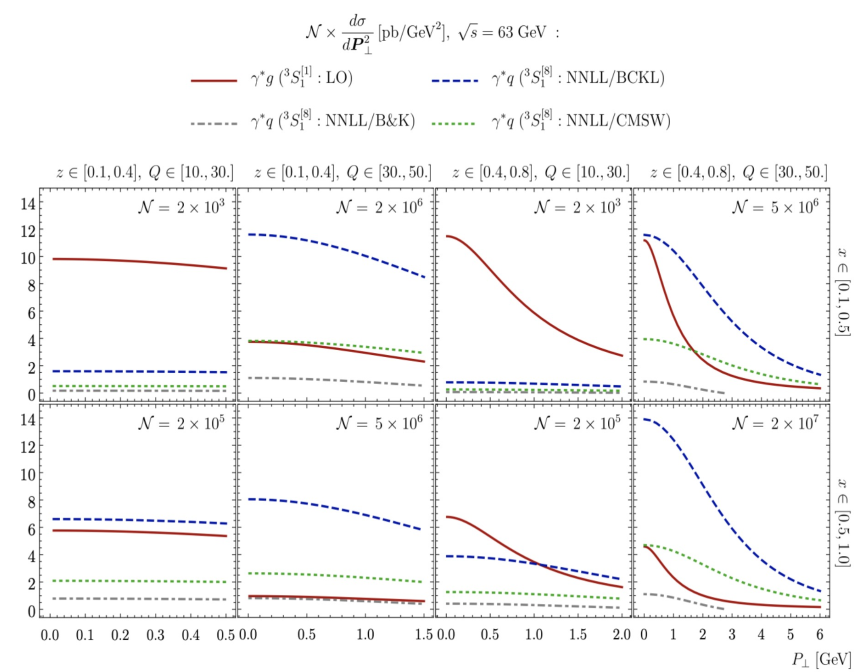
$$\frac{d\sigma}{dy\, d^2q_\perp} = \frac{4M^4\, H(M^2,\mu^2)}{2sM^2(N_c^2-1)}\, \Gamma^*_{\rho\sigma}\Gamma_{\mu\nu}(2\pi) \int d^2\boldsymbol{k}_{n\perp} d^2\boldsymbol{k}_{\bar{n}\perp} d^2\boldsymbol{k}_{s\perp}\, \delta^{(2)}\left(\boldsymbol{q}_\perp - \boldsymbol{k}_{n\perp} - \boldsymbol{k}_{\bar{n}\perp}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

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

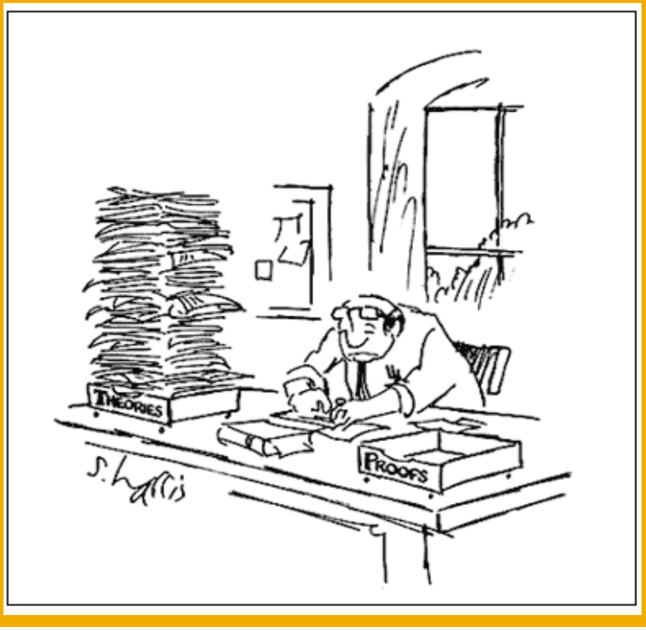
See talk by. I. Stewart

At small-x we have NRQCD + CGC

See talk by R. Venugopalan

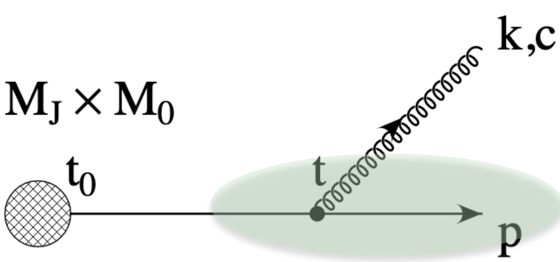
M. Echevarria et al. (2007)

Heavy flavor in nuclei – energy loss and in-medium showers



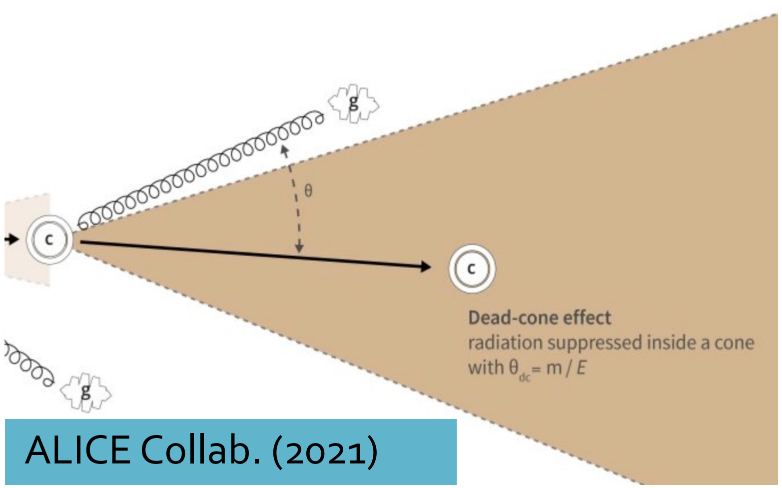
Heavy flavor propagation in matter

Vacuum



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

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

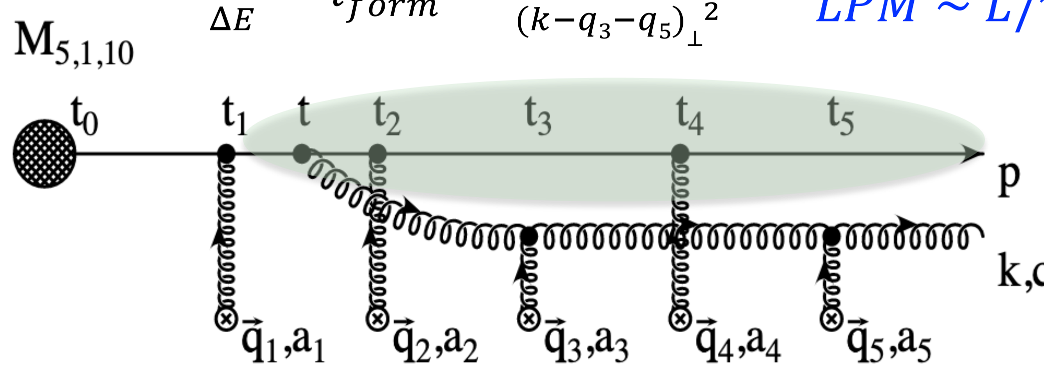


ALICE Collab. (2021)

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

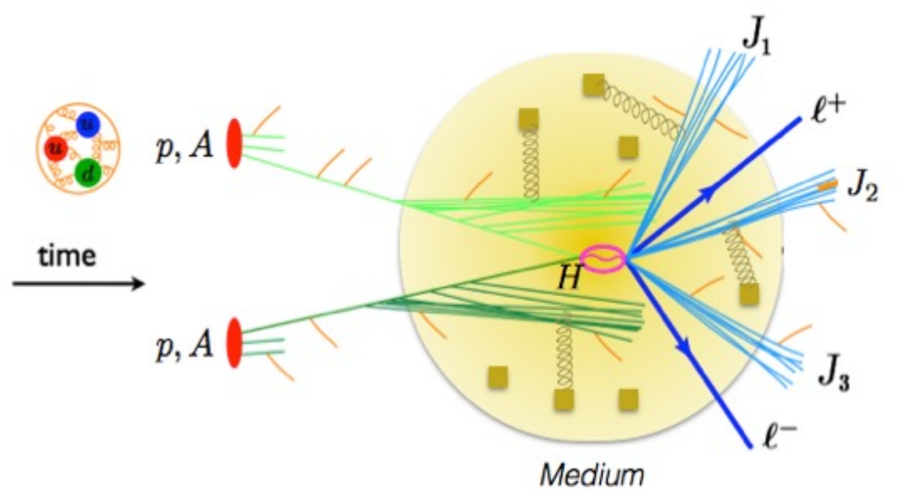
Parton propagation in SCET$_G$

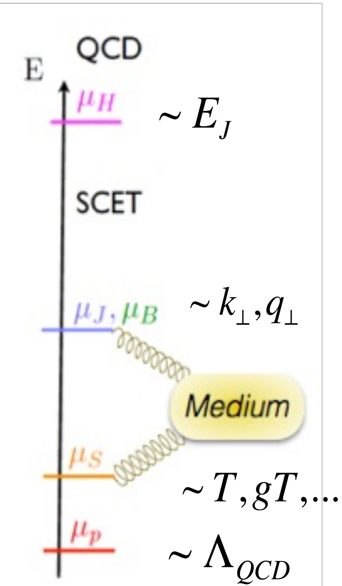
- There are no parton-matter interactions in SCET. Still a multiscale problem, but needs extension (new modes, Glauber gluons)

C. Bauer et al. (2001)

M .Beneke et al. (2002)

modes	$p^\mu = (+, -, \perp)$	p^2	fields
collinear	$Q(\lambda^2, 1, \lambda)$	$Q^2\lambda^2$	$\xi_n,\ A_n^\mu$
soft	$Q(\lambda, \lambda, \lambda)$	$Q^2\lambda^2$	$q_s,\ A_s^\mu$





A. Idilbi et al. (2008)

G. Ovanesyan et al. (2011)

V. Vaidya et al. (2021)

Glaubers in a different context

S. Fleming et al. (2015)

I. Rothstein et al. (2016)

- Factorization, with modified J, B, S

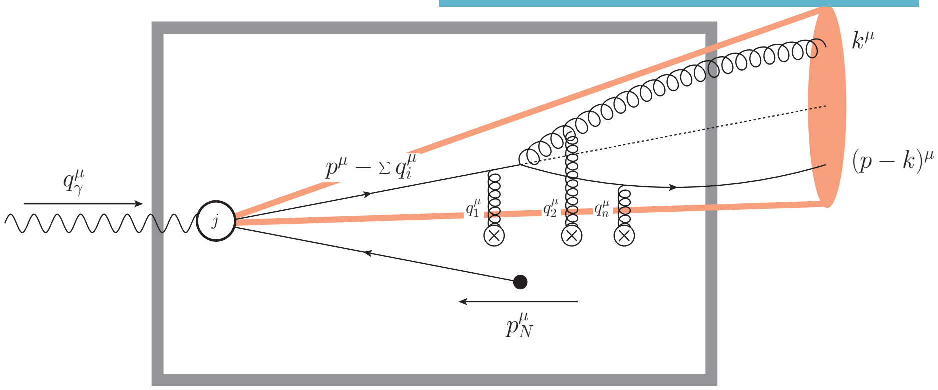
$$\sigma = \mathrm{Tr}(HS) \otimes \prod_{i=1}^{n_B} B_i \otimes \prod_{j=1}^{N} J_j$$

Heavy flavor showers in matter

- Full massless and massive in-medium splitting functions now available to first order in opacity
- SCET-based effective theories and lightcone wavefunction approach give the same result

SCET$_{M,G}$ approach Z. Kang et al. (2016)

LCWF approach M. Sievert et al. (2018)



Direct sum of vacuum and medium contributions

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

- Factorize form the hard part
- Gauge-invariant
- Depend on the properties of the medium
- **Different dead cone effect for different splittings**

Representative example

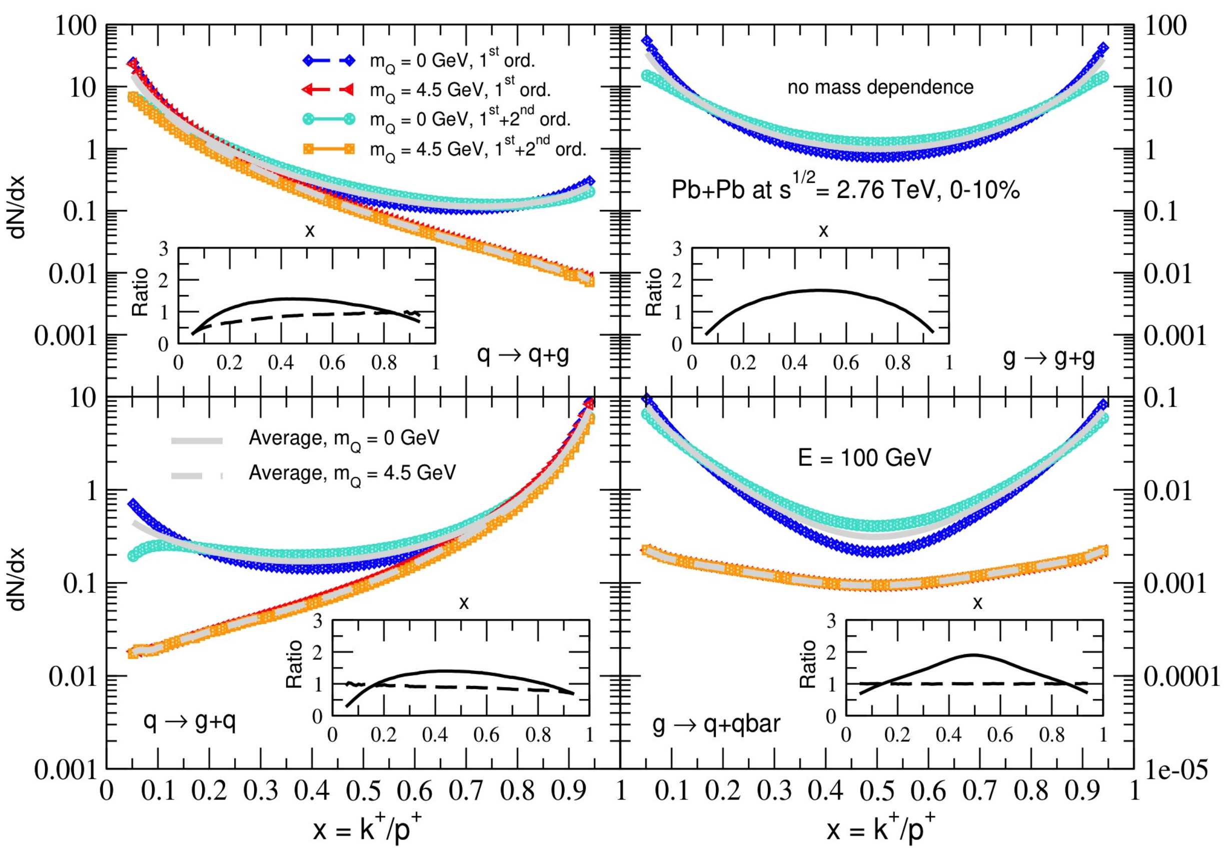
$$\begin{aligned}
\left(\frac{dN^{\rm med}}{dxd^2\boldsymbol{k}_\perp}\right)_{Q\to Qg} &= \frac{\alpha_s}{2\pi^2}C_F \int \frac{d\Delta z}{\lambda_g(z)} \int d^2\boldsymbol{q}_\perp \frac{1}{\sigma_{el}} \frac{d\sigma_{el}^{\rm med}}{d^2\boldsymbol{q}_\perp} \Bigg\{ \left(\frac{1+(1-x)^2}{x}\right)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

Done of course for all splitting functions

Differential branching spectra

B. Yoon et al. (2019)

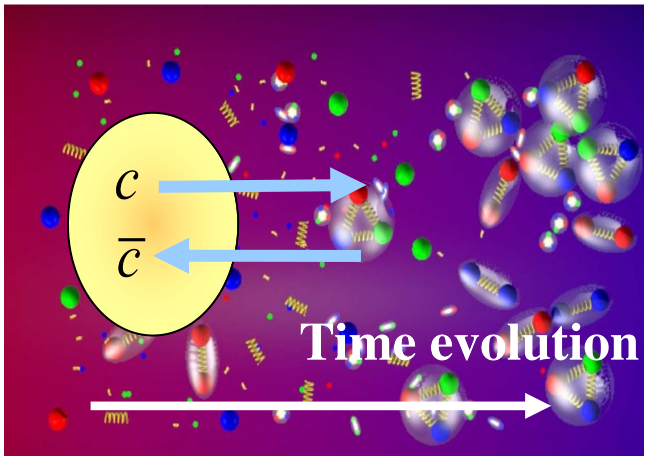
In-medium parton showers are softer **and** broader **than the ones in the vacuum. There is even more soft gluon emission – medium induced scaling violations, enhancement of soft branching**



There us also more wide-angle emission (which implies out-of-cone radiation for jet physics)

- There are significant differences due to the **heavy quark mass** between massless and massive splitting functions
- Higher orders in opacity **have minimal effect on heavy flavor splitting**

NRQCD in the nuclear medium



- At the Lagrangian level

Y. Makris et al. (2019)

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

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

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

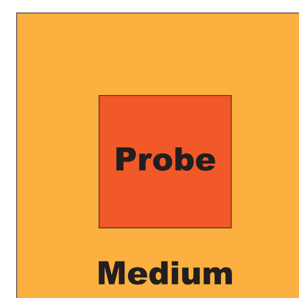
$$\mathcal{L}^{(1)}_{Q-G}(\psi, A^{\mu,a}_{G}) = g\sum_{\mathbf{p},q_T} \psi^\dagger_{\mathbf{p}+\mathbf{q}_T}\Big(\frac{2A^{\mathrm{n}}_G(\mathbf{n}\cdot\boldsymbol{\mathcal{P}}) - i\big[(\boldsymbol{\mathcal{P}}_\perp\times\mathbf{n})A^{\mathrm{n}}_G\big]\cdot\boldsymbol{\sigma}}{2m}\Big)\psi_{\mathbf{p}}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

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

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

- Results: depend on the type of the source of scattering in the medium

Transport and open quantum system approaches in nuclear matter have been developed. Typically applied to hot QCD but can be generalized to cold QCD



Y. Akamatsu et al. (2015)

N. Brambilla et al. (2022)

The physics of hadronization

Hadronization

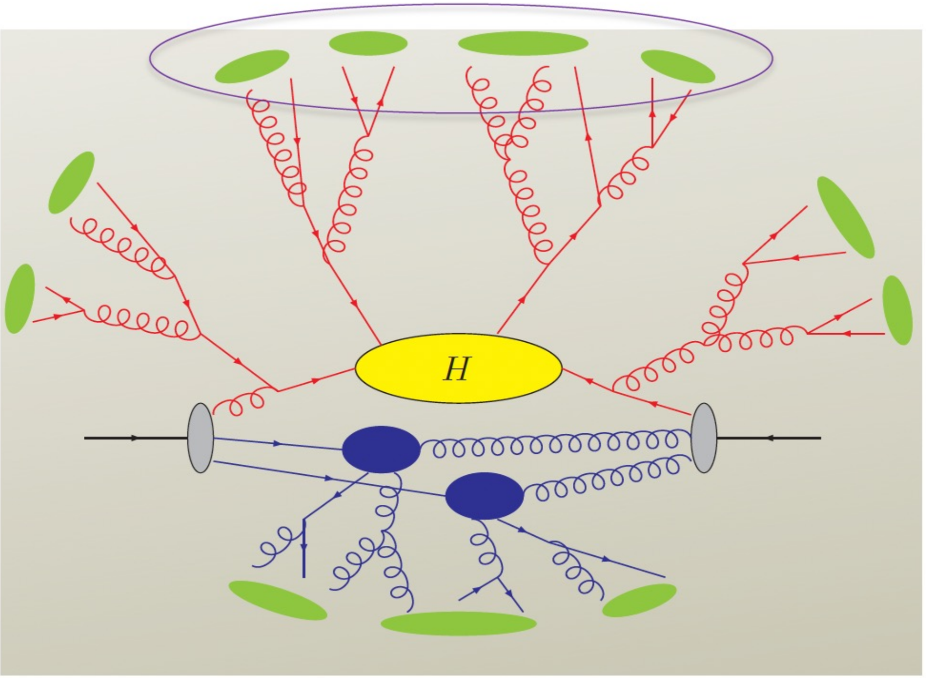
B. Webber (1999)

T. Sjostrand (2015)

Special request to cover this in more detail

- Hadronization is the inherently non-perturbative process where energy is converted to matter and the fundamentally unobservable in isolation degrees of freedom of QCD (quarks and gluons) form the elementary particles that we can measure

Note, fragmentation is not the same as hadronization. Fragmentation (and there are different varieties) is a model of hadronization



- Hadronization is a long-distance, late-stage phenomenon. We have no first principles understanding yet of the timescales involved

Independent fragmentation

See talk by N. Sato

Well defined matrix elements. DGLAP evolution

$$\mathcal{P}_{A/j}(z, P_T) = \frac{1}{2z(2\pi)^3}\int dx^-\, d^2x_T\, e^{ik^+x^- - ik_T\cdot x_T}$$
$$\times \tfrac{1}{3}\,\mathrm{tr}_{\mathrm{color}}\,\tfrac{1}{2}\,\mathrm{tr}_{\mathrm{Dirac}}\,\{\gamma^+\langle 0|\psi(x)a_A^\dagger(P^+,0)a_A(P^+,0)\bar{\psi}(0)|0\rangle\}$$

J. Collins et al. (1981)

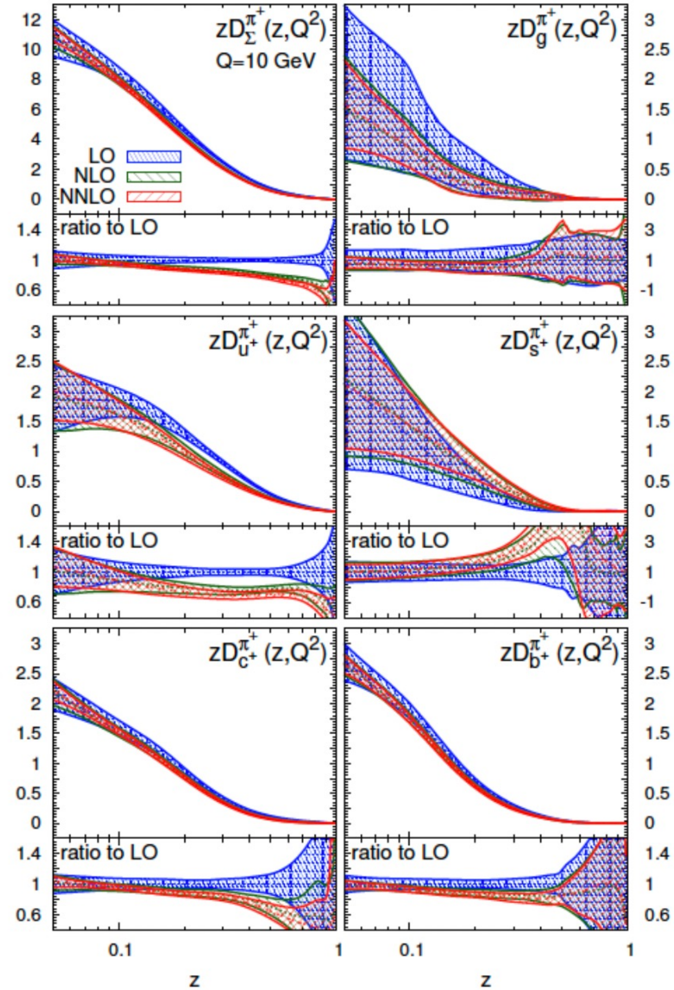
Example of SIA

$$d\sigma^h(x,Q^2) = \sum_{i=-n_f}^{n_f}\int_x^1 dz\, d\sigma^i\left(\frac{x}{z},\frac{Q^2}{\mu^2},\frac{m_i^2}{Q^2},\alpha_s(\mu^2)\right) D_i^h(z,\mu^2)$$

$$\frac{d\sigma^h}{dz} = F_T^h(z,Q^2) + F_L^h(z,Q^2) = F_2^h(x,Q^2)$$

$$F^h_{k=T,L,2} = \frac{4\pi\alpha^2_{\mathrm{em}}}{Q^2}\langle e^2\rangle\left\{D^h_\Sigma\otimes C^{\mathrm{S}}_{k,q} + n_f D^h_g\otimes C^{\mathrm{S}}_{k,g} + D^h_{\mathrm{NS}}\otimes C^{\mathrm{NS}}_{k,q}\right\}$$

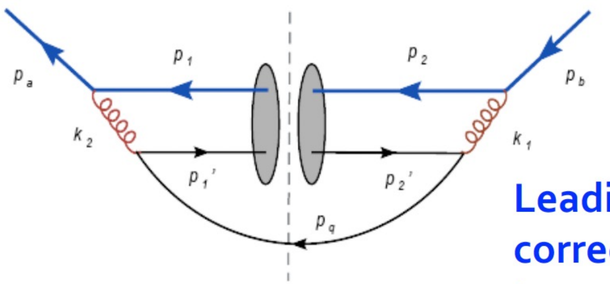
- Explicitly does not account for global energy flow, higher twist corrections, …
- Even with excellent χ^2 and fits, independent fragmentation cannot describe global particle flow in the event



E. Norcera et al. (2017) NNFF

Heavy quark fragmentation in HQET

Heavy quarks introduce a mass scale that allows the fragmentation function shape to be computed perturbatively.

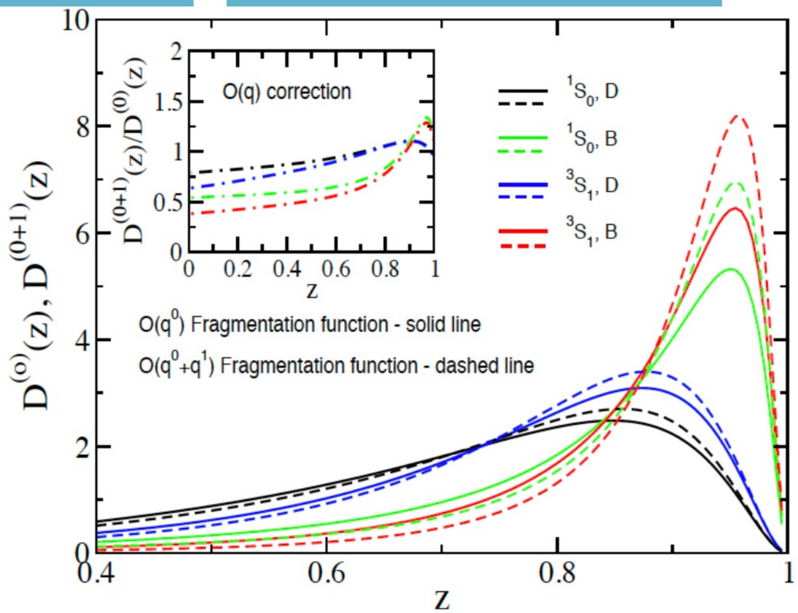


Chang et al. (1992)

Braaten et al. (1995)

Leading result and first correction from transverse motion

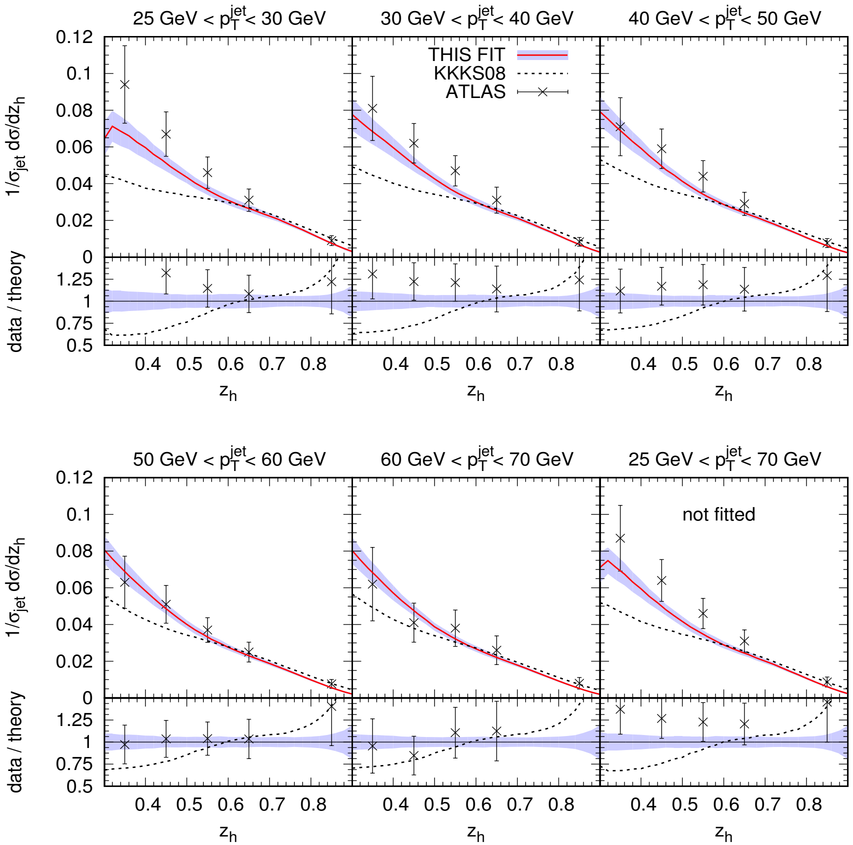
$$T_P^{(1)}(z) = \frac{(z-1)^2 z^2}{6M^3(1-r)r^3((r-1)z+1)^8}\left[\frac{p_Q^+}{q_{1P}^+}\frac{\mathbf{q}_{1T}^2}{M^2}+\frac{p_Q^+}{q_{2P}^+}\frac{\mathbf{q}_{2T}^2}{M^2}\right]\Big\{3(r-1)^4 r z^6+(r-1)^3(2r+5)z^5+3(r-1)^3(4r-7)z^4 -(r-1)(r(r(8r-63)+88)-36)z^3+[r((81-28r)r-90)+32]z^2+((25-8r)r-15)z+3\Big\},$$



R. Sharma et al. (2009)

- Still depends on non-perturbative parameters $r = m_q/M_Q$, the square of the wavefunction in the origin. Fitted to data

Constraints on fragmentation from heavy mesons in jets

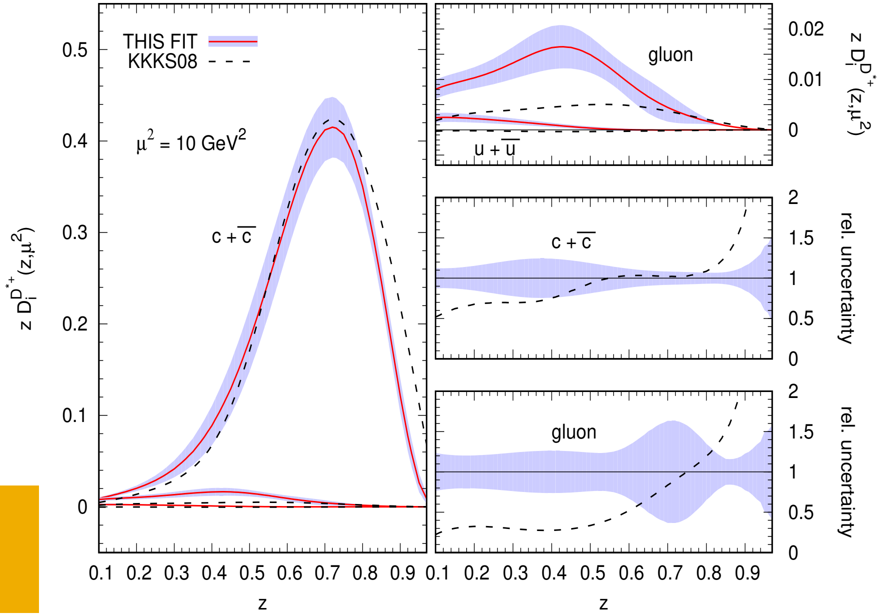


D. Anderle *et al.* (2017)

Using a new formalism of semi-inclusive fragmenting jet functions

$$\frac{d\sigma^{pp\to(\text{jet}\,h)X}}{dp_T^{\text{jet}}\,d\eta^{\text{jet}}\,dz_h} = \frac{2p_T^{\text{jet}}}{S}\sum_{a,b,c}\int_{x_a^{\min}}^{1}\frac{dx_a}{x_a}f_a(x_a,\mu)$$
$$\times\int_{x_b^{\min}}^{1}\frac{dx_b}{x_b}f_b(x_b,\mu)\int_{z_c^{\min}}^{1}\frac{dz_c}{z_c^2}\frac{d\hat{\sigma}_{ab}^{c}(\hat{s},\hat{p}_T,\hat{\eta},\mu)}{v\,dv\,dw}$$
$$\times\,\mathcal{G}_c^h(z_c,z_h,\mu,R)\,,$$

Z. Kang *et al.* (2016)

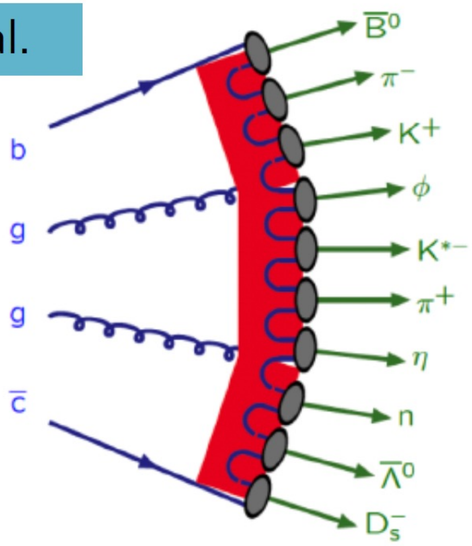


Significant enhancement of the gluon fragmentation component at small and intermediate z

Hadronization in Monte Carlo models

String fragmentation

PYTHIA et al.

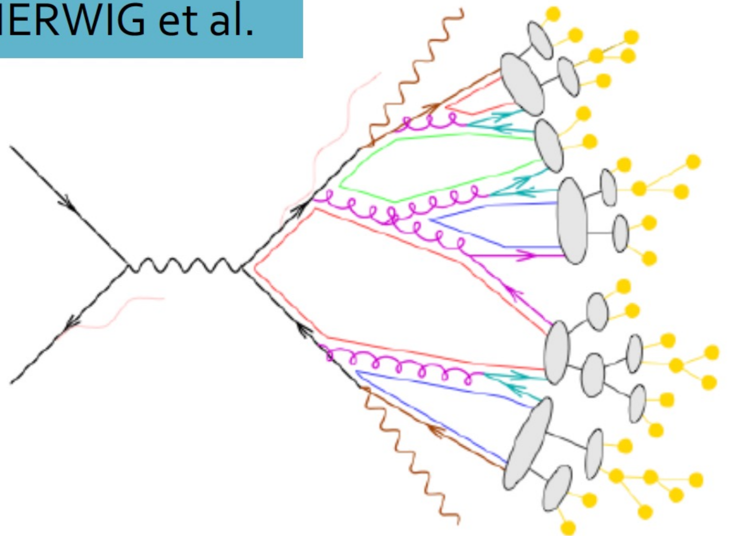


$$f(z) \propto \frac{1}{z}(1-z)^a \exp\left(-\frac{bm_\perp^2}{z}\right)$$

- This picture allows to derive the form of fragmentation functions (not as general) but comes from a model

Cluster hadronization

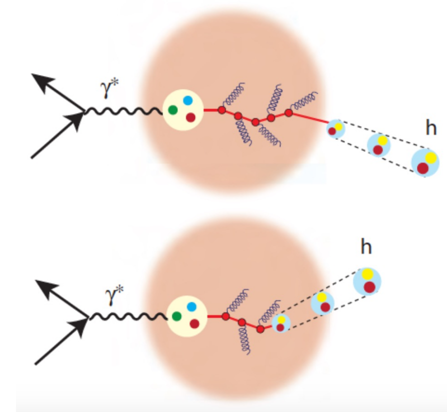
HERWIG et al.



program	PYTHIA	HERWIG
model	string	cluster
energy–momentum picture	powerful predictive	simple unpredictive
parameters	few	many
flavour composition	messy unpredictive	simple in-between
parameters	many	few

The space-time picture of hadronization

- The space-time picture of hadronization is unknown, but critical for e+A
- Competing physics explanations of HERMES hadron suppression data based on energy loss and absorption

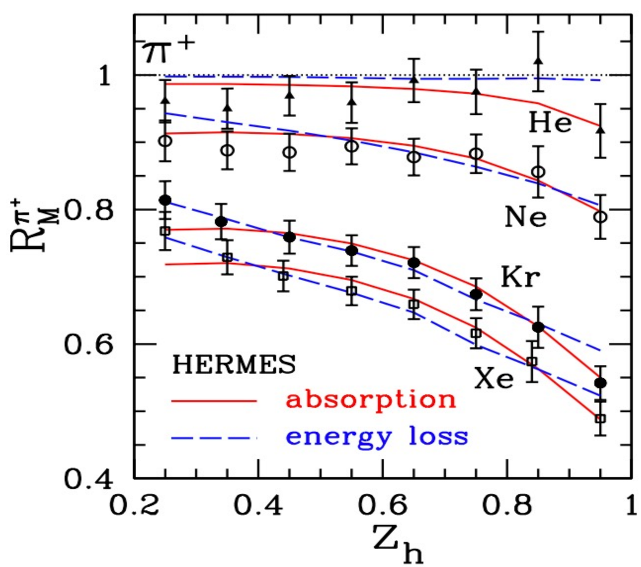


W. Wang et al. (2002)

B. Kopeliovich et al. (2003)

Light hadron measurements cannot differentiate between competing mechanisms

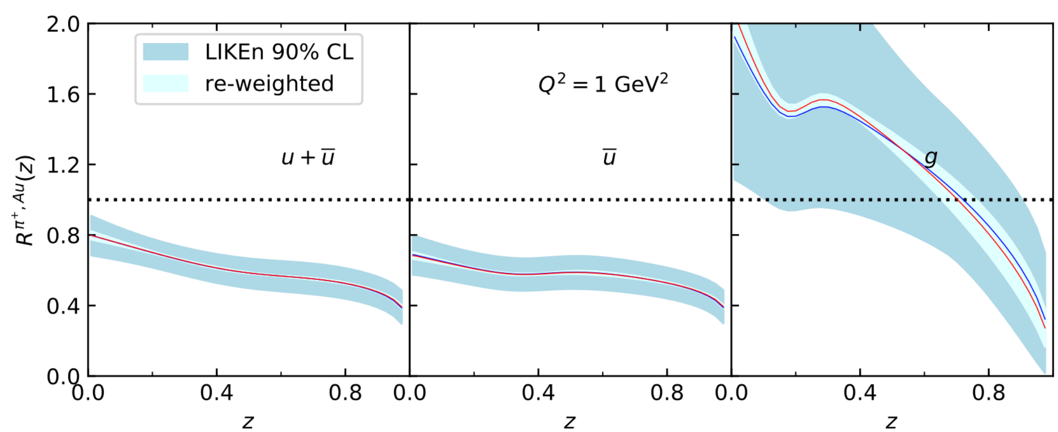
A. Accardi et al. (2009)



Ideas to parametrize nFFs assuming universality.
Effect of 10 fb-1 EIC data

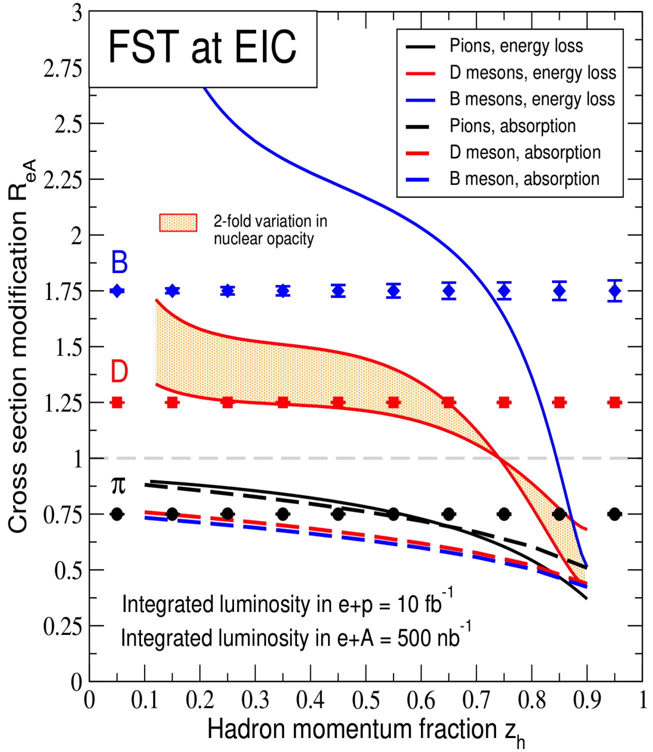
R . Sassot et al. (2009)

P . Zurita et al. (2021)



Heavy flavor observables at the EIC and connection to hadronization

Heavy meson tomography



Heavy flavor can be produced at the EIC. It will differentiate between energy loss and absorption models. Allows to develop e+A theory further.

The larger CM energies imply partonic interactions. Hybrid approach or full in-medium DGLAP

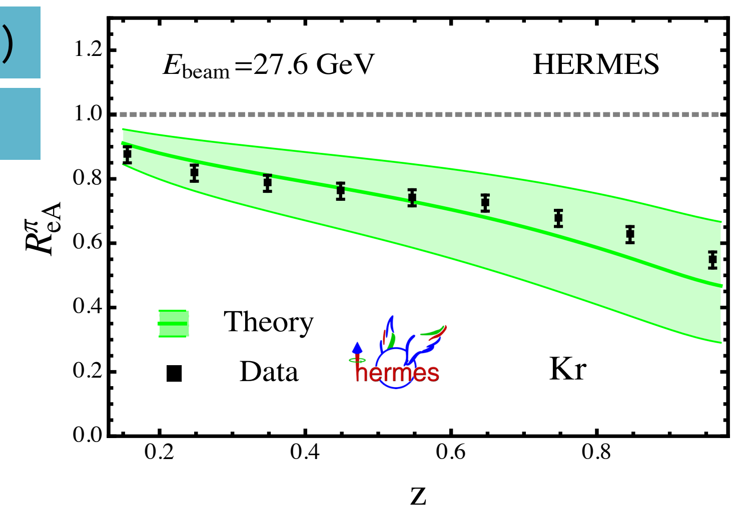
$$\frac{\mathrm{d}D_q(z,Q)}{\mathrm{d}\ln Q} = \frac{\alpha_s(Q^2)}{\pi}\int_z^1 \frac{\mathrm{d}z'}{z'}\left\{P_{q\to qg}(z',Q)D_q\left(\frac{z}{z'},Q\right) + P_{q\to gq}(z',Q)D_g\left(\frac{z}{z'},Q\right)\right\},$$

$$\frac{\mathrm{d}D_{\bar q}(z,Q)}{\mathrm{d}\ln Q} = \frac{\alpha_s(Q^2)}{\pi}\int_z^1 \frac{\mathrm{d}z'}{z'}\left\{P_{q\to qg}(z',Q)D_{\bar q}\left(\frac{z}{z'},Q\right) + P_{q\to gq}(z',Q)D_g\left(\frac{z}{z'},Q\right)\right\},$$

$$\frac{\mathrm{d}D_g(z,Q)}{\mathrm{d}\ln Q} = \frac{\alpha_s(Q^2)}{\pi}\int_z^1 \frac{\mathrm{d}z'}{z'}\left\{P_{g\to gg}(z',Q)D_g\left(\frac{z}{z'},Q\right)+P_{g\to q\bar q}(z',Q)\left(D_q\left(\frac{z}{z'},Q\right) + f_{\bar q}\left(\frac{z}{z'},Q\right)\right)\right\}.$$

N. Chang et al. (2014)

Z. Kang et al. (2014)

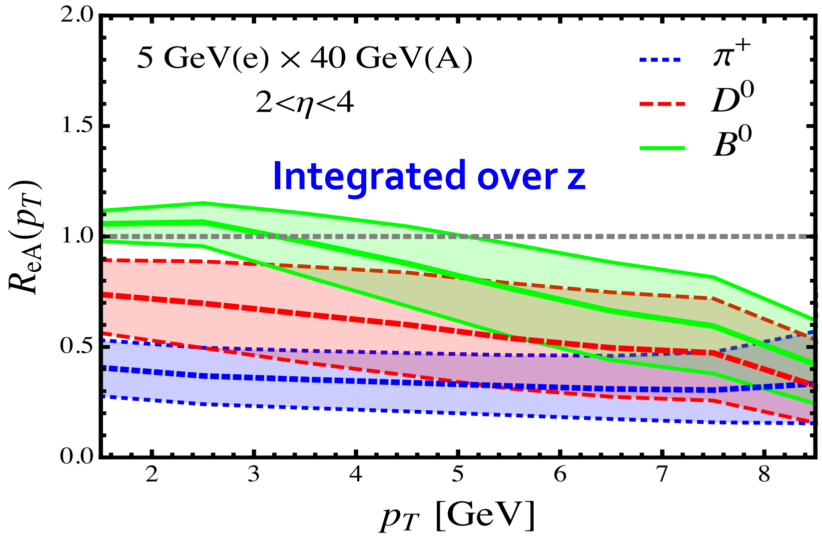


Help constrain the transport properties of nuclear matter:

$$qhat(q) = 0.05\frac{GeV^2}{fm}\ (vary \times 2,/2) \quad qhat(g) = 0.12\frac{GeV^2}{fm}\ (vary \times 2,/2)$$

H. Li et al. (2020)

Light and heavy flavor suppression at the EIC

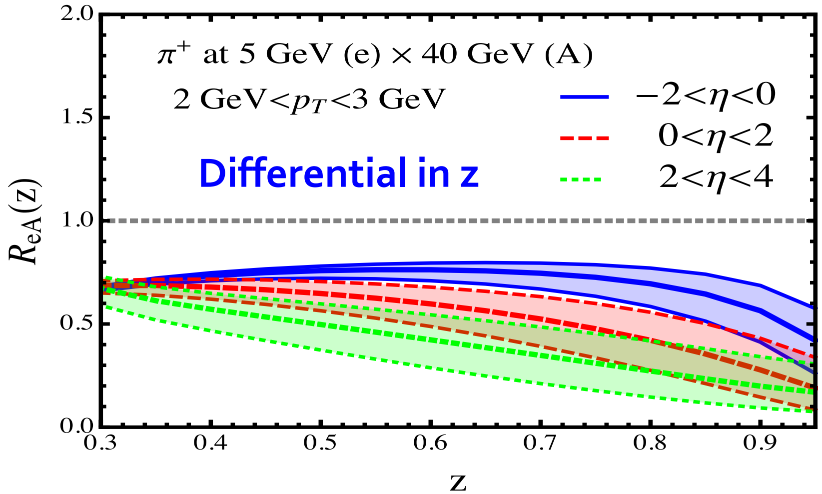


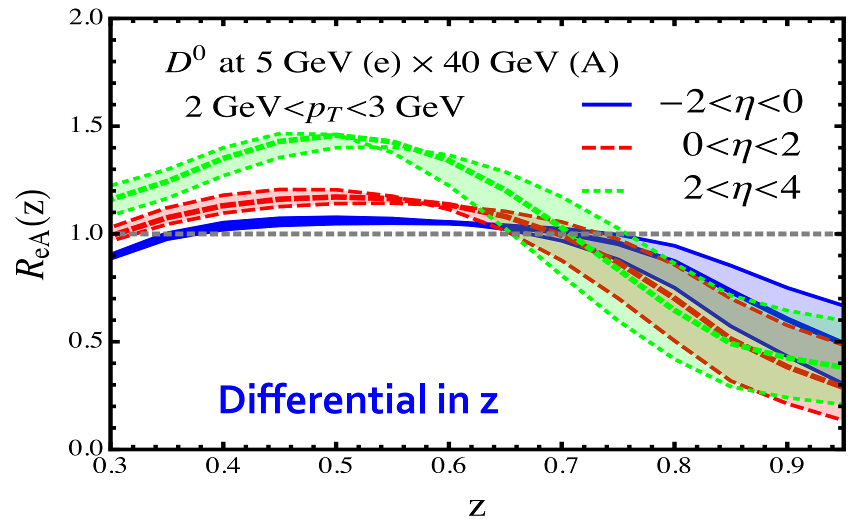
$$R^h_{eA}(p_T,\eta,z) = \frac{\left.\frac{N^h(p_T,\eta,z)}{N^{\mathrm{inc}}(p_T,\eta)}\right|_{\mathrm{e+Au}}}{\left.\frac{N^h(p_T,\eta,z)}{N^{\mathrm{inc}}(p_T,\eta)}\right|_{\mathrm{e+p}}}$$

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

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

Z. Liu et al . (2020)





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

Heavy flavor jets in matter

The semi-inclusive jet function theory can be generalized to heavy jet production in matter. Medium corrections to the NLO jet function are written in terms of integrals over splitting functions.

H. Li et al. (2018)

Z. Liu et al. (2021)

After summing over all diagrams

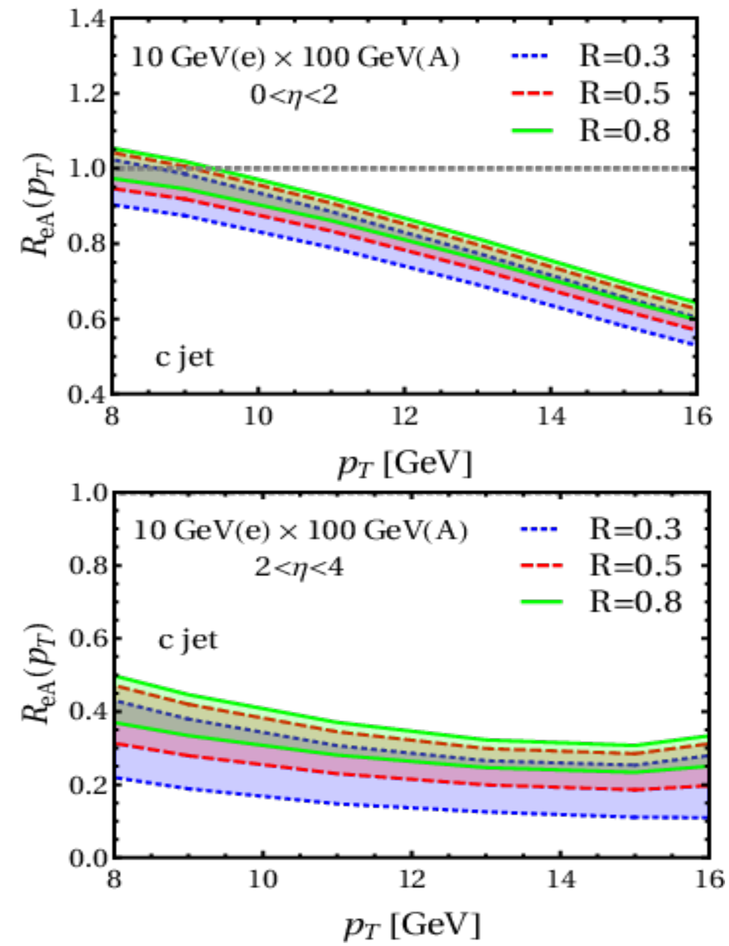
$$J^{\mathrm{med},(1)}_{J_Q/Q}(z,p_T R,m,\mu) = \left[\int_{z(1-z)p_T R}^{\mu} dq_\perp P^{\mathrm{med}}_{QQ}(z,m,q_\perp)\right]_+$$

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

Two types of nuclear effect play a role

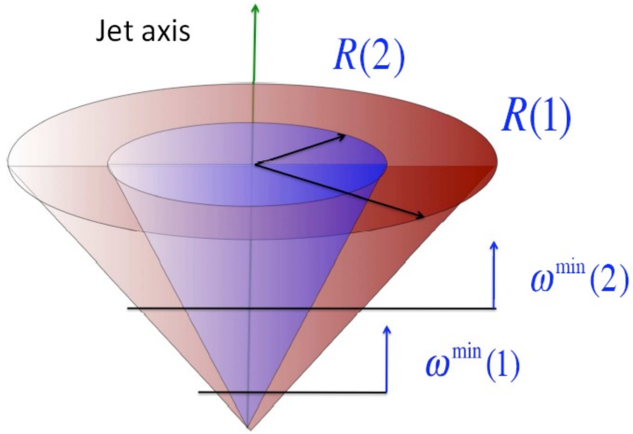
- **Initial-state effects parametrized in nuclear parton distribution functions or nPDFs**
- **Final-state effects from the interaction of the jet and the nuclear medium – in-medium parton showers and jet energy loss**

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



Heavy flavor jets at EIC

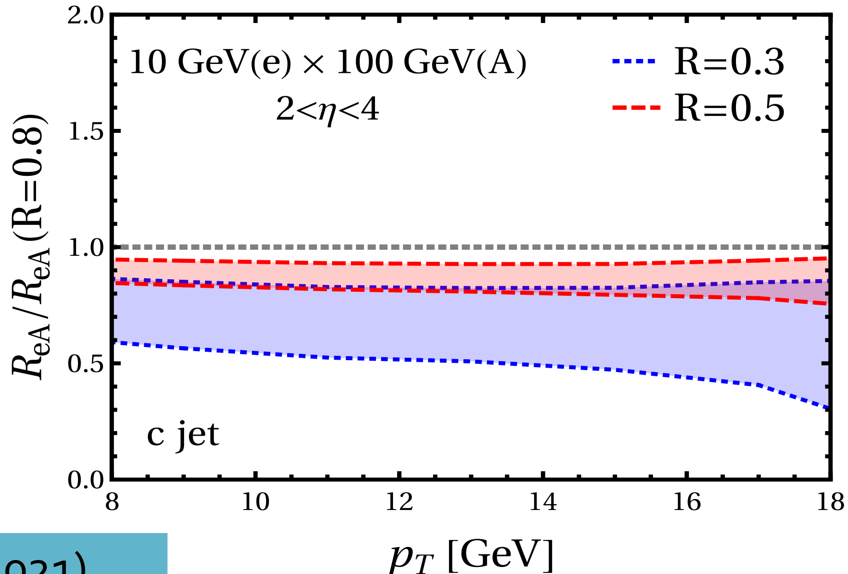
A key question – will benefit both nPDF extraction and understanding hadronization / nuclear matter transport properties - how to separate initial-state and final-state effects?



Leveraging the 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 interactions can be almost a factor of 2 for small radii. Remarkable as it approaches magnitudes observed in heavy ion collisions (QGP)

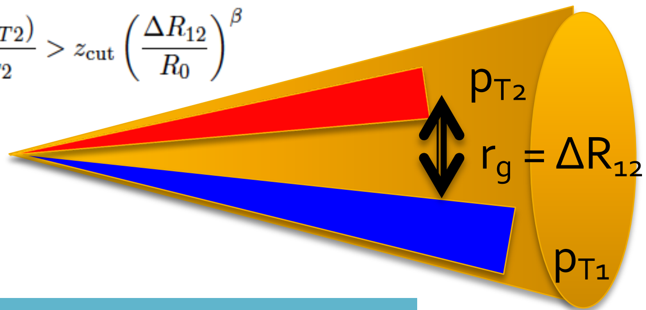


Results are similar for b-jets

Z. Liu et al. (2021)

Heavy flavor jet substructure in DIS

$z_g = \frac{\min(p_{T1}, p_{T2})}{p_{T1}+p_{T2}} > z_{\rm cut}\left(\frac{\Delta R_{12}}{R_0}\right)^{\beta}$



A. Larkoski et al. (2014)

Related to the modification of jet cross sections is the modification of jet substructure. Example - Soft dropped momentum sharing distributions

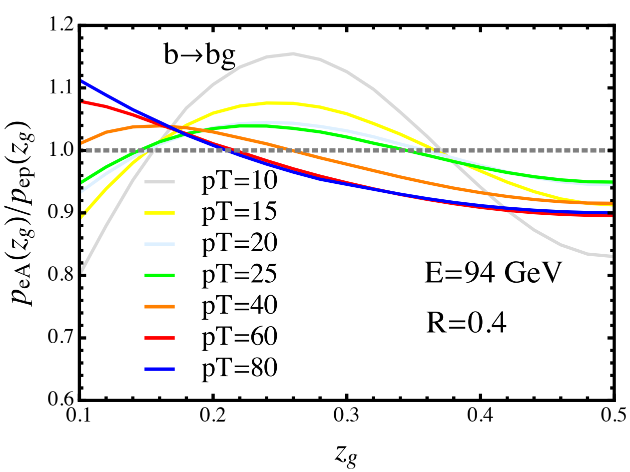
$$\frac{dN_j^{\rm vac,MLL}}{dz_g d\theta_g} = \sum_i \left(\frac{dN^{\rm vac}}{dz_g d\theta_g}\right)_{j\to i\bar{i}} \underbrace{\exp\left[-\int_{\theta_g}^{1} d\theta \int_{z_{\rm cut}}^{1/2} dz \sum_i \left(\frac{dN^{\rm vac}}{dz d\theta}\right)_{j\to i\bar{i}}\right]}_{\rm Sudakov\ \ Factor}$$

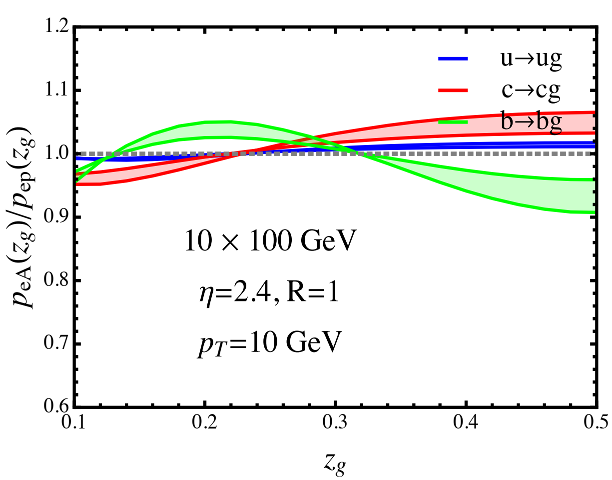
Provides access to the splitting functions

Illustrative study: DIS will cover a very different kinematic regime than HIC

Z. Liu et al. (2021)

Realistic example



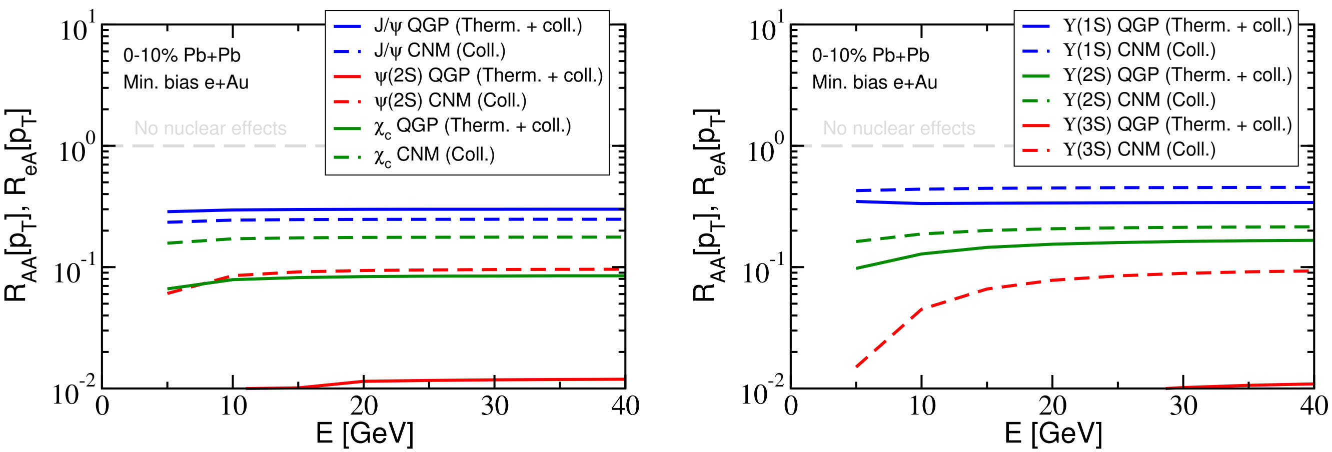


- Modification of both c-jets and b-jets substructure in e+A is relatively small
- It is dominated by limited phase space

Charmonia and bottomonia in cold QCD vs hot QCD matter

- Dissociation from collisional interactions in cold nuclear matter is very large. For the very weakly bound states the QGP suppression is larger but the CNM one is still a factor of 5 -10. For the tightly bound states suppression is comparable – sometimes slightly smaller, sometimes slightly larger.

I. Olivant et al. (2021)



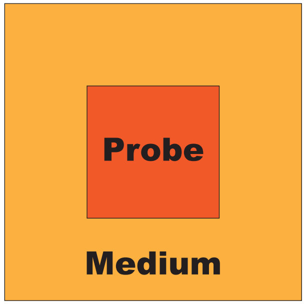
For full EIC predictions we need to explore feed down corrections, combine with prompt state cross sections, and explore the effect of the interaction onset

Transport and open quantum system approaches in nuclear matter have been developed. Typically applied to hot QCD but can be generalized to cold QCD

M. He et al. (2021)

Y. Akamatsu et al. (2015)

N. Brambilla et al. (2022)



Conclusions

- Flavor production, charm & beauty, has motivated important developments in QCD. Still, many open theoretical questions remain – form the flavor number schemes, to the relevant EFTs in multi-scale problems, to the non-perturbative hadronization into charm and beauty mesons. These must be resolved to fully utilize the EIC capabilities and we view this as an opportunity

- There are tremendous intellectual communalities in heavy flavor theory applied to hadronic, heavy ion, and DIS reactions. It is a natural point of convergence for the broad QCD community in the US and beyond. Now is an opportune time for a focused theory effort and investment to answer the most pressing HF puzzles and lay the groundwork for the EIC

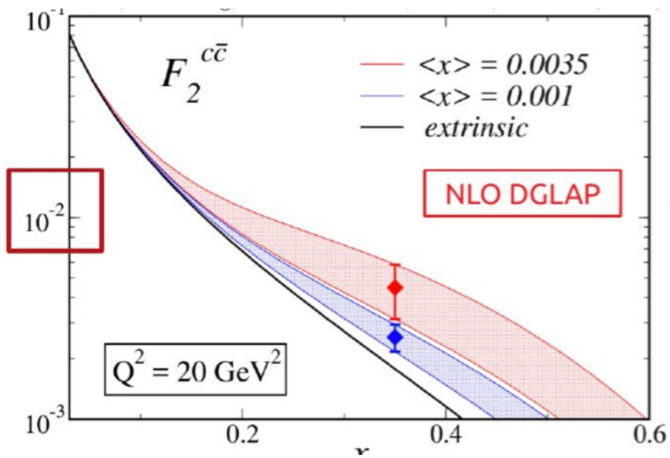
- At the EIC, heavy flavor will provide unique probes of hadronization, energy loss and the transport properties of cold nuclear matter, the TMD stricture of nucleons/nuclei, small-x saturation physics, parton distributions

- Heavy flavor theory, both open and quarkonia, is a key component of the the EIC theory initiative that we propose. We emphasize the need for analytic advancements and precision phenomenology

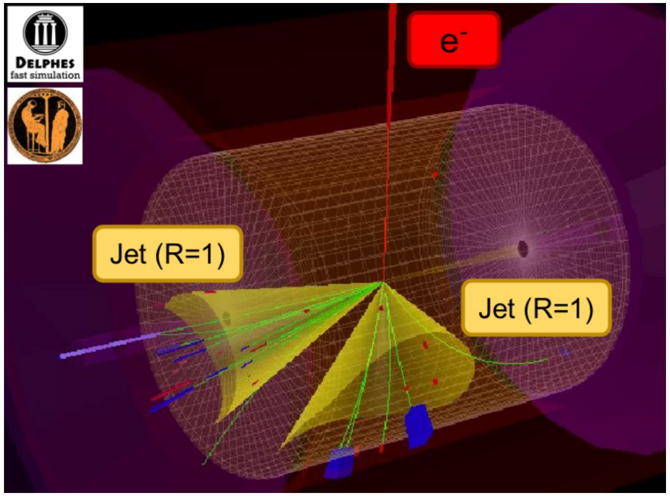
Intrinsic charm and strangeness at the EIC

EIC will finally have the precision to answer long standing questions about large-x structure – strangeness and intrinsic charm

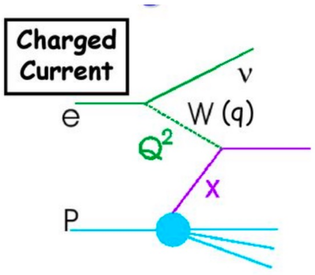
- Intrinsic charm – genuine non-perturbative contribution to the proton wave function – can affect HQ schemes, masses, global fits
- Strangeness – can be accessed via CC reactions. Requires high statistics, can look for enhanced strangeness

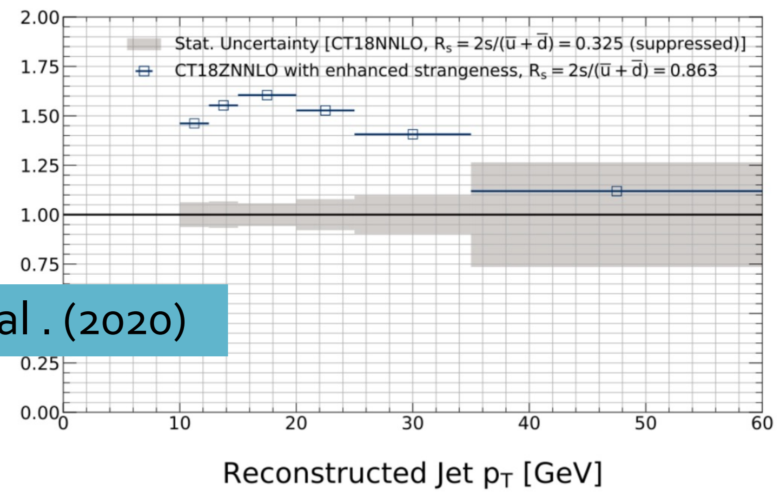


T. Hobbs et al . (2017)



Double charm jet NC event

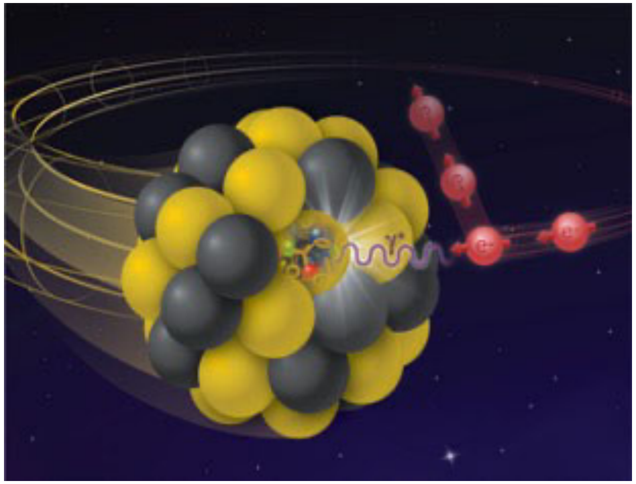




M. Arratia et al . (2020)

Heavy flavor in polarized reactions at the EIC

The EIC is a polarized machine – will constrain precisely the spin content of nucleons and nuclei and their 3D landscape



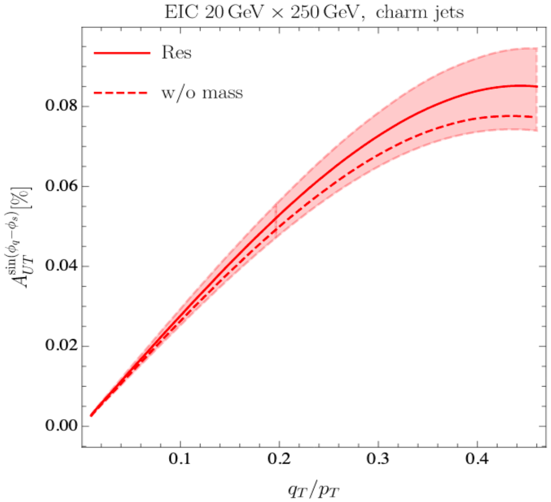
Hadrons (DD-bar)

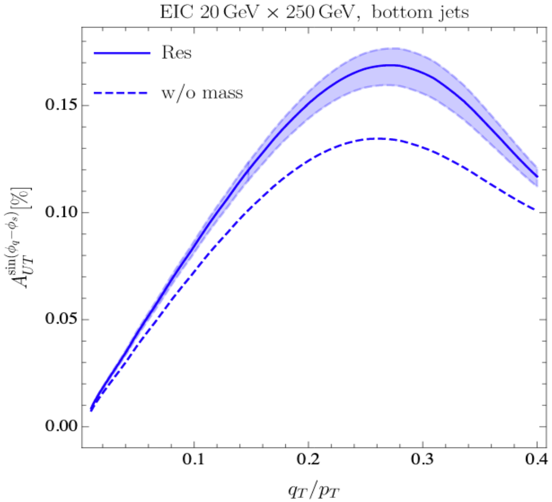
L. Zheng et al. 2018

$$\frac{d\sigma^{UT}(\boldsymbol{S}_T)}{dQ^2dyd^2\boldsymbol{q}_T dy_J d^2\boldsymbol{p}_T} = \sin(\phi_q-\phi_s)\, H(Q,y,p_T,y_J,\mu_h) \int_0^\infty \frac{b^2 db}{4\pi} J_1(b\, q_T) f^{\perp,f}_{1T,g/N}(x,\mu_{b*})$$
$$\times \exp\left[-\int_{\mu_{b*}}^{\mu_h}\frac{d\mu}{\mu}\Gamma^h(\alpha_s) - 2\int_{\mu_{b*}}^{\mu_j}\frac{d\mu}{\mu}\Gamma^{jQ}(\alpha_s) - \int_{\mu_{b*}}^{\mu_{cs}}\frac{d\mu}{\mu}\left(\bar{\Gamma}^{cs_Q}(\alpha_s)+\bar{\Gamma}^{cs_{\bar{Q}}}(\alpha_s)\right)\right]$$
$$\times \exp\left[-S^{\perp}_{\rm NP}(b,Q_0,n\cdot p_g)\right].$$

Jets

Z. Kang et al. 2020

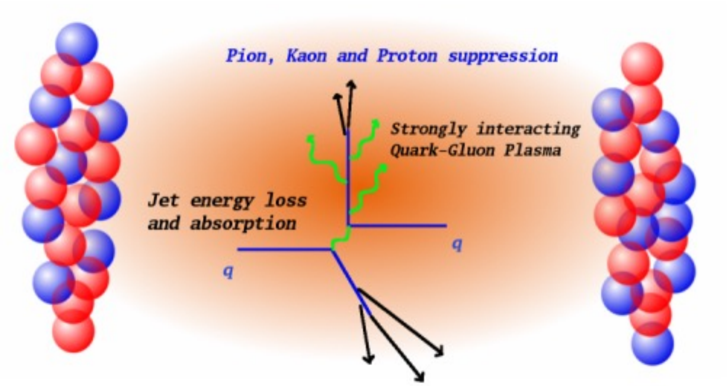




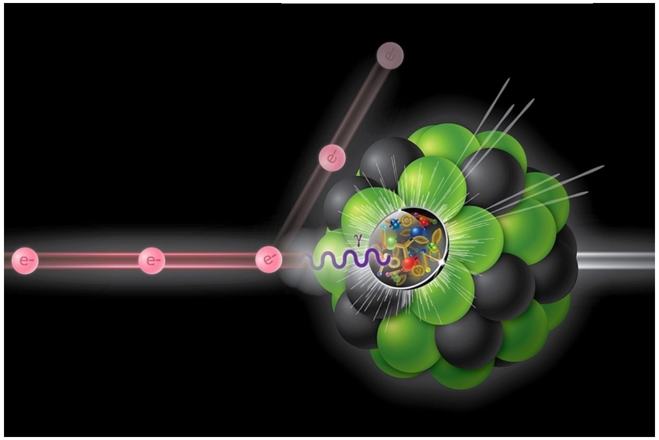
Rather significant asymmetries. Hadronization reduced the asymmetry. Experimental feasibility studies have also been performed (on charm meson)

Differences between AA and eA

- AA and eA collisions are very different. Due to the LPM effect the "energy loss" decreases rapidly. The kinematics to look for in-medium interactions / effects on hadronization very different

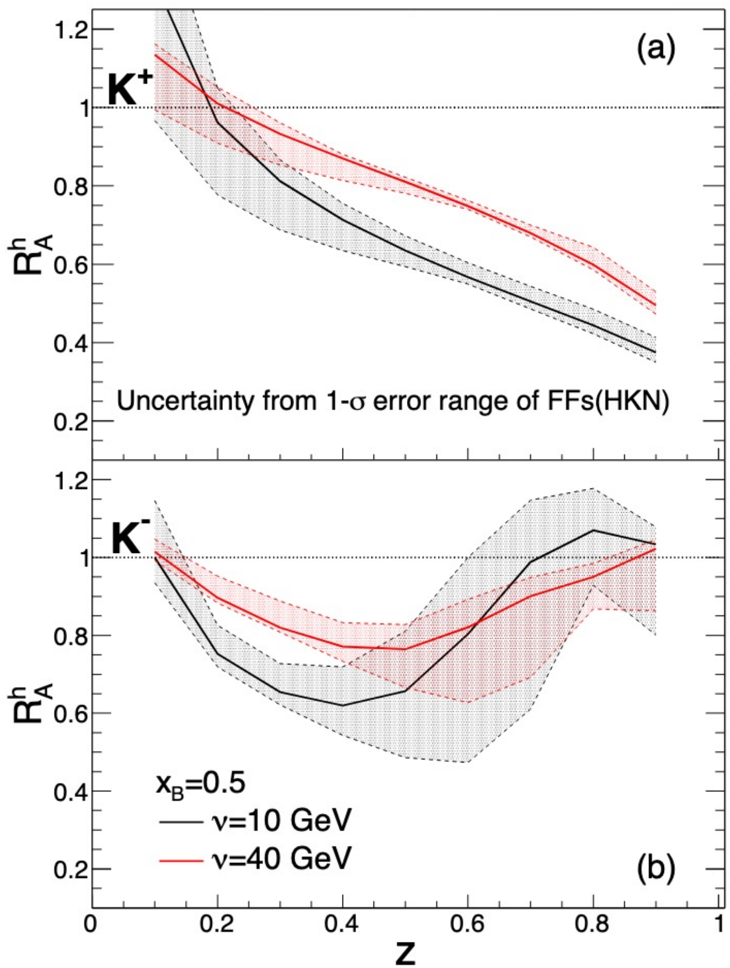


- Jets at any rapidity roughly in the co-moving plasma frame (Only~ transverse motion at any rapidity)
- Largest effects at midrapidity
- Higher C.M. energies correspond to larger plasma densities



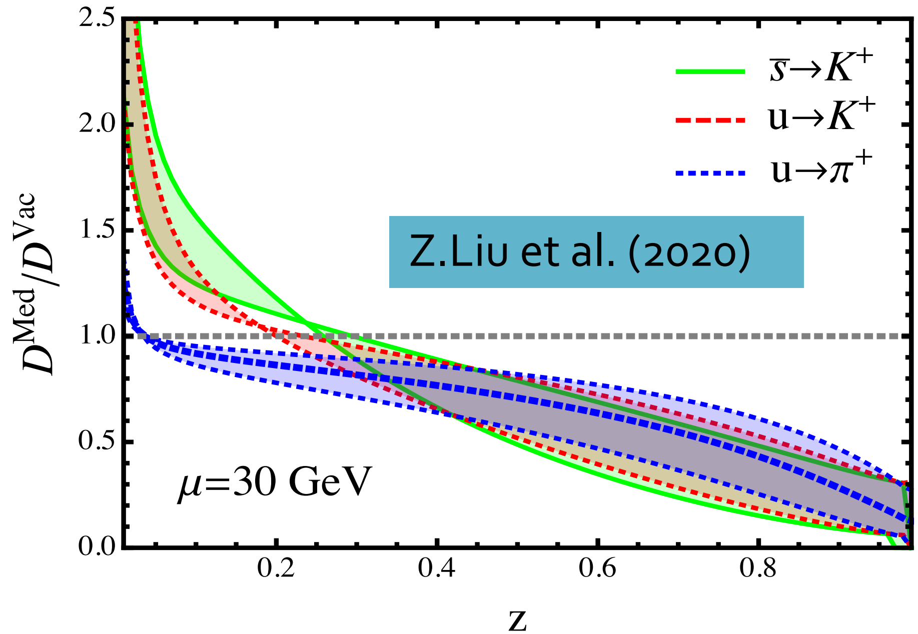
- Jets are on the nuclear rest frame. Longitudinal momentum matters
- Largest effects are at forward rapidities
- Smaller C.M. energies (larger only increase the rapidity gap)

Strangeness production in DIS



N. Chang et al. (2014)

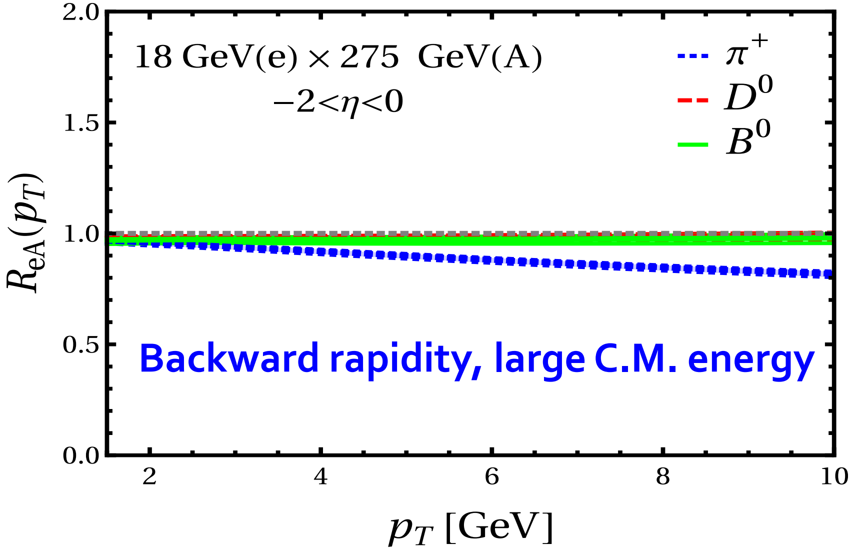
- One calculation finds enhancement of K- at large values of z. However this could be flavor specific differences and isospin effects in e+A

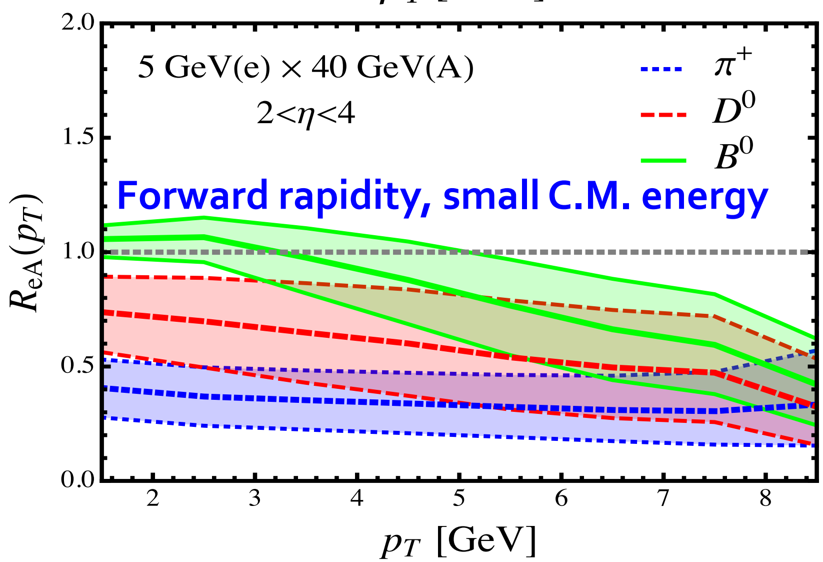


Z.Liu et al. (2020)

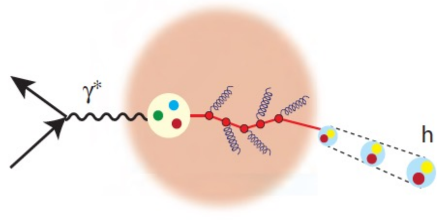
We find larger enhancement at small z relative to pions. The large z behavior has to be further explored

Light and heavy flavor suppression at the EIC

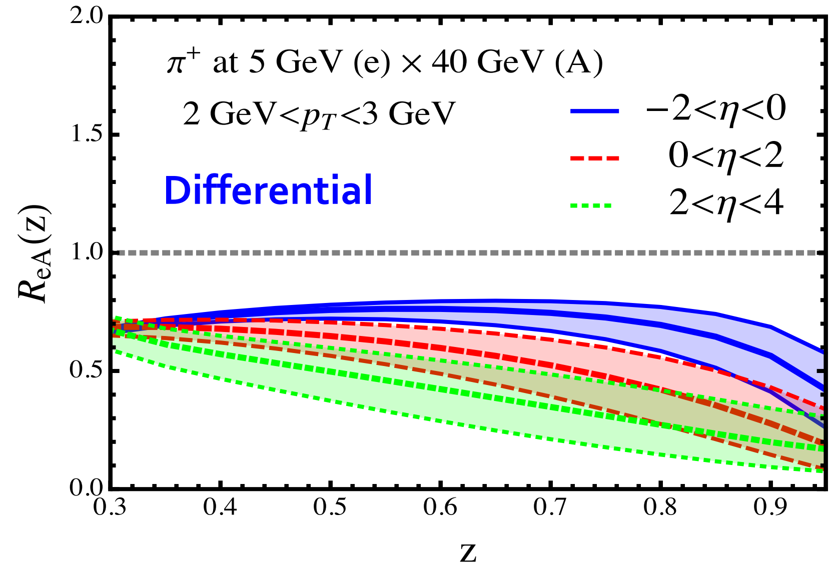




Given the much larger C.M. energy that at HERMES this is the picture to study first



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

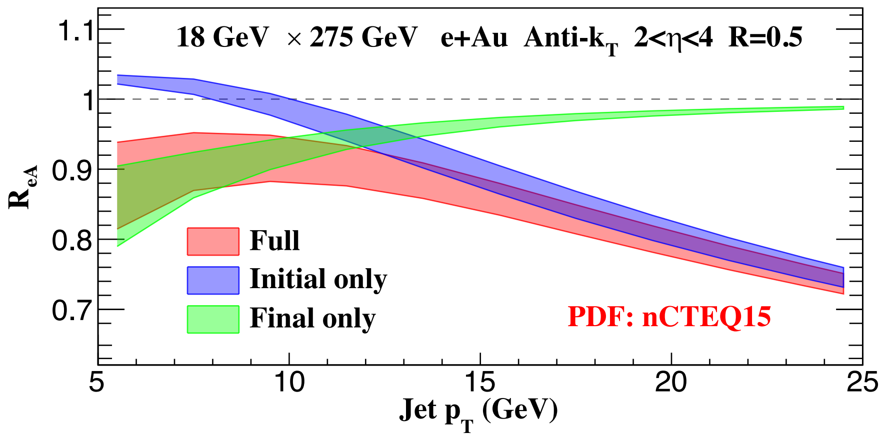


H. Li et al . (2020)

Jet results at the EIC

H. Li et al. (2020)

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

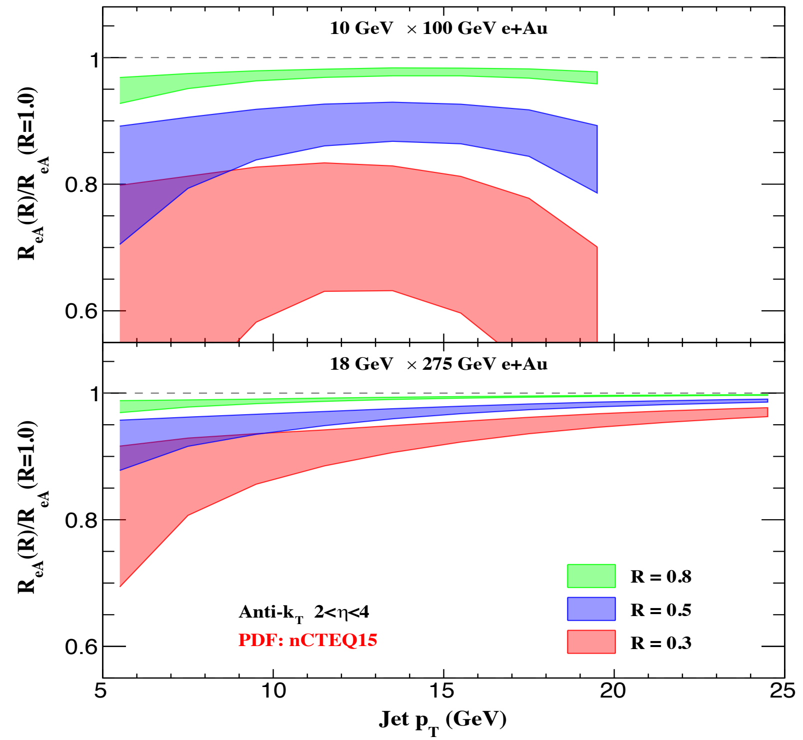


Two types of nuclear effect play a role

- 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 and jet energy loss

How to separate them? Define the ratio of modifications for 2 radii (it is a double ratio)

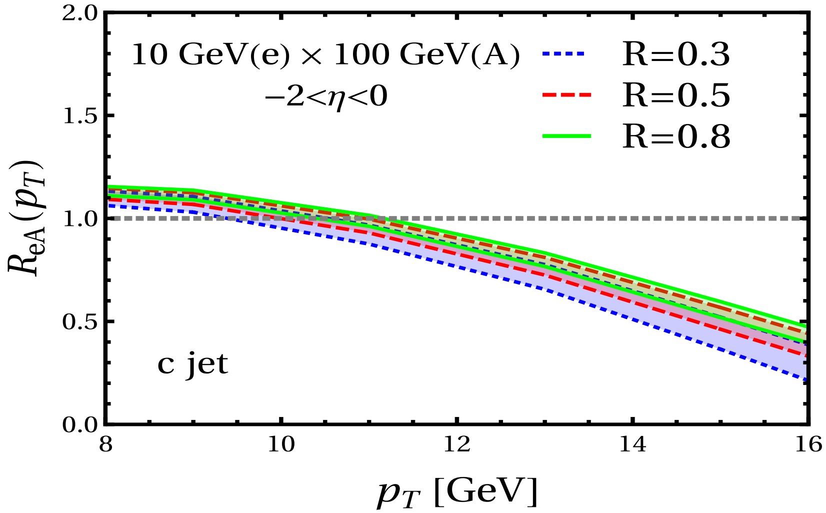
$$R_R = R_{eA}(R)/\,R_{eA}(R=1)$$



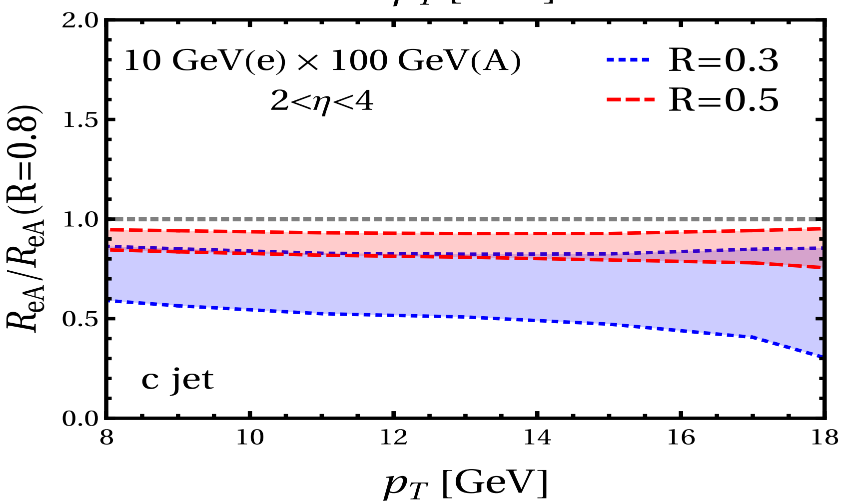
- Jet energy loss effects are larger at smaller C.M. energies
- Remarkably, effects can be almost a factor of 2!

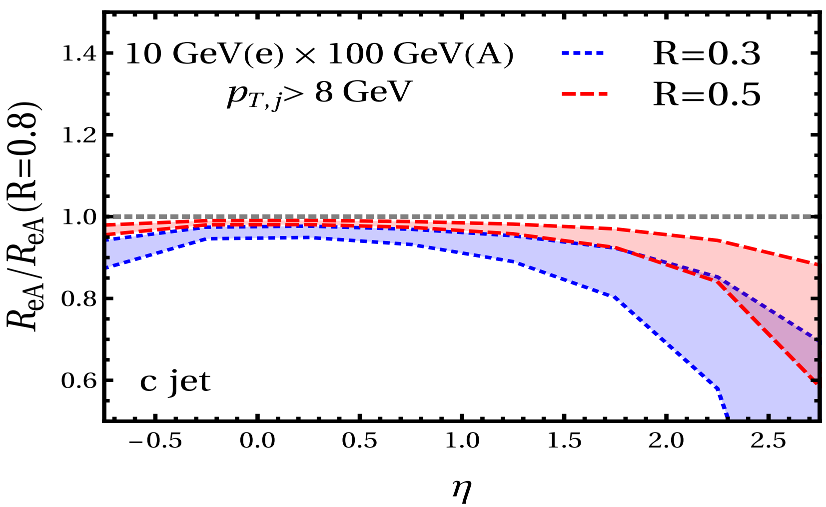
Heavy flavor jets at EIC

Z. Liu et al. (2021)



- The modification of heavy flavor jets in eA is significant
- There is much larger sensitivity to the gluon distributions but initial-state and final-state effects can still be separated
- There is a pronounced rapidity dependence of the heavy flavor jet suppression





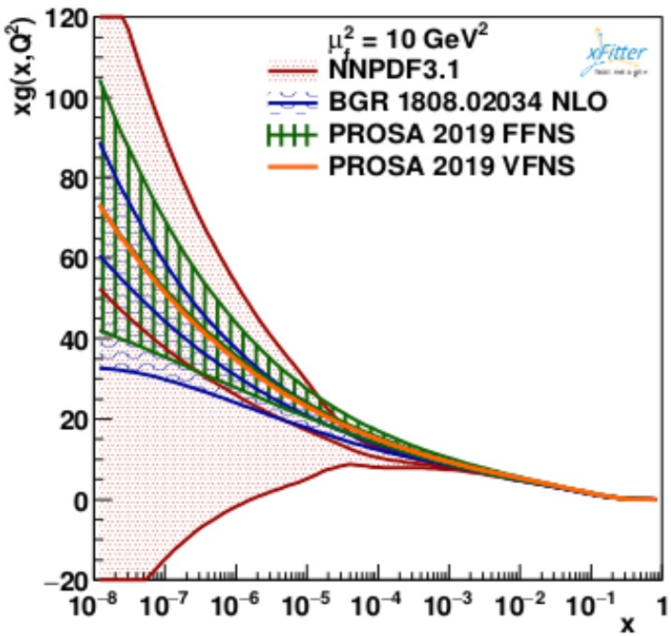
We have also done the calculation for b-jets and slightly smaller, but still significant modification

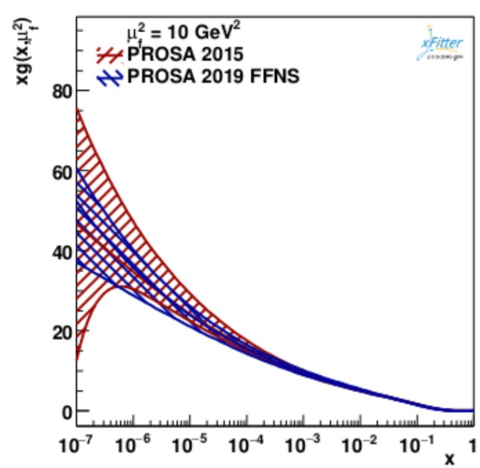
Use of LHC data to constrain heavy favor PDFs – PROSA collaboration

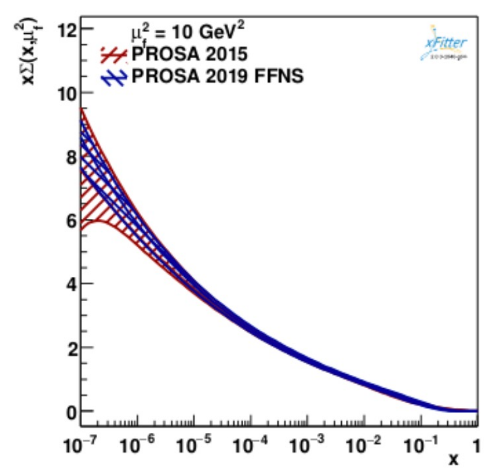
O. Zenaiev et al . (2018)

- Adding LHCb and ALICE data to the heavy flavor data from HERA

Inclusion of heavy flavor reduces PDF uncertainties for sea quarks and gluons at small x, especially FFNS





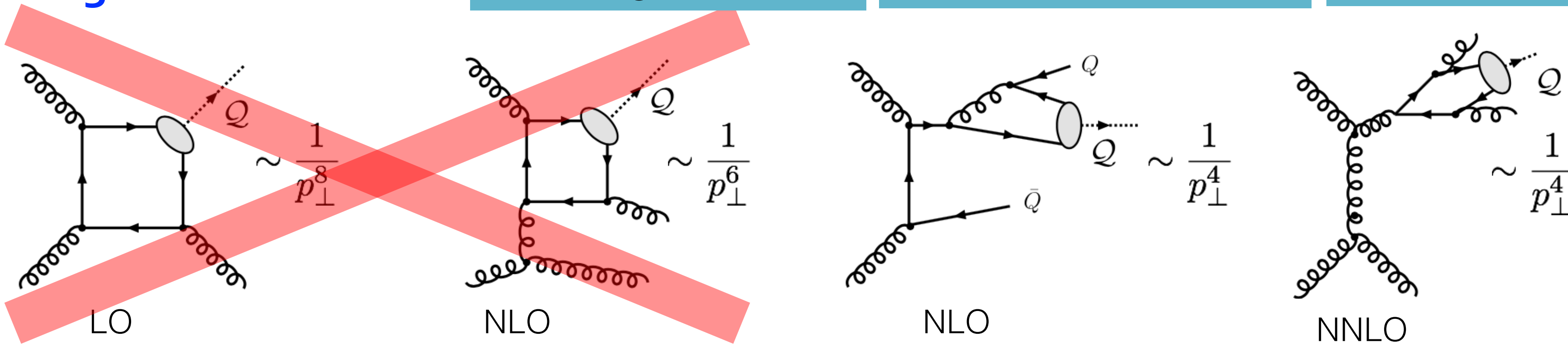


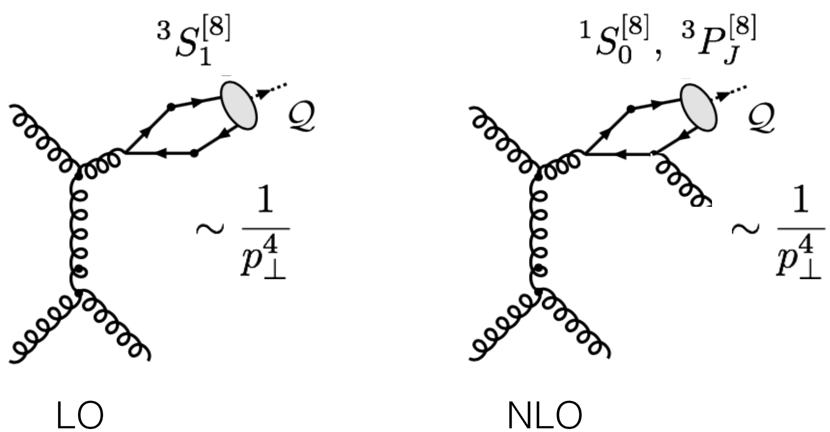
Important to do combined analysis at the EIC

Opportunities in e+p at the EIC

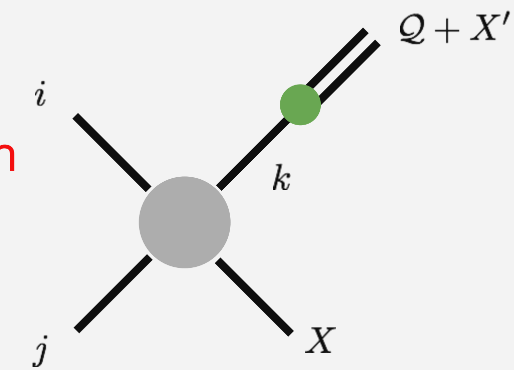
Singlet contribution

S. Fleming *et al.* (2012) | M. Baumgart *et al.* (2014) | Y. Ma *et al.* (2014)





(single) Parton fragmentation process



Octet contribution

Only a subset of contributions survive, now interpretable as parton fragmentation in quarkonia