Ivan Vitev

EIC Heavy Flavor Overview

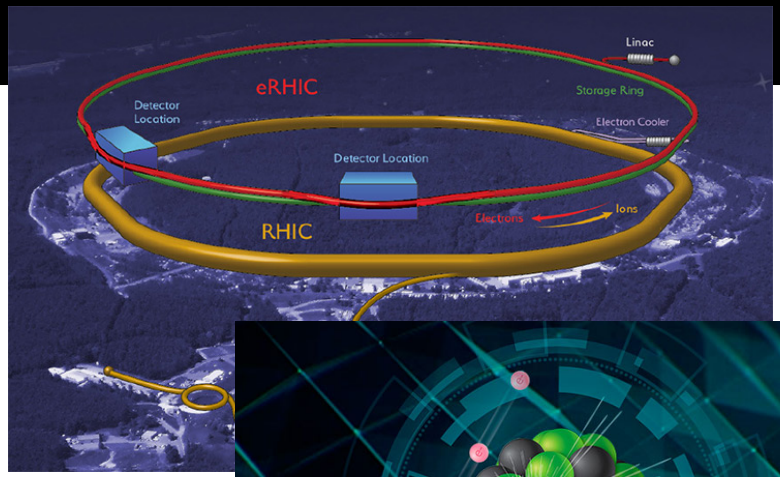


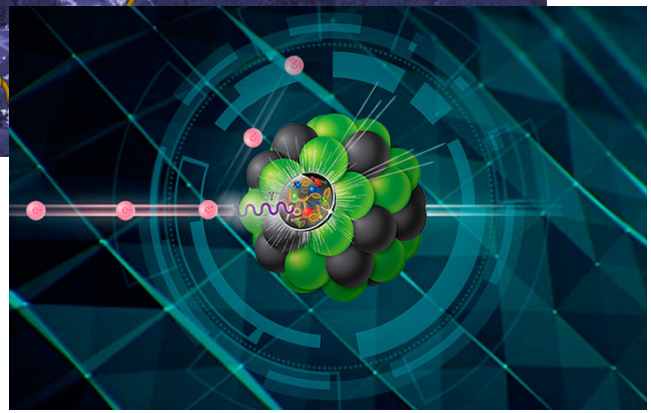
2020 RHIC/AGS Annual Users' Meeting
BNL, Upton, NY
October 22-23, 2020

Los Alamos NATIONAL LABORATORY EST. 1943

Outline of the talk

- Introduction
- Structure functions and parton distributions
- Heavy quark propagation in matter
- Heavy flavor fragmentation functions
- Toward heavy flavor jets at the EIC
- Quarkonia and exotics
- Conclusions





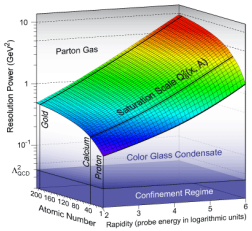
I thank the organizers, my collaborators, and the J&HF WG for the YR

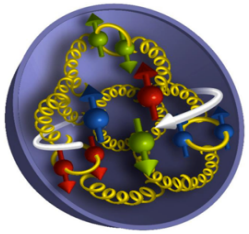
This work is supported by the TMD topical collaboration and the LANL LDRD program

TMD Collaboration

LDRD LABORATORY DIRECTED RESEARCH & DEVELOPMENT

Introduction





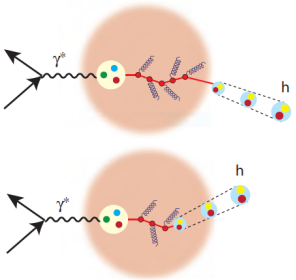
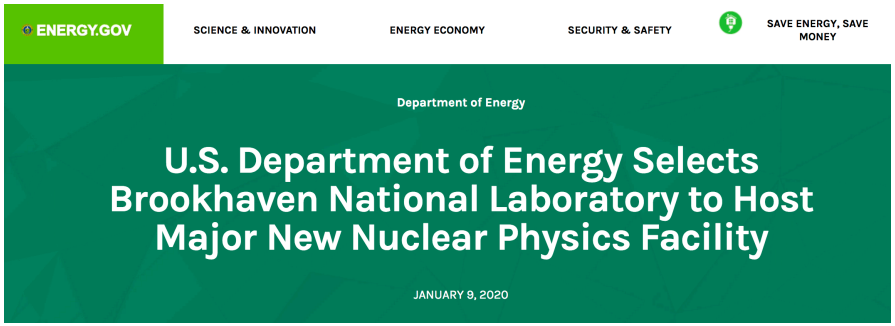


Illustration of EIC focus areas

C. Aidala et al. (2020)

- The origin of mass and the role of gluons
- The internal landscape of nucleons and nuclei, 3D tomography
- The phenomenon of gluon saturation
- Transport properties of large nuclei and the physics of hadronization



CD-0 and site selection announced Jan. 9, 2020



Tim Hallman, Director or Nuclear Physics at DOE's Office of Science



Chris Fall – Director of DOE's Office of Science



Dan Brouilette, Secretary of DOE

The purpose of this talk: How can we address some of those questions with heavy flavor – the theory, experimental measurements and detectors

HF theoretical underpinnings and tools for PDF analysis

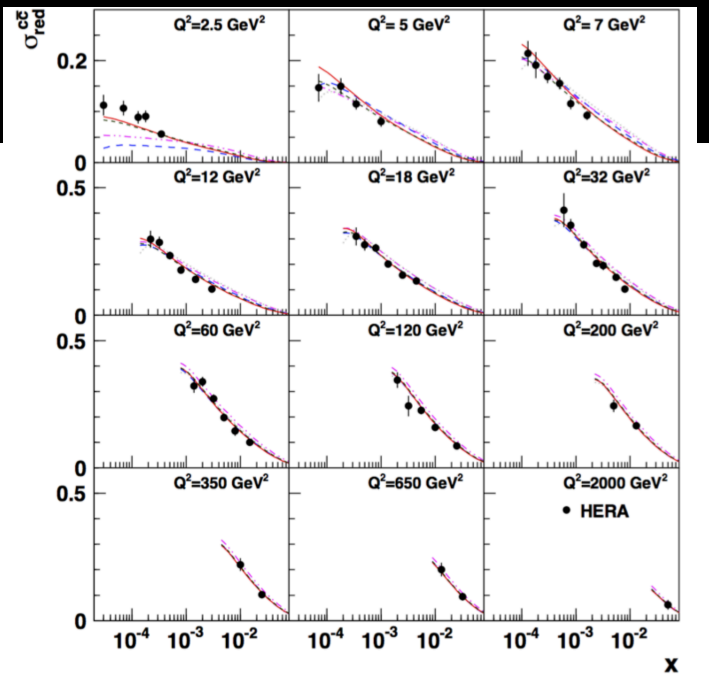
$$F_{2,h}^{FFN} = \sum_{k=1}^{\infty} a_s^k(n_f) \sum_{i=q,g} H_{2,i}^{(k)}(n_f) \otimes f_i(n_f),$$

Fixed flavor schemes – typically at low virtualities

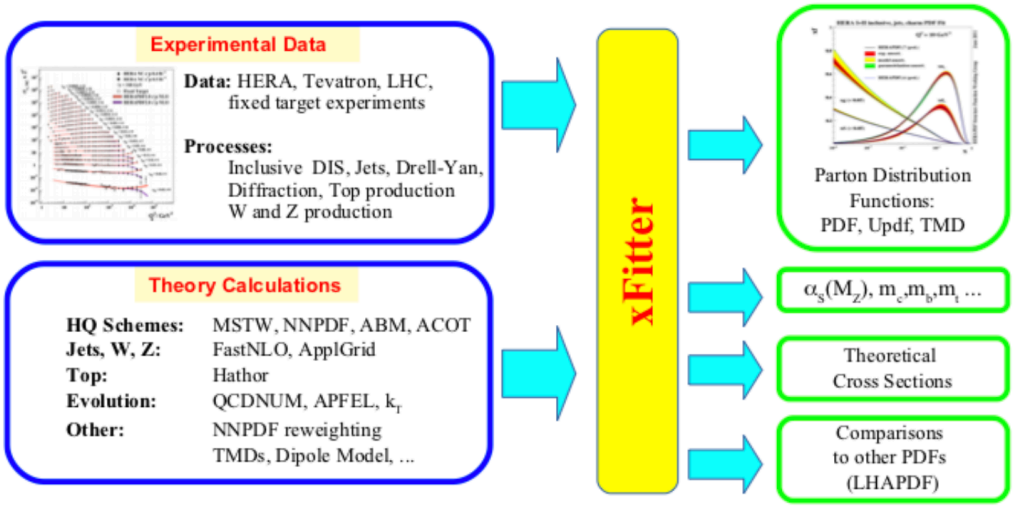
$$F_{2,h}^{ZMVFN} = \sum_{k=0}^{\infty} a_s^k(n_f+1) \sum_{i=q,g,h} C_{2,i}^{(k)}(n_f+1) \otimes f_i(n_f+1)$$

Variable flavor schemes – as one goes to higher energies

- Some schemes proven to all orders (ACOT), order-by order equivalence shown for the popular schemes
- Good description of HF data



Emphasizes the need for flexible tools for PDF analysis



- Can take input from various processes, notably DIS; can produce not only PDFs but also related alpha$_s$ values, heavy quark masses
- Include LHC HF data in the DIS analysis

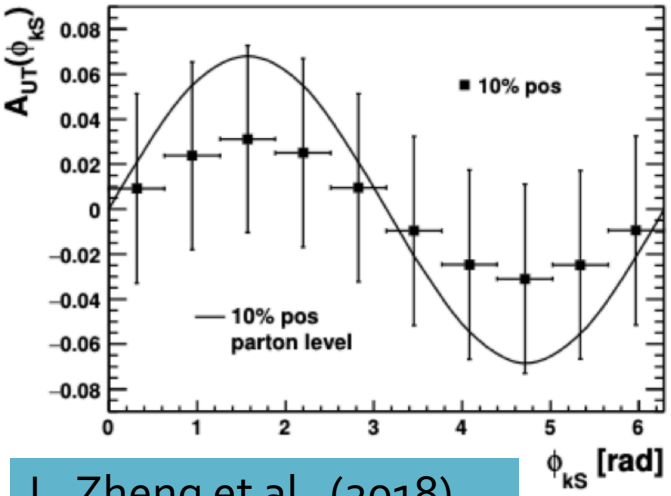
Constraining the proton and nuclear glue

- Charm can provide access to the gluon TMDs in unpolarized and polarized reactions (e.g. Sievers, Boer-Mulders)

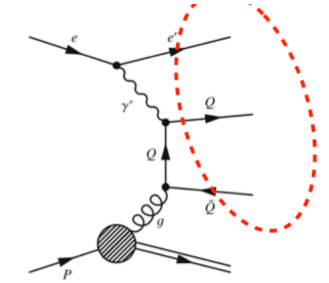
- Charm F2 can dramatically reduce the uncertainties in the large-x and small-x
- Give a handle on (nuclear-enhanced) higher twist corrections

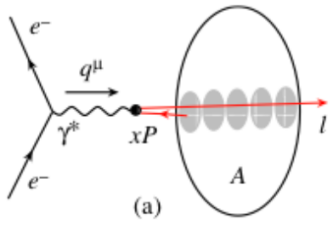
The expected effects are small. More theoretical work is needed – higher order calculations, higher twist effects

$$A_{UT}(\phi_{kS}, k_T) = \frac{d\sigma^{\uparrow}(\phi_{kS}, k_T) - d\sigma^{\downarrow}(\phi_{kS}, k_T)}{d\sigma^{\uparrow}(\phi_{kS}, k_T) + d\sigma^{\downarrow}(\phi_{kS}, k_T)}$$

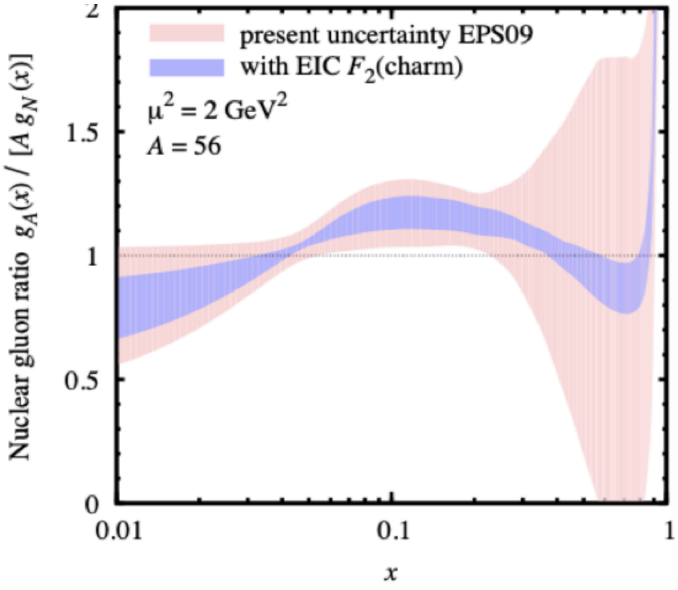


L. Zheng et al . (2018)





J.Qiu et al . (2004)



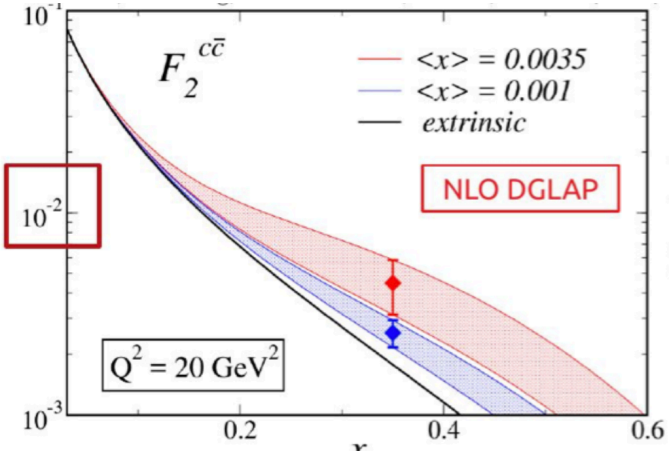
E. Chudakov et al . (2016)

E. Aschenauer et al . (2017)

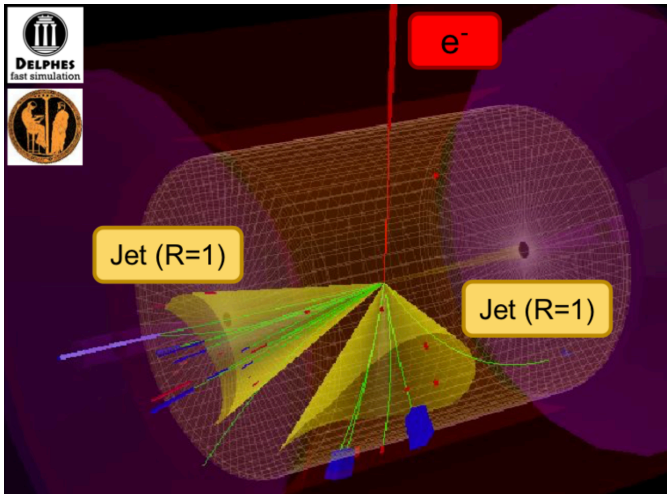
Intrinsic charm and strangeness at the EIC

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

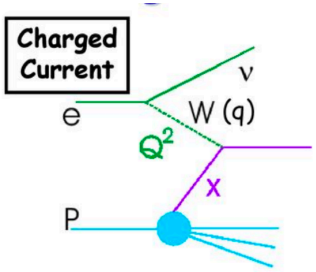
- Intrinsic charm – genuine non-perturbative contribution to the proton wave function – can affect HQ schemes, masses, global fits
- Strangeness – can be accessed via CC reactions. Requires high statistics, can look for enhanced strangeness

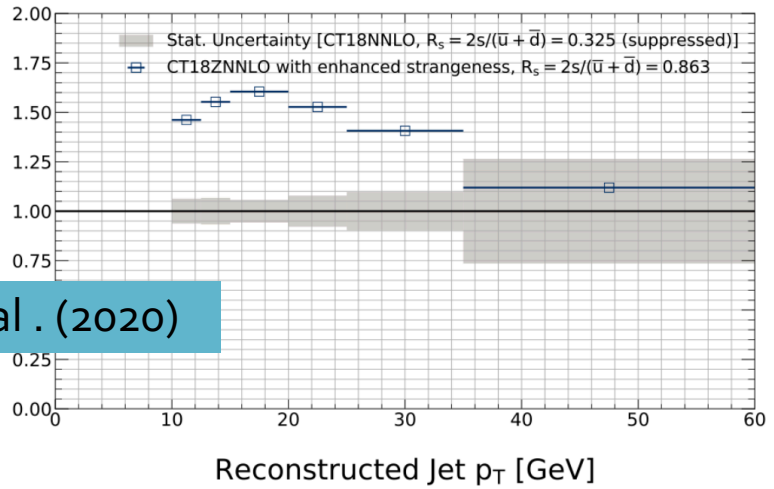


T. Hobbs et al . (2017)



Double charm jet NC event





M. Arratia et al . (2020)

Heavy meson production in e+p at EIC, fragmentation functions

Understand contributions at higher orders

H. Li *et al.* (2020)

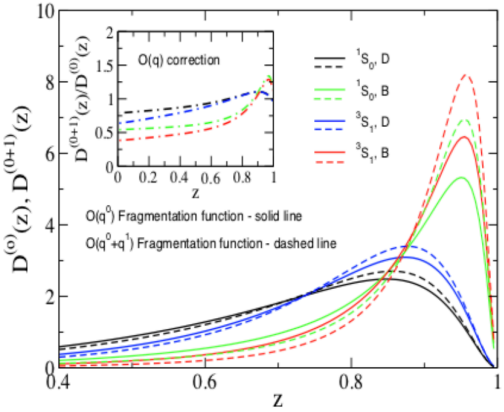
- The gluon contribution at EIC is small
- Resolved photon contribution gives large correction

$$E_h \frac{d^3\sigma^{\ell N\to hX}}{d^3P_h} = \frac{1}{S}\sum_{i,f}\int_0^1 \frac{dx}{x}\int_0^1 \frac{dz}{z^2} f^{i/N}(x,\mu) \times D^{h/f}(z,\mu)\left[\hat{\sigma}^{i\to f} + f^{\gamma/\ell}_{\text{ren}}\left(\frac{-t}{s+u},\mu\right)\hat{\sigma}^{\gamma i\to f}\right].$$

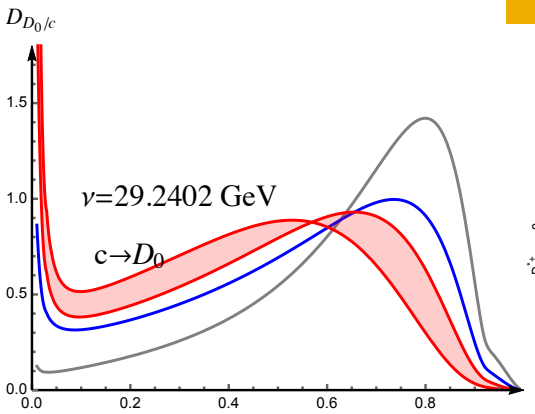
Evaluate or extract FFs, understand evolution

$$\frac{d}{d\ln\mu^2}\tilde{D}^{h/i}(x,\mu) = \sum_j \int_x^1 \frac{dz}{z}\tilde{D}^{h/j}\left(\frac{x}{z},\mu\right)P_{ji}(z,\alpha_s(\mu))$$

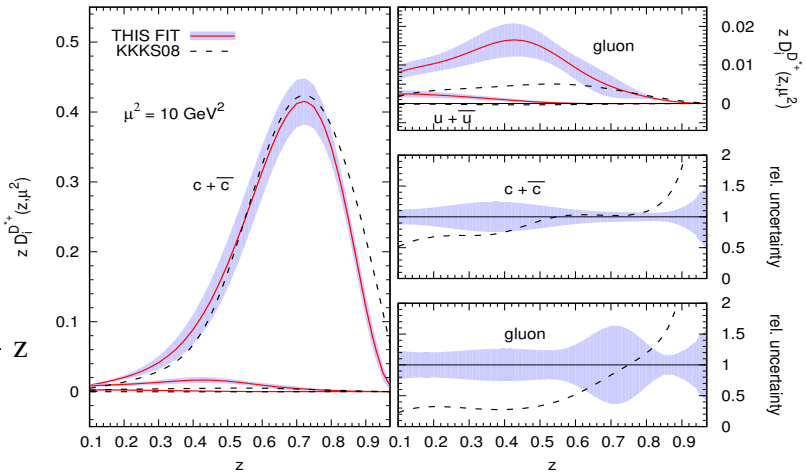
- Use of heavy meson in jet data to constrain fragmentation functions
- At the LHC – large gluon contribution. At the EIC we expect perhaps complementary constraints on HQ fragmentation



Braaten *et al.* (1995)

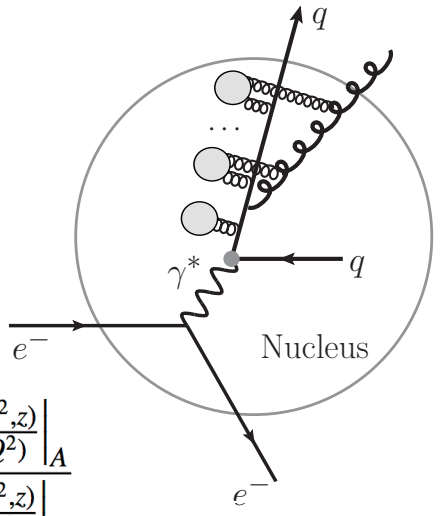


D. Anderle *et al.* (2017)



Parton showers in cold nuclear matter

- Both energy loss calculations and full sets of splitting functions exist for cold nuclear matter



Using the high twist approach, (D)GLV approach BDMPS approach

X. Guo et al. (2001) | F. Arleo (2003)

Using the SCET$_{(M)G}$ approach, Lightcone wavefunction approach

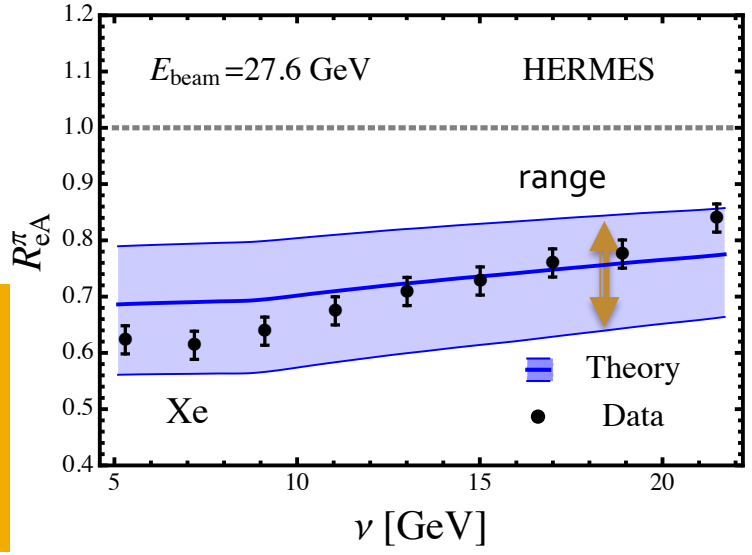
Z. Kang et al. (2016) | M. Sievert et al. (2018)

$$R_{eA}^{\pi}(\nu, Q^2, z) = \frac{\left.\frac{N^{\pi}(\nu,Q^2,z)}{N^{e}(\nu,Q^2)}\right|_{A}}{\left.\frac{N^{\pi}(\nu,Q^2,z)}{N^{e}(\nu,Q^2)}\right|_{D}}$$

- We constrain a range of transport properties to explore from HERMES

Transport properties:

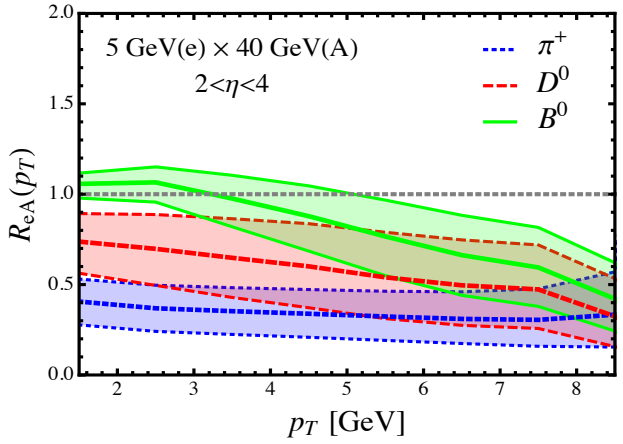
$$2\frac{\mu^2}{\lambda g} = 0.12\frac{GeV^2}{fm} \quad (vary \times 2,/2)$$



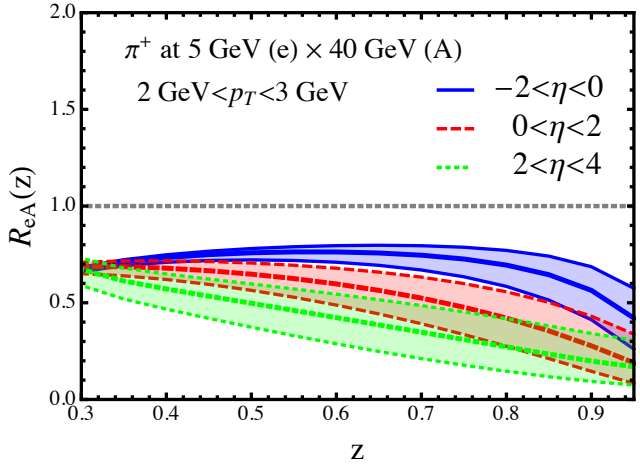
- Theoretical predictions are constrained by HERMES and realistic
- Depend on parton energy in the A rest frame. Minimize the rapidity gap between A and meson

Cross section modification in e+A

Less differential distribution



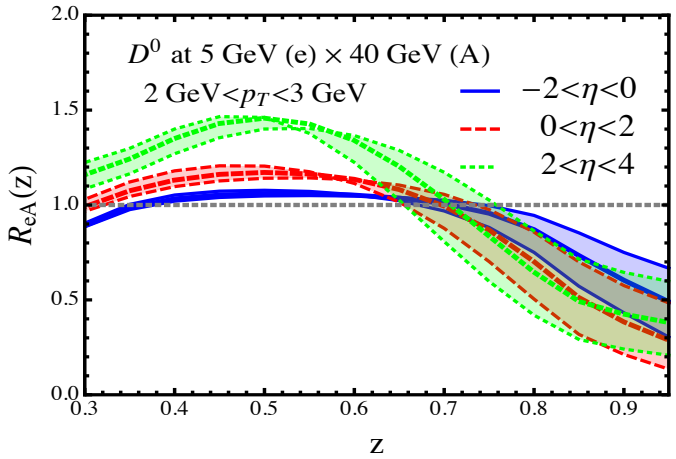
More differential distribution



First calculation of meson modification in e+A at EIC. Normalization is important. Aimed at minimizing the initial-state PDF effects

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

- Large effects on p_T distributions at forward η and lower CM energies. Factor of 2-3 suppression.
- More differential distributions vs momentum fraction z. Clear difference between light and heavy flavor. Characteristic transition – enhancement to suppression for parton showers / E-loss. Distinction from hadron absorption models

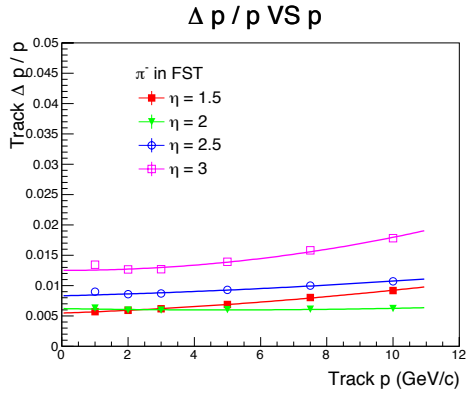


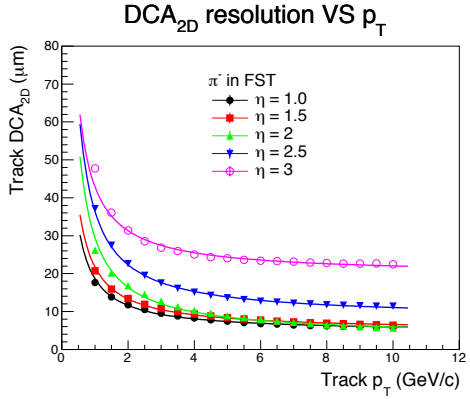
$$\frac{d}{d\ln\mu^2}\tilde{D}^{h/i}(x,\mu)=\sum_j\int_x^1\frac{dz}{z}\tilde{D}^{h/j}\left(\frac{x}{z},\mu\right)\times\left(P_{ji}(z,\alpha_s(\mu))+P_{ji}^{\rm med}(z,\mu)\right)$$

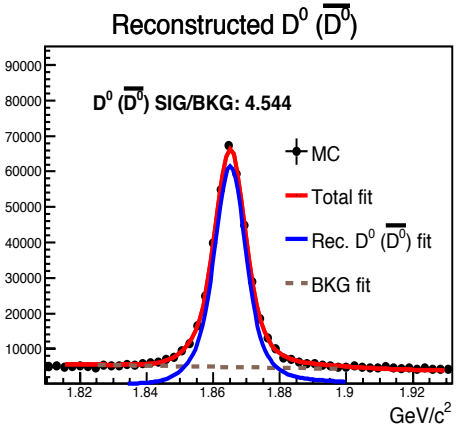
H Li et al. (2020)

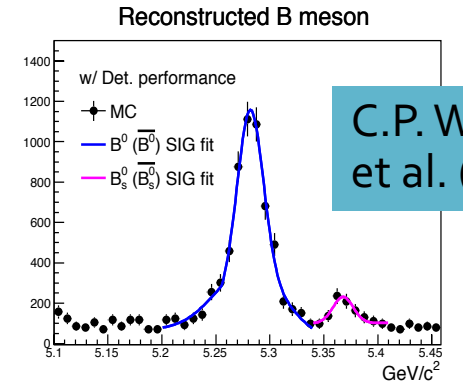
Experimental prospects for energy loss and hadronization

- Extensive experimental simulations of open heavy flavor
- Full simulation / detector parameter⟶ Fast simulation / full reconstruction ⟶ physics projections
- Excellent statistics for E-loss and hadronization studies

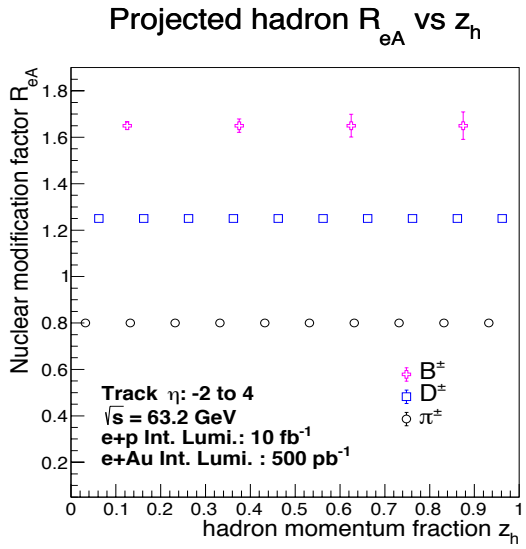


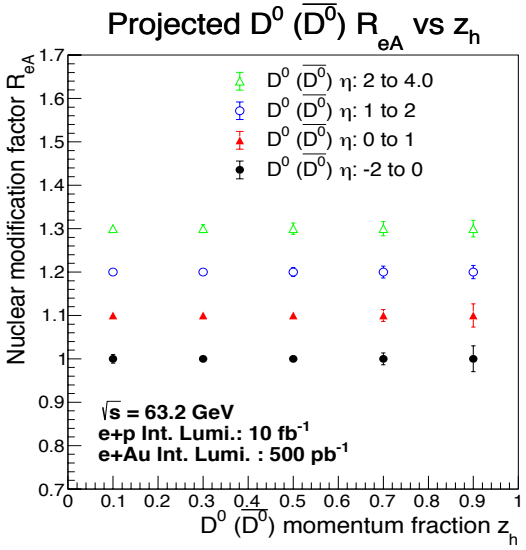




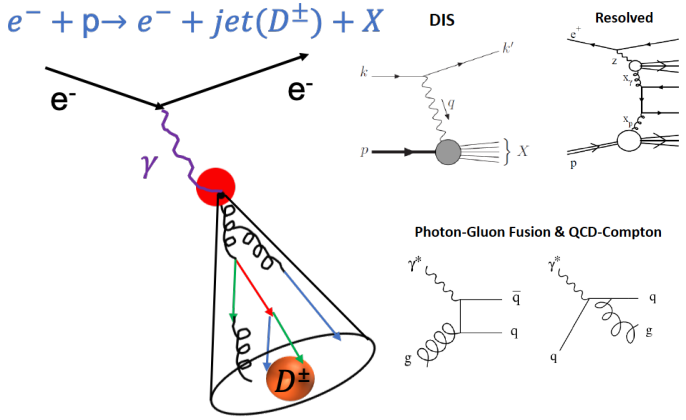


C.P. Wong et al. (2020)



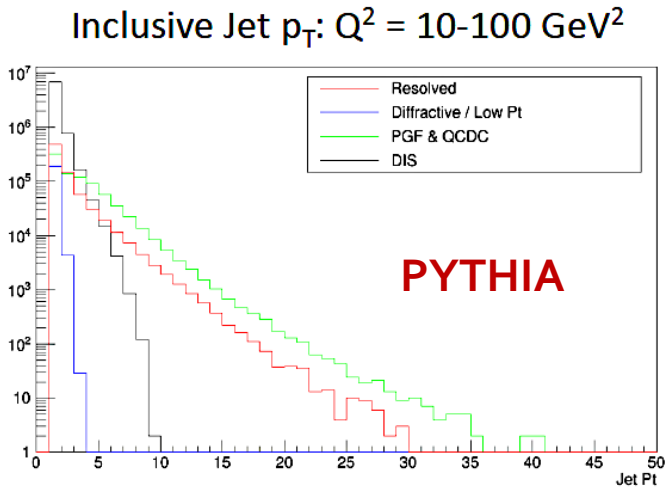


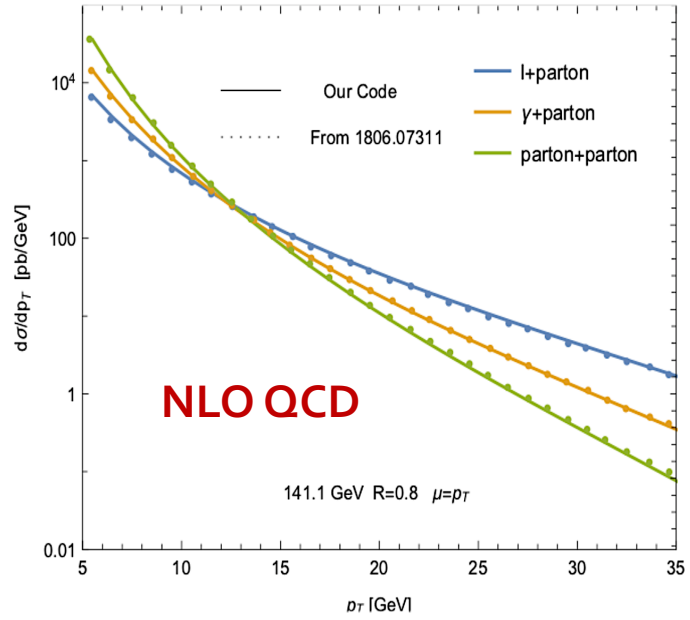
Jet production at the EIC



Large number of contributions to be taken into account – DIS, resolved, etc

B. Page et al. (2016)





A useful modern way semi-inclusive jet functions – can include lnR resummation

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

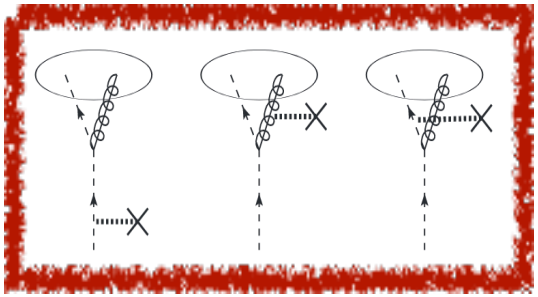
R. Boughezal et al. (2018)

Li et al. (2020)

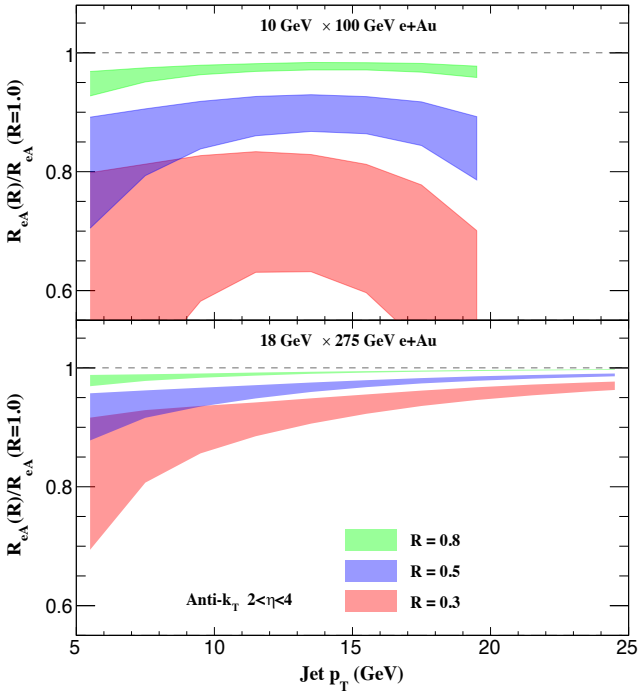
Has to be applied to inclusive jet production at EIC. Progress toward heavy-flavor tagged jet application

Heavy jet production in e+A

- Medium contribution to jet functions



$$J^{\text{med}}_{J_Q/i} = J^{\text{med},(0)}_{J_Q/i} + \frac{\alpha_s}{2\pi} J^{\text{med},(1)}_{J_Q/i}$$



First calculation of jets in eA at EIC

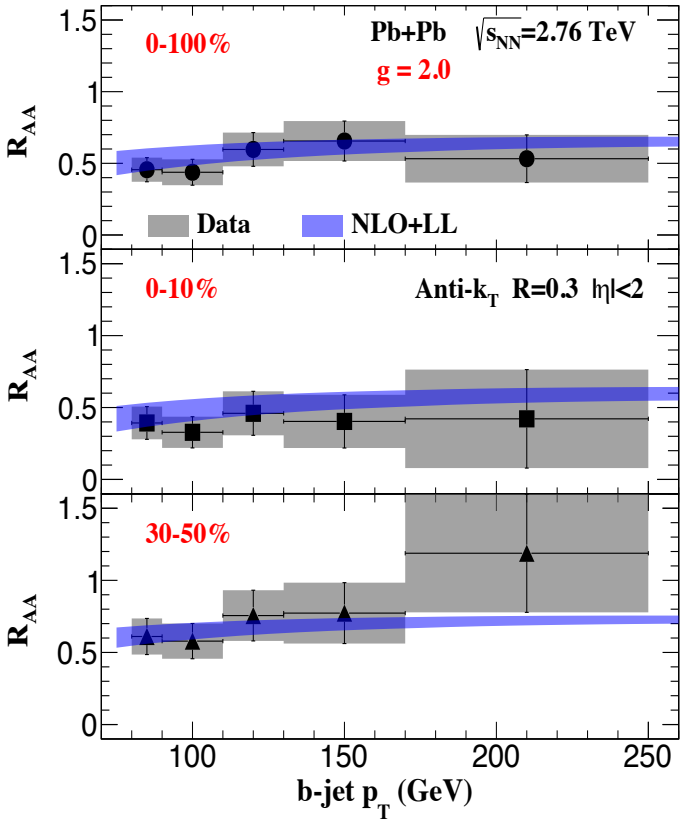
Large and measurable effects at forward rapidity

Devised a way to separate nPDF and final-state effects

Heavy flavor jets in the future

Example from heavy ion collisions

H. Li et al. (2018)



H. Li et al. (2020)

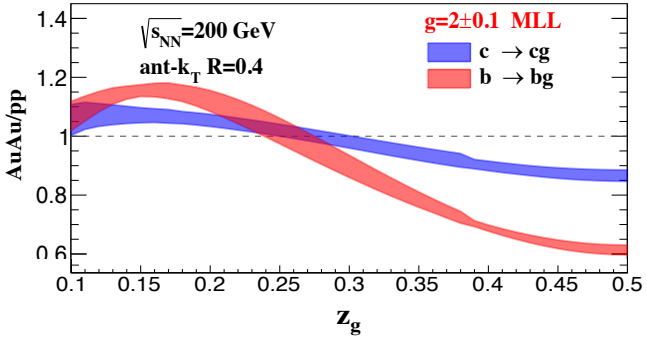
Heavy flavor jet substructure

Jet substructure – jet shapes, splitting functions, fragment. functions, charge … can improve the understanding of the role of heavy quark mass, dead cone effect, etc

A tool to discriminate between light and heavy flavor jets

Heavy flavor splitting functions

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

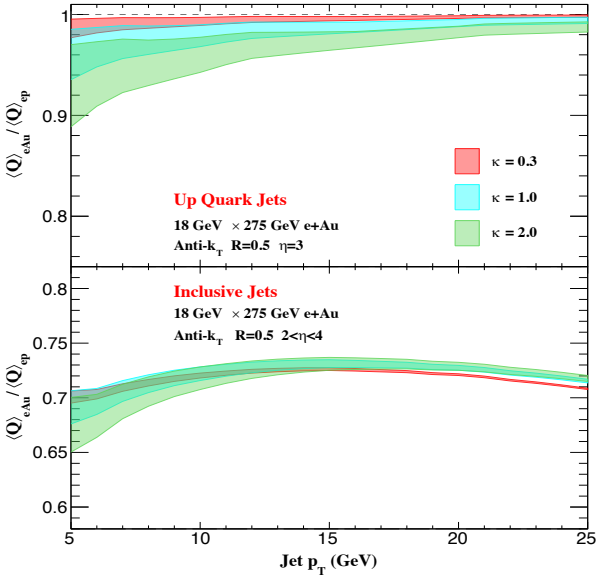


First calculation of the jet charge at EIC – understand medium-induced scaling violations and isospin symmetry braking in nuclei

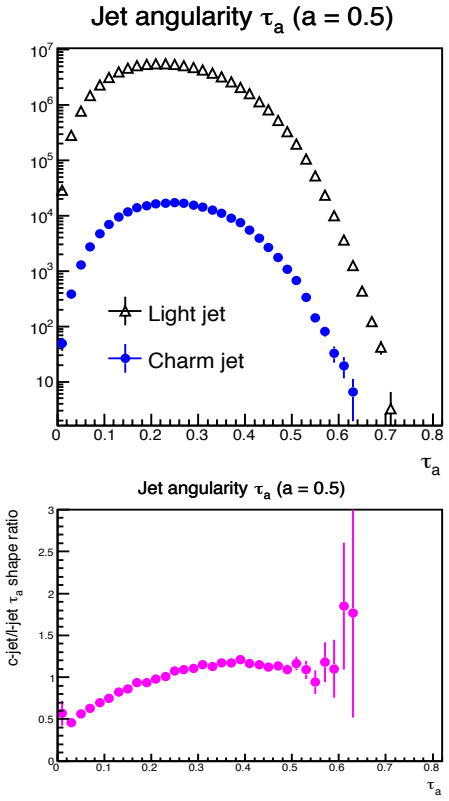
$$\langle Q_{q,\kappa}^{\text{pp}} \rangle \left(1 + \tilde{\mathcal{J}}_{qq}^{\text{med}} - J_q^{\text{med}}\right) \exp\left[\int_{\mu_0}^{\mu} \frac{d\bar{\mu}}{\bar{\mu}} \frac{\alpha_s(\bar{\mu})}{\pi} \tilde{P}_{qq}^{\text{med}}\right] + \mathcal{O}\left(\alpha_s^2, \chi^2\right)$$

$$Q_{\kappa,\text{ jet}} = \frac{1}{\left(p_T^{\text{jet}}\right)^{\kappa}} \sum_{\text{h in jet}} Q_h \left(p_T^h\right)^{\kappa}$$

R. Field (1978)



H. Li *et al.* (2020)

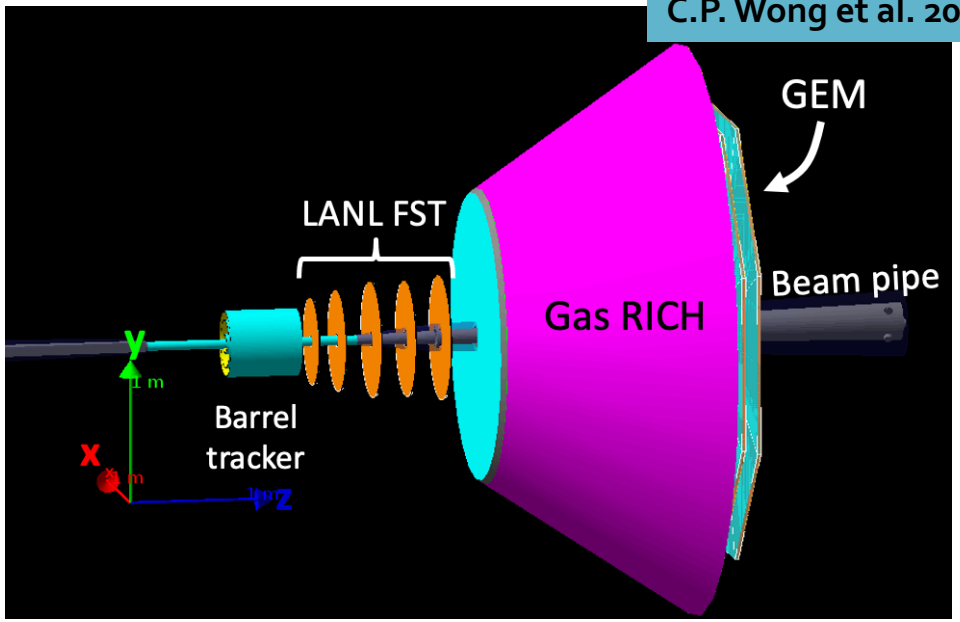


X. Li et al . (2020)

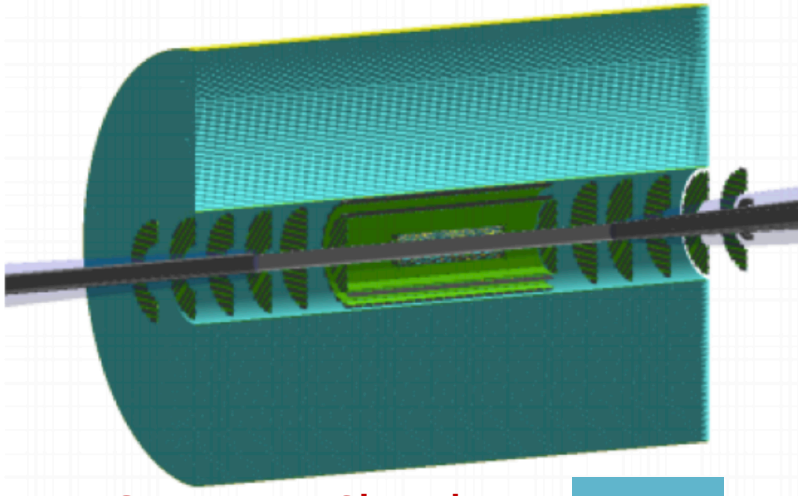
Detector developments

The asymmetric collisions nature at the EIC requires special focus on the forward going direction

C.P. Wong et al. 2020



Tracking/vertexing also needed at backward rapidity. Also very important are PID and calorimetry



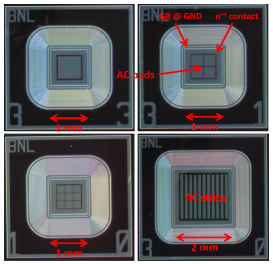
Gas outer + Si tracker

eRD 25

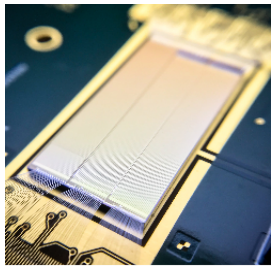
MAPS tech.



LGAD tech.



HV-MAPS tech.

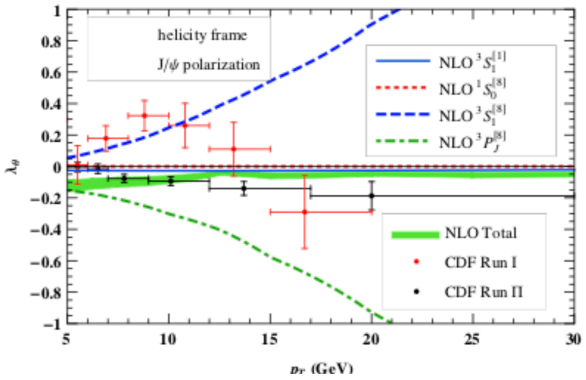


Technologies of interest to HEP and NP are being developed

- It is expected that in the future they will improve – integration time, pixel pitch, material budget, …

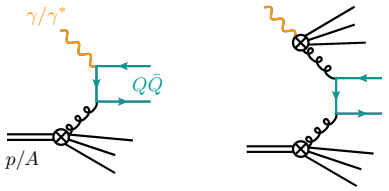
Quarkonium production at the EIC

DIS- excellent laboratory to study quarkonia. Photo-production (Q ~ 0 GeV) or lepto-production (Q> 1 GeV). Resolved, diffractive/exclusive, and inclusive productions



$$\frac{d\mathcal{N}}{d\cos\theta} \propto 1+\lambda_\theta \cos^2\theta, \lambda_\theta = \frac{d\sigma_{11}-d\sigma_{00}}{d\sigma_{11}+d\sigma_{00}}$$

$$d\sigma_{S_z S_z} = \sum_{ijn} \int dx_1 dx_2 f_{i/H_1}(x_1,\mu_F) f_{j/H_2}(x_2,\mu_F) \langle \mathcal{O}_n \rangle d\hat{\sigma}^{ij,n}_{S_z S_z},$$



HERA data has had important impact but interpretation subject of debate

Flore et al . (2020)

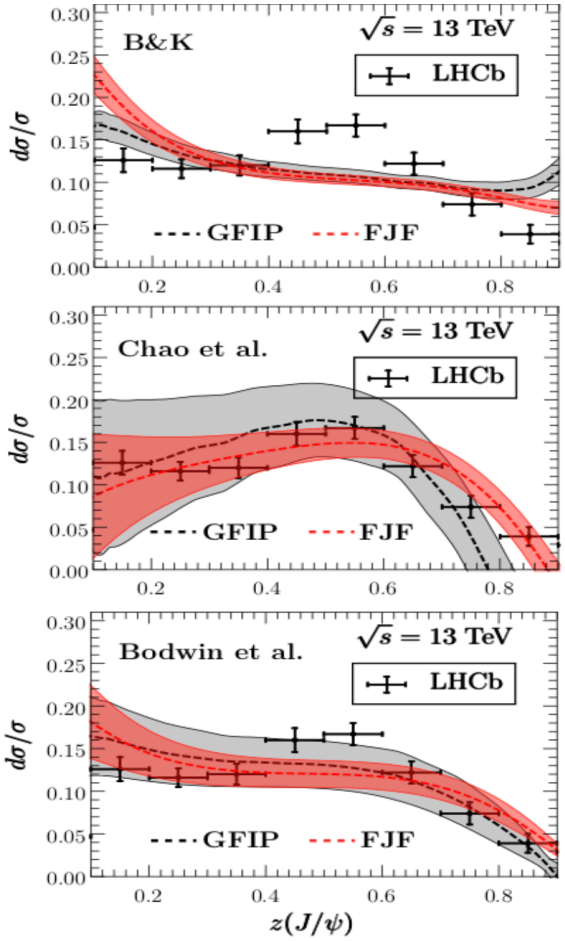
Better constrain matrix elements.
Possibility to use quarkonia in jets

Constrain TMD shape functions. Exclusive quarkonium production can be understood through the formalism of GPDs and the Wigner functions

Cui et al . (2018)

Chen et al . (2019)

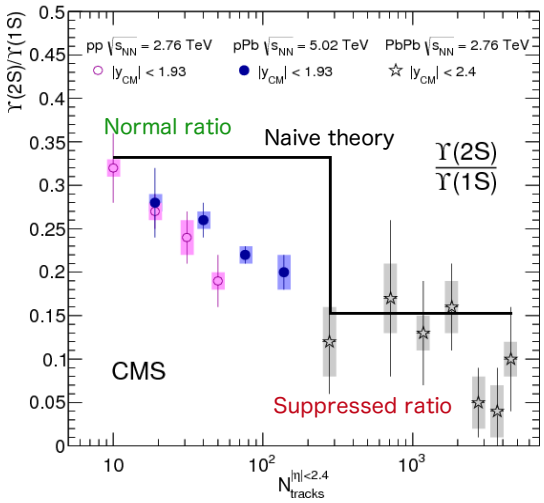
Example from LHCb



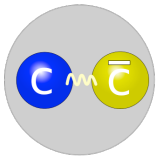
Bain et al . (2017)

Quarkonium production in reactions with nuclei

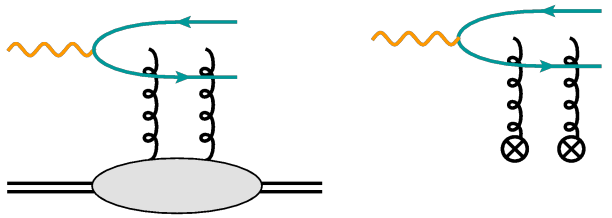
Excited Upsilon suppression



Similar dissociation behavior in A+A, p+A and even in p+p (where QGP is not expected)



NRQCD with Glauber Gluons



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

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

Microscopic description of dissociation

Y. Makris et al . (2019)

Open quantum systems

$$H = H_S + H_E + H_I\,, \qquad \frac{\mathrm{d}\rho^{(\mathrm{int})}(t)}{\mathrm{d}t} = -i[H_I^{(\mathrm{int})}(t), \rho^{(\mathrm{int})}(t)]$$

Akamatsu et al . (2014)

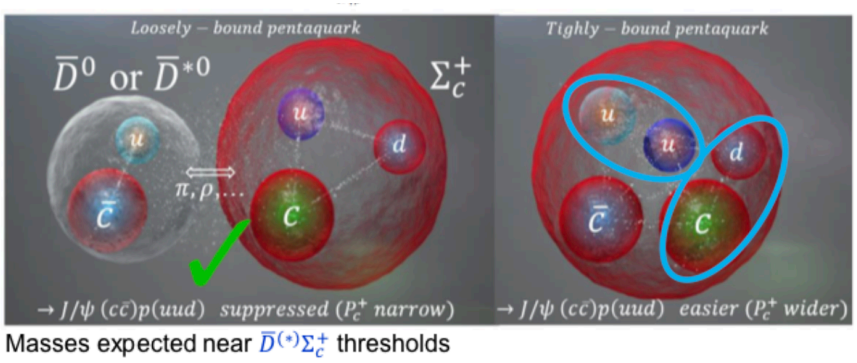
Yao et al . (2020)

The EIC will also offer the opportunity to observe quarkonium production in eA collisions where one can study the interactions with nuclear matter and the formation of quarkonia in a nuclear medium.

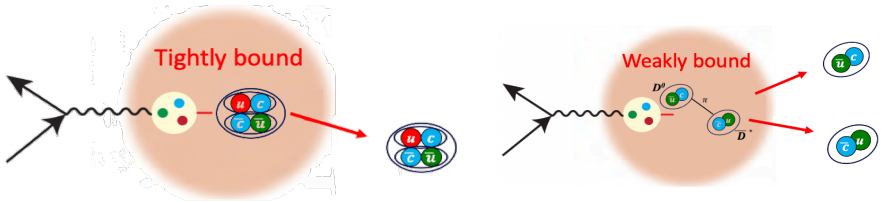
Heavy exotic states at the EIC

Many exotic states – mesons (tetraquarks) and baryons (pentaquarks) being observed

S. Olsen *et al.*, *R*MP(2018)



Masses expected near $\overline{D}^{(*)}\Sigma_c^+$ thresholds

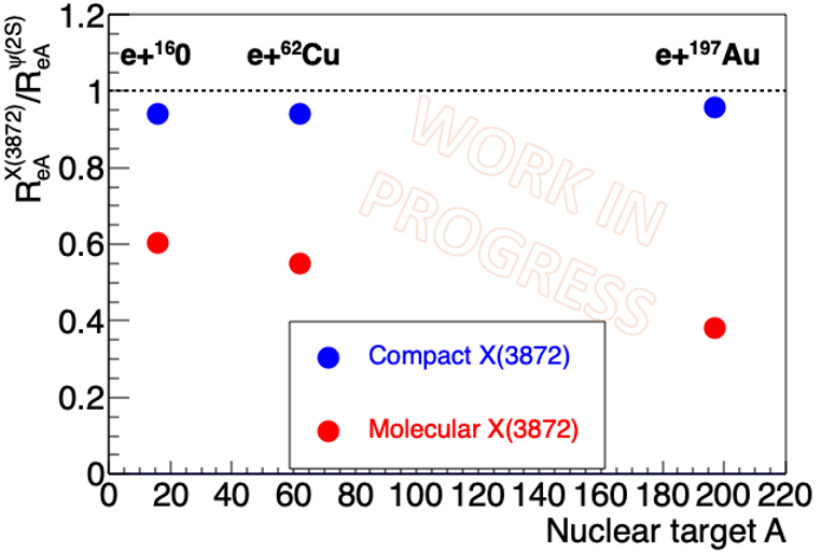


Use the nucleus as a "filter" for the heavy states

New physics observables

Structure and formation process of new exotic hadrons, e.g. X(3872) can be explored by measuring their suppression in e+A collisions.

Relative modification of X(3872)/ $\psi(2S)$ projection at $\sqrt{s}$ = 63.2GeV

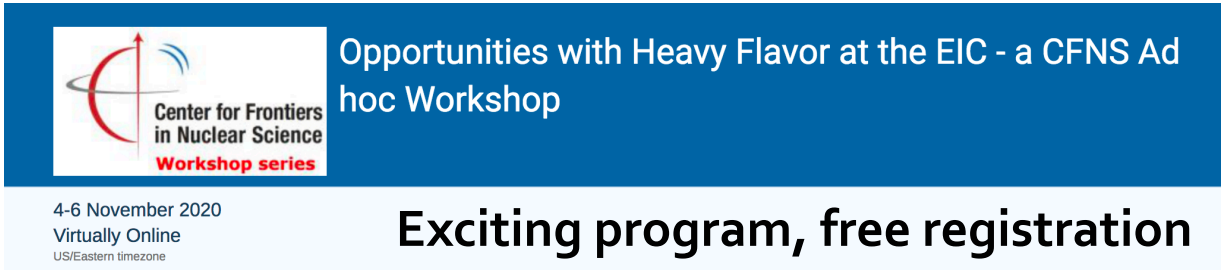


Arleo *et al.*, PRC, 61 054906 (2000)

Conclusions

- Heavy flavor physics at the EIC provides unique ways to pin down the structure of nucleons and nuclei, the nature of hadronization, the transport of energy and matter in the nuclear environment
- There has been tremendous progress in the past several years on all fronts theory, experiment, EIC hardware
- Notable progress includes precision QCD, tools for PDF analysis, fragmentation functions, heavy meson and jet calculations in e+p and e+A, theory developments for quarkonia; experimental simulations for those processes, physics projections; detector design and technology – specifically tracking/vertexing
- This is a young, exciting and growing field of EIC science – join it!

Expert level discussion of heavy flavor and implications for EIC



Link: https://indico.bnl.gov/event/9273/overview

Organizers

- Christian Weiss
- Fredrick Olness
- Ivan Vitev
- Jin Huang
- Xuan Li