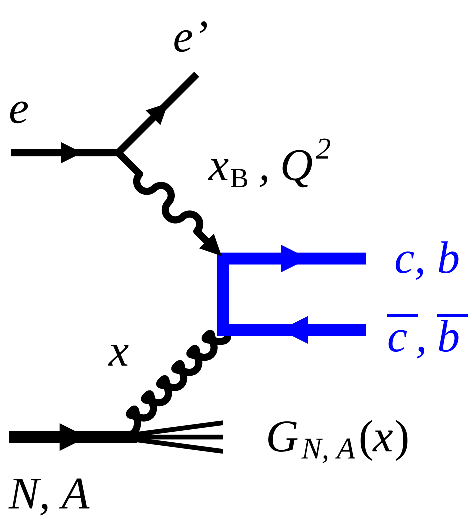
Heavy quark production and large-x nuclear gluons at EIC

C. Weiss (JLab), Santa Fe Jets and Heavy Flavor Workshop, 30-Jan-18

Jefferson Lab



- Nuclear partons

  Nuclear modifications $\leftrightarrow$ NN interactions in QCD

  Nuclear gluons at large x

- Heavy quark production in DIS

  LO, NLO, sensitivity to gluons

- Charm measurements with EIC

  Charm production rates at large x_B

  Charm reconstruction with exclusive D's, jets

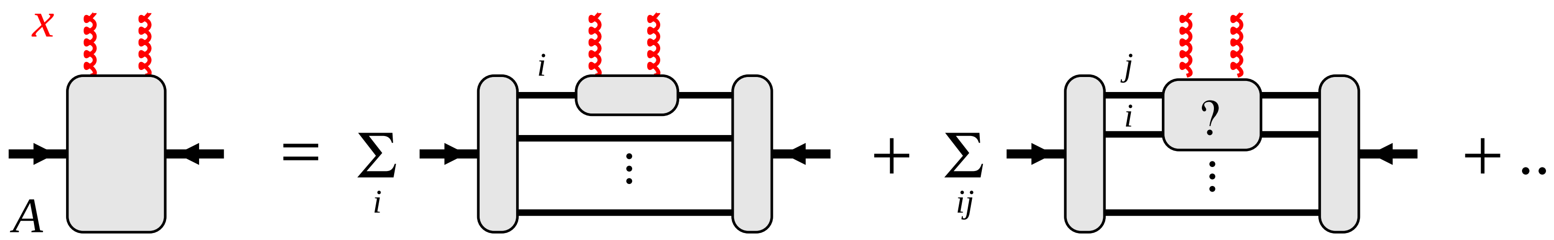
  Particle ID and vertex detection

  Impact on nuclear gluons

- Toward jets at EIC

E. Chudakov, D. Higinbotham, C. Hyde, S. Furletov, Yu. Furletova, D. Nguyen N. Sato, M. Stratmann, M. Strikman, C. Weiss∗, JLab 2016/17 LDRD Project
https://wiki.jlab.org/nuclear_gluons/
[arXiv:1610.08536], [arXiv:1608.08686]

Nuclear partons: Nucleon interactions



- Hard process, QCD factorization

- Nuclear matrix element $\langle A|\ \mathrm{Twist\text{-}2}\ |A\rangle$

  1-nucleon contribution $\langle N|\ \mathrm{Twist\text{-}2}\ |N\rangle$ — nucleon PDF, Fermi motion

  2-nucleon contribution $\langle NN|\ \mathrm{Twist\text{-}2}\ |NN\rangle$ — nucleon interactions!

  Well-defined operator, scale dependence μ^2, matching with LQCD, nuclear EFT

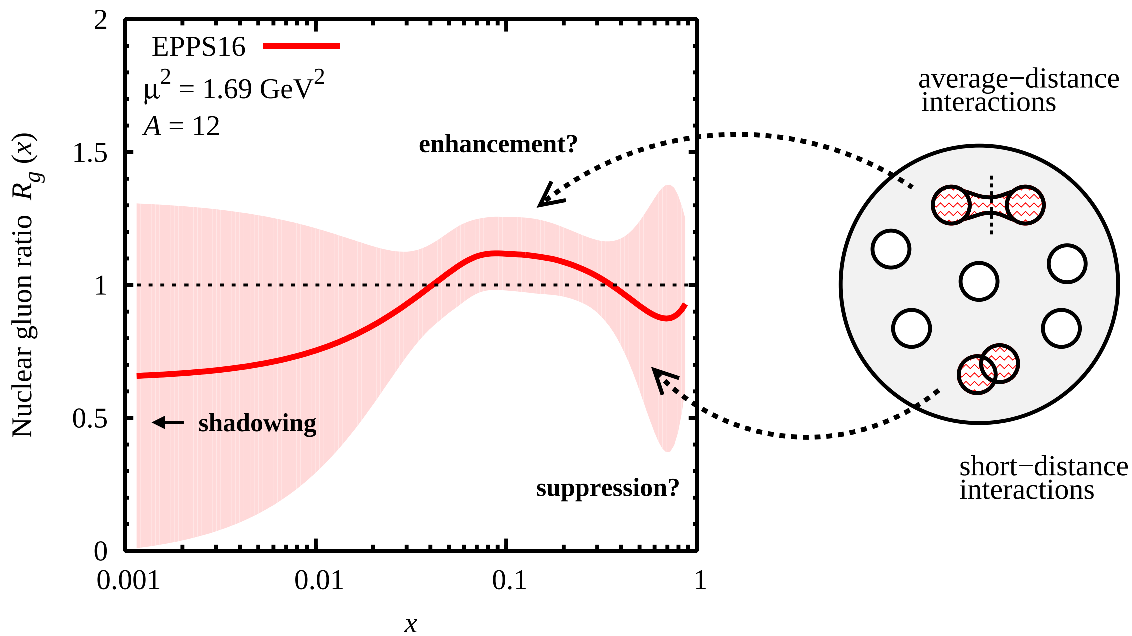
- Physics questions

  How do interactions modify quarks/gluons with different x?

  What are the relevant distances in the NN interactions?

  What are the relevant intermediate states? Non-nucleonic DoF!

Nuclear partons: Nuclear modifications



Status valence/sea quarks
→ Talk Olness

$0.3 < x < 0.8$	Suppression? EMC effect	Interactions at short distances cf. short-range NN correlations	JLab 6/12 GeV
$0.05 < x < 0.2$	Enhancement? Antishadowing	Interactions at average distances	
$x \ll 0.1$	Shadowing	Coherent interactions enabled by diffraction Suppression effect calculable Observed in J/ψ photoproduction on nuclei Suggests large antishadowing	Gribov 70s Frankfurt, Strikman Guzey 12+ ALICE, CMS

Nuclear partons: Probing gluons

- Determine nuclear gluon density at large x ($\gtrsim 0.05$)!

- Nuclear gluon probes

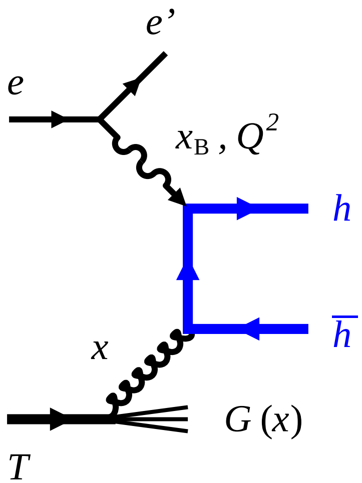
$eA/\mu A/\nu A$	Q^2 dependence of F_{2A}, F_{LA} + DGLAP
$eA/\gamma A$	Heavy quark production – direct probe! $\leftarrow$
$pA/eA/\gamma A$	Jets?

- EIC capabilities

Nuclear beams $A =$ 2–208	first eA collider
CM energy $\sqrt{s}_{eN} \sim$ 20–70 GeV	coverage at large x_B
Luminosity $L \sim 10^{34}$ cm^{-2} s^{-1}	rare processes
Next-gen detectors with PID and vertex	final states

E. Chudakov et al., JLab 2016/17 LDRD Project, https://wiki.jlab.org/nuclear_gluons/
see also: Aschenauer, Fazio, Lamont, Paukkunen, Zurita, PRD 96 114005 (2017)

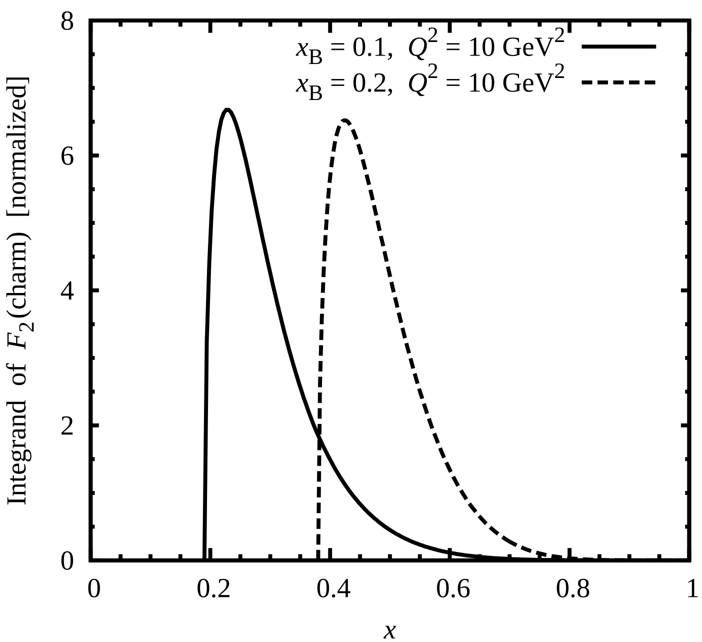
Heavy quark production: QCD description



$$F_2^h(x_B, Q^2) = \int_{ax}^{1} \frac{dx}{x}\, xG(x)\, \hat{F}_g^h(x_B/x, Q^2, m_h^2, \mu^2)$$

$$\hat{F}_g^h(\ldots) = e_h^2 g^2 Q^2/m_h^2 \times \text{fun}(x_B/x, Q^2)$$ coefficient function

$$a = 1 + 4m_h^2/Q^2$$ sets limit of x' integral



- QCD factorization $\gamma^* T \to h\bar{h} + X$

  Inclusive heavy structure functions F_2^h, F_L^h

  Differential cross section $d^4\sigma/dQ^2 d\eta d^2 p_T$

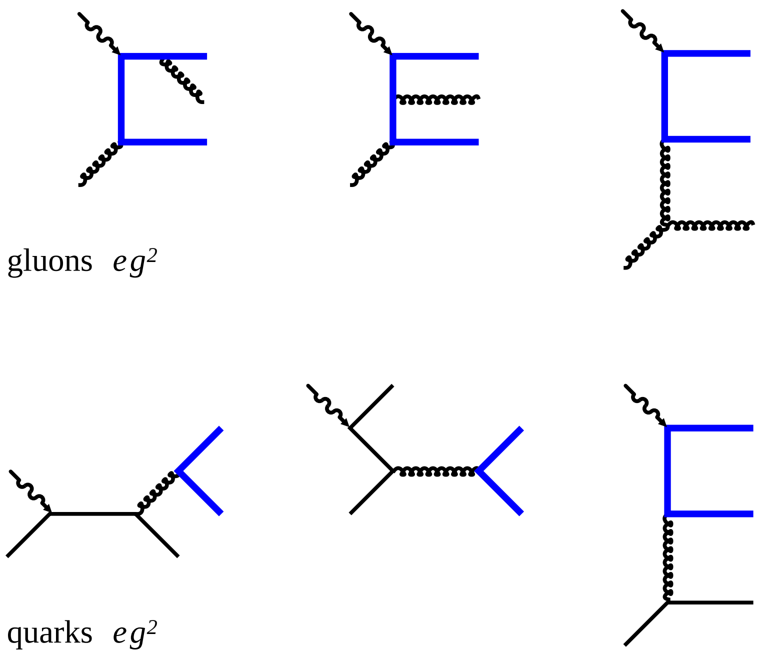
- Photon-gluon fusion at LO $\mathcal{O}(e_h g)$

  Couples to gluons only

  Integrand localized above $x \sim a x_B$,
  probes gluons almost locally in x

  Witten 76; Babcock, Sivers 78;
  Vainshtein, Shifman, Zakharov 78; Gluck, Reya 79

Heavy quark production: Higher orders



- Heavy quark production at NLO

  Sensitivity to light quarks at $\mathcal{O}(e_h g^2)$

  LO photon-gluon fusion large at $x > 0.1$

  Theoretical uncertainties quantified

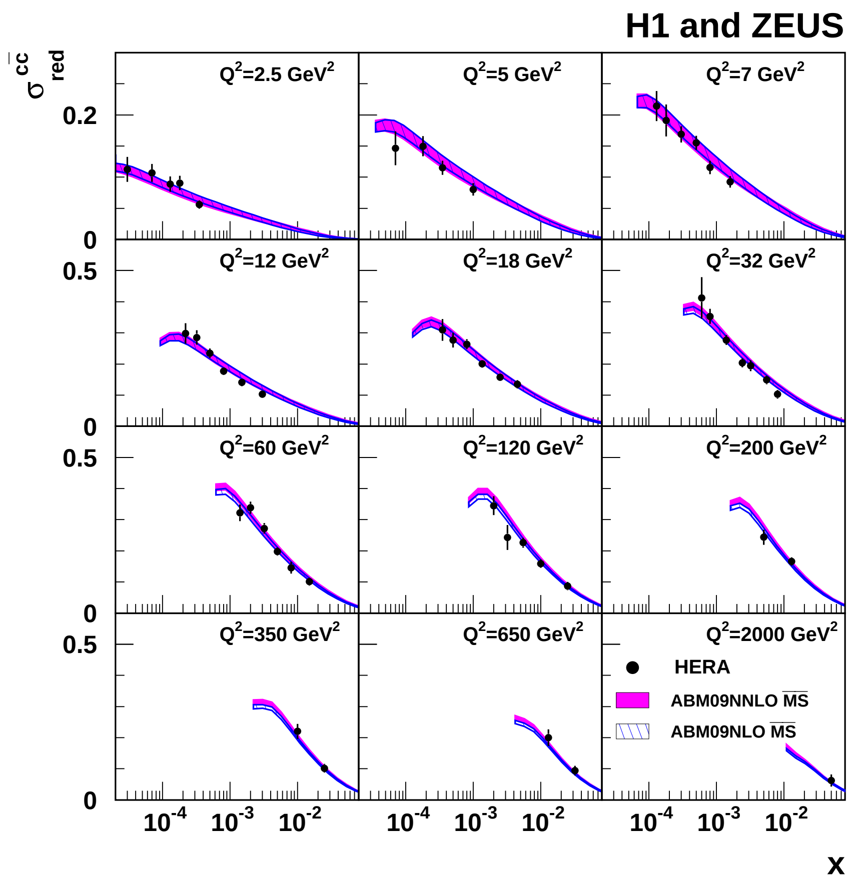
  Laenen, Riemersma, Smith Van Neerven, Harris 93+.
  Alekhin, Moch, Blümlein, Vogt, Kawamura et al. 11+

- Perturbative stability LO $\rightarrow$ NLO

  Good stability of F_2^c with choice of effective LO scale Gluck, Reya, Stratmann 94

  Rapidity, p_T distributions more sensitive

Heavy quark production: HERA



H1 + ZEUS summary. H. Abramowicz *et al.* EPJC 73 (2013) 2311

- $c\bar{c}$, $b\bar{b}$ production in $ep/\gamma p$

  Mostly $x < 10^{-2}$

  Various reconstruction methods

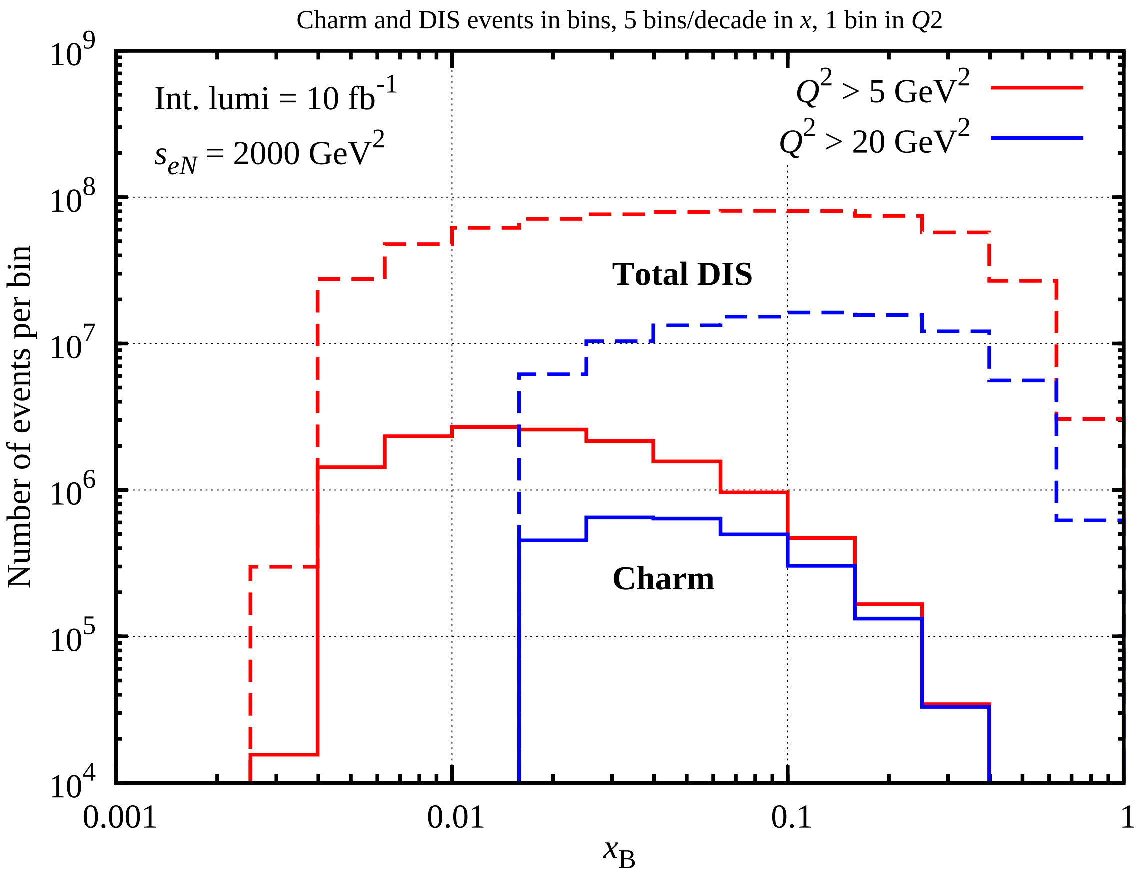
  Extensive tests of theory

  Measurements of $c \to D$ and $b \to B$ fragmentation functions

- Simulation tools

  HVQDIS LO/NLO cross secn + MC integration Harris, Smith 98

EIC: Charm production rates at large x_B



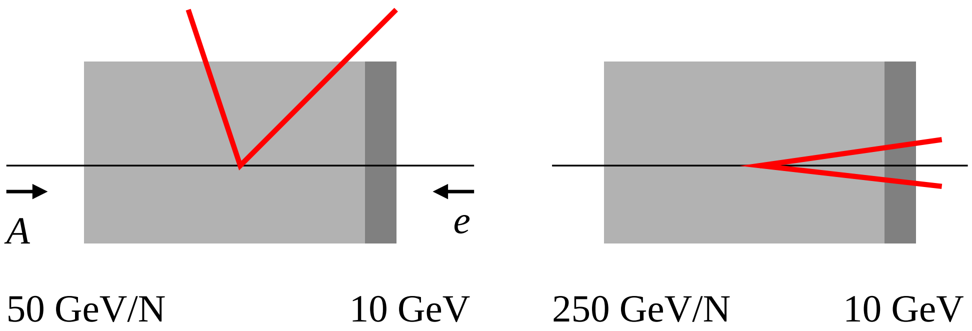
- Charm production rates drop rapidly at large x
- Charm production rates $\sim 10^5$ at $x_B \sim 0.1$ ($L_{\text{int}} = 10$ fb^{-1})

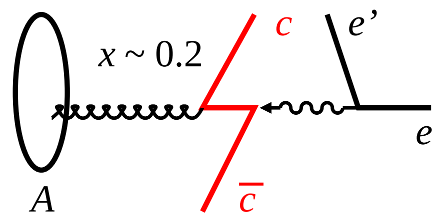
  Defines charm reconstruction efficiency needed for physics

- Charm/DIS ratio $\sim$ 2–3 % at $x \sim 0.1$

  Defines charm reconstruction environment

EIC: Charm angle and momentum distributions





- Large-x $c\bar{c}$ pairs produced almost at rest in low-ratio collider

  Example: Gluon with $x = 0.2$ and $10{\times}50$ GeV$/N$

  Contrast with high-ratio collider!

- π/K produced at large angles, with typical momenta $\lesssim 5$ GeV

  Favorable situation!

- Good PID and momentum resolution available in central detector

  Enables "new" methods of charm reconstruction

EIC: Charm reconstruction methods

- Exclusive D-meson decays
- Inclusive decays with displaced vertex

Questions

How well do the methods work at large x?

What are the overall efficiencies and uncertainties?

What detector performance is required?

Simulations at different levels

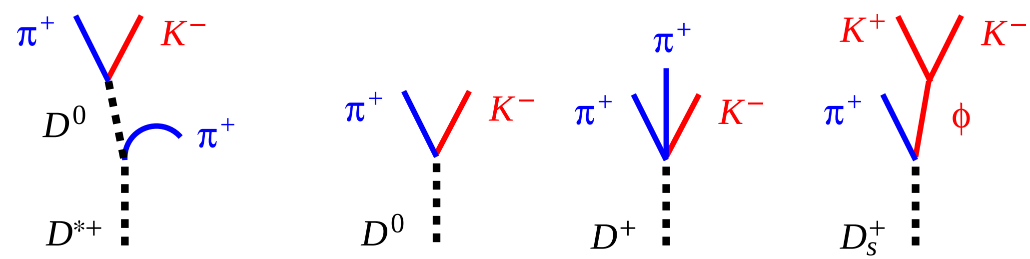
1) Theoretical estimates of reconstruction efficiency

2) Model acceptance and PID performance, describe resolution effects through smearing of vertex and momentum distributions

3) Tracking and vertexing based on schematic JLEIC detector model

EIC: Charm with exclusive D's

h_c	f	Decay	BR
D^0	59%	$K^-\pi^+$	3.9%
		$K^-\pi^+\pi^+\pi^-$	8.1%
D^+	23%	$K^-\pi^+\pi^+$	9.2%
D^{*+}	23%	$(K^-\pi^+)_{D0}\ \pi^+_{\text{slow}}$	2.6%
		$(K^-\pi^+\pi^+\pi^-)_{D0}\ \pi^+_{\text{slow}}$	5.5%
D_s^+	9%	$(K^+K^-)_\phi\ \pi^+$	2.3%
Λ_c^+	8%	$pK^-\pi^+$	5.0%



- Simple exclusive channel $D^{*+} \to \pi^+(\text{slow}) + (K^-\pi^+)_{D0}$

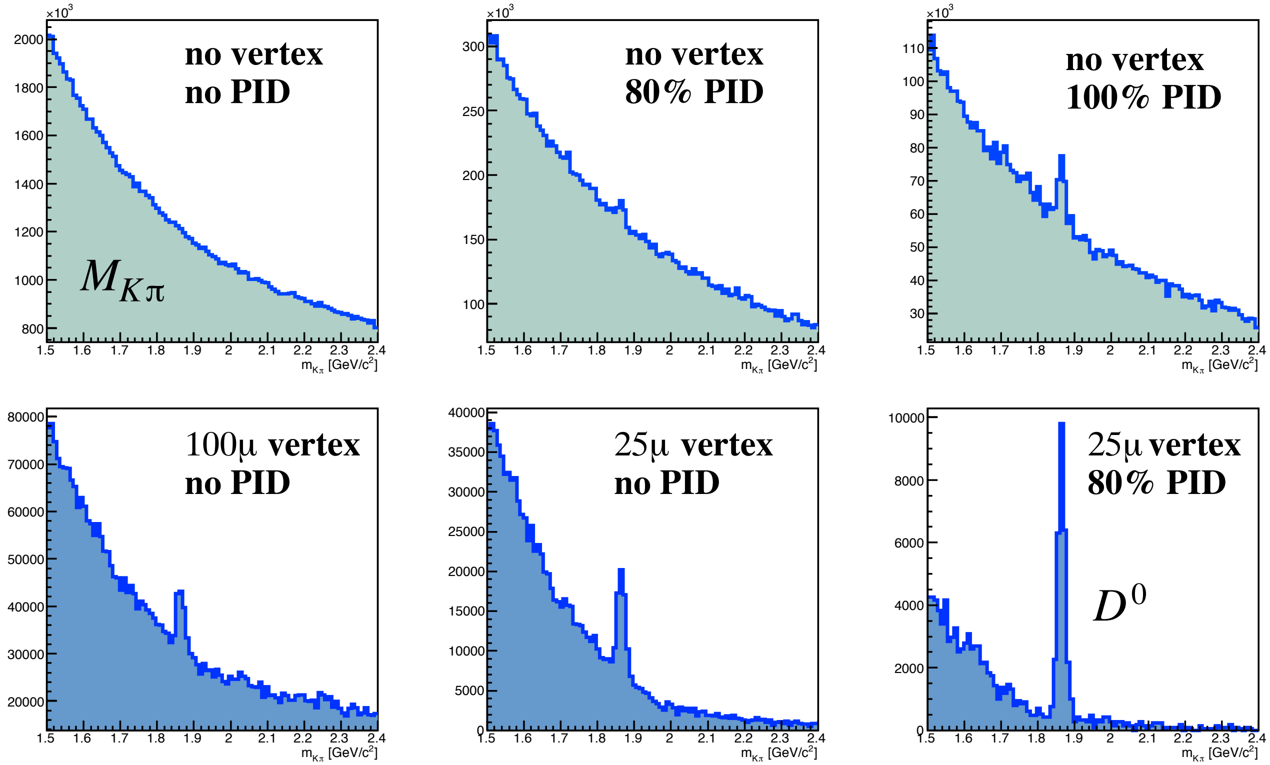
  Used at HERA without PID. Efficiency $< 1\%$

- EIC PID + vertex detection allow use of other exclusive channels D^0, D^+, D_s^+

- Theoretical efficiency $\sim 10\%$ summed over channels

  Fragmentation ratio f $\times$ Branching ratio BR

EIC: Charm reconstruction with exclusive D's



Invariant mass spectrum of two charged tracks/mesons in sample of charm events with $Q^2 > 10$ GeV^2 and $x_{\mathrm{B}} > 0.05$. PYTHIA 6 simulation, arbitrary normalization of event sample, no DIS background, vertex cut 100 μm.

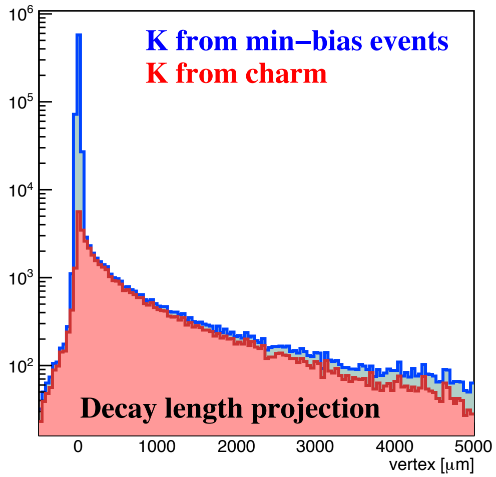
- Example: D^0 meson reconstruction using exclusive decay $D^0 \to K^- \pi^+$

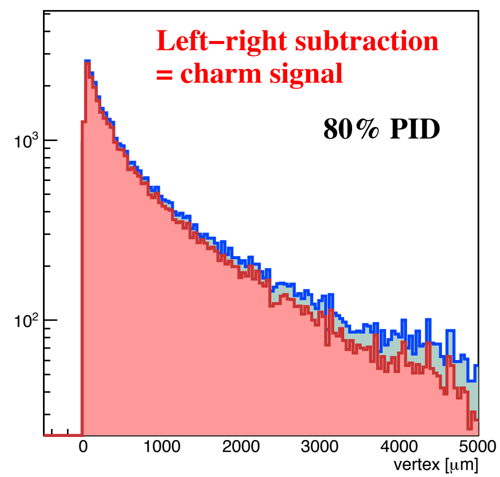
  Level-2 simulation with mass/momentum and vertex smearing

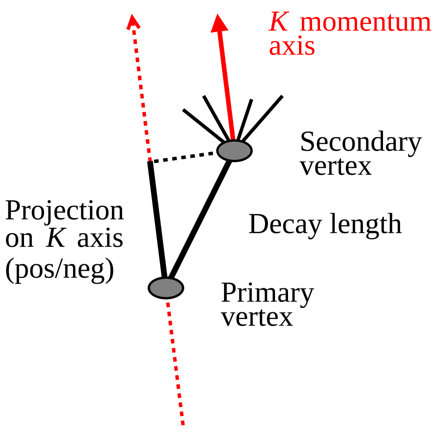
  Also other channels

- Impact of PID and vertex detection

EIC: Charm reconstruction with inclusive modes







- Decay length significance distribution

  Establish secondary vertex

  Project decay length on jet axis, positive/negative

  Identify D-meson decays through positive projection

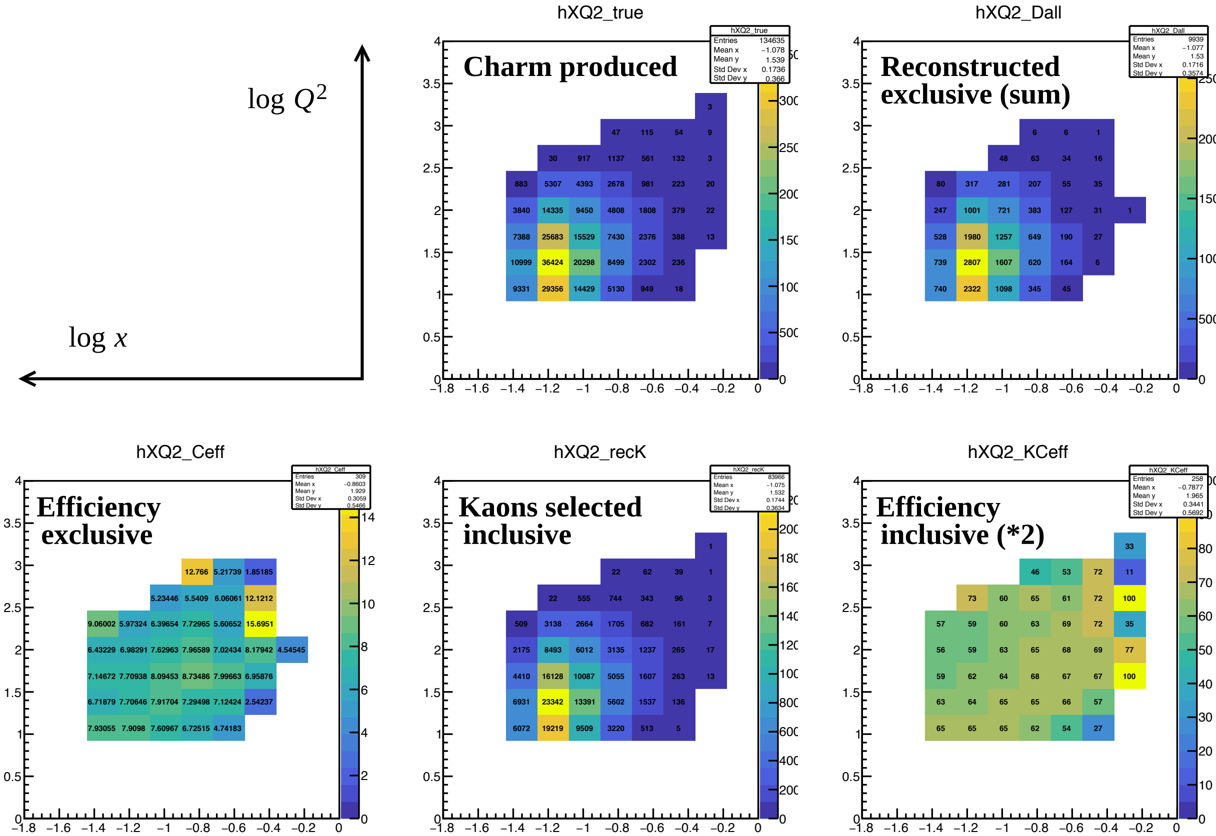
- Used at HERA with vertex detector

- Use for charm at EIC

  Identified K from PID

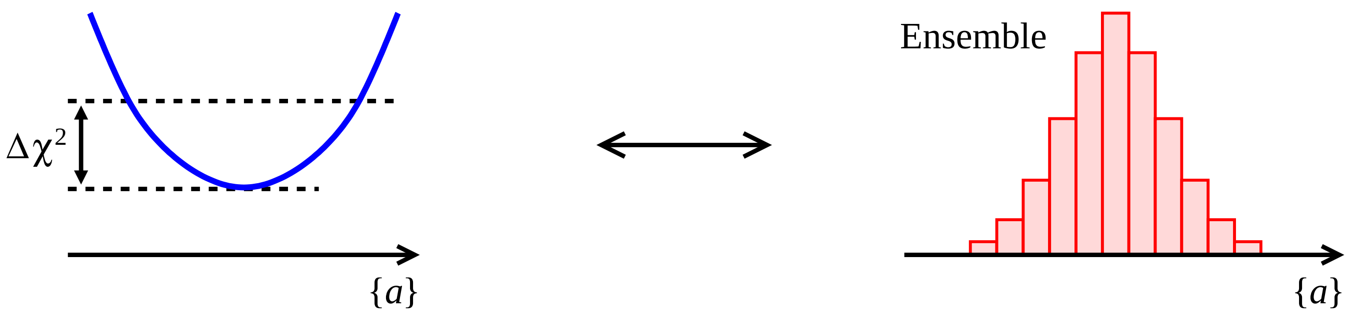
  Efficiency up to $\sim$ 30%

EIC: Charm reconstruction efficiency



- Total efficiency estimated ∼5-7% exclusive, ∼30% inclusive
- Little kinematic variation in (x, Q^2) region of interest
- Systematic uncertainties? HERA $\lesssim 10\%$
- Both vertex detection and PID are essential for charm reconstruction

Charm impact: PDF reweighting



- PDF reweighting

  Method for quantifying impact of new (pseudo-) data on existing global fit
  Giele, Keller 98; NNPDF Collab Ball et al 11; Paukkunen, Zurita 14; Sato et al 16

  Represents existing fit as statistical ensemble, uses Bayes' theorem

  Avoids costly re-fitting

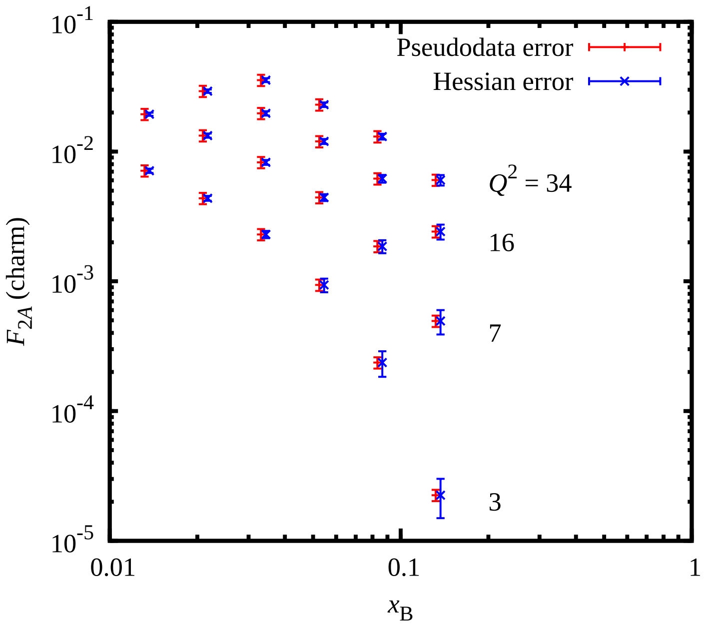
  Widely used in PDF analysis, HEP

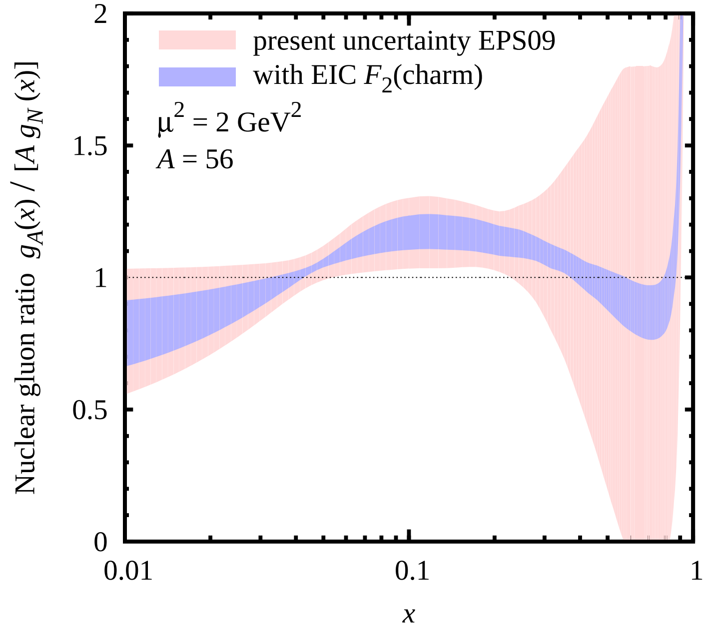
- Implemented for charm pseudodata from EIC

  Presently F_{2c}, can be extended to other observables

  Python code package, on github: `https://github.com/JeffersonLab/F2c`

Charm impact: Large-x gluons





- Charm pdeudodata

  $F_2^c(x, Q^2)$, assumed 10% total uncertainty, dominated by systematics, point-to-point

  Here EPS09, LO approximation. To be updated/refined

- Substantial impact on large–x nuclear gluons

  See also: Aschenauer et al, PRD 96 114005 (2017)

- Theoretical uncertainties to be estimated

  Nuclear final-state interactions vs. initial-state modifications

  Uncertainties of nuclear ratios

Summary

- Nuclear PDFs as window on nucleon interactions in QCD

  New physics topic — next step after nucleon structure

  Twist-2 operators — clear connections with EFT, LQCD, phenomenology

- Open charm production at EIC can constrain large–x nuclear gluons

  Natural measurement for medium-energy collider

  Particle ID and vertex detection essential for charm reconstruction

  Simulation tools available, can start detailed studies
  JLab LDRD Project LD1701/1601, https://wiki.jlab.org/nuclear_gluons/

- Toward jet measurements at EIC

  New applications: ΔG in ep, medium properties in eA → Talk Petriello

  Theoretical questions: Jet definition at moderate momenta $p \sim$ few 10 GeV

  Available tools can be used to simulate jet measurements at EIC
  Open for collaboration!