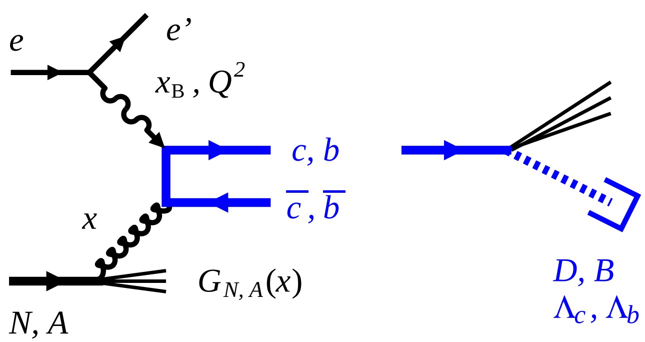
Open heavy flavor production and reconstruction at EIC

C. Weiss (JLab), ECT∗ Workshop "Spectroscopy at EIC," 19-Dec-18

Jefferson Lab



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]

- Context

  Physics interest, theory, HERA results

- HF production at EIC

  Rates and kinematic dependences

  Momentum and angle distributions

- HF reconstruction at EIC

  Challenges at large x_B

  π/K identification, vertex detection

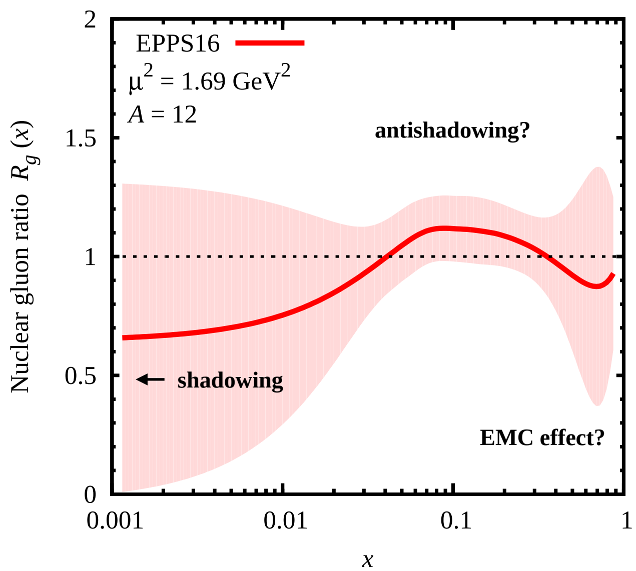
  Exclusive D meson decays

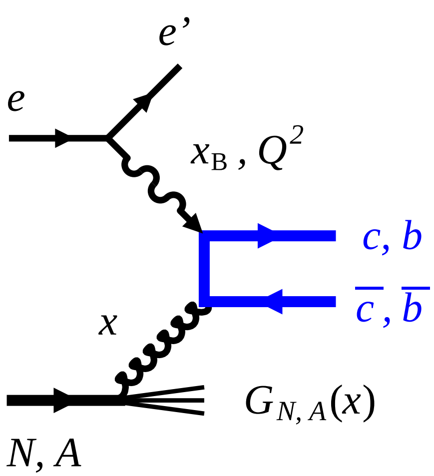
  Inclusive decays with displaced vertex

  Simulation tools

- Applications and extensions

Context: HF production in ep/eA





- Physics interest

  Direct probe of gluon density in target

  LDRD project: Nuclear gluons at $x \gtrsim 0.1$
  EMC effect, antishadowing $\leftrightarrow$ NN interactions in QCD

  HF propagation and hadronization in matter

  HF spectroscopy

- Theory of HF production in DIS

  LO photon-gluon fusion

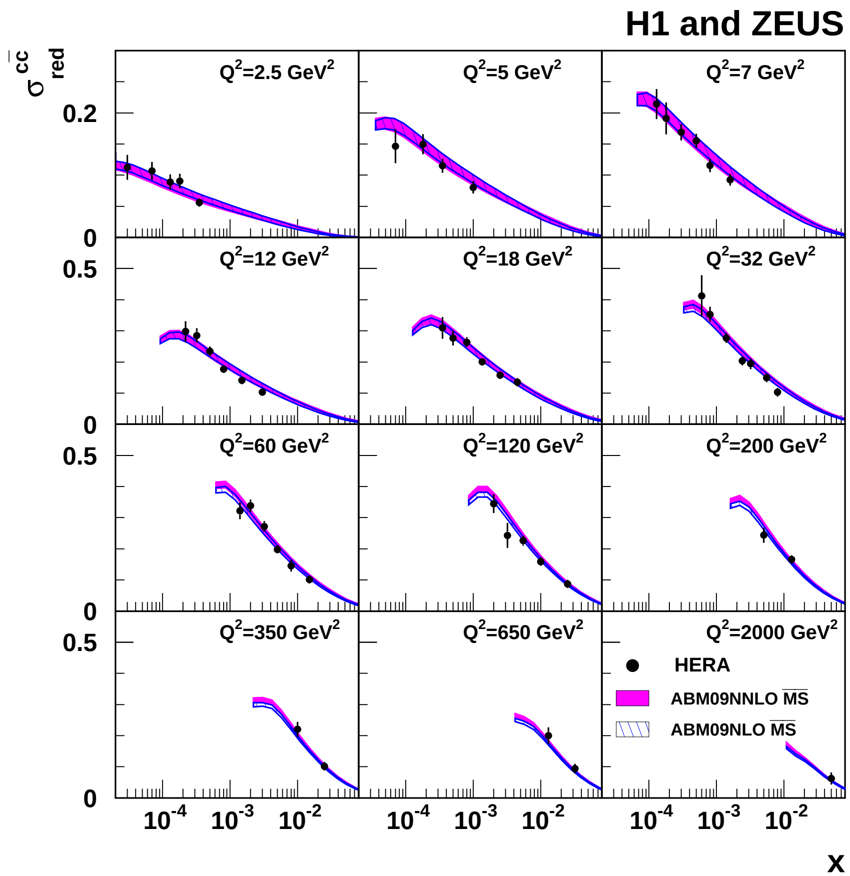
  Probes gluons at $x > ax_B, \quad a = (1 + 4m_h^2/Q^2)$

  Higher orders calculated, uncertainties estimated
  Laenen, Riemersma, Smith Van Neerven, Harris 93+.
  Alekhin, Moch, Blümlein, Vogt, Kawamura et al. 11+

  Inclusive σ^c and differential $d\sigma^c/d\eta dp_T$

  Photoproduction $Q^2 = 0$ also hard process

Context: HF production at 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

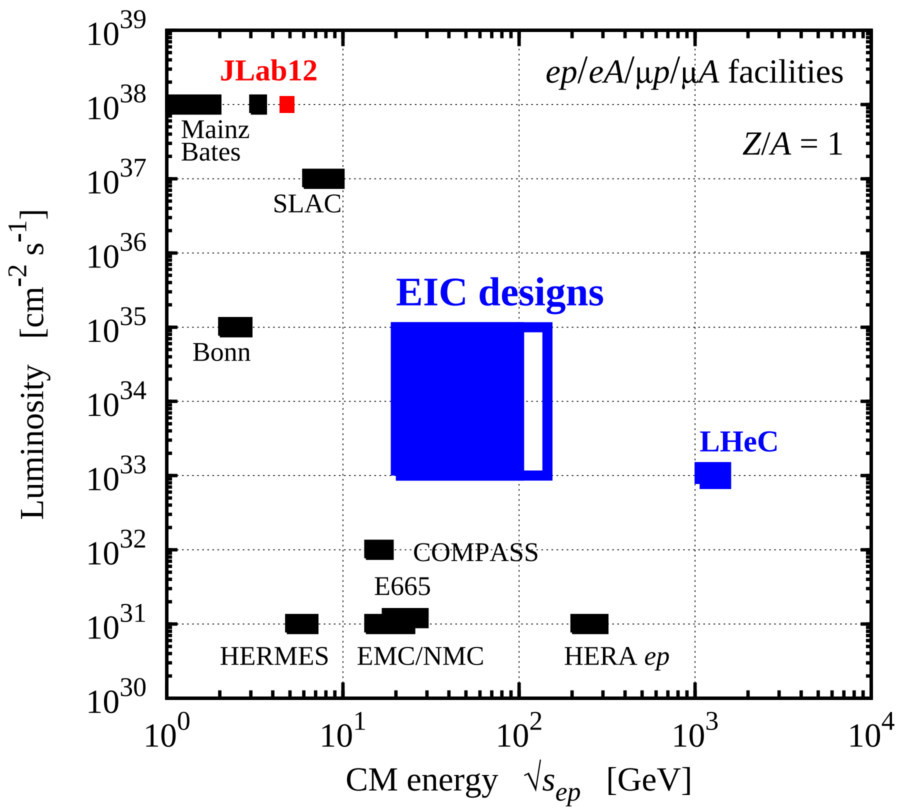
- Simulation tools

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

  Simple codes for QCD cross secns and rate estimates JLab LDRD

  PYTHIA, HERWIG generators for full DIS final state π, K, ...

Context: EIC capabilities



- CM energy $\sqrt{s_{ep}} \sim$ 20–100 GeV

  Factor $\sqrt{Z/A}$ in nuclei

- Luminosity $\sim 10^{33}$–10^{34} cm^{-2} s^{-1}

  $\sim 10^2$–$10^3\times$ HERA luminosity

  Simulations for int. lumi 10–100 fb^{-1}

[• Polarized protons and light ions]

[Parameters per EIC White Paper, NAS Study]

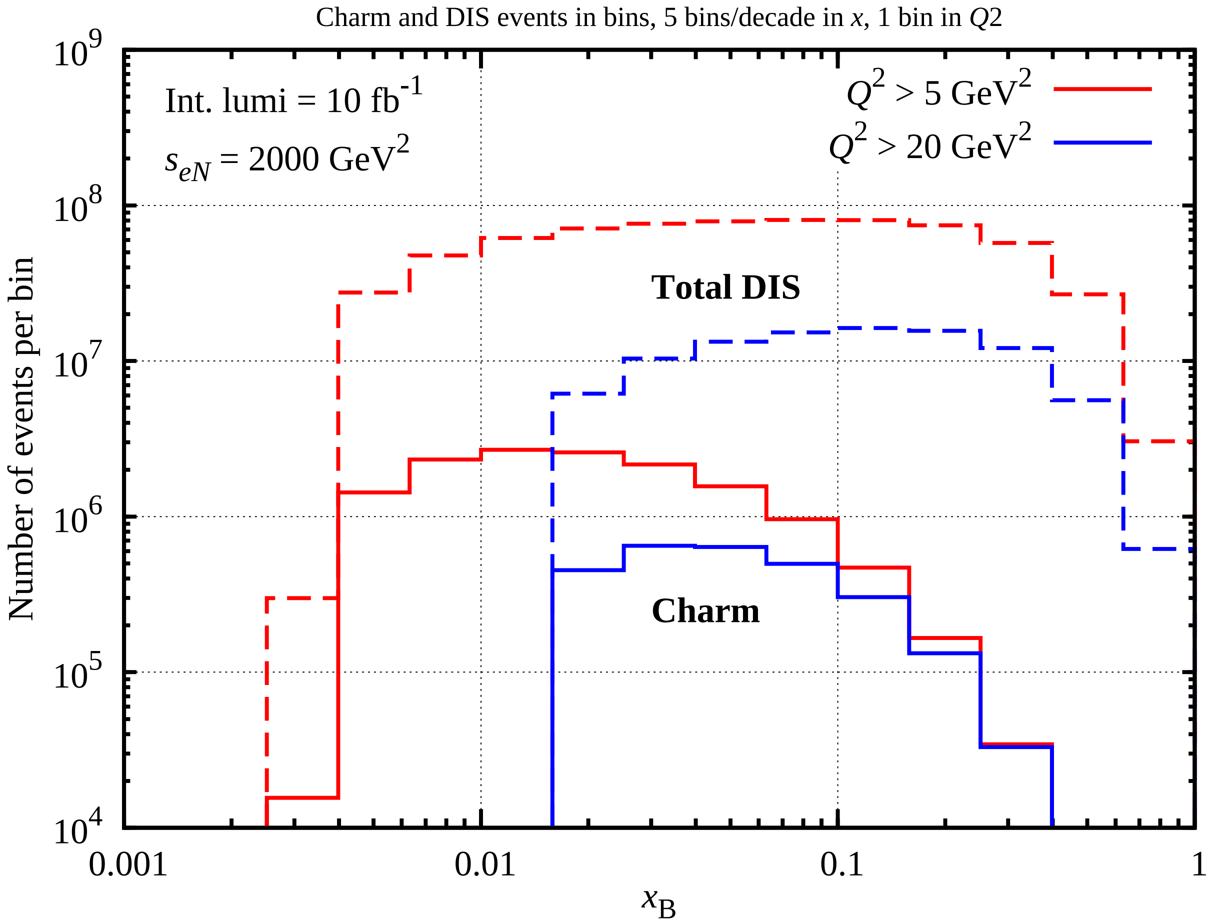
- Next-generation detectors

  Central & ion endcap: Calorimetry, tracking + PID, vertex detection $|\eta| \lesssim 3.5$

  Forward ion: Exclusive and diffractive p, coherent nuclear processes, fragments

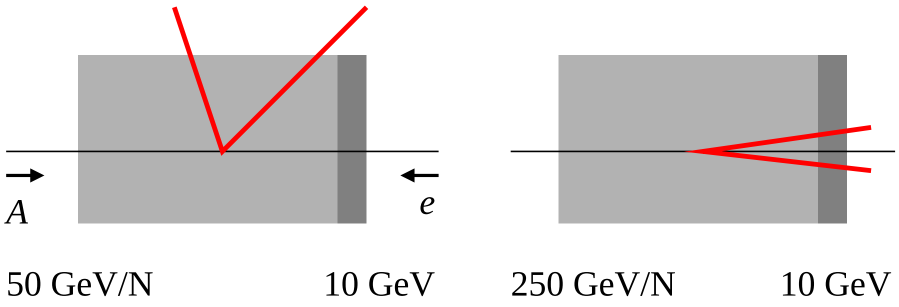
  Forward electron: Low-Q^2 tagger for quasireal photoproduction

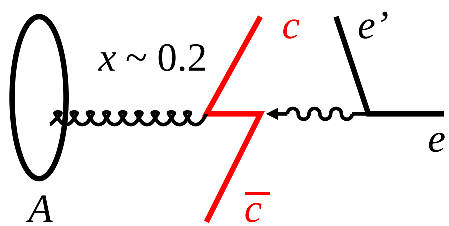
EIC: Charm production rates

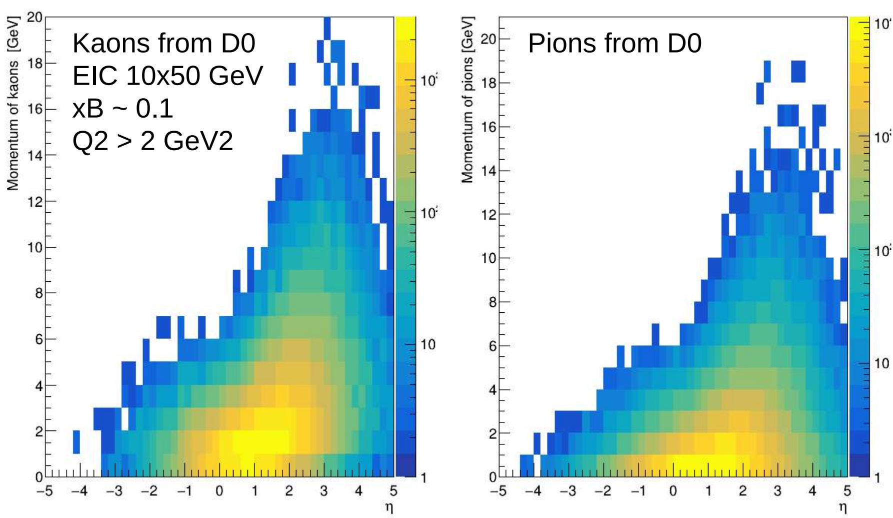


- Charm production rates drop rapidly at large x_B
- Charm production rates $\sim 10^5$ at $x_B \sim 0.1$ (int. lumi 10 fb^{-1})
  Defines charm reconstruction efficiency needed for physics at $O(10\%)$
- Charm/DIS ratio $\sim$ 2–3 % at $x_B \sim 0.1$
  Defines charm reconstruction environment

EIC: Charm angle/momentum distributions







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

  CM frame of electron-gluon collision
  Example: $x = 0.2$ and 10×50 GeV

  Forward-boosted in high-ratio collider

- π/K from D decays have typical momenta $\lesssim 5$ GeV

  Favorable situation

- Good PID and momentum resolution available in central detector

  Enables "new" methods of charm reconstruction with EIC

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

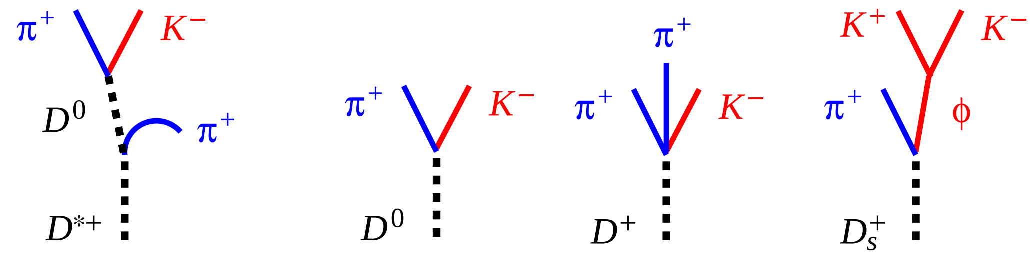
1) Theoretical estimates of reconstruction efficiency

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 reconstruction 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%	$(K^-\pi^+)_{D0}\ \pi^+_{\rm slow}$	2.6%
		$(K^-\pi^+\pi^+\pi^-)_{D0}\ \pi^+_{\rm slow}$	5.5%
D_s^+	9%	$(K^+K^-)_\phi\ \pi^+$	2.3%
Λ_c^+	8%	$pK^-\pi^+$	5.0%



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

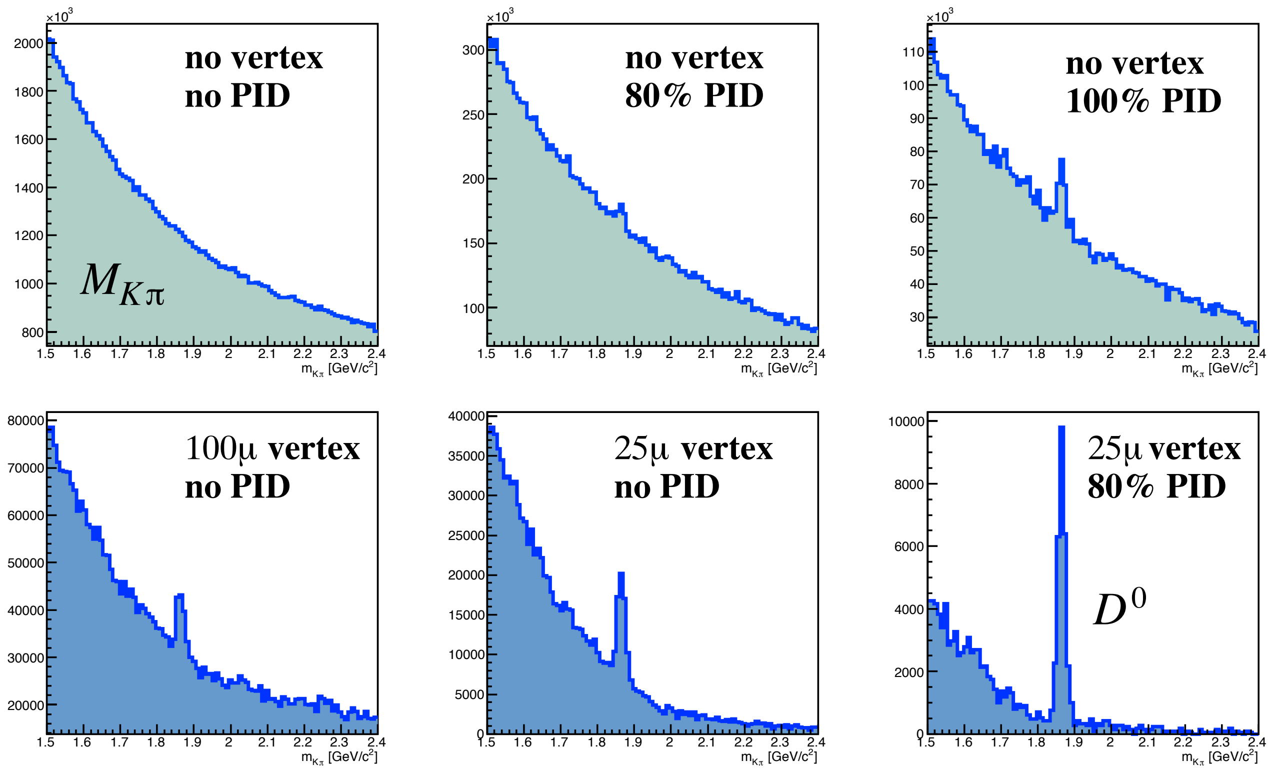
  Used at HERA without PID. Efficiency $< 1\%$

- 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: Impact of PID and vertex detection



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

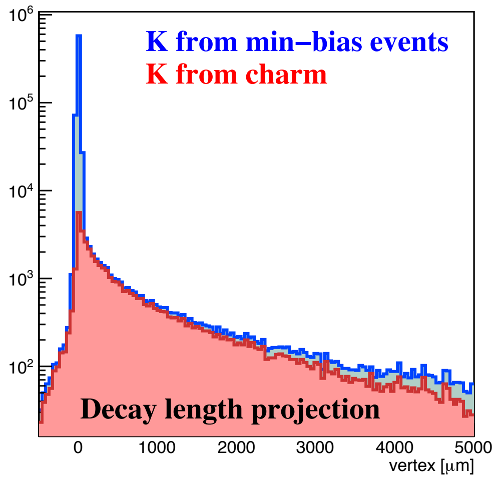
Yu. Furletova, S. Furletov

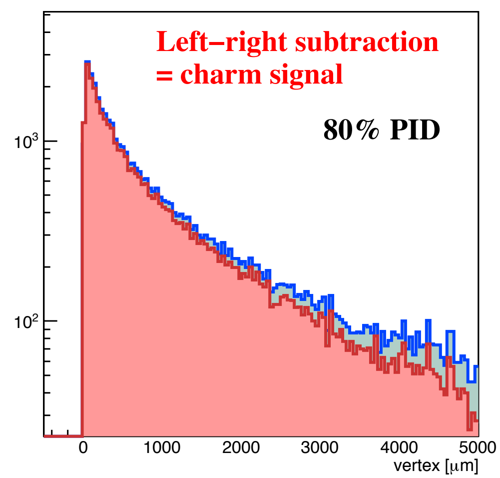
- Example: D^0 meson reconstruction using exclusive decay $D^0 \to K^-\pi^+$

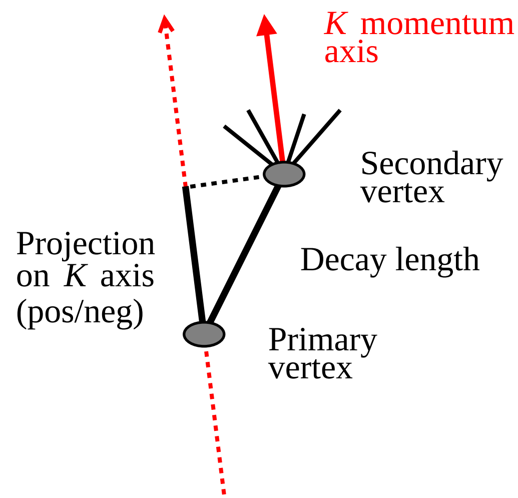
  Level-2 simulation with mass/momentum and vertex smearing

  Also other channels

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

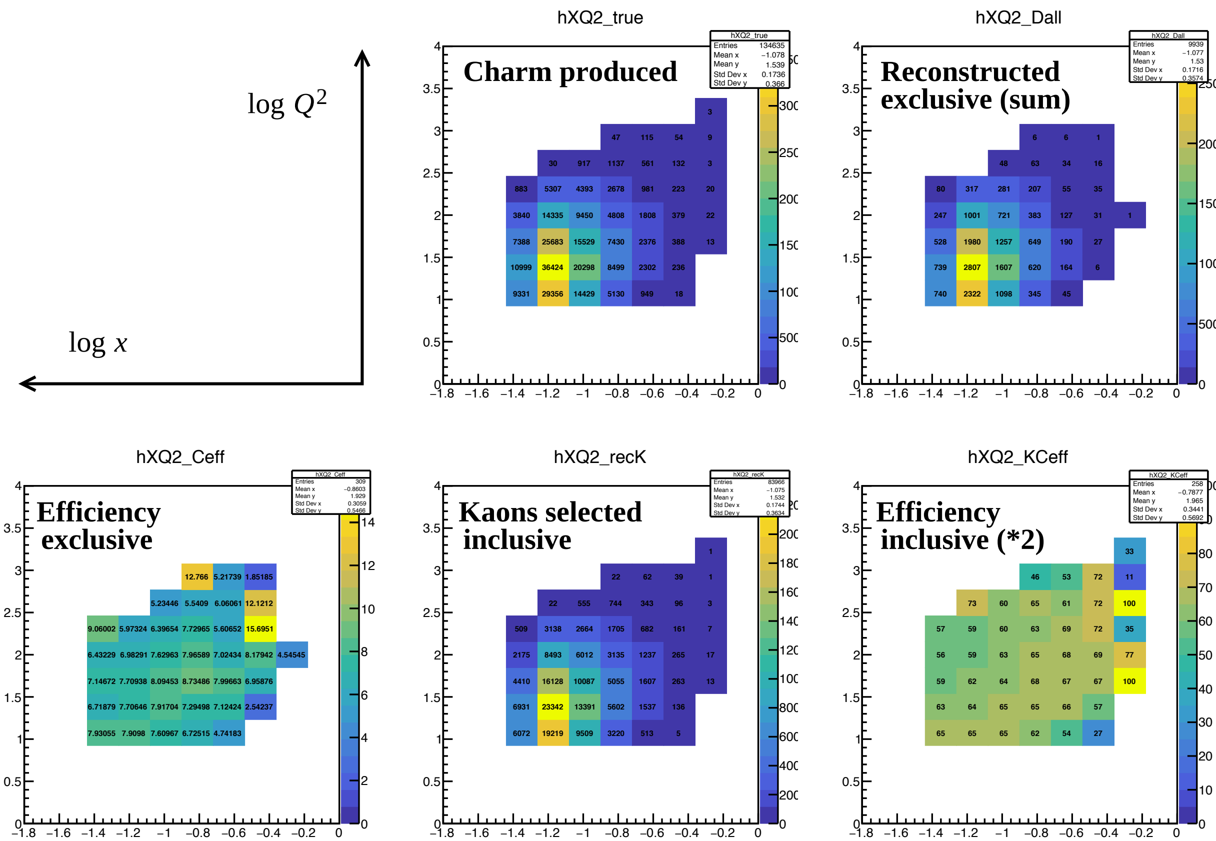
- Used at HERA with vertex detector

- Use for charm at EIC

  Identified K from PID

  Efficiency up to $\sim$ 30%

EIC: Charm reconstruction efficiency

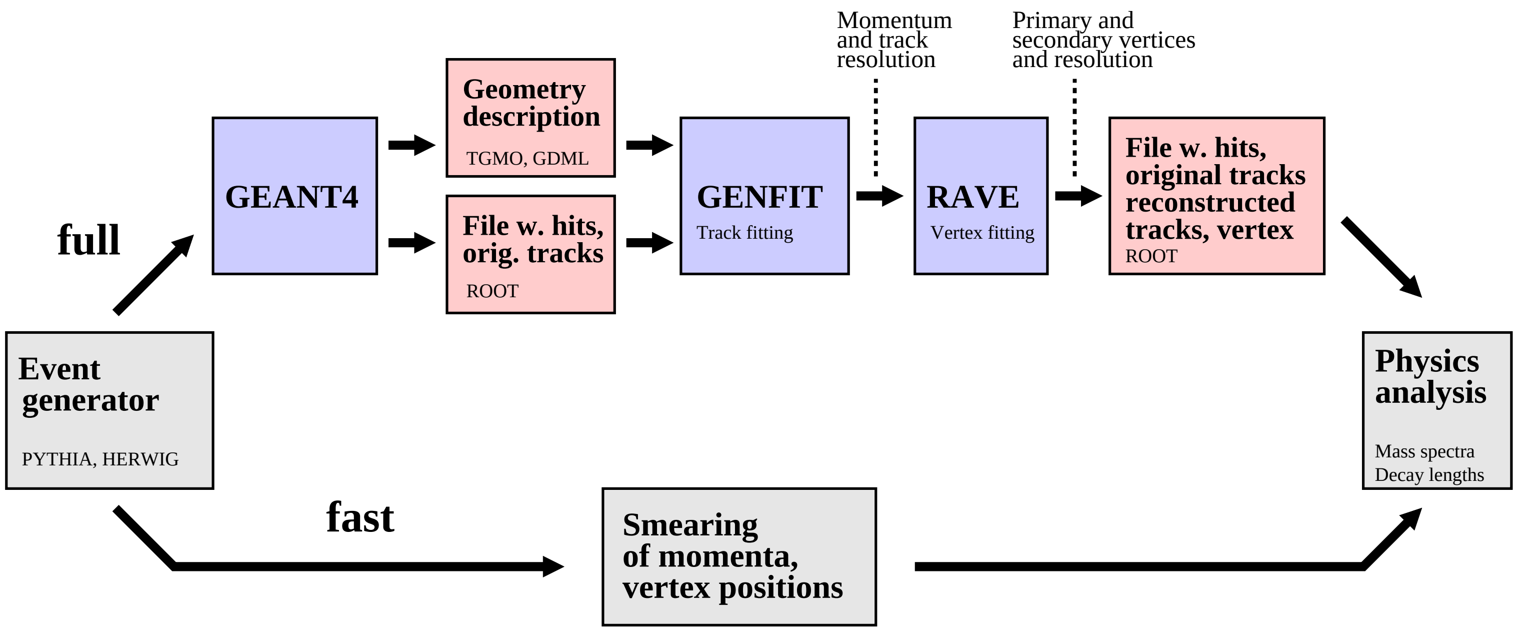


- Total efficiency estimated ∼5-7% exclusive, ∼30% inclusive

Yu. Furletova

- 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

EIC: Tracking and vertexing with JLEIC



- Analysis chain for tracking and vertexing with JLEIC — Yu. Furletova, S. Furletov

  Model of vertex detector and outer tracker/endcap geometry

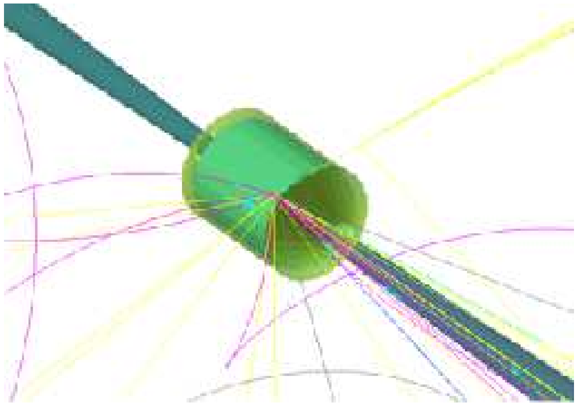
  Based on GEANT4/Root, uses available tools GENFIT, RAVE

- Can be used in two ways

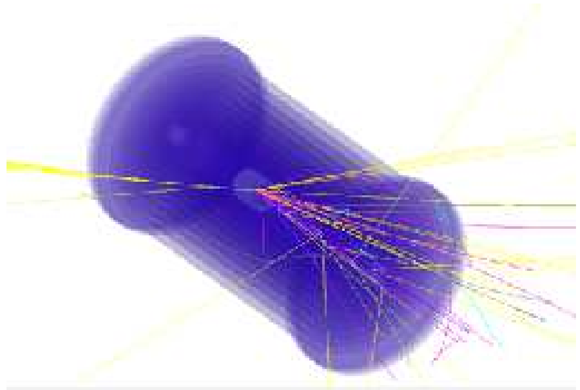
  Verify smearing parameters of Level-2 simulations

  Full event reconstruction

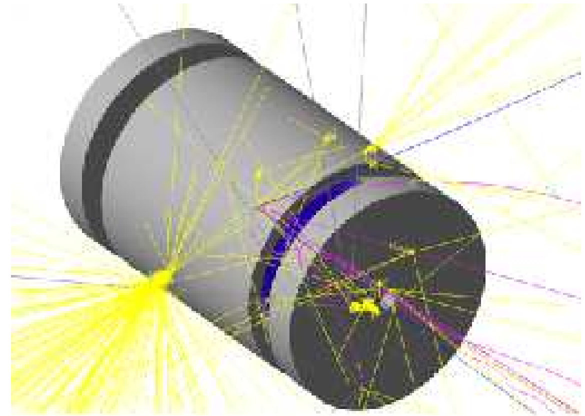
EIC: Tracking and vertexing with JLEIC



Vertex detector



Outer tracker and endcap



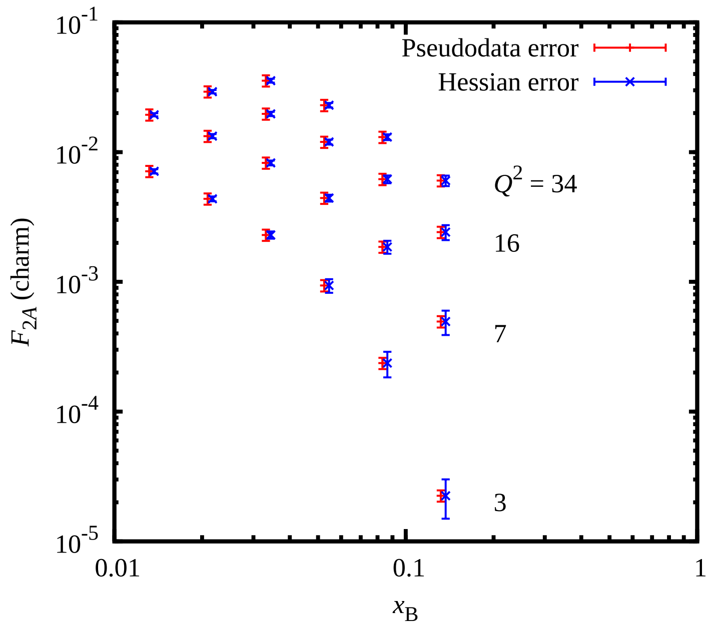
Iron calorimeter

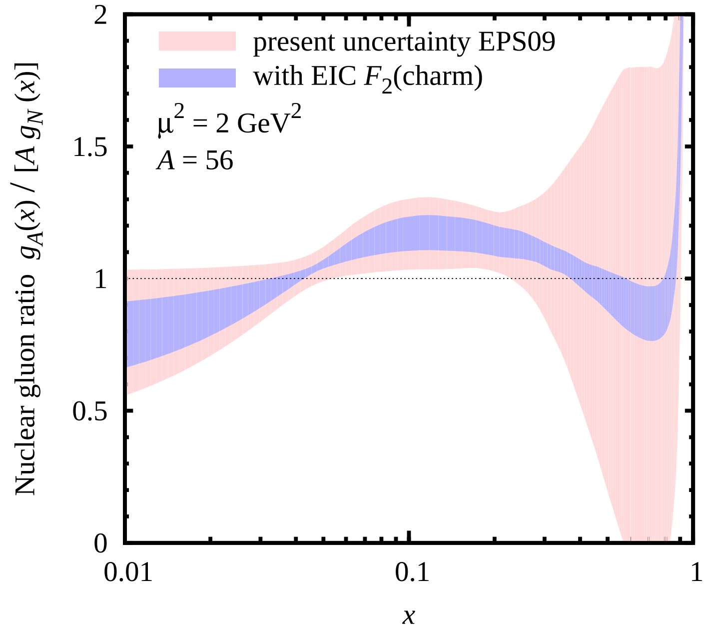
- Schematic detector model, describes geometry + magnetic field, implemented in GEANT4

- Can be adapted and optimized for HF simulations

- Open for collaboration
  JLab 2016/17 LDRD Project https://wiki.jlab.org/nuclear_gluons/

EIC: Charm impact on large-x gluons in nuclei





- Impact of charm production studied using PDF reweighting

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

- 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

Further applications and extensions

- Charm reconstruction with high-p_T pairs – rare but distinct events
- Charm reconstution with Λ_c using endcap and forward detector
- Beauty production and reconstruction
- HF photoproduction using low-Q^2 electron tagger

Summary

- Great opportunities for HF physics at EIC
- HF production & reconstruction at large x needs fresh thinking

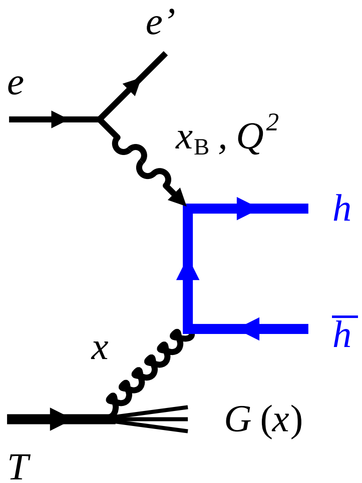
  Challenges: Low rates, large DIS background
  Capabilities: π/K PID, vertex detection
  Methods: Exclusive and/or inclusive reconstruction

- Detector design needs input from HF simulations

  Simulation tools available. Open for collaboration
  JLab 2016/17 LDRD Project `https://wiki.jlab.org/nuclear_gluons/`

Supplementary material

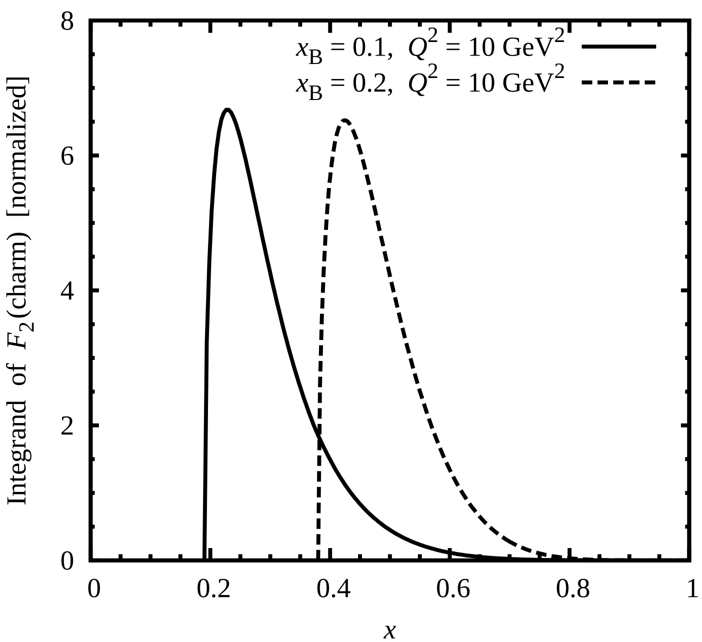
HF production: QCD description



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

$$\hat{F}_g^h(\ldots) = e_h^2 g^2 Q^2/m_h^2 \times \text{fun}(x_B/x, Q^2)$$ 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 $d^4\sigma/dQ^2 d\eta d^2 p_T$

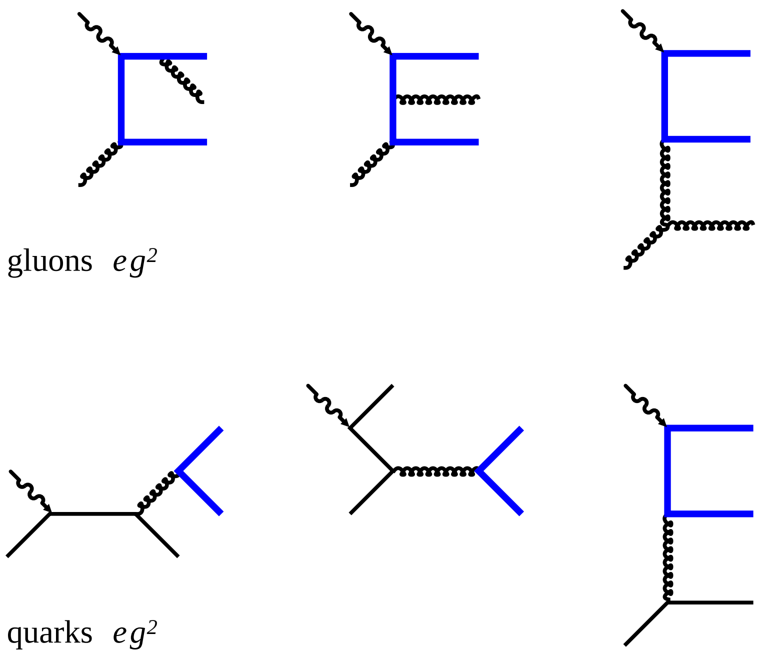
- Photon-gluon fusion at LO $\mathcal{O}(e_h g)$

  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

HF 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

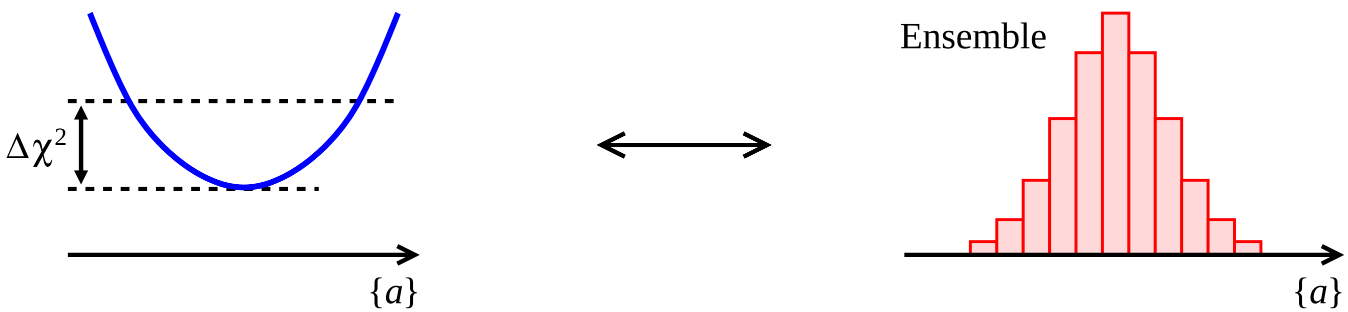
  Laenen, Riemersma, Smith Van Neerven, Harris 93+.
  Alekhin, Moch, Blümlein, Vogt, Kawamura et al. 11+

- 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

EIC: Charm impact using 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`