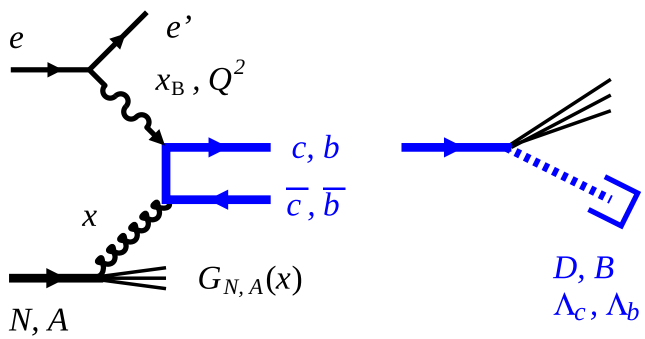
Probing nuclear gluons with heavy flavor production at EIC

C. Weiss (JLab), Jets and Heavy Flavors Yellow Report WG, 20-Apr-2020 Jefferson Lab



C. Andres Casas, 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]

See also: E. C. Aschenauer, S. Fazio, M. A. C. Lamont, H. Paukkunen, P. Zurita, PRD 96, 114005 (2017)

Other apps: HF as probe of nuclear medium, HF spectroscopy

- Physics

  Nuclear gluon densities

  HF production as direct probe

- Simulations

  Charm production: Rates, kinematic dependence

  Charm reconstruction: Exclusive, inclusive

  Role of PID and vertex detection

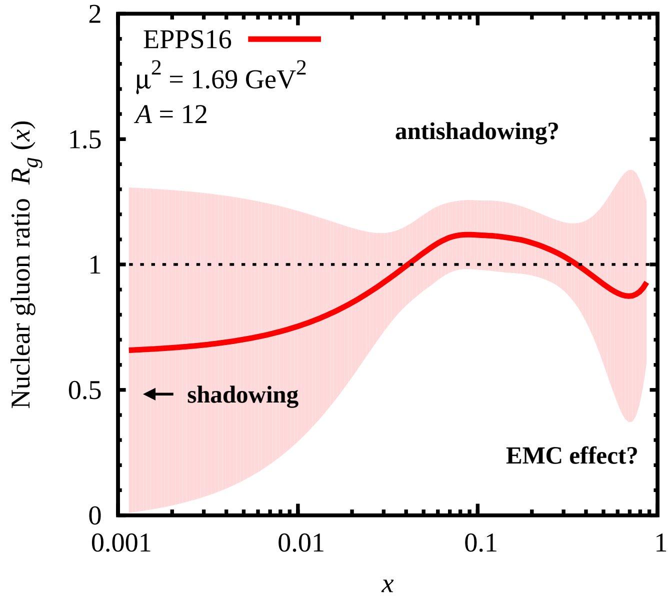
- Impact

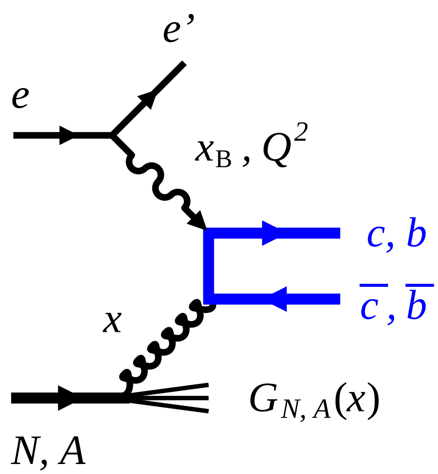
  PDF reweighting with EIC charm pseudodata

- Extensions

  High-p_T charm pairs, beauty, ...

Physics: Nuclear gluons and HF production





- Nuclear gluon density

  Modifications $\leftrightarrow$ nucleon interactions in QCD

  $x \gtrsim 0.1$: EMC effect? Antishadowing?

  Probes: $F_{2A,LA}$ + DGLAP, HF production $\leftarrow$

- HF production in DIS

  LO photon-gluon fusion

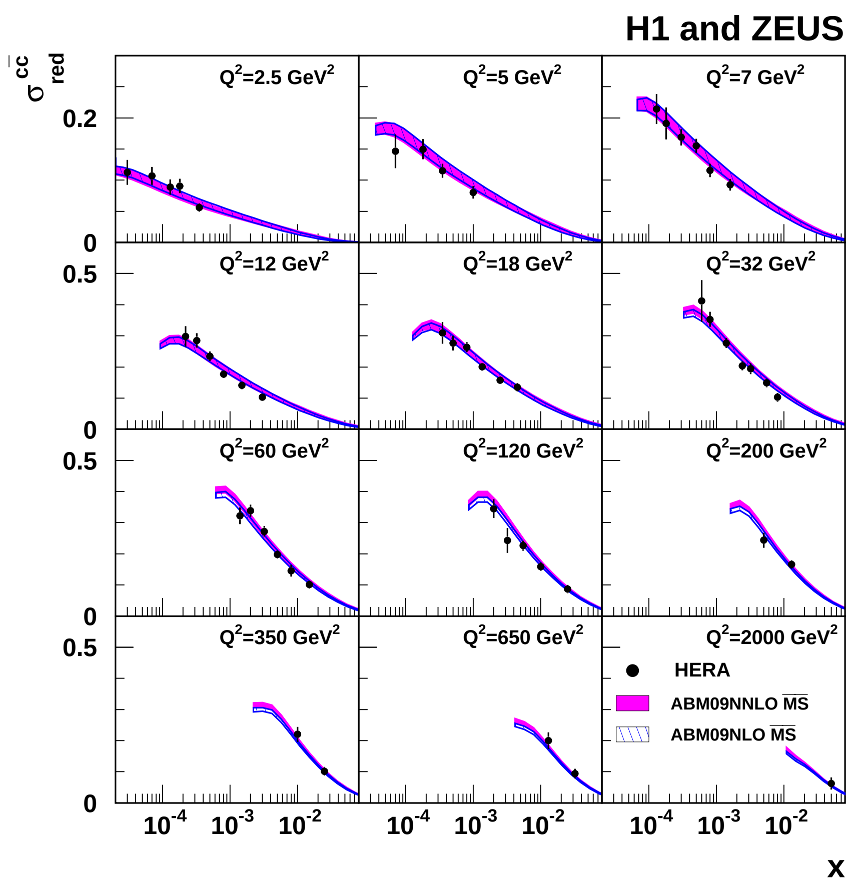
  Probes gluons at $x > ax_B, \quad a = (1 + 4m_h^2/Q^2)$

  NLO+ 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

Physics: 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

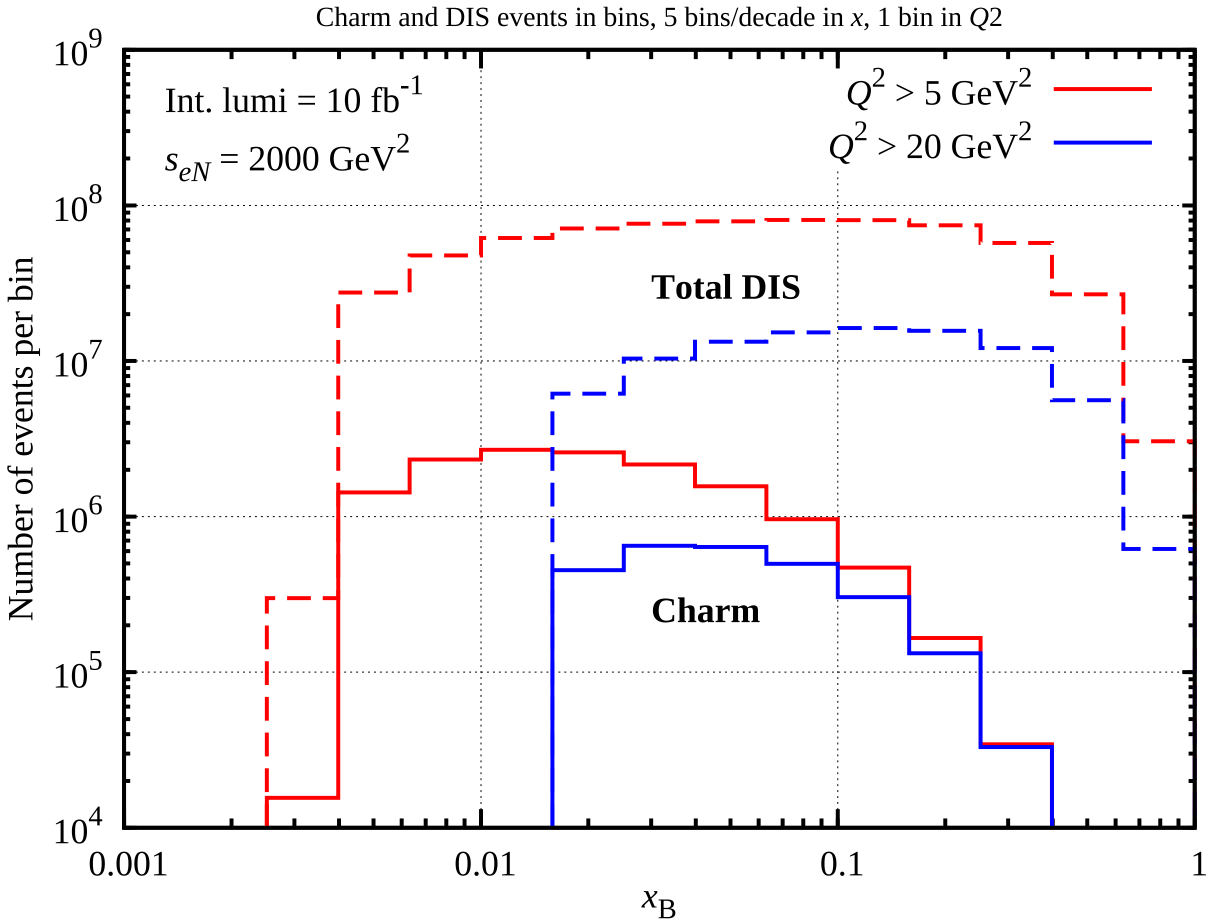
- Simulation tools

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

  Simple codes for QCD cross secns and rate estimates JLab LDRD

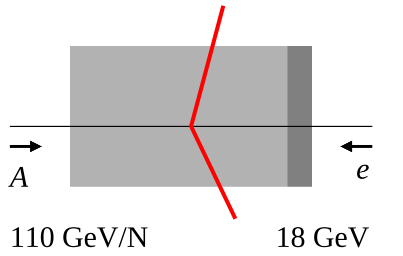
  PYTHIA, HERWIG MC for full DIS final state π, K, ...

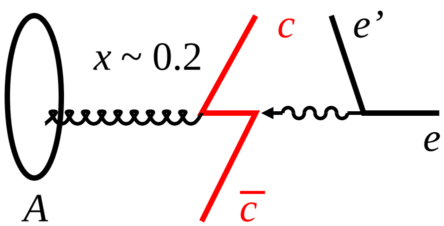
EIC: Charm production rates

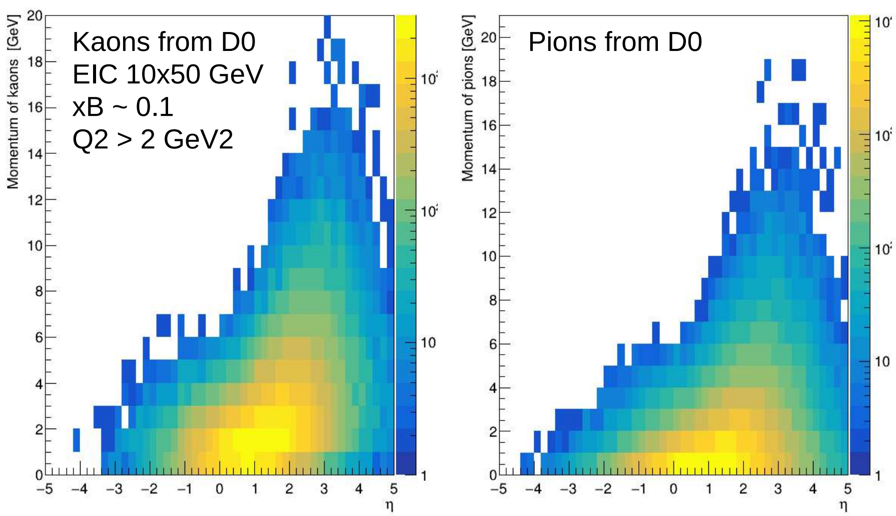


- Charm production rates drop rapidly at large x_B
- Charm production rates $\sim 10^5$ at $x_B \sim 0.1$ (int. lumi 10 fb^{-1})
  Defines charm reconstruction efficiency needed for physics at $O(10\%)$
- Charm/DIS ratio $\sim$ 2–3 % at $x_B \sim 0.1$
  Defines charm reconstruction environment

EIC: Charm angle/momentum distributions







[to be updated with 18 x 110 GeV]

- Large-x $c\bar{c}$ pairs produced at central rapidities if $x \sim E_e/E_N$

  CM frame of electron-gluon collision

  Example: $x = 0.2$ and 18×110 GeV

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

- PID and vertex detection 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

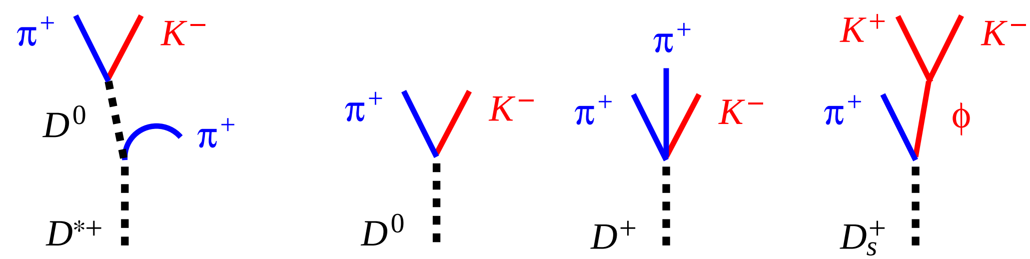
1) Theoretical estimates of reconstruction efficiency

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

[3) Tracking and vertexing based on EIC 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%	$(K^-\pi^+)_{D0}\ \pi^+_{\text{slow}}$	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 $D^{*+} \to \pi^+(\text{slow}) + (K^-\pi^+)_{D0}$

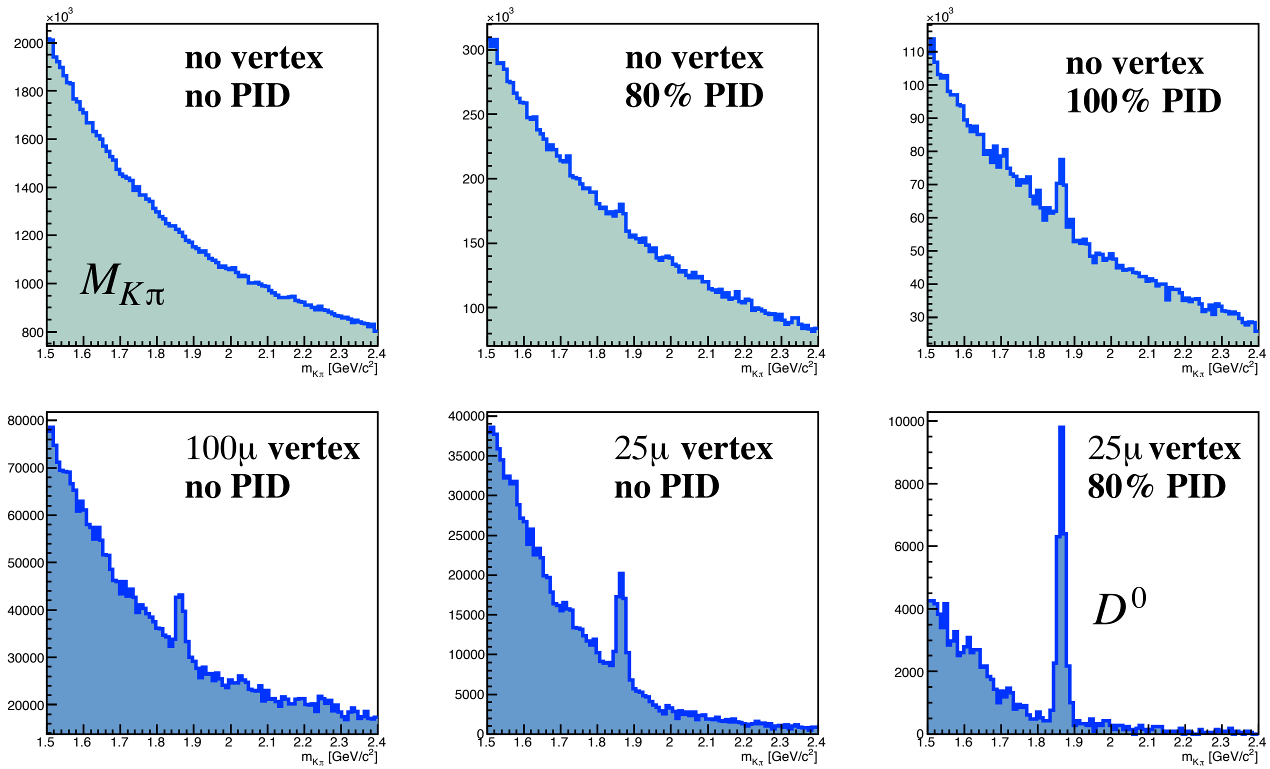
  Used at HERA without PID. Efficiency $< 1\%$

- 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: 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.

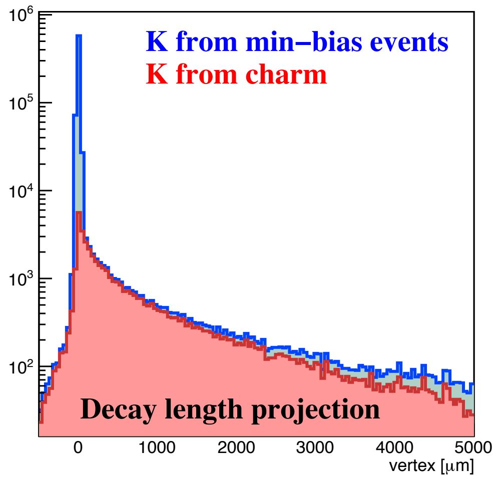
Yu. Furletova, S. Furletov

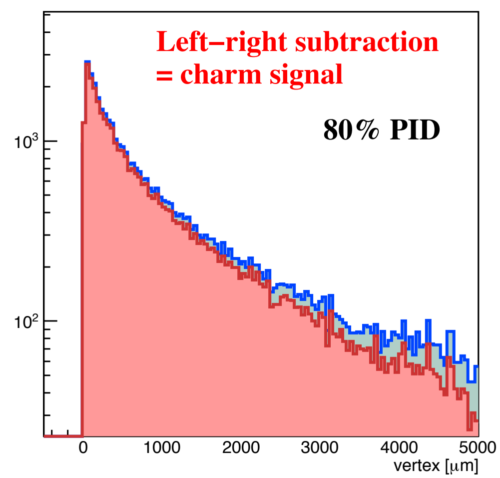
- Example: D^0 meson reconstruction using exclusive decay $D^0 \to K^-\pi^+$

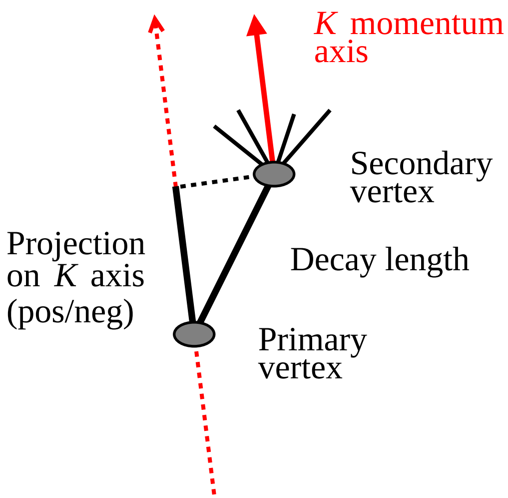
Level-2 simulation with mass/momentum and vertex smearing

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

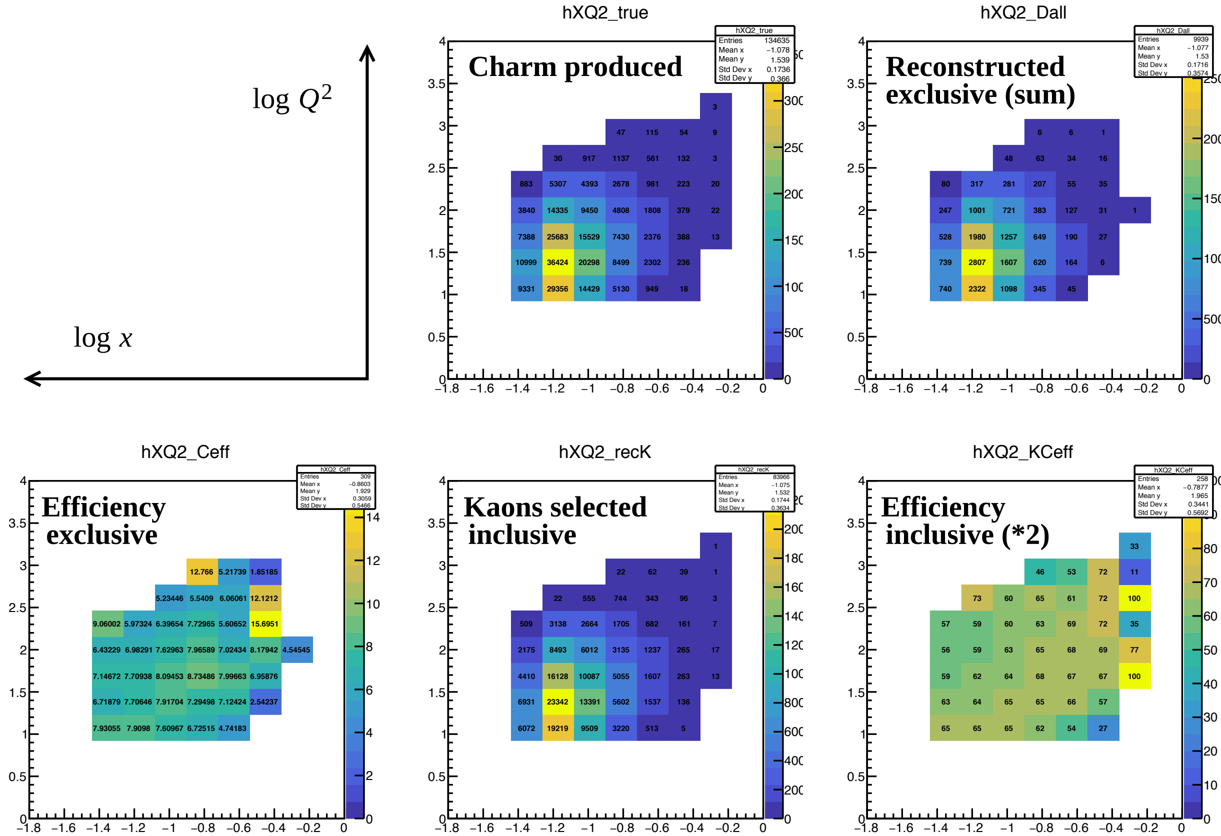
- Used at HERA with vertex detector

- Use for charm at EIC

  Identified K from PID

  Efficiency up to $\sim$ 30%

EIC: Charm reconstruction efficiency

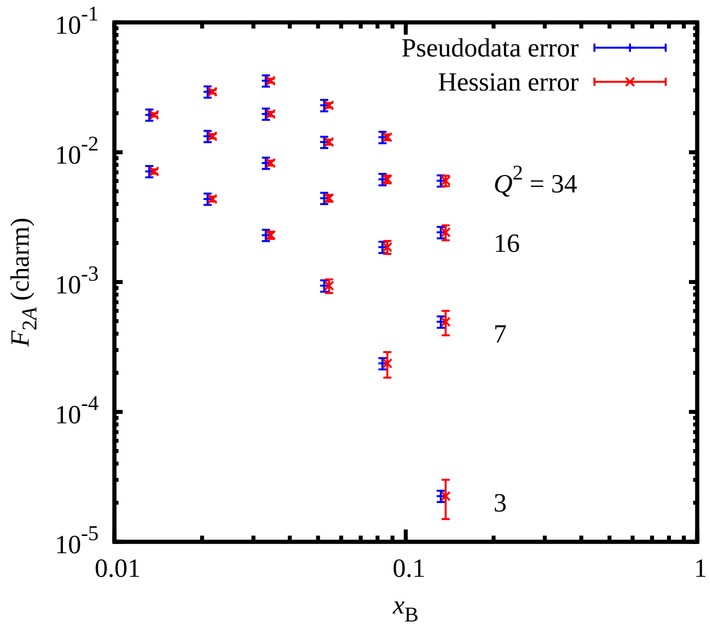


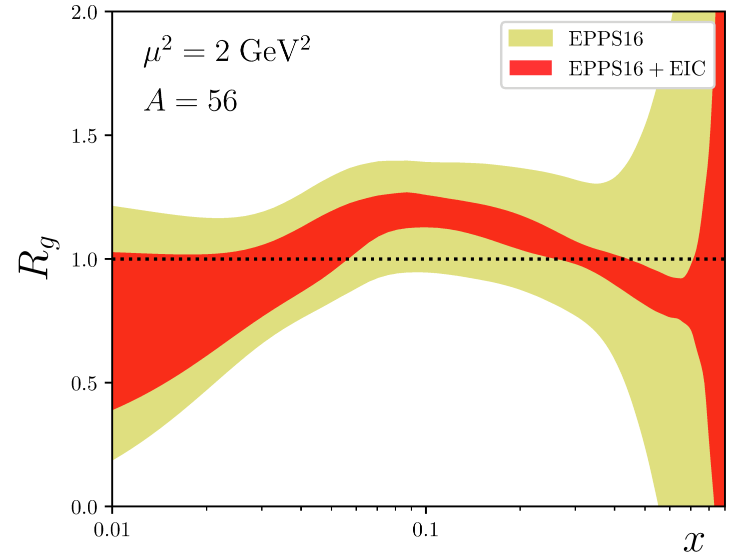
- Total efficiency estimated ∼5-7% exclusive, ∼30% inclusive

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

Impact: Charm and large-x gluons in nuclei





- PDF reweighting

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

  Impact on EPPS16 NLO PDF C. Andres Casas, N. Sato

- Charm data constrain gluon antishadowing and EMC effect
  See also: Aschenauer et al, PRD 96 114005 (2017)

- Theoretical uncertainties to be estimated

  Nuclear final-state interactions vs. initial-state modifications

Extensions and applications

- Use of differential charm cross sections for PDF analysis

- Charm reconstruction with high-p_T pairs – rare but distinct events, double tag

- Beauty production and reconstruction

- HF photoproduction using low-Q^2 electron tagger

Summary

- EIC enables HF production/reconstruction also at larger x_B ($\gtrsim 0.1$)

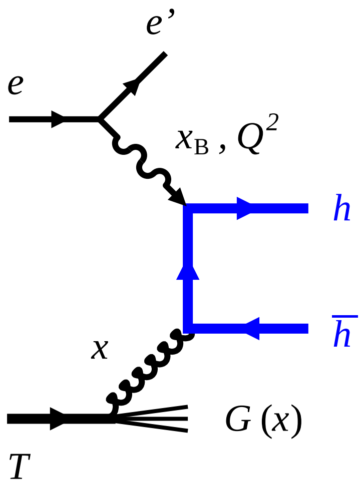
  Challenges: Low rates, large DIS background
  Capabilities: π/K PID, vertex detection
  Methods: Exclusive and/or inclusive reconstruction

- Impact on large-x nuclear gluons: EMC effect, antishadowing

- Simulation tools and results available for Yellow Report studies
  JLab 2016/17 LDRD Project `https://wiki.jlab.org/nuclear_gluons/`

Supplementary material

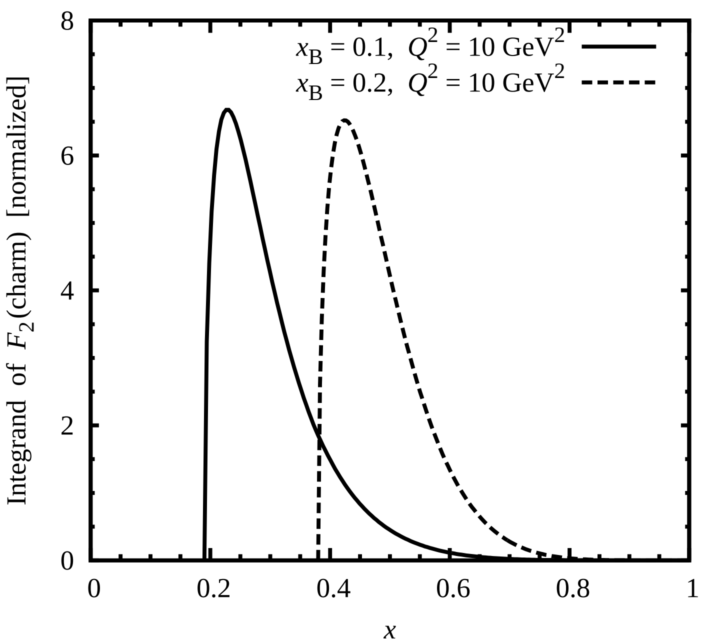
HF production: QCD description



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

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

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



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

  Inclusive heavy structure functions F_2^h, F_L^h

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

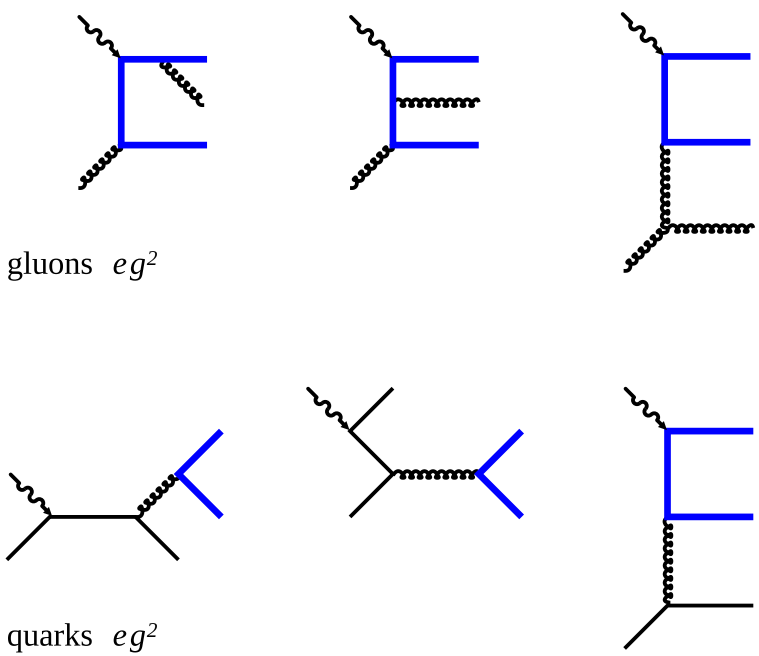
- Photon-gluon fusion at LO $\mathcal{O}(e_h g)$

  Couples to gluons only

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

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

Physics: HF production at higher orders



- Heavy quark production at NLO

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

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

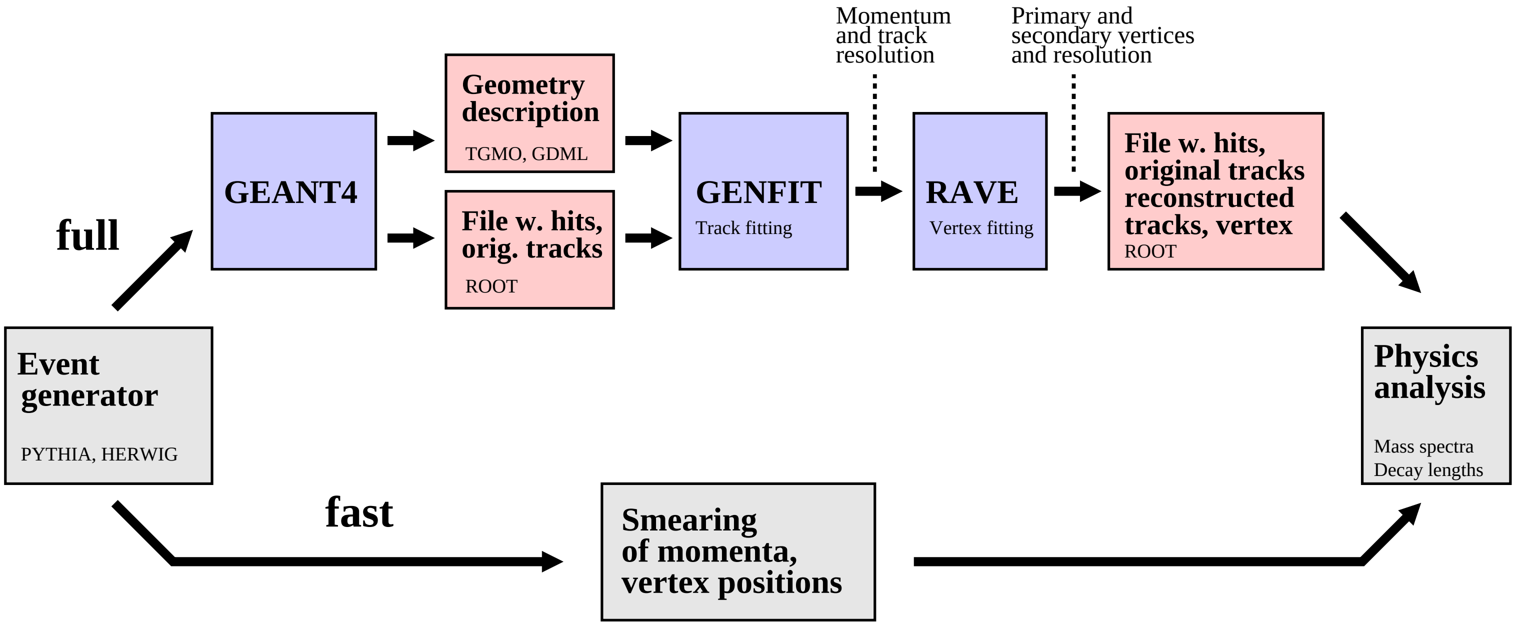
  Theoretical uncertainties quantified
  Laenen, Riemersma, Smith Van Neerven, Harris 93+.
  Alekhin, Moch, Blümlein, Vogt, Kawamura et al. 11+

- 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: Tracking and vertexing simulations



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

  Model of vertex detector and outer tracker/endcap geometry

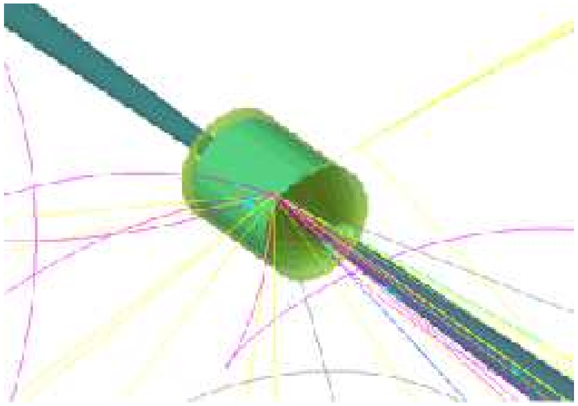
  Based on GEANT4/Root, uses available tools GENFIT, RAVE

- Can be used in two ways

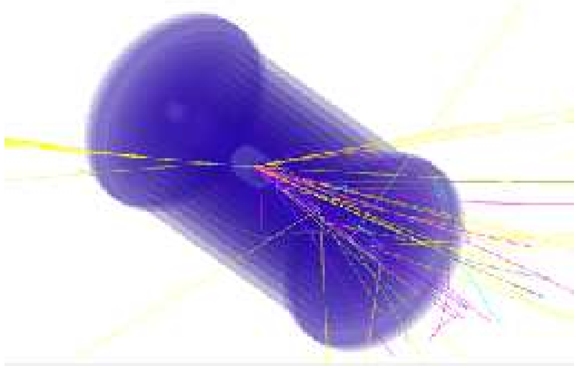
  Verify smearing parameters of Level-2 simulations

  Full event reconstruction

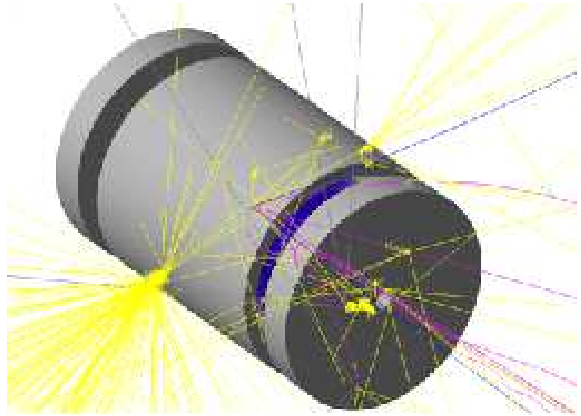
EIC: Tracking and vertexing simulations



Vertex detector



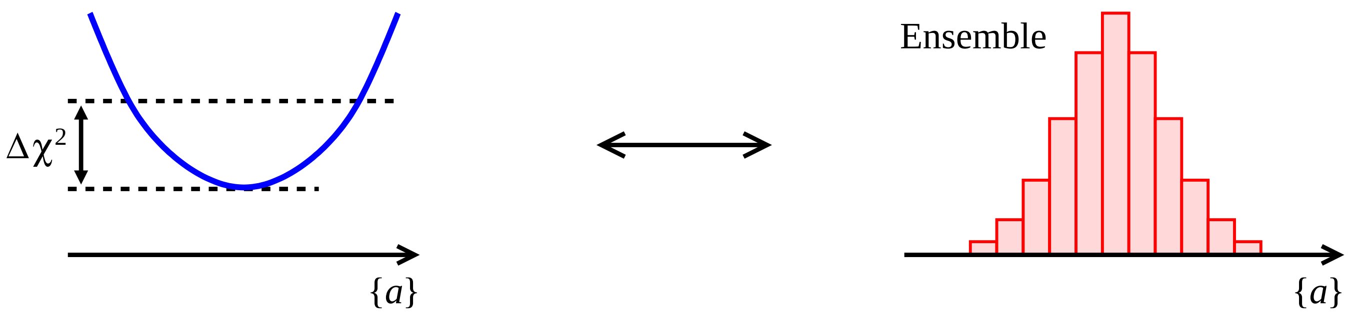
Outer tracker and endcap



Iron calorimeter

- Schematic detector model, describes geometry + magnetic field, implemented in GEANT4 [Here: JLEIC detector]
- Can be adapted and optimized for HF simulations
- Open for collaboration
  JLab 2016/17 LDRD Project https://wiki.jlab.org/nuclear_gluons/

Impact: 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`