Probing nuclear gluons with heavy flavors at an Electron-Ion Collider

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Overview

AIM: Study feasibility of direct measurements of nuclear gluons at x >~ 0.1 using heavy quark probes with a future Electron-Ion Collider

- Nuclear modification of gluons (large-x)
- Open charm/beauty as direct probe
- Charm reconstruction at EIC
  - Charm production rate at large-x
  - Charm reconstruction
  - PID and Vertex detectors at EIC
- Impact on nuclear gluons

LDRD- 1601/1701 project
("Nuclear gluons with charm at EIC")
https://wiki.jlab.org/nuclear_gluons/
[arXiv:1610.08536], [arXiv:1608.08686]

Nuclear partons: Physics interest

- DIS processes on nuclei $A > 1$ probe nuclear PDFs

Quark/gluon densities of entire nucleus
Nuclear matrix elements of QCD quark/gluon operators, DGLAP evolution

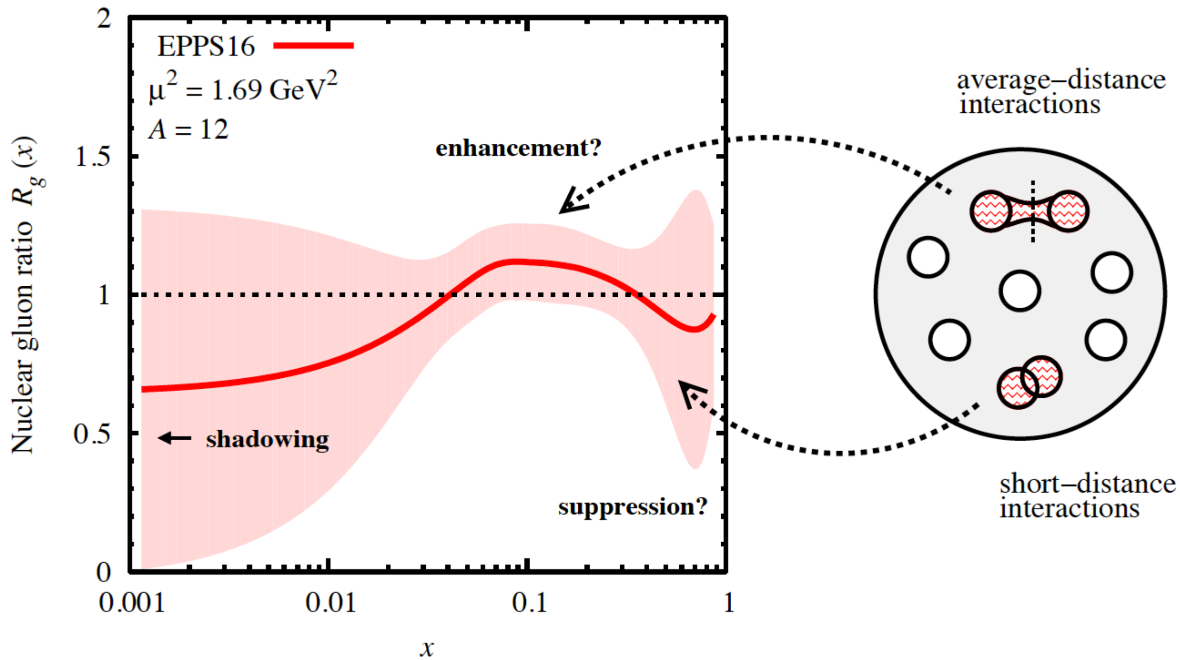
- Fundamental physics interest

➢ Compare quark/gluon densities of nucleus with those of a system of free nucleons: $A \neq \sum N$, "nuclear modifications"

➢ Learn about QCD substructure of nucleon interactions — how they emerge from the microscopic theory?

➢ "Next step" after exploring single nucleon structure!

Nuclear partons: Nucleon interactions



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 Gribov 70s Suppression effect calculable Frankfurt, Strikman Guzey 12+ Observed in J/ψ photoproduction on nuclei ALICE, CMS Suggests large antishadowing

Nuclear partons: Probing gluons

- Determine nuclear gluon density at large x (> 0.05)!
- Nuclear gluon probes:

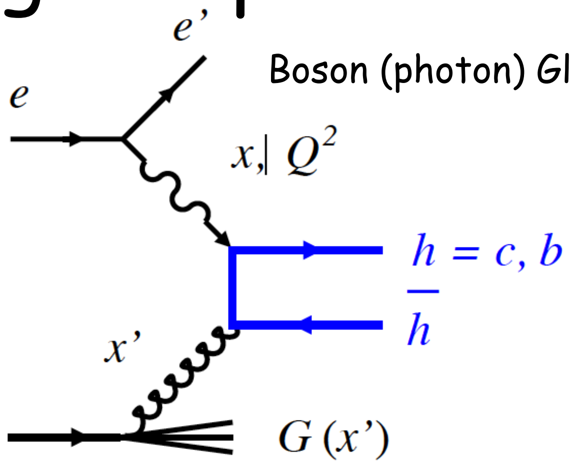
eA/μA/νA	Q^2 dependence of F_{2A}, F_{LA} + DGLAP
eA/γA	Heavy quark production – direct probe!
pA/eA/γA	Jets?

- EIC capabilities

Nuclear beams A = 2–208
CM energy $\sqrt{s}$ (eN) ~ 20–70 GeV
Luminosity L ~ 10^{34} cm^{-2} s^{-1}
Next generation of detectors with PID and vertex

first eA collider
coverage at large x_B
rare processes
final states

Open charm/beauty production as a direct gluon probe



Boson (photon) Gluon Fusion (BGF)

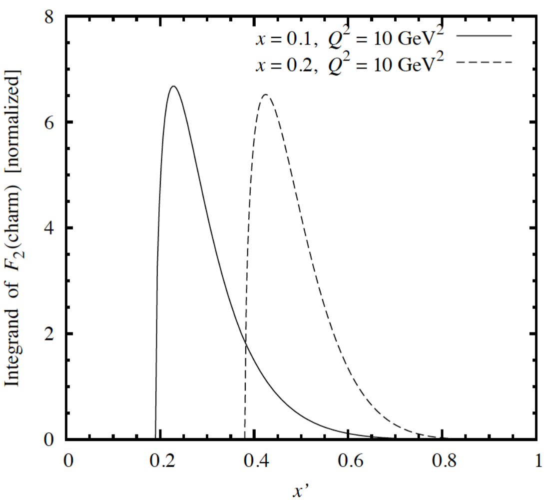
$$F_2^h(x,Q^2) = \int_{ax}^{1} \frac{dx'}{x'}\, x'G(x')\, \hat{F}_g^h(x/x',\, Q^2,\, m_h^2,\, \mu^2)$$

coefficient function

$$a = 1 + \frac{4m_h^2}{Q^2}$$

sets limit of x' integral

A

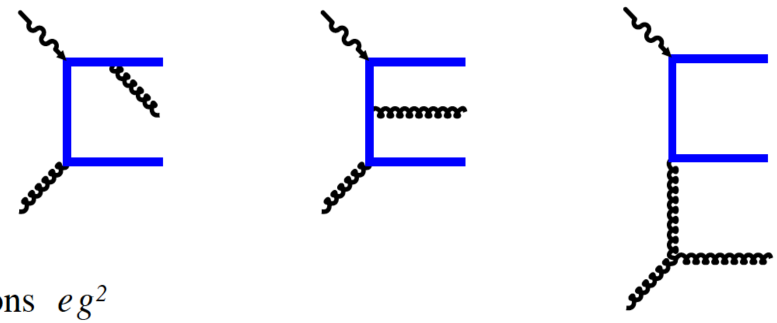


- Heavy quark production probes large-x' gluons "almost locally" at $x'_{glue} \geq x_{BJ}\,(1+4m_h^2/Q^2)$

- NLO corrections calculated, theory uncertainties quantified

Laenen, Riemersma, Smith, Van Neerven 93+, Kawamura et al. 12, Alekhin, Moch et al. 93+

Heavy quark production: Higher orders

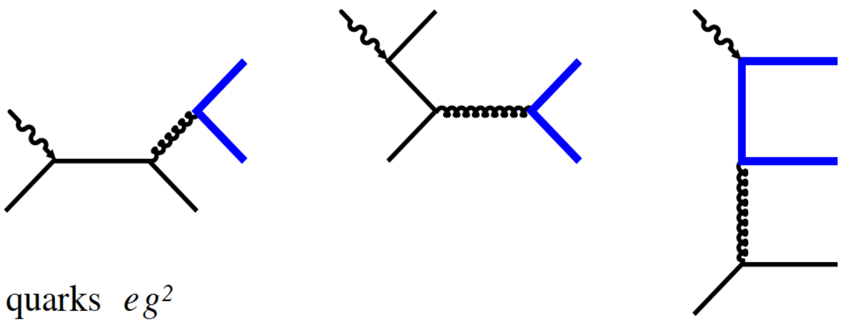


gluons $e g^2$

Heavy quark production at NLO

- Sensitivity to light quarks at O(ehg2)
- LO photon-gluon fusion large at x > 0.1
- Theoretical uncertainties quantified

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

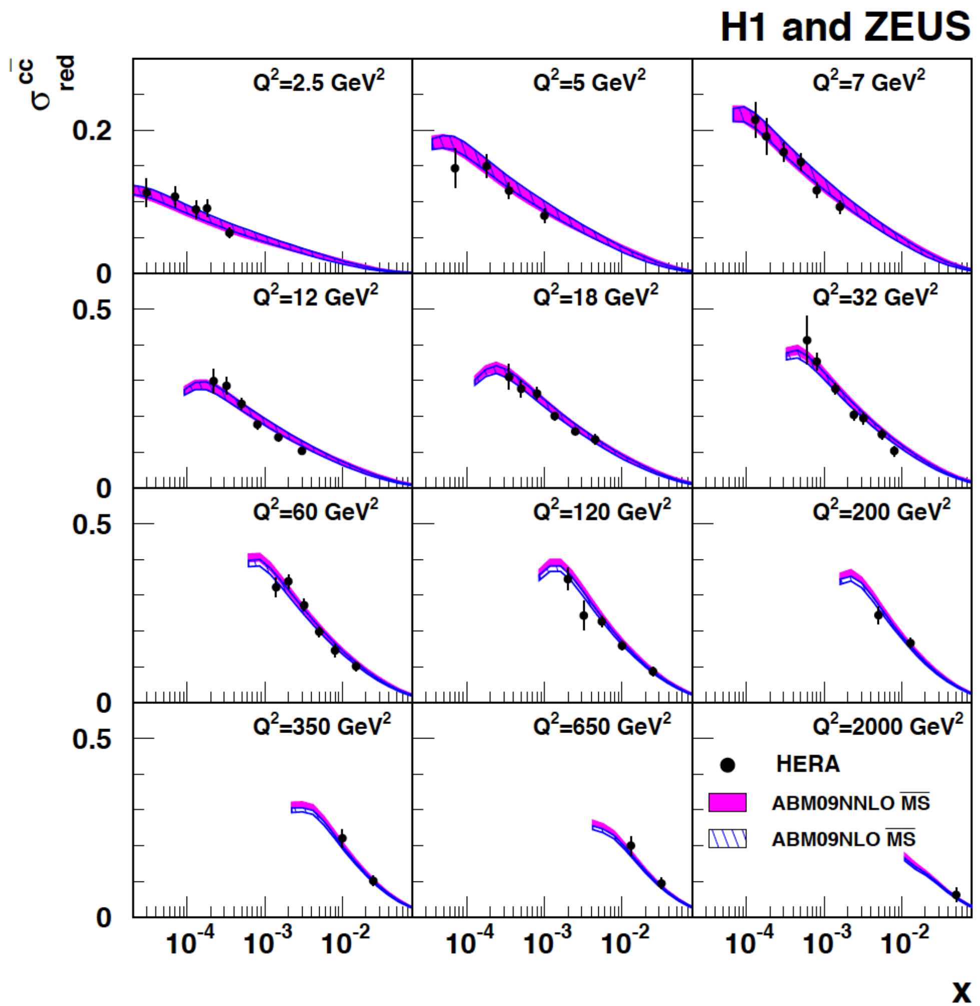


quarks $e g^2$

Perturbative stability LO → NLO

- Good stability of F^c_2 with choice of effective LO scale Gluck, Reya, Stratmann 94
- Rapidity, pT distributions more sensitive

Heavy quarks at HERA



$c\bar{c}$, $b\bar{b}$ production in ep/γp

- 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 sec.

+ MC integration Harris, Smith 98

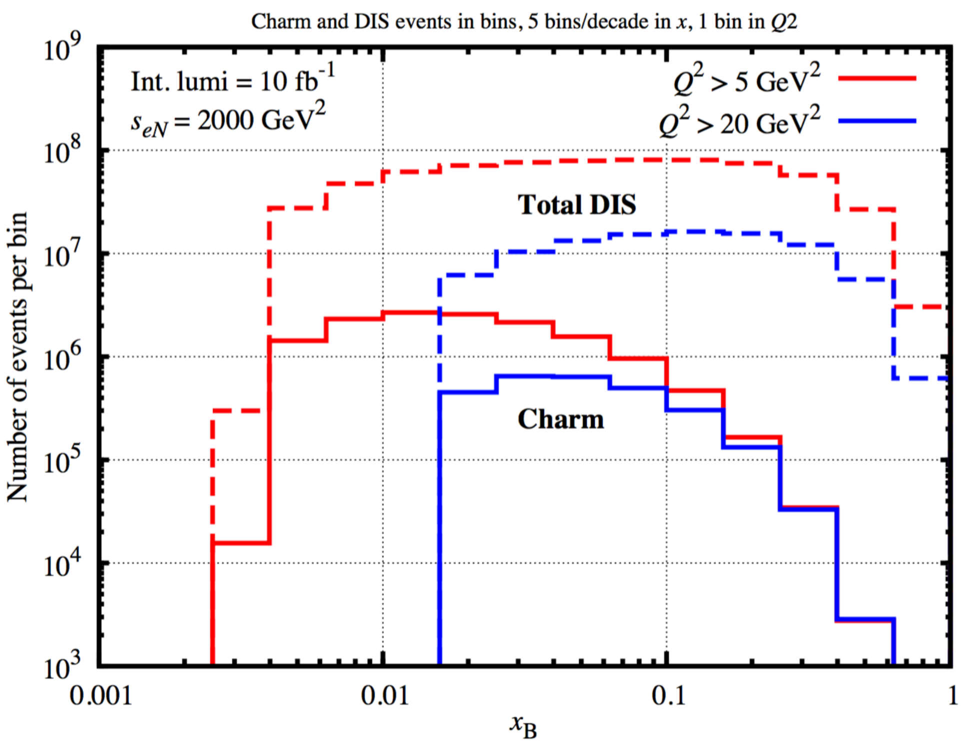
H1 + ZEUS summary. H. Abramowicz *et al.* EPJC 73 (2013) 2311

Charm production rate at large x at EIC

Differential cross sections using LO QCD formulas

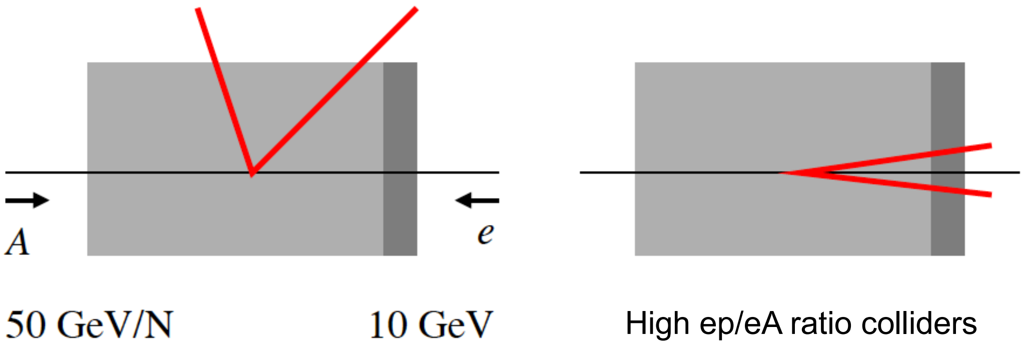
$$d\sigma(e + N \to e' + X) = \text{Flux}(x, y, Q^2)\, F_2(x, Q^2)\, dx\, dQ^2 \quad (1)$$

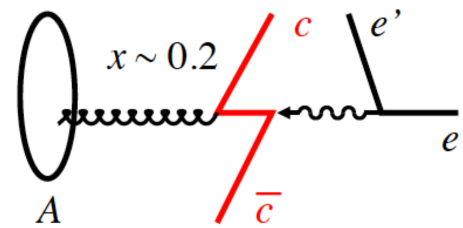
$$d\sigma(e + N \to e' + c\bar{c} + X') = \text{Flux}(x, y, Q^2)\, F_2^{c\bar{c}}(x, Q^2)\, dx\, dQ^2 \quad (2)$$



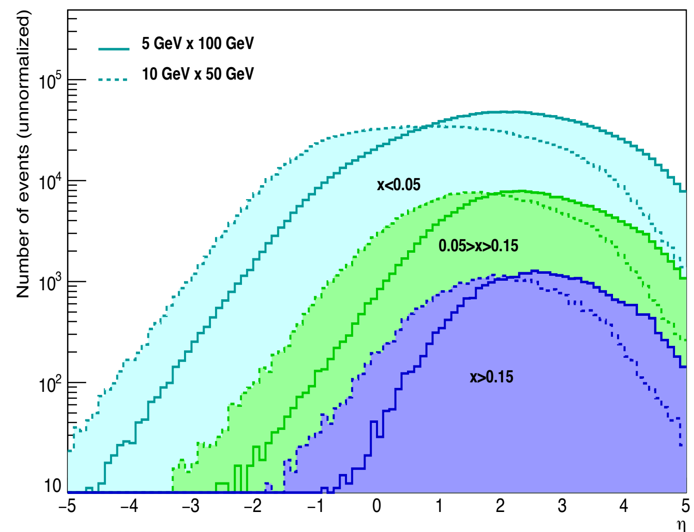
- Charm production rates drop rapidly at large x
- Charm production rates 10^5 at x~0.1 (int. lumi 10 fb^{-1})
  Defines charm reconstruction efficiency needed for physics
- Charm/DIS ratio 2-3 % at x ~0.1
  Defines charm reconstruction environment

Charm momentum and angle distributions





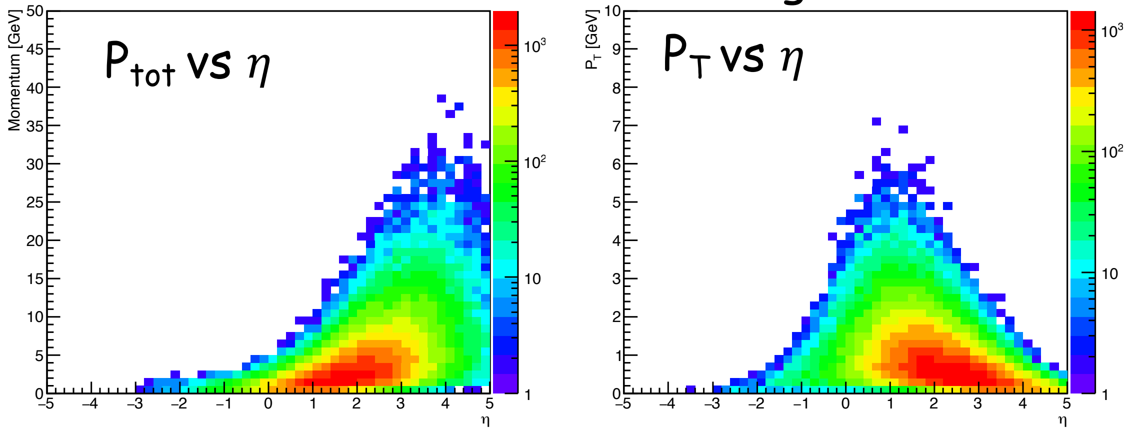
- Large-x $c\bar{c}$ pairs produced almost at rest in low-ratio collider
  - Example: Gluon with x = 0.2 and 10~50 GeV/N
  - Contrast with high-ratio collider!
- π/K produced at large angles, with typical momenta ~ 5 GeV
  - Favorable situation!
- Good PID and momentum resolution available in central detector
  - Enables "new" methods of charm reconstruction



EIC: charm event reconstruction

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

Kaons from charm at large-x



Questions

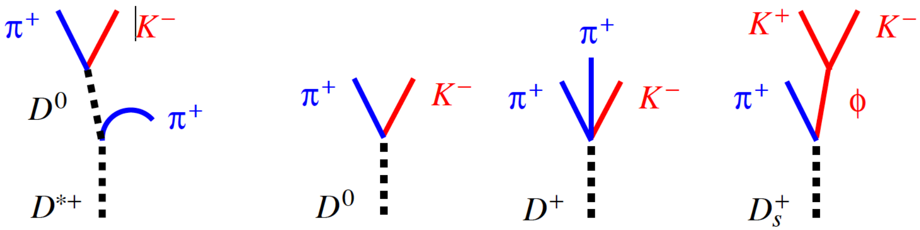
- ➢ How well do the methods work at large x?
- ➢ What are the overall efficiencies and uncertainties?
- ➢ What detector performance is required?

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

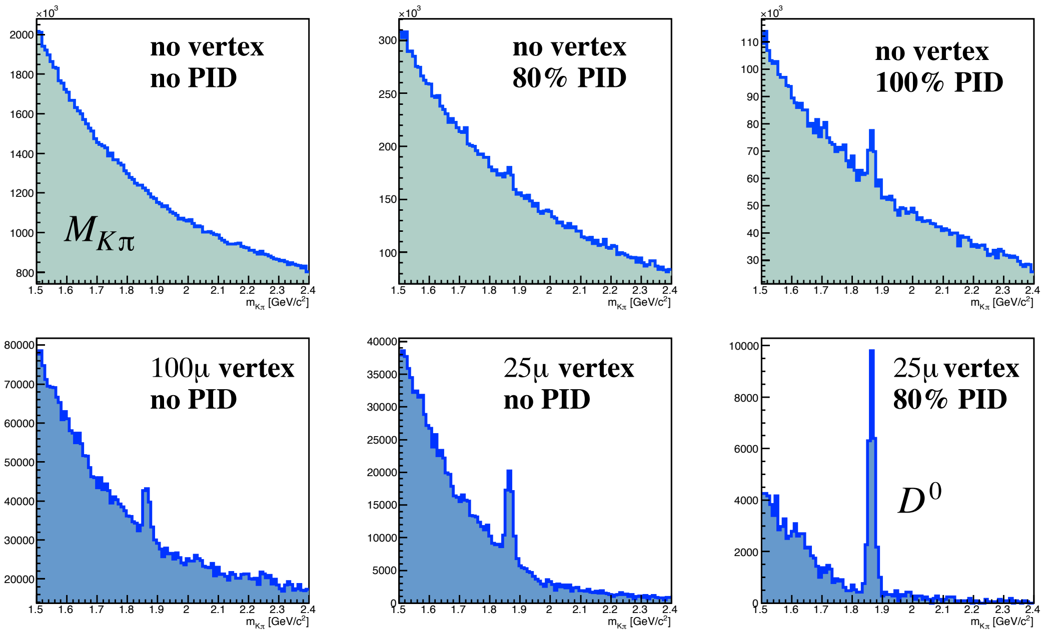
EIC: Charm reconstruction with exclusive D's

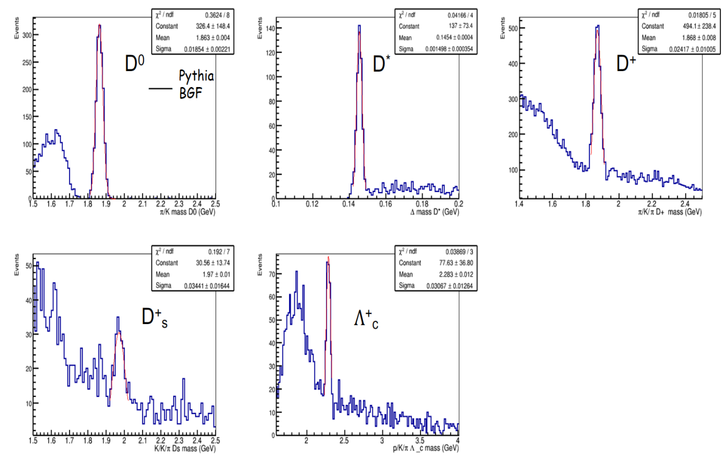
h_c	f	Decay	BR
D^0	59%	$K^-\pi^+$	3.9%
		$K^-\pi^+\pi^+\pi^-$	8.1%
D^+	23%	$K^-\pi^+\pi^+$	9.2%
D^{*+}	23%	$(K^-\pi^+)_{D0}\ \pi^+_{\rm slow}$	2.6%
		$(K^-\pi^+\pi^+\pi^-)_{D0}\ \pi^+_{\rm slow}$	5.5%
D_s^+	9%	$(K^+K^-)_\phi\ \pi^+$	2.3%
Λ_c^+	8%	$pK^-\pi^+$	5.0%



- Simple exclusive channel $D^{*+} \rightarrow \pi^+_{slow} + (K^-\pi^+)_{D0}$
- For reconstruction need to provide good vertex and PID
- At HERA1: no PID, no vertex , HERA2: no PID + vertex
  => Efficiency < 1%
- At EIC: PID + vertex detection
  => allow use of other exclusive channels D^0,D^+,D^+_s
- Theoretical efficiency ~ 10% summed over channels
  Fragmentation ratio f ~ Branching ratio BR

EIC: Charm reconstruction with exclusive D's

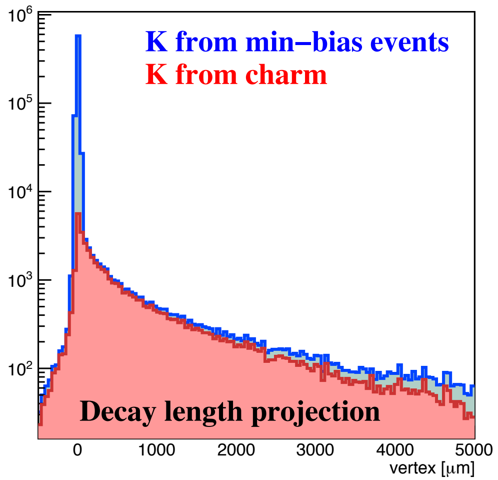


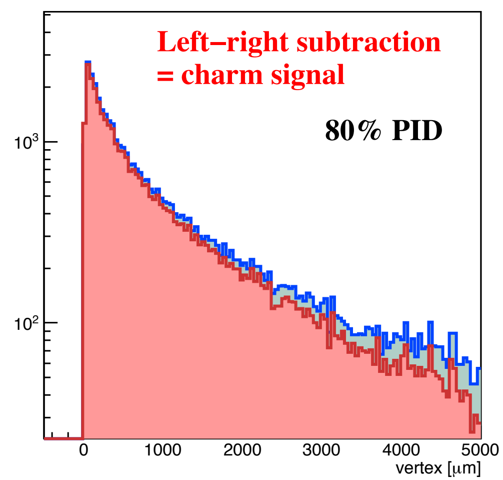


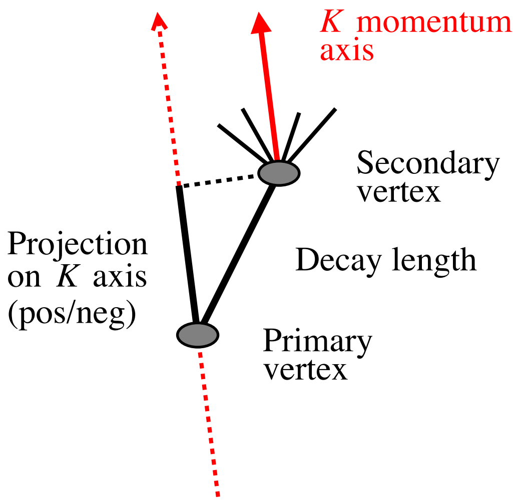
Example: D0 meson reconstruction using exclusive decay $D^0 \rightarrow K^-\pi^+$
ep (10 GeV x100 GeV) , $Q^2 > 10$ GeV^2 and $x_B > 0.05$, vertex > 100 μm

simulation with mass/momentum and vertex smearing
Impact of PID and vertex detection

EIC: Charm reconstruction with inclusive modes





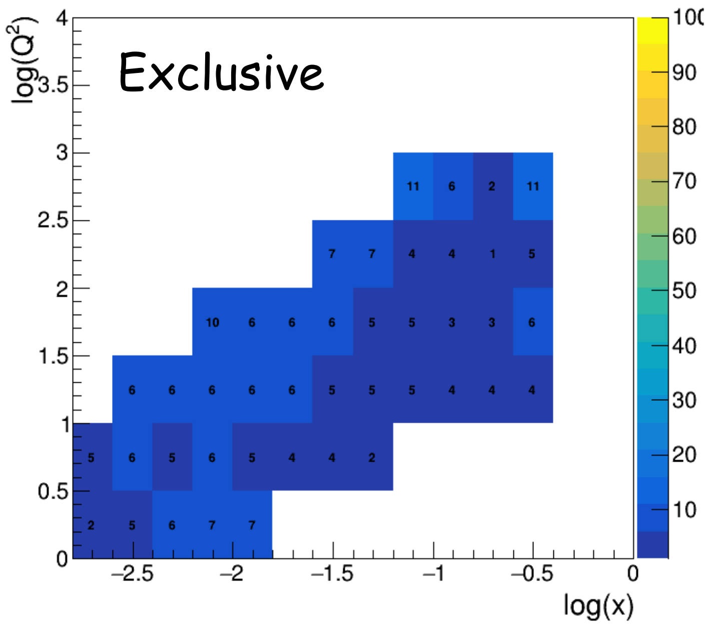


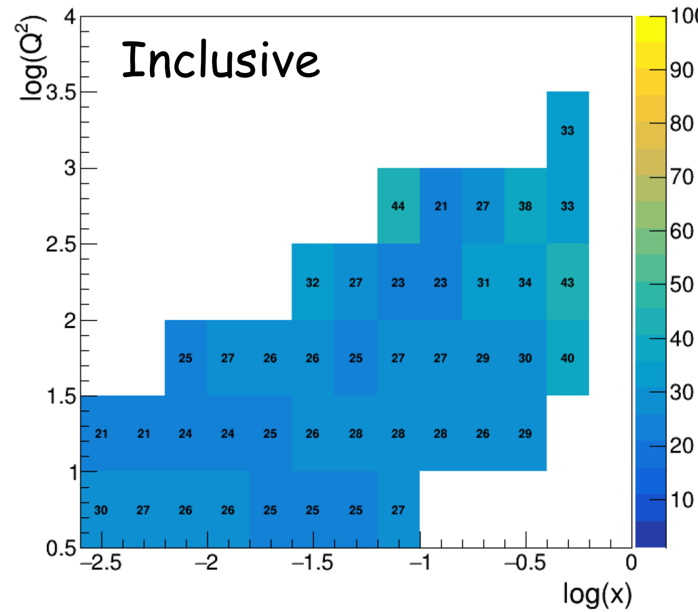
Decay length significance distribution:
- Establish secondary vertex
- Project decay length on jet axis, positive/negative

Identify D-meson decays through positive projection
- Used at HERA-I with vertex detector
- Use for charm at EIC

Identified K from PID.

EIC: Charm reconstruction efficiency



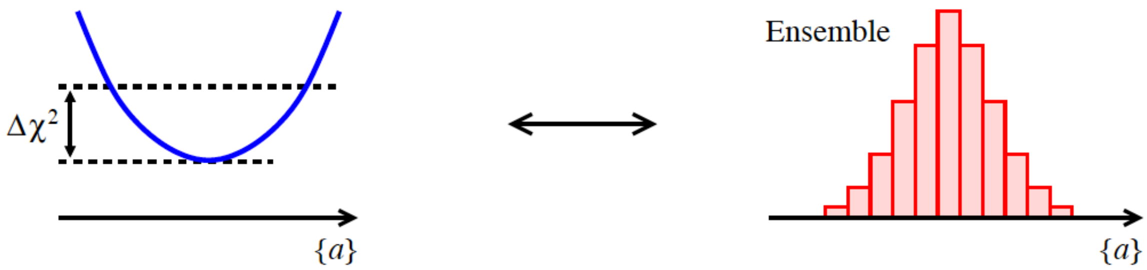


Total efficiency estimated:
~5-6% exclusive, ~25-30% inclusive

- 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

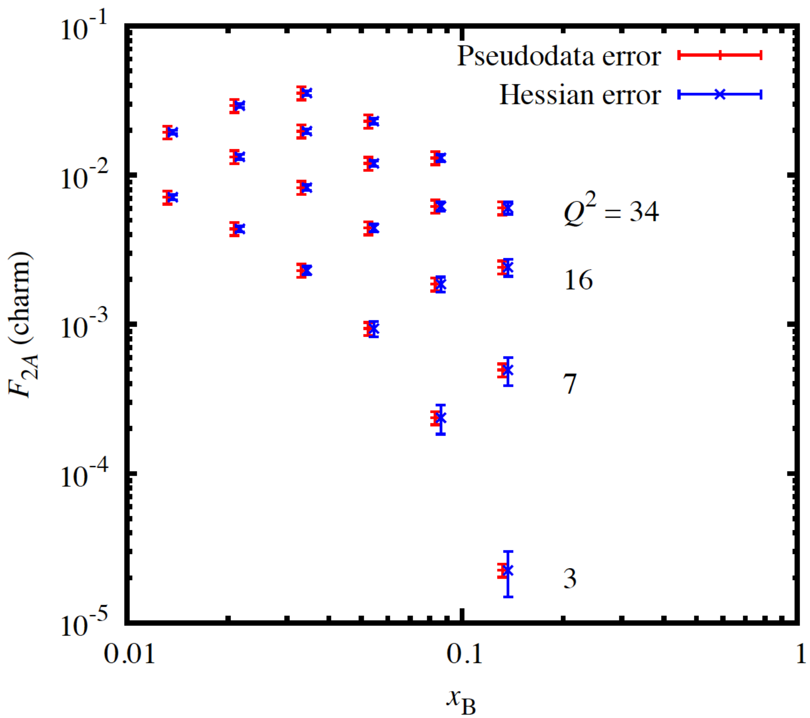
Giele, Keller 98; NNPDF Collab Ball et al 11; Paukkunen, Zurita 14; Sato et al 16

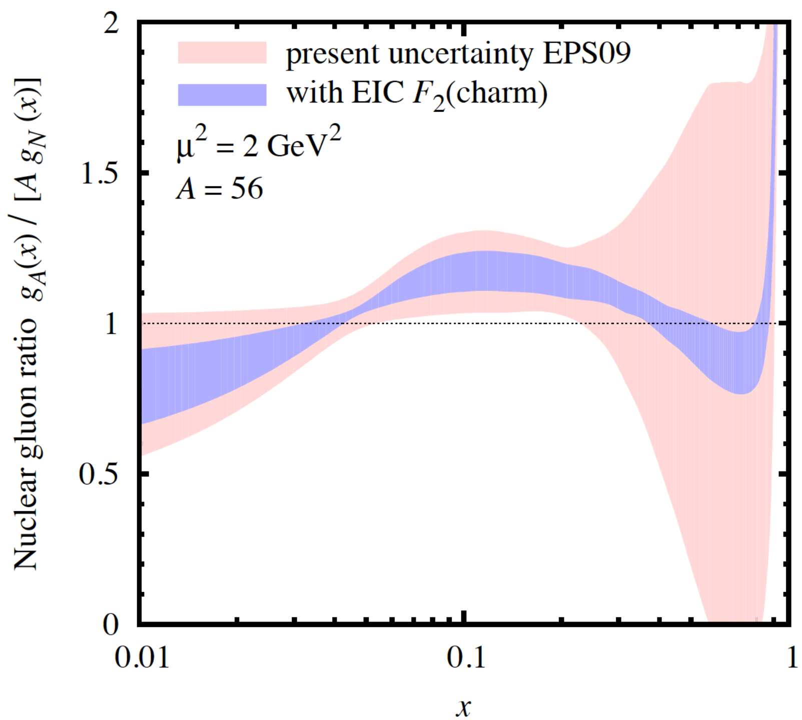
- Represents existing fit as statistical ensemble, uses Bayes' theorem
- Avoids costly re-fitting
- Widely used in PDF analysis, HEP

Implemented for charm pseudodata from EIC

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

Charm impact: Large-x gluons





- Charm pdeudodata
  Fc2 (x,Q2), 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

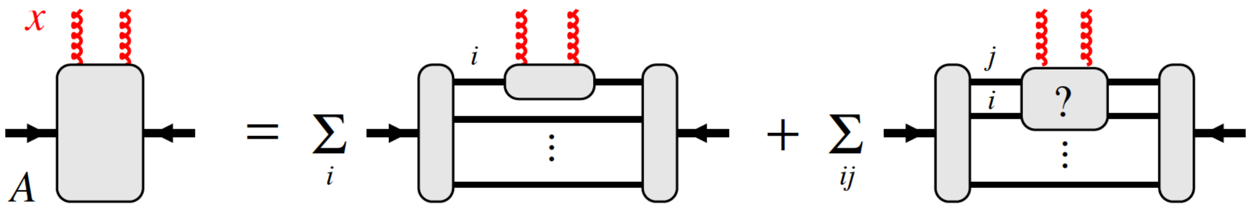
Summary

- Open charm production at EIC can constrain nuclear gluons at large–x
  Natural measurement for medium-energy collider
- Nuclear PDFs opens window on nucleon interactions in QCD
- High Luminosity (~$10^{34}cm^{-2} s^{-1}$) is essential for charm production at x>0.1
- Challenge to identify charm/beauty with overall high efficiency and in kinematic region with ~100 times larger DIS background
- PID and high-resolution vertex detector significantly improve charm reconstruction efficiency and overall charm to background ratio and should be integrated into EIC detector design

Open for collaboration!

Backup

Nuclear partons: Nucleon interactions



Hard process, QCD factorization

Nuclear matrix element <A| Twist-2 |A>

- 1-nucleon contribution < N| Twist-2 |N> — nucleon PDF, Fermi motion
- 2-nucleon contribution <NN| Twist-2 |NN> — nucleon interactions!
- Well-defined operator, scale dependence μ2, 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!