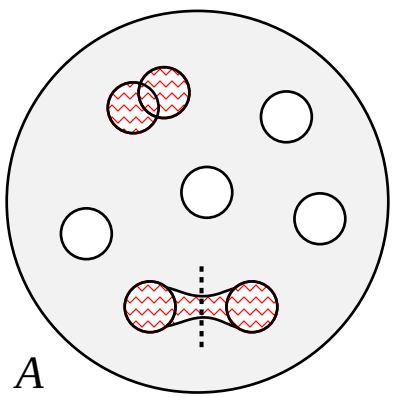
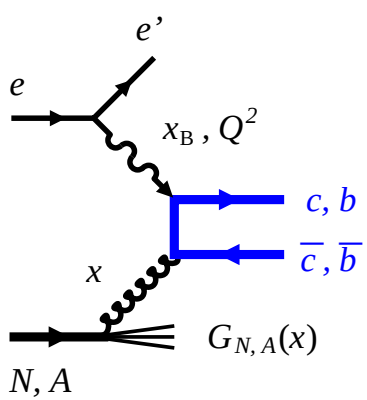
Nuclear PDFs at EIC: A window on nucleon interactions in QCD

C. Weiss (JLab), QCD Evolution 2017, JLab, 26-May-17

includes results of LDRD Projects LD1701/1601 and LD1506/1403

Jefferson Lab





- NPDFs and nucleon interactions

  Non-nucleonic DoF and high-energy probes

  Interaction mechanisms at different x:
  EMC effect, antishadowing, shadowing

- Nuclear gluons with charm at EIC

  Open charm production and reconstruction

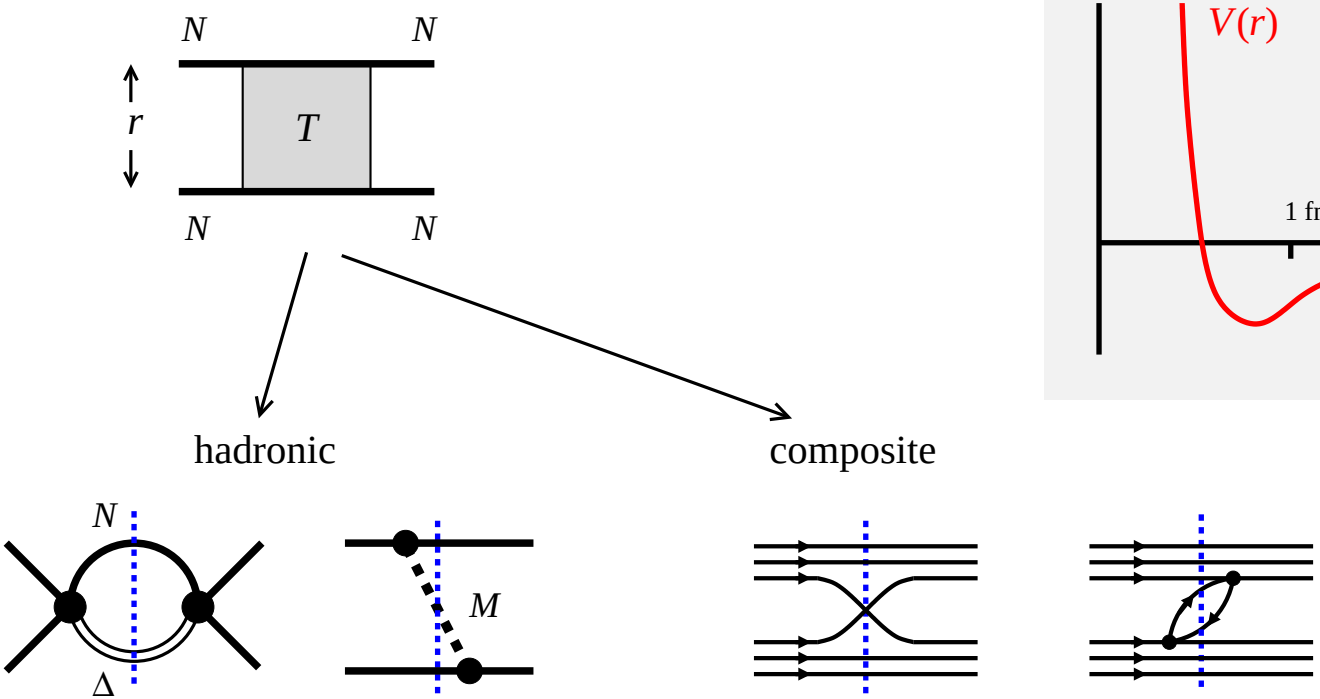
  Impact on large–x NPDFs

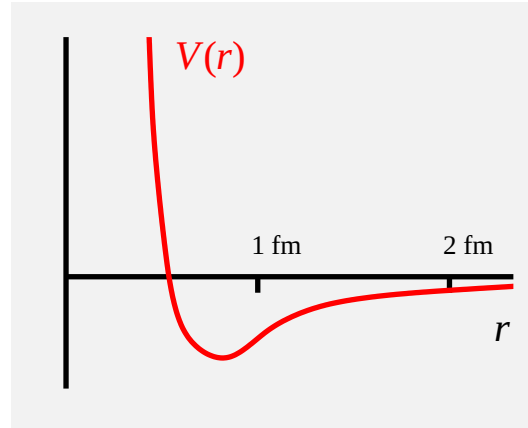
- Novel probes of NPDFs at EIC

  Quark charge/flavor separation with $\pi^{\pm}$

  Deuteron and spectator tagging:
  DIS in controlled nuclear configurations

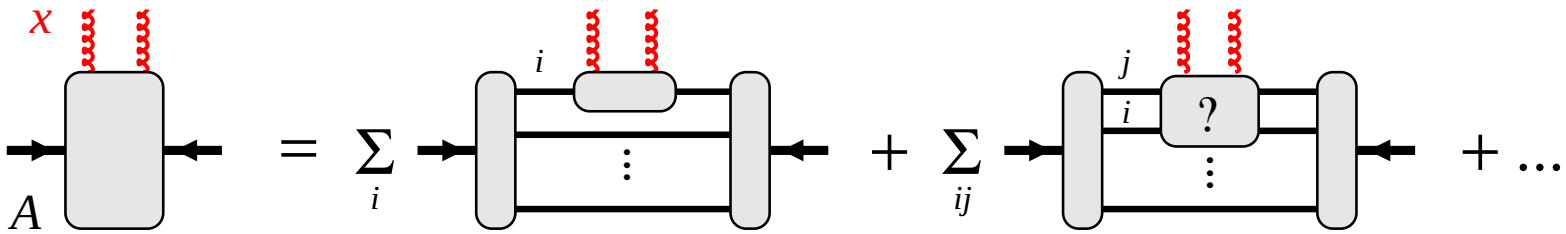
Nucleon interactions: Non-nucleonic DoF





- Interactions involve non-nucleonic degrees of freedom
- Low-energy nuclear structure and reactions ($k \sim k_{\mathrm{F}}$) do not resolve intermediate states: NN potential, EFT contact interactions
- High-energy processes can resolve intermediate states!
  Type of states "seen" depends on probe. . .

Nucleon interactions: Nuclear PDFs



- DIS: QCD factorization, measures $\langle A|\ \mathrm{Twist\text{-}2}\ |A\rangle$

  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 operators: Scale dependence μ^2, matching with LQCD, EFT

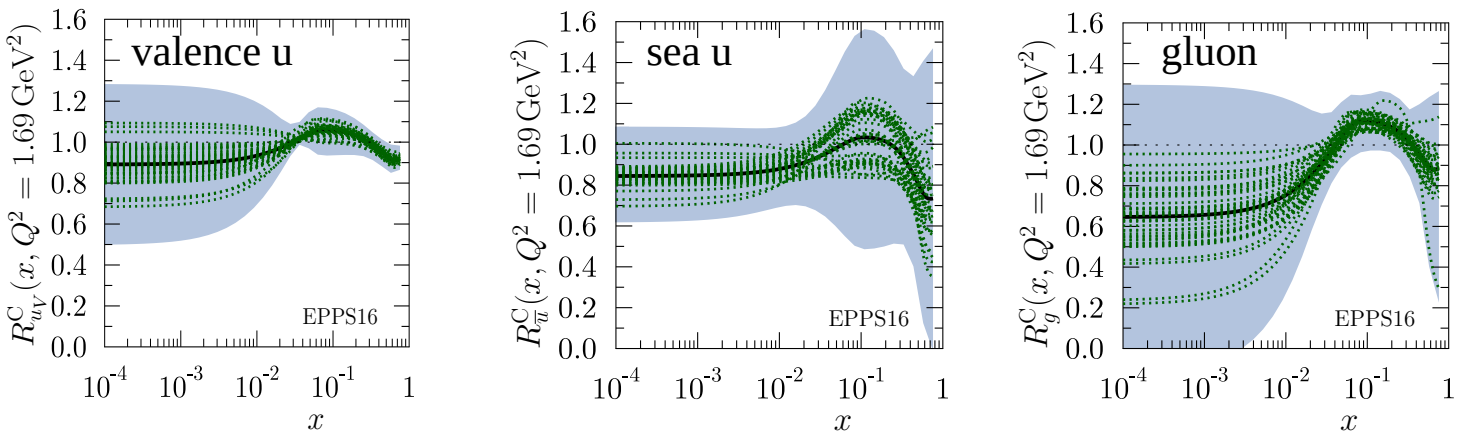
- Basic questions

  How are quarks/gluons with different x modified by interactions?

  What are the relevant distances in the NN interactions?

  What are the relevant configurations/intermediate states?

Nucleon interactions: Nuclear PDFs



- EMC effect $0.3 < x < 0.8$

  Suppression of valence quark density in nucleus

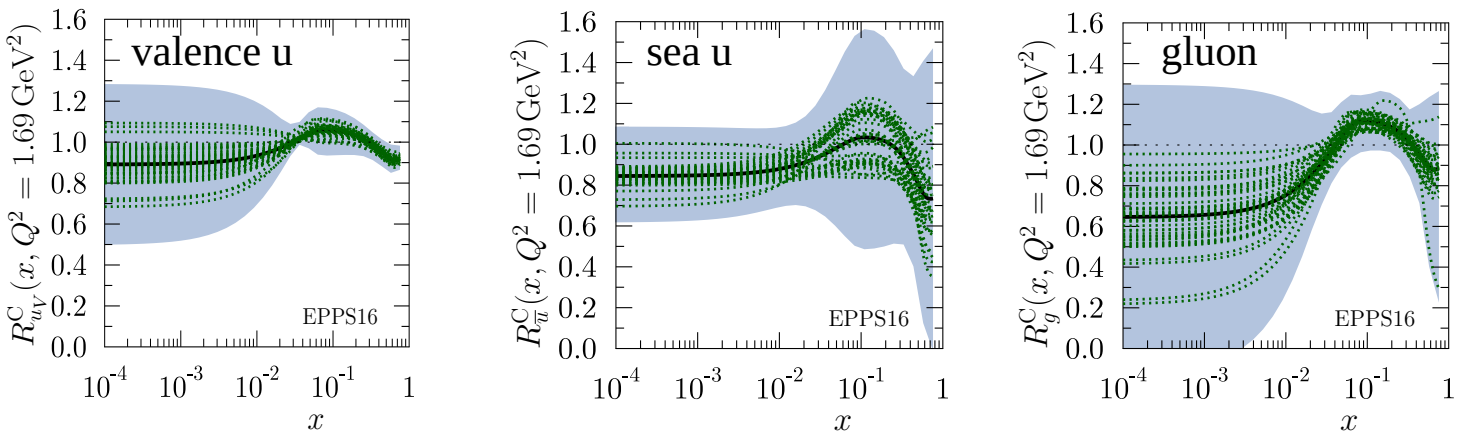
  Likely due to short-range NN interactions $r < 1$ fm

  Dynamical models and critique
  EFT/LQCD methods: Chen, Detmold, Lynn, Schwenk 16

  Further measurements with JLab12, including polarized

  Are gluons also suppressed?
  Large non-pert gluon density at $x > 0.2$

Nucleon interactions: Nuclear PDFs



- Antishadowing $x \sim$ 0.05–0.2

  Enhancement of valence quark density in nucleus

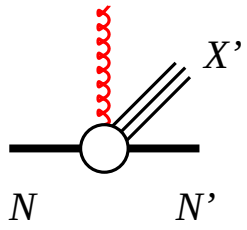
  Caused by NN interactions at average distances

  Valence vs. sea quarks, flavor separation?

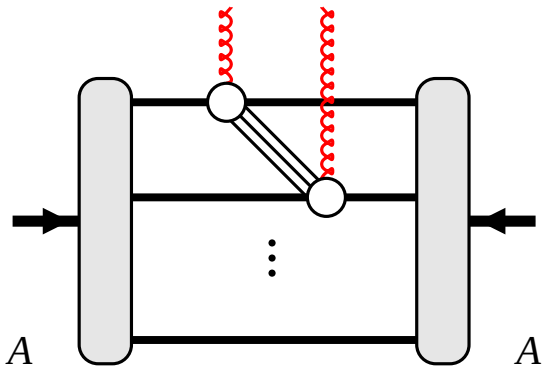
  Gluon antishadowing?

  Gluon shadowing at $x \ll 0.1$ requires compensating antishadowing for momentum sum rule
  Dynamical model: Frankfurt, Guzey, Strikman 17

Nucleon interactions: Nuclear PDFs



IA +



- Shadowing at $x \ll 0.1$

  Diffraction enables interference of gluon attachments to different nucleons
  QCD analogue of Gribov's theory of shadowing 70s

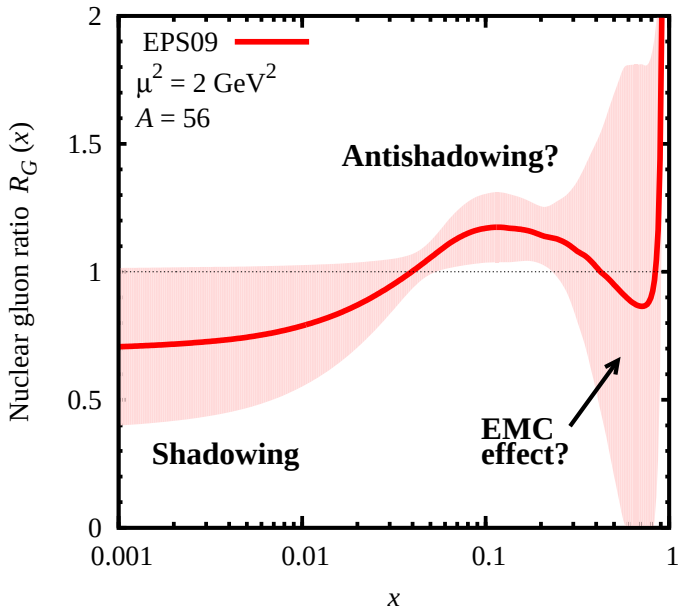
  Suppresses gluon density at small x

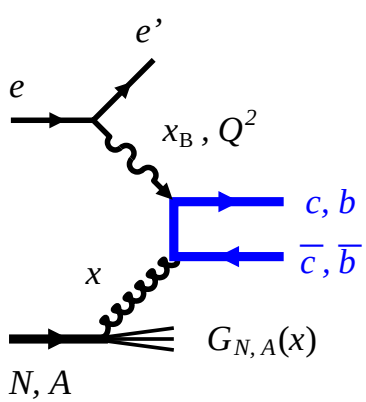
  Calculable in terms of diffractive nucleon PDF and nuclear WF
  Frankfurt, Guzey, Strikman 12+

  Leading-twist effect!

  Predicted gluon shadowing consistent with LHC J/ψ photoproduction data

Nuclear gluons: Large x with EIC





- Explore large-x nuclear gluons

  Gluonic EMC effect at $x > 0.3$?

  Gluon antishadowing at $x \sim 0.3$?

- Some information from inclusive DIS

  F_{2A}, F_{LA} + DGLAP
  EIC White Paper. Aschenauer et al. 16

- Heavy quarks as direct probe

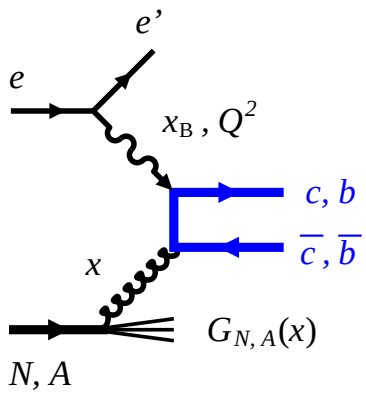
  Open charm/beauty production

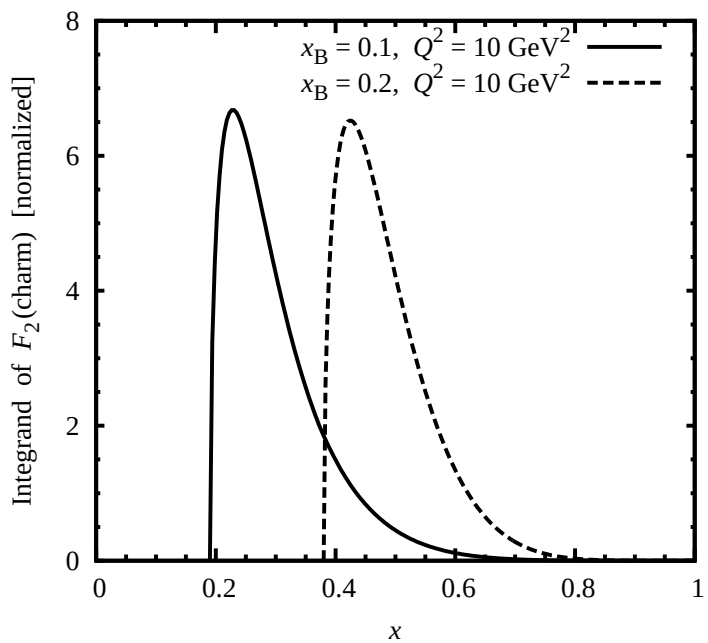
  New exp methods and challenges at large x

  Suitable for medium-energy EIC
  $s_{eN} \sim$ 200-2000 GeV^2

JLab LDRD Project LD1701/1601
https://wiki.jlab.org/nuclear_gluons/
Chudakov et al [arXiv:1610.08536], [arXiv:1608.08686]

Nuclear gluons: Charm production theory





- Heavy quark production in DIS

  Calculated at LO, NLO; uncertainties quantified
  Laenen, Riemersma, Smith Van Neerven, Harris 93+.
  Kawamura et al. 12. Alekhin, Moch et al. 93+

  Good sensitivity to gluons even at $x_B \gtrsim 0.1$

  Probes gluons at $x > x_B(1 + 4m_h^2/Q^2)$

  Integrand localized at $x \sim x_B$

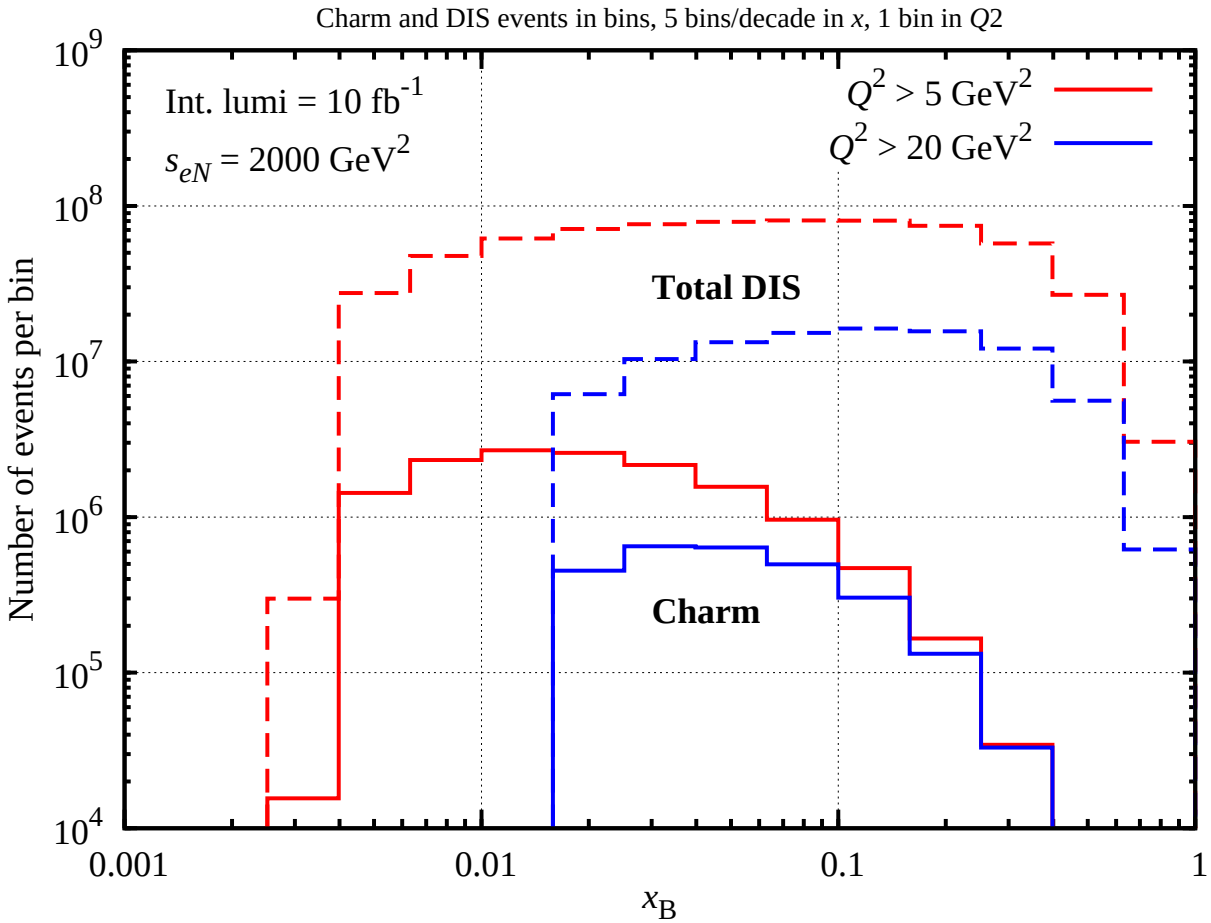
- Observables for analysis

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

  Inclusive charm structure function F_{2c}

- Tested with HERA results

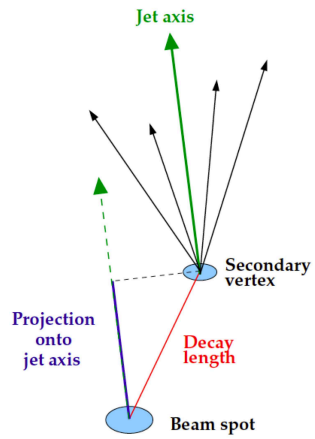
Nuclear gluons: Charm rates at large x



- Charm production rates drop rapidly at large x
- Charm production rates $\sim 10^5$ at $x \sim 0.1$ (int. lumi 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

Nuclear gluons: Charm reconstruction methods

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%



- Charm reconstruction using exclusive D-meson decays

  $D^{*+} \to \pi^+(\text{slow}) + (K^-\pi^+)_{D0}$ used at HERA w/o PID, efficiency $< 1\%$.

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

  Total efficiency estimated $\sim$ 5–7%

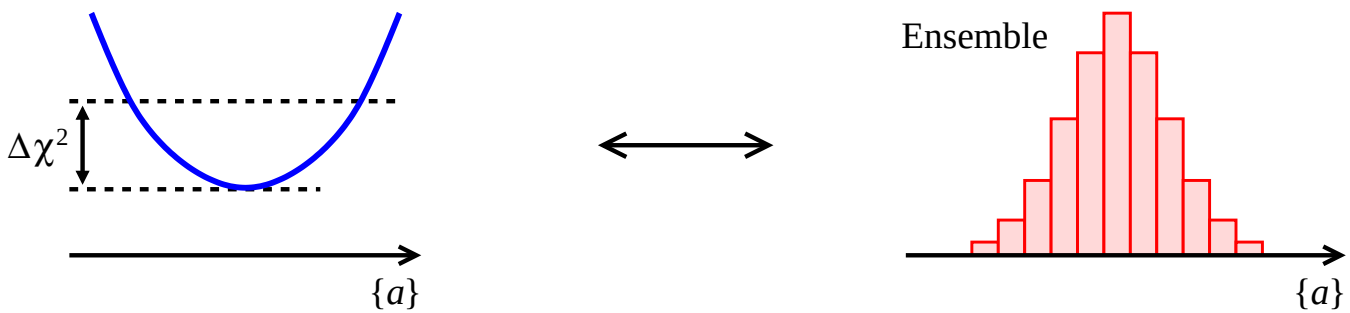
- Charm reconstruction using inclusive modes with displaced vertex

  D–meson decay length significance distribution used at HERA with vertex detector

  Efficiency estimated at $\sim$30% for EIC cf. Aschenauer et al., 2016

- High–p_T $c\bar{c}$ pairs: Low rates, but clean final state

Nuclear gluons: Charm impact at large x



- 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

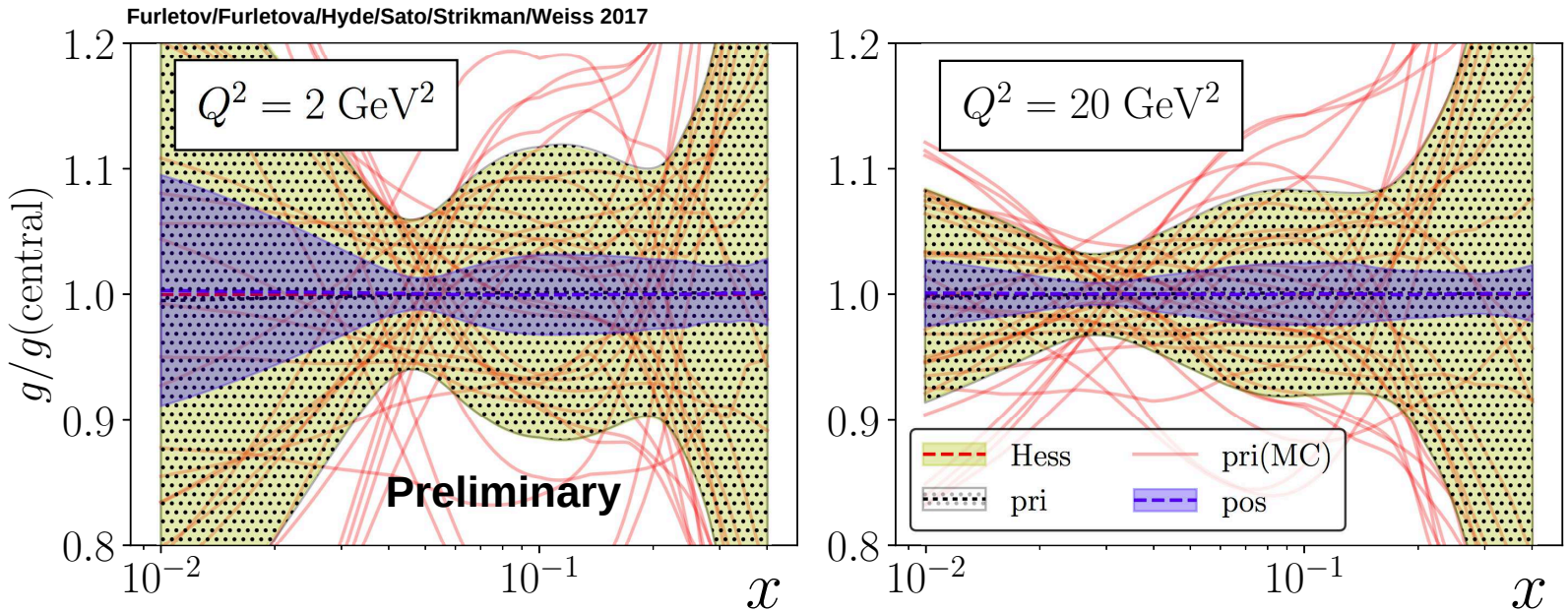
  Widely used in PDF analysis, HEP

- Implemented for charm pseudodata from EIC

  Presently F_{2c}, can be extended to other observables Sato, CW 17

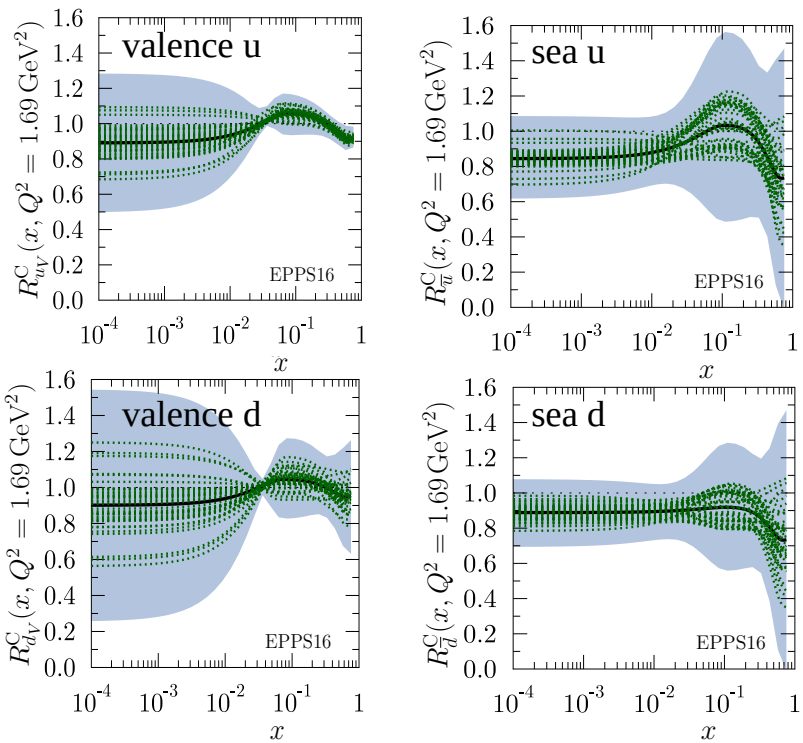
  Python code package, on github: `https://github.com/JeffersonLab/F2c`

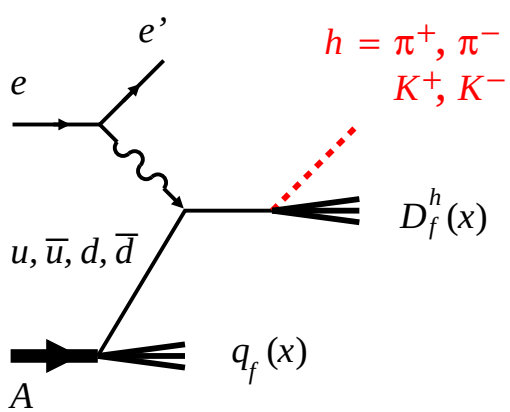
Nuclear gluons: Charm impact at large x



- Here: Assumed 10% total error, dominated by systematics, point-to-point
- Substantial impact on large–x nuclear gluons
- Will be updated/refined
- Theory errors from nuclear ratio, final-state interactions, to be estimated

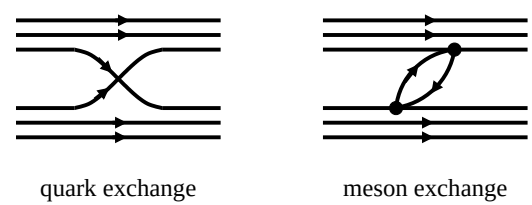
Nuclear quarks: Charge-flavor separation





- Charge-flavor separation at $x \sim 0.1$?

  NN interaction by quark or meson exchange?



- EIC: Semi-inclusive $\pi^\pm, K^\pm$

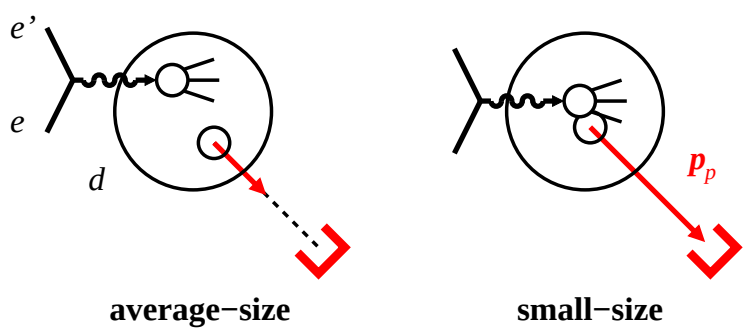
  Extensive experience with ep

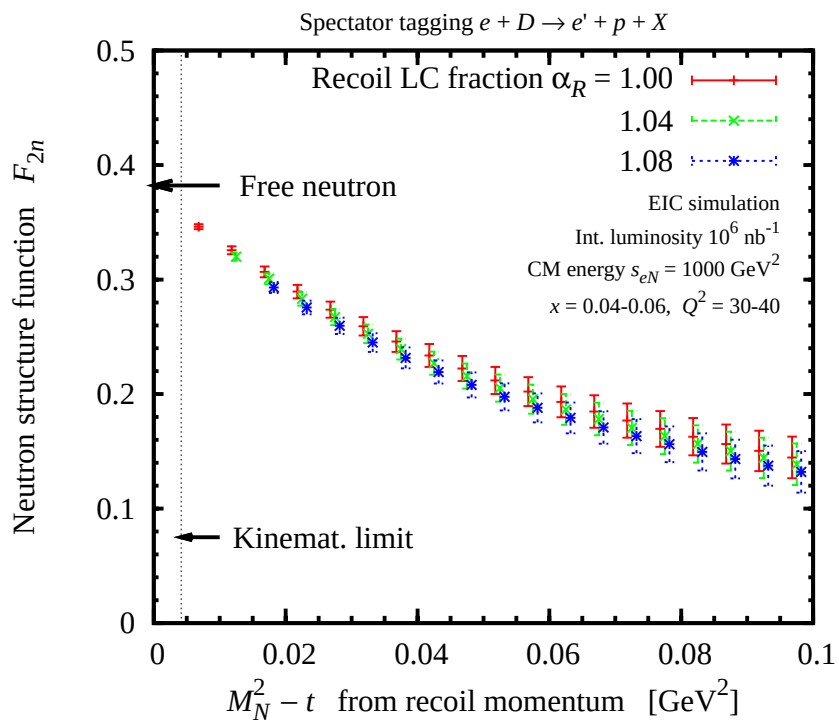
  eA: Separate initial-state modifications from nuclear final-state interactions using A–dependence

- Simulations in progress

  Zhihong Ye, D. Higinbotham, CW

Deuteron and spectator tagging





Cosyn et al. [arXiv:1409.5768] [arXiv:1601.06665]

- Tagged DIS $e + d \to e' + p + X$

  Recoil proton momentum controls size of pn configuration during DIS

  $p_p \sim 0$ neutron on-shell, free

  $p_p \neq 0$ neutron off-shell, virtuality $\sim 2p_p^2$

- Tagged EMC effect

  Study nuclear modification as function of recoil momentum $\leftrightarrow$ off-shellness

  FSI as theoretical challenge
  EIC energies: Strikman, CW; in progress

- Feasible with EIC

  Spectator carries $\sim 1/2$ beam momentum, forward detectors

  Polarized deuteron possible
  JLab LDRD Project LD1403/1506
  `https://www.jlab.org/theory/tag/`

See also: Miller, Sievert, Venugopalan 16

Summary

- Nuclear PDFs as window on nucleon interactions in QCD

  Unifying theme — 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

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

- Spectator tagging in ed permits DIS in controlled nuclear configurations

  Free neutron structure and nuclear modification

  Polarized deuteron possible

  Requires dedicated forward detector

  Simulation tools and results
  JLab LDRD Project LD1403/1506 `https://www.jlab.org/theory/tag/` Open for collaboration!