3D imaging of sea quarks and gluons at an Electron-Ion Collider

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Jefferson Lab

QCD Evolution Workshop: from collinear to non collinear case
Jefferson Lab, April 8, 2011

Outline

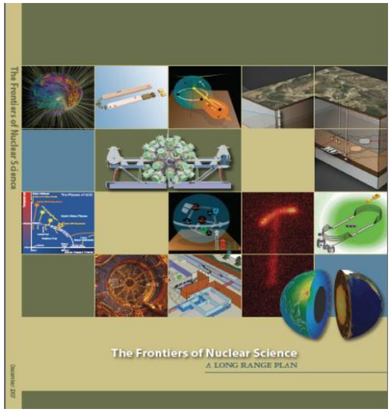
- Introduction: Nucleon and nuclear structure in QCD and the Electron-Ion Collider (EIC) Project

- Obtaining a 3D image of sea quarks and gluons at an EIC:
  - GPDs and exclusive reactions
  - TMDs and semi-inclusive reactions

Nucleon and nuclear structure in QCD

- Understanding the internal structure of nucleons and nuclei on the basis of the fundamental theory of strong interactions, Quantum Chromodynamics (QCD), is one of the central problems of modern nuclear physics.

2007 DOE/NSF NSAC Long-Range Plan

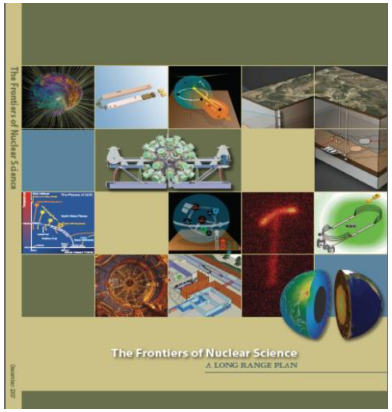


The major science questions:

- What is the internal landscape of the nucleon?
- What is the role of gluons and their self-interactions in nucleons and nuclei?
- What governs the transition of quarks and gluons in pions and nucleons?

The Electron-Ion Collider Project

Informal recommendation (for accelerator and physics R&D) in 2007 DOE/NSF NSAC Long-Range Plan:



"An Electron-Ion Collider (EIC) with polarized beams has been embraced by the U.S. nuclear science community as embodying the vision for reaching the next QCD frontier.

EIC would provide unique capabilities for the study of QCD well beyond those available at existing facilities worldwide and complementary to those planned for the next generation of accelerators in Europe and Asia."

The science of an EIC

Three major science questions for an EIC from NSAC LRP07:

- What is the internal landscape of the nucleon?
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EIC science goals:

- Map the spin and spatial structure of quarks and gluons in nucleons
- Discover the collective effects of gluons in atomic nuclei
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topic relevant for this workshop

Basic requirements for EIC

- Lepton beam: clean and well-understood probe

- Range of c.m. energies from s=few 100 GeV^2 to s=few 1000 GeV^2, variable and upgradable:
  - electrons up to 20 - 30 GeV
  - protons up to 250 – 325 GeV; ions up to 100 - 130 GeV/A (^{208}Pb)

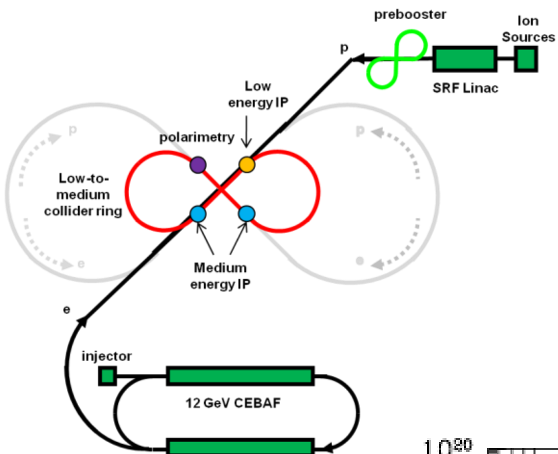
- Polarized e and p beams (> 70%), longitudinal and transverse polarization of the proton beam, polarized light nuclei (D, ^{3}He)
  essential for imaging program

- High luminosity ~10^{34} cm^{-2} s^{-1} (> 100x HERA)
  required for precision measurements, multidim. binning, rare processes

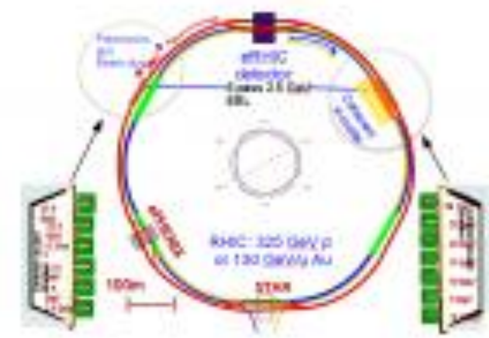
- Range of nuclei, from D to ^{208}Pb
  light nuclei for flavor separation; heavy nuclei for medium modif. and saturation

EIC: JLab and BNL designs

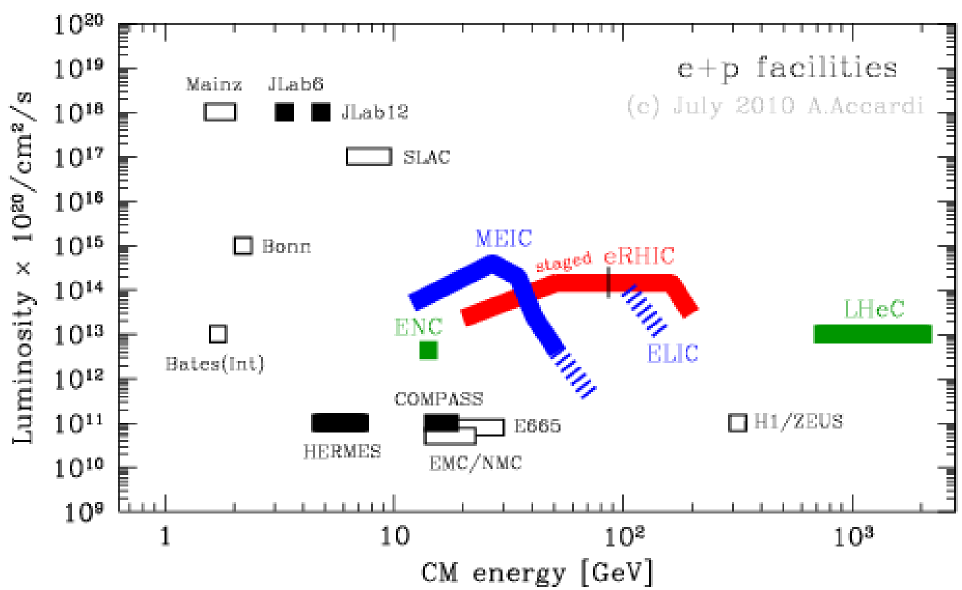
- Two competing designs of EIC at Jefferson Lab and Brookhaven National Lab
- Both involve "staging" (medium-energy phase)
- Recent designs converge in main parameters



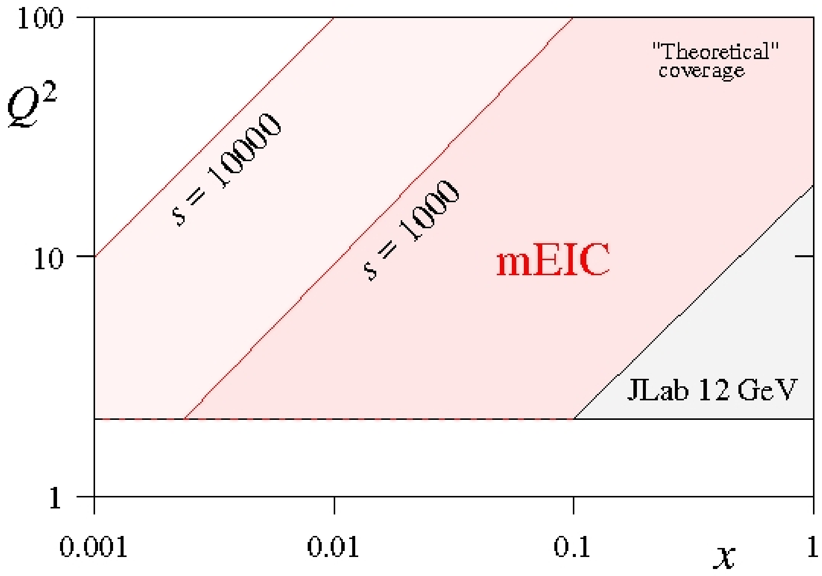
Ring-ring design at JLab



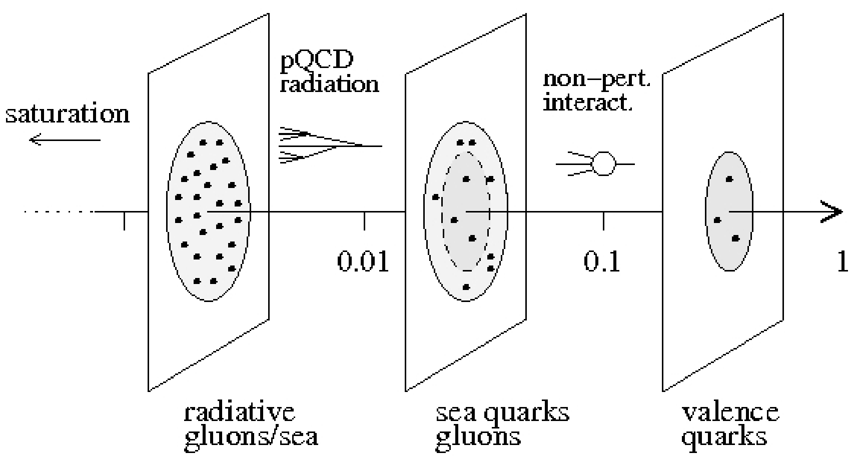
Linac-ring design at BNL



Accessing sea quarks and gluons at EIC



"Theoretical" kinematic coverage of DIS at EIC



EIC is the machine to study the sea quark and gluon structure of protons/nuclei !

Plot and figure due to C. Weiss

The program of mapping spin and spatial structure of sea quarks and gluons at EIC

- Helicity distributions from inclusive and semi-inclusive polarized DIS
- Generalized parton distributions (GPDs) from exclusive processes
- Transverse momentum dependent distributions (TMDs) from semi-inclusive processes

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• require wide coverage in x → access to gluons and sea quarks

Q2 → factorization, QCD evolution

P_T → connection to collinear formalism; P_T weighting

• L and T polarization of the proton beam

• require high luminosity → precision, multi-dimensional binning

• variable energy → L/T separation

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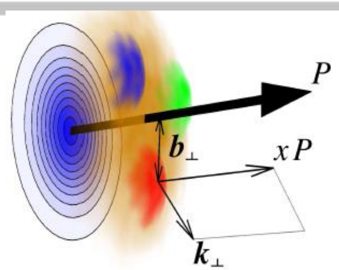
• require high luminosity

• variable energy

EIC meets these Requirements !

Physics of 3D imaging of parton distributions



From discussions and talks at INT 10-03 program

TMDs:
Distributions in (x,k_T)

- indicate orbital angular momentum
- encode spin-orbit correlations
- dynamics of gluons accompanying colored particles (physics of gauge links)
- probe interplay pert. and non-pert. phenomena (k_T matching)
- essentially unknown for sea quarks and gluons

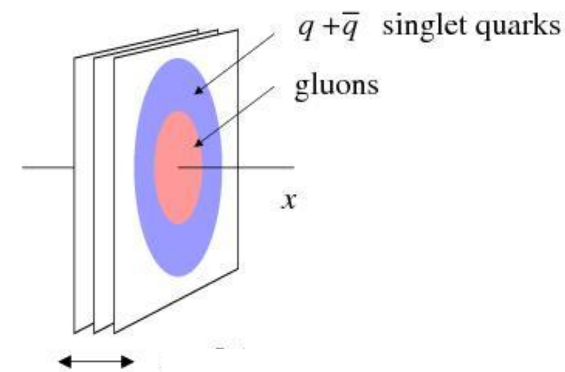
GPDs and dipole amplitudes:
Distributions in (x,b_T)

- pheno indicate large orbital momentum; give access to the total angular momentum (GPD E)
- parton correlations in nucleon wf
- chiral physics at large b_T
- important for pp and pA pheno (info on b_T dependence) for RHIC and LHC
- essentially unknown for sea quarks and gluons

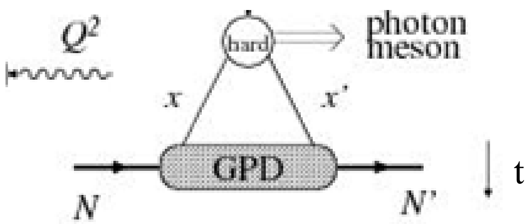
No model-independent connections between TMDs and GPDs are known, but they are connected at the fundamental level via Wigner $W(x,k_T,b_T)$ and model-dependently though the nucleon light-cone wave function

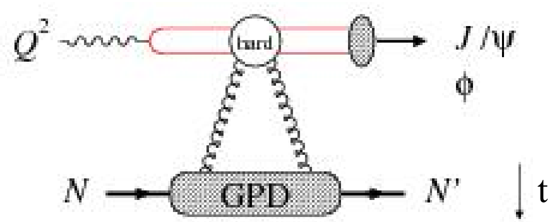
The GPD program at an EIC

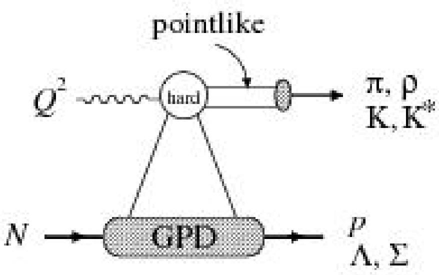
- GPDs are accessed in exclusive reactions
- Distributions in transverse plane (transverse size) derived from t-dependence
- Input for modeling pp collisions at LHC



changes with x







DVCS: singlet quarks
(and gluon at NLO)
ρ and ω: sea quarks and
gluons;
flavor separation

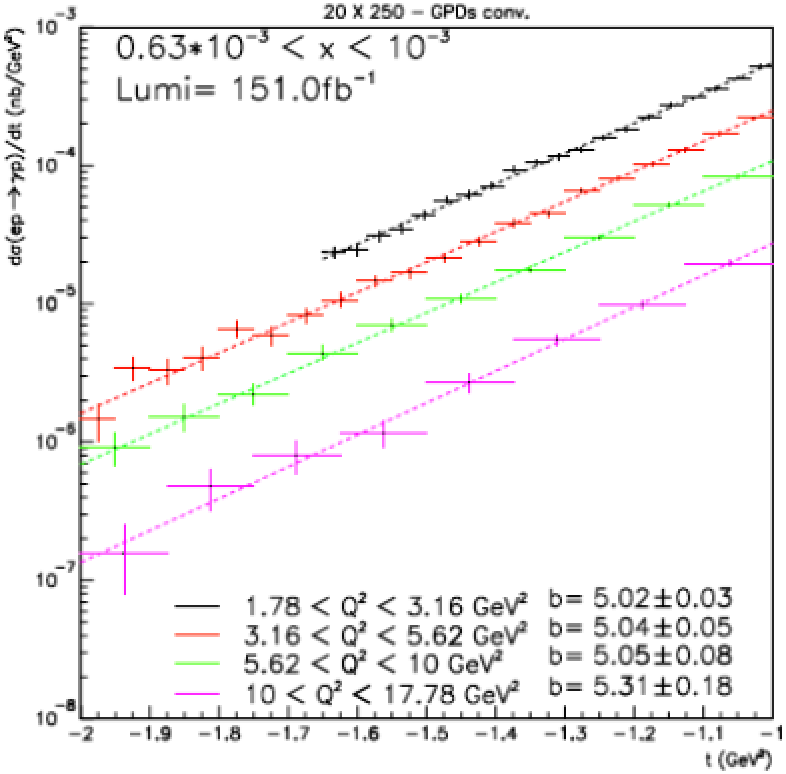
gluon

polarized valence and sea quarks, including strangeness

Figures due to C. Weiss

Simulation of DVCS cross section for EIC

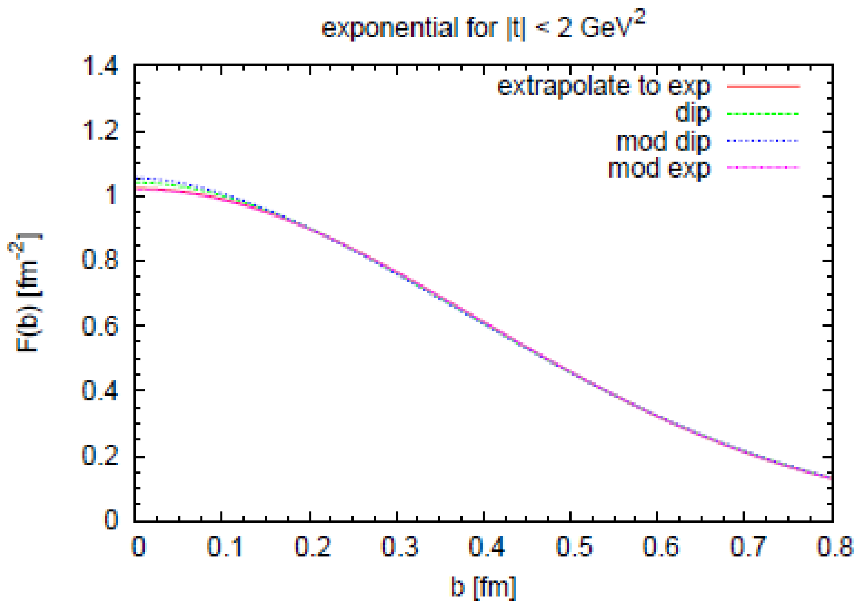
Simulated DVCS cross section



S. Fazio

F.T.

Accuracy of extracted "image" in the impact parameter space



E. Aschenauer, M. Diehl, S. Fazio
(from the write-up of the INT10-03 program)

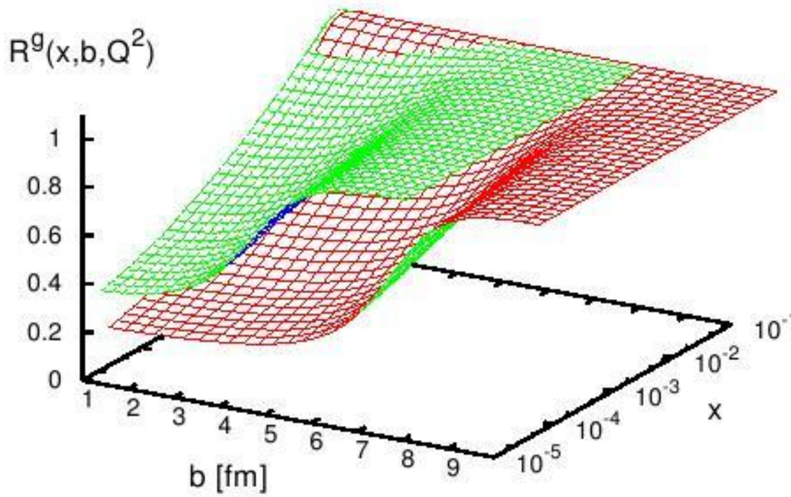
This is just one example: many more observables will be accessible at an EIC.

EIC: spatial imaging of sea quarks and gluons in nuclei

- Can be accessed in exclusive reactions with nuclei
- Very (!) important for modeling pA collisions at RHIC and LHC
- Predicted theoretically in the leading twist theory of nuclear shadowing

Frankfurt, Guzey, Strikman, 2010

$$R^j(x,b,Q^2) = \frac{f_{j/A}(x,Q^2,b)}{A\,T_A(b) f_{j/N}(x,Q^2)} = \frac{H_A^j(x,\xi=0,b,Q^2)}{A\,T_A(b) f_{j/N}(x,Q^2)}.$$



gluon PDF,
FGS10_H, Q^2=4 GeV^2

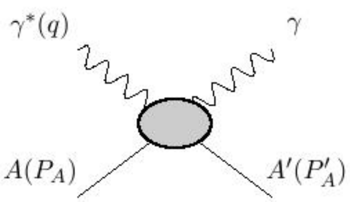
Spatial image of nuclear shadowing

- Nuclear shadowing is larger at small b and x
- Shadowing introduces x-b correlations

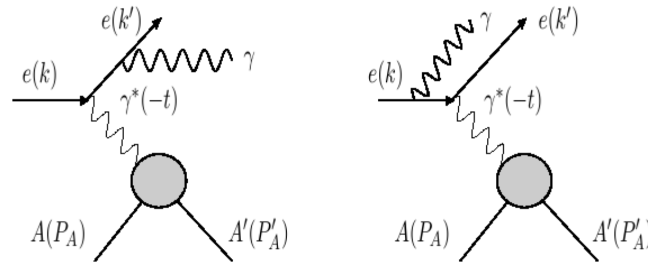
- Average transverse size of the distribution of partons in b-plane, $\langle b^2 \rangle$, increases
  → can be tested experimentally in DVCS and VM production

EIC: spatial imaging of sea quarks and gluons in nuclei

DVCS interferes with Bethe-Heitler (BH) process



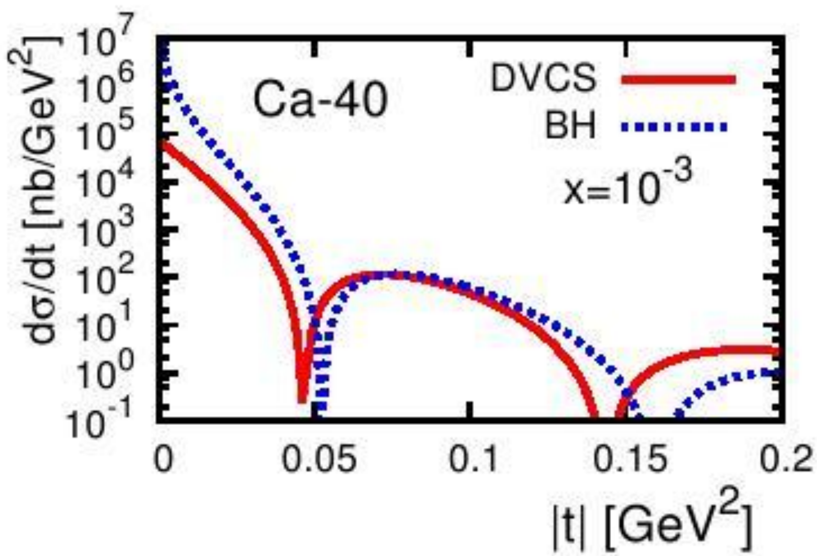
shadowed

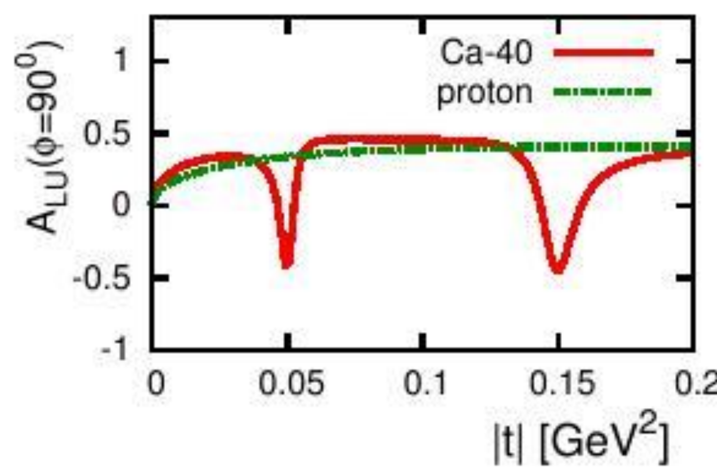


non-shadowed

$\langle b^2\rangle_{DVCS} > \langle b^2\rangle_{BH}$

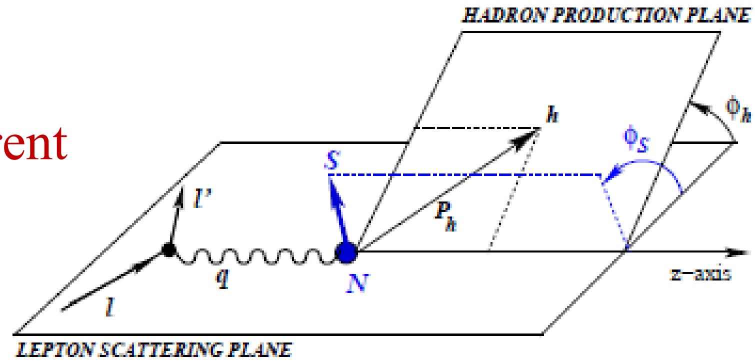
$$A_{LU}(\phi) = \frac{\overrightarrow{\sigma} - \overleftarrow{\sigma}}{\overrightarrow{\sigma} + \overleftarrow{\sigma}} \propto \sin\phi \frac{H_A(\xi,\xi,t)F_A(t)}{F_A^2(t)}$$





The TMD program at an EIC

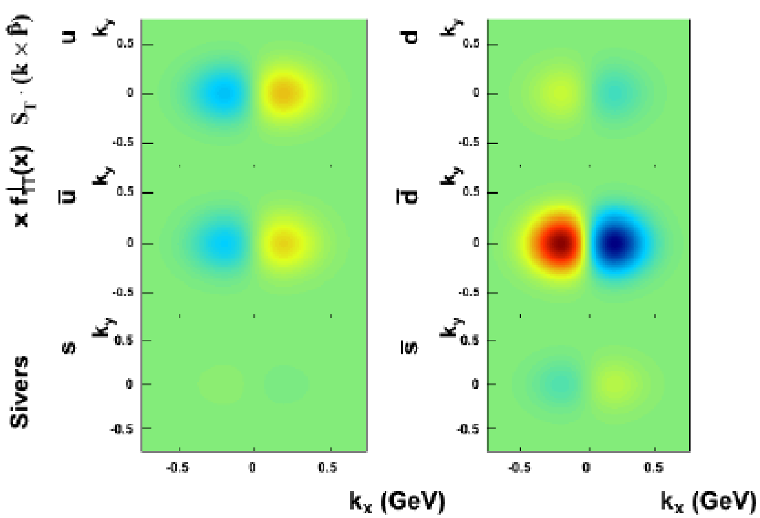
- Transverse momentum dependent distributions (TMDs) can be accessed in semi-inclusive DIS



- Various TMDs can be projected out by taking different combinations of beam and spin polarization and different moments w.r.t. angles φ_S and φ_h

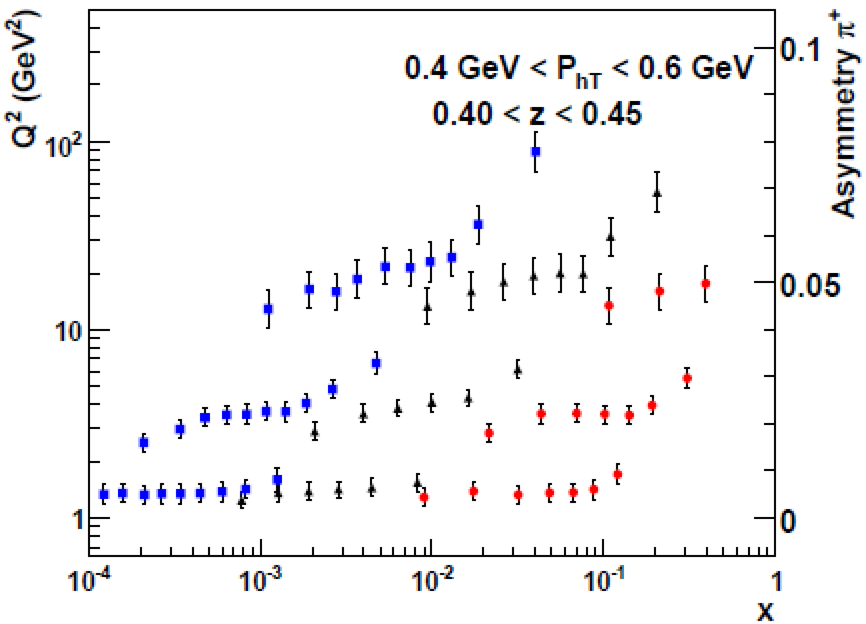
- While all TMDs (8 twist-2 quark + 8 twist-2 gluon TMDs) are interesting in their own right, the quark **Sivers function** seems to be most representative of the TMD physics (and easy to measure)

Sivers function describing deformation of distrib. of unpol. quarks inside trans. pol. proton

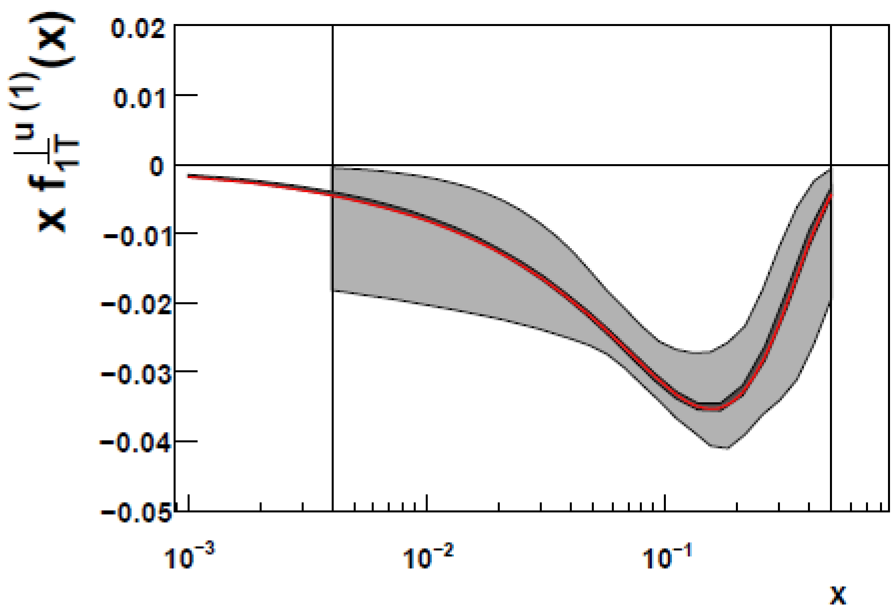


Simulation of Sivers function for EIC

Example of pseudo-data:
Event distribution for π+ SIDIS
(event rates proportional to error bars)



Improvement in precision of extraction of Sivers function from pseudo-data (red curve) over the existing data (shaded area)



From the write-up of the INT10-03 program (to be published)

This is just one example: many more observables (e.g., gluon Sivers) will be accessible at an EIC.

Summary

A future high-energy and high-luminosity Electron-Ion Collider with polarized beams will have excellent capabilities for precision studies of the 3D sea quark and gluon structure of the nucleon and nuclei.