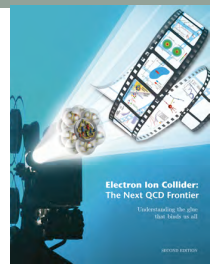
Center for Frontiers in Nuclear Science



Spin Physics at the Electron Ion Collider

RHIC AGS Meeting at BNL
June 5, 2019

Stony Brook University
Abhay Deshpande
BROOKHAVEN NATIONAL LABORATORY

Outline

Spin physics with at the EIC ➔ "hadron structure" most measurements will require that one or both colliding beams are polarized. A couple will not require polarization.

The spin orientations could be ➔ transverse or longitudinal

Vast repertoire of measurements ➔ I will only present a few highlights

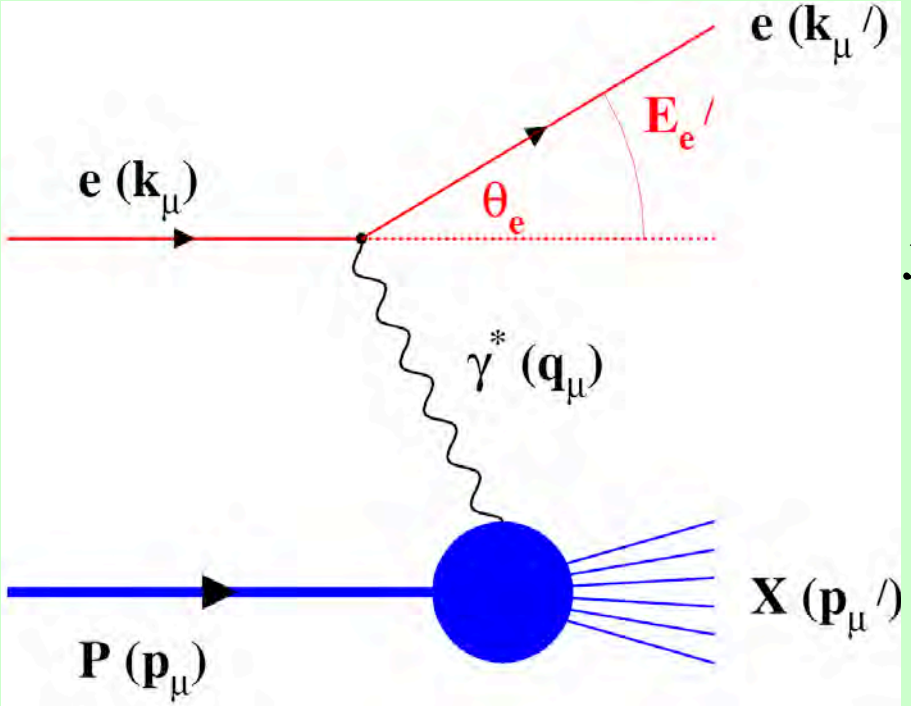
History: Why spin physics at the collider with longitudinal and transverse spin orientations (lessons drawn from e/μ-p and in p-p)

Highlights of possible **spin physics at the EIC**: mostly from the EIC White Paper ➔ understanding emergence of spin and mass…

New initiatives **Beyond the White Paper** (BWP)

Conclusion and outlook

Deep Inelastic Scattering: Precision & Control



Kinematics:

$$Q^2 = -q^2 = -(k_\mu - k'_\mu)^2$$

$$Q^2 = 2E_e E'_e(1 - \cos\Theta_{e'})$$

Measure of resolution power

$$y = \frac{pq}{pk} = 1 - \frac{E'_e}{E_e}\cos^2\left(\frac{\theta'_e}{2}\right)$$

Measure of inelasticity

$$x = \frac{Q^2}{2pq} = \frac{Q^2}{sy}$$

Measure of momentum fraction of struck quark

Hadron **:**

$$z = \frac{E_h}{\nu}; p_t$$ with respect to γ

Inclusive events: e+p/A → e'+X

Semi-Inclusive events: e+p/A → e'+h(π,K,p,jet)+X

Exclusive events: e+p/A → e'+ p'/A'+ h(π,K,p,jet)

Spin structure (function) of the proton: $g_1(x,Q^2) \rightarrow \Delta\Sigma$

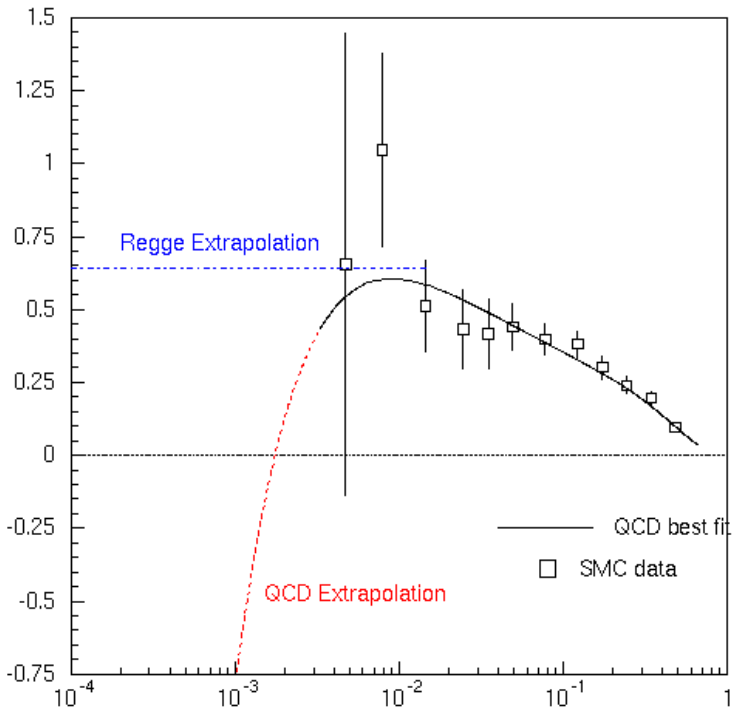
$$g_1(x) = \frac{1}{2}\Sigma_f e_f^2 \{q_f^+(x) - q_f^-(x)\} = \frac{1}{2}\Sigma_f e_f^2 \Delta q_f(x)$$

$$\Delta\Sigma = \Delta u + \Delta d + \Delta s$$

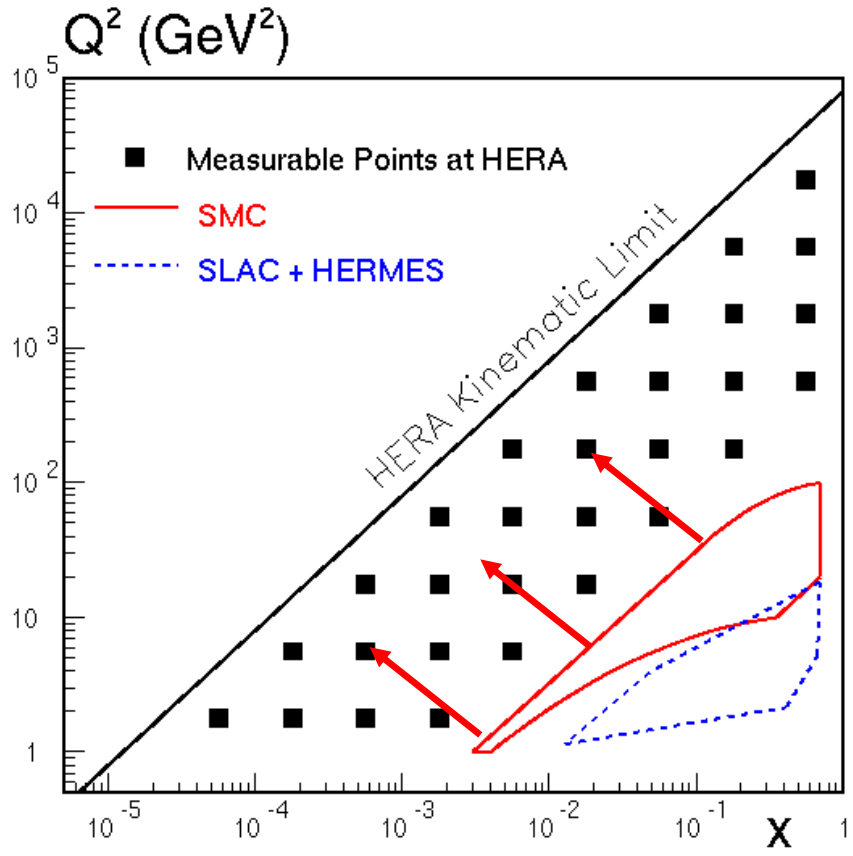
- Before 2000, this was (one of the) the principle measurement focused by all fixed target experiments in the world… CERN, SLAC, DESY.
  - Needs longitudinally polarized targets (protons, deuterons or helium) and longitudinally polarized muon or electron beams.
- One only gets the full picture of contributions from the quarks ($\Delta\Sigma$ = quark's contribution to nucleon's spin) only after INTEGRATING over x, at a fixed Q^2

- Fixed target experiments have a significantly limited x-Q^2 reach, as such heavy reliance on model dependent EXTRAPOLATIONS at low-x

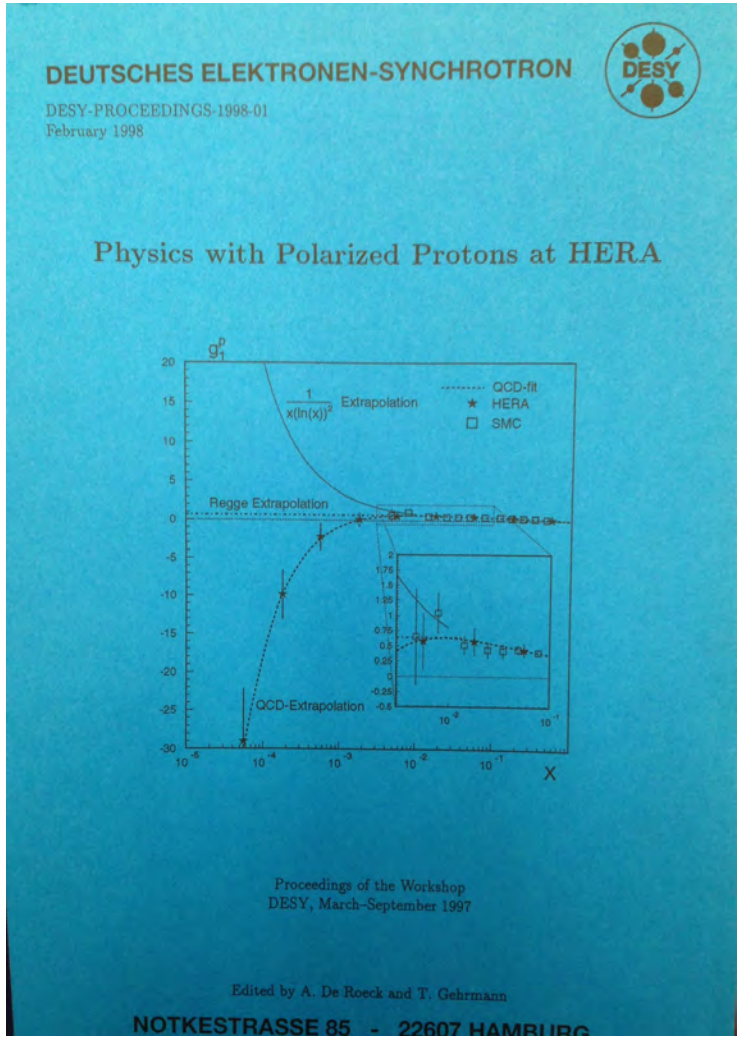
Low x behavior of $g_1(p)$ ➔ case for polarized HERA



Regge : $g_1(x \to 0) \sim x^{-\alpha}; \quad 0 < \alpha < 0.5$



Clear need for low x measurements!



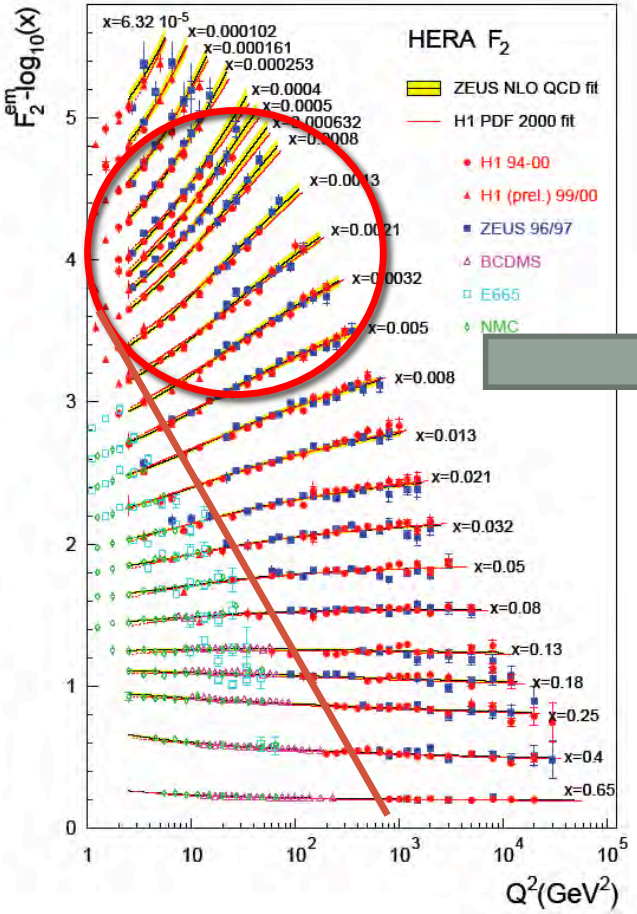
A. Deshpande & V. W. Hughes ~1996 SMC (internal) analysis meeting

To G from $F_2(x,Q^2)$ or ΔG from g1(x,Q2)

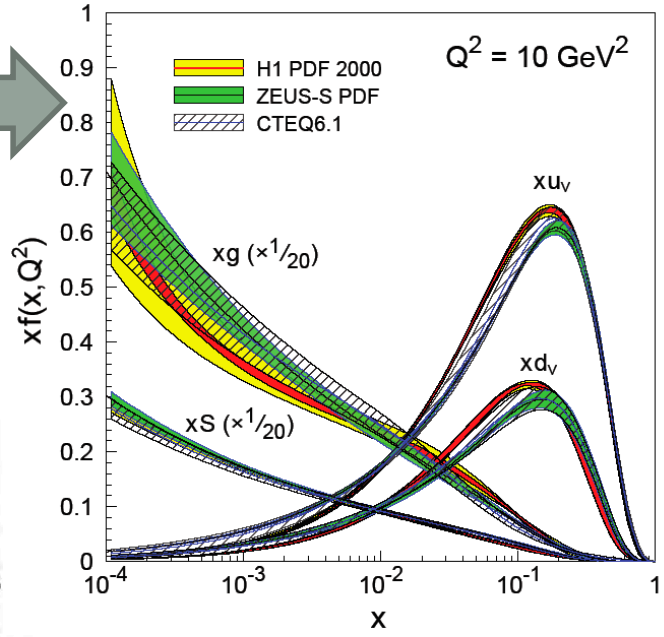
scaling violation

Global analysis: of $F_2(x,Q^2)$ → $G(x,Q^2_0)$ ➔ Next-to-Leading Order pQCD fits

Global analysis: of $g_1(x,Q^2)$ → $\Delta G(x,Q^2_0)$ ➔ Also NLO pQCD fits



$$\frac{dF_2}{dlnQ^2} \propto G(x,Q^2)$$



To G from $F_2(x,Q^2)$ or ΔG from g1(x,Q2)

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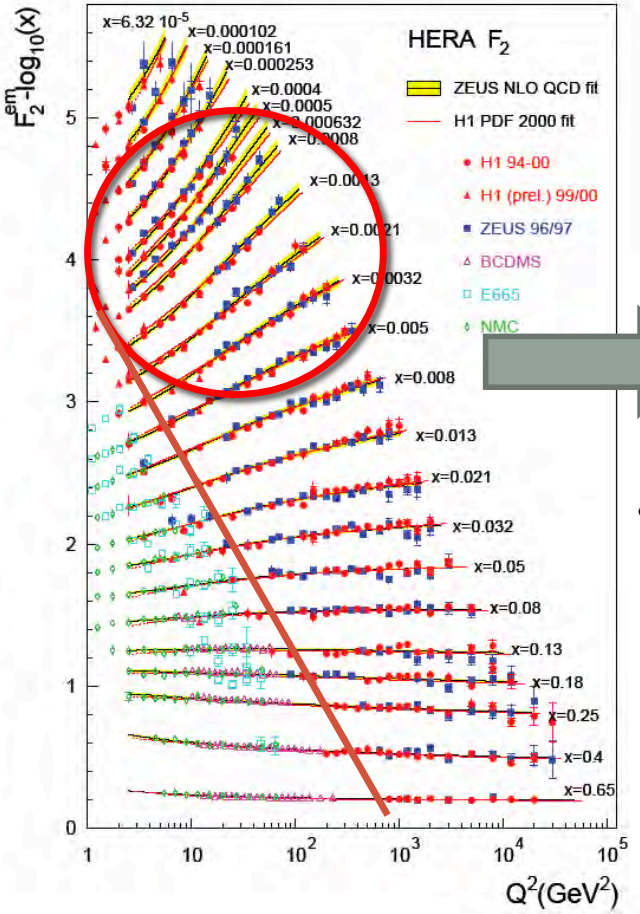
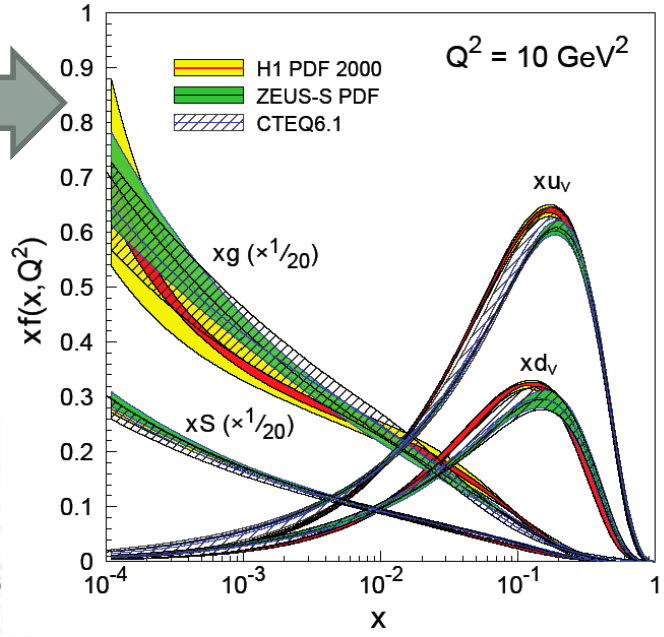
Global analysis: of $F_2(x,Q^2) \rightarrow G(x,Q^2_0)$ ➔ Next-to-Leading Order pQCD fits

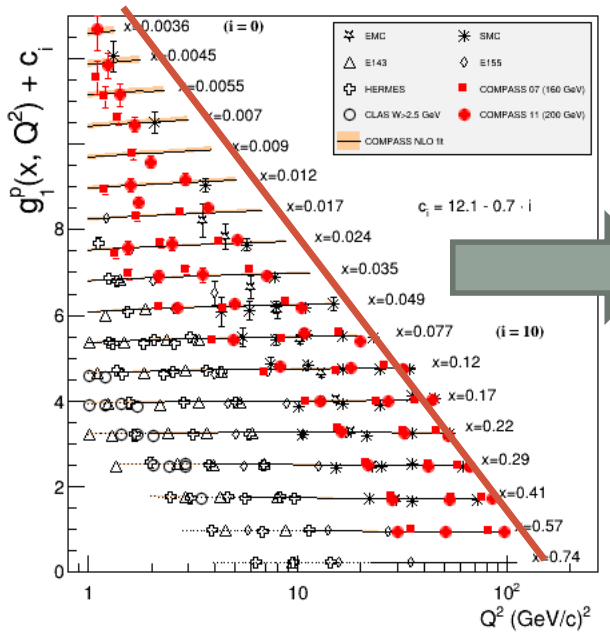
Global analysis: of $g_1(x,Q^2) \rightarrow \Delta G(x,Q^2_0)$ ➔ Also NLO pQCD fits



$$\frac{dF_2}{dlnQ^2} \propto G(x,Q^2)$$

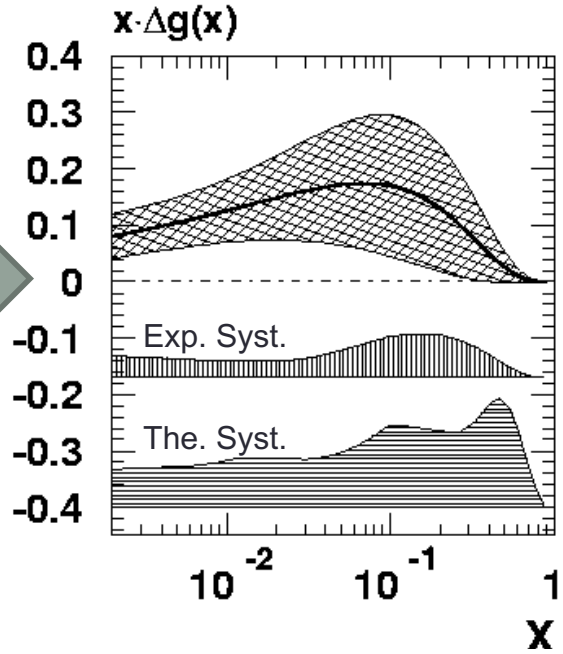


$$\frac{dg_1}{dlnQ^2} \propto -\Delta G(x,Q^2)$$

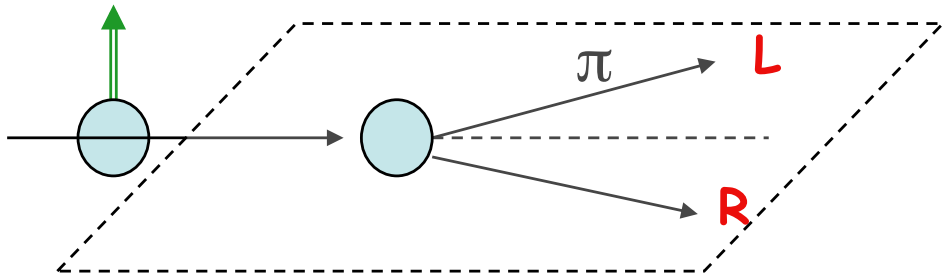


Large uncertainty in polarized gluon distribution

PRD58, (1998) 112002



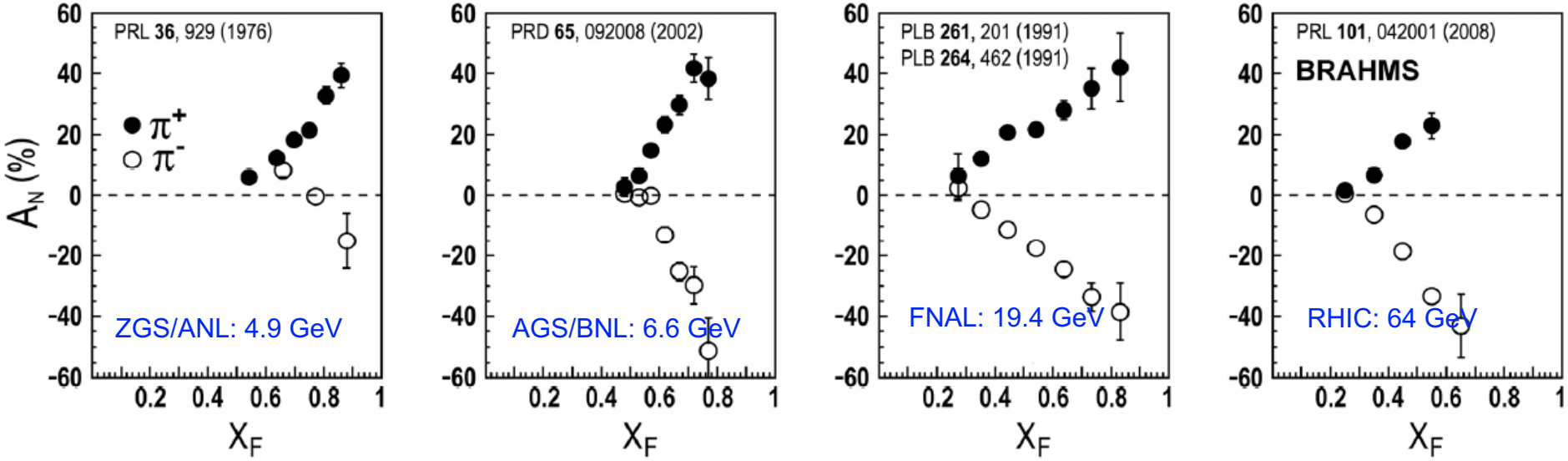
Transverse Spin Asymmetries

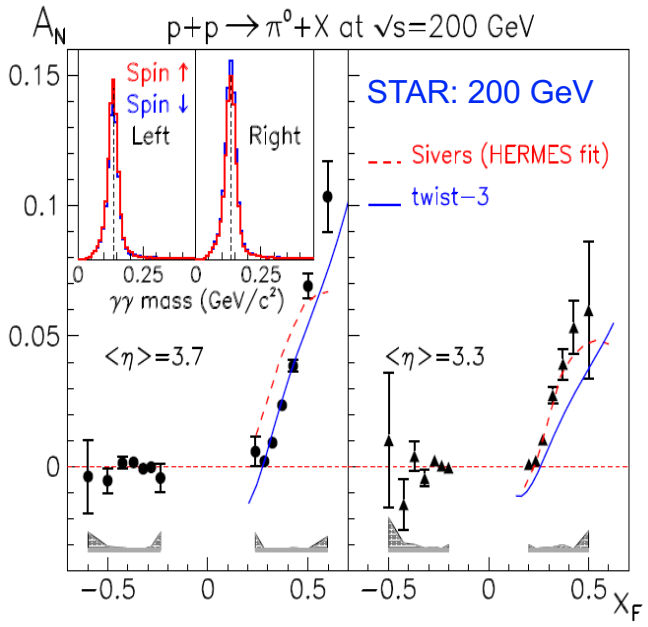


Kane, Pumplin and Repko PRL 41 1689 (1978)

$$A_N = \frac{N_L - N_R}{N_L + N_R} \approx \frac{m_q \cdot \alpha_S}{p_T} \approx 0.001$$

Contrary to theoretical expectations VERY large (40%) asymmetries in data





Distinguishing between initial state and final state interactions difficult in p-p, ultimately e-p to resolve completely

General consensus started forming that:

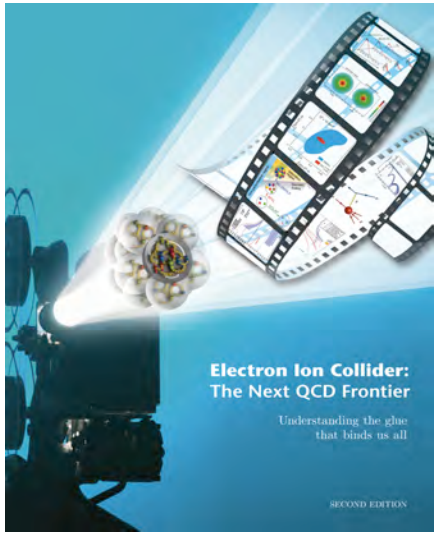
A new facility with significant increase in the x-Q^2 range, sufficiently large luminosity, and control to study longitudinal as well as transverse spin phenomena was needed.

The precision and control possible in polarized DIS, was considered essential beyond the already underway RHIC-Spin program.

QCD (spin) theory evolved to reliably interpret data available at these and future facilities. Enabled ideas for fundamental tests of QCD as complementary facilities.

(see talks on Cold-QCD program)

The Electron Ion Collider



1212.1701.v3
A. Accardi et al
Eur. Phy. J. A, 52 9(2016)

For e-N collisions at the EIC:

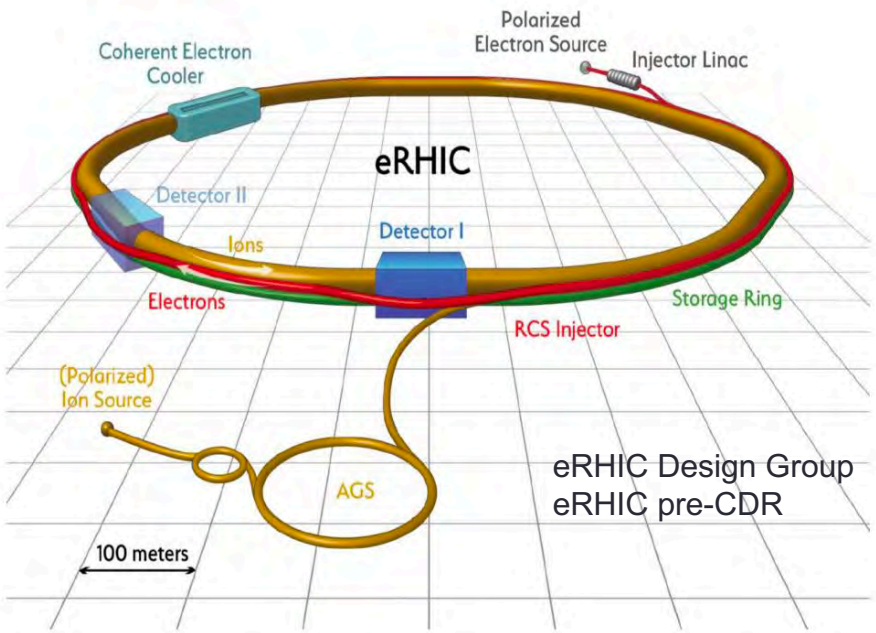
- ✓ Polarized beams: e, p, d/^{3}He
- ✓ e beam 5-10(20) GeV
- ✓ Luminosity $L_{ep} \sim 10^{33\text{-}34}$ cm^{-2}sec^{-1}
  100-1000 times HERA
- ✓ 20-100 (140) GeV Variable CoM

For e-A collisions at the EIC:

- ✓ **Wide range in nuclei**
- ✓ Luminosity per nucleon same as e-p
- ✓ Variable center of mass energy

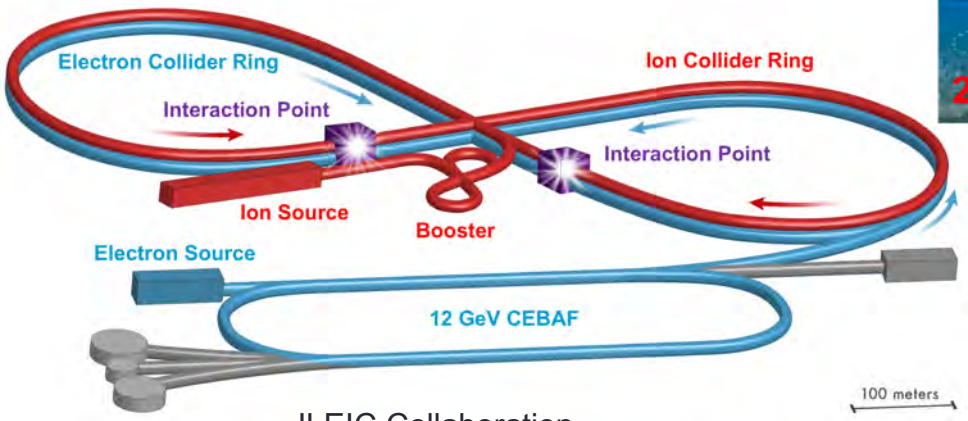
World's first
Polarized electron-proton/light ion and electron-Nucleus collider

Both designs use DOE's significant investments in infrastructure



eRHIC Design Group
eRHIC pre-CDR

2018

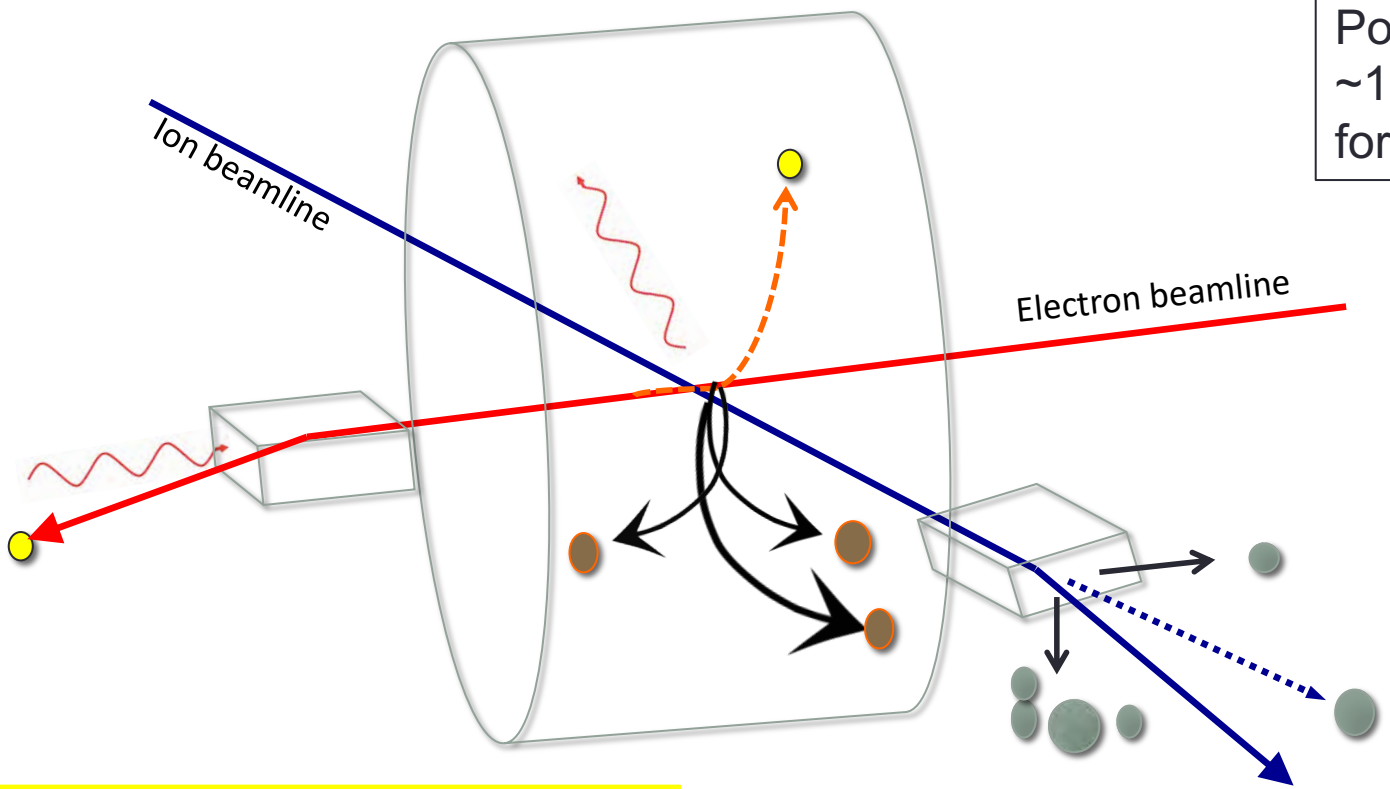


JLEIC Collaboration
JLEIC Pre-CDR

Detector integration with the Interaction Region

Lessons learned from HERA

Possible to get ~100% acceptance for the whole event



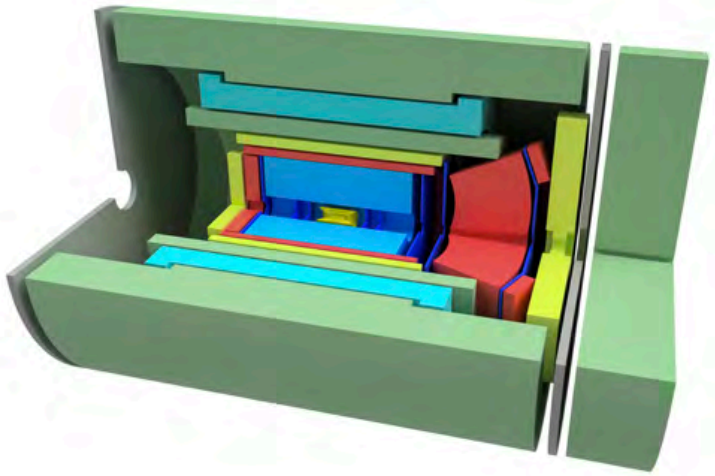
Total acceptance detector (and IR)

Crossing angles:
eRHIC: 25 mrad
JLEIC : 50 mrad

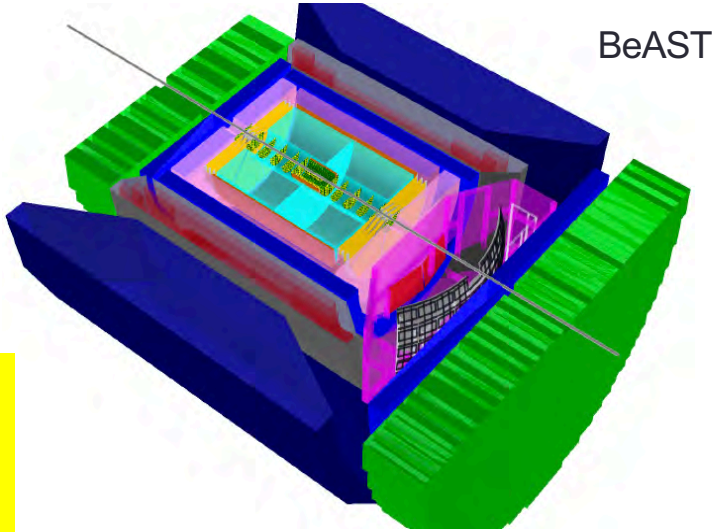
Figure Courtsey: Rik Yoshida

EIC Detector Concepts, others expected to emerge

EIC Day 1 detector, with BaBar Solenoid

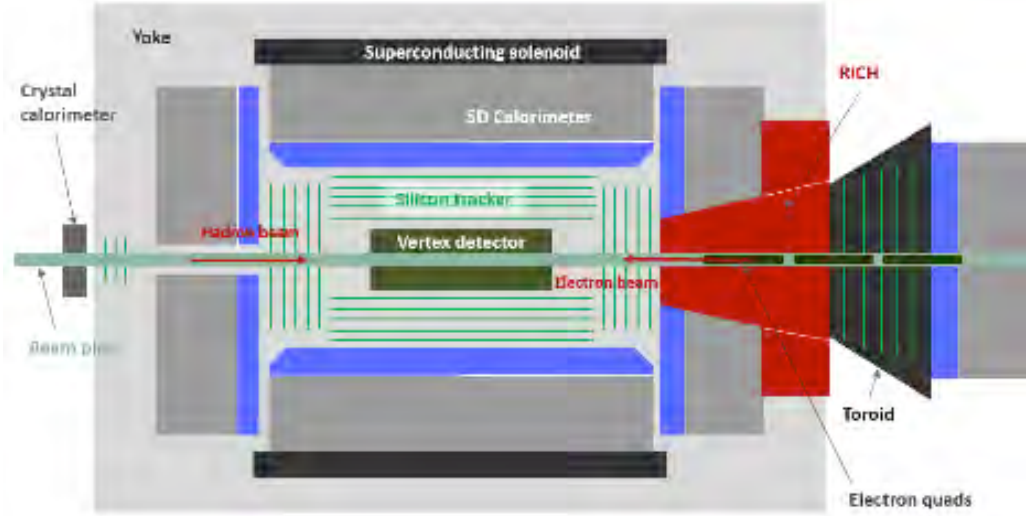


BeAST at BNL

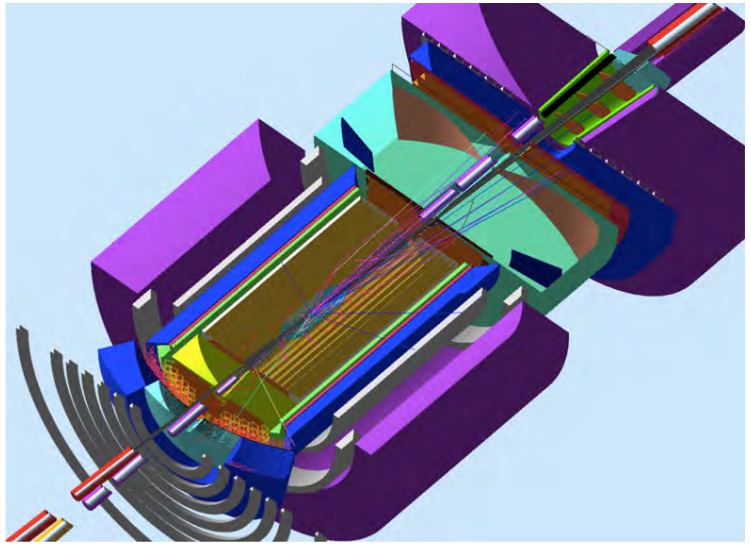


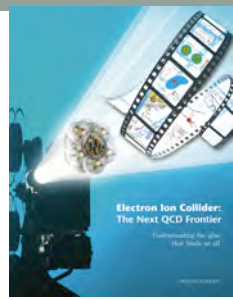
Ample opportunity and need for additional contributors and collaborators

TOPSiDE: Time Optimized PID Silicon Detector for EIC



JLEIC Detector Concept, with CLEO Solenoid

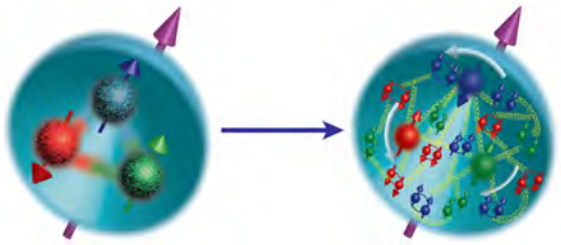


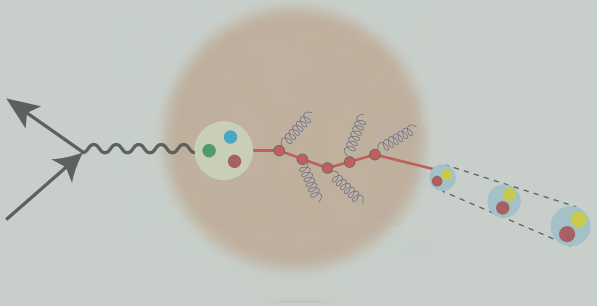


A new facility is needed to investigate, with precision, the dynamics of gluons & sea quarks and their role in the structure of visible matter

How are the sea quarks and gluons, and their spins, distributed in space and momentum inside the nucleon?

How do the nucleon properties emerge from them and their interactions?

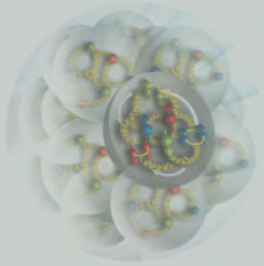




How do color-charged quarks and gluons, and colorless jets, interact with a nuclear medium?

How do the confined hadronic states emerge from these quarks and gluons?

How do the quark-gluon interactions create nuclear binding?



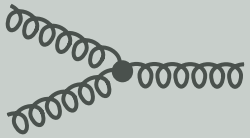
How does a dense nuclear environment affect the quarks and gluons, their correlations, and their interactions?

What happens to the gluon density in nuclei? Does it saturate at high energy, giving rise to a gluonic matter with universal properties in all nuclei, even the proton?

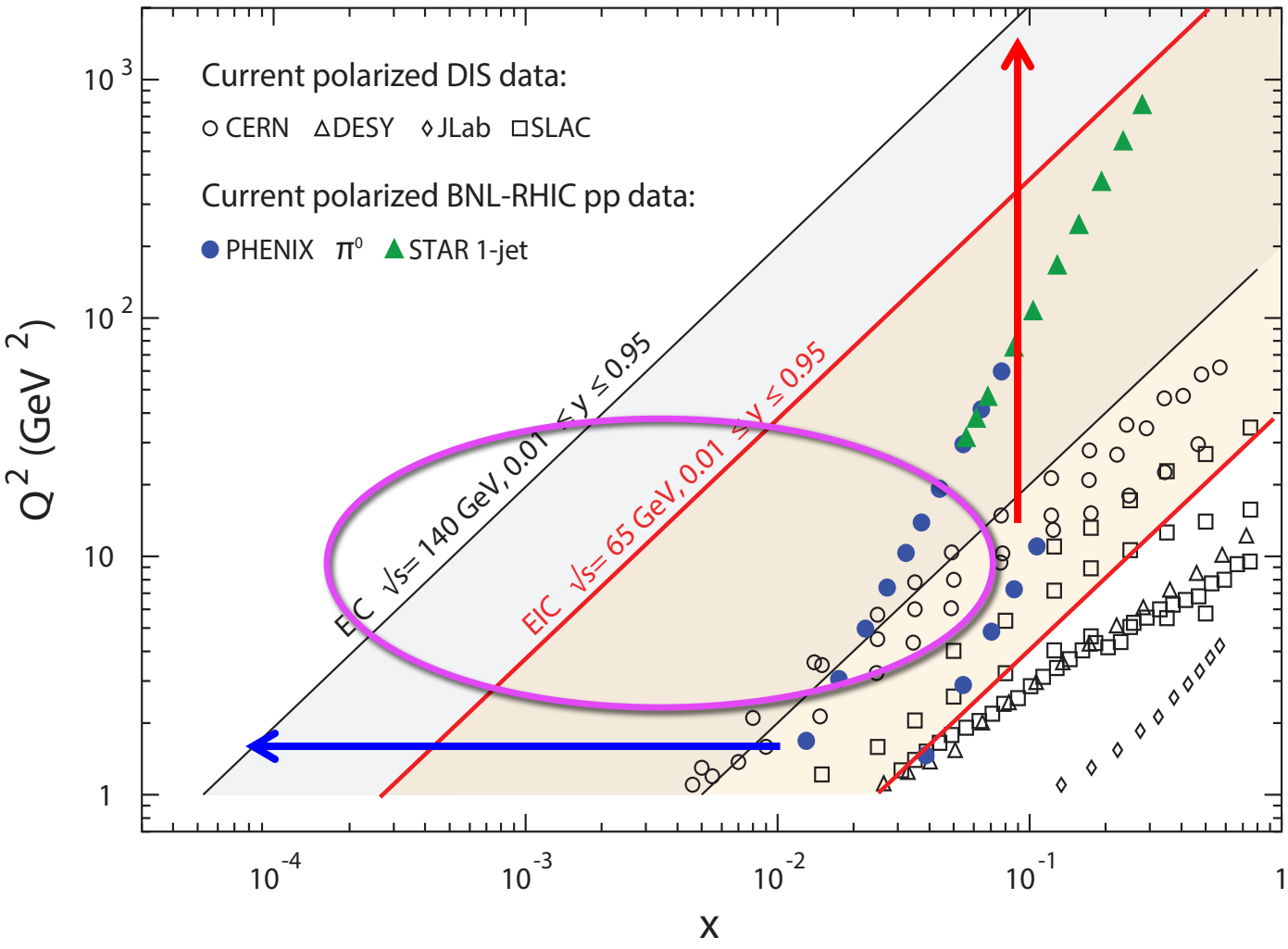
gluon emission

?=

gluon recombination



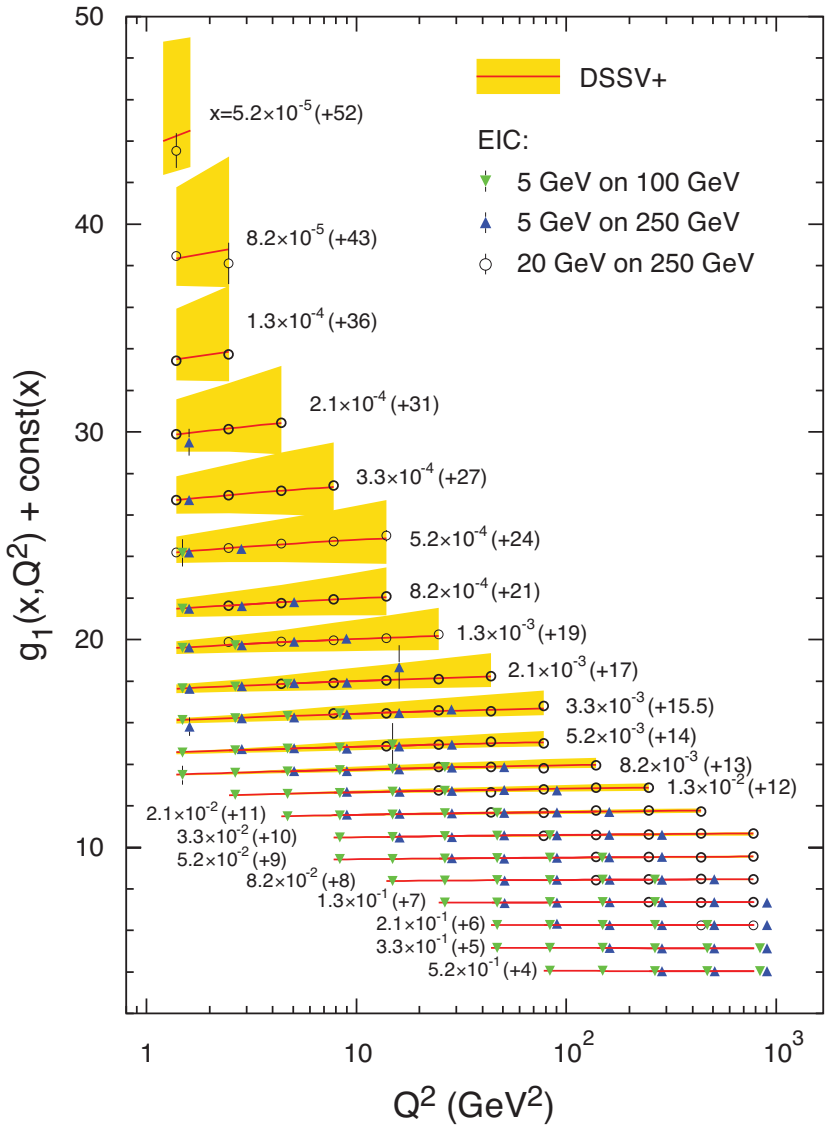
EIC: Kinematic reach with polarized e-p



For e-N collisions at the EIC:

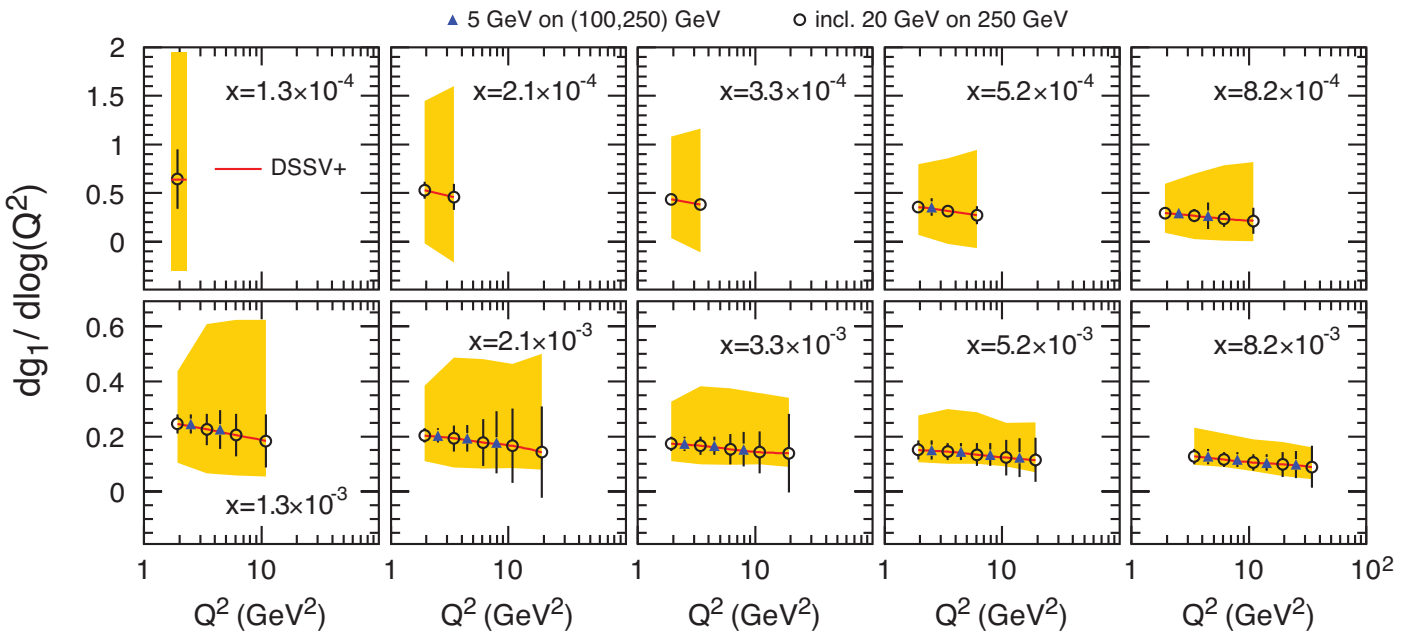
- ✓**Polarized** beams: e, p, d/^{3}He
- ✓Variable center of mass energy
- ✓Wide Q^2 range → evolution
- ✓Wide range in x, access low x

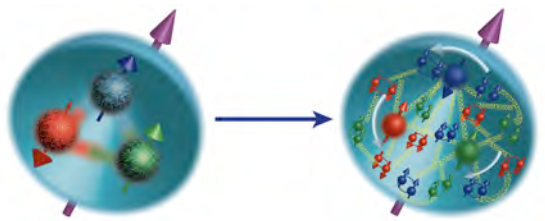
EIC's precision ➔ Significant reduction in uncertainties



Simulated data shown in best fits DSSV+ fits (DIS+ RHIC Spin)

- Statistical errors significantly lower than uncertainty bands
- Left (g_1) spin structure functions
- Below $dg_1/d\ln Q^2$ ➔ proportional to $-\Delta G$
- EIC will constrain the data in the region where gluons dominate the proton's internal dynamics



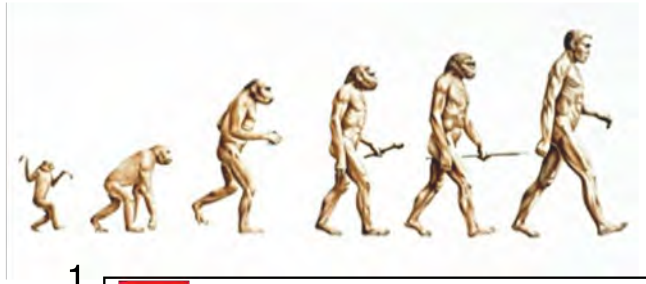


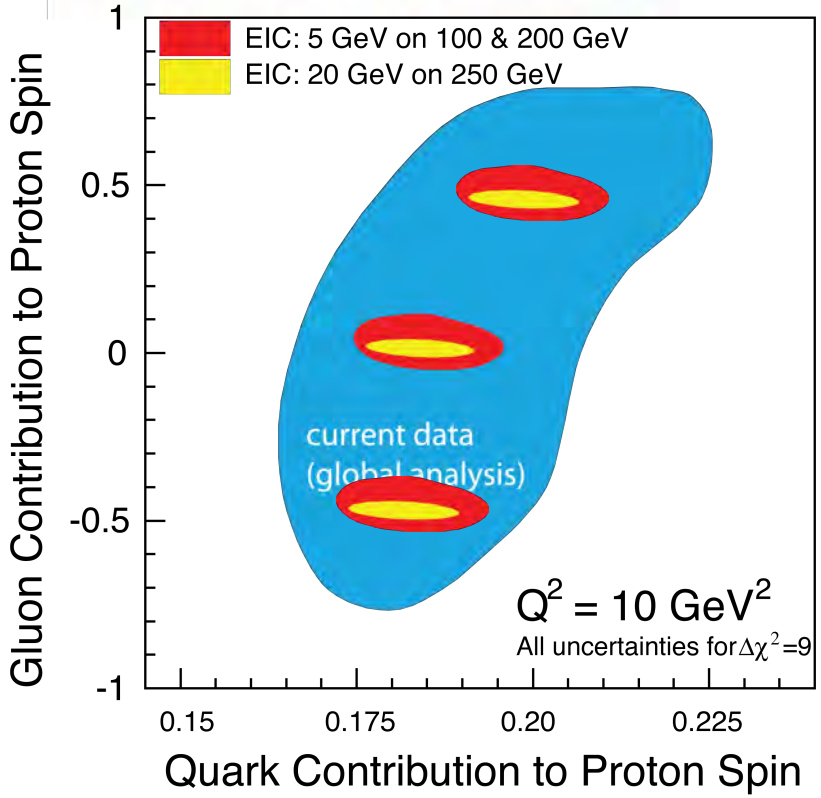
Understanding of Nucleon Spin

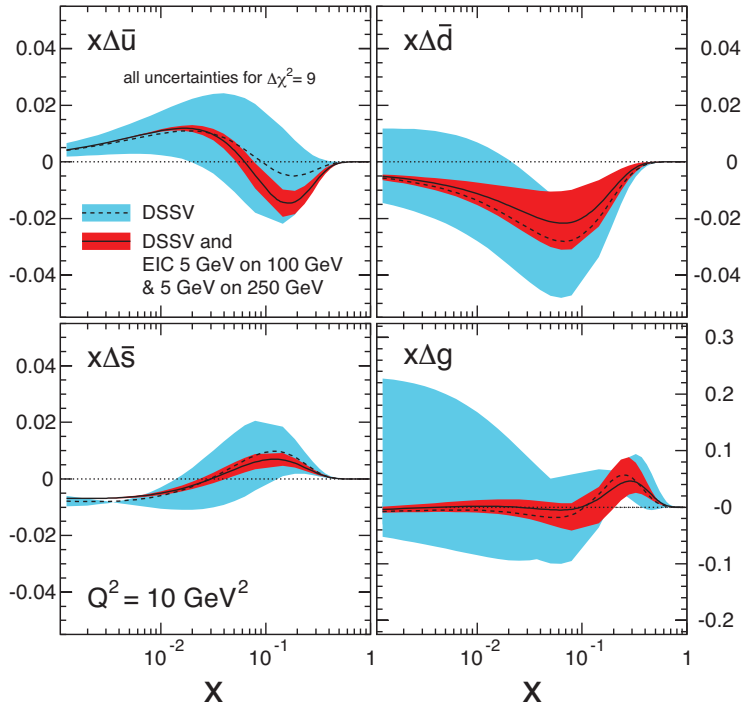
$$\frac{1}{2} = \left[\frac{1}{2}\Delta\Sigma + L_Q\right] + [\Delta g + L_G]$$

$\Delta\Sigma/2$ = Quark contribution to Proton Spin
L_Q = Quark Orbital Ang. Mom
Δg = Gluon contribution to Proton Spin
L_G = Gluon Orbital Ang. Mom

Precision in $\Delta\Sigma$ and Δg ➔ A clear idea Of the magnitude of L_Q+L_G



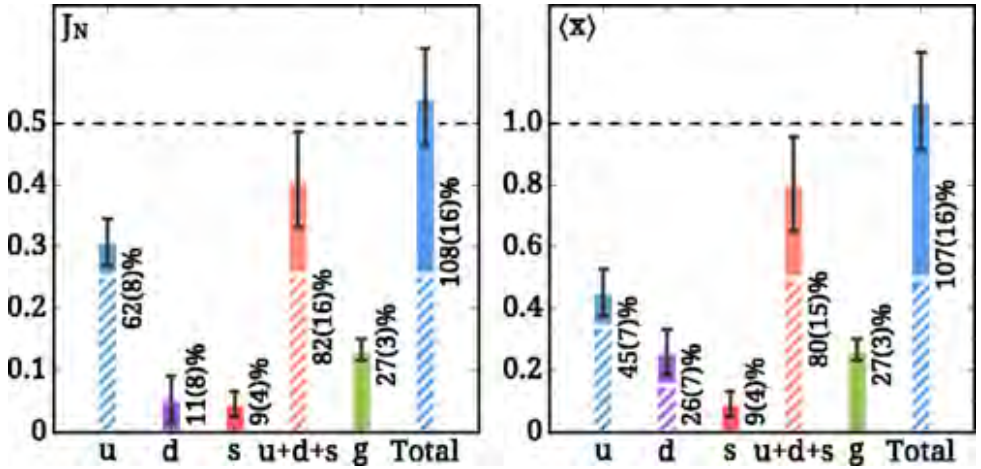




Recent progress in Lattice QCD

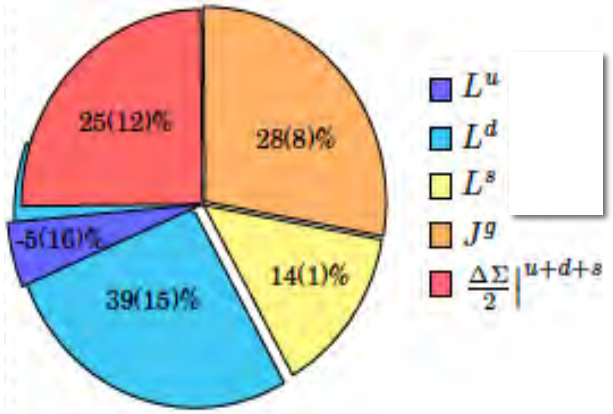
- For the first time PDFs are attempted to being calculated on the lattice! While the current uncertainty estimates are hotly debated amongst experts, *eventual* precision lattice calculations will need precision experimental measurements….
  - Accessing Gluon Distribution in Large Momentum Effective Theory, Jian-Hui Zhang et al., PRL 122, 142001, April 2019
  - First Direct lattice-QCD calculation of the x-dependence of the pion PDF, J-W.Chen et al, arXiv 1804.01483
  - Parton Distribution functions and one loop matching, https://doi.org/10.1142/S2010194516600533 , X. Ji et al.

C. Alexandrou et al. PRL 119, 142002 (2017)



Nucleon spin and momentum distribution

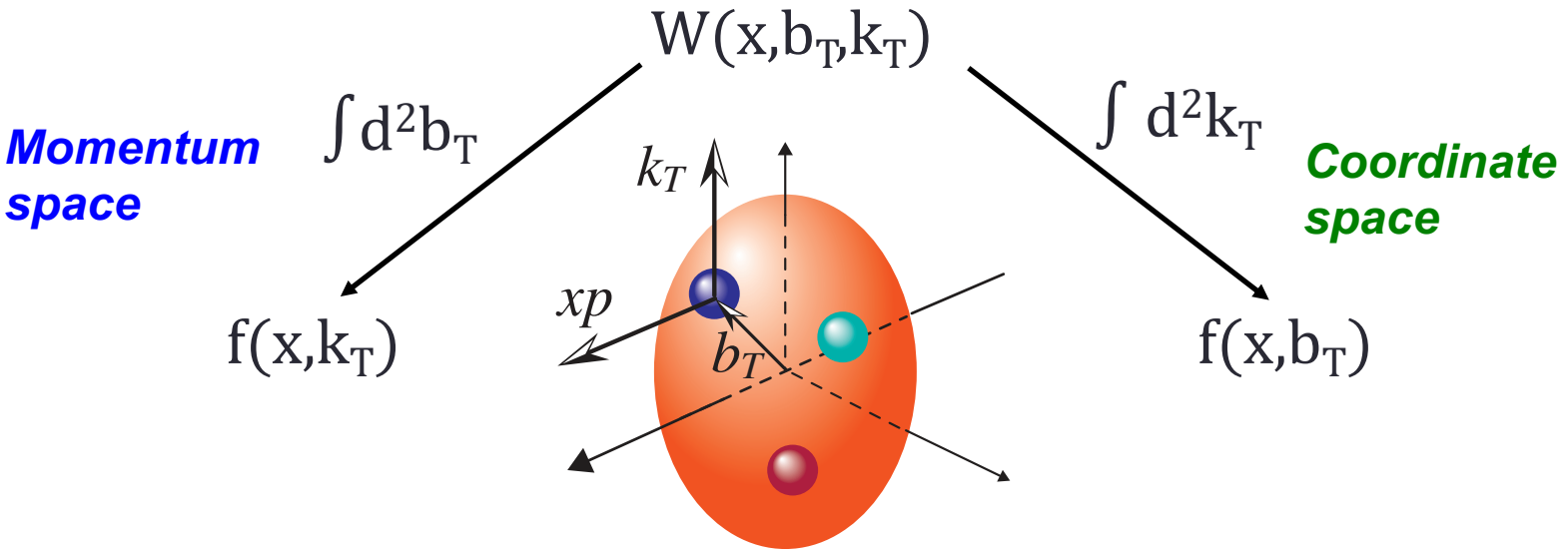
- **Gluon's spin contribution on Lattice: S_G = 0.5(0.1):** Yi-Bo Yang et al. PRL **118**, 102001 (2017)
- **J_q calculated on Lattice QCD:** χQCD Collaboration, PRD91, 014505, 2015



3-Dimensional Imaging Quarks and Gluons

Wigner functions $W(x,b_T,k_T)$

offer unprecedented insight into confinement and chiral symmetry breaking.



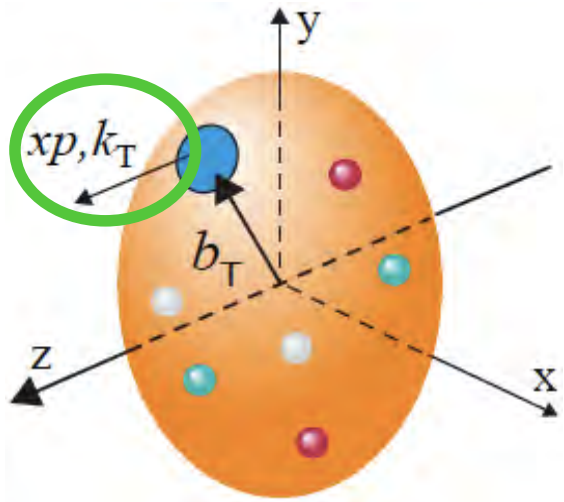
Spin-dependent 3D momentum space images from semi-inclusive scattering → **TMDs**

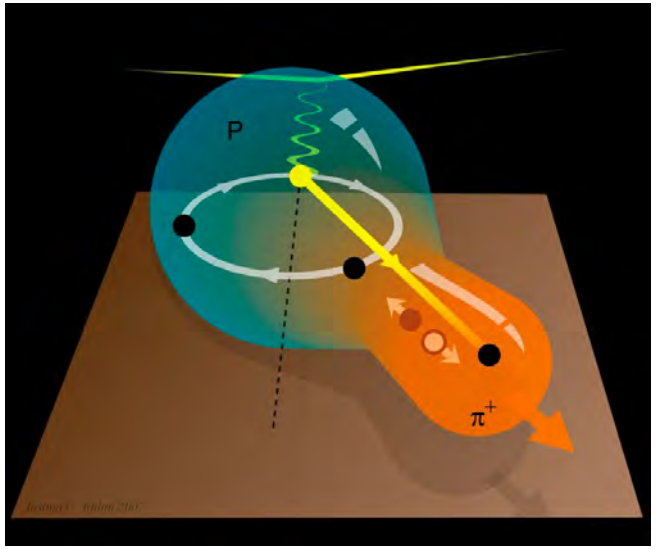
Spin-dependent 2D coordinate space (transverse) + 1D (longitudinal momentum) images from exclusive scattering → **GPDs**

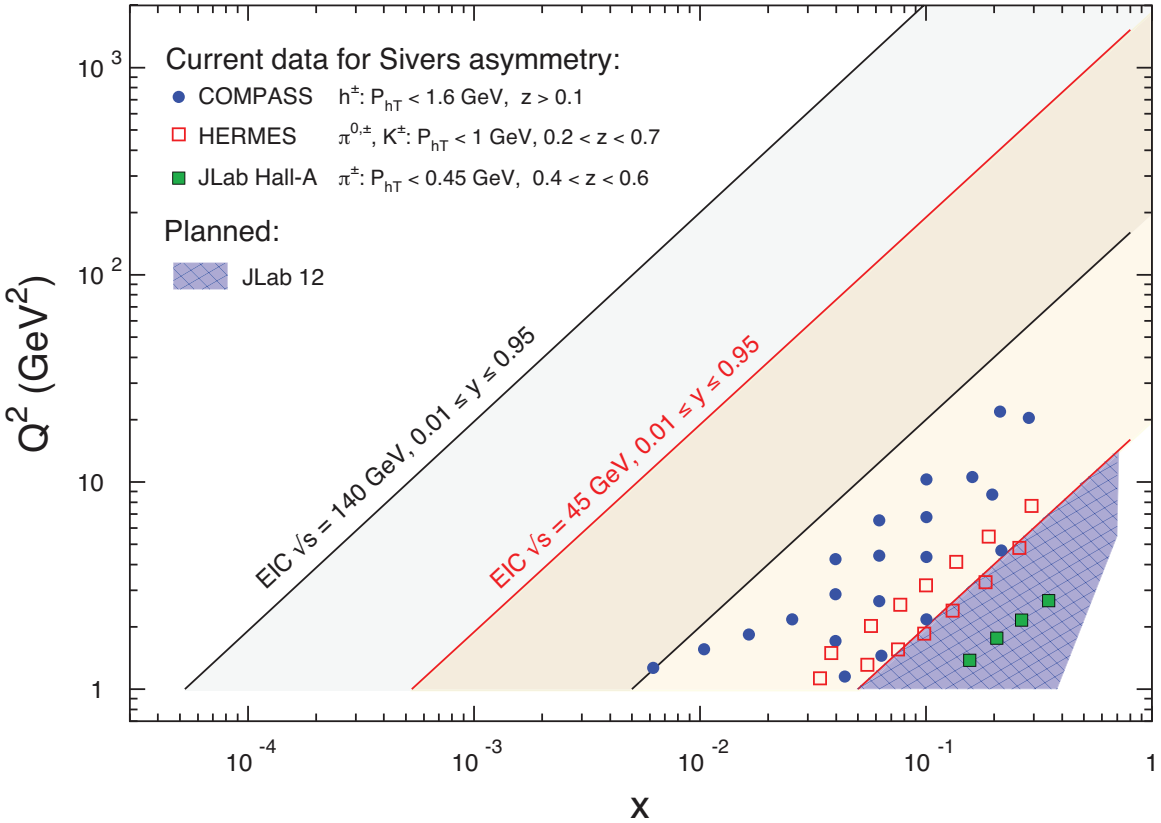
Position and momentum → Orbital motion of quarks and gluons

Measurement of Transverse Momentum Distribution

Semi-Inclusive Deep Inelastic Scattering







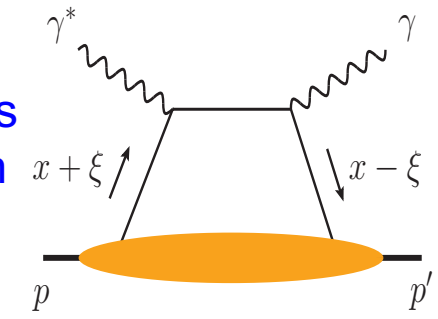
- ❑ Naturally, two scales:
  - ✧ high Q – localized probe To "see" quarks and gluons
  - ✧ Low p_T – sensitive to confining scale to their confined mo
  - ✧ *Theory – QCD TMD factorization*
  - ✧ *Experiment – Particle ID critical for these measurements*

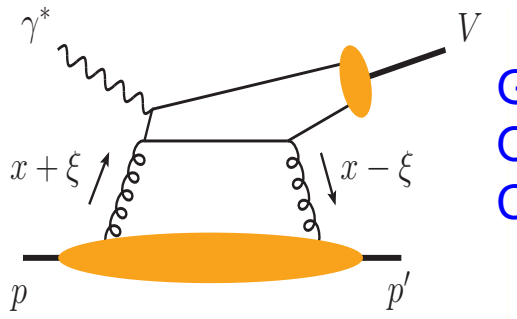
EIC will expand the x-Q^2 range significantly

Spatial Imaging of quarks & gluons

Generalized Parton Distributions

Quarks Motion





Gluons: Only @ Collider

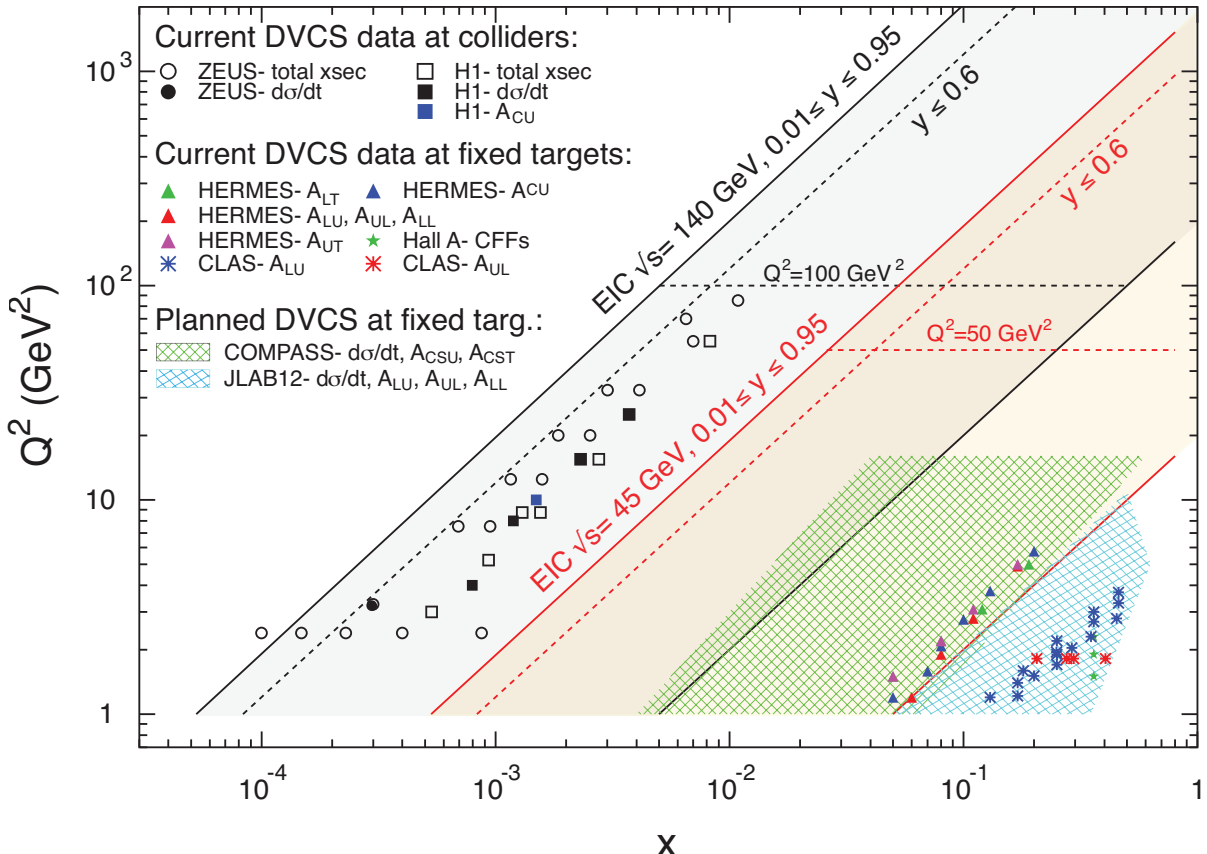
Deeply Virtual Compton Scattering Measure all three final states

e + **p** → e'+ **p'**+ γ

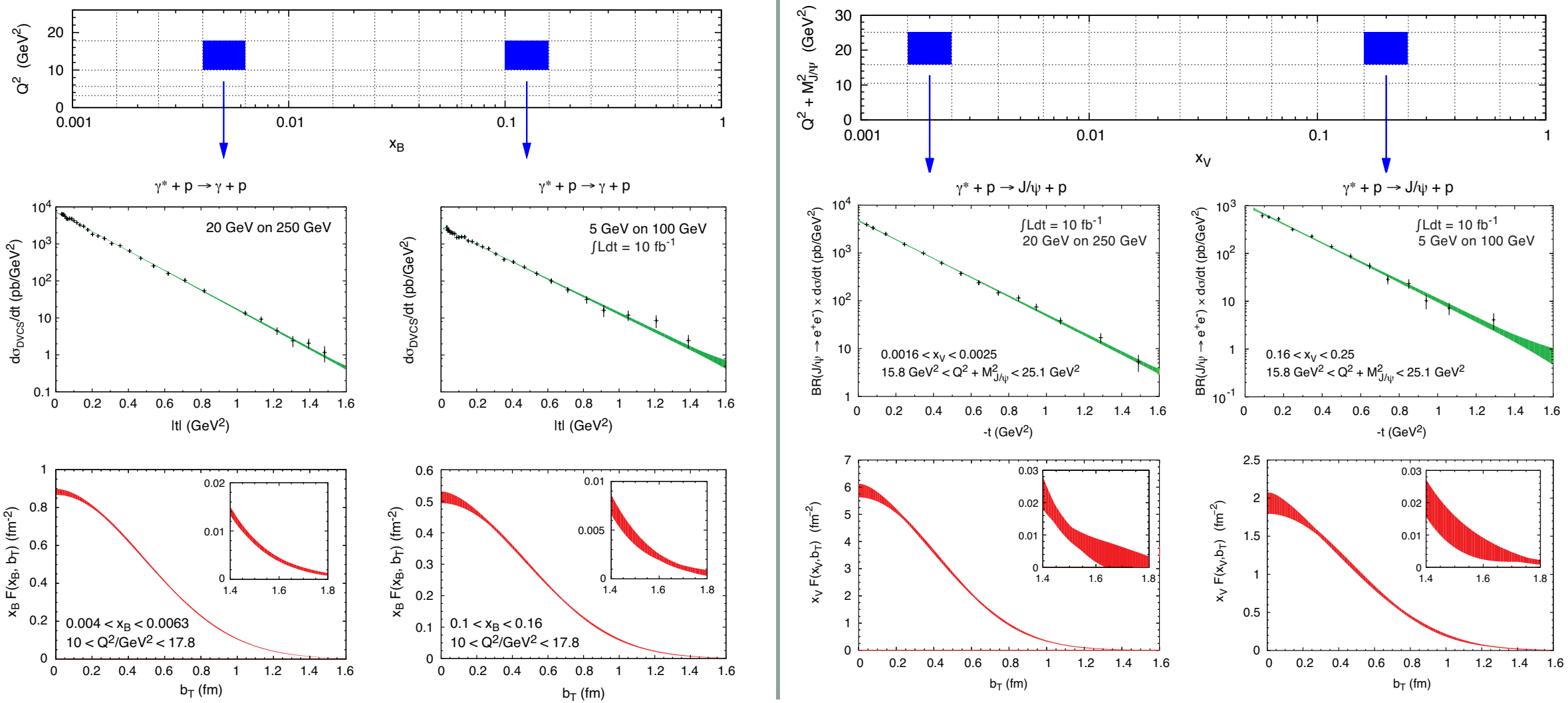
Fourier transform of momentum transferred=(p-p') → Spatial distribution

Requires forward detection of scattered target close to its original direction: Detector/IR/Machine interface critical

Does not require polarization, But if it is there ➔ should affect observations



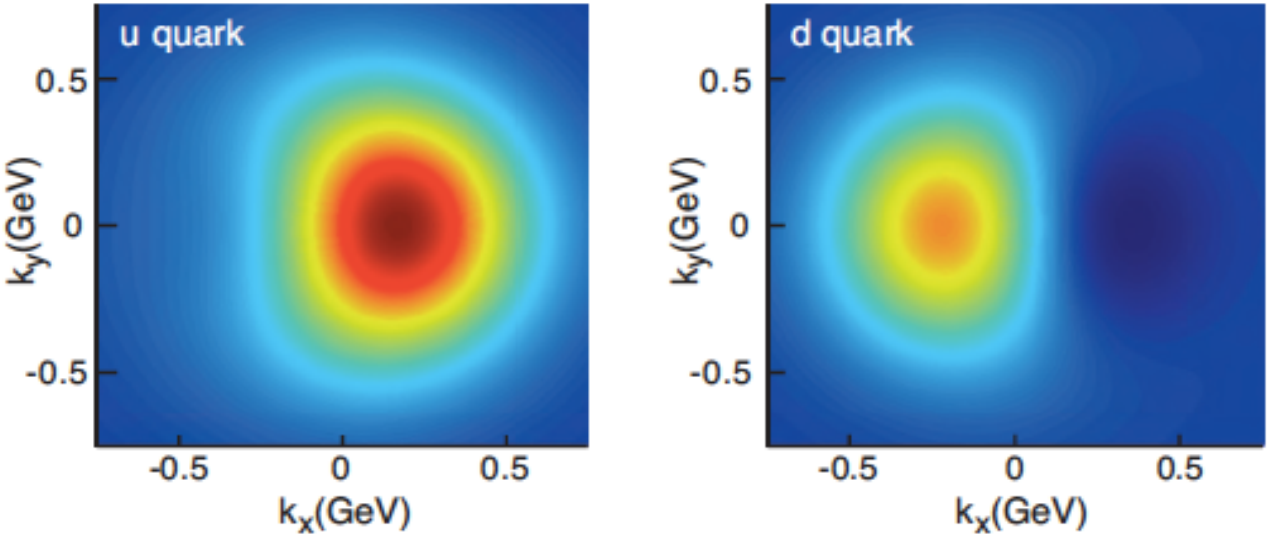
Spatial distribution of partons



2+1 D partonic image of the proton with the EIC

Spin-dependent 2D momentum space images from semi-inclusive scattering

Transverse Momentum Distributions

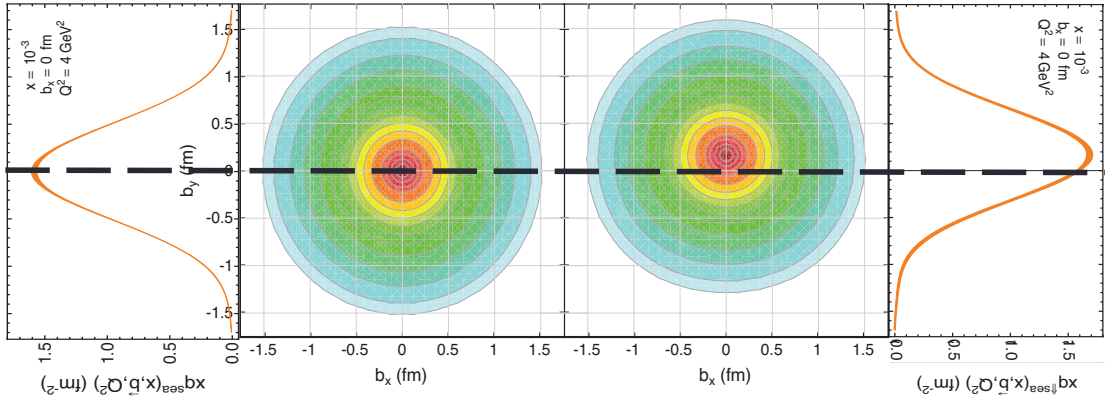


Spin-dependent 2D coordinate space (transverse) + 1D (longitudinal momentum) images from exclusive scattering

Transverse Position Distributions

sea-quarks

unpolarized polarized



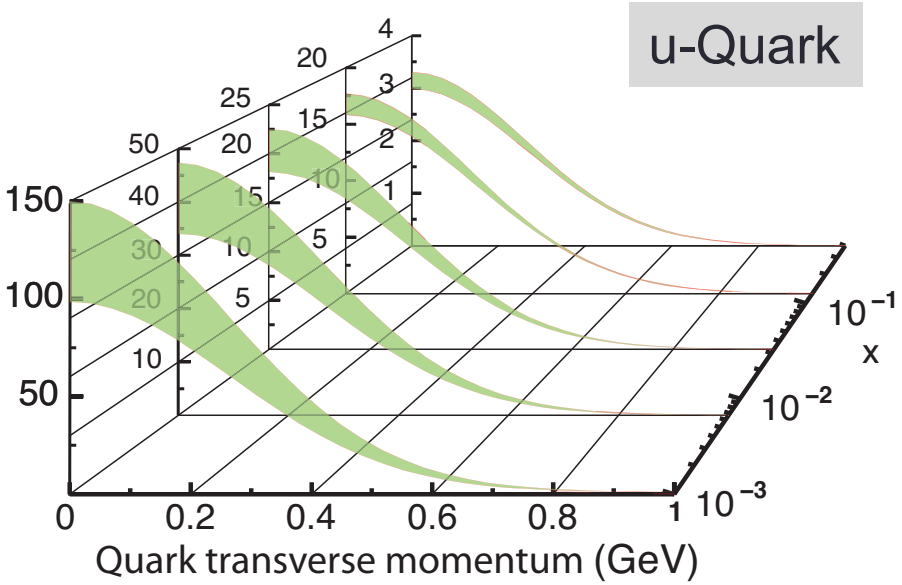
2+1 D partonic image of the proton with the EIC

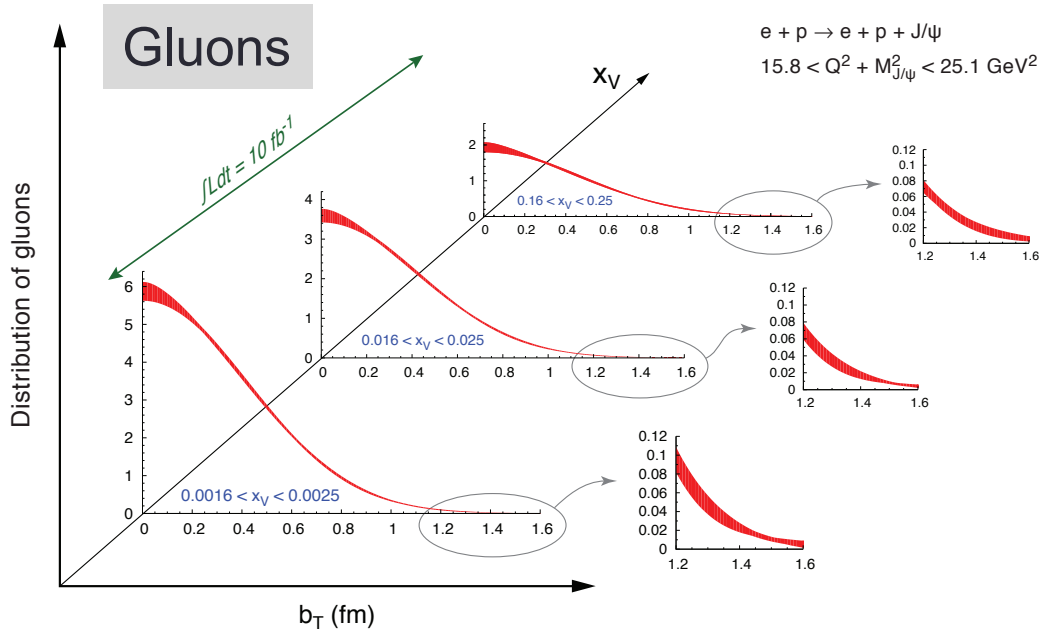
Spin-dependent 3D momentum space images from semi-inclusive scattering

Transverse Momentum Distributions

Spin-dependent 2D coordinate space (transverse) + 1D (longitudinal momentum) images from exclusive scattering

Transverse Position Distributions



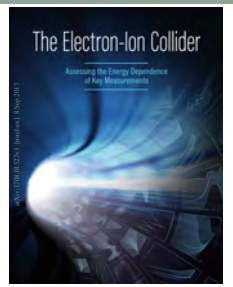


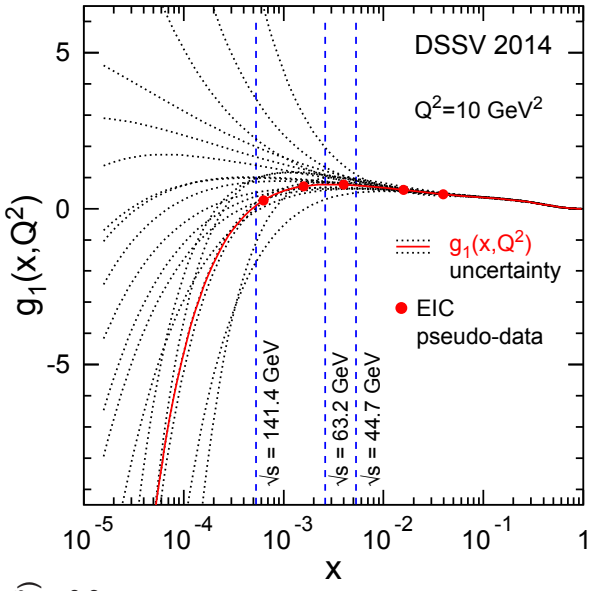
Only a collider with wide x-Q^2 range can achieve this

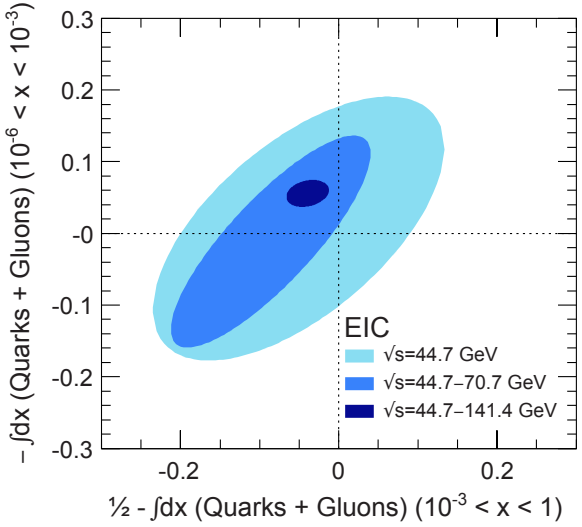
Argument for the highest possible energy:

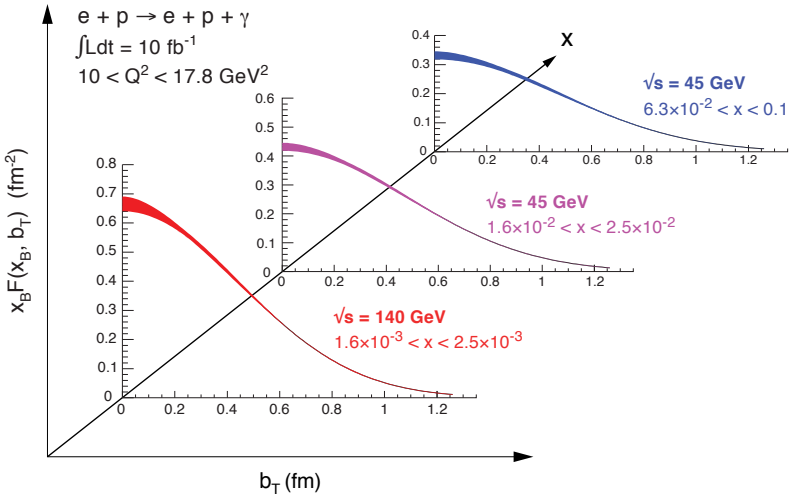
Phy. Rev. D 96 (2017) 11, 114005

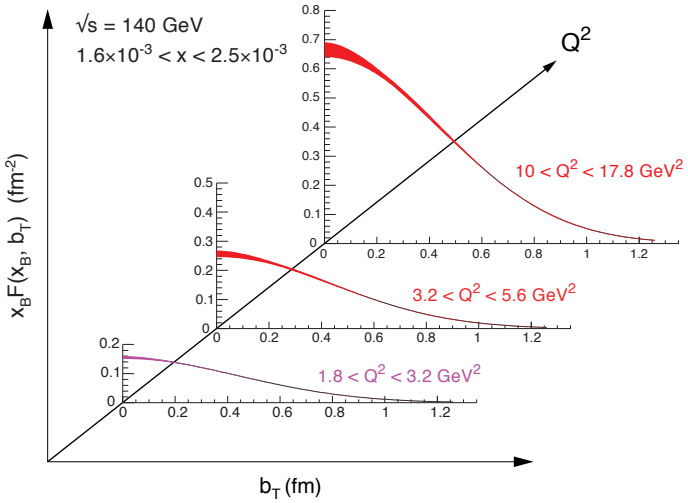
E.C. Aschenauer, S. Fazio, J. H. Lee, H. Mantysaari, B. Page, B. Schenke, T. Ullrich, R. Venugopalan, & P. Zurita







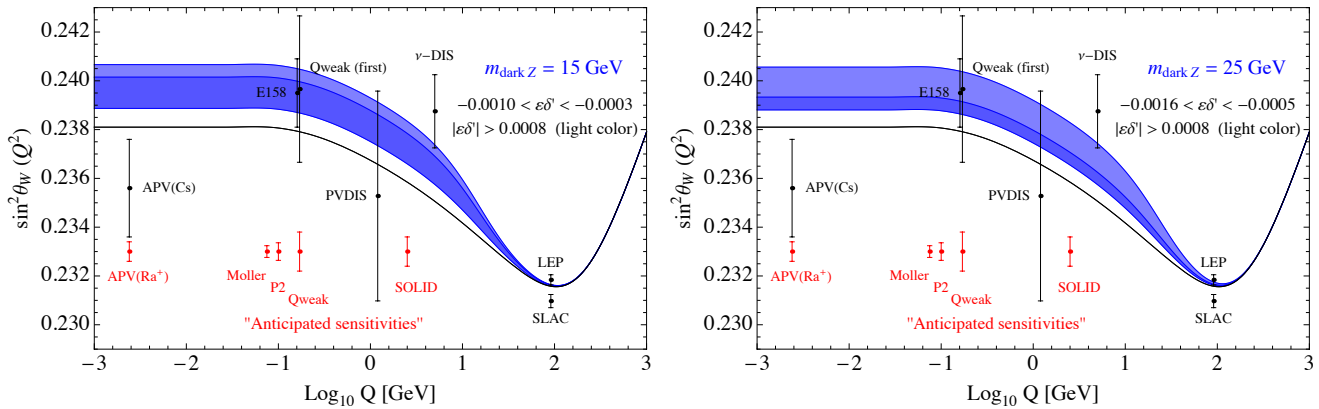




Message from these studies: High energy is not only good for the low-x physics with nuclei, but it also helps hadron structure studies…

$\sin^2\Theta_W$ with the EIC: Physics Beyond SM searches:

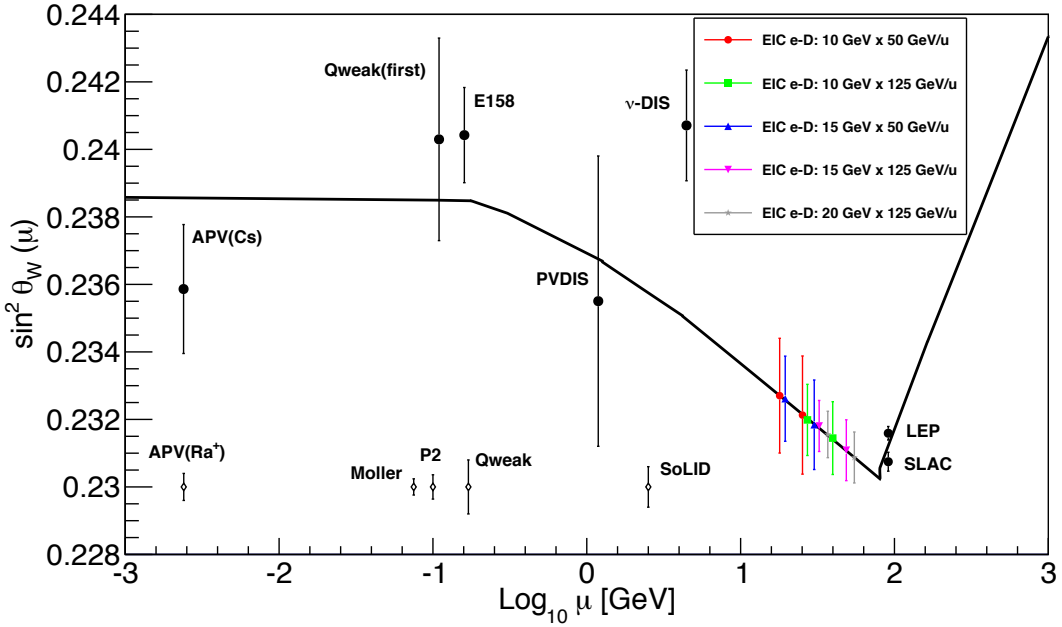
Case for high -uminosity and high-energy



H. Davoudiasl, H. S. Lee, W. J. Marciano, Low Q^2 Weak Mixing Angle Measurement and Rare Higgs Decays, arXiv: 1507.00352 Phys. Rev. D 92, 5, 05505 (2015)

- Precision parity violating asymmetry measurements e/D
- Deviation from the "curve" may be hints of BSM scenarios including: Lepto-Quarks, RPV SUSY extensions, E_6/Z' based extensions of the SM
- Caveat: Requires high luminosity i.e. will take time, but also other competitive searches around the world.

Y. X. Zhao, A.D., K. Kumar, Eur. Phys. J. A53 (2017) 3, 55



Other recent publications

- The Deepest Recesses of The Atom, A. Deshpande & R. Yoshida, Scientific American, June 2019
- SIDIS, Parton Distributions, and Fragmentation Functions at the future EIC; E. C. Aschenauer, I. Borsa, R. Sassot, C. Van Hulse, PRD99, 094004 (2019)
- Measuring Weizsaecker-Williams dirtsibution of linearly polarized gluons in an EIC thorugh di-jet asymmetries, A. Dumitru, V. Skokov, T. Ullrich PRC 99, 015204 (2019)
- Accessing the energy dependence of Key Measurements, E.C. Aschenauer et al. Rep. Prog. Phys. 82 vol.2 (2019)
- Measuring gluon Sivers at the future EIC, L. Zheng et al., Int. J. Mod. Phys. Conf. Ser. 46 (2018) 1860021
- Di-Jets the path to the (un)polarized partonic photon structure at the EIC, X. Chu & E.C. Aschenauer, PoS DIS2018 (2018) 168

See: https://wiki.bnl.gov/eic/index.php/Publications_and_presentations

Opportunities for YOU: Physics beyond the EIC White Paper:

- Heavy quark and quarkonia (c, b quarks) studies beyond HERA, with 100-1000 times luminosities (??) Does polarization of hadron play any role?
- Quark Exotica: 4,5,6 quark systems…?
- Impact of precision measurements of unpolarized PDFs, especially at high x, for LHC
- What role would TMDs in e-p play in W-Production at LHC?
- Study of jets: Internal structure of jets
- Jet propagation in nuclei… energy loss in cold QCD medium: a topic interest
- Initial state affects QGP formation!….. p-A, d-A, A-A at RHIC and LHC: many puzzles
- Gluon TMDs at low-x!
- Polarizedd light nuclei in the EIC
- Entanglement entropy in nuclear medium and its connections to fragmentation, hadronization and confinement

Summary & outlook

- The electron ion collider with polarized beams will be an extremely versatile facility to study QCD; and via precision/controlled afforded by high-luminosity high-energy DIS, unprecedented study of hadron structure and partonic dynamics is possible.

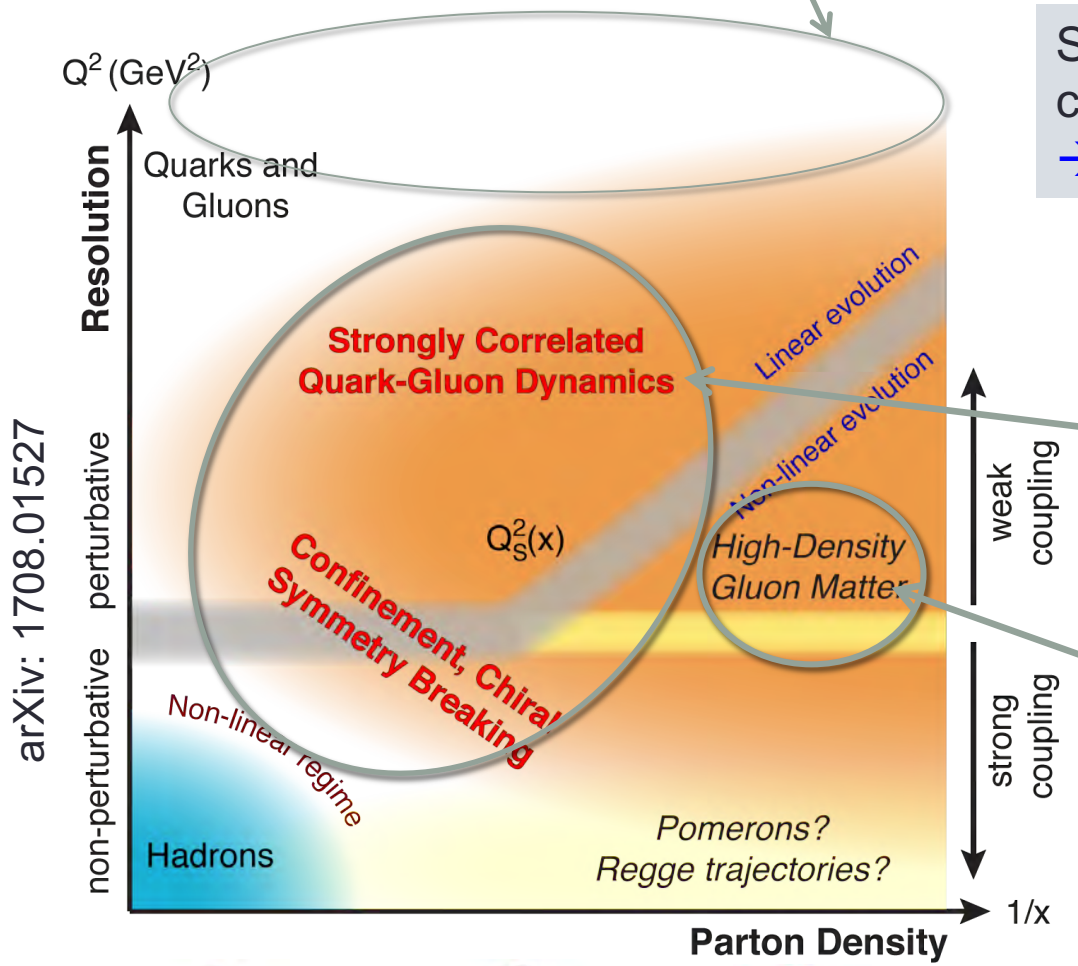
- The hugely expanded x-Q^2 coverage coupled with high luminosity (large acceptance detector, & polarimetry which was not discussed in this talk) is the key to its success.

- A recent review of EIC science by the US National Academy of Sciences, Engineering and Medicine (NAS) declared the science of EIC : fundamental and compelling and its realization, timely. ➔ We await formal process of EIC realization to get started.

QCD Landscape to be explored by EIC

QCD at high resolution (Q^2) —weakly correlated quarks and gluons are well-described

Strong QCD dynamics creates many-body correlations between quarks and gluons
→ hadron structure emerges

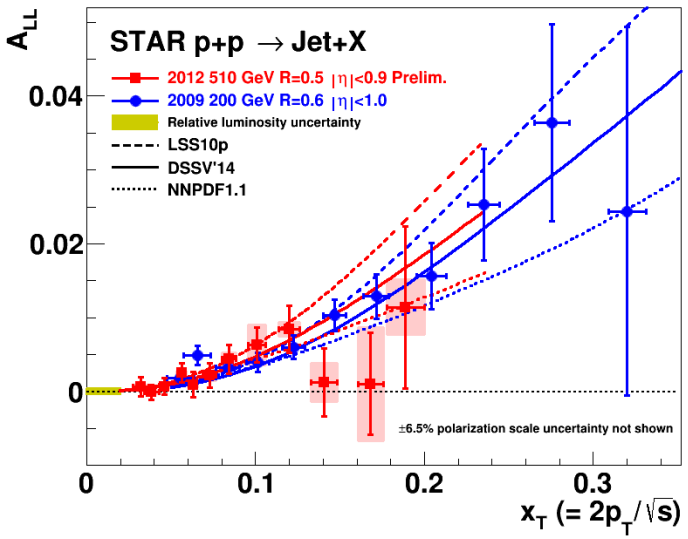


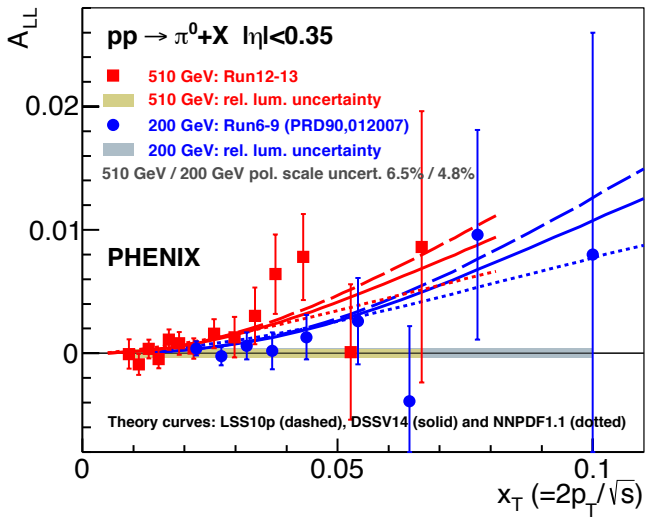
EIC will systematically explore correlations in this region.

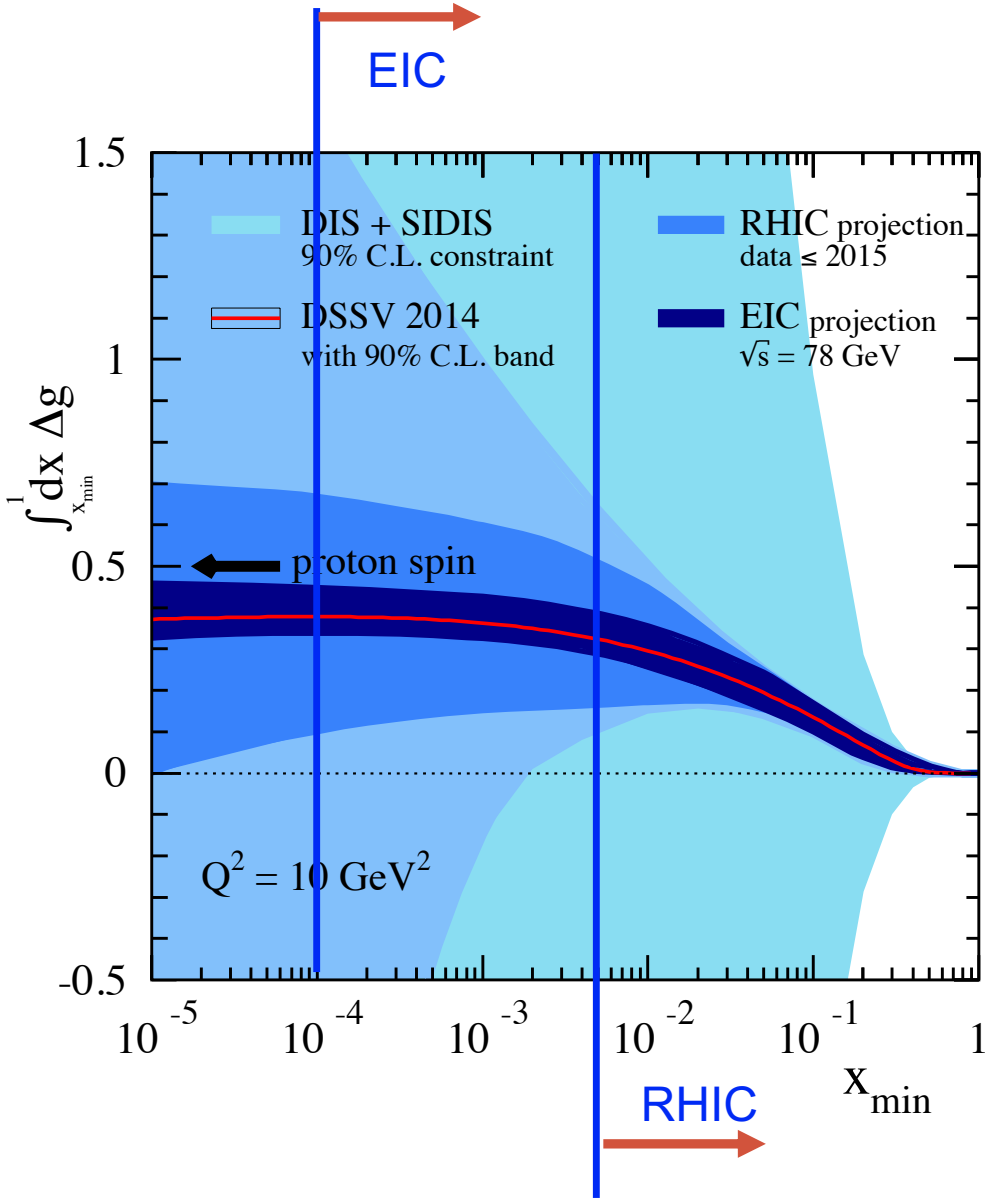
An exciting opportunity: Observation by EIC of a new regime in QCD of weakly coupled high density matter

Cold QCD plan

RHIC Spin: ΔG Impact







Double longitudinal asymmetries for jets and p0 production from STAR and PHENIX Collaborations, respectively