Spin Physics at an Electron Ion Collider

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Disclaimer:
Neither complete nor comprehensive review

Results of simulations based on the U.S. EIC white paper Arxiv:1212.1701
Thanks to my co-editors, Abhay Deshpande and Jianwei Qiu

"It is difficult and often impossible to judge the value of a problem correctly in advance; for the final award depends upon the gain which science obtains from the problem."

David Hilbert, 1900 Paris

Nucleon Spin: Why should we/you care?

- Has been a laboratory for QCD in the last 30 years
  - An important example: Test of the Bjorken Sum Rule
- The nucleon is a strongly interacting many body confined system
- Turns out to be an important window into QCD dynamics

Nature: http://www.nature.com/milestones/milespin/index.html

Milestone 13: Supersymmetry

"Despite its success, the standard model is unsatisfactory for a number of reasons. First, although the electromagnetic and weak forces have been unified into a single force, a 'grand unified theory' that brings the strong interaction into the fold remains elusive. Second, the origins of mass are not fully understood. Third, gravity is not included."

Missed the Bjorken sum rule test and the spin decomposition

The Overarching Science Problem ?

- The structure of all nuclear matter in Quantum Chromodynamics (QCD) and ultimately confinement

What do we know?

- QCD successes in the perturbative regime are impressive, many experimental tests led to this conclusion

But

- Many non-perturbative aspects of QCD including confinement are still puzzling. Confinement has been identified as one of the top millenium problems in Physics! (Gross, Witten,….) Many conferences have been devoted to this problem

Present theoretical tools:

Quoting from F. Wilczek (XXIV Quark Matter 2014)

Emergent Phenomena

Quarks (and Glue) at Frontiers of Knowledge

Challenges, Opportunities

The study of the strong interactions is now a mature subject - we have a theory of the fundamentals* (QCD) that is correct* and complete*.

In that sense, it is akin to atomic physics, condensed matter physics, or chemistry. The important questions involve emergent phenomena and "applications".

Two Protons - Or More?

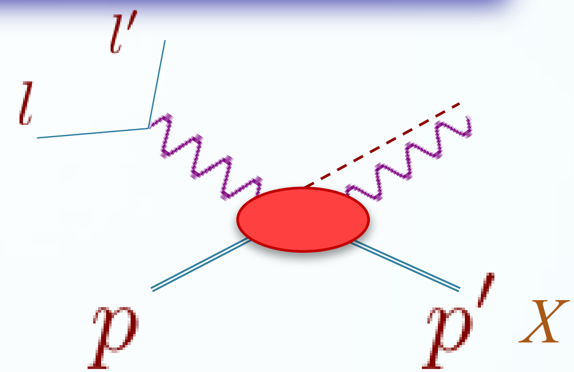
We have two very different pictures of protons, in the lab frame (quark model) and in the infinite momentum frame (parton model). Each is very successful.

How does one proton manage to become the other? Are there intermediate pictures?

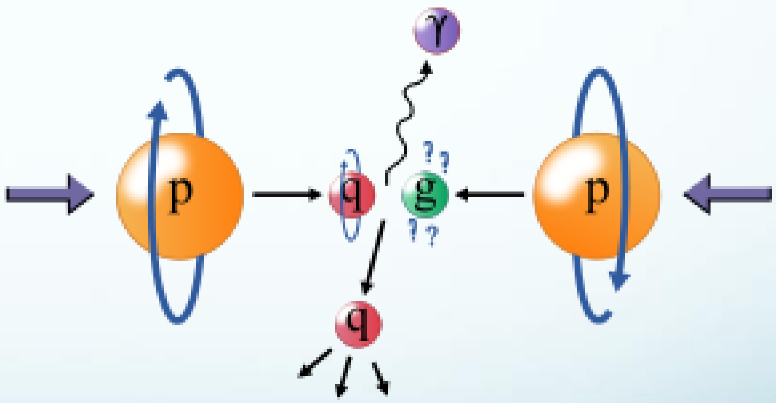
One Proton Spin- Two or More Sum Rules?

See Xiandong Ji's talk

Experimental Tools



- Electromagnetic Probes
  - Deep inelastic scattering (DIS)
  - Semi-inclusive DIS
  - Deep virtual Compton scattering (DVCS)/meson production



- Hadronic Probes
  - Inclusive hadron production
  - Inclusive Jet production
  - Drell-Yan
- Use of Protons and Nuclei targets
  - polarized p, D, HD, NH_3, ND_3, ^{6}LiD ^{3}He

Impressive experimental progress in QCD spin physics in the last 30 years

- **Inclusive spin-dependent DIS**
  - CERN: EMC, SMC, COMPASS
  - SLAC: E80, E142, E143, E154, E155
  - DESY: HERMES
  - JLab: Hall A, B and C

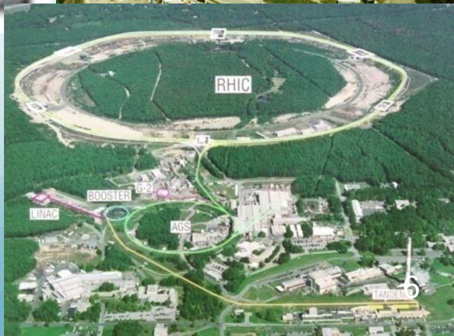
- **Semi-inclusive DIS**
  - SMC, COMPASS
  - HERMES, JLab

- **Polarized pp collisions**
  - ANL: ZGS
  - FERMILAB: E704,….
  - BNL: AGS, PHENIX, STAR and BRAHMS

- **Polarized e+e- collisions**
  - KEK: Belle





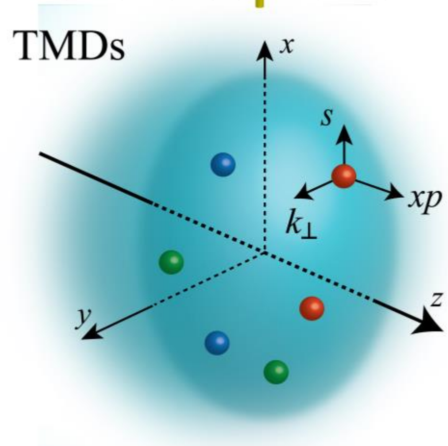
Unified View of Nucleon Structure

5D Dist.

$W_p^u(x,k_T,r_T)$ *Wigner distributions*

dr_T $\qquad$ d^2k_T

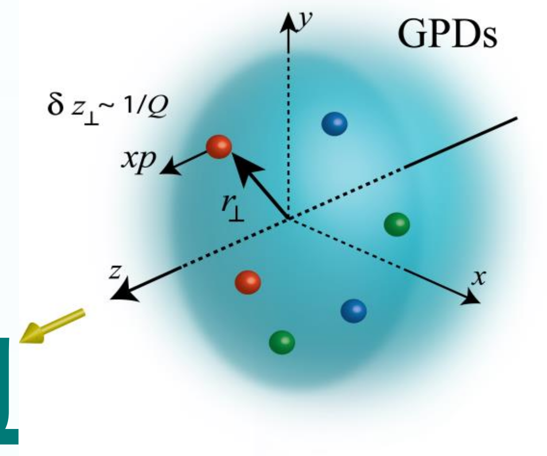
Transverse Momentum Dist.



TMD $f_1^u(x,k_T)$, $h_1^u(x,k_T)$

GPD

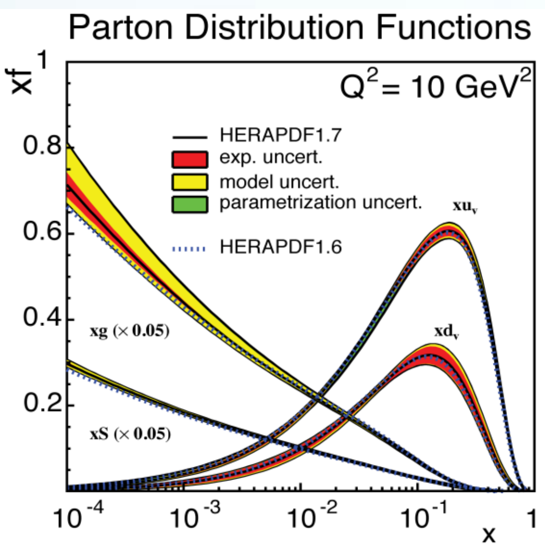
Generalized Parton Dist.



"3D" imaging

d^2k_T $\qquad$ d^2r_T

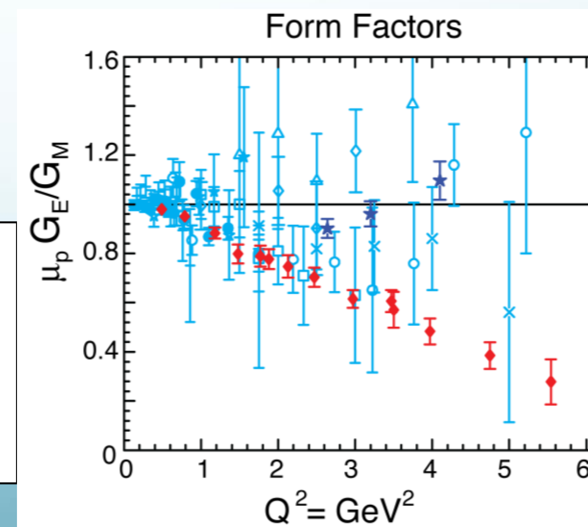
dx &Fourier Transformation



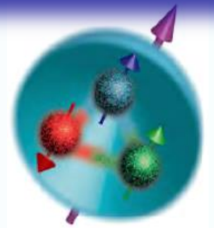
PDFs
$f_1^u(x)$, ..
$h_1^u(x)$

1D

Form Factors
$G_E(Q^2)$,
$G_M(Q^2)$



Proton spin and hadron structure?
Beyond a one dimensional view



- **Proton spin "puzzle":**

  Quarks carry $\sim 30\%$ of proton's spin

  How does quark and gluon dynamics generate the rest of the proton spin?

- **3D structure of nucleon: (2D space +1 in momentum or 3D in momentum)**

Color Confinement — **Asymptotic freedom** — Q (GeV)

200 MeV (1 fm) — 2 GeV (1/10) fm) — Probing momentum

How to explore the "full" gluon and sea quark contribution?

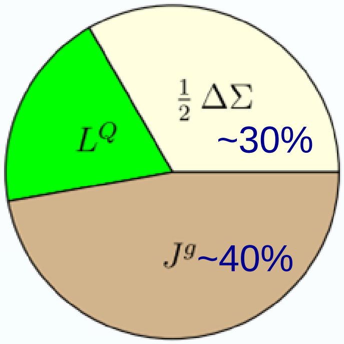
How to quantify the role of orbital motion?

Can we scan the nucleon to reveal its 3D structure?

Where are we?

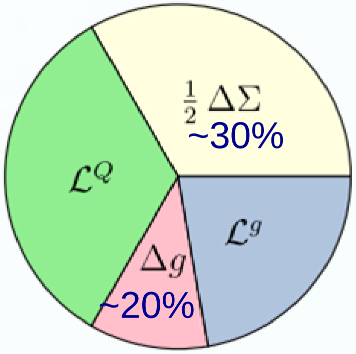
http://www.int.washington.edu/news_12-49w.html

Ji
1997



Two Views

Jaffe-Manohar
1990



3-dimensional mapping of the nucleon structure has just begun allowing for the determination of the orbital angular momentum of partons

- **Continuing near-term studies**:
  - COMPASS-II, JLab 12 GeV
  - RHIC-Spin

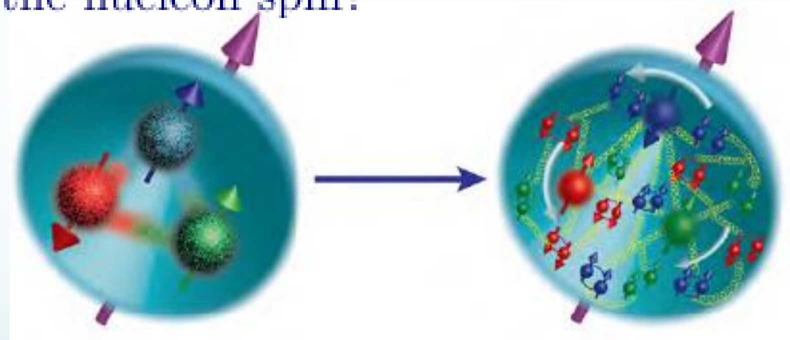
Fundamental QCD Question

How do quarks and gluons confine themselves into a proton?

The color confinement

"Hints" from knowing hadron structure

- **Hadron structure:**
  - **How are the sea quarks and gluons, and their spins, distributed in space and momentum inside the nucleon?** How are these quark and gluon distributions correlated with overall nucleon properties, such as spin direction? What is the role of the orbital motion of sea quarks and gluons in building the nucleon spin?



- **Proton spin:**

If we do not understand proton spin from QCD, we do not understand QCD!

It is more than the number ½! It is the interplay between the intrinsic properties and interactions of quarks and gluons

Electron-Ion Collider

- **An ultimate machine to provide answers to QCD questions**

  - ✧ A collider to provide kinematic reach well into the gluon-dominated regime

  - ✧ An electron beam to bring to bear the unmatched precision of the electromagnetic interaction as a probe

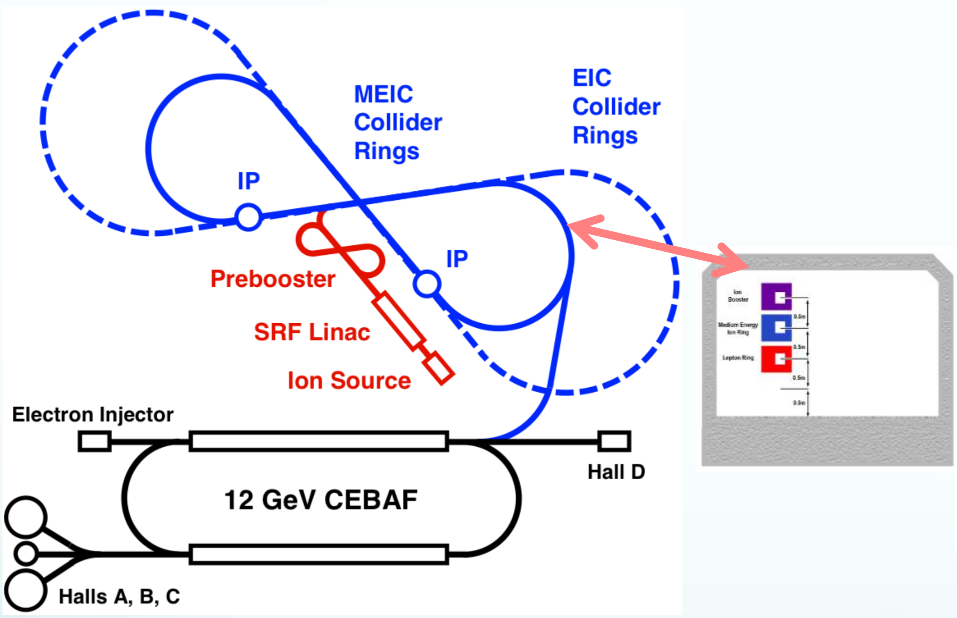
  - ✧ Polarized nucleon beams to determine the distributions and correlations of sea quark and gluon distributions with the nucleon spin

- **A machine at the frontier of polarized luminosity, combined with versatile kinematics and beam species**

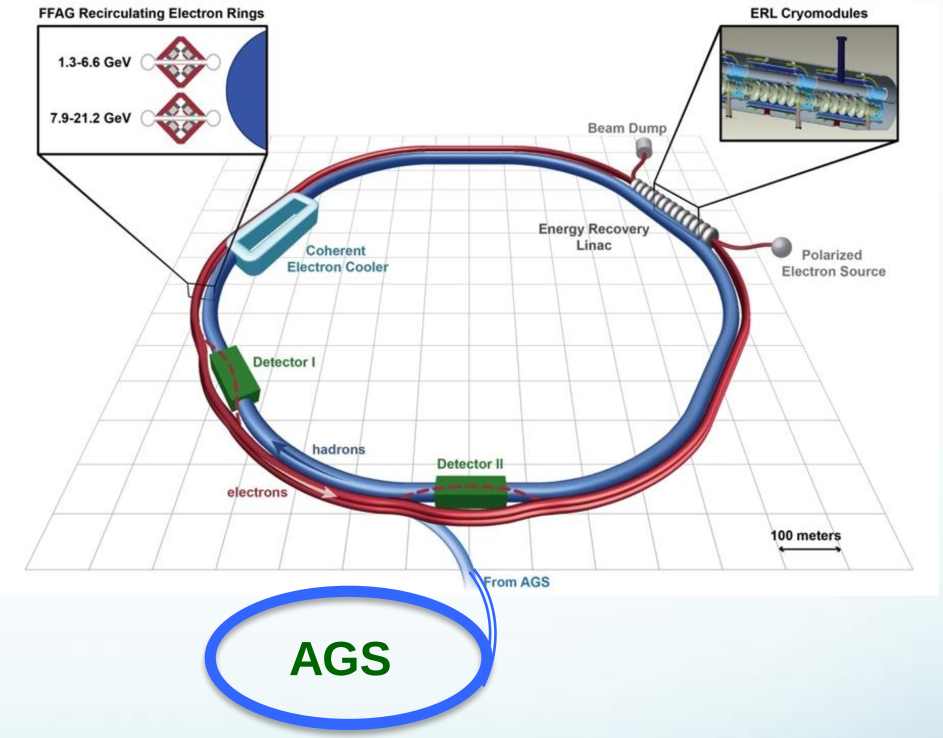
Answers all above QCD questions at a single facility

U.S.-based EICs – the Machines

MEIC (JLab)



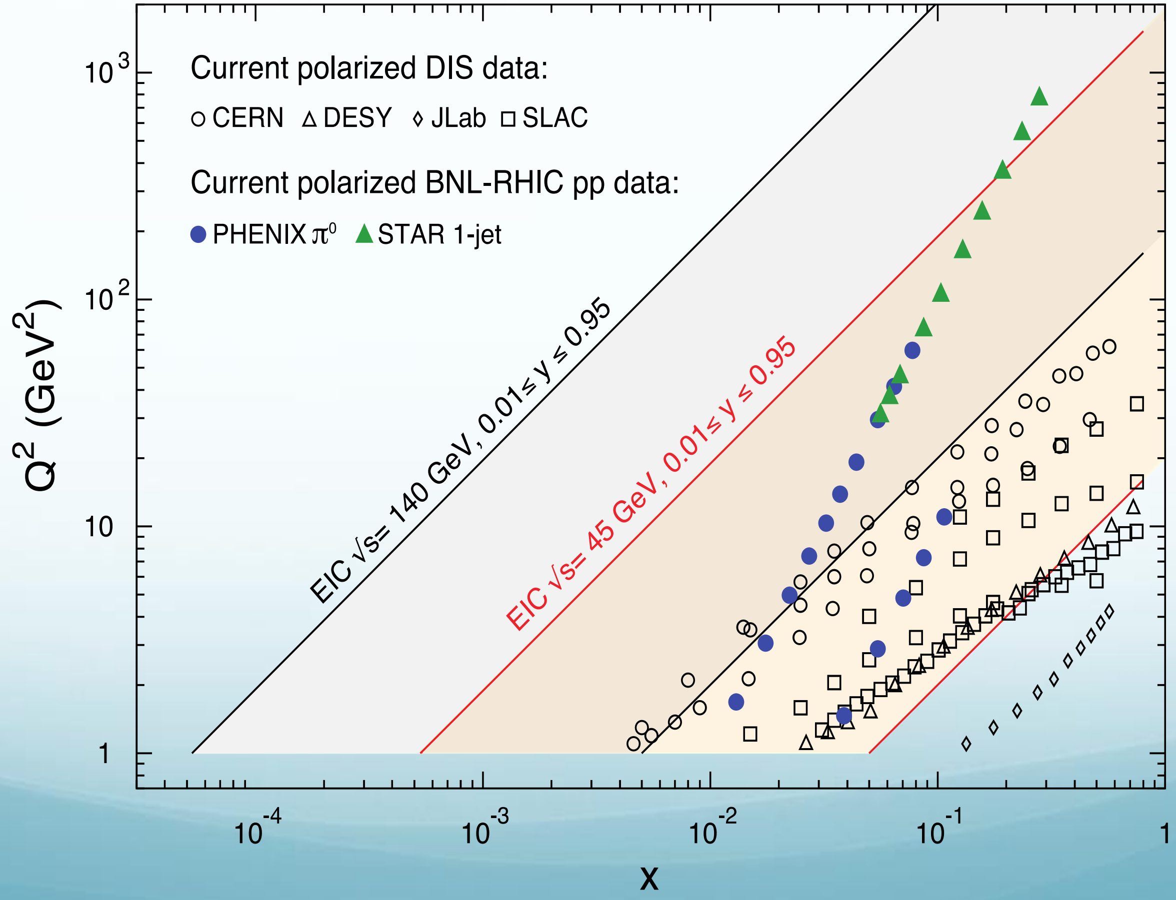
eRHIC (BNL)



- ✧ First polarized electron-proton/light ions collider in the world
- ✧ First electron-nucleus (various species) collider in the world
- ✧ Both cases make use of existing facilities

Kinematics and machine properties for e-N collisions

- ✓ First polarized e-p collider
- ✓ Polarized beams: e, p, d/^{3}He
- ✓ Variable center of mass energy
- ✓ **Luminosity L_{ep} ~ $10^{33\text{-}34}$ $cm^{-2}s^{-1}$**, HERA luminosity ~ 5×10^{31} cm^{-2} s^{-1}



EIC: Goals and deliverables

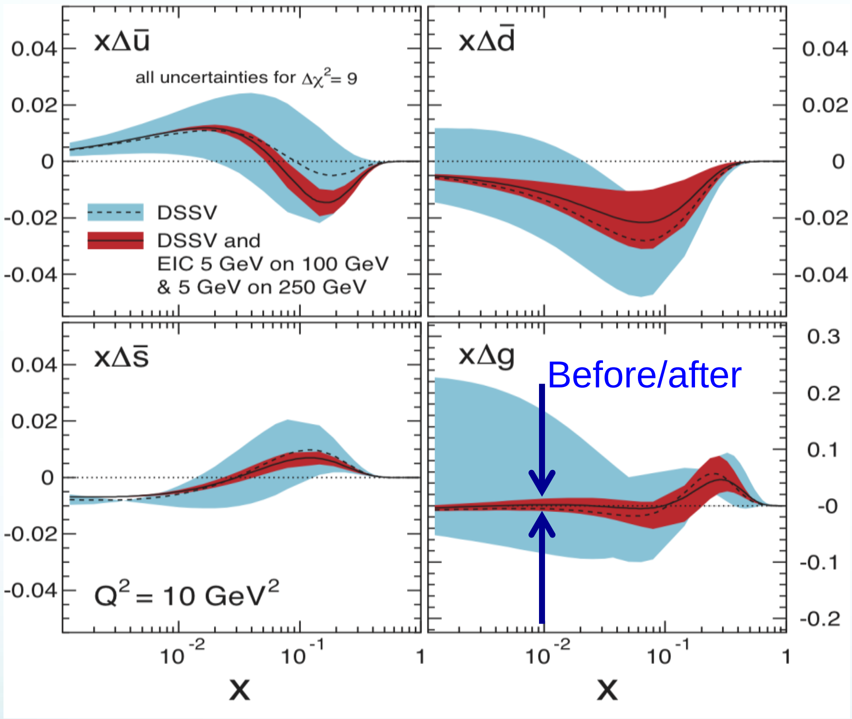
The key measurements

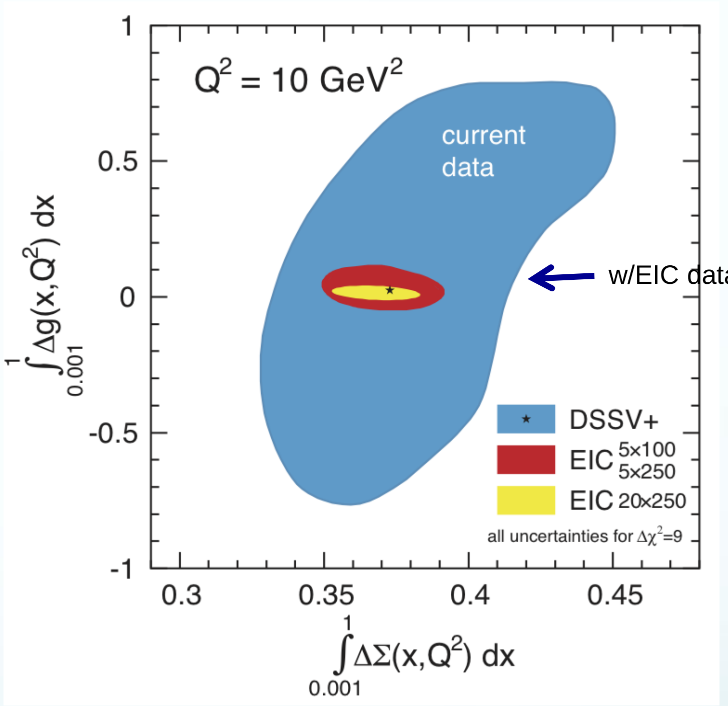
Why is it a unique facility with capabilities unmatched by existing and planned facilities?

Proton spin and hadron structure?

- **The EIC – the decisive measurement** (1st year of running):

(Wide Q^2, *x* including low *x* range at EIC)

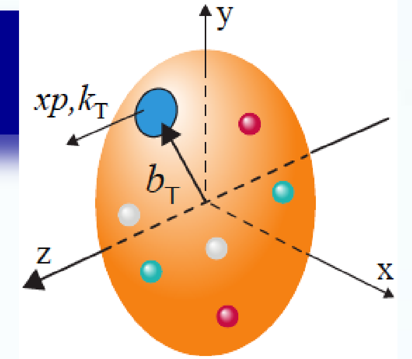




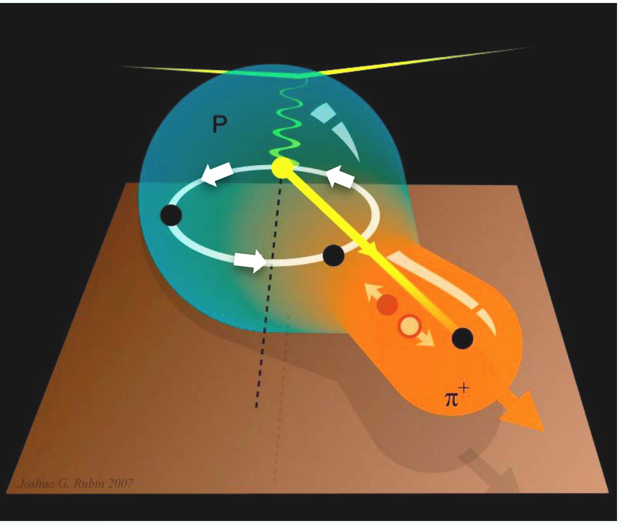
No other machine in the world can achieve this!

- **Solution to the proton spin puzzle:**
  - ***Precision measurement of ΔG – extends to smaller x regime***
  - ***Orbital angular momentum – motion transverse to proton's momentum***

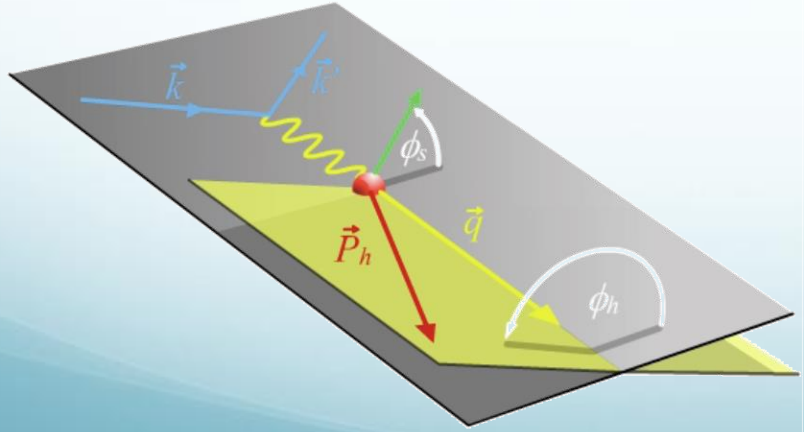
EIC is the best for probing TMDs



- **TMDs - rich quantum correlations:**



- **Naturally, two scales and two planes:**
  - Two scales (theory-QCD TMD factorization):
    high Q - localized probe
    Low p_T - sensitive to confining scale
  - Two planes:
    angular modulation to separate TMDs



$$A_{UT}(\varphi_h^l, \varphi_S^l) = \frac{1}{P}\frac{N^\uparrow - N^\downarrow}{N^\uparrow + N^\downarrow}$$

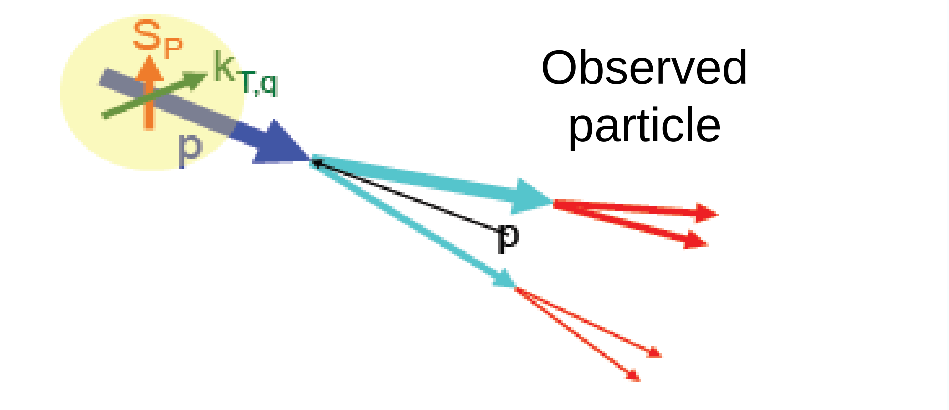
$$= A_{UT}^{Collins}\sin(\phi_h + \phi_S) + A_{UT}^{Sivers}\sin(\phi_h - \phi_S)$$

$$+ A_{UT}^{Pretzelosity}\sin(3\phi_h - \phi_S)$$

Hard to separate TMDs in hadronic collisions

Confined motion in a polarized nucleon

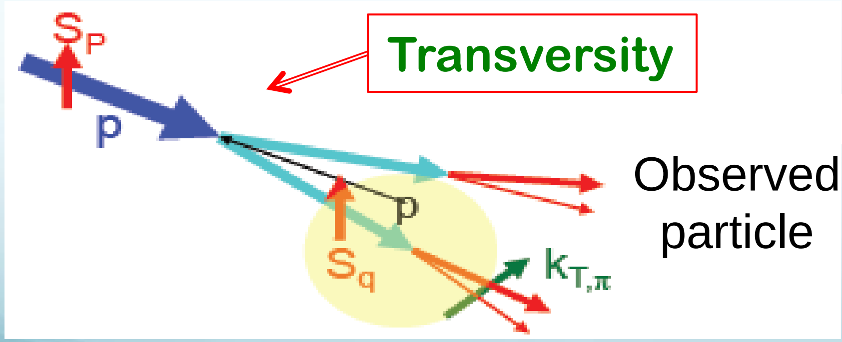
- **Quantum correlation between hadron spin and parton motion:**



Sivers effect – Sivers function

Hadron spin influences parton's transverse motion

- **Quantum correlation between parton spin and hadronization:**



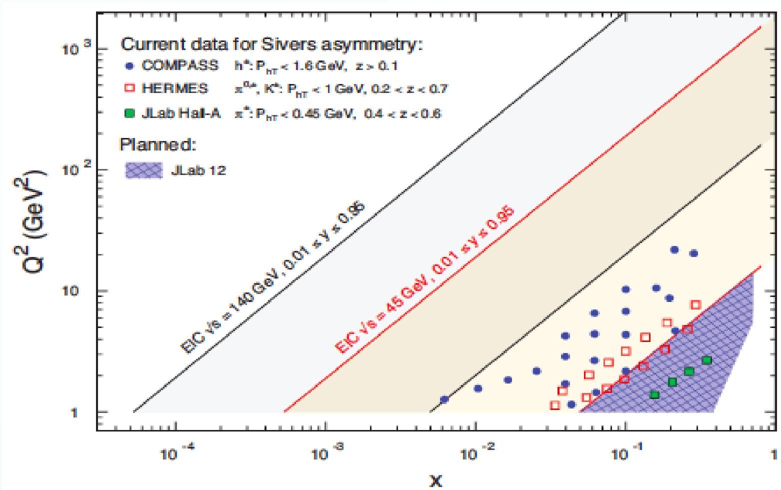
Collins effect – Collins function

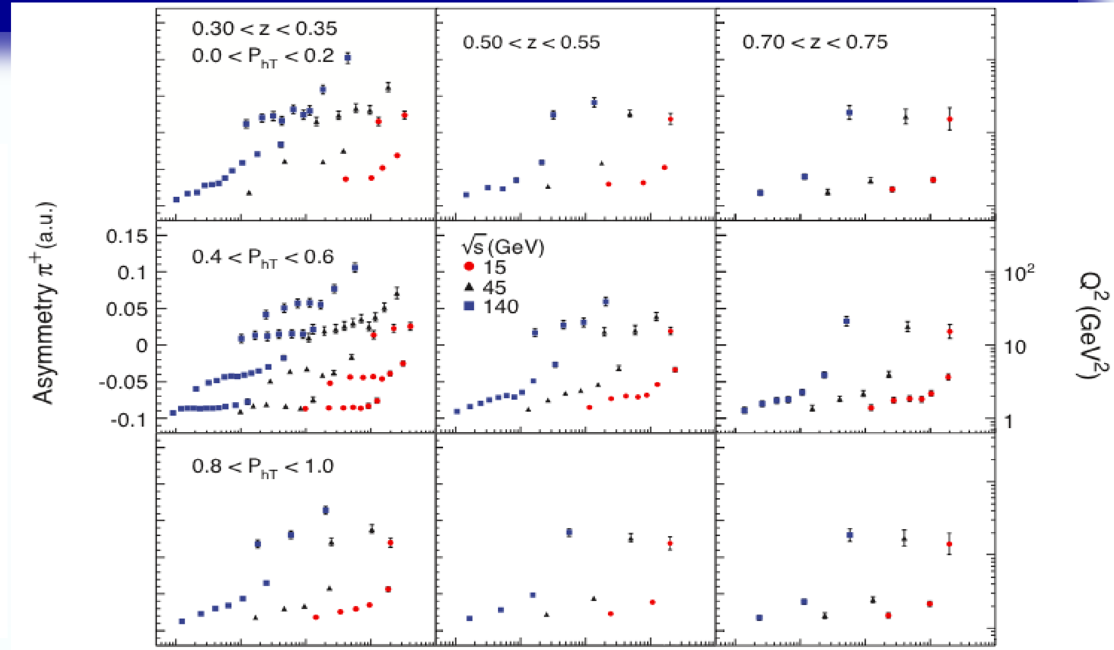
Parton's transverse spin influence its hadronization

JLab12 and COMPASS for valence, EIC covers the sea and gluon!

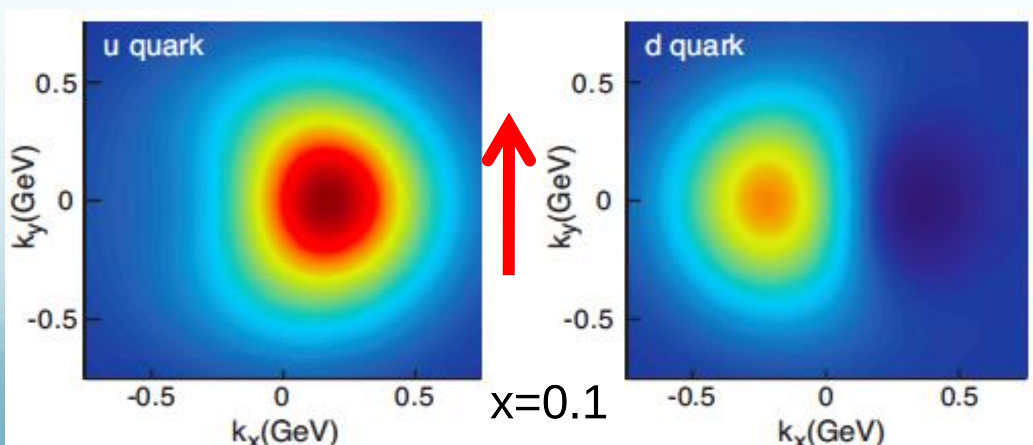
What can EIC do for the Sivers function?

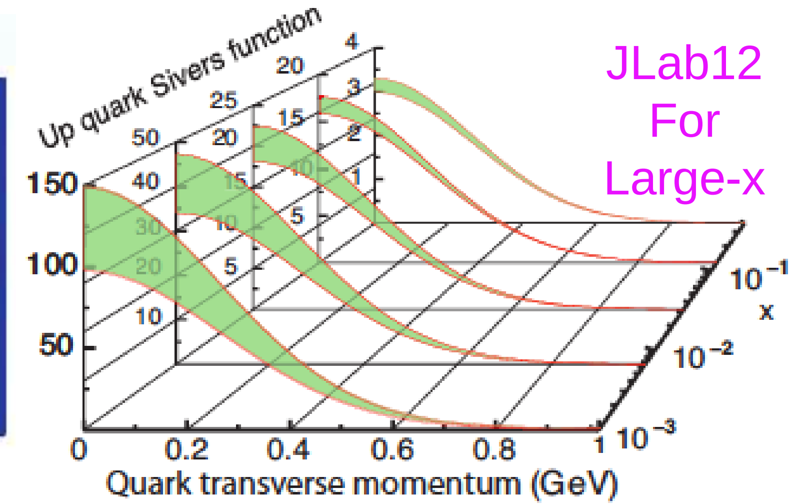
- Coverage and Simulation:





- Unpolarized quark inside a transversely polarized proton:



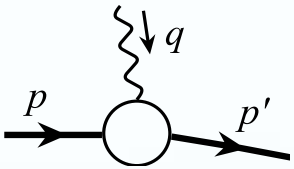


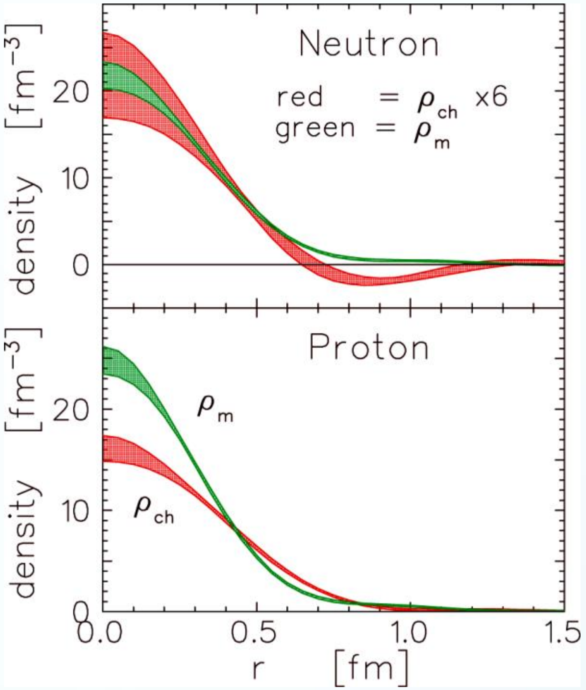
No other machine in the world can do this!

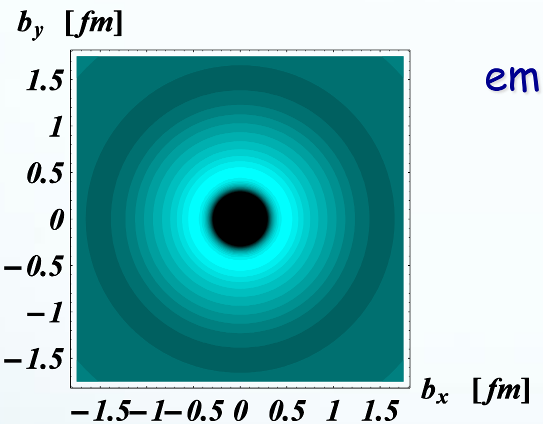
How is color distributed inside the proton?

- **Electric charge distribution:**

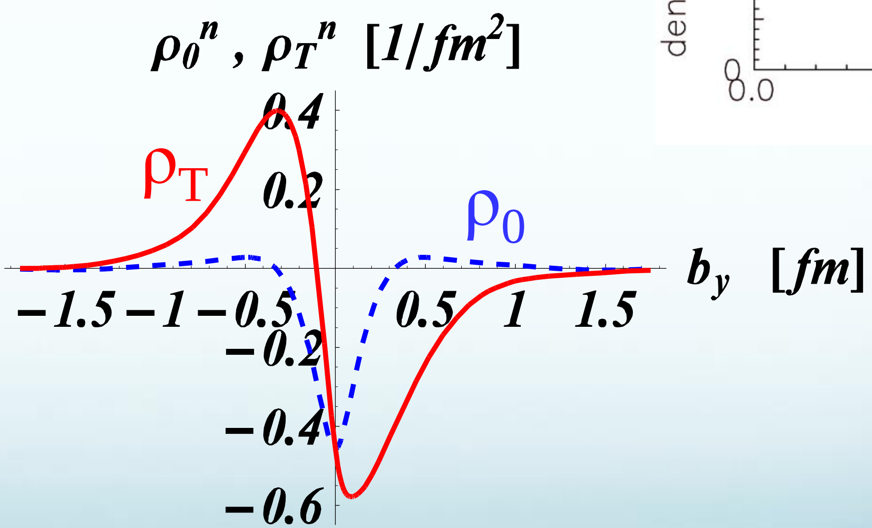
Elastic electric form factor
→ **Charge distributions**

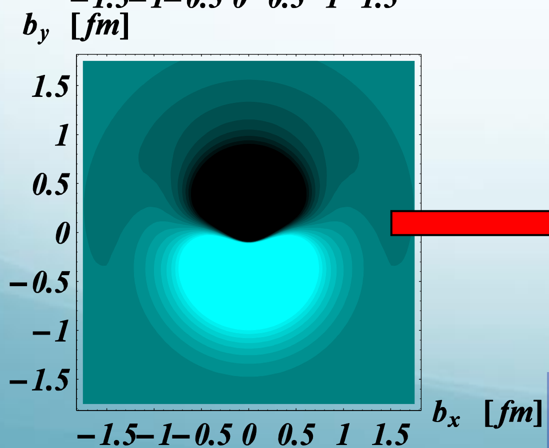






empirical quark transverse densities in Neutron





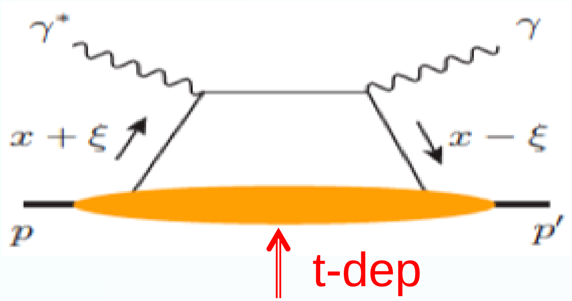
densities : Miller (2007); **Carlson, Vanderhaeghen** 2007)

induced EDM : $d_y = F_{2n}(0) \cdot e / (2 M_N)$

Spatial imaging of sea quarks

EIC: Sea quarks

- **Exclusive processes - DVCS:**



$$\frac{d\sigma}{dx_B dQ^2 dt}$$

$t = (p' - p)^2$

$\xi = (P' - P) \cdot n/2$

CFFs→GPDs

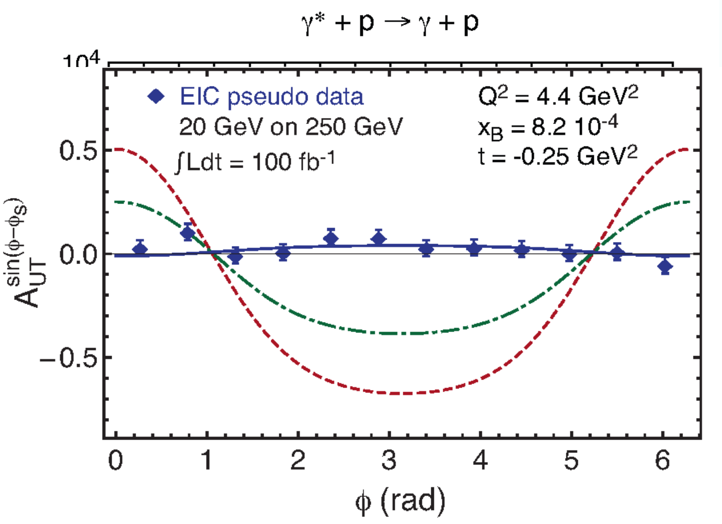
→ $H_q(x,\xi,t,Q), E_q(x,\xi,t,Q), \ldots$

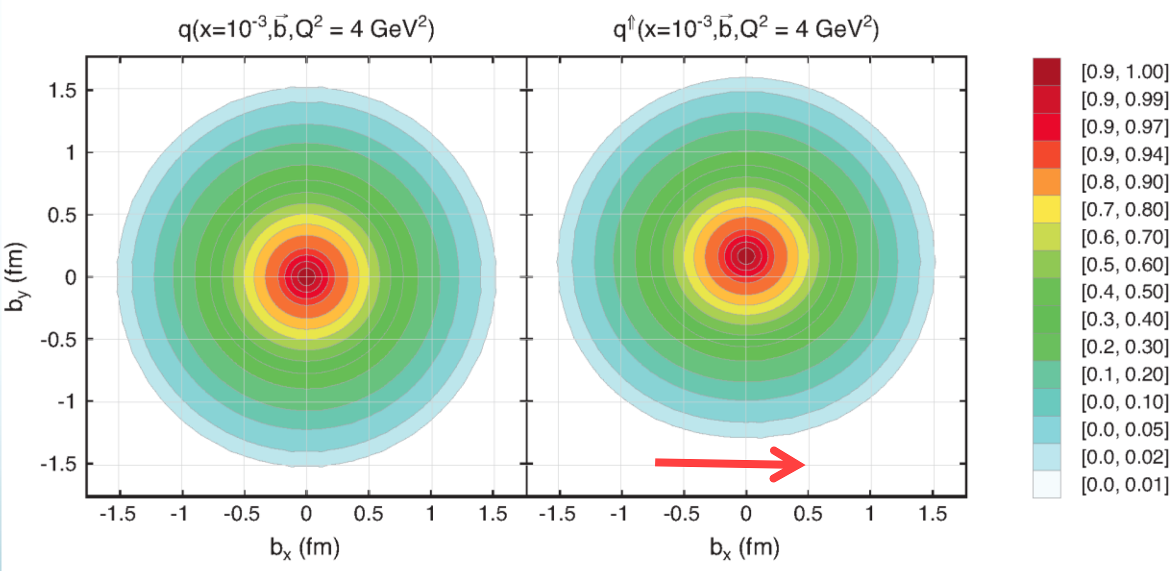
F.T. of t-dep

→ Spatial distributions

JLab 12: Valence quarks

EIC: Sea quarks



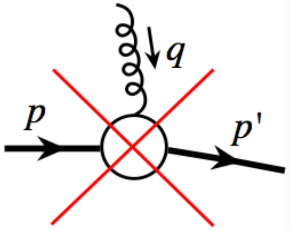


How about the glue?

A big question!

- **How is color distributed inside a hadron? (clue for color confinement?)**

- **Unfortunately NO color elastic nucleon form factor!**

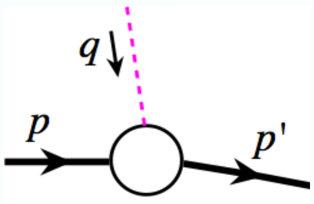


Hadron is colorless and gluon carries color

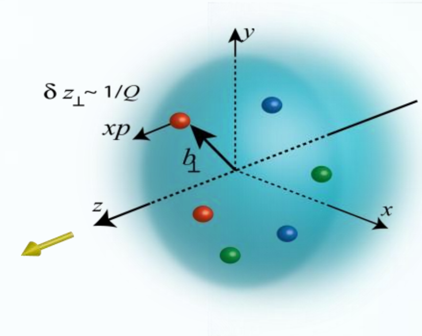
What to do?

Spatial imaging of gluons

- **Need Form Factor of density operator**:

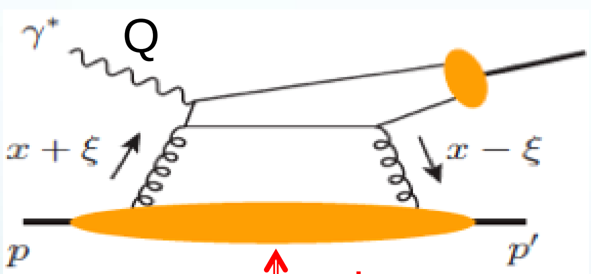


✧ Exchange of a colorless “object”
✧ “Localized” probe
✧ Control of exchanged momentum



- **Exclusive vector meson production:**

$$\frac{d\sigma}{dx_B dQ^2 dt}$$



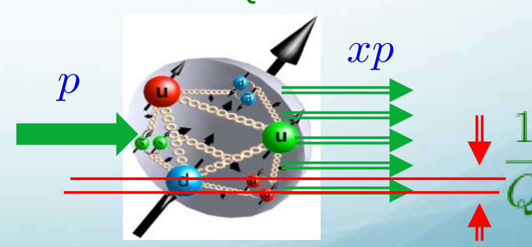
J/Ψ, Φ, …

↑ t-dep

✧ Fourier transform of the t-dep

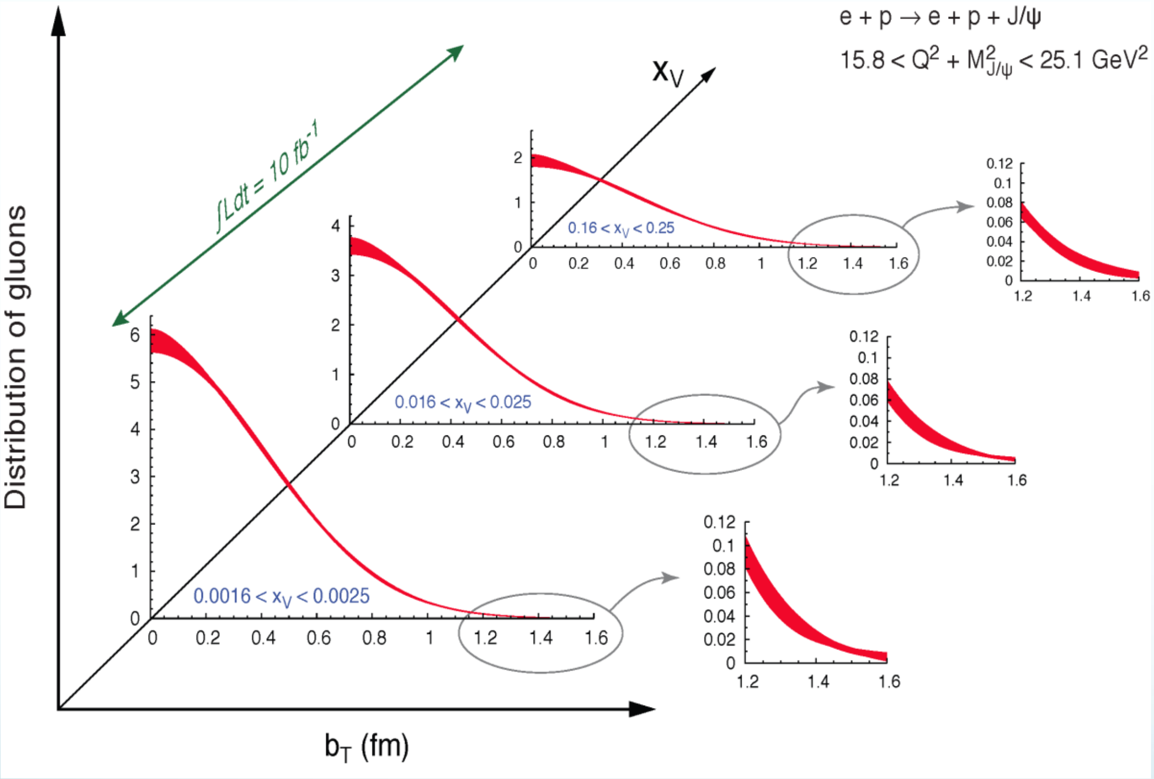
➡ Spatial imaging of glue density

✧ Resolution ~ 1/Q or $1/M_Q$



Spatial imaging of gluon density

➢ **Gluon imaging from simulation:**



$$x_V = \frac{M_{J/\psi}^2 + Q^2}{W^2 + Q^2 - M_N^2}$$

$$W^2 = (p+q)^2; \qquad M_N^2 = p^2$$

Images of gluons from exclusive J/ψ production

Only possible at the EIC: From the valence quark region deep into the sea quark region

A direct consequence!

➢ **Quark GPDs and its orbital contribution to the proton spin:**

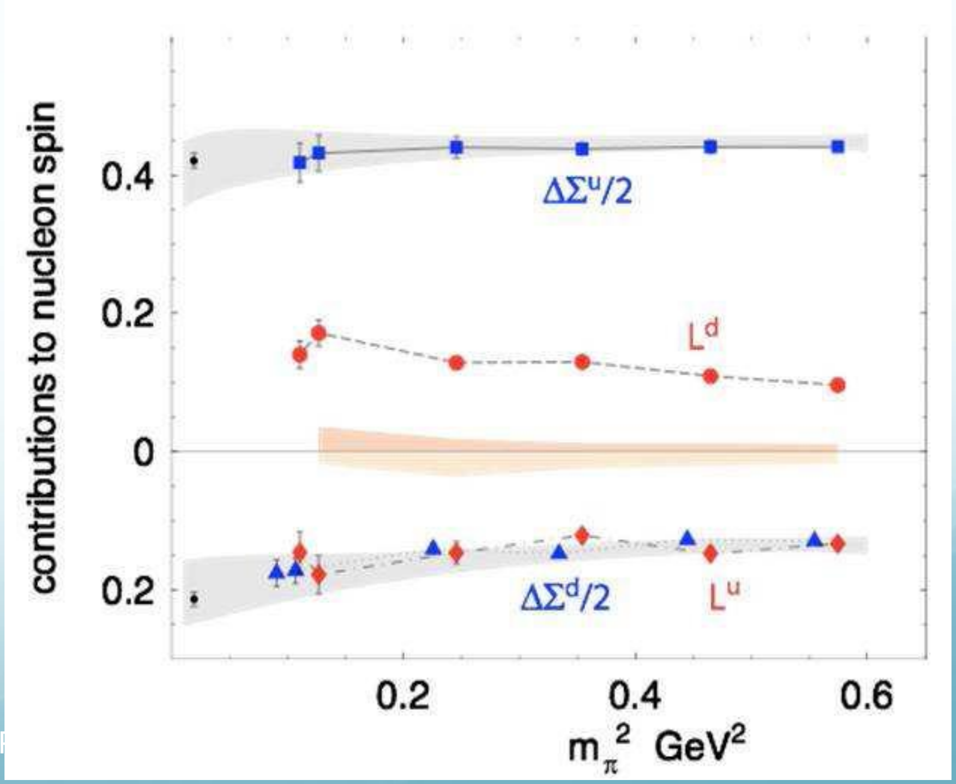
$$J_q = \frac{1}{2}\lim_{t\to 0}\int dx\, x\,[H_q(x,\xi,t) + E_q(x,\xi,t)] = \frac{1}{2}\Delta q + L_q$$

The first meaningful constraint on quark orbital contribution to proton spin by combining the sea from the EIC and valence region from JLab 12

This can be checked by Lattice QCD.

$L_u + L_d \sim 0$

Rapid developments on ideas of calculating parton distribution functions on Lattice:
X. Ji et al. arXiv 1310.4263; 1310.7471; 1402.1462
& Y.-Q. Ma, J.-W. Qiu 1404.6860



Physics opportunities at EIC

Machine parameters

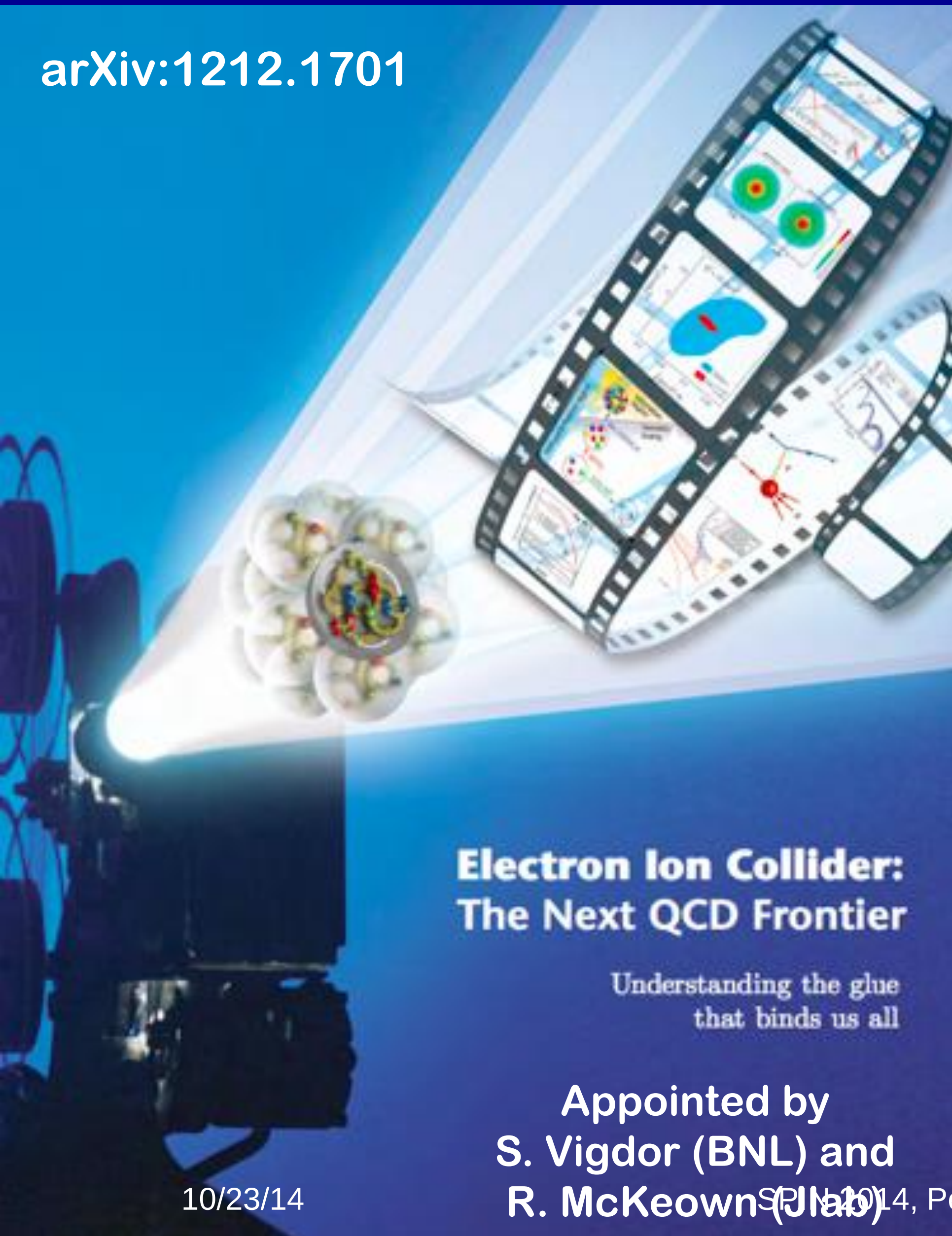
- Collision energy: $\sqrt{s} \sim 20 - 100\ \mathrm{GeV}$ Upgradable to $\sim 150\ \mathrm{GeV}$
- Luminosity: **$10^{33\text{-}34}$ cm^{-2} s^{-1}** (compare to **HERA luminosity ~** 5x10^{31} **cm^{-2} s^{-1}**)
- Polarized proton and various nuclei

Key Deliverables

Deliverables	Observables	What we learn
Sea/gluon x~10^{-2} -10^{-4} S.F.	Inclusive DIS at low-x, in e-p	**Sea/gluon contrib. to proton spin, flavor separation**
Polarized and unpolarized TMDs	SIDIS e-p, single hadron, Dihadron and heavy flavors	**3D momentum images of quarks and gluons**
Sea quarks and gluon GPDs	DVCS, Exclusive J/Ψ, ρ,φ production	**Spatial images of sea and gluon, angular mom. J_q , J_g**
Weak mixing angle	PV asymmetries in DIS	**EW symmetry breaking, BSM**

U.S.-based EICs – the White Paper

arXiv:1212.1701



Appointed by
S. Vigdor (BNL) and
R. McKeown (JLab)

Overall Editors:
A. Deshpande (Stony Brook), Z-E. Meziani (Temple), J. Qiu (BNL)

Gluon Saturation in e+A:
T. Ullrich (BNL) and Y. Kovchegov (Ohio State)

Nucleon spin structure (inclusive e+N):
E. Sichtermann (LBNL) and W. Vogelsang (Tübingen)

GPD's and exclusive reactions:
M. Diehl (DESY) and F. Sabatie (Saclay)

TMD's and hadronization and SIDIS:
H. Gao (Duke) and F. Yuan (LBNL)

Parton Propagation in Nuclear Medium:
W. Brooks (TSFM) and J. Qiu(BNL)

Electroweak physics:
K. Kumar (U Mass) and M. Ramsey-Musolf (Wisconsin)

Accelerator design and challenges:
A. Hutton (JLab) and T. Roser (BNL)

Detector design and challenges:
E. Aschenauer (BNL) and T. Horn (CUA)

Senior Advisors:
A. Mueller (Columbia) and R. Holt (ANL)

Successful thanks to many other co-authors and contributions

Summary

- EIC is "the" machine to understand the glue that bind us all
- It is "the" brightest sub-femtometer scope to ANSWER fundamental questions in QCD in ways that no other facility in the world can
- Extends the QCD programs developed at BNL and JLab in dramatic and fundamentally important ways
- EIC would benefit fundamental nuclear science and accelerator / detector technology

"It is by the solution of problems that the investigator tests the temper of his steel; he finds new methods and new outlooks, and gains a wider and freer horizon."

D. Hilbert Paris, 1900