Electron Ion Collider Project

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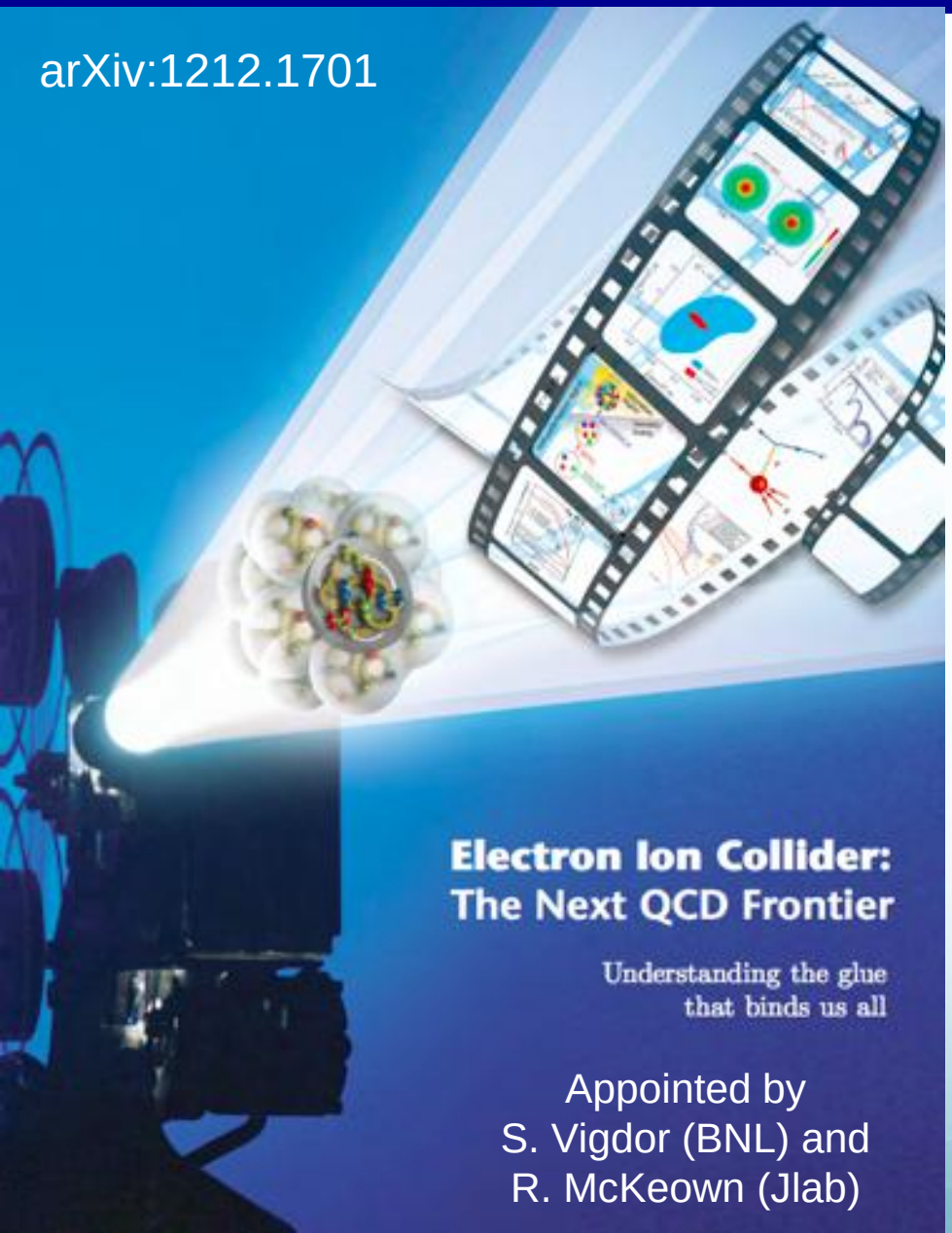
"It is difficult and often impossible to judge the value of a problem correctly in advance; for the final award depends upon the gain which science obtains from the problem."

David Hilbert, 1900 Paris

U.S.-based EICs – the White Paper

arXiv:1212.1701



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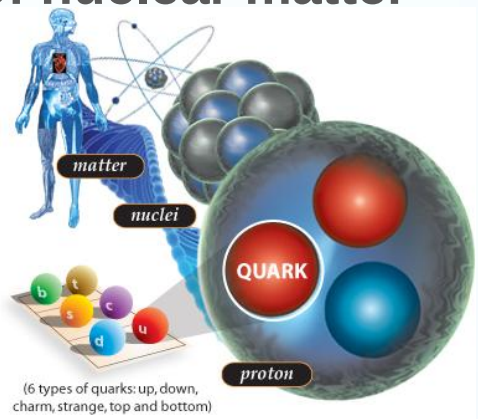
Successful thanks to many other co-authors and contributions

Nuclear Science and QCD

- Nuclear Science
  - **To discover, explore and understand all forms of nuclear matter**
- Nuclear Matter
  - Quarks + Gluons + Interactions →Nucleons →Nuclei
  - At the heart of the visible universe, accounting for essentially all its mass



- Experimental Tools:
  - Giant electron microscopes opened the gateway to nucleon structure at Stanford and at SLAC using electron proton scattering.
  - Modern microscopes are pushing the frontiers of resolution, brightness and polarization combined.
- Theory Tools: Quantum Chromodynamics (QCD)
  - A fundamental theory of quarks and gluons
  - Describes the formation of all forms of nuclear matter

Understanding of QCD is a fundamental and compelling goal of Nuclear Science

The 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

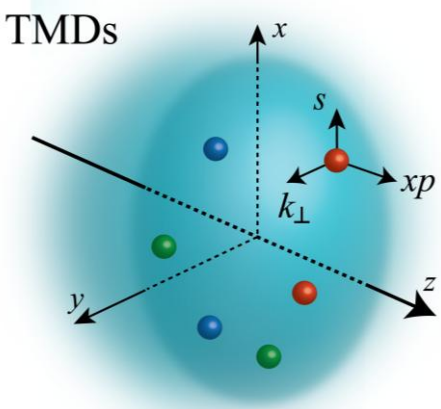
Present theoretical tools:

Unified View of Nucleon Structure

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

5D Dist.

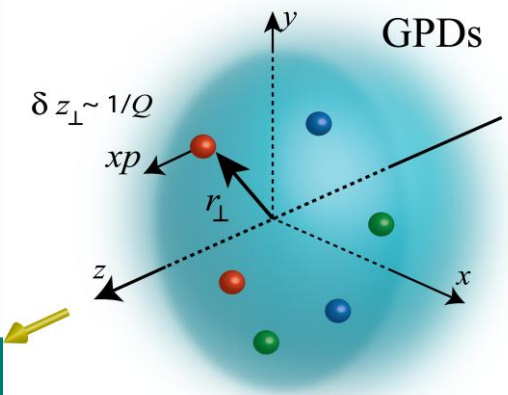
Transverse Momentum Dist.



dr_T

d^2k_T

Generalized Parton Dist.



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

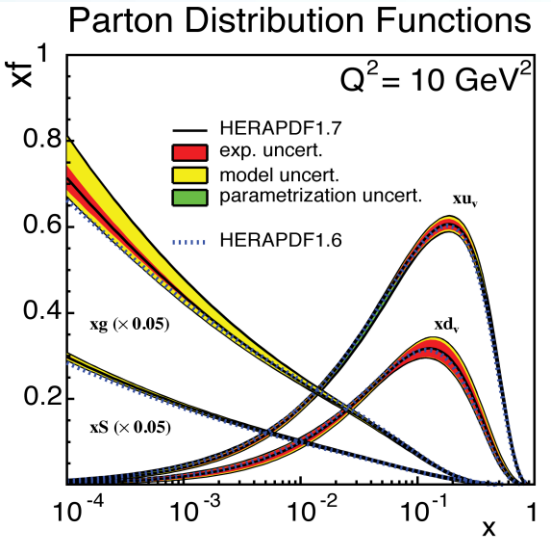
GPD

"3D" imaging

d^2k_T

d^2r_T

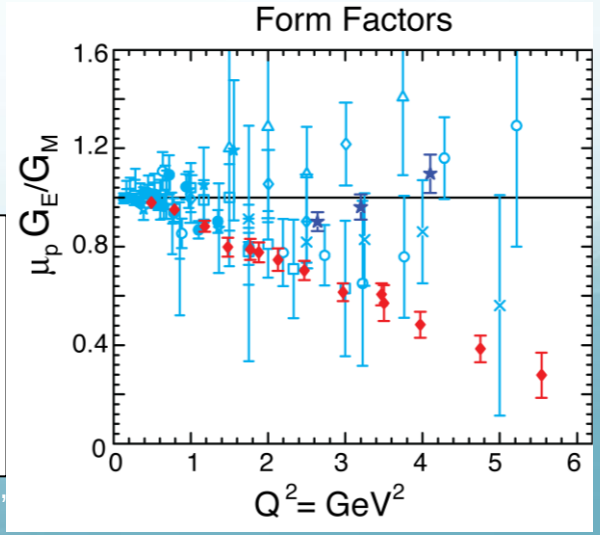
dx &Fourier Transformation



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

1D

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



The many fronts of experimental studies in an EIC

Inclusive

Generalized Parton Distributions

Since 1998

Exclusive reactions In nucleons and nuclei

Elastic form factors
Deep Virtual Compton Scattering
Deep Virtual Meson Production

Parton distributions
Sum rules and polarizabilities

Transverse Momentum Distributions

Since 2002

Semi-Inclusive DIS In nucleons and nuclei

Distributions and Fragmentation functions

Saturation in Nucleon and Nuclei
Inclusive, Semi-Inclusive and Exclusive reactions in Nucleon and Nuclei
Structure functions, hadron correlations and diffractive scattering

Electroweak probe to hadronic systems

Precision electroweak/Beyond the standard Model

Quoting from F. Wilczek (XXIV Quark Matter 2014)

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".

Emergent Phenomena

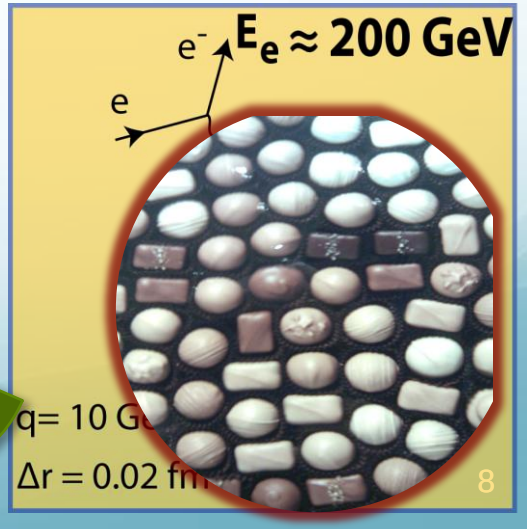
Two Protons - Or More?

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?

Probing deeper for the fundamental degrees of freedom, quarks and gluons

Quarks & Gluons



Emergent Phenomenon

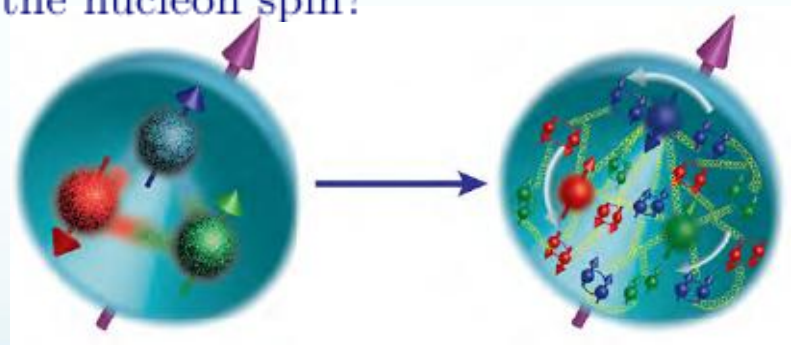
Fundamental QCD question - I

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

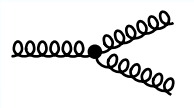
***Need a polarized proton beam*!**

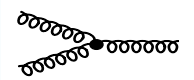
Fundamental QCD question - II

How do gluons saturate themselves into a new form of matter?

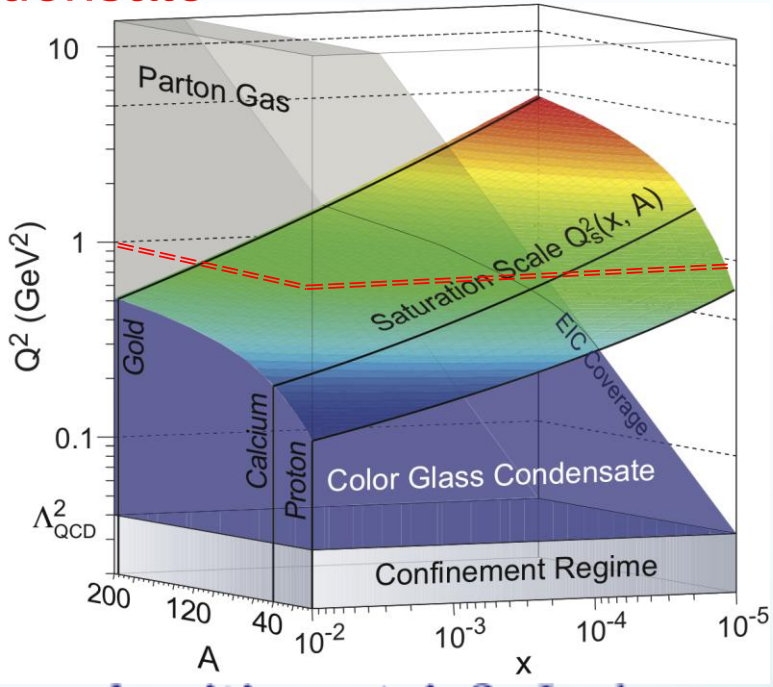
Color Glass Condensate

- Gluon, unlike photon:

  Radiate: 

  Recombine: 

  - Dynamical scale Q_s from the balance
  - New mathematical framework
  - Universal properties (CGC)



From the EIC White Paper

- **Where does the saturation of gluon densities set in?** Is there a simple boundary that separates this region from that of more dilute quark-gluon matter? If so, how do the distributions of quarks and gluons change as one crosses the boundary? Does this saturation produce matter of universal properties in the nucleon and all nuclei viewed at nearly the speed of light?

Need a heavy ion beam!

Fundamental QCD question - III

How do hadrons emerge from a created quark or gluon?

Neutralization of color - hadronization

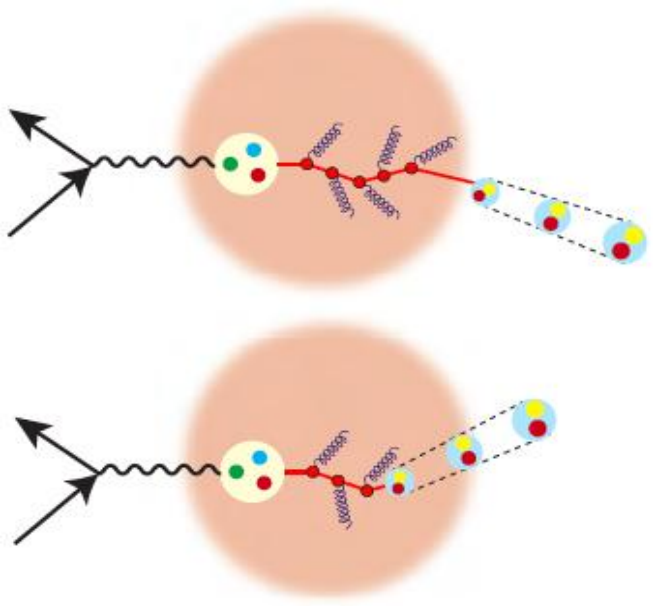
- Femtometer detector/scope:

  Nucleus, a laboratory for QCD

- Quark/gluon properties:

  Initial-condition for hadronization

  Semi-inclusive DIS



From the EIC White Paper

- **How does the nuclear environment affect the distribution of quarks and gluons and their interactions in nuclei?** How does the transverse spatial distribution of gluons compare to that in the nucleon? How does nuclear matter respond to a fast moving color charge passing through it? Is this response different for light and heavy quarks?

Need an EM probe to precisely control the initial-condition for hadronization!

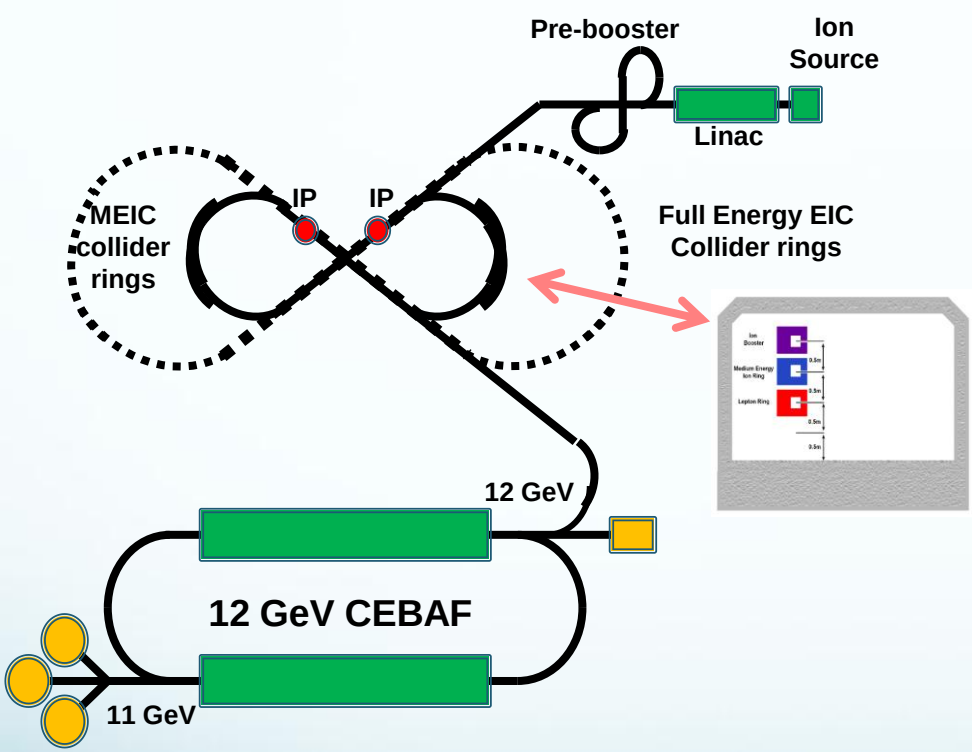
Electron-Ion Collider

- **An ultimate machine to provide answers to fundamental 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 EM interaction as a probe
  - Polarized nucleon beams to determine the correlations of sea quark and gluon distributions with the nucleon spin
  - Heavy ion beams to provide precocious access to the regime of saturated gluon densities, and to offer a precise dial in the study of propagation-length for color charges in nuclear matter
- **A machine at the frontier of polarized luminosity, combined with versatile kinematics and beam species**

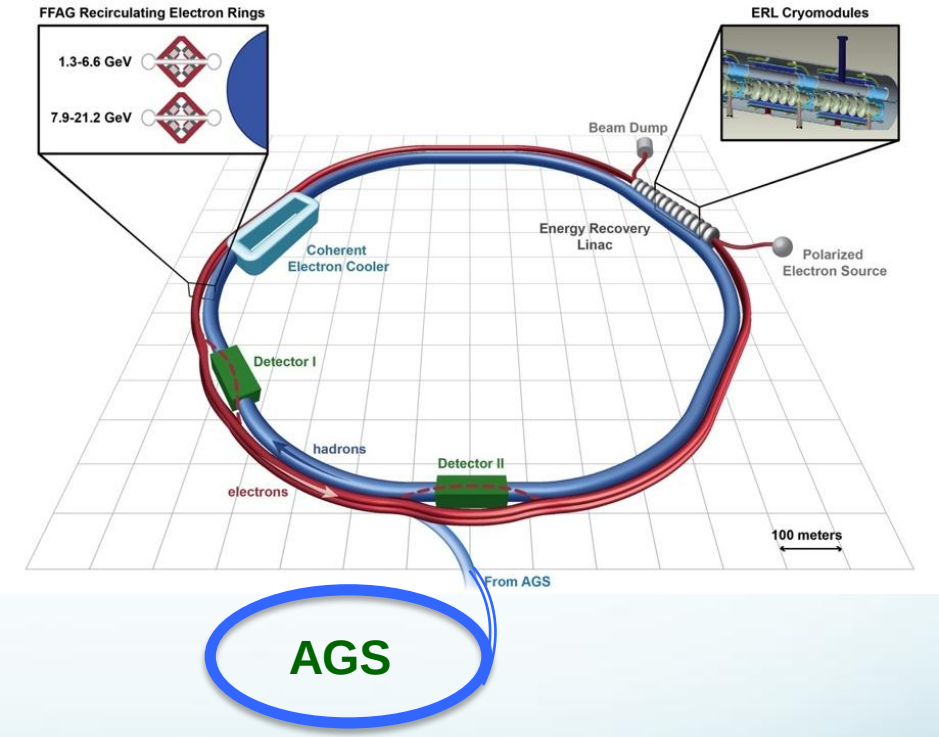
Allows all important QCD questions at a single facility

U.S.-based EICs – the Machines

MEIC (JLab)

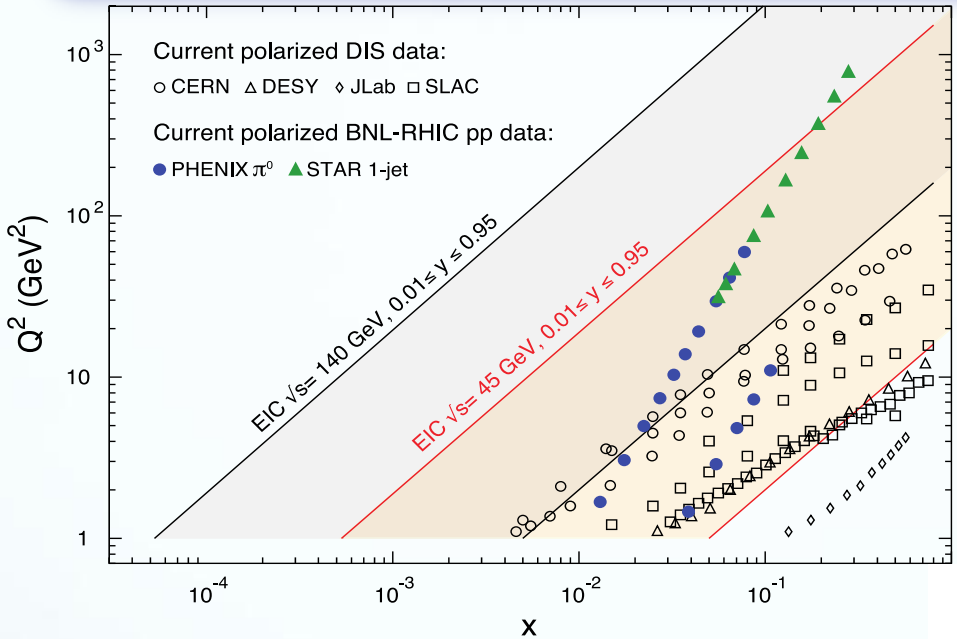


eRHIC (BNL)



- 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



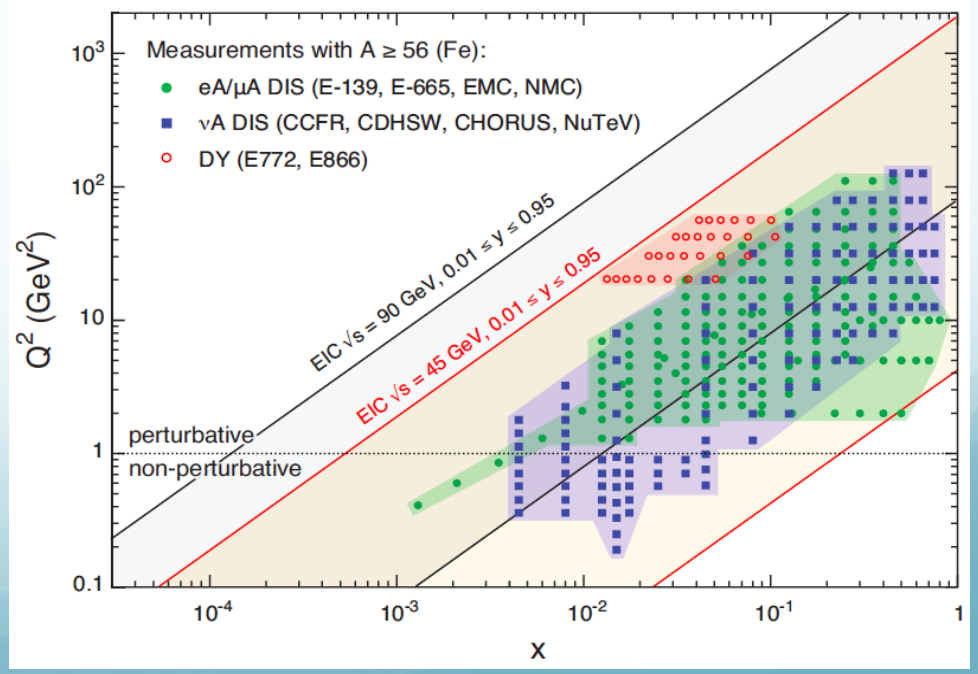
For e-N collisions at the EIC:

- ✓ 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}

For e-A collisions at the EIC:

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



EIC: Goals and deliverables

The key measurements

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

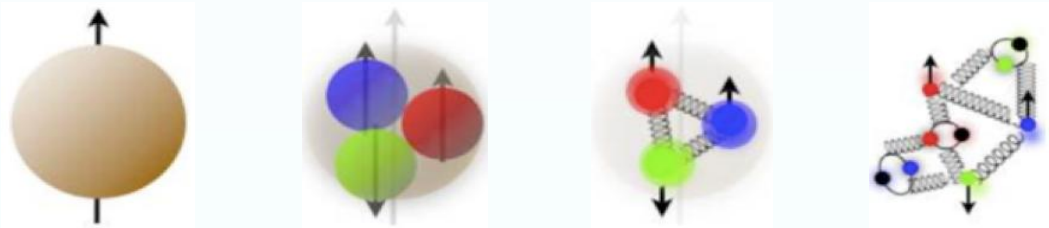
Proton spin and hadron structure?
Beyond a one dimensional view

- Proton – composite particle of quarks and gluons:

Mass = intrinsic (quark masses) + quarks motion (kinetic + potential)
+ gluon motion (kinetic + potential) + trace anomaly

Spin = intrinsic (partons spin) + motion (orbital angular momentum)

$$S(\mu) = \frac{1}{2}$$



$$\mu \Rightarrow \infty$$

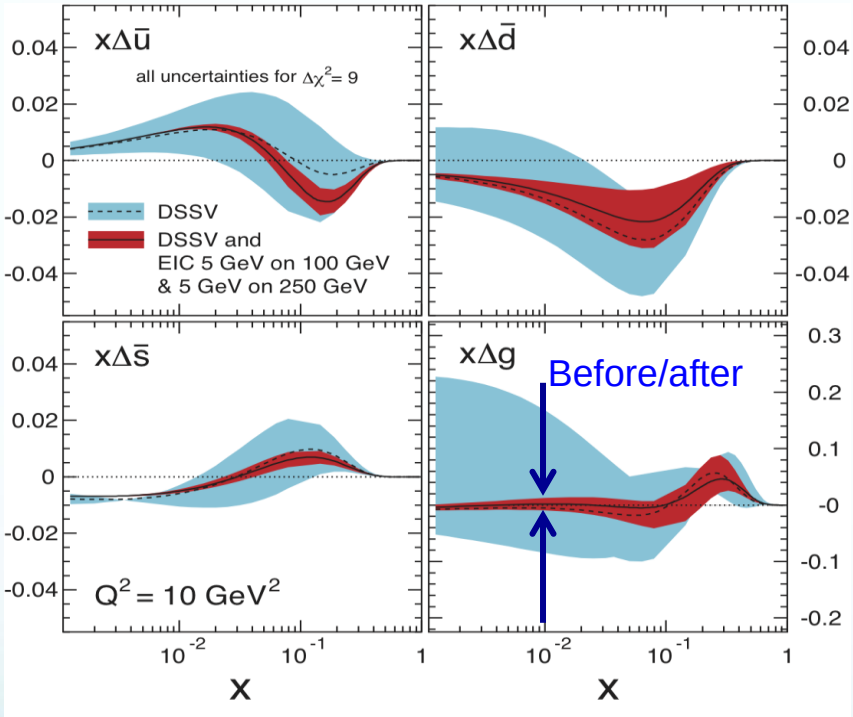
- Over 20 years effort (following EMC discovery)
  - Quark (valence + sea) helicity: $\sim 30\%$ of proton spin
  - Gluon helicity: positive with large uncertainty from limited x range

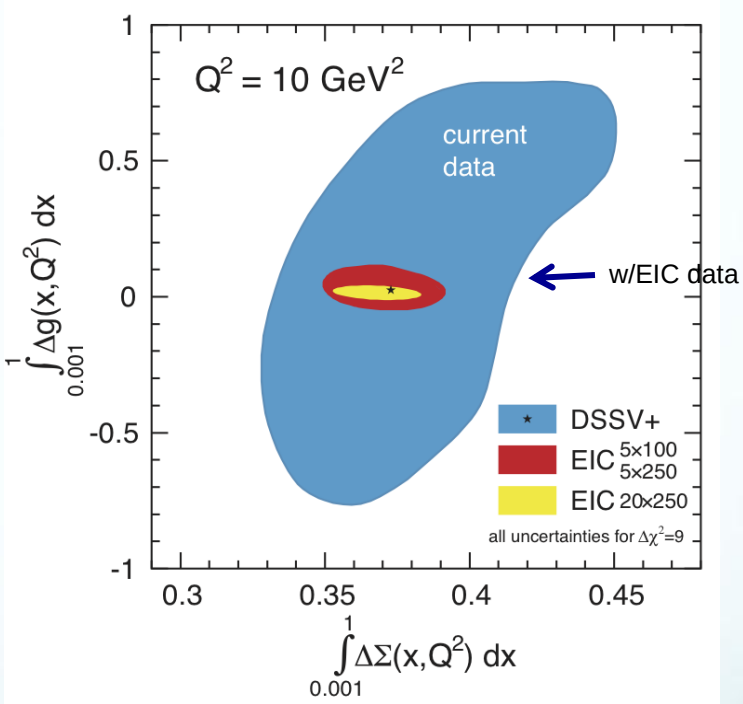
How to explore the "full" gluon and sea quark contribution?
How to quantify the role of orbital motion?

Proton spin and hadron structure?

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

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

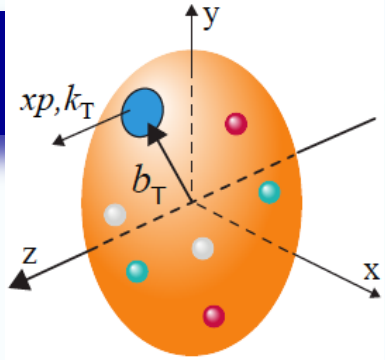




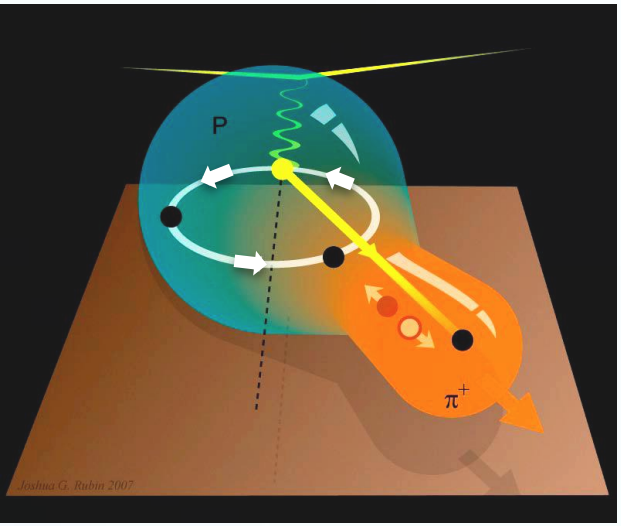
No other machine in the world can achieve this!

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

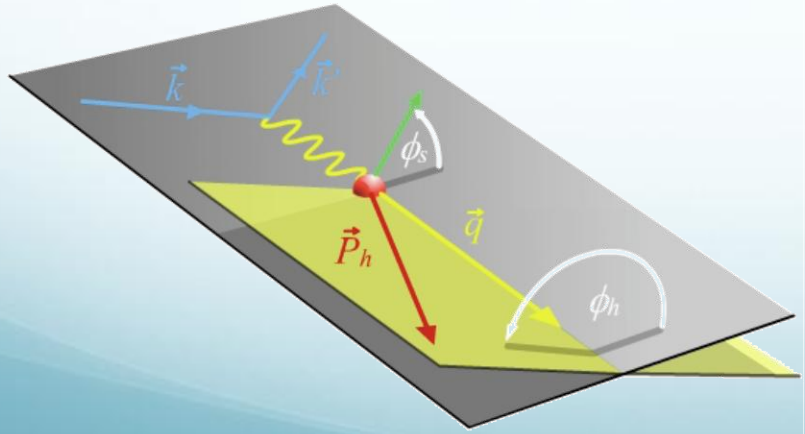
EIC is the best for probing TMDs



- 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



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

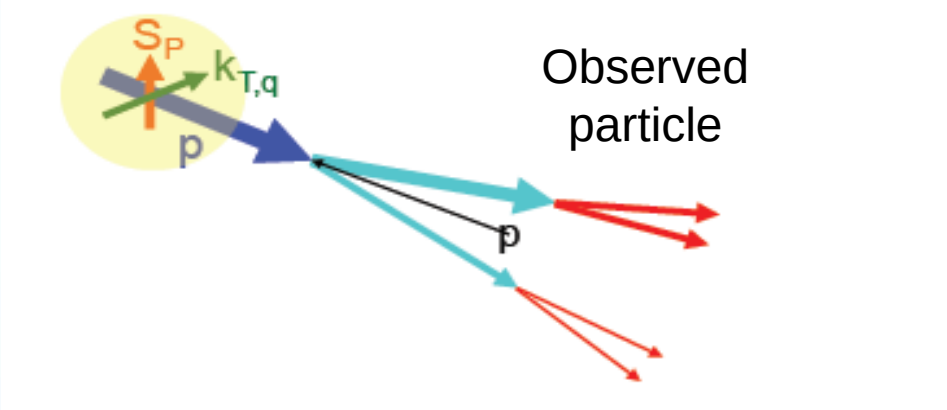
$$= A_{UT}^{Collins} \sin(\phi_h + \phi_S) + A_{UT}^{Sivers} \sin(\phi_h - \phi_S)$$

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

Hard to separate TMDs in hadronic collisions

Confined motion in a polarized nucleon

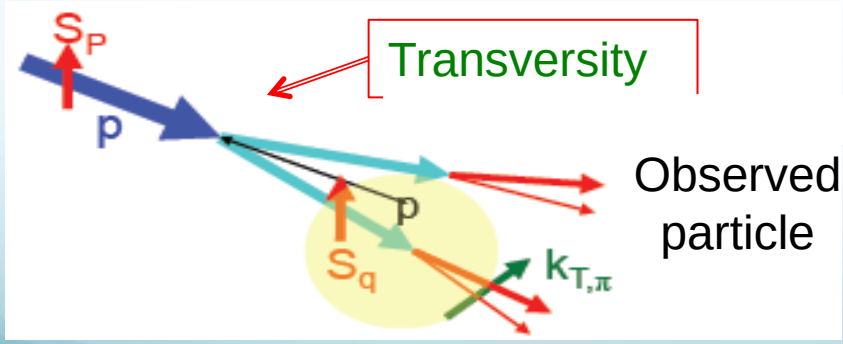
- Quantum correlation between hadron spin and parton motion:



Sivers effect – Sivers function

Hadron spin influences parton's transverse motion

- Quantum correlation between parton spin and hadronization:



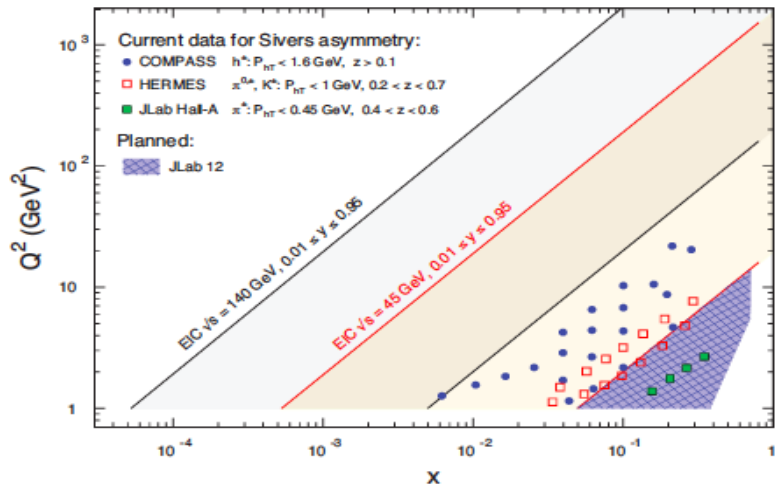
Collins effect – Collins function

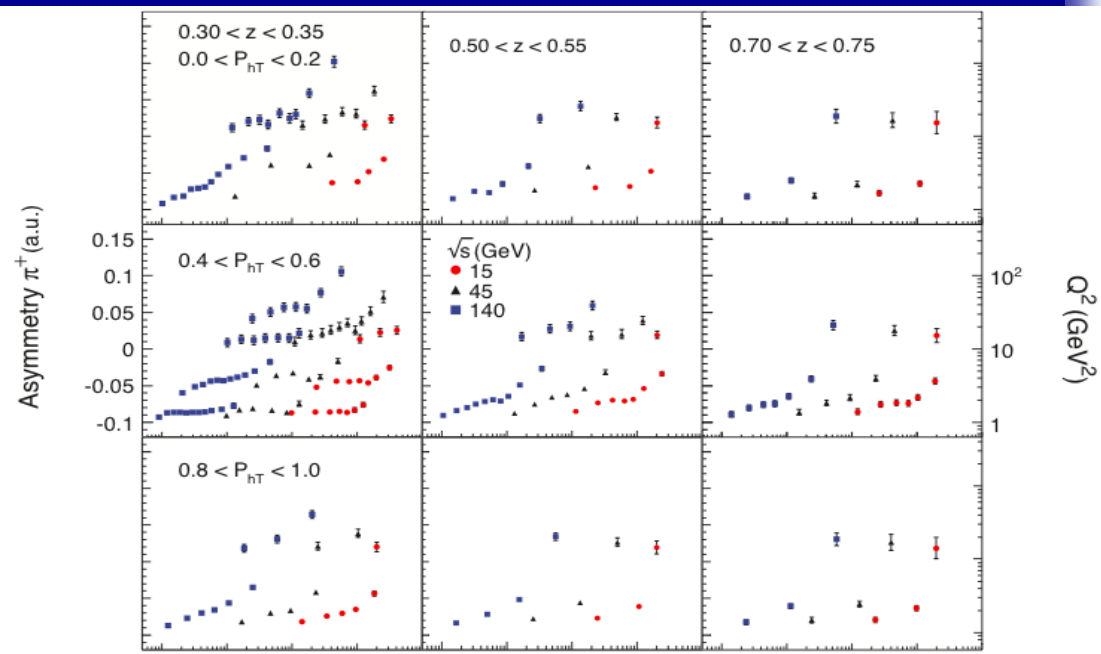
Parton's transverse spin influence its hadronization

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

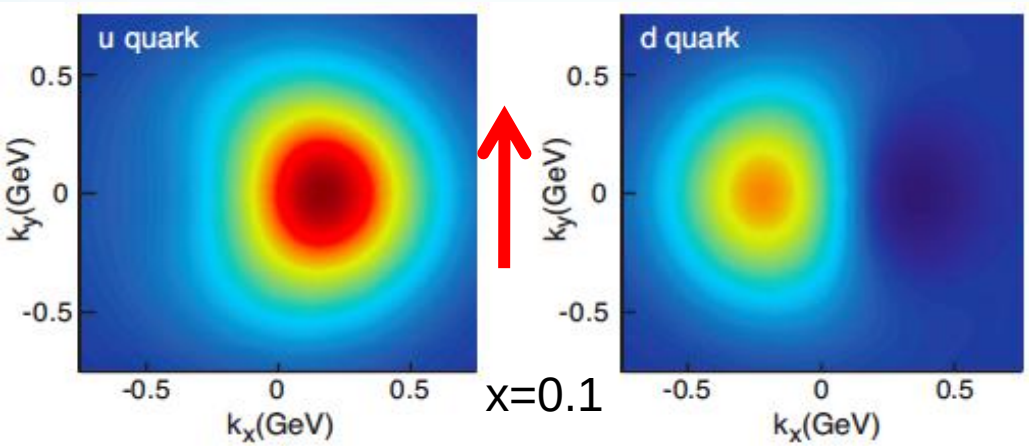
What can EIC do for the Sivers function?

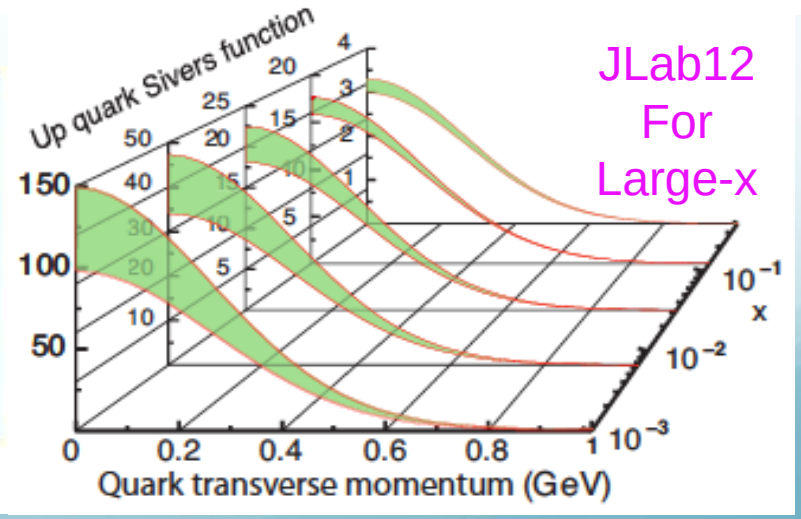
- Coverage and Simulation:





- Unpolarized quark inside a transversely polarized proton:



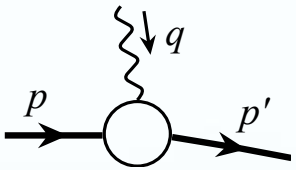


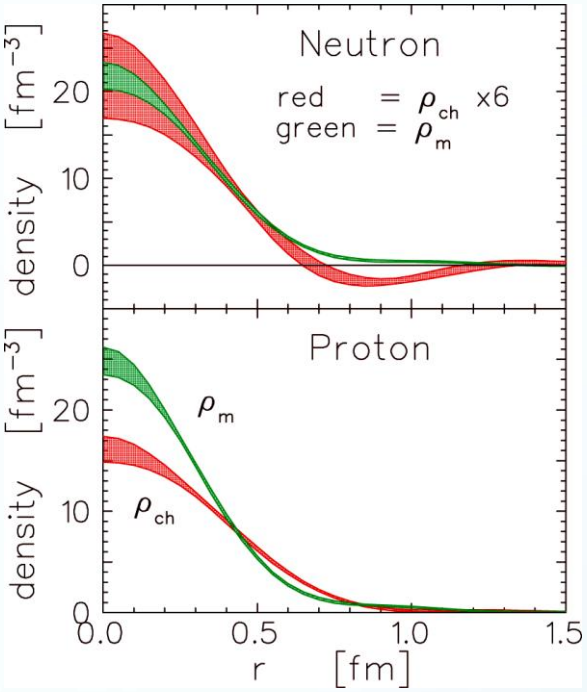
No other machine in the world can do this!

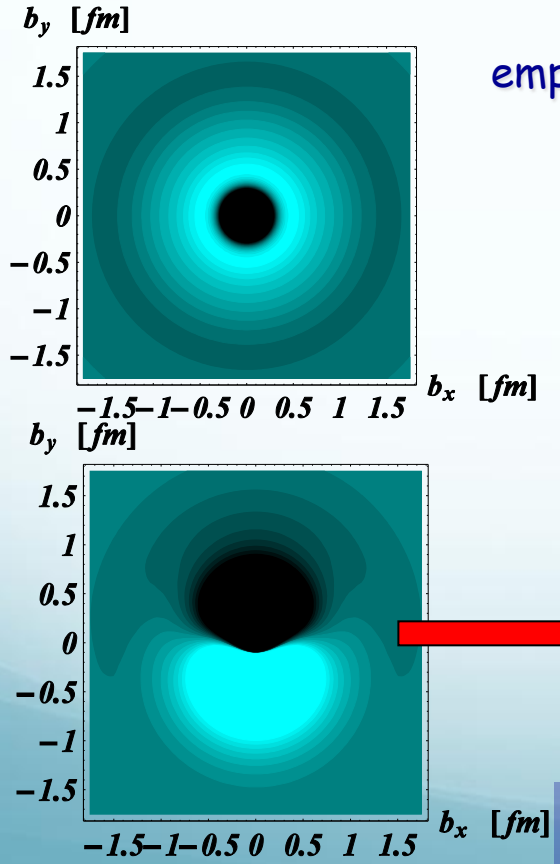
How is color distributed inside the proton?

- Electric charge distribution:

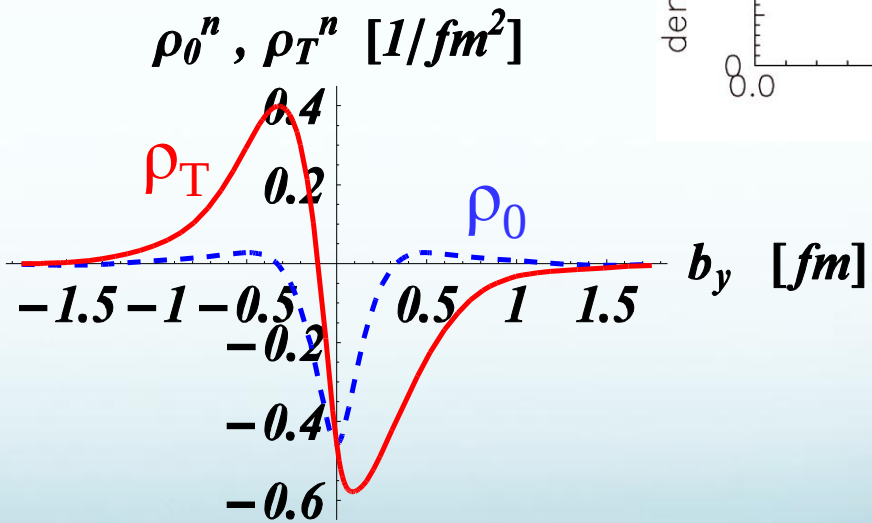
Elastic electric form factor
→ Charge distributions







empirical quark transverse densities in Neutron



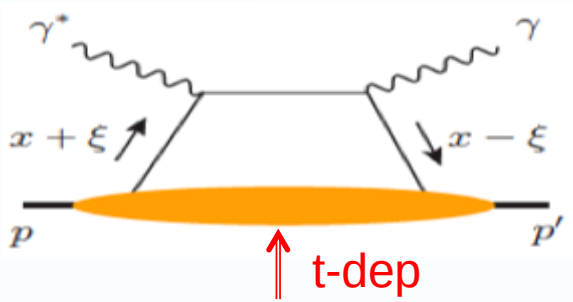
densities : **Miller** (2007); **Carlson, Vanderhaeghen** 2007)

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

Spatial imaging of sea quarks

EIC: Sea quarks

- **Exclusive processes - DVCS**:



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

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

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

F.T. of t-dep

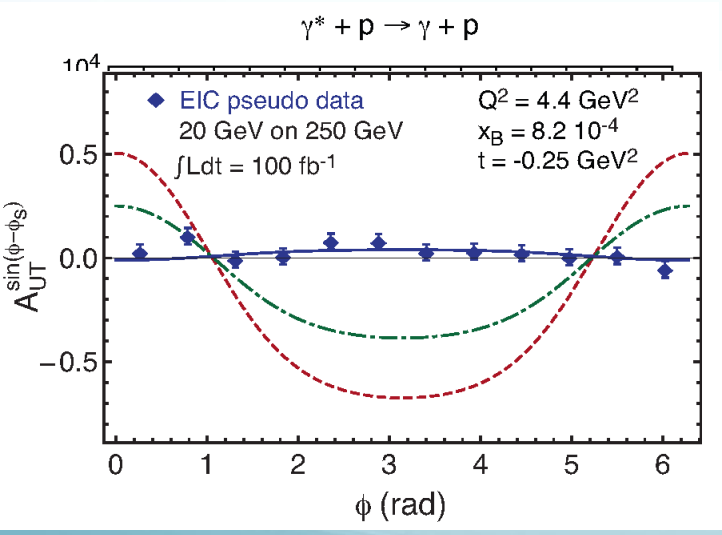
CFFs→GPDs

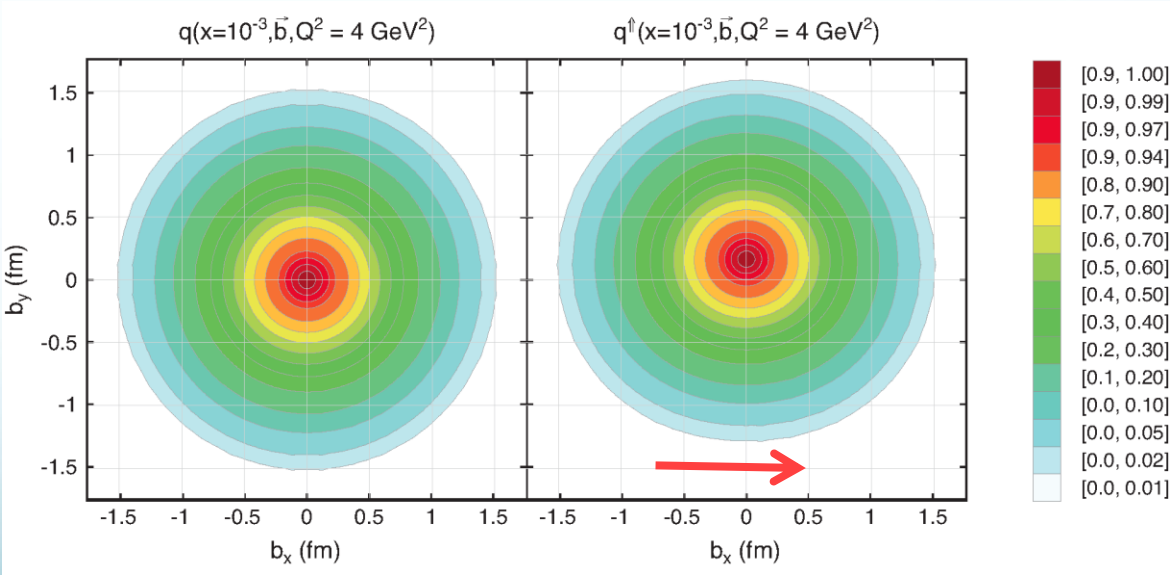
$$H_q(x,\xi,t,Q), E_q(x,\xi,t,Q), \ldots$$

Spatial distributions

JLab 12: Valence quarks

EIC: Sea quarks



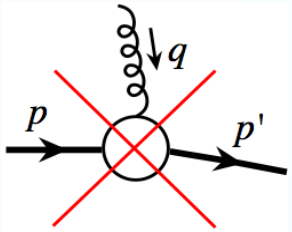


How about the glue?

A big question!

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

- Unfortunately NO color elastic nucleon form factor!

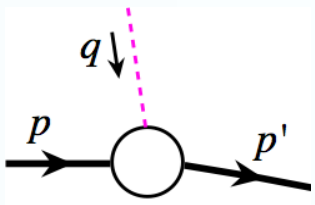


Hadron is colorless and gluon carries color

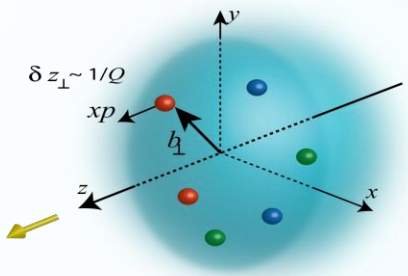
What to do?

Spatial imaging of gluons

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

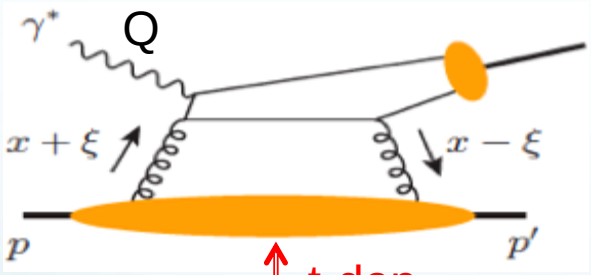


- ✧ Exchange of a colorless "object"
- ✧ "Localized" probe
- ✧ Control of exchanged momentum



- Exclusive vector meson production:

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



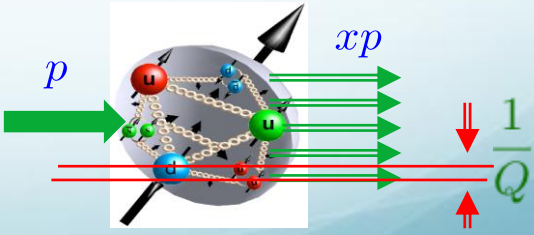
t-dep

J/Ψ, Φ, …

- ✧ Fourier transform of the t-dep

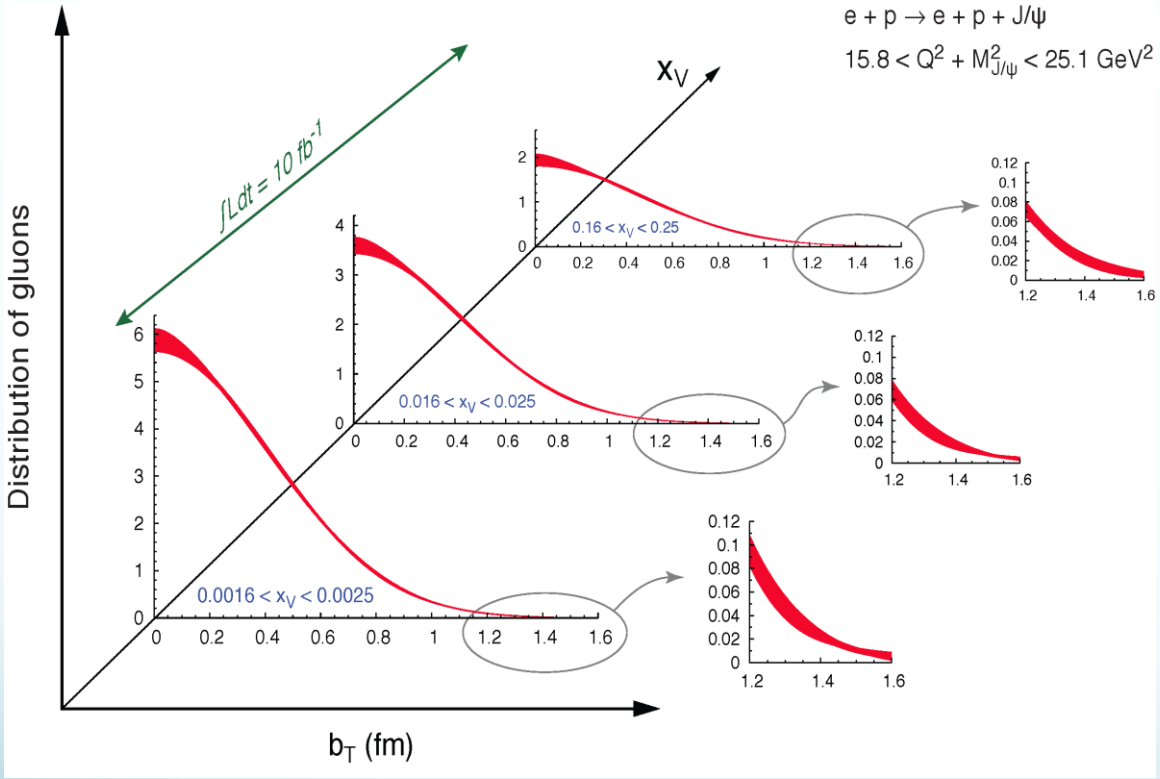
➡ Spatial imaging of glue density

- ✧ 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:

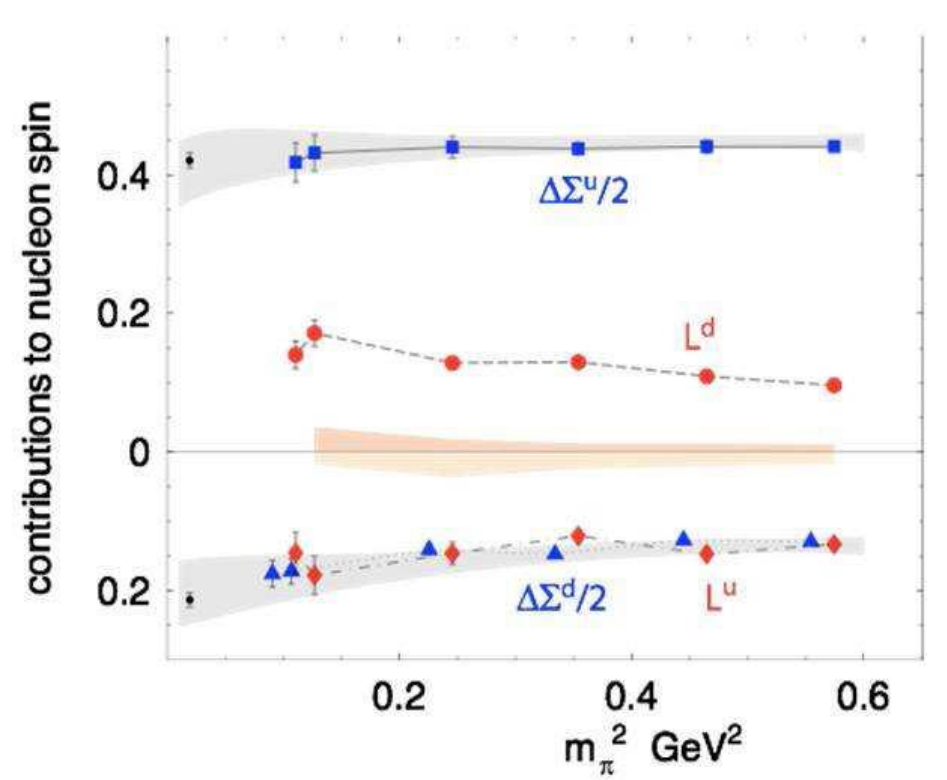
$$J_q = \frac{1}{2}\lim_{t\to 0}\int dx\, x\,[H_q(x,\xi,t) + E_q(x,\xi,t)] = \frac{1}{2}\Delta q + L_q$$

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.

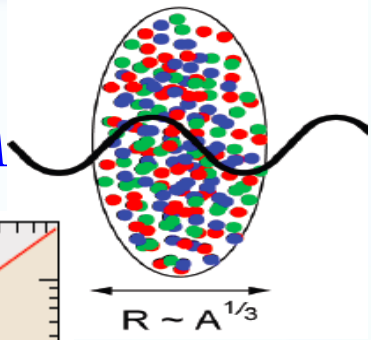
$L_u + L_d \sim 0$

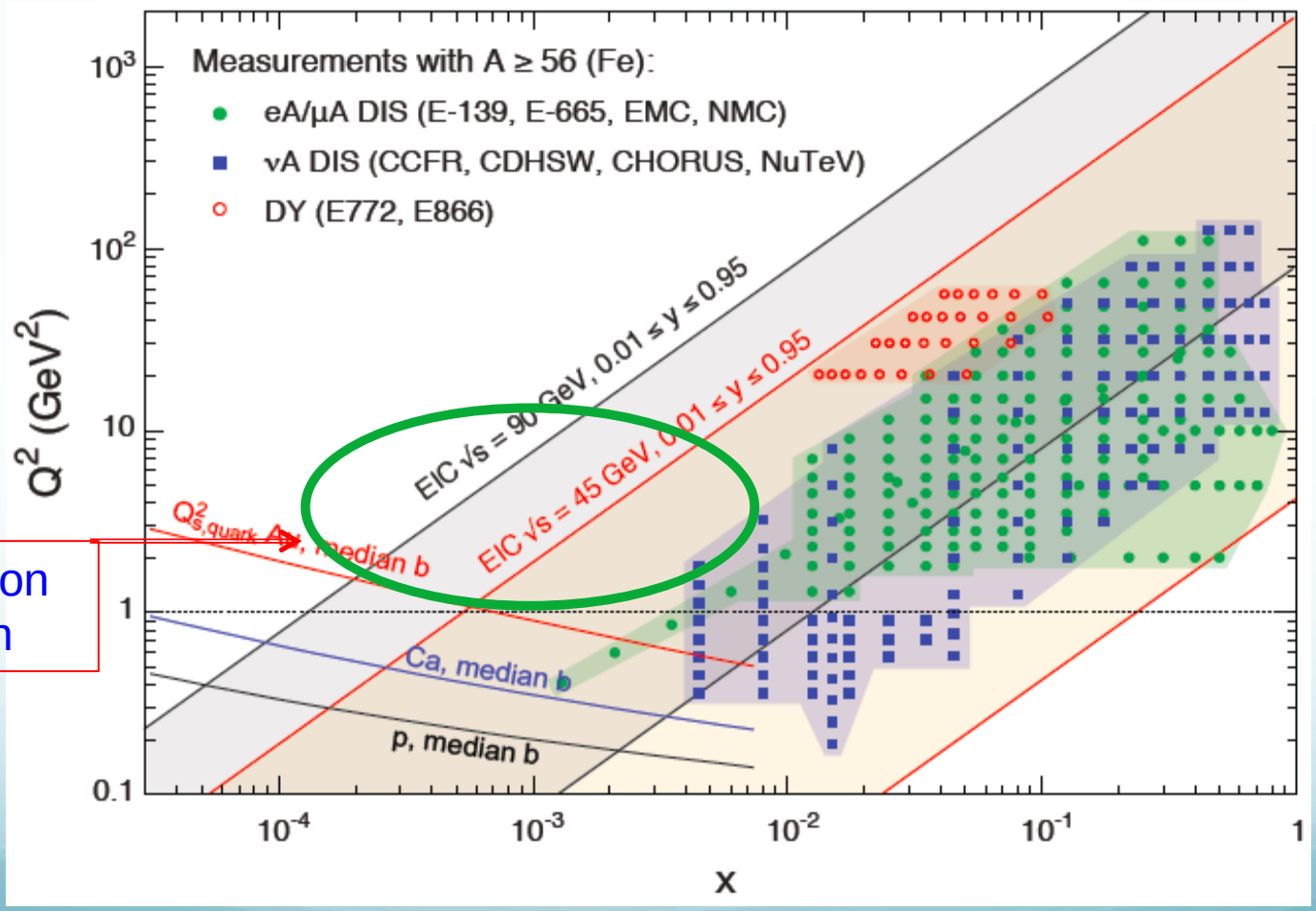
Rapid developments on ideas of calculating parton distribution functions on Lattice:
X. Ji et al. arXiv 1310.4263; 1310.7471; 1402.1462
& Y.-Q. Ma, J.-W. Qiu 1404.6860



Reaching saturation with eA

- Many more soft gluons in nucleus at the same impact parameter: $Q_s^2(eA) \propto Q_s^2(ep)\ A$





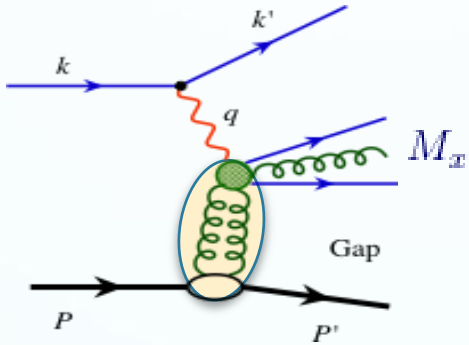
Transition region

With a gold ion beam: EIC can reach the saturation regime

Saturation/CGC: What to measure?

- **Inclusive events – structure functions, F_2 and F_L:**
  - High energy – smaller x, and larger range of Q^2
  - Search for deviation from DGLAP and BFKL

- **Diffractive cross section:**



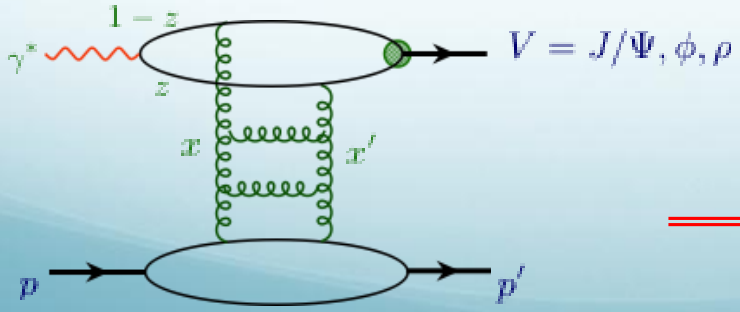
$$\sigma_{\rm diff} \propto [g(x, Q^2)]^2$$

At HERA: ep observed 10-15% / total

If CGC/Saturation – multiple coherent gluons
⟹ Diffraction eA expect ~25-30%/total

Nucleus with 8 MeV/N binding can stay intact at 1 in 4 times when hit by a "TeV" bea

- **Diffractive vector meson production:**

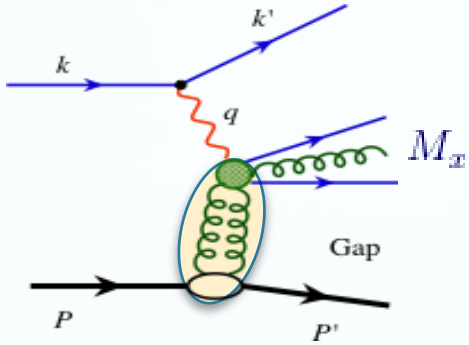


Cross section ratio for eA/ep: *J/ψ* and Φ

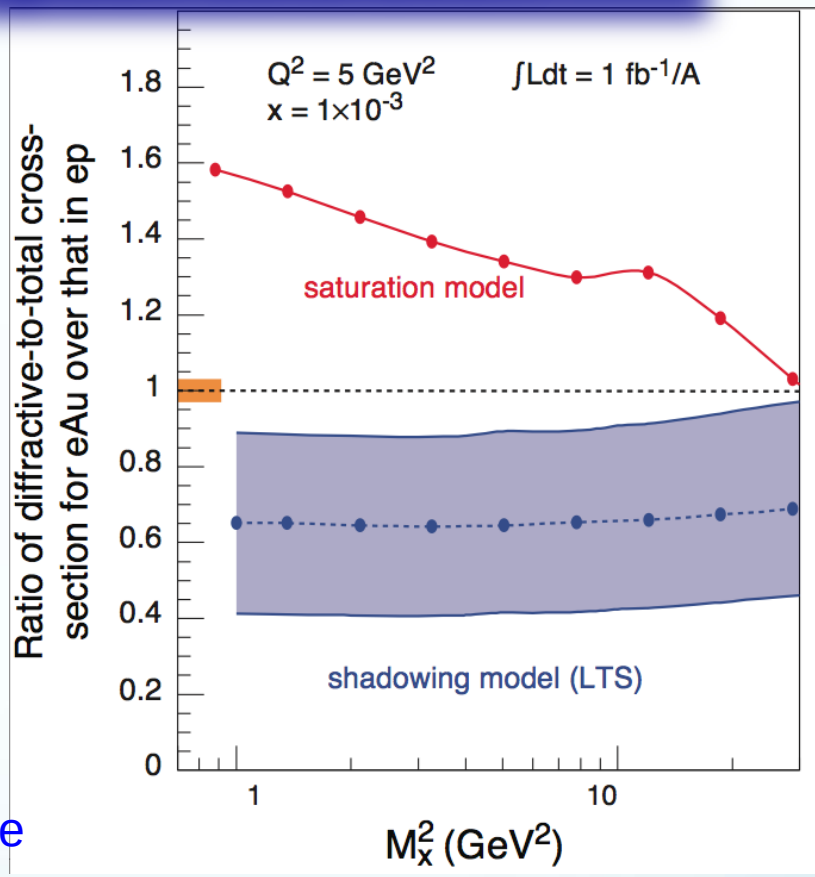
⟹ **Imaging of gluons in nuclei**

The best signature for gluon saturation

- Hard scattering with a rapidity gap:



Double ratios:
Diffractive over total cross section
eA over ep



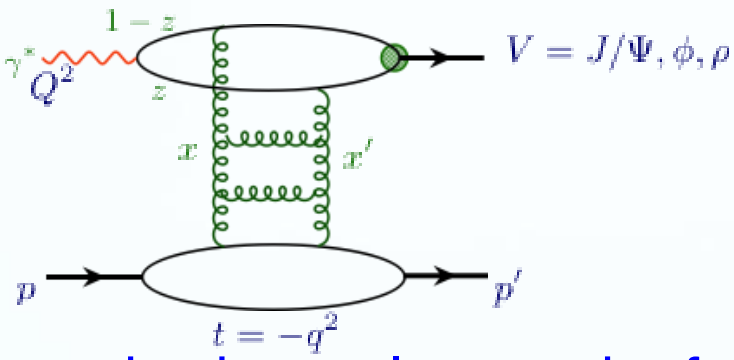
- ✧ Strong non-linear effect, color singlet exchange
- ✧ Factorization for diffractive process works in DIS, not in pp, pA, AA

The enhancement is only for eA no equivalent in pA!

This is a clean and unambiguous signal of saturation

Spatial imaging of the glue in a nucleus

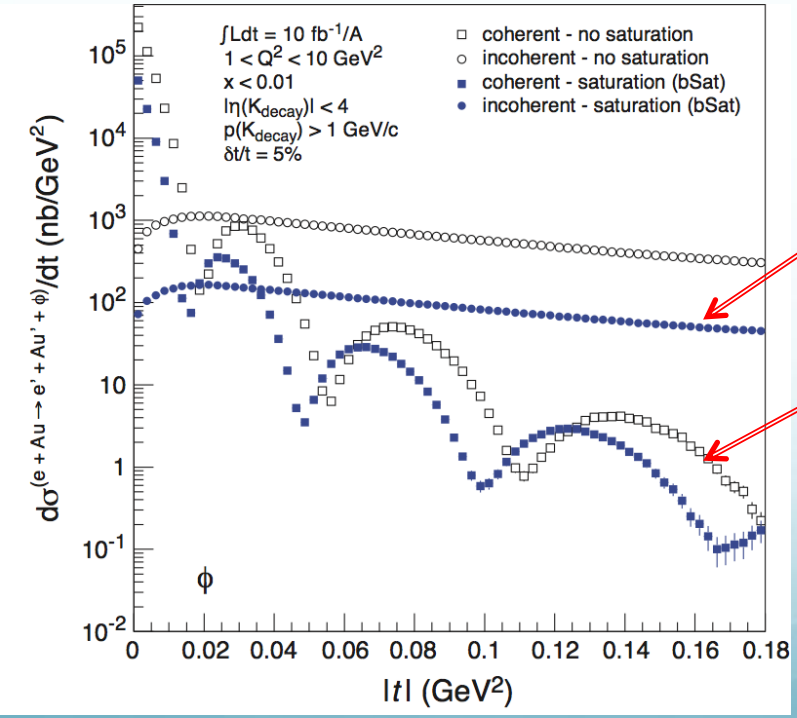
- Diffractive vector meson (Φ, J/ψ, ..) production:



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

Fourier transform
of the t-dependence

- Φ-production – clean probe for spatial distributions:



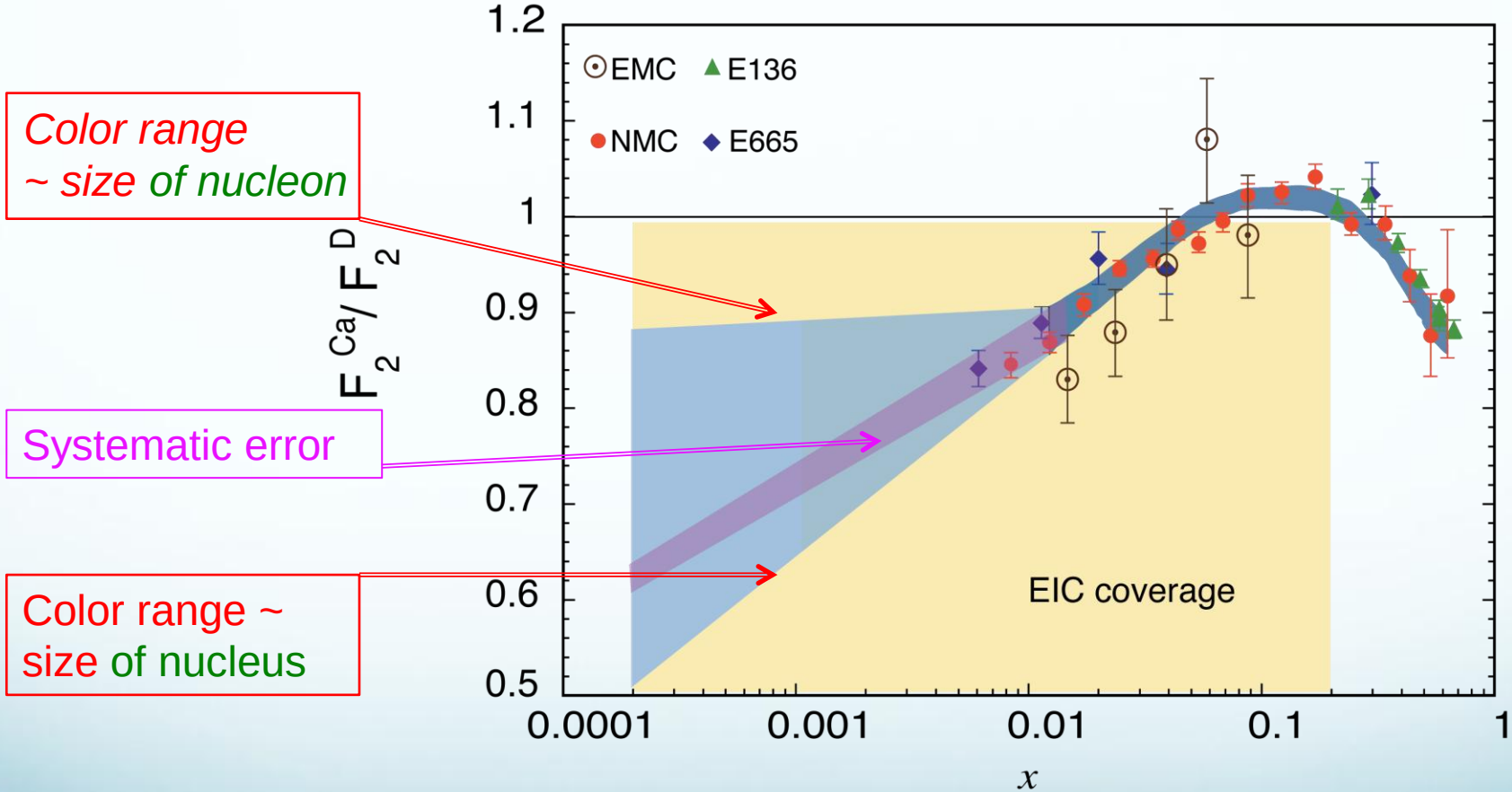
✧ Incoherent:
Nucleus breaks up

✧ Coherent:
Nucleus stays intact

Need EIC's
energy to do this!

Range of color correlation inside a nucleus?

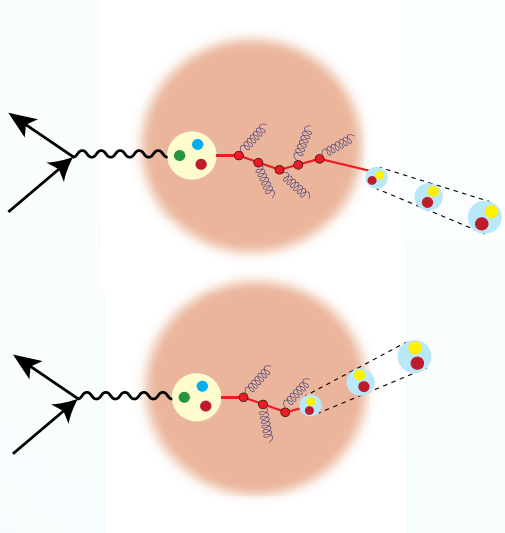
- Ratio of DIS F_2 structure functions:



A clean measurement at EIC (statistical error < systematic error)

Hadronization – energy loss

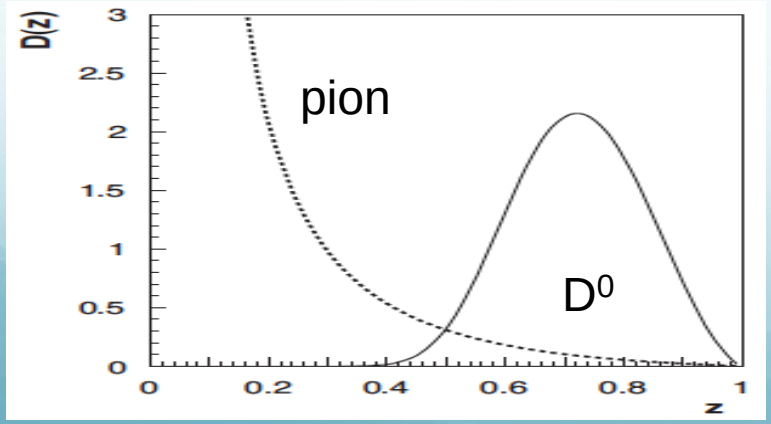
- Unprecedented ν range at EIC:

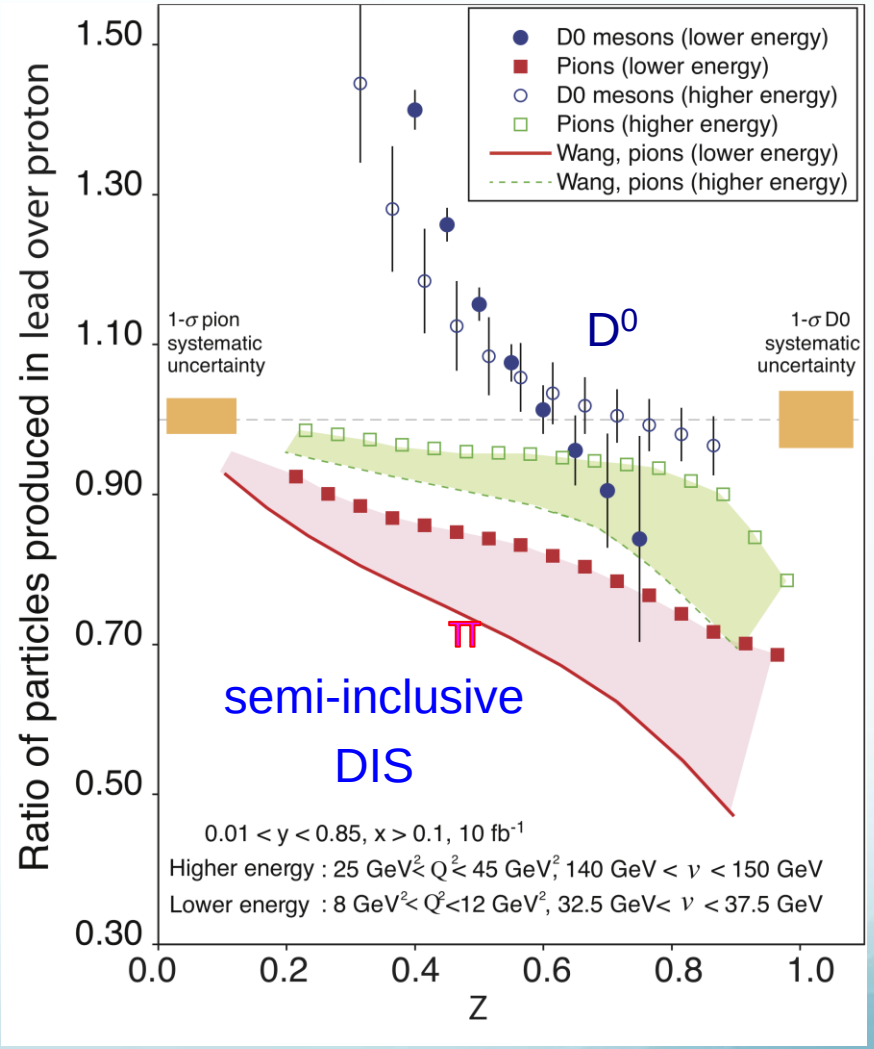


$$\nu = \frac{Q^2}{2mx}$$

semi-inclusive DIS

- Heavy quark energy loss:
  - Mass dependence of fragmentation





Need the collider energy of EIC and its control on parton kinematics

Physics opportunities at EIC

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

Deliverables	Observables	What we learn
Sea/gluon x~10^{-2} -10^{-4} S.F.	Inclusive DIS at low-x, in e-p and e-A	**Sea/gluon contrib. to proton spin, flavor sep., EMC in a new regime**
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**
Nuclear gluon density in new regime	SIDIS e-A, single hadron, Dihadron, diffract. x-section	**Non-linear QCD evolution Gluon saturation**
Color transport coefficient in medium	SIDIS for light and heavy flavors	**Color propagation, energy loss, hadronization, color fluctuation**
Weak mixing angle	PV asymmetries in DIS	**EW symmetry breaking, BSM**

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