QCD Evolution 2014 Workshop at Santa Fe, NM (May 12 – 16, 2014)

Electron-Ion Collider
Taking us to the next QCD Frontier

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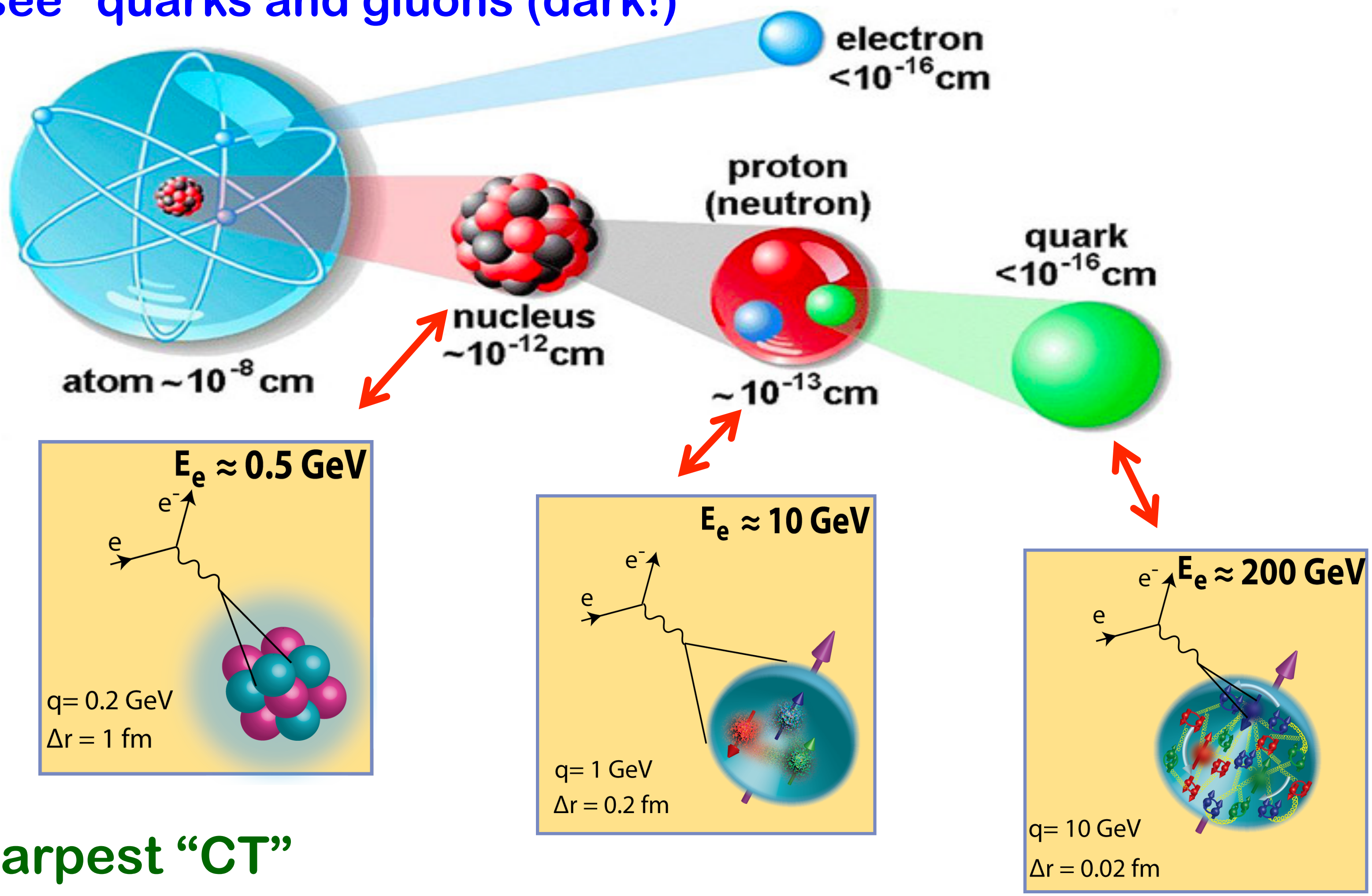
Brookhaven National Laboratory

Acknowledgement: Much of the physics presented here are based on the work of EIC White Paper Writing Committee put together by BNL and JLab managements, …

Electron-Ion Collider (EIC)

- ❑ **A giant "Microscope"**

  To "see" quarks and gluons (dark!)



- ❑ **A sharpest "CT"**

  To "cat-scan" nucleons and nuclei

EIC: the world wide interest

	HERA@DESY	LHeC@CERN	eRHIC@BNL	MEIC@JLab	HIAF@CAS	ENC@GSI
E_{CM} (GeV)	320	800-1300	45-175	12-140	12 → 65	14
proton x_{min}	1×10^{-5}	5×10^{-7}	3×10^{-5}	5×10^{-5}	$7 \times 10^{-3} \rightarrow 3 \times 10^{-4}$	5×10^{-3}
ion	p	p to Pb	p to U	p to Pb	p to U	p to ~ ^{40}Ca
polarization	-	-	p, ^{3}He	p, d, ^{3}He (^{6}Li)	p, d, ^{3}He	p,d
L [cm^{-2} s^{-1}]	2×10^{31}	10^{33}	10^{33-34}	10^{33-34}	$10^{32-33} \rightarrow 10^{35}$	10^{32}
IP	2	1	2+	2+	1	1
Year	1992-2007	2022 (?)	2022	Post-12 GeV	2019 → 2030	upgrade to FAIR

The past

Possible future

EIC: the world wide interest

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High Energy

Medium Energy

Low Energy

U.S. - based EIC

❑ NSAC 2007 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."

❑ NSAC Facilities Subcommittee (2013):

The Subcommittee ranks an EIC as **Absolutely Central** in its ability to contribute to world-leading science in the next decade."

❑ NSAC NEXT Long-Range Process:

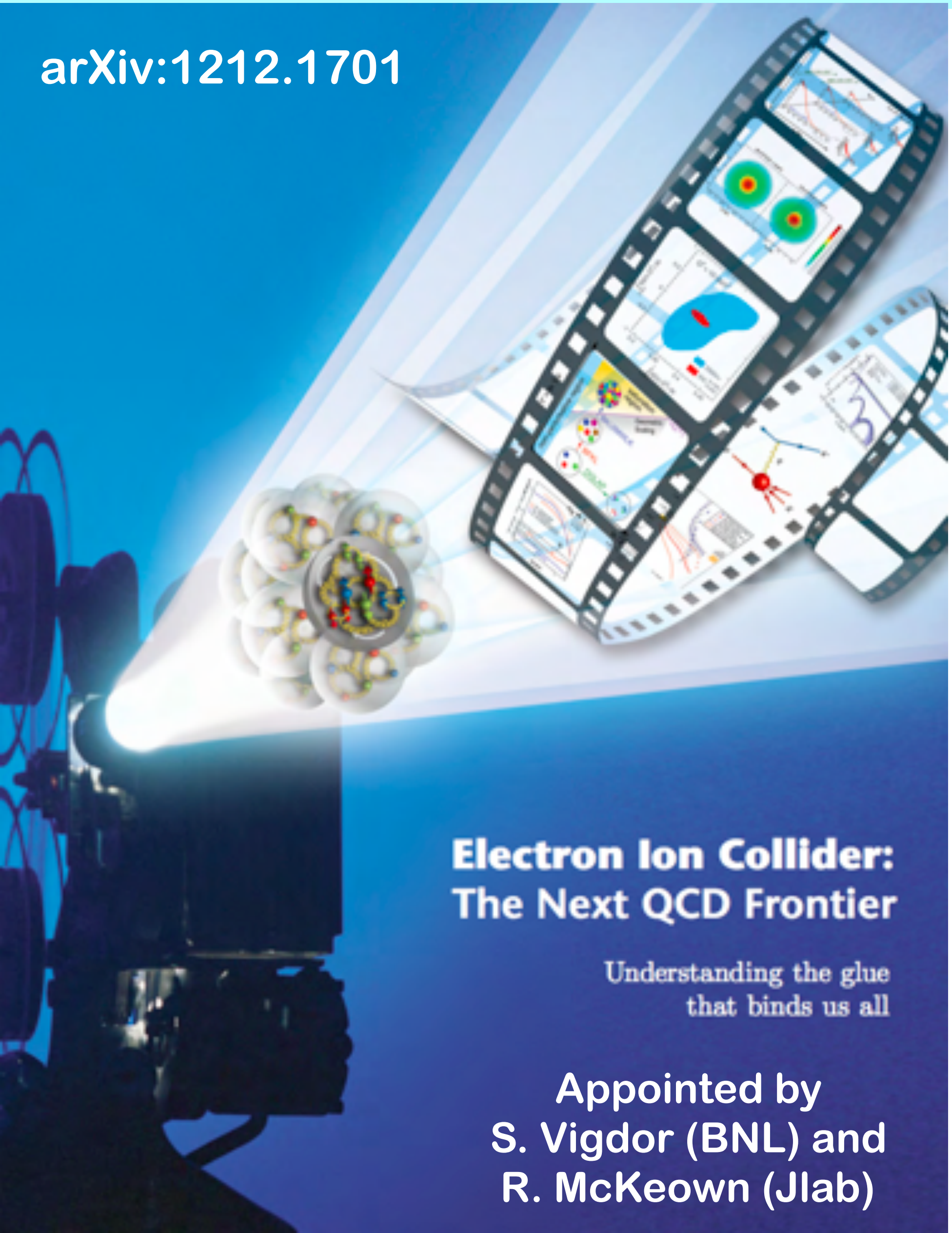
Officially started! Final report due on October 15, 2015

❑ EIC Users Meeting @ Stony Brook University, June 24-27, 2014

http://skipper.physics.sunysb.edu/~eicug/meetings/SBU.html

U.S.-based EICs – the White Paper

arXiv:1212.1701



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

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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)

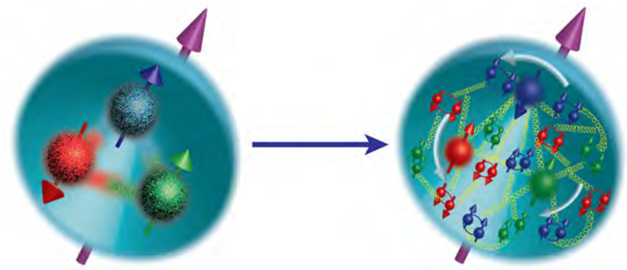
Senior Advisors:
A. Mueller (Columbia) and R. Holt (ANL)

Successful thanks to many other co-authors and contributions

U.S.-based EICs – the Physics

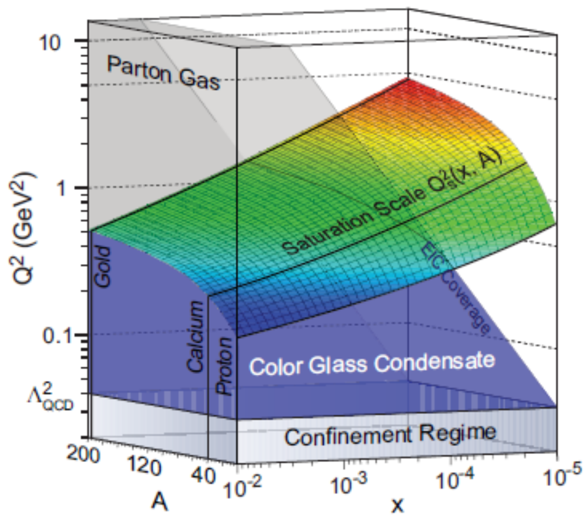
- Explore and image the spin and 3D structure of the nucleon

  Need a "machine" capable of exploring how do quarks and gluons move and distribute inside a hadron?



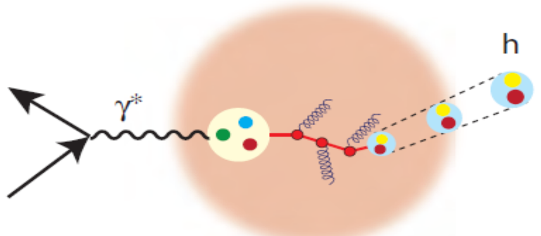
- Discover the role of gluons in structure and dynamics

  Need a "machine" capable of exploring QCD dynamics of gluons with quantum occupation number near ONE



- Understand the evergence of hadrons from color charge

  Need a "vertex detector" at a femtometer scale – the nuclei



U.S.-based EICs – the Measurement

Key questions:

- *How are the sea quarks and gluons, and their spins, distributed in space and momentum inside the nucleon?*
- *Where does the saturation of gluon densities set in?*
- *How does the nuclear environment affect the distribution of quarks and gluons and their interactions in nuclei?*

Key measurements:

- *Inclusive Deep-Inelastic Scattering (DIS)*
- *Semi-inclusive DIS with one or two of the particles in the final-state*
- *Exclusive DIS – DVCS, …*
- *Diffractive DIS – rapidity gap, …*

U.S.-based EICs – the Requirement

Key requirements:

- *Electron identification – scattered lepton*
- *Momentum and angular resolution –* x, Q^2
- *Particle identification, and acceptance:* γ, π^+, π^-, K^+, K^-, p^+, p^-, …
- *Rapidity coverage, t-resolution*

Key measurements:

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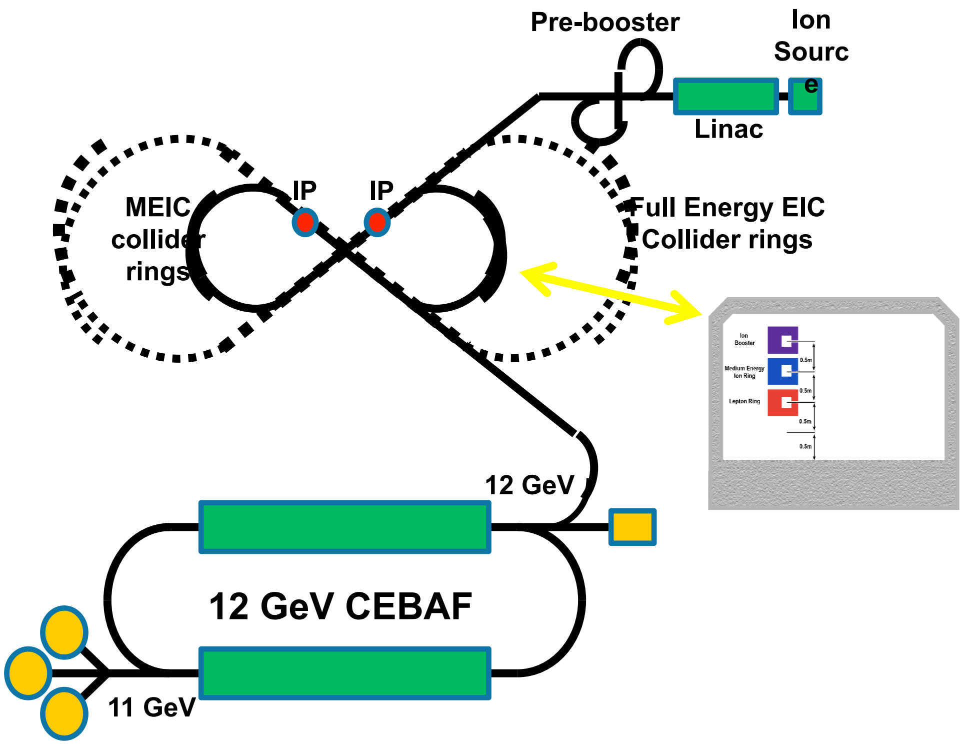
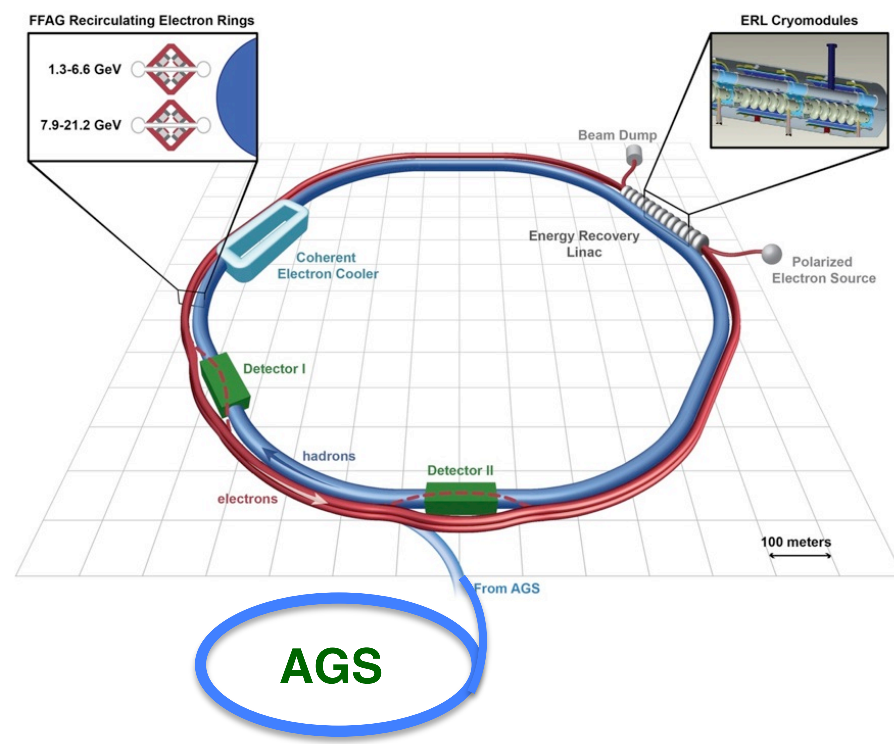
U.S.-based EICs – the Machines

MEIC (JLab)

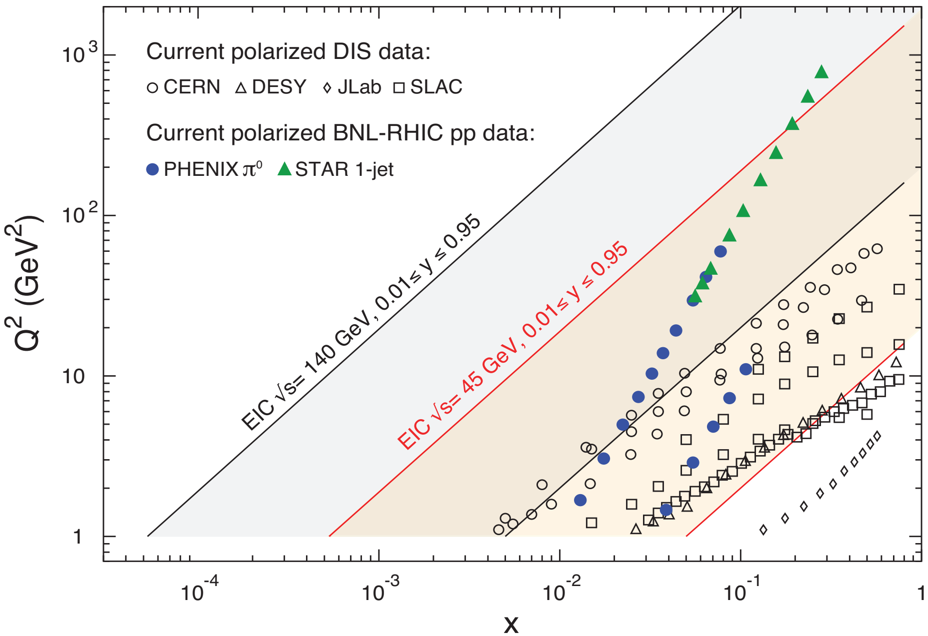


eRHIC (BNL)



- ✧ First (might be the only) polarized electron-proton collider in the world
- ✧ First electron-nucleus (various species) collider in the world
- ✧ Both using the existing facilities

U.S.-based EICs – the Coverage



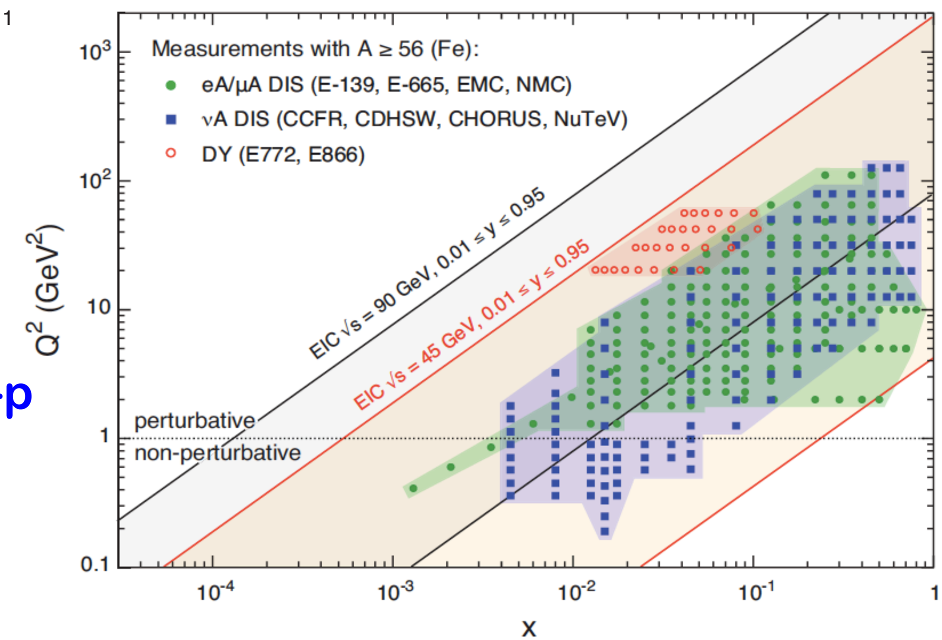
For e-N collisions at the EIC:

- ✓ 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 ~ 5x10^{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



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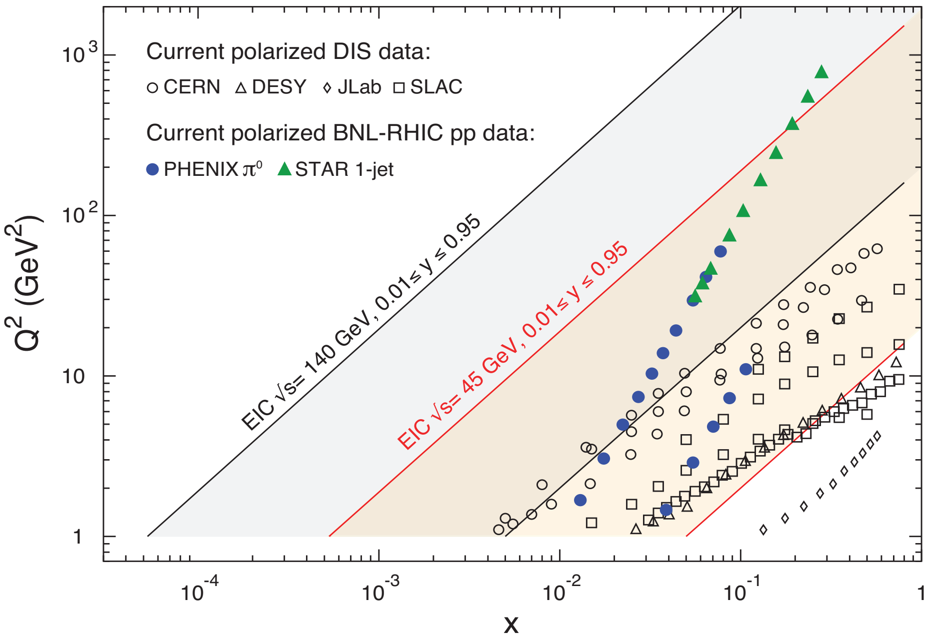

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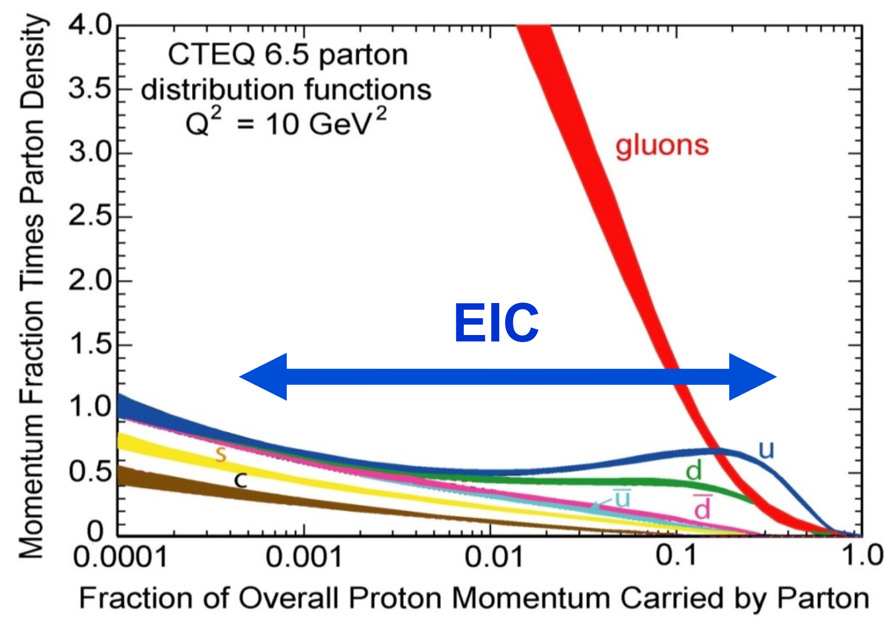
For e-A collisions at the EIC:

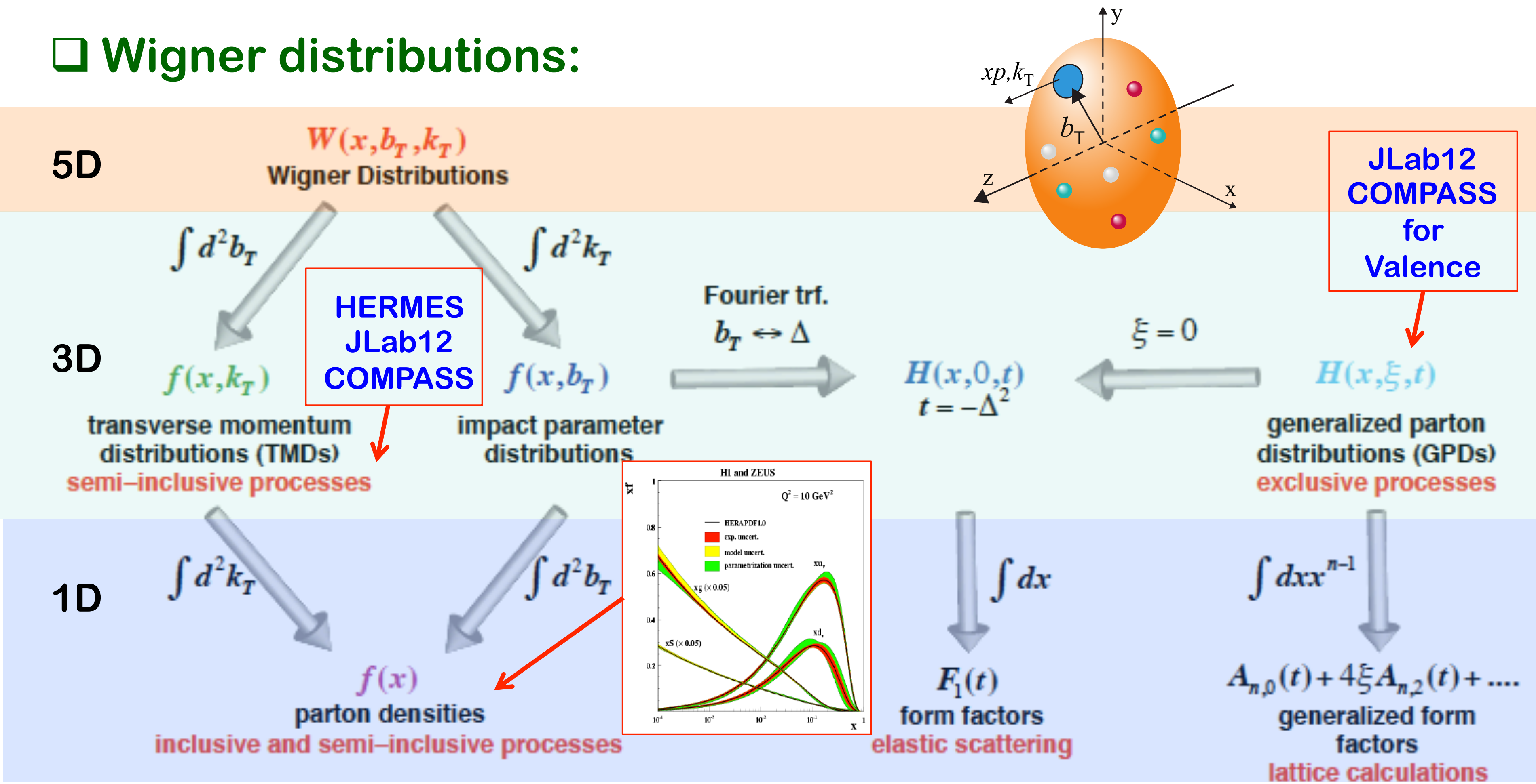
- ✓ First e-A collider
- ✓ Wide range in nuclei
- ✓ Variable center of mass energy
- ✓ Luminosity per nucleon same as e-p

EIC explores the "sea" and the glue!



Unified view of nucleon structure

❑ Wigner distributions:



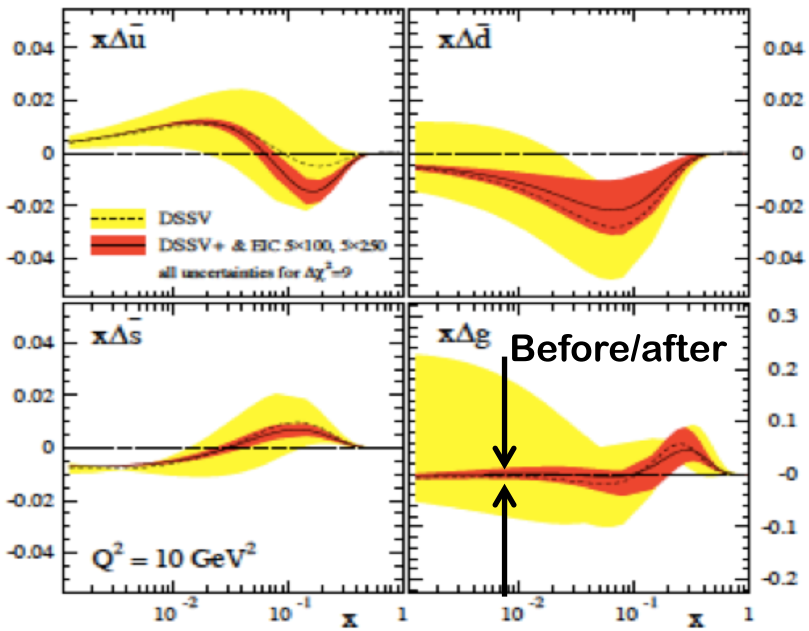
❑ EIC – 3D imaging of sea and gluons:

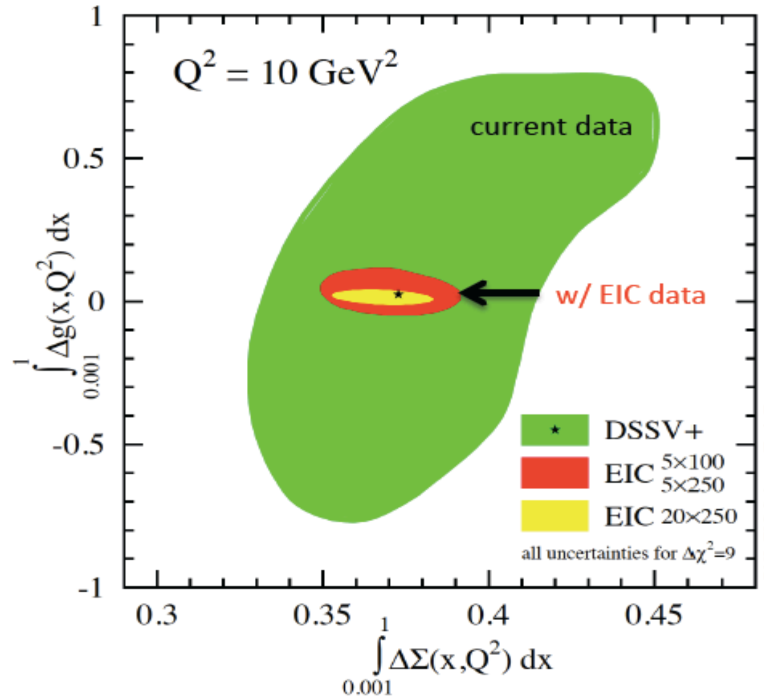
- ✧ TMDs – confined motion in a nucleon (semi-inclusive DIS)
- ✧ GPDs – Spatial imaging of quarks and gluons (exclusive DIS)

Helicity contribution to proton spin

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

(Low x and wide x range at EIC)

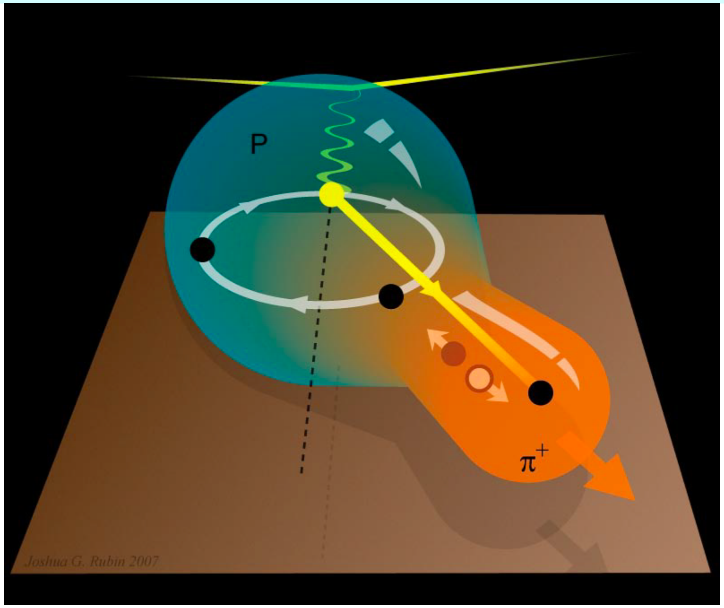




No other machine in the world can achieve this!

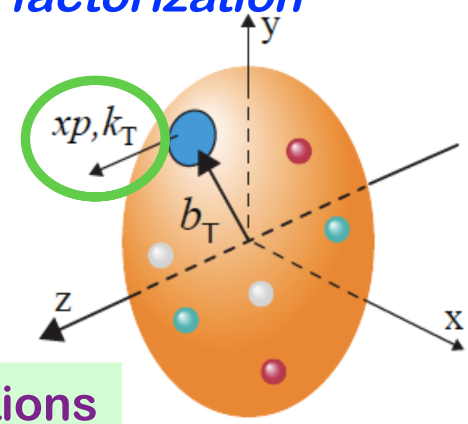
- Solution to the proton spin puzzle:
  - *Precision measurement of $\Delta G(x)$ – extend to smaller x regime*
  - *Quantify the role of orbital angular momentum contribution - GPDs*

Semi-inclusive DIS

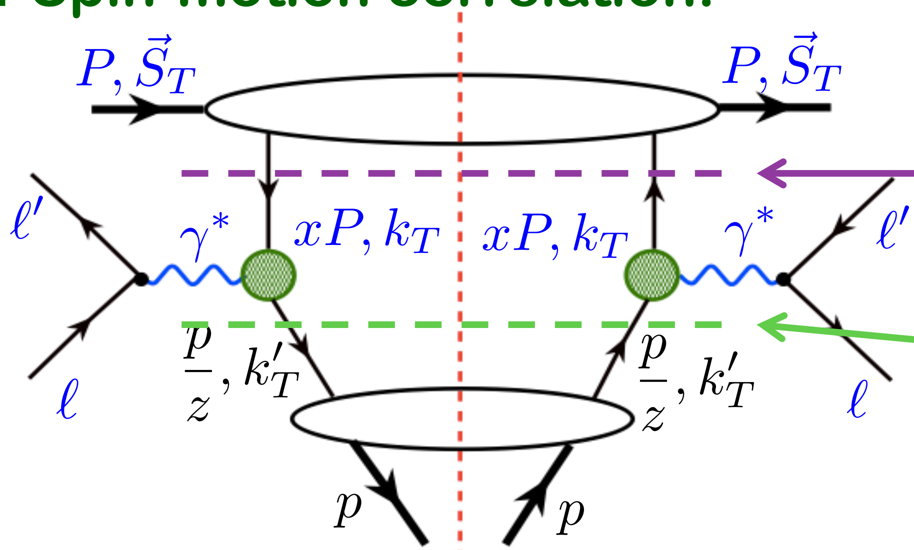


- **Naturally, two scales:**
  - ✧ high Q – localized probe
    To "see" quarks and gluons
  - ✧ Low p_T – sensitive to confining scale
    To "see" their confined motion
  - ✧ *Theory – QCD TMD factorization*

Best process to probe TMDs



- **Spin-motion correlation:**

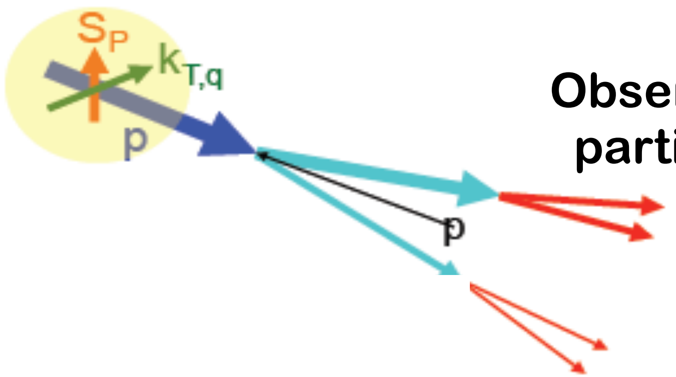


4 spin combinations
$\gamma^+, \gamma^+\gamma_5, \gamma^+\gamma_\perp^\alpha$

4 spin combinations
$\gamma^+, \gamma^+\gamma_5, \gamma^+\gamma_\perp^\alpha$

Quantum correlation between hadron and parton

- Sivers effect – between hadron spin and parton motion:

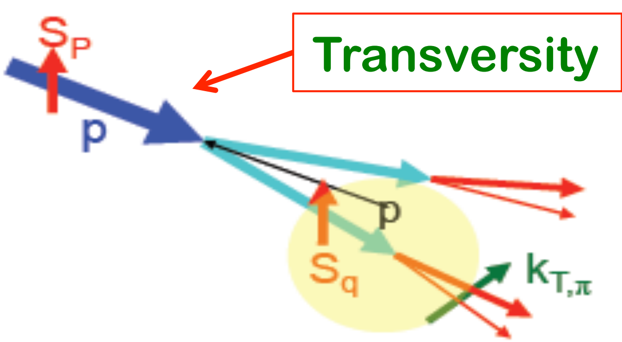


Observed particle

Sivers function

Hadron spin influences parton's transverse motion

- Collins effect – between parton spin and hadronization:



Observed particle

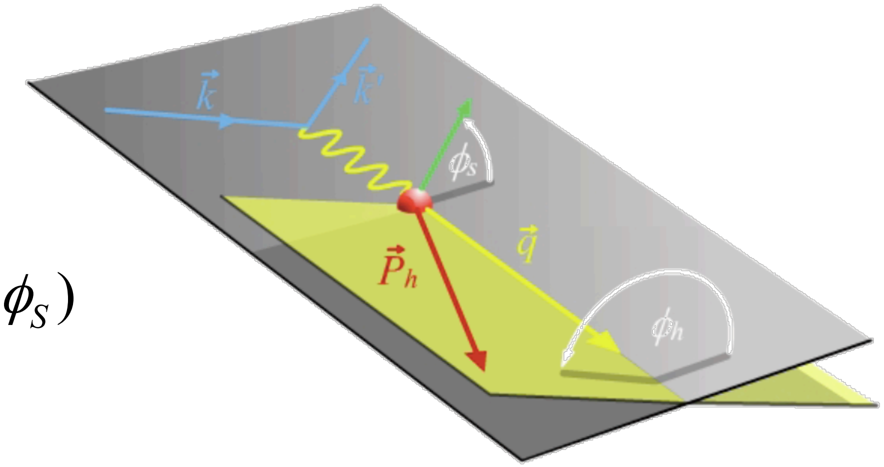
Collins function

Parton's transverse spin influence its hadronization

JLab12, COMPASS, and low energy EIC for valence, EIC@US covers the sea and gluon!

EIC is the best for probing TMDs

- **Naturally, two planes:**



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

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

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

- **Separation of TMDs:**

$$A_{UT}^{Collins} \propto \langle \sin(\phi_h + \phi_S) \rangle_{UT} \propto h_1 \otimes H_1^\perp$$

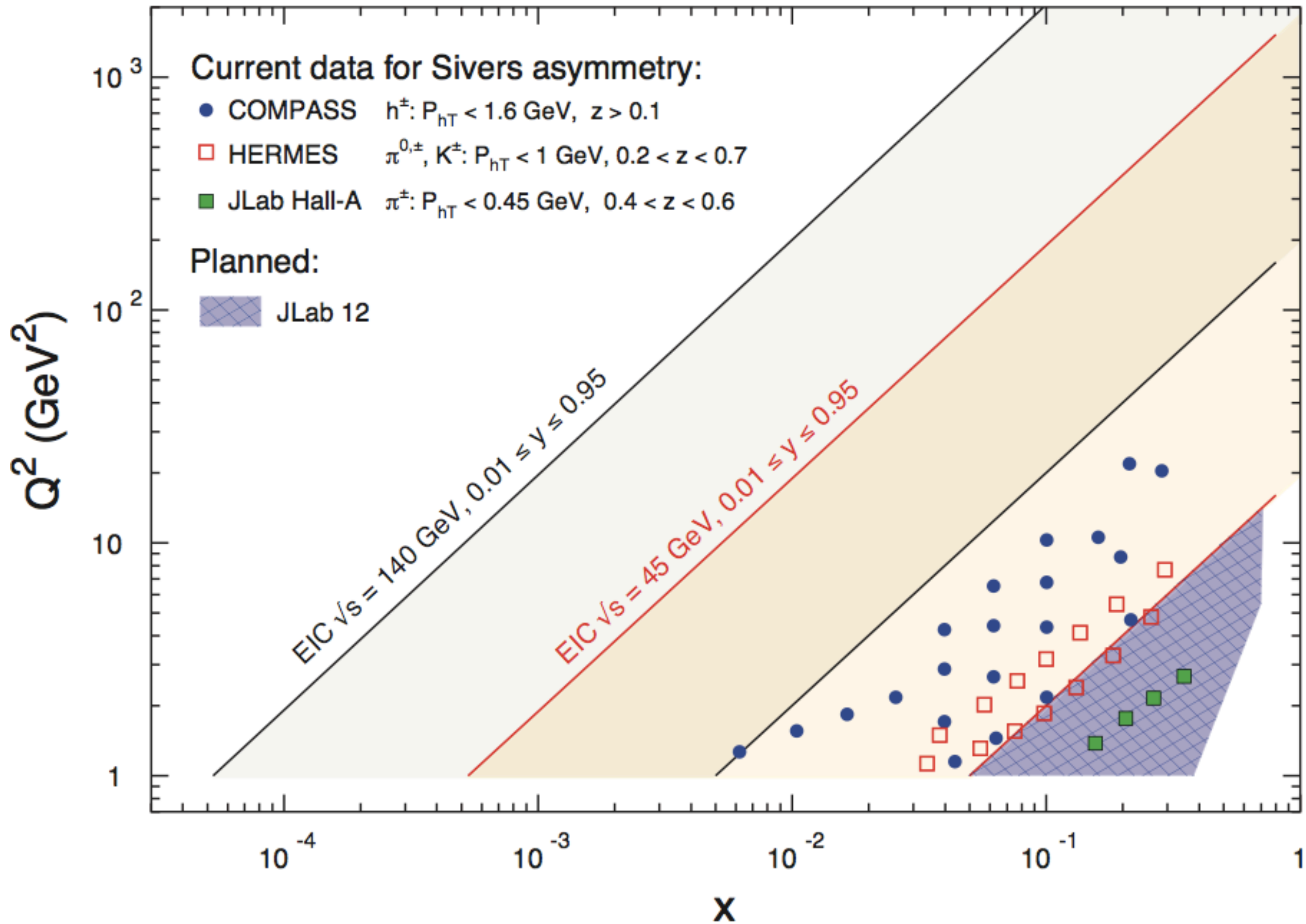
$$A_{UT}^{Sivers} \propto \langle \sin(\phi_h - \phi_S) \rangle_{UT} \propto f_{1T}^\perp \otimes D_1$$

$$A_{UT}^{Pretzelosity} \propto \langle \sin(3\phi_h - \phi_S) \rangle_{UT} \propto h_{1T}^\perp \otimes H_1^\perp$$

Collins frag. Func. from e^+e^- collisions

Hard, if not impossible, to separate TMDs in hadronic collisions

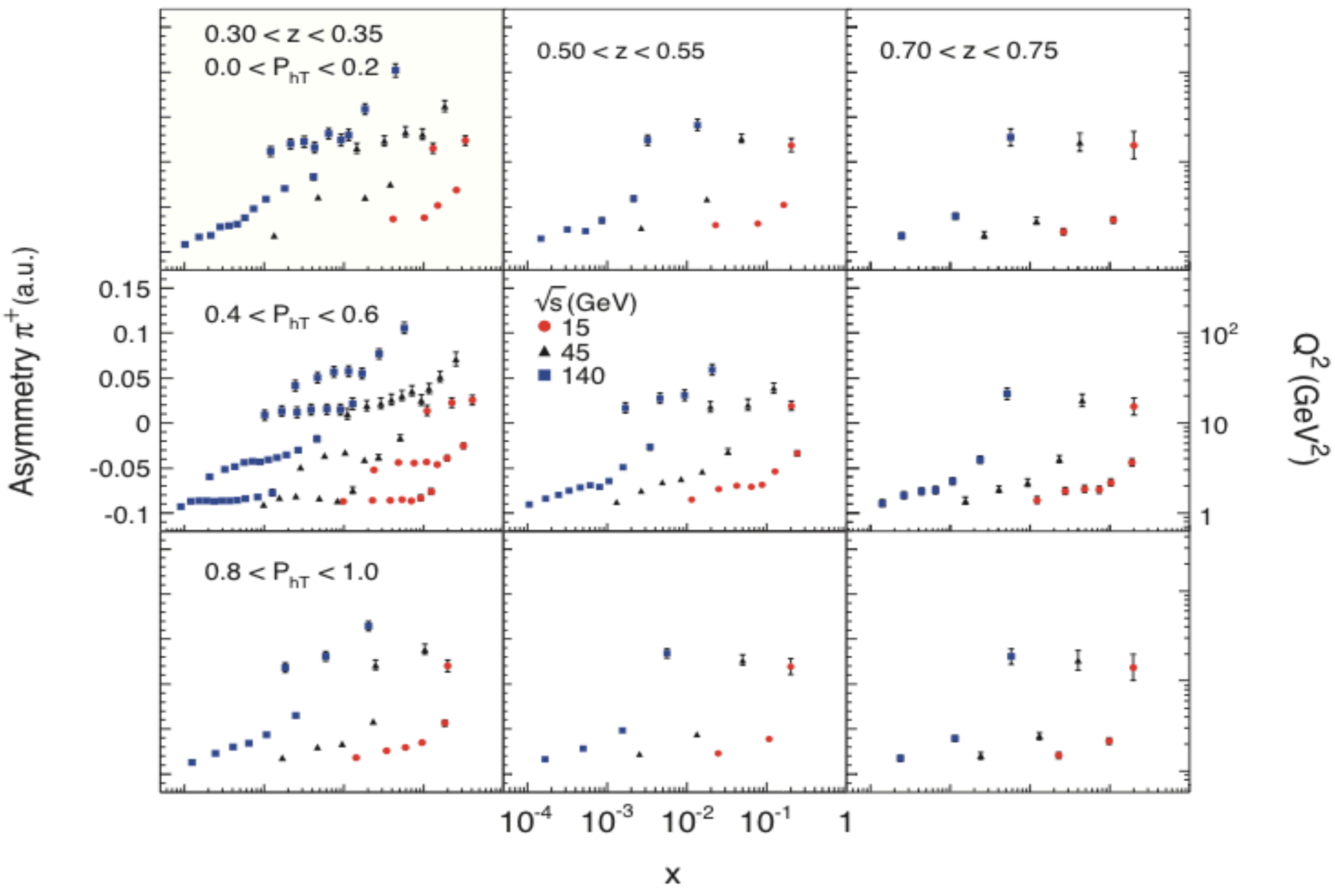
EIC coverage on TMDs



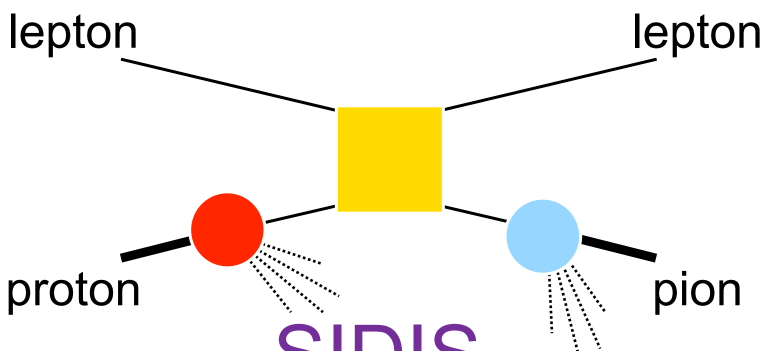
First, maybe only, measurement of polarized sea and gluon TMDs

Precision of TMDs @ EIC

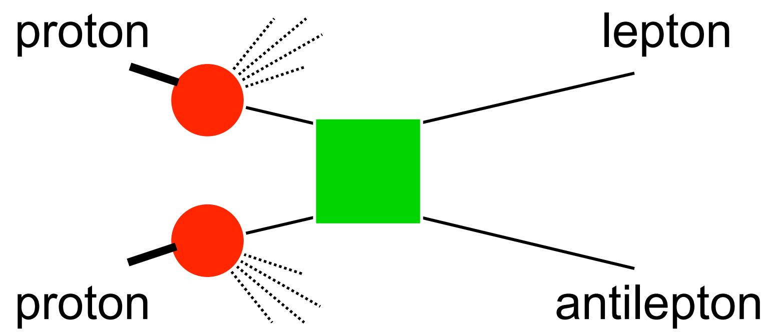
- Single transverse-spin asymmetry:



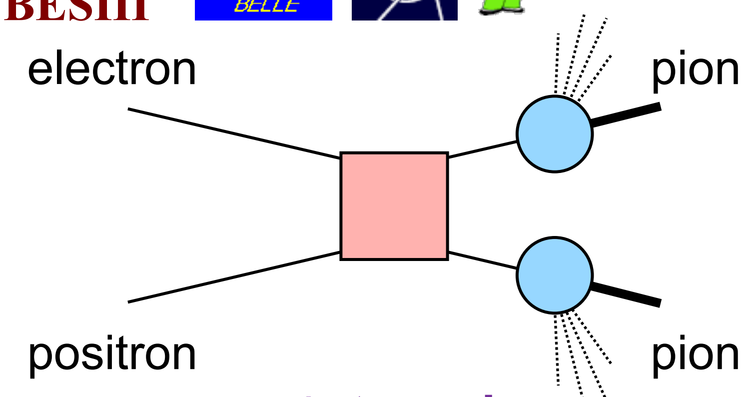
World effort on TMDs



SIDIS



Drell-Yan



$e^{-}e^{+}$ to pions

Partonic scattering amplitude

Fragmentation amplitude

Distribution amplitude

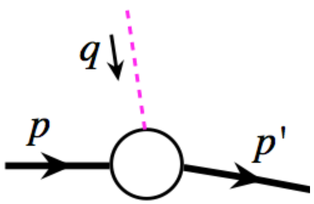
Test of the sign change!

$$f_{1T}^{\perp q}(\text{SIDIS}) = -f_{1T}^{\perp q}(\text{DY})$$

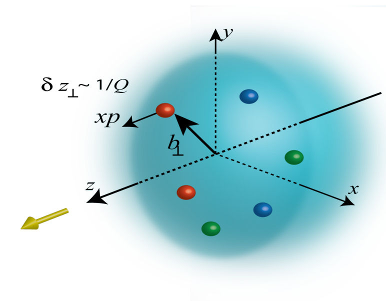
$$h_1^{\perp}(\text{SIDIS}) = -h_1^{\perp}(\text{DY})$$

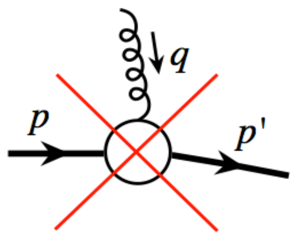
Spatial imaging of quarks and gluons

❑ Need Form Factor of density operator:

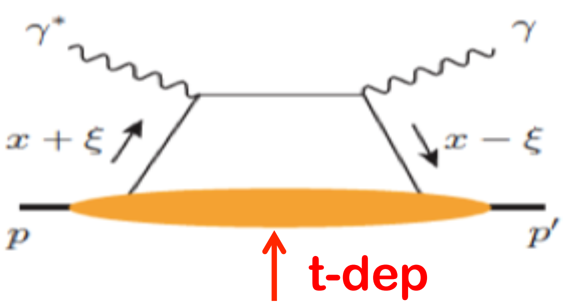


- ✧ Exchange of a colorless "object"
- ✧ "Localized" probe
- ✧ Control of exchanging momentum





❑ Exclusive processes – DVCS:



$$\frac{d\sigma}{dx_B dQ^2 dt} \Rightarrow$$ **GPDs** $H_q(x,\xi,t,Q), E_q(x,\xi,t,Q), \ldots$

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

F.T. of t-dep

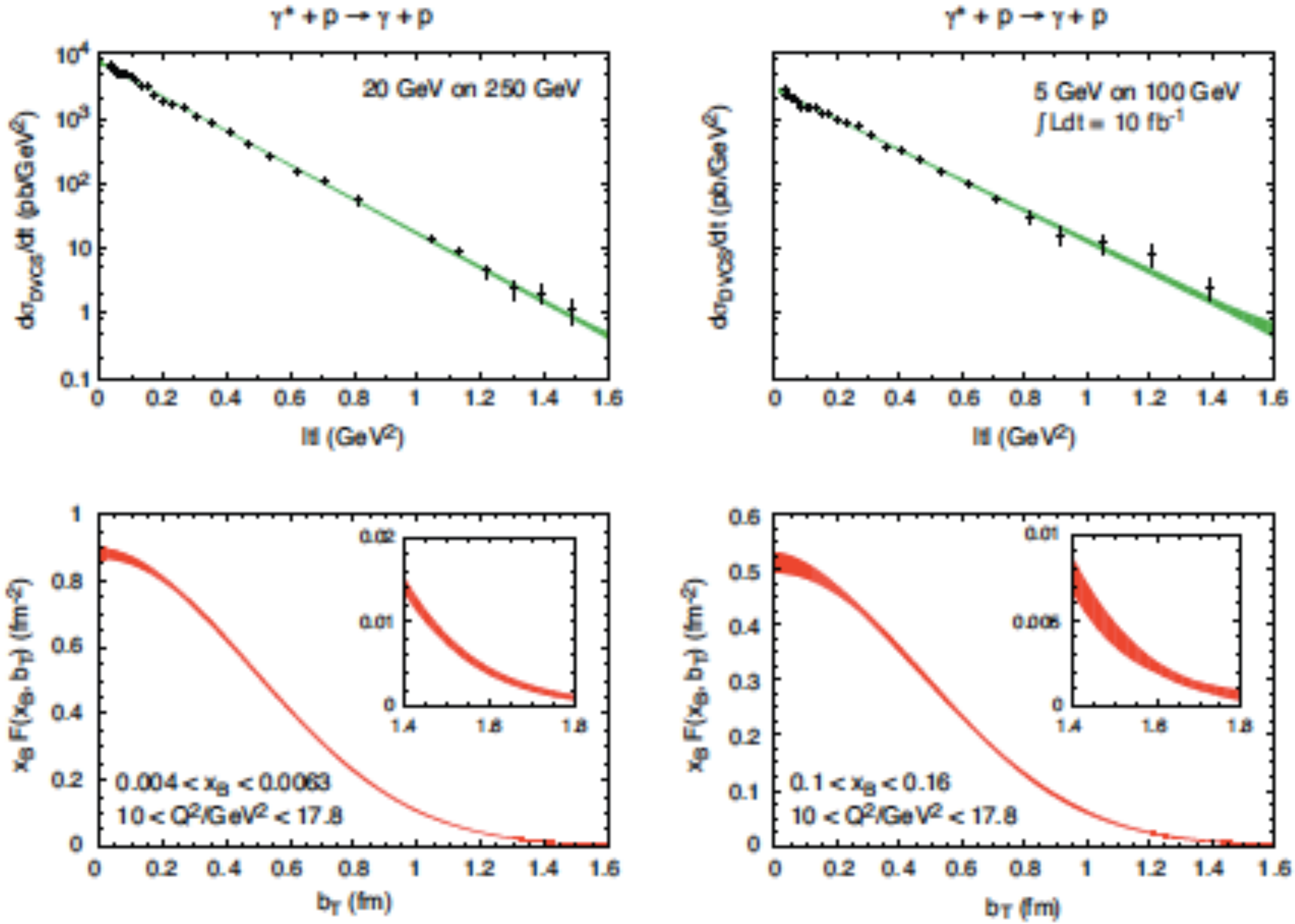
$$\xi = (P' - P)\cdot n/2 \Rightarrow$$ **Spatial distributions**

JLab 12: Valence quarks

EIC: Sea quarks

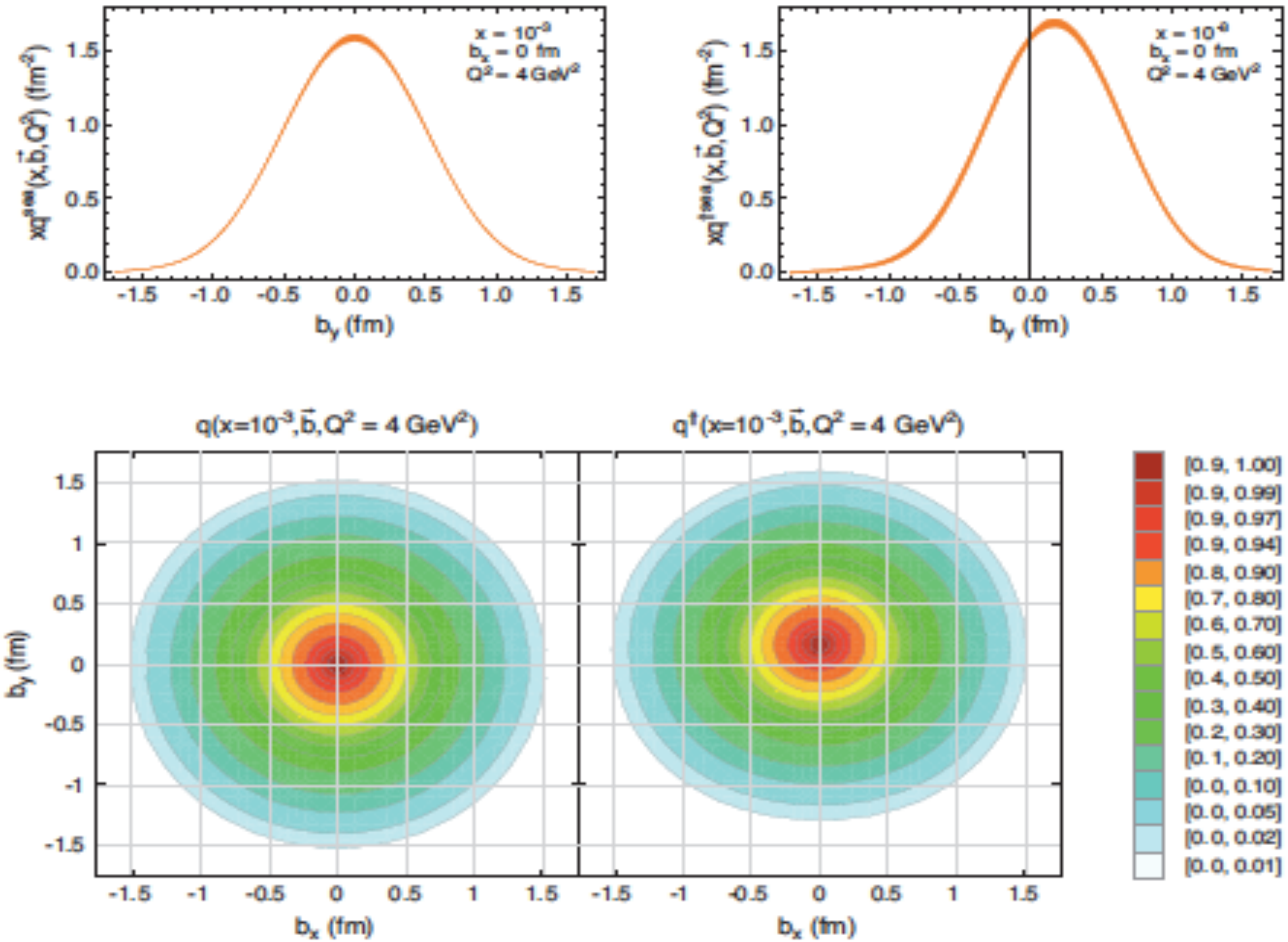
Also for light meson production (EIC@China)

DVCS @ EIC

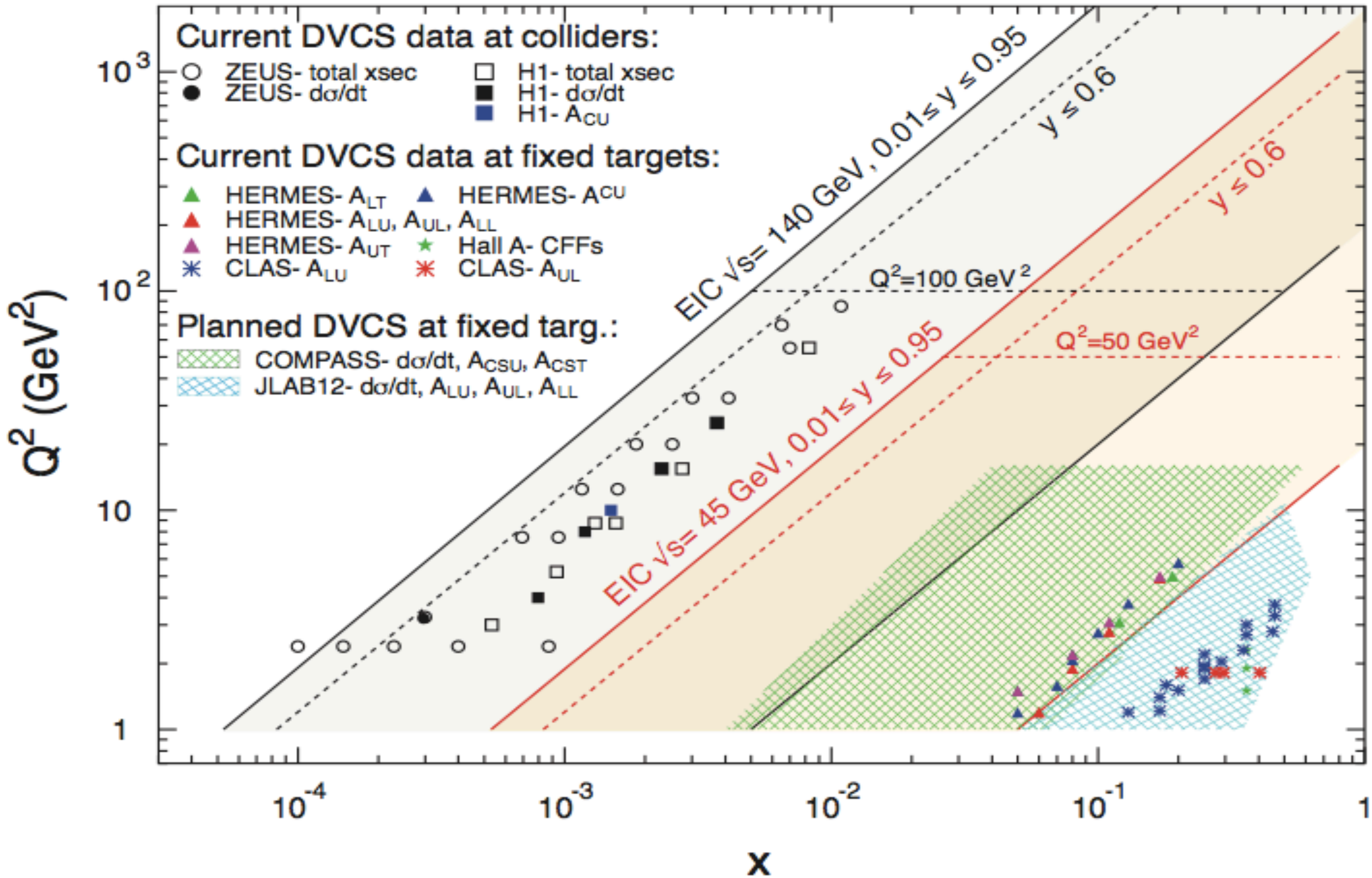


γ* + p → γ + p
20 GeV on 250 GeV
5 GeV on 100 GeV
∫Ldt = 10 fb⁻¹
dσ_DVCS/dt (pb/GeV²)
|t| (GeV²)
x_B F(x_B, b_T) (fm⁻²)
b_T (fm)
0.004 < x_B < 0.0063
10 < Q²/GeV² < 17.8
0.1 < x_B < 0.16
10 < Q²/GeV² < 17.8

Polarized DVCS @ EIC



EIC coverage on GPDs

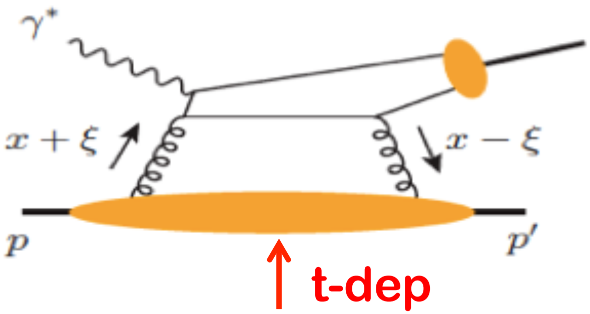


First, maybe only, measurement of polarized sea and gluon GPDs

Spatial imaging of gluon density

❑ Exclusive vector meson production:

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



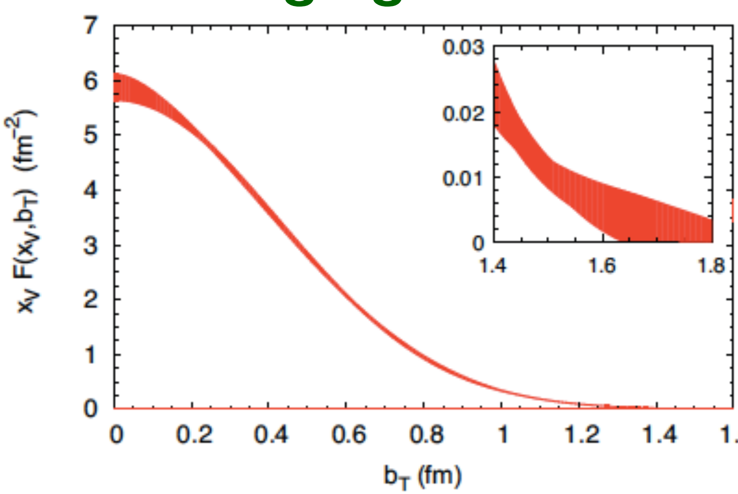
J/Ψ, Φ, …

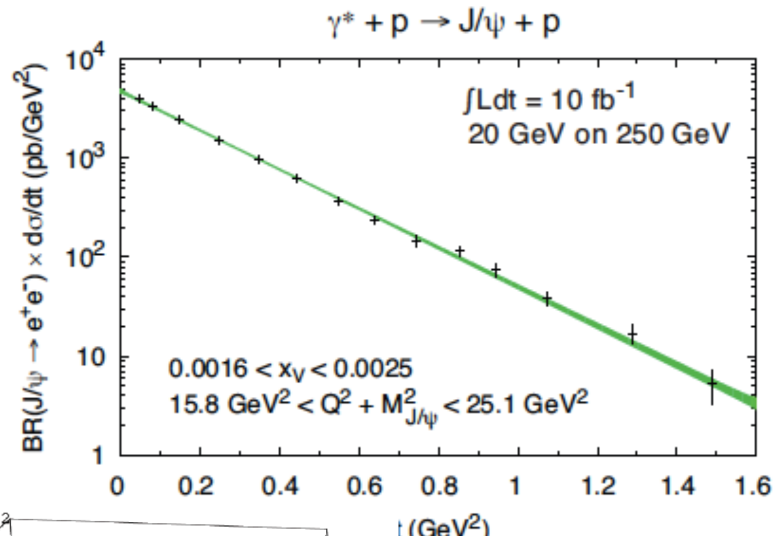
✧ Fourier transform of the t-dep

➡ Spatial imaging of glue density

✧ Resolution ~ 1/Q or 1/M_Q

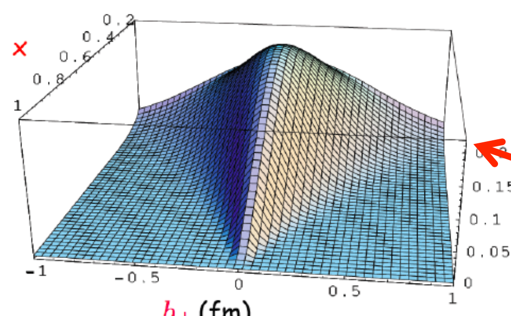
❑ Gluon imaging from simulation:





Only possible at the EIC

Gluon radius?



How spread at small-x?

An immediate consequence

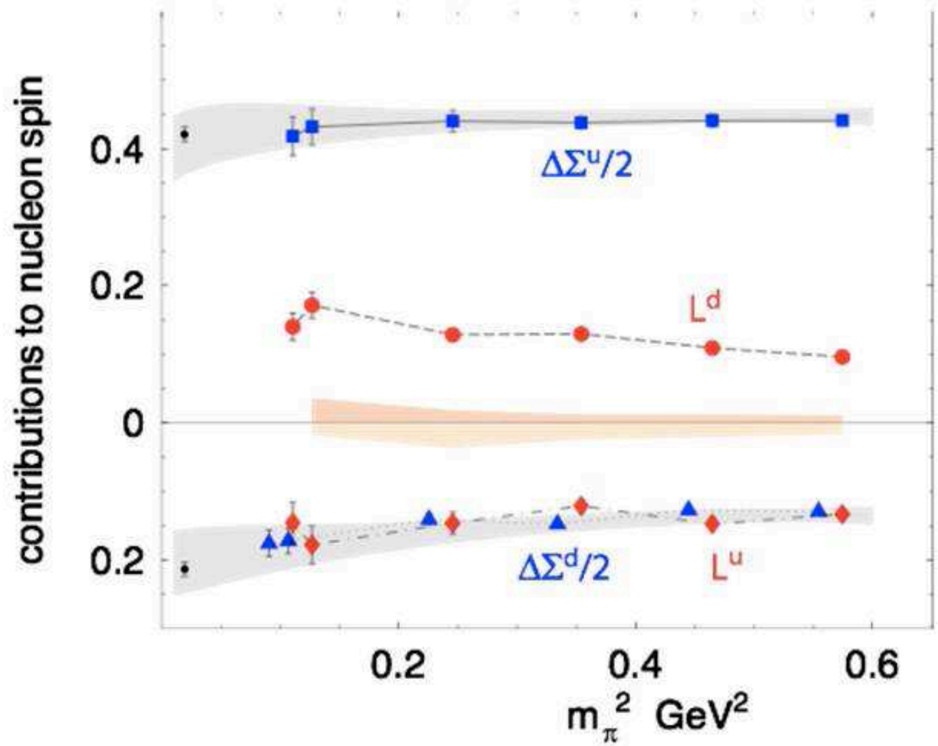
- ❑ **Quark GPDs and its orbital contribution to proton's spin:**

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

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 could be checked by Lattice QCD

$L_u + L_d \sim 0$?



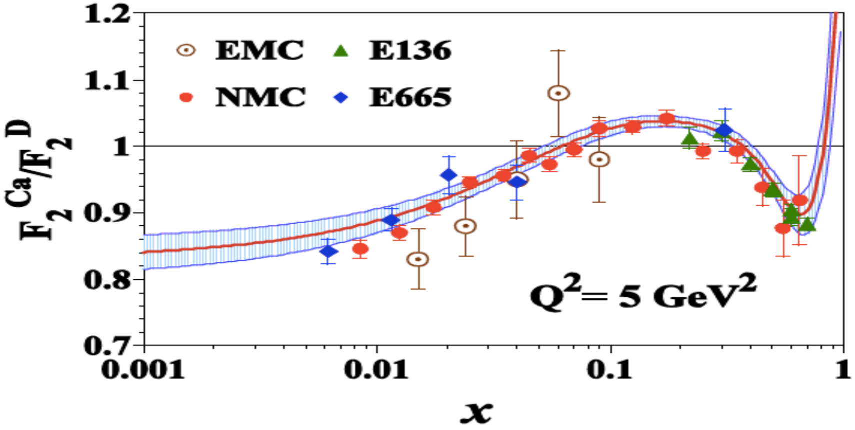
Nuclear landscape

- EMC discovery:

Nuclear landscape

≠ superposition

of nucleon landscape

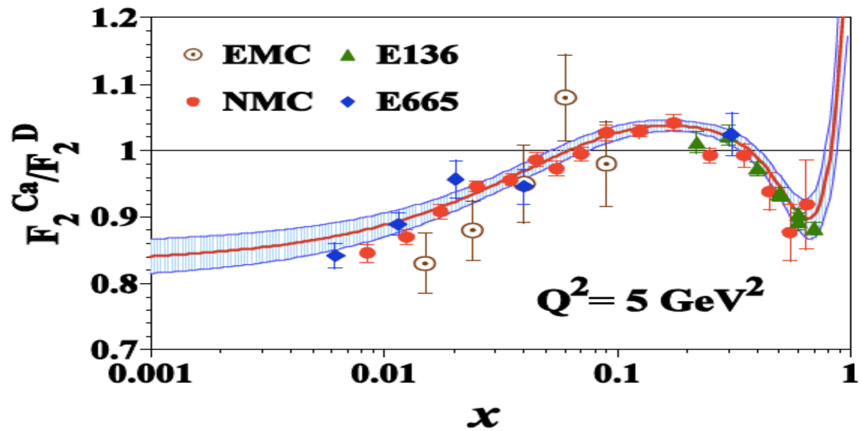


How would/does a nucleus look if we only saw its quarks and gluons?

Nuclear landscape

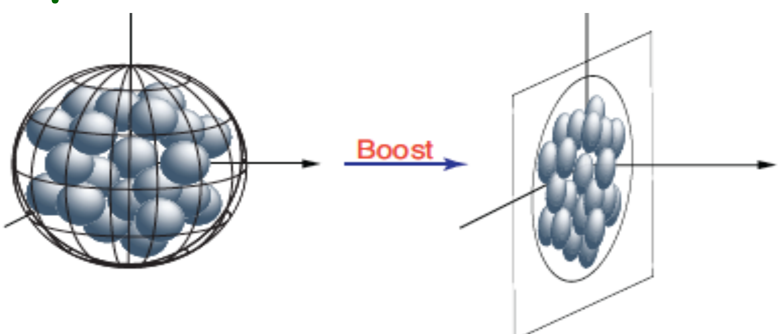
- **EMC discovery:**

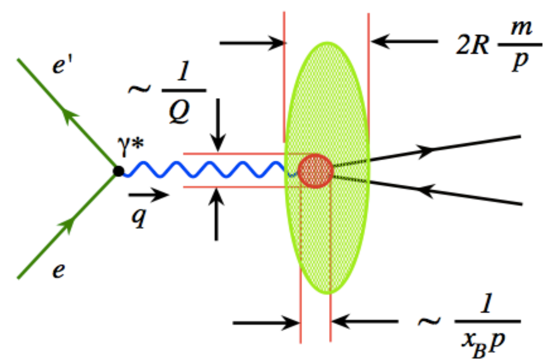
Nuclear landscape
$\neq$ superposition
of nucleon landscape



How would/does a nucleus look if we only saw its quarks and gluons?

- **"Snapshot" does not have a "sharp" depth at small x_B**





✧ Hard probe is very "sharp" in space:

Transverse size - $\dfrac{1}{Q} \ll 1\ \mathrm{fm}$, longitudinal size - $\dfrac{1}{xp} \sim \dfrac{1}{Q} \ll 1\ \mathrm{fm}$

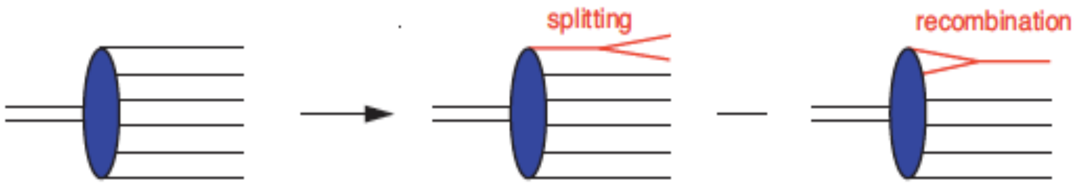
✧ Longitudinal size > Lorentz contracted nucleon:

$$\frac{1}{xp} > 2R_A\frac{m}{p} \quad \text{or} \quad x \lesssim 0.01$$

Hard probe can "see" gluons from all nucleons at the same impact parameter!

Non-linear evolution and saturation in QCD

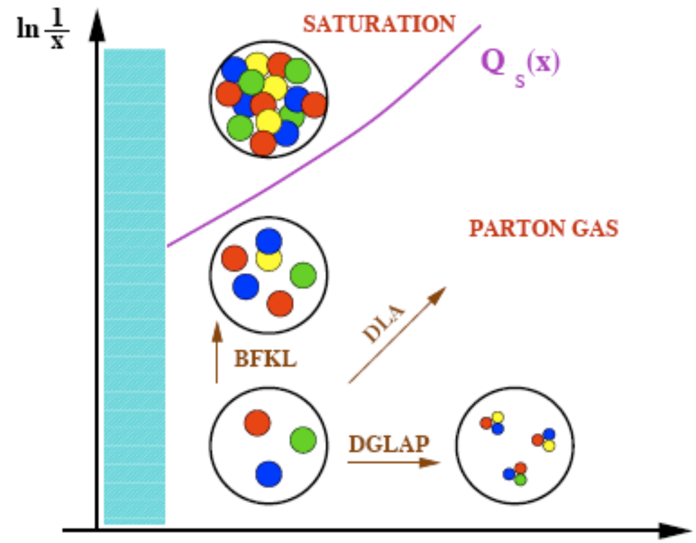
- **Gluon recombination:**



- **Modified DGLAP:**

$$\frac{\partial}{\partial \ln Q^2} xg(x,Q^2) \approx \frac{\alpha_s N_c}{\pi} \int_x^1 \frac{dx'}{x'} x'g(x',Q^2)$$
$$- \frac{K}{Q^2 R^2} \left[\frac{\alpha_s N_c}{\pi}\right]^2 \int_x^1 \frac{dx'}{x'} [x'g(x',Q^2)]^2 + \mathcal{O}\left[\left(\frac{Q_s^2}{Q^2}\right)^2\right]$$

Power corrections



Saturation: All power correction terms are equally important

→ Saturation scale: $Q_s^2(x) \sim \frac{\alpha_s(Q_s)}{\pi R^2} xg(x,Q_s^2) \sim \frac{1}{x^\lambda}$

Counting single parton is not effective! → Scattering amplitude, Effective fields, …

Non-linear evolution and saturation in QCD

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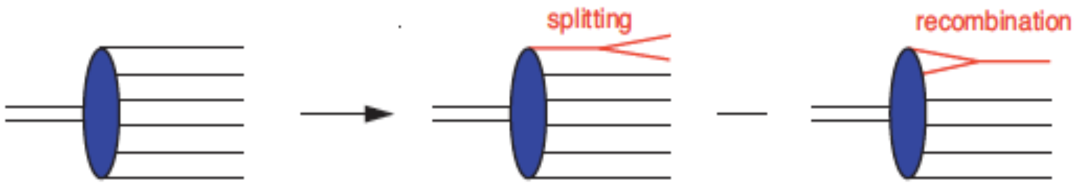

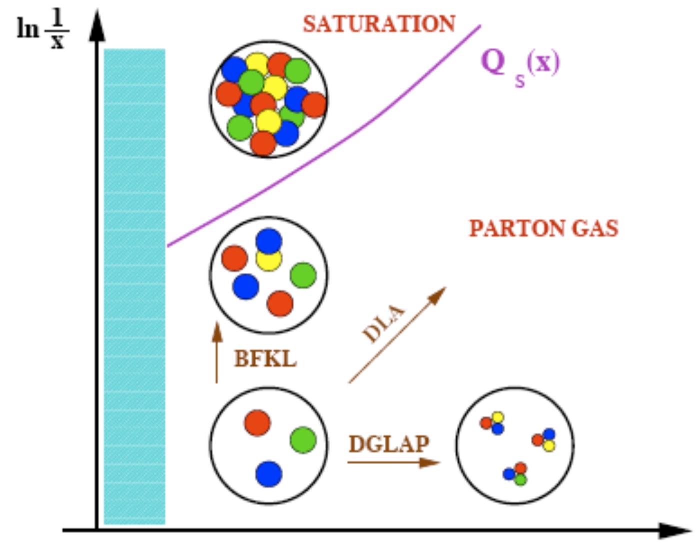

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Counting single parton is not effective! → Scattering amplitude, Effective fields, …

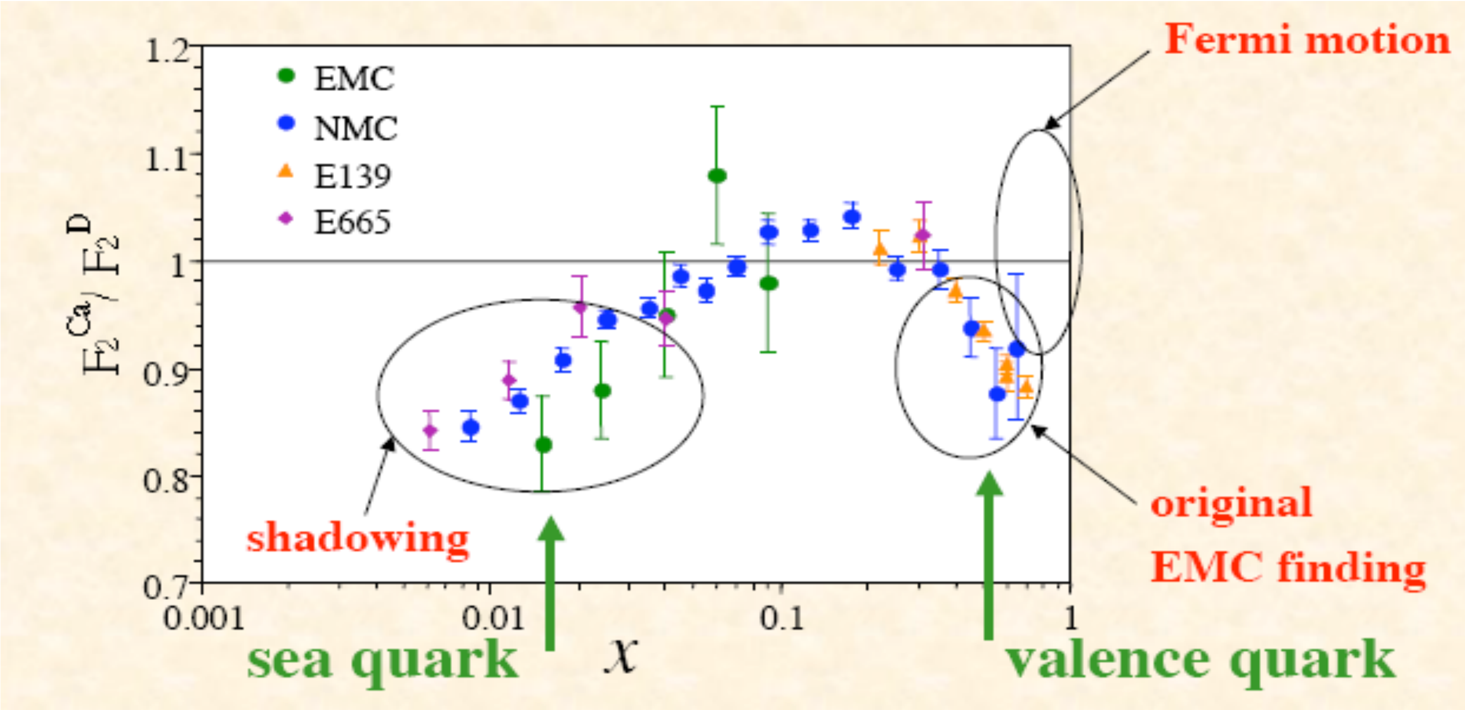
- **Modified BFKL – BK equation:**

$$\frac{\partial N(x,r_T)}{\partial \ln(1/x)} = \alpha_s K_{\mathrm{BFKL}} \otimes N(x,r_T) - \alpha_s [N(x,r_T)]^2$$

→ *JIMWLK - equation*

An “easiest” measurement

- EMC effect, Shadowing and Saturation:



- Questions:

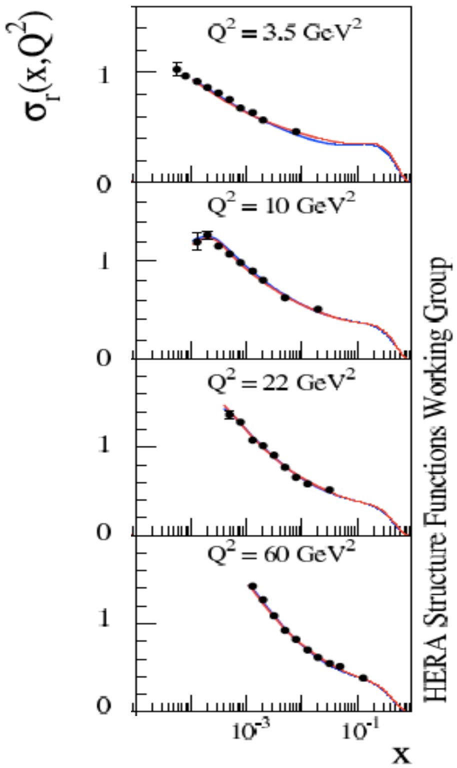
  Why nuclear structure function suppressed at small x?

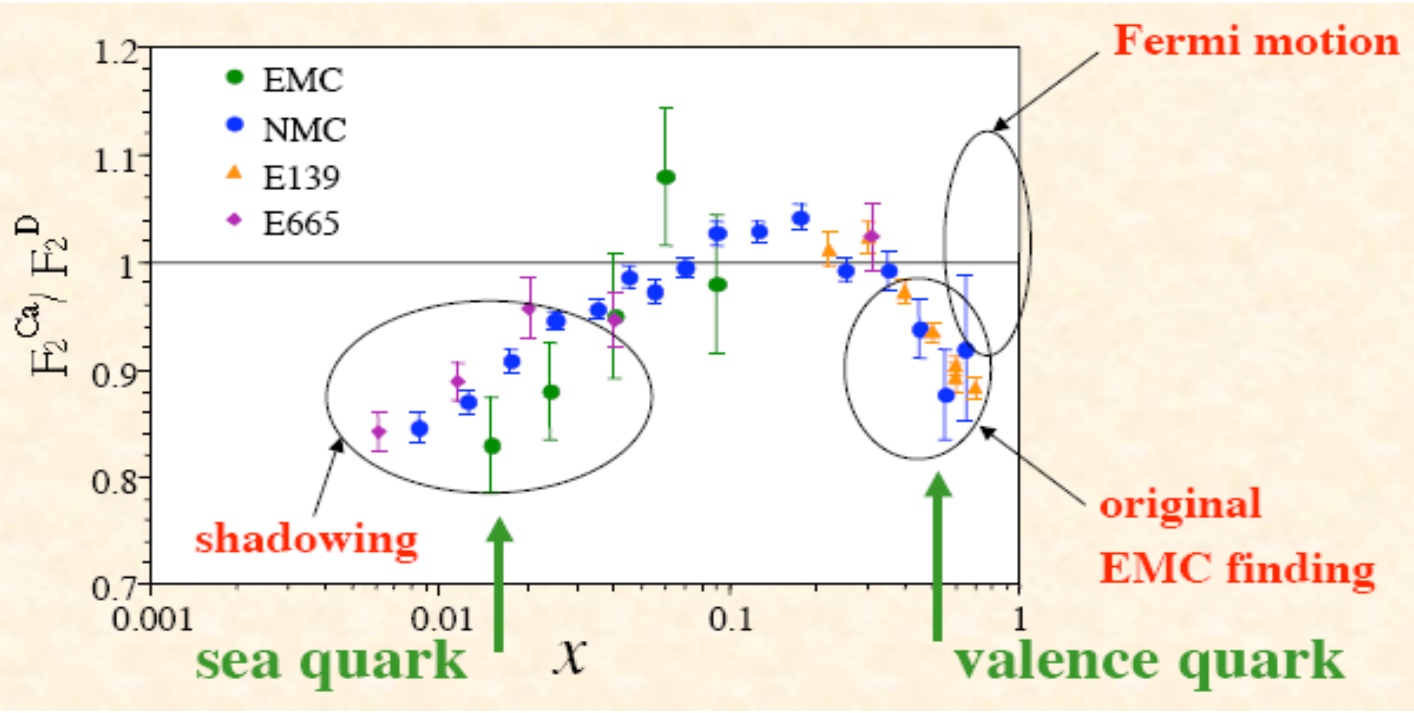
  Will the suppression/shadowing continue fall as x decreases?

  Range of color correlation – could impact the center of neutron

An “easiest” measurement

❑ EMC effect, Shadowing and Saturation:





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An "easiest" measurement

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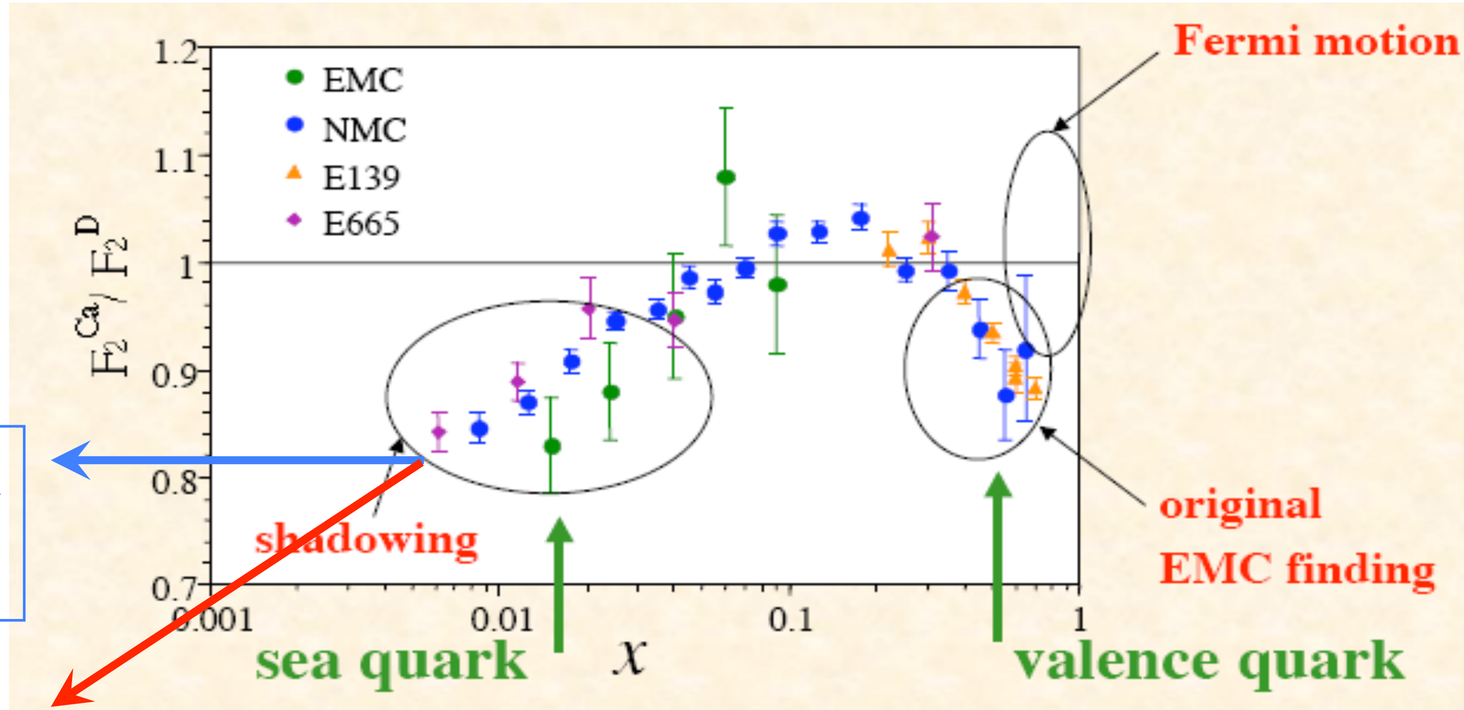


Saturation in R_{F2}
$\neq$
Saturation in F_2

Saturation in $F_2(A) = R_{F2}$ decreases until saturation in $F_2(D)$

❑ Questions:

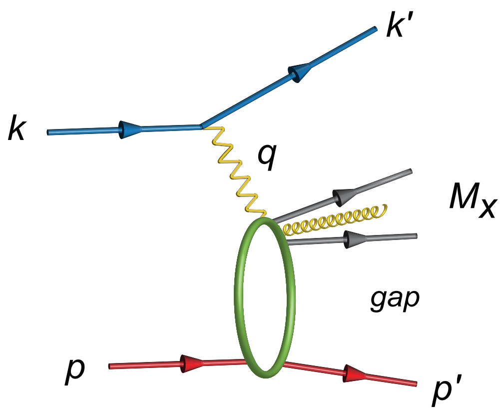
Why nuclear structure function suppressed at small x?

Will the suppression/shadowing continue fall as x decreases?

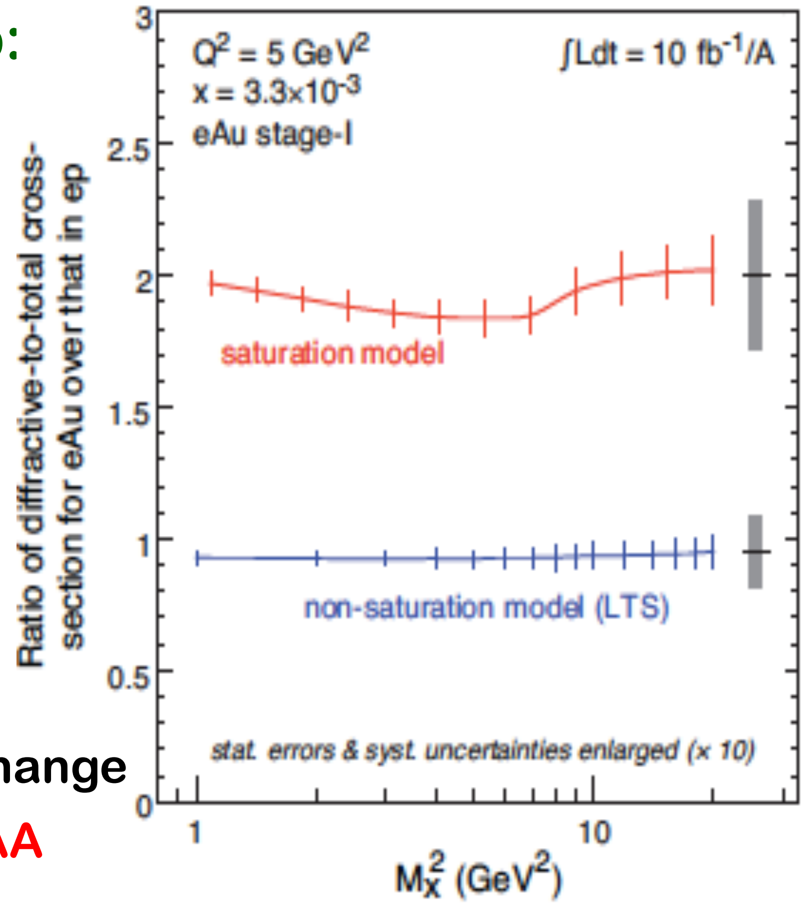
Range of color correlation – could impact the center of neutron

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

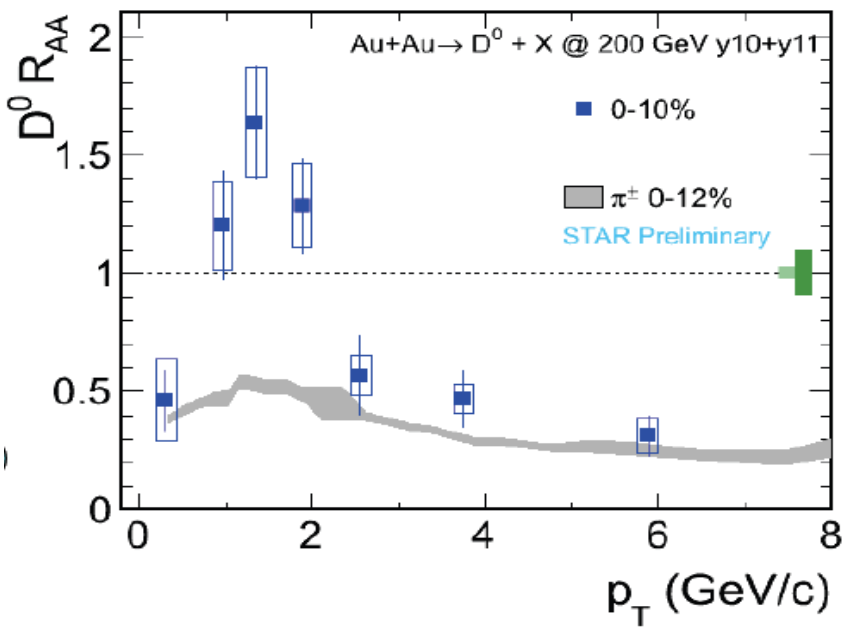
✧ Factorization works in DIS, not in pp, pA, AA

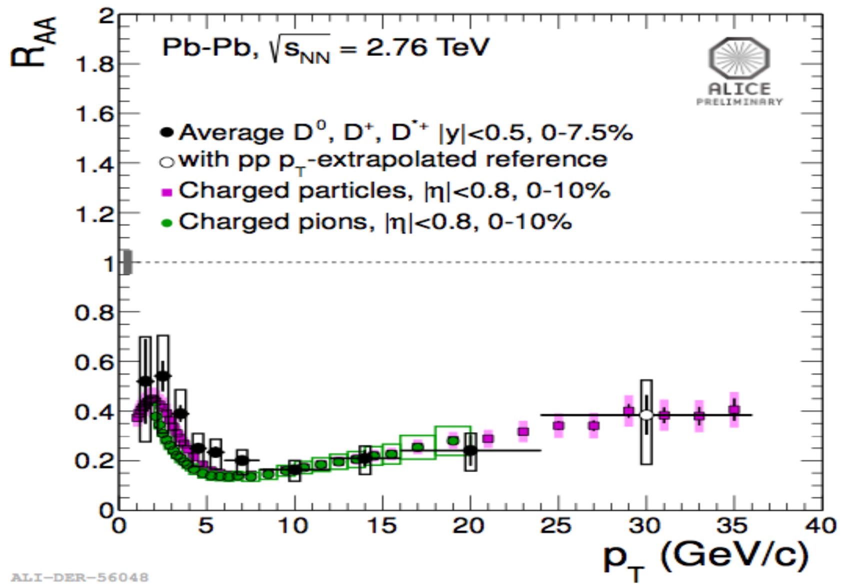
The factor of 2 enhancement is only for eA
(no equivalent in pA!)

This is a clean and unambiguous signal of saturation physics at EIC

Hadronization puzzle

- Strong suppression of heavy flavors in AA collisions:





- Emergence of hadrons:

How do hadrons emerge from a created quark or gluon?
How is the color of quark or gluon neutralized?

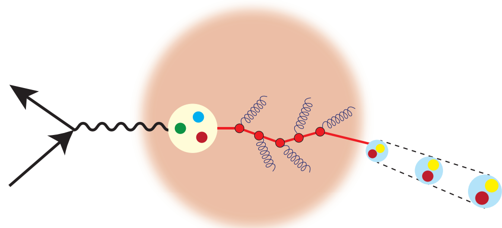
- Need a femtometer detector or “scope”:

Nucleus, a laboratory for QCD
Evolution of partonic properties

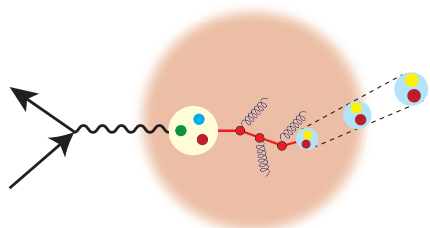
Hadronization – energy loss

How hadrons emerge from quarks and gluons?

- **Unprecedented ν range at EIC:**

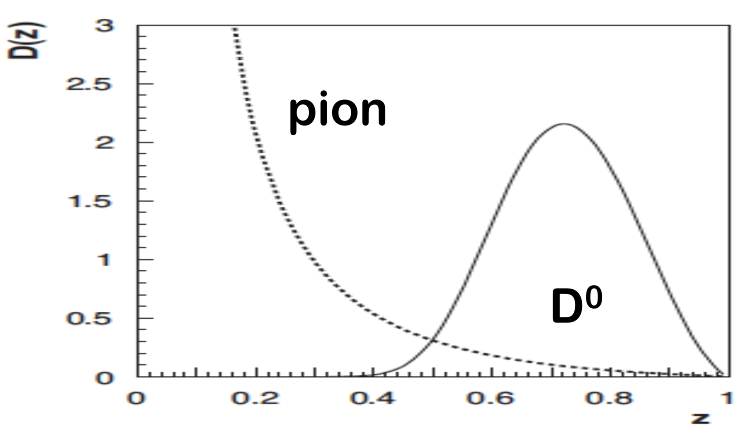


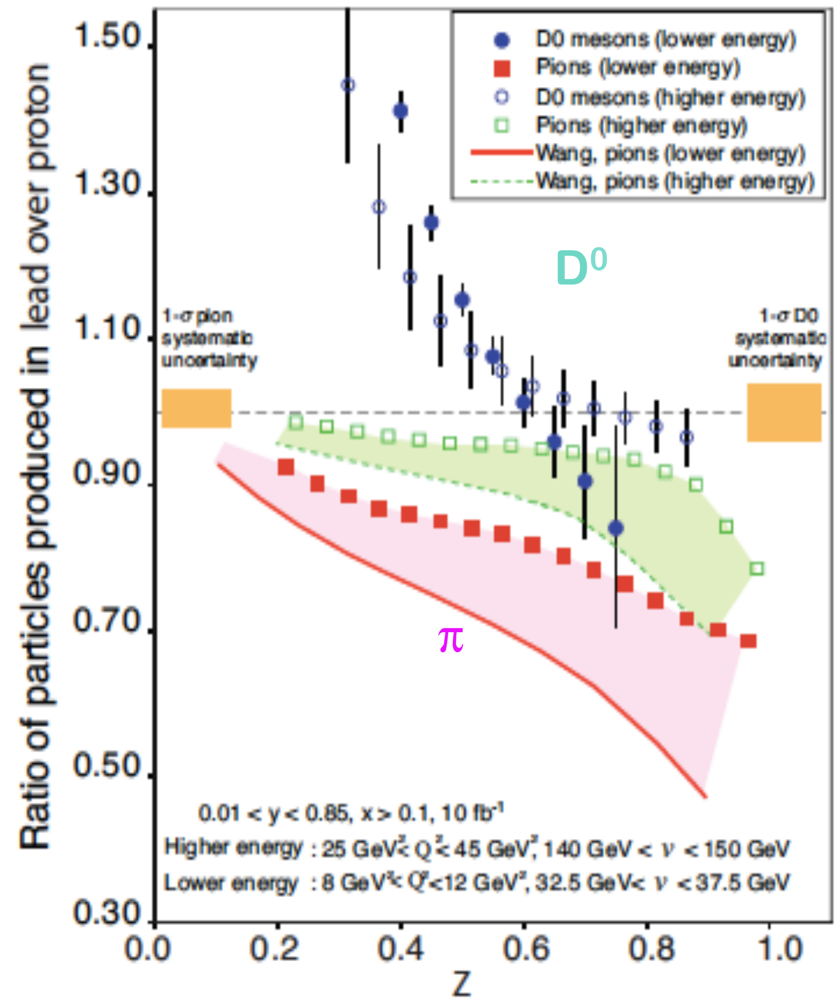
$$\nu = \frac{Q^2}{2mx}$$



Control of ν and medium length!

- **Heavy quark energy loss:**
  - **Mass dependance of fragmentation**

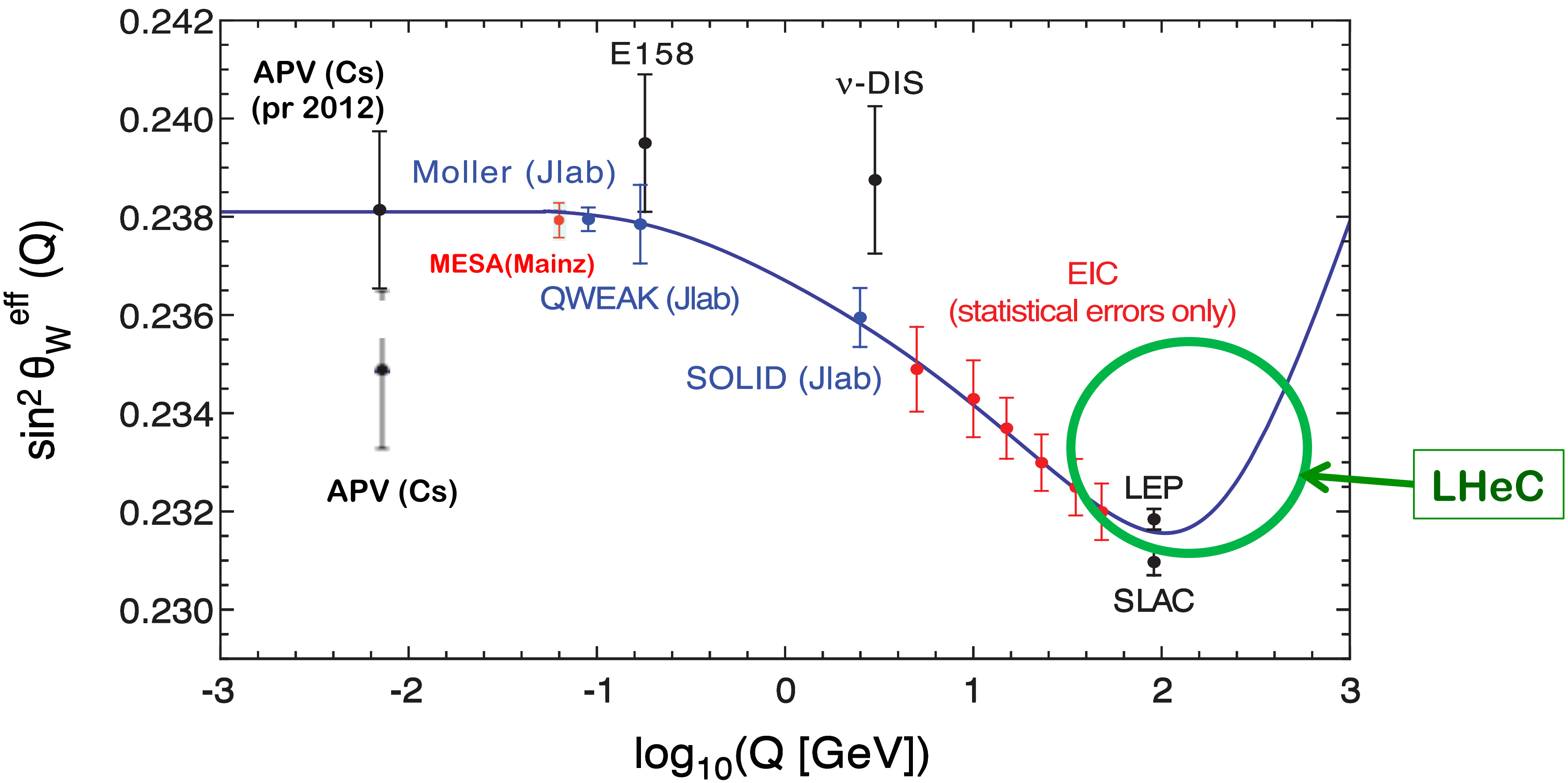




Need the collider energy of EIC and its control on parton kinematics

Electroweak physics at EIC

❑ Running of weak interaction – high luminosity:



✧ **Fills in the region that has never been measured**

✧ ***have a real impact on testing the running of weak interaction***

Summary

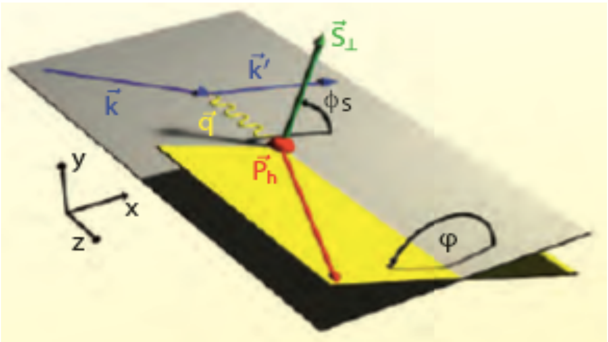
- EIC is a ultimate QCD machine:
  1) to discover and explore the quark/gluon structure and properties of hadrons and nuclei,
  2) to search for hints and clues of color confinement, and
  3) to measure the color fluctuation and color neutralization
- EIC is a tomographic machine for nucleons and nuclei with a resolution better than 1/10 fm
- EIC designs explore the polarization and intensity frontier, as well as the frontier of new accelerator/detector technology
- Complementary designs of EIC around the world have been proposed to cover different kinematic regimes of QCD – EIC@US is sitting at a sweet spot for rich QCD dynamics

Thanks!

Color fluctuation – azimuthal asymmetry

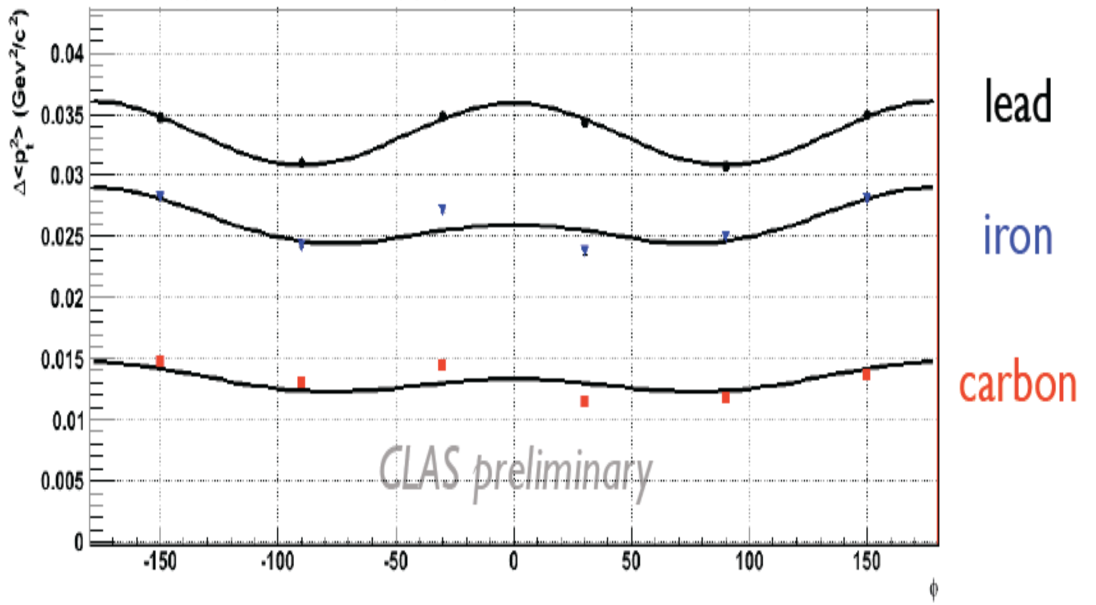
Hicks, KEK-JPAC2013

- ❑ Preliminary low energy data:



$$\langle p_T^2(\phi_{pq})\rangle_A = \int dp_T^2\, p_T^2 \frac{d\sigma_{eA}}{dx_B dQ^2 dp_T^2 d\phi} \Big/ \frac{d\sigma_{eA}}{dx_B dQ^2}$$

$$\langle \Delta p_T^2(\phi)\rangle_{AN} \equiv \langle p_T^2(\phi)\rangle_A - \langle p_T^2(\phi)\rangle_N$$



Contain terms in cos(ϕ_{pq}) and cos(2ϕ_{pq})
only statistical uncertainties shown

- ❑ Classical expectation:

  Any distribution seen in Carbon should be washed out in heavier nuclei

- ❑ Surprise:

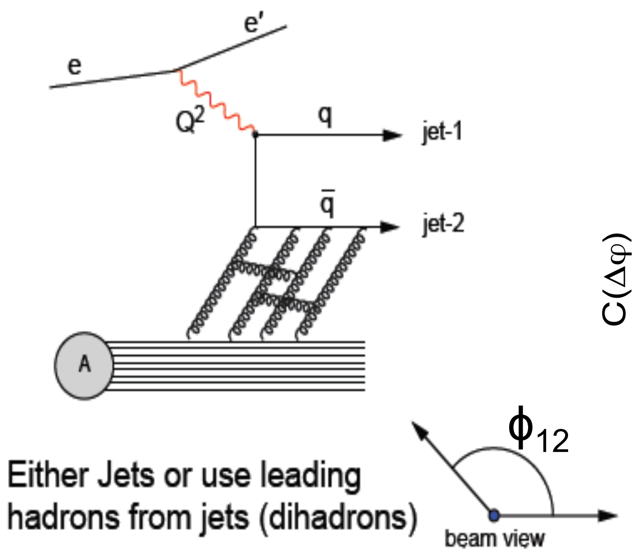
  Azimuthal asymmetry in transverse momentum broadening

  ➡ *Fluctuation and v_n at EIC too!*

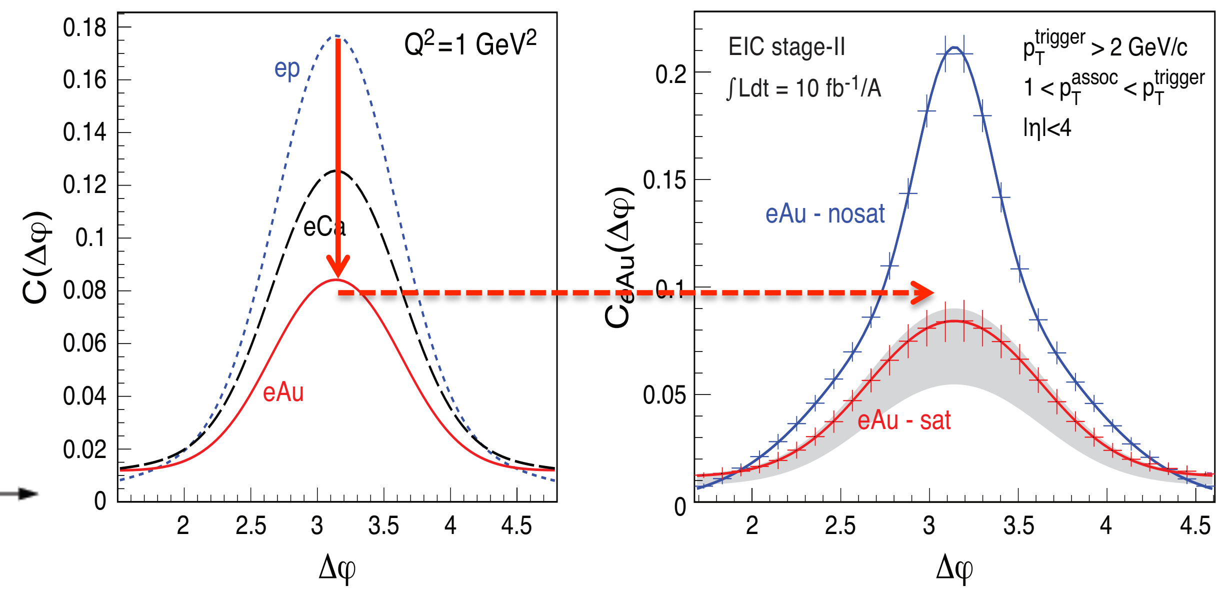
See Brooks talk at EICA

Another clean signature for gluon saturation

❑ Strong suppression of dihadron correlation in eA:



Theory | Simulation



- ✧ Never been measured!
- ✧ Directly probe Weizsacker-Williams (saturated) gluon distribution in a large nucleus
- ✧ A factor of 2 suppression of away-side hadron-correlation!
- ✧ No-sat: Pythia + nPDF (EPS09)