Nucleon Spin Structure in DIS with EIC

Next Generation Nuclear Physics JLab12 & EIC

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JLab12 → EIC: Some general remarks

Deep Inelastic Scattering Experiments

JLab12:

- Fixed target experiments
- Low center of mass
  - Predominantly will explore the valence quark (high x) region

EIC:

- Collider
- High center of mass
  - Predominantly will explore the sea quarks & gluons (low x)

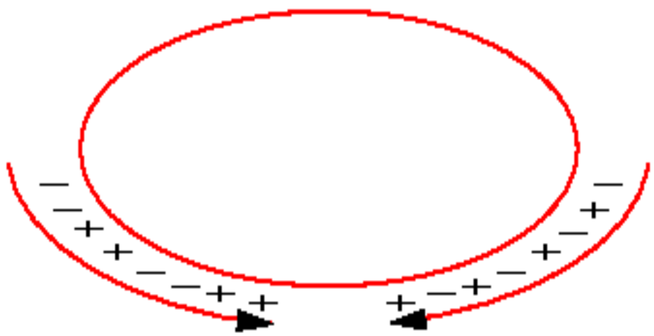
Why collider in the future?

- Past and current polarized e-p, e-A DIS exp.s fixed target
- Collider (geometry) has some distinct advantages

- Better angular separation between scattered lepton and nuclear fragments
  - Better resolution of electro-magnetic probe
  - Recognition of **rapidity gap** events (like diffractive physics)
- Better measurement of the nuclear fragments
- Tricky: Interaction region and beam pipe design….

Advantage of a collider for spin experiments:

- (Example) The proton bunches separated by about 100 ns in the RHIC ring can be filled with any controlled polarization orientation.



- Effective target spin reversal every 100 ns! A huge gain in control over experimental systematics (especially the false asymmetries arising from time variations in detector acceptances and efficiencies)

- The future EIC will/could have similar arrangement for electron and hadron beam bunches.

Another difference between fixed target & collider experiments

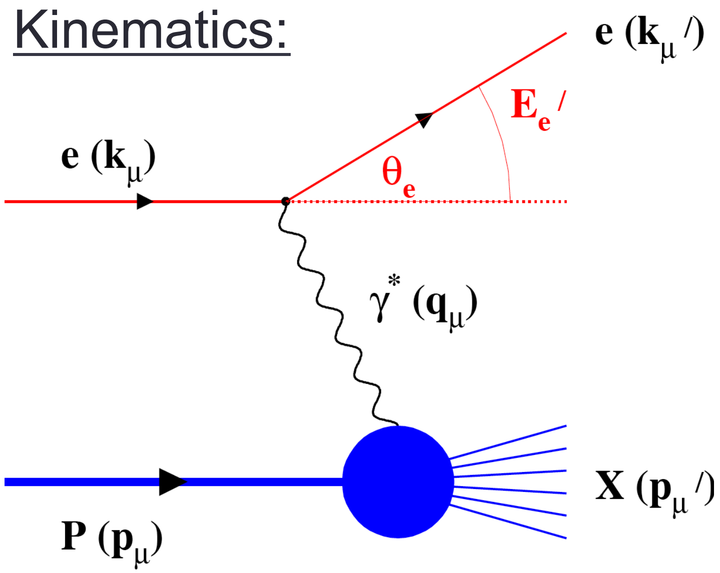
The dilution factor:

For NH_3 target (for example) effectively only 3/(14+3) scatters occur from (useful) polarized H's. (**3/17 is hence the dilution factor**)

For a collider experiment, the singly charged polarized hydrogen IS the target…. At RHIC we fill the beam with 2.1 x 10^{11} protons/bunch, and there are 110 bunches at a single time circulating (**effective dilution factor 1**).

Deep Inelastic Scattering

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 measurements:

e+p/A → e'+X

Detect only the scattered lepton in the detector

Semi-inclusive measurements:

e+p/A → e'+h(π,K,p,jet)+X

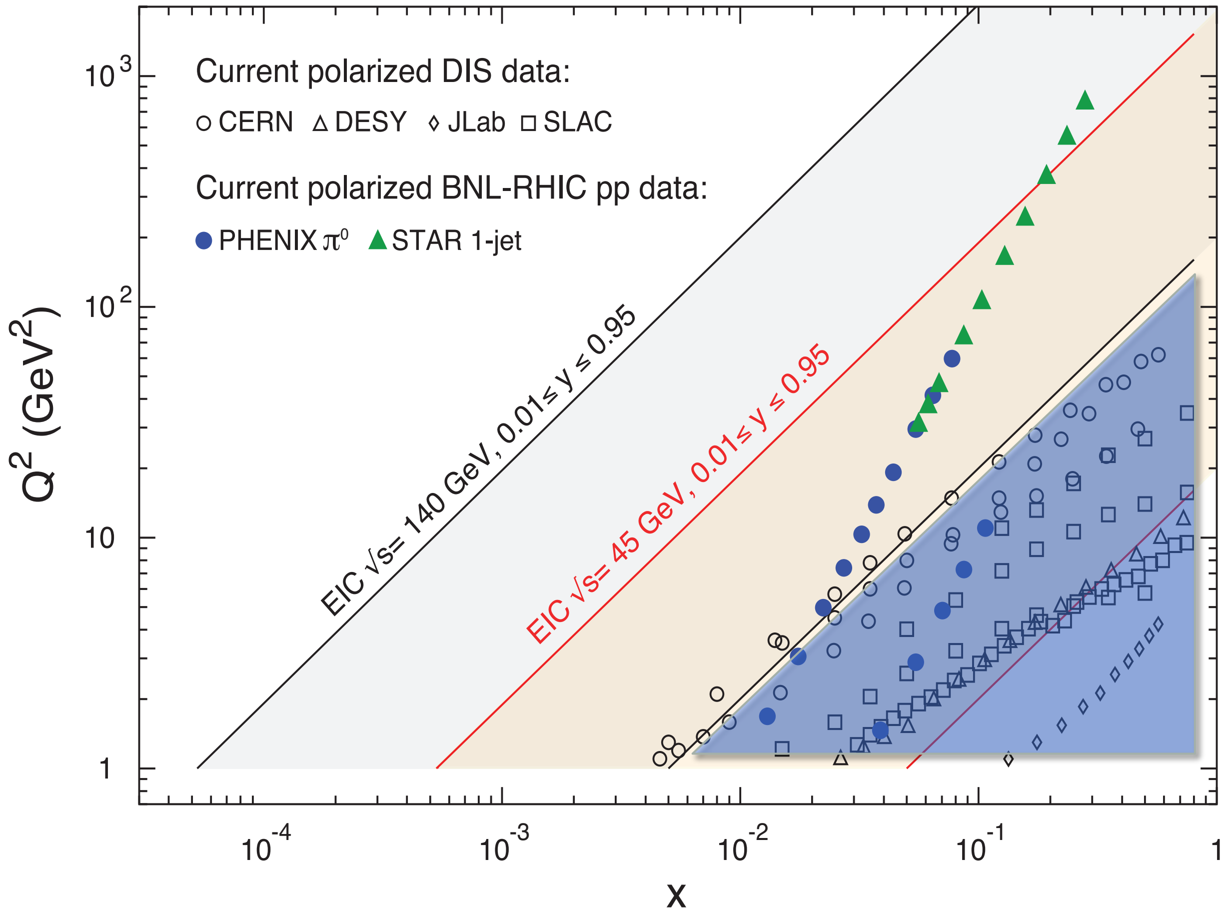
Detect the scattered lepton in coincidence with identified hadrons/jets

Exclusive measurements:

e+p/A → e'+h(π,K,p,jet)+p'/A'

Detect scattered lepton, identify produced hadrons/jets and measure target remnants

Complementary kinematic regions of Collider vs. fixed target experiments



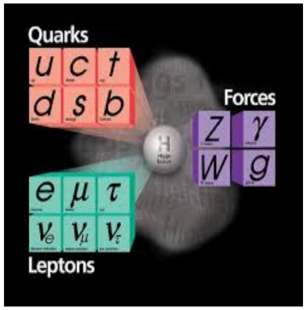
$$Q^2 = Sxy$$

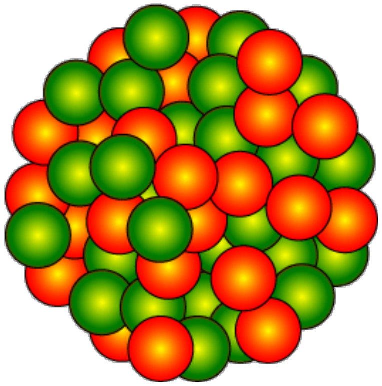
$$S = \sqrt{4 \cdot E_1 \cdot E_2}$$

Colliders enable significant enhancement in x and Q^2 reach of any measurement

Why we need an EIC?

A new facility, EIC, with a versatile range of kinematics, beam polarizations, high luminosity and beam species, is required to ***precisely image*** *the sea quarks and gluons in nucleons and nuclei,* to explore the new QCD frontier of strong color fields in nuclei, and to resolve outstanding issues in understanding nucleons and nuclei in terms of fundamental building blocks of QCD



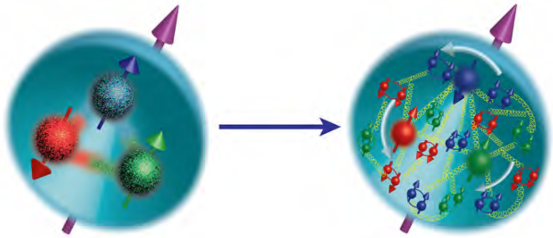


Puzzles and challenges in understanding these QCD many body emergent dynamics

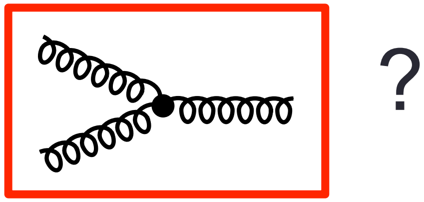
How are the gluons and sea quarks, and their intrinsic spins distributed in space & momentum inside the nucleon?

Role of Orbital angular momentum?

How do they constitute the nucleon Spin?

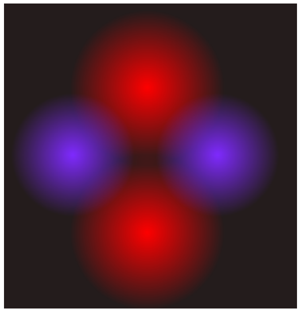


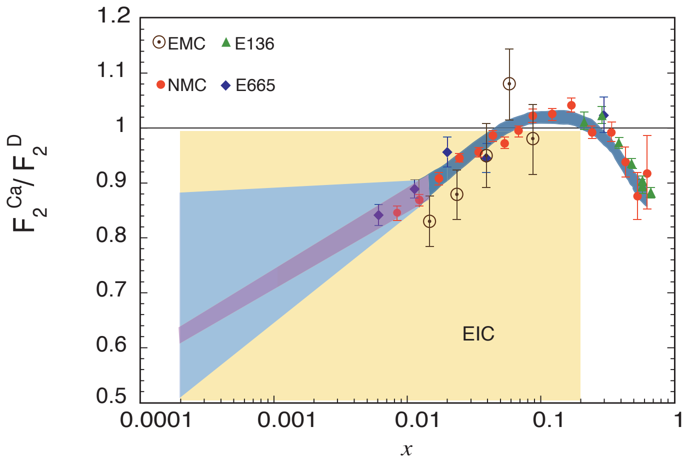
What happens to the gluon density in nuclei at high energy? Does it saturate in to a gluonic form of matter of universal properties?



Puzzles and challenges….

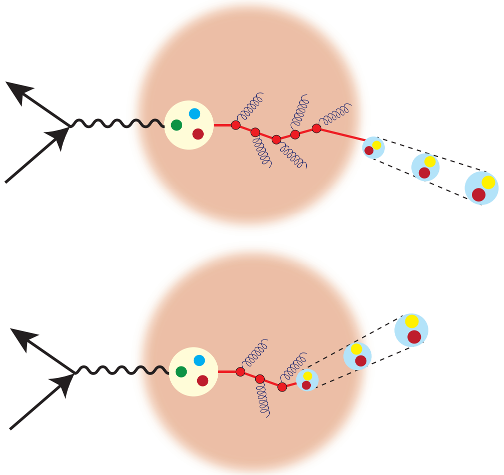
How do gluons and sea quarks contribute to the nucleon-nucleon force?





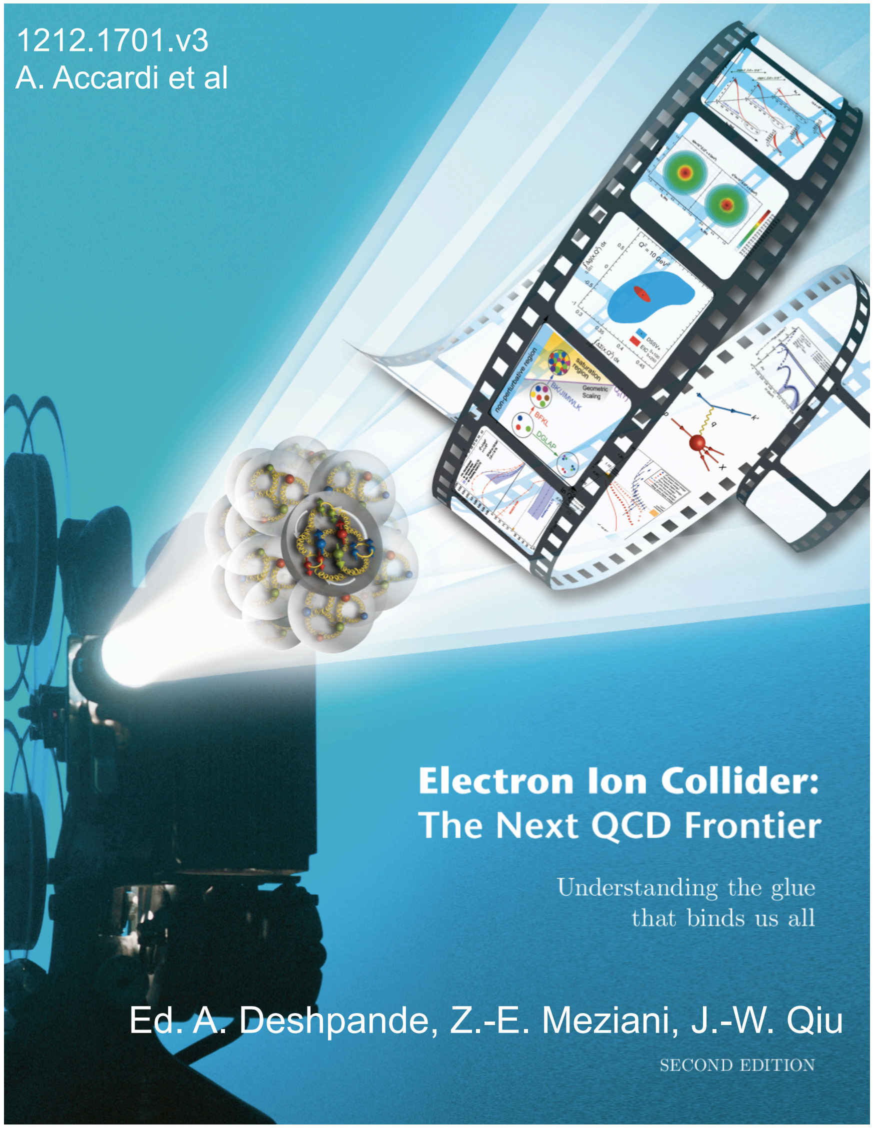
How does the nuclear environment affect the distributions of quarks and gluons and their interactions inside nuclei?

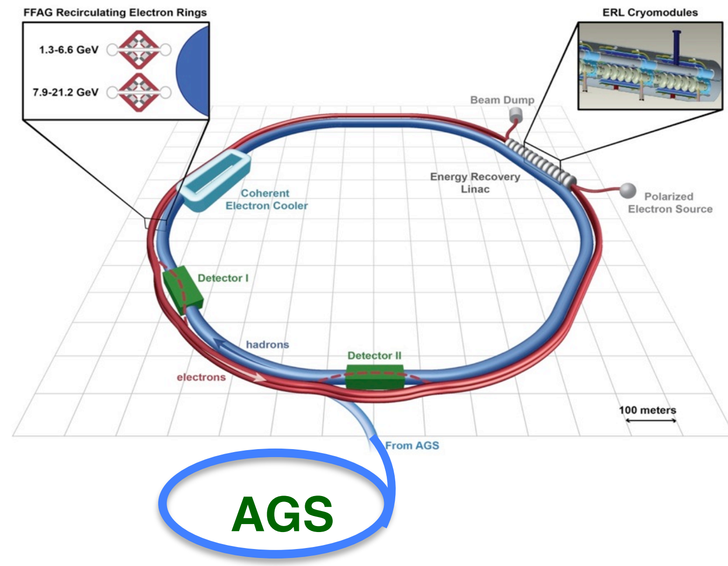
How does nuclear matter respond to fast moving color charge passing through it? (hadronization…. confinement?)

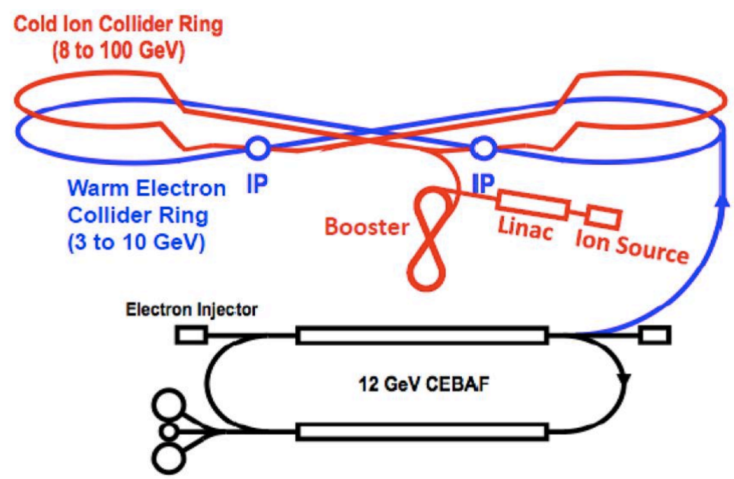


The Electron Ion Collider

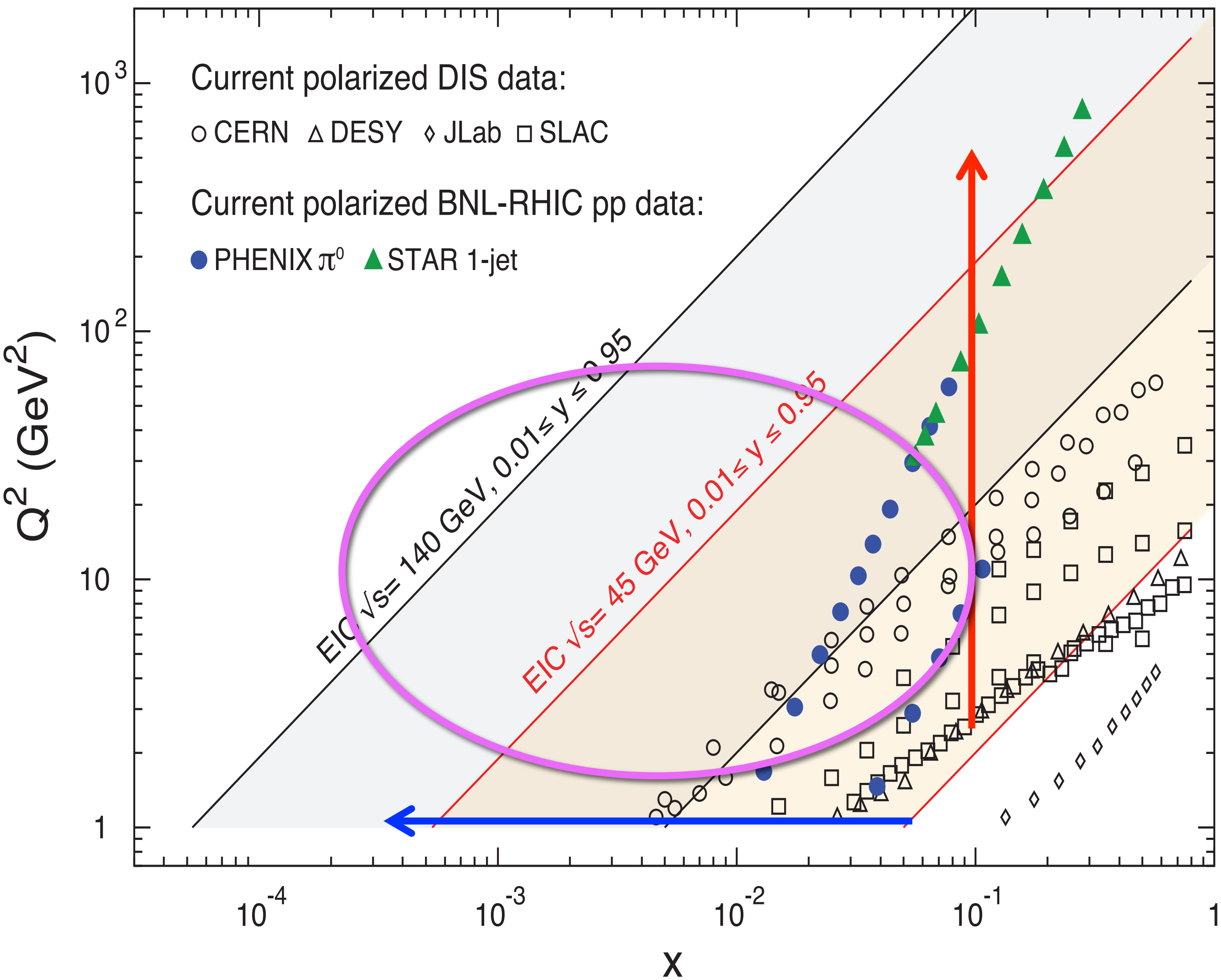
Two options of realization!







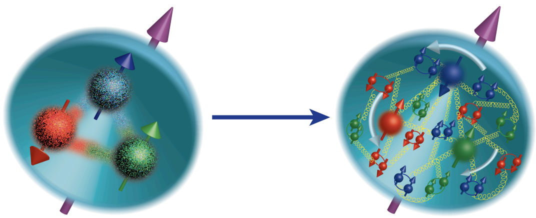
EIC: Kinematic reach & properties



For e-N collisions at the EIC:

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

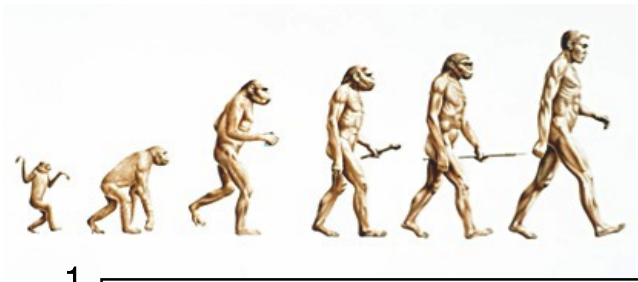
Our Understanding of Nucleon Spin

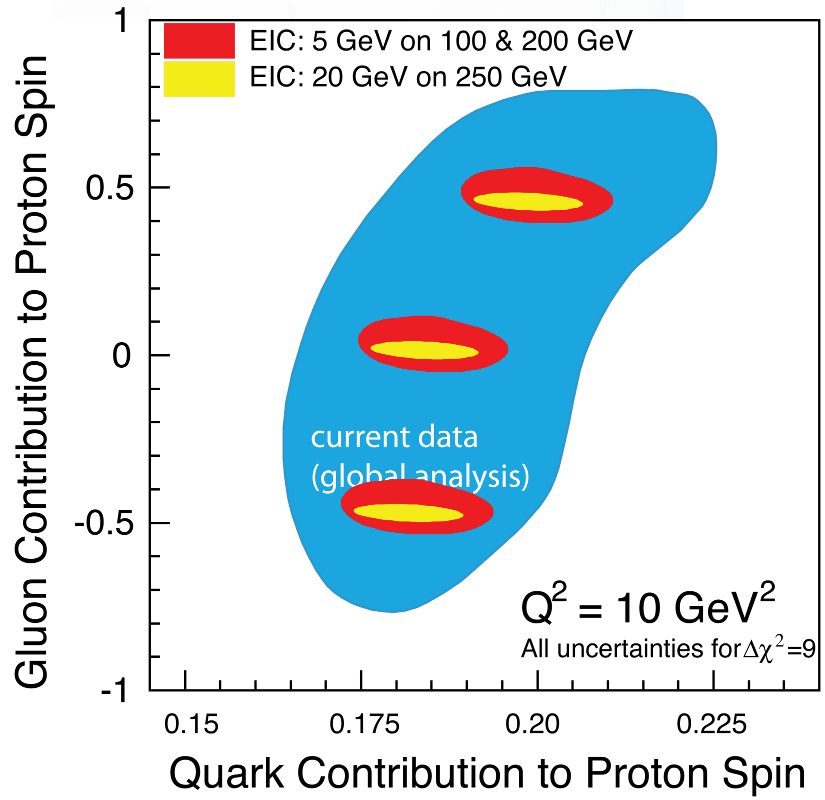


$$\frac{1}{2} = \left[\frac{1}{2}\Delta\Sigma + L_Q\right] + [\Delta g + L_G]$$

$\Delta\Sigma/2$ = 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





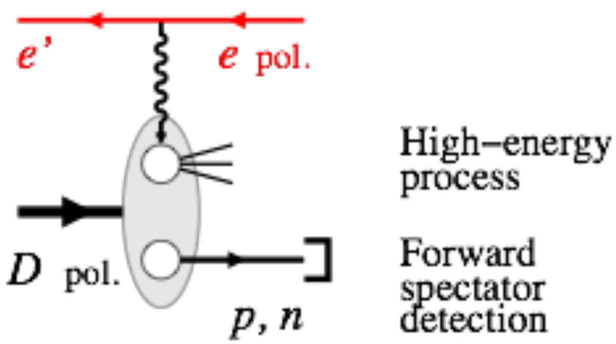
Topics not directly covered in this talk but implied… and covered elsewhere...

- With longitudinally polarized D or ^3He in the EIC, one could explore the spin structure of the NEUTRON, not unlike the past fixed target experiments (measure g_1^n) over a wide range in x and Q^2 *(Kijun Park's talk, this meeting)*

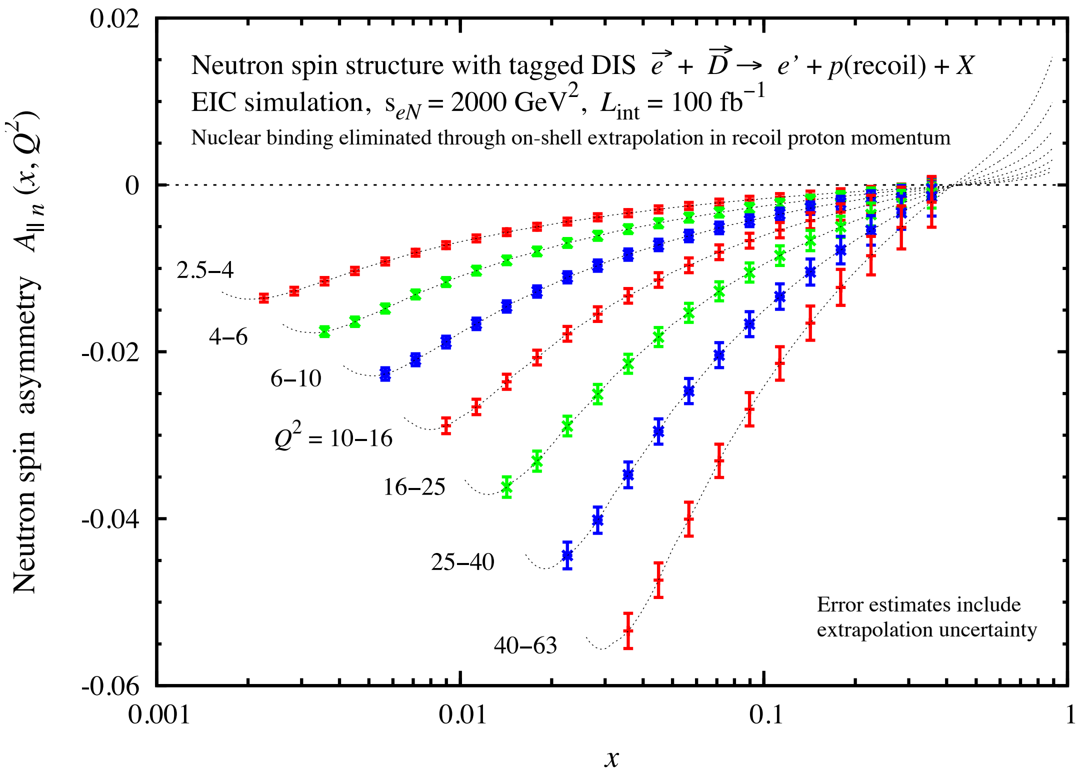
- Tagging the spectator protons (in D or ^3He) will maximize the effectiveness of this measurement ➔ improve dilution factor

- Unprecedented measurement of the Bjorken Spin Sum Rule, and hence also possibly a very precise measurement of Strong Coupling Constant from the fit to non-singlet $g_1^{(p-n)}$. *(Limited by the experimental systematics: polarization measurements of the hadrons: A. Deur, HE NP with Spectator Tagging, ODU, 2015)*

Nucleon spin the structure & study of nuclear binding



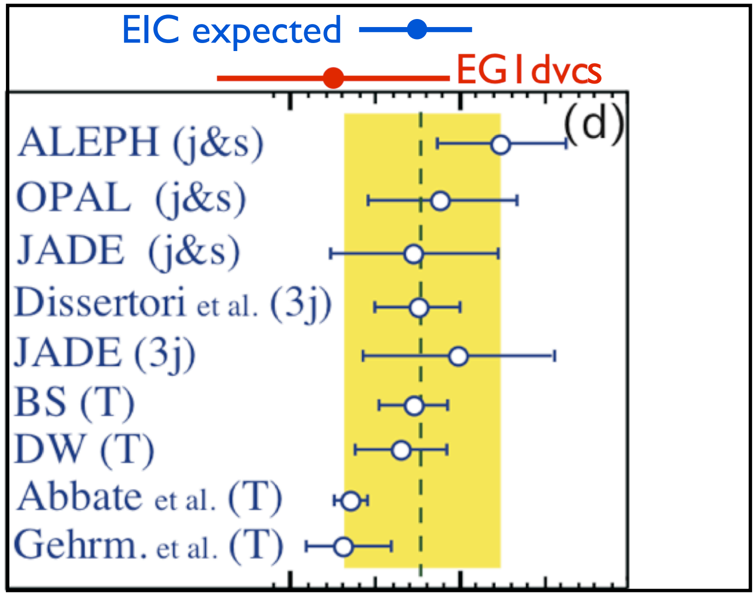
Tag the recoil proton:
Study the neutron's q-g spin structure function.
Also for other few body nuclei



- Another area of interest: Measurement of the kinematics of the spectator nucleon indicator of the strength and (hence) the nature of its *binding* with the in-play nucleon(s):

→ quark-gluon origin of the nuclear binding

Compared to EG1dvcs and best world data (PDG 2014):



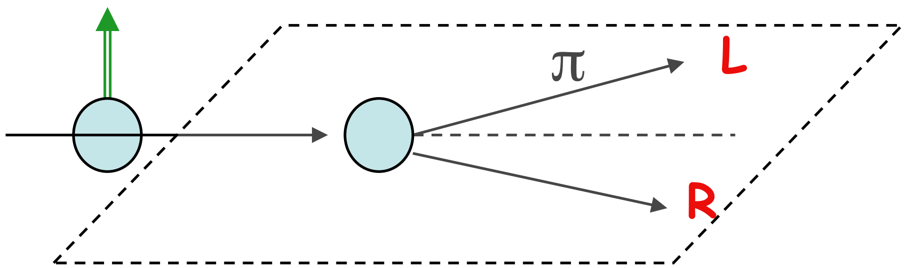
A. Deur @ ODU , 2015

Conclusion:

- Reasonable assumptions for EIC yield a very accurate measurement of acceptable precision. Tagging not necessary as long as we are statistics (really stat+point-to-point uncor.) dominated.
- Assumed statistics similar to a typical CLAS experiment aiming at measuring inclusive spin structure functions.
- Increasing statistics by factor10 would yield: $\Delta\alpha_s(M_{Z_0})=\pm0.0021\pm0.0003$.
- Then, adding tagging would yield: $\Delta\alpha_s(M_{Z_0})=\pm0.0016\pm0.0003$. A very competitive measurement.

Transverse Spin Physics Phenomena & its understanding

Transverse spin introduction



$$A_N = \frac{N_L - N_R}{N_L + N_R}$$

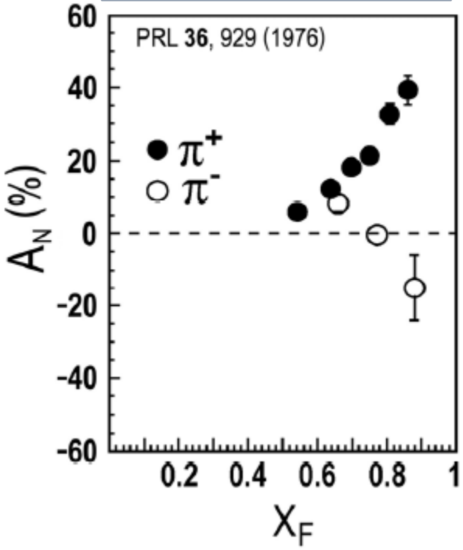
$$A_N \sim \frac{m_q}{p_T} \alpha_S$$

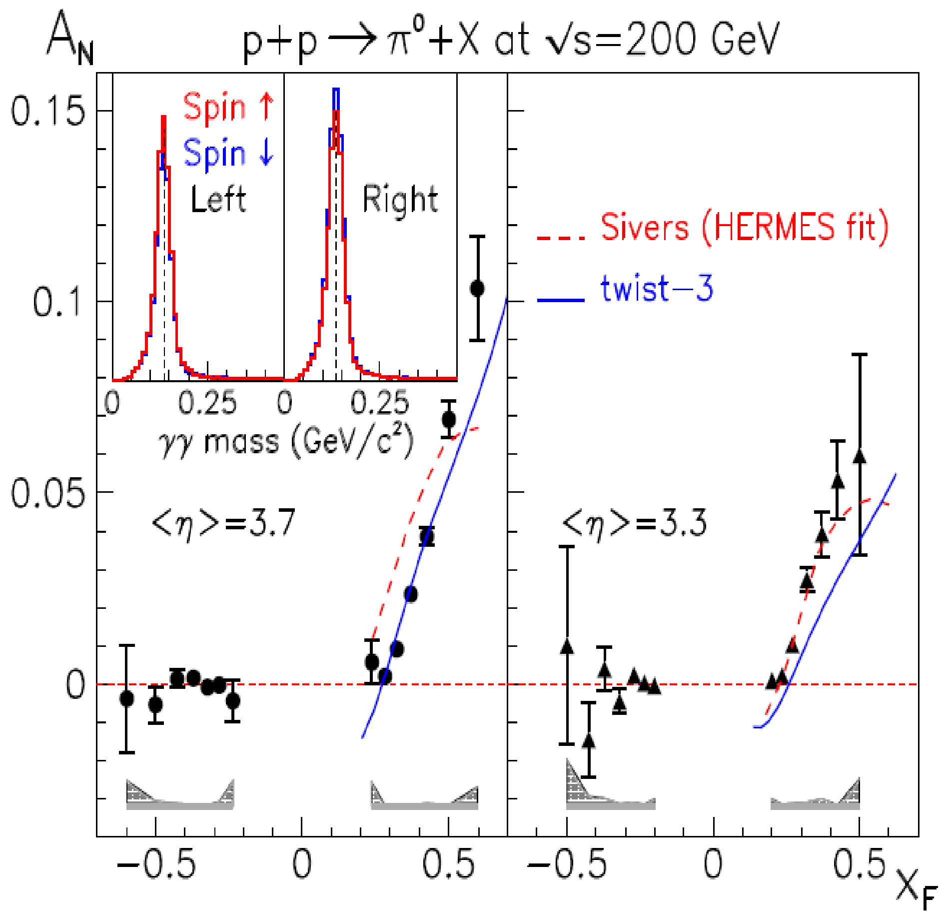
Kane, Pumplin, Repko 1978

- Since people starved to measure effects at high p_T to interpret them in pQCD frameworks, this was "neglected" as it was expected to be small….. However….
- Pion production in single transverse spin collisions showed us something different….

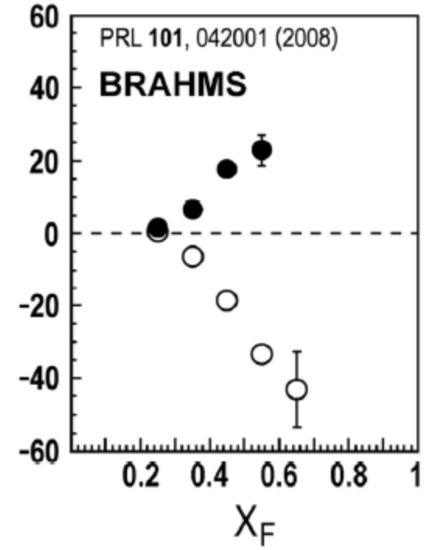
Pion asymmetries: at most CM energies!

ZGS/ANL
√s=4.9 GeV





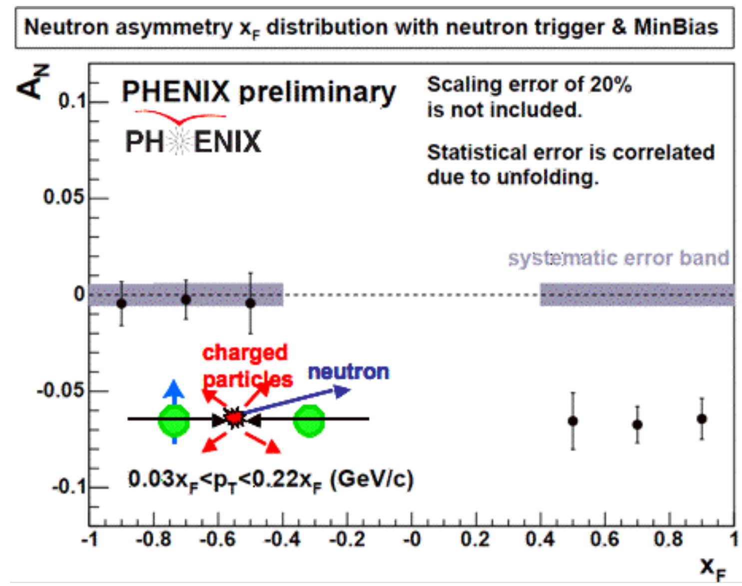
RHIC
√s=62.4 GeV

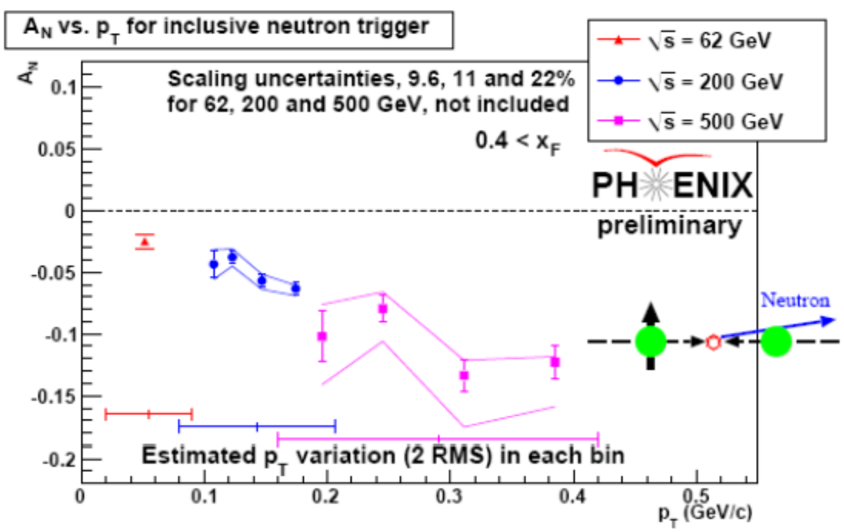


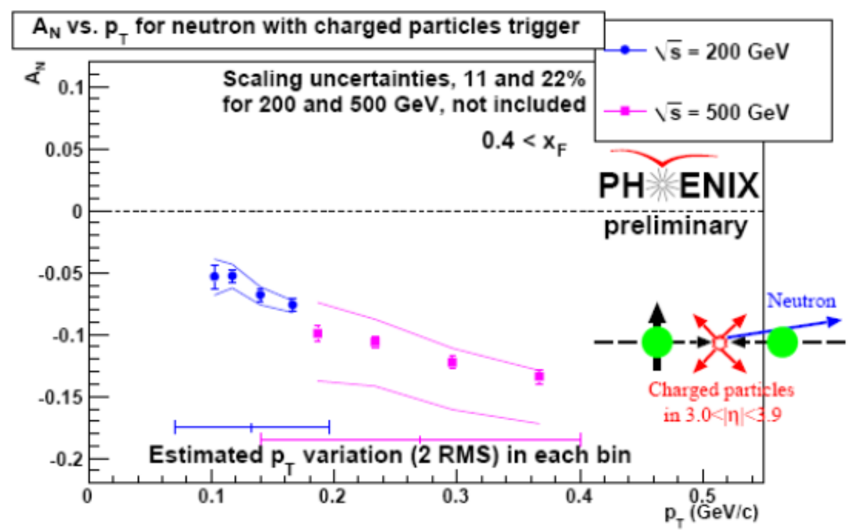
Suspect soft QCD effects at low scales, but they seem to remain relevant to perturbative regimes as well

Other unexpected discoveries…

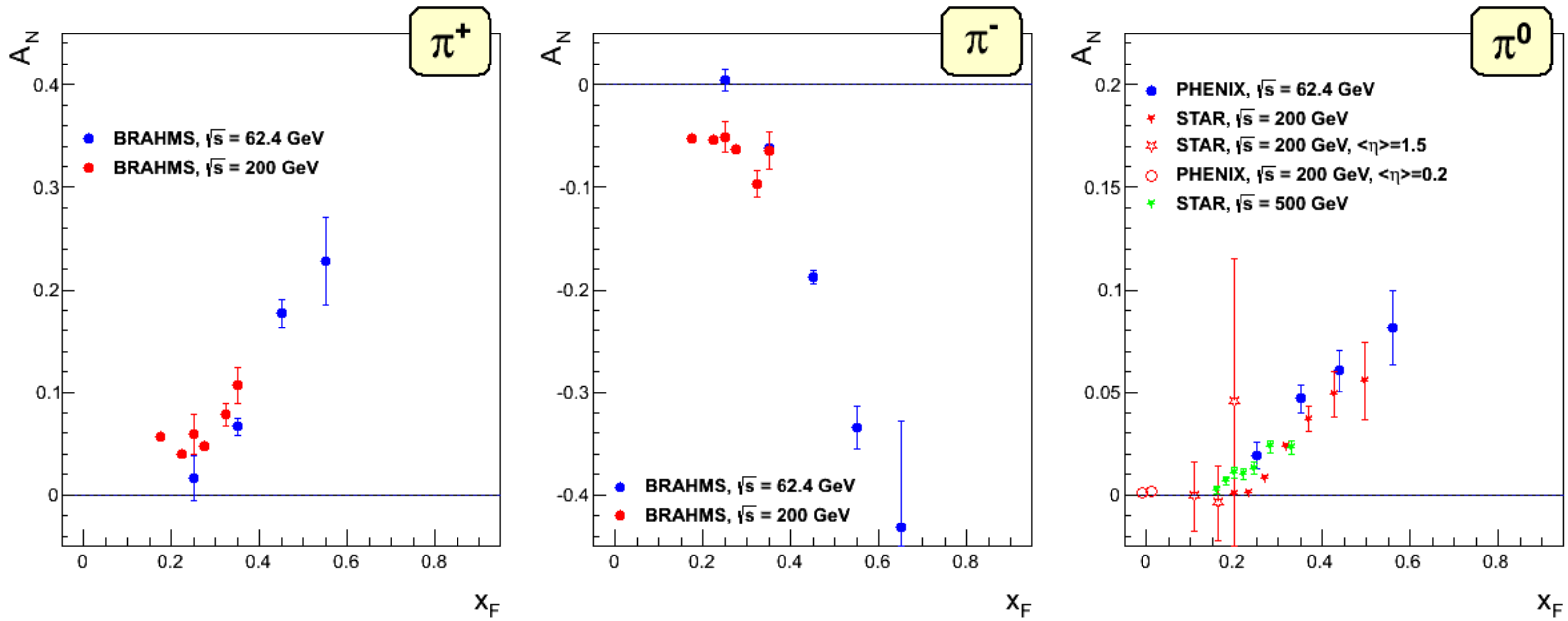
- Large very forward neutron asymmetry found at RHIC.
- Center of Mass & p_T dependence studied
- Not understood how it arises: a challenge to theorist







Transverse spin data @ RHIC:



Large transvers spin asymmetries at high Center of Mass → Surprise! Various questions being studied…

What is the underlying mechanism?

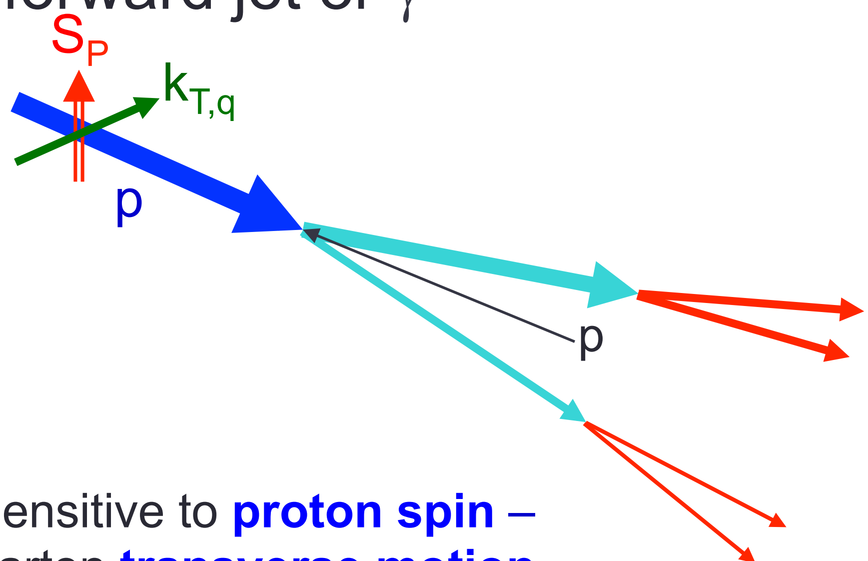
Observed p_T dependence A_N consistent with expectations?

Can TMD evolution be seen in RHIC data?

Can the we study factorization breaking using RHIC p+p data?

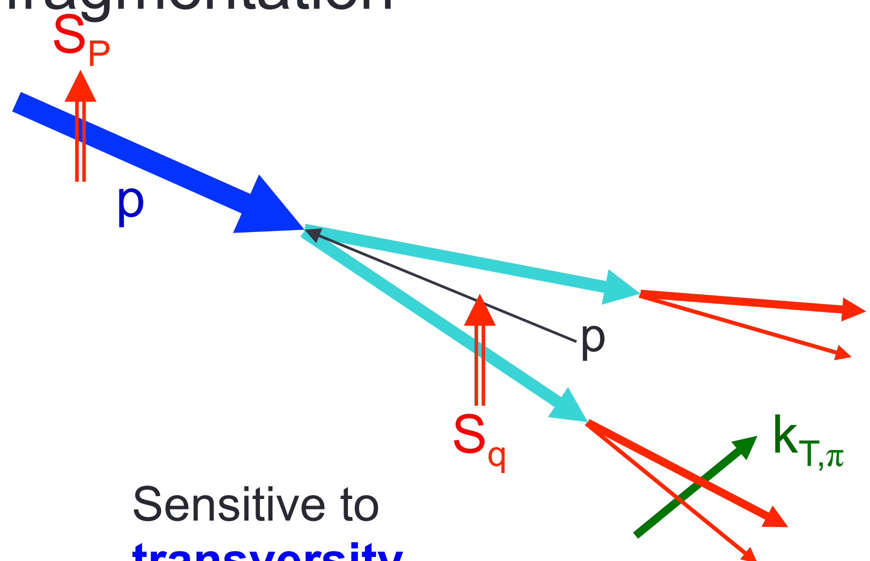
Possible origins for A_N

Sivers mechanism:
asymmetry in production of forward jet or γ



Sensitive to **proton spin – parton transverse motion** correlations

Collins mechanism:
asymmetry in the forward jet fragmentation



Sensitive to **transversity**

- Need to go beyond inclusive hadron measurements
- Possibilities include jets, direct photons, di-hadron correlations, etc.

RHIC 2014/15

Transverse Spin: 400+ times the expected values of asymmetries have been routinely observed: both in ep and pp systems.

Systematic investigations now underway to study and understand them.

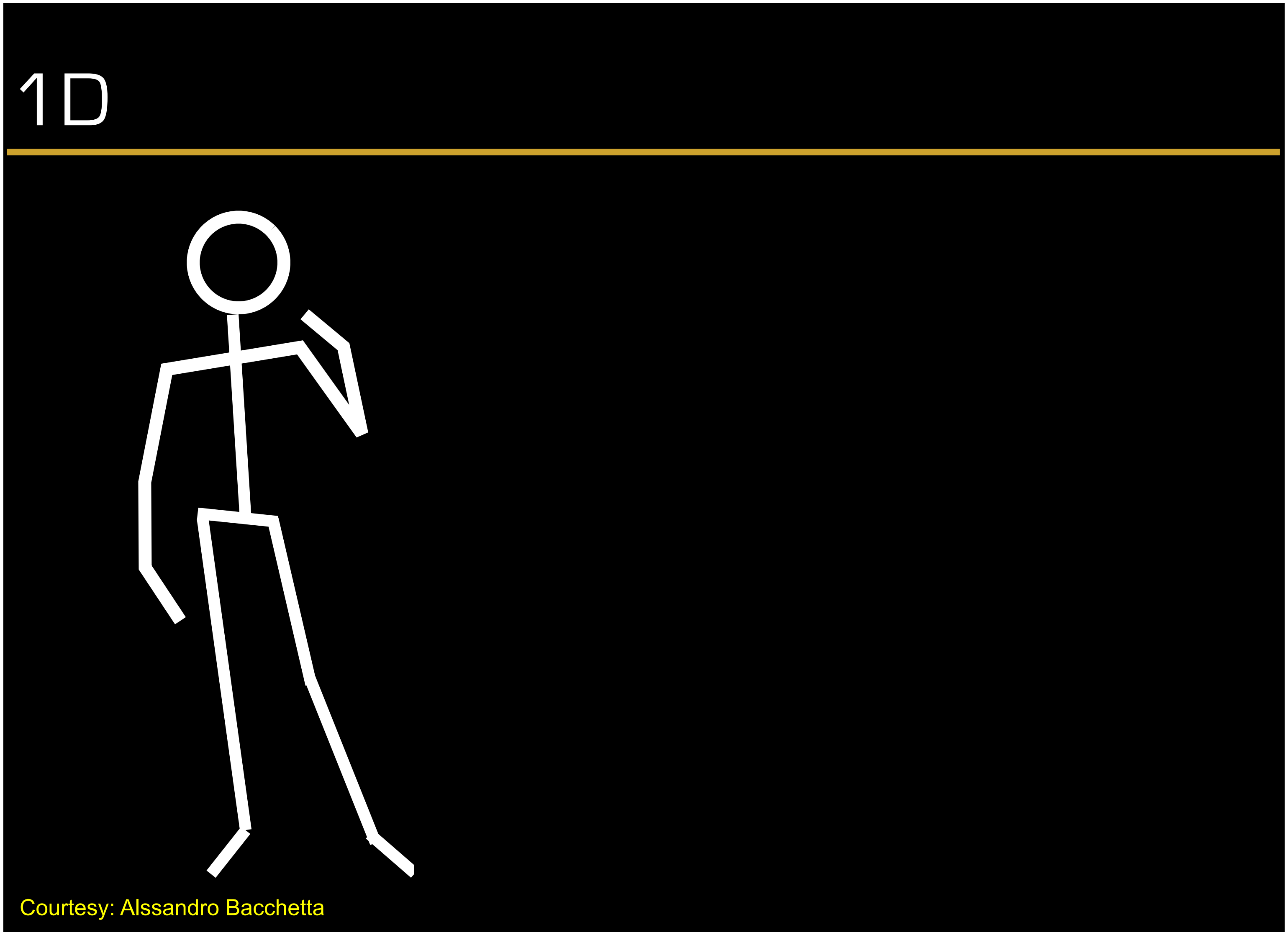
What could their origin be?

- Transverse motion/momentum of partons (initial state: Sivers Function)?
  - Related to orbital motion… remaining part of the nucleon spin?
  - How do we quantify this? Through quark GPDs? ➔JLab 12GeV
- Asymmetry in fragmentation process (final state: Collins Function)?
  - This too has been recently measured in e+e- collisions at Belle
- **In p-p combination of both!!**

- **Need a better probe to study this: *A polarized e-p collider!***

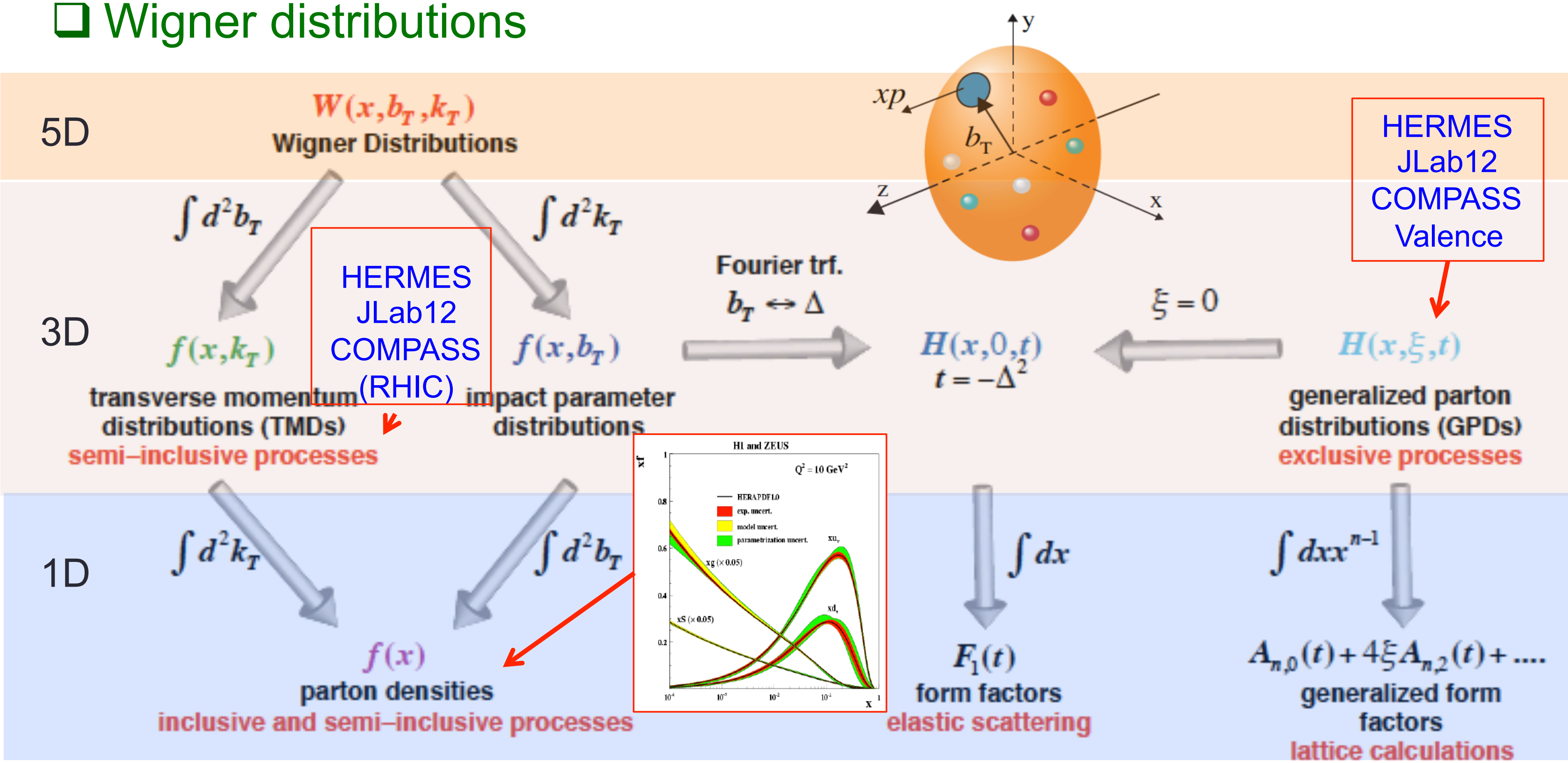
FUTURE….

World is not one dimensional!



Unified view of the Nucleon Structure

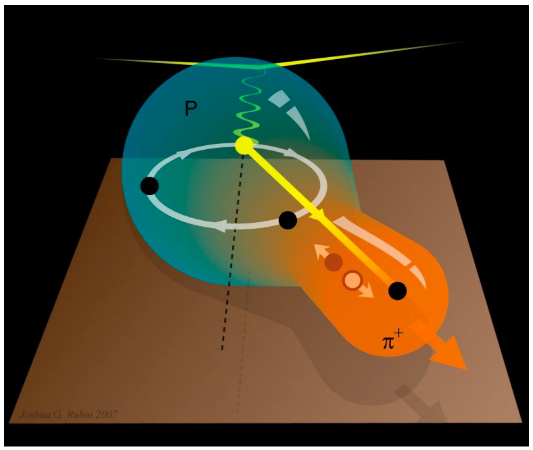
❑ Wigner distributions

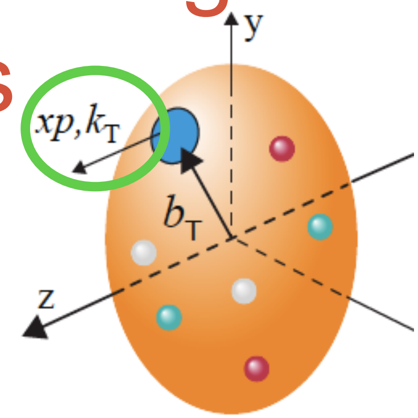


❑ (2+1)D imaging Quarks (Jlab/COMPASS) , **Gluons (EIC)**

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

Semi-Inclusive DIS ➔ Best for measuring Transverse Momentum Distributions



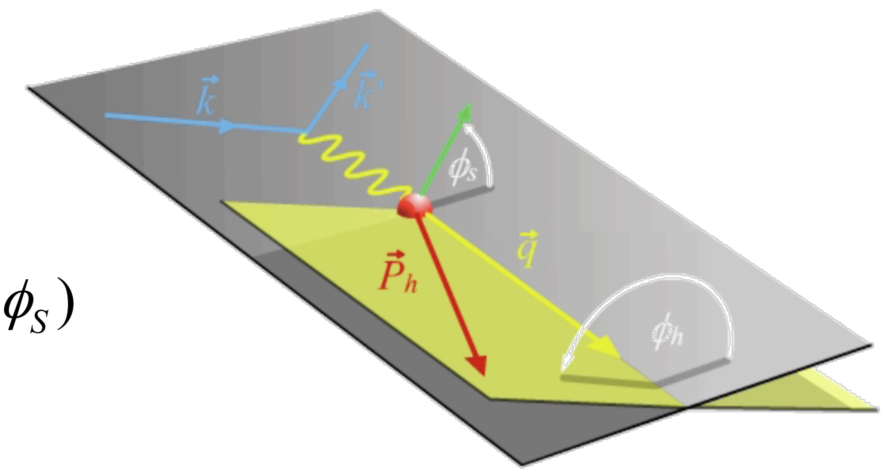


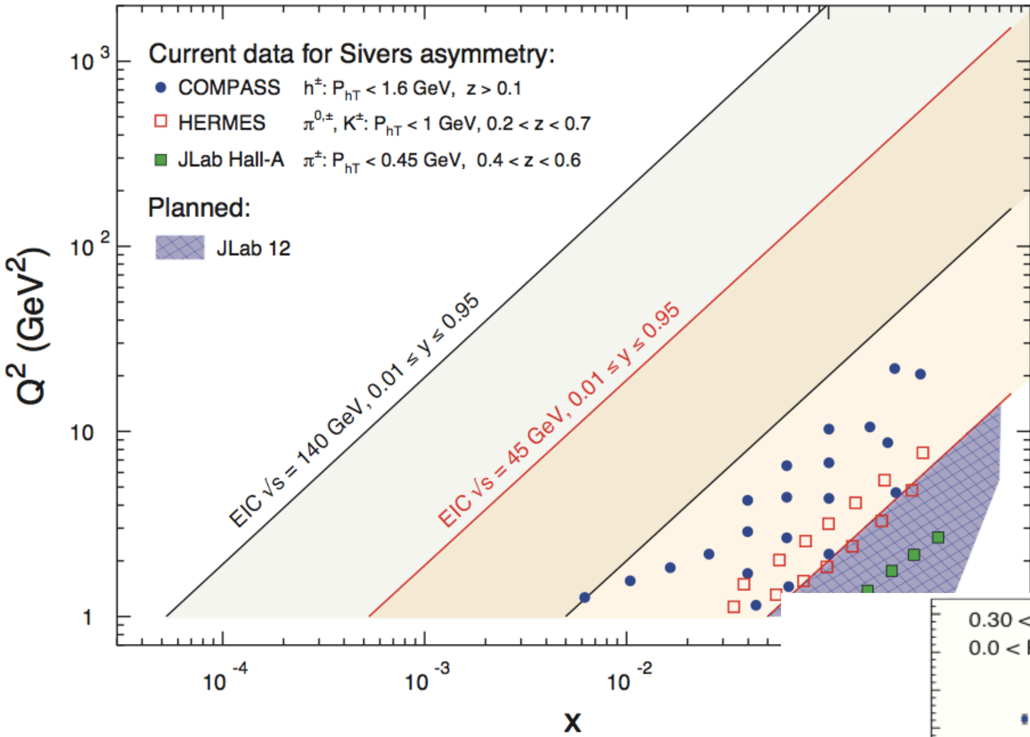
- Naturally, two scales:
  - ✧ high Q – localized probe
    To "see" quarks and gluons
  - ✧ Low p_T – sensitive to confining scale
    To "see" their confined motion
  - ✧ *Theory – QCD TMD factorization*
- Naturally, two planes:

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

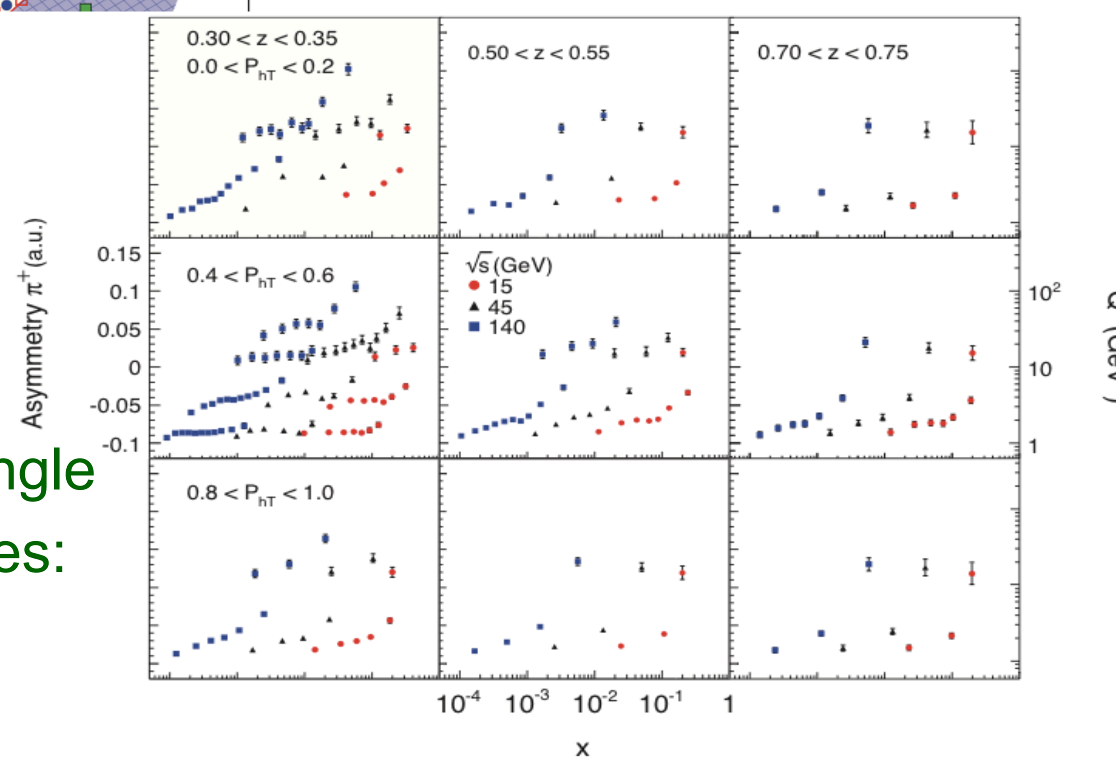
$$= A_{UT}^{Collins}\sin(\phi_h + \phi_S) + A_{UT}^{Sivers}\sin(\phi_h - \phi_S)$$

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





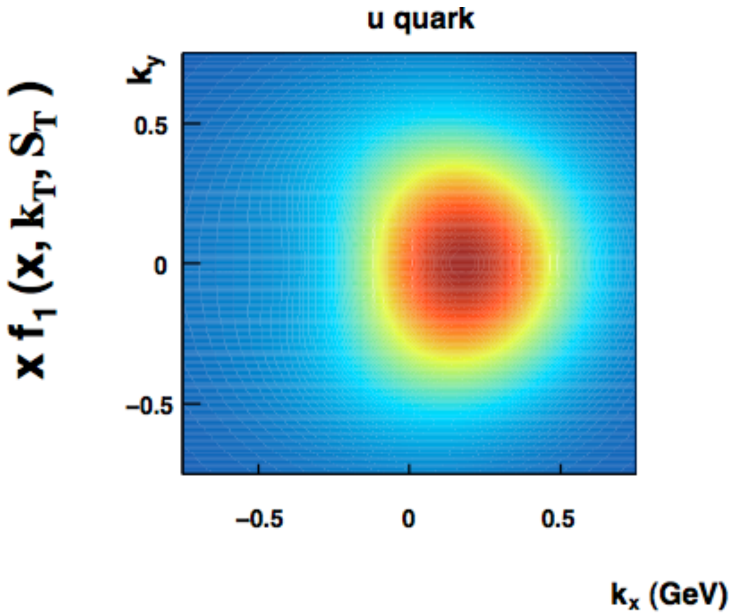
First, maybe the only, measurement of polarized sea and gluon TMDs

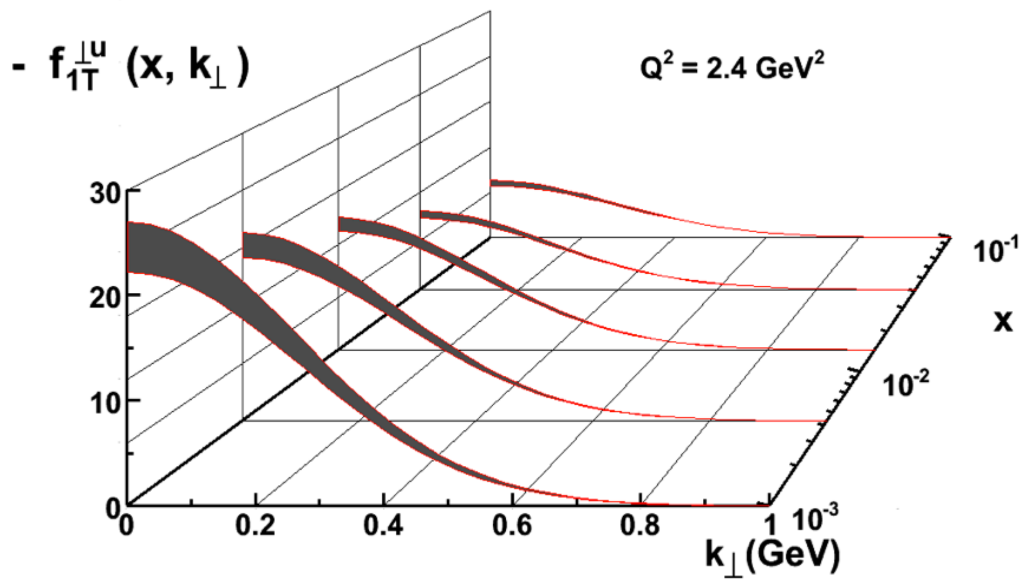


- High luminosity implies: Single transverse-spin asymmetries: high resolution & multidimensional

Momentum tomography of the nucleon

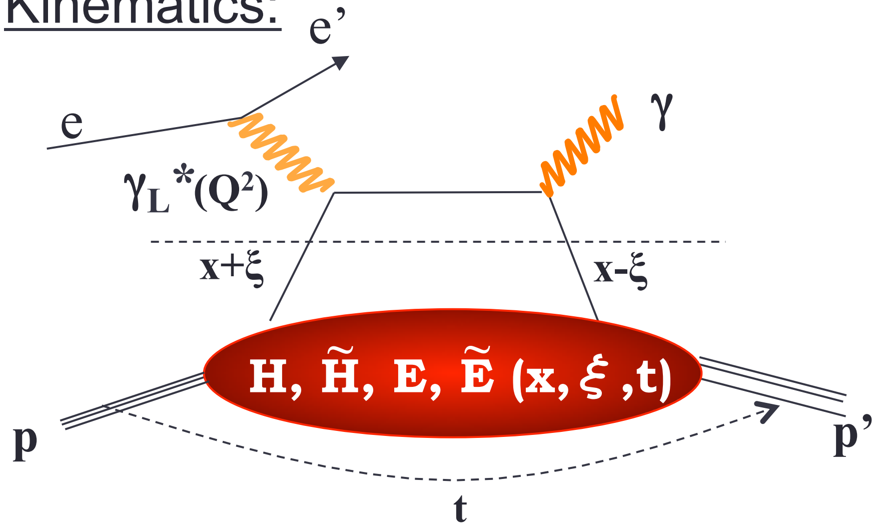
- Tomographic images of K_X/K_y of partons as functions of Bjorken-x: u quark distribution for transversely polarized proton.
- ***With EIC: low x partonic plots like these possible!***





Exclusive DIS

Kinematics:



$$Q^2 = -q^2 = -(k_\mu - k'_\mu)^2$$ Measure of resolution power

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

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

$$x_B = \frac{Q^2}{2pq} = \frac{Q^2}{sy}$$ Measure of momentum fraction of struck quark

$$t = (p - p')^2, \xi = \frac{x_B}{2 - x_B}$$

Exclusive events:
e + **(p/A)** → e'+ **(p'/A')**+ γ / J/ψ / ρ / φ
detect **all** event products in the detector

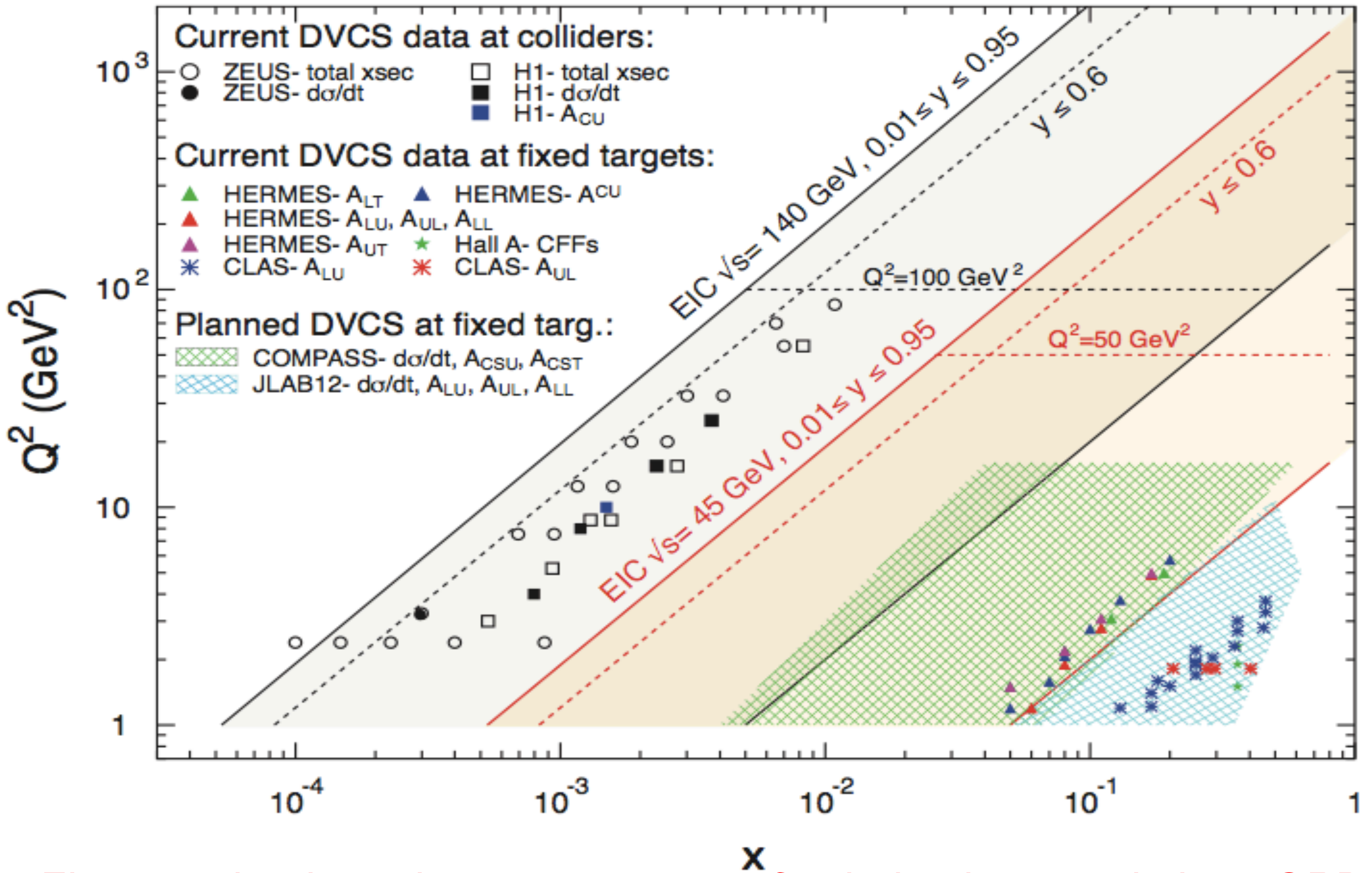
Allow access to the spatial distribution of partons in the nucleon
Fourier transform of spatial distributions → GPDs
GPDs → Orbital Angular Momenta!

$$\frac{1}{2} = J_Q + J_G$$

$$J_Q = \frac{1}{2}\Delta\Sigma + L_Q$$

$$J_G = \Delta G + L_G$$

EIC coverage for GPDs

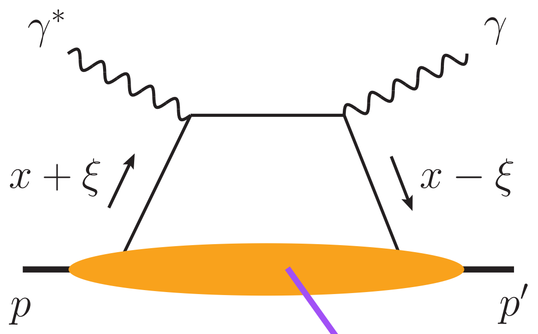


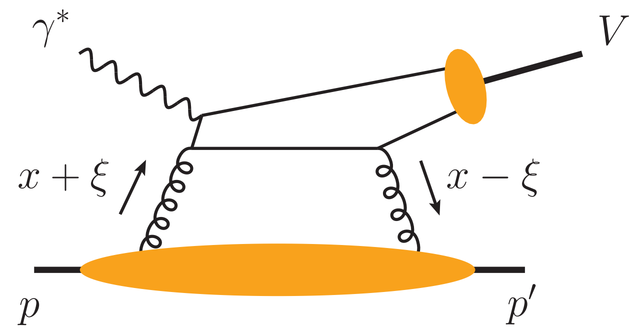
First, maybe the only, measurement of polarized sea and gluon GPDs

Spatial Imaging of quarks & gluons

access to Generalized Parton Distributions

Quarks:
At fixed
Target

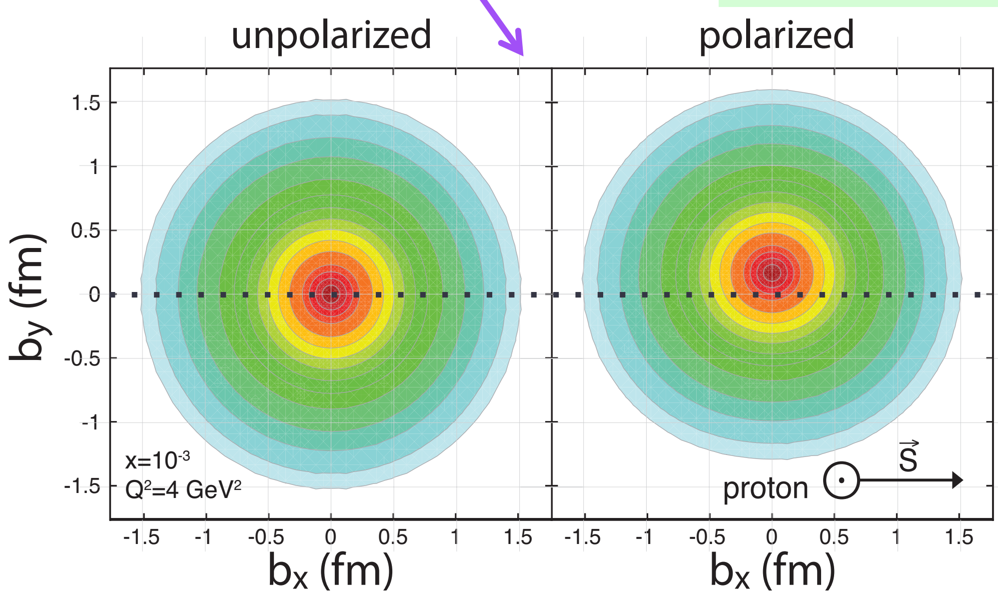




Gluons:
Only @
Collider

Exclusive/Diffractive events:
e + **p** → e'+ **p'**+ γ

Fourier transform of t=(p-p') →
Spatial distribution



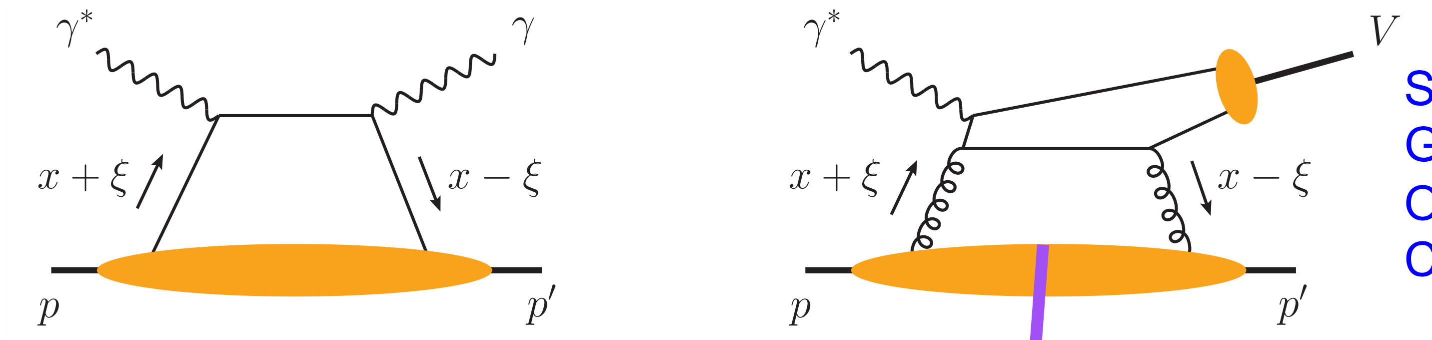
Images of
Quark's spatial distribution
via deeply virtual photon
Production @ the EIC

DVCS on Neutrons:
Carlos M. Camacho's talk

Spatial Imaging of quarks & gluons

access to Generalized Parton Distributions

Quarks:
At fixed
Target

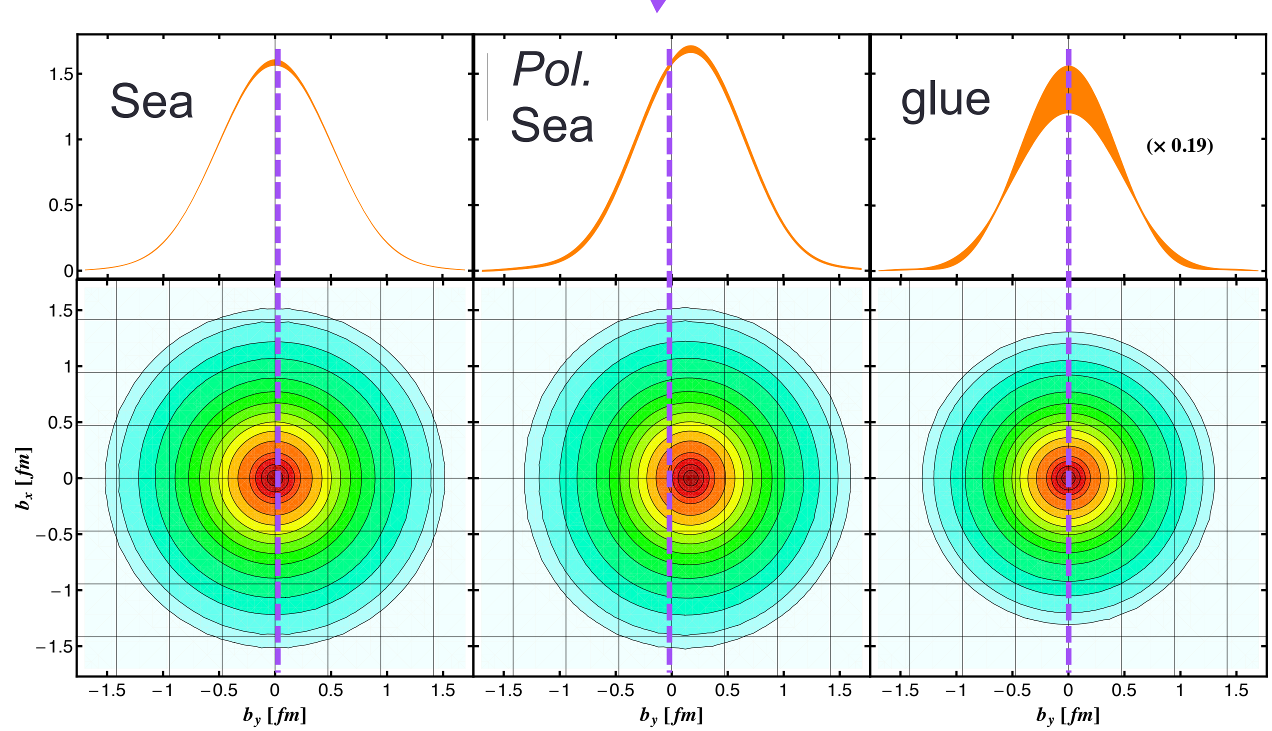


Sea quarks,
Gluons:
Only @ the
Collider

Exclusive/Diffractive events:
e + **p** → e'+ **p'**+ J/ψ

Fourier transform of
t=(p-p') →
Spatial distribution

Images of sea Quarks
& Gluon's spatial dist.
Via J/Ψ production
With the EIC



An immediate check/impact:

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

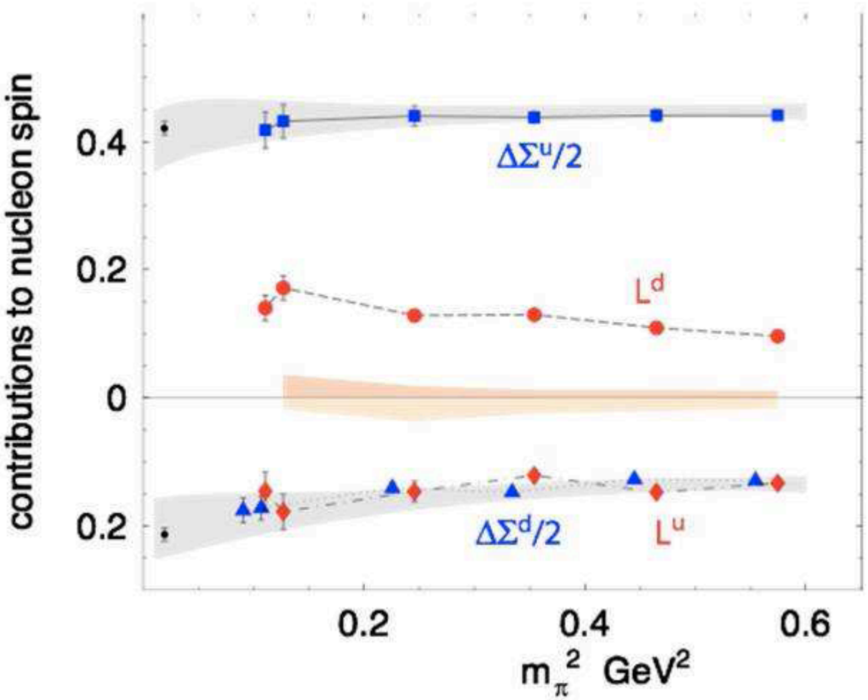
$$J_q = \frac{1}{2} \lim_{t \to 0} \int dx\, x \left[H_q(x, \xi, t) + E_q(x, \xi, t) \right] = \frac{1}{2} \Delta q + L_q$$

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

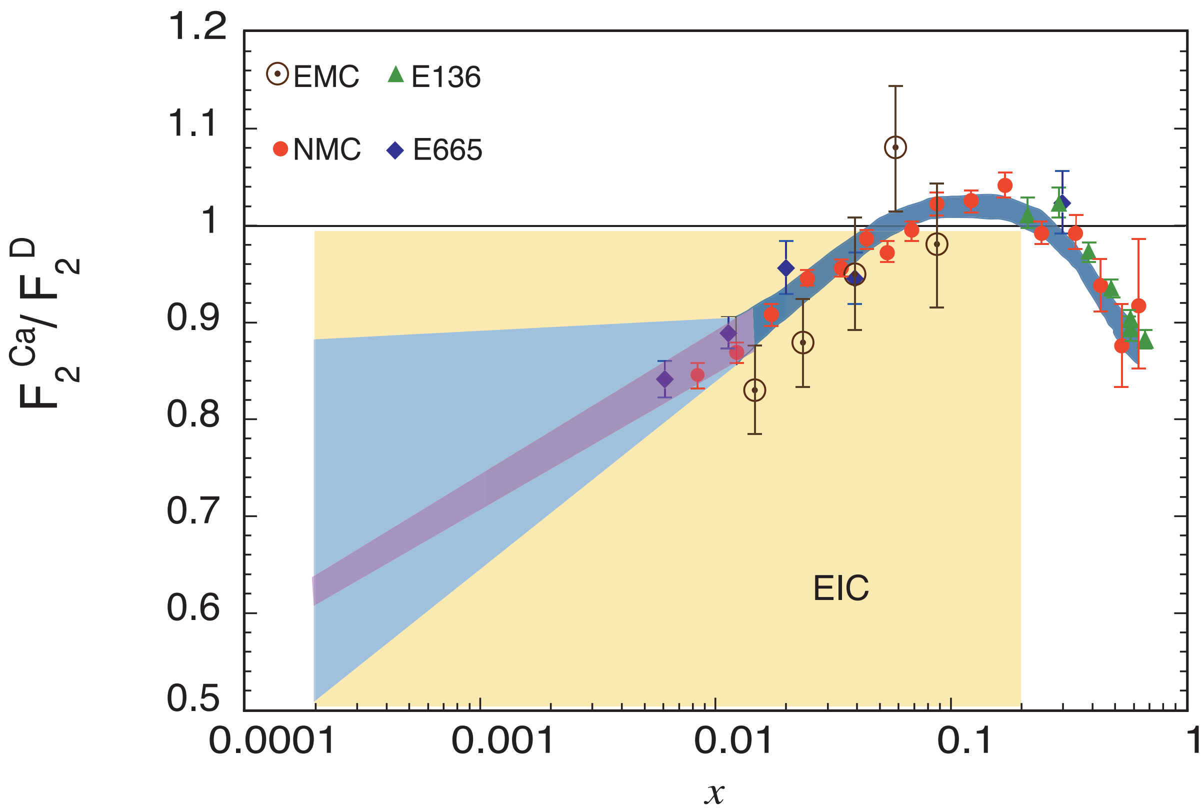
This could be checked by Lattice QCD

$L_u + L_d \sim 0$?

There are also more recent 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



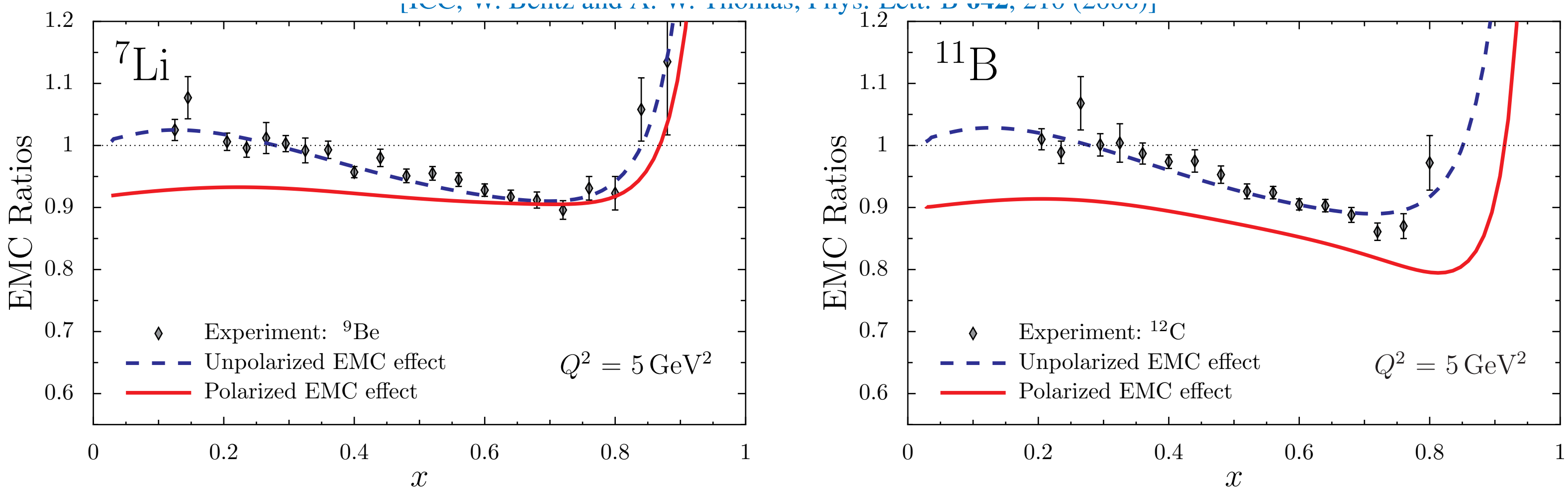
EMC effect… medium modification of PDFs



30 + years of activity to understand this, but with only limited Success.

Cloet et al. proposed polarized EMC Study
Could the future EIC could add to?

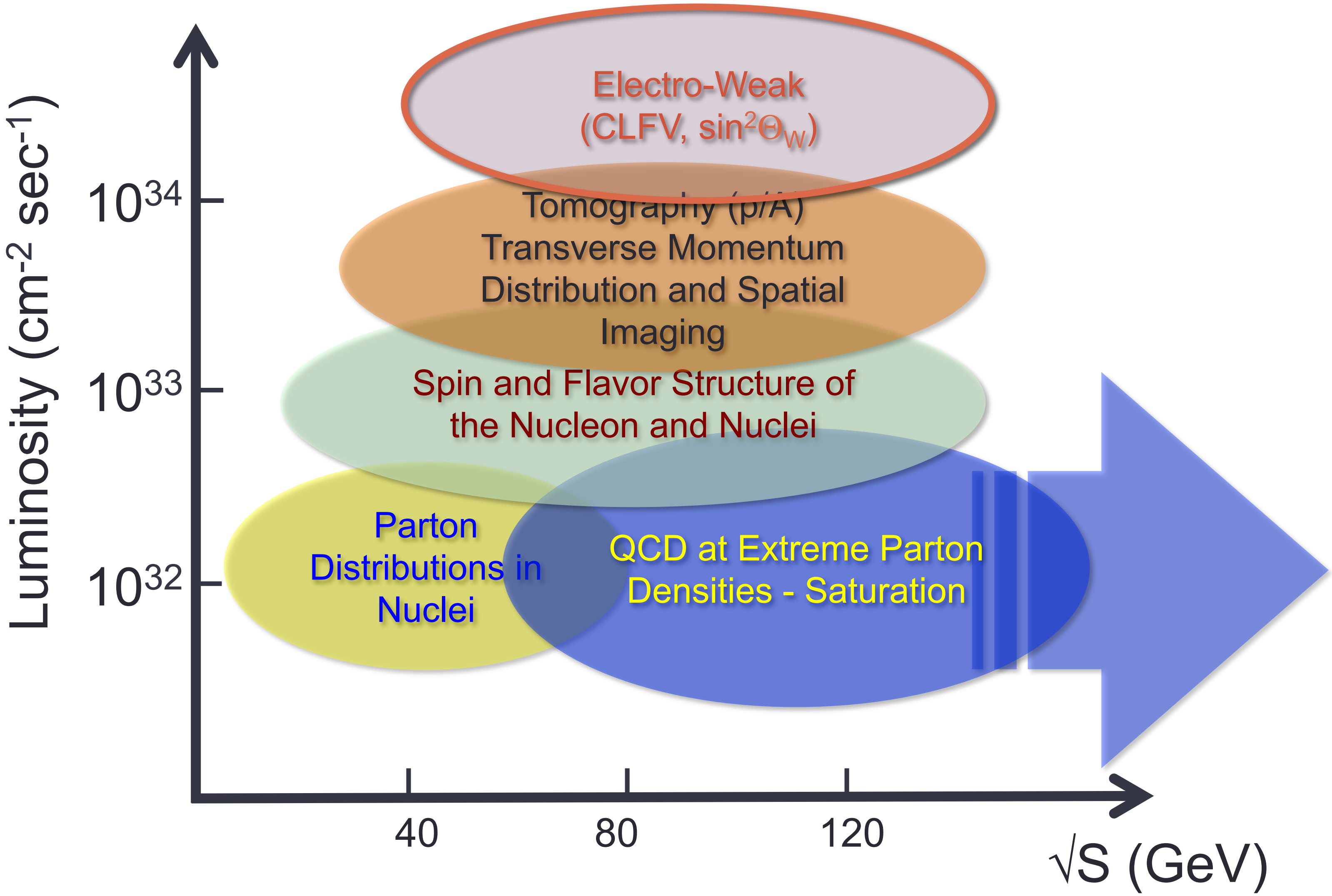
Ian Cloet, NP Town meeting, Temple U.

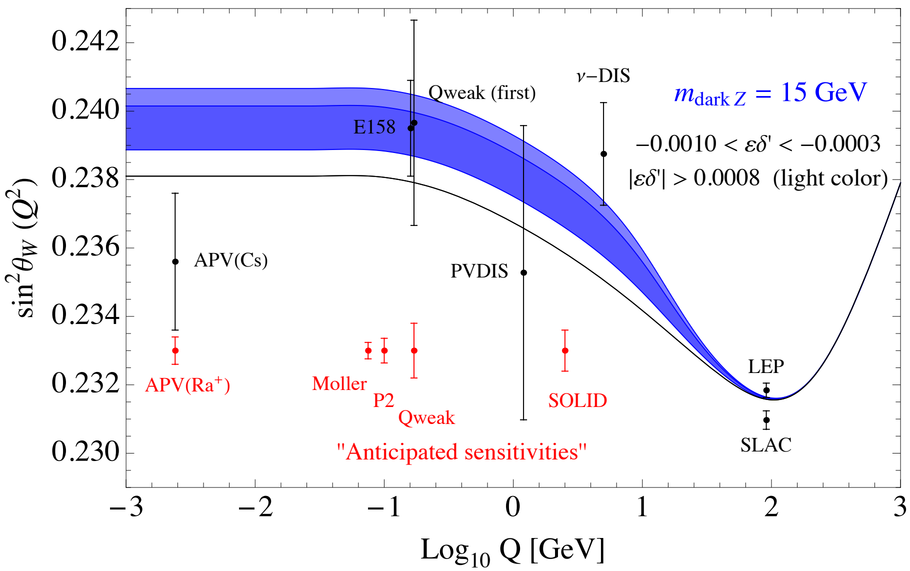


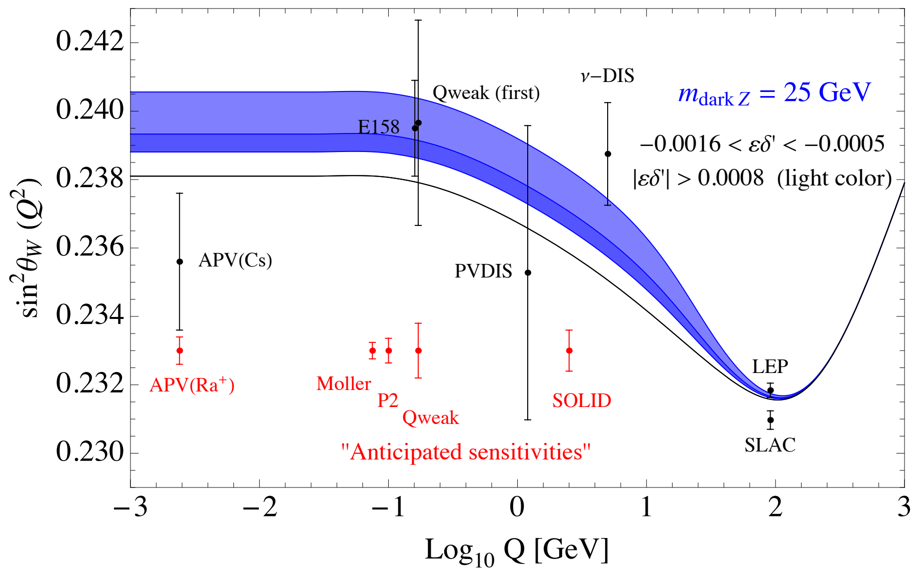
- Polarized EMC ratio: $\Delta R = \frac{g_{1A}}{g_{1A}^{\text{naive}}} = \frac{g_{1A}}{P_p\, g_{1p} + P_n\, g_{1n}}$
- Spin-dependent cross-section is suppressed by $1/A$
  - must choose nuclei with $A \lesssim 27$
  - protons should carry most of the spin e.g. $\Longrightarrow$ ^{7}Li, ^{11}B, ...
- Ideal nucleus is probably ^{7}Li
  - from Green Function Quantum Monte–Carlo: $P_p = 0.86$ & $P_n = 0.04$

Should we
Push for
Polarized light
Ions at the EIC?
(JLEIC may already
Have it?)

EIC Physics vs. Luminosity & Energy

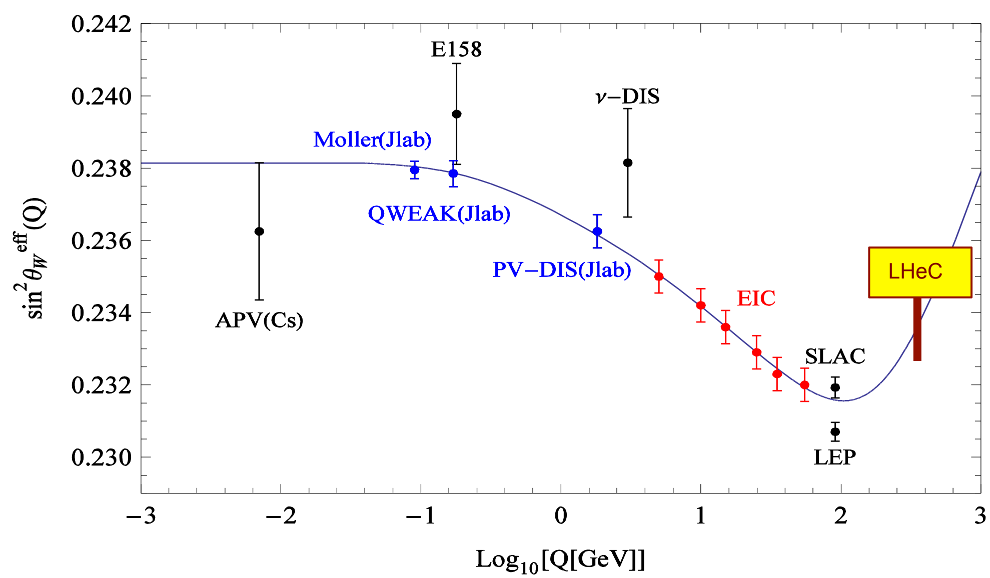






Low Q^2 Weak Mixing Angle Measurements and Rare Higgs Decays

Hooman Davoudiasl,[1] Hye-Sung Lee,[2] and William J. Marciano[1]



Dark Z Study: arXiv:1507.00352

EIC Study by William Marciano et al.

A more detailed study underway:
Y. Zang, A. Deshpande & K. Kumar et al.

Summary

- Colliders have some natural advantages (energy, geometry, dilution factor etc…)
- Wide kinematic range of polarized DIS experiment at the EIC will profoundly enhance our ability to study q-g interactions & understand the underlying features and dynamics.
- Complementary to JLab12 physics program, the EIC will take us to low-x (sea & gluon dominated) regions
- Physics of Strong Gluon Fields covered in other talks in this meeting.