

The Apex of RHIC Physics

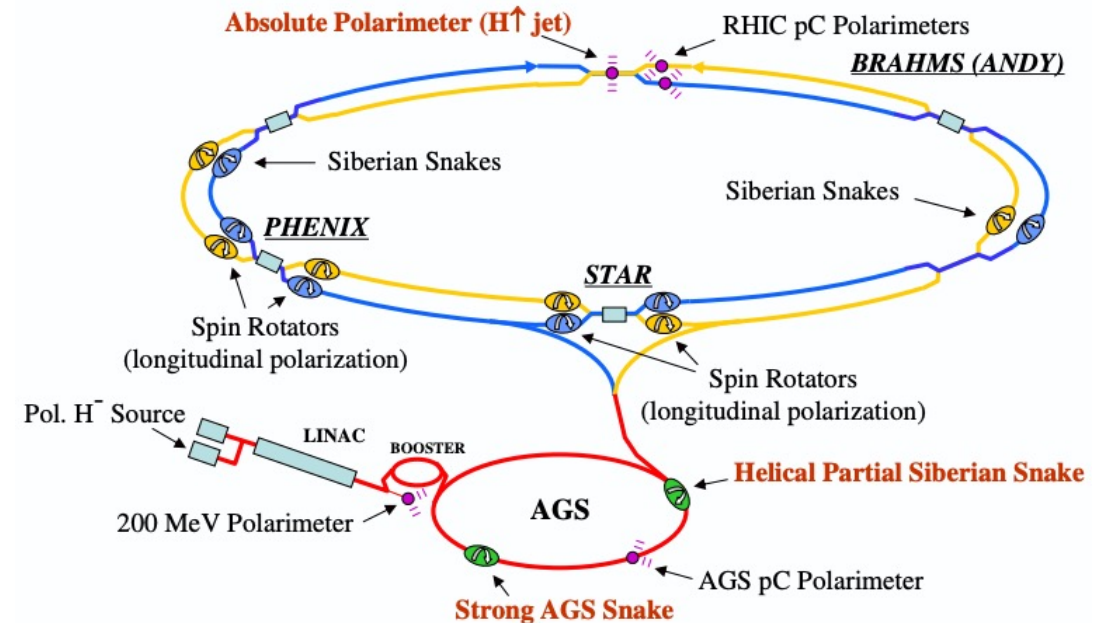
Resolving the Strong Force

May 11–15, 2026

Science and User Support Center
Brookhaven National Laboratory
Upton, New York, USA

Impact of RHIC on understanding the nucleon spin

- ❑ Curiosity and Fascination of the Spin, ...
- ❑ Proton Spin “Crisis” and RHIC Spin Program
- ❑ Discoveries of RHIC Spin Program and Impact
- ❑ From RHIC Spin to Spin Program at the EIC
- ❑ Summary & Outlook



Jianwei Qiu
Jefferson Lab, Theory Center

Curiosity and Fascination of Spin, ...

□ Spin = an **intrinsic** and **quantum** property of all particles regardless if they are **elementary** or **composite**

- Pauli (1924): “two-valued quantum degree of freedom” of electron – 1st formulation of spin
- Pauli/Dirac: $S = \hbar\sqrt{s(s+1)}$ (fundamental constant \hbar)
- Composite particle = Total angular momentum when it is at rest

□ Nucleon Spin – Fundamental emergent property:

- Without it, our visible world would NOT be the same!

Nucleon is a fundamental building block of all atomic nuclei and visible hadronic matter

□ Spin of a nucleon – Naïve Quark Model:

- Nucleon is made of three constituent (valence) quarks
- Spin of a nucleon = sum of the constituent quark's spin

$$\text{State: } |p \uparrow\rangle = \sqrt{\frac{1}{18}} [u \uparrow u \downarrow d \uparrow + u \downarrow u \uparrow d \uparrow - 2u \uparrow u \uparrow d \downarrow + \text{perm.}]$$

$$\text{Spin: } S_p = \langle p \uparrow | S | p \uparrow \rangle = \frac{1}{2}, \quad S = \sum_i S_i$$

Carried by valence quarks

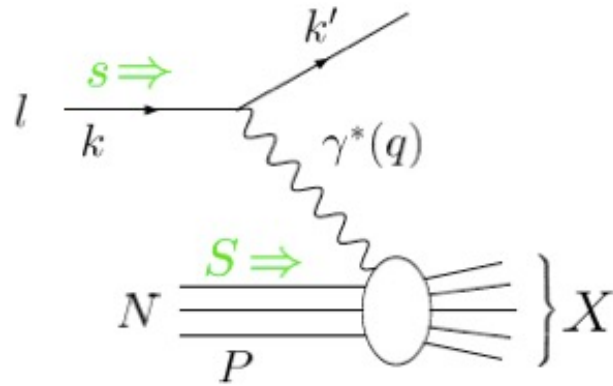


Pauli and Bohr observing spin, 1954



Polarized Deep Inelastic Scattering

DIS with polarized beam(s):



“Resolution” $Q \equiv \sqrt{-q^2} > 2 \text{ GeV}$

$$\frac{\hbar}{Q} = \frac{2 \times 10^{-16} \text{ m}}{Q/\text{GeV}} \lesssim 10^{-16} \text{ m} = 1/10 \text{ fm}$$

“Inelasticity” – known as Bjorken variable

$$x_B = \frac{Q^2}{2P \cdot q} = \frac{Q^2}{Q^2 + M_X^2 - m^2}$$

DIS hadronic tensor:

$$W_{\mu\nu} = -\left(g_{\mu\nu} - \frac{q_\mu q_\nu}{q^2} \right) F_1(x_B, Q^2) + \frac{1}{p \cdot q} \left(p_\mu - q_\mu \frac{p \cdot q}{q^2} \right) \left(p_\nu - q_\nu \frac{p \cdot q}{q^2} \right) F_2(x_B, Q^2) \\ + iM_p \varepsilon^{\mu\nu\rho\sigma} q_\rho \left[\frac{S_\sigma}{p \cdot q} g_1(x_B, Q^2) + \frac{(p \cdot q) S_\sigma - (S \cdot q) p_\sigma}{(p \cdot q)^2} g_2(x_B, Q^2) \right]$$

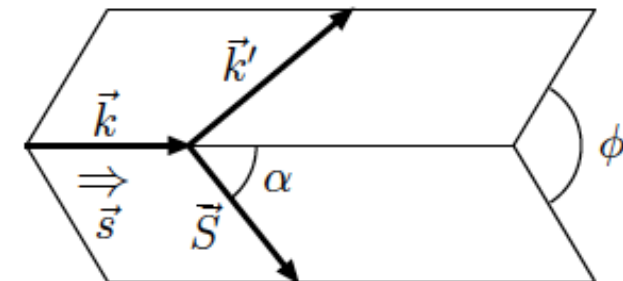
Polarized structure functions:

$$g_1(x_B, Q^2), g_2(x_B, Q^2)$$

“Hadron spin orientation”

$$\alpha = 0 : \Rightarrow g_1$$

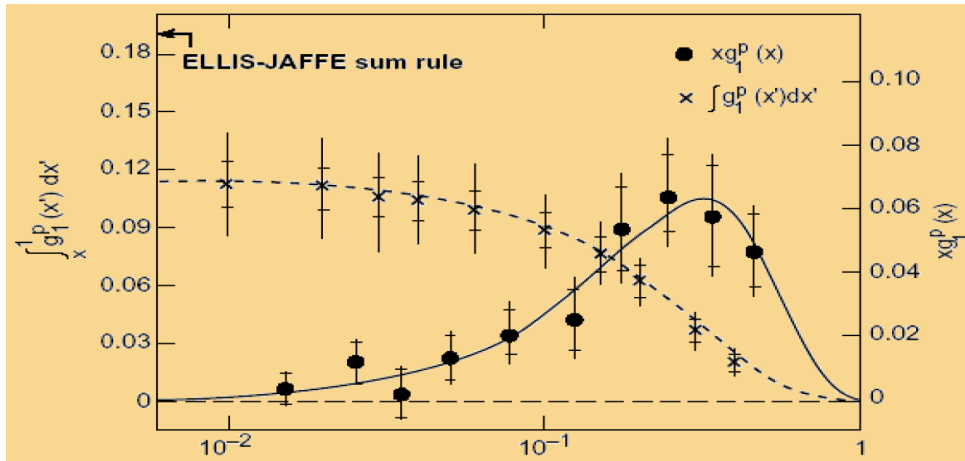
$$\alpha = \pi/2 : \Rightarrow y g_1 + 2 g_2$$



Proton “Spin Crisis” – Excited the Field

□ EMC (European Muon Collaboration '87) – “the Plot”:

J. Ashman et al.
Phys. Lett. B206, 364 (1988)
Nucl. Phys. B328, 1 (1989)



✧ Combined with earlier SLAC data:

✧ Combined with: $g_A^3 = \Delta u - \Delta d$ and $g_A^8 = \Delta u + \Delta d - 2\Delta s$

from low energy neutron & hyperon β decay



$$\Delta\Sigma = \sum_q [\Delta q + \Delta\bar{q}] = 0.12 \pm 0.17$$

□ “Proton spin crisis” or puzzle:

- Strange sea polarization is sizable & negative
- Very little of the proton spin is carried by quarks



*What about the gluon?
New era of spin physics!*

Proton “Spin Crisis” – Excited the Field

Early responses from the theory community:

“We show that, **due to the anomaly**, the gluon contribution to the first moment of the polarized proton structure function, as measured in deep inelastic scattering, is not suppressed by a power of the strong coupling evaluated at a large scale. As a result, **the EMC result for the first moment of polarized proton electroproduction is consistent with a large quark spin component.**”

$$\Delta q \Rightarrow \Delta q - \frac{\alpha_s N_f}{2\pi} \Delta G \quad \text{G. Altarelli, G.G. Ross, Phys.Lett.B 212 (1988) 391}$$

“... We suggest measuring two-jet production in deep inelastic scattering off polarized targets as a means of **determining the spin-dependent gluonic component of j_5^μ** ”

R.D. Carlitz, J.C. Collins, A.H. Mueller, Phys.Lett.B214 (1988) 229

The g_1 Problem: Fact and Fantasy on the Spin of the Proton – MIT CTP#1706, 1989

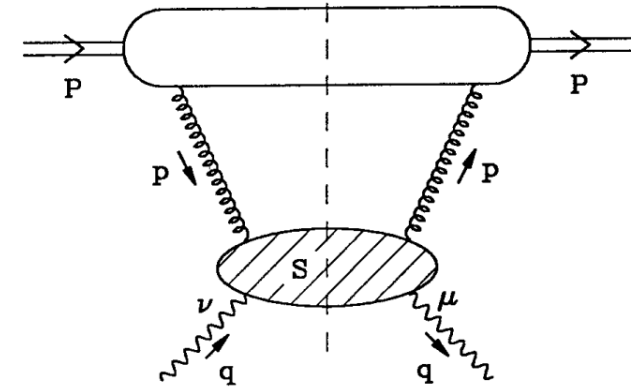
“We ... **show that the anomalous (gluonic) U(1)A current, K_μ , is not to be identified with the gluon spin.**”

R.L. Jaffe, A. Manohar, Nucl.Phys.B337 (1990) 509

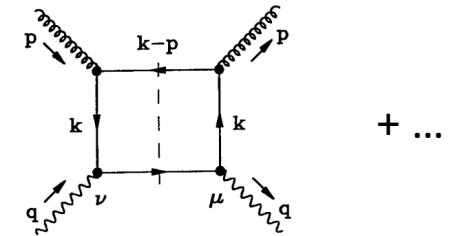
“We show that **the first moment of the resulting hard gluonic contribution vanishes, provided that the UV regulator for the spin-dependent quark distributions respects both gauge invariance ...**”

– ANL-HEP-PR-89-83

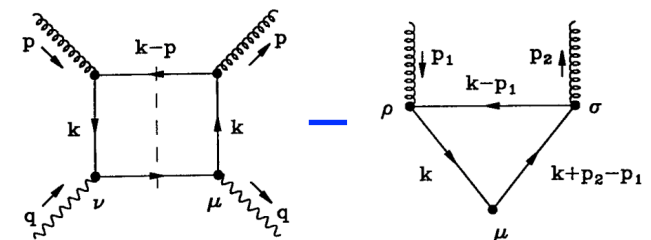
G.T. Bodwin, J.W. Qiu, Phys.Rev.D 41 (1990) 2755



Leading order:



Factorization:



RHIC Spin Program

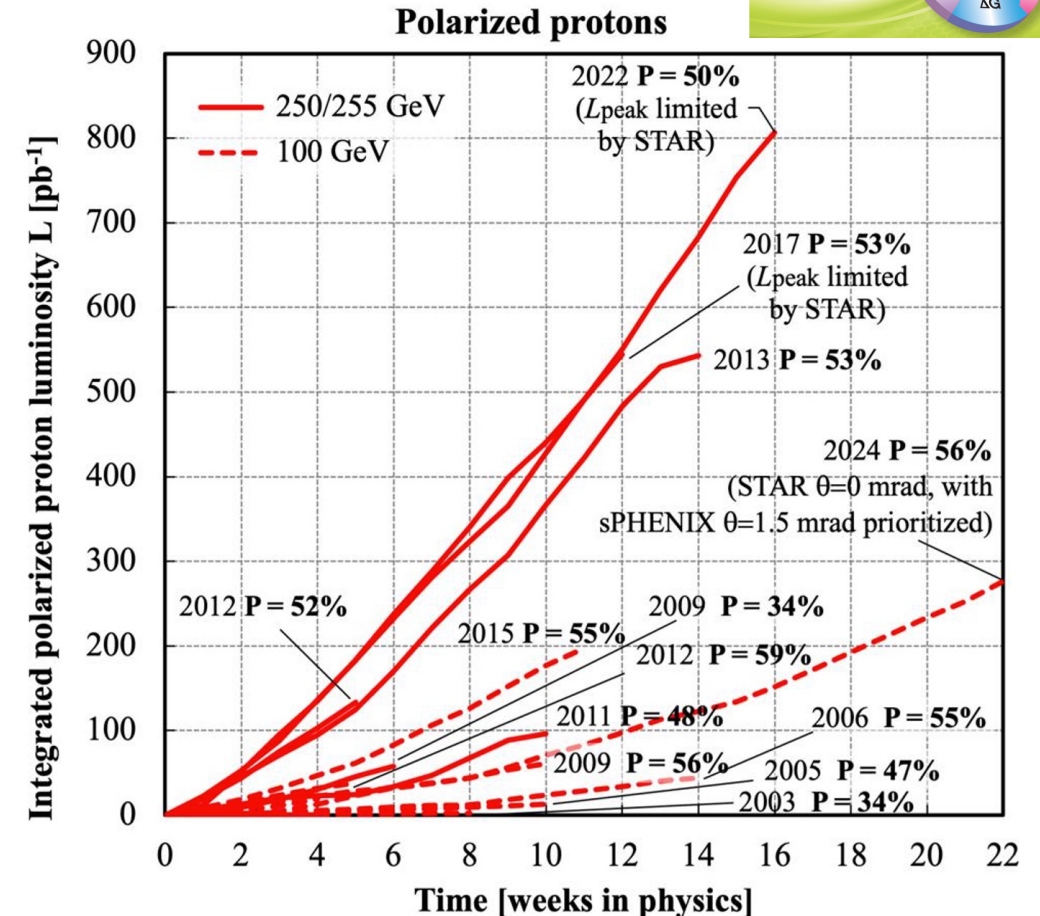
Need a hadron collider to see the gluon more directly – RHIC Spin Program

□ Critical RHIC spin review:

ABSTRACT: Colliding beams of 70% polarized protons at up to $\sqrt{s}=500$ GeV, with high luminosity, $L=2\times 10^{32}$ $\text{cm}^{-2}\text{sec}^{-1}$, will represent a new and unique laboratory for studying the proton. RHIC-Spin will be the first polarized-proton collider and will be capable of copious production of jets, directly produced photons, and W and Z bosons. Features will include direct and precise measurements of the polarization of the gluons and of u bar, d bar, u , and d quarks in a polarized proton. Parity violation searches for physics beyond the standard model will be competitive with unpolarized searches at the Fermilab Tevatron. Transverse spin will explore transversity for the first time, as well as quark-gluon correlations in the proton. Spin dependence of the total cross section and in the Coulomb nuclear interference region will be measured at collider energies for the first time. These qualitatively new measurements can be expected to deepen our understanding of the structure of matter and of the strong interaction.

G. Bunce, N. Saito, J. Soffer, W. Vogelsang
Ann. Rev. Nucl. Part. Sci. 50, 525 (2000)

The RHIC Spin Program, 1501.01220



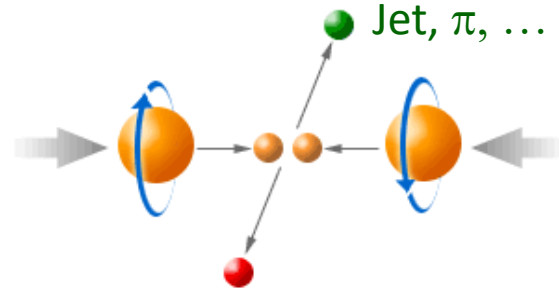
Discoveries of RHIC Spin Program and their Impact

□ First direct evidence that gluons are polarized:

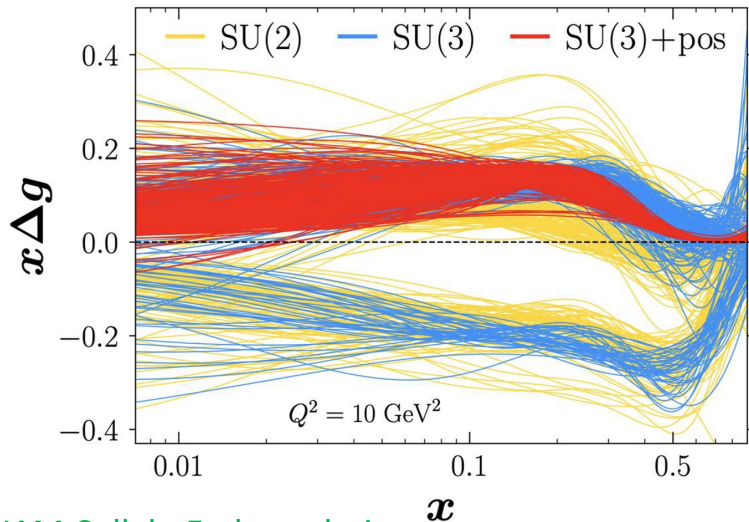
This is probably the single most important RHIC spin discovery

Using double spin-asymmetries in pp collisions:
$$A_{LL} = \frac{[\sigma(+,+) - \sigma(+,-)] - [\sigma(-,+) - \sigma(-,-)]}{[\sigma(+,+) + \sigma(+,-)] + [\sigma(-,+) + \sigma(-,-)]}$$
 for $\sigma(s_1, s_2)$

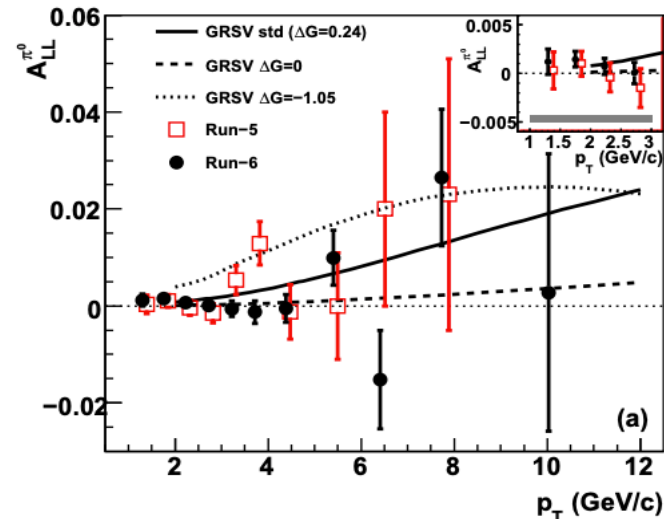
- in
- inclusive jet production,
 - pion production,
 - direct photons,
 - heavy flavor production.



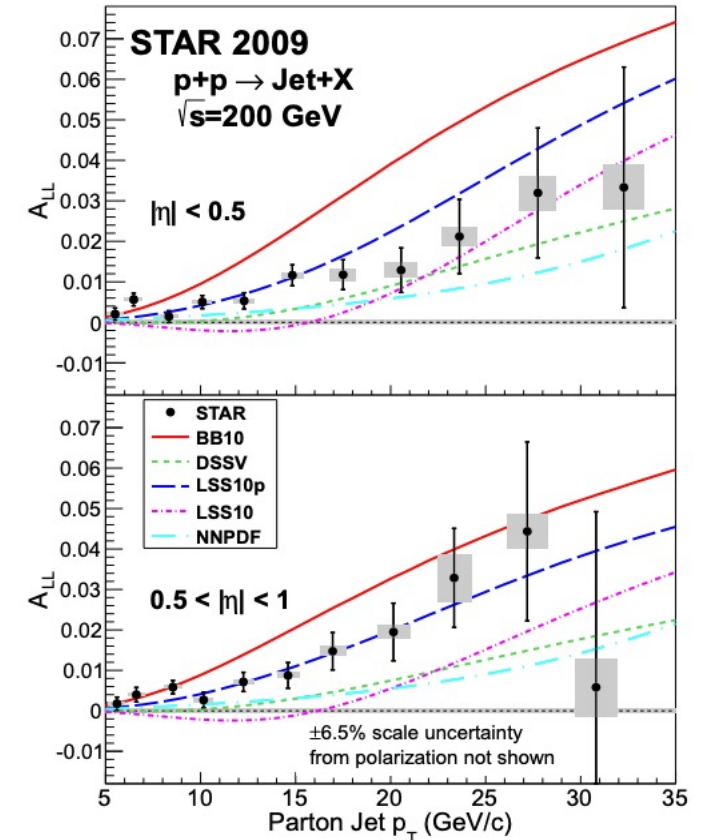
□ QCD Global analyses:



JAM Collab. Early analysis



PHINIX Collab. PRL103, 012003 (2009)



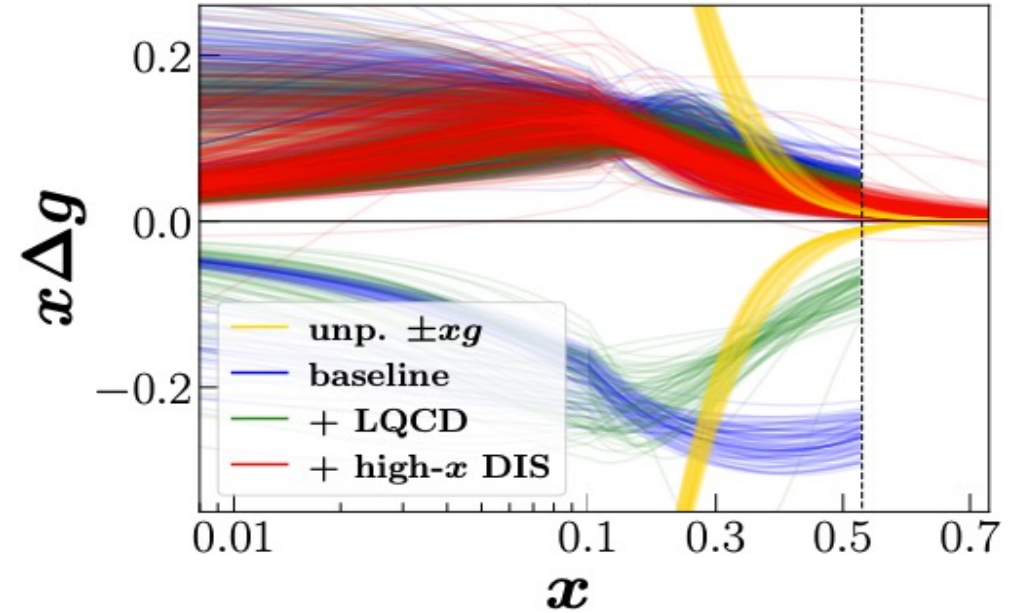
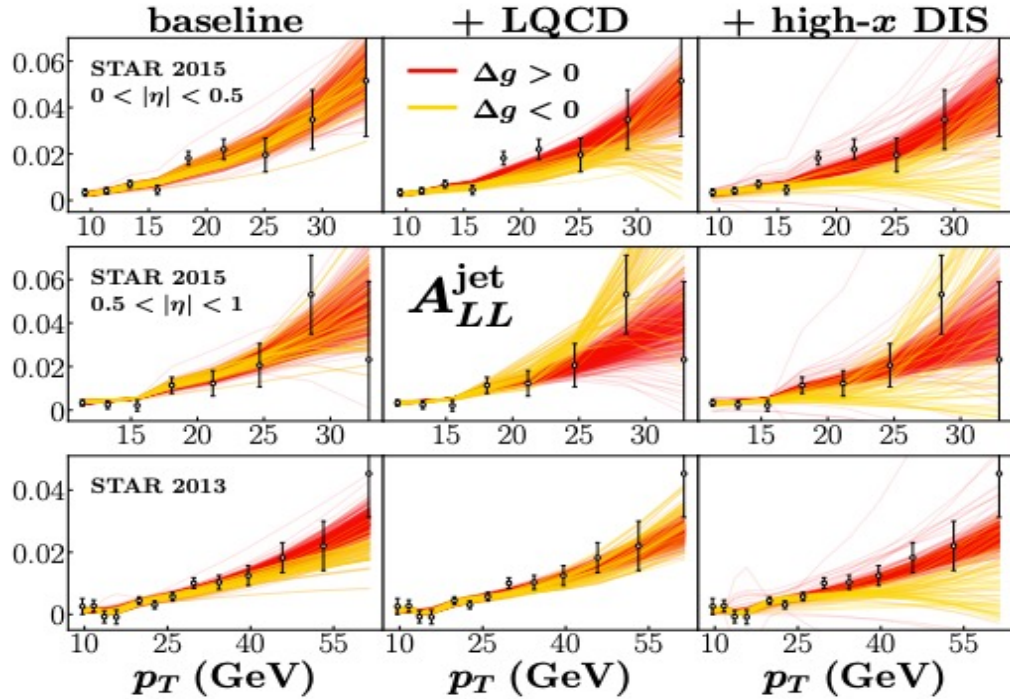
Star Collab. PRL115, 092002 (2015) 

Discoveries of RHIC Spin Program and their Impact

Sign of net gluon contribution to the proton spin:

Hunt-Smith *et al.*, PRL133, 161901 (2024)

Global QCD analysis of RHIC old & new data, LQCD data, large- x JLab data



$$\Delta G(x \gtrsim 0.05) > 0$$

The impact:

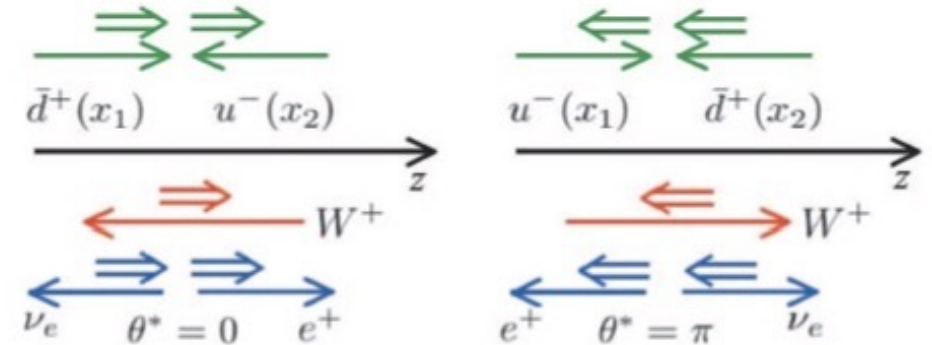
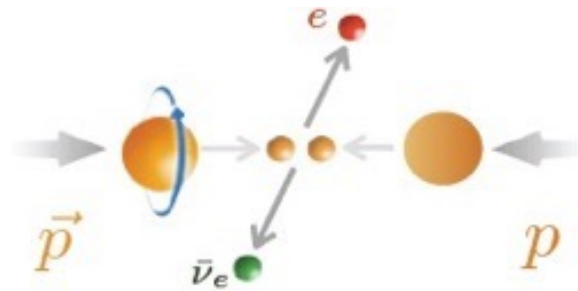
- RHIC Spin program established that gluons carry part of the proton spin, and
- demonstrated experimentally that spin in QCD is fundamentally a many-body dynamical property.

Discoveries of RHIC Spin Program and their Impact

□ Quark spins contribute to the proton spin :

In addition to the polarized DIS experiments such as EMC, SMC, HERMES, and COMPASS, RHIC provided the direct access to anti-quark helicity distributions via parity violation single longitudinal spin asymmetry

□ W's are left-handed:



□ Flavor separation:

■ Lowest order:

$$A_L^{W^+} = -\frac{\Delta u(x_1)\bar{d}(x_2) - \Delta\bar{d}(x_1)u(x_2)}{u(x_1)\bar{d}(x_2) + \bar{d}(x_1)u(x_2)}$$

$$x_1 = \frac{M_W}{\sqrt{s}} e^{y_W}, \quad x_2 = \frac{M_W}{\sqrt{s}} e^{-y_W}$$

■ Forward W⁺ (backward e⁺):

$$A_L^{W^+} \approx -\frac{\Delta u(x_1)}{u(x_1)} < 0$$

■ Backward W⁺ (forward e⁺):

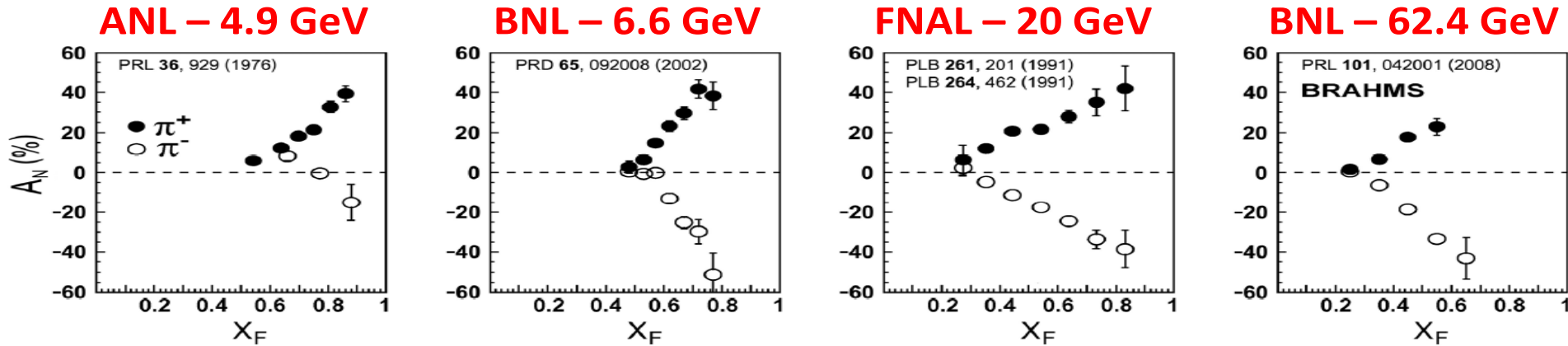
$$A_L^{W^+} \approx -\frac{\Delta\bar{d}(x_2)}{\bar{d}(x_2)} < 0$$

The RHIC results help further establish:

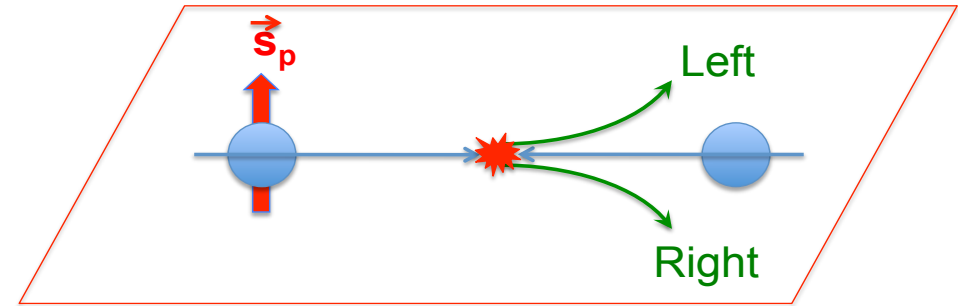
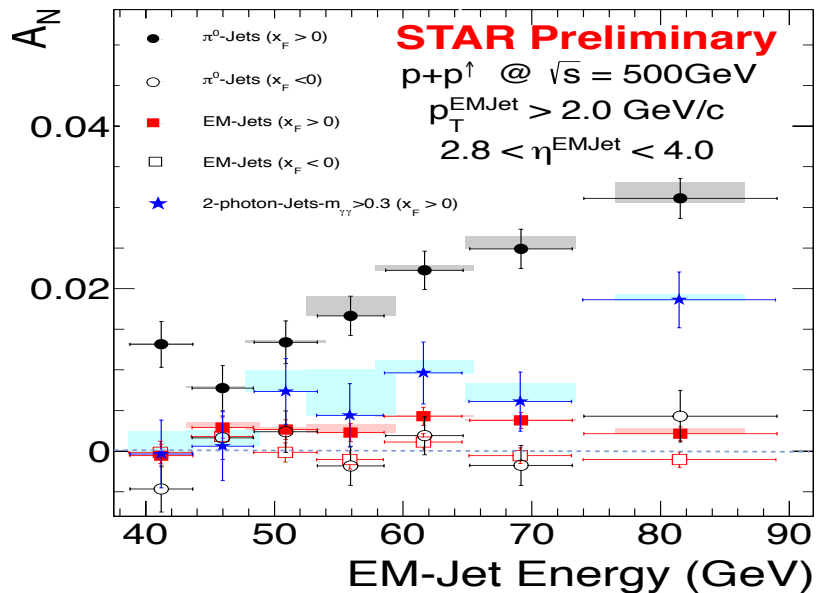
The quark and antiquark helicities contribute only about 20–30% of the proton spin.

Discoveries of RHIC Spin Program and their Impact

Discovery of surprisingly large transverse single-spin asymmetries (over 40 years):



Survived the highest RHIC energy:



$$A_N \equiv \frac{\Delta\sigma(l, \vec{s})}{\sigma(l)} = \frac{\sigma(l, \vec{s}) - \sigma(l, -\vec{s})}{\sigma(l, \vec{s}) + \sigma(l, -\vec{s})}$$

Do we understand this?

A_N in Hadronic Collisions

□ Early attempt:

Cross section:

$$\sigma_{AB}(p_T, \vec{s}) \propto \left[\text{diagram 1} + \text{diagram 2} + \dots \right] \quad \mathbf{2}$$

Kane, Pumplin, Repko, PRL, 1978

Asymmetry:

$$\sigma_{AB}(p_T, \vec{s}) - \sigma_{AB}(p_T, -\vec{s}) = \left[\text{diagram} \right] \propto \alpha_s \frac{m_q}{p_T}$$

Too small to explain available data!

□ What do we need?

$$A_N \propto i\vec{s}_p \cdot (\vec{p}_h \times \vec{p}_T) \Rightarrow i\epsilon^{\mu\nu\alpha\beta} p_{h\mu} s_\nu p_\alpha p'_{h\beta}$$

Need a phase, a spin flip, enough vectors

□ Vanish without parton's transverse motion:

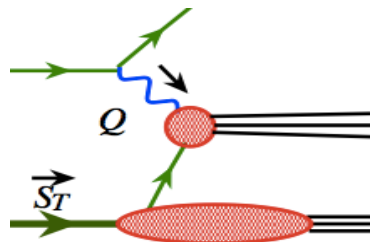


A direct probe for parton's transverse motion,

Spin-orbital correlation, QCD quantum interference

RHIC helped to establish the current Understanding of A_N

□ Symmetry plays important role:



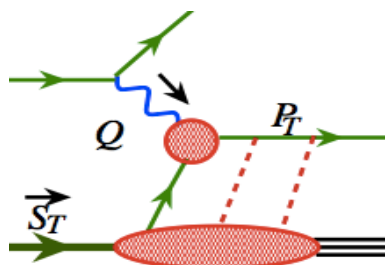
Inclusive DIS
Single scale
 Q

Parity
Time-reversal

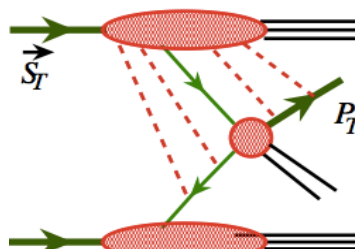


$A_N = 0$

□ One scale observables – $Q \gg \Lambda_{\text{QCD}}$:



SIDIS: $Q \sim P_T$

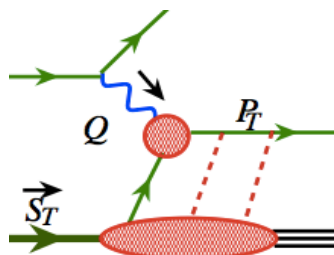


DY: $Q \sim P_T$; Jet, Particle: P_T

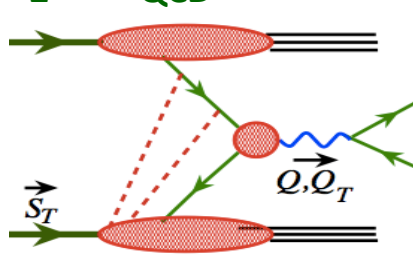
Collinear factorization
Twist-3 distributions

Open to direct QCD quantum interference

□ Two scales observables – $Q_1 \gg Q_2 \sim \Lambda_{\text{QCD}}$:



SIDIS: $Q \gg P_T$



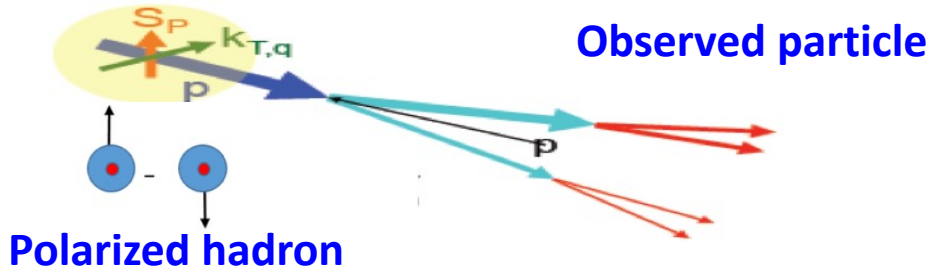
DY: $Q \gg P_T$ or $Q \ll P_T$

TMD factorization
TMD distributions

Open to correlations of parton 3D motion and hadron properties

TMDs: Correlation between Hadron Property and Parton Flavor-Spin-Motion

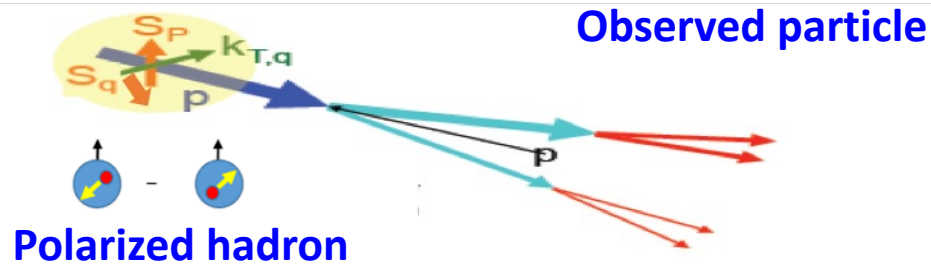
- Quantum correlation between hadron spin and parton motion:



Sivers effect – Sivers function

Hadron spin influences parton's transverse motion

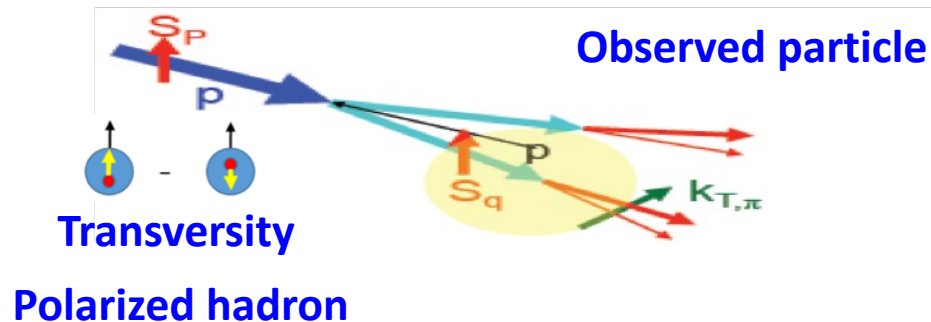
- Quantum correlation between hadron spin and parton spin:



Pretzelosity – model OAM

Hadron spin and parton spin influence parton's transverse motion

- Quantum correlation between parton's spin and its hadronization:



Collins effect – Collins function

Parton's transverse polarization influences its hadronization

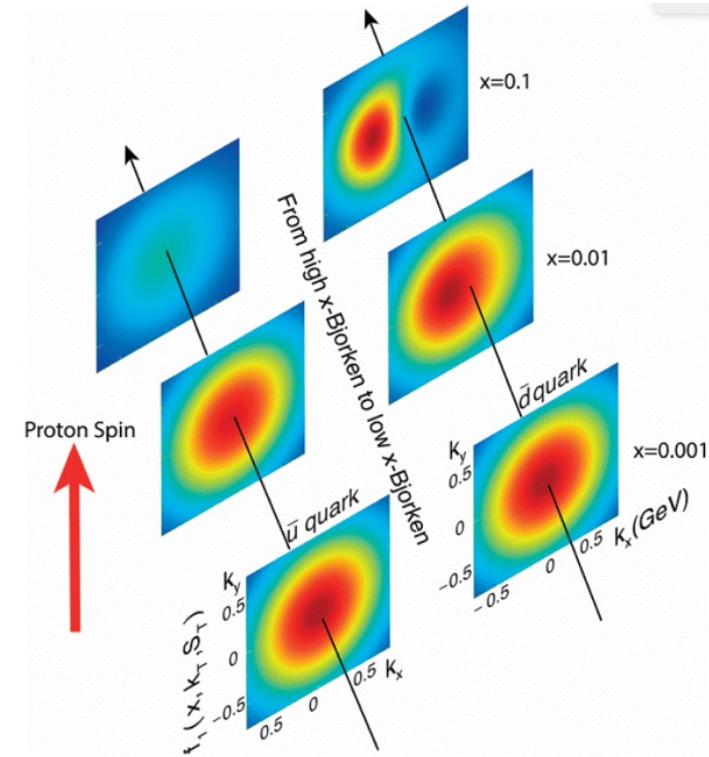


Fig. 2.7 NAS Report

Discoveries of RHIC Spin Program and their Impact

□ First evidence for the sign change of the Sivers function:

- Parity – Time reversal invariance of QCD: $f_{q/h\uparrow}^{\text{SIDIS}}(x, \mathbf{k}_\perp, \vec{S}) = f_{q/h\uparrow}^{\text{DY}}(x, \mathbf{k}_\perp, -\vec{S})$
- Definition of Sivers function: $f_{q/h\uparrow}(x, \mathbf{k}_\perp, \vec{S}) \equiv f_{q/h}(x, k_\perp) + \frac{1}{z} \Delta^N f_{q/h\uparrow}(x, k_\perp) \vec{S} \cdot \hat{p} \times \hat{\mathbf{k}}_\perp$
- Modified universality – QCD Prediction: $\Delta^N f_{q/h\uparrow}^{\text{SIDIS}}(x, k_\perp) = -\Delta^N f_{q/h\uparrow}^{\text{DY}}(x, k_\perp)$

□ RHIC measurements:

Spin-averaged TMD is process independent

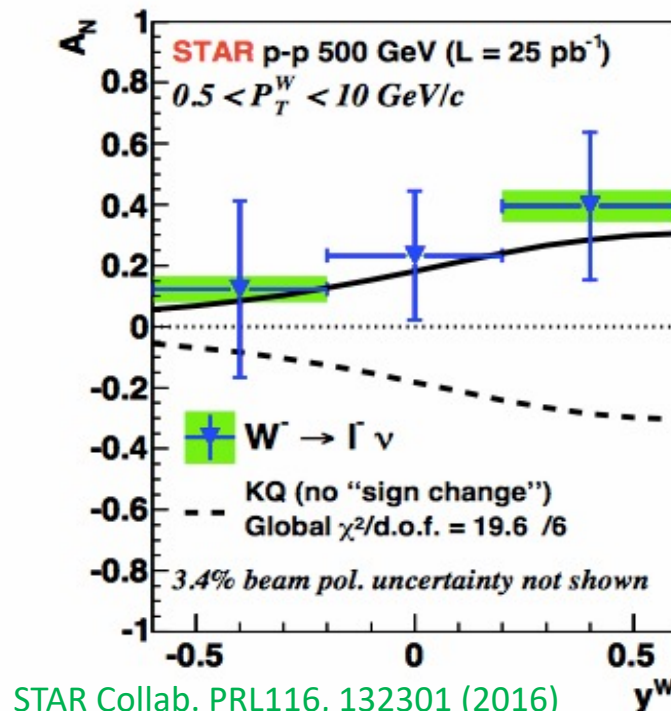
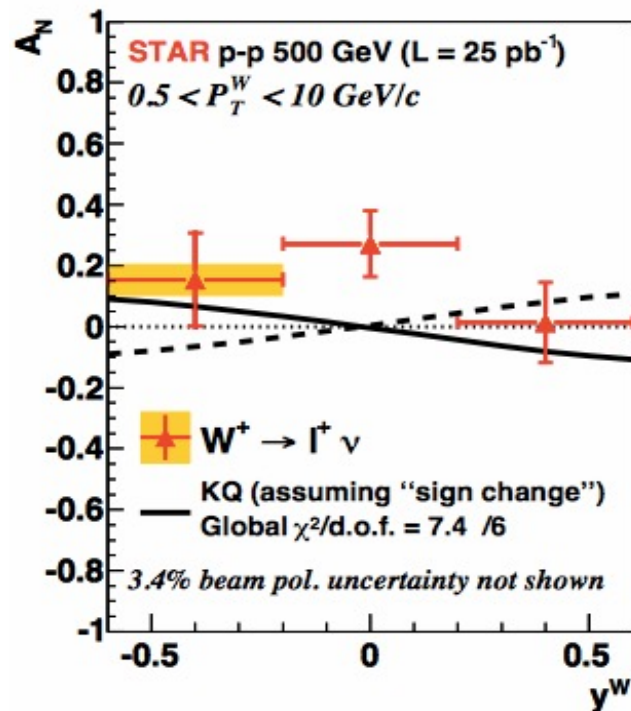
Polarized W/Z production

– Drell-Yan type observables

1st indication of the consistency!

A major milestone in understanding:

- Color gauge links,
- Initial/final state interactions,
- and QCD factorization.



STAR Collab. PRL116, 132301 (2016)

Discoveries of RHIC Spin Program and their Impact

□ RHIC established polarized proton collisions as precision QCD tools:

Before RHIC, polarized pp collisions at high energy were viewed as extremely difficult

■ RHIC demonstrated that one can:

- Accelerate,
- Preserve polarization,
- and collide polarized proton beams at high luminosity

This was itself a major technological and scientific achievement

■ RHIC enabled:

- Precision spin asymmetry measurements with a polarized proton beam,
- Flavor separation via W bosons,
- Gluon helicity extraction,
- Studies of TMDs and twist-3 effects, beyond simple probabilities.

All of these are the achievements for the first time – unprecedented, discovery, ...

■ RHIC satisfied the pre-requisite of the Spin Program at the EIC:

Polarized lepton-hadron collisions is one of the three required key advances of the EIC in comparison with what HERA was able to do.

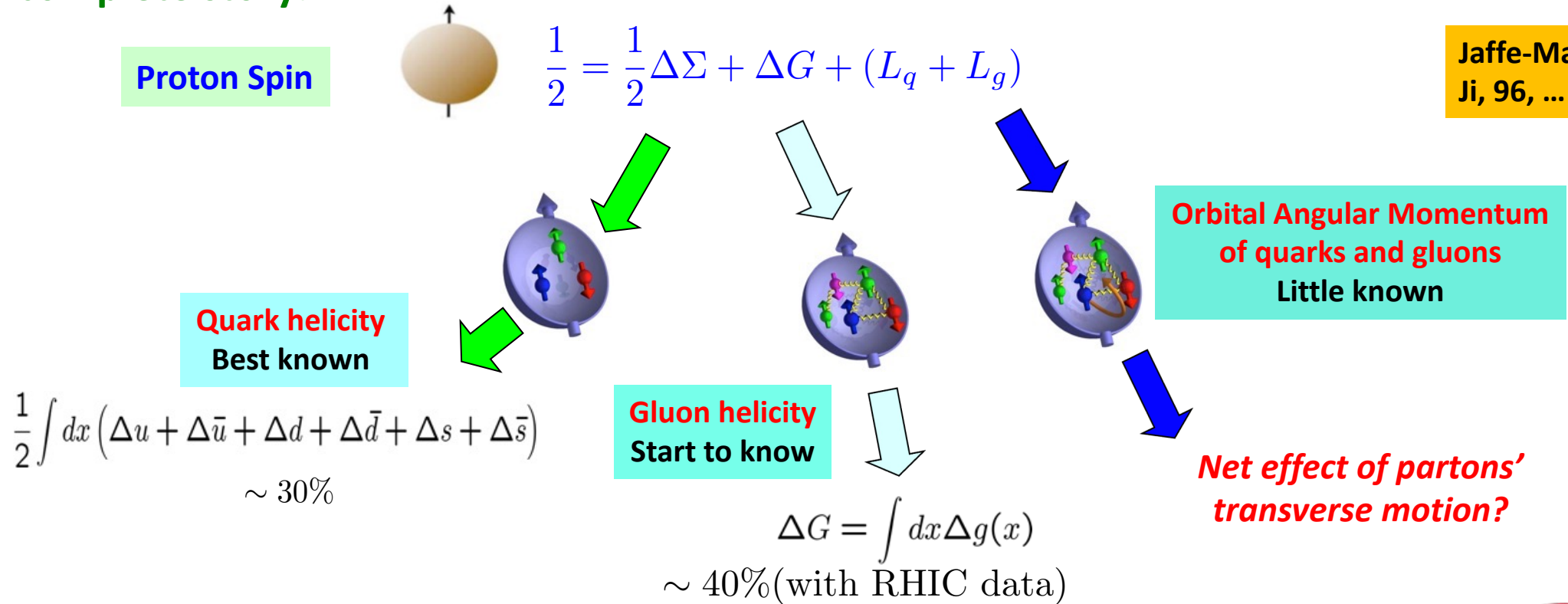
Impact on understanding the proton spin

□ The sum rule:

$$S(\mu) = \sum_f \langle P, S | \hat{J}_f^z(\mu) | P, S \rangle = \frac{1}{2} \equiv J_q(\mu) + J_g(\mu)$$

- Infinite possibilities of decompositions – connection to observables?
- Intrinsic properties + dynamical motion and interactions

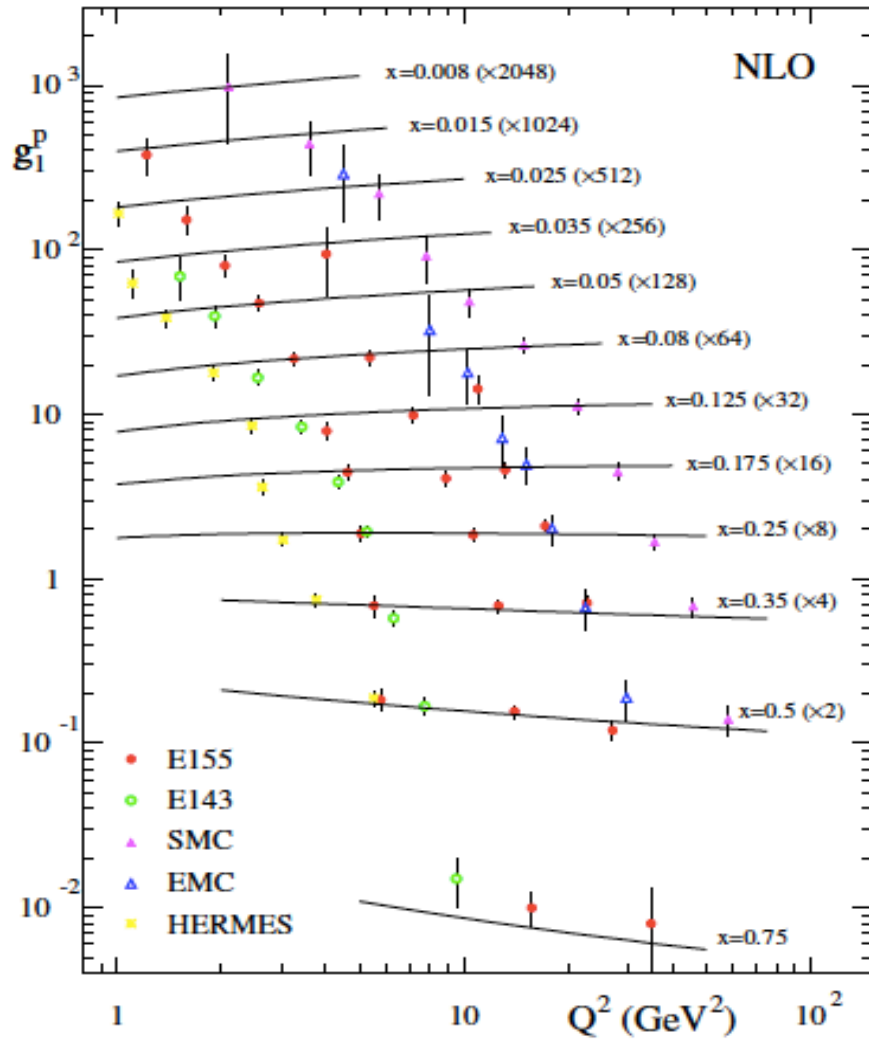
□ An incomplete story:



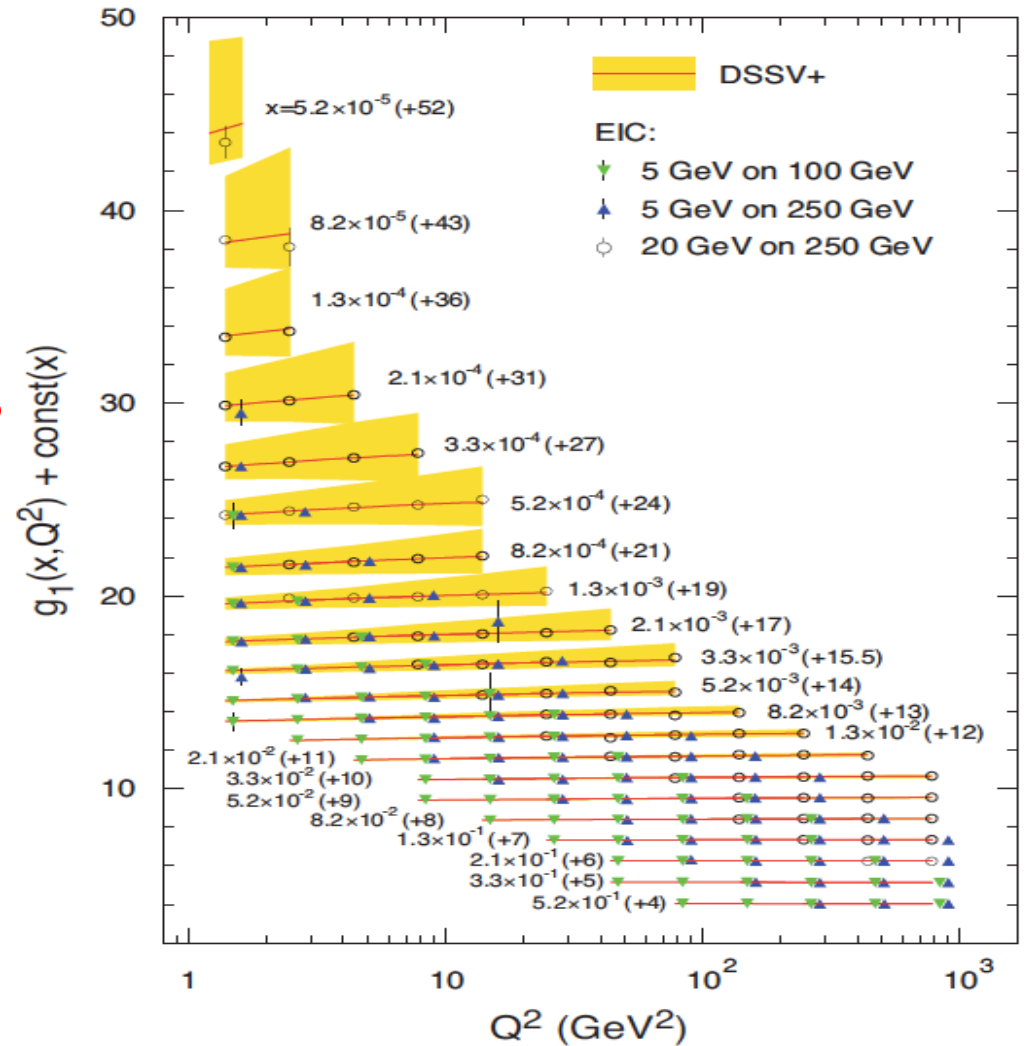
Jaffe-Manohar, 90
Ji, 96, ...

From RHIC Spin to Spin Program at the EIC

□ With the polarized proton beam at the EIC,



Polarized DIS
at EIC

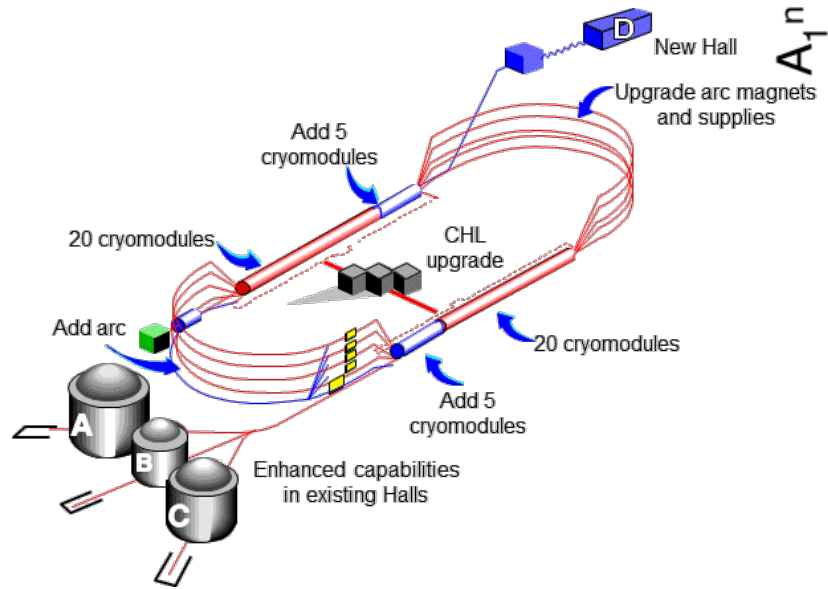


Complementary of JLab12 in between, ...

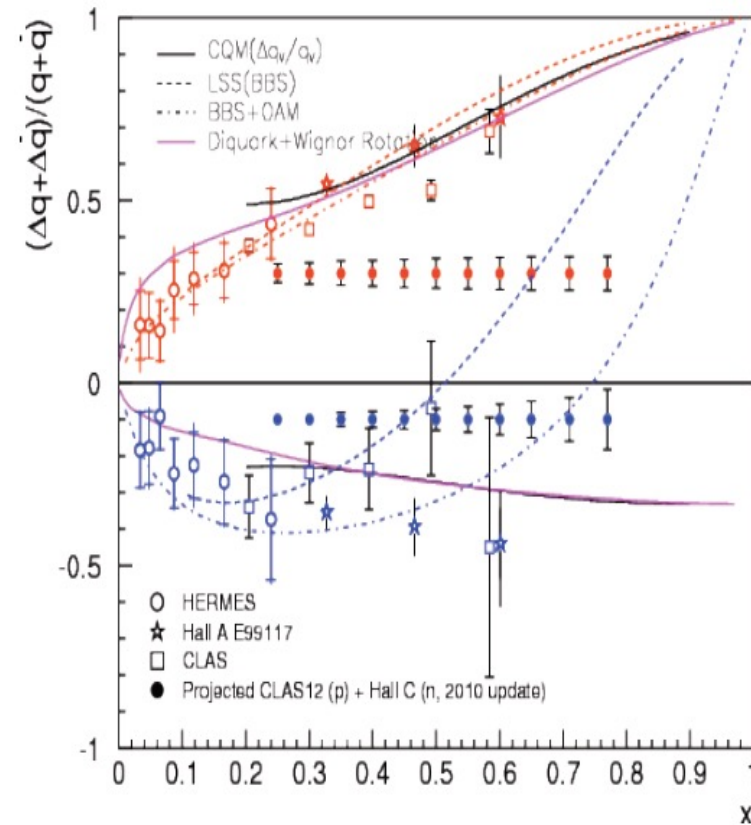
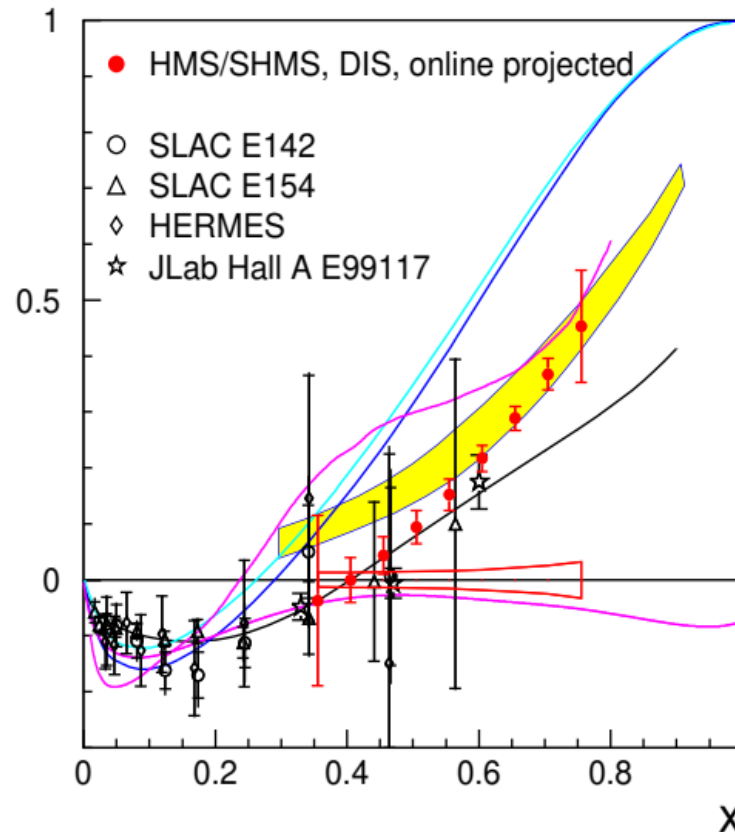
□ JLab 12GeV – Expectations::

12 GeV CEBAF Program is now
in full swing, and
all 4-Halls are taking data

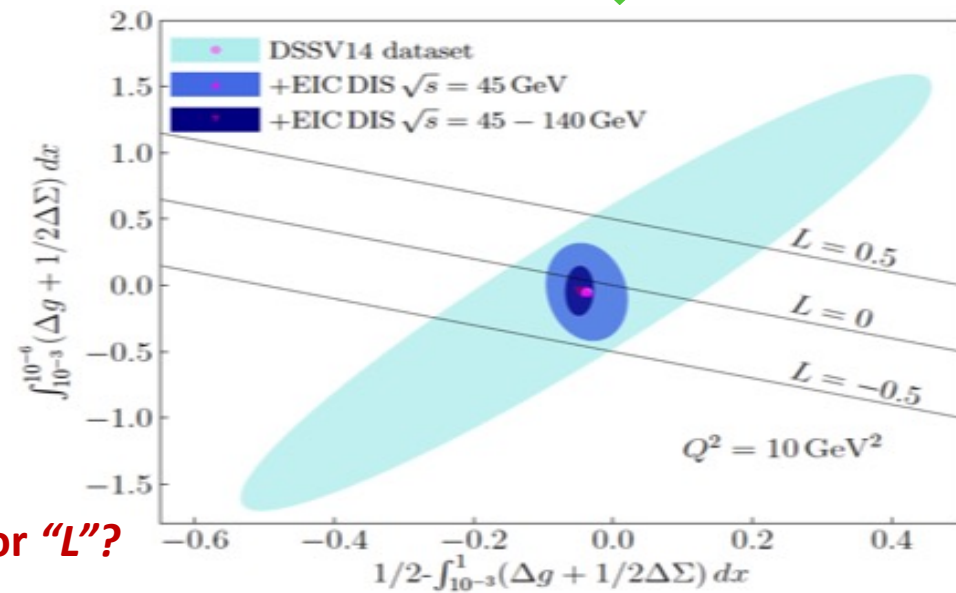
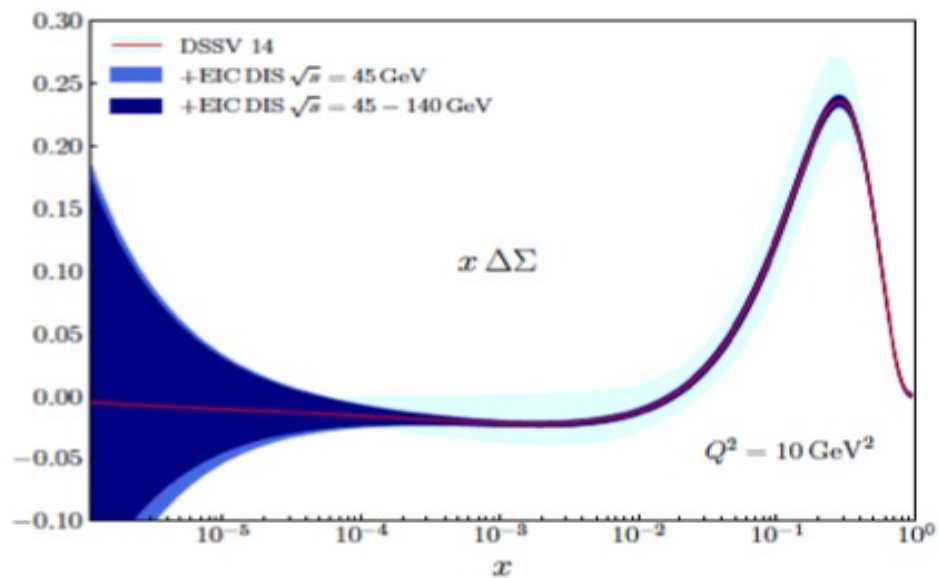
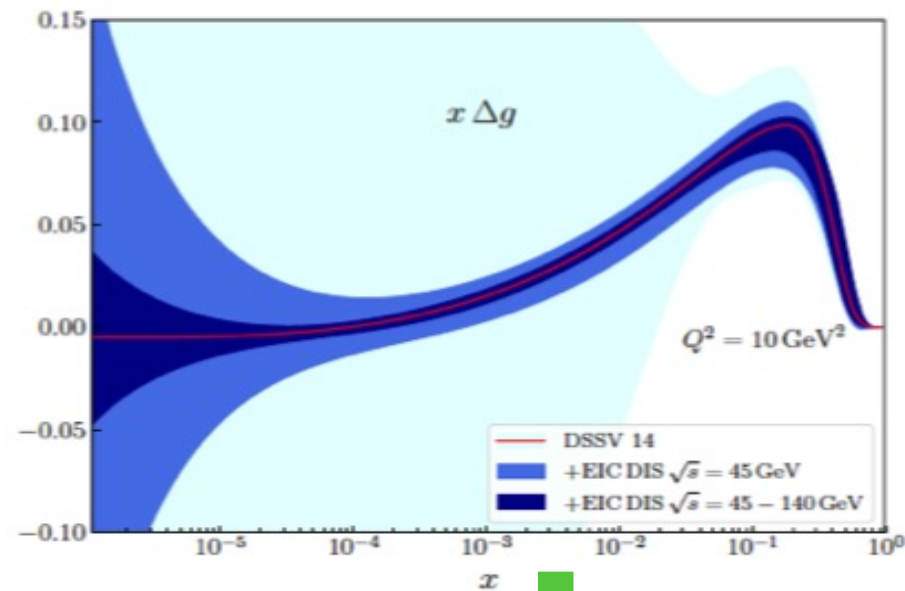
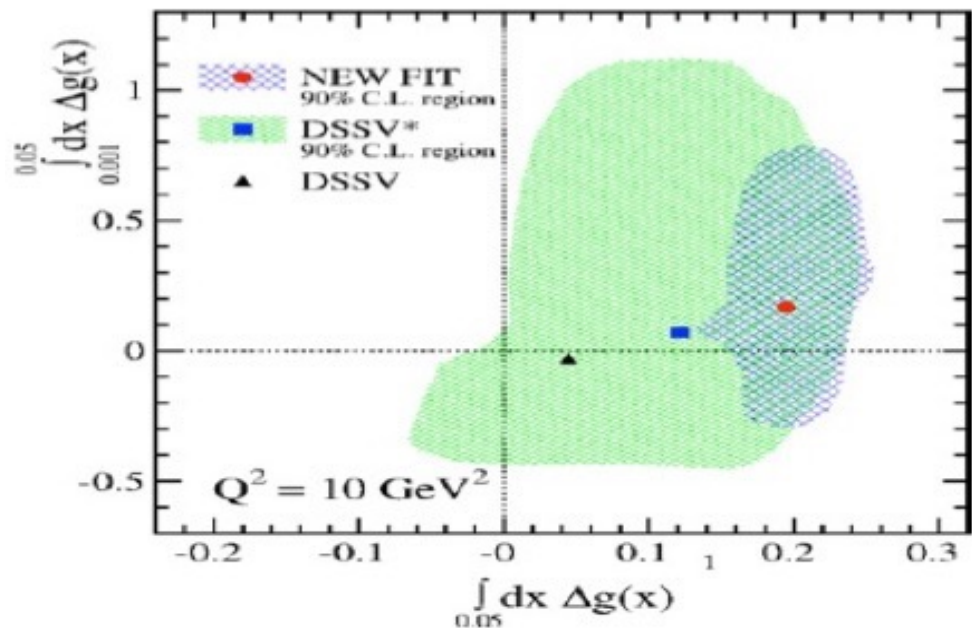
| Model | F_2^n/F_2^p | d/u | $\Delta u/u$ | $\Delta d/d$ | A_1^n | A_1^p |
|-------------------------------|---------------|------|--------------|--------------|---------|---------|
| SU(6) = SU3 flavor + SU2 spin | 2/3 | 1/2 | 2/3 | -1/3 | 0 | 5/9 |
| Valence Quark + Hyperfine | 1/4 | 0 | 1 | -1/3 | 1 | 1 |
| pQCD + HHC | 3/7 | 1/5 | 1 | 1 | 1 | 1 |
| DSE-1 (realistic) | 0.49 | 0.28 | 0.65 | -0.26 | 0.17 | 0.59 |
| DSE-2 (contact) | 0.41 | 0.18 | 0.88 | -0.33 | 0.34 | 0.88 |



Example combined results from Hall C (neutron) and Hall B CLAS12 (proton)



What the EIC can do and learn?



Room for "L"?

Orbital Angular Momentum

OAM: Correlation between parton's position and its motion
– in an averaged (or probability) sense

□ **Jaffe-Manohar's quark OAM density:**

$$\mathcal{L}_q^3 = \psi_q^\dagger \left[\vec{x} \times (-i\vec{\partial}) \right]^3 \psi_q$$

□ **Ji's quark OAM density:**

$$L_q^3 = \psi_q^\dagger \left[\vec{x} \times (-i\vec{D}) \right]^3 \psi_q$$

□ **Difference between them:**

✧ **generated by a “torque” of color Lorentz force**

$$\begin{aligned} \mathcal{L}_q^3 - L_q^3 \propto & \int \frac{dy^- d^2y_T}{(2\pi)^3} \langle P' | \bar{\psi}_q(0) \frac{\gamma^+}{2} \int_{y^-}^{\infty} dz^- \Phi(0, z^-) \\ & \times \underbrace{\sum_{i,j=1,2} [\epsilon^{3ij} y_T^i F^{+j}(z^-)]}_{\text{“Chromodynamic torque”}} \Phi(z^-, y) \psi(y) | P \rangle_{y^+=0} \end{aligned}$$

Hatta, Yoshida, Burkardt,
Meissner, Metz, Schlegel,
...

Similar color Lorentz force generates the single transverse-spin asymmetry (Qiu-Sterman function), and is also responsible for the twist-3 part of g_2

Fascination of Spin Physics with and without Breaking the Proton

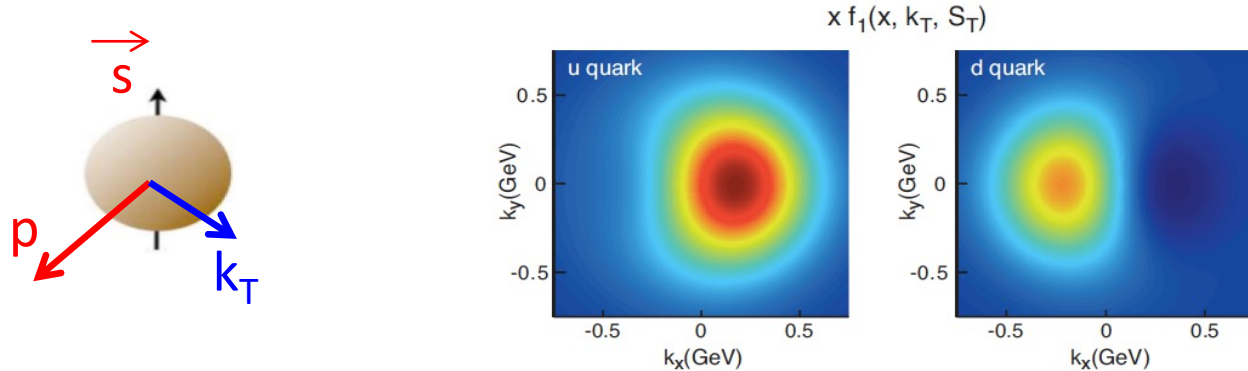
□ How do quarks/gluons + their dynamics make up the proton spin?



Hadron's response to a probe depends on the scale it is probed

Spin of quarks and gluons + their helicity distributions + their orbital contributions

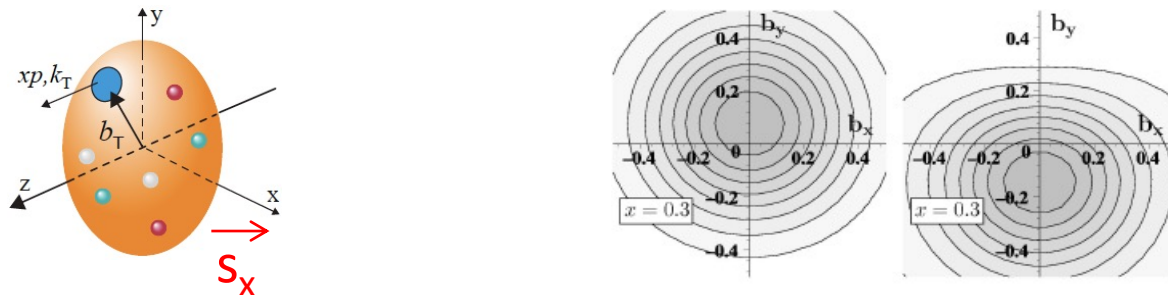
□ How is proton's spin correlated with the motion of quarks/gluons?



Deformation of parton's *confined motion* when hadron is polarized?

TMDs!

□ How does proton's spin influence the spatial distribution of partons?



Deformation of parton's *spatial distribution* when hadron is polarized?

GPDs!

+ ...

Lattice QCD Calculation of Hadron Structure

□ Hadron structure measured with a hard probe:

Probing operators living on the “light-Cone”,

$$q(x) \propto \text{F.T.} \langle P | \bar{\psi}_q(-y^-) \Gamma \Phi \psi_q(y^-) | P \rangle |_{y^+=0, y_\perp=0_\perp}$$

PDFs are boost invariant with twist-2 operators

Such matrix elements are non-perturbative, and Cannot be calculated by lattice QCD directly, because of its Euclidean space formulation

□ Quasi-PDFs approach:

$$\tilde{q}(\tilde{x}, P_z) \propto \text{F.T.} \langle P | \bar{\psi}_q(-z) \Gamma \Phi \psi_q(z) | P \rangle |_{y^0=0, y_\perp=0_\perp}$$

$$\rightarrow q(x) \text{ as } P_z \rightarrow \infty$$

Calculable in LQCD

Quasi-PDFs are NOT boost invariant, not by twist-2 operators

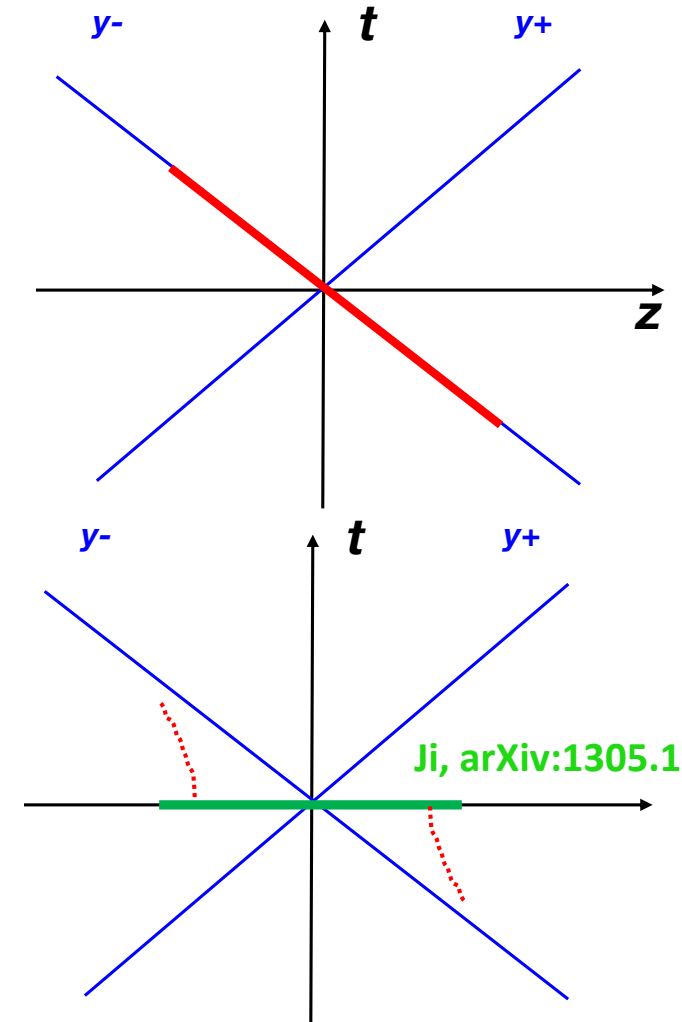
In Lattice QCD calculation, difficult to take

$$P_z \rightarrow \infty$$

Matching - Formulated in LaMET:

$$\tilde{q}(\tilde{x}, P_z) = \int_x^1 \frac{dx}{x} Z \left(\frac{\tilde{x}}{x}, \frac{\mu}{P_z} \right) q(x, \mu^2) + \mathcal{O} \left(\frac{\Lambda_{\text{QCD}}^2}{\tilde{x}^2 (1 - \tilde{x}) P_z^2}, \frac{M^2}{P_z^2} \right)$$

Extracting PDFs requires solving the inverse problem



Ji, arXiv:1305.1539

Approach to light-cone
under a boost $P_z \rightarrow \infty$

Lattice QCD Calculation of Hadron Structure

Ma and Qiu, arXiv:1404.6860
arXiv:1709.03018

Short-distance factorization approach:

- Single hadron matrix element:

$$\sigma_n(\omega, \xi^2, P^2) = \langle P | T \{ \mathcal{O}_n(\xi) \} | P \rangle$$

with Ioffe time: $\omega \equiv P \cdot \xi$, $\xi^2 \neq 0$, and $\xi_0 = 0$;

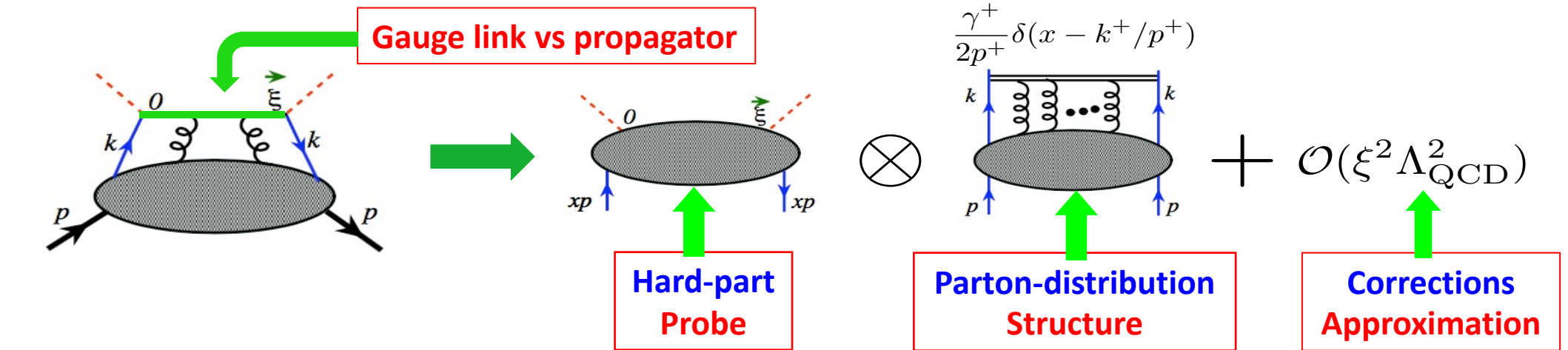
- Two-parton correlator:

$$\mathcal{O}_q(\xi) = Z_q^{-1}(\xi^2) \bar{\psi}_q(\xi) \gamma \cdot \xi \Phi(\xi, 0) \psi_q(0)$$

Same operator for quasi-PDFs $\Phi(\xi, 0) = \mathcal{P} e^{-ig \int_0^1 \xi \cdot A(\lambda \xi) d\lambda}$

- Two-current correlator:

$$\mathcal{O}_{j_1 j_2}(\xi) \equiv \xi^{d_{j_1} + d_{j_2} - 2} Z_{j_1}^{-1} Z_{j_2}^{-1} j_1(\xi) j_2(0)$$



$$\sigma_n(\omega, \xi^2, P^2) = \sum_a \int_{-1}^1 \frac{dx}{x} f_a(x, \mu^2) \times K_n^a(x\omega, \xi^2, x^2 P^2, \mu^2) + \mathcal{O}(\xi^2 \Lambda_{\text{QCD}}^2)$$

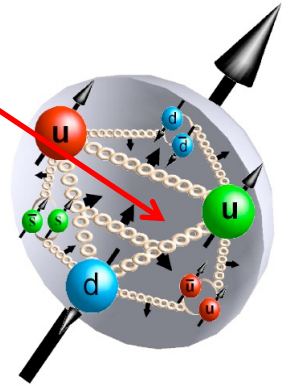
Extracting PDFs requires solving the inverse problem – global analysis with exp't data  Jefferson Lab

Summary and Outlook

- QCD has been extremely successful in interpreting and predicting high energy experimental data!
- Since the “proton spin crisis” in the 80th, RHIC Spin program has
 - not only made tremendous contributions to our knowledge of the proton spin structure,
 - but also established the fact that high energy collisions with a polarized proton beam can be precision QCD tools!
- The proton is a composite and dynamical bound system of quarks and gluons, and is a fundamental building block of all atomic nuclei and our visible world.
- Understanding the emergence of proton’s spin is a necessary task for understanding fully the QCD and strong interactions.

No “still pictures”, but quantum distributions, for hadron structure!

Probes
< 1/10 fm



Thank you!