核子自旋结构的实验研究进展

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广州 2026-7-16

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SCNT 南方核科学理论研究中心 Southern Center for Nuclear-Science Theory

Proton has structure

Nobel Prize 1943

1933 O. Stern: Magnetic moment of the proton

- expected: $\mu_p = e\hbar/2m_p c$ (since S_p =1/2)
- measured: $\mu_p = e\hbar/2m_p c(1+\kappa_p)$! *first spin crisis*

  anomalous magnetic moment (a.m.m) $\kappa_p = 1.5 \pm 10\%$

1958 R. Hofstadter: Elastic Electron Scattering

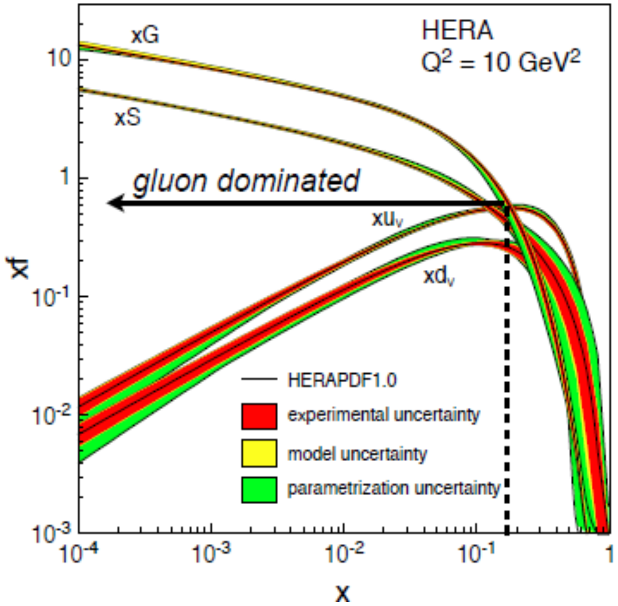
- Significant divergency from Mott cross section
- Charged radius: $(0.74\pm0.24)\times10^{-15}$ m

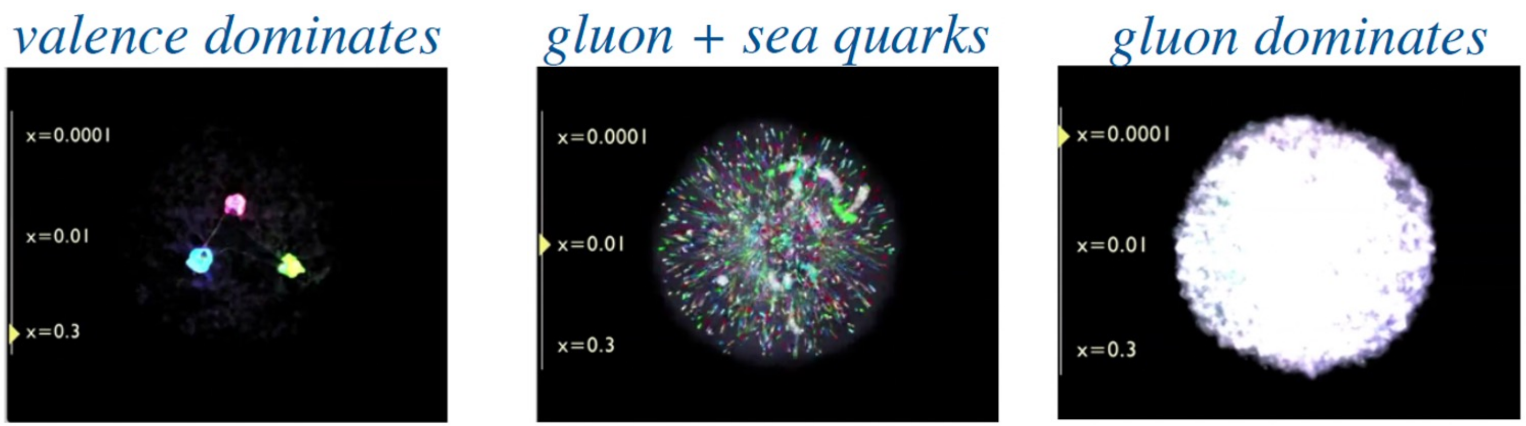
proton has internal structure

Robert Hofstadter, Nobel Prize 1961

Precise unpolarized picture

From unpolarized fixed target and collider DIS experiments





R.G. Milner and R. Ent, *Visualizing the proton* 2022

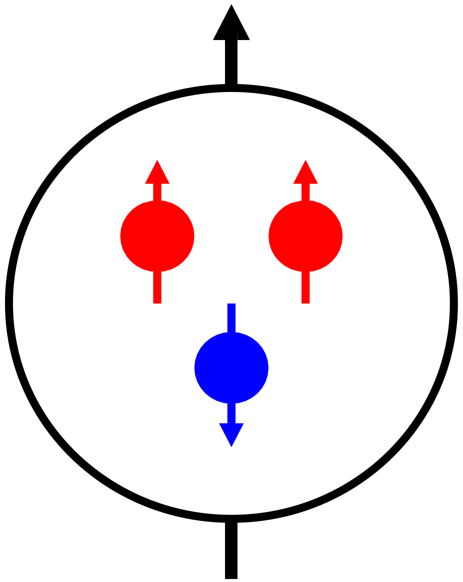
Probability of finding a quark or gluon inside the proton carrying a fraction *x* of the total momentum of the proton

- Find **more gluons** than anything else
- Gluons carry **half the momentum** of the proton

But, how do they constitute the nucleon Spin?

Proton in quark model

- The 2 up quarks and 1 down quark together explain the proton quantum numbers: charge, parity, *spin*, …
- Relativistic quark model
  - Quarks are no longer restricted to *s*-wave states
  - Quark spin accounts for ~60% of the proton spin
  - Rest of proton spin comes from quark orbital angular momentum

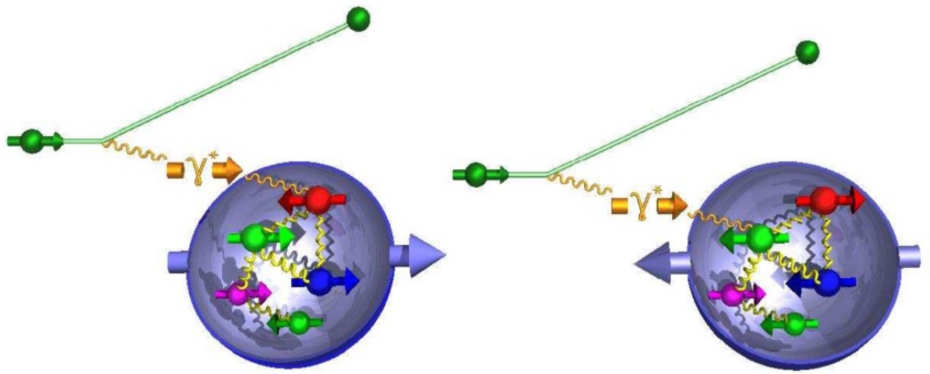


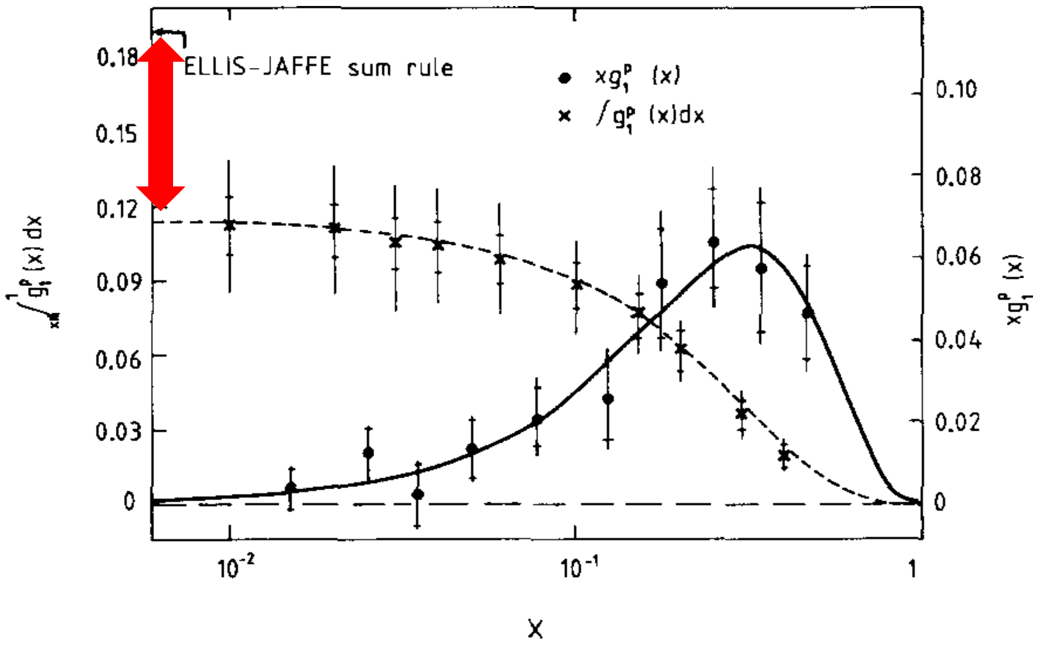
$$< S_p > = \frac{1}{2} = \frac{1}{2}\Delta\Sigma$$

Proton spin crisis

EMC, PLB 206, 364 (1988)

Deep-inelastic scattering with polarized leptons off polarized protons

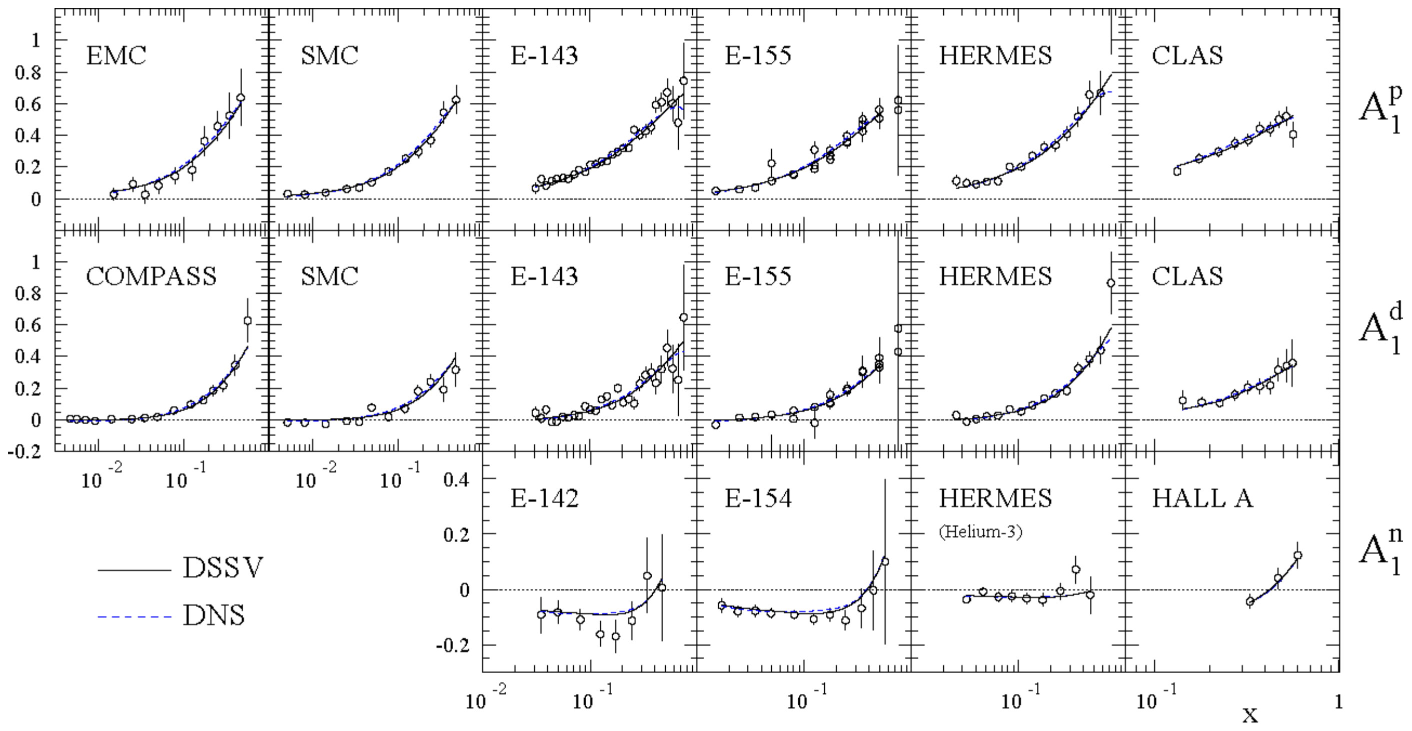


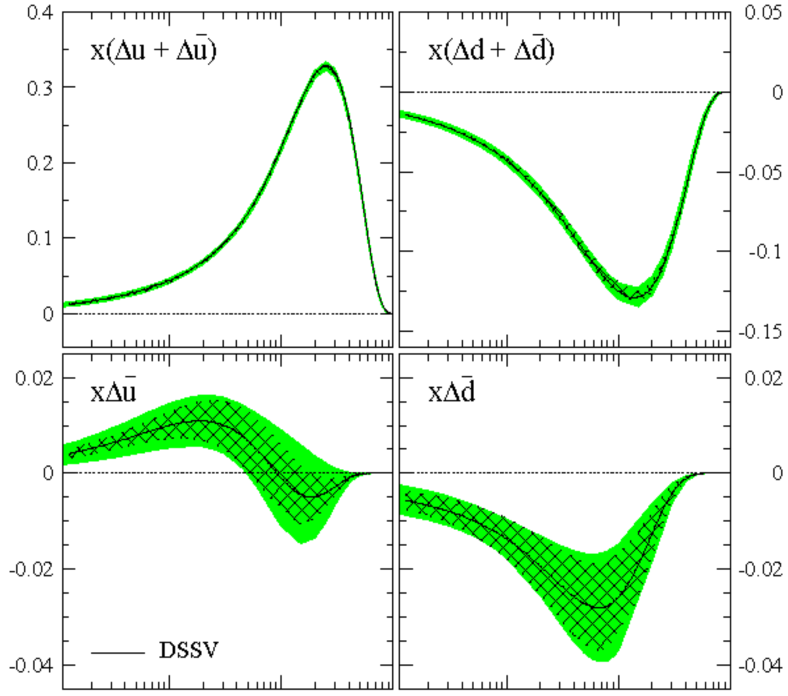


- First polarized DIS over a broad kinematic region was performed by EMC in the mid-'80s
- Found that quarks contribute only (14 ± 9 ± 21)% of the proton spin
- Many follow-up fixed target pDIS experiments, one ~25% of the proton spin arises from quarks and antiquarks

Since EMC

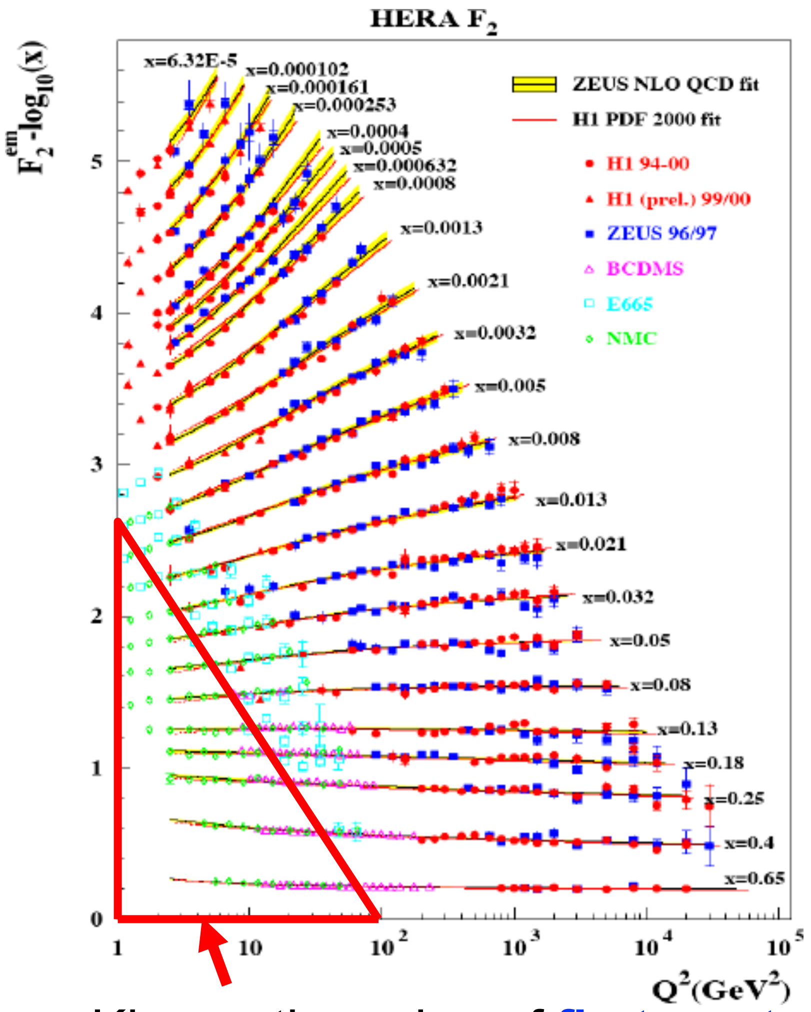
DSSV, PRD 80, 034030 (2009)





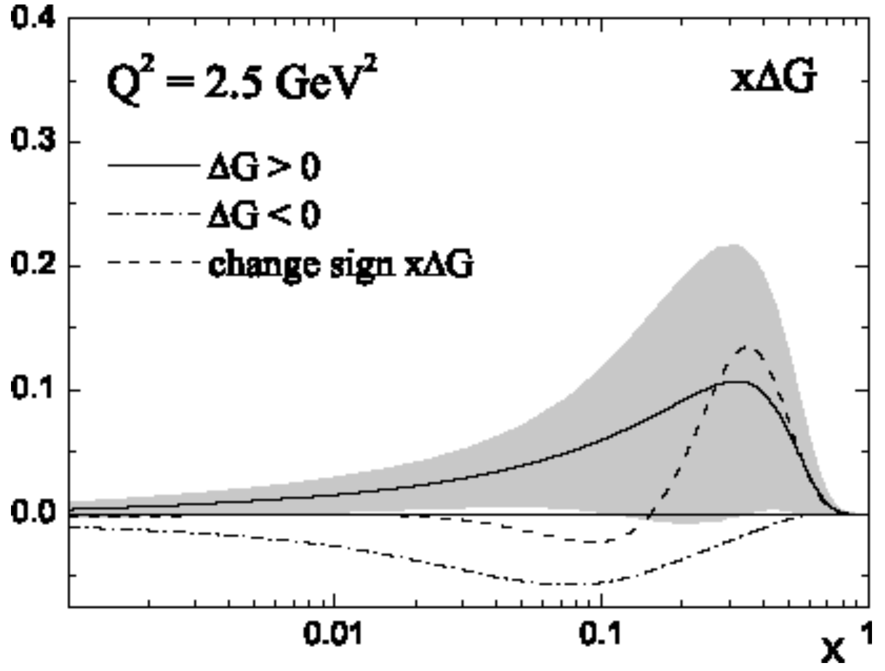
- Many subsequent measurements
- Results are well described by "global analyses" that find best-fit *polarized* PDF
- Polarization of $u + \bar{u}$ and $d + \bar{d}$ quarks well determined
  - Individual u, $\bar{u}$, d, $\bar{d}$ polarizations have much larger uncertainty
- Only **~25% of the proton spin** arises from quarks and antiquarks

What about gluons?



Kinematic region of **fix-target**
Polarized DIS measurements

Leader et al, PRD 75, 074027 (2007)



Extraction of gluon polarization needed large Q2 arm, and fixed target experiments did not allow

Limitations of fixed target DIS experiments

- Does not allow exploration of low-x region
- Extraction of gluon polarization needed large Q2 arm, and fixed target experiments did not allow that either….

  Ideally we needed a polarized e-p collider!

- In 1990's ideas to achieve high energy polarized proton beams evolved… Siberian Snake Magnets
- High energy polarized proton beam polarimetry was developed as a future need …
- Polarized HERA was proposed, but failed! EIC/EicC in the future.

Motivation of RHIC spin

If gluons really carry the bulk of nucleon’s spin, why not use polarized proton? (*known by then to be predominantly made of gluons!*)

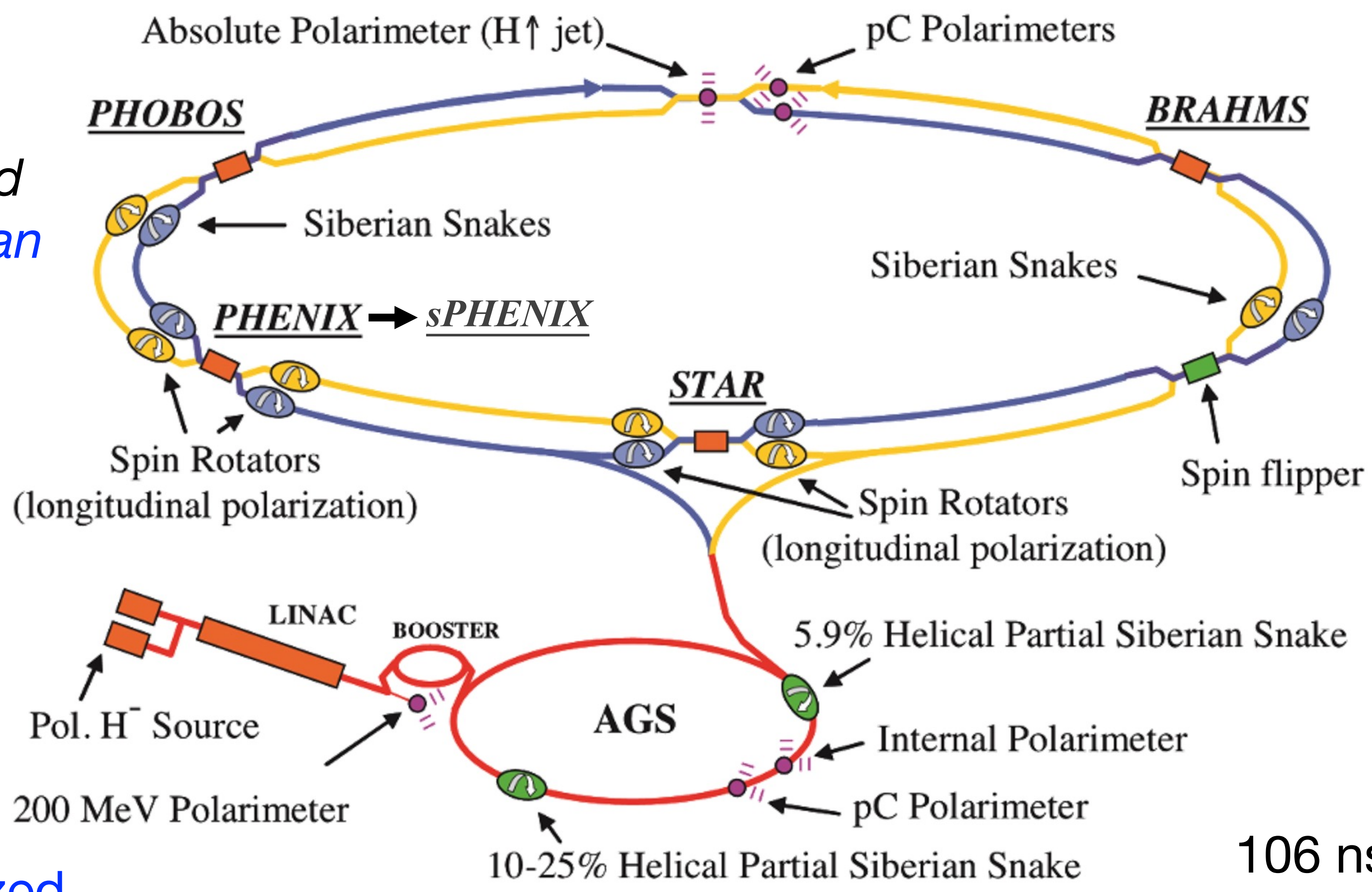
Why $\Delta\Sigma$ (quark + anti-quark’s spin) small? Are quark and antiquark spins anti-aligned? Polarized p+p at high energy, through W+/- production could address this

A severe need for investigations of the surprising transverse spin effects was naturally possible and needed with the proposed polarized p+p collider…

Polarized RHIC

Accelerate polarized protons with Siberian Snakes

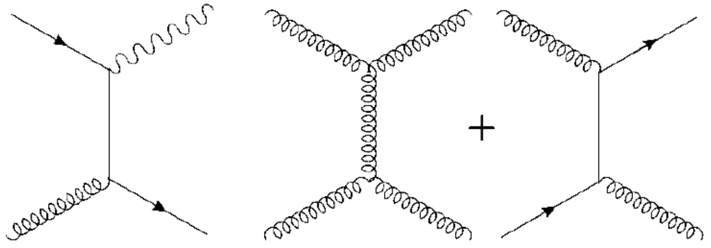
High current polarized proton source



Manipulate spin direction with spin rotator

106 ns bunch crossing with pre-determined spin directions

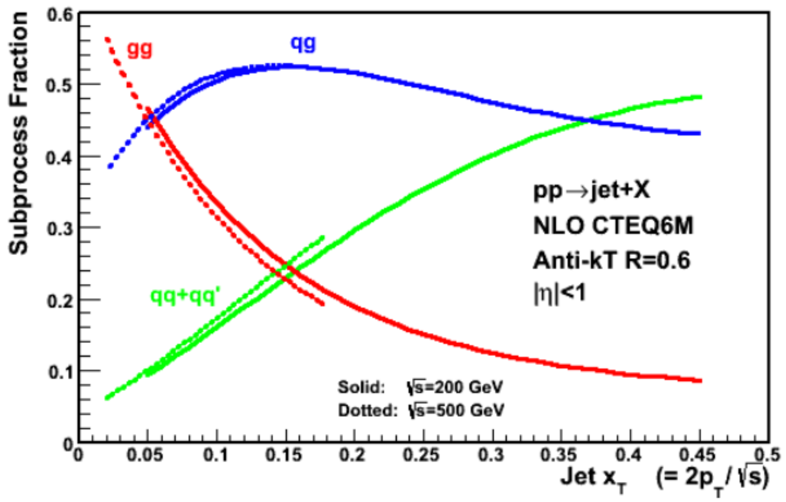
Probe gluon polarization



QCD Compton scattering

Quark-gluon, gluon-gluon elastic scattering

- Abundant yields of π and jets at RHIC
- Sub-processes directly sensitive to gluon
- $x_{g,q} \sim p_T^{\pi^0,\text{jets}} / \sqrt{s} \cdot e^{-\eta}$
- Constrain gluon helicity-dependent PDFs

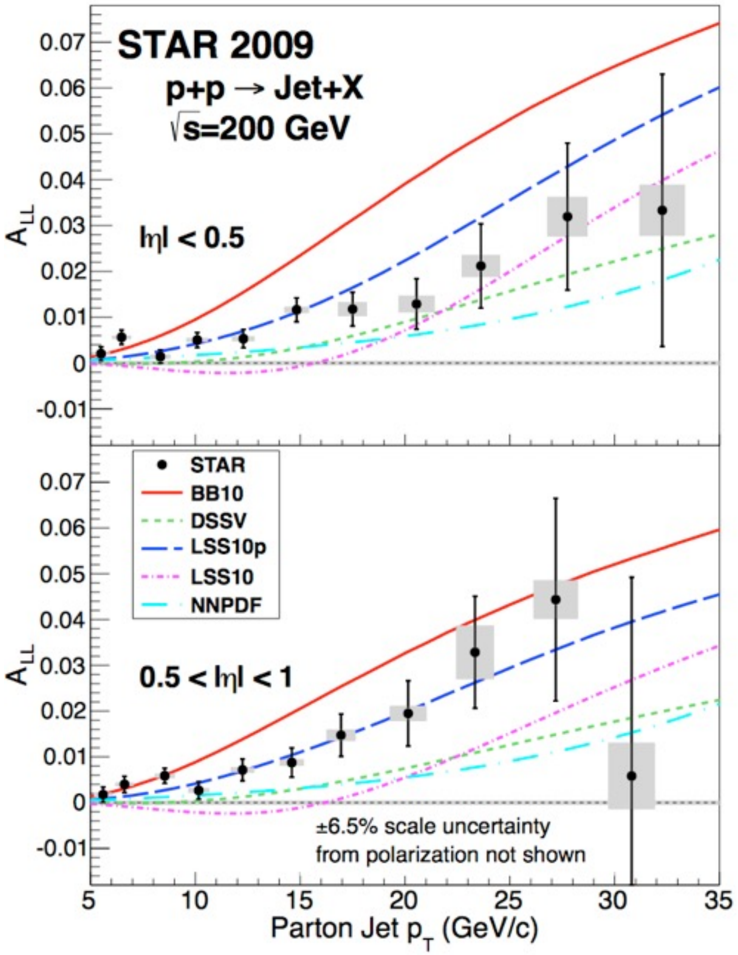


Measured double-spin asymmetry:

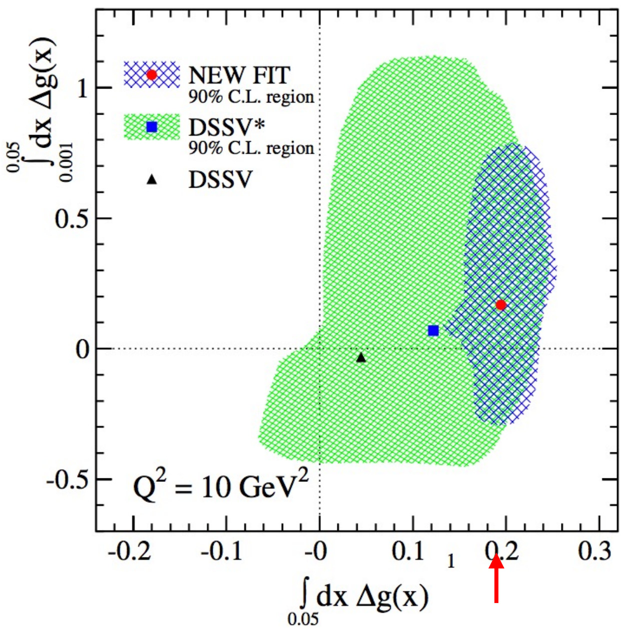
$$A_{LL} = \frac{\sigma^{\uparrow\uparrow} - \sigma^{\uparrow\downarrow}}{\sigma^{\uparrow\uparrow} + \sigma^{\uparrow\downarrow}} \propto \overbrace{\frac{\Delta f_1}{f_1} \otimes \frac{\Delta f_2}{f_2}}^{\text{probed}} \otimes \overbrace{\hat{a}_{LL} \otimes D_f^h}^{\text{inputs}}$$

Clear evidence for a positive gluon polarization

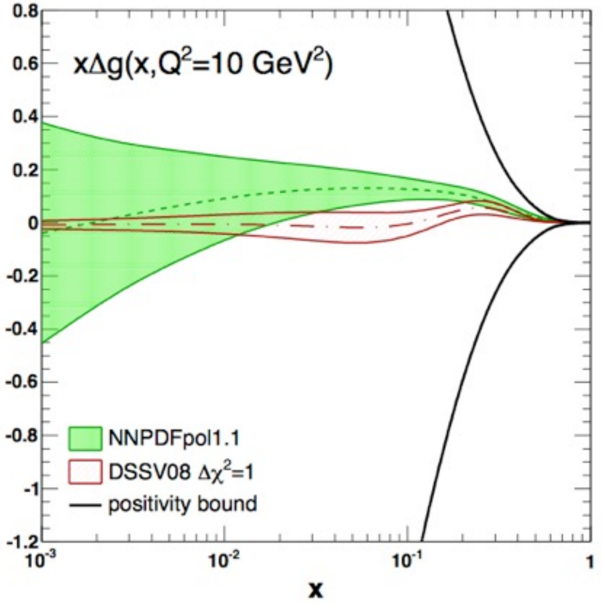
STAR, PRL115 (2015) 092002



DSSV, PRL113 (2014) 012001

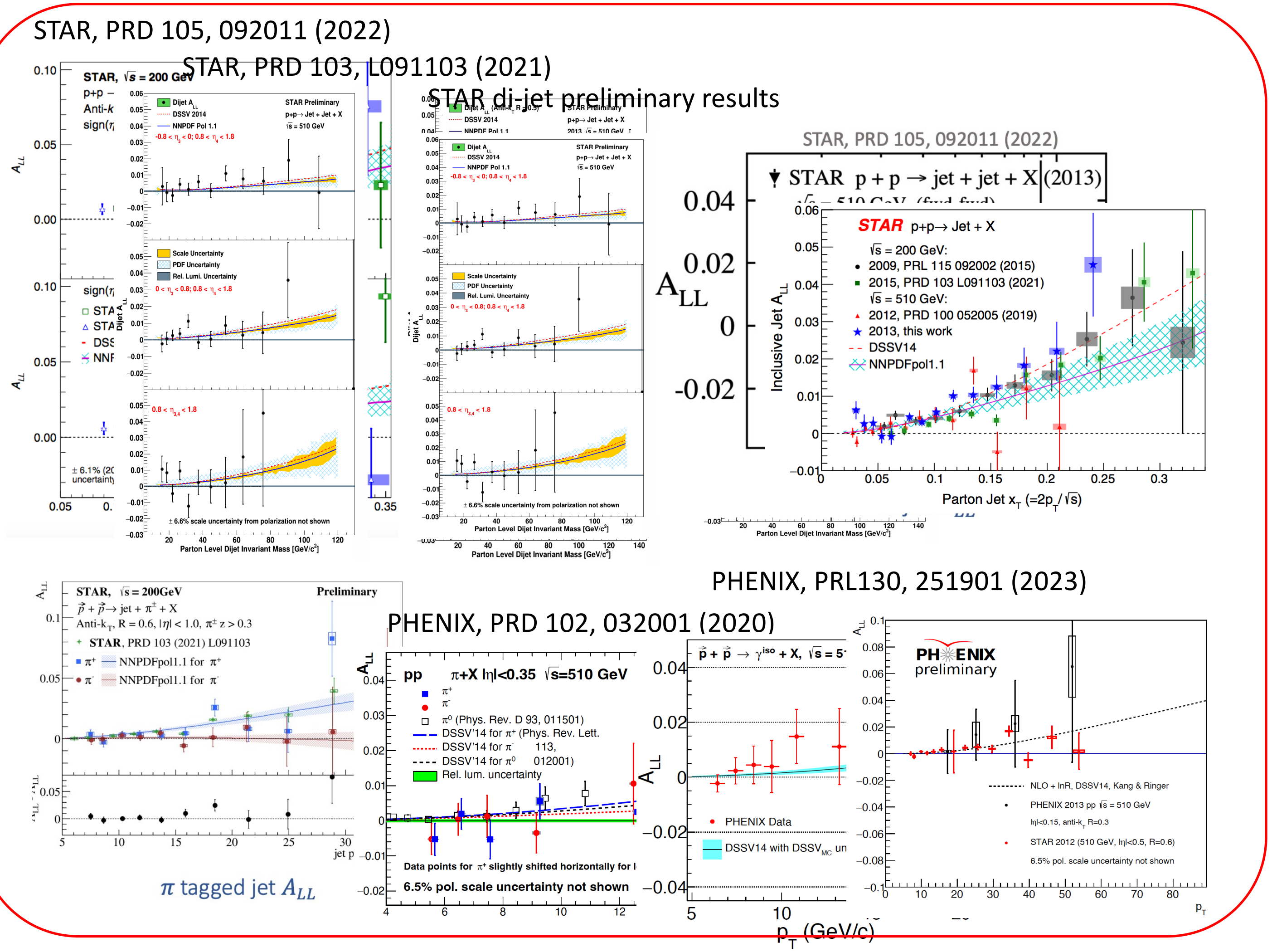


NNPDF, NPB887 (2014) 276

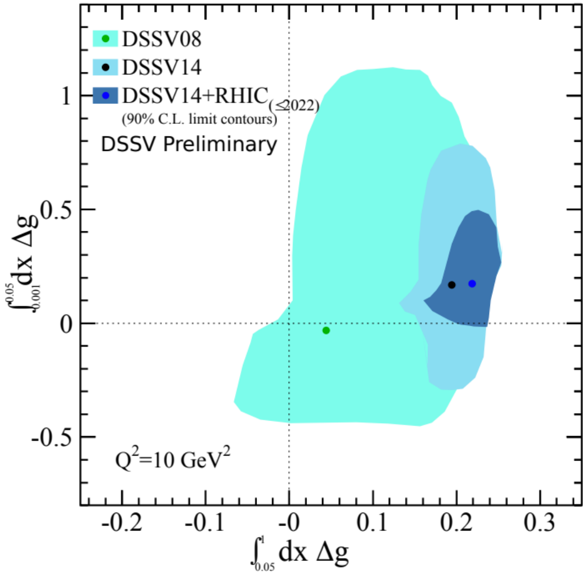


- **First evidence** of non-zero contributions from gluon spin at Q^2~10 GeV^2

Precision constraints on gluon polarization



The RHIC Cold QCD Program, White Paper, arXiv:2302.00605



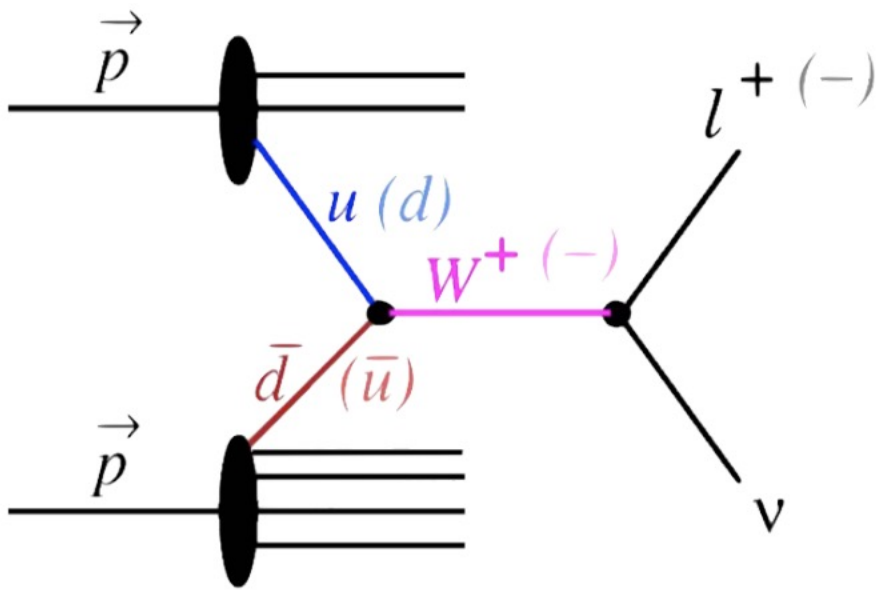
DSSV14 + RHIC (≤2022):

- $\Delta G = \int_{0.05}^{1} \Delta g(x)dx = 0.22^{+0.03}_{-0.06}$
- $\Delta G = \int_{0.001}^{0.05} \Delta g(x)dx = 0.17^{+0.33}_{-0.17}$

Flavor separation with W boson

Elegant way to study proton spin-flavor structure:

- W boson selects quarks/antiquarks with specific helicity.
- W bosons are measured via leptonic decay.

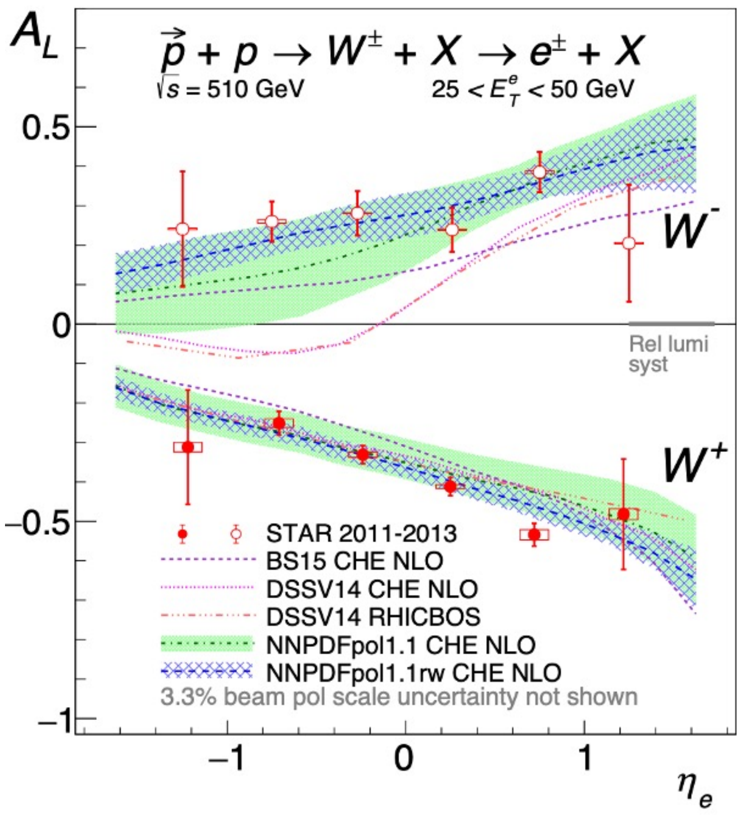


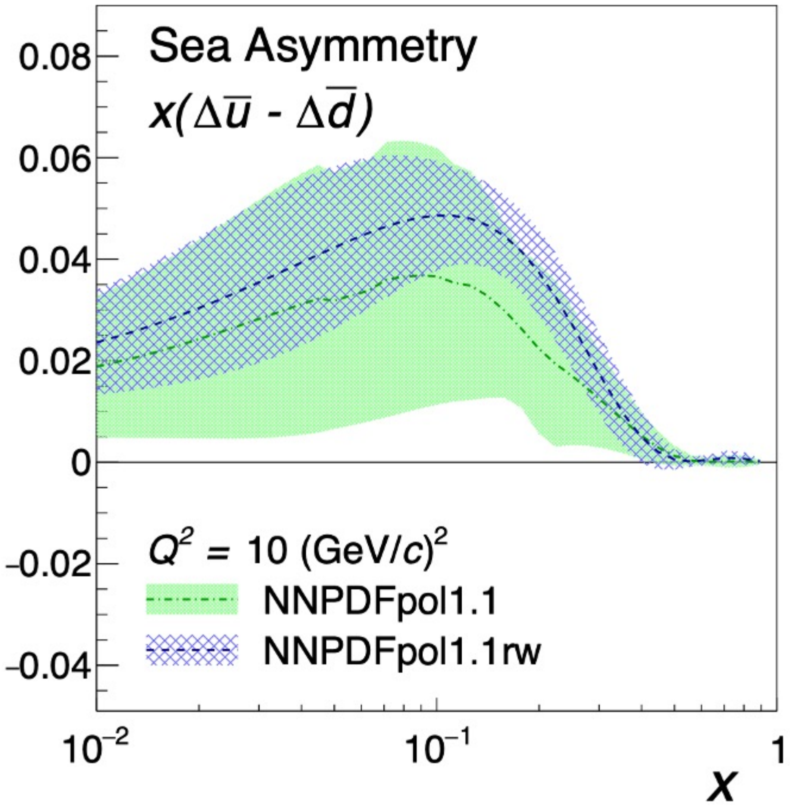
Parity violating single-spin asymmetry:

$$A_L = \frac{\sigma^+ - \sigma^-}{\sigma^+ + \sigma^-}$$

Impact of W results

STAR, PRD99, 051102(R) (2019)

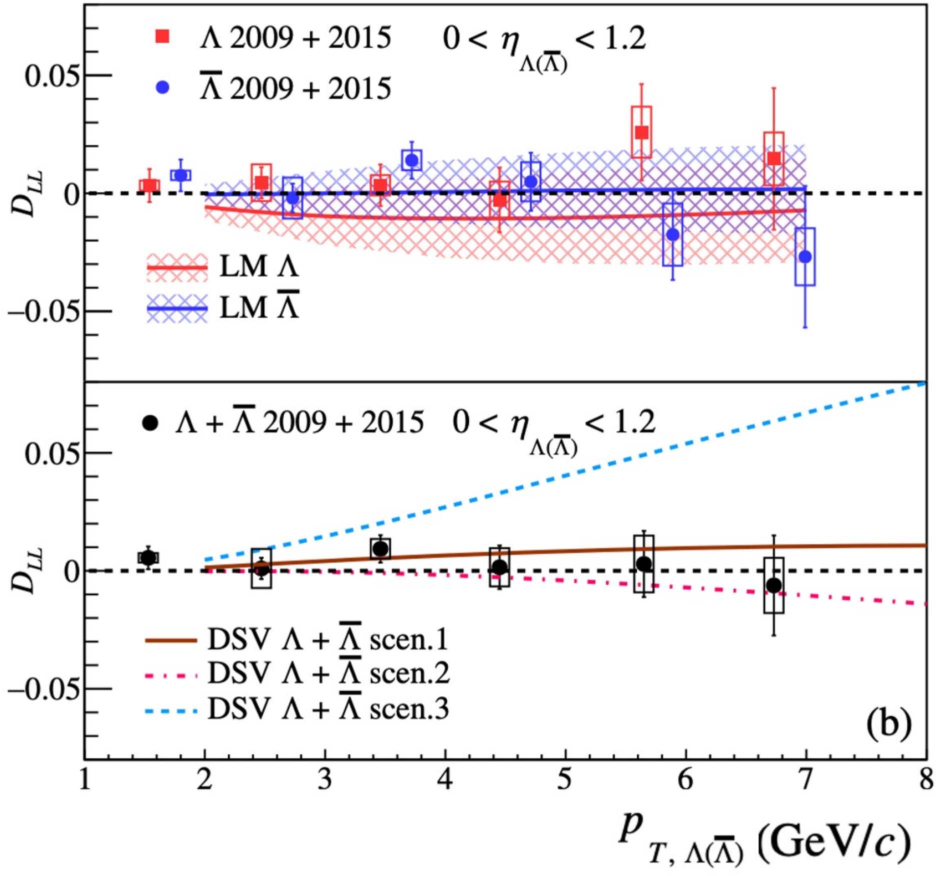




- Now we know: $\Delta\bar{u} > 0$ and $\Delta\bar{d} < 0$
- **Flavor asymmetry** $\Delta\bar{u} - \Delta\bar{d}$ similar size but opposite sign to the unpolarized case.

Strange quarks polarization via Lambda spin transfer

STAR, PRD109, 012004 (2024)



Spin transfer:

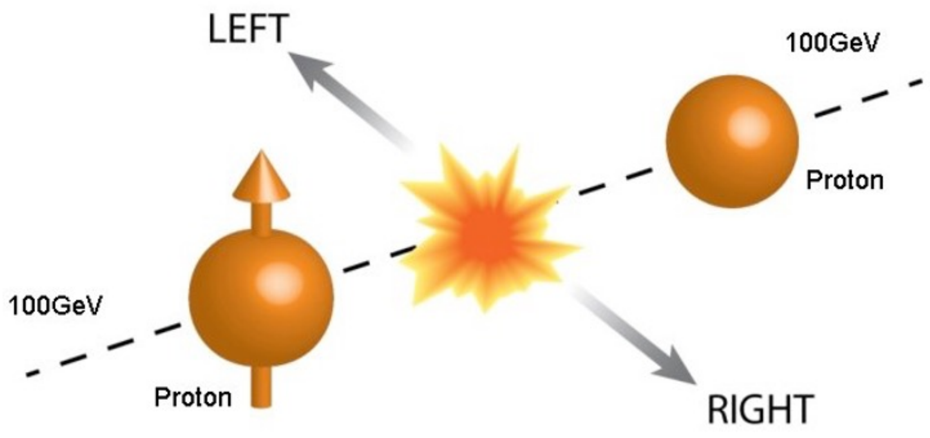
$$D_{LL}^{\Lambda} \equiv \frac{d\sigma(p^+p \to \Lambda^+ X) - d\sigma(p^+p \to \Lambda^- X)}{d\sigma(p^+p \to \Lambda^+ X) + d\sigma(p^+p \to \Lambda^- X)} = \frac{d\Delta\sigma^{\Lambda}}{d\sigma^{\Lambda}}$$

$$d\Delta\sigma^{\Lambda} = \sum \int dx_a dx_b dz \underbrace{\Delta f_a(x_a)}_{\text{Polarized PDFs}} f_b(x_b) \Delta\sigma(ab \to cd) \underbrace{\Delta D^{\Lambda}(z)}_{\text{Polarized FFs}}$$

Access polarized FFs and PDFs of strange quarks

- Final state polarization accessible via weak decay
- Lambda’s spin is expected to be carried mostly by its constituent strange quark

Another longstanding spin puzzle



Transverse single spin asymmetry:

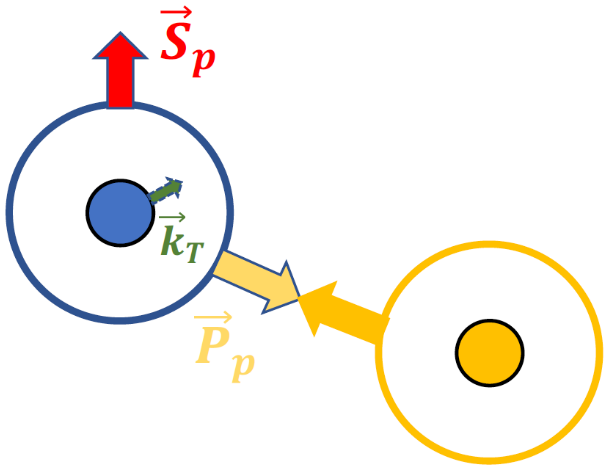
$$A_N = \frac{\sigma^{\uparrow} - \sigma^{\downarrow}}{\sigma^{\uparrow} + \sigma^{\downarrow}}$$

Transverse spin effect expected to be small at high energies…

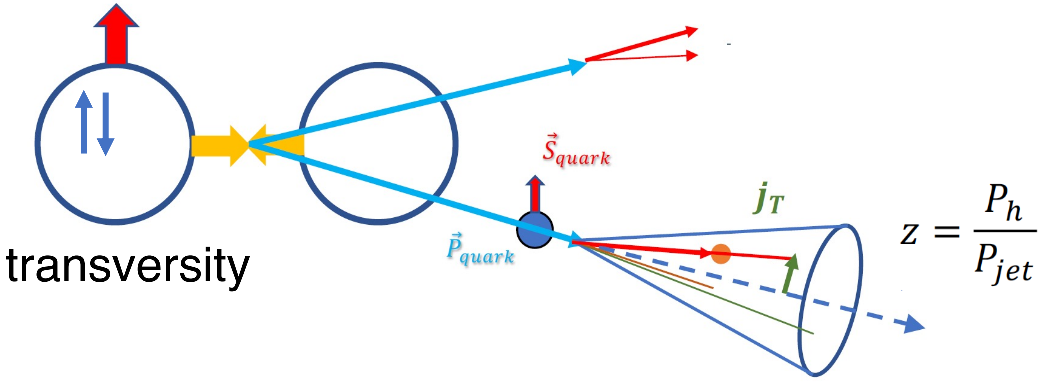
--- but FNAL came with a big surprise: it is very large!

Possible origins of puzzling TSSA

Sivers effect



Collins effect

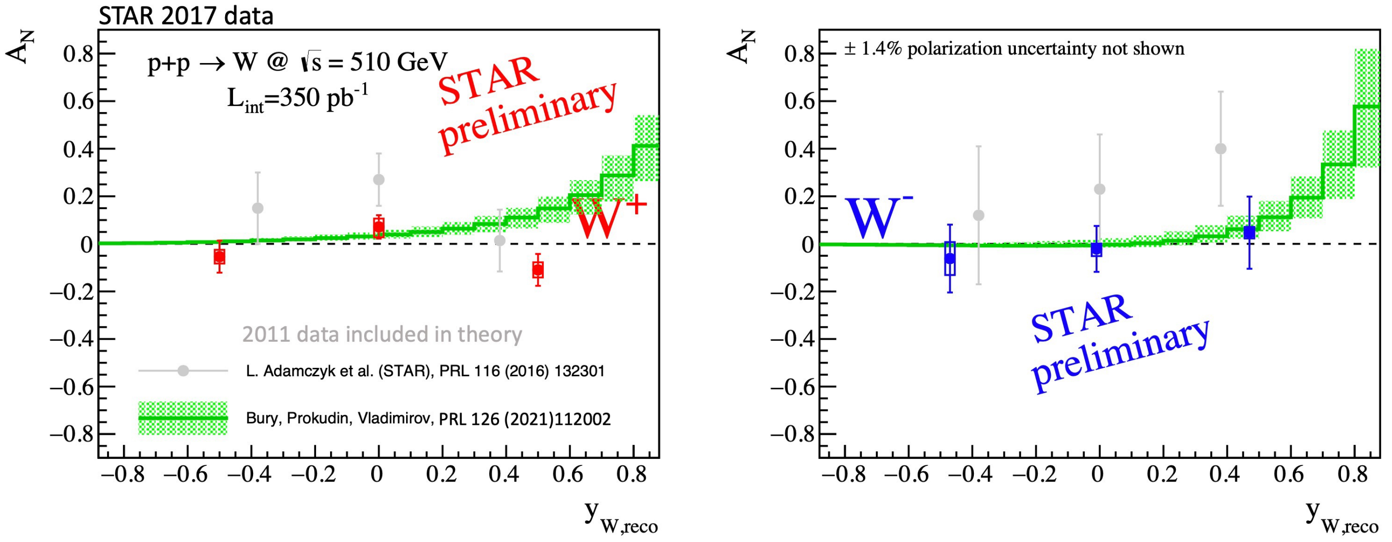


Due to transverse motion of quarks in the nucleon: initial state effect

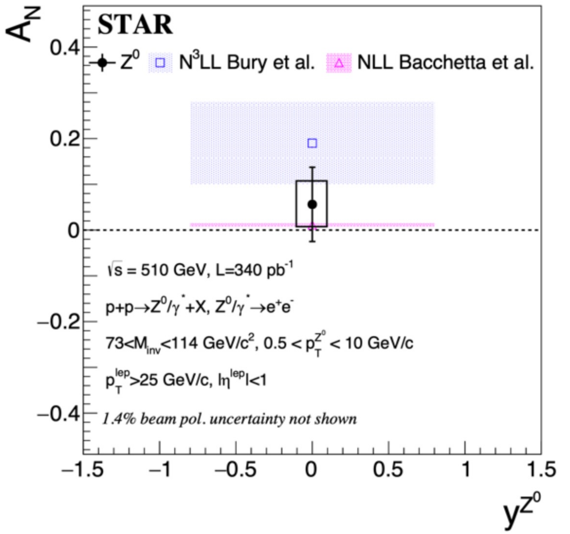
Asymmetry in the fragmentation hadrons: final state effect

Weak bosons A_N – Sivers

- Universality test of Sivers function: sign-change from DIS to DY/W/Z



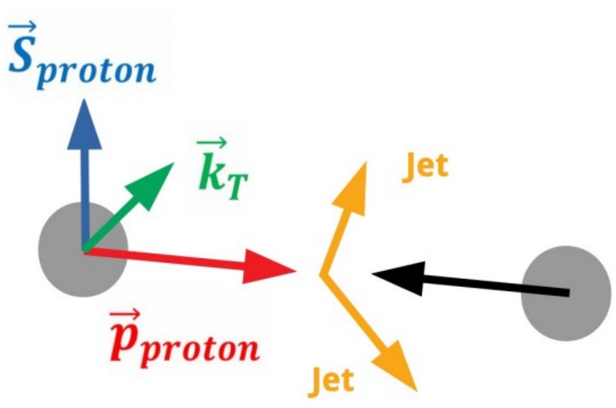
PLB 854, 138715 (2024)

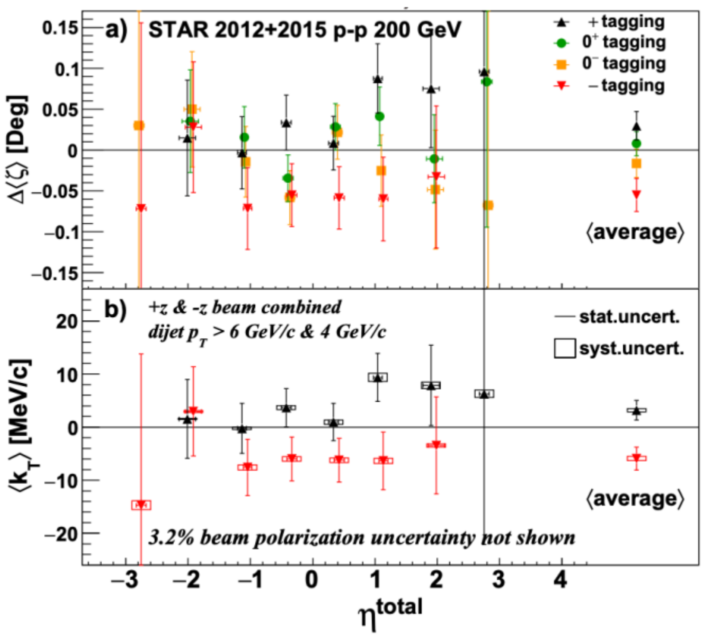


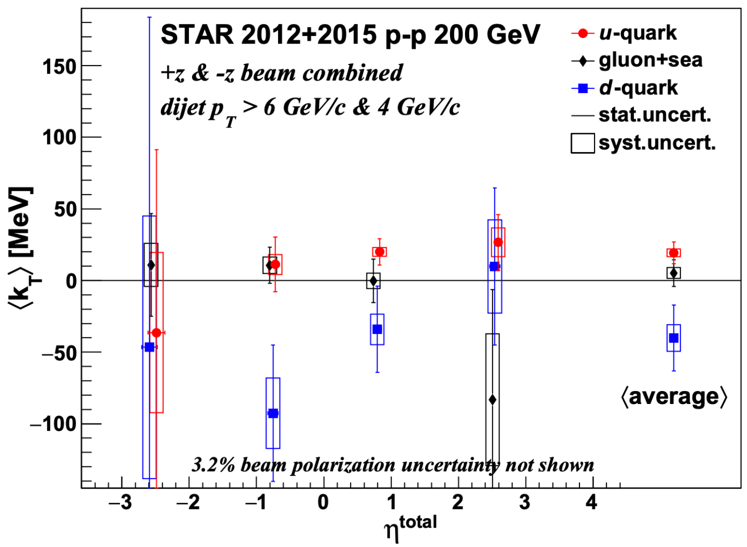
- Theoretical (PRL126,112002): extraction includes SIDIS, DY and 2011 STAR data with N3LO and NNLO accuracy of the TMD evolution *assuming sign-change*
- STAR preliminary with 2017 data with much improved precision, expect big impact in Sivers function at high-x in next global TMD fit

Dijet A_N – Sivers

arXiv: 2305.10359 (accepted by PRD Letter)



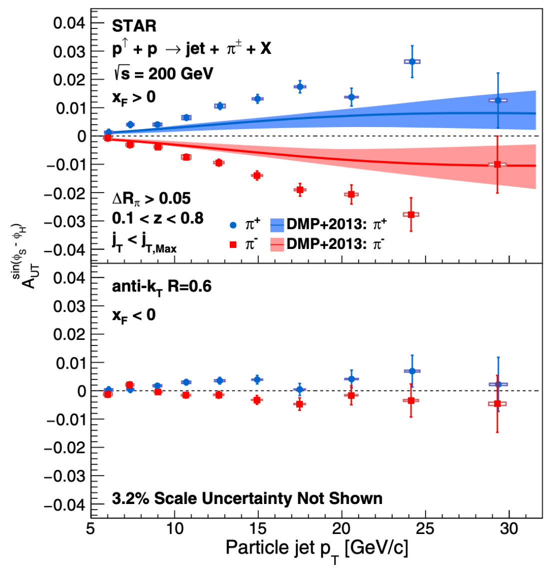


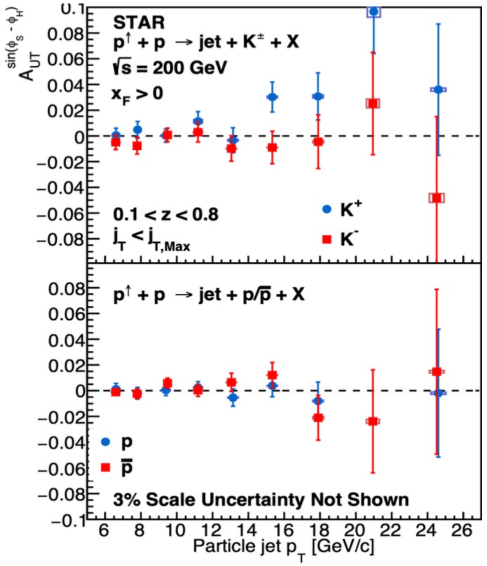


- Spin-dependent dijet opening angle sensitive to Sivers
- First observation of non-zero Sivers asymmetries in dijet production in polarized *p+p* collisions

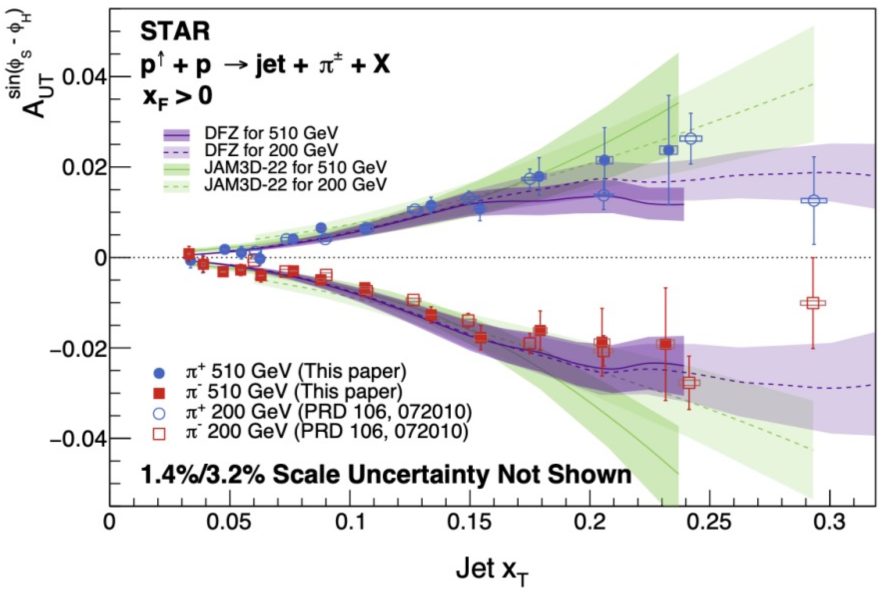
Hadron in Jet A_N – Transversity + Collins

STAR, PRD 106, 072010 (2022)





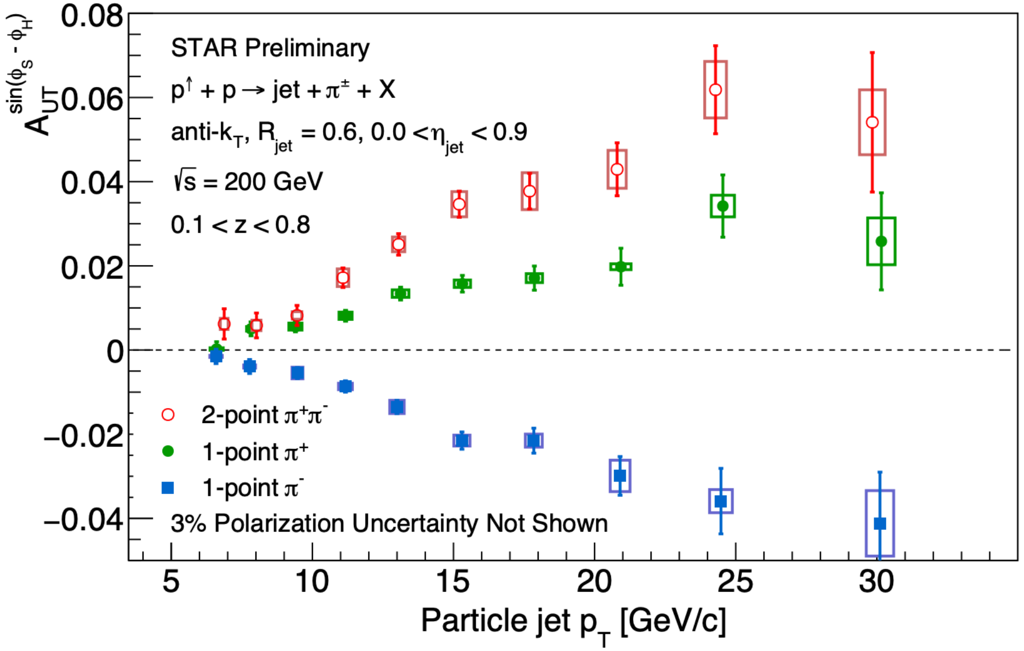
STAR, PRL 135, 261902 (2025)

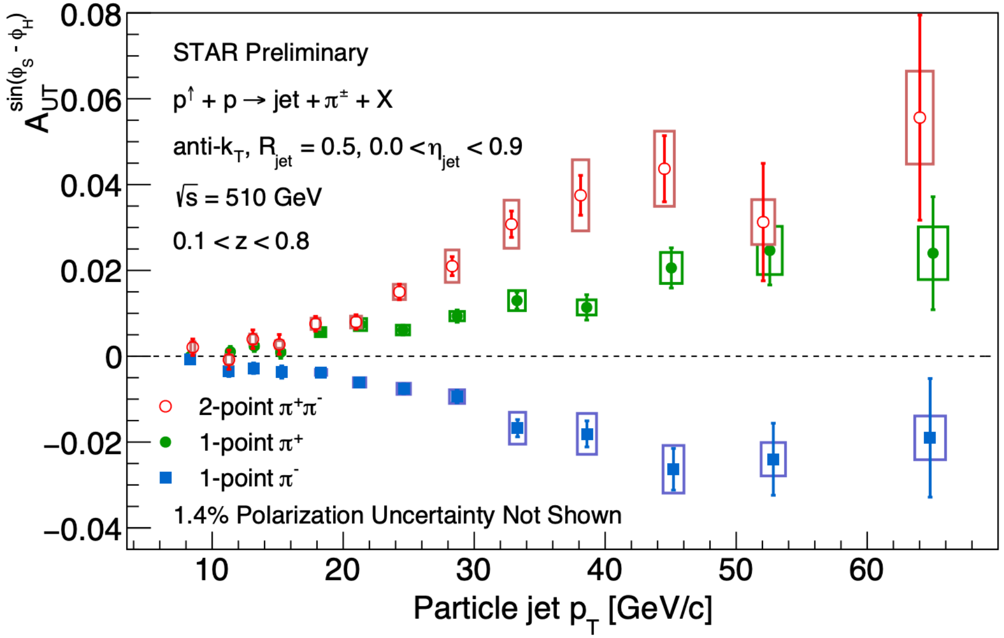


- Significant Collins asymmetries have been observed in 200 and 500 GeV
- New results show weak energy dependence and provide important constraints on the scale evolution for Collins asymmetry

Energy correlators within Jets

STAR, arXiv:2604.15543

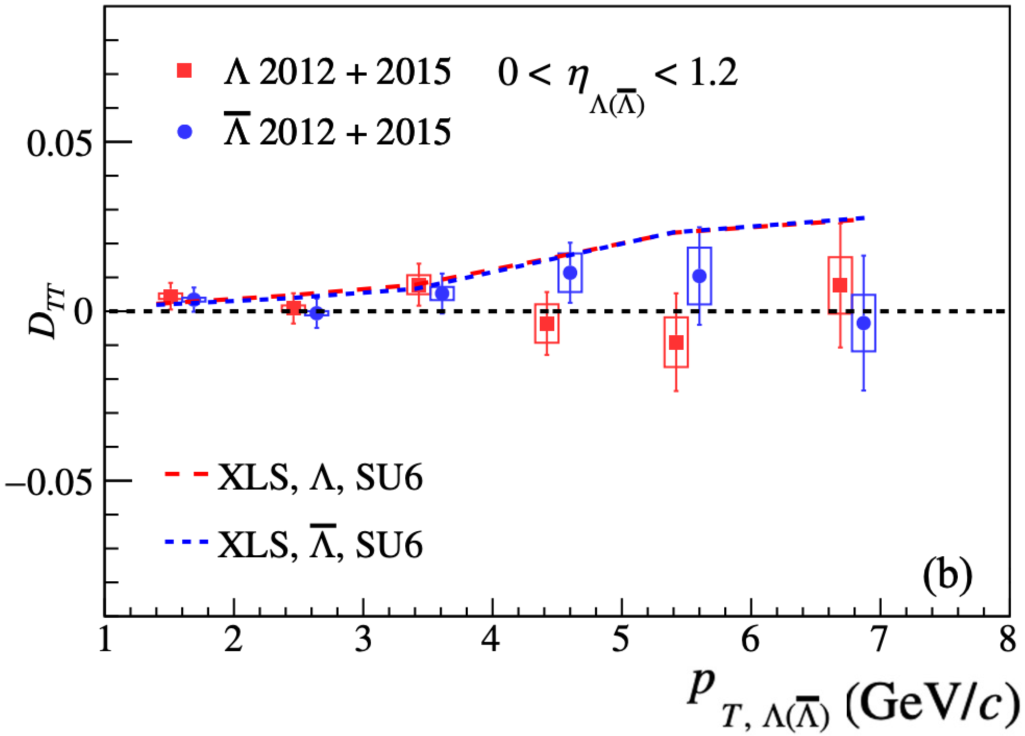




- Significant asymmetries and jet p_T dependence observed for one- and two-point EEC
- Establishes EECs as new observables for transverse spin physics

Lambda transverse spin transfer – Transversity + FFs

STAR, PRD109, 012004 (2024)



The results are consistent with model calculations within uncertainties.

Transverse spin transfer:

$$D_{TT}^{\Lambda} \equiv \frac{\sigma^{(p^\uparrow p \to \Lambda^\uparrow X)} - \sigma^{(p^\uparrow p \to \Lambda^\downarrow X)}}{\sigma^{(p^\uparrow p \to \Lambda^\uparrow X)} + \sigma^{(p^\uparrow p \to \Lambda^\downarrow X)}} = \frac{d\delta\sigma^{\Lambda}}{d\sigma^{\Lambda}}$$

$$d\delta\sigma^{\Lambda} = \sum_{abcd} \int dx_a\, dx_b dz \underbrace{\delta f_a(x_a)}_{\text{Transversity PDF}} f_b(x_b) \boxed{\delta\sigma^{(a^\uparrow b \to c^\uparrow d)}} \underbrace{\boxed{\delta D_c^{\Lambda}(z)}}_{\text{Transversity FF}}$$

Access transversity fragmentation functions (FF) and transversity distributions (PDF) of strange quarks

- Final state polarization accessible via weak decay
- Lambda's spin is expected to be carried mostly by its constituent strange quark

RHIC spin is concluding

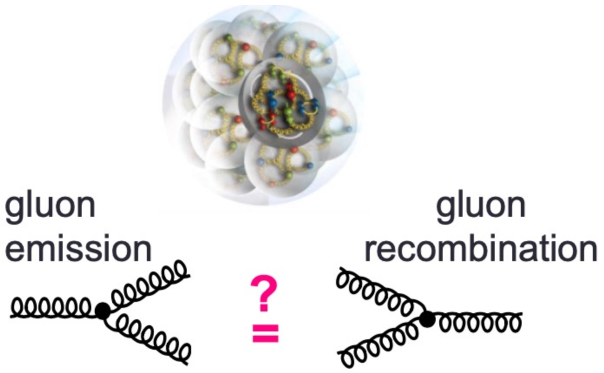
RHIC operation completed, transitioning to the construction of the US EIC

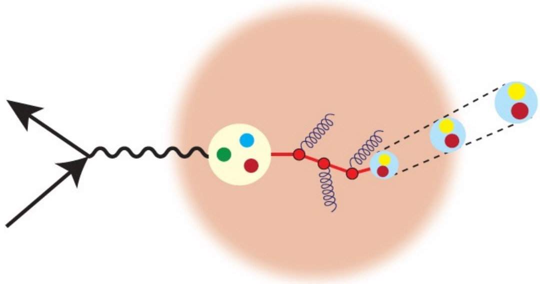
Significant contributions to three poorly constrained pieces of the proton spin puzzle

- **Gluon polarization** $\Delta G > 0$
- **Flavor-separated quark and anti-quark polarizations** $\Delta\bar{u} > \Delta\bar{d}$
- **Transverse** program in progress: existing data being published/analyzed and more data taken in 2022/2024 with forward upgrade.

Next generation: polarized Electron-ion Collider

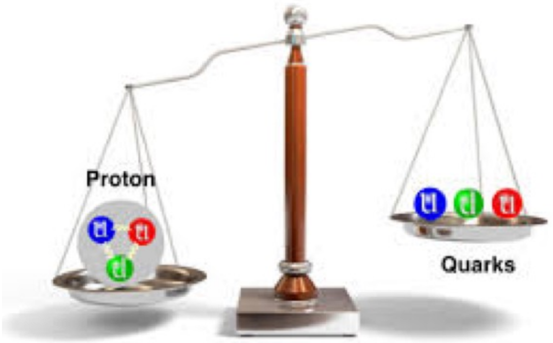
Questions expecting EIC to answer

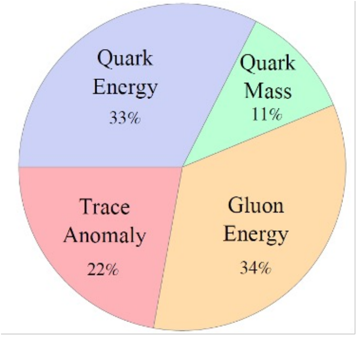


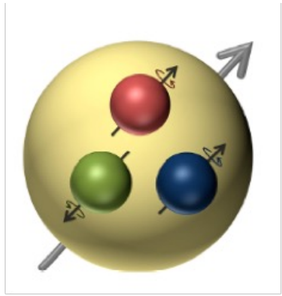


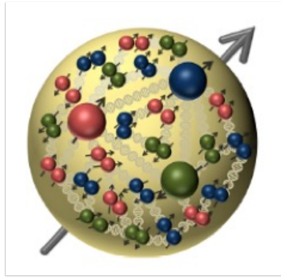
Does gluon saturate at high energy?
How does a dense nuclear environment affect the quarks and gluons, their correlations, and their interactions?

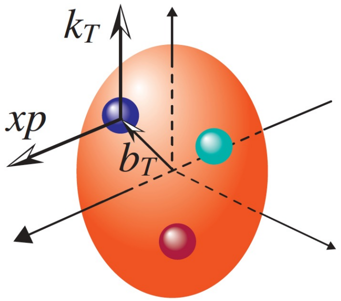
How do the nucleon properties (mass & spin) emerge from their interactions?









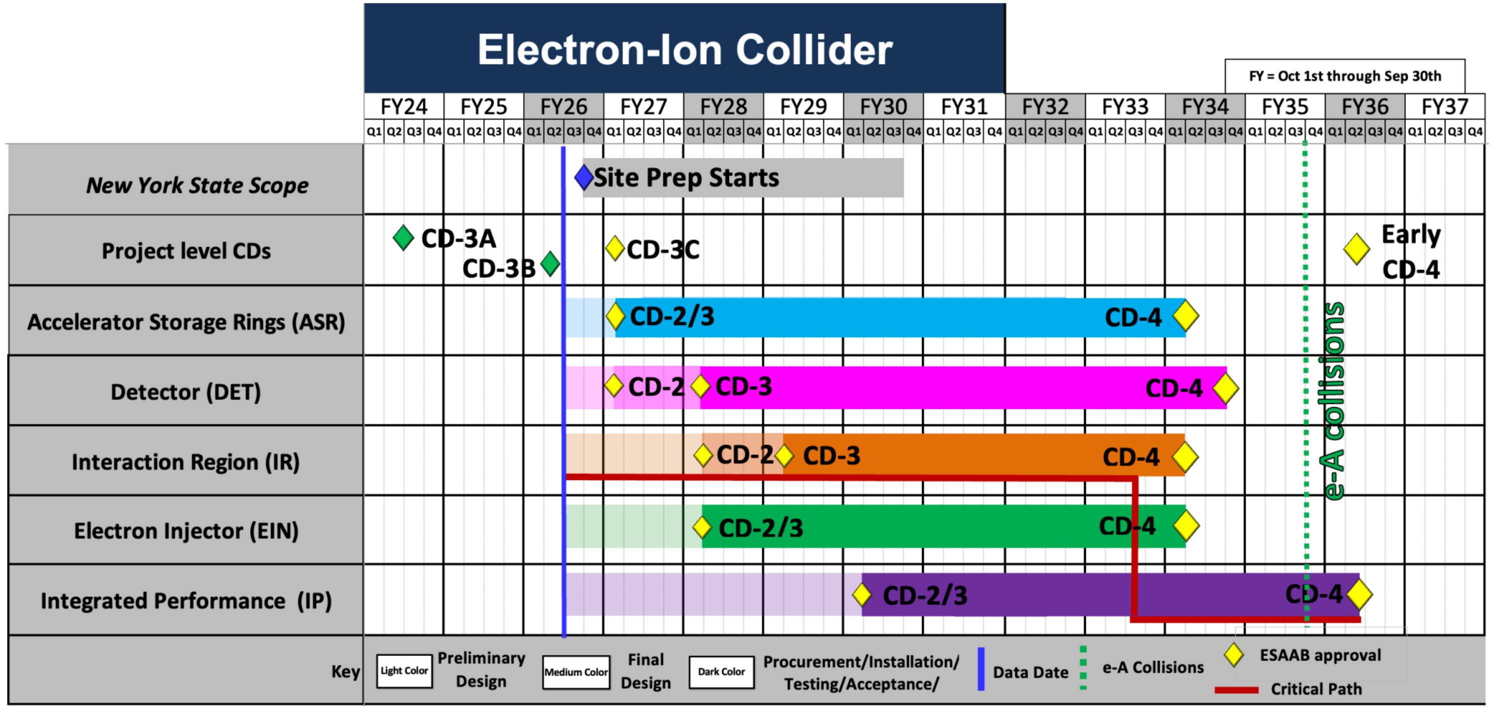


How are the sea quarks and gluons, and their spins, distributed in space and momentum inside the nucleon?

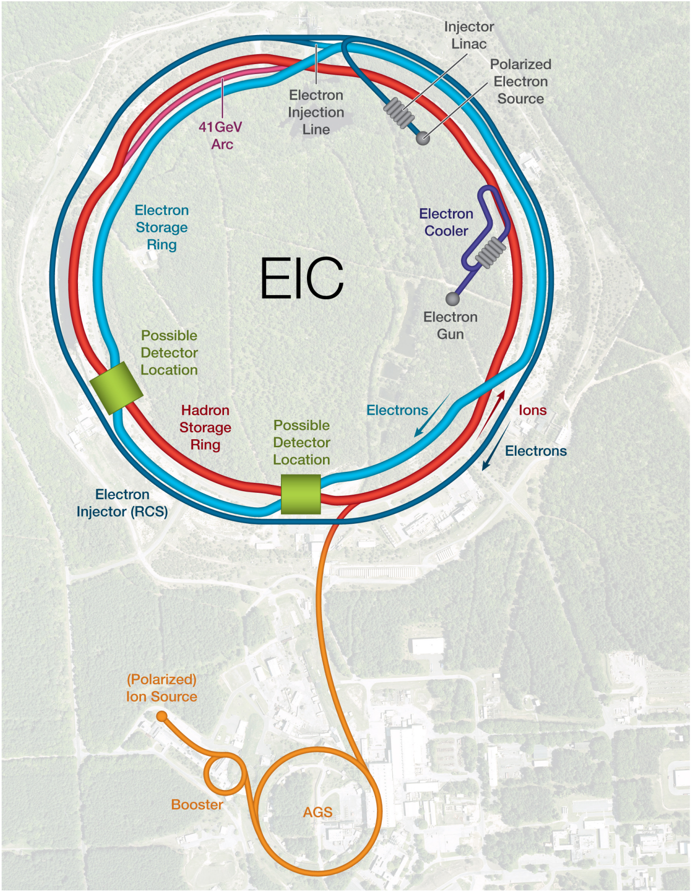
US-EIC Status

Approved in Dec 2019 (CD0)

- US EIC is based on the RHIC complex: proton/ion ring, injectors, ion sources, infrastructure
- Add a 5 to18 GeV electron storage ring and its injector complex to the RHIC facility



This is a high-level technically driven schedule – needs to be adjusted when funding profile is known

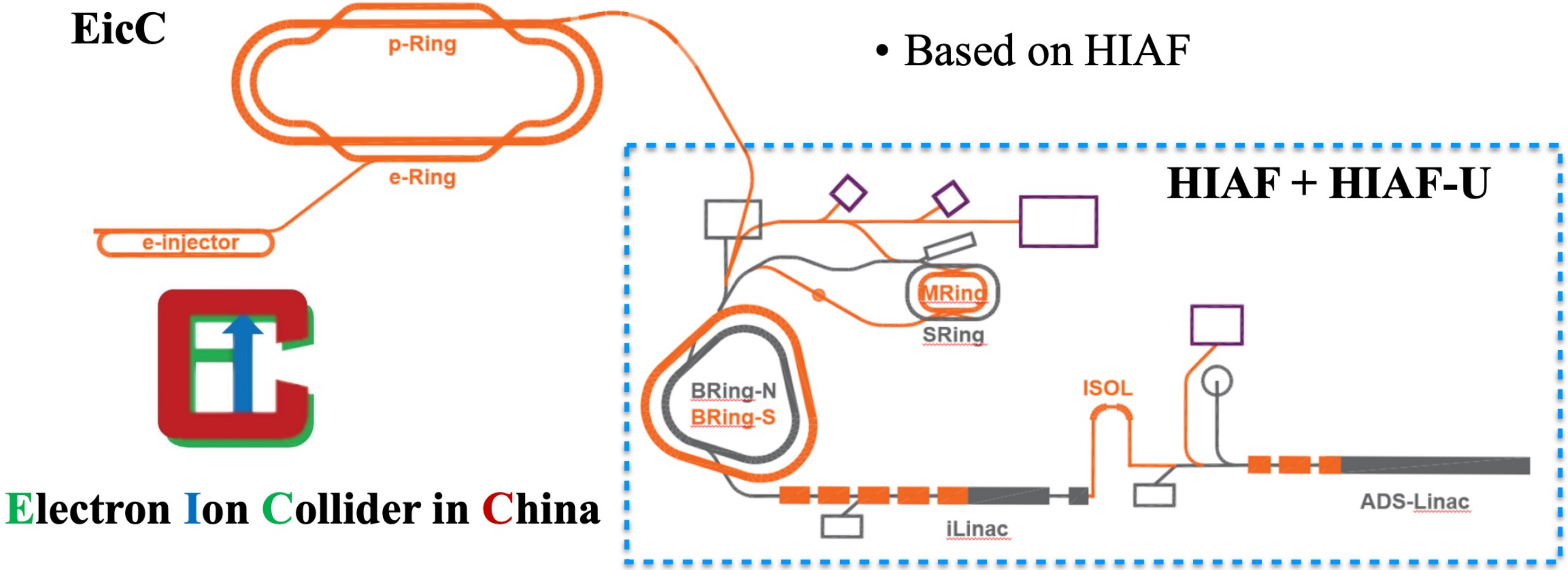


J Lajoie, DIS2026

EicC Status

中国极化电子-离子对撞机
Polarized electron ion collider in China

• Based on HIAF



[Figure by EicC Accelerator WG]

High Intensity heavy-ion Accelerator Facility in Huizhou, Guangdong province

- a national facility on nuclear physics, atomic physics, heavy-ion applications …

- beam commissioned in 2025

EicC is based on HIAF

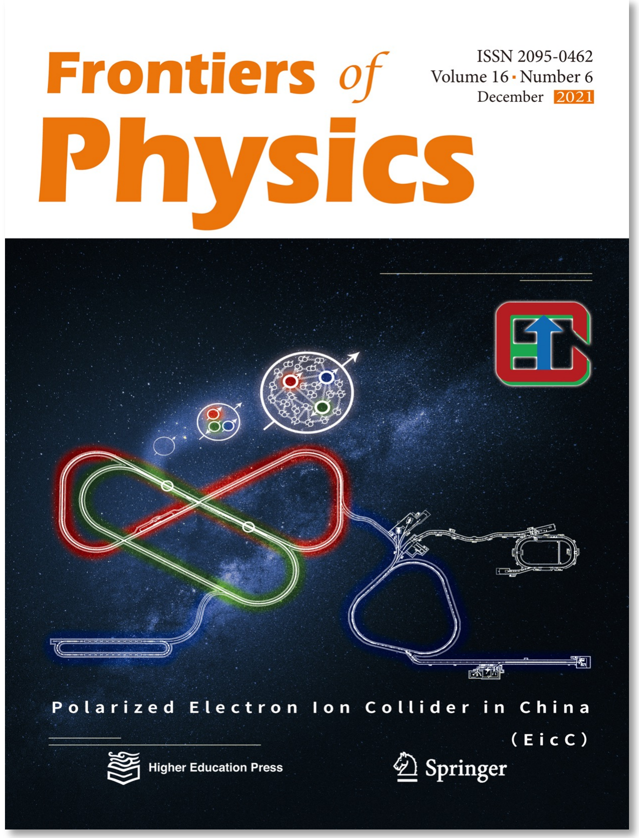
- electron: 3.5 GeV, polarization ~ 80%

- ion: p, d, ${}^{3}He^{++}$, ${}^{7}\mathrm{Li}^{3+}$, ${}^{12}\mathrm{C}^{6+}$, ${}^{40}\mathrm{Ca}^{20+}$, ${}^{197}\mathrm{Au}^{79+}$, ${}^{208}\mathrm{Pb}^{82+}$, ${}^{238}\mathrm{U}^{92+}$

EicC Status

中国极化电子-离子对撞机
Polarized electron ion collider in China

EicC white paper



Published in 2021
(Chinese version in 2020)

EicC Conceptual Design Report (CDR)

Volume I: Accelerator

Contents

Volume II: Physics and Detectors

Contents

Submitted, under review

Summary

- Polarized DIS revealed the “proton spin crisis,” showing that quark helicities account for only a limited fraction of the proton spin.
- RHIC spin measurements have constrained gluon polarization and enabled flavor-separated studies of quark and antiquark helicities.
- Transverse-spin observables provide access to spin–momentum correlations and multidimensional nucleon structure.
- Future polarized Electron–Ion Collider will greatly extend the kinematic reach and precision of nucleon spin studies.

Thank you for your attention!