XXIX Cracow EPIPHANY Conference

on Physics at the Electron-Ion Collider and Future Facilities

16-19 January 2023

Longitudinal spin structure of the nucleon: data and perspective on EIC

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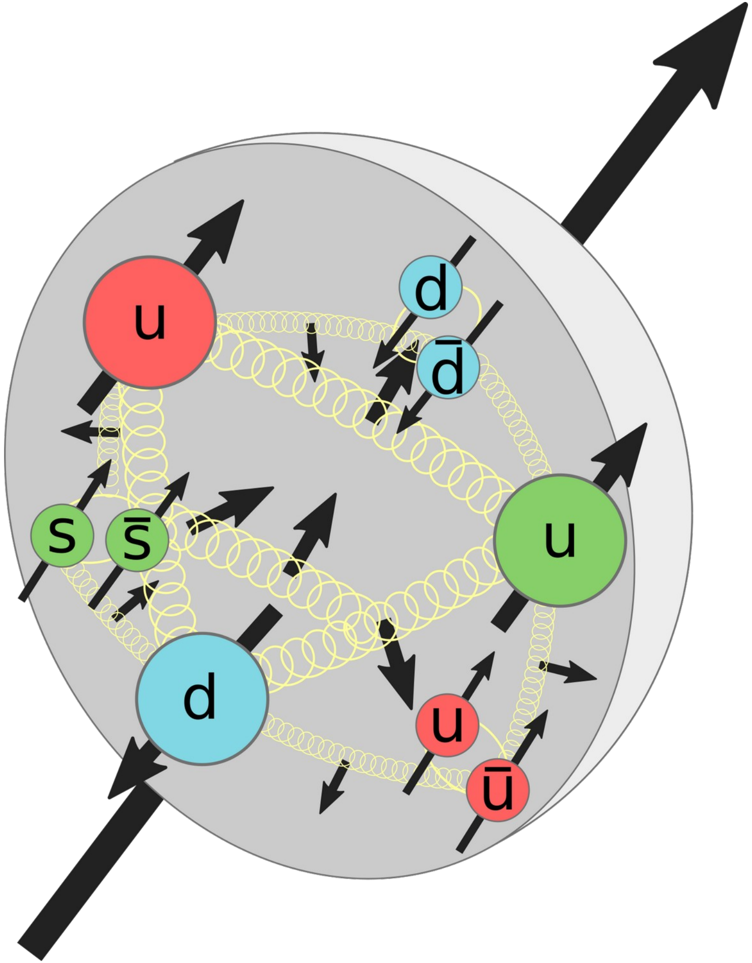
JANUARY 16-19, 2023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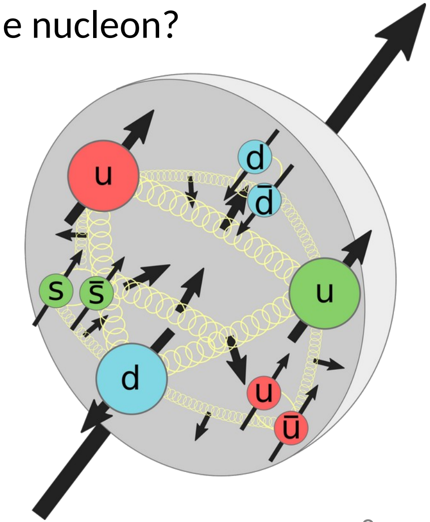
PHYSICS QUESTIONS - OUTLOOK

Questions

How does the **spin of the nucleon originate** from its **quark, anti-quark,** and **gluon** constituents and their dynamics?

1. How do **gluons** contribute to the proton spin?
2. What is the **landscape of the polarized valence quarks and quark-sea** in the nucleon?
3. What is the **spin structure of nucleon at high x**?



PHYSICS QUESTIONS

How does the **spin of the nucleon originate** from its **quark, anti-quark,** and **gluon** constituents and their dynamics?

Composition of the proton spin:

Jaffe-Manohar sum rule:

$$\Delta\Sigma/2 + \Delta G + \ell_q + \ell_g = \hbar/2$$

Quark helicity

Gluon helicity

Quark canonical orbital angular momentum

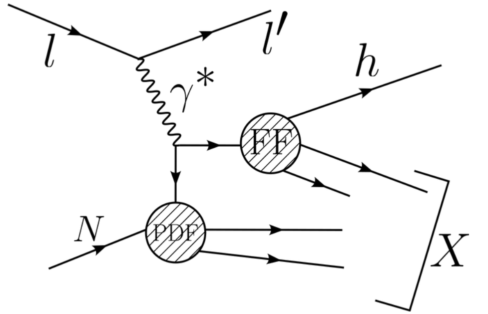
Gluon canonical orbital angular momentum

- All terms have **partonic interpretation**
- In infinite-momentum frame
- **ℓq and ℓg** (Twist-3 quantities) can be extracted **from GPDs**
- Nucl. Phys. B 337, 509–546 (1990)

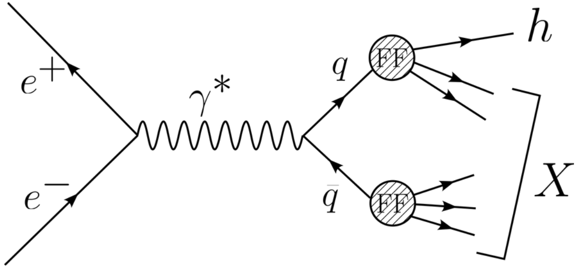
EXPERIMENTAL PROBES

How to access nucleon spin structure?

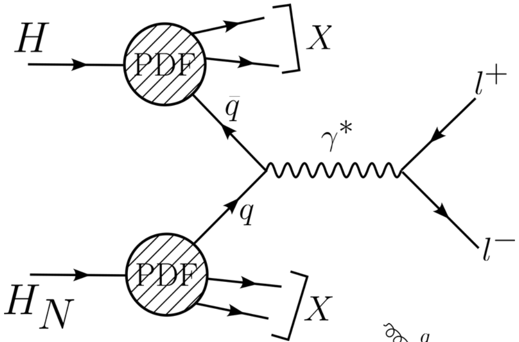
(Semi-Inclusive) Deep Inelastic Scattering

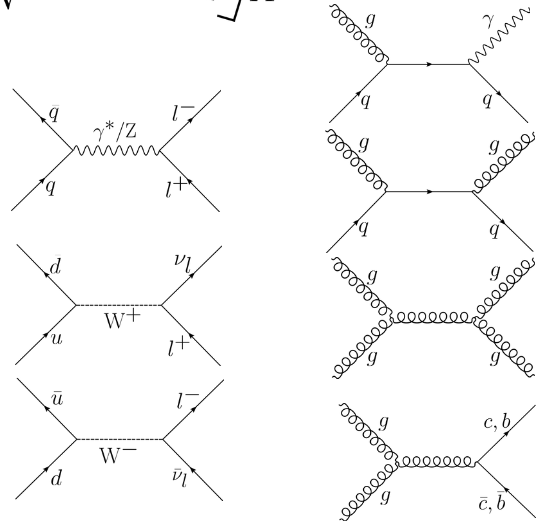


e+e- annihilation (access to FF)



Hadron-hadron interactions





LONGITUDINAL SPIN STRUCTURE

- Decades of studies in **Deep Inelastic Scattering**, as well as **Semi-Inclusive Deep Inelastic Scattering** and **proton-proton** collisions
- **Polarized DIS cross section** studied at **SLAC, CERN, DESY, JLab** encodes information about **helicity structure of quarks** inside the proton (double spin asymmetries)

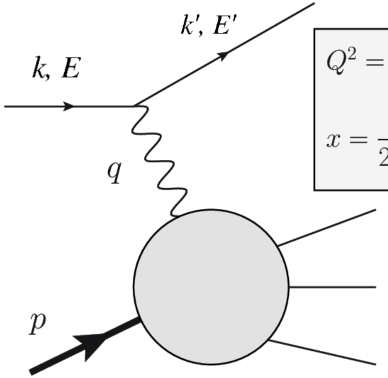
$$\frac{d^2\sigma_{LL}(x,Q^2)}{dx\,dQ^2} = \frac{8\pi\alpha^2 y}{Q^4}\left[\left(1-\frac{y}{2}-\frac{y^2}{4}\gamma^2\right)g_1(x,Q^2) - \frac{y}{2}\gamma^2 g_2(x,Q^2)\right]$$

$$\nu = E - E'$$
$$y = \nu/E,\ \gamma^2 = Q^2/\nu^2$$

$$g_1(x) = \frac{1}{2}\sum_q e_q^2\ \Delta q(x)$$

In (LO QCD) Quark Parton Model

Quark helicity distribution



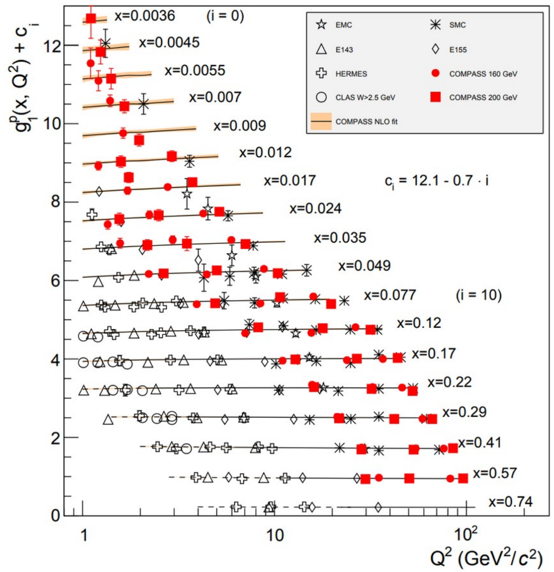
$$Q^2 = -q^2$$
$$x = \frac{Q^2}{2\,p\cdot q}$$

Experimental access through spin asymmetries

$$A_{\parallel} = \frac{\sigma_{LL}}{\sigma_{UU}} = \frac{1}{P_B P_z}\cdot\frac{\sigma^{\overset{\rightarrow}{\Leftarrow}} - \sigma^{\overset{\rightarrow}{\Rightarrow}}}{\sigma^{\overset{\rightarrow}{\Leftarrow}} + \sigma^{\overset{\rightarrow}{\Rightarrow}}}$$

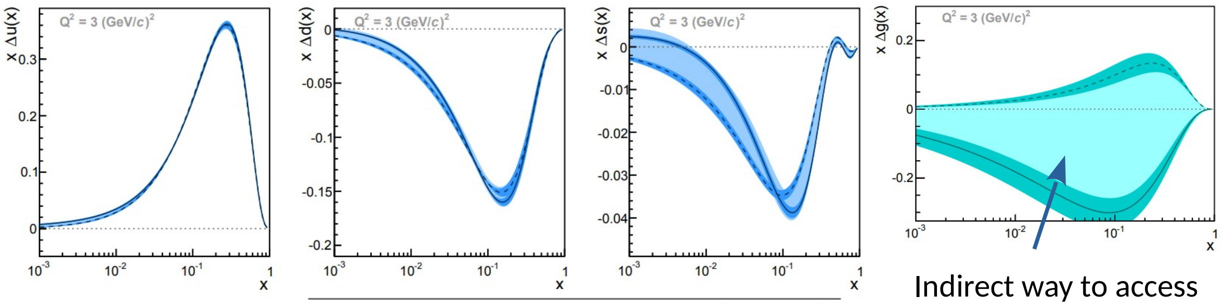
LONGITUDINAL SPIN STRUCTURE

COMPASS, PLB 753 (2016) 18



QCD fit to g_1 world data

COMPASS, PLB 753 (2016) 18

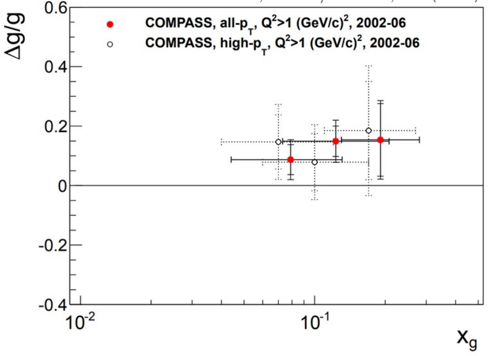


First moment	Value range at $Q^2 = 3$ (GeV/c)^2
$\Delta\Sigma$	[0.26, 0.36]

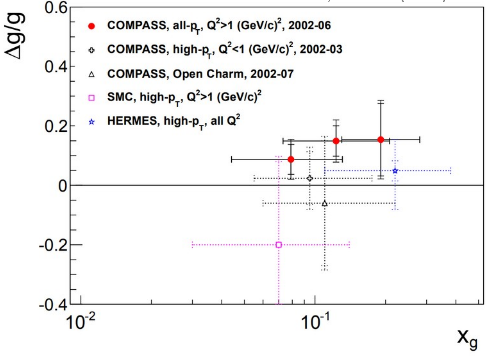
Indirect way to access gluon spin

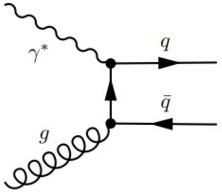
Direct access to Δg from SIDIS

COMPASS, Eur. Phys. J. C 77, 209 (2017)



COMPASS, PLB 718 (2013) 922





Photon-Gluon Fusion
Sensitive to Δg

SIDIS events with hadrons of large p_T

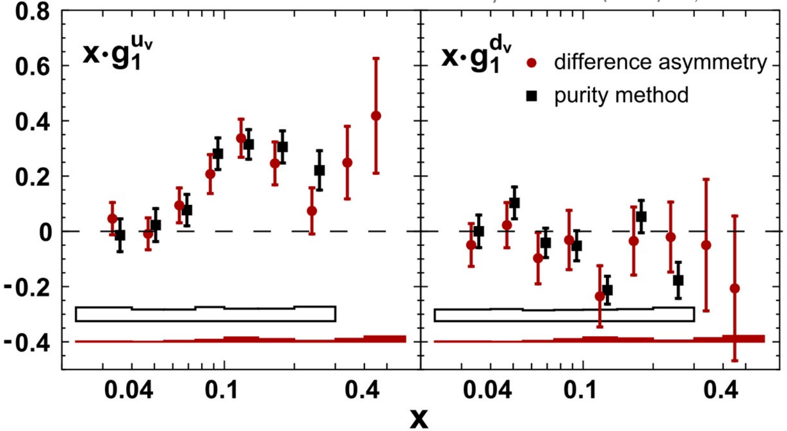
- Enhanced contribution of higher-order processes

VALENCE QUARKS HELICITY

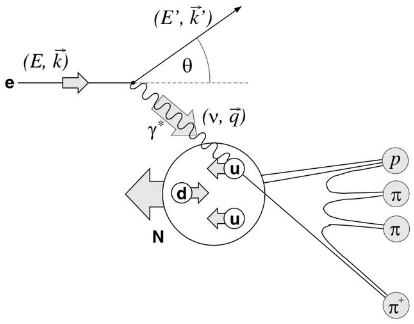
Flavor-separated valence-quark helicities from SIDIS (HERMES, COMPASS)

- Example for **final HERMES valence quark helicities** from electron and positron SIDIS with charged **pions and kaons** on **p and d targets**

Phys.Rev.D99 (2019) 11, 112001



virtual-photon-nucleon asymmetry



$$A_1^h \equiv \frac{\sigma_{1/2}^h - \sigma_{3/2}^h}{\sigma_{1/2}^h + \sigma_{3/2}^h}$$

Hadron charge-difference asymmetry: direct way to extract valence-quark helicities (depends on isospin-symmetry assumption of FF)

$$A_{1,d}^{h^+-h^-} \overset{\text{LO LT}}{=} \frac{g_1^{u_v} + g_1^{d_v}}{f_1^{u_v} + f_1^{d_v}} \qquad A_{1,p}^{h^+-h^-} \overset{\text{LO LT}}{=} \frac{4g_1^{u_v} - g_1^{d_v}}{4f_1^{u_v} - f_1^{d_v}}$$

Here g_1 - helicity

Purity method: includes conditional probability that a hadron originated from a struck quark of flavor q (depends on a fragmentation model)

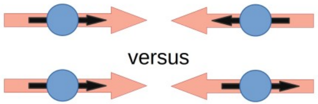
$$A_1^{\mathrm{h}}(x, Q^2, z) = \sum_q \mathcal{P}_q^{\mathrm{h}}(x, Q^2, z) \cdot \frac{\Delta q(x, Q^2)}{q(x, Q^2)}$$

Gluon Helicity

GLUON HELICITY FROM PROTON-PROTON

$$A_{LL} = \frac{\sigma_{++} - \sigma_{+-}}{\sigma_{++} + \sigma_{+-}} = \frac{\Sigma \Delta f_a \otimes \Delta f_b \otimes \hat{\sigma} a\hat{_{LL}} \otimes D}{\Sigma f_a \otimes f_b \otimes \hat{\sigma} \otimes D}$$

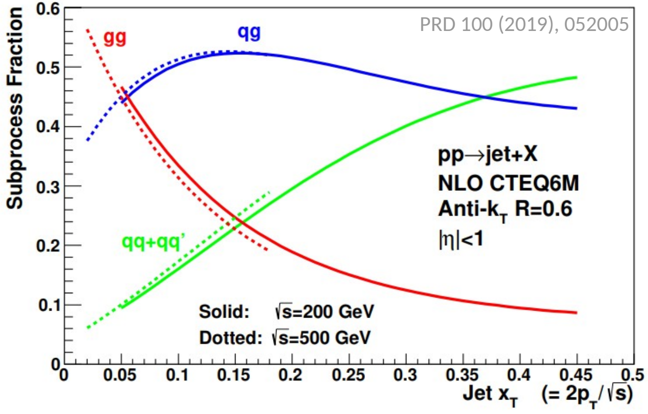
$$\vec{p} + \vec{p} \rightarrow \text{jet/dijet/hadrons} + X$$



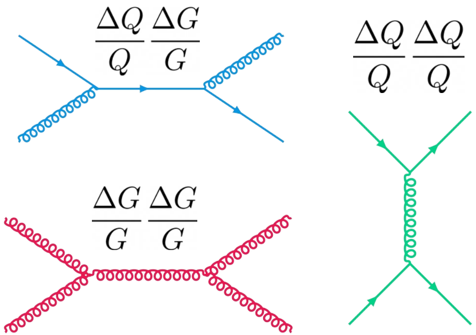
LO for illustration

- At RHIC energies: sensitivity to qg and gg – Access to **Δg(x)/g(x)**
- Cross-section measurement to support the NLO pQCD interpretation of asymmetries

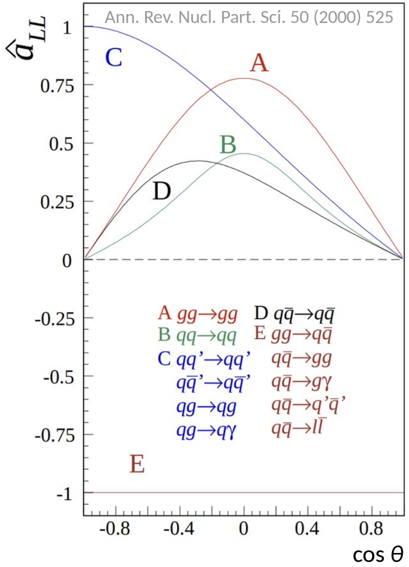
Which processes dominate at RHIC?



Subprocess fraction in central jet production



What are a_{LL} for these processes?

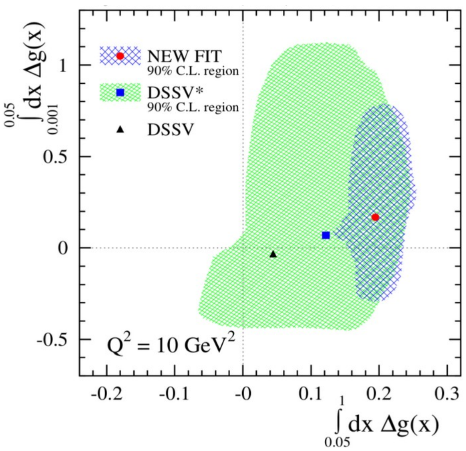


GLUON HELICITY FROM PROTON-PROTON

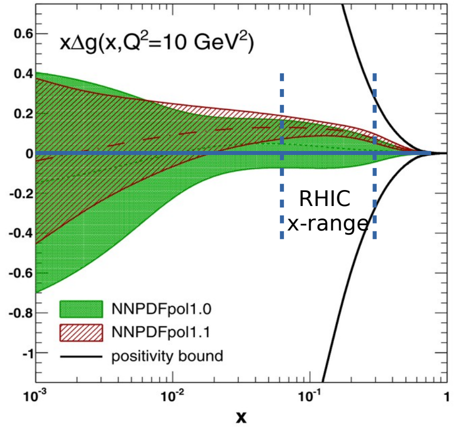
STAR inclusive jet A_{LL} from 2009 data at $\sqrt{s}$ = 200 GeV PRL 115 (2015) 9, 092002

- Included in global pQCD analysis provided evidence for **positive gluon polarization for x > 0.05 at Q^2 = 10 GeV**

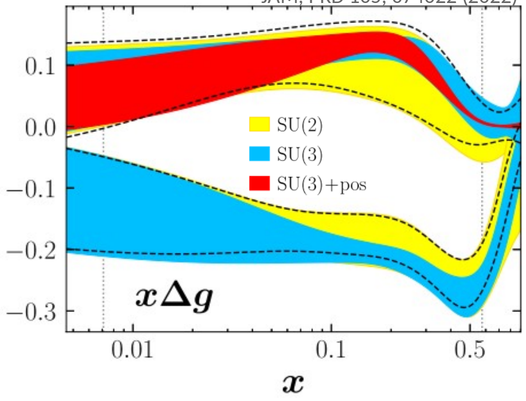
DSSV, PRL 113 (2014) 1, 012001



NNPDF, Nucl. Phys. B 887 (2014) 276



JAM, PRD 105, 074022 (2022)



$$\mathbf{SU(3) + pos}: \ 0.25 \pm 0.03 \qquad x > 0.05$$

$$\text{DSSV:} \quad 0.20^{+0.06}_{-0.05}, \quad \text{at } 90\% \text{ C.L.}\ , x > 0.05$$

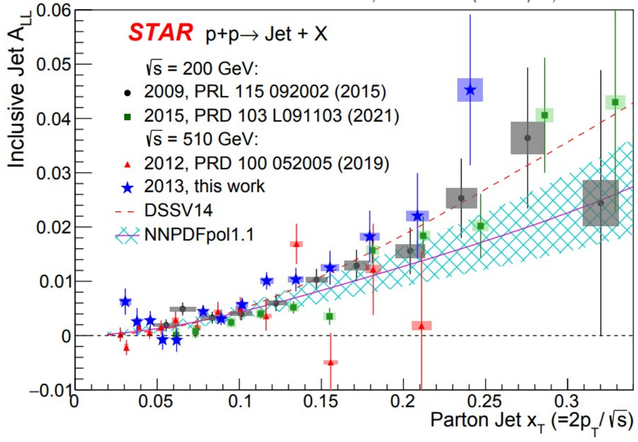
$$\text{NNPDF:} \quad 0.23 \pm 0.07, \quad 0.05 < x < 0.5$$

Global fit including single jet data (≤2015) from unpolarized and polarized hadron collisions (+ DIS and DY)

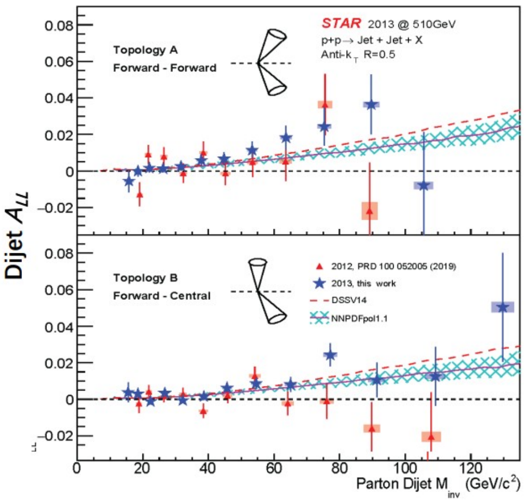
NNPDFpol1.0, DSSV*: STAR 2009 jet data not included
NNPDFpol1.1, DSSV new fit: STAR 2009 jet data included

GLUON HELICITY FROM PROTON-PROTON

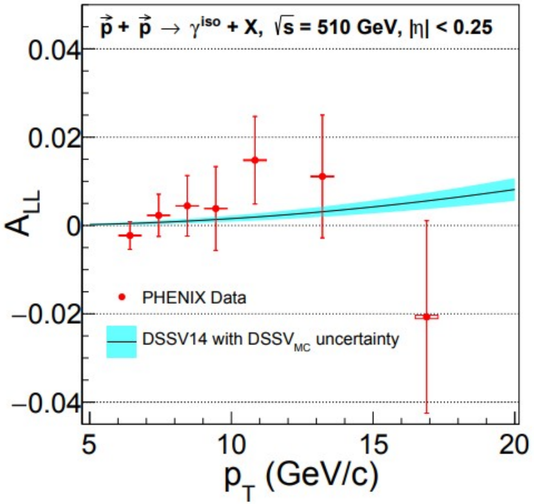
STAR, PRD 105 (2022) 9, 092011



STAR, PRD 105 (2022) 9, 092011



PHENIX, arXiv:2202.08158



Higher √s and more forward rapidity push sensitivity to lower x

- Down to ~0.004 with STAR Endcap (η < 1.8) dijets at 510 GeV (analysis being finalized)
- **Dijets** provide stricter constraints to underlying partonic kinematics - **better constraints on functional form of ΔG(x)**
- **Direct photon** sensitive to gq → γq LO process; **clean access to Δg(x)** (no hadronization)
- **Consistent results from both energies and both experiments**

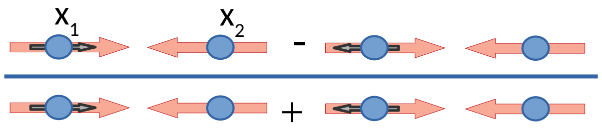
RHIC concluded data taking with longitudinally polarized protons in 2015

The data are anticipated to provide the most precise insights in Δg(x) well into the future

Quark Flavor Separation

SEA QUARK HELICITY

Single spin asymmetry and cross sections for **W production**



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

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

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

LO for illustration

Separation of quark flavor

- $W^+(W^-)$: predominantly u(d) and $\bar{d}(\bar{u})$

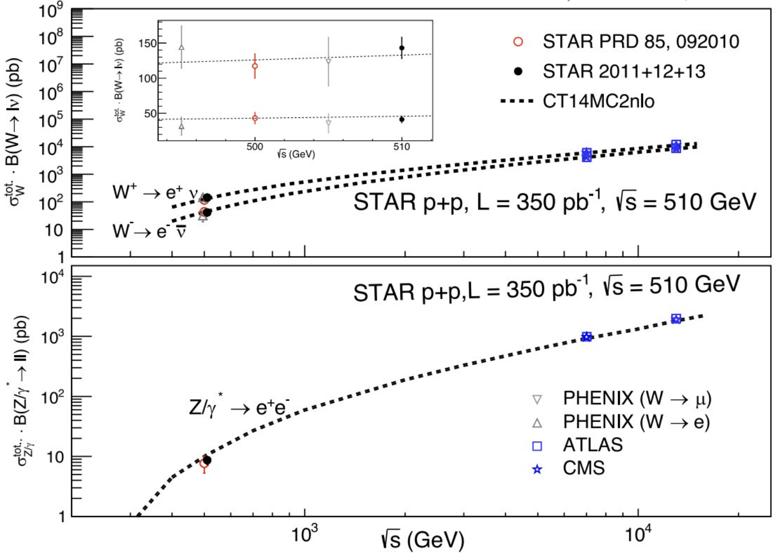
Maximal parity violation

- W couples to left-handed particles or right-handed antiparticles

The decay process is calculable

- Free from fragmentation function

Phys. Rev. D 103, 012001

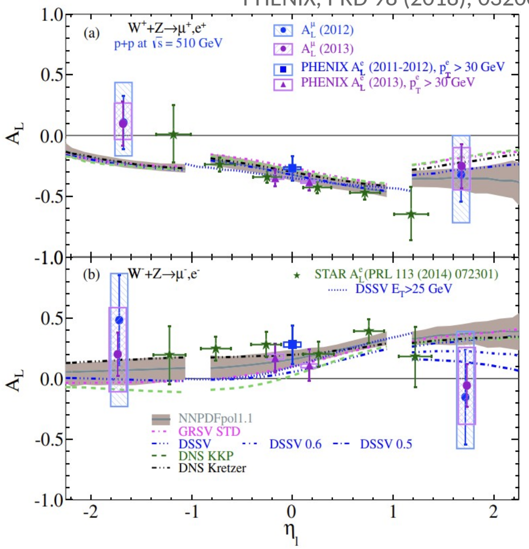


$W^{+/-}$ and Z cross section

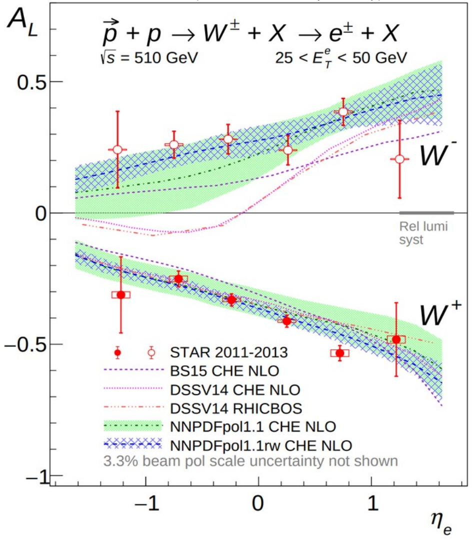
- Agreement between theory and experiment
- Support for the NLO pQCD interpretation of asymmetry measurements

SEA QUARK HELICITY

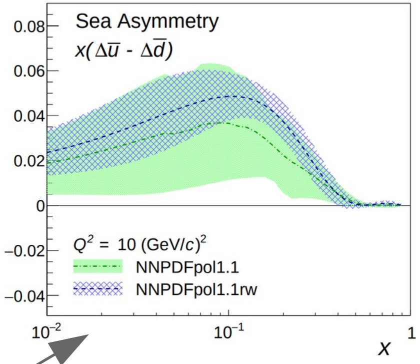
PHENIX, PRD 98 (2018), 032007



STAR, PRD RC 99 (2019), 051102



Flavor asymmetry for quark sea



Covered lepton η: $0.05 < x_1 < 0.25$

Full available data set analyzed from STAR (shown) and PHENIX (PHENIX, PRD 98 (2018), 032007)

- **Significant preference for $\Delta\bar{u}$ over $\Delta\bar{d}$** → Opposite to the spin-averaged quark-sea distributions
- Evaluations from DSSV and NNPDF agree with data in sea and valence quark region

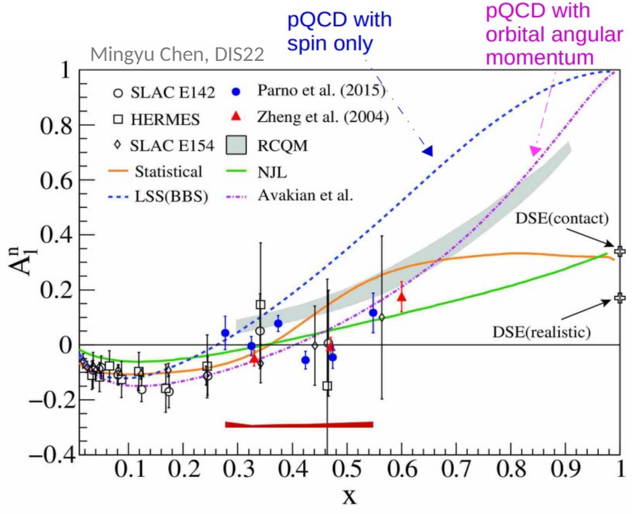
High-x Structure

NUCLEON STRUCTURE AT HIGH X

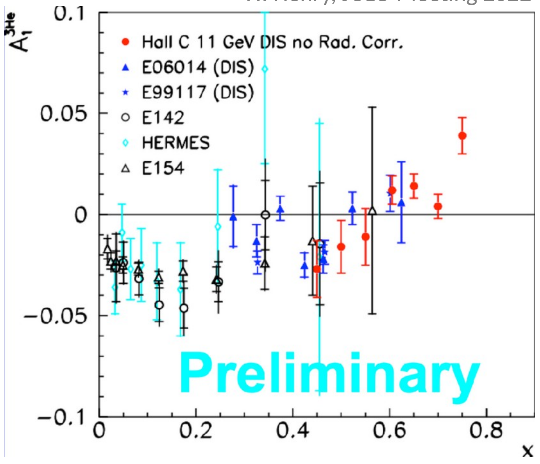
Hall C A1n experiment with polarized ^{3}He target (E12-06-110)

- Measurement of the virtual-photon-nucleon asymmetry A_1 on polarized neutron (^{3}He) target
  $A_1(x) \approx g_1(x)/F_1(x)$ for large Q^2
- Measurement of A_1 for proton (CLAS12) and neutron: extraction of **polarized to unpolarized parton distribution function** ratios **Δu/u** and **Δd/d** for large x region **0.61 < x < 0.77**
- Explore the **Q^2 dependence of A1n** at large x

Mingyu Chen, DIS22



W. Henry, JULO Meeting 2022



- Without radiative corrections
- Statistical uncertainties only
- Nuclear corrections to be applied

$$A_1^n = \frac{F_2^{^3\text{He}}\left[A_1^{^3\text{He}} - 2\frac{F_2^p}{F_2^{^3\text{He}}}P_pA_1^p\left(1 - \frac{0.014}{2P_p}\right)\right]}{P_nF_2^n\left(1 + \frac{0.056}{P_n}\right)}$$

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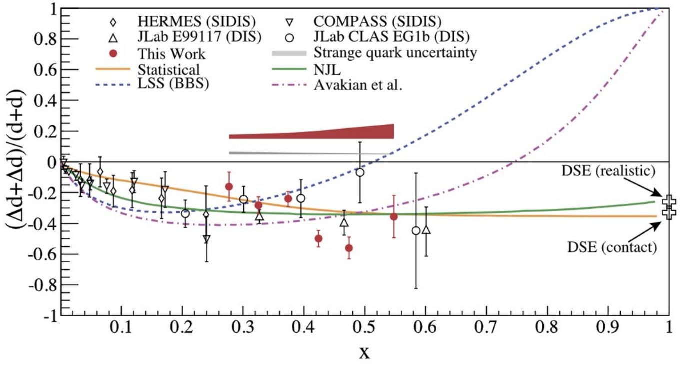
- Measurement of A_1 for proton (CLAS12) and neutron: extraction of **polarized to unpolarized parton distribution function** ratios **Δu/u** and **Δd/d** for large x region **0.61 < x < 0.77**
- Explore the **Q^2 dependence of A1n** at large x
- Example extraction of Δu/u and Δd/d from E06-014 Hall A Jlab (predecessor measurement, red) with previous world DIS data and selected model predictions and parameterizations

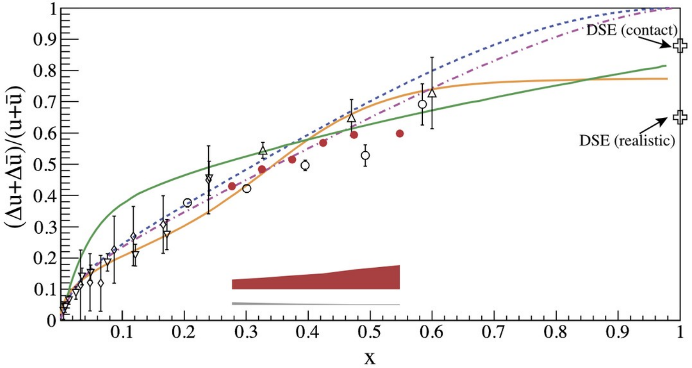
$$\frac{\Delta u + \Delta\bar{u}}{u + \bar{u}} = \frac{4}{15}\frac{g_1^p}{F_1^p}\left(4 + R^{du}\right) - \frac{1}{15}\frac{g_1^n}{F_1^n}\left(1 + 4R^{du}\right)$$

$$\frac{\Delta d + \Delta\bar{d}}{d + \bar{d}} = \frac{-1}{15}\frac{g_1^p}{F_1^p}\left(1 + \frac{4}{R^{du}}\right) + \frac{4}{15}\frac{g_1^n}{F_1^n}\left(4 + \frac{1}{R^{du}}\right)$$

where $R^{du} \equiv (d + \bar{d})/(u + \bar{u})$ and is taken from the CJ12

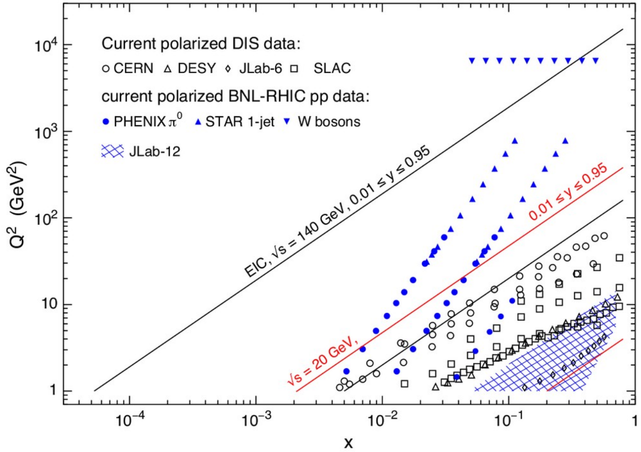
PLB 744, 2015, 309-314





ΔΣ AND ΔG WITH THE ELECTRON-ION COLLIDER

Nucl. Phys. A 1026 (2022) 122447



Values of **ΔΣ and, in particular, ΔG** still with **very large uncertainties**

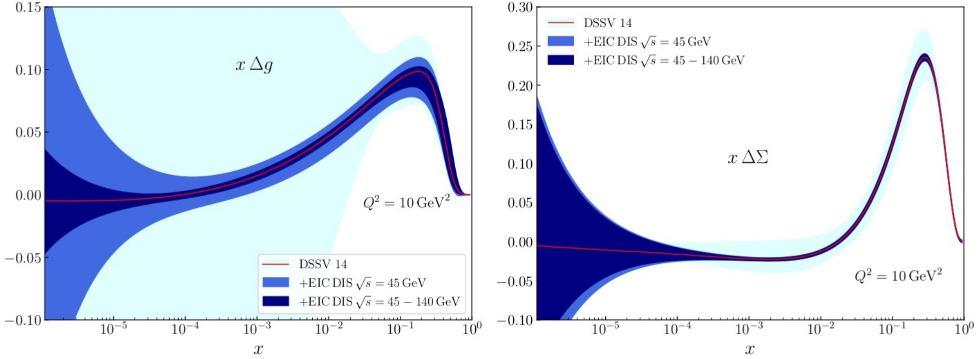
Current world data

- Helicity distributions known for **x > ~0.01** with good precision

Deep insight with EIC

- Precision down to **$x \sim 10^{-4}$**
- In addition to the sensitivity to the **quark sector**, scaling violation in $g_1(x, Q^2)$ in inclusive DIS to access **gluons**

Phys. Rev. D 102 (9) (2020), 94018



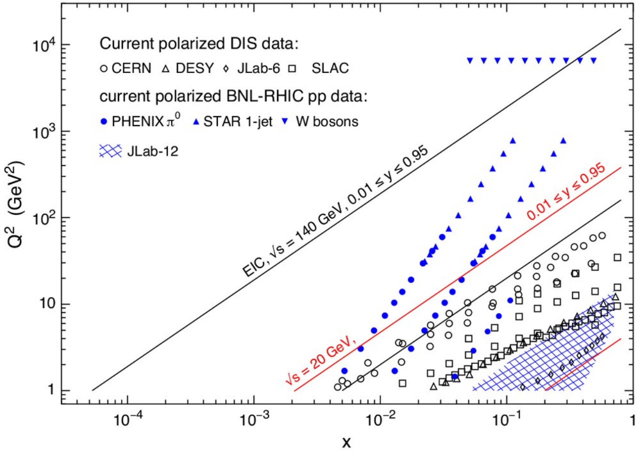
Impact of the projected EIC A_{LL} pseudodata (L = 10 fb^{-1}) on the gluon helicity and quark singlet helicity

In addition to golden channel g1 measurements, direct access to gluons in higher-order photon-gluon fusion:

- dijet A_{LL}
- Heavy-quark A_{LL}

SEA QUARK HELICITIES FROM EIC

Nucl. Phys. A 1026 (2022) 122447

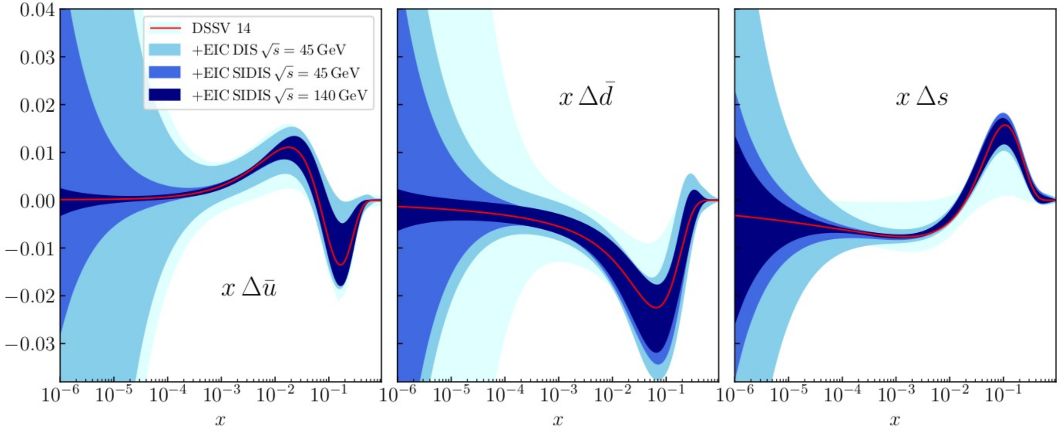


Sea quark helicities via SIDIS measurements with pions and kaons

- **Highest impact at low x** from the data at the **highest collision energies**
- Tackle question of sea quark helicities contributions to the spin, in particular, the **strange sea polarization**

Impact studies of expected EIC measurements with p and ^{3}He beams following the previous DSSV extractions

Phys. Rev. D 102 (9) (2020), 94018



SUMMARY

- Experiments utilizing both lepton scattering processes and hadron-hadron interactions unravel **complex nucleon spin structure**
- Decades of studies in **Deep Inelastic Scattering**, as well as **Semi-Inclusive Deep Inelastic Scattering and proton-proton collisions**
- **Polarized DIS cross section studied at SLAC, CERN, DESY, JLab encodes information about helicity structure of quarks inside the proton (double spin asymmetries)**
- **Complimentary approach of studying longitudinal spin structure via strong interactions in pp collisions (RHIC) to access gluons and polarized quark sea**
- The **Electron Ion Collider** precision in longitudinal spin structure of nucleons from low to high x and high Q^2