

Studying the Light Sea Quark Asymmetry Using SIDIS with SoLID using Longitudinally Polarized ^3He Target at 11 GeV

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On behalf of the spokespersons

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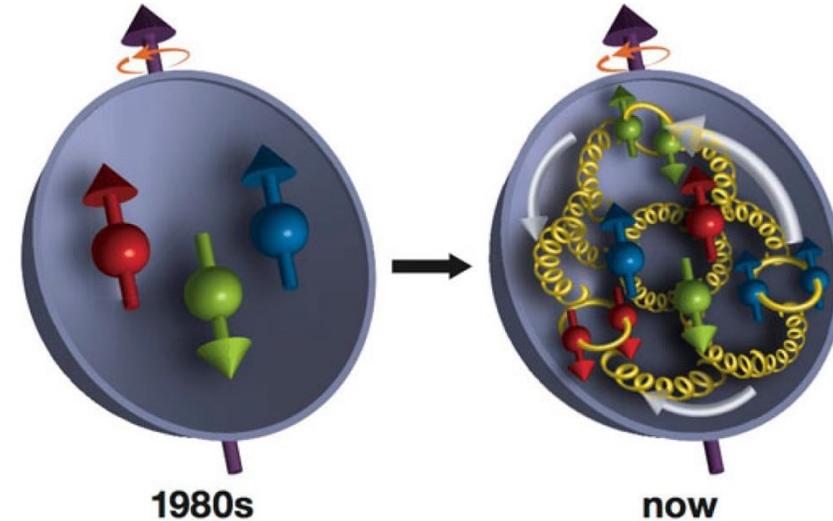
Ye Tian

Outline

- Motivation and experimental setup
- SIDIS process and double spin asymmetry
- Estimated systematic uncertainties for the experiment
- Impact on global analysis
- Theoretical uncertainties
- Summary

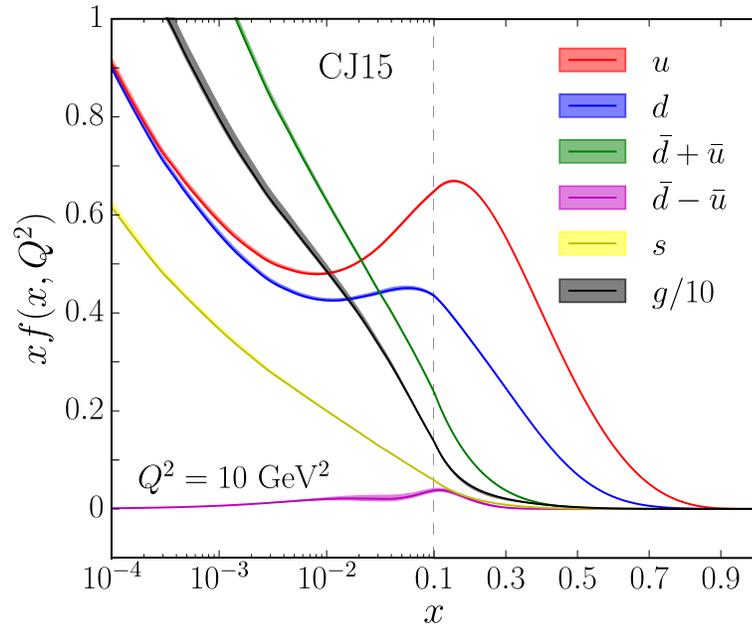
Structure of nucleons

- The nucleon is a dynamical QCD system consists of quarks and gluons
- What is the origin of the nucleon sea?
- What is the flavor dependence of the sea quarks?
- How much do the antiquarks contribute to the nucleon spin?

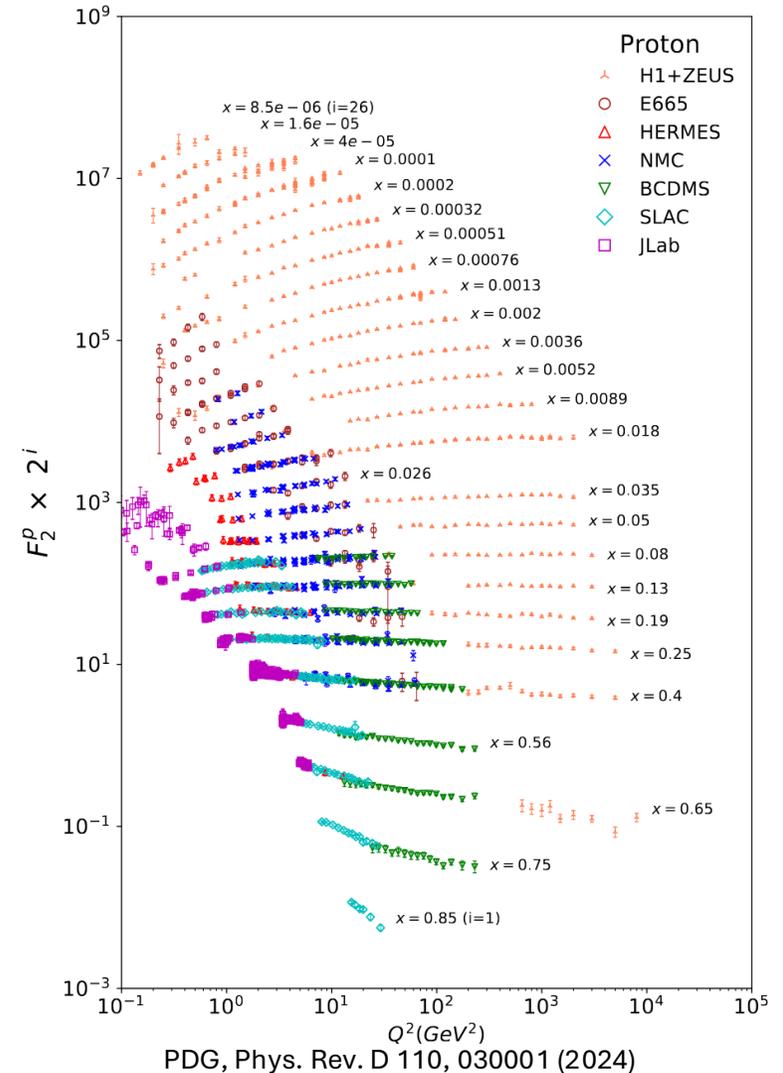


Unpolarized Structure Functions

- The unpolarized structure functions have been extensively studied by various experiments



A. Accardi et al
Phys. Rev. D 93, 114017

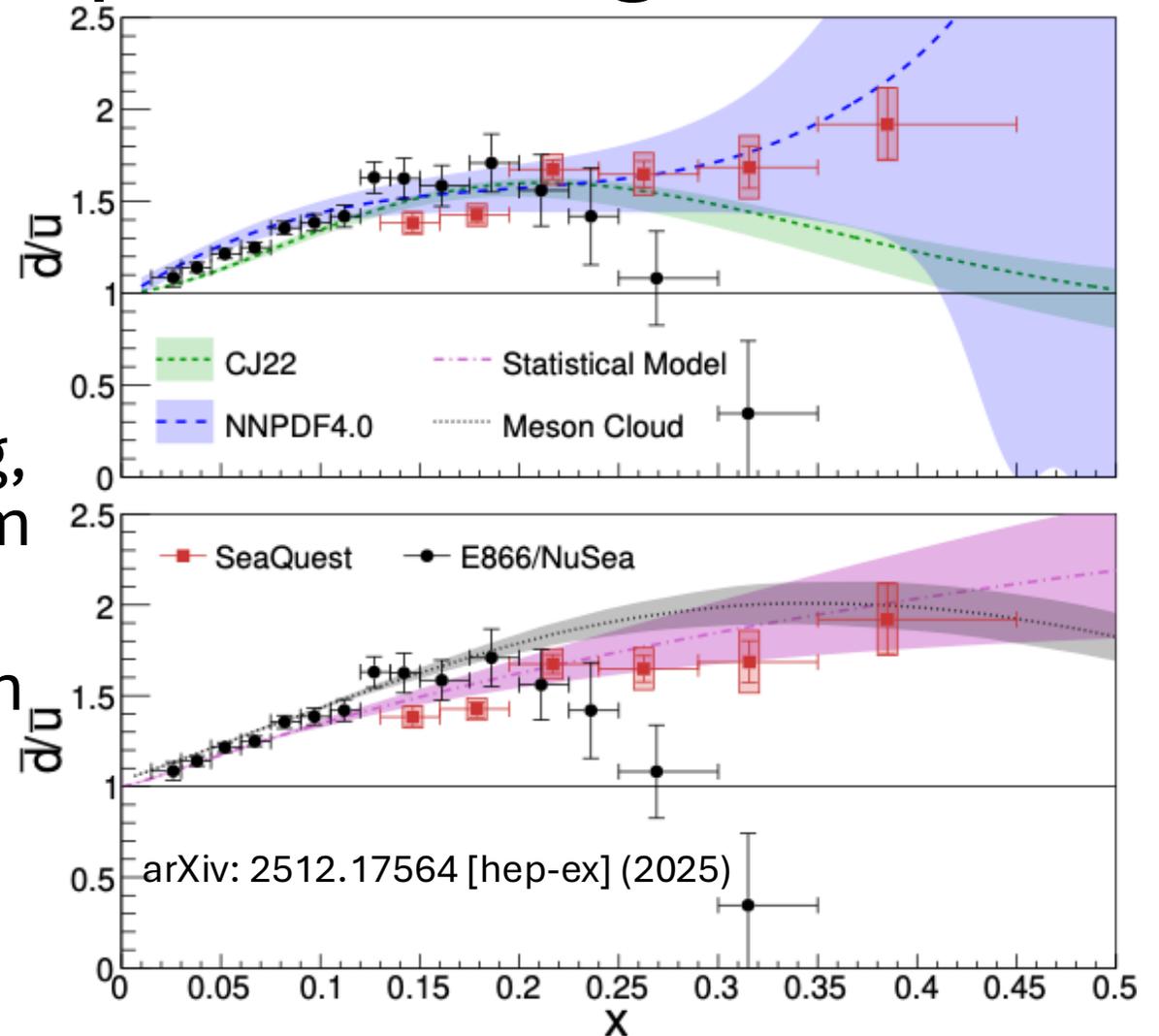


PDG, Phys. Rev. D 110, 030001 (2024)

SEAQUEST Results: Unpolarized Light Sea

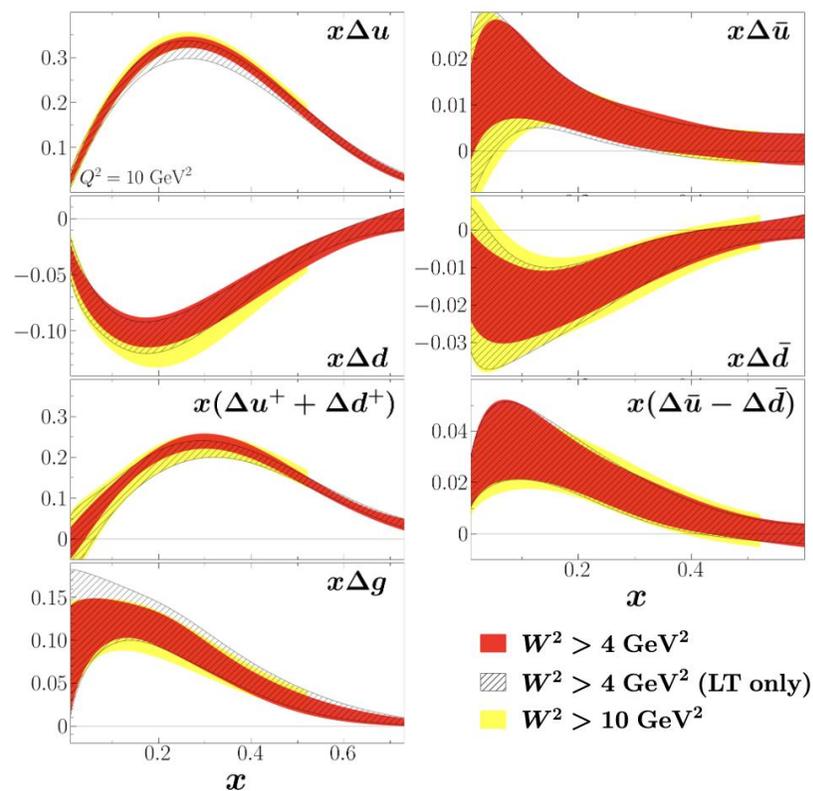
- SeaQuest results show that nature prefers $\bar{d} > \bar{u}$ in the proton
- This flavor asymmetry cannot be explained by gluon splitting, a non-perturbative mechanism is needed
- The results are consistent with various models, including meson cloud and statistical model

$$\left. \frac{\sigma_{pd}^{DY}}{2\sigma_{pp}^{DY}} \right|_{x_1 \gg x_2} \approx \frac{1}{2} \left(1 + \frac{\bar{d}(x_2)}{\bar{u}(x_2)} \right)$$

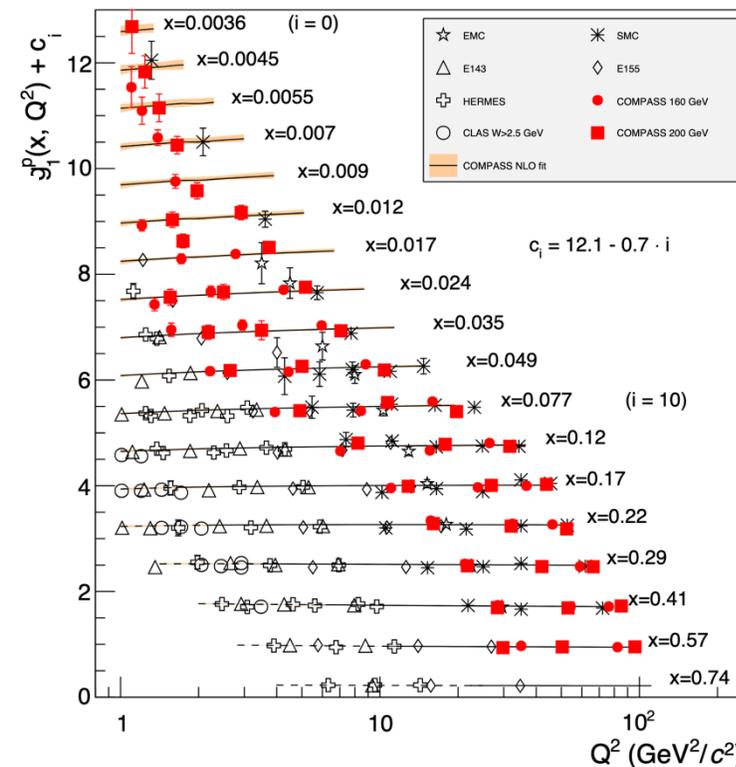


Polarized Structure Functions

- These models can also be used to predict polarized PDFs, with different predictions between different models



JAM, Phys. Rev. D 112 (2025) 11, 114017



PDG, Phys. Rev. D 110, 030001 (2024)

Quark helicity distributions in the nucleon for up, down, and strange quarks from semi-inclusive deep-inelastic scattering

HERMES (2005)

- Polarized e^+/e^- beam on gas polarized deuteron and proton target
- $x(\Delta\bar{u}(x) - \Delta\bar{d}(x))$ extraction has modest uncertainties

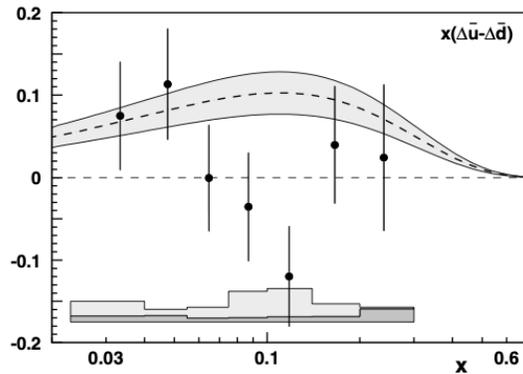
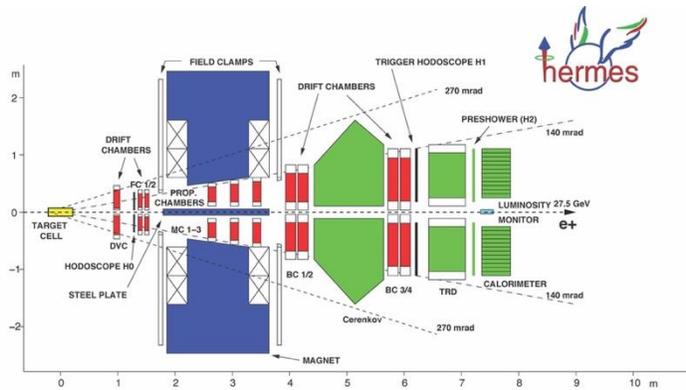
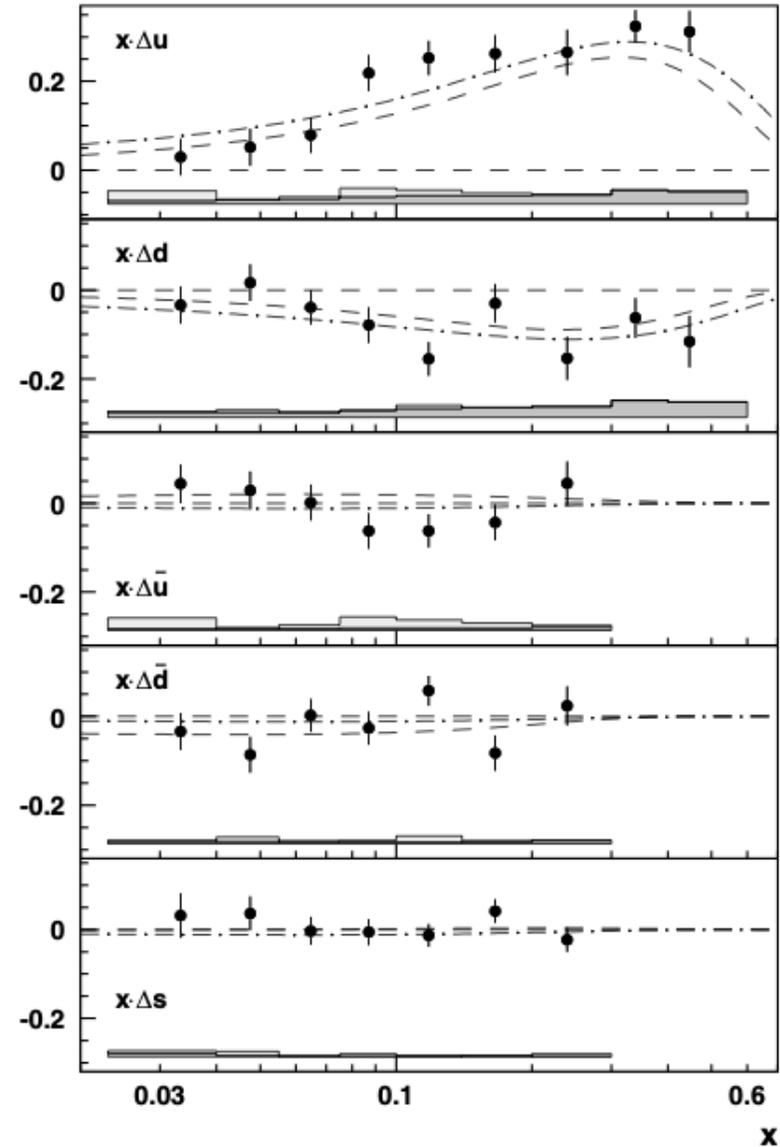


FIG. 3. The light quark sea flavor asymmetry $x \cdot (\Delta\bar{u} - \Delta\bar{d})$ in the helicity distributions, at $\langle Q^2 \rangle = 2.5 \text{ GeV}^2$, compared to a theoretical prediction [30] (dashed curve with theoretical uncertainty band). The experimental error bars and bands have the same meaning as in Fig. 2.



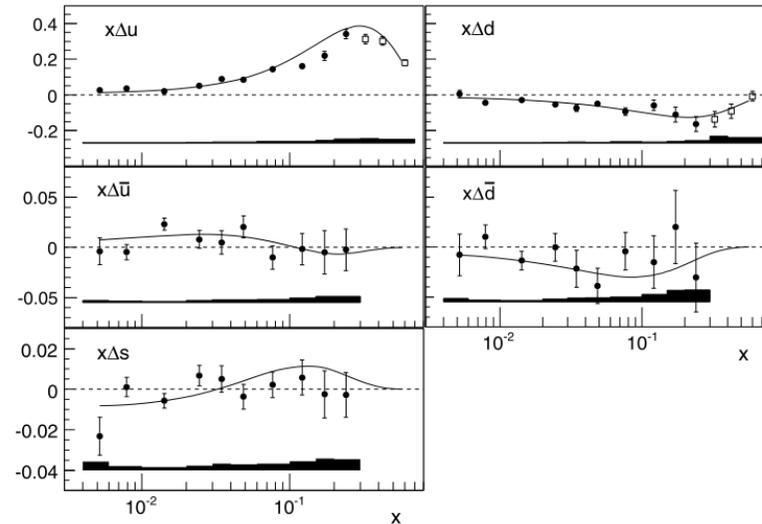
COMPASS (2010)

- Measured longitudinal spin asymmetries for charged pions and kaons in SIDIS 160 GeV muon scattering on a polarized NH_3 target
- Anti-quark moments do not show significant variation in the measured range
- $\Delta\bar{u}(x) - \Delta\bar{d}(x)$ is slightly positive about 1.5 deviations from 0.
- High precision data is essential to map down the contributions and the difference in helicity PDFs.

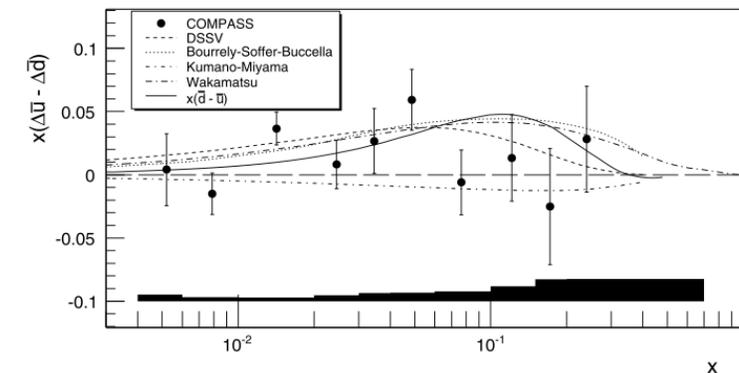
Quark helicity distributions from longitudinal spin asymmetries in muon-proton and muon-deuteron scattering

COMPASS Collaboration

COMPASS Collaboration / Physics Letters B 693 (2010) 227–235



COMPASS Collaboration / Physics Letters B 693 (2010) 227–235



RHIC (2013)

- Polarized p + p collisions
 - STAR data shown
 - PHENIX data also collected

$$W^+ \rightarrow e^+ \nu \text{ and } W^- \rightarrow e^- \bar{\nu}.$$

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

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

Measurement of the longitudinal spin asymmetries for weak boson production in proton-proton collisions at $\sqrt{s} = 510$ GeV

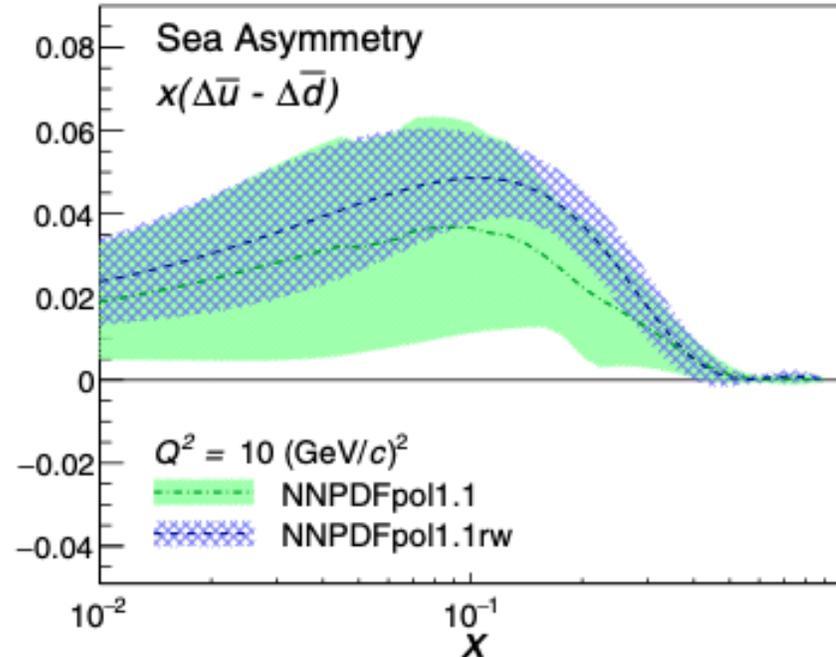


FIG. 6. The difference of the light sea-quark polarizations as a function of x at a scale of $Q^2 = 10 \text{ (GeV}/c)^2$. The green band shows the NNPDFpol1.1 results [1] and the blue hatched band shows the corresponding distribution after the STAR 2013 W^\pm data are included by reweighting.

Unpolarized \Leftrightarrow Polarized Sea connection

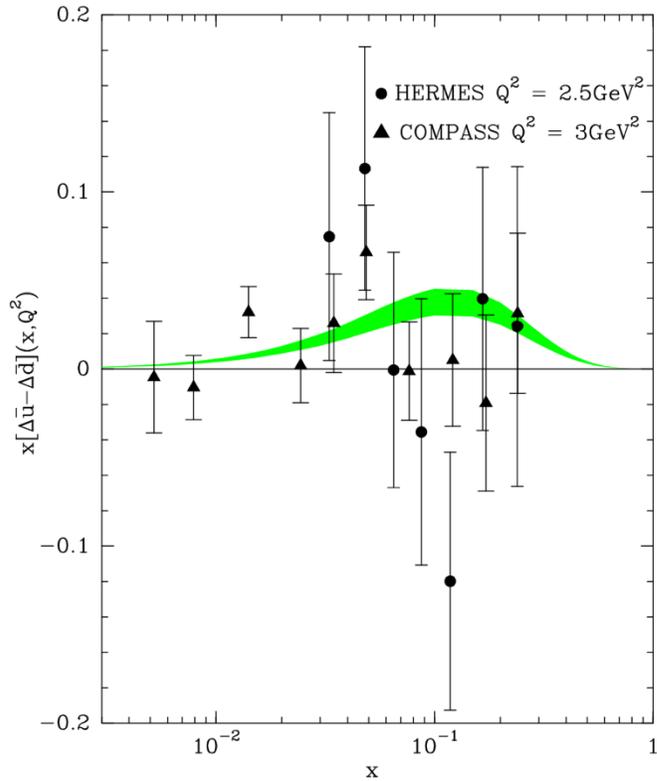
- Various non-perturbative models of the nucleon have predictions for the polarization of the sea
- They have vastly different predictions for $\Delta\bar{u}(x) - \Delta\bar{d}(x)$

Model	I_Δ prediction	Authors and References
Meson cloud	0	Eichten <i>et al.</i> [20], Thomas[21]
(π -meson)	$\simeq -0.007$ to -0.027	Fries <i>et al.</i> [22]
(ρ -meson)	$= -6 \int_0^1 g_1^p(x) dx \simeq -0.7$	Boreskov <i>et al.</i> [23]
($\pi - \rho$ interference)	$\simeq -0.004$ to -0.033	Cao <i>et al.</i> [24]
(ρ and $\pi - \rho$ interference)	< 0	Kumano <i>et al.</i> [25]
(ρ -meson)	$\simeq 0.12$	Fries <i>et al.</i> [26]
($\pi - \sigma$ interference)	$\simeq 0.09$	Cao <i>et al.</i> [24]
Pauli-blocking (bag model)	$\simeq 0.3$	Gluck <i>et al.</i> [27]
Pauli-blocking (ansatz)	$\frac{5}{3} \int_0^1 [\bar{d}(x) - \bar{u}(x)] dx \simeq 0.2$	Steffens[28]
Chiral-quark soliton	0.31	Dressler[29]
Chiral-quark soliton	$\simeq \int_0^1 2x^{0.12} [\bar{d}(x) - \bar{u}(x)] dx$	Wakamatsu <i>et al.</i> [30]
Instanton	$\frac{5}{3} \int_0^1 [\bar{d}(x) - \bar{u}(x)] dx \simeq 0.2$	Dorokhov[31]
Statistical	$\simeq \int_0^1 [\bar{d}(x) - \bar{u}(x)] dx \simeq 0.12$	Bourrely <i>et al.</i> [32, 33]
Statistical	$> \int_0^1 [\bar{d}(x) - \bar{u}(x)] dx \simeq 0.12$	Bhalerao[34]

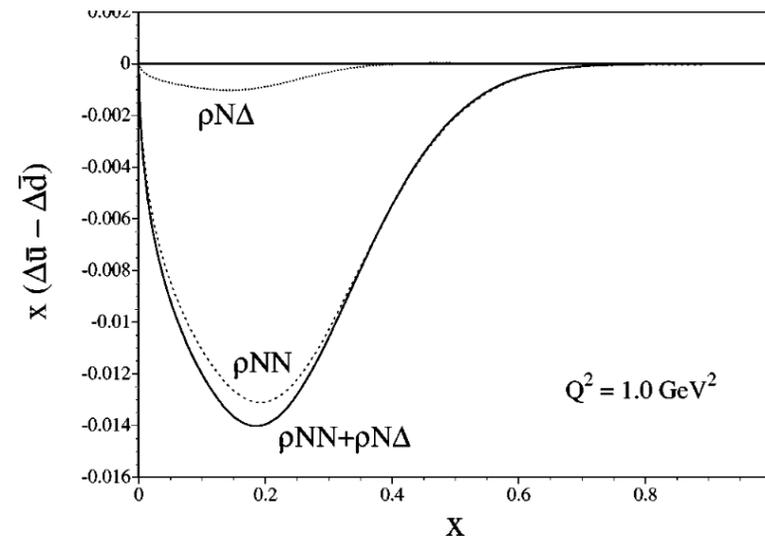
Table 1.1: A summary of theoretical predictions of $I_\Delta = \int_0^1 [\Delta\bar{u}(x) - \Delta\bar{d}(x)] dx$. [35]

Adapted from J-C Peng,
Eur.Phys.J.A18:395-399,2003

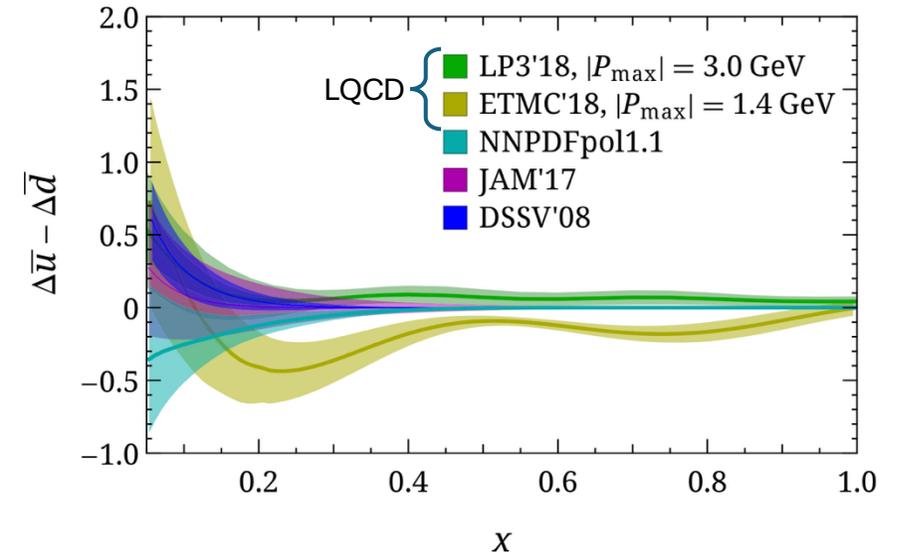
Model predictions



Soffer, Bourrely, Nucl. Phys A 991 (2019) 121607



Kumano, Miyama, Phys. Rev. D 65, 034012

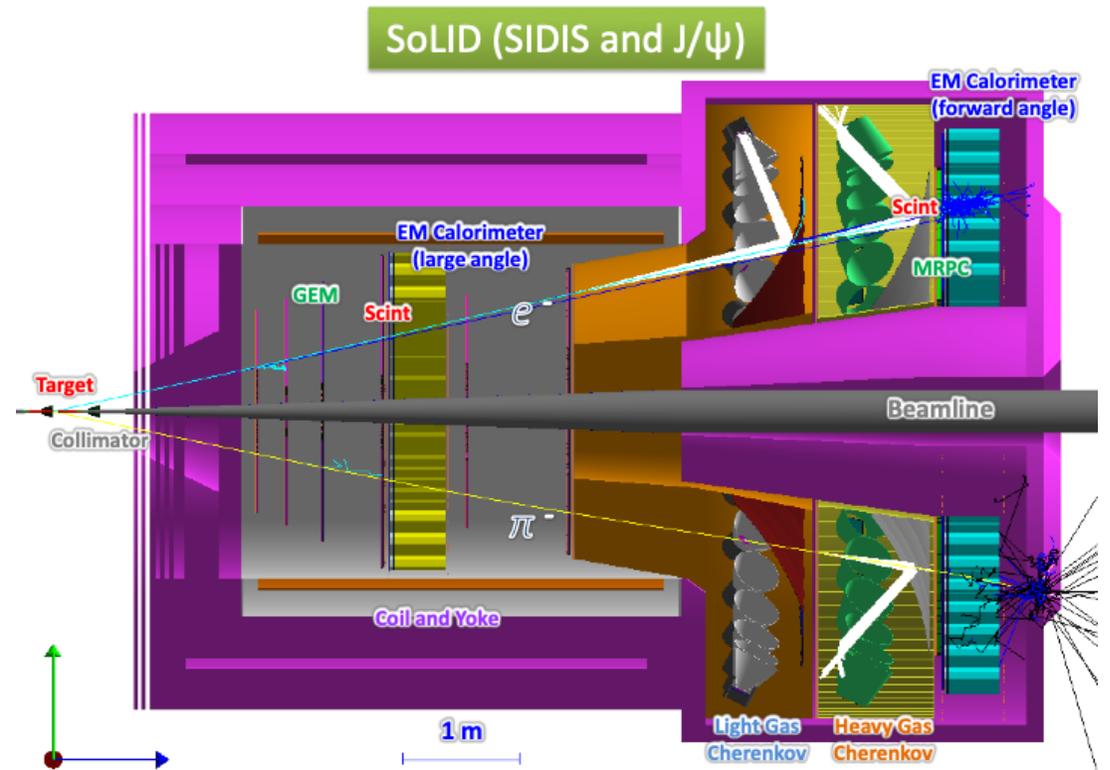


Constantinou et al, Prog.Part.Nucl.Phys. 121 (2021) 103908

- As Lattice QCD calculations became more reliable, there is more demand for precise experimental data

Experimental Setup

- ^3He target can act as an effective neutron target
 - When combined with proton data can provide flavor-separated spin observables
- The JLab beam energy allows access to moderate x ($\sim 0.1-0.5$) region
- SoLID's SIDIS measurement on polarized ^3He offers a powerful opportunity to determine the polarized sea flavor asymmetry



Measuring double spin asymmetry

- We propose to measure the double spin asymmetry

$$A_{LL}^h(x_{bj}, P_t, z_h, Q^2) = \frac{1}{P_b P_T} \frac{N^{\uparrow\uparrow} - N^{\uparrow\downarrow}}{N^{\uparrow\uparrow} + N^{\uparrow\downarrow}},$$

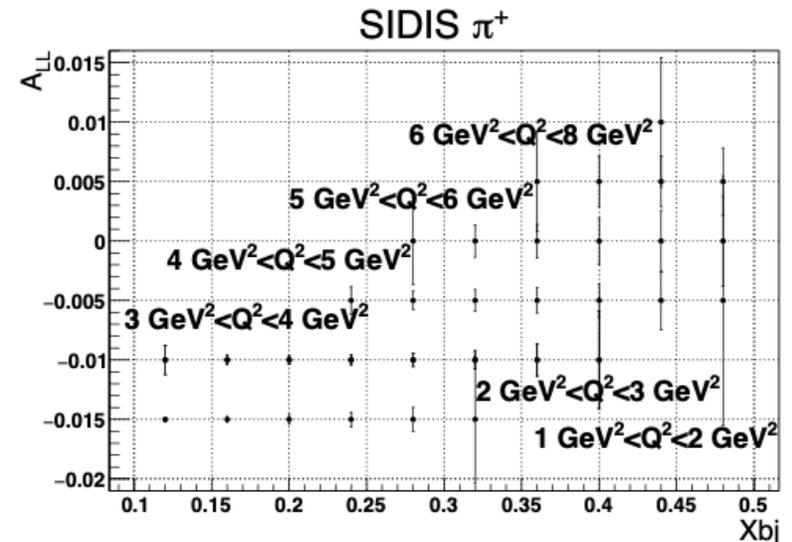
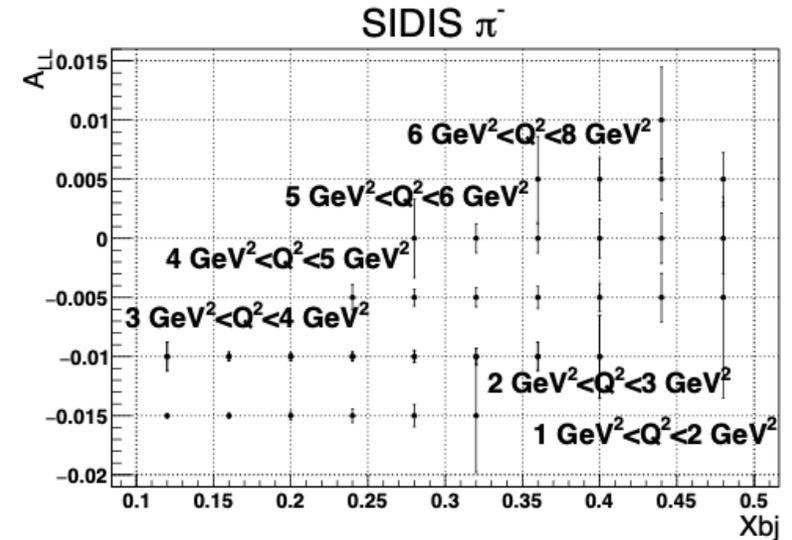
- With 22.5 PAC days, we expect the statistical error on the ratio to be well within 1%
- At Leading Order, assuming factorization

$$A_{LL}^h = f^h P_B P_T \cdot P_{kin} \cdot (A_{1N}^h + \eta A_{2N}^h)$$

$$A_{1N}^h(x, Q^2, z) \equiv \frac{\Delta\sigma^h(x, Q^2, z)}{\sigma^h(x, Q^2, z)} = \frac{\sum_f e_f^2 \Delta q_f(x, Q^2) \cdot D_{qf}^h(z, Q^2)}{\sum_f e_f^2 q_f(x, Q^2) \cdot D_{qf}^h(z, Q^2)}$$

- By measuring both the π^+ and π^- , we can also provide information on the flavor dependence

The definition of A_{LL} is added to sec 1.4 as response to comment 3.1

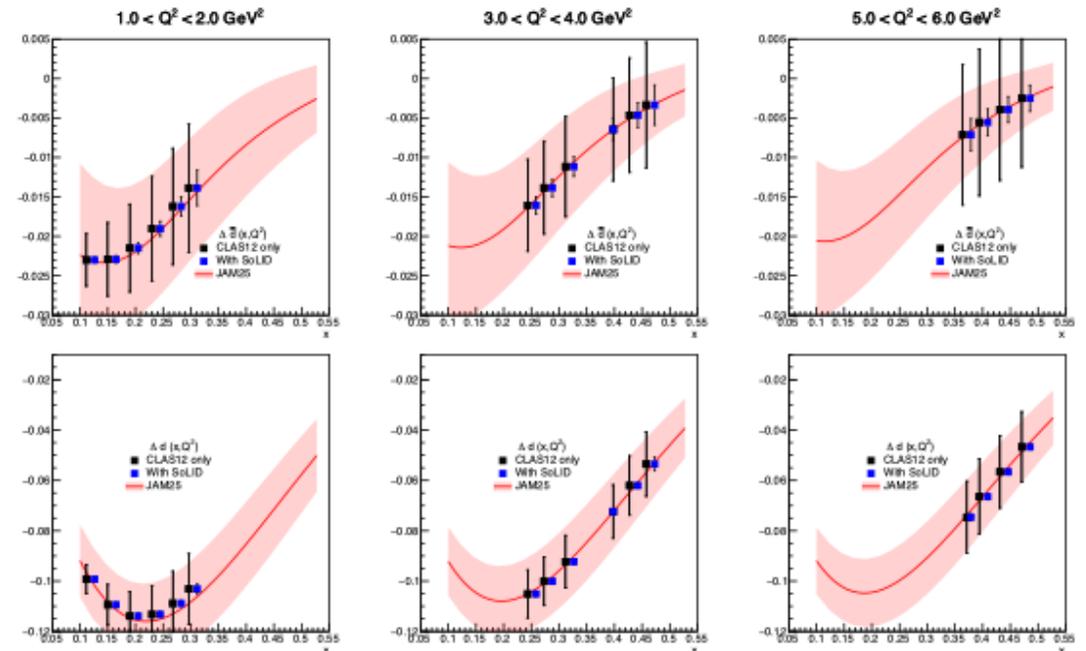


Leading order extraction

- By assuming $x - z$ factorization

$$A_{1N}^h(x, Q^2, z) \equiv \frac{\Delta\sigma^h(x, Q^2, z)}{\sigma^h(x, Q^2, z)} = \frac{\sum_f e_f^2 \Delta q_f(x, Q^2) \cdot D_{qf}^h(z, Q^2)}{\sum_f e_f^2 q_f(x, Q^2) \cdot D_{qf}^h(z, Q^2)}$$

- Here, only the projected uncertainties from CLAS12 proposal is used as the proton data
- From the leading order projection, the solid data will have a significant impact on the flavor separated PDF.



The study has been added to address comment 3.1.2 and 3.1.5

Systematic Uncertainties (Experimental)

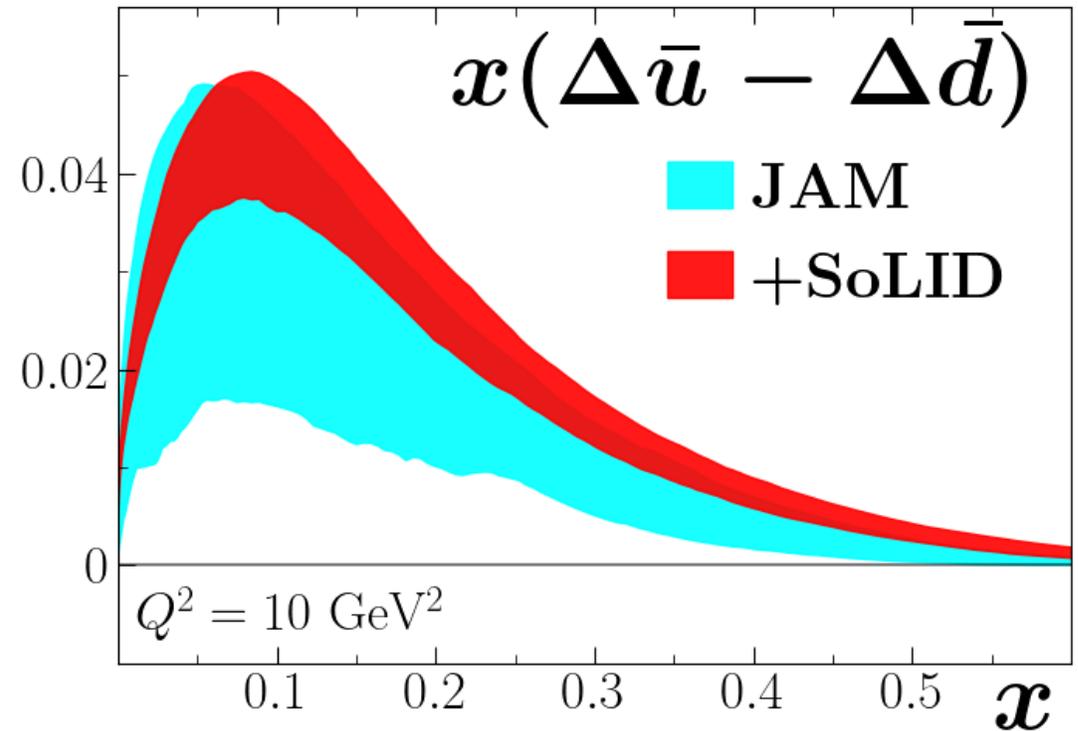
- Due to the rapid helicity reversal of the beam at 30 Hz, we expect the systematic uncertainty on the raw asymmetry due to normalization errors, and detector efficiency to largely cancel out in the ratio.
- The main source of uncorrelated experimental systematic uncertainty is expected to be from the random coincidence, which simulations suggest to be around 1%.
- The relative uncertainties on polarimetry are 3% for the target, and 2% for the beam polarization, based on previous experiment.

Sources	Uncertainty
Raw asymmetry (abs.)	negligible
Random coincidence (Rel.)	1%
Polarimetry (Rel.)	< 4%
Nuclear effects (Rel.)	1–8%
Diffractive vector meson (Rel.)	3%
Radiative corrections (Rel.)	3%
Total (Abs.)/Total (Rel.)	Negligible/< 9.9%

Table 3.1: Systematic uncertainty budget of A_{LL}

Impact to global PDF analysis

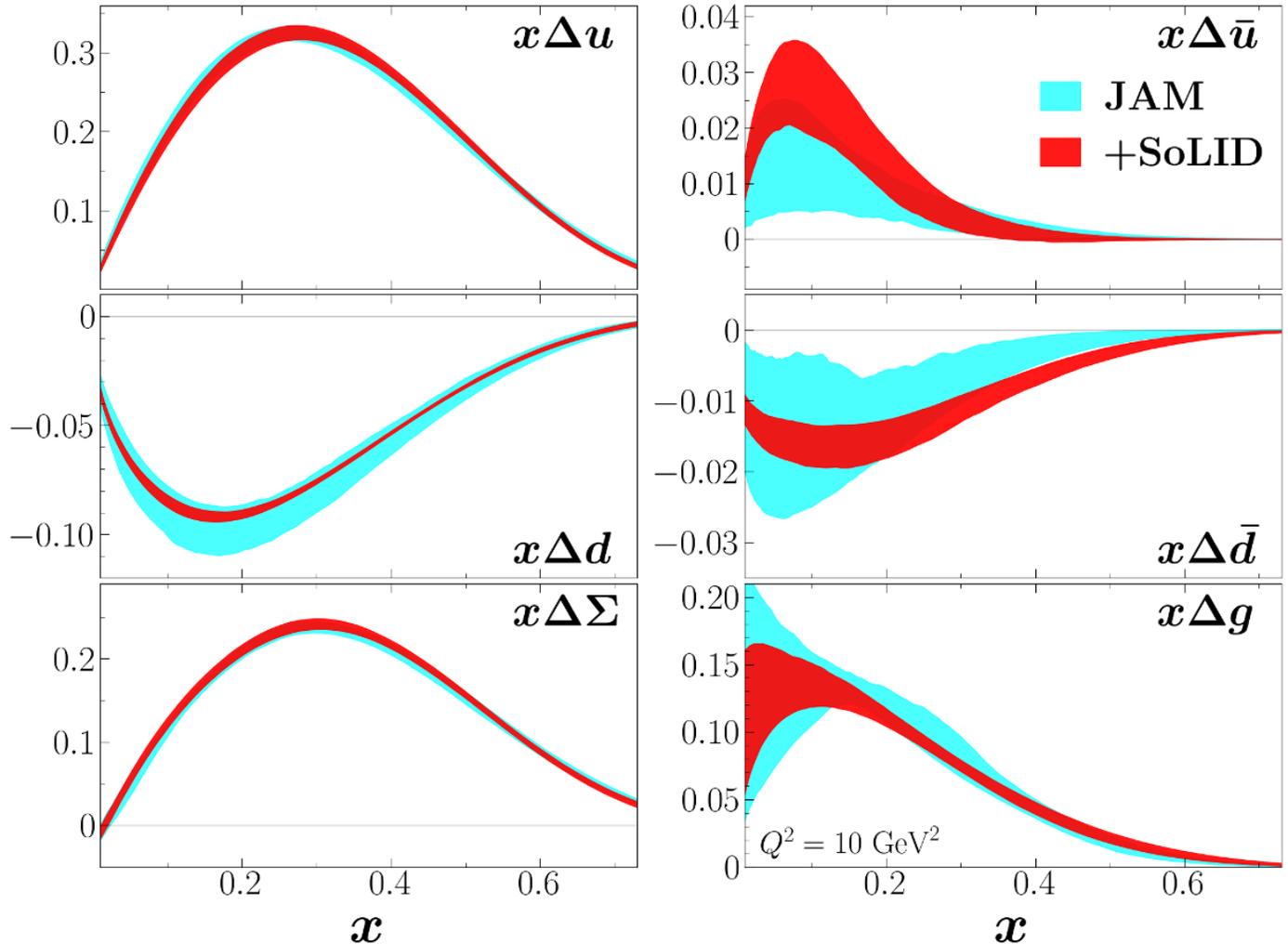
- JAM QCD global analysis framework
 - Including data from:
 - Jet production in polarized pp collisions
 - W/Z boson production at RHIC
 - As well as the pseudo data on SoLID SIDIS A_{LL}
- SoLID's polarized ^3He SIDIS data will directly constrain the difference between $\Delta\bar{u} - \Delta\bar{d}$ in the intermediate-x region



The impact study has been updated to address comment 3.2.7

Impact to global PDF analysis

- The impact study also shows that this measurement will significantly reduce the uncertainties of Δd and $\Delta \bar{d}$
- Strong constraints on nonperturbative origin of sea quark
- Allow better understanding of the decomposition of the nucleon spin

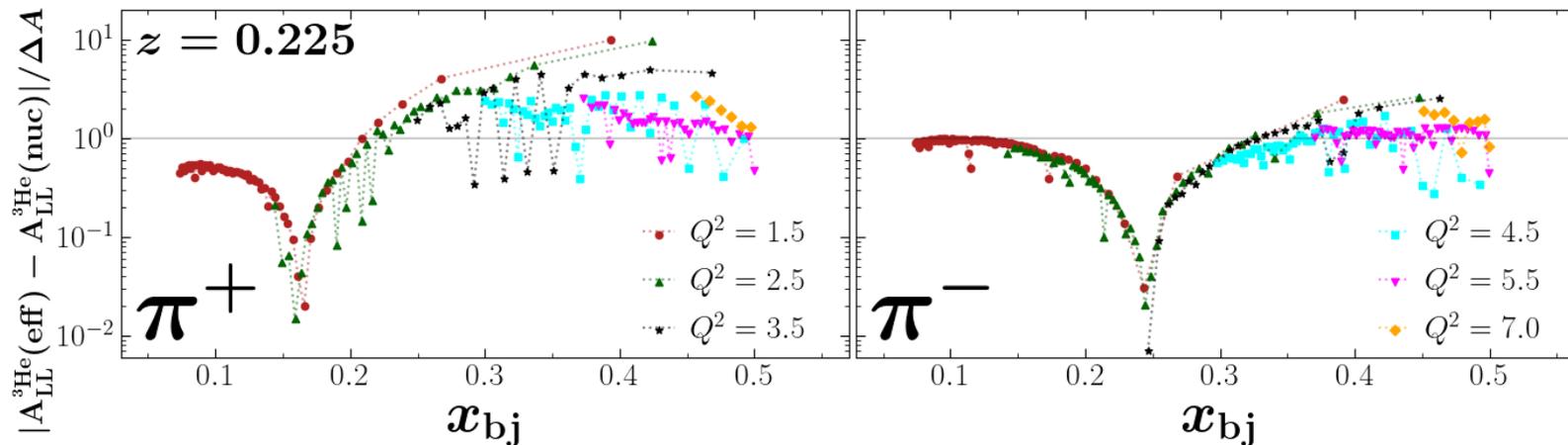


Theoretical uncertainties

- Hadron Mass Corrections
 - Small kinematic shifts in x_B and z_h ; partly cancel in ALL asymmetries.
- Higher Twist Corrections
 - <5% effect at $Q^2 \sim 2 \text{ GeV}^2$
- Uncertainty from High-PT Region
 - We expect the the size of the missing high- P_T is non-negligible, which varies across different kinematic regions.
- Vector Meson Contamination
 - Exclusive rho mesons may affect large- z , low- P_T region.
 - Early studies suggest the effect is small.
- Nuclear corrections in ^3He treated for neutron extraction
- Radiative correction

Nuclear correction

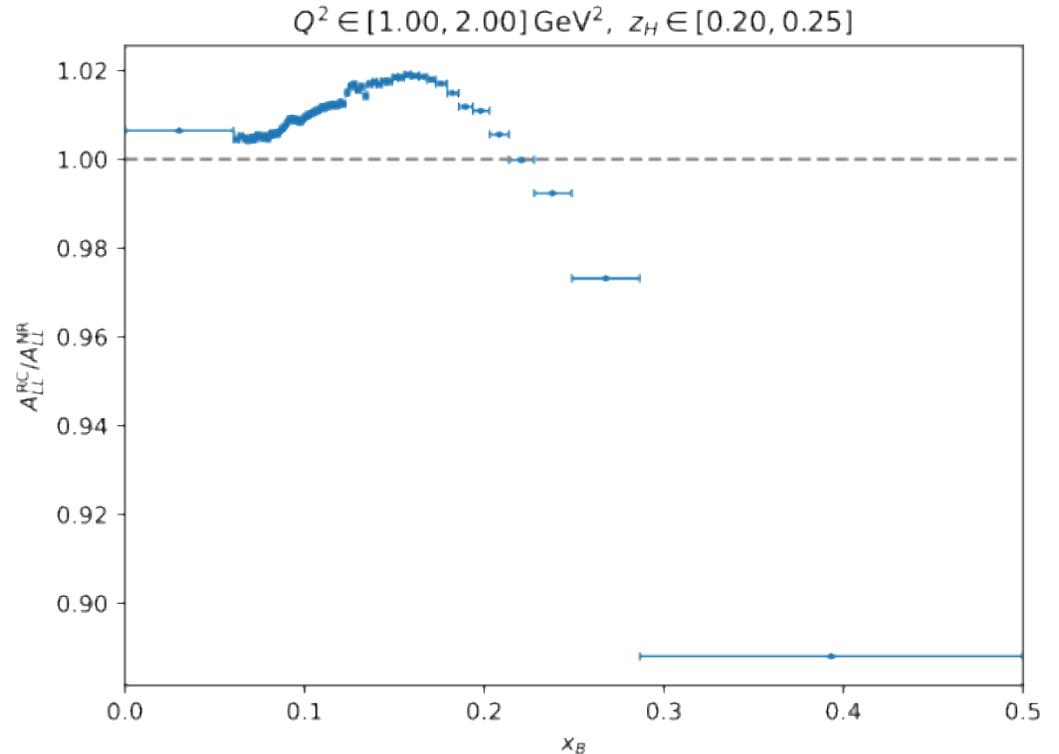
- The effects on nuclear correction ^3He is estimated by comparing the fit performed using effective polarizations and a prediction using nuclear smearing
- It is expected the overall effect is less than 8%, and is much smaller compared the projected statistical uncertainty of the asymmetry



This new figure is suggested in comment 3.2.9

Radiative correction

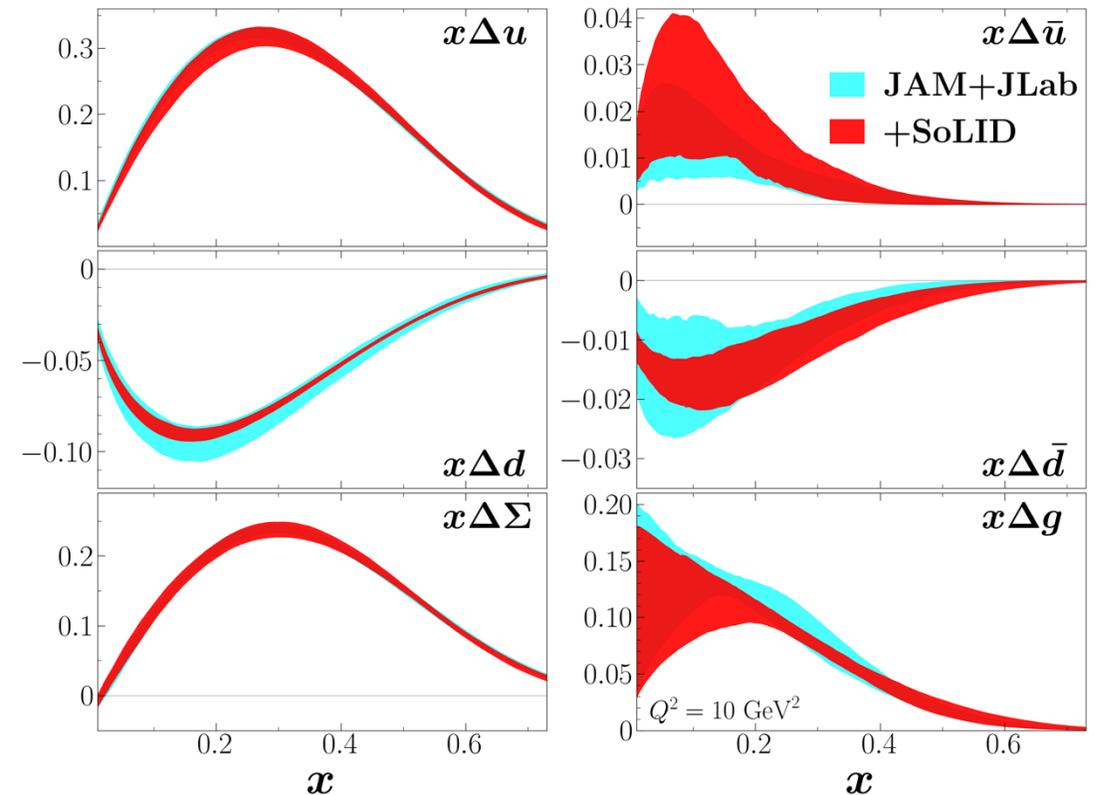
- The radiative correction is evaluated using a joint QED and QCD factorization formalism
- The results suggest the effect is most significant at large x_B and small z_H .



The impact of the radiative correction has been updated in response to comment 3.1.6

Comparison with other experiment

- An impact study was performed by including the preliminary results from JLab Hall C 11 GeV A1n experiment in the baseline
- This does not qualitatively change the impact of the SoLID data



This comparison is suggested in comment 3.1.3

Summary

- The polarized light quarks at intermediate x (0.1-0.5) are of great interest
- With high luminosity and large acceptance, SoLID will provide much needed SIDIS data for constraining the flavor-separated helicity PDFs, especially for the down-quark sector
- All the comments from the last review has been addressed:
 - Updated JAM impact study continue to show significant impact
 - Estimate of radiative correction is now estimate using a joint QCD+QED framework

Summary of response to comments

- 3.1.1: Definition of A_{LL} was not shown
 - As mentioned in slide 14, the definition is added in sec 1.4
- 3.1.2: Traditional presentation of “projected results”
 - A leading order projection is presented in slide 15
- 3.1.3: Comparison with Hall C A1n
 - The comparison is shown in slide 22
- 3.1.4: The inclusive A_{LL} data can be used to structure function $g_1^n(x)$
 - The current proposal focuses on the unique flavor-separated sensitivity of SIDIS. This point has also added in page 19
- 3.1.5: Comparison with CLAS12 proposal E12-09-007
 - A leading order comparison is presented in slide 15
- 3.1.6: Systematics uncertainties
 - QED radiative correction is shown in slide 21
 - The most up-to-date contamination from diffractive ρ -meson is already included in sec 3.6.4

Summary of response to comments

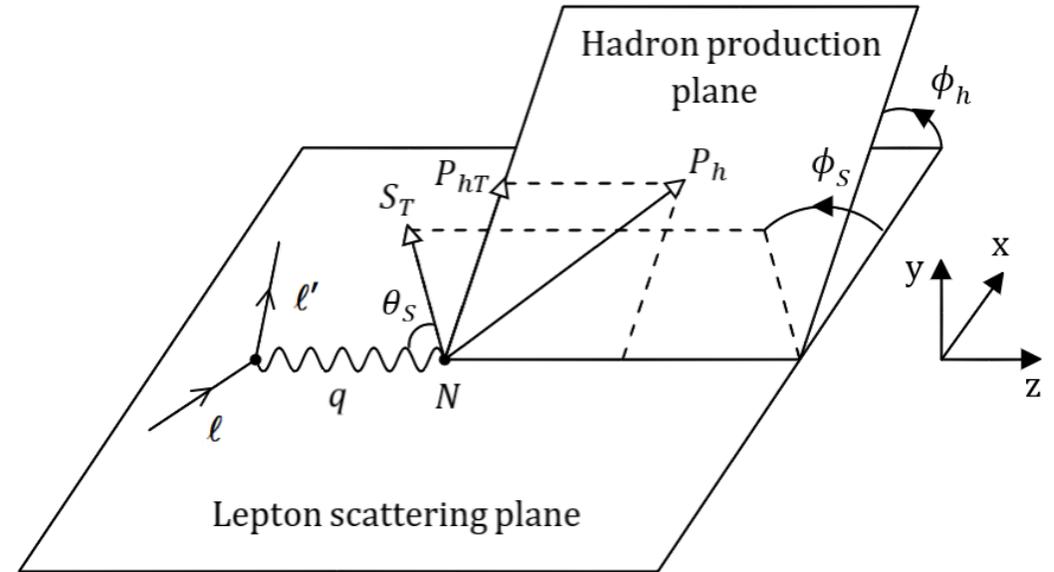
- 3.2.1: Nitrogen dilution factors was missing
 - The dilution factor due to unpolarized nitrogen has been included in page 11 of the updated proposal
- 3.2.2: $\Delta\Sigma$ was not defined in the original proposal
 - This has been added to page 20
- 3.2.3: Meaning of $\sigma_{p,n}$ in p12, eq 3.1
 - It is explicitly stated to mean SIDIS cross section
- 3.2.4: Wording of effective polarization on p.14 can be misleading
 - The wording has been modified
- 3.2.5: The ratio $2\sigma_p/\sigma_n$ is kinematic dependent and not a constant
 - This effect is taken into account in the updated nuclear effect study
- 3.2.6: Table 3.1, presenting estimate of uncertainty from nuclear correction, is shown before the explanation
 - The organization of the discussion has been rearranged to improve clarity

Summary of response to comments

- 3.2.7: The uncertainties of the impact study
 - The new impact study is performed with more replicas, which has reduced the increase in uncertainties in region outside of the SoLID coverage.
 - This is shown in slide 17 and 18
- 3.2.8: The formalism of SIDIS was missing in the original proposal
 - This is added in sec 2.6.1
- 3.2.9: Estimation of the nuclear correction uncertainty should be compared with the projected statistical uncertainty
 - This is presented in slide 20

SIDIS

- $\ell + N \rightarrow \ell' + h + X$
- The kinematic variables involved are:
- $x_B = \frac{Q^2}{2P \cdot q}$ (Bjorken scaling variable)
- $Q^2 = -q^2$ (negative squared four-momentum transfer)
- $z_h = \frac{P \cdot P_h}{P \cdot q}$ (fractional energy of the detected hadron)
- $P_t = |\vec{P}_{hT}|$ (transverse momentum of the detected hadron with respect to the virtual photon)



Double-Spin Asymmetry LL and Helicity PDFs

- The double-spin asymmetry for a longitudinally polarized beam on a longitudinally polarized target is:

$$A_{LL}^h = f^h P_B P_T \cdot P_{kin} \cdot (A_{1N}^h + \eta A_{2N}^h)$$

- Where P_B and P_T are the beam and target polarization, f^h is the dilution factor ($\sigma_{pol N}^h / \sigma_{all N}^h$)

- The kinematic factor

$$\eta = \frac{2\gamma(1-y)}{2-y}, D = \frac{1 - (1-y)\epsilon}{1 + \epsilon \cdot R}, \epsilon^{-1} = 1 + 2(1 + \nu^2/Q^2 \tan^2(\theta_e/2)),$$

$$P_{kin} = D \cdot \left(1 + \gamma\eta \cdot \frac{1 + R}{1 + \gamma^2}\right)$$

- D is the virtual photon polarization, $R(x, Q^2) = \sigma_L / \sigma_T$ accounts for the longitudinal component of the virtual photon and $y = \nu/E_0$, $\gamma^2(x, Q^2) = 4M^2 x^2 / Q^2$