Studying the Light Sea Quark Asymmetry Using SIDIS with the SoLID using a Longitudinally Polarized 3He Target at 11 GeV (E12-11-007A)

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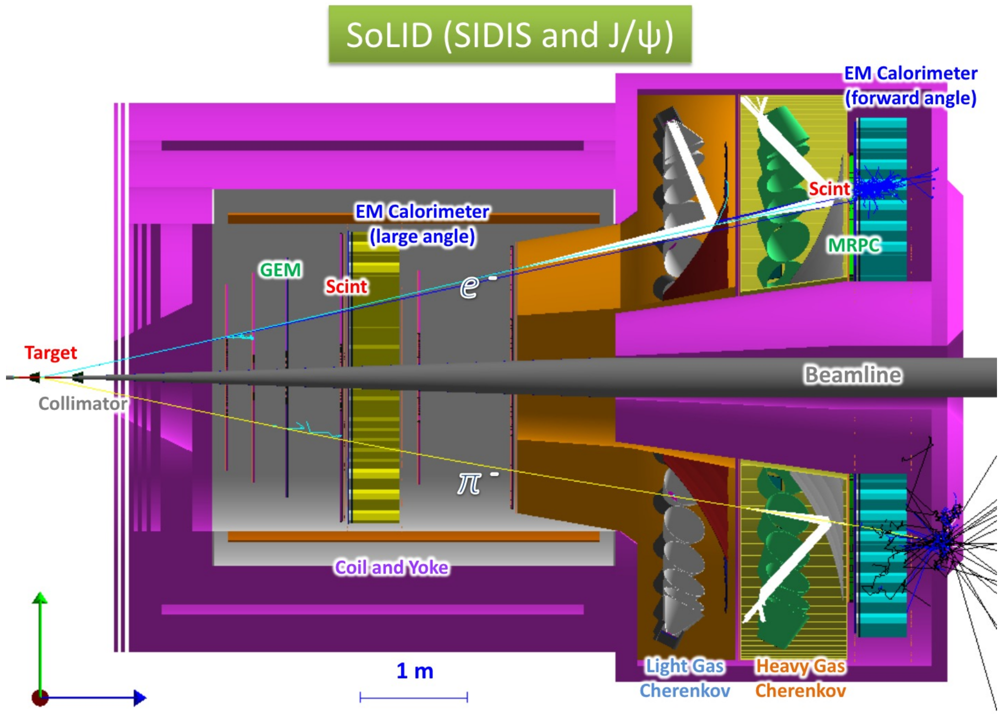
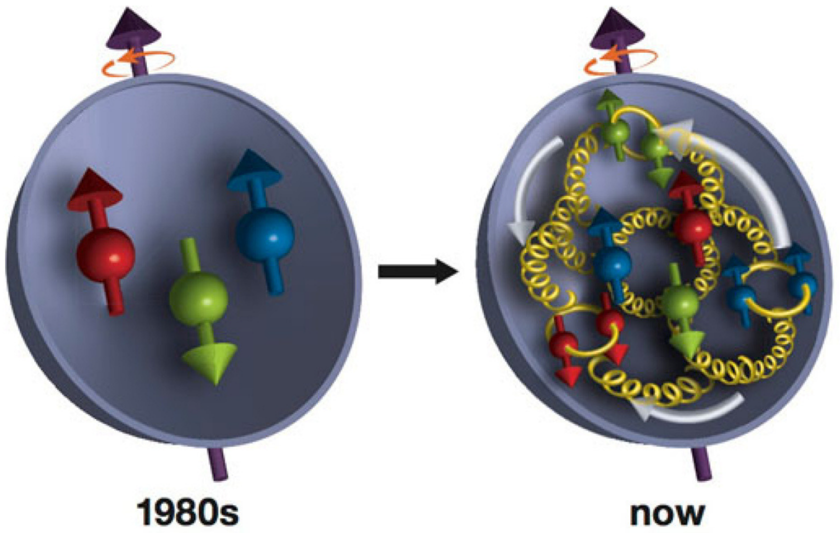
A run group experiment run in conjunction with SoLID ^{3}He SIDIS experiment:

- E12-11-007: Single and Double Spin Asymmetries on Longitudinally Polarized ^{3}He (neutron):
  - Approved number of PAC days: 22.5 days (11 GeV) & 9.5 day (8.8 GeV)
- Reviewed and endorsed by the SoLID collaboration in Feb 2026



Structure of nucleons

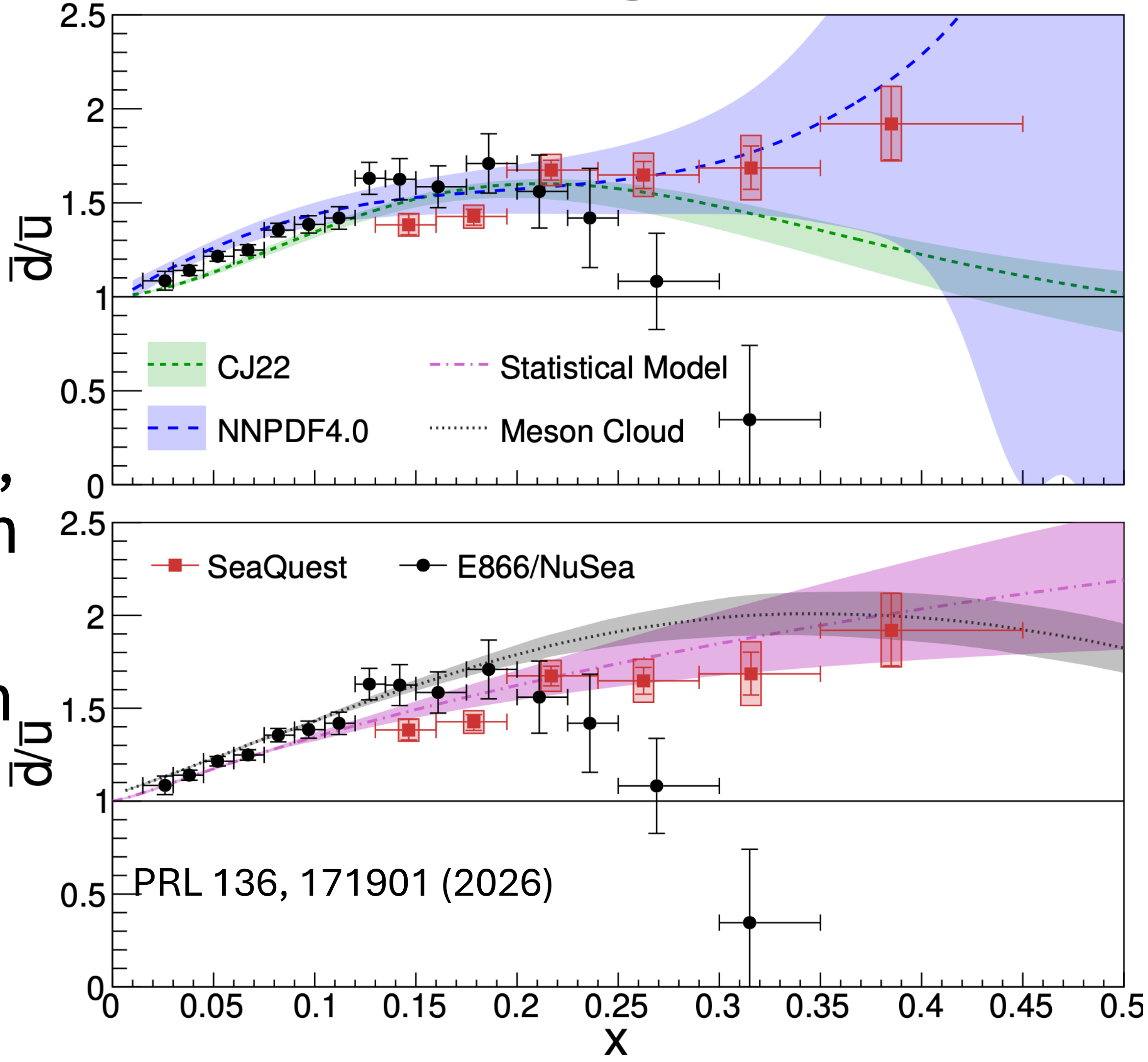
- The nucleon is a dynamical QCD system which consists of quarks and gluons.
- What is the origin of the nucleon sea?
- What is the flavor dependence of the sea quarks?
- How much do the antiquarks contribute to the nucleon spin?



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.

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



Unpolarized ⇆ Polarized Sea connection

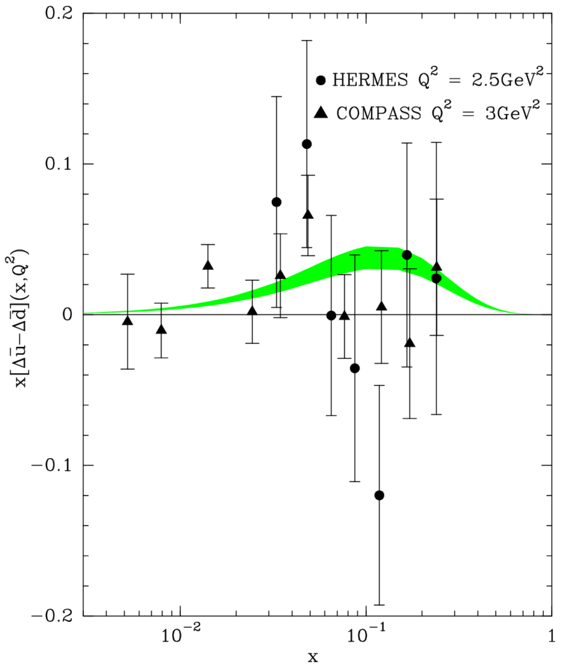
- Various models of the nucleon proposed to understand the non-perturbative nature of the nucleon.
  - Some describe the unpolarized structure very well.
- They have vastly different predictions for $\Delta\bar{u}(x) - \Delta\bar{d}(x)$.

Model	I_Δ prediction	Authors and References
Meson cloud	0	Eichten *et al.*[20], Thomas[21]
(π-meson)	$\simeq -0.007$ to -0.027	Fries *et al.*[22]
(ρ-meson)	$= -6\int_0^1 g_1^p(x)dx \simeq -0.7$	Boreskov *et al.*[23]
($\pi - \rho$ interference)	$\simeq -0.004$ to -0.033	Cao *et al.*[24]
(ρ and $\pi - \rho$ interference)	< 0	Kumano *et al.*[25]
(ρ-meson)	$\simeq 0.12$	Fries *et al.*[26]
($\pi - \sigma$ interference)	$\simeq 0.09$	Cao *et al.*[24]
Pauli-blocking (bag model)	$\simeq 0.3$	Gluck *et al.*[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 *et al.*[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 *et al.*[32, 33]
Statistical	$> \int_0^1[\bar{d}(x) - \bar{u}(x)]dx \simeq 0.12$	Bhalerao[34]

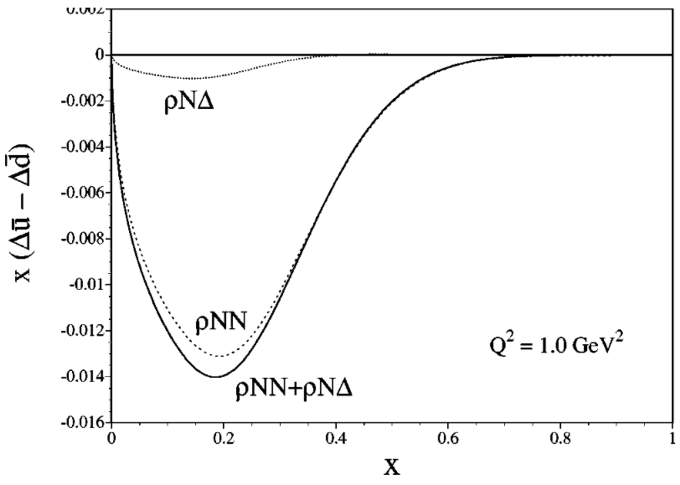
Table 1.1: A summary of theoretical predictions of $I_\Delta = \int_0^1[\Delta\bar{u}(x) - \Delta\bar{d}(x)]dx$. [35]

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

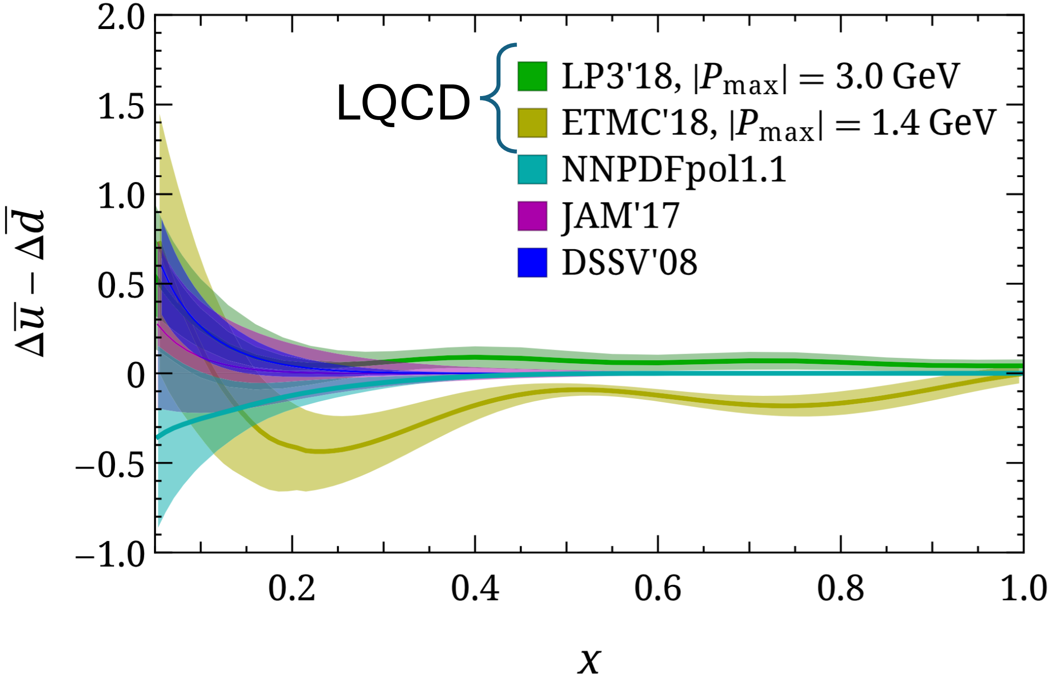
LQCD and Model Predictions



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



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

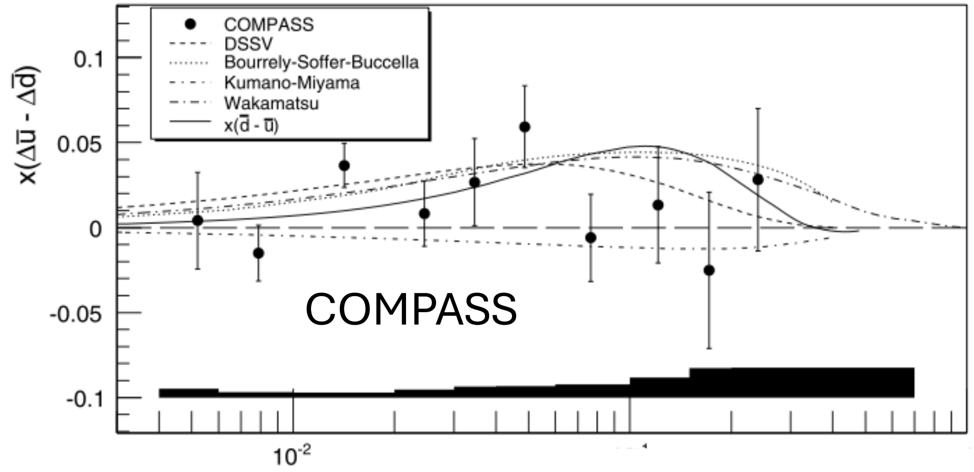


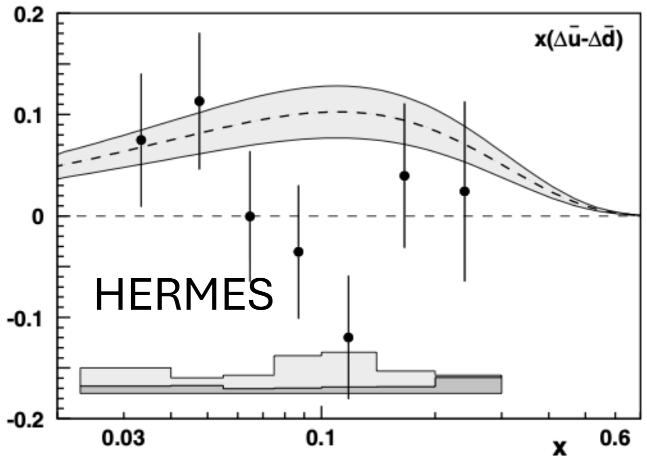
Constantinou etal, Prog.Part.Nucl.Phys. 121 (2021) 103908

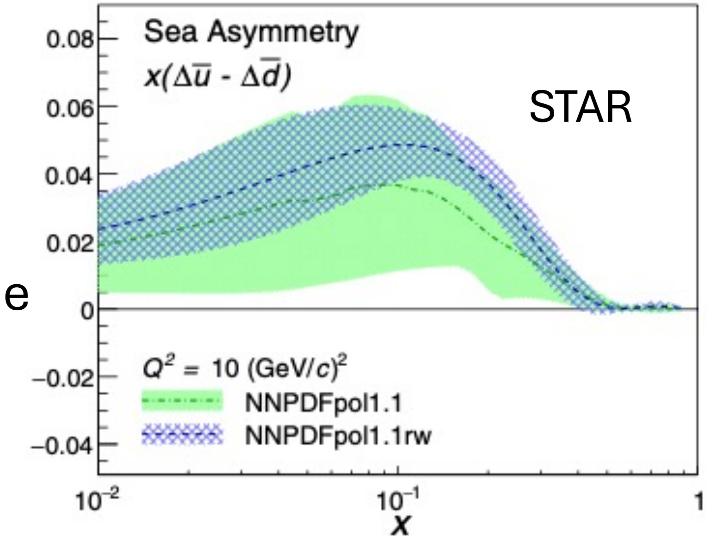
- As Lattice QCD calculations became more reliable, there is more demand for precise experimental data.
  - The difference in the two LQCD results reflect some of the systematic uncertainties in the calculations.

Existing measurements

- HERMES and COMPASS had reported their measurement on the $\Delta\bar{u}(x) - \Delta\bar{d}(x)$ using SIDIS.
  - Both results have modest uncertainties.
- Measurements at RHIC using W production provide some constraints at low x.
- High precision data is essential to map down the contributions and the difference in helicity PDFs.
  - Particularly at modest x, where the current data is sparse.

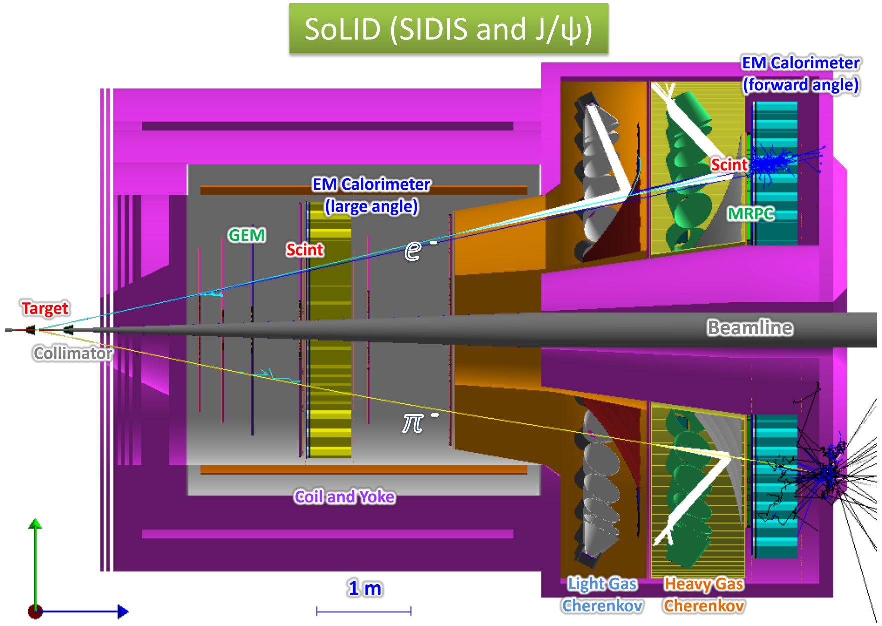






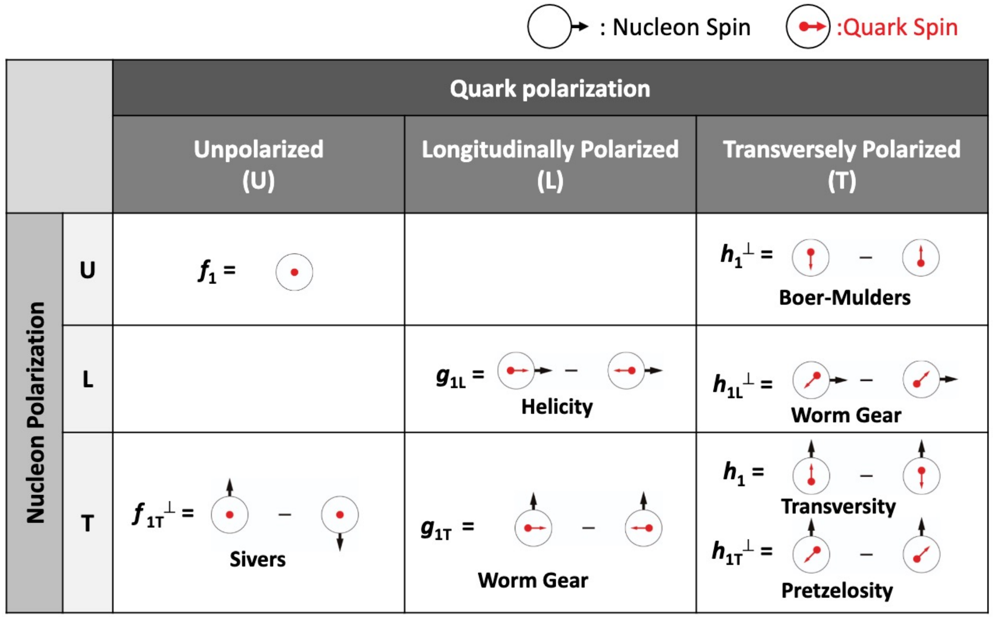
SIDIS with SoLID on polarized ^{3}He

- This run group proposal will run in conjunction with approved SoLID ^{3}He SIDIS experiment.
- ^{3}He target can act as an effective polarized neutron target.
  - The spin of the two protons largely canceled, and less likely to contribute to spin asymmetries.
  - When combined with proton data can provide flavor-separated spin observables.
- The forward angle detectors cover the polar angle from 6.6 to 12 degrees while the large angle side covers 13 to 22 degree.
- Allows access to moderate x (~0.1-0.5) region.
- Offers a powerful opportunity to determine the polarized sea flavor asymmetry.



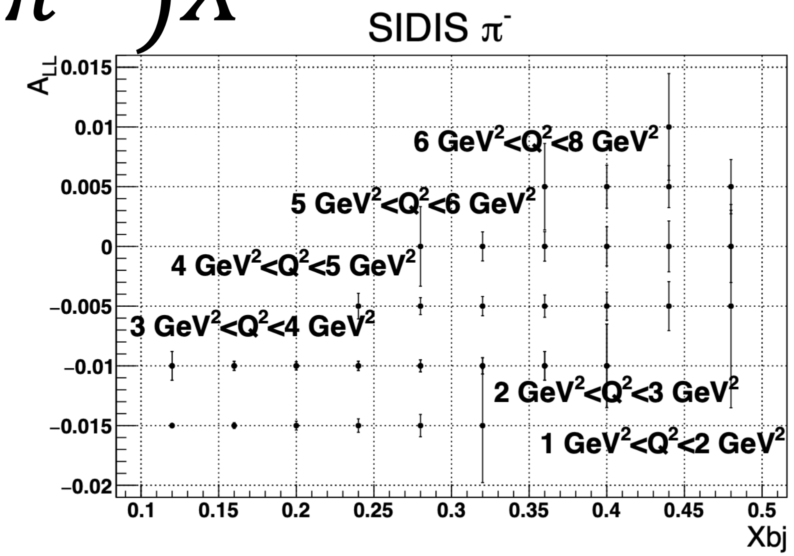
Addition to E12-11-007

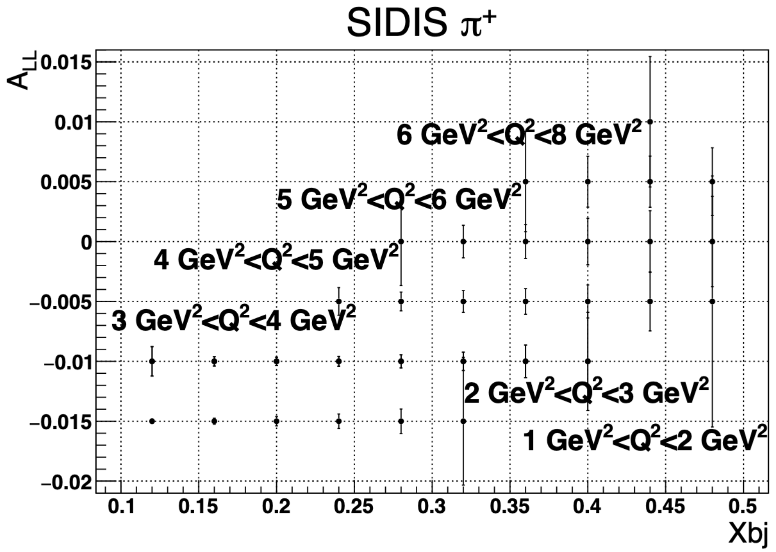
- E12-11-007 mainly focuses on measuring the double spin asymmetry $A_{LT}^{\cos(\phi_h-\phi_s)}$ and the beam single spin asymmetries $A_{UL}^{\sin(2\phi_h)}$
  - Related to the "Worm-gear" TMDs, g_{1T} and $h_{1L}^{\perp}$.
- This proposal would extend it to include the helicity PDF g_{1L} through measuring the double spin asymmetry A_{LL}



Proposed Measurements: Double Spin Asymmetries with $e^{\uparrow}(\,^{3}\mathrm{He}^{\uparrow}, e'\pi^{\pm})X$

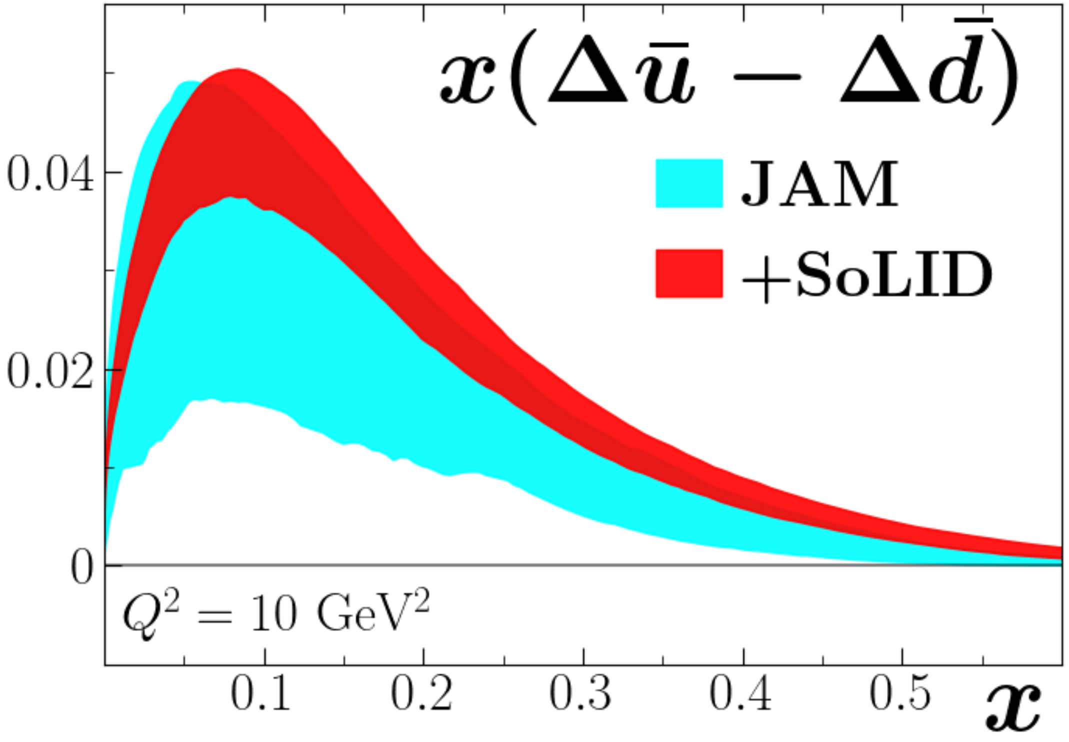
- We propose to measure the double spin asymmetry
$$A^h_{LL}(x_{bj}, P_t, z_h, Q^2) = \frac{1}{P_b P_T}\frac{N^{\uparrow\uparrow} - N^{\uparrow\downarrow}}{N^{\uparrow\uparrow} + N^{\uparrow\downarrow}},$$
- With 22.5 PAC days and 11 GeV beam energy, we expect the statistical error on the ratio to be well within 1%.
- At Leading Order, assuming factorization
$$A^h_{LL} = f^h P_B P_T \cdot P_{kin} \cdot (A^h_{1N} + \eta A^h_{2N})$$
$$A^h_{1N}(x, Q^2, z) \equiv \frac{\Delta\sigma^h x, Q^2, z}{\sigma^h(x, Q^2, z)} = \frac{\Sigma_f e_f^2 \Delta q_f(x, Q^2) \cdot D^h_{qf}(z, Q^2)}{\Sigma_f e_f^2 q_f(x, Q^2) \cdot D^h_{qf}(z, Q^2)}$$
- By measuring both the π^+ and π^-, we can also provide information on the flavor dependence.





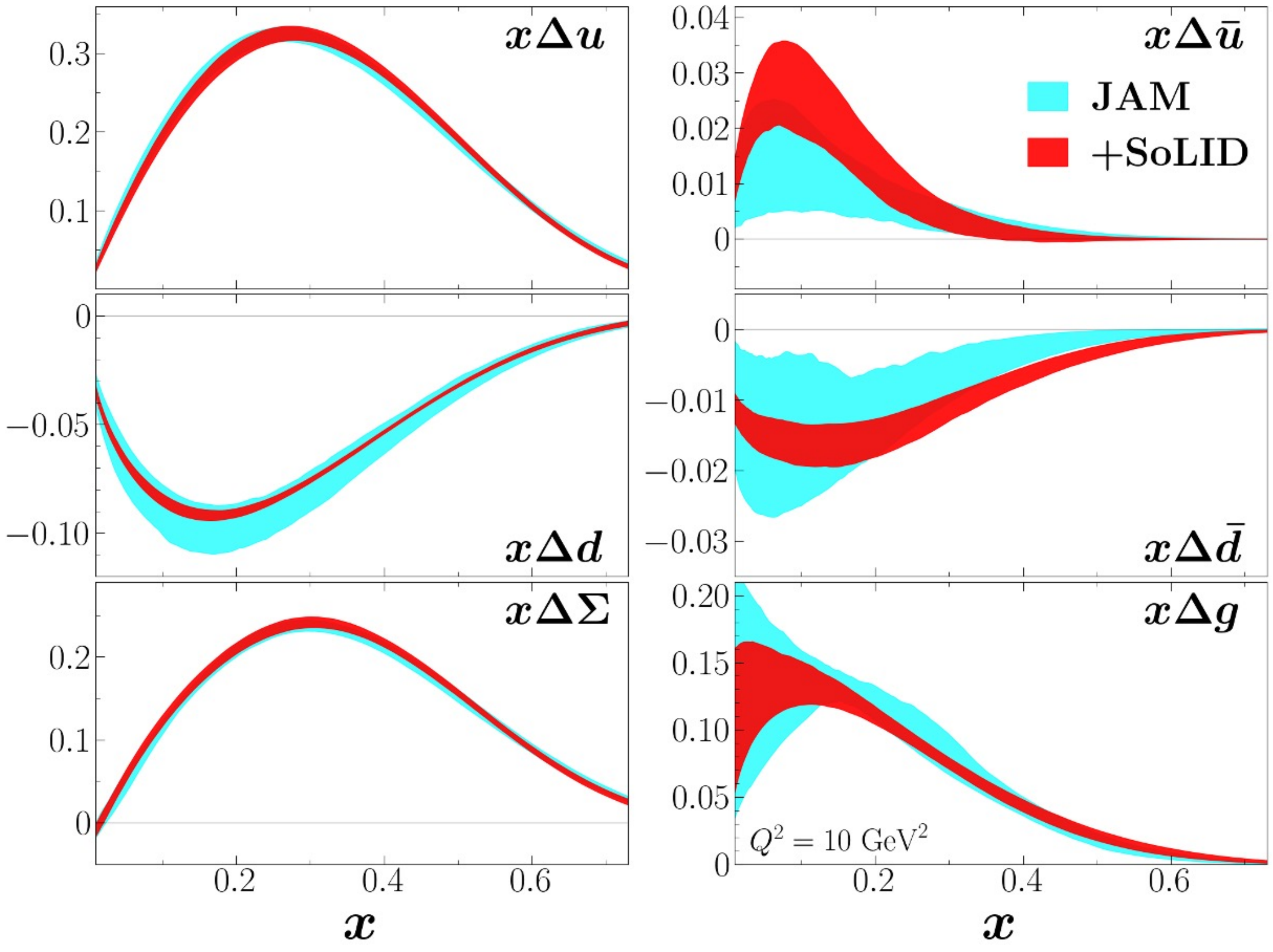
Impact on global PDF analysis

- JAM QCD global analysis framework
  - Next-to-leading order
  - With positivity constraint
  - Including data from:
    - World data on DIS and SIDIS
    - Jet production in polarized pp collisions
    - W/Z boson production at RHIC
    - (And e^+e^- and Drell-Yan for the FF and unpolarized PDFs)
  - With (red) and without (blue) SoLID SIDIS A_{LL} pseudo data
- SoLID's polarized ^{3}He SIDIS data will directly constrain the difference between $\Delta\bar{u} - \Delta\bar{d}$ in the intermediate-x region.



Impact on 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.



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 experiments.

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/$< 9.9\%$

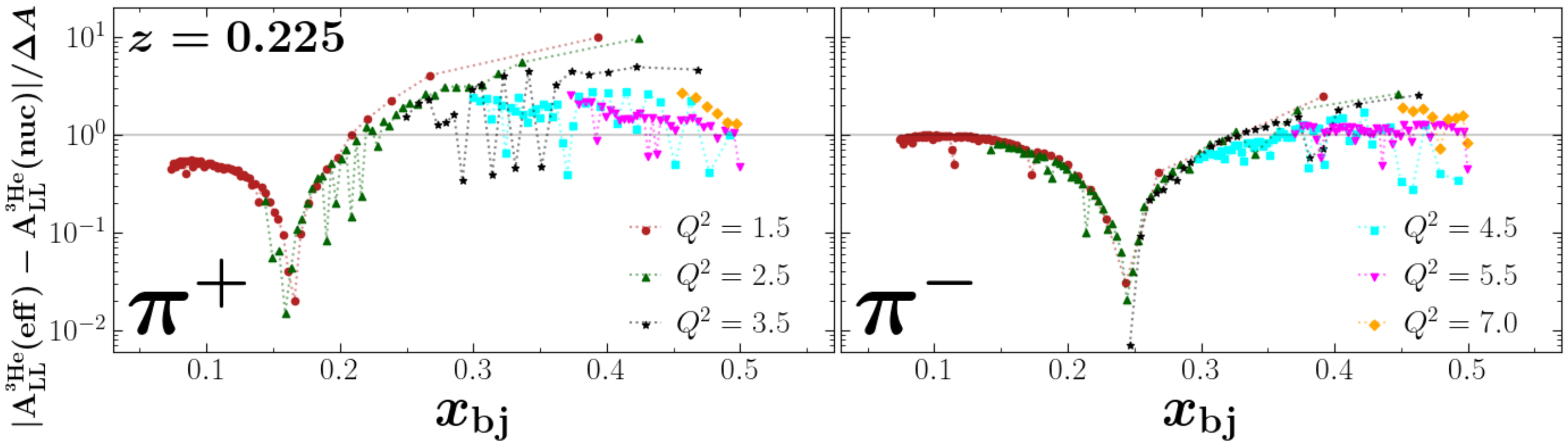
Table 3.1: Systematic uncertainty budget of A_{LL}

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 $Q^2 \sim 2\ \mathrm{GeV}^2$.
- Vector Meson Contamination
  - Exclusive rho mesons may affect large-z, but our choice of kinematics should minimize the effect.
  - Early studies suggest the effect is small.
- Nuclear corrections in ^{3}He treated for neutron extraction
- Radiative correction

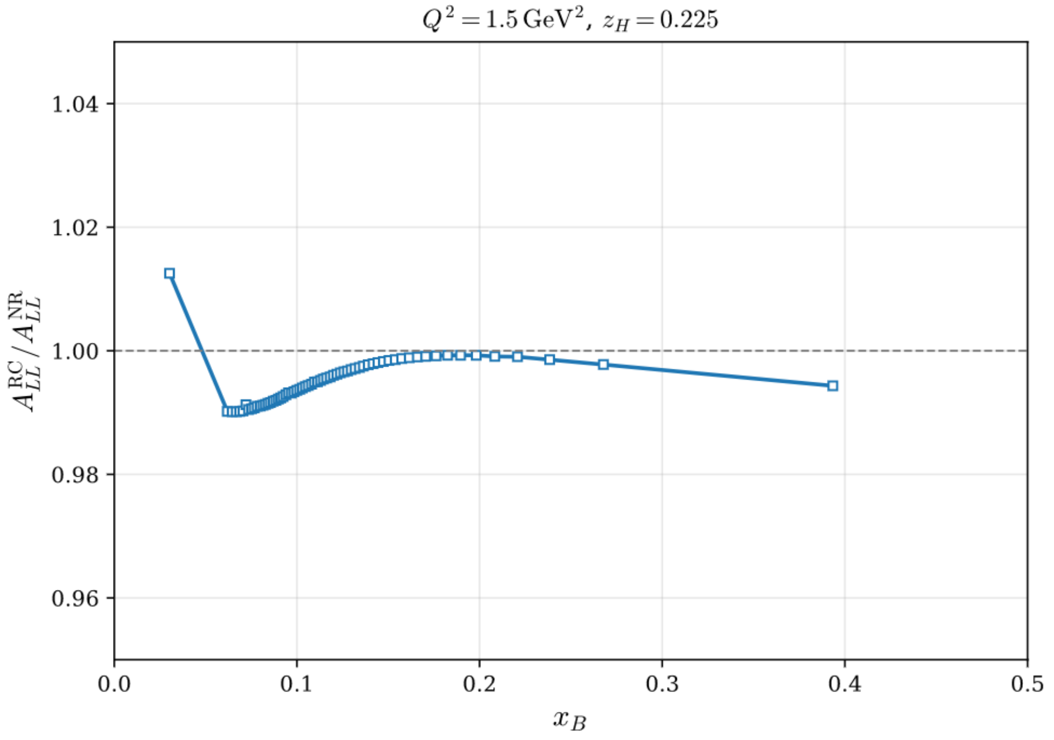
Nuclear corrections

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



Radiative corrections

- The radiative correction effects on the double spin asymmetry A_{LL} are estimated with a traditional approach, with a tuned version of PYTHIA with RADGEN.
- The main uncertainties arise in the high-z, near the exclusive regions, though in our kinematics, contamination from exclusive channels is estimated to be less than 3%.
- A joint QCD-QED factorization is currently being developed.
  - Currently limited to LO, with NLO in the works.
  - Difference in both methods will be compared and contrasted as part of future theoretical work.



SoLID collaboration review

- Extensive recommendations and comments were given in the July 2025 SoLID review
  - Committee: Haiyan Gao, Mark Jones, Zein-Eddine Meziani and Xiaochao Zheng (chair)
1. Comparison with Hall C A1n and CLAS12 proposal E12-09-007
   - A leading order projection is also added to the revised proposal to address suggestions for a more traditional “data point” presentation of “projected results”
2. New theoretical developments on the systematics studies
   - Recent developments regarding QED radiative effects in SIDIS was added to the revised proposal.
3. Several comments on the organization of the text.
   - They were also addressed in the revised proposal.

The revised proposal was reviewed in the February 2026 by the collaboration, and found the comments were thoroughly addressed, and recommends approval.

- Committee: Paul Souder (chair), Zhiwen Zhao, Chao Peng and Mark Jones

PAC Review Comments

- P_T dependence of the asymmetry
  - This proposal focuses on the P_T integrated asymmetry.
  - Some small model uncertainties will be introduced due to the finite acceptance.
- Radiative corrections
  - The joint QED and QCD factorization framework is still being developed.
  - And it is currently limited to leading-order only.
  - Work is ongoing to extend to NLO, and to understand the difference between traditional and joint factorization framework .
- Fragmentation function uncertainties
  - The pion FF should be relatively well understood, should have small impact on the light quarks.
  - The impact study performed under the JAM framework uses projected pion measurement and includes the uncertainties from the fragmentation functions.
  - Future SoLID Kaon SIDIS data could be useful to constrain FF uncertainties.

The full comments and response are listed in the backup slides

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.
- This run group proposal was reviewed and endorsed by the SoLID collaboration.
- The JAM impact study suggests significant impact on global analysis, particularly on the d and $\bar{d}$ quark.

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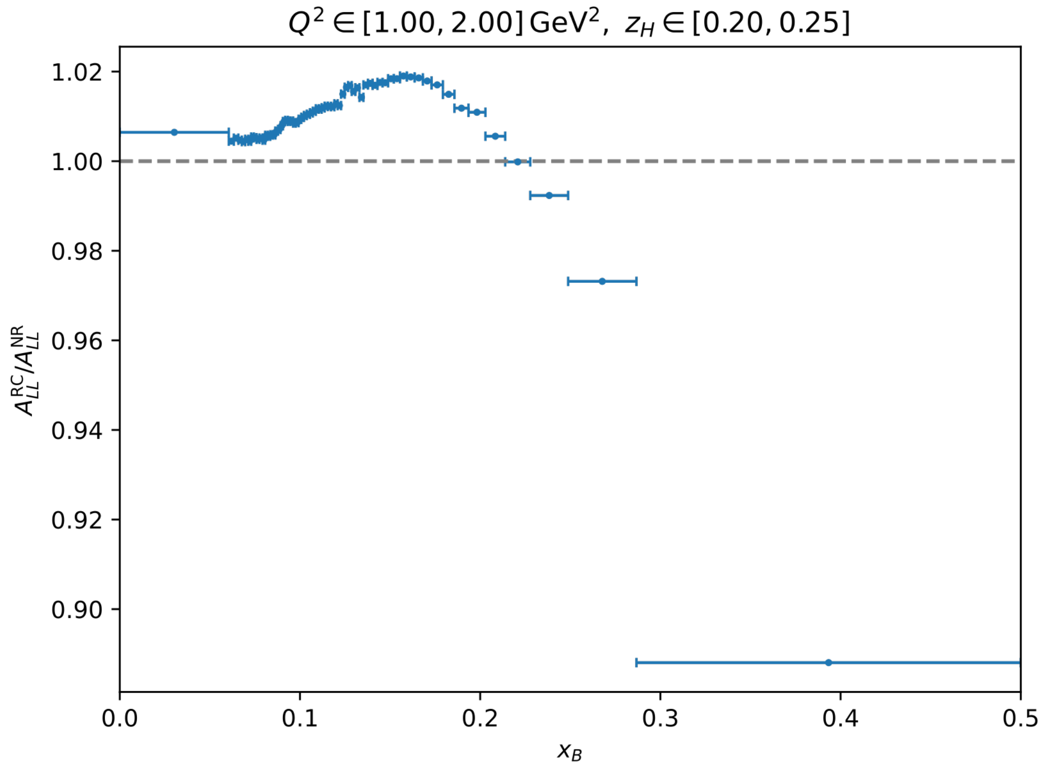
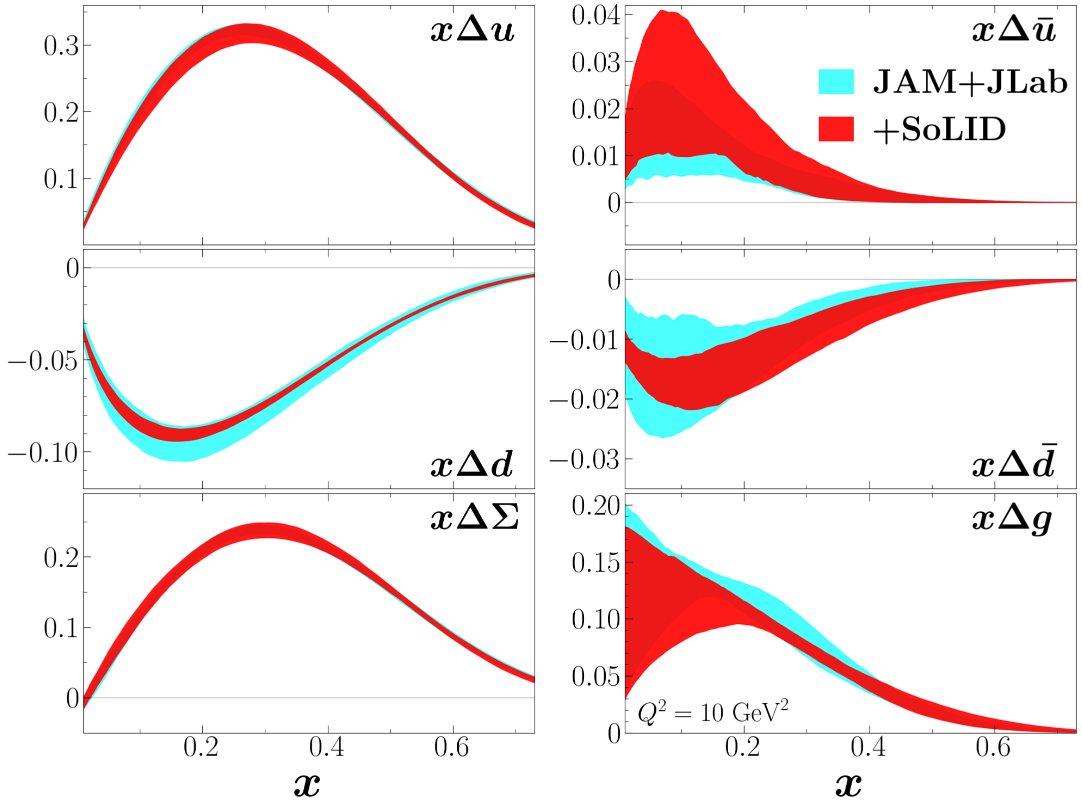
Joint QED and QCD factorization

- Limited to Leading order only, with work on NLO in progress
- The results suggest the effect is most significant at large x_B and small z_H.



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

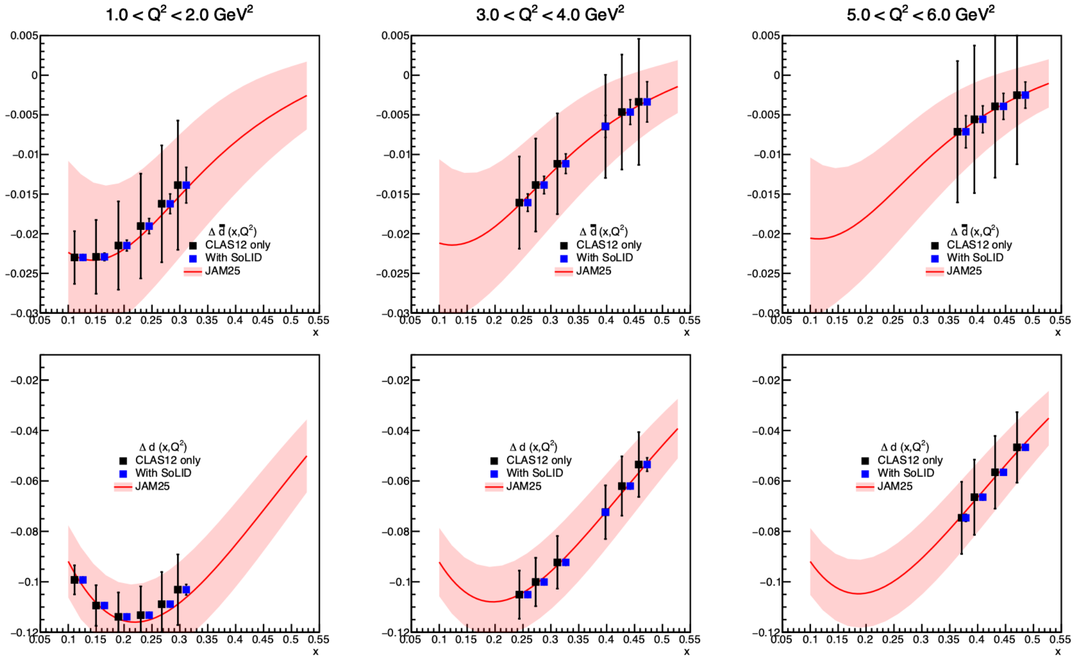


Leading order extraction

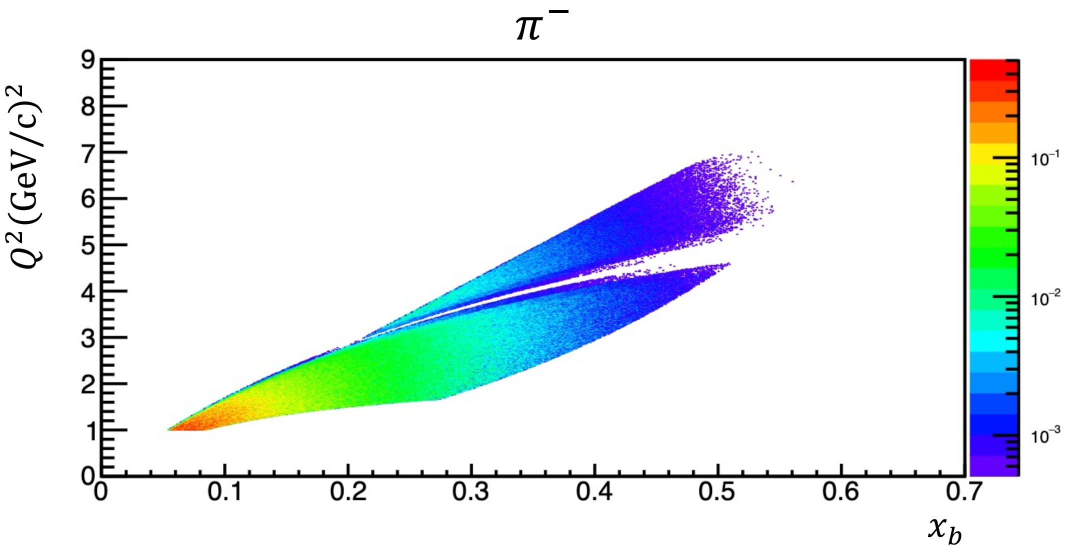
- By assuming $x - z$ factorization

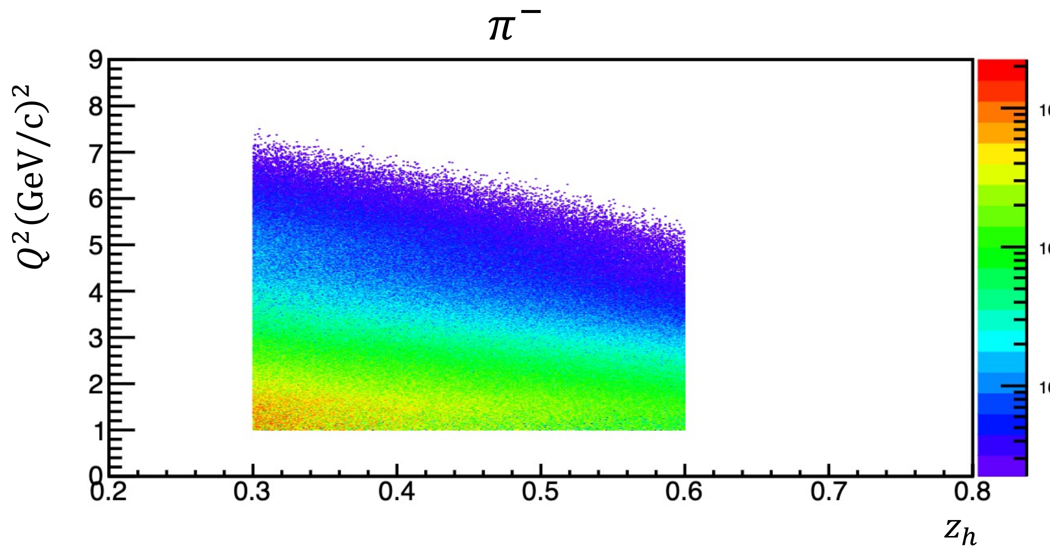
$$A_{1N}^{h}(x, Q^2, z) \equiv \frac{\Delta\sigma^h x, Q^2, z}{\sigma^h(x, Q^2, z)} = \frac{\Sigma_f e_f^2 \Delta q_f(x, Q^2) \cdot D_{qf}^h(z, Q^2)}{\Sigma_f e_f^2 q_f(x, Q^2) \cdot D_{qf}^h(z, Q^2)}$$

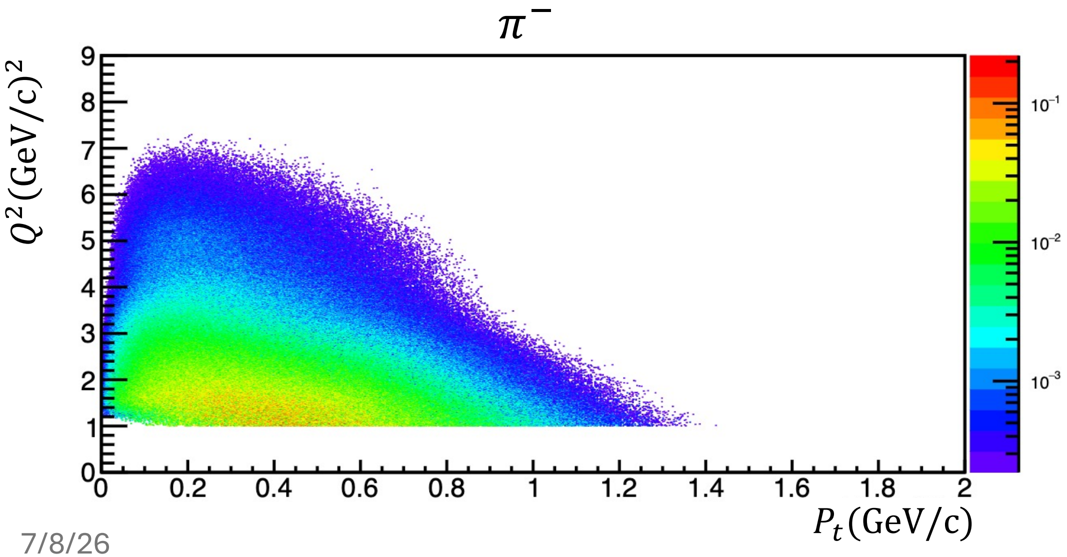
- Here, only the projected uncertainties from CLAS12 proposal is used as the proton data
- From the leading order projection, the solid data will have a significant impact on the flavor separated PDF.

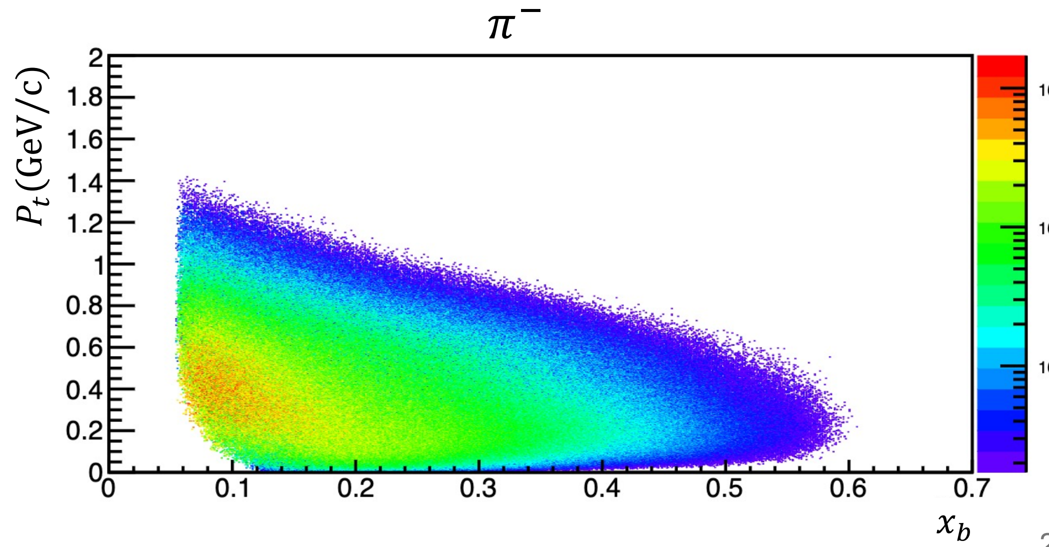


Kinematic coverage









PAC comments

1. At beginning of Sec.2, it is explicitly declared that the proposal wants to extract the light sea-quark helicity asymmetries from measurements of the double longitudinally polarized SIDIS cross section off polarized He3 targets covering the $0.1 < x < 0.5$ and $1.5 < Q^2 < 8 GeV^2$ ranges. Why in several parts of the text the asymmetry A_{LL} is presented as a function also of the transverse momentum p_T of the detected final hadron, like in Eq.(8)? And why is the data going to be binned in 4-dim (x, p_T, z, Q^2) bins (see Secs. 2.6.2, 3.1, 3.6.4) ? And why the need of the detailed discussion about effects from high p_T's in Sec.3.6.3? The proposed helicity asymmetries are collinear objects, functions only of x (apart from the hard scale). Is the collaboration going to measure A_{LL} as a function of x, or also of p_T ?

   Response 1: The experimental data will contain the p_T information. The proposed measurement will integrate over p_T up to the detector acceptance. The finite p_T acceptance introduces some theoretical uncertainties during PDF extraction. The main focus of Sec.3.6.3 is to quantify these uncertainties due to the assumed p_T dependence in the region outside of the SoLID acceptance, and its impact on the PDF extraction. As p_T information will be available, this could lead to a future extension that focuses on TMDs.

PAC comments

2. When comparing with E12-09-007, which runs with polarized deuterium and hydrogen targets, the text stresses the advantage of using ^{3}He targets because the "proton polarization in ^{3}He is much smaller than the proton polarization in deuteron". What has this to do with the claimed reduction in the systematic uncertainty when using ^{3}He vs. deuterium and hydrogen?

   Response 2: The intended point is that polarized ^{3}He serves as an effective polarized neutron target because the two proton spins largely cancel, suppressing the proton's contribution. This reduces the sensitivity of the neutron asymmetry extraction to proton contamination corrections as compared to a deuteron target, where both proton and neutron contributions are significant.

PAC comments

3. The Sec. 2.6.1 could more efficiently be anticipated just before Sec. 1.4, as it describes the general formalism.

   Response 3: Thank you for the comment. We agree this could improve the flow of the proposal.

PAC comments

4. In Sec. 3.3.4, the radiative corrections are discussed in a "traditional" method, leading to the results displayed in Fig.12 and Figs.21-24 of Appendix. And Tab.2 lists the corresponding contribution to the systematic error budget, estimated to be around 3%. However, Appendix A describes the newly proposed joint QED and QCD factorization framework of Refs.[56,57], where the effect at $x > 0.3$ is much larger, of the order of $20 - 30\%$ and more, across all covered values of z and Q^2 (see Figs.17-20). The proposal does not contain any discussion about this issue, nor an estimate of how this different method could impact the total systematic error budget.

   Response 4: The traditional method has been well established and well understood, whereas the joint QED and QCD factorization framework is new and still being developed. For SIDIS double spin asymmetry, currently the joint QED and QCD factorization framework is limited to leading-order only. We expect the NLO effects to be significant, especially at large x. Work to include NLO using the approach is planned. A paper by some of our collaborators is in preparation and its purpose is to compare and contrast these two approaches for SIDIS cross sections, and single spin asymmetries.

PAC comments

5. Sec. 3.4 discusses the impact of projected asymmetries on the helicities of down and anti-down (see Fig.14). The plots contain also the uncertainty band produced by the JAMpol25 global analysis, which however is superseded by the global analysis performed by the same group and described in the following Sec. 3.5. So, what's the purpose of showing the pink bands in Fig.14? Also because that JAMpol25 analysis is affected by a serious theoretical limit, namely that it does not implement positivity constraints, for example allowing the helicity to become in modulus larger than the corresponding unpolarized distribution.

   Response 5: We agree the leading order extraction shown in Fig. 14 is limited compared to the JAM analysis shown in Sec 3.5. However, Fig. 14 demonstrates that the projected impact can be reasonably estimated using leading order methods. JAM25pol was chosen as it is the most recent helicity PDF publicly available at the time. And the uncertainties are similar or smaller than other global analyses, such as NNPDFpol2.0 and DSSV14.

PAC comments

6. I also share the recommendations raised in the Theory Report about a detailed analysis of the propagation of fragmentation function uncertainties in the final extraction, a more careful analysis of nuclear effects in ^{3}He and of possible vector-meson contaminations, and a cautious use of Kaon projections because of potential larger uncertainties in fragmentation functions and particle identification.

   Response 6: The pion FF should be relatively well understood. The impact study performed under the JAM framework includes the uncertainties from the FF. The nuclear effect and vector meson contamination were addressed in sec 3.3.5 and 3.3.6. We agree the Kaon FF is not as well understood. The current proposal impact studies are based on pion projections only. As Kaon data (that is collected using the same detector setup) becomes available, there could be a future proposal that focuses on improving our understanding of strangeness content.

PAC comments

7. Finally, the text should also be revised because of misprints (pi+ and K+ in captions of right panels of Figs.10,11; few lines after Eq.(17), the "GeV^2" should be moved closer to "$Q^2 = 2.5$"), repetitions (few lines after Eq.(14): "the estimated impact of helicity PDFs for d and anti-d are shown in Fig.14", few lines below: "the comparison of the CLAS12 measurement, JAM25pol analysis, and the lead order extraction is shown in Fig.14". Few lines from the end of Sec. 3.6.2: ".. implementation implementation..". Few lines before Eq.(18): "..the the..").

   Response 7: Thank you for pointing these out. We have cleaned them up in the revised text.