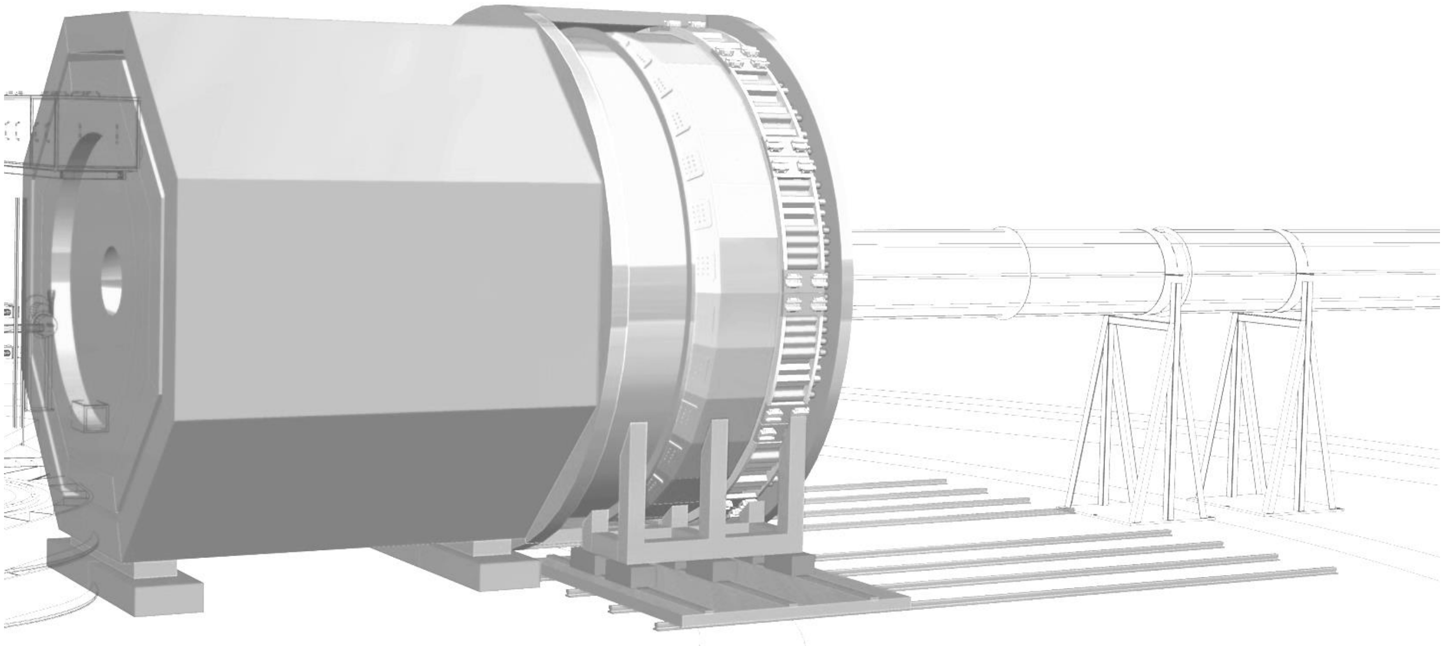
New Developments in SoLID Physics Program



Ye Tian For SoLID Collaboration
6/18/2025

New Development List

Proposals:

- ❑ Double Deeply Virtual Compton Scattering with SoLIDμ spectrometer
  - *Submitted to PAC53---Alexandre Camsonne's talk*
- ❑ TMD Study with SIDIS on Tensor Polarized Deuteron
  - *Under development* https://indico.jlab.org/event/757/contributions/13741/attachments/10537/15866/SoLID-WInter-2023.pdf

Run group proposals:

- ❑ Measurement of the Unpolarized SIDIS Cross Section from a ^{3}He Target with SoLID
  - *Resubmitted to PAC53*
- ❑ Studying the Light Sea Quark Asymmetry Using Semi-Inclusive Deep Inelastic Scattering (SIDIS) with the SoLID using a Longitudinally Polarized ^{3}He Target at 8.8 and 11 GeV
  - *Under development; will be submitted to SoLID ad-hoc review committee and targeted for PAC54*

Other Developments:

- ❑ A1n/g1n measurements
- ❑ Inclusive pion measurements

Measurement of the Unpolarized SIDIS Cross Section from a ^{3}He Target with SoLID

Spokespersons

Umberto D'Alesio — Università di Cagliari & INFN Sezione di Cagliari
Matteo Cerutti — Christopher Newport University & Jefferson Lab
Haiyan Gao* — Duke University
Shuo Jia — Duke University
Vlad Khachatryan — Indiana University & Duke University
Ye Tian — Syracuse University

E12-10-006 collaboration, E12-11-007 collaboration, and the SoLID Collaboration

- **This run group experiment parasitic to SoLID SIDIS experiments of**

- **E12-10-006: Single Spin Asymmetries on Transversely Polarized ^{3}He (neutron):** Rating A
  Approved number of days: *48 days* (*11 GeV*) & *21 day* (*8.8 GeV*)
- **E12-11-007: Single and Double Spin Asymmetries on Longitudinally Polarized ^{3}He (neutron):** Rating A
  Approved number of days: *22.5 days* (*11 GeV*) & *9.5 day* (*8.8 GeV*)

SIDIS Process

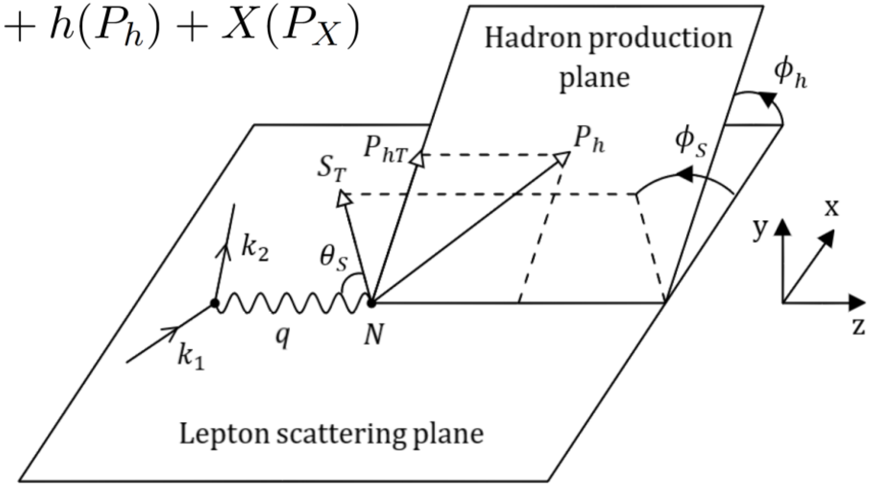
- The SIDIS process represented as (four-momenta given in parentheses)

$$l(k_1) + N(P) \rightarrow l'(k_2) + h(P_h) + X(P_X)$$

- l - lepton beam
- N - nucleon target
- h - produced hadron
- X - undetected hadron
- q – virtual photon momentum

$q \equiv l - l'$

$Q^2 \equiv -q^2$



Azimuthal angle between hadron production and lepton scattering planes designated as ϕ_h

Kinematics of the SIDIS process:
assume one-photon exchange approximation

$$x_{bj} = \frac{Q^2}{2P\cdot q}, \qquad y = \frac{P\cdot q}{P\cdot k_1}, \qquad z_h = \frac{P\cdot P_h}{P\cdot q}, \qquad \gamma = \frac{2M_N x_{bj}}{Q}$$

- Project unpolarized cross-section pseudo-data in **5-D binning**

$$x_{bj}, \; P_{hT}, z_h, Q^2, \phi_h$$

Why Measure SIDIS Unpolarized Cross Section

Multiplicities (HERMES/COMPASS) constrain TMDs, but cross-section measurements are essential to test both the shape and normalization, providing a critical test of TMD factorization beyond leading order.

$$\frac{d\sigma}{dx_{bj}\,dy\,dz_h\,dP_{hT}^2\,d\phi_h} = 2\pi\,\frac{\alpha^2}{x_{bj}\,y\,Q^2}\left(1+\frac{\gamma^2}{2x_{bj}}\right)\times$$

$$\times\left[c_1\,F_{UU} + c_2\cos(\phi_h)\,F_{UU}^{\cos(\phi_h)} + c_3\cos(2\phi_h)\,F_{UU}^{\cos(2\phi_h)}\right]$$

SoLID impact study on F_{UU} is performed using the MAPTMD24 framework with TMD evolution up to NNNLL accuracy.

There are no ϕ_h-dependent terms computed within TMD factorization (obtained within LO parton model)

test of TMD factorization theorems

Access to angular modulations and higher-twist physics

NNNLL means next-to-next-to-next-to-leading-log

SIDIS Unpolarized Cross Section

In LO factorization scheme

$$\frac{d\sigma}{dx_{bj}\,dy\,dz_h\,dP_{hT}^2\,d\phi_h} = 2\pi\frac{\alpha^2}{x_{bj}yQ^2}\left(1+\frac{\gamma^2}{2x_{bj}}\right)\times$$

$$\times\left[c_1\,F_{UU}+c_2\cos(\phi_h)\boxed{F_{UU}^{\cos(\phi_h)}}+c_3\cos(2\phi_h)\boxed{F_{UU}^{\cos(2\phi_h)}}\right],$$

- Use the following Gaussian parameterizations for the TMD PDF and TMD FF

Twist 3 effect: cos ϕ_h dependence

$$F_{UU}^{\cos(\phi_h)} = F_{UU}^{\cos(\phi_h)}\Big|_{\mathrm{Cahn}} + F_{UU}^{\cos(\phi_h)}\Big|_{\mathrm{BM}}$$

- Cahn effect $\propto f_1 \otimes D_1$
  - Non-zero Cahn effect solely requires **non-zero quark transverse momentum**
  - Related to quarks' **intrinsic transverse momentum distribution**

Twist-4 Cahn & twist-2 Boer-Mulders: cos(2ϕ_h) dependence

$$F_{UU}^{\cos(2\phi_h)} \approx F_{UU}^{\cos(2\phi_h)}\Big|_{\mathrm{Cahn}} + F_{UU}^{\cos(2\phi_h)}\Big|_{\mathrm{BM}}$$

- Boer-Mulders effect $\propto h^{\perp}_1 \otimes H^{\perp}_1$
- Twist-4 Cahn effect could have similar size of contribution to cos(2ϕ_h) as Boer- Mulders [Phys. Rev. D. 81:114026 (2010) based on HERMES/COMPASS results]

Systematic Uncertainty Budget for Unpolarized Cross Section

Charged pions

Sources	Uncertainty
Coincidence acceptance correction	8.2%
Experimental resolution	3.5%
Pion detection efficiency	4%
Electron detection efficiency	$< 2\%$
Radiative corrections	2.1%
Vector meson production	1%
Luminosity determination	$\lesssim 3\%$
Total	$\lesssim 11\%$

Charged kaons

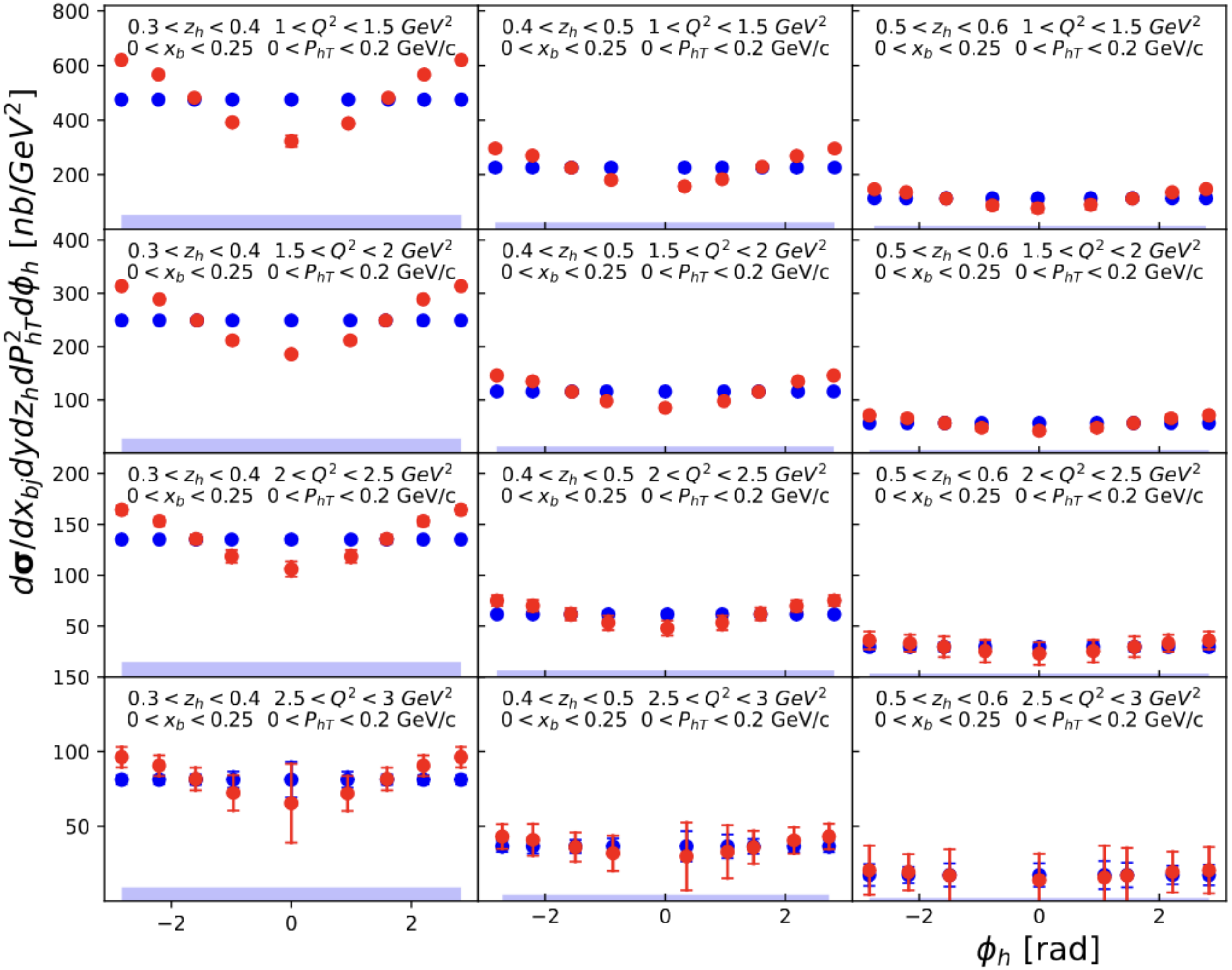
Sources	Uncertainty
Coincidence acceptance correction	$\sim 13\%$
Experimental resolution	3.5%
Kaon detection efficiency	11%
Electron detection efficiency	$< 2\%$
Radiative corrections	2.1%
Vector meson production	1%
Luminosity determination	$\lesssim 3\%$
Total	$\lesssim 18\%$

Total uncertainty calculated by rounding off the quadrature sum of separate contributions

Physics Projections

- Produced **π^+** unpolarized cross section at **11 GeV** beam energy

SoLID low-Q^2 region

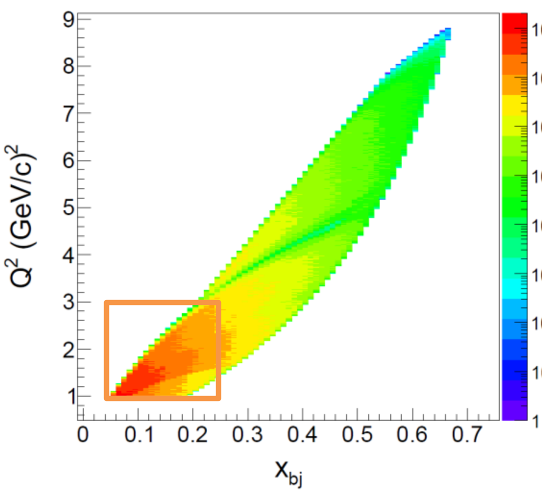


<u>SoLID pseudo-data</u>

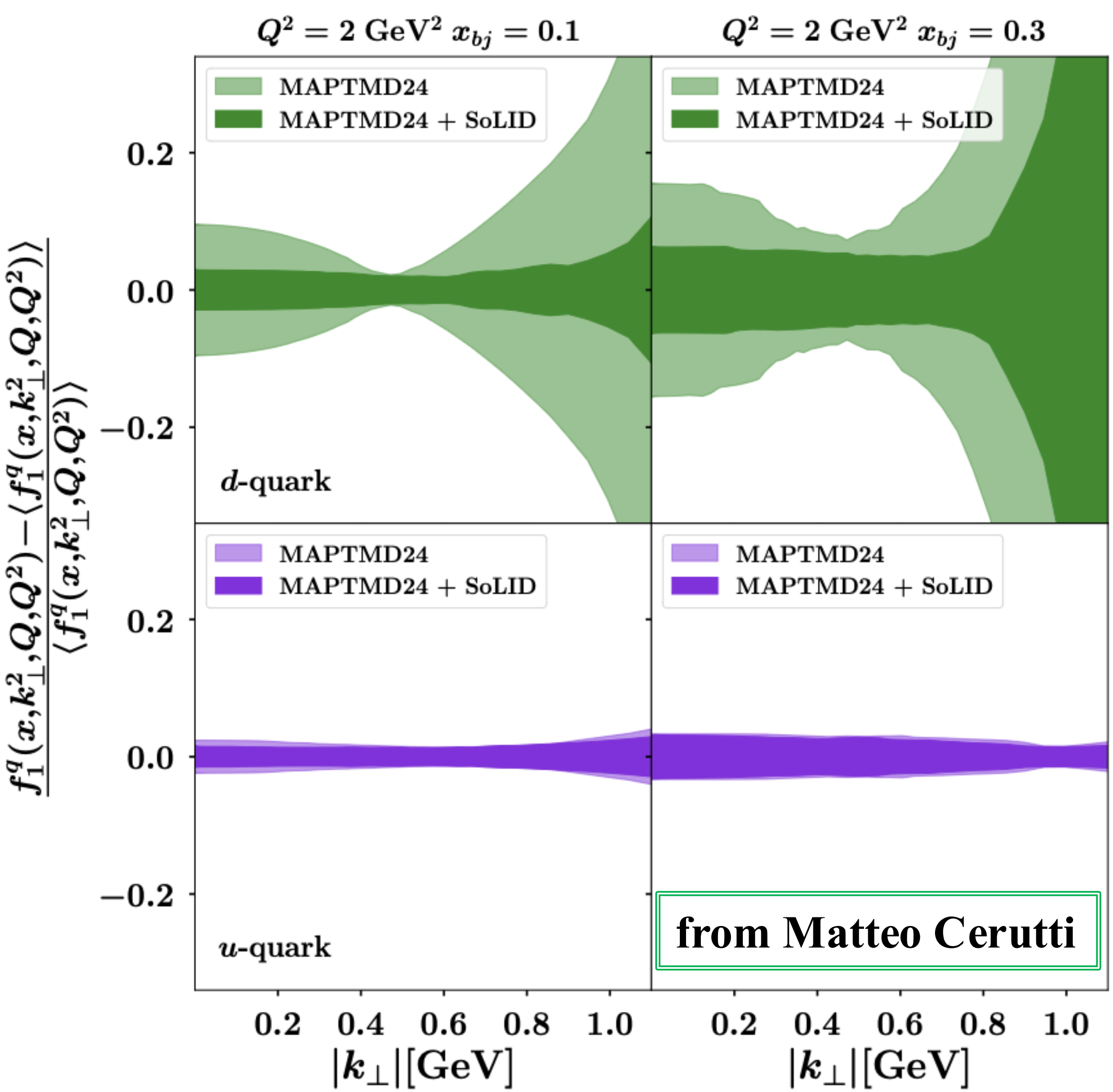
Central points from simple TMD model

Blue points: Integrated cross section

Red points: Cross section including azimuthal modulations



Impact Study of SoLID Pseudo Data



- Final-state hadrons

  π^+ π^-

  K^+ K^-

- Plotted quantity

  $$\frac{f_1^q(x,k_\perp^2,Q,Q^2) - \langle f_1^q(x,k_\perp^2,Q,Q^2)\rangle}{\langle f_1^q(x,k_\perp^2,Q,Q^2)\rangle}$$

- Uncertainty bans account for 68% CL

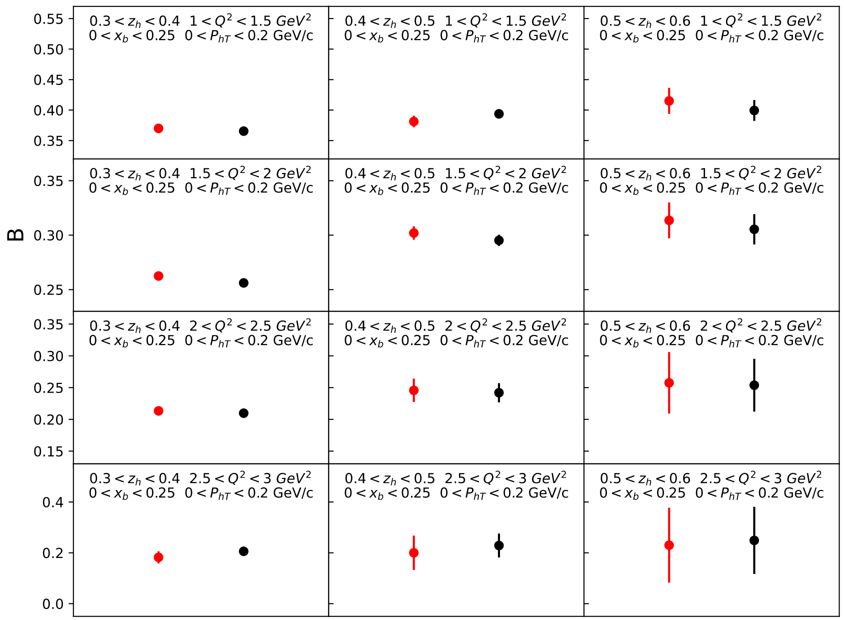
- SoLID greatly reduces the uncertainty on $k_\perp$-dependence for the d-quark.

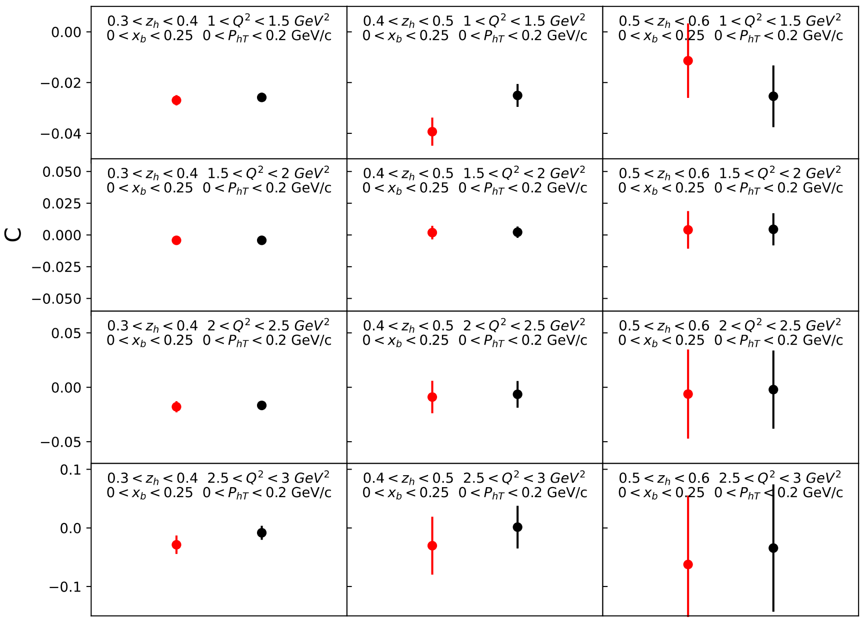
More Physics Projections

- Azimuthal modulation effect

$$\frac{d\sigma}{dx_{bj}dydz_h dP_{hT}^2 d\phi_h} \equiv \mathcal{F}_{UU} = \mathcal{F}_{UU,\mathcal{A}} \cos 0 + \mathcal{F}_{UU,\mathcal{B}} \cos(\phi_h) + \mathcal{F}_{UU,\mathcal{C}} \cos(2\phi_h)$$

Fitting ϕ_h distribution with a simple function: $A(1 - B \cdot \cos(\phi_h) - C \cdot \cos(2\phi_h))$





Red points for π^+, black points for π^-

Transverse Momentum Widths from Azimuthal Modulations

- Transverse momentum widths

$$F_{UU} = \sum_q e_q^2 x_{bj} f_q(x_{bj}) D_q(z_h) \frac{e^{-P_{hT}^2/\langle P_{hT}^2\rangle}}{\pi\langle P_{hT}^2\rangle}$$

$$F_{UU}^{\cos(\phi_h)} = F_{UU}^{\cos(\phi_h)}\Big|_{\text{Cahn}} + F_{UU}^{\cos(\phi_h)}\Big|_{\text{BM}}$$

$$F_{UU}^{\cos(2\phi_h)} \approx F_{UU}^{\cos(2\phi_h)}\Big|_{\text{Cahn}} + F_{UU}^{\cos(2\phi_h)}\Big|_{\text{BM}}$$

where $\langle P_{hT}^2\rangle = \langle p_\perp^2\rangle + z_h^2\langle k_\perp^2\rangle$

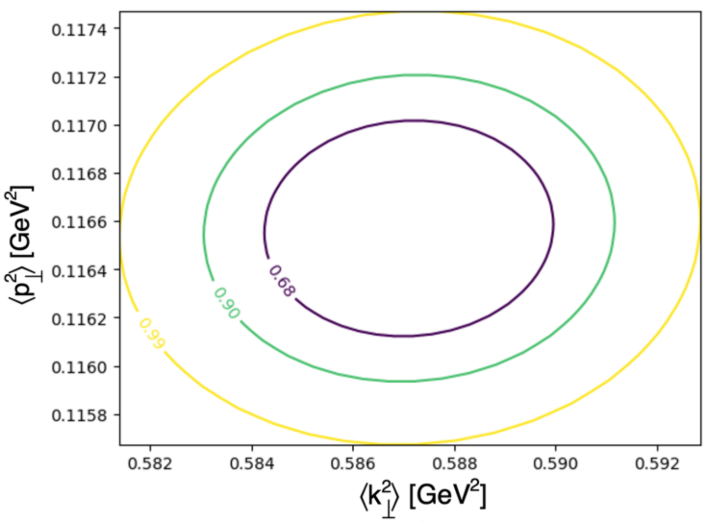
In model, we have (in GeV²)

$< k_\perp^2 >= 0.604, < p_\perp^2 >= 0.114$

$$\text{Least\_Square} = \sum(pseudodata - Model)^2/(stat + sys)^2$$

The fitting results shows (in GeV²):

$$\langle k_\perp^2\rangle = 0.5871 \pm 0.0002 \ (\text{GeV/c})^2$$
$$\langle p_\perp^2\rangle = 0.1165 \pm 0.0003 \ (\text{GeV/c})^2$$



Three contours corresponding to confidence levels of 68%, 90% and 99%

Both Cahn and Boer-Mulders contributions included

All data from positive and negative polarities are considered

The fitting results differs from the model by 4%

By measuring the unpolarized cross section with and without azimuthal modulations, we will be able to extract the Gaussian width parameters $\langle\kappa_\perp^2\rangle$ and $\langle p_\perp^2\rangle$

Studying the Light Sea Quark Asymmetry Using Semi-Inclusive Deep Inelastic Scattering (SIDIS) with the SoLID using a Longitudinally Polarized ^{3}He Target at 8.8 and 11 GeV

Alberto Accardi, Matteo Cerutti
Christopher Newport University and Jefferson Lab, Newport News, VA

Jian-ping Chen, Dave Gaskell, Ching Him Leung, Wally Melnitchouk, Nobuo Sato, and Arun Tadepalli
Thomas Jefferson National Accelerator Facility, Newport News, VA

Christopher Cocuzza
William & Mary, Williamsburg, VA

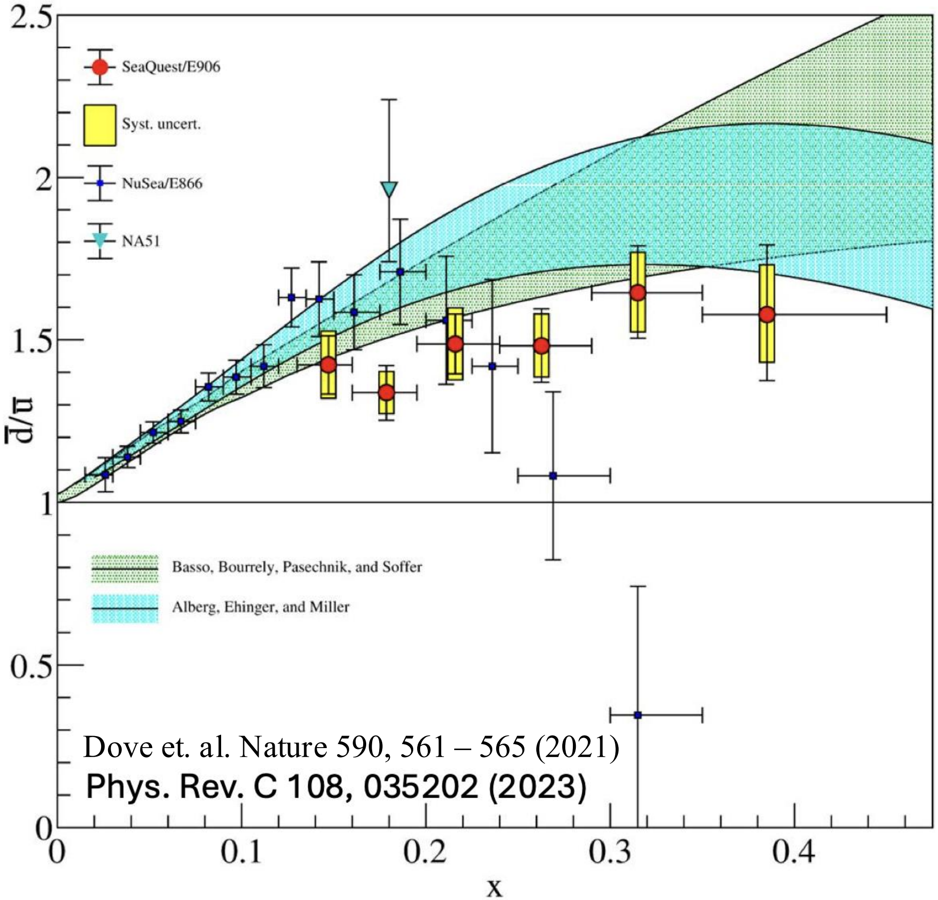
Ye Tian
Syracuse University, Syracuse, NY

E12-11-007 collaboration[†], and the SoLID Collaboration

- **This run group proposal parasitic to SoLID SIDIS experiments of**

- **E12-11-007: Single and Double Spin Asymmetries on Longitudinally Polarized ^{3}He (neutron):**
  Approved number of days: *22.5 days* (*11 GeV*) & *9.5 day* (*8.8 GeV*)

Flavor Asymmetry in Unpolarized Light Sea



✓ **SeaQuest and earlier experiments show $\bar{d} > \bar{u}$ in the proton sea**

- Indicates strong flavor asymmetry in the unpolarized sea

✓ **Consistent with non-perturbative models:**

- Meson cloud models
- Statistical models

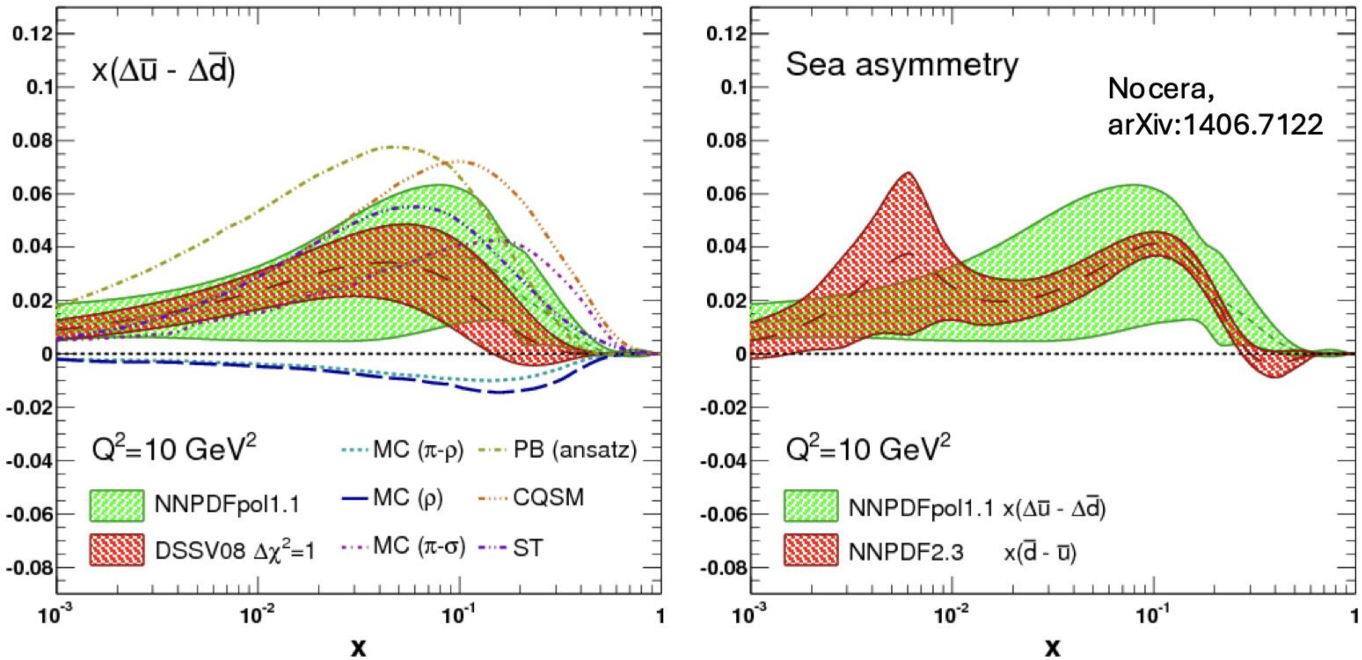
$$\left.\frac{\sigma^{pd}}{2\sigma^{pp}}\right|_{(x_{beam}>>x_{targ})} \approx \frac{1}{2}\left[1+\frac{\bar{d}(x_{targ})}{\bar{u}(x_{targ})}\right]$$

What about spin?

Flavor Asymmetry in Polarized Sea

Models of non-perturbative physics that drive the flavor asymmetry for the unpolarized sector have implications for the spin contribution of the polarized light quark sea.

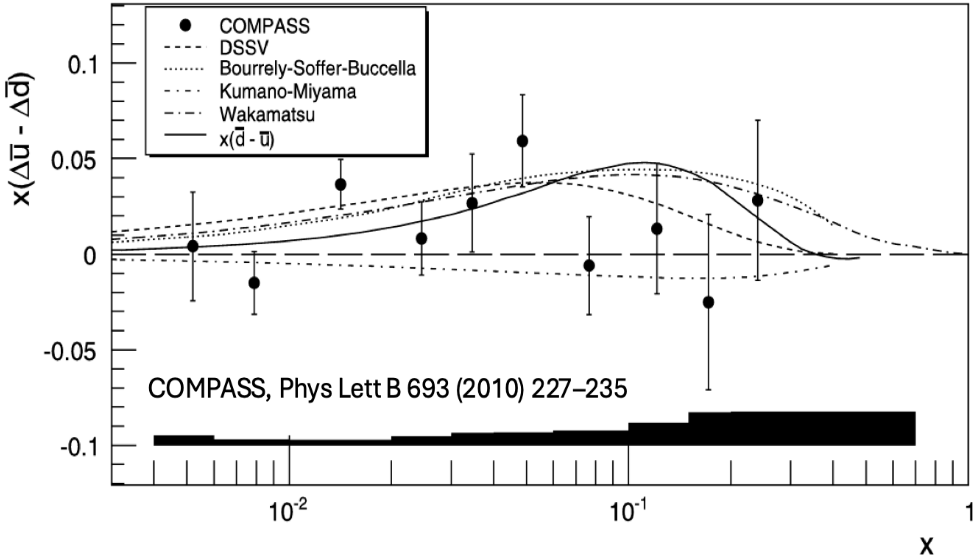
Model Predictions vs Global Fits



- Large uncertainties in $x(\Delta\bar{u} - \Delta\bar{d})$
- Unpolarized flavor asymmetry is well established and attributed to non-perturbative effects (e.g., meson cloud).

- Polarized sea flavor asymmetry $\Delta\bar{u} - \Delta\bar{d}$ is still poorly constrained .
- High-precision SIDIS with polarized ^{3}He targets can provide key insight

Why JLab is Complementary and Promising



- No significant polarized sea asymmetry observed by COMPASS

✓ COMPASS reports a small asymmetry for $x < 0.3$ although with modest uncertainties -> no discriminatory power between models

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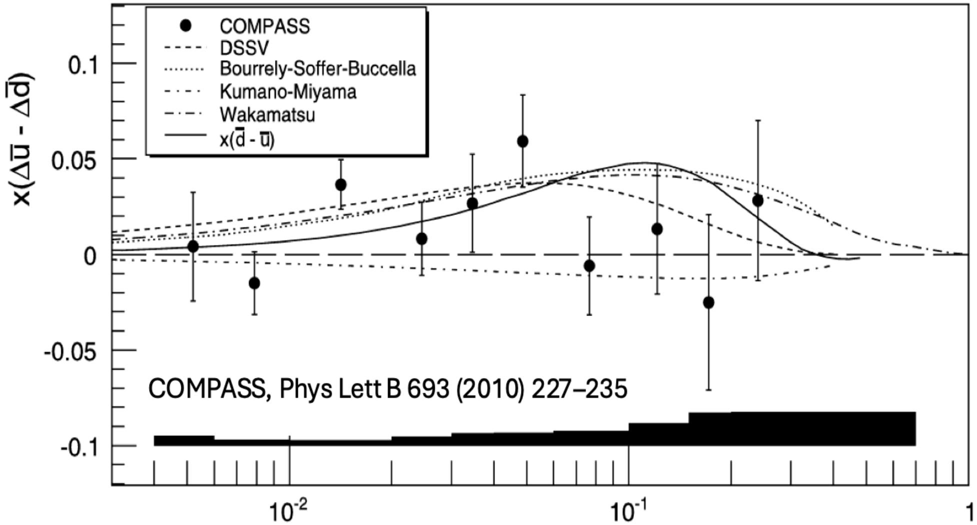

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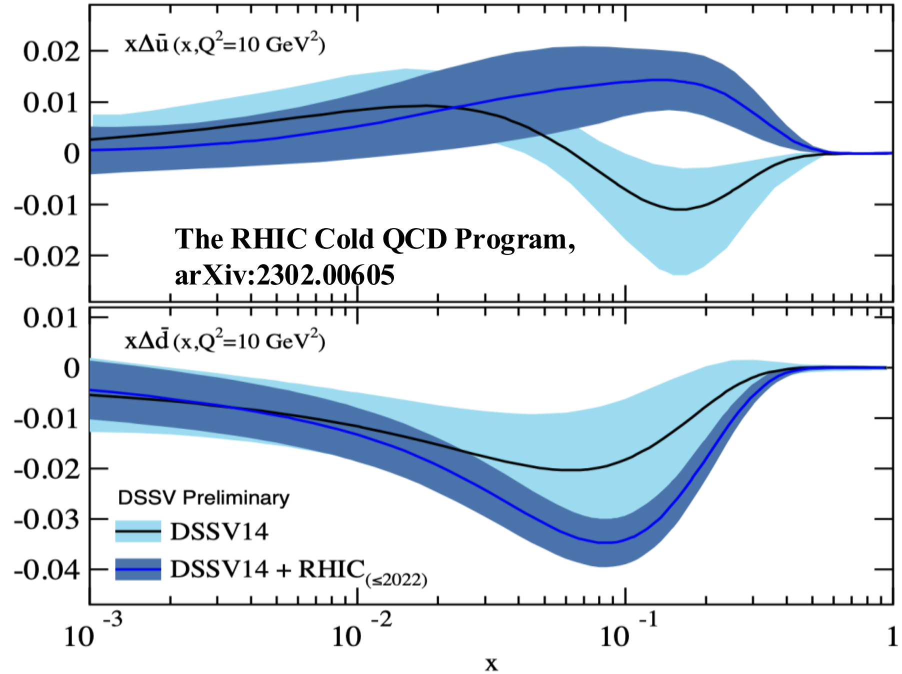
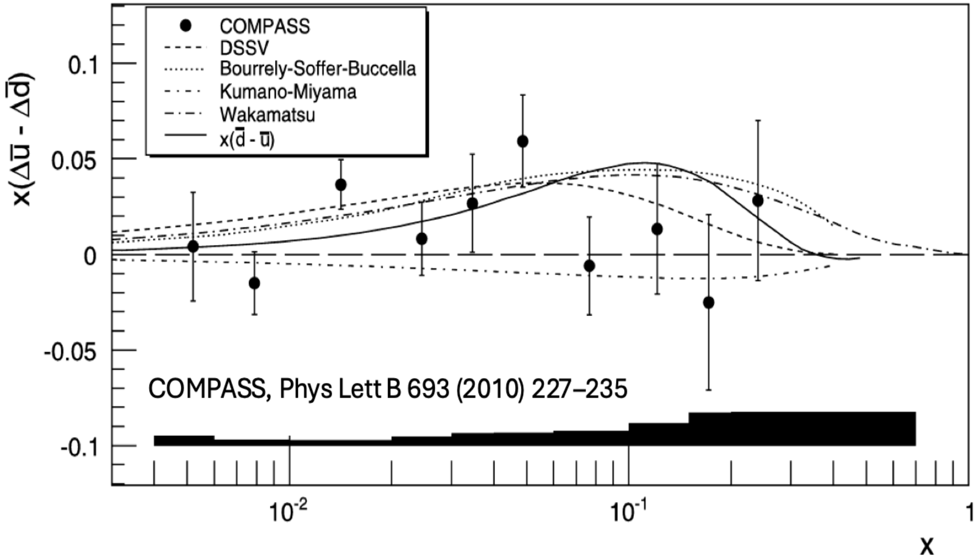


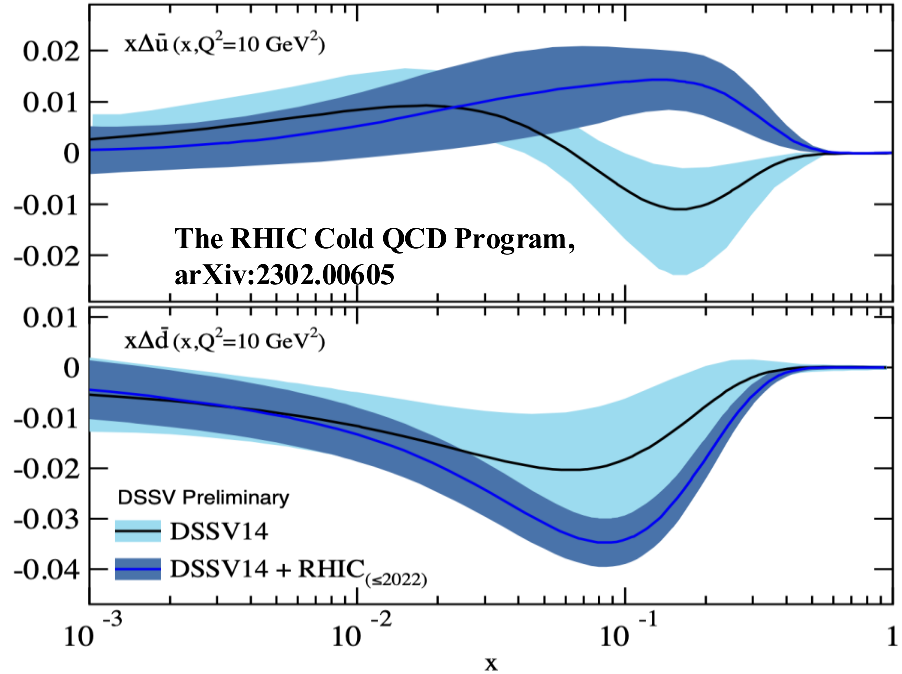
- DSSV14+RHIC indicates an unambiguous non-zero polarized sea asymmetry:

$$x\Delta\bar{u} > 0, x\Delta\bar{d} < 0$$

- The inclusion of RHIC data tightens the uncertainties, improving confidence in the flavor separation.
- **SIDIS on neutron targets** still needed to constrain high-x behavior and full shape

Why JLab is Complementary and Promising





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JLab SoLID SIDIS

- ➢ ^{3}**He target** acts as an effective neutron → gives access to flavor-separated spin observables when combined with proton data.
- ➢ **Valence region** ($x \sim 0.1-0.5$), where some models predict larger polarized sea asymmetry

- DSSV14+RHIC indicates an unambiguous non-zero polarized sea asymmetry:

$$x\Delta\bar{u} > 0, x\Delta\bar{d} < 0$$

- The inclusion of RHIC data tightens the uncertainties, improving confidence in the flavor separation.
- **SIDIS on neutron targets** still needed to constrain high-x behavior and full shape

SoLID's valence-enhanced SIDIS on polarized ^{3}He offers a powerful opportunity to uncover polarized sea flavor asymmetry.

SoLID@JLab: QCD Intensity Frontier

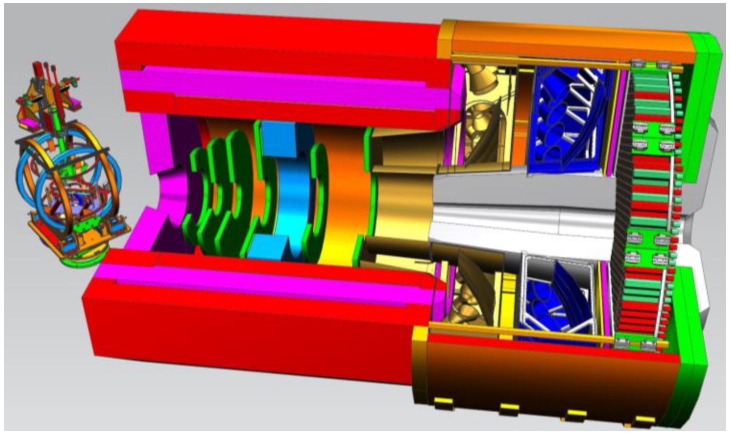
- Nucleon spin, proton mass, beyond standard model experiments require precision measurements of small cross sections and asymmetries, combined with multiple particle detection

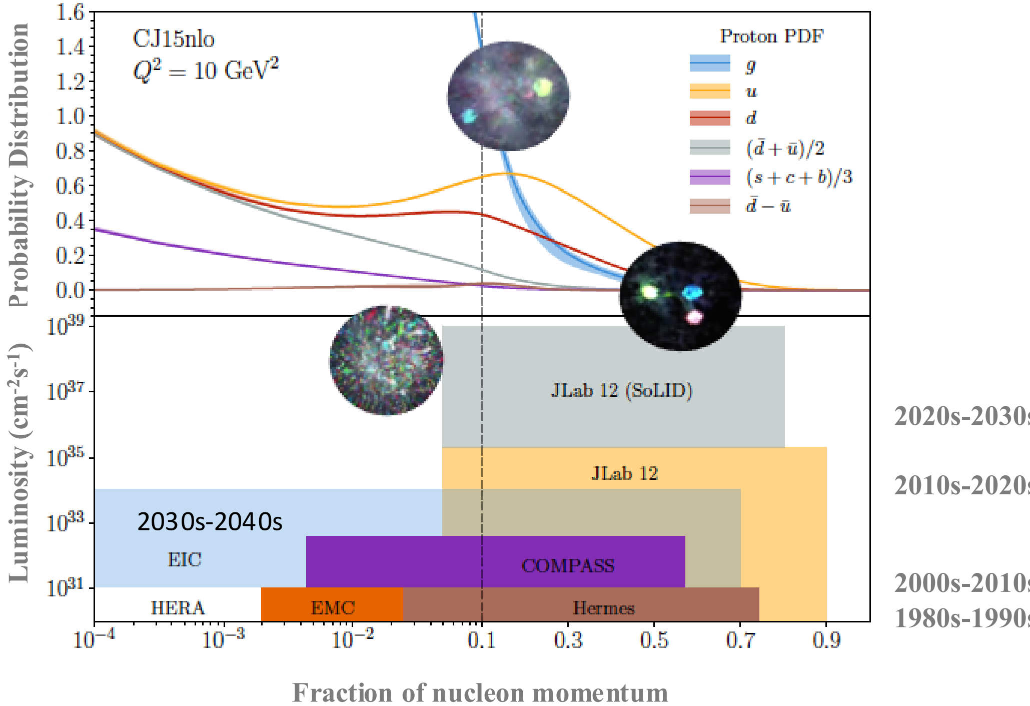
High Luminosity
$10^{37\text{-}39}/cm^2/s$

+

Large Acceptance
Full azimuthal ϕ coverage

- Science reach:
  - Precision 3D imaging of the nucleon in the valence quark region
  - Beyond Standard Model searches
  - Exploring the origin of the proton mass and gluonic force in the non-perturbative regime.





Uncertainty Budget for A_{LL} Measurement

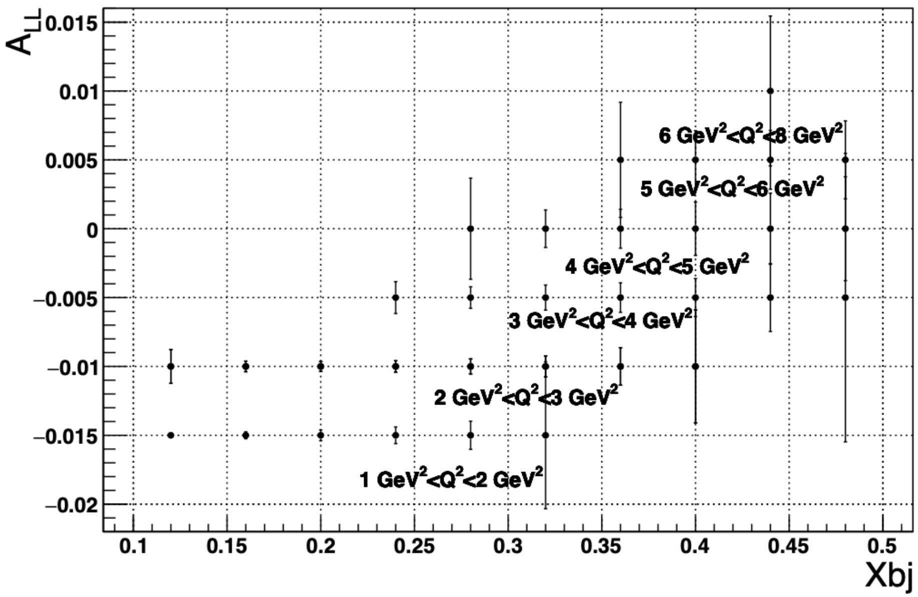
- **Systematic Uncertainty**

^3He	Uncertainty
Raw asymmetry (abs.)	negligible
Random coincidence (Rel.)	1%
Polarimetry (Rel.)	4%
Nuclear effects (Rel.)	$<$ 4%
Diffractive vector meson (Rel.)	3%
Radiative corrections (Rel.)	3%
Total (Abs.)/Total (Rel.)	Negligible/7.1%

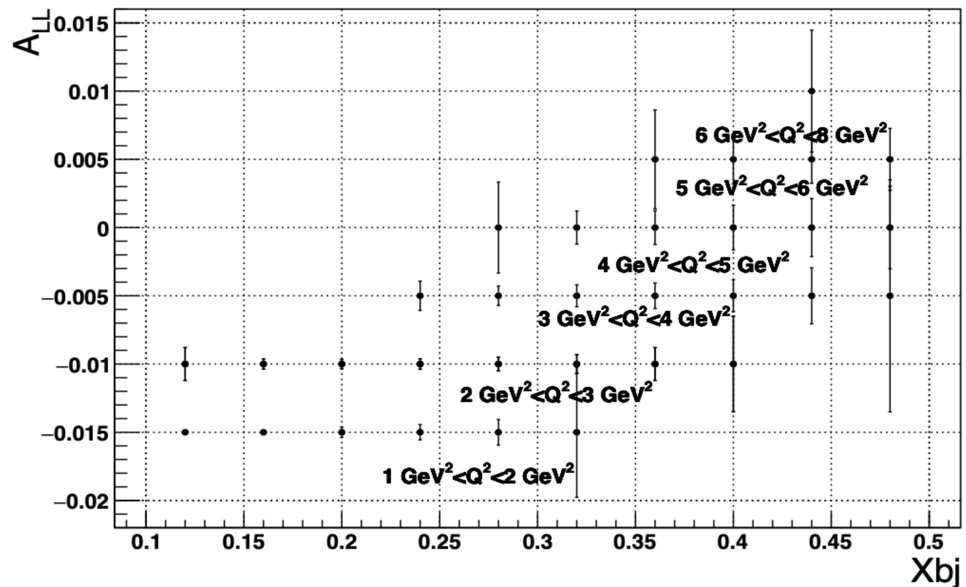
- **Statistic Uncertainty:** $\delta A_{LL} = \frac{1}{P_n P_t P_b}\sqrt{\frac{1}{N_{acc}}}$
  - ✓ Polarized neutron target: ^{3}He
  - ✓ PDF: **CJ15lo; **Fragmentation function: **DSSFFlo**
  - ✓ Dilution factor bin by bin $\boldsymbol{P_n}$ **~ 0.86**
  - ✓ In-beam target polarization $\boldsymbol{P_t}$**: 60%**
  - ✓ Beam polarization $\boldsymbol{P_b}$: 85%
  - ✓ 0 GeV < P_t < 1 GeV, 0.2 < z < 0.6

SoLID @ 11GeV SIDIS Polarized Asymmetries: π/K on n

SIDIS π^+



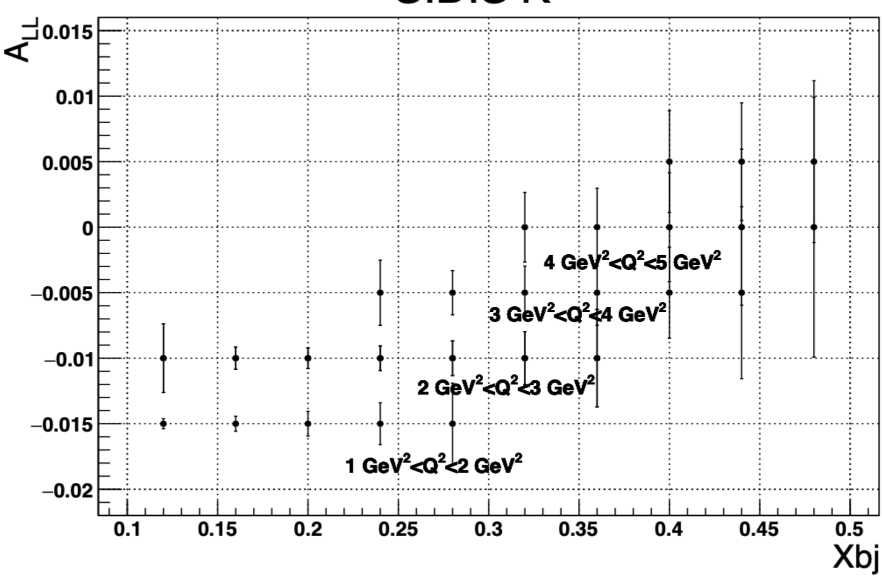
SIDIS π^-

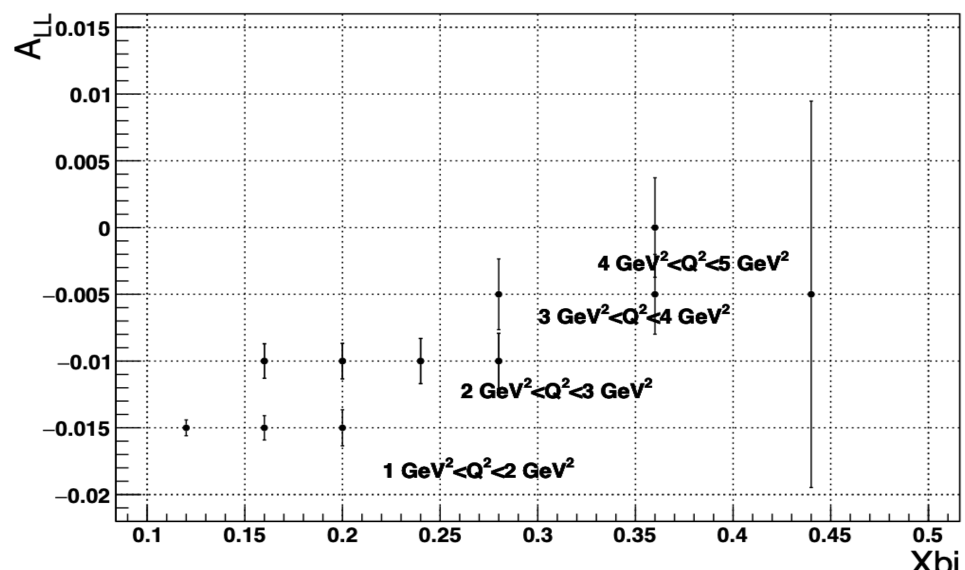


SIDIS K^+

Statistical uncertainty only

SIDIS K^-



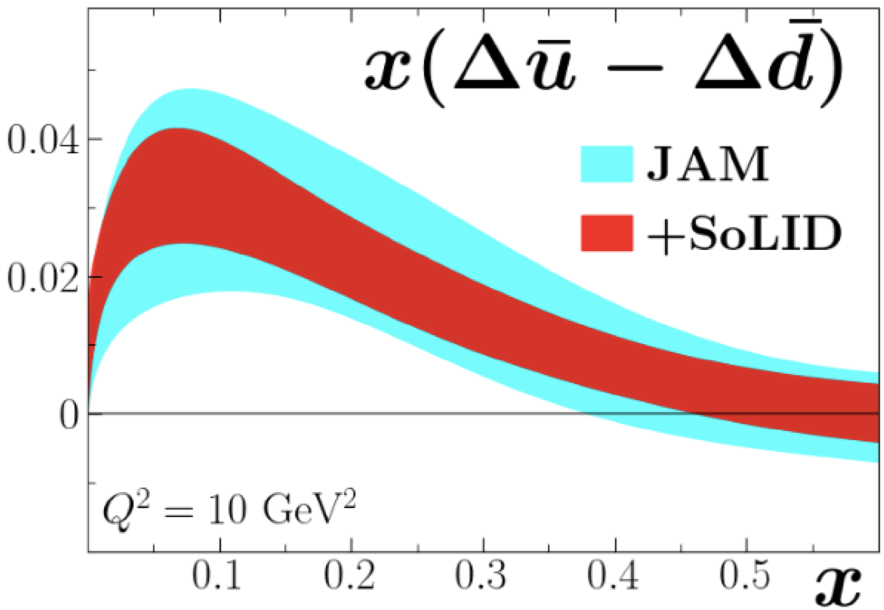


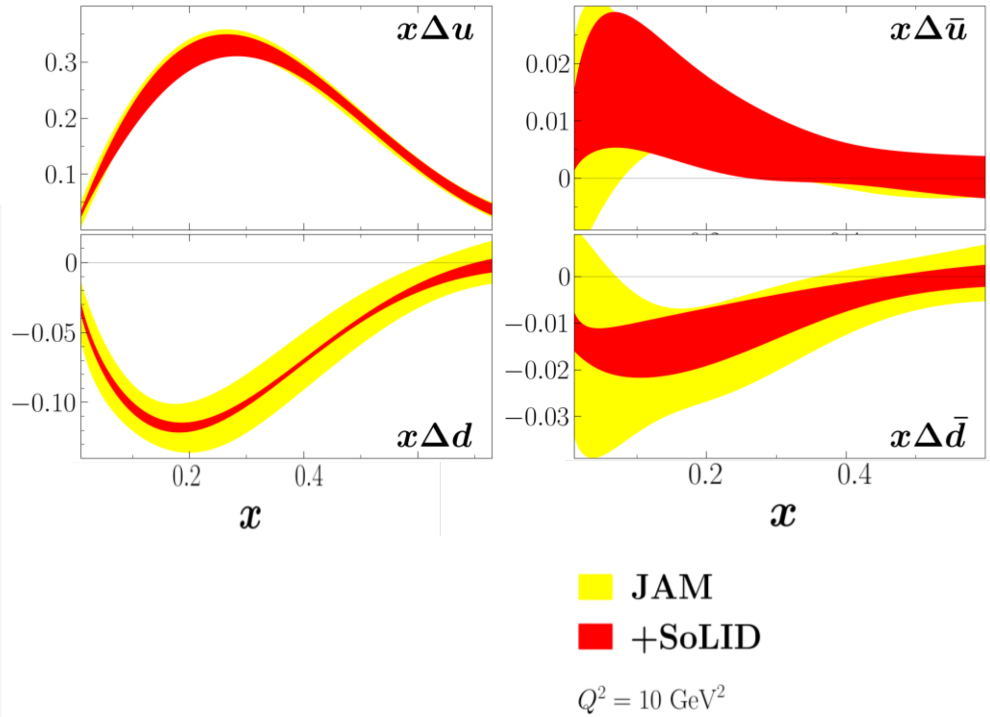
SoLID Constrains Both Sea Asymmetry and Total Sea Polarization

JAM QCD global analysis framework: next-to-leading order accuracy in perturbative QCD

– Inclusive & semi-inclusive DIS A_LL
– Jet production in polarized pp collisions
– W/Z boson production at RHIC

from Christopher Cocuzza





- SoLID helps test if the polarized sea is **flavor asymmetric**, just like the unpolarized sea

- SoLID's polarized ^{3}He SIDIS data will tighten uncertainties on both valence and sea helicity PDFs, with key impact on flavor decomposition and the polarized sea asymmetry.

Theoretical Uncertainties

- **Hadron Mass Corrections**
- Small kinematic shifts in x_B and z_h; **partly cancel in A_{LL} asymmetries**.
- Estimated <10% for pions; kaons may show larger effects.

- **Higher Twist Corrections**
- <5% effect at $Q^2 \sim 2$ GeV^2; **often cancel in spin asymmetries.**
- Absorb residual theory effects in global fits.

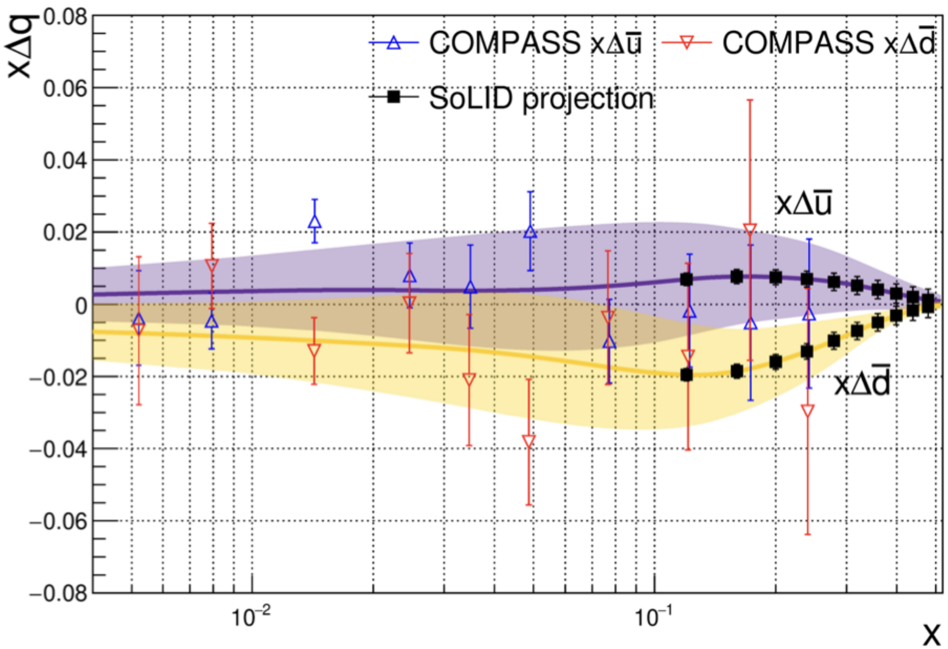
- **Uncertainty from High-P_T Region**
- SIDIS at large P_T not well constrained; TMD factorization not valid.
- We expect the the size of the missing high-P_T is non-negligible, which varies across different kinematic regions.

- **Vector Meson Contamination**
- Exclusive rho mesons may affect large-z, low-P_T region.
- **Small effect on A_{LL} seen in early studies**; more work needed.

- Other Considerations--- collaborate with theorist to address
- Assumptions: charge and isospin symmetry in FFs.
- Nuclear corrections in ^{3}He treated for neutron extraction.
- Possible contamination from non-current fragmentation.

SoLID @ JLab22 SIDIS Polarized $\bar{u}$ and $\bar{d}$ PDFs

- At LO, assuming $x - z$ factorization
- $A_{LL}(x, Q^2, z) = \frac{\sum_f e_f^2 \Delta q_f(x,Q^2) \cdot D_f^h(z,Q^2)}{\sum_f e_f^2 q_f(x,Q^2) \cdot D_f^h(z,Q^2)}$
- Using LO Fragmentation Function DSSFFLO
- The band represent the 67% uncertainty band in NNPDFpol1.1
- The SoLID measurement can reach higher x than previous measurements
- With much reduced statistical uncertainty in the light sea quarks compared to COMPASS



from Ching Him Leung

Summary

SoLID is at the intensity frontier with JLab 12 GeV upgrade:

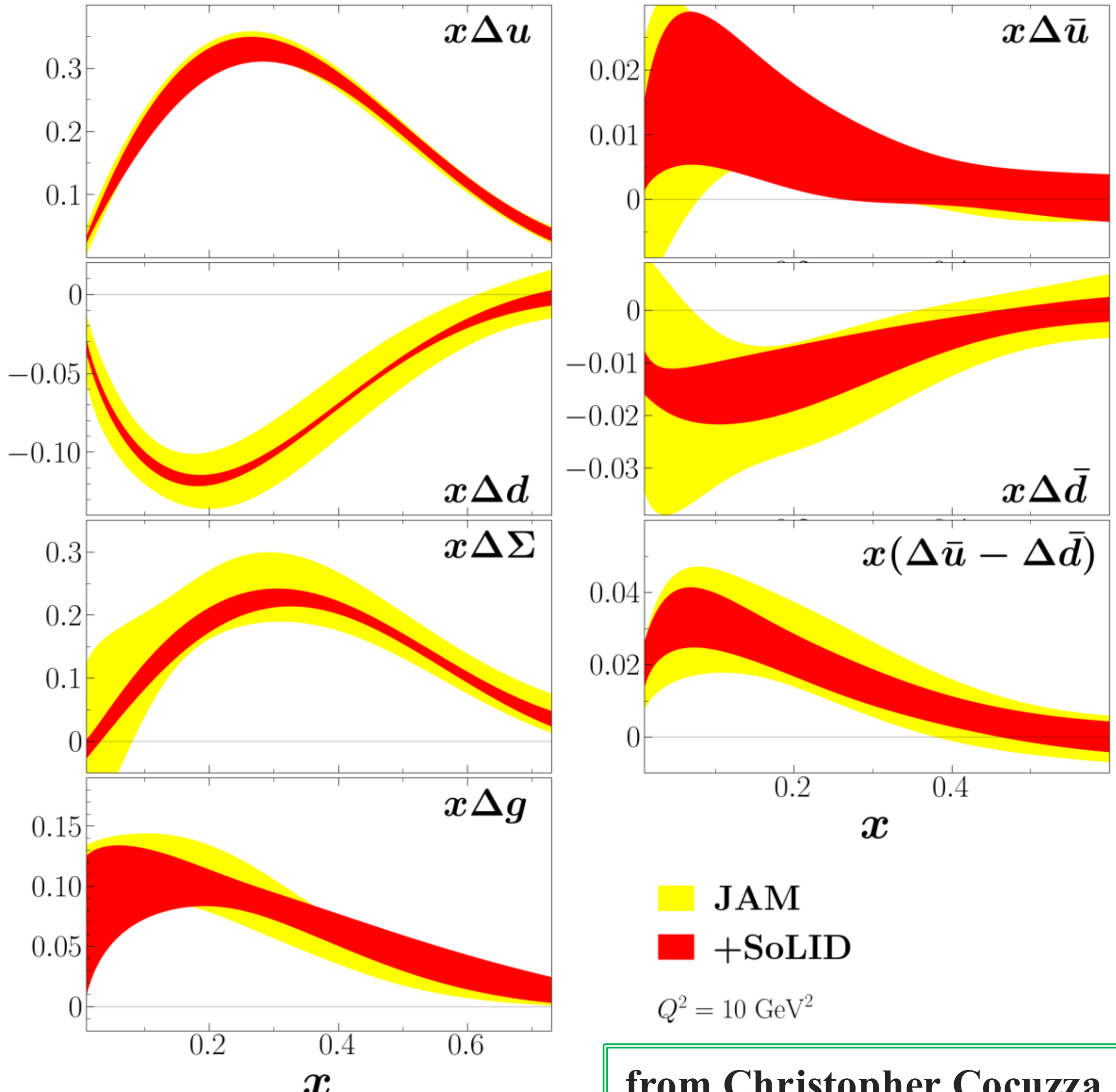
- Rich and highly rated physics programs
- Many other experiments in development
- Address important questions in Nuclear Physics
- Complementary and synergistic to the EIC science programs

Run Group Proposals:

- Unpolarized SIDIS cross section from ^{3}He target (will present at the July 2025 SoLID Collaboration meeting)
  - Simultaneous study of the **shape and absolute normalization of the cross section** enables direct **tests of TMD factorization theorems**.
  - Access to **azimuthal modulations** and **flavor dependence** of TMDs; potential to explore **higher-twist effects** and their angular signatures.
  - Measurements with a ^{3}He target are sensitive to **EMC effect**, **nuclear binding**, **Fermi motion**, and **off-shell corrections**
- Light Sea Quark Asymmetry via SIDIS with polarized ^{3}He at 8.8 & 11 GeV (under development, targeting PAC54 submission)
  - Global QCD fits using the **JAM framework at NLO accuracy** show promising sensitivity to polarized sea asymmetry and total sea polarization
  - SoLID's **high-statistics neutron SIDIS** measurements offer precision in the valence-to-sea transition region.
  - Improve the text and address the remaining theoretical systematics

Backup

SoLID ^{3}He SIDIS Sharply Improves Constraints Across All Polarized PDFs



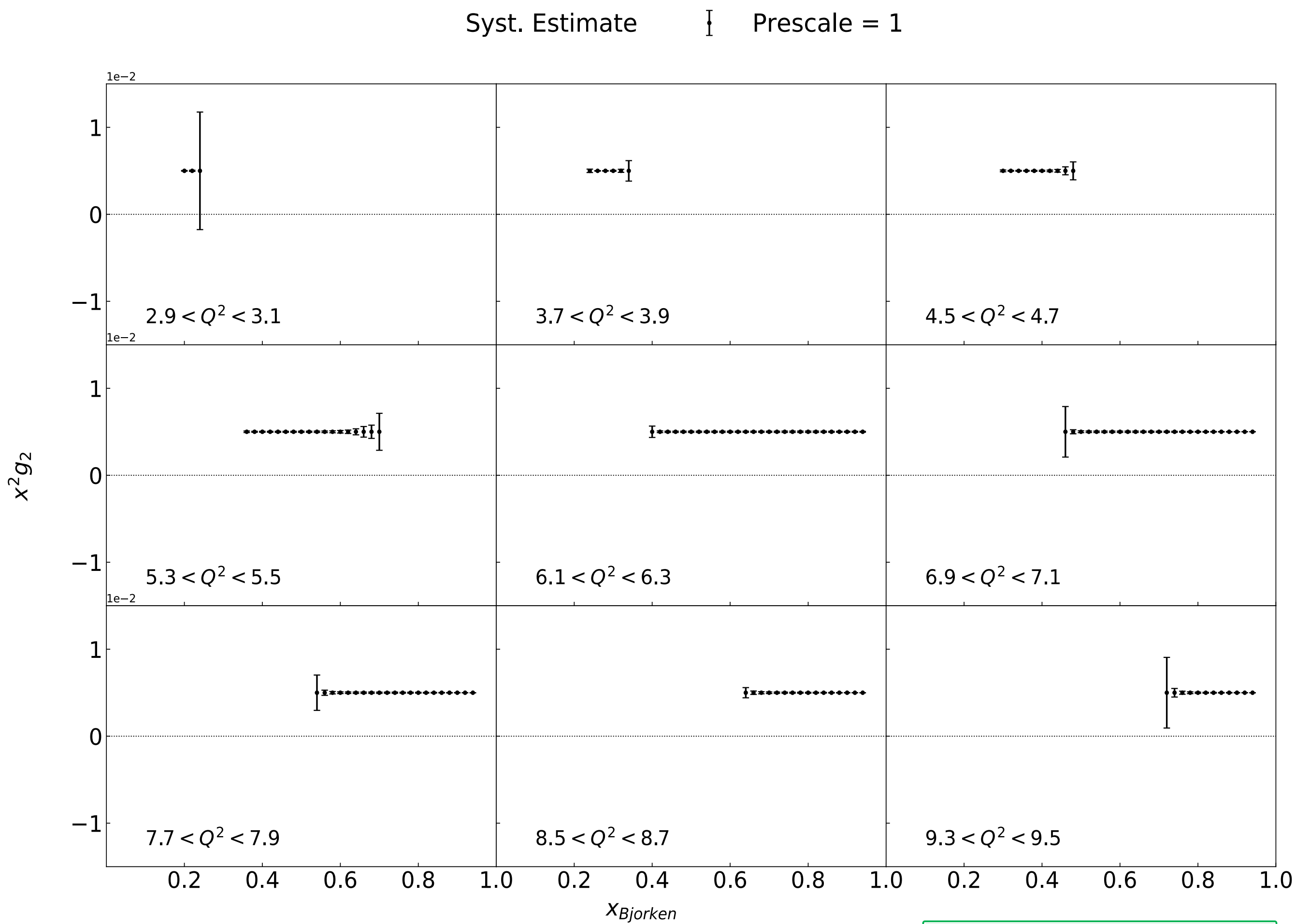
from Christopher Cocuzza

JAM QCD global analysis framework:
– Inclusive & semi-inclusive DIS A_{LL}
– Jet production in polarized pp collisions
– W/Z boson production at RHIC

- SIDIS on polarized ^{3}He provides strong **constraints on the d-quark helicity distributions**, including both valence and sea components.
- SoLID helps test if the polarized sea is **flavor asymmetric**, just like the unpolarized sea

A Precision Measurement of Inclusive g_2, d_2 with SoLID on a Transversely Polarized ^{3}He Target at 8.8 and 11 GeV

55% target polarization, 85% beam polarization, and 0.17 nitrogen dilution



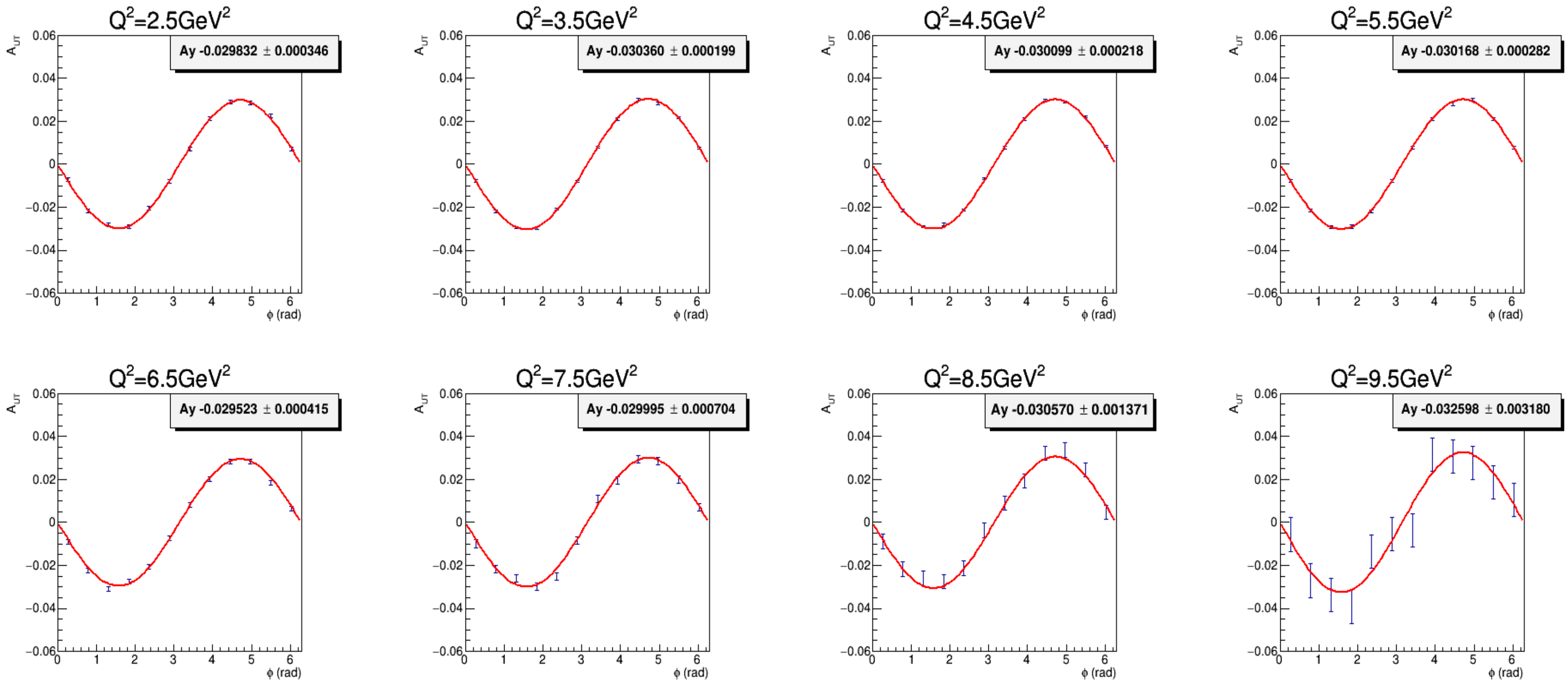
- F2 from New Muon Collaboration (NMC) parameterization
- $R = g^n_1/F^n_1$ from SLAC
- Errors:
  - error bars ---- statistic errors
  - shadow regions---- systematic error

from Peng Chao

Target Single Spin Asymmetry Measurements in the Inclusive Deep-Inelastic Reaction on Transversely Polarized Proton and Neutron (^{3}He) Targets using the SoLID Spectrometer

- A_{UT} projection of SoLID He3 large angle detector (LD)

$A_{UT} = A_y * \sin(\varphi_s)$ with Ay=-0.03 and stat error

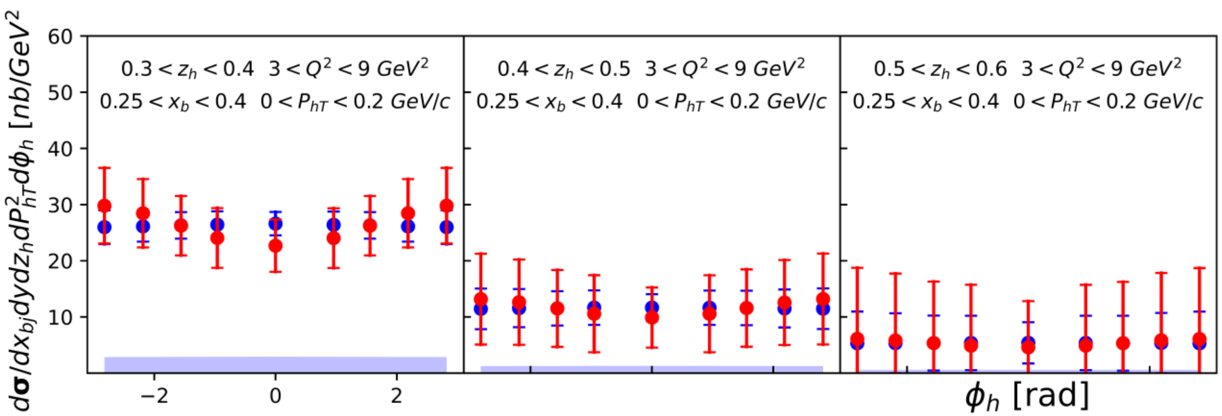


from Zhiwen Zhao

More Physics Projections

- Produced **π^+** unpolarized cross section at **11 GeV** beam energy

SoLID high-Q^2 region

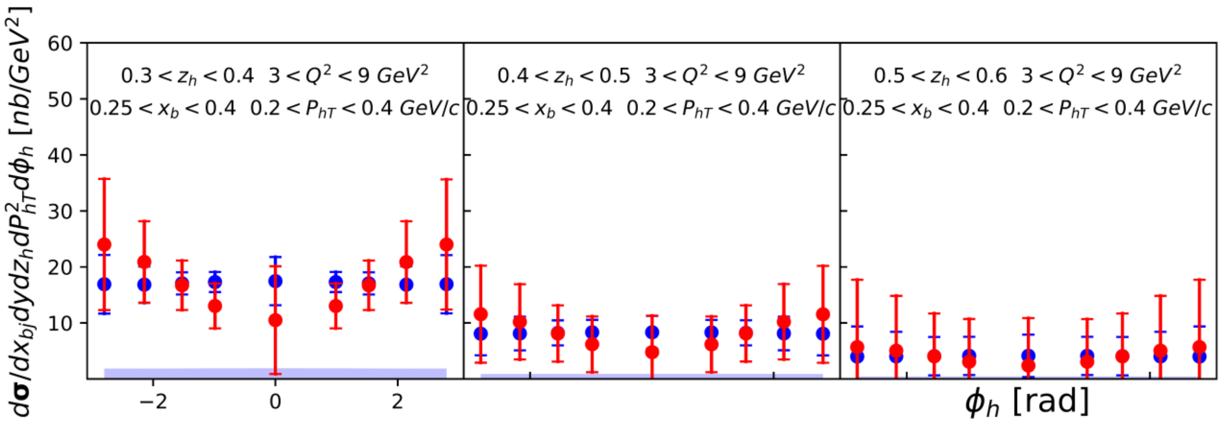


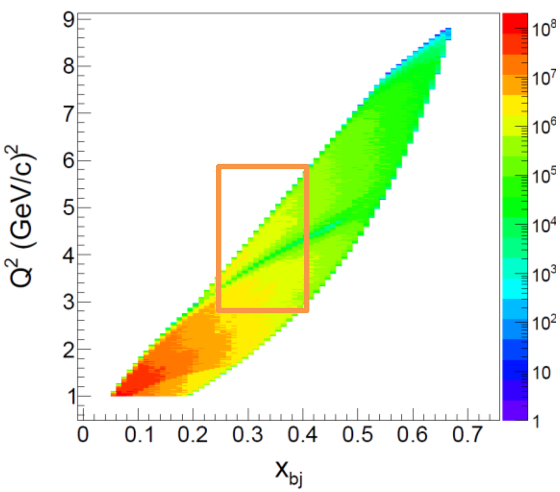
SoLID pseudo-data

Central points from simple TMD model

Blue points: Integrated cross section

Red points: Cross section including azimuthal modulations





Naïve x-z factorization & Gaussian ansatz

- Analytical forms of the Cahn and Boer-Mulders azimuthal modulation given by

$$
\begin{aligned}
F_{UU} &= \sum_q e_q^2\, x_{bj}\, f_q(x_{bj})\, D_q(z_h)\, \frac{e^{-P_{hT}^2/\langle P_{hT}^2\rangle}}{\pi\langle P_{hT}^2\rangle}, \\
F_{UU}^{\cos(\phi_h)}\big|_{\rm Cahn} &= -2\,\frac{P_{hT}}{Q}\sum_q e_q^2\, x_{bj}\, f_q(x_{bj})\, D_q(z_h)\, \frac{z_h\langle k_\perp^2\rangle}{\langle P_{hT}^2\rangle}\, \frac{e^{-P_{hT}^2/\langle P_{hT}^2\rangle}}{\pi\langle P_{hT}^2\rangle}, \\
F_{UU}^{\cos(\phi_h)}\big|_{\rm BM} &= 2e\,\frac{P_{hT}}{Q}\sum_q e_q^2\, x_{bj}\, \frac{\Delta f_{q^\uparrow/p}(x_{bj})}{M_{\rm BM}}\, \frac{\Delta D_{h/q^\uparrow}(z_h)}{M_{\rm C}}\, \frac{e^{-P_{hT}^2/\langle P_{hT}^2\rangle_{\rm BM}}}{\pi\langle P_{hT}^2\rangle_{\rm BM}^4} \\
&\quad\times \frac{\langle k_\perp^2\rangle_{\rm BM}^2\,\langle p_\perp^2\rangle_{\rm C}^2}{\langle k_\perp^2\rangle\langle p_\perp^2\rangle}\left[z_h^2\langle k_\perp^2\rangle_{\rm BM}\left(P_{hT}^2-\langle P_{hT}^2\rangle_{\rm BM}\right)+\langle p_\perp^2\rangle_{\rm C}\langle P_{hT}^2\rangle_{\rm BM}\right], \\
F_{UU}^{\cos(2\phi_h)}\big|_{\rm Cahn} &= 2\,\frac{P_{hT}^2}{Q^2}\sum_q e_q^2\, x_{bj}\, f_q(x_{bj})\, D_q(z_h)\, \frac{z_h^2\langle k_\perp^2\rangle^2}{\langle P_{hT}^2\rangle^2}\, \frac{e^{-P_{hT}^2/\langle P_{hT}^2\rangle}}{\pi\langle P_{hT}^2\rangle}, \\
F_{UU}^{\cos(2\phi_h)}\big|_{\rm BM} &= -eP_{hT}^2\sum_q e_q^2\, x_{bj}\, \frac{\Delta f_{q^\uparrow/p}(x_{bj})}{M_{\rm BM}}\, \frac{\Delta D_{h/q^\uparrow}(z_h)}{M_{\rm C}}\, \frac{e^{-P_{hT}^2/\langle P_{hT}^2\rangle_{\rm BM}}}{\pi\langle P_{hT}^2\rangle_{\rm BM}^3} \\
&\quad\times \frac{z_h\langle k_\perp^2\rangle_{\rm BM}^2\,\langle p_\perp^2\rangle_{\rm C}^2}{\langle k_\perp^2\rangle\langle p_\perp^2\rangle},
\end{aligned}
$$

where

$$\langle P_{hT}^2\rangle_{\rm BM} = \langle p_\perp^2\rangle_{\rm C} + z_h^2\langle k_\perp^2\rangle_{\rm BM}$$

$$\langle p_\perp^2\rangle_{\rm C} = \frac{\langle p_\perp^2\rangle\, M_{\rm C}^2}{\langle p_\perp^2\rangle + M_{\rm C}^2}$$

$$\langle k_\perp^2\rangle_{\rm BM} = \frac{\langle k_\perp^2\rangle\, M_{\rm BM}^2}{\langle k_\perp^2\rangle + M_{\rm BM}^2}$$

$M_{\rm C}^2$ and $M_{\rm BM}^2$ and all the other functional forms to be found in

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and

https://github.com/TianboLiu/LiuSIDIS

Unpolarized ⇆ Polarized Sea connection

Review

Flavor structure of the nucleon sea

Wen-Chen Chang[a,*], Jen-Chieh Peng[b]

[a] Institute of Physics, Academia Sinica, Taipei 11529, Taiwan

[b] Department of Physics, University of Illinois at Urbana-Champaign Urbana, IL 61801, USA

- Various non-perturbative models of the nucleon have predictions for the polarization of the sea
- While $\bar{d}(x)/\bar{u}(x)$ was + for all $0 < x < 0.45$, same models have predictions for:
  $\Delta u(x) - \Delta d(x)$
  $\Delta\bar{u}(x) - \Delta\bar{d}(x)$
- Mapping out the polarized sea flavor contribution is timely and necessary since the valence, sea, gluons and non-perturbative mechanisms are all interconnected!

Table 5

Prediction of various theoretical models on the integral $I_\Delta = \int_0^1 [\Delta\bar{u}(x) - \Delta\bar{d}(x)]dx$.

Model	I_Δ prediction	Ref.
Meson cloud (π-meson)	0	[31,127]
Meson cloud (ρ-meson)	$\simeq -0.0007$ to -0.027	[117]
Meson cloud ($\pi - \rho$ interf.)	$= -6\int_0^1 g^p(x)dx$	[118]
Meson cloud (ρ and $\pi - \rho$ interf.)	$\simeq -0.004$ to -0.033	[119]
Meson cloud (ρ-meson)	<0	[120]
Meson cloud ($\pi - \sigma$ interf.)	$\simeq 0.12$	[132]
Pauli-blocking (bag-model)	$\simeq 0.09$	[119]
Pauli-blocking (ansatz)	$\simeq 0.3$	[128]
Pauli-blocking	$= \frac{5}{3}\int_0^1 [\bar{d}(x) - \bar{u}(x)]dx \simeq 0.2$	[129]
Chiral-quark soliton	0.31	[130]
Chiral-quark soliton	$\simeq \int_0^1 2x^{0.12}[\bar{d}(x) - \bar{u}(x)]dx$	[131]
Instanton	$= \frac{5}{3}\int_0^1 [\bar{d}(x) - \bar{u}(x)]dx \simeq 0.2$	[123]
Statistical	$\simeq \int_0^1 [\bar{d}(x) - \bar{u}(x)]dx \simeq 0.12$	[41]
Statistical	$> \int_0^1 [\bar{d}(x) - \bar{u}(x)]dx > 0.12$	[126]

from Arun Tadepalli

SIDIS Unpolarized Cross Section

In LO factorization scheme

$$\frac{d\sigma}{dx_{bj}\, dy\, dz_h\, dP_{hT}^2\, d\phi_h} = 2\pi \frac{\alpha^2}{x_{bj} y Q^2} \left(1 + \frac{\gamma^2}{2x_{bj}}\right) \times$$
$$\times \left[c_1 F_{UU} + c_2 \cos(\phi_h)\, F_{UU}^{\cos(\phi_h)} + c_3 \cos(2\phi_h)\, F_{UU}^{\cos(2\phi_h)} \right],$$

➢ Use the following Gaussian parameterizations for the TMD PDF and TMD FF

Twist 2 effect

$$F_{UU} = \sum_q e_q^2\, x_{bj}\, f_q(x_{bj})\, D_q(z_h)\, \frac{e^{-P_{hT}^2/\langle P_{hT}^2\rangle}}{\pi \langle P_{hT}^2\rangle}$$

Gaussian widths

where $\langle P_{hT}^2\rangle = \langle p_\perp^2\rangle + z_h^2 \langle k_\perp^2\rangle$

SIDIS Unpolarized Cross Section

In LO factorization scheme

$$\frac{d\sigma}{dx_{bj}\,dy\,dz_h\,dP_{hT}^2\,d\phi_h} = 2\pi\,\frac{\alpha^2}{x_{bj}\,y\,Q^2}\left(1+\frac{\gamma^2}{2x_{bj}}\right)\times$$
$$\times\left[c_1\,F_{UU} + c_2\cos(\phi_h)\,F_{UU}^{\cos(\phi_h)} + c_3\cos(2\phi_h)\,\boxed{F_{UU}^{\cos(2\phi_h)}}\right],$$

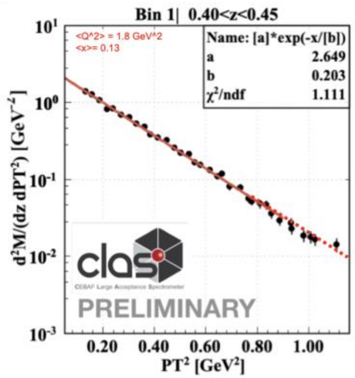
Twist-4 Cahn & twist-2 Boer-Mulders: $\cos(2\phi_\mathrm{h})$ dependence

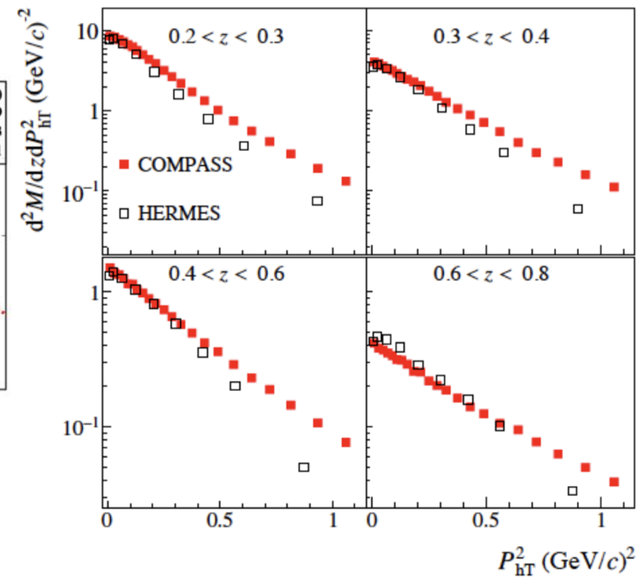
$$F_{UU}^{\cos(2\phi_h)} \approx F_{UU}^{\cos(2\phi_h)}\big|_{\mathrm{Cahn}} + F_{UU}^{\cos(2\phi_h)}\big|_{\mathrm{BM}}$$

- Boer-Mulders effect $\propto h^{\perp}_1 \otimes H^{\perp}_1$
- Twist-4 Cahn effect could have similar size of contribution to $\cos(2\phi_\mathrm{h})$ as Boer- Mulders [Phys. Rev. D. 81:114026 (2010) based on HERMES/COMPASS results]

- Studies on Multiplicities of hadrons in SIDIS are available

$$\frac{d^2M^h(x_{bj}, Q^2,\ z_h, P_{hT}^2)}{dzdP_{hT}^2} = \left(\frac{d^4\sigma^h}{dxdQ^2dzdP_{hT}^2}\right) / \left(\frac{d^2\sigma^{DIS}}{dxdQ^2}\right)$$

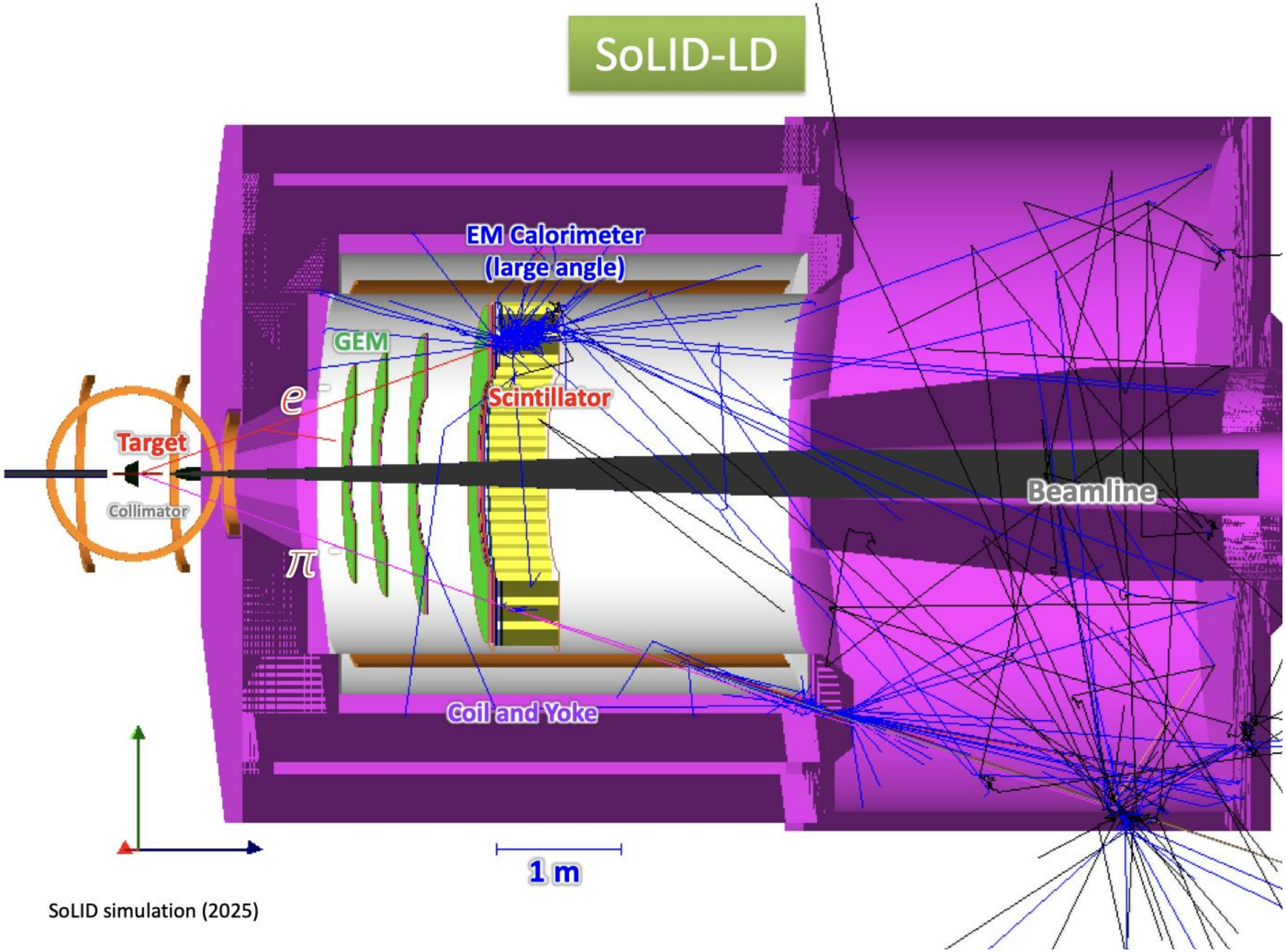




❑ Lack of data on SIDIS unpolarized absolute cross sections

- Study both the shape and the normalization of the SIDIS cross sections
- Ascertain the validity of the factorization theorems
- Nuclear corrections: EMC effect, nuclear binding, Fermi motion, and off-shell effects
- higher-twist effects on azimuthal angular modulations
- TMD flavor dependence

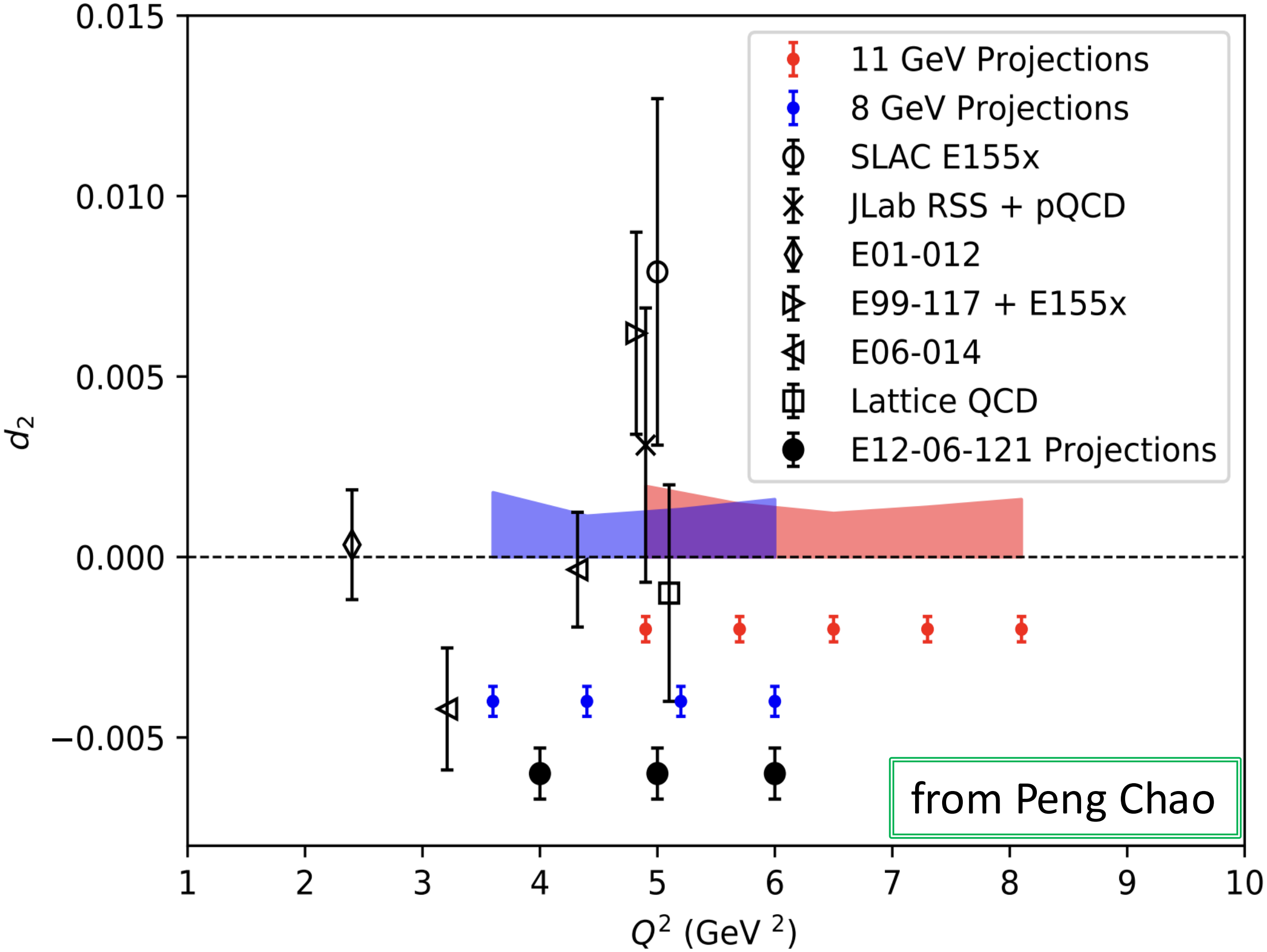
SoLID Large Angle Detectors



from Zhiwen Zhao

A Precision Measurement of Inclusive g_2 , d_2 with SoLID on a Transversely Polarized ^3He Target at 8.8 and 11 GeV

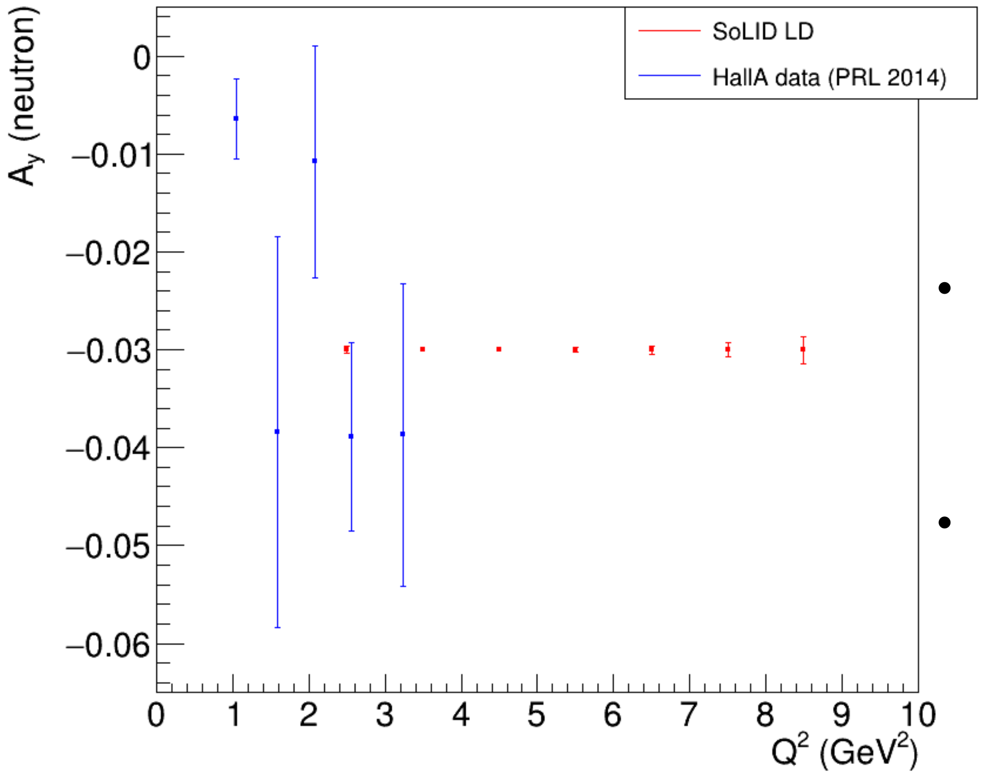
$$d_2(Q^2) = 3\int_0^1 x^2\,[g_2(x,Q^2) - g_2^{ww}(x,Q^2)]dx = \int_0^1 x^2\,[2g_1(x,Q^2) + 3g_2(x,Q^2)]dx$$



- ✧ Results from single e⁻ trigger
- ✧ Assigned 0.0025 error for the extrapolation
- ✧ Statistic and systematic errors combined
- ✧ Systematic errors dominate

Target Single Spin Asymmetry Measurements in the Inclusive Deep-Inelastic Reaction on Transversely Polarized Proton and Neutron (^{3}He) Targets using the SoLID Spectrometer

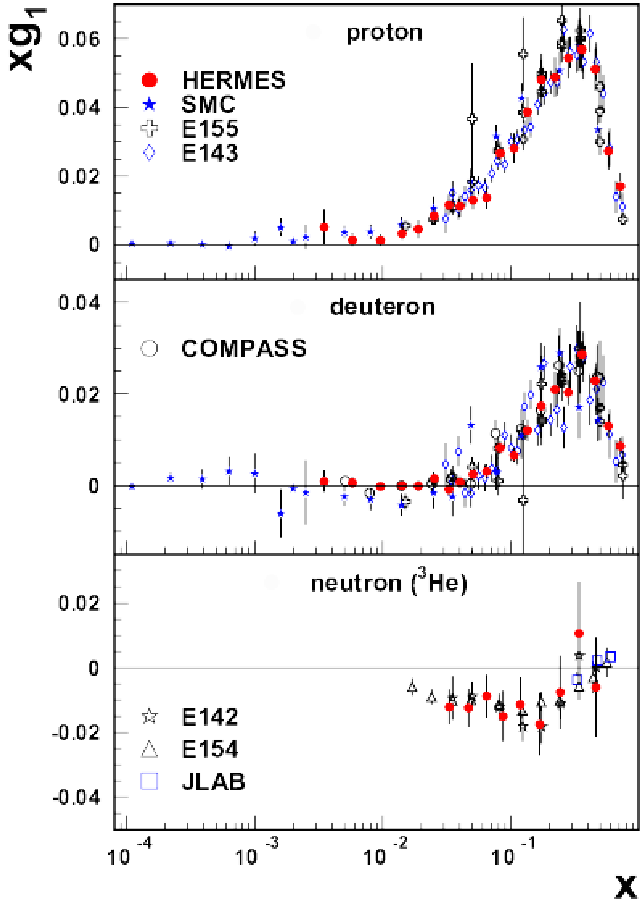
- A_y projection of SoLID ^{3}He large angle detector (LD)



from Zhiwen Zhao

- SoLID ^{3}He running condition
  - 15uA e- beam (48 days at 11GeV and 21 days at 8.8GeV)
  - 40cm 10amg ^{3}He target with window collimator
- Hall A data from *Phys. Rev. Lett. 113, 022502 (2014)* are at individual Q^2 and x bins, while SoLID LD projection are integral over all x bins
- The comparison shows stat error only. Hall A data has sys error similar to stat error and SoLID LD sys error is about 7%

Why SIDIS is Essential to Access the Polarized Sea Asymmetry



- Inclusive DIS xg1(x) measures
  — it cannot separate valence from sea.

✓ **SIDIS** enables flavor separation by detecting hadrons (e.g. π+, π−) in the final state:
  - Tags the **flavor of the struck quark**.
  - Proton + neutron (via 3He) SIDIS → separates Δu and Δd̄.

- Global fits (e.g. DSSV) depend heavily on SIDIS and RHIC data for resolving sea structure.

Precision SIDIS data are essential to constrain models and test the symmetry breaking in the polarized sea.