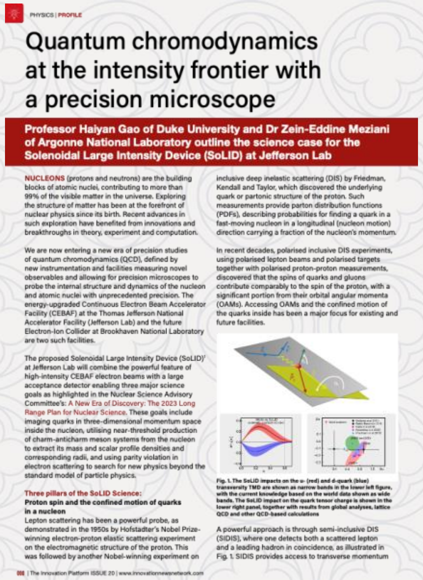
Solenoidal Large Intensity Device (SoLID) SIDIS Program

Haiyan Gao
Duke University
On behalf of the SoLID Collaboration
The Tensor SIDIS Workshop and b_1/A_{ZZ} Collaboration Meeting
June 3-5, 2026, JLab

Outline

- Introduction
- Nucleon 3-D momentum tomography with **SIDIS**
- SoLID run-group proposals
- Summary



Quantum chromodynamics at the intensity frontier with a precision microscope

Professor Haiyan Gao of Duke University and Dr Zein-Eddine Meziani of Argonne National Laboratory outline the science case for the Solenoidal Large Intensity Device (SoLID) at Jefferson Lab

NUCLEONS (protons and neutrons) are the building blocks of atomic nuclei, contributing to more than 99% of the visible matter in the universe. Exploring the structure of matter has been at the forefront of nuclear physics since its birth. Recent advances in such exploration have benefited from innovations and breakthroughs in theory, experiment and computation.

We are now entering a new era of precision studies of quantum chromodynamics (QCD), defined by new instrumentation and facilities measuring novel observables and allowing for precision microscopes to probe the internal structure and dynamics of the nucleon and atomic nuclei with unprecedented precision. The energy-upgraded Continuous Electron Beam Accelerator Facility (CEBAF) at the Thomas Jefferson National Accelerator Facility (Jefferson Lab) and the future Electron-Ion Collider at Brookhaven National Laboratory are two such facilities.

The proposed Solenoidal Large Intensity Device (SoLID)[1] at Jefferson Lab will combine the powerful feature of high-intensity CEBAF electron beams with a large acceptance detector enabling three major science goals as highlighted in the Nuclear Science Advisory Committee's: A New Era of Discovery: The 2023 Long Range Plan for Nuclear Science. These goals include imaging quarks in three-dimensional momentum space inside the nucleon, utilising near-threshold production of charm-anticharm meson systems from the nucleon to extract its mass and scalar profile densities and corresponding radii, and using parity violation in electron scattering to search for new physics beyond the standard model of particle physics.

Three pillars of the SoLID Science:

Proton spin and the confined motion of quarks in a nucleon

Lepton scattering has been a powerful probe, as demonstrated in the 1950s by Hofstadter's Nobel Prize-winning electron-proton elastic scattering experiment on the electromagnetic structure of the proton. This was followed by another Nobel-winning experiment on inclusive deep inelastic scattering (DIS) by Friedman, Kendall and Taylor, which discovered the underlying quark or partonic structure of the proton. Such measurements provide parton distribution functions (PDFs), describing probabilities for finding a quark in a fast-moving nucleon in a longitudinal (nucleon motion) direction carrying a fraction of the nucleon's momentum.

In recent decades, polarised inclusive DIS experiments, using polarised lepton beams and polarised targets together with polarised proton-proton measurements, discovered that the spins of quarks and gluons contribute comparably to the spin of the proton, with a significant portion from their orbital angular momenta (OAMs). Accessing OAMs and the confined motion of the quarks inside has been a major focus for existing and future facilities.

Fig. 1. The SoLID impacts on the u- (red) and d-quark (blue) transversity TMD are shown as narrow bands in the lower left figure, with the current knowledge based on the world data shown as wide bands. The SoLID impact on the quark tensor charge is shown in the lower right panel, together with results from global analyses, lattice QCD and other QCD-based calculations

A powerful approach is through semi-inclusive DIS (SIDIS), where one detects both a scattered lepton and a leading hadron in coincidence, as illustrated in Fig. 1. SIDIS provides access to transverse momentum

dependent (TMD) PDFs (TMD-PDFs, or simply TMDs), providing three-dimensional imaging of the nucleon in momentum space.

Most TMDs stem from the coupling of the quark transverse momentum to the spin of the nucleon and quark, therefore probing rich nonperturbative QCD dynamics and phenomena and providing essential information on quark orbital motion and spin-orbit correlations inside the nucleon.

The SoLID SIDIS programme[2] will employ both transversely and longitudinally polarised helium-3 (^{3}He) as a proxy for a polarised neutron and transversely polarized ammonia (NH_3) targets to access TMDs in both the proton and the neutron. Such measurements will enable quark flavor separation of these TMDs. We highlight two important TMDs below.

One is the transversity TMD, which provides a direct signature for relativistic effects inside the nucleon. Its integral determines the tensor charge, an intrinsic nucleon property as important as charge or mass that has been calculated by lattice QCD. This nucleon property is also connected to the electric dipole moment of the nucleon and thus has an impact on searches for new physics beyond the standard model.[3]

Another is the Sivers TMD, describing a correlation between the nucleon transverse spin and the quark orbital motion. This TMD would vanish without quark OAM. With high luminosity and large acceptance, SoLID SIDIS measurements will be essential to perform the 3D momentum space imaging of the nucleon with unprecedented precision. Fig. 1 shows the impact of the SoLID SIDIS programme on the transversity TMD and the tensor charge of the u- and the d-quark. The SoLID is just as impactful on the Sivers TMD.

Proton mass, gravitational form factors, and mass and scalar radii

The electromagnetic properties of the proton have been extensively studied since Hofstadter's pioneering electron-proton scattering experiment.[4] Over the years, researchers have determined with increasing precision both the charge and the magnetic moment densities carried by the quark constituents across its size. Unfortunately, the electromagnetic probe does not directly couple to the salient gluons (strong force carriers) responsible for confining the quarks in a proton, making them difficult to explore.

Nevertheless, it is well known that gluons play a crucial role in the structure of the proton. For example, their strong colour interaction with the quarks, as well as their self-interaction, provide for a large fraction of the proton's mass. In fact, a set of fundamental intrinsic mechanical properties, first proposed as early as the 1960s[5,6] and important to characterise the proton's structure, is still missing.

These properties are related to the proton's energy-momentum tensor and are known as its gravitational form factors. For example, they allow one to unravel the energy density of quarks and gluons across the size of the proton, as well as describe the pressure and shear forces experienced by quarks and gluons inside the proton. Only recently have researchers been successful in providing a glimpse of these properties.[7,8]

Fig. 2. The simulated total electro- (red) and photo- (blue) production of J/Ψ on a proton (far right panel). Each data point represents the integral of the measured differential cross section as a function of the Mandelstam variable 't', from which the A and D gluonic gravitational form factors would be extracted with the precision shown by the red band. Also plotted is our present knowledge of these form factors from experiment J/Ψ-007 (orange), together with the lattice QCD calculations (blue)

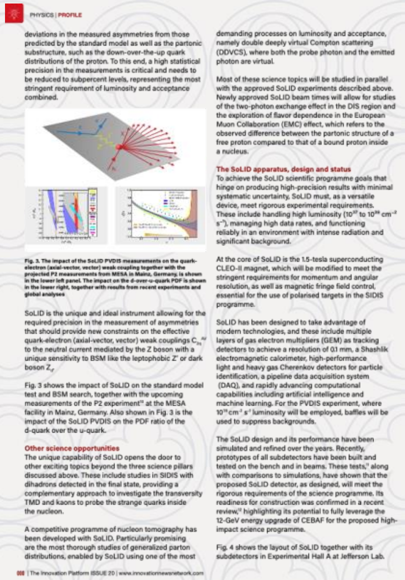
For both quarks and gluons, the first attempts at extracting these properties appear promising but will need validation across facilities in the US, from CEBAF to the Electron-Ion Collider. The preferred process to explore the gluons in the proton, as illustrated in Fig. 2, is to produce a heavy meson that then acts as a direct gluon probe in the nucleon. However, to achieve this goal, we need to operate CEBAF at high luminosities in tandem with a large acceptance detector.

SoLID at Jefferson Lab beautifully meets these requirements. Its direct impact in the determination of two critical gravitational form factors known as A and D, at an unprecedented precision, is shown in Fig. 2.

Search for physics beyond the standard model of particle physics via PVDIS

Since the late 1970s, parity violation in inclusive deep inelastic scattering (PVDIS), as illustrated in Fig. 3, of polarised electrons off unpolarised deuterium and hydrogen has emerged as a powerful tool to test the standard model of particle physics.[9] It allowed researchers to confirm the electroweak theory. Over recent years, this measurement technique was enhanced to reach a level of unprecedented precision and reduced systematic uncertainty.

Today, this tool is used to explore physics beyond the standard model (BSM) through the search for small



deviations in the measured asymmetries from those predicted by the standard model as well as the partonic substructure, such as the down-over-the-up quark distributions of the proton. To this end, a high statistical precision in the measurements is critical and needs to be reduced to subpercent levels, representing the most stringent requirement of luminosity and acceptance combined.

Fig. 3. The impact of the SoLID PVDIS measurements on the quark-electron (axial-vector, vector) weak coupling together with the projected P2 measurements from MESA in Mainz, Germany, is shown in the lower left panel. The impact on the d-over-u-quark PDF is shown in the lower right, together with results from recent experiments and global analyses

SoLID is the unique and ideal instrument allowing for the required precision in the measurement of asymmetries that should provide new constraints on the effective quark-electron (axial-vector, vector) weak couplings C_{2q}^{AV} to the neutral current mediated by the Z boson with a unique sensitivity to BSM like the leptophobic Z' or dark boson Z_d.

Fig. 3 shows the impact of SoLID on the standard model test and BSM search, together with the upcoming measurements of the P2 experiment[10] at the MESA facility in Mainz, Germany. Also shown in Fig. 3 is the impact of the SoLID PVDIS on the PDF ratio of the d-quark over the u-quark.

Other science opportunities

The unique capability of SoLID opens the door to other exciting topics beyond the three science pillars discussed above. These include studies in SIDIS with dihadrons detected in the final state, providing a complementary approach to investigate the transversity TMD and kaons to probe the strange quarks inside the nucleon.

A competitive programme of nucleon tomography has been developed with SoLID. Particularly promising are the most thorough studies of generalized parton distributions, enabled by SoLID using one of the most demanding processes on luminosity and acceptance, namely double deeply virtual Compton scattering (DDVCS), where both the probe photon and the emitted photon are virtual.

Most of these science topics will be studied in parallel with the approved SoLID experiments described above. Newly approved SoLID beam times will allow for studies of the two-photon exchange effect in the DIS region and the exploration of flavor dependence in the European Muon Collaboration (EMC) effect, which refers to the observed difference between the partonic structure of a free proton compared to that of a bound proton inside a nucleus.

The SoLID apparatus, design and status

To achieve the SoLID scientific programme goals that hinge on producing high-precision results with minimal systematic uncertainty, SoLID must, as a versatile device, meet rigorous experimental requirements. These include handling high luminosity (10^{37} to 10^{39} cm^{-2} s^{-1}), managing high data rates, and functioning reliably in an environment with intense radiation and significant background.

At the core of SoLID is the 1.5-tesla superconducting CLEO-II magnet, which will be modified to meet the stringent requirements for momentum and angular resolution, as well as magnetic fringe field control, essential for the use of polarised targets in the SIDIS programme.

SoLID has been designed to take advantage of modern technologies, and these include multiple layers of gas electron multipliers (GEM) as tracking detectors to achieve a resolution of 0.1 mm, a Shashlik electromagnetic calorimeter, high-performance light and heavy gas Cherenkov detectors for particle identification, a pipeline data acquisition system (DAQ), and rapidly advancing computational capabilities including artificial intelligence and machine learning. For the PVDIS experiment, where 10^{39} cm^{-2} s^{-1} luminosity will be employed, baffles will be used to suppress backgrounds.

The SoLID design and its performance have been simulated and refined over the years. Recently, prototypes of all subdetectors have been built and tested on the bench and in beams. These tests,[11] along with comparisons to simulations, have shown that the proposed SoLID detector, as designed, will meet the rigorous requirements of the science programme. Its readiness for construction was confirmed in a recent review,[12] highlighting its potential to fully leverage the 12-GeV energy upgrade of CEBAF for the proposed high-impact science programme.

Fig. 4 shows the layout of SoLID together with its subdetectors in Experimental Hall A at Jefferson Lab.

Fig. 4. The proposed SoLID apparatus is shown with its subdetectors inside Hall A of CEBAF at Jefferson Lab.

The SoLID collaboration consists of more than 270 collaborators from more than 70 institutions in 13 countries, with many theorists actively engaged and ready to unearth the science that would be revealed with the high-precision data. The SoLID science programme has received strong support from the Nuclear Physics community, as evidenced by its inclusion in both the 2015 and 2023 Long Range Plans (LRP) for Nuclear Science, led by the Nuclear Science Advisory Committee (NSAC). SoLID was highlighted in Recommendation 4 of the 2023 NSAC LRP as one of the projects that "... lay the foundation for the discovery science of tomorrow."

Summary

Operating a large acceptance detector with a high-luminosity electron beam has long been a challenge. However, achieving this at the luminosity frontier is essential to fully harness the potential of CEBAF's 12-GeV upgrade. SoLID, with its cutting-edge instrumentation and approved experimental programme, is a major technological leap that offers a unique opportunity to significantly expand Jefferson Lab's scientific capabilities. It not only enhances research at the current 12-GeV beam energy but also positions CEBAF for potential higher-energy upgrades with broad scientific and societal impacts.

Acknowledgements

We thank Matthew Cahill and Joanna Griffin from Jefferson Lab for their help, along with the SoLID Collaboration. The authors acknowledge the support from Nuclear Physics, Office of Science of the U.S. Department of Energy.

References:

1. J Arrington *et al.*, Journal of Physics G: Nuclear and Particle Physics, 50, 110501 (2023)
2. H Gao *et al.*, EJPA-Plus, 126, 1-16 (2011); Z Ye et al., PLB 767, 91 (2017)
3. T Liu, Z Zhao and H Gao, PRD 97, 074018 (2018)
4. R Hofstadter, Rev. Mod. Phys. 28, (1956) 214-254
5. I Y Kobzarev, L.B.Okun, Zh. Eksp. Teor. Fiz. 43(1962) 1904-1909.
6. H Pagels, Phys. Rev. 144, (1966)
7. V D Burkert, L. Elouadrhiri and F. X Girod, Nature 557, no.7705, 396-399 (2018)
8. B Duran *et al.*, Nature 615, no.7954, 813-816 (2023)
9. C Y Prescott *et al.*Phys. Lett. B77, 347 (1978); Phys. Lett. B84, 524 (1979)
10. D Becker *et al.*EPJA 54, 208 (2018)
11. D Sharma *et al.*NIMA 1061, 169080 (2024); J Xie et al, JIST 19, P08011 (2024)
12. https://science.osti.gov/np/nsac/Reports

Professor Haiyan Gao
Duke University
Department of Physics

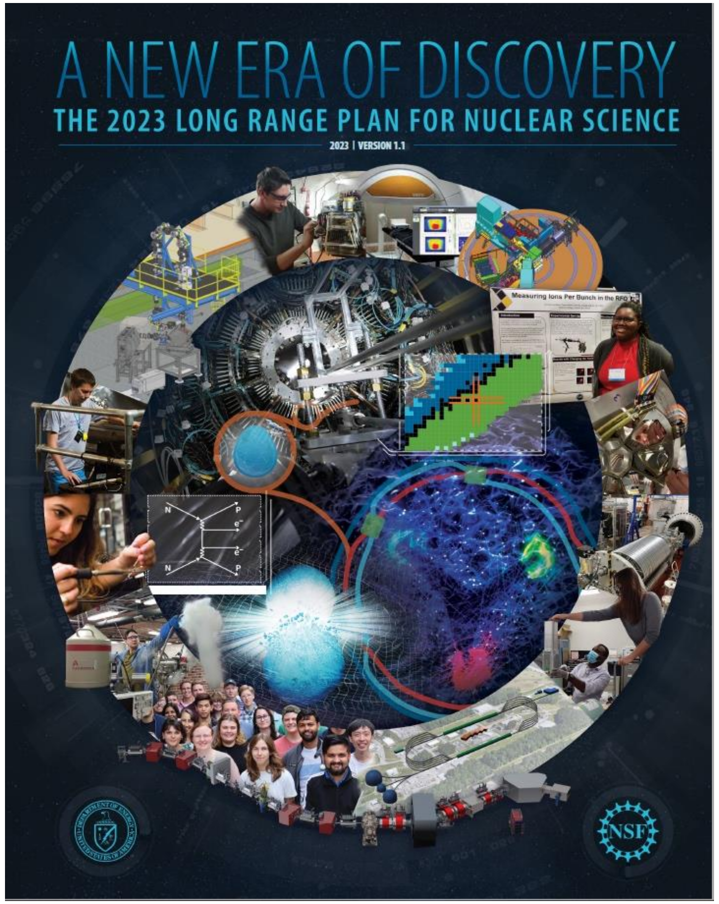
Dr Zein-Eddine Meziani
Argonne National Laboratory
Physics Division

https://www.innovationnewsnetwork.com/quantum-chromodynamics-at-the-intensity-frontier-with-a-precision-microscope/52920/

*Arrington et al., J. Phys. G: Nuclear and Particle Physics **50,** 110501 (2023)*

*Arrington et al., Progress in Particle and Nuclear Physics **127**, 103985 (2022)*

Major Nuclear Science Questions

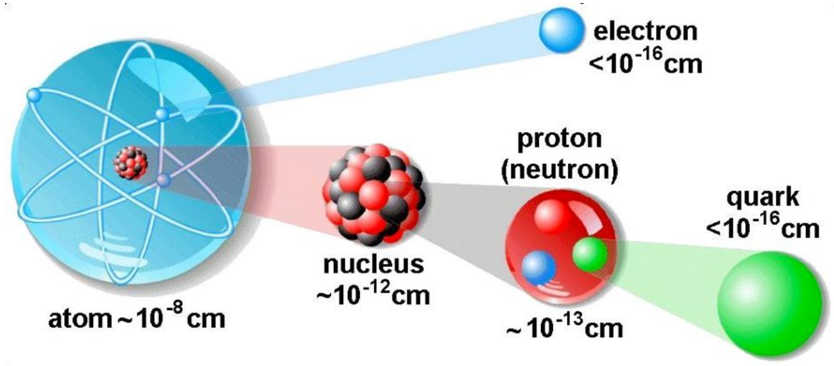

A NEW ERA OF DISCOVERY

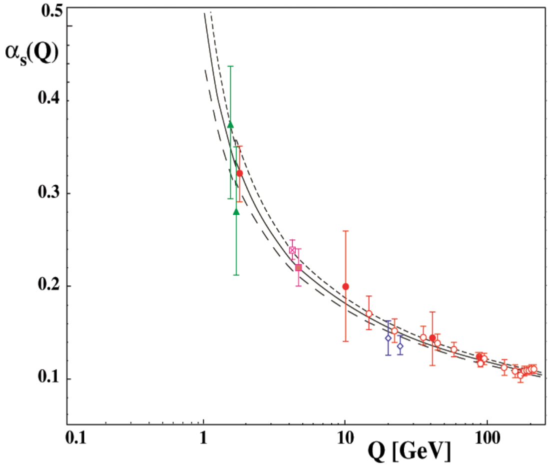
THE 2023 LONG RANGE PLAN FOR NUCLEAR SCIENCE

2023 | VERSION 1.1

https://science.osti.gov/-/media/np/nsac/pdf/202310/NSAC-LRP-2023-v12.pdf
https://arxiv.org/abs/2303.02579

- **How do quarks and gluons make up protons, neutrons, and, ultimately, atomic nuclei?**
- How do the rich patterns observed in the structure and reactions of nuclei emerge from the interactions between neutrons and protons?
- What are the nuclear processes that drive the birth, life, and death of stars?
- **How do we use atomic nuclei to uncover physics beyond the Standard Model?**

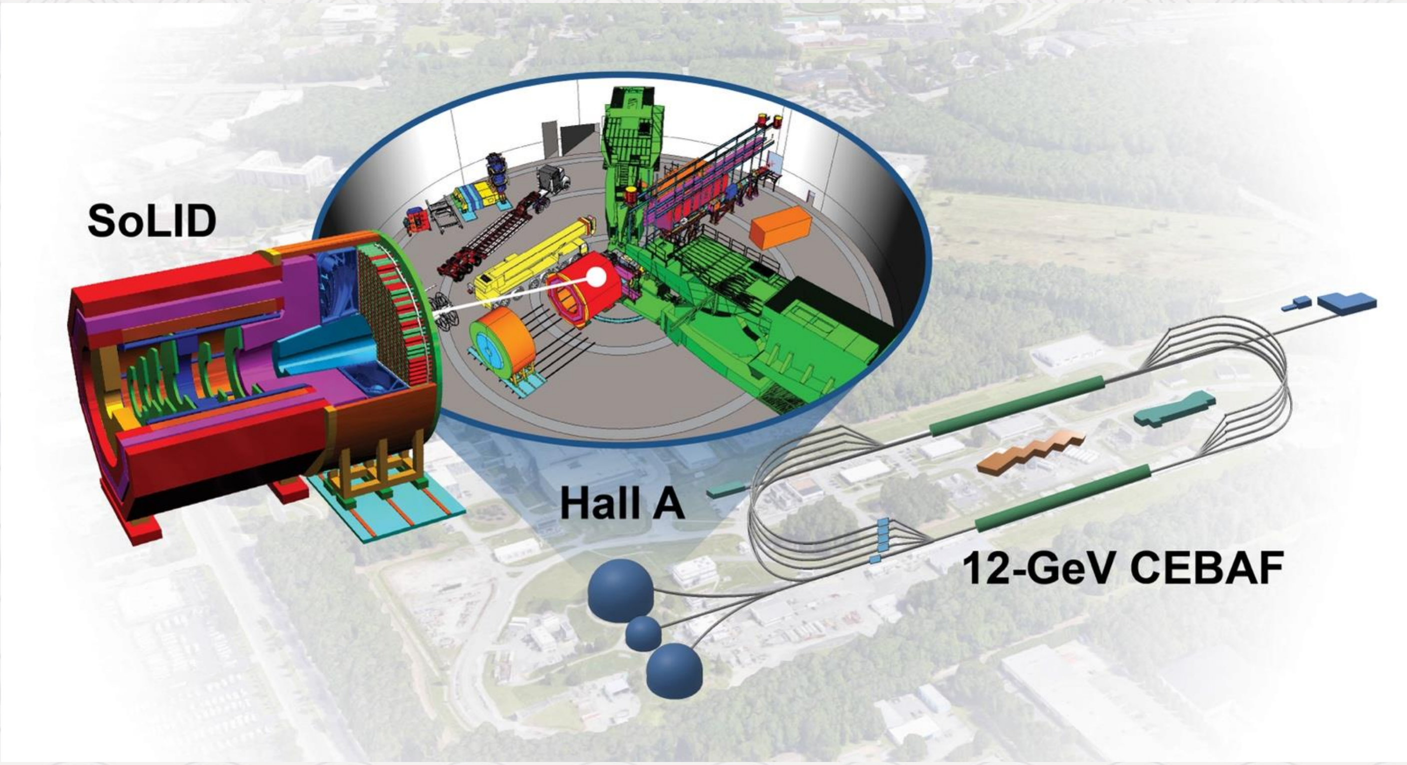


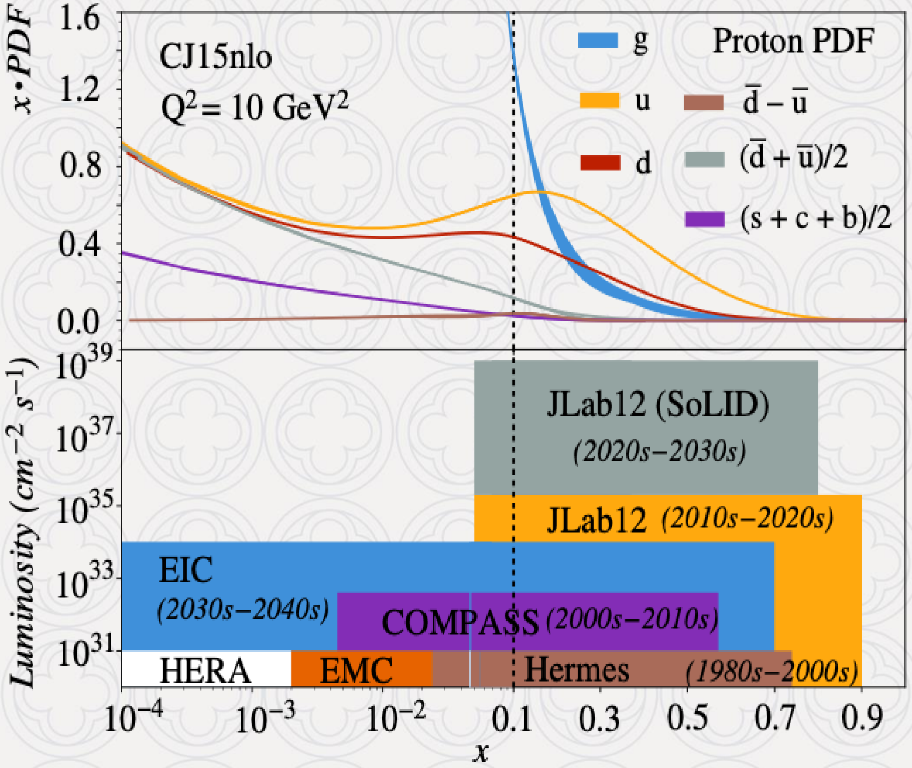


Interplay of Energy and Intensity

Structure of visible matter probed at JLab and the future EIC

Discoveries in Physics are often enabled by high-precision measurements and that is where
Solenoidal Large Intensity Device (SoLID) comes!

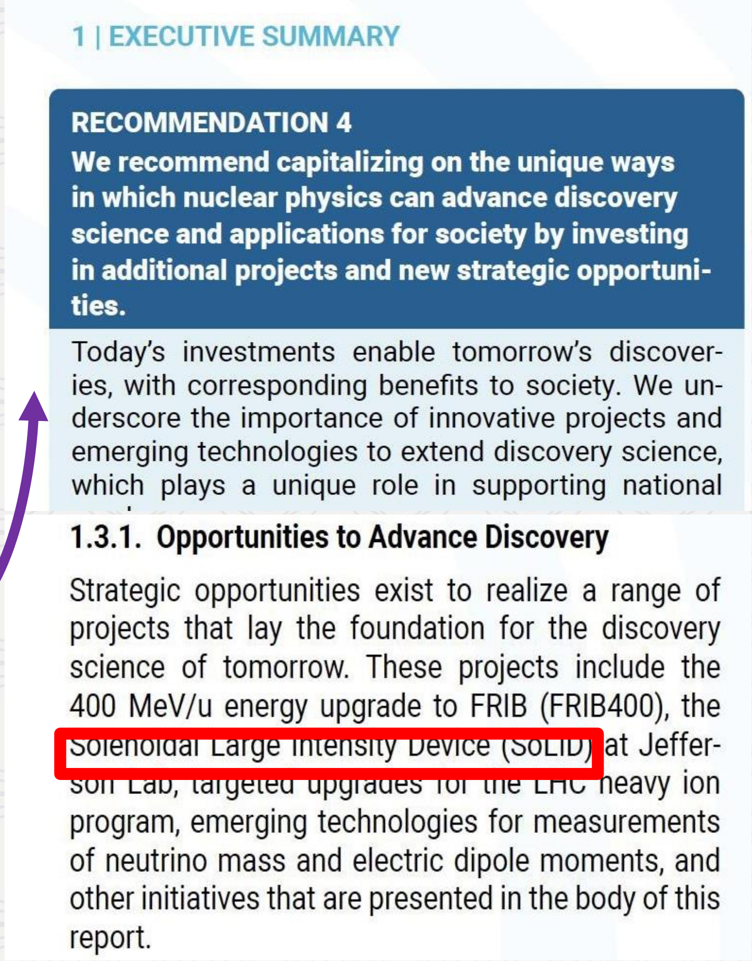




Haiyan Gao (Duke), Zein-Eddine Meziani (ANL)
https://www.innovationnewsnetwork.com/quantum-chromodynamics-at-the-intensity-frontier-with-a-precision-microscope/52920/

SoLID Science and Project Development Timeline

- **Rich physics program:** (2010-now)
    - 6 SoLID experiments approved by PAC with high rating (5 A, 1 A-)
    - 3 SIDIS (3d structure), 1 PVDIS (search for new physics),
    - 1 threshold J/ψ (gluon force), 1 A- on BNSSA (new phenomena)
    - + 2 conditional approval (1 C1 approval on DDVCS with A rating
    - + 7 run-group experiments (3d/spin structure)
- **Pre-conceptual design, Pre-R&D, reviews and status**
    - 2014: pCDR submitted to JLab with cost estimation, updated in 2017, 2019
    - Director's Reviews in 2015, 2019 and 2021
    - 2015 NSAC LRP – SoLID, sPHENIX strongly endorsed by the QCD community
    - 2020: SoLID MIE (with updated pCDR/estimated cost) submitted to DOE
    - 2020-now: DOE funded pre-R&D activities
    - 2021: DOE **Science Review for SoLID, positive feedback**
    - 2023: **Long Range Plan, SoLID highlighted, one of the recommendations**
    - 2024: DOE Office of Science Facility Review: Ready to Launch



1 | EXECUTIVE SUMMARY

RECOMMENDATION 4

We recommend capitalizing on the unique ways in which nuclear physics can advance discovery science and applications for society by investing in additional projects and new strategic opportunities.

Today's investments enable tomorrow's discoveries, with corresponding benefits to society. We underscore the importance of innovative projects and emerging technologies to extend discovery science, which plays a unique role in supporting national

1.3.1. Opportunities to Advance Discovery

Strategic opportunities exist to realize a range of projects that lay the foundation for the discovery science of tomorrow. These projects include the 400 MeV/u energy upgrade to FRIB (FRIB400), the Solenoidal Large Intensity Device (SoLID) at Jefferson Lab, targeted upgrades for the LHC heavy ion program, emerging technologies for measurements of neutrino mass and electric dipole moments, and other initiatives that are presented in the body of this report.

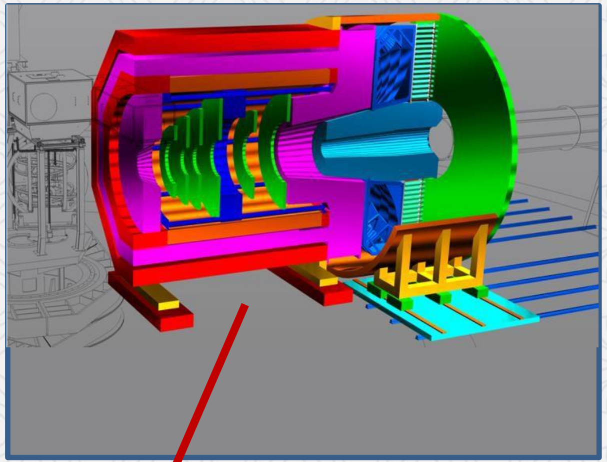
Solenoidal Large Intensity Device (SoLID)

SoLID will ***maximize*** the science return of the 12-GeV CEBAF upgrade by **combining**

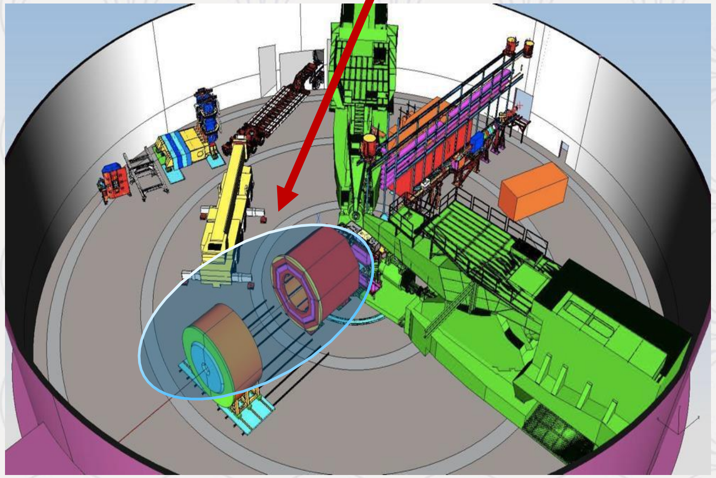
High Luminosity
$10^{37\text{-}39}$ /cm^2/s
[>100x CLAS12][>1000x EIC]

+

Large Acceptance
Full azimuthal ϕ coverage



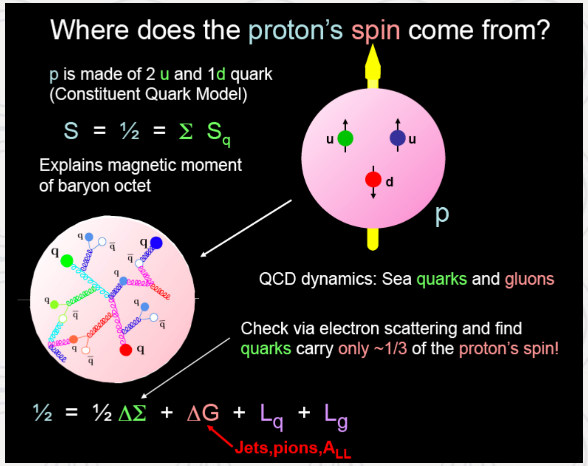
Research at **SoLID** will have the ***unique*** capability to **explore** the QCD landscape while **complementing** the research of other key facilities including the future EIC



Two science pillars of the SoLID (**proton spin** and **mass**):
high-luminosity valence quark tomography and precision J/ψ production near threshold (EIC in the sea/gluon region, **both needed!)**
PVDIS: test of Standard Model & search for new physics

Duke

Nucleon Structure from 1D to 3D & orbital motion



Where does the proton's spin come from?

p is made of 2 u and 1d quark
(Constituent Quark Model)

$S = ½ = \Sigma S_q$

Explains magnetic moment of baryon octet

QCD dynamics: Sea quarks and gluons

Check via electron scattering and find quarks carry only ~1/3 of the proton's spin!

$½ = ½ \Delta\Sigma + \Delta G + L_q + L_g$

Jets,pions,A_{LL}

$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + (L_q + L_g)$$

Jaffe-Manohar sum rule
Nucl. Phys. B337, 509 (1990)

Ji sum rule $\frac{1}{2} = J_q + J_g$

Ji, PRL 78, 610(1997)

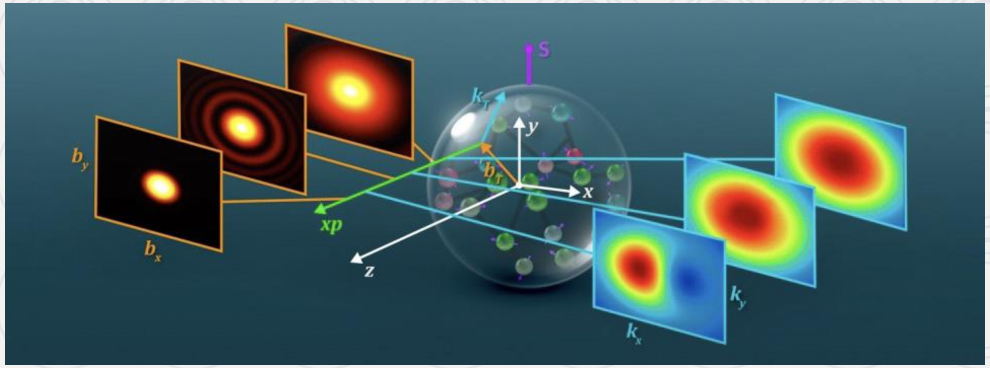
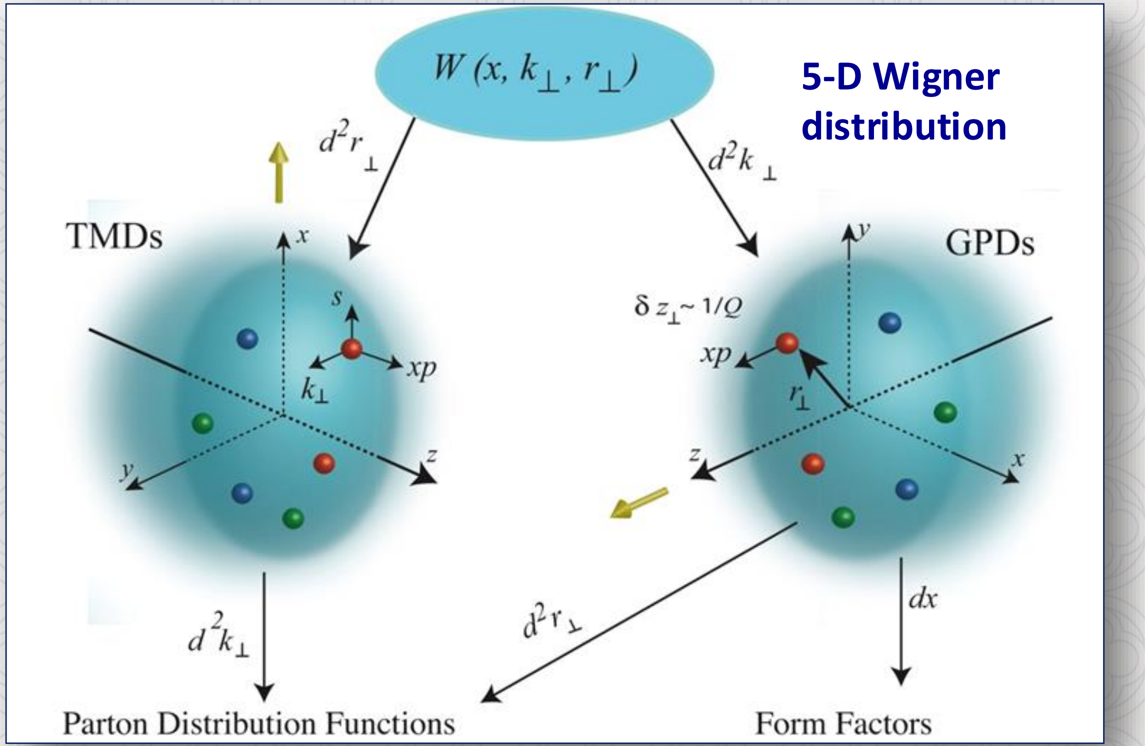


Image from 2023 NSAC LRP



5-D Wigner distribution

Generalized parton distribution (GPD)
Transverse momentum dependent parton distribution (TMD)

X.D. Ji, PRL91, 062001 (2003);
Belitsky, Ji, Yuan, PRD69,074014 (2004)

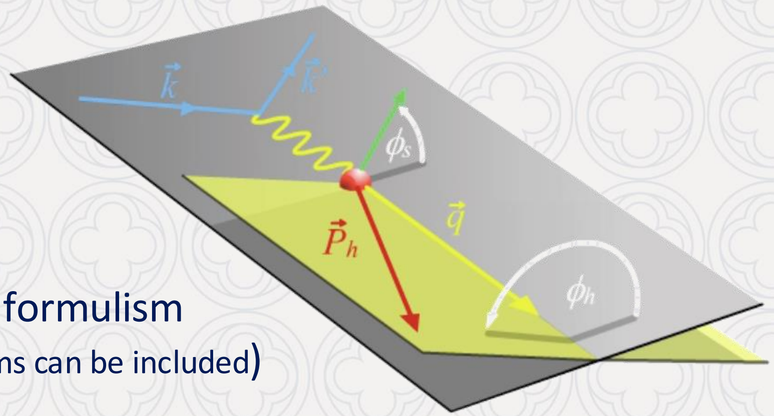
Image from J. Dudek et al., EPJA 48,187 (2012)

Many talks at this workshop already

Separation of Collins, Sivers and Pretzelosity through angular dependence

SIDIS SSAs depend on 4-D variables (x, Q^2, z, P_T) and small asymmetries demand **large acceptance** + **high luminosity** allowing for measuring symmetries in 4-D binning with precision!

(2π azimuthal coverage)



$$A_{UT}(\phi_h, \phi_S) = \frac{1}{P_{t,pol}} \frac{N^{\uparrow} - N^{\downarrow}}{N^{\uparrow} + N^{\downarrow}}$$

Leading twist formulism
(higher-twist terms can be included)

$$= \underbrace{A_{UT}^{Collins}} \sin(\phi_h + \phi_S) + \underbrace{A_{UT}^{Pretzelosity}} \sin(3\phi_h - \phi_S) + \underbrace{A_{UT}^{Sivers}} \sin(\phi_h - \phi_S)$$

$$\boxed{A_{UT}^{Collins}} \propto \langle \sin(\phi_h + \phi_S) \rangle_{UT} \propto h_1 \otimes H_1^{\perp}$$

$$\boxed{A_{UT}^{Pretzelosity}} \propto \langle \sin(3\phi_h - \phi_S) \rangle_{UT} \propto h_{1T}^{\perp} \otimes H_1^{\perp}$$

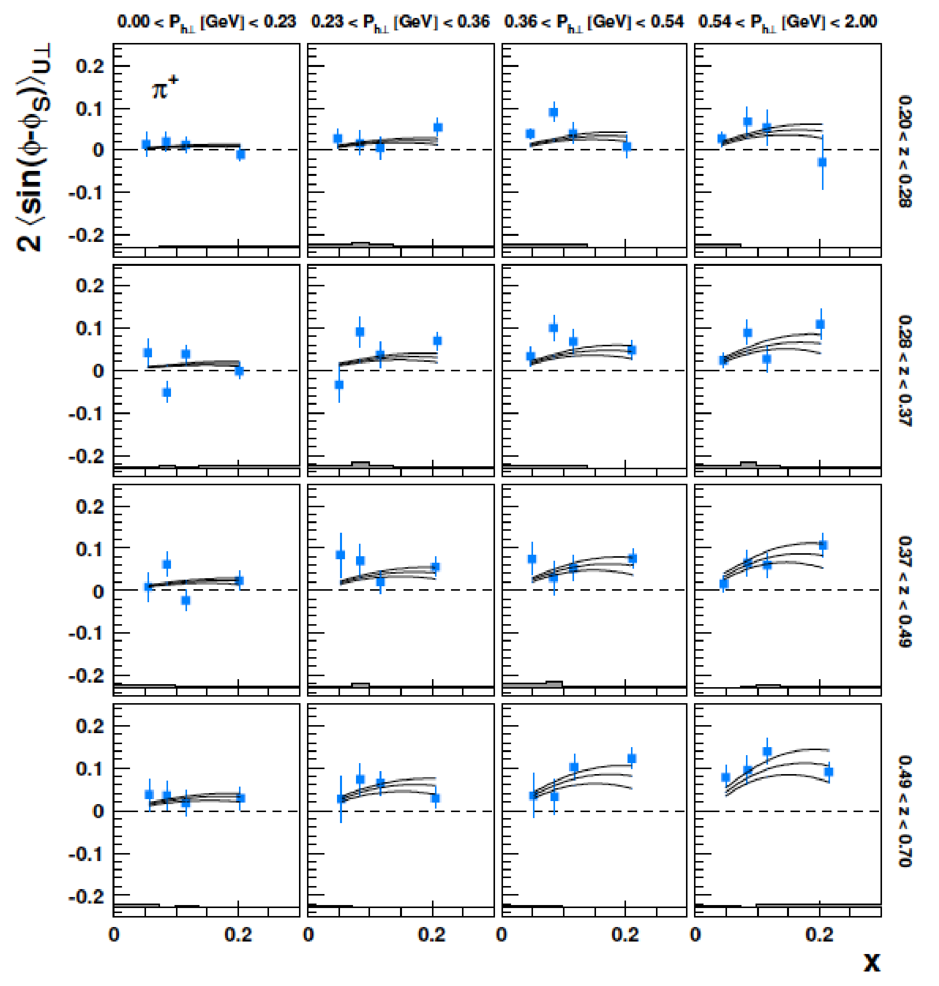
Collins fragmentation function from e^+e^- collisions

$$\boxed{A_{UT}^{Sivers}} \propto \langle \sin(\phi_h - \phi_S) \rangle_{UT} \propto f_{1T}^{\perp} \otimes D_1$$

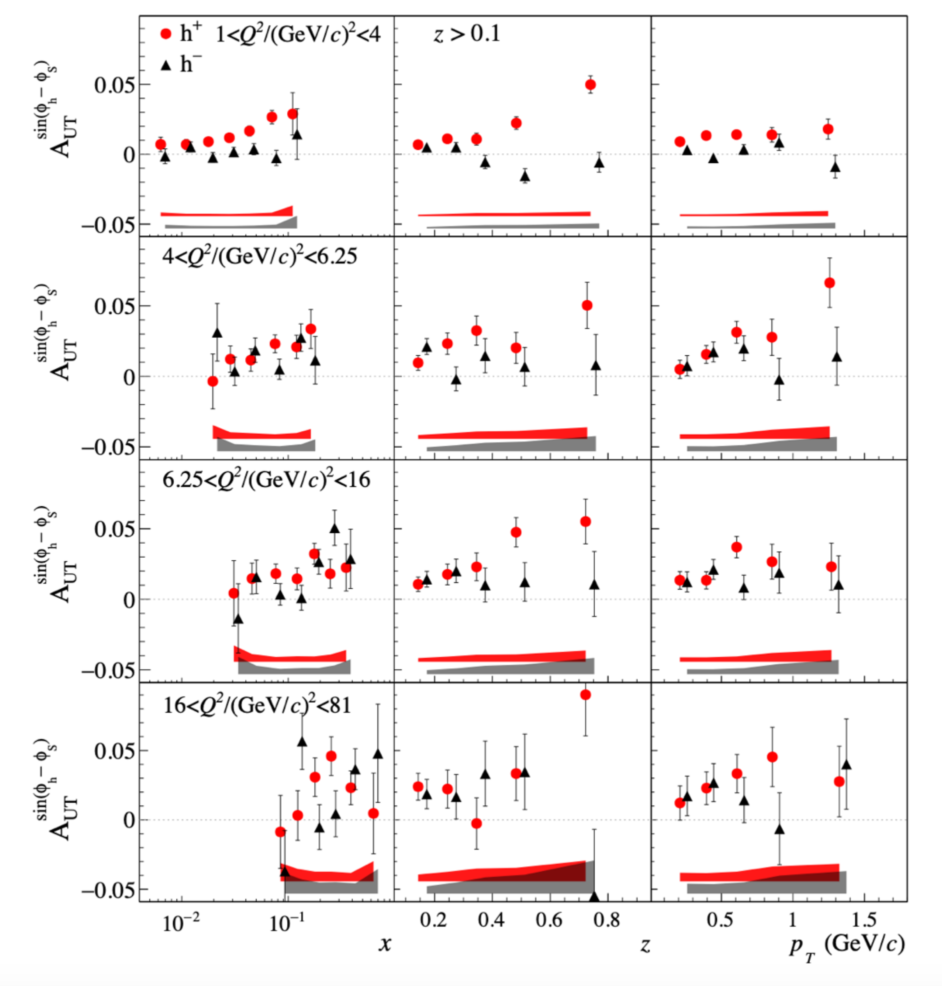
Unpolarized fragmentation function

Pioneering Studies by HERMES and COMPASS

Multi-dimensional binning with precision – reduces systematics, constrain models, forms of TMDs, disentangle correlations, isolate phase-space region with large signal strength (HERMES, COMPASS)



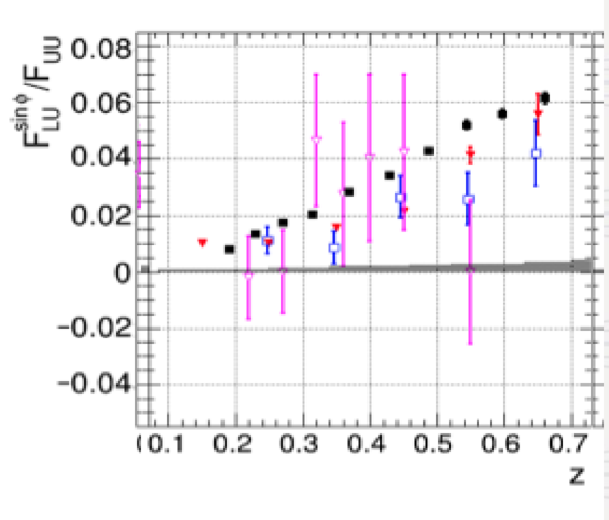
A. Airapetian et al., arXiv:2007.07755

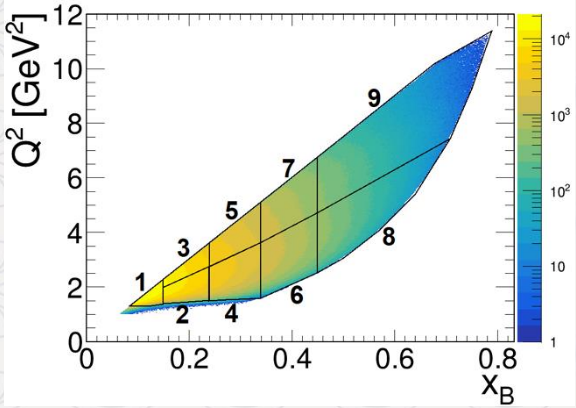


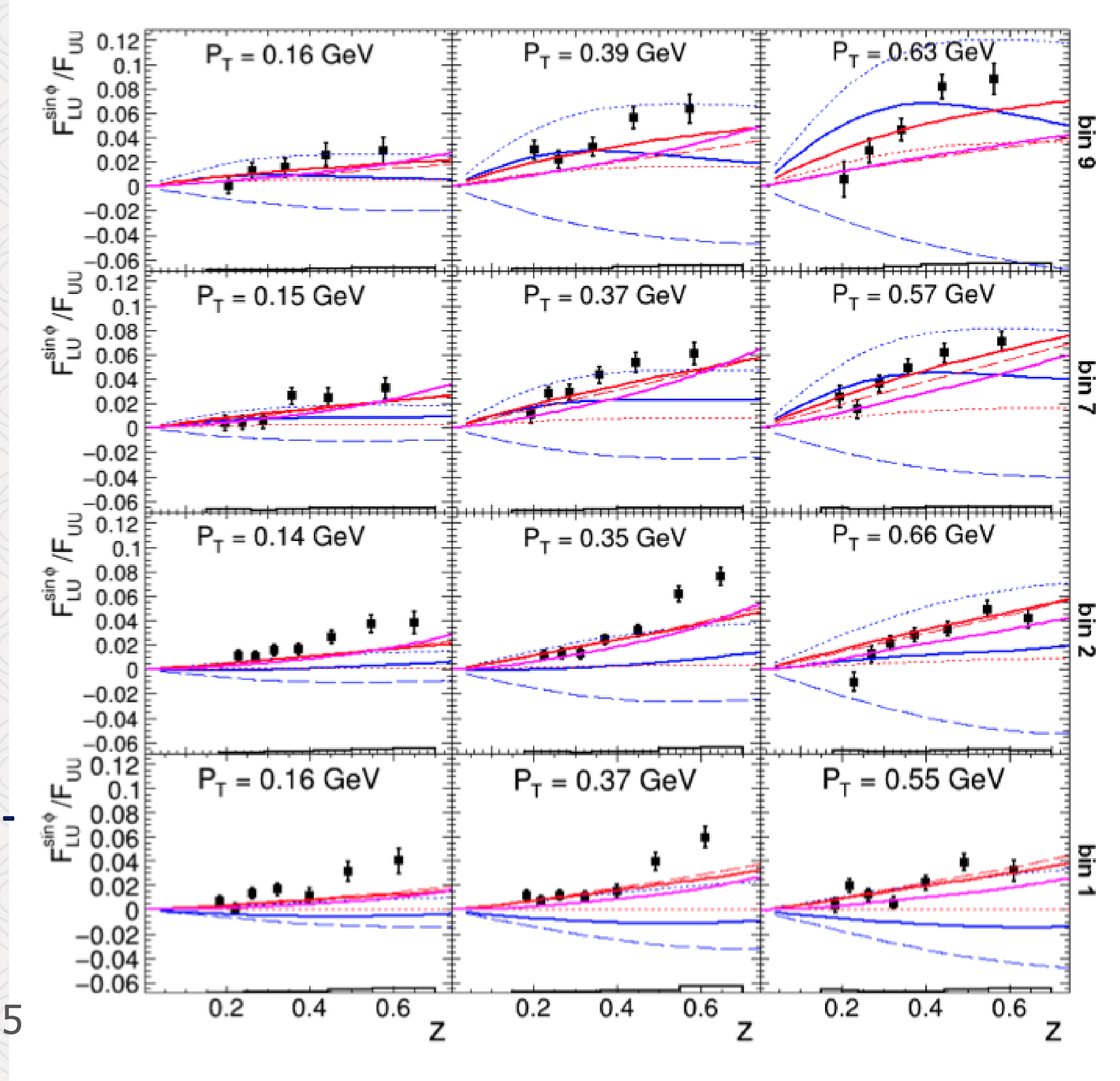
C. Adolph et al. PLB 770, 138 (2017)

State-of-the-art from CLAS 12

multi-dimensional binning with precision – reduces systematics, constrain models, forms of TMDs, disentangle correlations, isolate phase-space region with large signal strength (CLAS12)



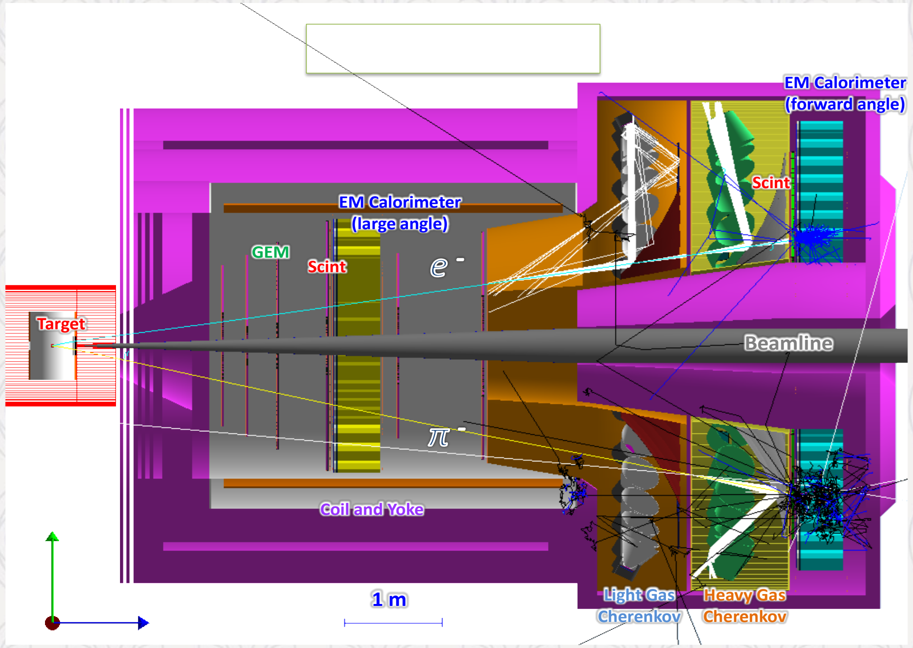


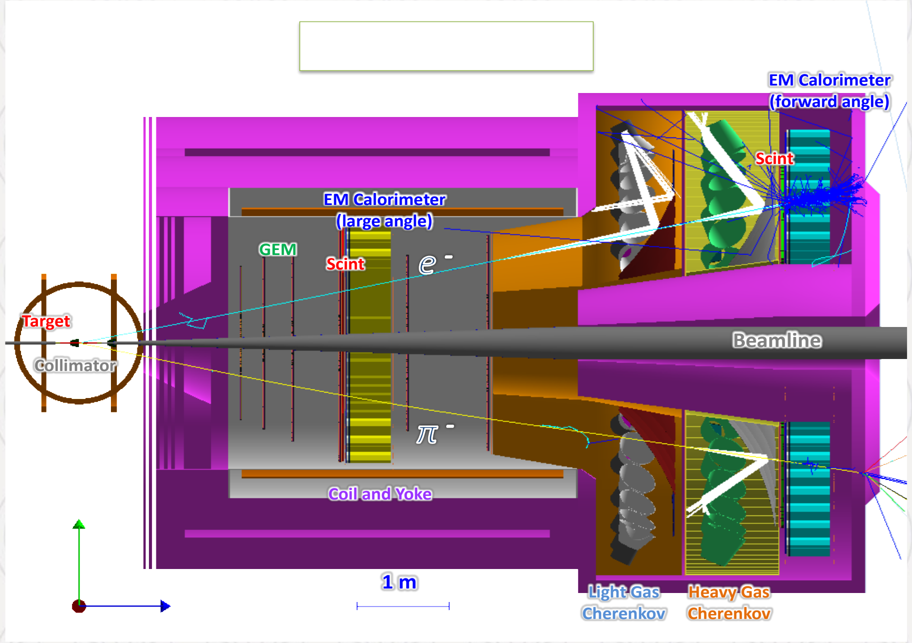


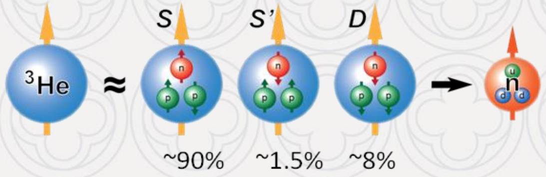
First multidimensional, high precision measurements of semi-inclusive π+ beam single spin asymmetries from the proton over a wide range of kinematics

S. Diehl *et al.* (CLAS Collaboration), Phys. Rev. Lett. **128**, 062005

SIDIS with polarized "neutron" and proton @ SoLID





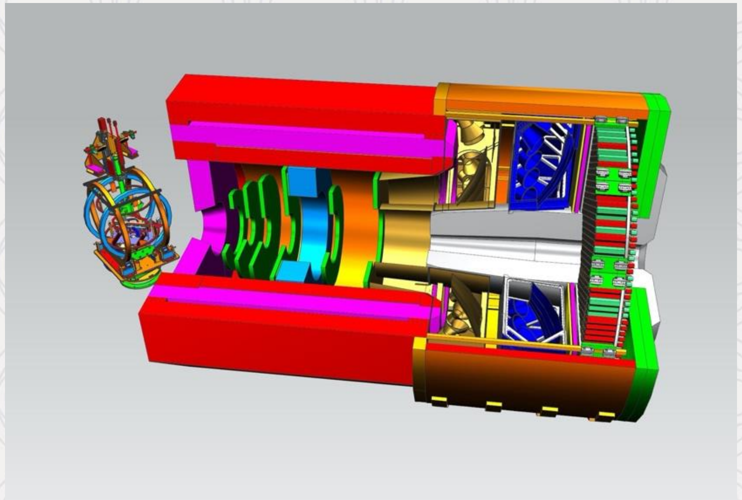


E12-10-006: Single Spin Asymmetries on Transversely Polarized ^{3}He @ 90 days
Rating A Spokespersons: J.P. Chen, H. Gao (contact), J.C. Peng, X. Qian

E12-11-007: Single and Double Spin Asymmetries on Longitudinally Polarized ^{3}He @ 35 days
Rating A Spokespersons: J.P. Chen (contact), J. Huang, W.B. Yan

E12-11-108: Single Spin Asymmetries on Transversely Polarized Proton @ 120 days
Rating A Spokespersons: J.P. Chen, H. Gao (contact), X.M. Li, Z.-E. Meziani

SoLID: large-acceptance & high luminosity



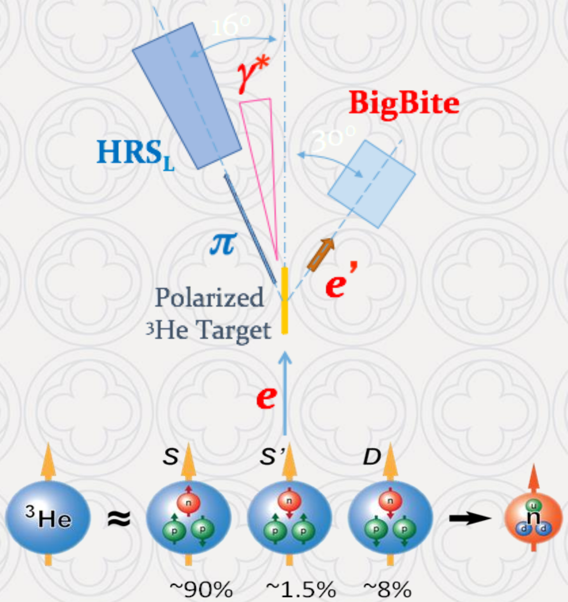
Big leap: 4-D binning for the first time!

SoLID-SIDIS program: Large acceptance, Full azimuthal coverage + High luminosity

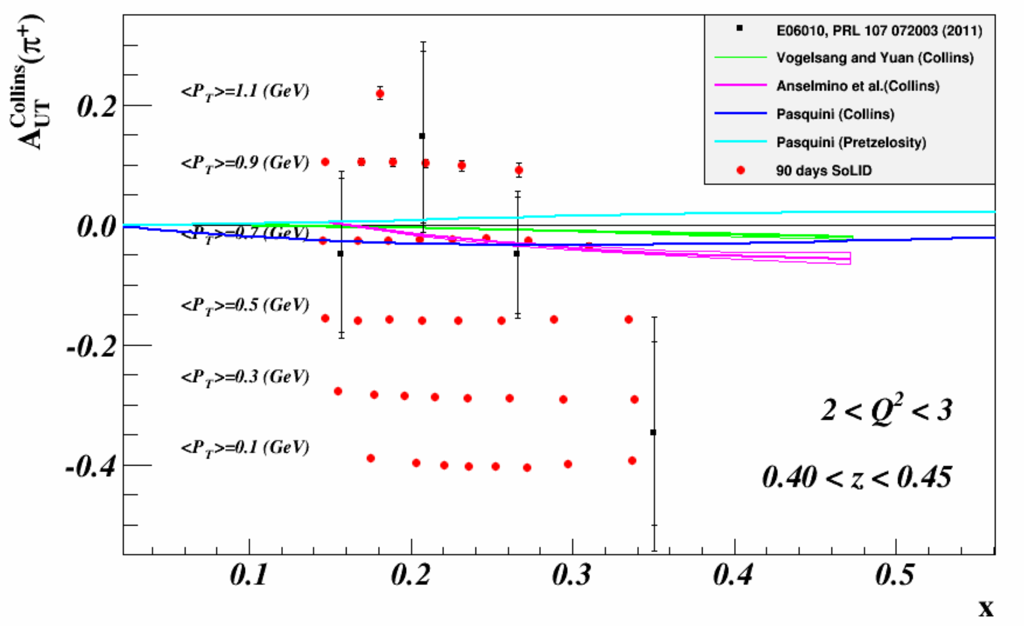
- 4-D mapping of asymmetries with precision

$\Delta z = 0.05$, $\Delta P_T = 0.2$ GeV, $\Delta Q^2 = 1$ GeV^2, x bin sizes vary with median bin size 0.02 (statistical uncertainty for each bin: $\delta A \leq 0.02$)

- Constrain models and forms of TMDs, Tensor charge, …
- Lattice QCD, QCD dynamics, models



X. Qian et al., PRL107, 072003(2011)



- **More than 1400 bins in x, Q^2, P_T and z for 11/8.8 GeV beam.**

SoLID SIDIS Projection

Compare SoLID with World Data

- Fit Collins and Sivers asymmetries in SIDIS and e^+e^- annihilation
- World data from HERMES, COMPASS
- e^+e^- data from BELLE, BABAR, and BESIII
- Monte Carlo method is applied
- Including both systematic and statistical uncertainties

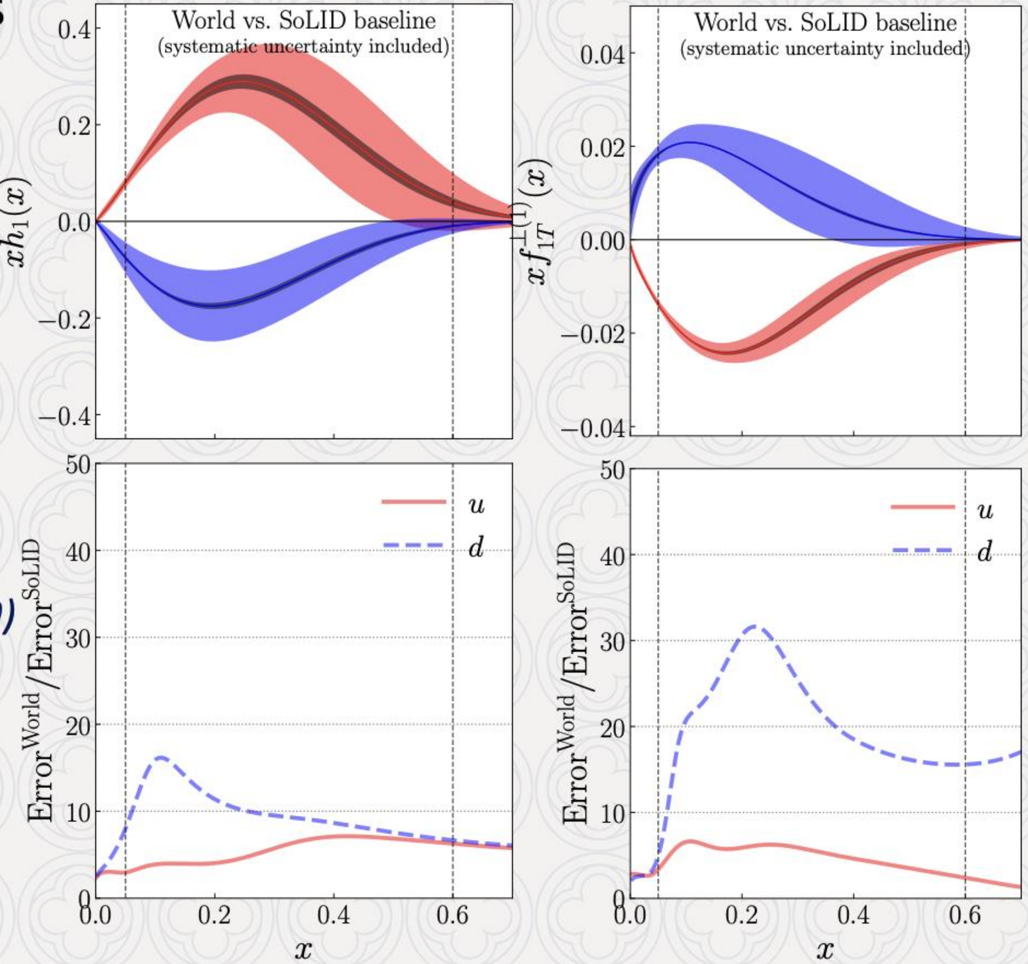
World data according to SoLID preCDR (2019)
https://solid.jlab.org/experiments.html

SoLID baseline used

D'Alesio et al., Phys. Lett. B 803 (2020)135347
Anselmino et al., JHEP 04 (2017) 046

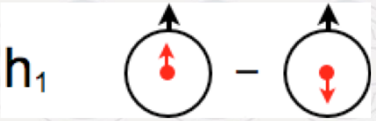
Z. Ye et al., PLB 76, 91 (2017)
T. Liu (2018): https://pos.sissa.it/317/036

Transversity **Sivers**



Transversity and Tensor Charge

Transversity distribution



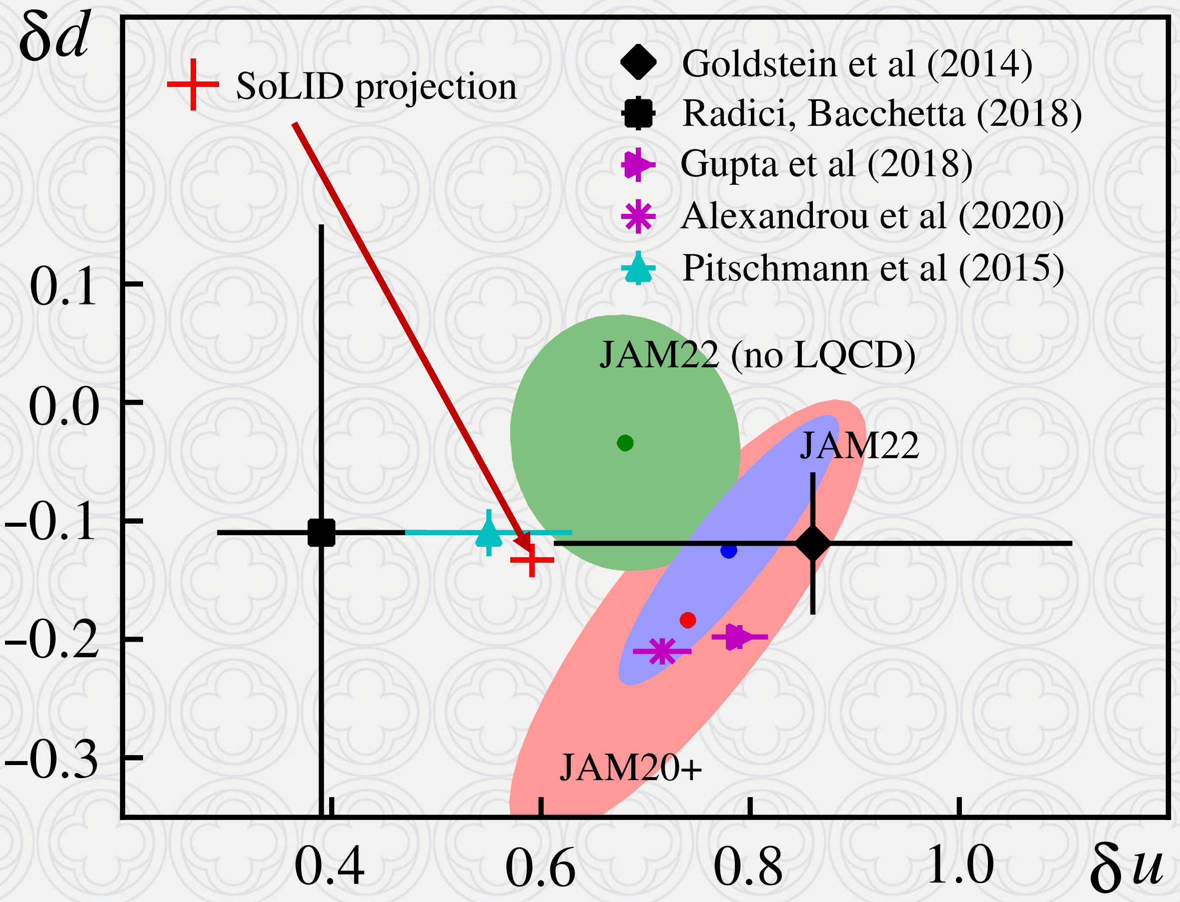
(Collinear & TMD)

- Chiral-odd, unique for the quarks
- No mixing with gluons, simpler evolution effect
- Tensor charge:

$$\langle \mathrm{P,S}|\overline{\psi}_q i\sigma^{\mu\nu}\psi_q|\mathrm{P,S}\rangle = g_T^q \overline{u}(\mathrm{P,S}) i\sigma^{\mu\nu} u(\mathrm{P,S})$$

$$g_T^q = \int_0^1 \left[h_1^q(x) - h_1^{\overline{q}}(x)\right] dx$$

- A fundamental QCD quantity dominated by valence quarks
- Precisely calculated on the lattice
- Difference from nucleon axial charge is due to relativity
- SoLID measurements allows for high-precision test of LQCD predictions
- Global analysis including LQCD (PRL 120 (2018) 15, 152502

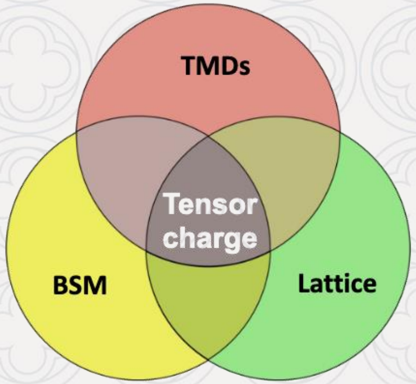


SoLID projection: statistical and systematic uncertainties included (shifted for visibility)
Z. Ye *et al.*, PLB 767, 91 (2017)

J. Cammarota et al, PRD 102, 054002 (2020) (JAM20+)
L. Gamberg et al., PRD 106, 034014 (2022) (JAM22)

Constraint on Quark EDMs and Sensitivity on BSM

Constraint on quark EDMs with combined proton and neutron EDMs



	d_u upper limit	d_d upper limit
Current g_T + current EDMs	$1.27\times10^{-24}e$ cm	$1.17\times10^{-24}e$ cm
SoLID g_T + current EDMs	$6.72\times10^{-25}e$ cm	$1.07\times10^{-24}e$ cm
SoLID g_T + future EDMs	$1.20\times10^{-27}e$ cm	$7.18\times10^{-28}e$ cm

Include 10% isospin symmetry breaking uncertainty

Nucleon Electric Dipole Moment and Tensor Charge

$$d_n = g_T^d\, d_u + g_T^u\, d_d + g_T^s\, d_s$$

$$d_p = g_T^u\, d_u + g_T^d\, d_d + g_T^s\, d_s$$

Sensitivity to new physics

$$d_q \sim em_q/(4\pi\Lambda^2)$$

Three orders of magnitude improvement on quark EDM limit → Probe to 30 ~ 40 times higher scale

Current quark EDM limit: $10^{-24}e$ cm → ~ 1 TeV

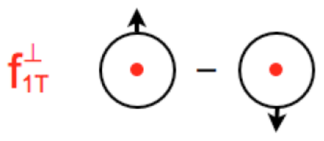
Future quark EDM limit: $10^{-27}e$ cm → 30 ~ 40 TeV

H. Gao, T. Liu, Z. Zhao, PRD 97, 074018 (2018)

Duke

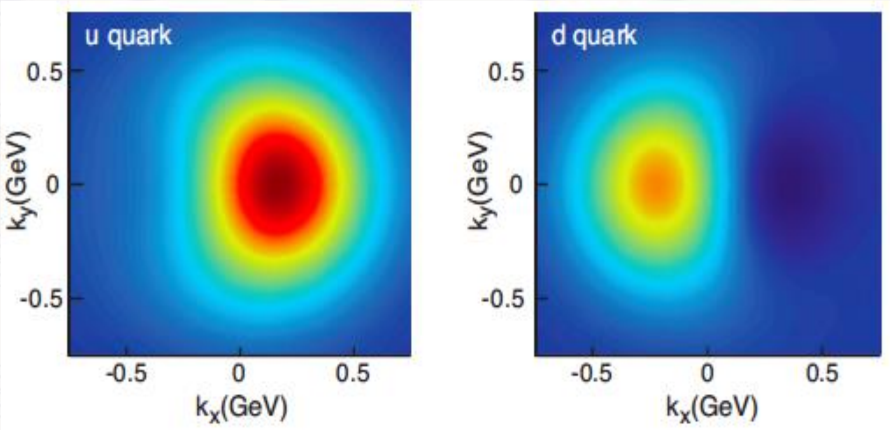
TMDs – confined motion inside the nucleon

Sivers distribution

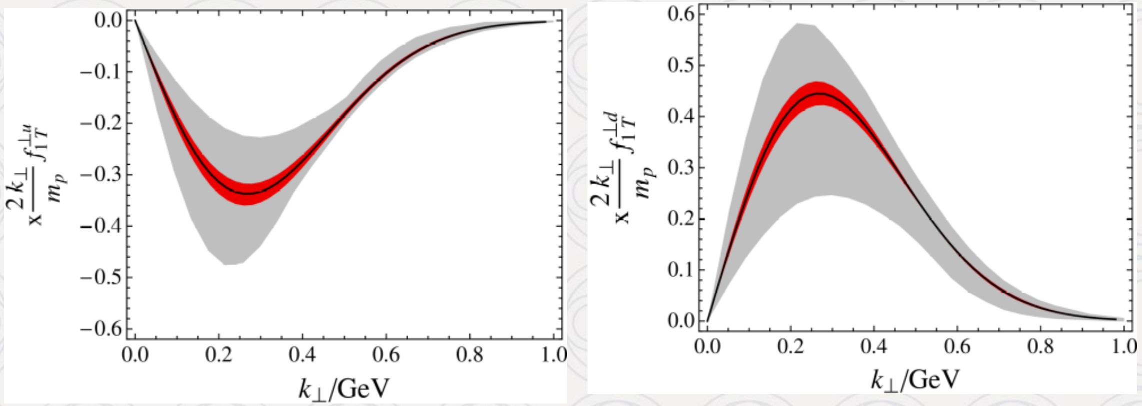


naively time-reversal odd

$$f_{1T}^{\perp q}(x,k_\perp)\Big|_{\text{SIDIS}} = -f_{1T}^{\perp q}(x,k_\perp)\Big|_{\text{DY}}$$



Nucleon spin - quark orbital angular momentum (OAM) correlation
– zero if no OAM (collinear, massless quarks)



$$f_{q/p\uparrow}(x,\mathbf{k}_\perp) = f_1^q(x,k_\perp) - f_{1T}^{\perp q}(x,k_\perp)\frac{\widehat{\mathbf{P}}\times\mathbf{k}_\perp\cdot\mathbf{S}}{M}$$

$$\langle\mathbf{k}_\perp\rangle = -M\int dx\, f_{1T}^{\perp(1)}(x)(\mathbf{S}\times\widehat{\mathbf{P}})$$

▨ Parametrization by M. Anselmino et al., EPJ A 39, 89 (2009)

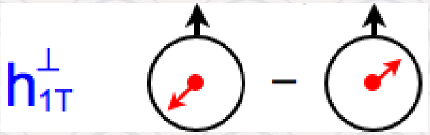
🟥 SoLID projection with transversely polarized n/p

	$\langle k_\perp\rangle^u$	$\langle k_\perp\rangle^d$
▨	96^{+60}_{-28} MeV	-113^{+45}_{-51} MeV
🟥	$96^{+2.8}_{-2.4}$ MeV	$-113^{+1.3}_{-1.7}$ MeV

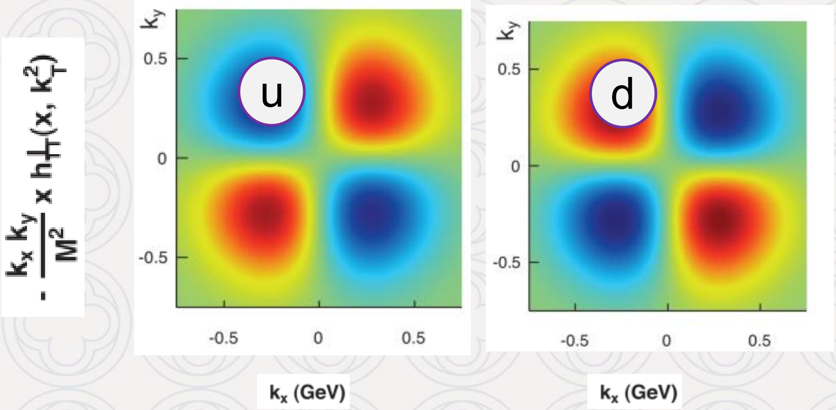
T. Liu (2018): https://pos.sissa.it/317/036

TMDs – confined motion inside the nucleon

Pretzelocity distribution



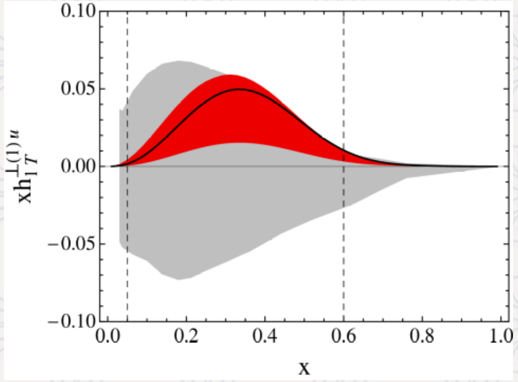
- Chiral-odd, no gluon analogy
- Quadrupole modulation of parton density in the distribution of transversely polarized quarks in a transverse polarized nucleon
- Interference of light-front wave functions differing by ΔL = 2 (seen in many models)
- Measuring the difference between helicity and transversity, i.e. relativistic effects
- Expected to be small – high luminosity-large acceptance crucial



Images from PRD 91 034010 (2015)

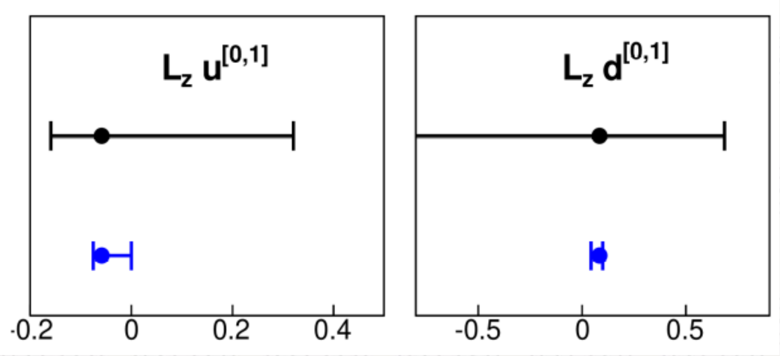
▨ Parametrization by C. Lefky et al., PRD 91, 034010 (2015)

🟥 SoLID projection with transversely polarized n and p data



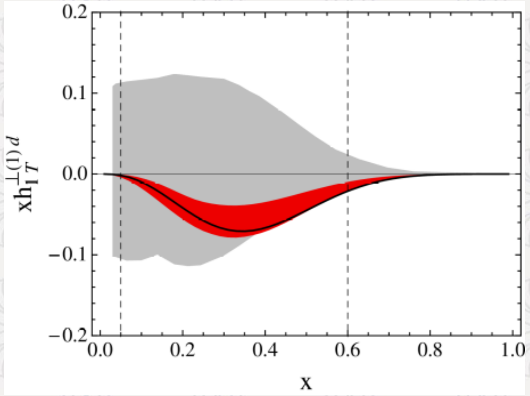
Relation to OAM (canonical)

$$L_z^q = -\int dx d^2\mathbf{k}_\perp \frac{\mathbf{k}_\perp^2}{2M^2} h_{1T}^{\perp q}(x, k_\perp) = -\int dx h_{1T}^{\perp(1)q}(x)$$



Lefky and Prokudin PRD 91, 034010 (2015)

SoLID projection



SoLID SIDIS run group experiments

- ✓SIDIS Dihadron with Transversely Polarized ^{3}He
  - J.-P. Chen, A. Courtoy, H. Gao, A. W. Thomas, Z. Xiao, J. Zhang, Approved as run group (E12-10-006A)
- ✓SIDIS in Kaon Production with Transversely Polarized ^{3}He
  - T. Liu, S. Park, Z. Ye, Y. Wang, Z.W. Zhao, Approved as run group (E12-10-006D)
- Ay with Transversely Polarized ^{3}He
  - T. Averett, A. Camsonne, N. Liyanage, Approved as run group (E12-10-006A)
- g_2^n and d_2^n with Transversely and Longitudinally Polarized ^{3}He
  - C. Peng, Y. Tian, Approved as run group (E12-10-006E)
- Deep exclusive π^- Production with Transversely Polarized ^{3}He
  - Z. Ahmed, G. Huber, Z. Ye, Approved as run group (E12-10-006B)
- Timelike Compton TCS circular polarized beam and unpolarized LH2 target M. Boer, P. Nadel-Turonski, J. Zhang, Z. Zhao, Approved as run group (E12-12-006A)
- ✓Measurement of the Unpolarized SIDIS Cross Section from a ^{3}He Target with SoLID U. D'Alesio, M. Cerutti, H. Gao, S. Jia, V. Khachatryan, T. Ye, Approved as run group (E12-11-007B/E12-10-006F)

E12-10-006A: SIDIS Dihadron with Transversely Polarized ^{3}He

$$A_{UT}^{\sin(\phi_R+\phi_S)\,\sin\theta}(x,y,z,M_h,Q) = \frac{1}{|\boldsymbol{S}_T|}\,\frac{\frac{8}{\pi}\int d\phi_R\,d\cos\theta\,\sin(\phi_R+\phi_S)\,(d\sigma^\uparrow - d\sigma^\downarrow)}{\int d\phi_R\,d\cos\theta\,(d\sigma^\uparrow + d\sigma^\downarrow)}$$

$$= \frac{\frac{4}{\pi}\,\varepsilon\int d\cos\theta\,F_{UT}^{\sin(\phi_R+\phi_S)}}{\int d\cos\theta\,(F_{UU,T} + \varepsilon\,F_{UU,L})} \quad .$$

where

$$F_{UU,T} = x\,f_1(x)\,D_1\big(z,\cos\theta,M_h\big) \qquad ,$$

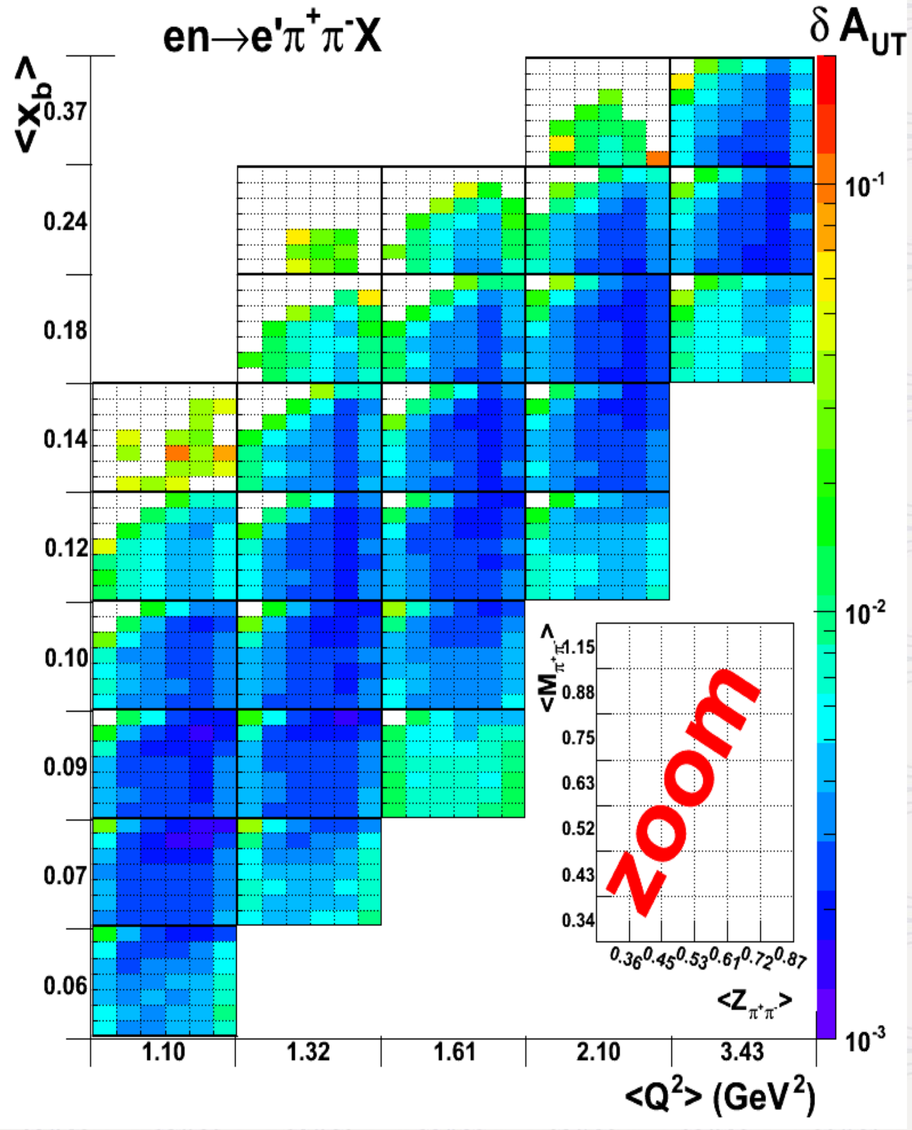
$$F_{UU}^{\cos\phi_R} = -x\frac{|\boldsymbol{R}|\sin\theta}{Q}\,\frac{1}{z}\,f_1(x)\,\widetilde{D}^{\sphericalangle}\big(z,\cos\theta,M_h\big) \quad ,$$

$$F_{UT}^{\sin(\phi_R+\phi_S)} = x\frac{|\boldsymbol{R}|\sin\theta}{M_h}\,h_1(x)\,H_1^{\sphericalangle}\big(z,\cos\theta,M_h\big) \quad ,$$

$$|\boldsymbol{R}| = \frac{1}{2}\sqrt{M_h^2 - 2(M_1^2 + M_2^2) + (M_1^2 - M_2^2)^2}$$

This is what we proposed to measure. The transversity (h_1) is in a linear framework with the DiFFs, which makes it relatively easy to extract comparing to single SIDIS analysis…

- Only for statistic error illustration in the right:
- 48 days of 11 GeV data on polarized ^{3}He target
- Lumi=10^{36} (n)/s/cm^2
- Wide x_b and Q^2 coverages
- Measure transversity via $\pi^+\pi^-$ dihadron channel



Z scale (color) represent stat. error

Combine with proton data one can do a flavor separation

Duke

E12-10-006D: SIDIS in Kaon Production with polarized ^{3}He and NH$_3$

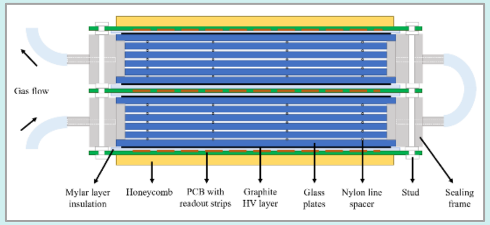
- **$K^\pm$ production in SIDIS using both the transversely polarized ^{3}He and NH$_3$ Targets**

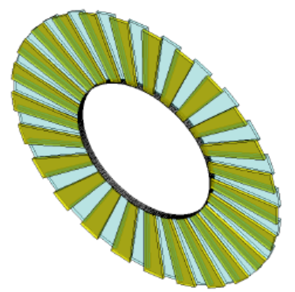
✓ Extract $K^\pm$ Collins, Sivers and other TMD asymmetries

✓ Flavor decomposition of u, d and sea quarks' TMDs

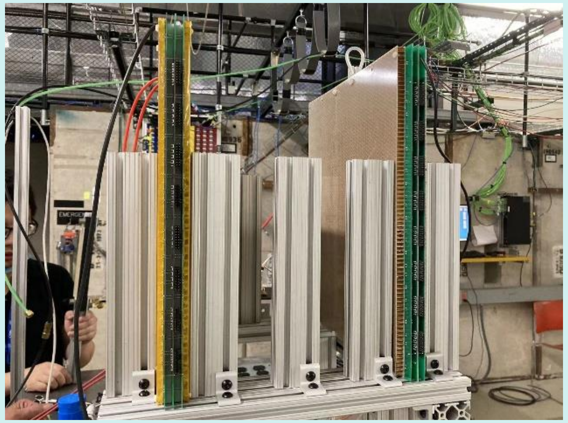
✓ Kaon detection: 30ps MRPC

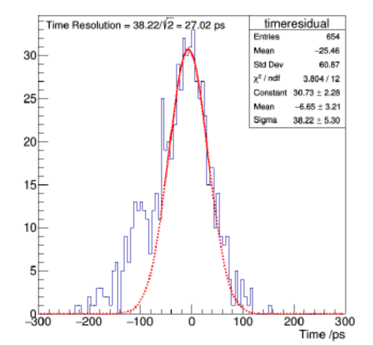
Kaon Identification: 30ps TOF + Veto of HGC





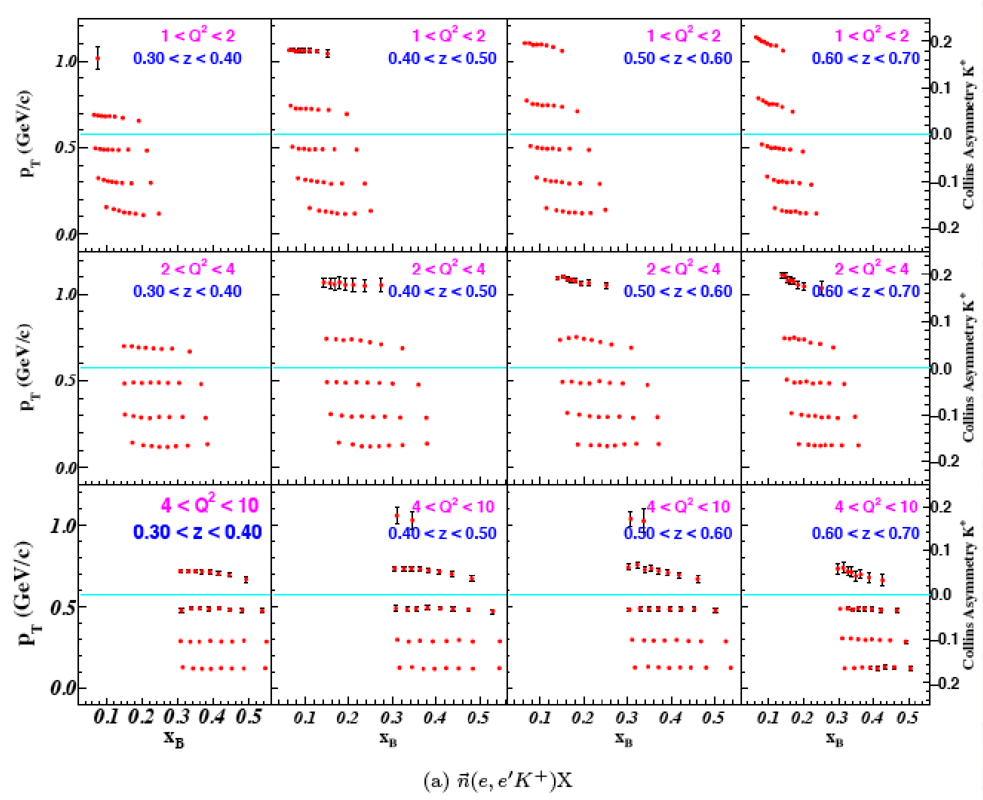
(a) The layout of the MRPC





MRPC beam test at Fermilab (Tsinghua+UIC)

Projection on Collins K^+

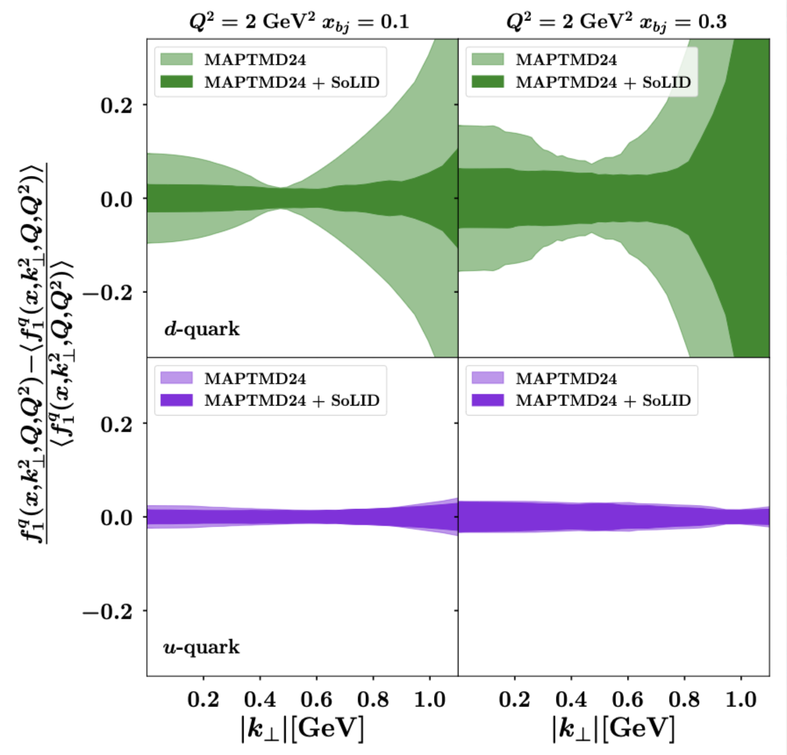


(a) $\vec{n}(e, e'K^+)X$

Unpolarized SIDIS cross section

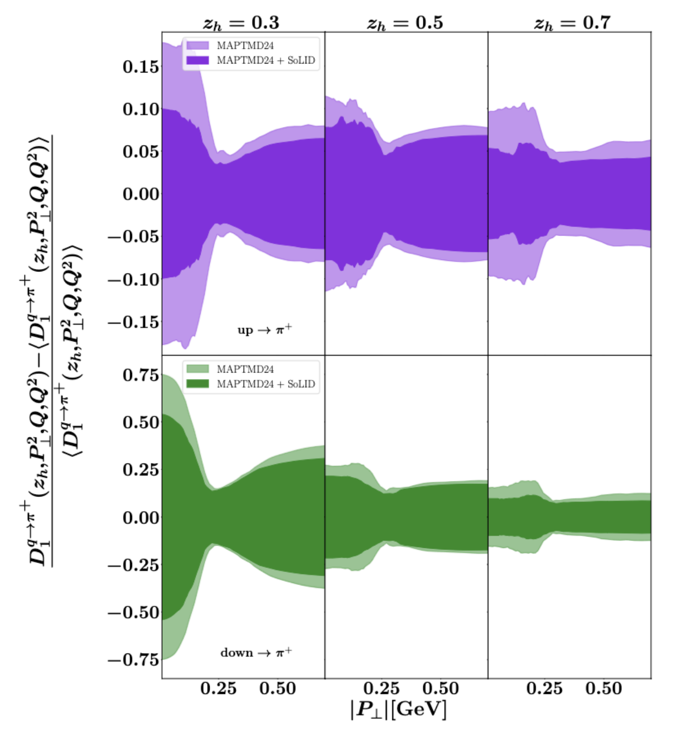
Multiplicities from HERMES and COMPASS help constrain TMDs, but absolute cross-section measurements provide significantly more information. They offer a critical test of TMD factorization beyond leading order.

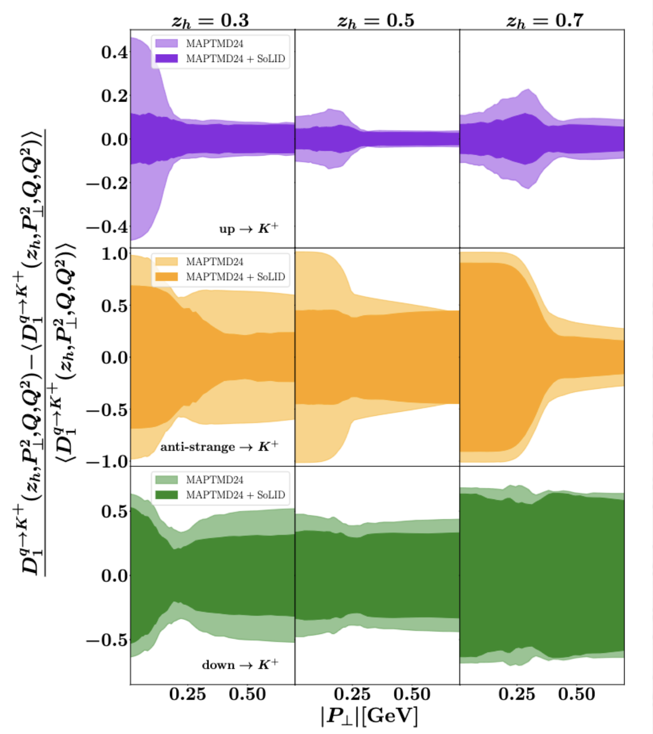
Constraint on unpol TMDs

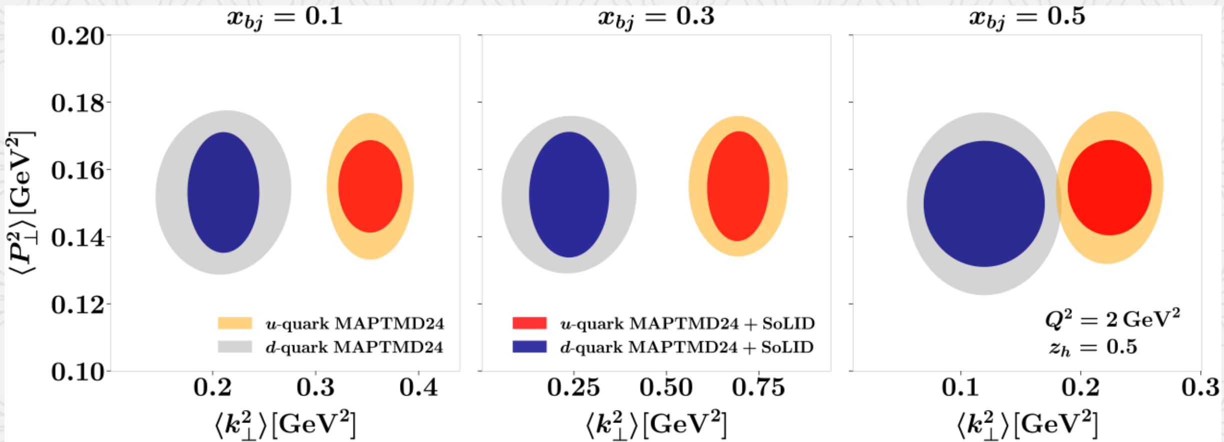


M. Cerutti et al. to appear in PRC

Constraint on unpol FFs





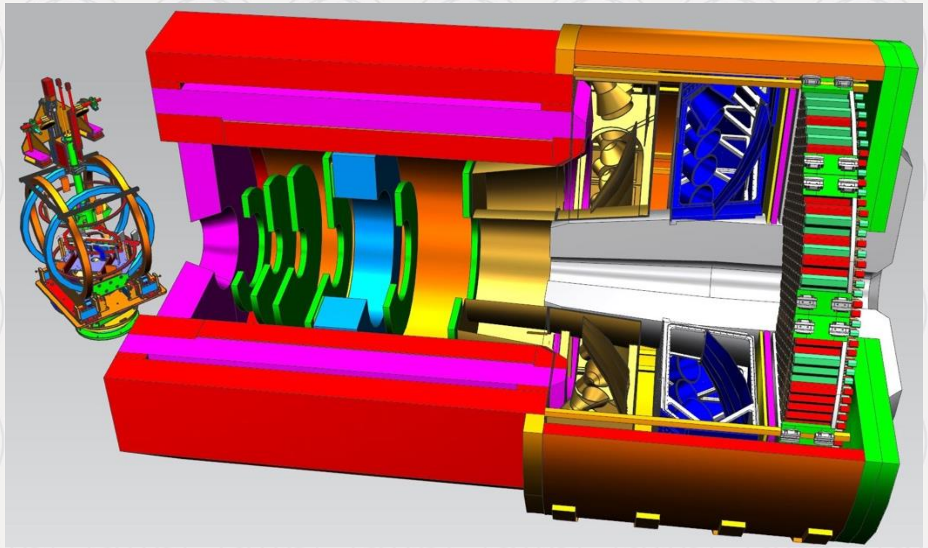


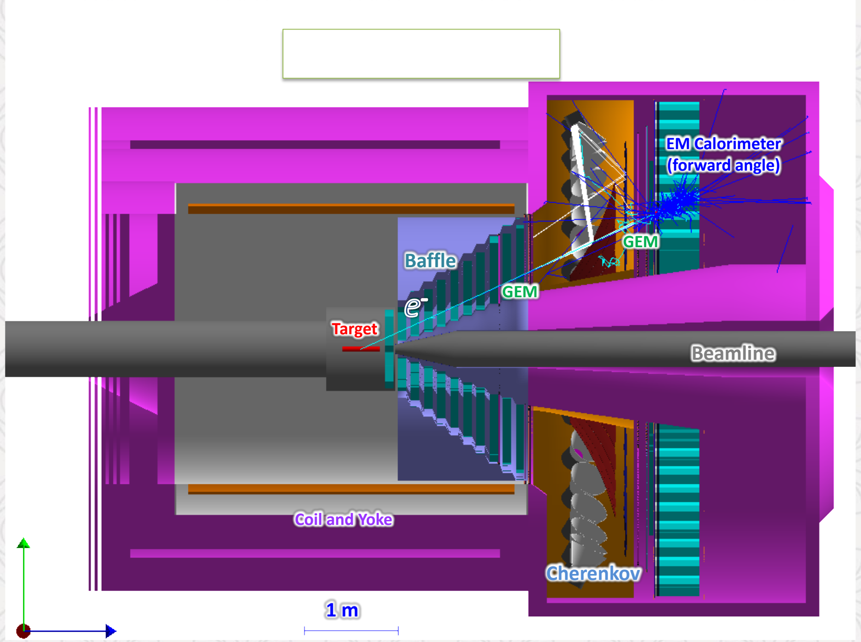
SoLID Apparatus

Polarized ^{3}He (``neutron”) @ SoLID and Pol. NH3

Requirements are Challenging

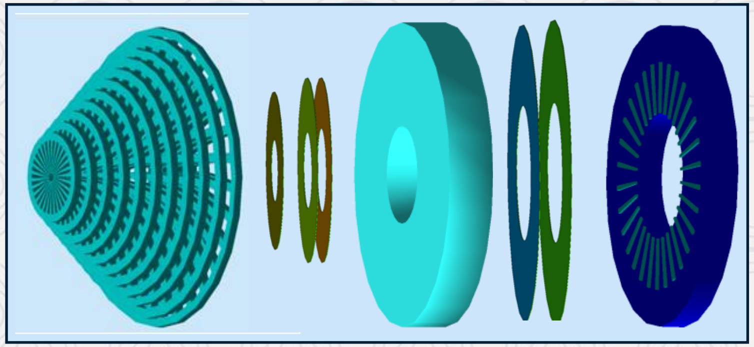
- High Luminosity (10^{37}-10^{39})
- High data rate
- High background
- Low systematics
- High Radiation
- Large scale
- Modern Technologies
  - GEM’s or other MPGD detectors
  - Shashlik ECal
  - Pipeline DAQ
  - Rapidly Advancing Computational Capabilities including AI/ML
- High Performance Cherenkov
- Baffles



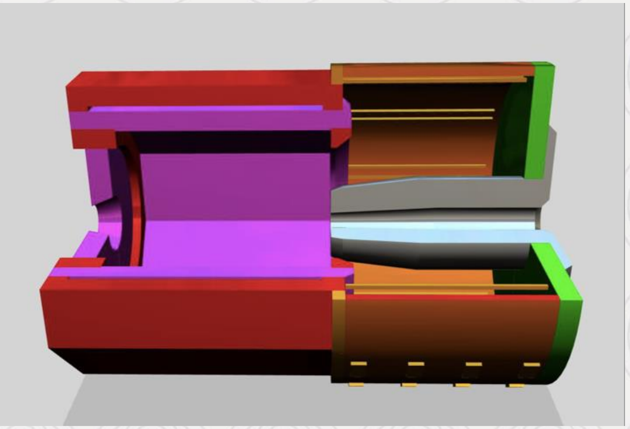


SoLID Detector Subsystems

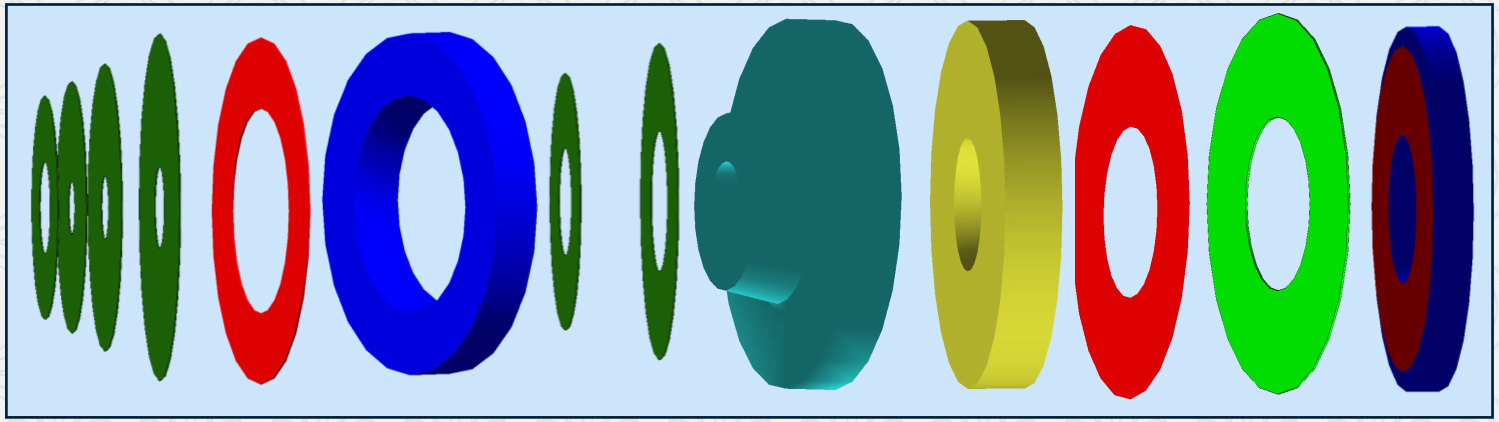
PVDIS



Uses full capability of JLab electronics



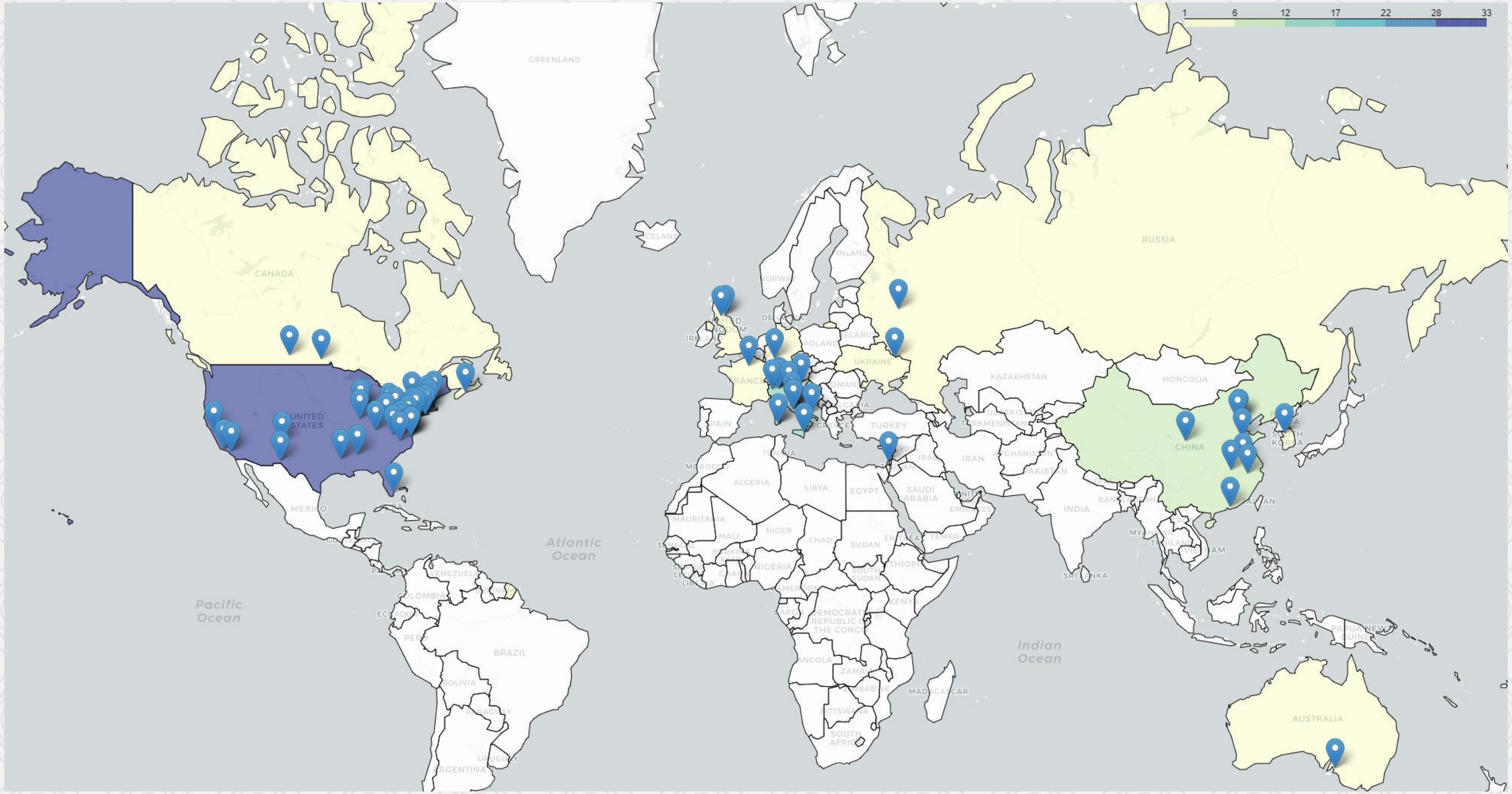
SIDIS-J/ψ



Pre-R&D items: **LGC, HGC, GEM's, EC, DAQ/Electronics, Magnet**

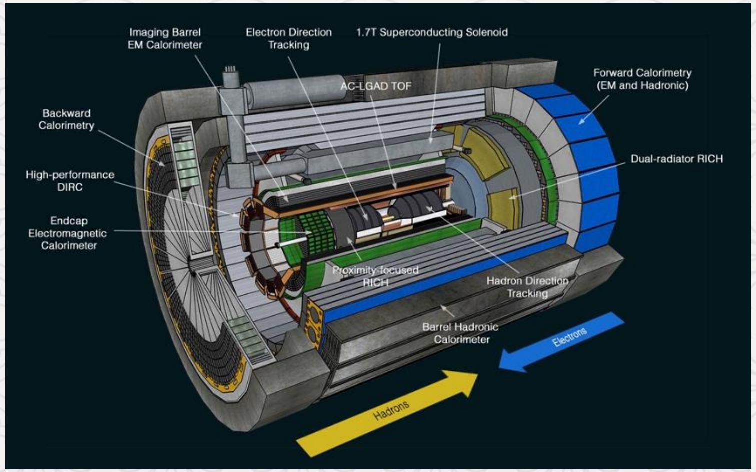
Strong Collaboration

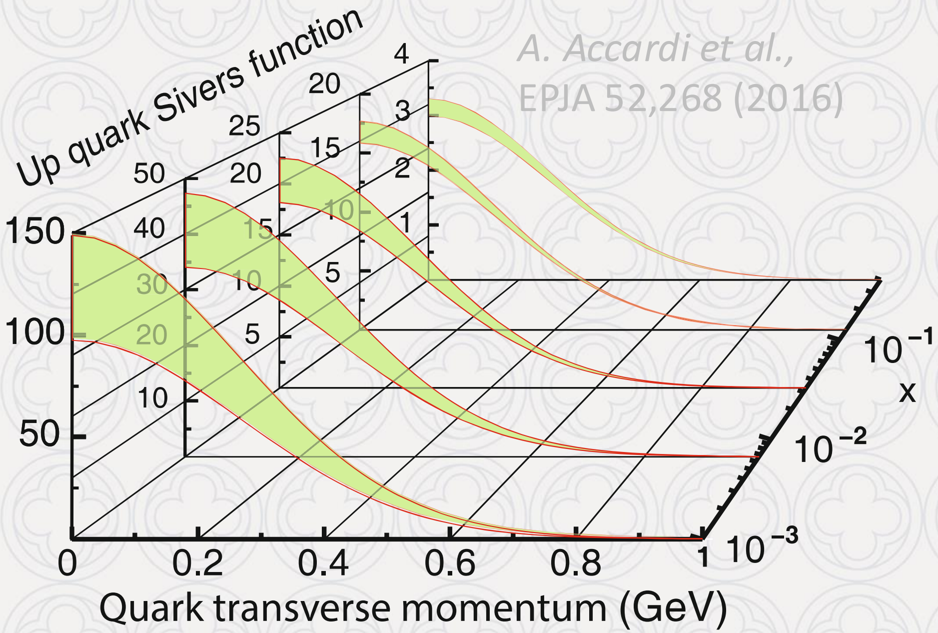
- 270+ collaborators, 70+ institutions from 13 countries
- Large international participations and anticipated contributions
- Strong theory support



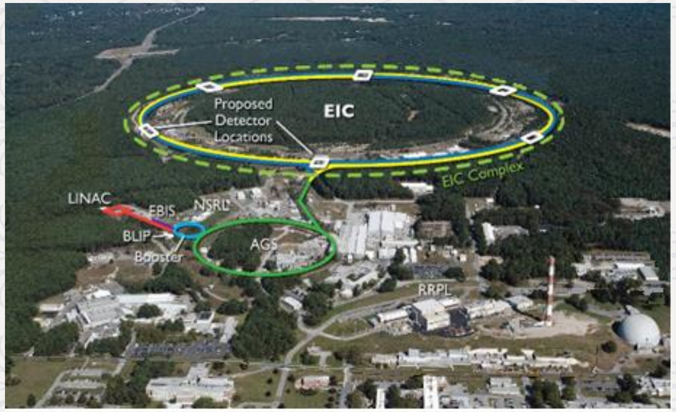
https://solid.jlab.org/

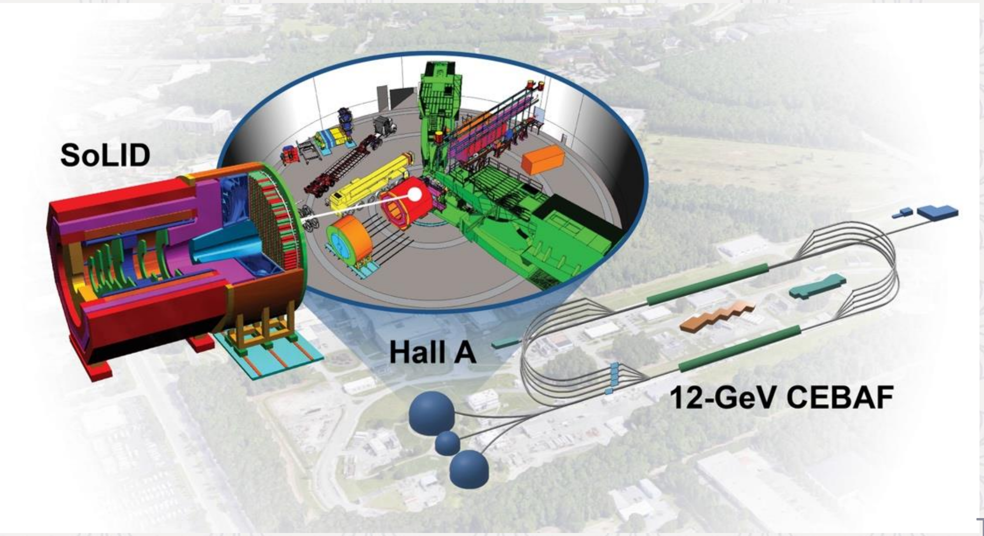
Precision tomography of the nucleon requires both valence quark and gluon region

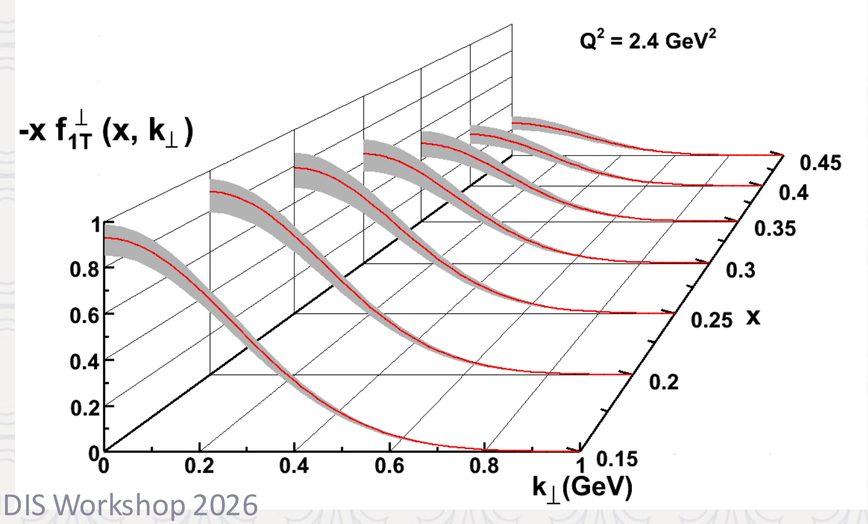




A. Accardi et al.,
EPJA 52,268 (2016)

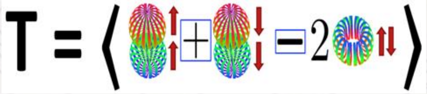






J. Dudek et al.,
EPJA 48,187 (2012)

Spin-1 Tensor TMDs at Jefferson Lab



J. Poudel et al., *Eur. Phys. J. A* 61 (2025) 4, 81

- SIDIS Cross-section considering longitudinal polarization of target

$$\frac{d\sigma}{dx\,dy\,d\psi\,dz\,d\phi_h\,dP_{h\perp}^2} = \frac{y^2\alpha^2}{2(1-\epsilon)xyQ^2}\left(1+\frac{\gamma^2}{2x}\right)\Bigg[F_{UU,T} + \epsilon F_{UU,L} + \sqrt{2\epsilon(1+\epsilon)}\cos\phi_h\;F_{UU}^{\cos\phi_h}$$

$$+\,\epsilon\cos(2\phi_h)\;F_{UU}^{\cos(2\phi_h)} + \lambda_e\sqrt{2\epsilon(1-\epsilon)}\sin\phi_h\;F_{LU}^{\sin\phi_h}$$

Vector polarization:

$$+\,S_{\|}\left\{\sqrt{2\epsilon(1+\epsilon)}\sin\phi_h\;F_{UL}^{\sin\phi_h} + \epsilon\sin(2\phi_h)\;F_{UL}^{\sin 2\phi_h}\right\}$$

$$+\,S_{\|}\lambda_e\left\{\sqrt{1-\epsilon^2}\;F_{LL} + \sqrt{2\epsilon(1-\epsilon}\cos\phi_h\;F_{LL}^{\cos\phi_h}\right\}$$

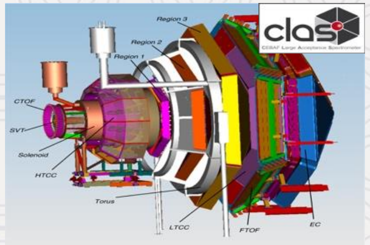
Tensor Polarization:

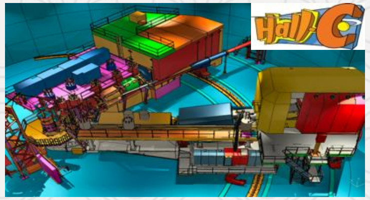
$$+\,T_{\|\|}\left\{\boxed{F_{U(LL),T}} + \epsilon\;F_{U(LL),L} + \sqrt{2\epsilon(1+\epsilon)}\cos\phi_h\;F_{U(LL)}^{\cos\phi_h}\right.$$

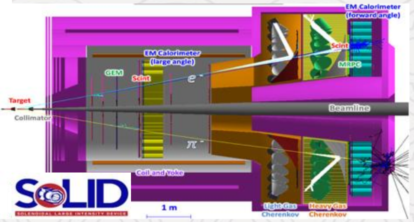
$$\left.+\,\epsilon\cos(2\phi_h)\boxed{F_{U(LL)}^{\cos 2\phi_h}} + \lambda_e\sqrt{2\epsilon(1-\epsilon)}\sin\phi_h\;F_{L(LL)}^{\sin\phi_h}\right\}\Bigg]$$

$$\boxed{F_{U(LL),T} = C[f_{1LL}D_1]}$$

$$\boxed{F_{U(LL)}^{\cos 2\phi_h} = C\left[-\frac{2(\hat{\mathbf{h}}\cdot\mathbf{k_T})(\hat{\mathbf{h}}\cdot\mathbf{p_T}) - \mathbf{k_T}\cdot\mathbf{p_T}}{MM_h}h_{1LL}^{\perp}H_1^{\perp}\right]}$$







1. Use CLAS12 existing data (RG-C) to find the upper limit of $F_{U(LL),T}$ (data mining)
2. Dedicated measurement of $F_{U(LL),T}$ in Hall C
3. **Precise measurement of $F_{U(LL),T}$, $F_{U(LL)}^{cos\,\phi_h}$ and $F_{U(LL)}^{cos\,2\phi_h}$ in SoLID**

Summary

- SoLID science is more compelling in the era of the EIC as demonstrated in the 2015 and 2023 NSAC LRPs
- SoLID will address two EIC science questions highlighted in 2018 NAS 2018 report – both valence and sea/gluon regions required for a complete picture of the nucleon
- SoLID: A **large acceptance** device which can handle **very high luminosity** → pushing the limit of the luminosity frontier and allow for precision study of the nucleon 3D structure
- A mature pre-conceptual design with expected performance to meet the science requirements (DOE 2021 Science review and 2024 facilities review) following a decade of hard work and pre-R&D activities
- The collaboration formed more than 15 years ago with many international collaborators and theory colleagues

Acknowledgement: J.P. Chen, Z.-E. Meziani, P. Souder, Xiaochao Zheng, and many others in the SoLID collaboration, supported in part by the U.S. Department of Energy under contract number DE-FG02-03ER41231