TMD Program with SoLID

Haiyan Gao
BNL & Duke University

Zhiwen Zhao
Duke University

SoLID Collaboration

Workshop on "**SoLID Opportunities and Challenges of Nuclear Physics at the Luminosity Frontier**"
June 17-20, 2024
Argonne National Laboratory

Outline

- SoLID Introduction
- Nucleon 3-D momentum tomography with **SIDIS**
- SoLID **SIDIS** program
- Summary

SoLID@12-GeV JLab: QCD at the intensity frontier

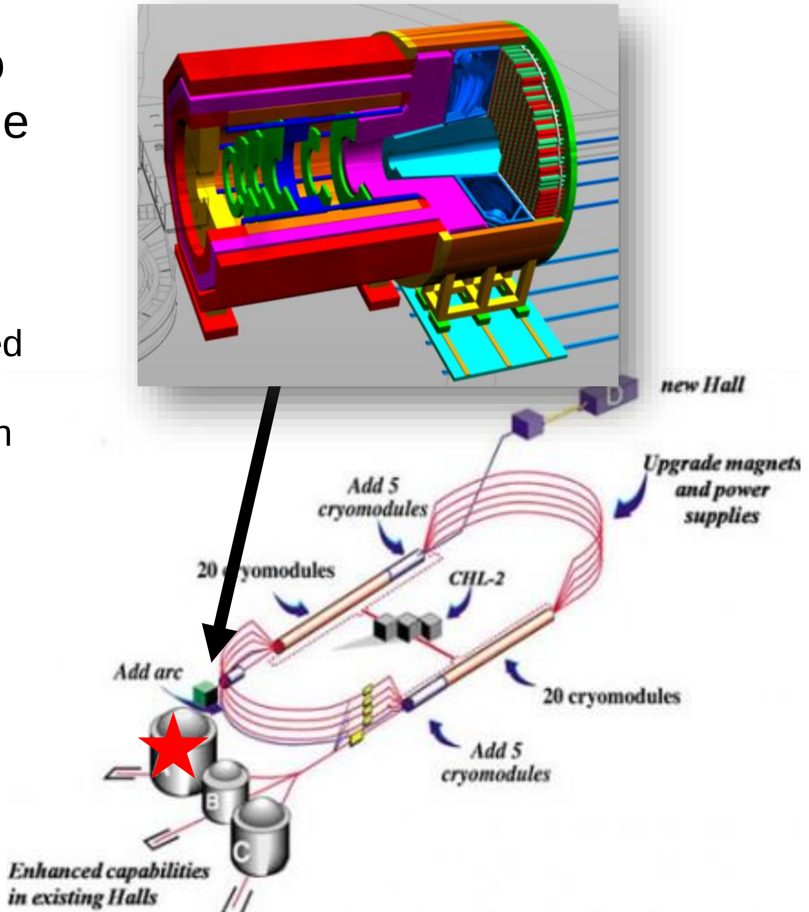
SoLID will ***maximize*** the science return of the 12-GeV CEBAF upgrade by **combining...**

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

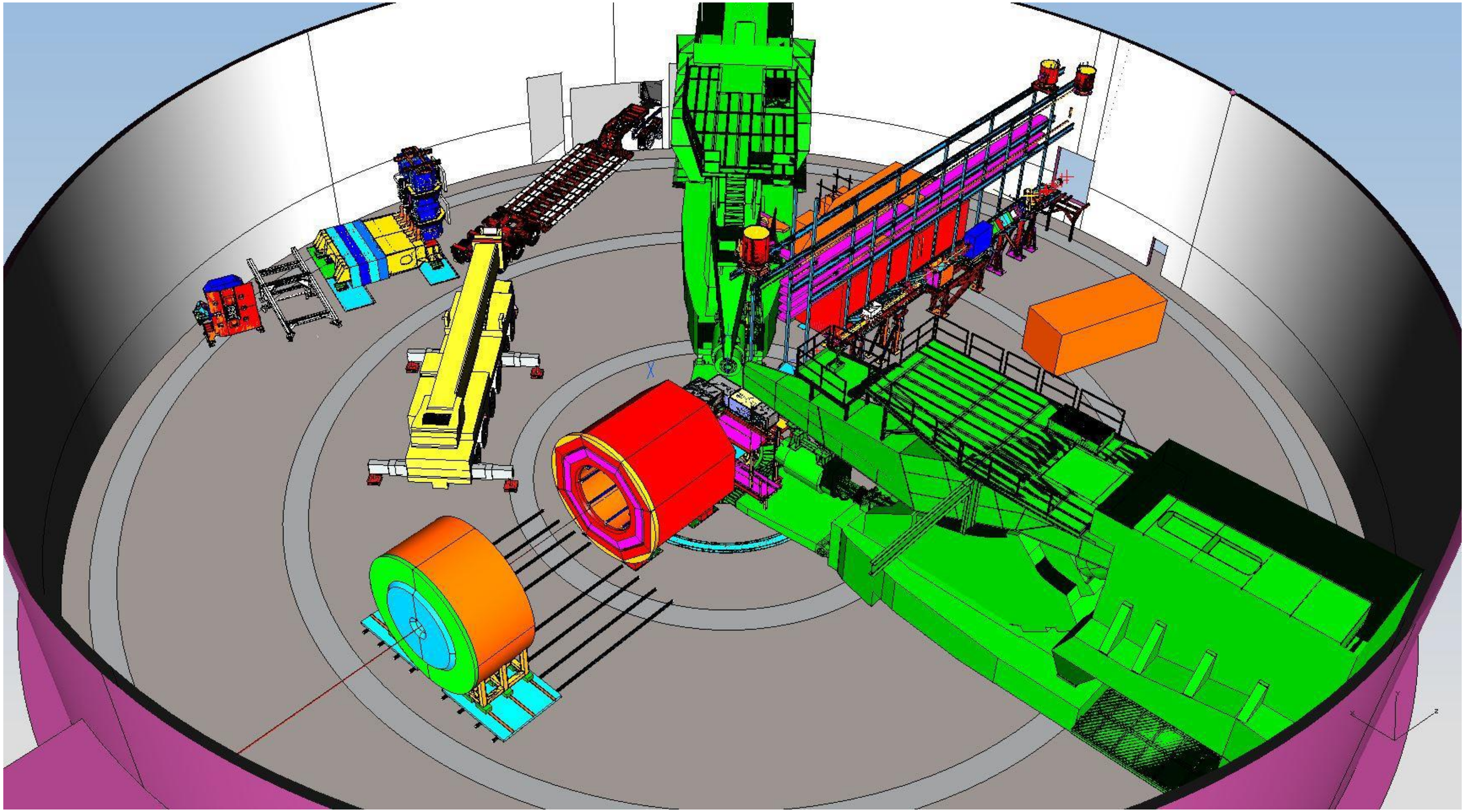
- Pushing the phase space in the search of new physics and of hadronic physics (**PVDIS**)
- 3D momentum imaging of a relativistic strongly interacting confined system (**nucleon spin**)
- Superior sensitivity to the differential electro- and photo-production cross section of J/ψ near threshold (**proton mass**)

Synergizing with the pillars of EIC science (**proton spin** and **mass**) through high-luminosity valence quark tomography and precision J/ψ production near threshold



SoLID whitepaper: *J. Phys. G: Nuclear and Particle Physics* ***50,*** *110501 (2023)*
12GeV physics: Progress in Particle and Nuclear Physics ***127****, 103985 (2022)*

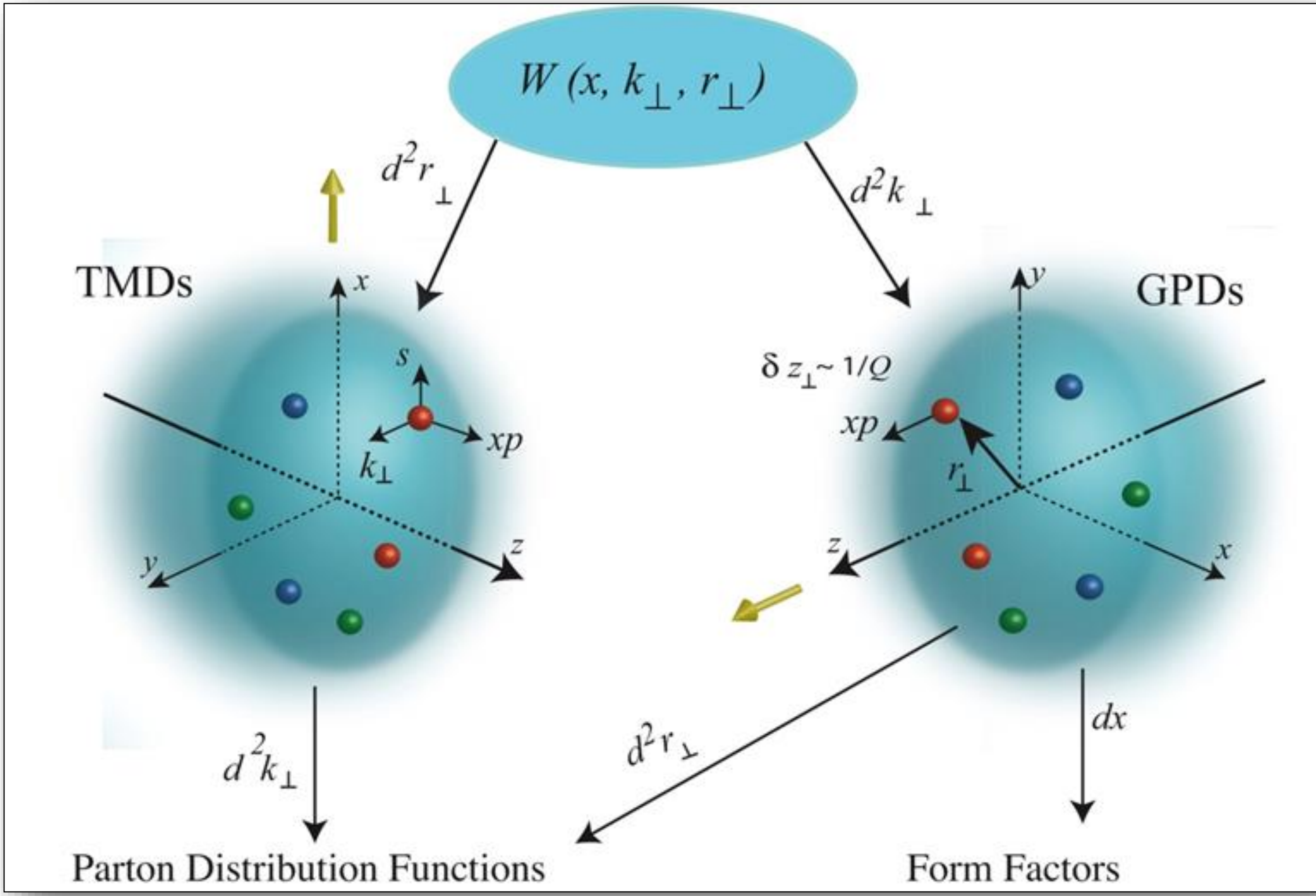
SoLID in Hall A



Plan for installing SoLID in Hall A with other equipment moved out of the way.

Nucleon Structure from 1D to 3D – orbital motion

5-D Wigner distribution



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

Generalized parton distribution (GPD)

Transverse momentum dependent parton distribution (TMD)

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

TMDs – confined motion inside the nucleon

Leading twist: 8 TMDs

→ Nucleon Spin
→ Quark Spin

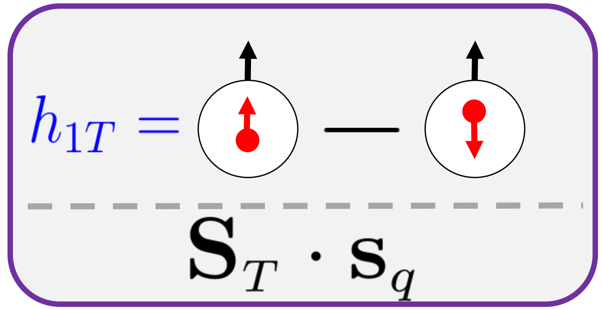
Nucleon Polarization		Quark polarization: Un-Polarized	Quark polarization: Longitudinally Polarized	Quark polarization: Transversely Polarized
	U	f_1 =		$h_1^{\wedge}$ = − **Boer-Mulder**
	L		g_1 = − **Helicity**	$h_{1L}^{\wedge}$ = − Worm gear
	T	$f_{1T}^{\wedge}$ = − **Sivers**	$g_{1T}^{\wedge}$ = − Worm gear	h_{1T} = − **Transversity** $h_{1T}^{\wedge}$ = − **Pretzelosity**

TMDs – confined motion inside the nucleon

Transversely Polarized Nucleon TMDs

→ Nucleon Spin
→ Quark Spin

Transversity

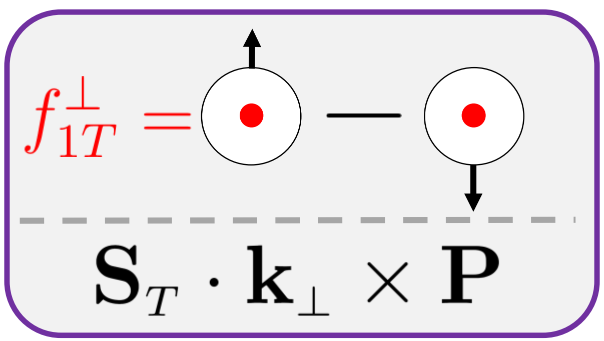


Relevant Vectors

S_T: Nucleon Spin
s_q: Quark Spin
$k_\perp$: Quark Transverse Momentum
P: Virtual photon 3-momentum (defines z-direction)

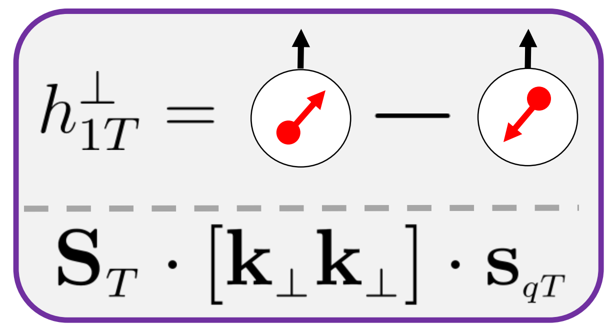
- h_{1T} (h_1) = g_1 (no relativity)
- h_{1T} → tensor charge (lattice QCD calculations)
- Connected to nucleon beta decay and EDM

Sivers



- Nucleon spin - quark orbital angular momentum (OAM) correlation – zero if no OAM (model dependence)

Pretzelosity

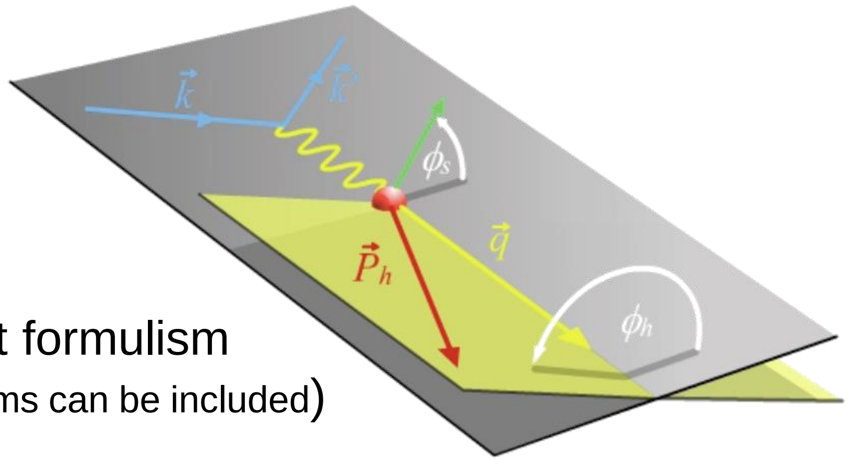


- Interference between components with OAM difference of 2 units (i.e., s-d, p-p) (model dependence)
- Signature for relativistic effect

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)

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

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

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

Collins fragmentation function from e^+e^- collisions

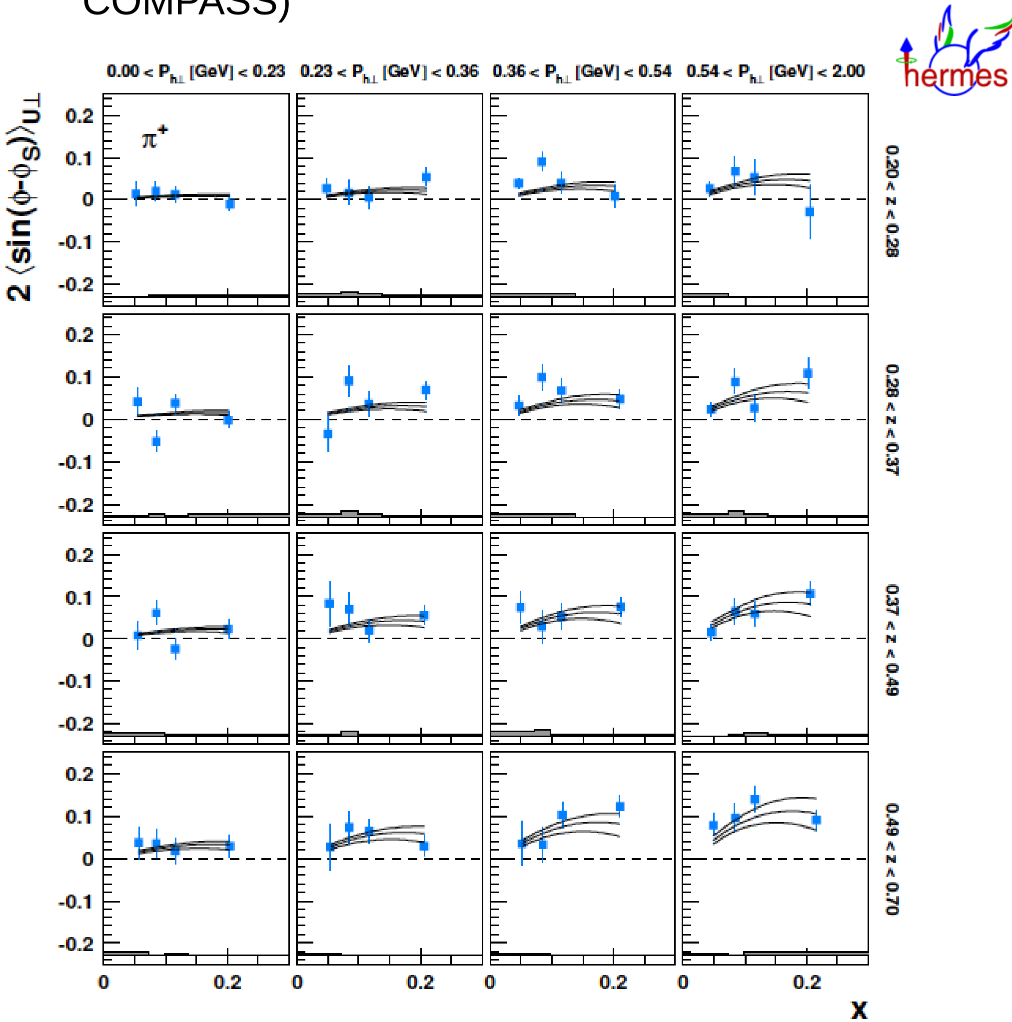
$$A_{UT}^{Sivers} \propto \langle\sin(\phi_h-\phi_S)\rangle_{UT} \propto f_{1T}^{\perp} \otimes D_1$$

Unpolarized fragmentation function

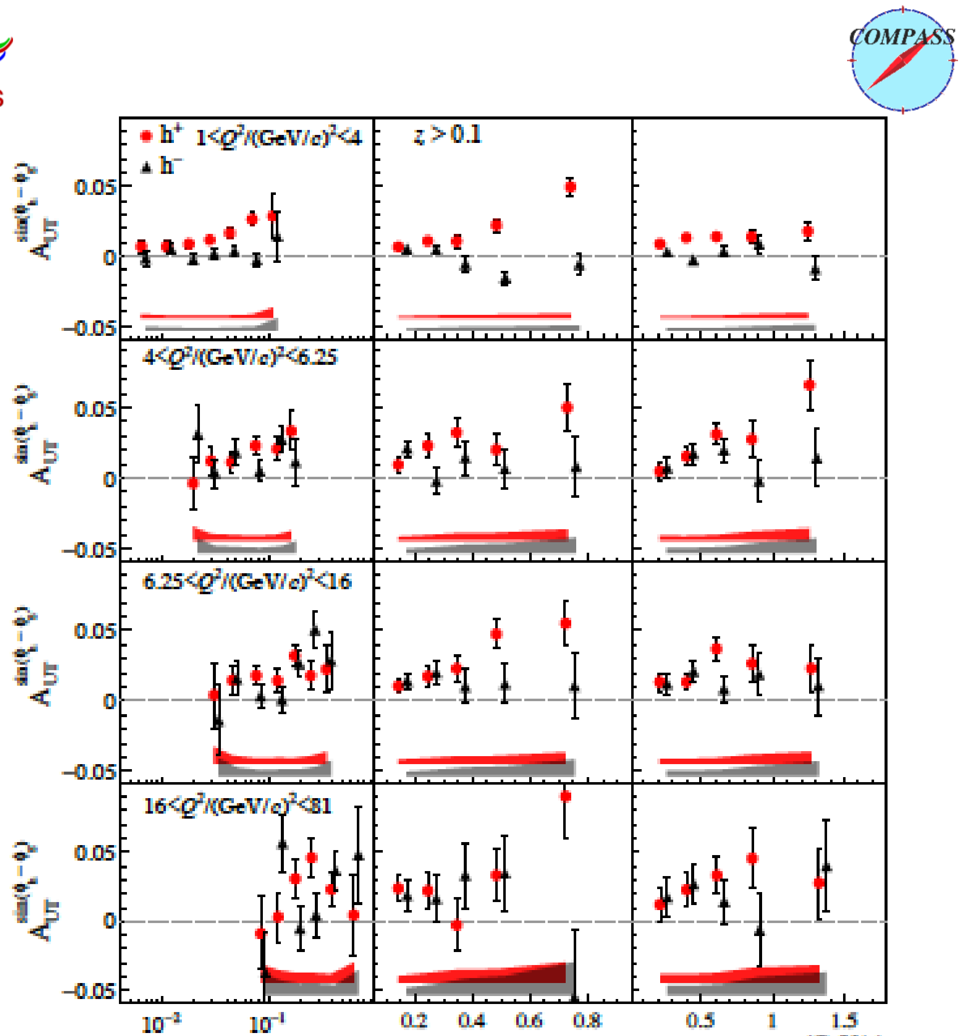
SoLID Jefferson Lab

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

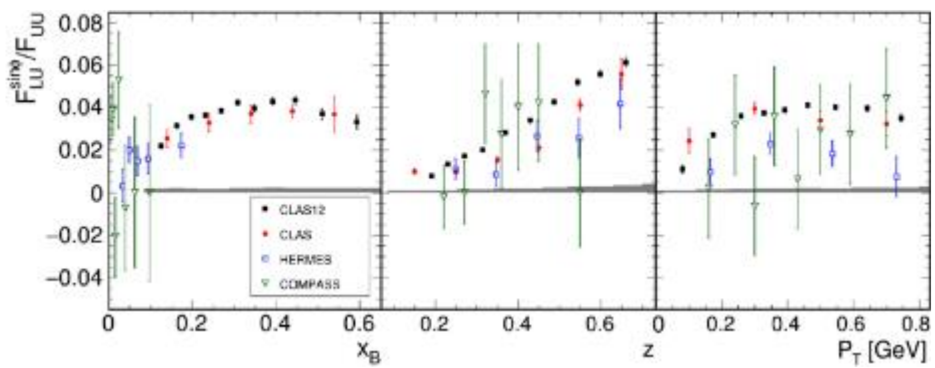


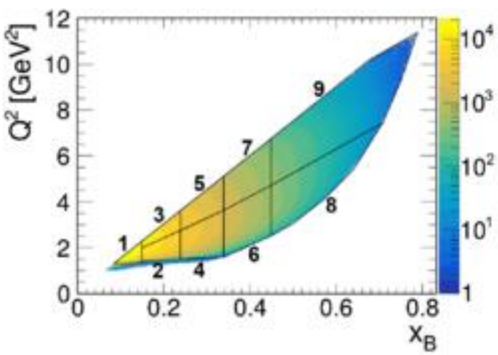
C. Adolph et al. PLB 770, 138 (2017)

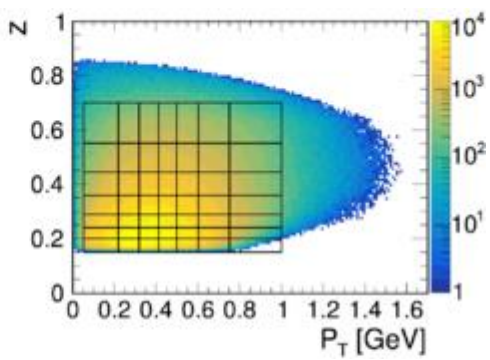
TSSA ~100 bins

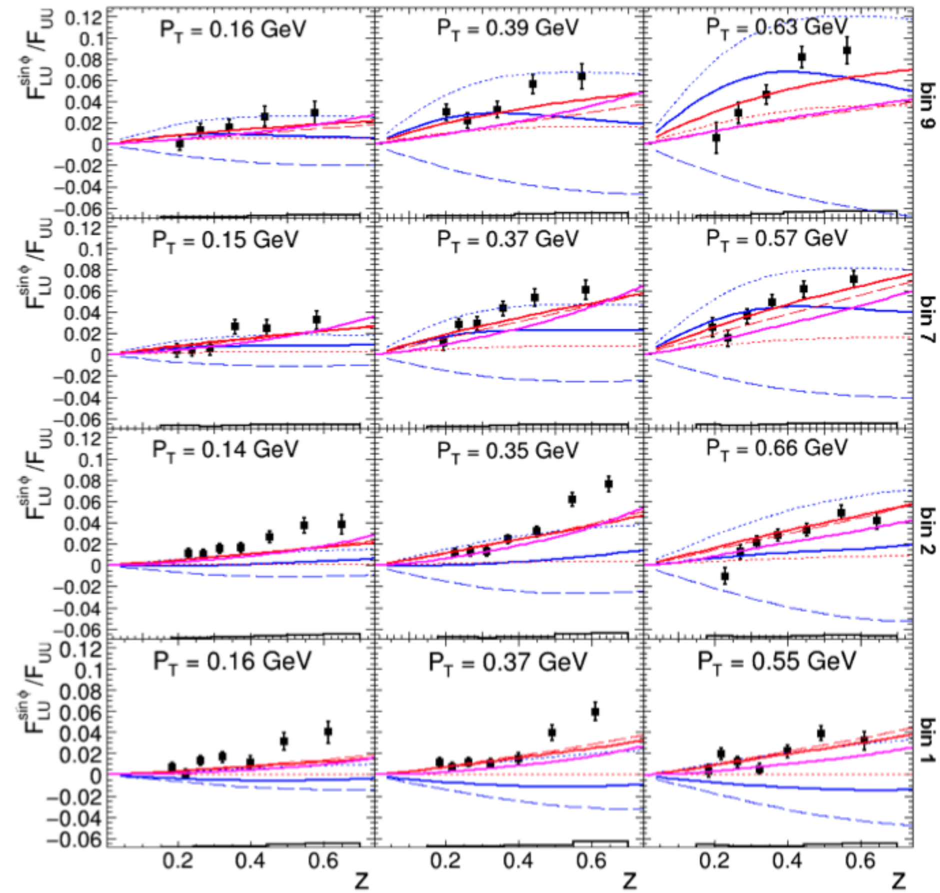
State-of-the-art from CLAS 12

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









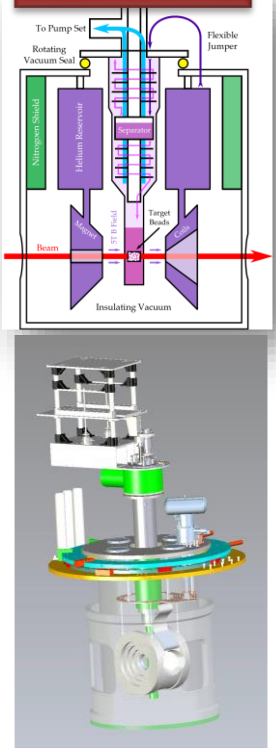
BSSA ~400 bins

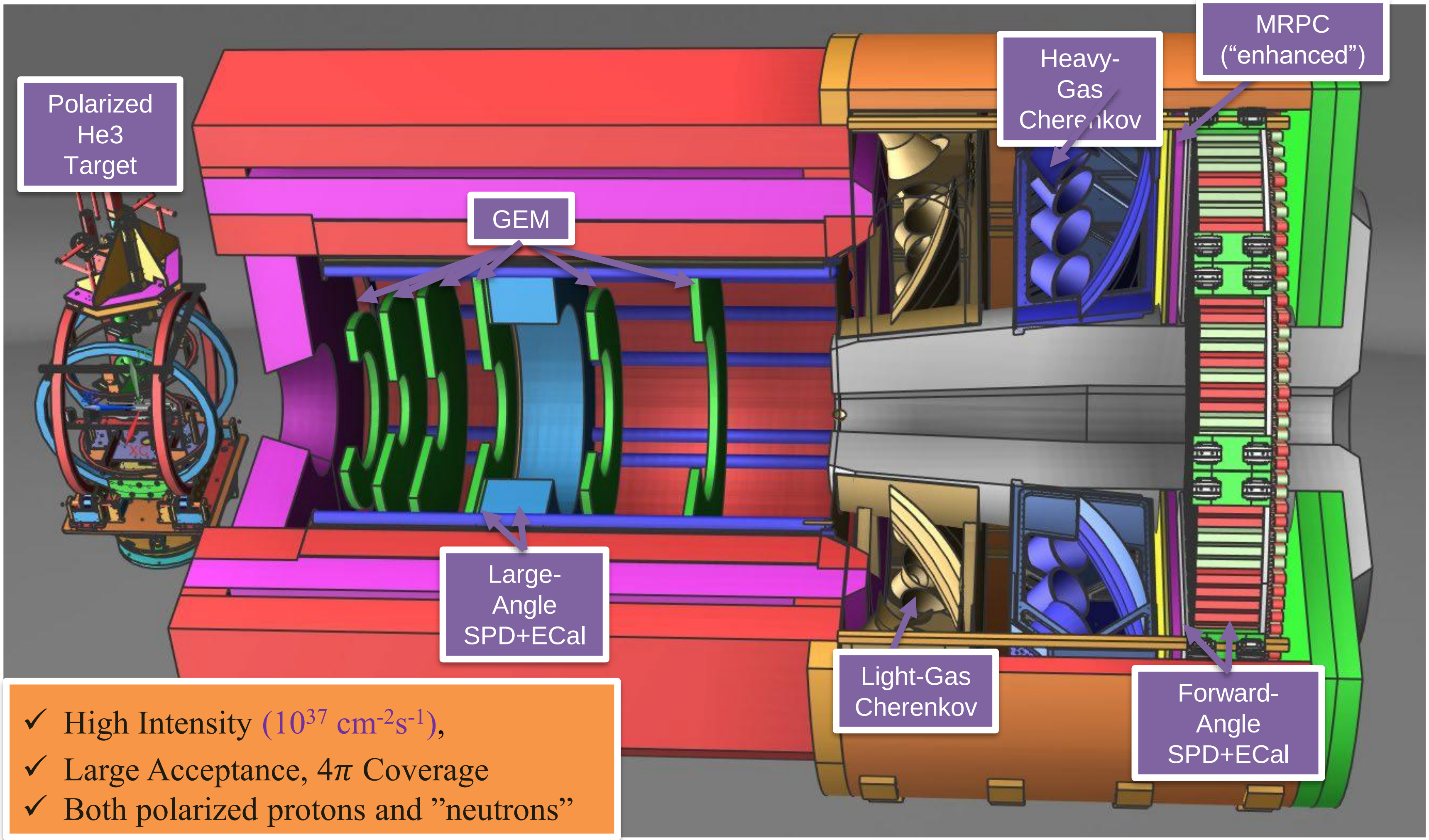
First multidimensional, high precision measurements of semi-inclusive π+ beam single spin asymmetries from the proton over a wide range of kinematics

S. Diehl *et al.* (CLAS Collaboration), Phys. Rev. Lett. **128**, 062005 (2022)

SoLID SIDIS Configuration

Polarized NH3 (DNP) Target



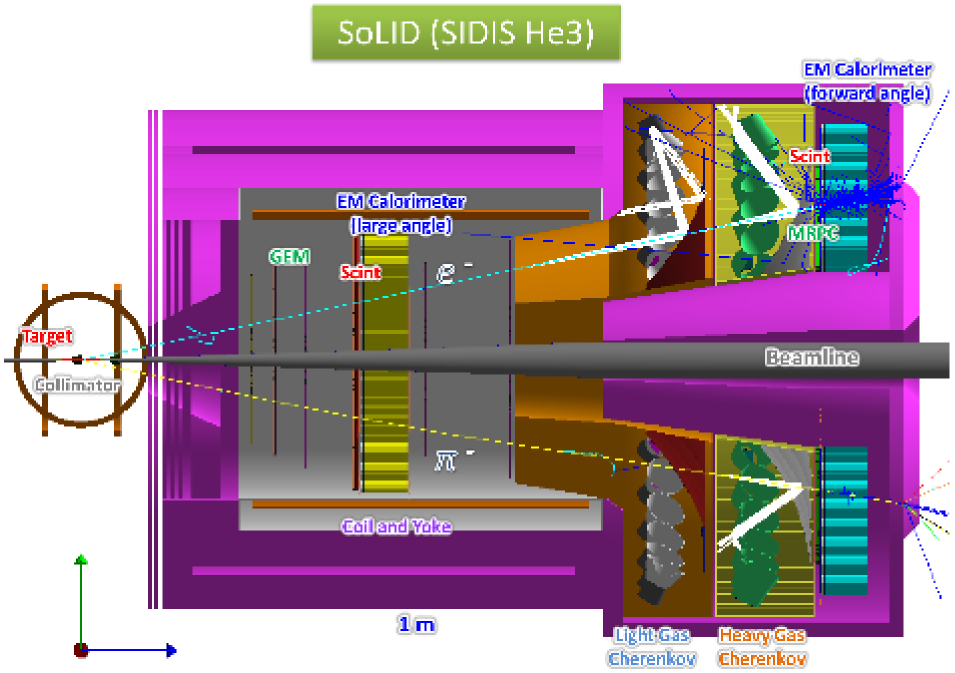


- ✓ High Intensity (10^{37} cm^{-2}s^{-1}),
- ✓ Large Acceptance, 4π Coverage
- ✓ Both polarized protons and ”neutrons”

https://solid.jlab.org/experiments.html

SoLID SIDIS He3 Setup

- E12-10-006: SIDIS pion on transversely polarized ^{3}He, 90 days, **rated A**
- E12-11-007: SIDIS pion on longitudinally polarized ^{3}He, 35 days, **rated A**
- SIDIS kaon and dihadron as run groups



Detection

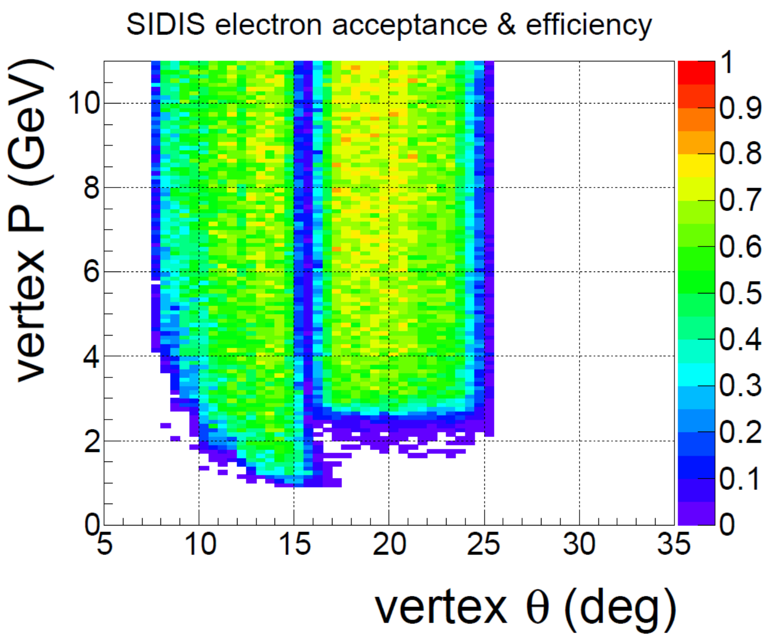
- e- at forward angle with EC and Cerenkov to reject pions
- e- above 3GeV detected at large angle with EC to reject pions
- pions detected at forward angle with TOF and Cerenkov to suppress kaons

Polarized lumi ~1e^{36}/cm^2/s

Unpolarized lumi ~1e^{37}/cm^2/s

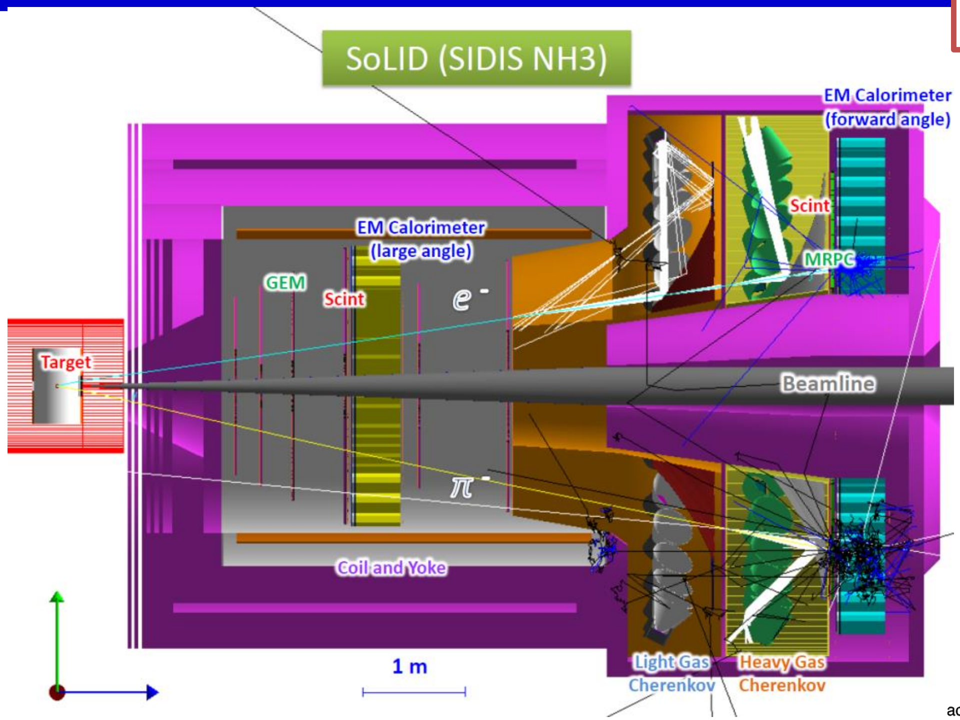
Coverage

- Polar angle: e^- 8-24 deg, π^-/π^+ 8-15deg
- Azimuthal angle: full



SoLID SIDIS NH3 Setup

- E12-10-008: SIDIS pion on transversely polarized proton (NH_3), 120 days, **rated A**
- SIDIS kaon and dihadron as run groups



Detection is similar to He3 setup

Coverage is similar to He3 setup except some distortion from the target field

5T transverse target field

High radiation sheet of flame areas need to be cut away or shielded

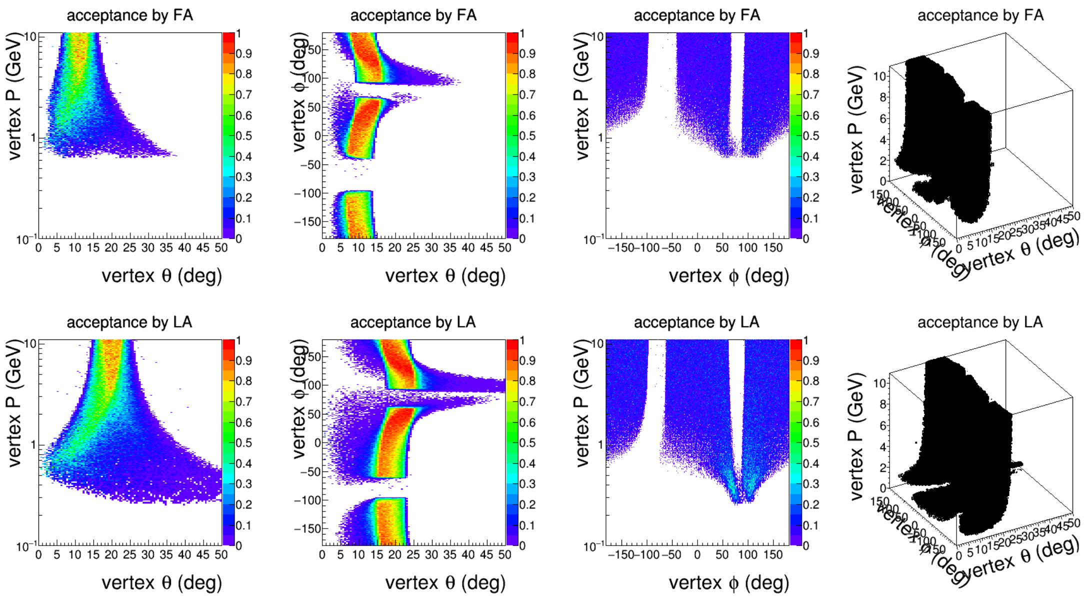
Polarized lumi ~1e^{35}/cm^2/s

Unpolarized lumi ~6e^{35}/cm^2/s

e- acceptance shown

π^- acceptance is similar

π^+ acceptance is reversed along phi=0 plane

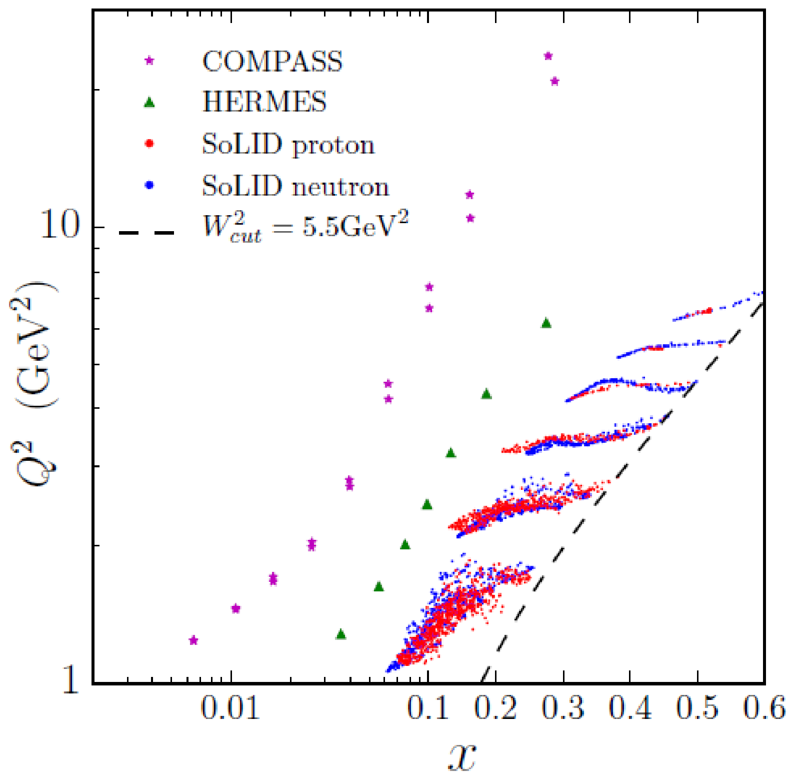


SoLID SIDIS Kinematic Coverage

Quantum 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



$0.05 < x < 0.6$
$1\text{GeV}^2 < Q^2 < 8\text{GeV}^2$
$0.3 < z < 0.7$
$0 < P_T < 1.6\text{GeV}$
~ 2000 bins for n
~ 1000 bins for p

large acceptance and high luminosity enable wide coverage in all 4D kinematic bins with well controlled systematics

Z. Ye et al, Phys. Lett. B 767, 91 (2017)

SoLID-SIDIS Measurements

- Deep inelastic kinematics at 8.8 GeV and 11 GeV incident electron beam energies
  - Coincidence detection of electrons and charged pions
  - Good electron PID and moderate charged pion PID

- Single and double spin asymmetries and flavor separation
  - ^{3}He target with both transverse and longitudinal in-beam polarizations of ~60%
  - NH3 target with transverse in-beam polarizations of ~80%
  - Electron beam with polarization ~85% allows both single and double spin asymmetries

- Small asymmetries, 4-dimensional binning and high precision require high luminosity (polarized) ~ 10^{36} cm^{-2} s^{-1} (n) and ~ 10^{35} cm^{-2} s^{-1} (p), and large acceptance

- Extracting various azimuthal angular dependences and suppressing systematic uncertainties require full azimuthal coverage

$$A^h_{UT}(\phi_h,\phi_S) = \frac{2}{P^1_T + P^2_T} \cdot \frac{\sqrt{N_1(\phi_h,\phi_S)N_2(\phi_h,\phi_S+\pi)} - \sqrt{N_1(\phi_h,\phi_S+\pi)N_2(\phi_h,\phi_S)}}{\sqrt{N_1(\phi_h,\phi_S)N_2(\phi_h,\phi_S+\pi)} + \sqrt{N_1(\phi_h,\phi_S+\pi)N_2(\phi_h,\phi_S)}}$$

- Four-dimensional binning in (x, z, Q^2 and P_T): requires reasonably good momentum and angular resolutions
  - GEM detectors provide excellent tracking capability

- The capability to handle high rates and backgrounds associated with high luminosity and large acceptance
  - DAQ rate: less than 100 KHz

SoLID-SIDIS: Systematic Uncertainties

- *Raw asymmetries*: control the syst. uncertainties corresponding to detector efficiencies (time dependent part) by monitoring the single e^-, π^+, π^+ rates

- *Target polarization*: knowledge of the target pol. at 3% level $\rightarrow$ a 3% rel. syst. uncertainty of the SSAs

- *Random coincidence*: obtained from the signal to noise ratio and background within 6 ns timing window

- *Diffractive meson*: the pion contribution from the diffractive production decay estimated based on HERMES tuned Pythia at SoLID SIDIS kinematics

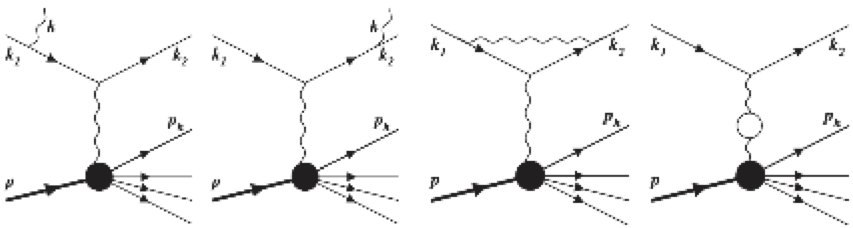
- *Radiative corrections*: use both traditional and factorized method

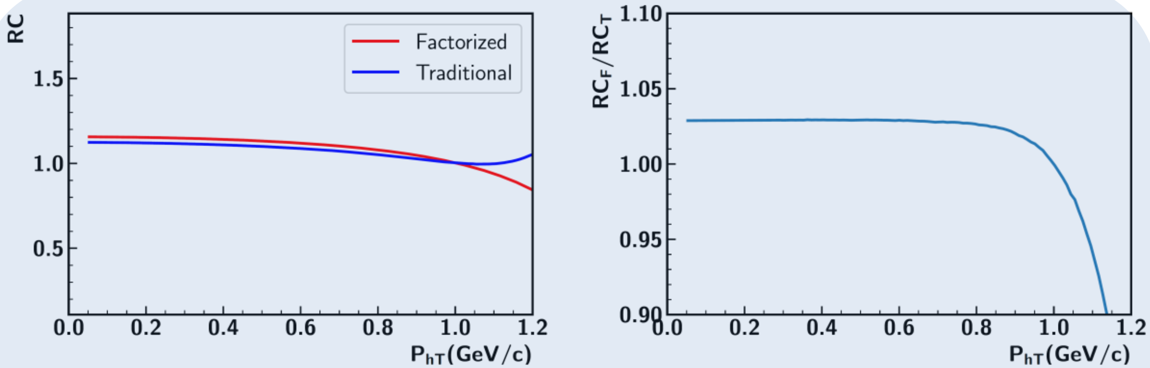
- *Detector resolution*: estimated based on the track fitting studies

- *Nuclear effects*: estimated based on theoretical calculations of the neutron SSA extraction at SoLID SIDIS kinematics

SoLID-SIDIS: Radiative Correction

- Radiative Correction being one of dominant sources of systematic uncertainties, due to radiation of photons off leptons





Left panel: RC factor computed at $\sqrt{s} = 4.9$ GeV, $Q^2 = 8\ (\mathrm{GeV}/c)^2$, $z_h = 0.375$, $x_{Bj} = 0.48$, $\phi_h = 0$

Right panel: RC factor ratios from two methods at given **JLab** kinematics

$$\ell(k_1, \xi) + N(P, \eta) \to \ell'(k_2) + h(P_h) + X(\tilde{P}_X) + \gamma(k)$$

Traditional

- Three additional photonic variables introduced
  - ϕ_k to be angle between $(\mathbf{k_1}, \mathbf{k_2})$ and $(\mathbf{k}, \mathbf{q})$ planes

$$R = 2k \cdot P, \qquad \tau = \frac{k \cdot q}{k \cdot P}, \qquad \phi_k$$

I. Akushevich et al. PRD, 100, 033005 (2019)

Factorized

- Simultaneously treats QED and QCD effects on the same footing.
- Good approximation for QED radiative contributions by collinear factorization

T. Liu et al JHEP11(2021)157

$\sqrt{s}$ (GeV)	x_B	Q^2 $(\mathrm{GeV}/c)^2$	z_h	RC ratio
Jefferson Lab Kinematics				
3.2	0.32	2.3	0.55	1.025
4.9	0.48	8	0.375	1.025
6.7	0.48	15	0.375	1.025
EIC Kinematics				
140	0.01	9	0.5	1.042
140	0.01	25	0.5	1.038
140	0.01	100	0.5	1.06

https://indico.bnl.gov/event/18419/contributions/80386/attachments/49832/85265/Jia_Khachatryan_SIDIS-RC.pdf

SoLID SIDIS Projection

Compare SoLID with World Data

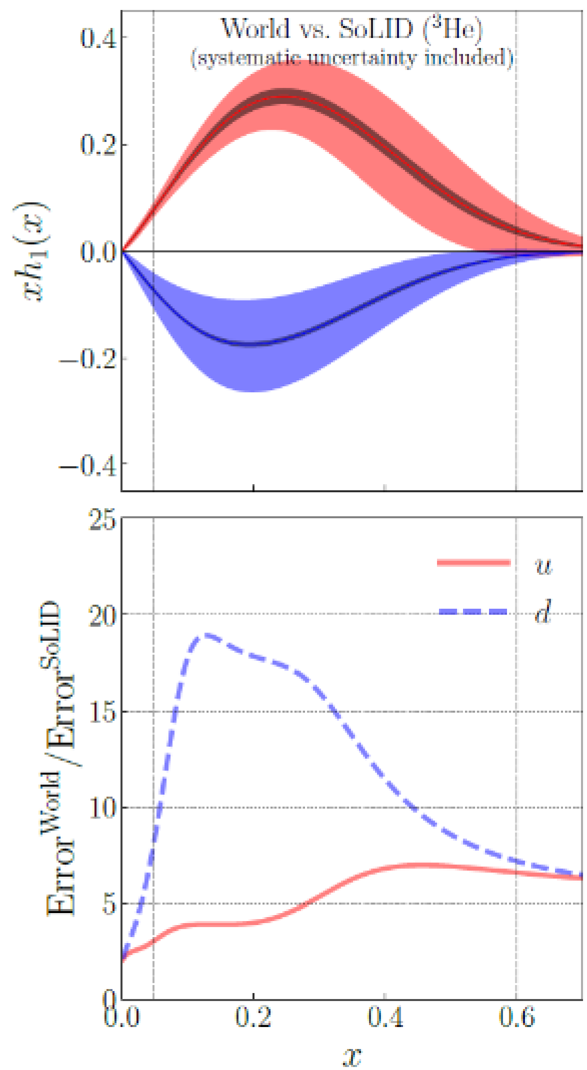
- Fit Collins and Sivers asymmetries in SIDIS and e^+e^- annihilation
- World data from HERMES, COMPASS
- e^+e^- data from BELLE, BABAR, and BESIII
- Monte Carlo method is applied
- Including both systematic and statistical uncertainties

SoLID preCDR (2019)

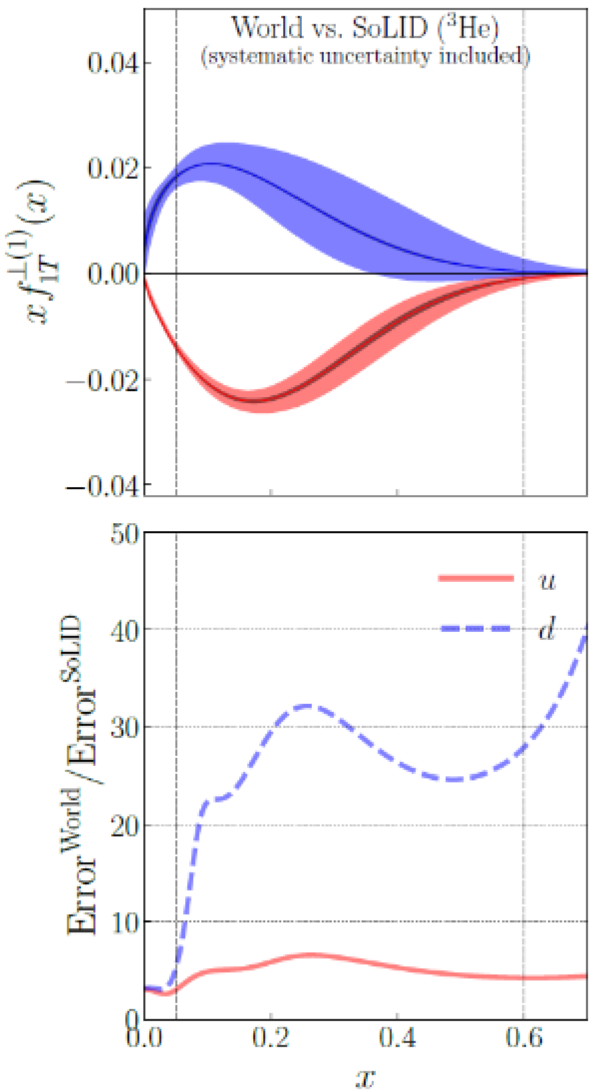
SoLID baseline used

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

Transversity

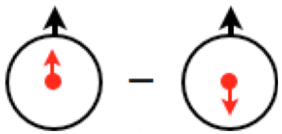


Sivers



Transversity and Tensor Charge

Transversity distribution

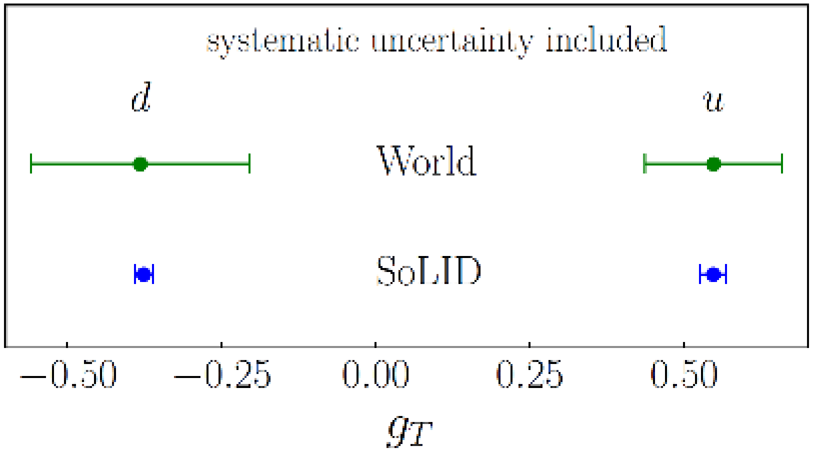
h_1  (Collinear & TMD)

- 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



g_T Flavor separation	World data	SoLID
u / *d* value	0.548 / -0.382	0.547 / -0.376
u / *d* error	0.112 / 0.177	0.021 / 0.014

SoLID projection: statistical and systematic uncertainties included

- **Tensor charge also connected to neutron and quark EDM, unique opportunity for SM tests and new physics**

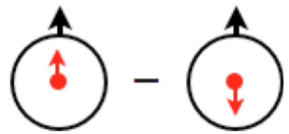
$$d_n = g_T^d d_u + g_T^u d_d + g_T^s d_s$$

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

SoLID Jefferson Lab

Transversity and Tensor Charge

Transversity distribution

h_1  (Collinear & TMD)

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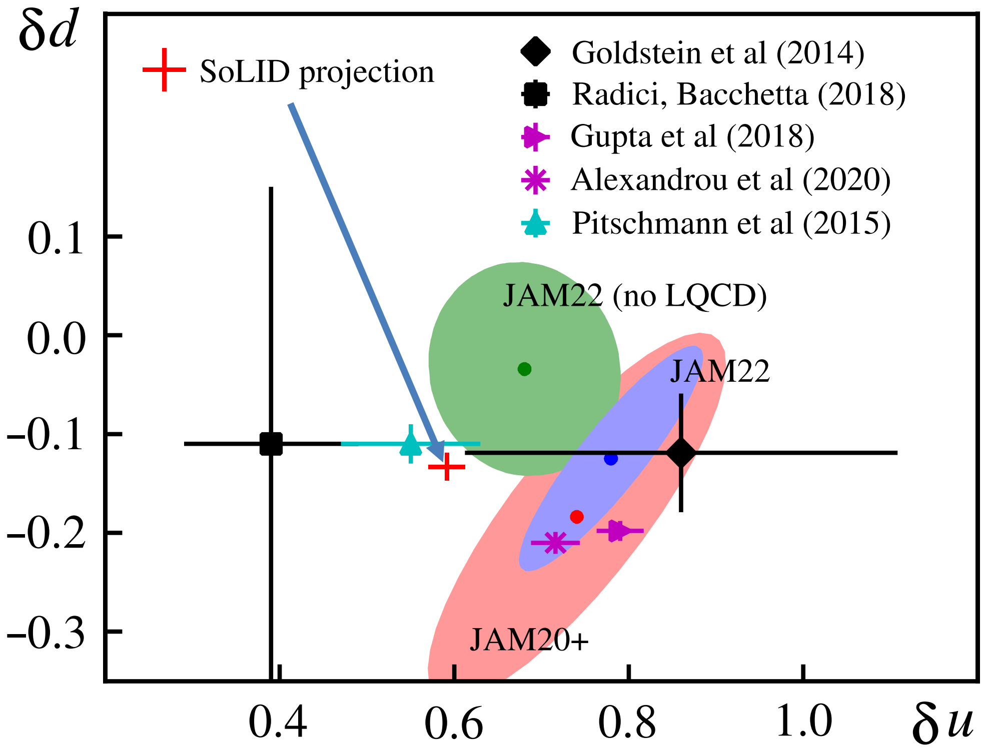


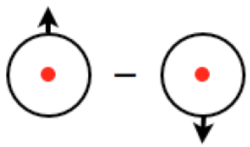
Combining E12-10-006 & E12-11-108

SoLID projection: statistical and systematic uncertainties included (shifted for visibility)

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

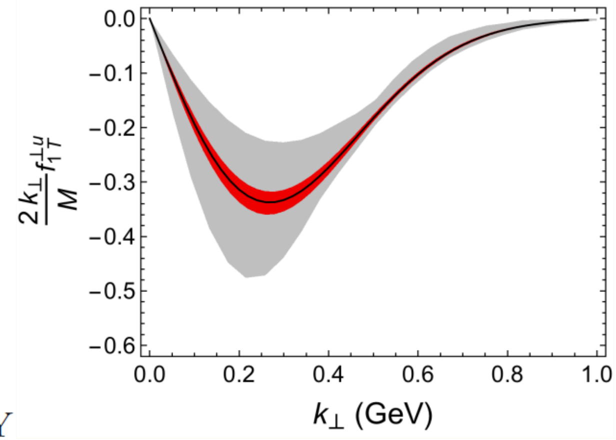
Confined motion inside the nucleon

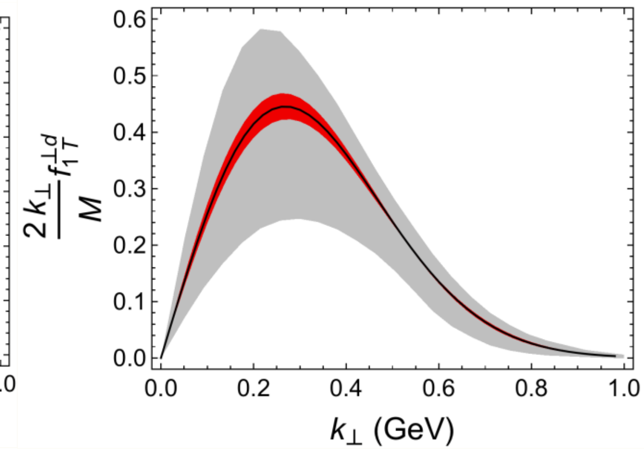
Sivers distribution

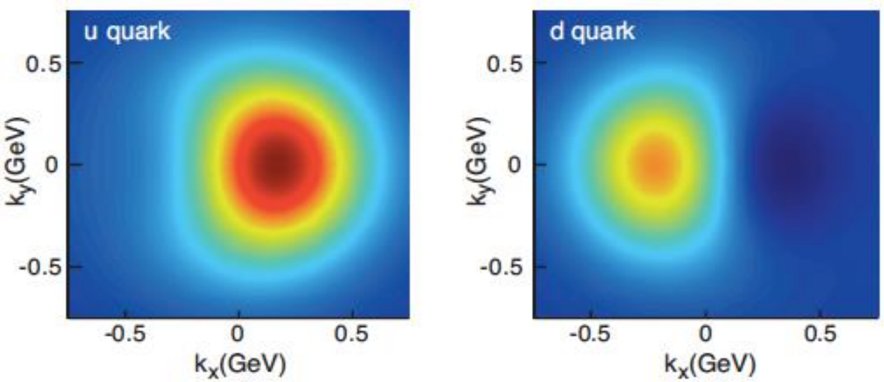
$f_{1T}^{\perp}$ 

naively time-reversal odd

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







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

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

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

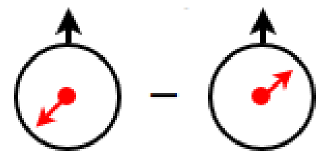
Nucleon spin - quark orbital angular momentum (OAM) correlation
– zero if no OAM (collinear, massless quarks)

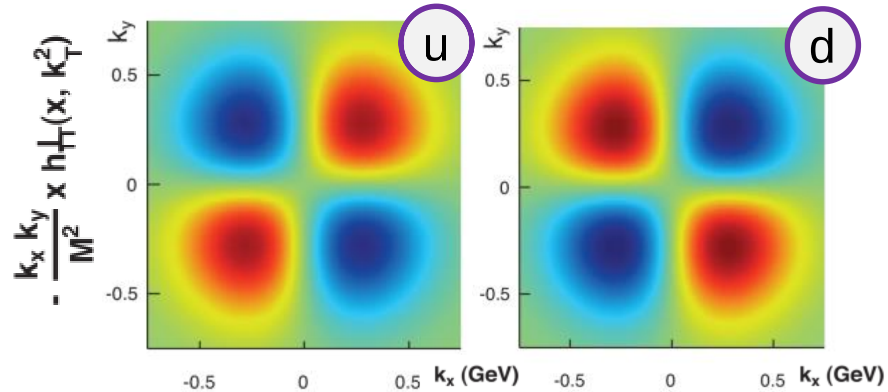
Exact finding is model dependent but SoLID impact is model-independent!

Confined motion inside the nucleon

Pretzelocity distribution

$h_{1T}^{\perp}$



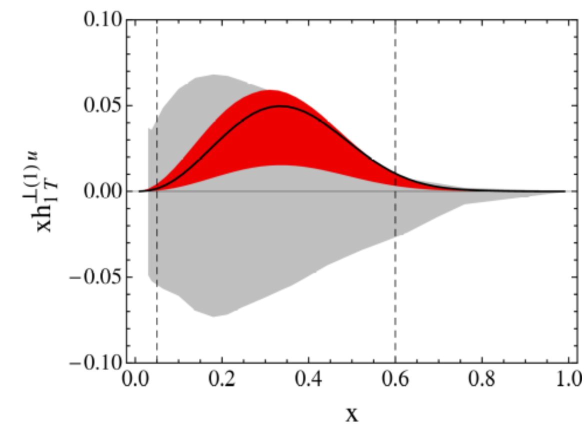


Images from PRD 91 034010 (2015)

- Chiral-odd, no gluon analogy
- Quadrupole modulation of parton density in the distribution of transversely polarized quarks in a transversely polarized nucleon
- Measuring the difference between helicity and transversity (relativistic effects)

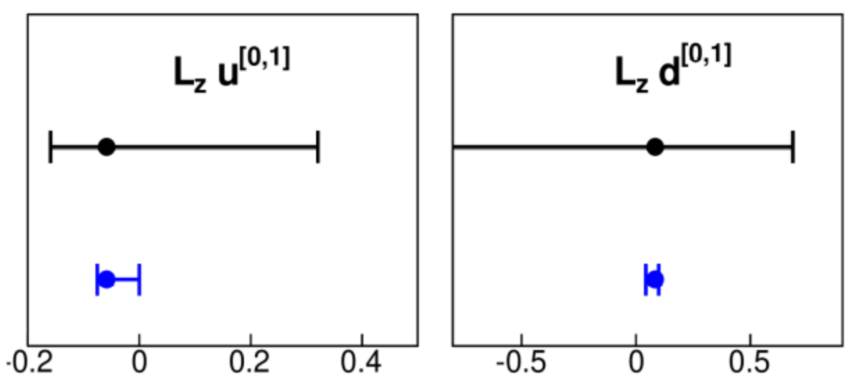
Parametrization by C. Lefky et al., PRD 91, 034010 (2015)

SoLID projection with transversely polarized n and p data



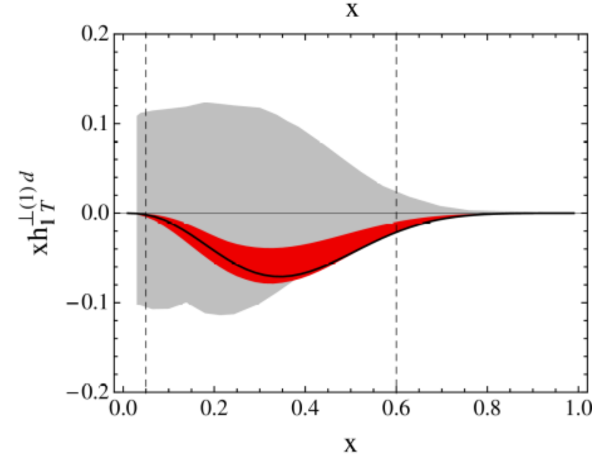
Relation to OAM (canonical)

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



Lefky and Prokudin PRD 91, 034010 (2015)

SoLID projection

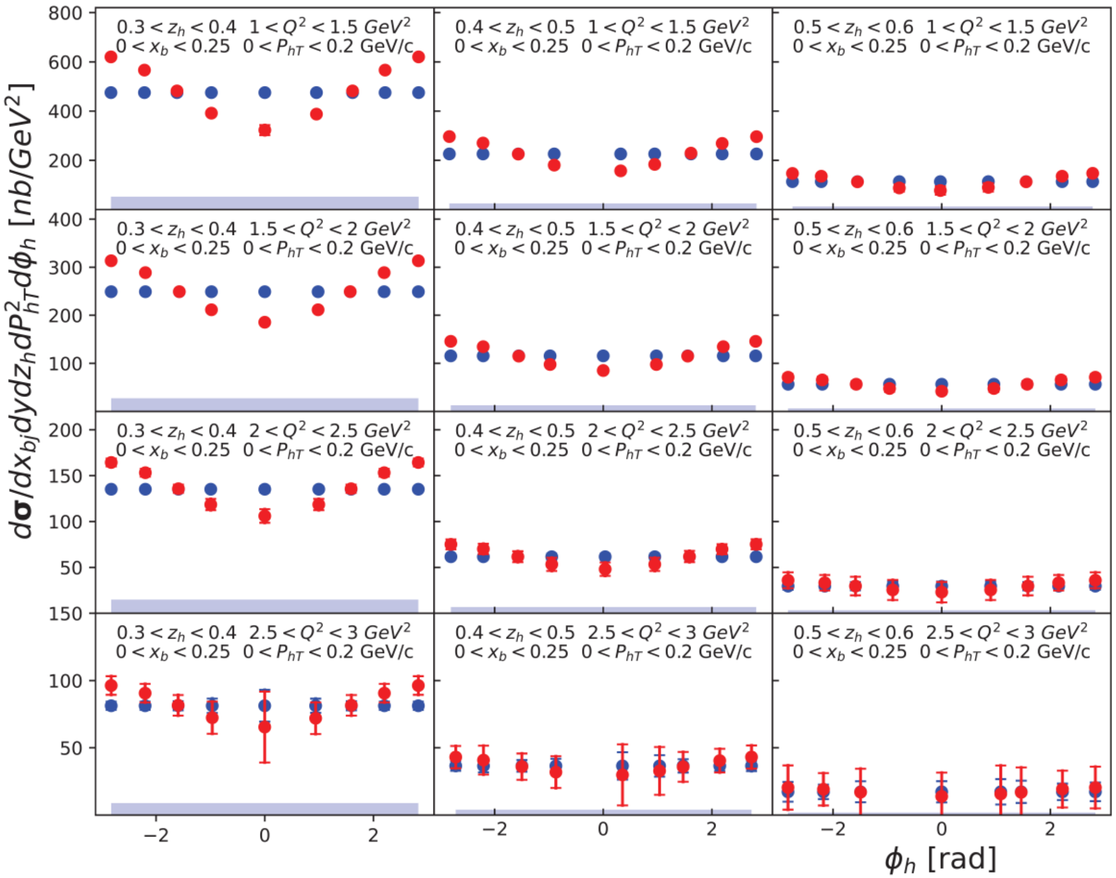


Combining E12-10-006 & E12-11-108

Unpolarized Cross Section off He3

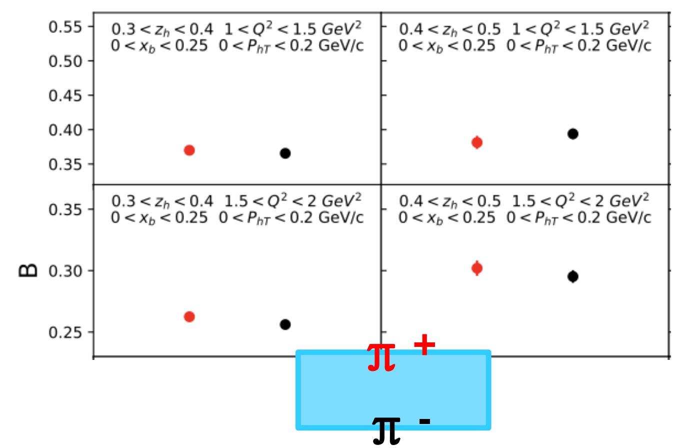
$$\frac{d\sigma}{dx_{bj}\,dy\,dz_h\,dP_{hT}^2\,d\phi_h} \equiv \mathcal{F}_{UU} = \mathcal{F}_{UU,\mathcal{A}} + \mathcal{F}_{UU,\mathcal{B}}\cos(\phi_h) + \mathcal{F}_{UU,\mathcal{C}}\cos(2\phi_h)$$

Projected π^+ unpolarized cross section errors with and without azimuthal terms. **~2000 bins in 5D**



- A naive probe for the azimuthal modulation effect

$$A(1 - B \cdot \cos(\phi_h) - C \cdot \cos(2\phi_h))$$



- We can also fit the the pseudo data to get transverse momentum width

Summary

https://solid.jlab.org/

- SoLID: a **large acceptance** device which can handle **very high luminosity** to allow full exploitation of JLab12 potential
  - pushing the limit of the luminosity frontier
  - highlighted in 2023 NSAC LRP and facility review
- SoLID TMD program using SIDIS process is rich and vibrant with unprecedented high precision data in 4D/5D bins to constrain models and examine LQCD, perfect for global fitting
- Synergy with EIC and extend into 22GeV

Thank you!

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