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

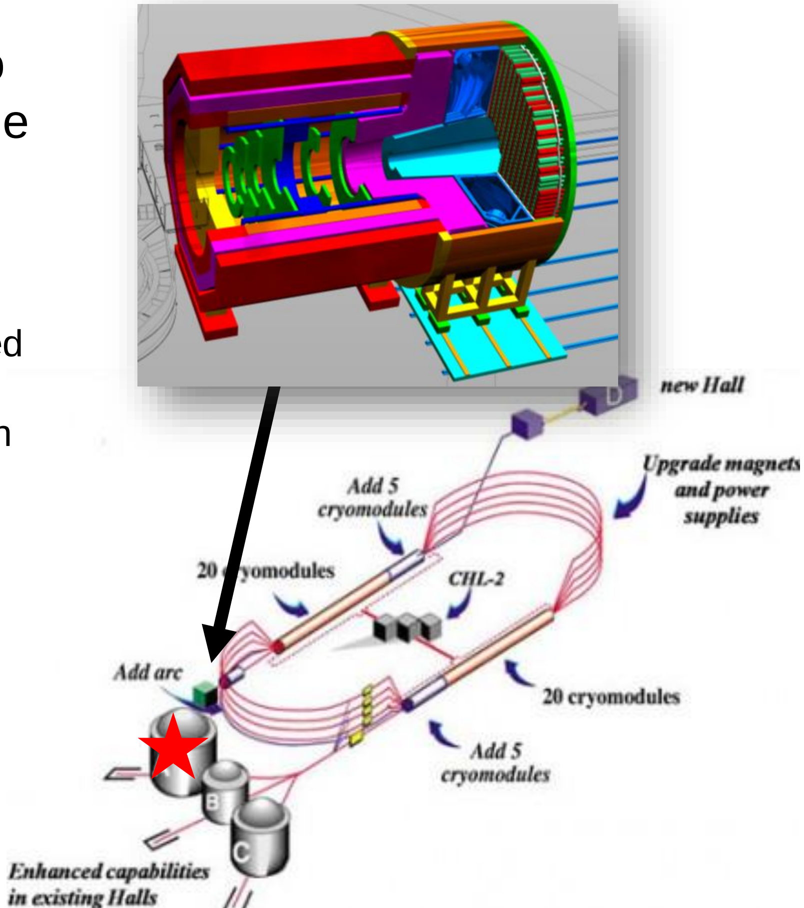
+

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

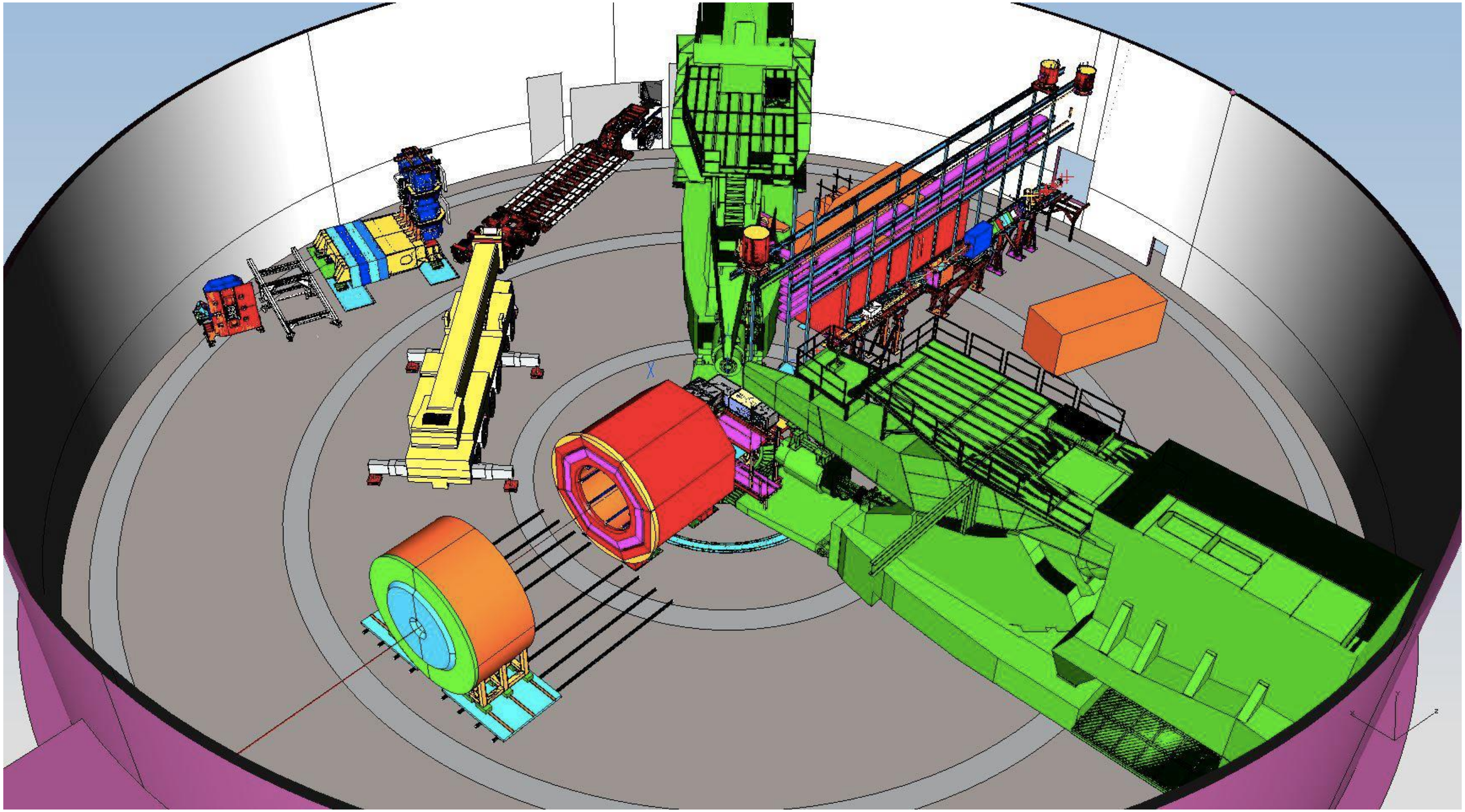
- Pushing the phase space in the search of new physics and of hadronic physics (**PVDIS**)
- 3D momentum imaging of a relativistic strongly interacting confined system (**nucleon spin**)
- Superior sensitivity to the differential electro- and photo-production cross section of J/ψ near threshold (**proton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

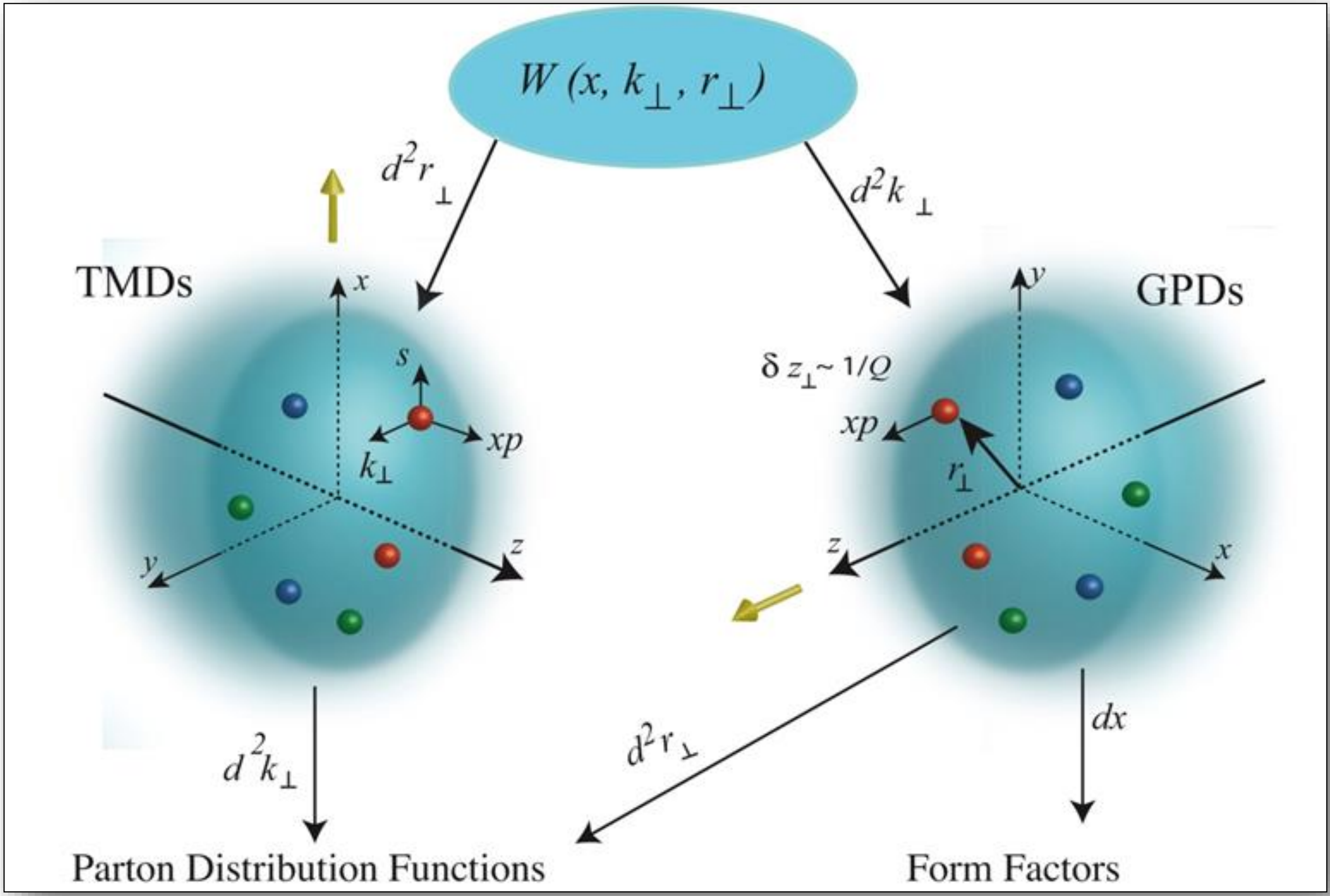
SoLID in Hall A



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

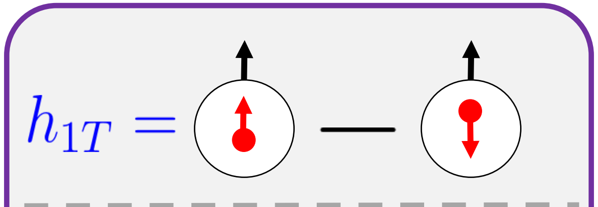
		Quark polarization		
		Un-Polarized	**Longitudinally Polarized**	**Transversely Polarized**
Nucleon Polarization	U	$f_1 =$		$h_1^\perp = \ - \$ **Boer-Mulder**
	L		$g_1 = \ - \$ **Helicity**	$h_{1L}^\perp = \ - \$ Worm gear
	T	$f_{1T}^\perp = \ - \$ **Sivers**	$g_{1T}^\perp = \ - \$ Worm gear	$h_{1T}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

TMDs – confined motion inside the nucleon

Transversely Polarized Nucleon TMDs

→ Nucleon Spin
→ Quark Spin

Transversity



$$h_{1T} = \; (\text{spin-up quark in spin-up nucleon}) - (\text{spin-down quark in spin-up nucleon})$$

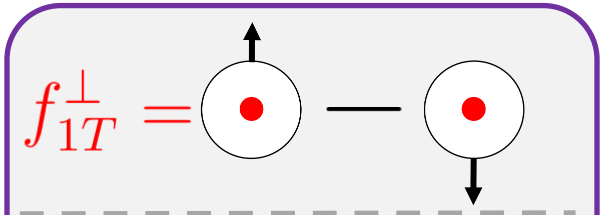
$$\mathbf{S}_T \cdot \mathbf{s}_q$$

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

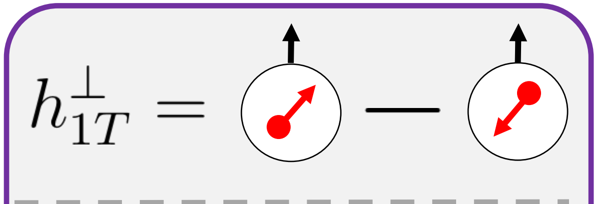
Sivers



$$\mathbf{S}_T \cdot \mathbf{k}_\perp \times \mathbf{P}$$

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

Pretzelosity



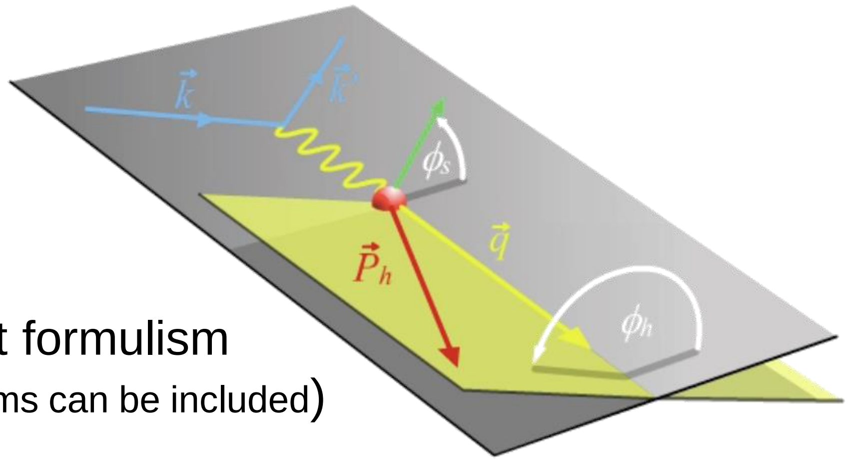
$$\mathbf{S}_T \cdot [\mathbf{k}_\perp \mathbf{k}_\perp] \cdot \mathbf{s}_{qT}$$

- 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

(2π azimuthal coverage)

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!



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

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

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

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

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

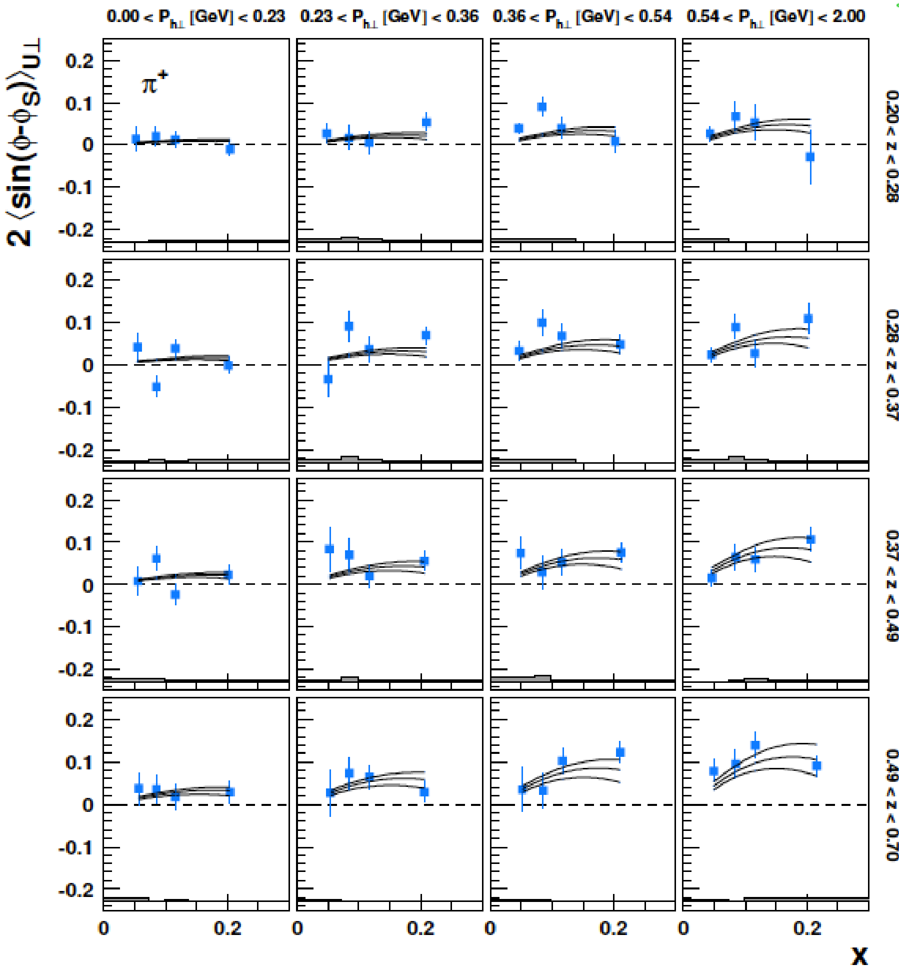
Collins fragmentation function from e^+e^- collisions

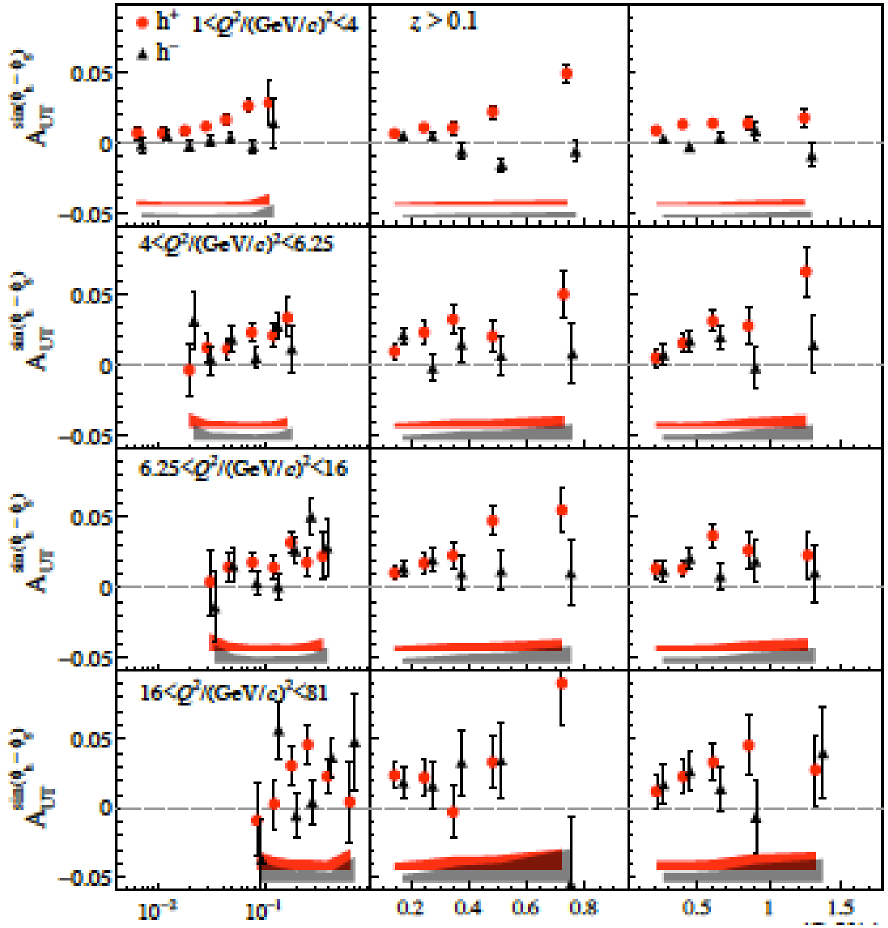
$$A_{UT}^{Sivers} \propto \langle \sin(\phi_h - \phi_S) \rangle_{UT} \propto f_{1T}^{\perp} \otimes D_1$$

Unpolarized fragmentation function

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)





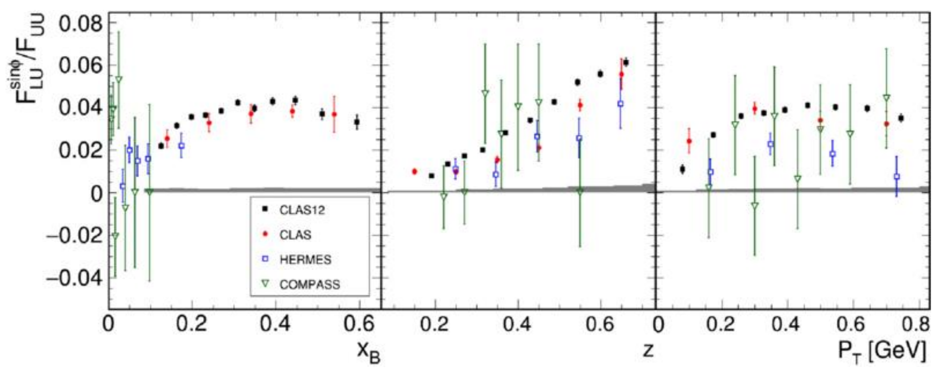
A. Airapetian et al., arXiv:2007.07755

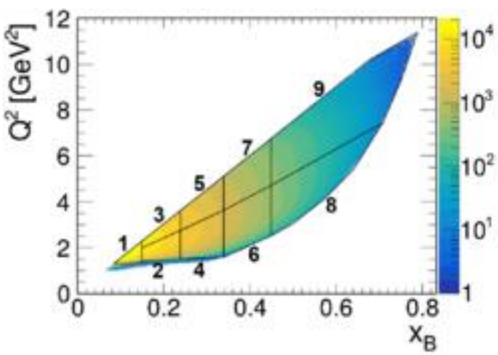
C. Adolph et al. PLB 770, 138 (2017)

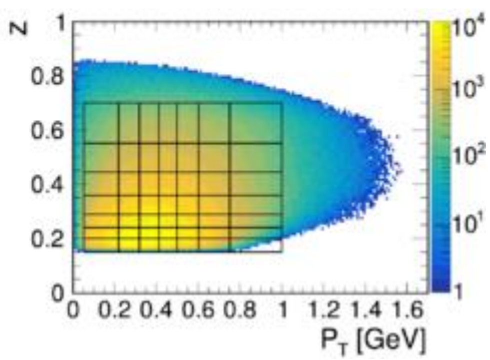
TSSA ~100 bins

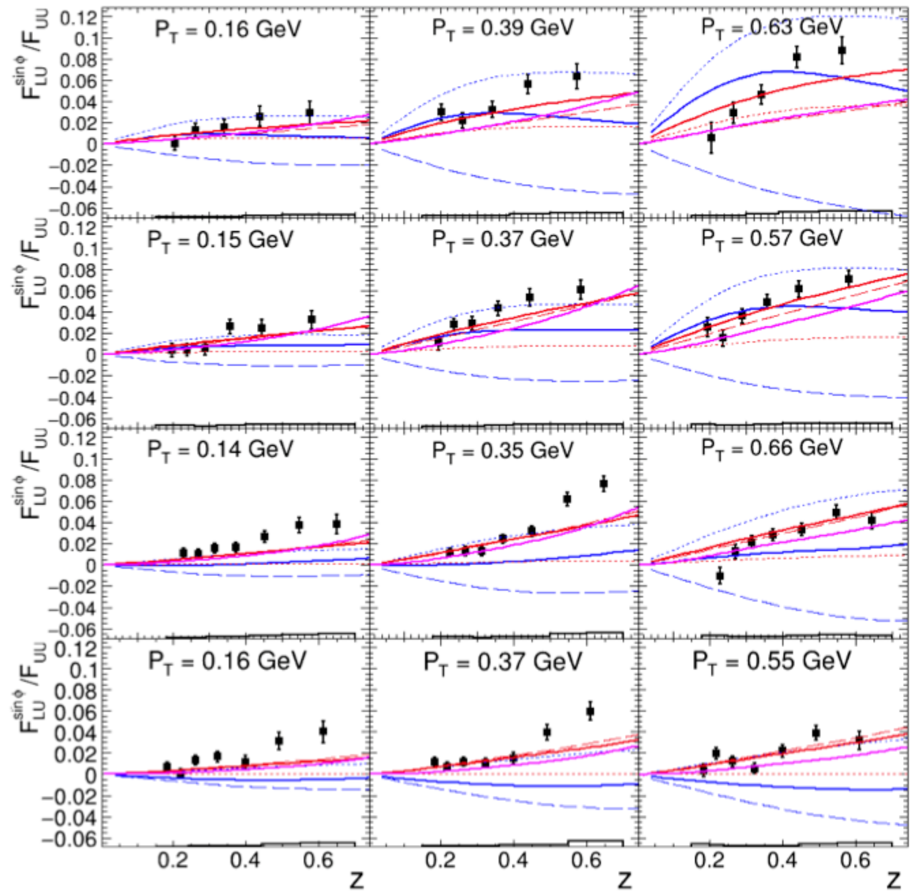
State-of-the-art from CLAS 12

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









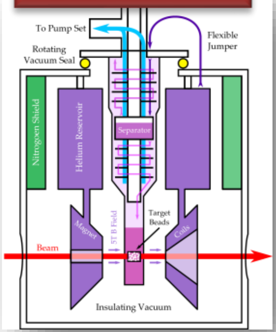
BSSA ~400 bins

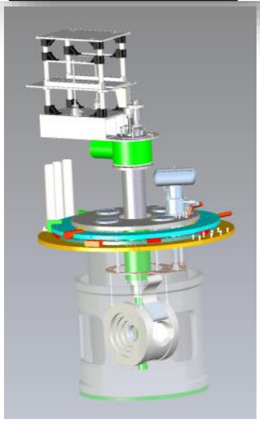
First multidimensional, high precision measurements of semi-inclusive π+ beam single spin asymmetries from the proton over a wide range of kinematics

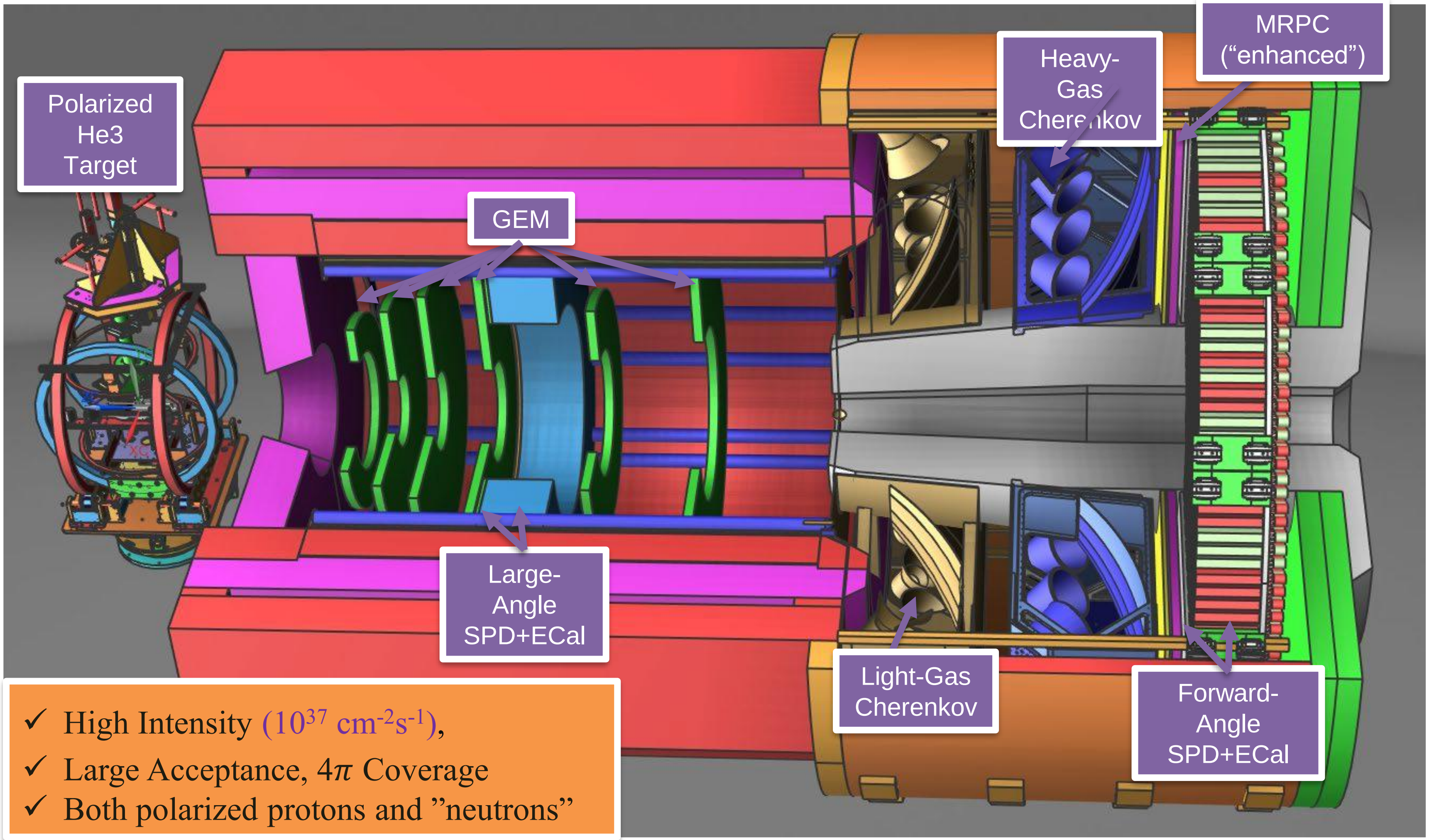
S. Diehl *et al.* (CLAS Collaboration), Phys. Rev. Lett. **128**, 062005 (2022)

SIDIS SIDIS Configuration

Polarized NH3 (DNP) Target



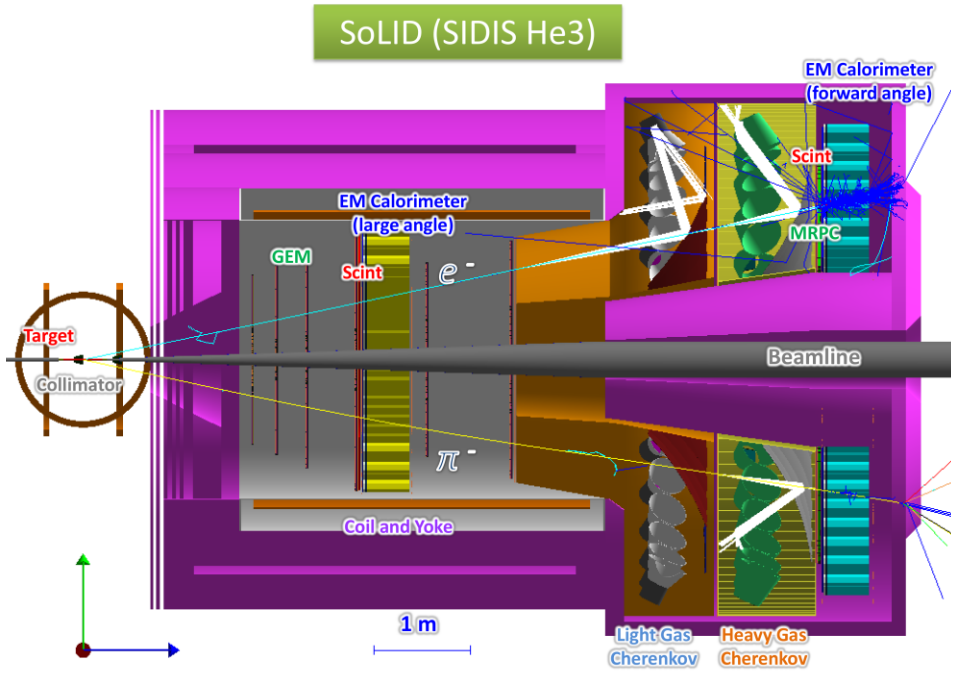




- ✓ High Intensity (10^{37} cm^{-2}s^{-1}),
- ✓ Large Acceptance, 4π Coverage
- ✓ Both polarized protons and ”neutrons”

SoLID SIDIS He3 Setup

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



Detection

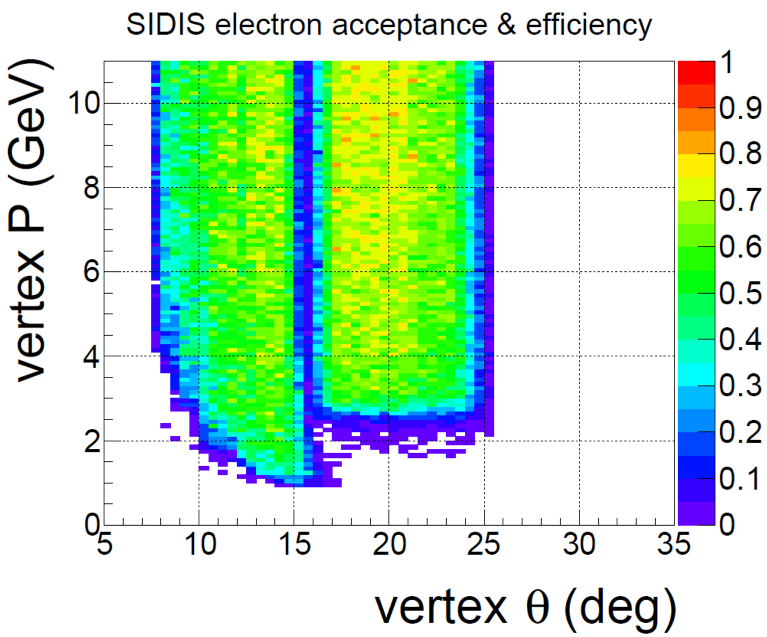
- e- at forward angle with EC and Cerenkov to reject pions
- e- above 3GeV detected at large angle with EC to reject pions
- pions detected at forward angle with TOF and Cerenkov to suppress kaons

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

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

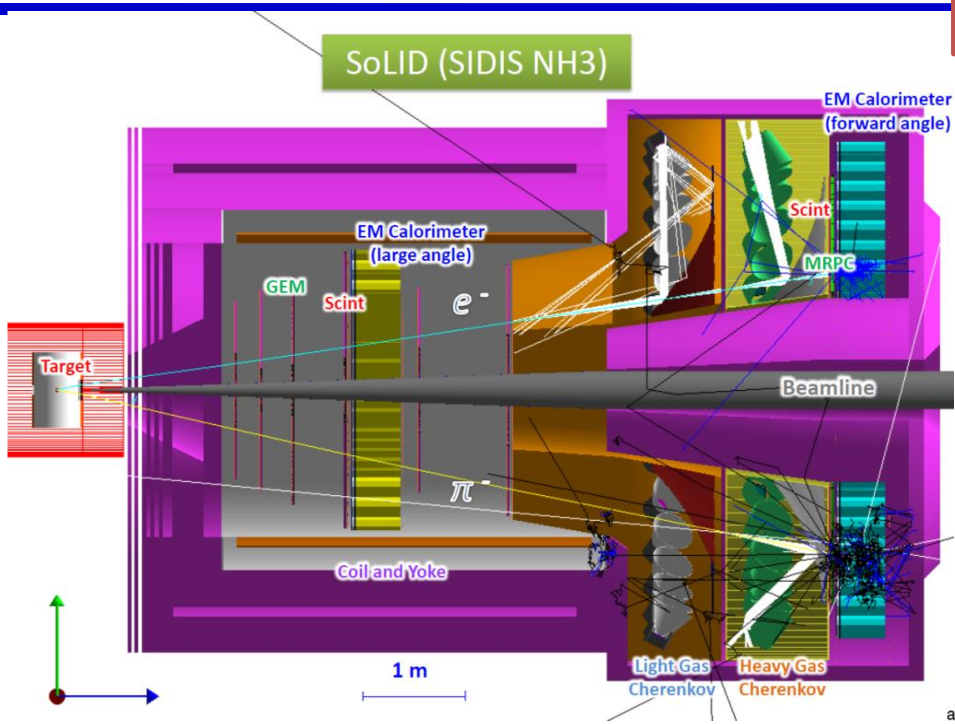
Coverage

- 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



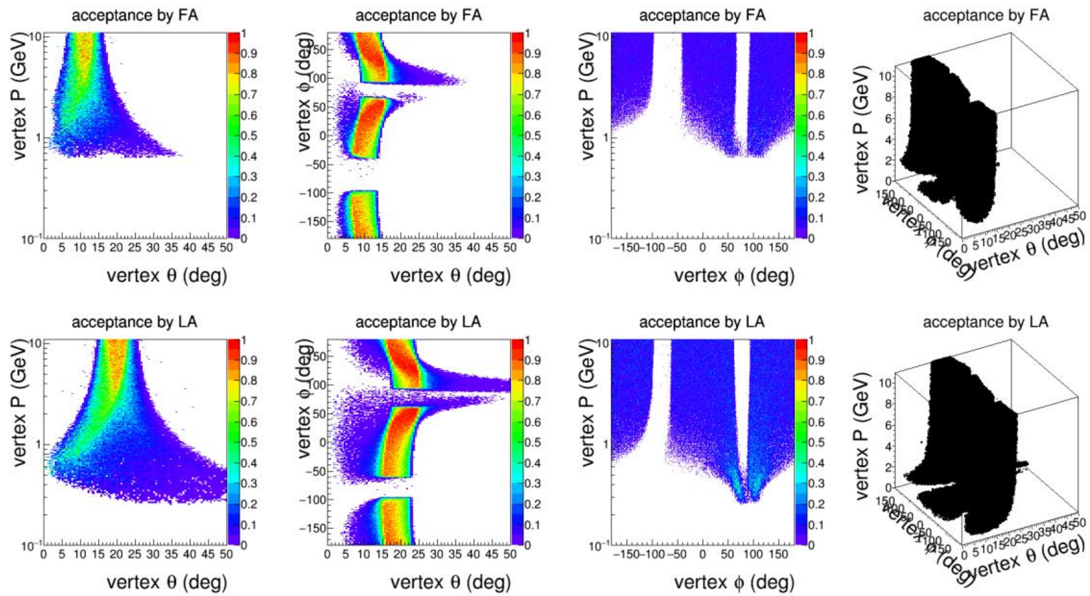
Detection is similar to He3 setup

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

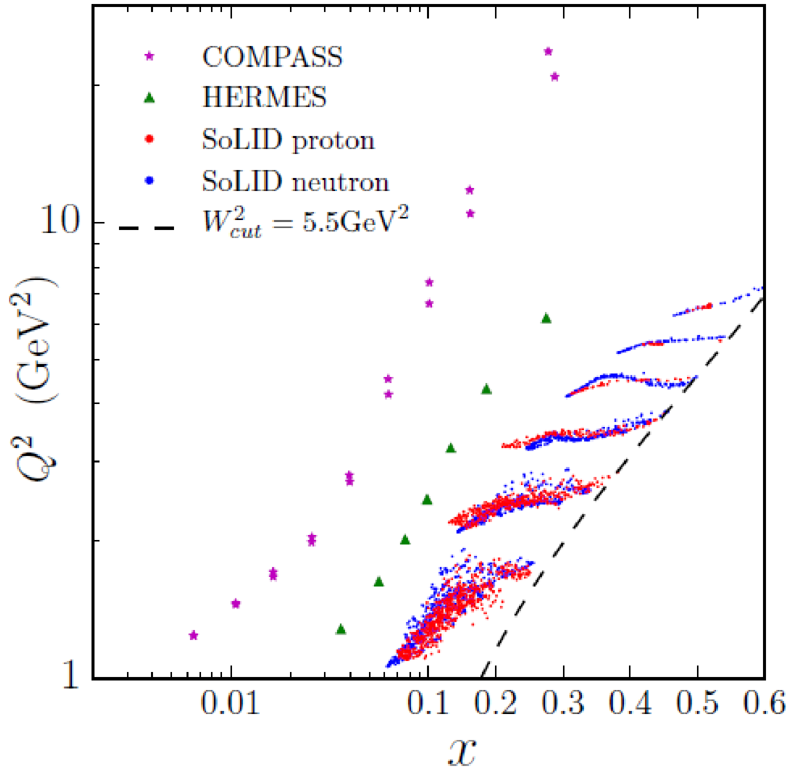


SoLID SIDIS Kinematic Coverage

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
  - ^3He 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

$$A_{UT}^h(\phi_h,\phi_S) = \frac{2}{P_T^1 + P_T^2} \cdot \frac{\sqrt{N_1(\phi_h,\phi_S)N_2(\phi_h,\phi_S+\pi)} - \sqrt{N_1(\phi_h,\phi_S+\pi)N_2(\phi_h,\phi_S)}}{\sqrt{N_1(\phi_h,\phi_S)N_2(\phi_h,\phi_S+\pi)} + \sqrt{N_1(\phi_h,\phi_S+\pi)N_2(\phi_h,\phi_S)}}$$

- 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

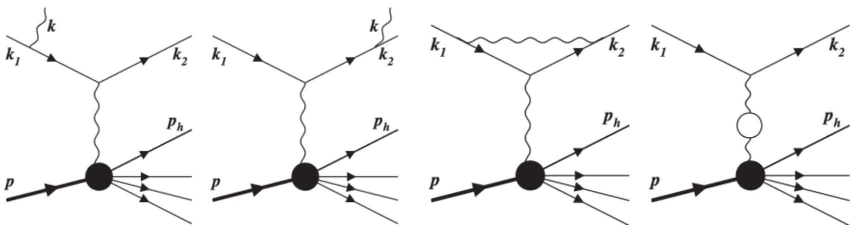
- *Radiative corrections*: use both traditional and factorized method

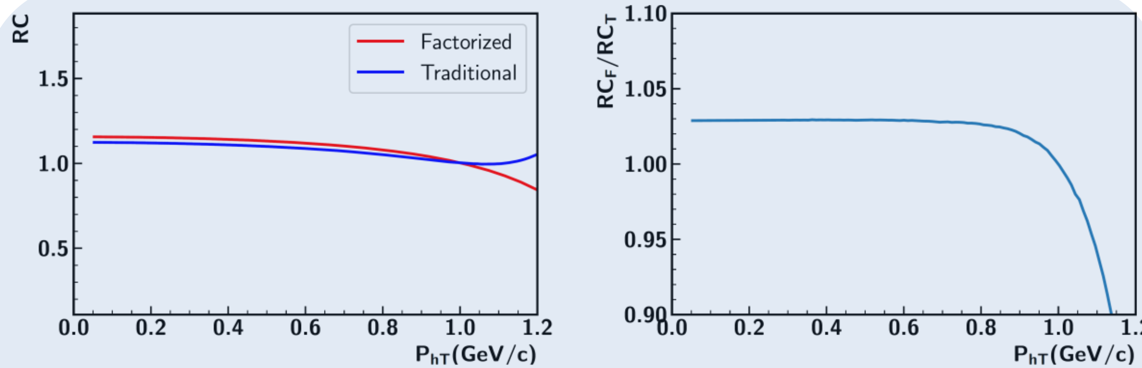
- *Detector resolution*: estimated based on the track fitting studies

- *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

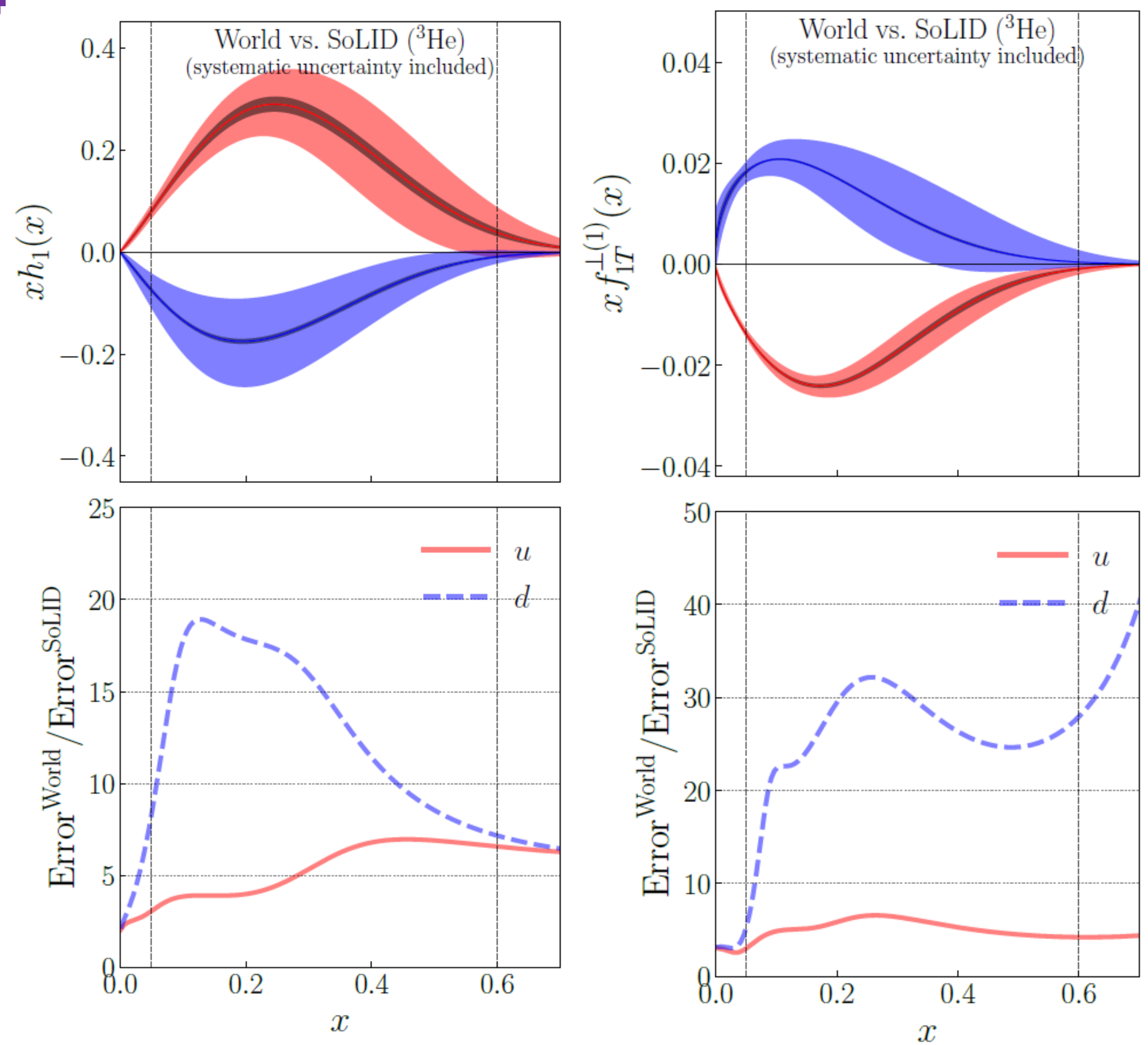
- Fit Collins and Sivers asymmetries in SIDIS and e^+e^- annihilation
- World data from HERMES, COMPASS
- e^+e^- data from BELLE, BABAR, and BESIII
- Monte Carlo method is applied
- Including both systematic and statistical uncertainties

SoLID preCDR (2019)

SoLID baseline used

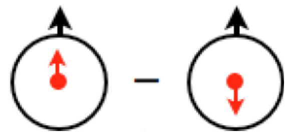
D'Alesio et al., Phys. Lett. B 803 (2020)135347
Anselmino et al., JHEP 04 (2017) 046

Transversity **Sivers**



Transversity and Tensor Charge

Transversity distribution

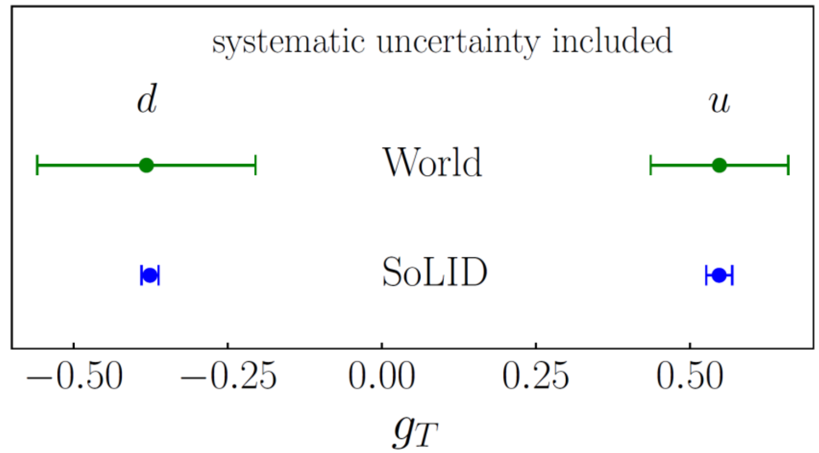
h_1  (Collinear & TMD)

- 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

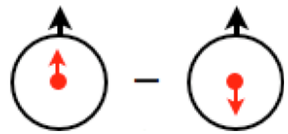
- **Tensor charge also connected to neutron and quark EDM, unique opportunity for SM tests and new physics**

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

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

Transversity and Tensor Charge

Transversity distribution

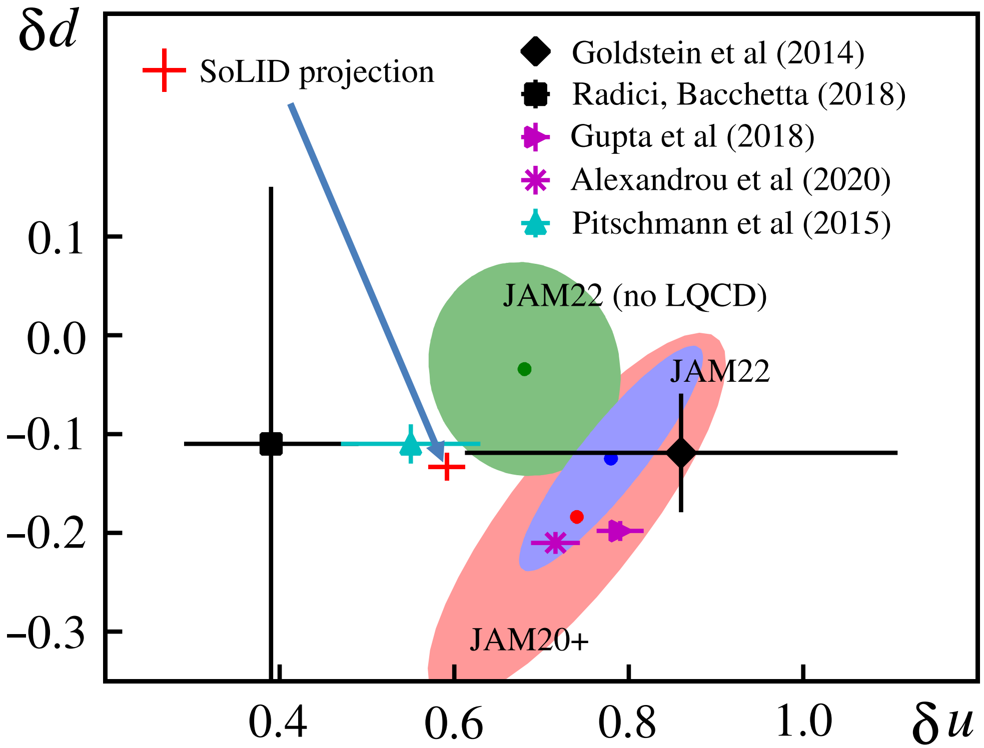
h_1  (Collinear & TMD)

- 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



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

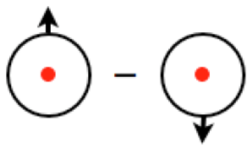
SoLID projection: statistical and systematic uncertainties included (shifted for visibility)

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

Confined motion inside the nucleon

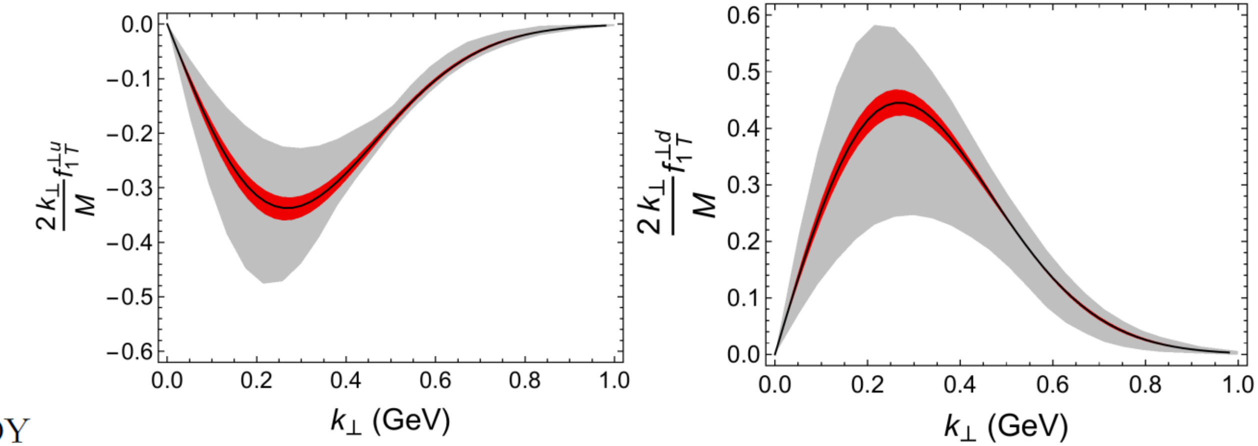
Sivers distribution

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



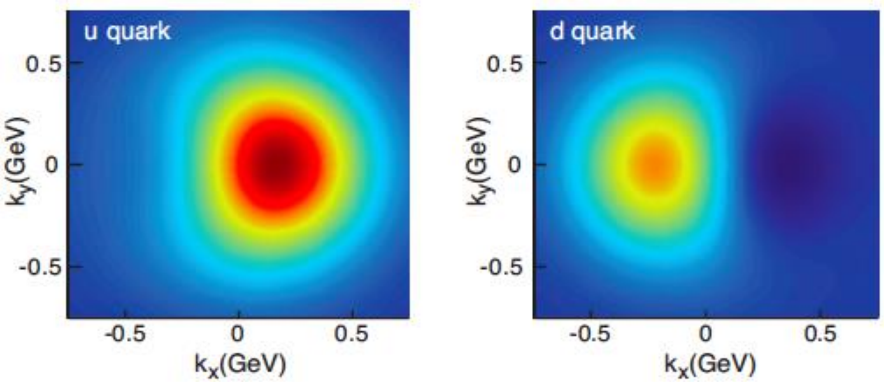
naively time-reversal odd

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



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

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



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

Red: SoLID projection with transversely polarized n/p

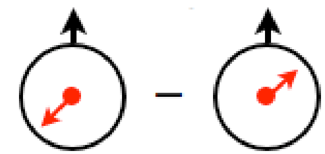
	$\langle k_\perp\rangle^u$	$\langle k_\perp\rangle^d$
Gray	96^{+60}_{-28} MeV	-113^{+45}_{-51} MeV
Red	$96^{+2.8}_{-2.4}$ MeV	$-113^{+1.3}_{-1.7}$ MeV

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

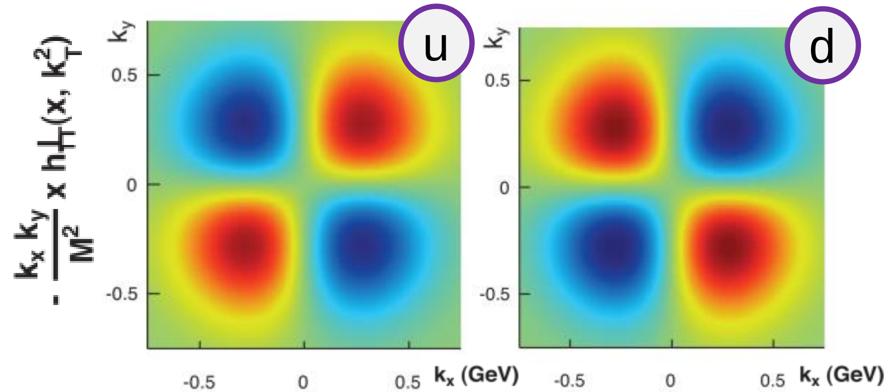
Exact finding is model dependent but SoLID impact is model-independent!

Confined motion inside the nucleon

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



- 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)



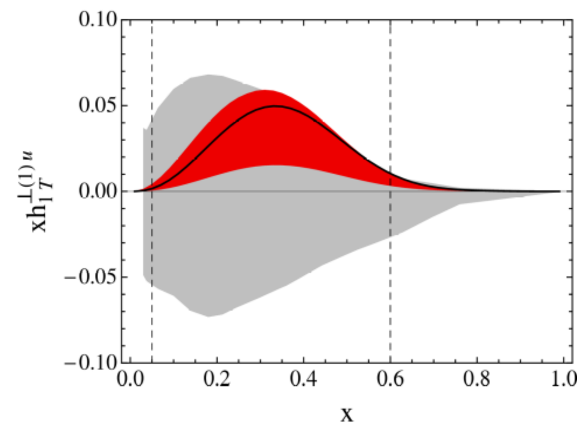
Images from PRD 91 034010 (2015)

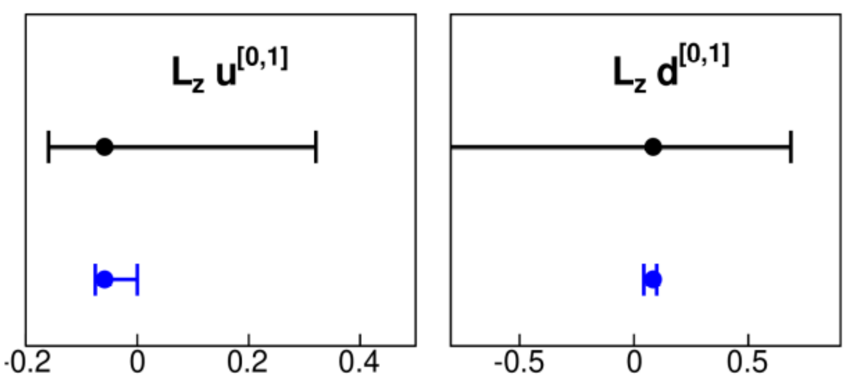
Parametrization by C. Lefky et al., PRD 91, 034010 (2015)

SoLID projection with transversely polarized n and p data

Relation to OAM (canonical)

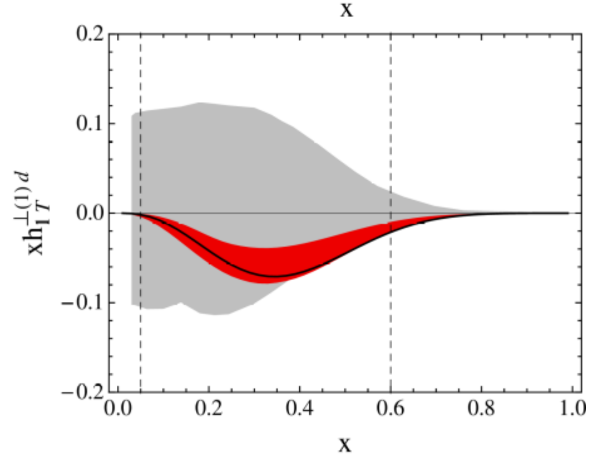
$$L_z^q = -\int dx d^2\mathbf{k}_\perp \frac{\mathbf{k}_\perp^2}{2M^2} h_{1T}^{\perp q}(x, k_\perp) = -\int dx h_{1T}^{\perp(1)q}(x)$$





Lefky and Prokudin PRD 91, 034010 (2015)

SoLID projection

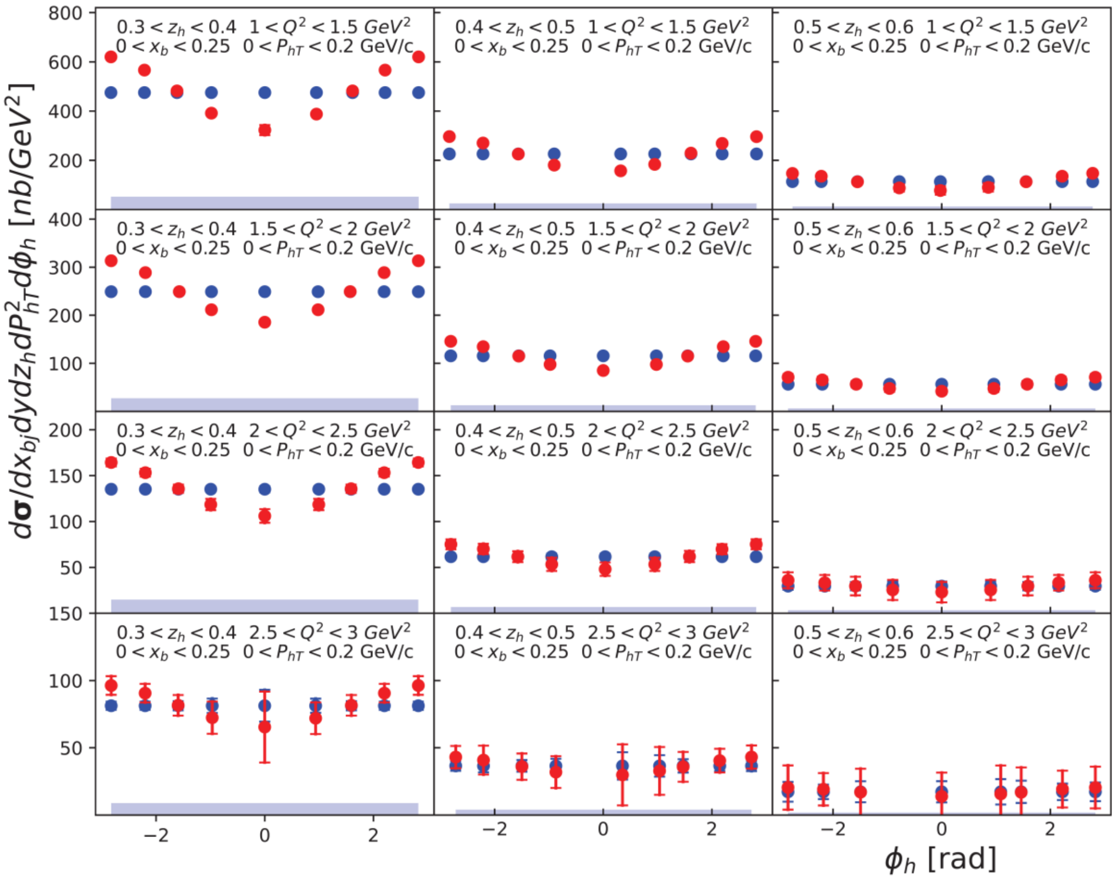


Combining E12-10-006 & E12-11-108

Unpolarized Cross Section off He3

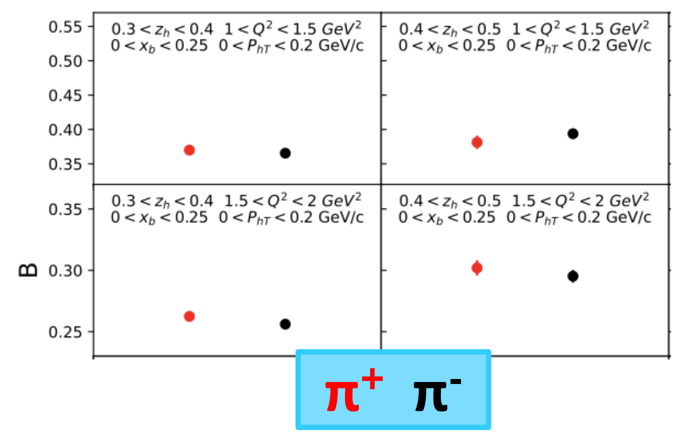
$$\frac{d\sigma}{dx_{bj}\,dy\,dz_h\,dP_{hT}^2\,d\phi_h} \equiv \mathcal{F}_{UU} = \mathcal{F}_{UU,\mathcal{A}} + \mathcal{F}_{UU,\mathcal{B}}\cos(\phi_h) + \mathcal{F}_{UU,\mathcal{C}}\cos(2\phi_h)$$

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



- A naive probe for the azimuthal modulation effect

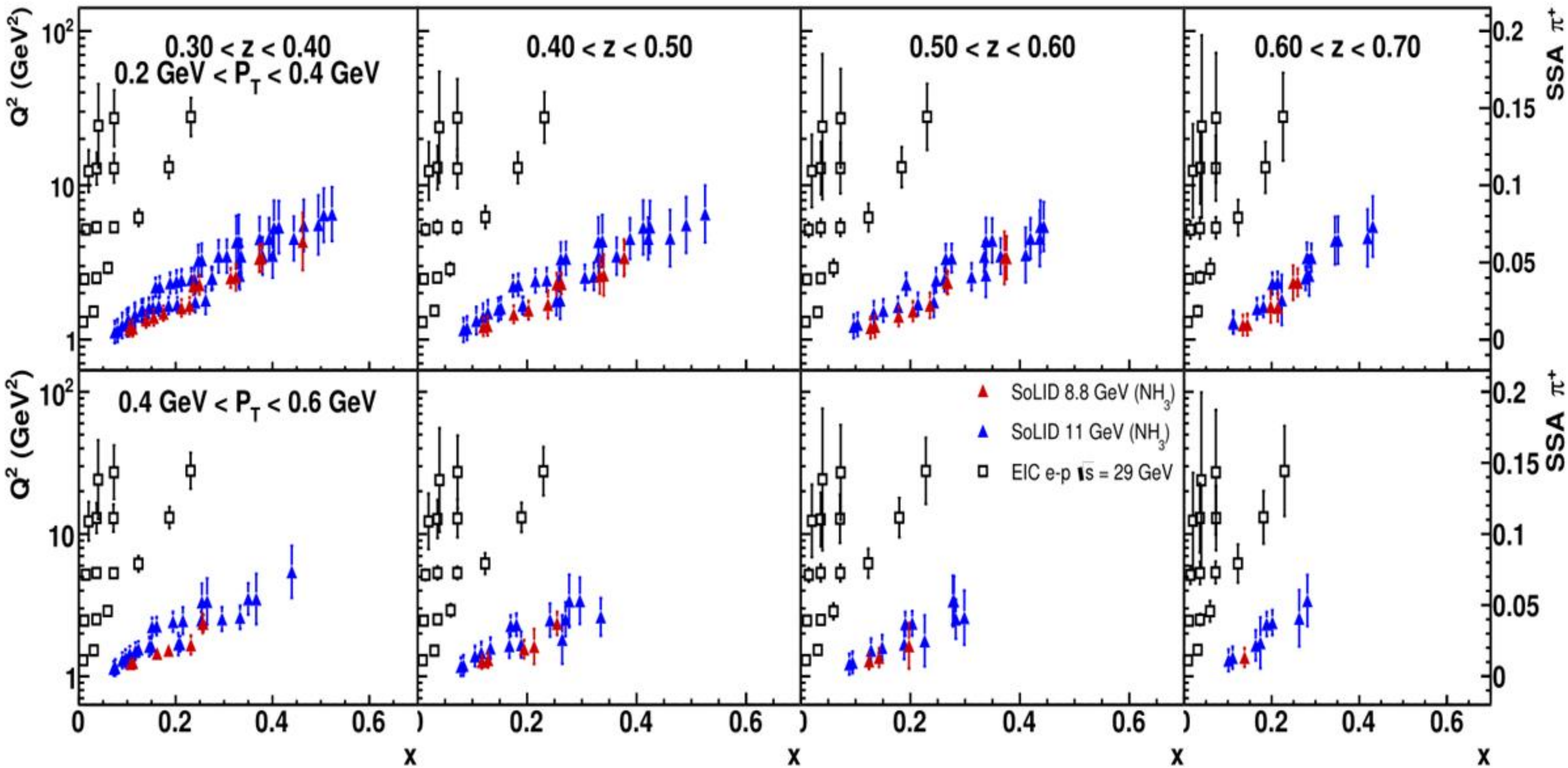
$$A(1 - B \cdot \cos(\phi_h) - C \cdot \cos(2\phi_h))$$



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

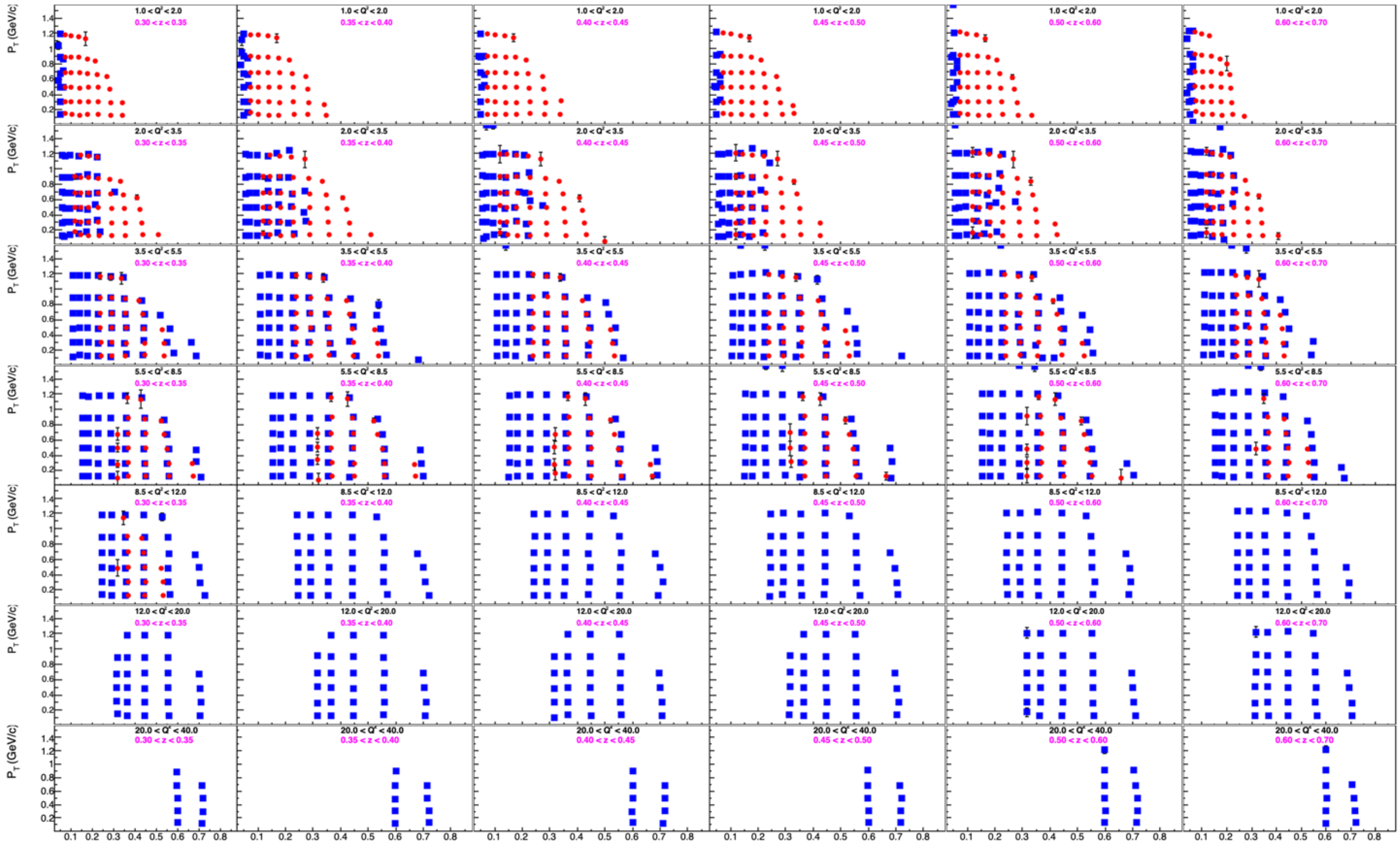
Transverse SSA projections: Complementarity to EIC

- SoLID SIDIS projections of A_{UT} in various 4-D bins at 11 / 8.8 GeV beam energies
- Projections at EIC kinematics for the same observable at 29 GeV center-of-mass energy
- SSA scale and uncertainties shown on the right-side axis of the right two figures
- SoLID and EIC projections synergistic towards each other, by covering different x and Q^2 ranges



SoLID SIDIS at 22GeV

Extend to lower x and higher Q^2 without detector modification



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

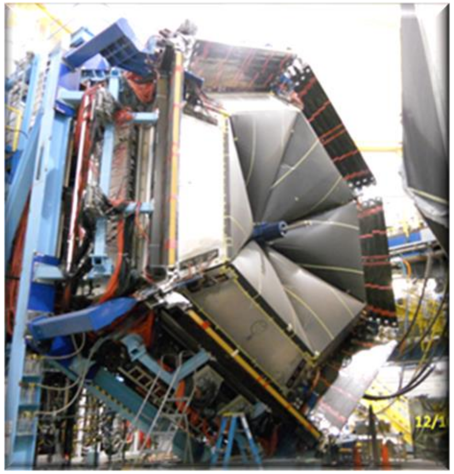
- Synergy with EIC and extend into 22GeV

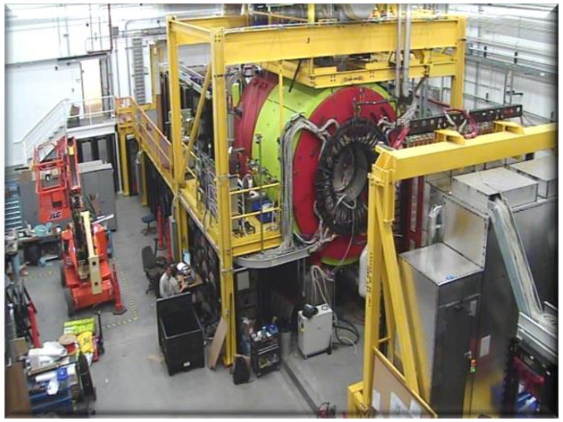
Thank you!

supported in part by the U.S. Department of Energy under contract number DE-FG02-03ER41231

BACKUP slides

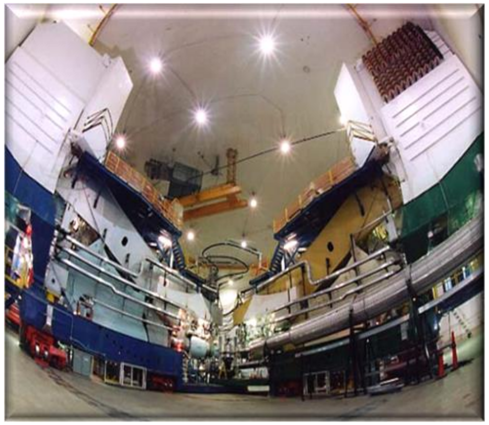
JLab 12 GeV Scientific Capabilities





Hall D – exploring origin of confinement by studying exotic mesons

Hall B – understanding nucleon structure via generalized parton distributions and transverse momentum distributions



Hall C – precision determination of valence quark properties in nucleons and nuclei

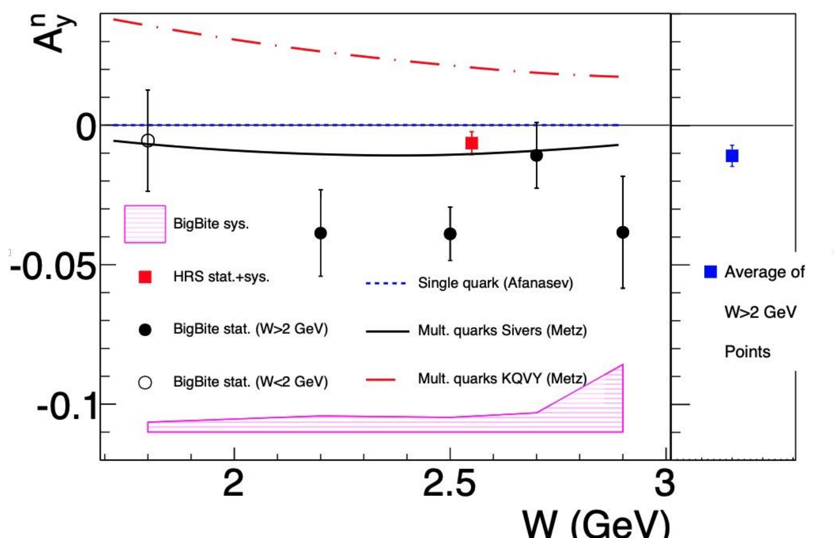
Hall A – short range correlations, form factors, hyper-nuclear physics, SBS program
future new experiments (e.g., SoLID and MOLLER)

E12-11-108A/E12-10-006A: Transversely Polarized Target Single Spin Asymmetry, A_y: Accessing TPEX through inclusive scattering from protons and neutrons

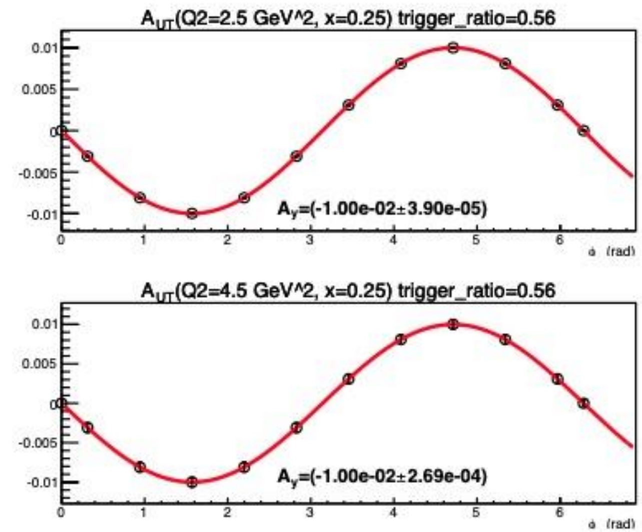
$$\vec{N}(e,e')X \qquad \langle A_{UT} \rangle = \frac{1}{P \cdot \eta_n \cdot d}\left(\frac{N^{\uparrow} - N^{\downarrow}}{N^{\uparrow} + N^{\downarrow}}\right) \qquad A_{UT} = A_y \cos\varphi$$

- No contribution from single photon exchange
- Leading contribution from TPEX – direct access
- Measure using polarized NH_3 and ^3He targets during SIDIS
  - Theoretical calculations predict both positive and negative neutron asymmetry
  - Current data consistent with input from Siver's, inconsistent with Drell-Yan

World Neutron Data, PRL 113, 022502 (2014)



SoLID Projected Neutron Uncertainties



SoLID's large acceptance and high luminosity well-suited to this measurement

- **World unique, cannot be done anywhere else!**

E12-10-006E: A Precision Measurement of Inclusive g2n and d2n

Inclusive scatterings of longitudinally polarized electrons @**11 GeV** and **8.8 GeV** off transversely and longitudinally polarized ^{3}**He** targets.

❑ g_2: carries information of quark-gluon interaction (x>0.1 and 1.5 GeV^2<Q^2< 10 GeV^2)

$$g_2(x,Q^2) = g_2^{WW}(x,Q^2) + \overline{g_2}(x,Q^2)$$

Wandzura-Wilczek relation

$$g_2^{WW}(x,Q^2) = -g_1(x,Q^2) + \int_x^1 g_1(y,Q^2)\frac{dy}{y}$$

$$\bar{g}_2(x,Q^2) = -\int_x^1 \frac{\partial}{\partial y}\left[\frac{m_q}{M}h_T(y,Q^2) + \zeta(y,Q^2)\right]\frac{dy}{y}$$

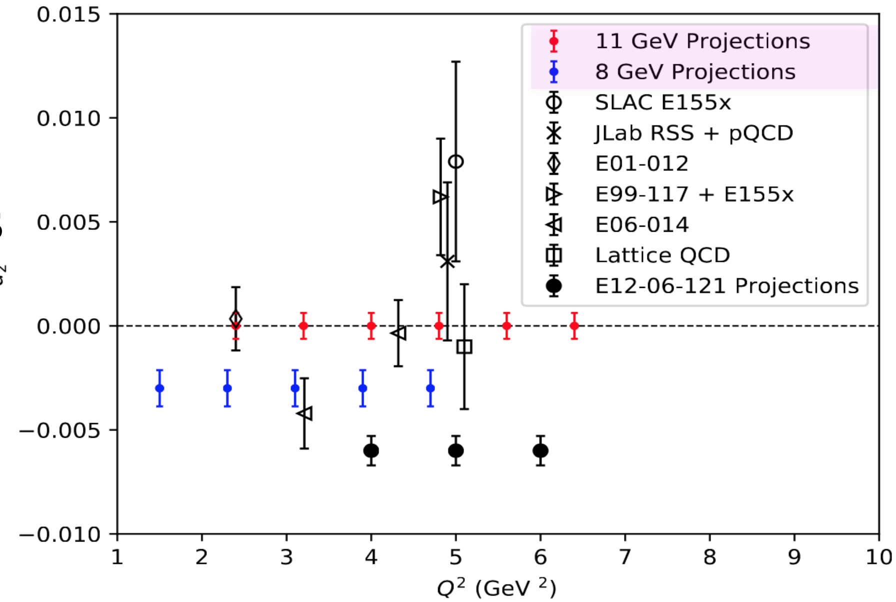
quark transverse momentum contribution

twist-3 part which arises from quark-gluon interactions

❑ d_2: the x^2 moment of $\overline{g_2}(x,Q^2)$

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

- Calculable on the Lattice.
- A clean way to access twist-3 contribution
- Dominated by high x data because of weighting



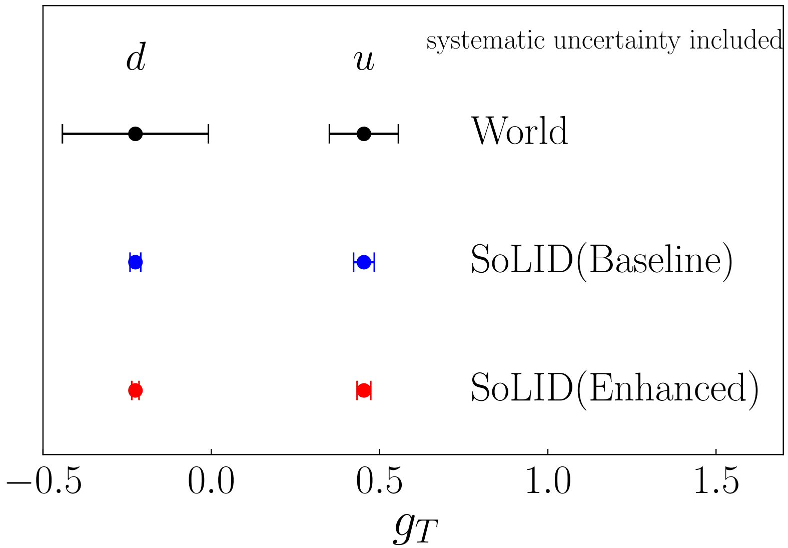
- ✧ d_2 projection to the region of $Q^2 < 6.5$ GeV^2
- ✧ x_{min}>0.4 to obtain d_2
- ✧ Assigned 15% error for the unmeasured region
- ✧ Statistic and systematic errors combined
- ✧ Systematic errors dominate

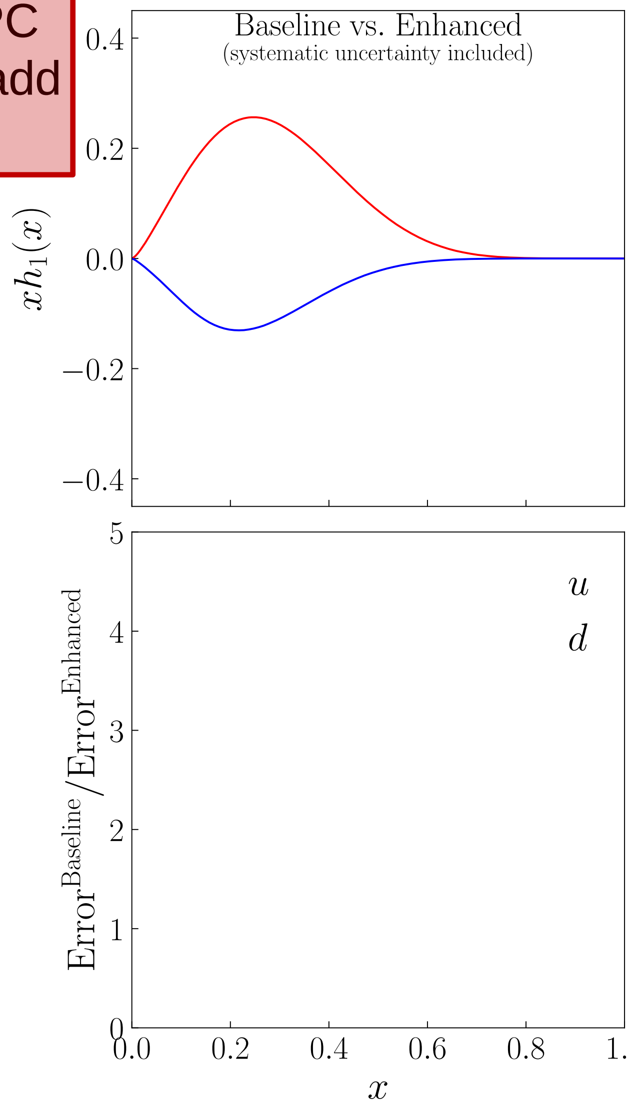
SoLID Jefferson Lab

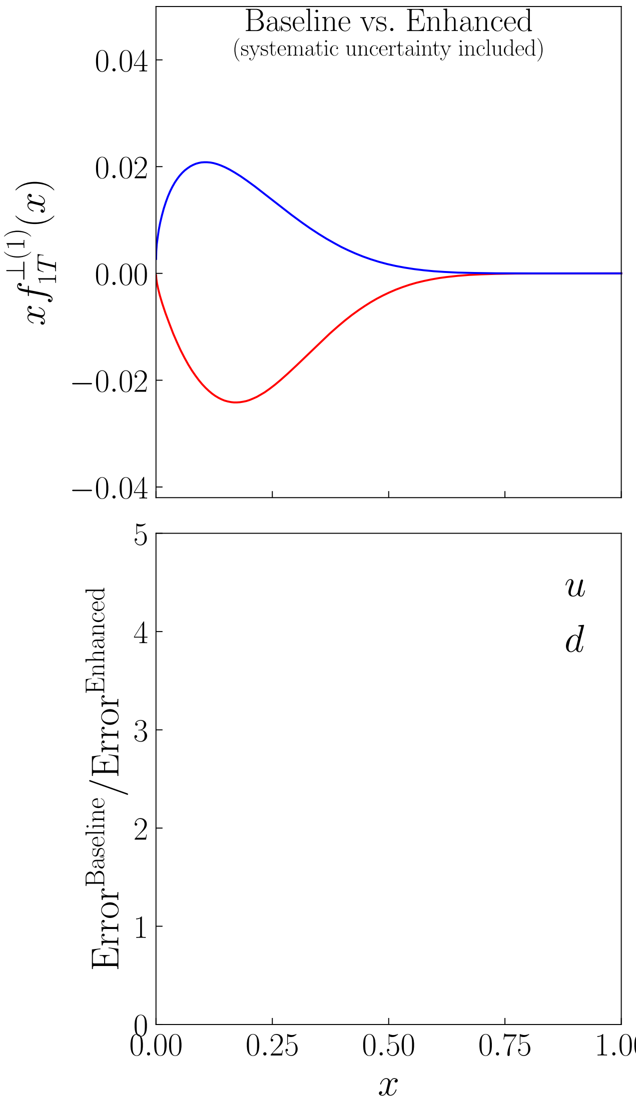
SoLID projections: baseline and enhanced baseline

Enhanced baseline: baseline + MRPC
Enhance PID in pion detection and add kaon detection capability

Tensor charge







Enhanced baseline has ~1.5 higher precision than baseline

Systematic uncertainties for transversely polarized ^3He and NH_3 targets

Source (Type): ^3He (preCDR and E12-10-006)	Collins π^+	Collins π^-	Sivers π^+	Sivers π^-
Raw asymmetry (Abs.) / Detector resolution (Abs.)	1.4×10^{-4} / < 10^{-4}	1.4×10^{-4} / < 10^{-4}	1.4×10^{-4} / < 10^{-4}	1.4×10^{-4} / < 10^{-4}
Target polarization (Rel.)	3% + 0.5%	3% + 0.5%	3% + 0.5%	3% + 0.5%
Random coincidence (Rel.)	0.2%	0.2%	0.2%	0.2%
Nuclear effects (Rel.)	4% + 1.2%	4% + 1.2%	5% + 1.2%	5% + 1.2%
Diffractive meson (Rel.)	3%	2%	3%	2%
Radiative corrections (Rel.)	2%	2%	3%	3%
Total (Abs.) / Total (Rel.)	1.4×10^{-4} / 6.3%	1.4×10^{-4} / 5.9%	1.4×10^{-4} / 7.3%	1.4×10^{-4} / 7.0%

Source (Type): NH_3 (preCDR and E12-11-108)	Collins π^+	Collins π^-	Sivers π^+	Sivers π^-
Raw asymmetry (Abs.) / Detector resolution (Abs.)	6.5×10^{-4} / < 10^{-4}	6.5×10^{-4} / < 10^{-4}	6.5×10^{-4} / < 10^{-4}	6.5×10^{-4} / < 10^{-4}
Target polarization (Rel.)	3% + 0.5%	3% + 0.5%	3% + 0.5%	3% + 0.5%
Random coincidence (Rel.)	0.2%	0.2%	0.2%	0.2%
Dilution (Rel.)	5%	5%	5%	5%
Diffractive meson (Rel.)	3%	2%	3%	2%
Radiative corrections (Rel.)	2%	2%	3%	3%
Total (Abs.) / Total (Rel.)	6.5×10^{-4} / 6.9%	6.5×10^{-4} / 6.5%	6.5×10^{-4} / 7.2%	6.5×10^{-4} / 6.9%

TMDs – confined motion inside the nucleon

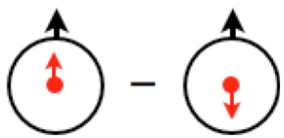
Leading twist: 8 TMDs

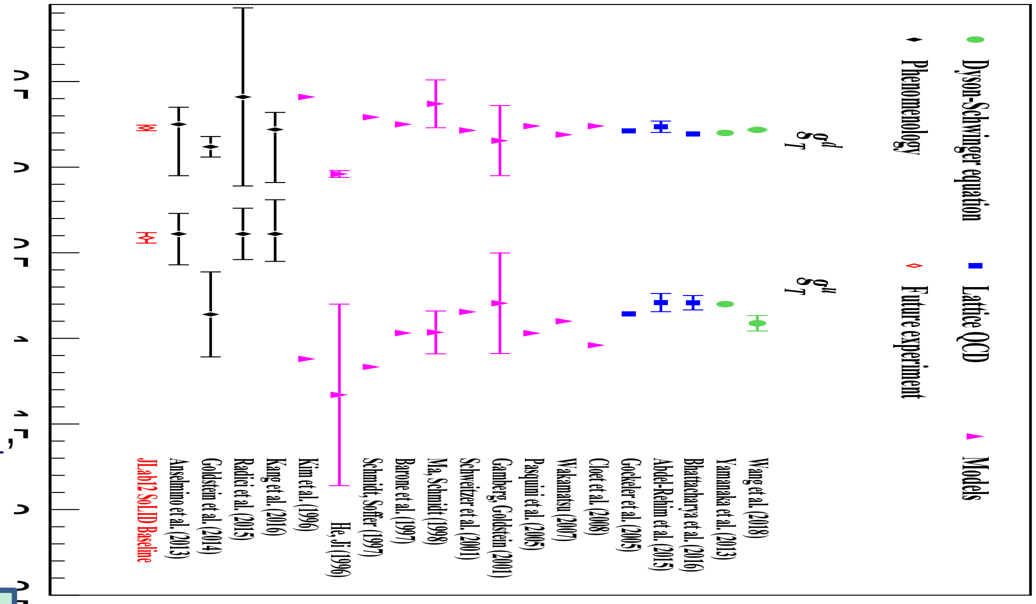
Kinematic Function	TMD	Name
1	f_1	Structure Function
$\mathbf{S_L} \cdot \mathbf{s_q}$	g_1	Spin-Structure Function
$\mathbf{S_T} \cdot \mathbf{s_q}$	h_1	Transversity
$\mathbf{S_L} \cdot \mathbf{k}_\perp \times \mathbf{s}_q$	$h_{1L}^\perp$	Worm Gear
$\mathbf{S_T} \cdot \mathbf{k}_\perp \times \mathbf{s}_q$	g_{1T}	Worm Gear
$\mathbf{S_T} \cdot \mathbf{k}_\perp \times \mathbf{P}$	$f_{1T}^\perp$	Sivers
$\mathbf{k}_\perp \times \mathbf{P} \cdot \mathbf{s}_q$	$h_1^\perp$	Boer-Mulder
$\mathbf{S_T} \cdot [\mathbf{k}_\perp \mathbf{k}_\perp] \cdot \mathbf{s}_{qT}$	$h_{1T}^\perp$	Pretzelocity

S: nucleon spin, $\mathbf{s_q}$**:** quark spin, **k :** quark transverse momentum
P: virtual photon 3-momentum, defines z direction

TMDs – confined motion inside the nucleon

Transversity distribution function

h_1  (Collinear & TMD)



- Chiral-odd, unique for the quarks
- No mixing with gluons, simpler evolution effect
- A transverse counter part to longitudinal spin g_1, difference shows the relativistic effect
- Zeroth moment gives tensor charge:

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

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

- A fundamental QCD quantity, valence quarks dominate
- Precisely calculated on the lattice
- Difference from nucleon axial charge is due to relativity
- High luminosity-large acceptance allows for high-precision test of LQCD predictions

- Tensor charge also connected to neutron and proton EDMs, unique opportunity for SM tests and new physics

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

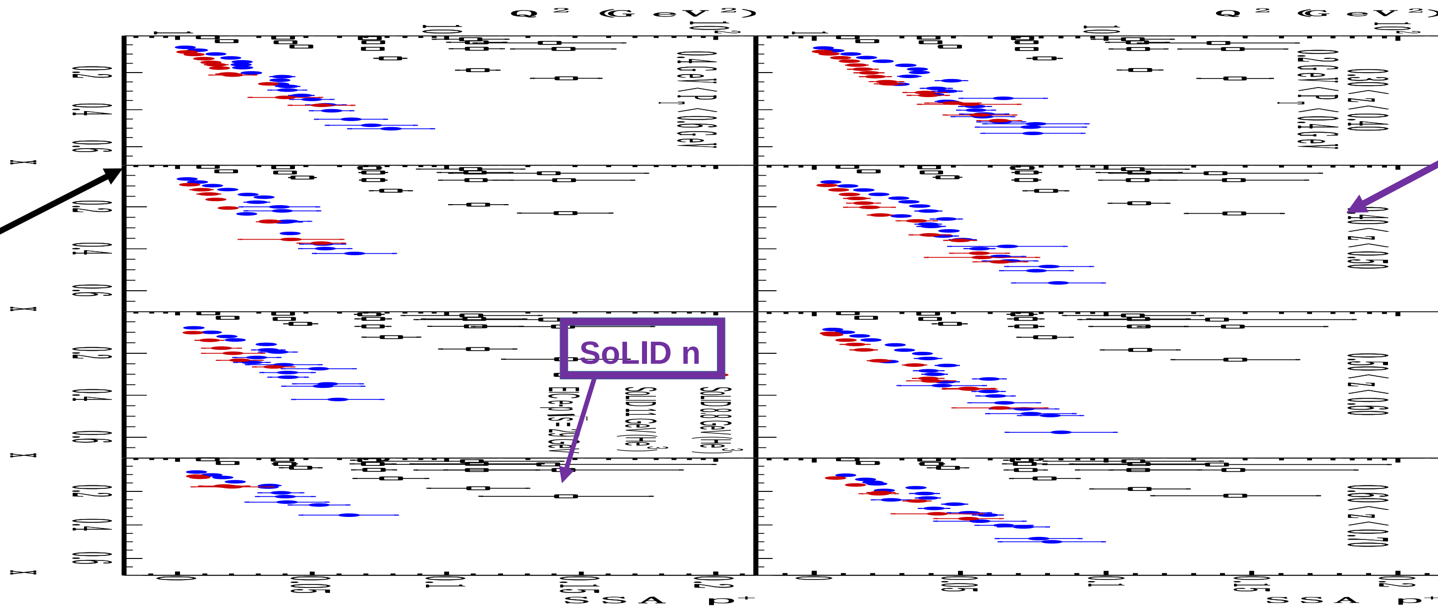
Z. Ye *et al.*, PLB 767, 91 (2017)
H. Gao, T. Liu and Z. Zhao, PRD 97, 074018 (2018)

SoLID: precision and complementary kinematic reach

C2

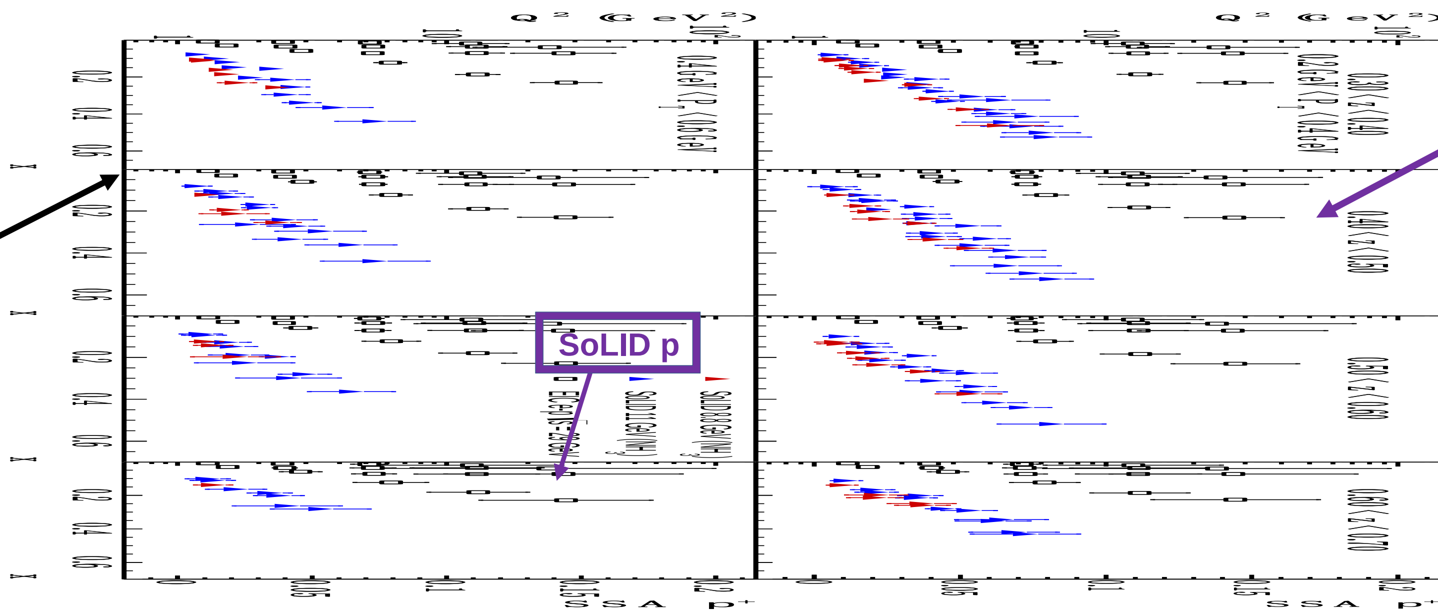
SoLID n

EIC-ep



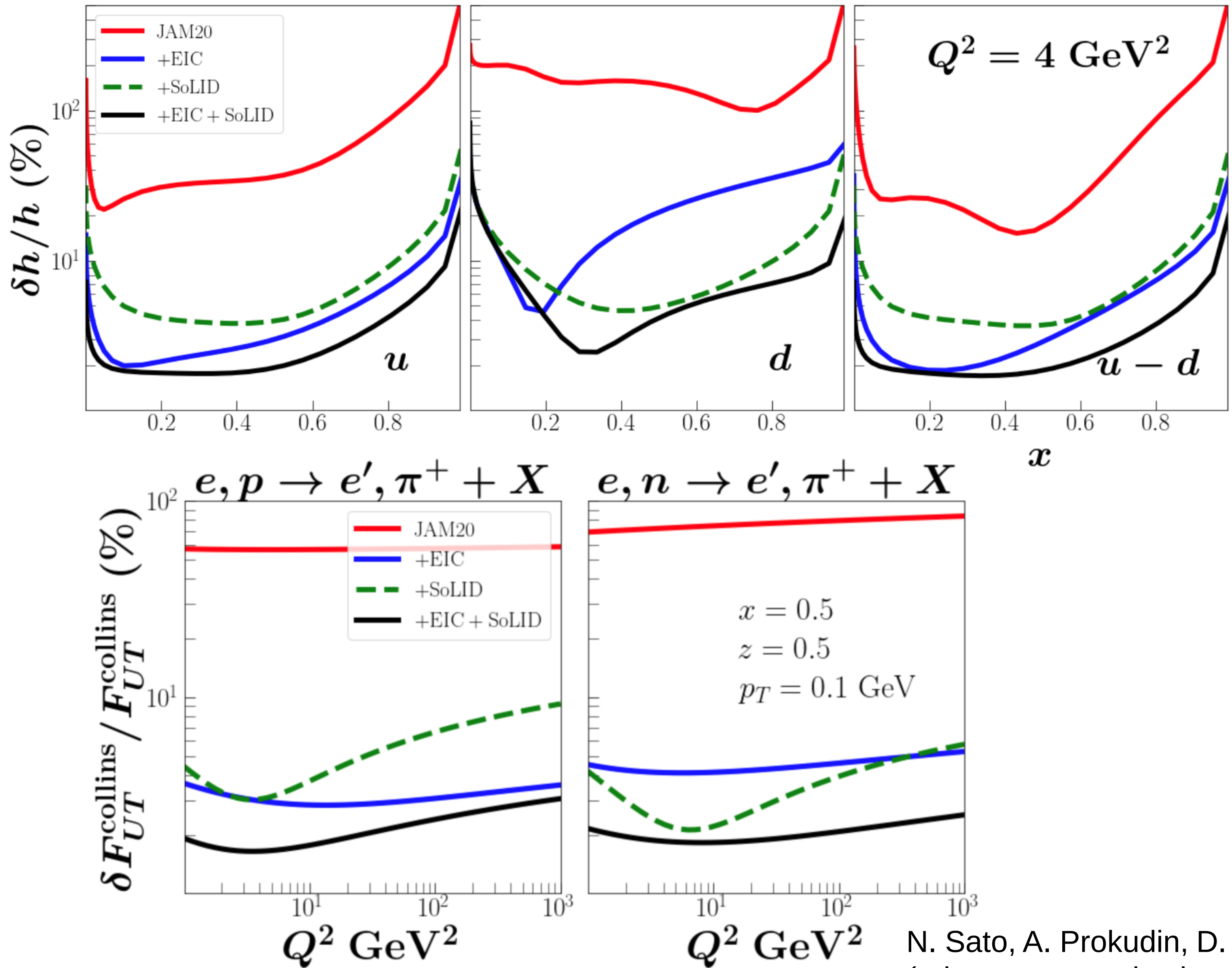
SoLID p

EIC-ep



EIC (e-p): integrated luminosity 10 fb^{-1}

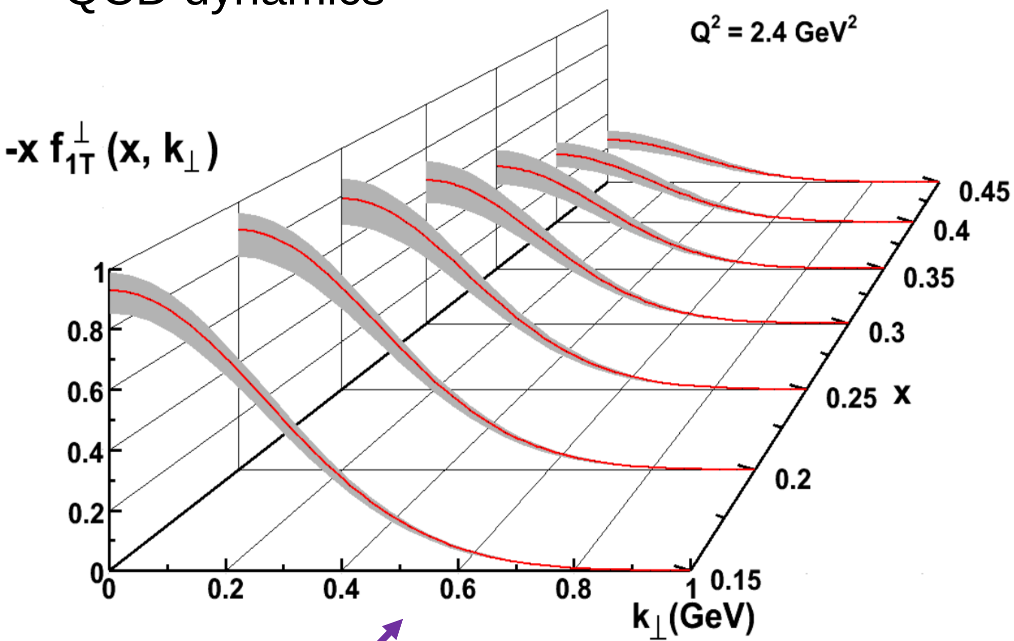
SoLID: precision and complementary kinematic reach

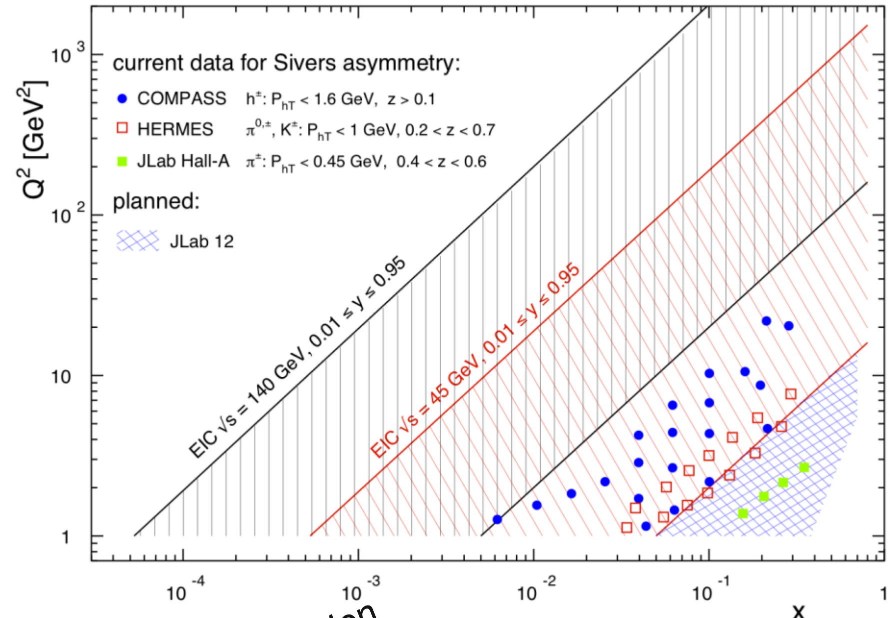


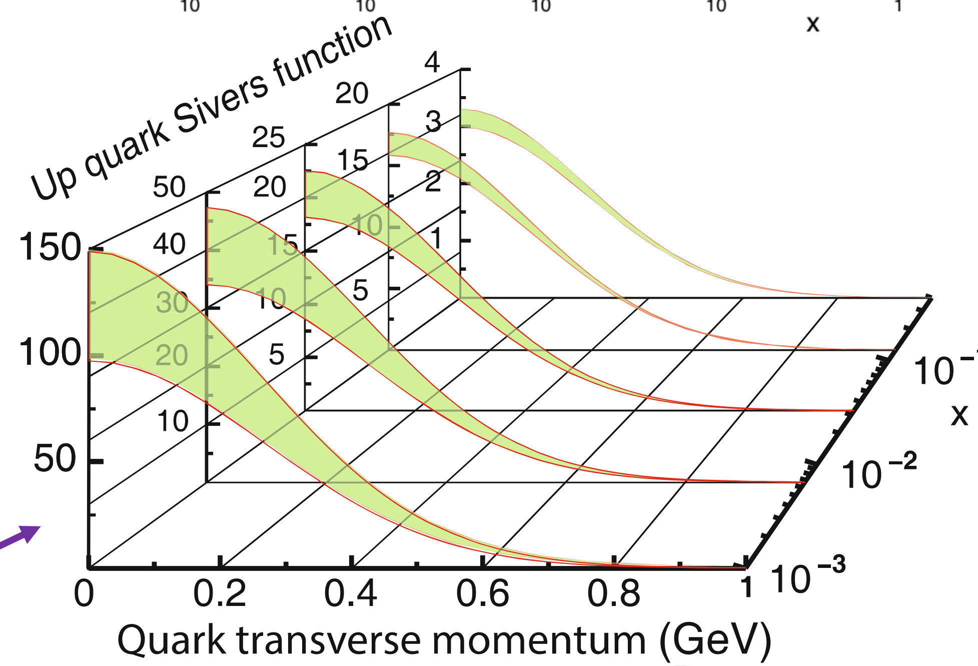
N. Sato, A. Prokudin, D. Pitonyak (private communications)

SoLID: precision and complementary kinematic reach

- Sivers: an example of TMDs
- Confined quark motion inside nucleon
- Quantum correlations between nucleon spin and quark motion
- QCD dynamics







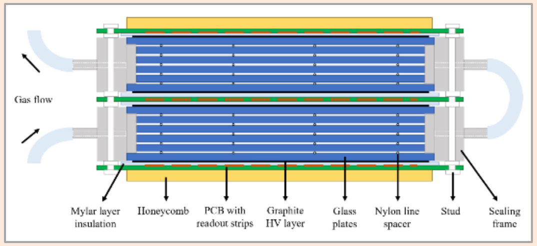
J. Dudek et al., EPJA 48,187 (2012)

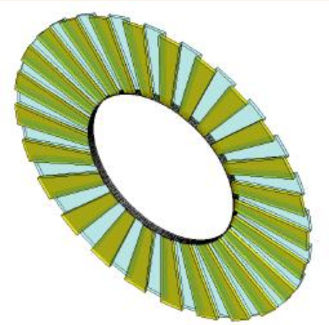
A. Accardi et al., EPJA 52,268 (2016)

E12-10-006D: SIDIS in Kaon Production with polarized ^3He and NH_3

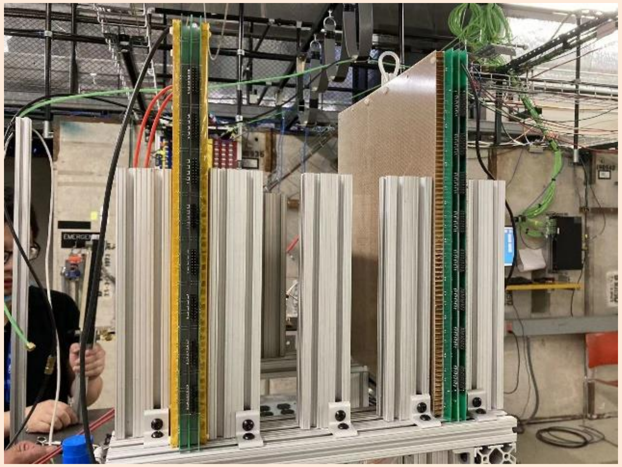
- **Measurements of $K^\pm$ production in SIDIS using both the transversely polarized ^3He and NH_3 Targets**
  - ✓ Run in parallel with E12-10-006 and E12-11-108
  - ✓ Extract $K^\pm$ Collins, Sivers and other TMD asymmetries
  - ✓ Flavor decomposition of u, d and sea quarks' TMDs
  - ✓ Enhanced SIDIS configuration: 30ps MRPC

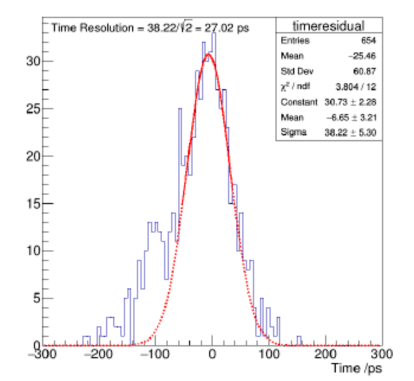
Kaon Identification: 30ps TOF + Veto of HGC





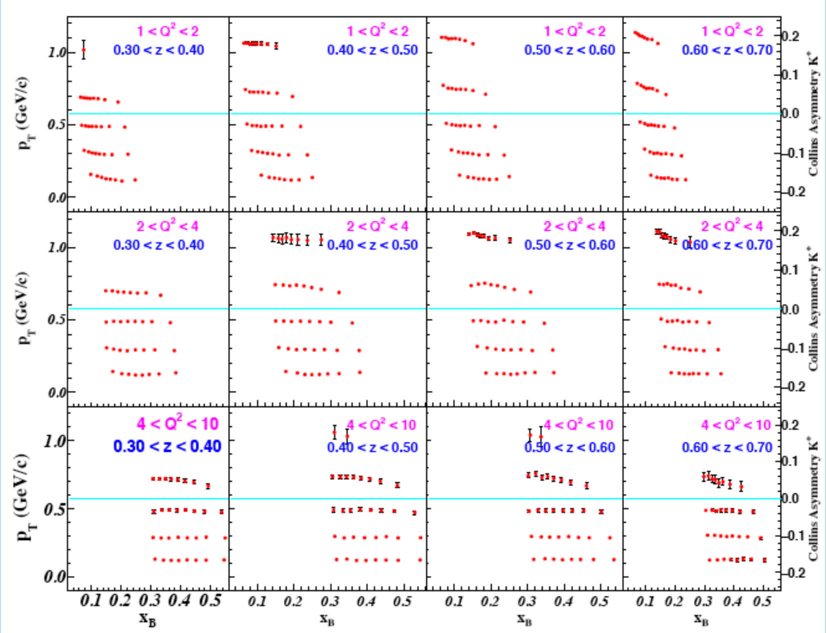
(a) The layout of the MRPC



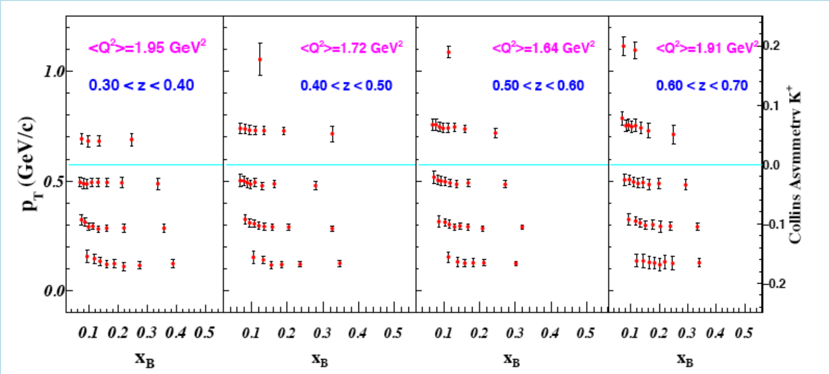


Sealed MRPC beam test at FermiLab (Tsinghua+UIC)

Projection (Collins, K+):



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



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

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

$$A_{UT}^{\sin(\phi_R+\phi_S)\sin\theta}(x,y,z,M_h,Q) = \frac{1}{|S_T|}\frac{\frac{8}{\pi}\int d\phi_R\, d\cos\theta\, \sin(\phi_R+\phi_S)\,(d\sigma^{\uparrow}-d\sigma^{\downarrow})}{\int d\phi_R\, d\cos\theta\,(d\sigma^{\uparrow}+d\sigma^{\downarrow})}$$
$$= \frac{\frac{4}{\pi}\,\varepsilon\int d\cos\theta\, F_{UT}^{\sin(\phi_R+\phi_S)}}{\int d\cos\theta\,(F_{UU,T}+\varepsilon\, F_{UU,L})} \quad .$$

where

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

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

$$F_{UT}^{\sin(\phi_R+\phi_S)} = x\frac{|\boldsymbol{R}|\sin\theta}{M_h}\, h_1(x)\, H_1^{\sphericalangle}(z,\cos\theta,M_h^2) \quad ,$$

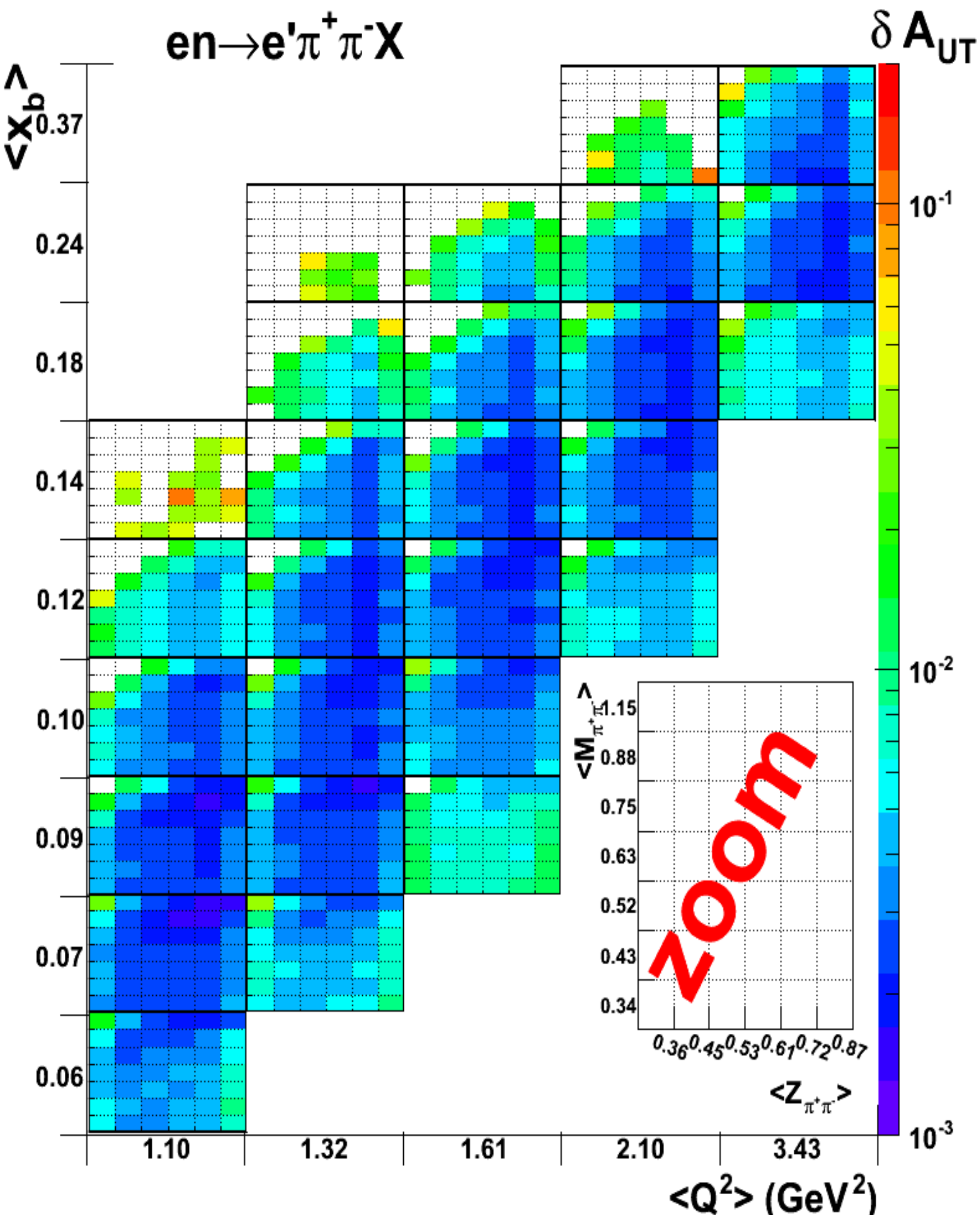
$$|\boldsymbol{R}| = \frac{1}{2}\sqrt{M_h^2 - 2(M_1^2+M_2^2) + (M_1^2-M_2^2)^2}$$

This is what we proposed to measure. The transvesity (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:

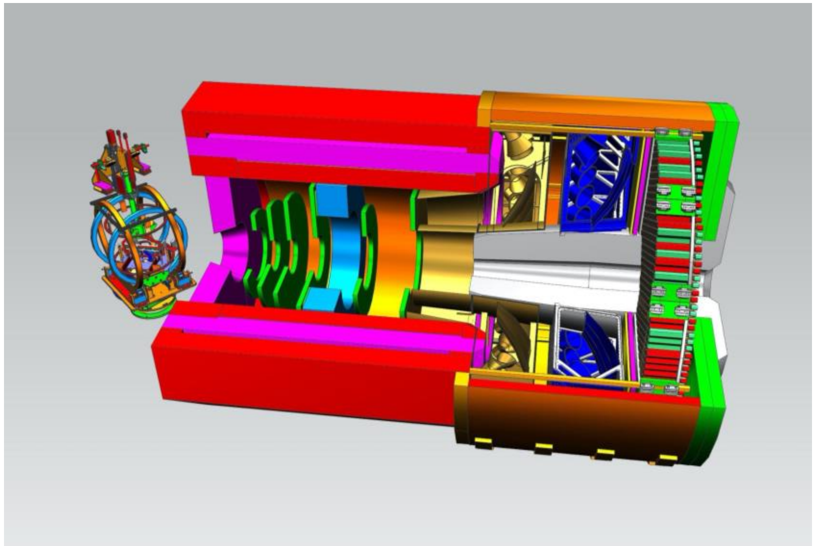
- 48 days of 11 GeV data on polarized ^{3}He target
- Lumi=10^{36} (n)/s/cm^2
- Wide x_b and Q^2 coverages
- Measure transversity via $\pi^+\pi^-$ dihadron channel

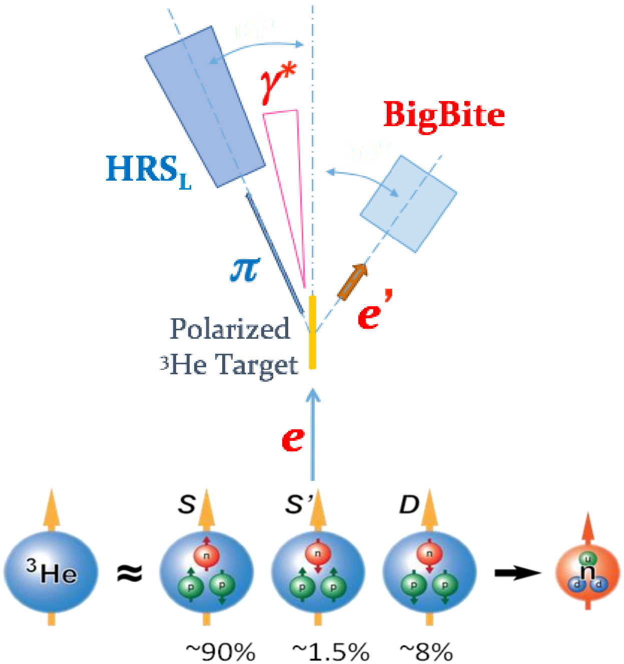
Combine with proton data can do flavor separation



Z scale (color) represent stat. error

QCD intensity frontier with SoLID: large-acceptance & high luminosity



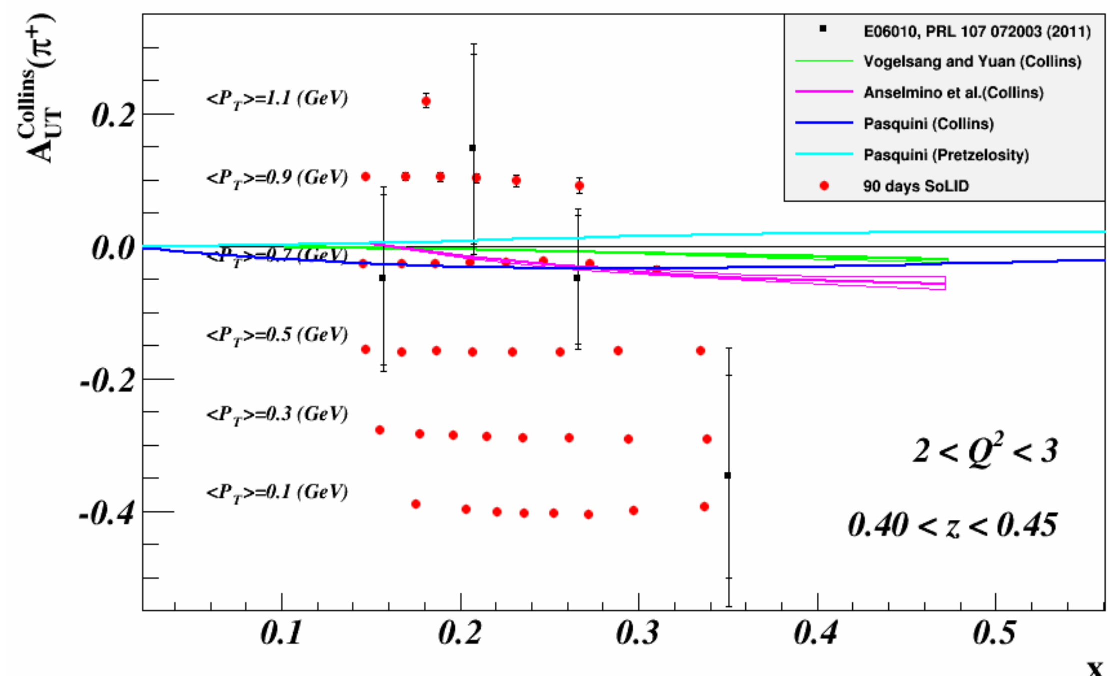


X. Qian et al., PRL107, 072003(2011)

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

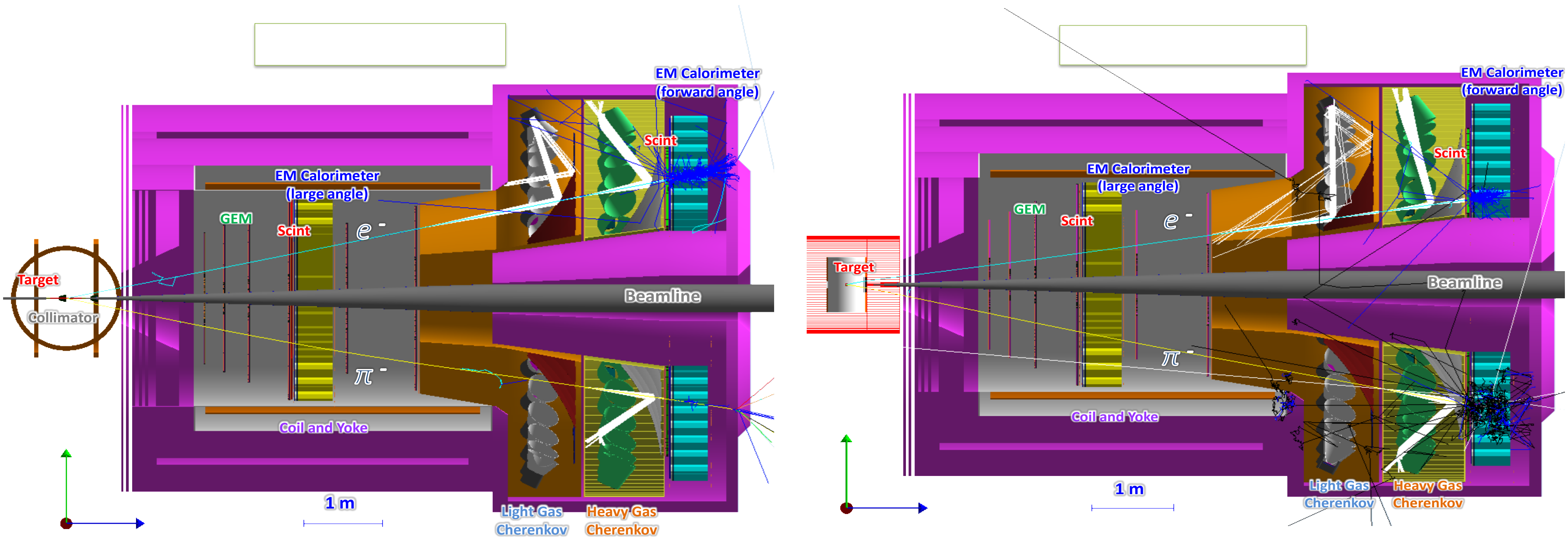
SoLID-SIDIS program: Large acceptance, Full azimuthal coverage + High luminosity

- 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



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

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

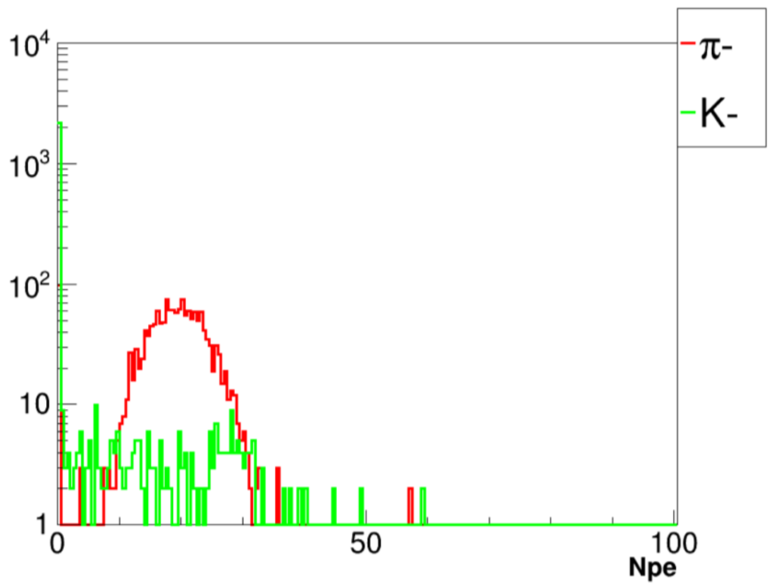
E12-11-108: Single Spin Asymmetries on Transversely Polarized Proton @ 120 days
Rating A Spokespersons: J.P. Chen, H. Gao (contact), X.M. Li, Z.-E. Meziani

Run group experiments with SIDIS Kaon and dihadron

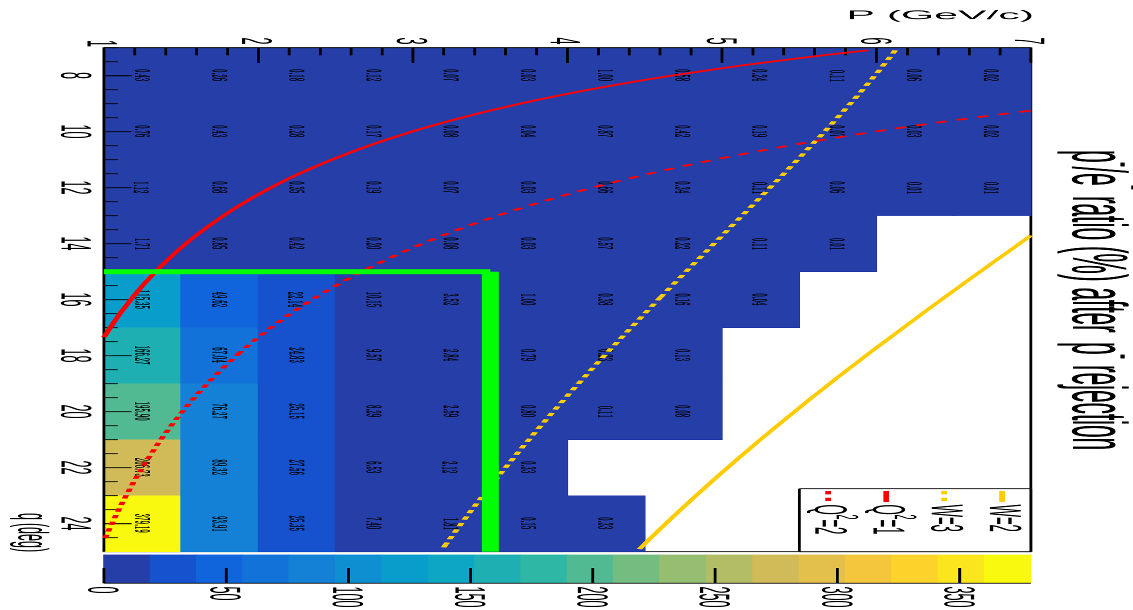
https://solid.jlab.org/experiments.html

SoLID-SIDIS and Subsystems

Heavy gas Cherenkov: pion efficiency ~90% with kaon rejection factor of 10

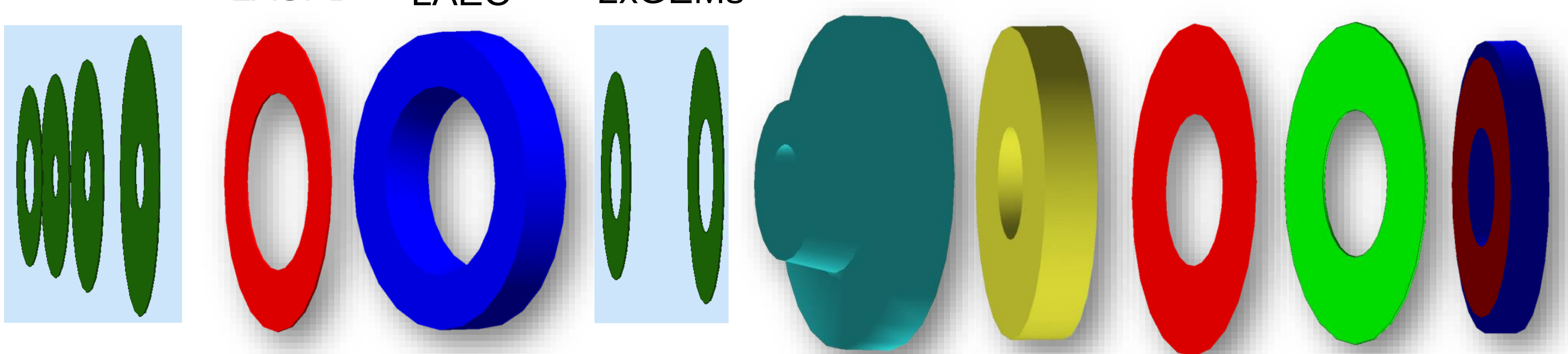


Combined light gas Cherenkov and Calorimeter detector performance



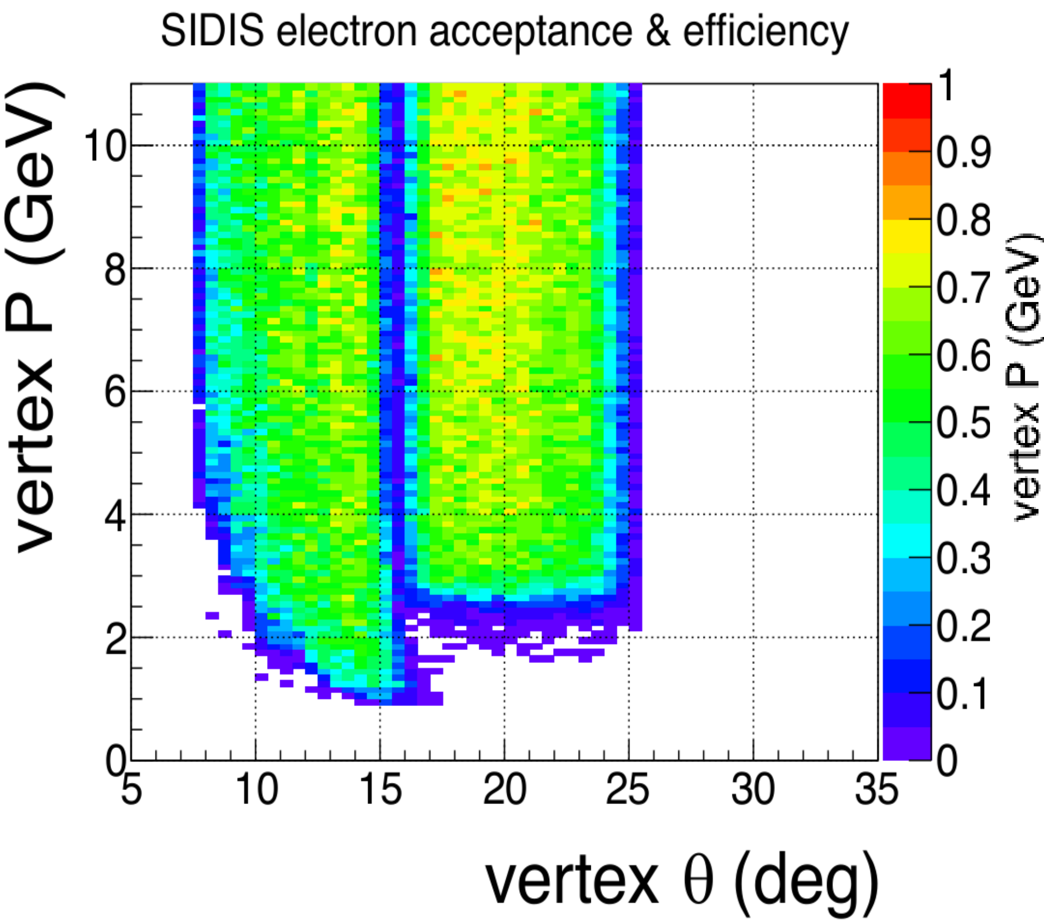
SIDIS&J/Ψ :

4xGEMs LASPD LAEC 2xGEMs LGC HGC FASPD MRPC FAEC

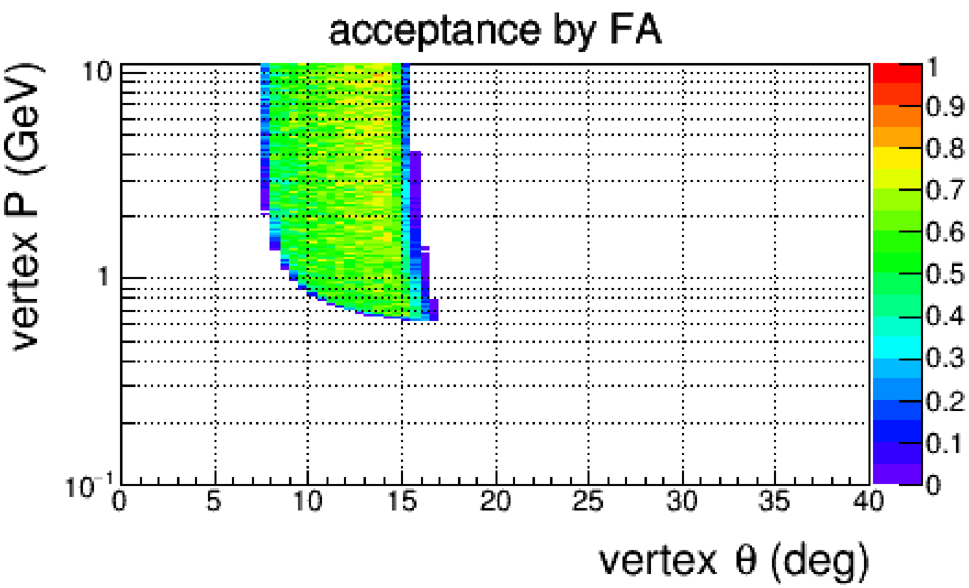


MRPC for kaon and improved pion identification

SoLID-SIDIS acceptance & efficiency



π acceptance



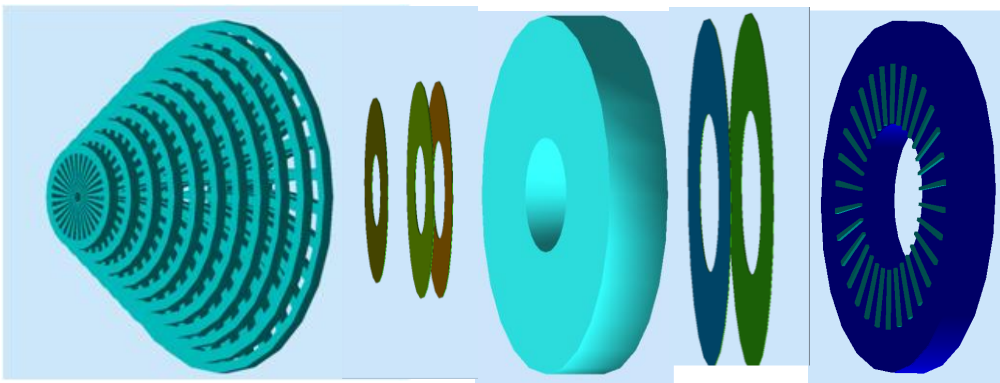
charged pion acceptance: $8^o < \theta < 15^o$, full 2π azimuthal angle

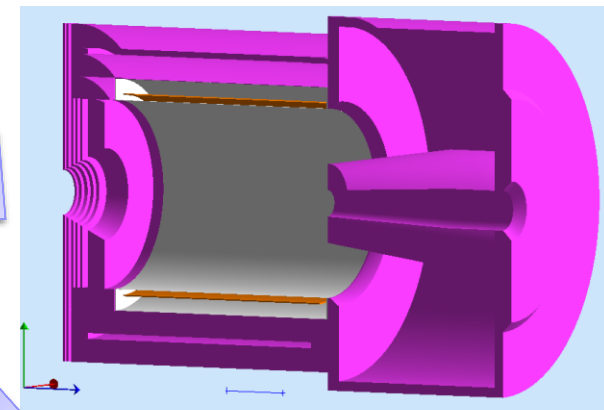
Combined effect of acceptance and efficiency (except tracking)

SoLID Detector Subsystems

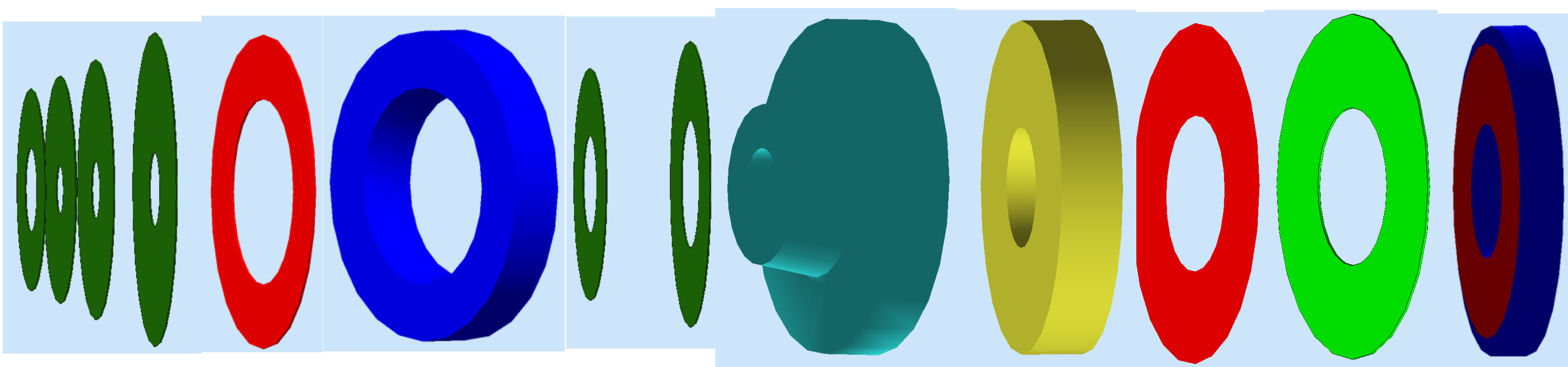
Uses full capability of JLab electronics

PVDIS: Baffle 3xGEMS LGC 2xGEMs EC





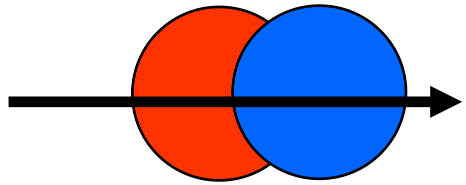
SIDIS&J/y:
4xGEMs LASPD LAEC 2xGEMs LGC HGC FASPD (MRPC) FAEC



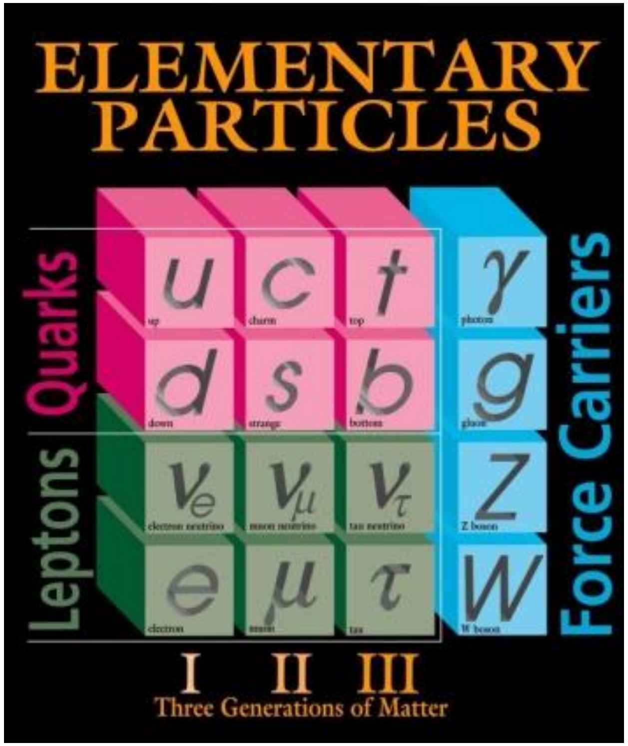
Pre-R&D items: LGC, HGC, GEM's, DAQ/Electronics, Magnet

Nucleon Electric Dipole Moment and Tensor Charge

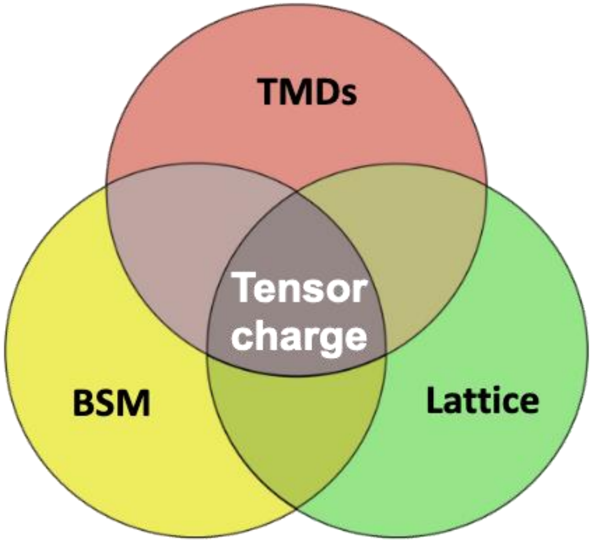
$\vec{d}\bullet\vec{E}$



s = 1/2



If neutron possesses EDM, in an electric field, Hamiltonian $H = -d_n \vec{\sigma} \bullet \vec{E}$ changes sign under T (P) symmetry operation d_n is more sensitive to θ than it is to d_{CKM}



CP violation in Standard Model:
(i) Flavor changing weak current, CKM mixing matrix (kaon, D meson, B meson decay)
(ii) θ term in QCD Lagrangian

Image credit: D. Pitonyak

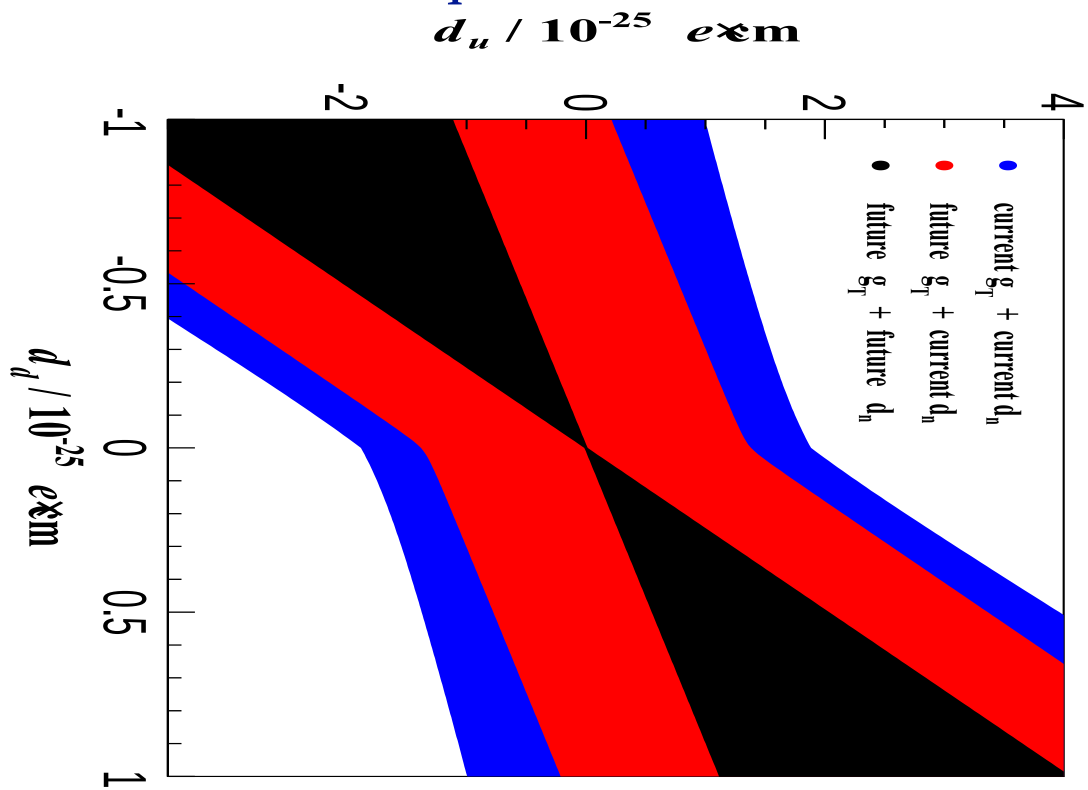
Constraint on Quark EDMs

Current upper limit on the neutron EDM

$$3.0 \times 10^{-26}\, e\,\text{cm} \quad (90\%\ \text{CL})$$

J.M. Pendlebury et al., Phys. Rev. D 92, 092003 (2015). [Re-analysis]
C.A. Baker et al., Phys. Rev. Lett. 97, 131801 (2006).

Constraint on quark EDMs with tensor charge



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

Using g_T^s from lattice calculation

- Future g_T: SoLID projected tensor charge
- Future d_n: $3.0\times10^{-28} e$ cm

H. Gao, T. Liu, Z. Zhao, arXiv:1704.00113, PRD 97, 074018 (2018)

Constraint on Quark EDMs

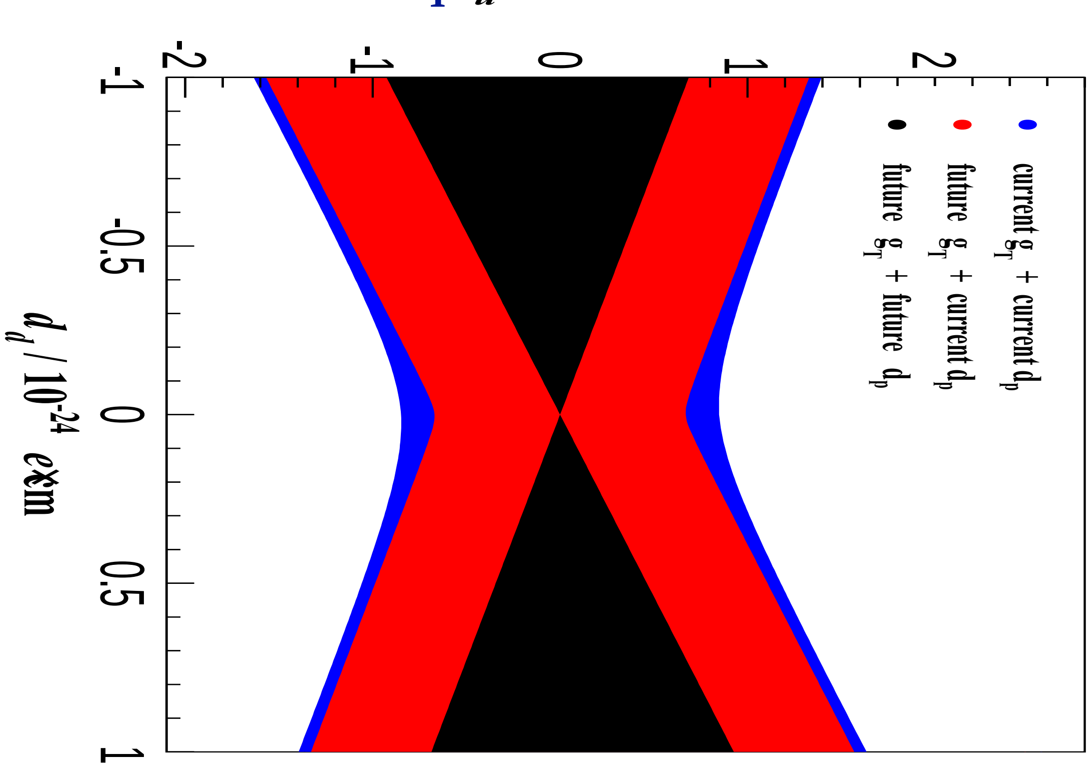
Current upper limit on the proton EDM

- Mercury atom EDM limit: $7.4 \times 10^{-30}\, e\,\text{cm} \quad (95\%\ \text{CL})$
- Derived proton EDM limit: $2.6 \times 10^{-25}\, e\,\text{cm}$

B. Graner et al., Phys. Rev. Lett. 116, 161601 (2016).

Schiff moment method including the uncertainty among different theoretical models

Constraint on quark EDMs with tensor charge



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

Using g_T^s from lattice calculation

- Future g_T: SoLID projected tensor charge
- Future d_p: $2.6\times10^{-29} e$ cm

H. Gao, T. Liu, Z. Zhao, arXiv:1704.00113, PRD 97, 074018 (2018)

Constraint on Quark EDMs

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

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)

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

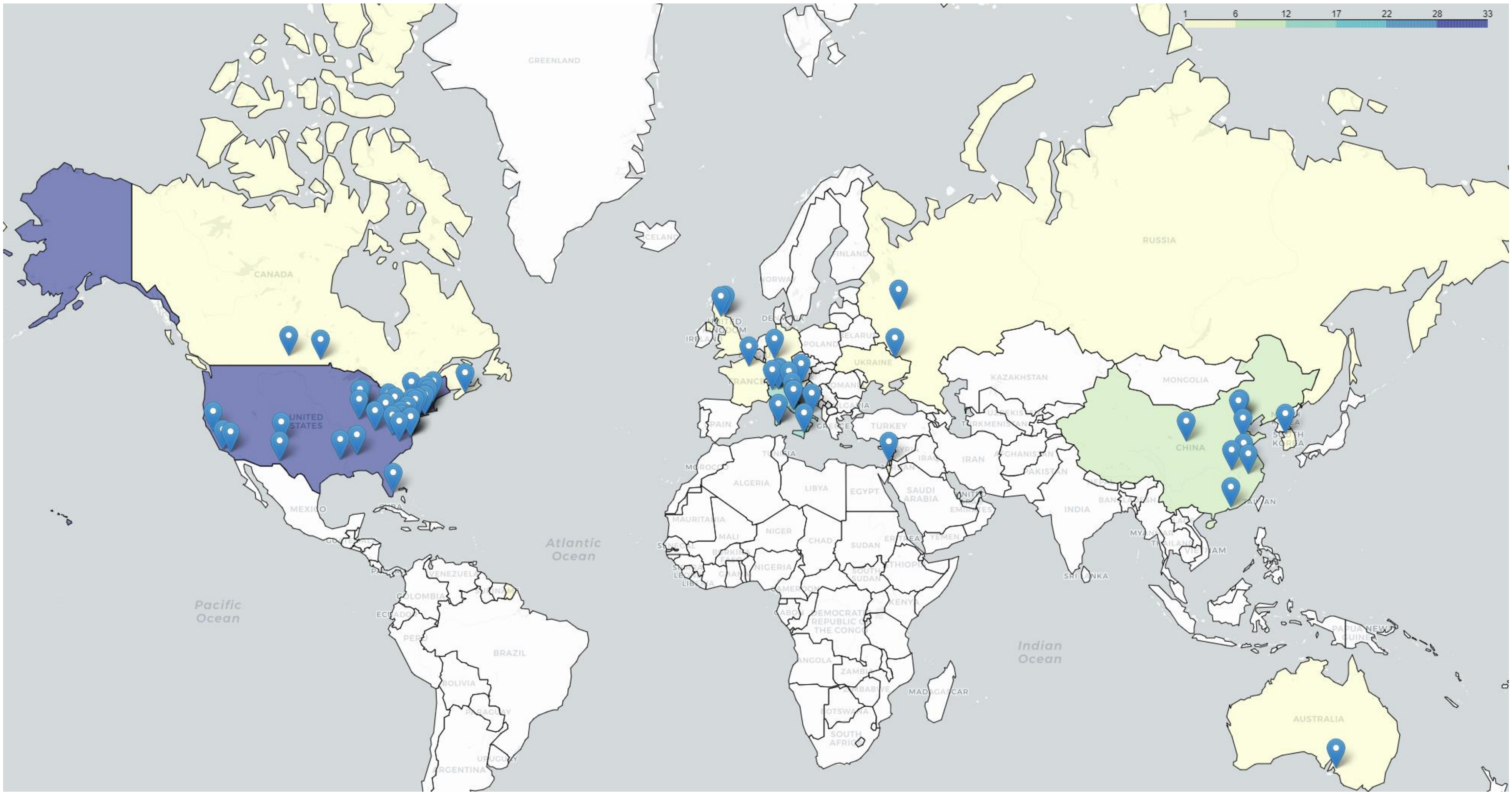
C. Peng, Y. Tian, Approved as run group (E12-10-006E)

- Deep exclusive π^- Production with Transversely Polarized ^{3}He

Z. Ahmed, G. Huber, Z. Ye, Approved as run group (E12-10-006B)

Strong Collaboration

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



SoLID Jefferson Lab