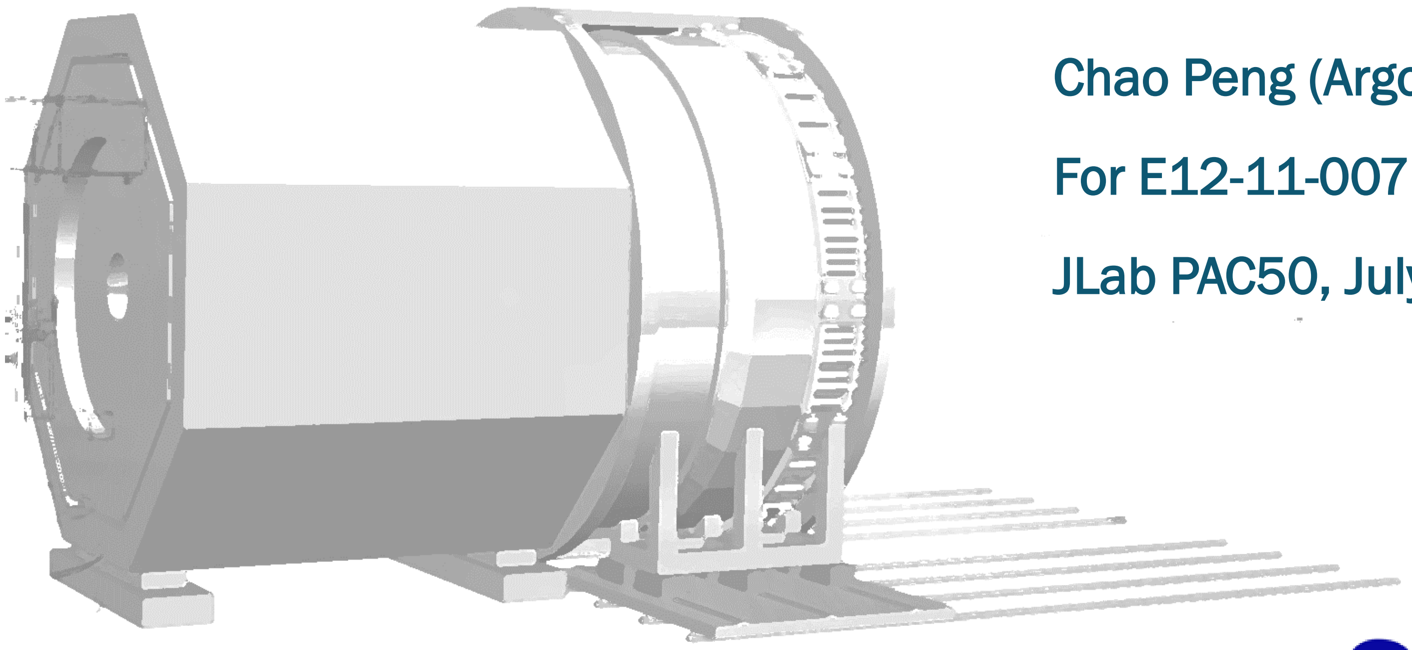
E12-11-007: Asymmetries in Semi-Inclusive Deep-Inelastic $(e, e'\pi^{\pm})$ Reactions on a Longitudinally Polarized ^{3}He Target at 8.8 and 11 GeV



Chao Peng (Argonne National Laboratory)

For E12-11-007 and SoLID Collaborations

JLab PAC50, July 11-15, 2022

Outline

- Solenoid Large Intensity Device (SoLID) and E12-11-107
- 3D nucleon structure, TMDs, and SIDIS
- Update for E12-11-107
  - Worm-gear functions
  - Beam request and projections

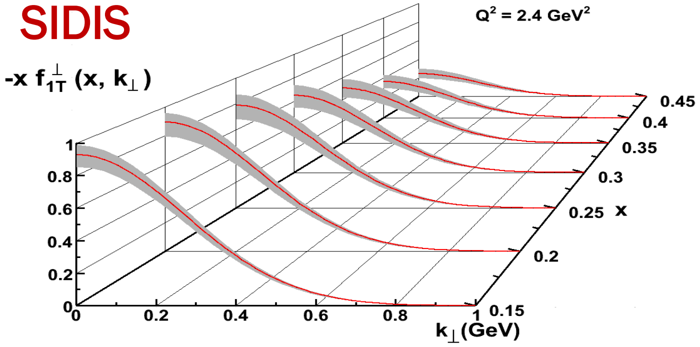
Solenoidal **L**arge **I**ntensity **D**evice (**SoLID**)

- Maximize scientific outcome of JLab 12 GeV upgrade
  - QCD Intensity frontier (high luminosity $10^{37\text{-}39}/\text{cm}^2/\text{s}$)
  - Large detector acceptance with full azimuthal coverage

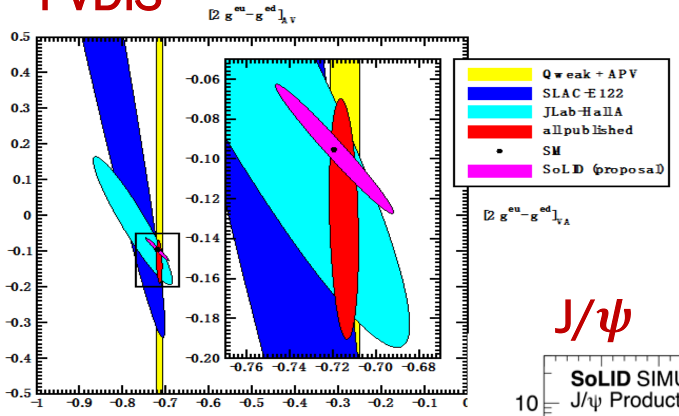
- Rich physics programs
  - Precision test of SM and search of new physics
  - 3D momentum imaging of nucleon spin
  - Precision J/ψ production near the threshold

- Complementary and synergistic with the EIC science
  - Proton spin and mass
    - **Spin:** valence quark tomography in momentum space
    - **Mass:** precision J/ψ production near threshold

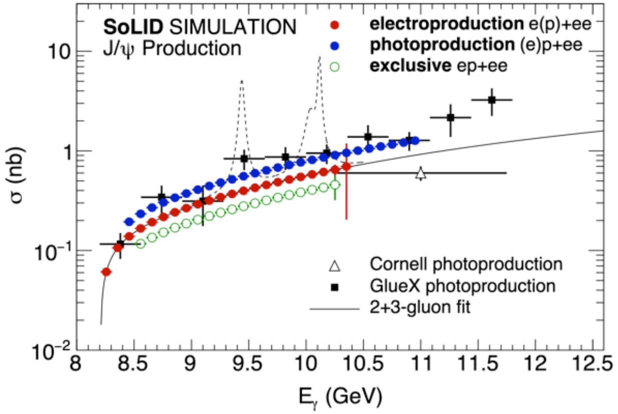
SIDIS



PVDIS

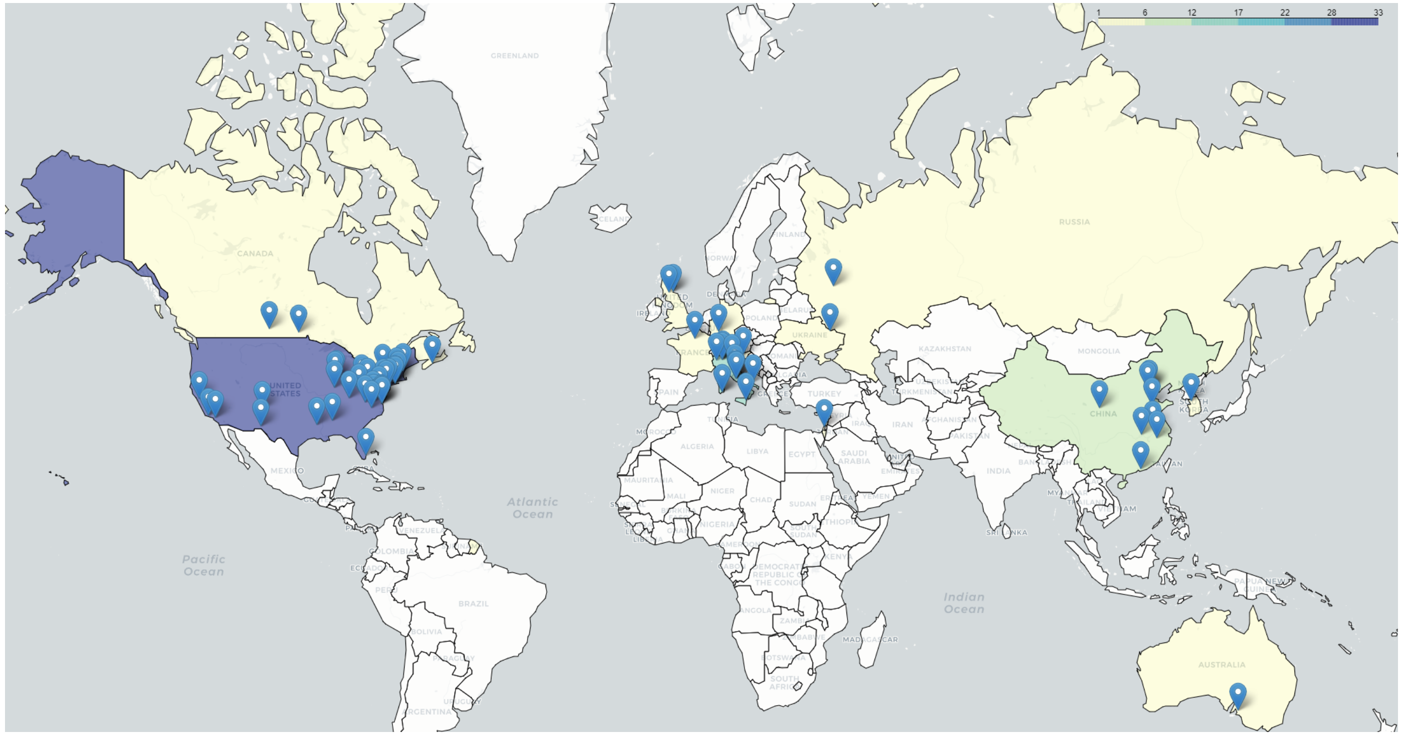


J/ψ



Strong Collaboration

- 270+ collaborators, 70+ institutes from 13 countries
- Strong theory support
- Active development and validation of the pre-conceptual design and physics programs



Progresses Since Approval of SoLID Experiments

- Since **2010:** Five SoLID experiments approved by PAC with high rating
  - 3 SIDIS (including **E12-11-007**), 1 PVDIS, 1 threshold J/ψ
  - 6 run group experiments
- CLEO-II magnet arrived at JLab in 2016, cold test on-going
- 2014: pCDR submitted to JLab with cost estimation, updated in 2017 and 2019
- **Director's Reviews in 2015, 2019 and 2021**
- 02/2020: SoLID MIE (with updated pCDR/estimated cost) submitted to DOE
- DOE funded Pre-R&D on Cherenkov/GEM and DAQ tests started 02/2020 and mostly completed
- 03/2021: **SoLID Science Review, went successfully**
- **Consistent effort on pre-conceptual design and pre-R&D with the support of JLab and DOE.**
- **New beam test to verify high luminosity (high rate/high radiation) capability of the detectors and DAQ.**

CLEO II coil at JLab

Overview of E12-11-007

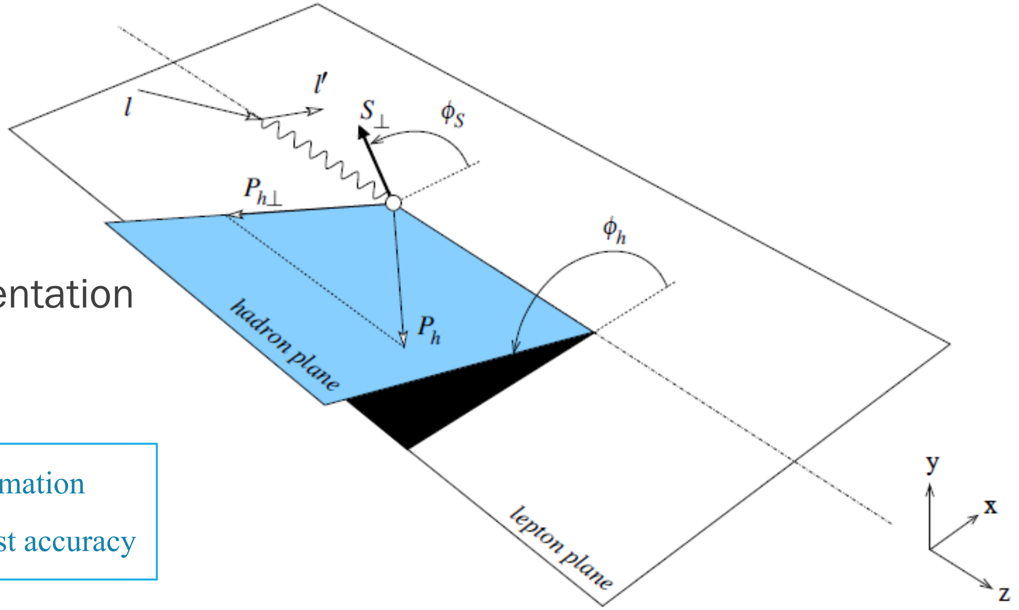
- SoLID SIDIS program: Azimuthal Asymmetries (SSA and DSAs) from SIDIS $\pi^{\pm}$
  - Longitudinally polarized ^{3}He target and polarized electron beam
  - Combined with DSA ($\mathrm{A_{LT}}$) from E12-10-006 with transversely ^{3}He polarized target
  - Access to helicity g_{1L} and “worm-gear” functions $g_{1T}, h_{1L}^{\perp}$
  - Study quark spin-orbit correlations

- Approved by PAC37
  - 35 PAC days of 11 GeV and 8.8 GeV beam at 15 μA
  - Match statistics of E12-10-006
  - Precision 4D mapping of $\mathrm{A_{UL}}, \mathrm{A_{LT}}$, and $\mathrm{A_{LL}}$ for neutron

- Jeopardy at PAC50

SIDIS and Structure Functions

- SIDIS differential cross sections
  - 18 Structure functions F(x, z, Q^2, P_T)
  - In parton model, F(x, z, Q^2, P_T) -> convolution of TMDs and fragmentation functions

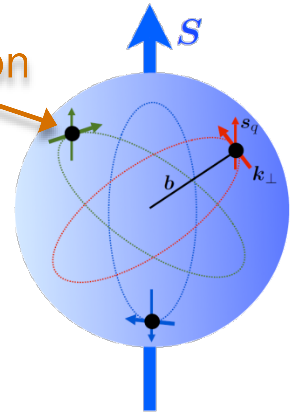


One-photon exchange approximation
at leading and sub-leading twist accuracy

$$\frac{d\sigma}{dx\,dy\,dz\,dP_T^2\,d\phi_h\,d\phi_S} = \frac{\alpha^2}{xyQ^2}\frac{y^2}{2(1-\epsilon)}\left(1+\frac{\gamma^2}{2x}\right)$$
$$\times\Big\{F_{UU,T}+\epsilon F_{UU,L}+\sqrt{2\epsilon(1+\epsilon)}F_{UU}^{\cos\phi_h}\cos\phi_h+\epsilon F_{UU}^{\cos 2\phi_h}\cos 2\phi_h+\lambda_e\sqrt{2\epsilon(1-\epsilon)}F_{LU}^{\sin\phi_h}\sin\phi_h$$
$$+S_L\Big[\sqrt{2\epsilon(1+\epsilon)}F_{UL}^{\sin\phi_h}\sin\phi_h+\epsilon F_{UL}^{\sin 2\phi_h}\sin 2\phi_h\Big]+\lambda_e S_L\Big[\sqrt{1-\epsilon^2}F_{LL}+\sqrt{2\epsilon(1-\epsilon)}F_{LL}^{\cos\phi_h}\cos\phi_h\Big]$$
$$+S_T\Big[\big(F_{UT,T}^{\sin(\phi_h-\phi_S)}+\epsilon F_{UT,L}^{\sin(\phi_h-\phi_S)}\big)\sin(\phi_h-\phi_S)+\epsilon F_{UT}^{\sin(\phi_h+\phi_S)}\sin(\phi_h+\phi_S)+\epsilon F_{UT}^{\sin(3\phi_h-\phi_S)}\sin(3\phi_h-\phi_S)$$
$$+\sqrt{2\epsilon(1+\epsilon)}F_{UT}^{\sin\phi_S}\sin\phi_S+\sqrt{2\epsilon(1+\epsilon)}F_{UT}^{\sin(2\phi_h-\phi_S)}\sin(2\phi_h-\phi_S)\Big]$$
$$+\lambda_e S_T\Big[\sqrt{1-\epsilon^2}F_{LT}^{\cos(\phi_h-\phi_S)}\cos(\phi_h-\phi_S)$$
$$+\sqrt{2\epsilon(1-\epsilon)}F_{LT}^{\cos\phi_S}\cos\phi_S+\sqrt{2\epsilon(1-\epsilon)}F_{LT}^{\cos(2\phi_h-\phi_S)}\cos(2\phi_h-\phi_S)\Big]\Big\}$$

Leading Twist TMD PDFs

L $\neq^{?}$ 0 ⟶ Transverse motion



- TMD PDFs link the intrinsic motion of partons with quark spin and nucleon spin
  - Probes orbital motion of quarks
  - Access to all leading twist terms through SIDIS differential cross sections

Nucleon Polarization		Quark polarization: Unpolarized (U)	Quark polarization: Longitudinally Polarized (L)	Quark polarization: Transversely Polarized (T)
	U	f_1 =		$h_1^{\perp}$ = − Boer-Mulders
	L		g_1 = − Helicity	$h_{1L}^{\perp}$ = − Worm Gear (Kotzinian-Mulders)
	T	$f_{1T}^{\perp}$ = − Sivers	g_{1T} = − Worm Gear	h_1 = − Transversity $h_{1T}^{\perp}$ = − Pretzelosity

⟶ quark spin ⟶ nucleon spin

E12-11-007:

Single Spin Asymmetry and Double Spin Asymmetries:

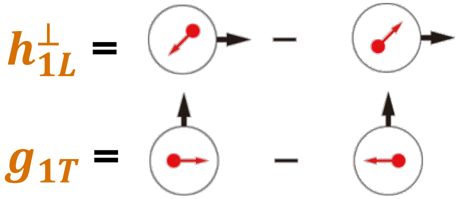
$$A_{UL}^{\sin 2\phi_h} \propto h_{1L}^{\perp} \otimes H_1^{\perp}$$

$$A_{LT}^{\cos(\phi_h - \phi_S)} \propto g_{1T} \otimes D_1$$

$$A_{LL} \propto g_{1L} \otimes D_1$$

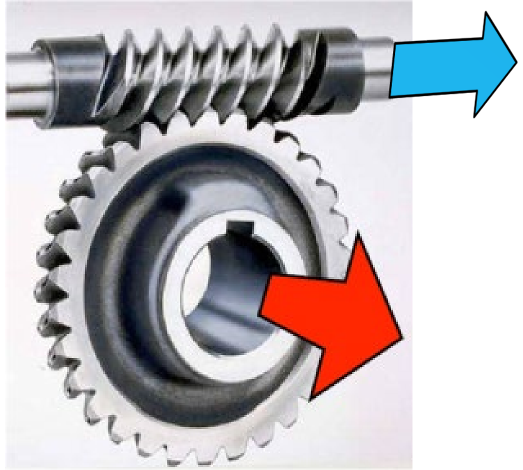
Large acceptance, high statistics, and precision measurement with SoLID is essential for 4D mapping and separation of azimuthal angular modulation

"Worm-gear" Functions



- Dominated by interference between wave function components that differ by one unit of quark OAM
  - $\mathrm{Re}[(L=0)_q \times (L=1)_q]$
  - Complementary information about imaginary part from Boer-Mulders effects and Sivers effects
  - OAM-spin correlations

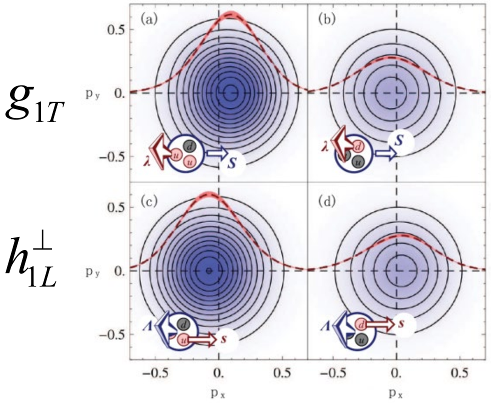
- A genuine sign of intrinsic transverse motion
  - No analogous terms in GPD
  - No dynamical generation by FSI from coordinate space densities



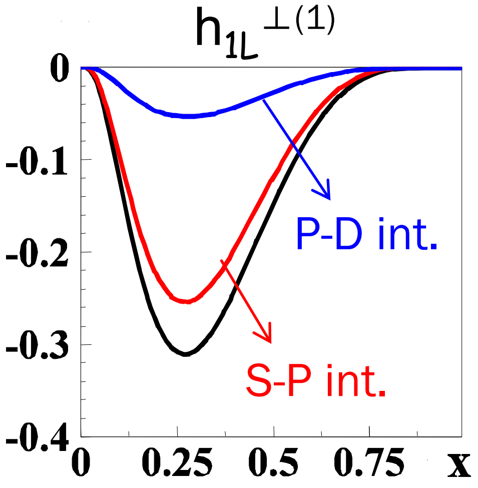
Worm Gear

Test of Theoretical Predictions

- Various theoretical predictions available
  - Lattice QCD calculations
  - Quark models
- $h_{1L}^{\perp} = -g_{1T}$?
  - Cylindrical symmetry around y direction
  - Valid in many quark models
  - Favored by Lattice QCD calculations
- WW & WW-type approximations
  - Assume "pure twist-3" and quark mass terms are small
  - Indirect information on transversity



Lattice QCD, arXiv:0908.1283



Light-Cone CQM
B. Pasquini B.P., Cazzaniga, Boffi, RD78, 2008

$$h_{1L}^{\perp q(1)}(x) \overset{WW-type}{\approx} -x^2 \int_x^1 \frac{dy}{y^2} h_1^q(y)$$

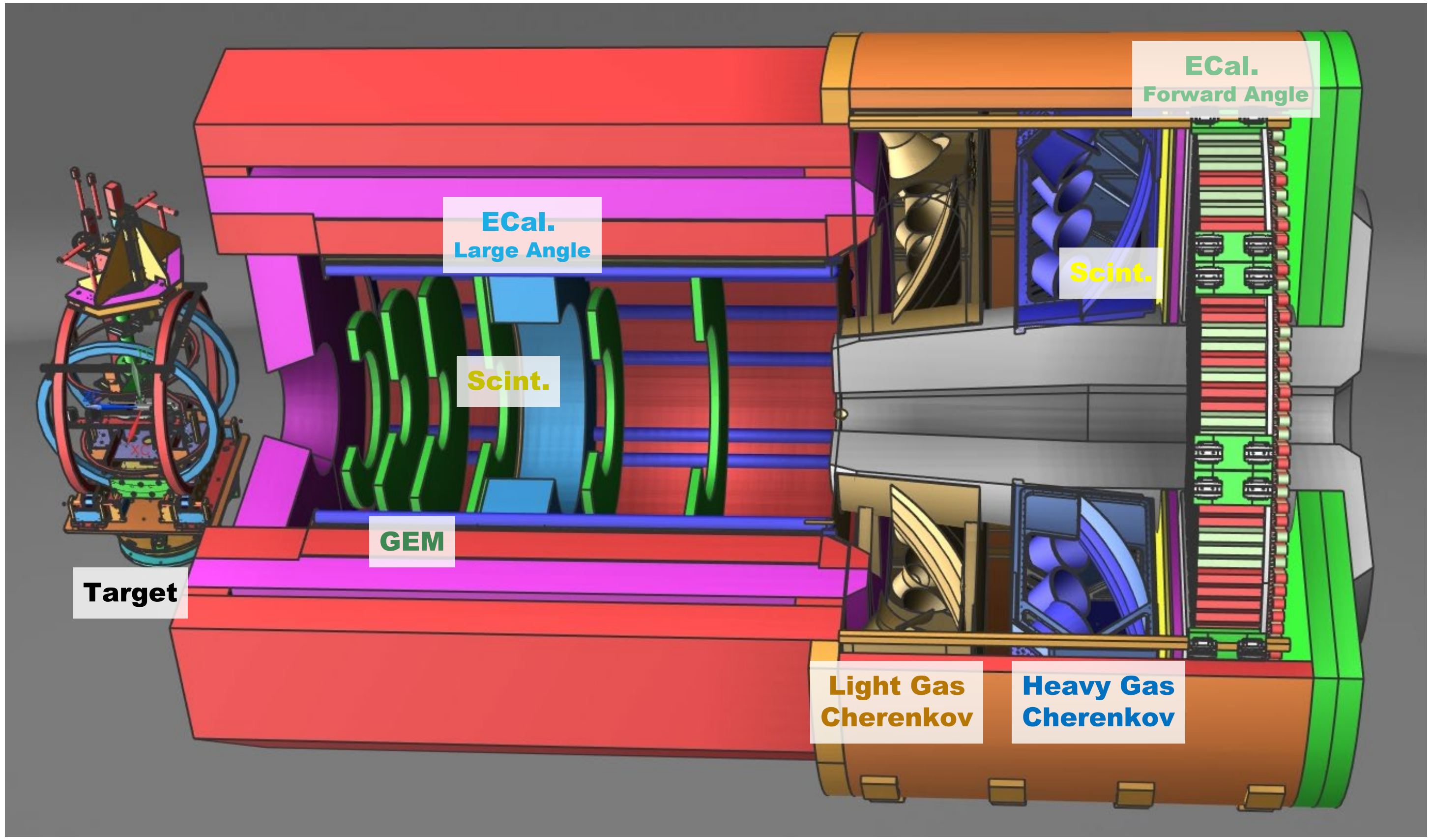
$$g_{1T}^{q(1)}(x) \overset{WW-type}{\approx} x \int_x^1 \frac{dy}{y} g_1^q(y)$$

Experimental Observables

- One SSA and two DSAs: A_{UL}, A_{LT}, and A_{LL}
  - Share commissioning and A_{LT} data with E12-10-006
- 35 PAC days for Longitudinally polarized target and polarized electron beam
  - 11 and 8.8 GeV beam at 15 uA, with high beam polarization (85%)
  - High in-beam longitudinal target polarization (60%), with transverse target polarization from E12-10-006 (g_{1T})
  - High polarized luminosity 10^{36} $cm^{-2}s^{-1}$
- High statistics and well controlled systematic uncertainty
  - Precise 4D mapping with 1000-1400 bins for each asymmetry and charged pion
  - Neutron Asymmetries: $\delta A_{stat.} \approx 0.005$
  - Expected systematics $\delta A_{sys.}/A \approx 7\%$ (relative) with the large symmetric acceptance from SoLID

Experimental Setup

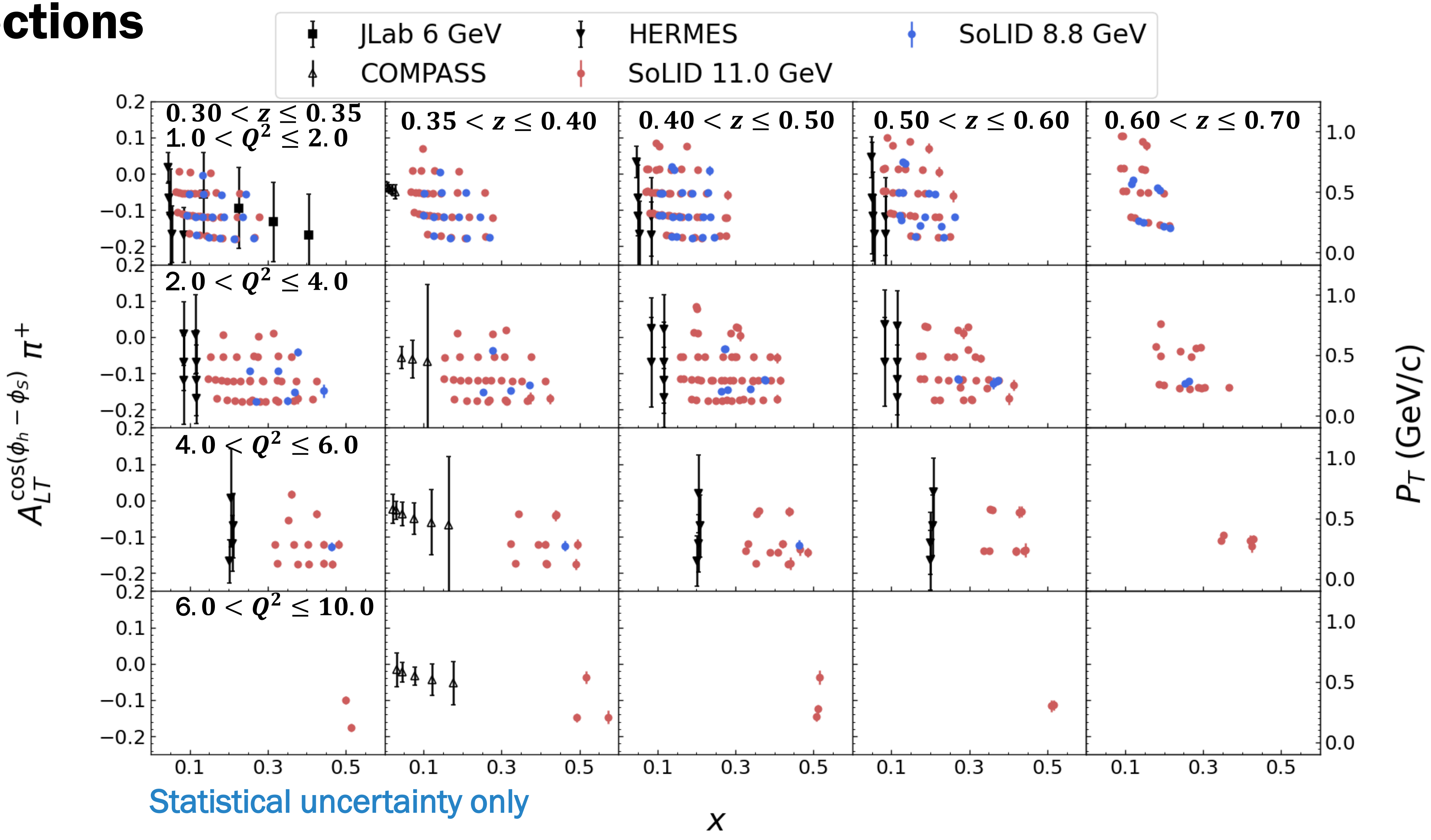
- SoLID-SIDIS configuration
- Longitudinally polarized ^{3}He Target
- Full 2π coverage of polar angle from 8°-24°
  - $8° < \theta < 14.8°, 1 < P < 7$ GeV/c
  - $16° < \theta < 24°, 3.5 < P < 7$ GeV/c (electron)
  - $\delta p/p \sim 2\%, \delta\theta \sim 0.6\, mrad, \delta\phi \sim 5\, mrad$
- High luminosity, high data rate



Technical Requirements

- High polarized luminosity
  - High precision measurement of small asymmetries in 4-dimensional binning
- Full azimuthal coverage
  - Control systematic uncertainties over the angular modulation
- Good momentum and angular resolutions
  - Four-dimensional binning over the kinematic variables (x, z, Q^2, and P_T)
- High data rates
  - Trigger in electron: FAEC + SPD + LGC, LAEC + SPD; or hadron: FAEC + SPD
  - DAQ rate < 100 kHz
- SoLID will fulfill all the requirements

Projections



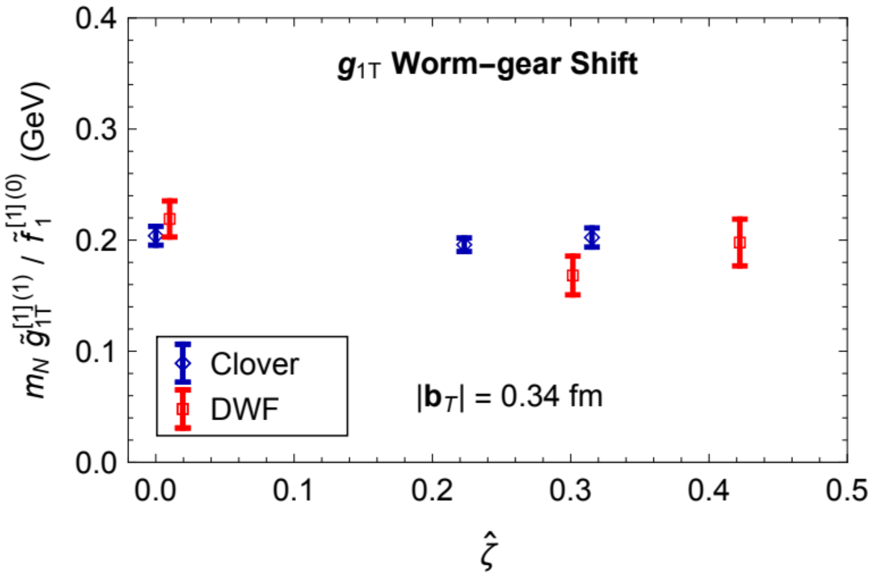
Statistical uncertainty only

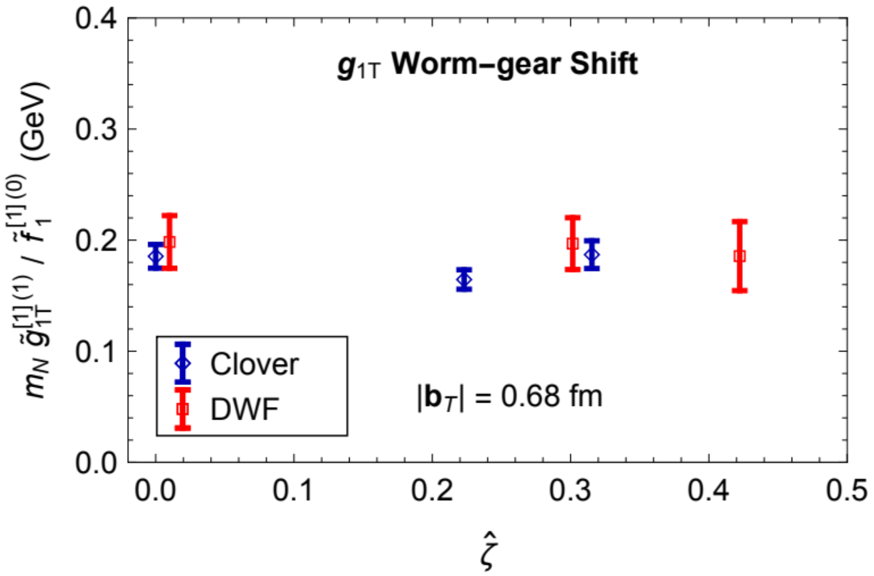
Lattice Calculation on Worm-gear Shift

- Lattice calculations on worm-gear shift

$$[\langle k_x \rangle_{TL}](Q^2) \sim \frac{\int_0^1 dx\,[g_{1T}^u(x,Q^2) - g_{1T}^d(x,Q^2)]}{\int_0^1 dx\,[f_1^u(x,Q^2) - f_1^d(x,Q^2)]}$$

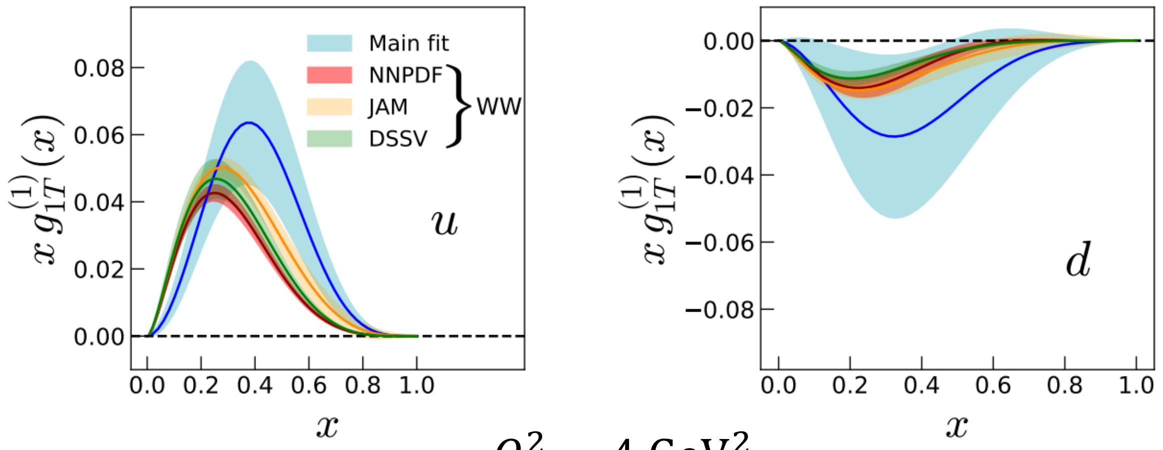
  - B. Yoon et al., Phys. Rev. D96, 094508 (2017)
  - Consistent results from two discretization schemes at quark separation b_T > 0.3



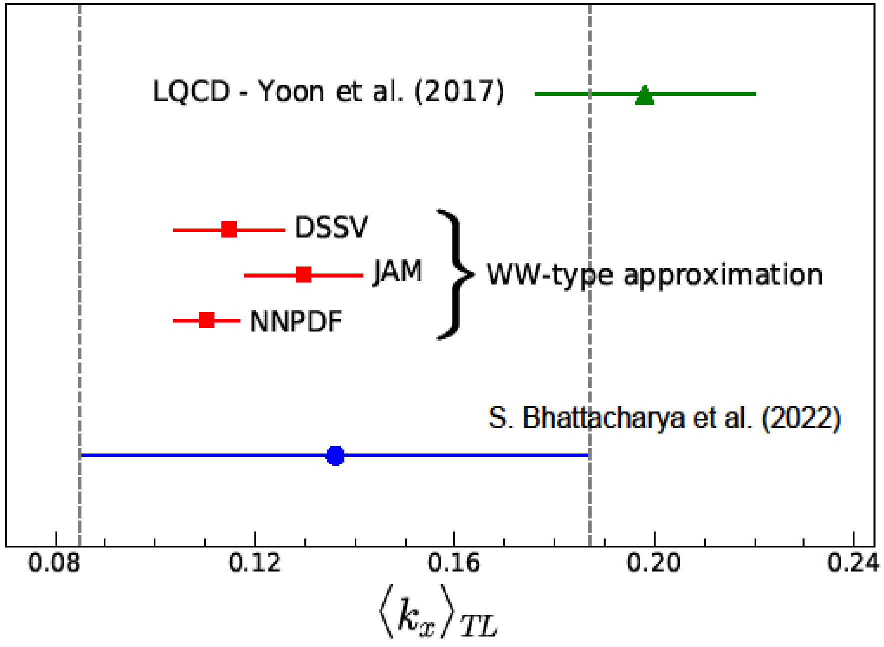


First Global Extraction of Worm-gear Function g_{1T}

- S. Bhattacharya et al., Phys. Rev. D105, 034007 (2022)
  - COMPASS, HERMES, and JLab 6 GeV data
  - Working with the authors for SoLID projections



$Q^2 = 4\ \mathrm{GeV}^2$



More precise neutron data are needed for a better flavor separation

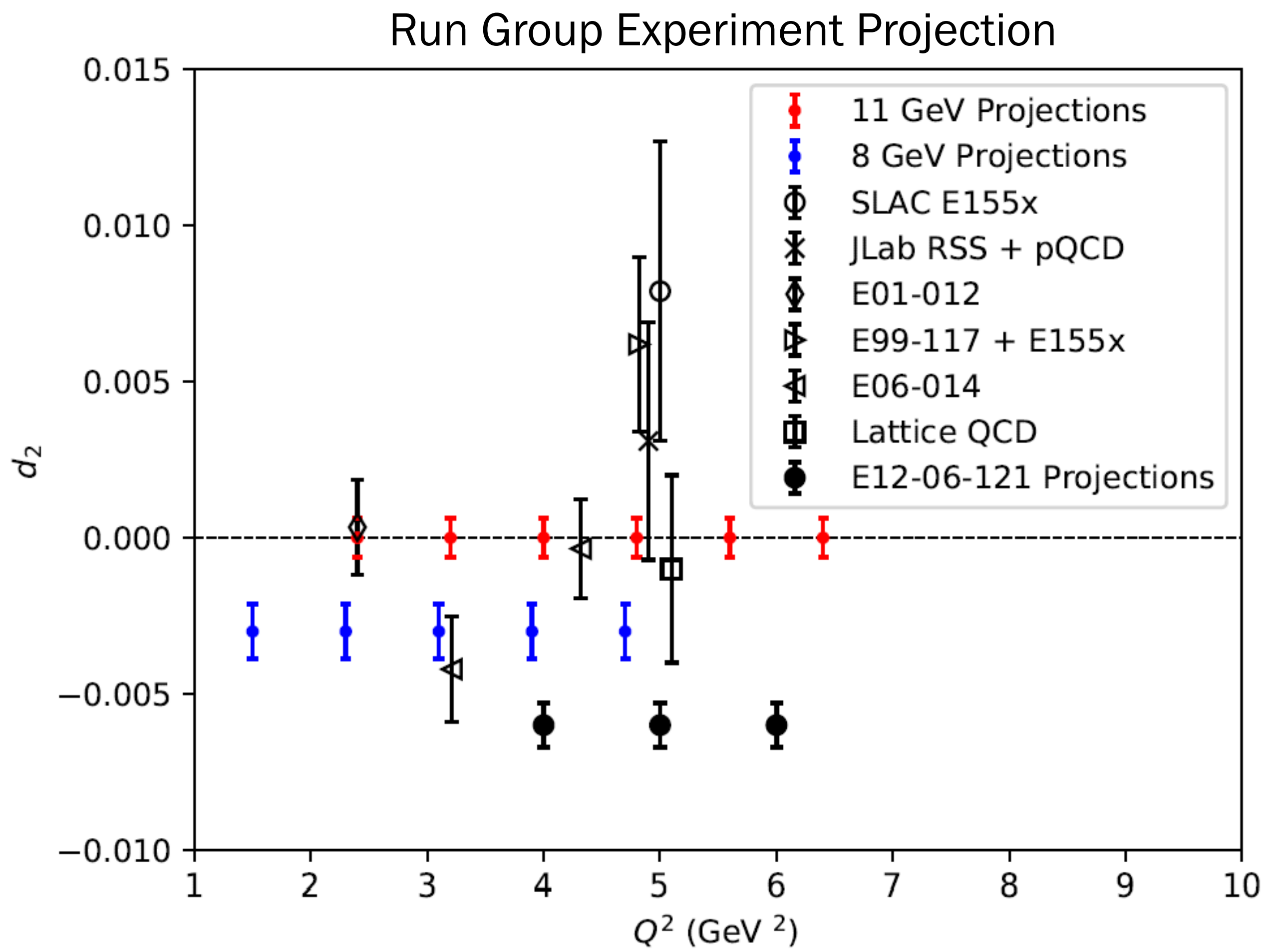
Run Group Proposal: g_2^n/d_2^n measurement

E12-11-007A/E12-10-006E, Approved in 2020. Spokesperson: T. Ye and C. Peng

- A run group proposal with E12-11-007 and E12-10-006
- Measurement of g_2^n with $1.5 < Q^2 < 10$ GeV^2 and $x > 0.1$
- Extraction of x^2 moment of $\bar{g}_2^n$

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

  - $1.5 < Q^2 < 6.5$ GeV^2
  - Access to twist-3 contributions
  - Carry information about quark-gluon correlations



Answers to Jeopardy Charge

Is there any new information that would affect the scientific importance or impact the experiment since it was originally approved?

- First global extraction of worm-gear function g_{1T}, new lattice calculations (worm-gear shift)
- More precise neutron data are needed

If the experiment has already received a portion of its allocated beam? N/A

What is the status of the collaboration in terms of institutes, committed staff, and prospective students?

- Active and developing collaboration with 70+ institutes from 13 countries
- Recent example: successful pre-R&D with committed staff and students

Should the remaining beam time allocation and experiment grade be reconsidered?

- Beam time request remains the same
- Recent theoretical calculation and g_{1T} extraction further strengthen the importance of more precise data from this experiment – It should remain the highest rating.

Summary

- Active and successful development of SoLID
  - Mature pre-conceptual design and successful pre-R&D
  - Positive feedback from DOE science review

- E12-11-007 requires 35 PAC days of 11 GeV and 8.8 GeV beam at 15 uA
  - Precision measurement of SIDIS at the QCD luminosity frontier
  - Same setup with E12-10-006, with a high polarization beam and a longitudinally polarized ^{3}He Target

- Physics impact on TMDs
  - $A_{UL} \rightarrow h_{1L}$
  - $A_{LT} \rightarrow g_{1T}$
  - $A_{LL} \rightarrow g_{1L}$

  } "worm-gear" distribution, $Re[(L=0)_q \times (L=1)_q]$

  - Probe the 3D spin structure of nucleon and investigate OAM-spin correlations
  - Precise neutron data from this experiment is needed to test various theoretical predictions

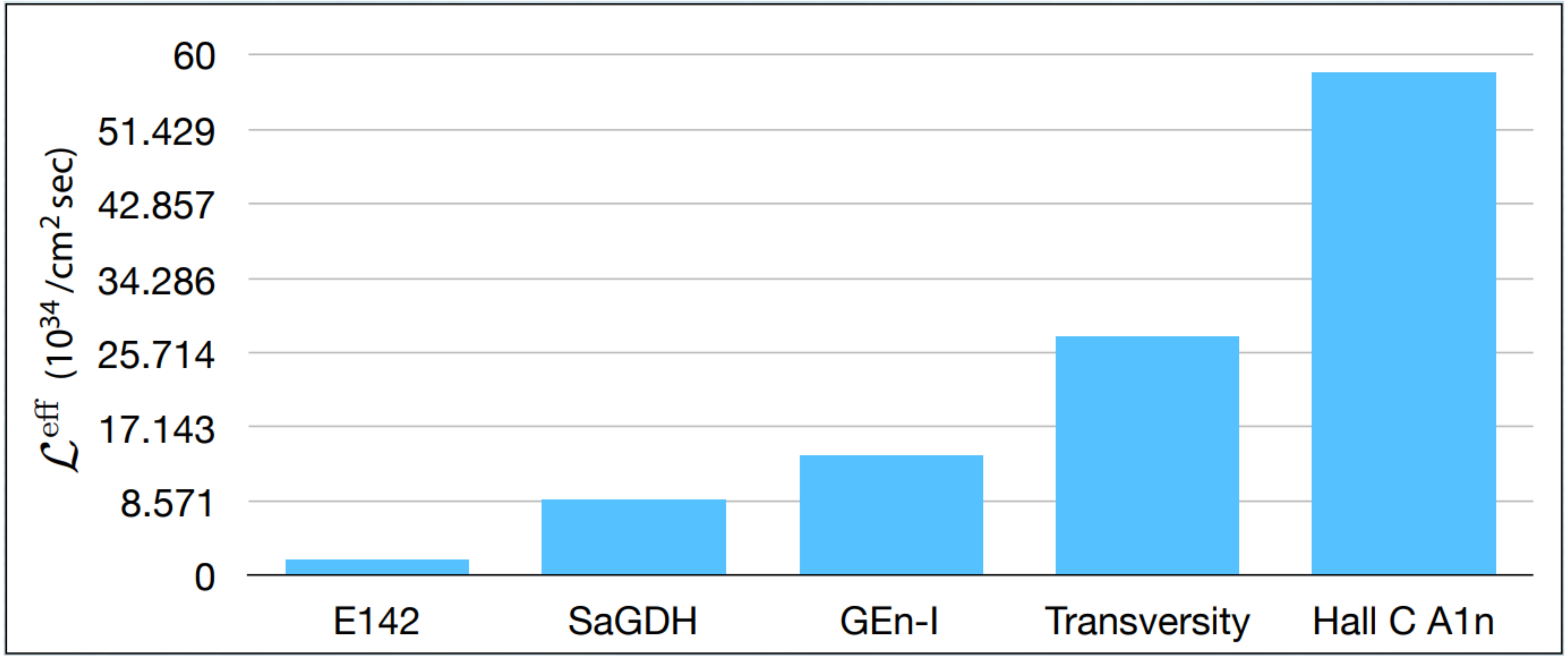
BACKUP

Systematic Uncertainties

Source	Type	$A_{UL}^{\sin 2\phi_h}$	$A_{LT}^{\cos(\phi_h-\phi_S)}$	A_{LL}
Raw Asymmetries	absolute	1×10^{-3}	negligible	negligible
Random Coinc. Background Subtraction	relative	1%	1%	1%
polarimetry	relative	3%	4%	4%
Nuclear Effects	relative	4%	4%	4%
Diffractive Vector Meson	relative	3%	3%	3%
Radiative Corrections	relative	2%	3%	3%
Total	**absolute**	1×10^{-3}	negligible	negligible
	relative	7%	7%	7%
Stat. Uncertainty for a Typical Bin	absolute	5×10^{-3}	4×10^{-3}	4×10^{-3}

Systematic < Statistical uncertainties

Polarized Target Development



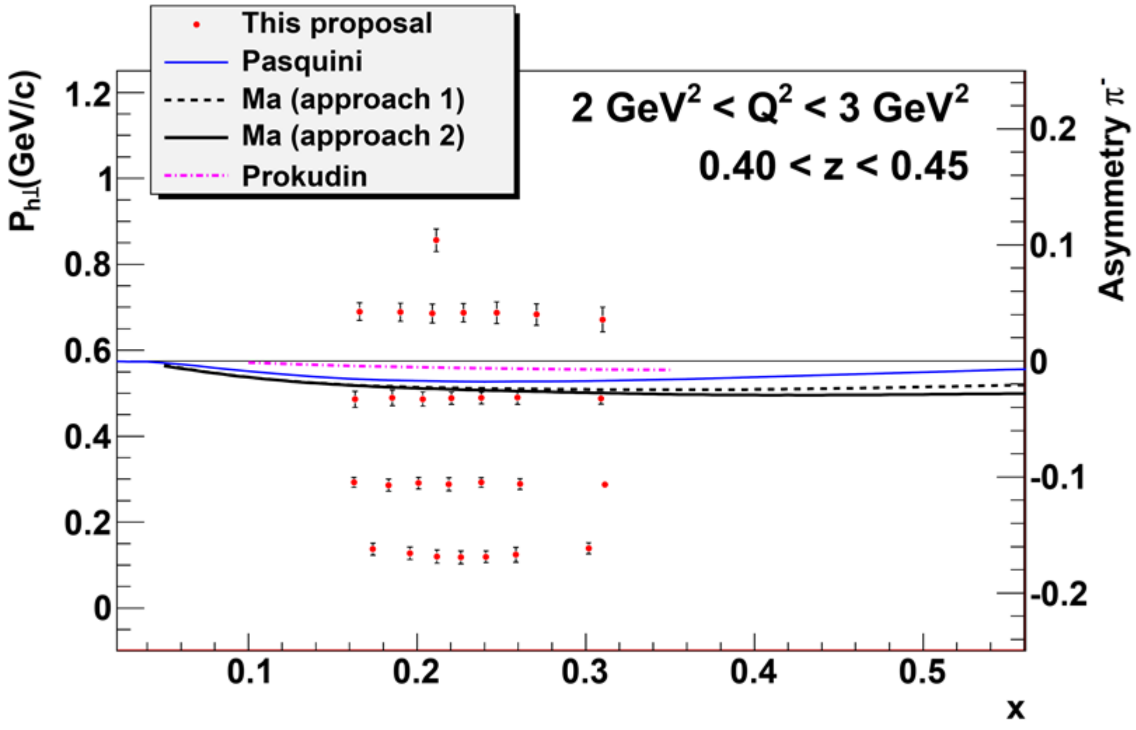
The effective luminosity is defined as $\mathbf{P}^2_{\mathbf{t,pol}} \times \mathbf{L}$ where $\mathbf{P}_{\mathbf{t,pol}}$: target polarization, $\mathbf{L}$: luminosity

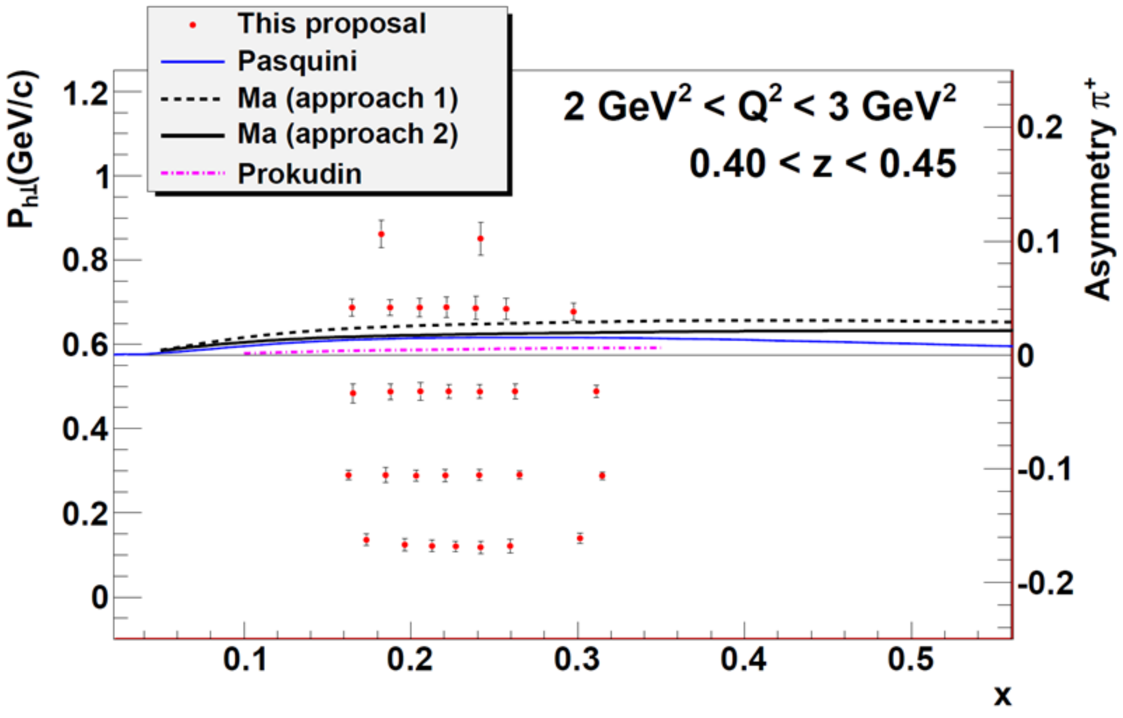
SoLID-SIDIS proposed effective luminosity: $36 \times 10^{34}/(\mathrm{cm}^2\ \mathrm{sec})$

Image credit: G. Cates

Projections: A_{UL}

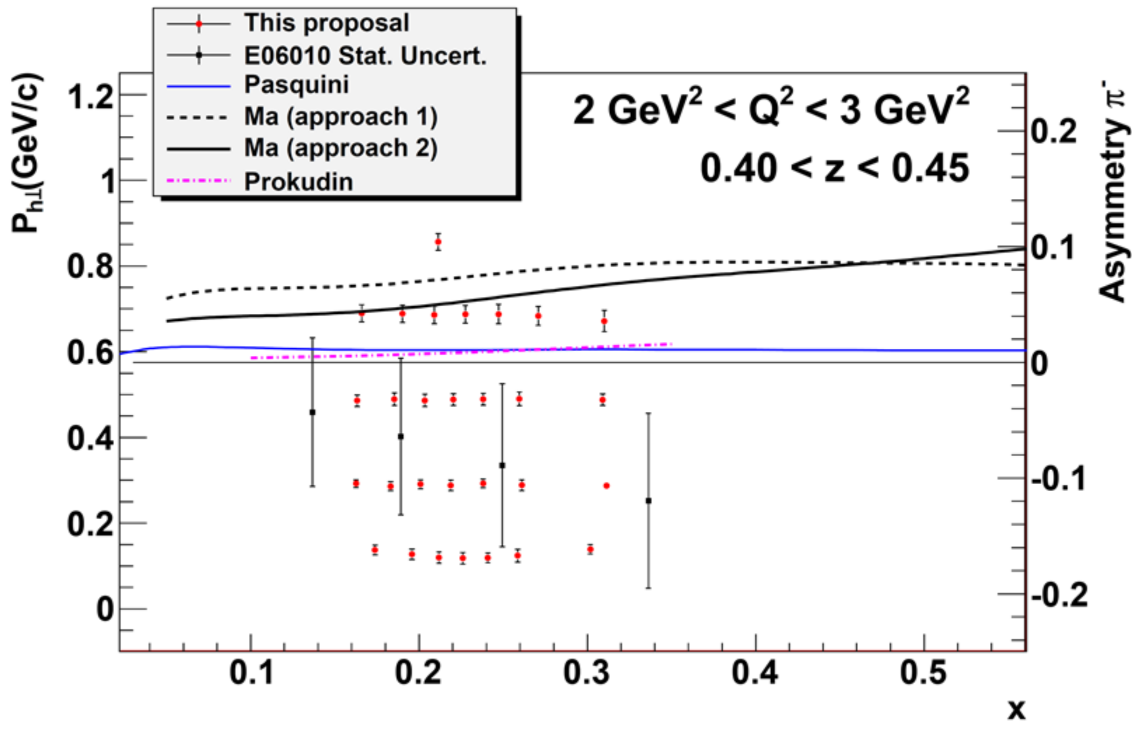
1 of 48 Z-Q^2 bins for the asymmetry of π^- and π^+

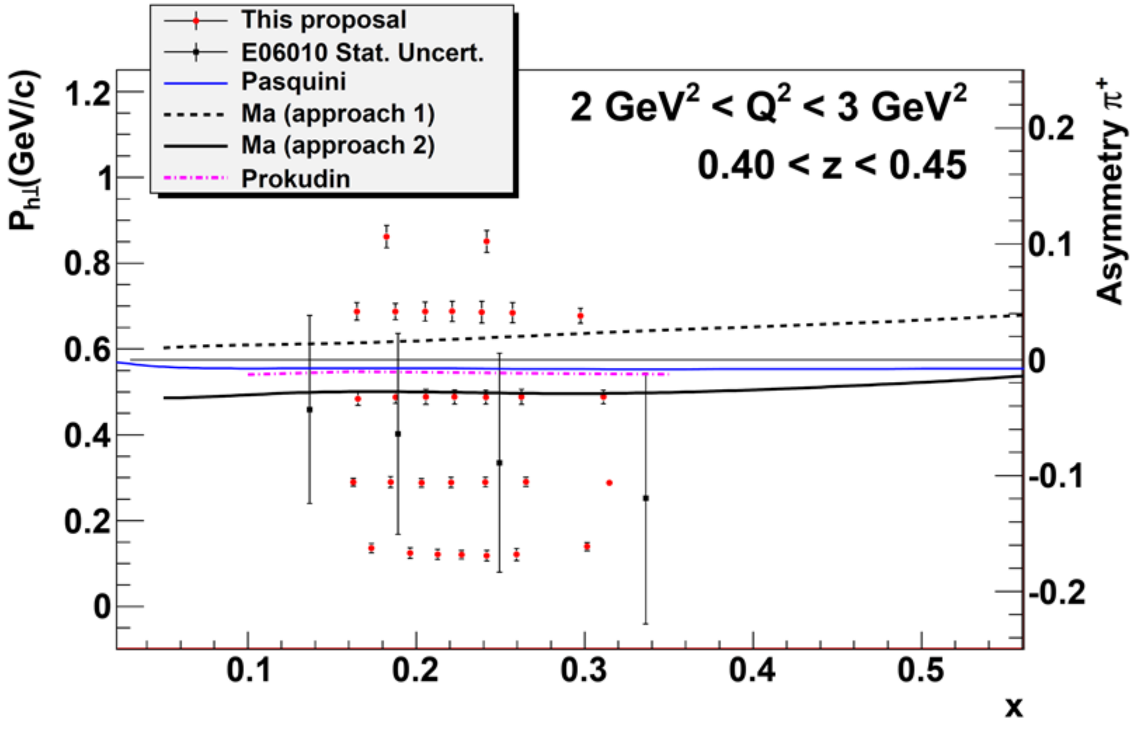




Projections: A_{LT}

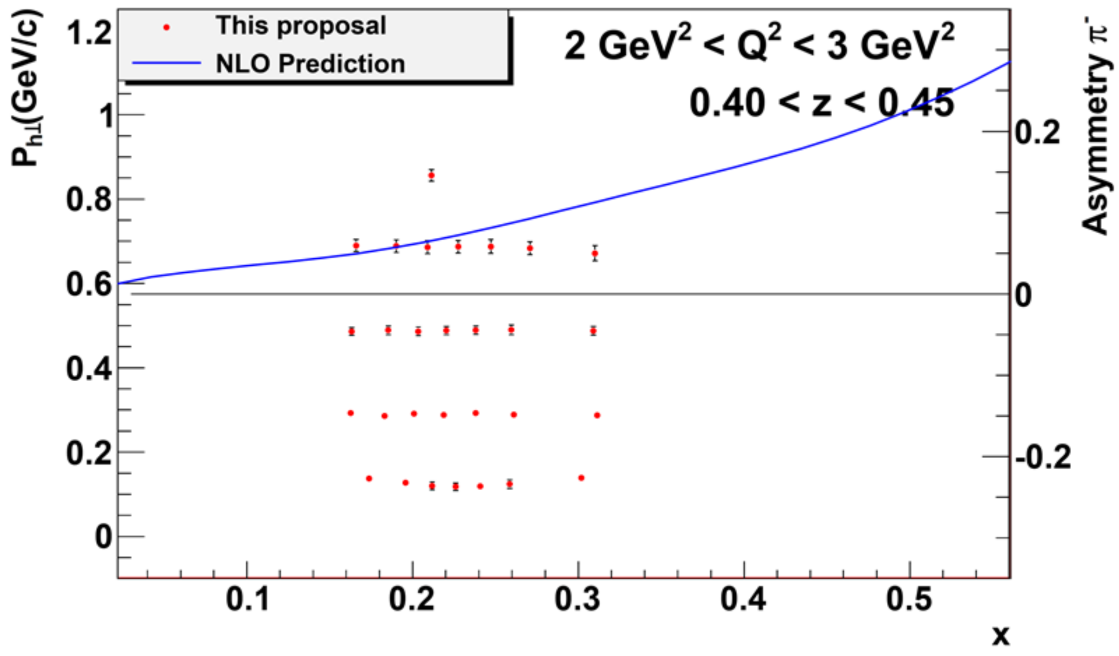
1 of 48 Z-Q^2 bins for the asymmetry of π^- and π^+

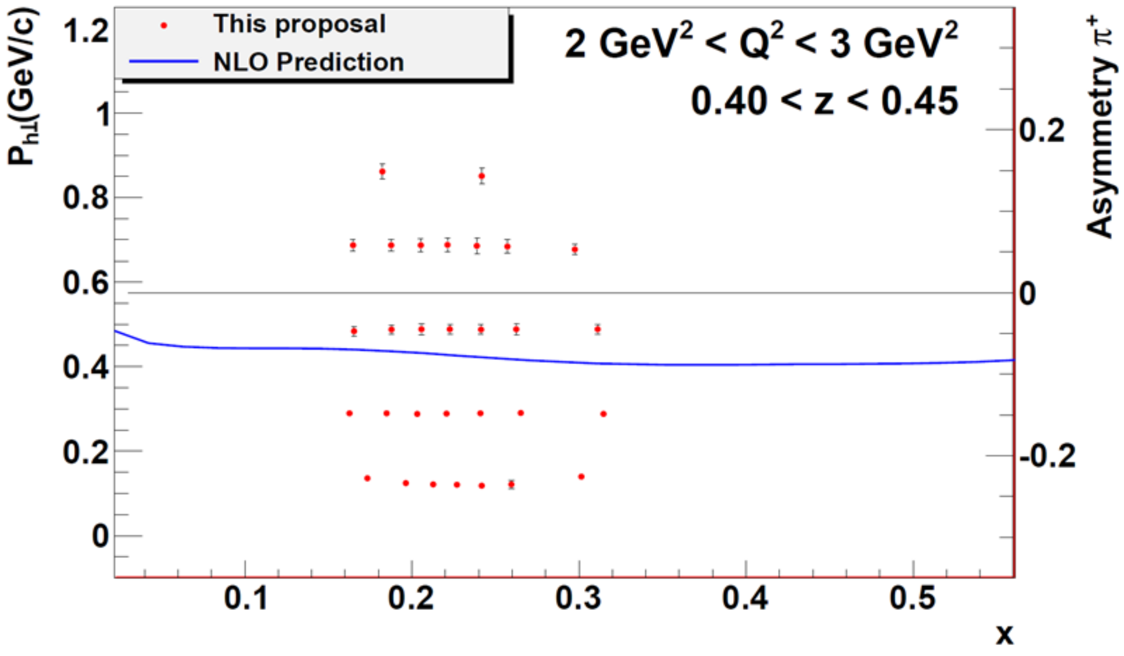




Projections: A_{LL}

1 of 48 Z-Q^2 bins for the asymmetry of π^- and π^+





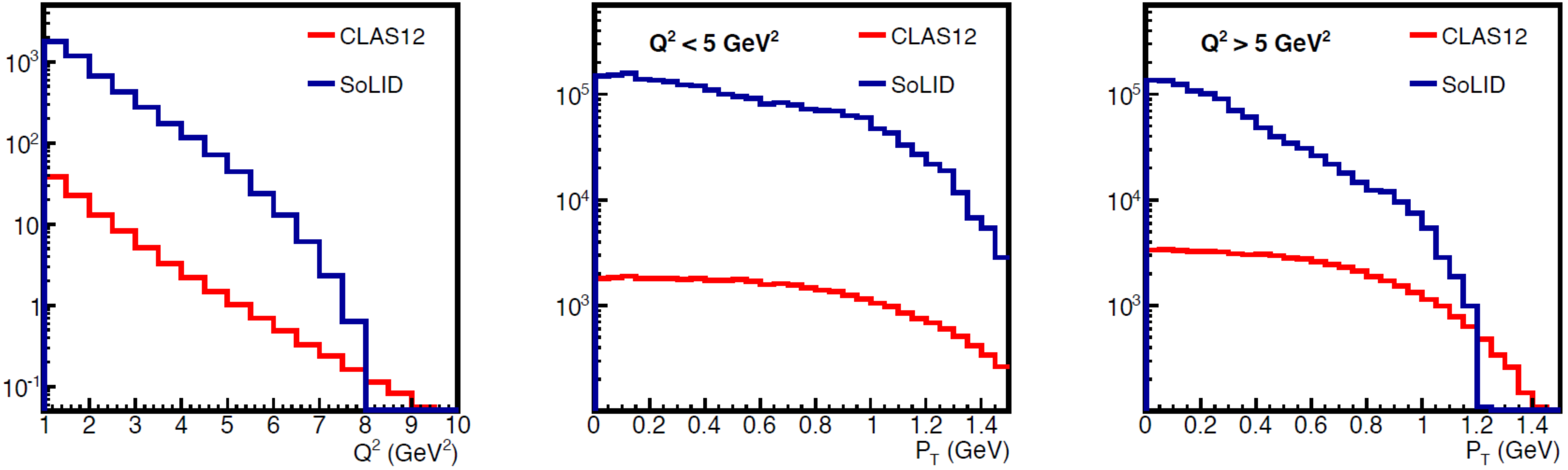
SoLID Collaboration Strength

- Each sub-system has several groups participating in pre-conceptual design and pre-R&D, efforts are ramping up
- These groups have experience with the type of detector.

1. Ecal/SPD: UVa, Shandong, Tsinghua, ANL, UIC, ...
2. LGC: ANL, Temple, NMSU
3. HGC: Duke, Regina, Stony Brook
4. GEM: UVa, GWU/Bates, USTC, CIAE, Lanzhou, Tsinghua, IMP
5. DAQ: JLab, U-Mass, Rutgers
6. Magnet, Infrastructure/supporting structure, project management: JLab, ANL
7. Simulation/Software: Duke, Syracuse, ANL, UVa, Temple, NMSU, JLab,...
8. MRPC (enhanced): Tsinghua, USTC, ...

Possible contributions from Canadian group (HGC)
Chinese groups (MRPC)

SIDIS (charged pions) Rates Comparison between SoLID and CLAS12

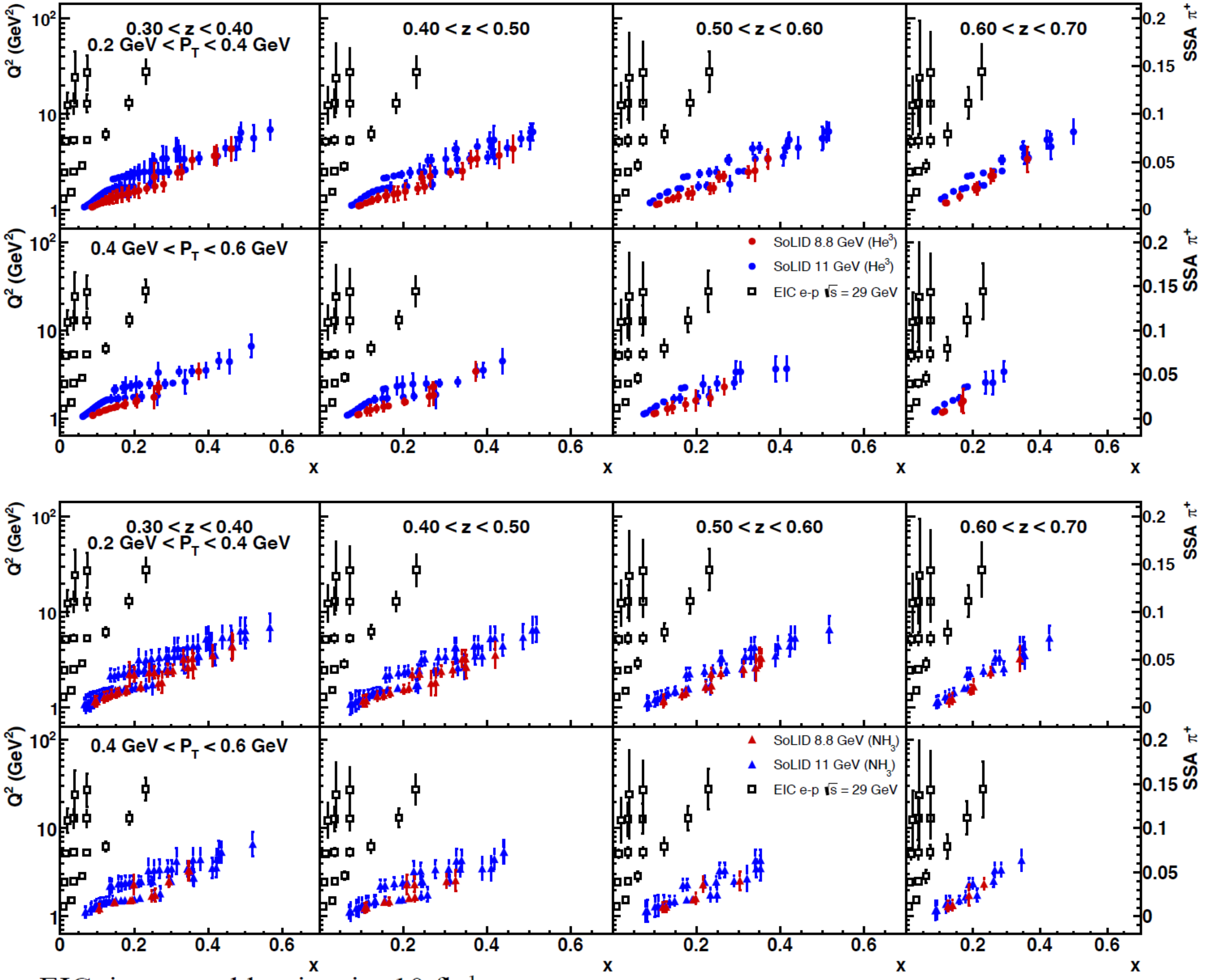


DIS cuts: $Q^2 > 1$ (GeV/c)^2, W > 2.3 GeV, W' > 1.6 GeV applied (longitudinal polarization)

SoLID: pol ^{3}He target 1 * 10^{36} /cm^2/s
acceptance:
1.0 GeV < P_e < 7.0 GeV, $8^0 < \theta_e < 24^0$,
2.5 GeV < P_π < 7.5 GeV, $8^0 < \theta_\pi < 15^0$, $\phi = 2\pi$

CLAS12: pol ^{3}He target 0.9 * 10^{34} /cm^2/s
acceptance:
0.5 GeV < P_e < 7.0 GeV, $5^0 < \theta_e < 125^0$,
0.5 GeV< P_π < 7.5 GeV, $5^0 < \theta_\pi < 125^0$, $\phi = \pi$

Complementary to EIC



EIC: integrated luminosity 10 fb^{-1}