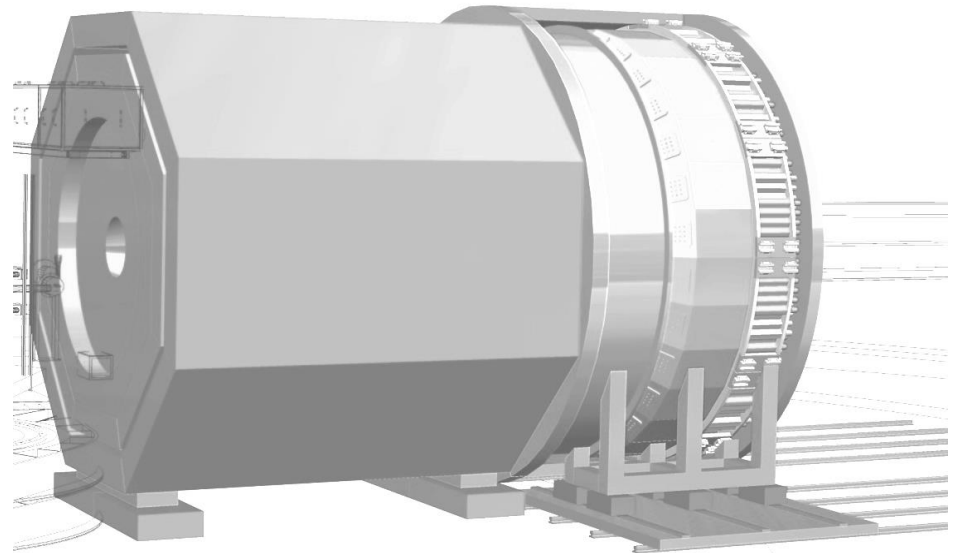


Overview on SoLID SIDIS and SoLID-Lite SIDIS

Workshop on the Physics Program with High Luminosity Facilities
October 5-9, 2026; Jefferson Lab

Vladimir Khachatryan
Mississippi State University



Acknowledgements: Jian-Ping Chen, Haiyan Gao, Zein-Eddine Meziani, Paul Souder, Xiaochao Zheng, Zhiwen Zhao, Sylvester Joosten, Ye Tian, Henry Klest, Garth Huber, Bill Li, Michael Nycz, Eric Fuchey, and the rest of the SoLID Collaboration

<https://solid.jlab.org/>

1. Introduction
2. Original SoLID-SIDIS (or SoLID-Full SIDIS) Physics Program
 - Transverse-Momentum-Dependent Parton Distributions (TMDs)
 - Single-spin Asymmetries (SSAs)
3. SoLID-Lite SIDIS Ideas and Recent Developments
 - Options for Lite SIDIS
 - TMD fits' comparisons including World Data
4. Summary and Current Status

Introduction

SoLID has been proposed to *maximize* science gain of 12-GeV CEBAF upgrade by **combining...**

High Luminosity
 $10^{36-39} / \text{cm}^2/\text{s}$
[>100x CLAS12] [>1000x EIC]

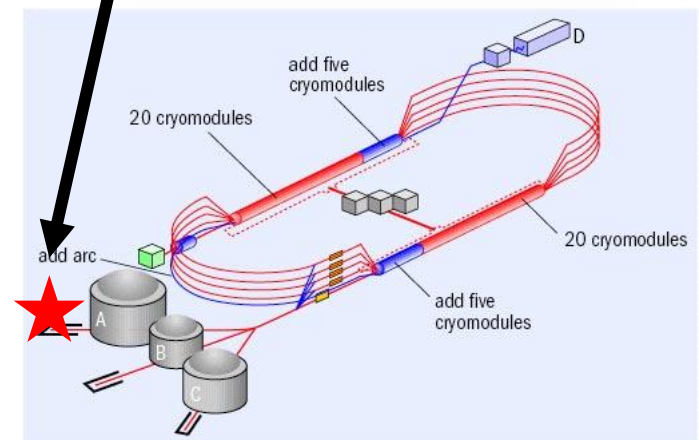
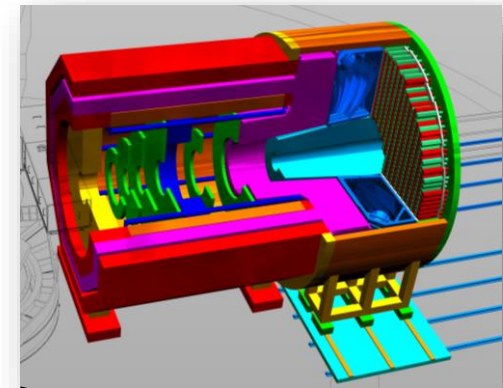


Large Acceptance
Full azimuthal ϕ coverage

SoLID with *unique* capability to **explore** QCD landscape while **complementing** the research at other key facilities

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

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

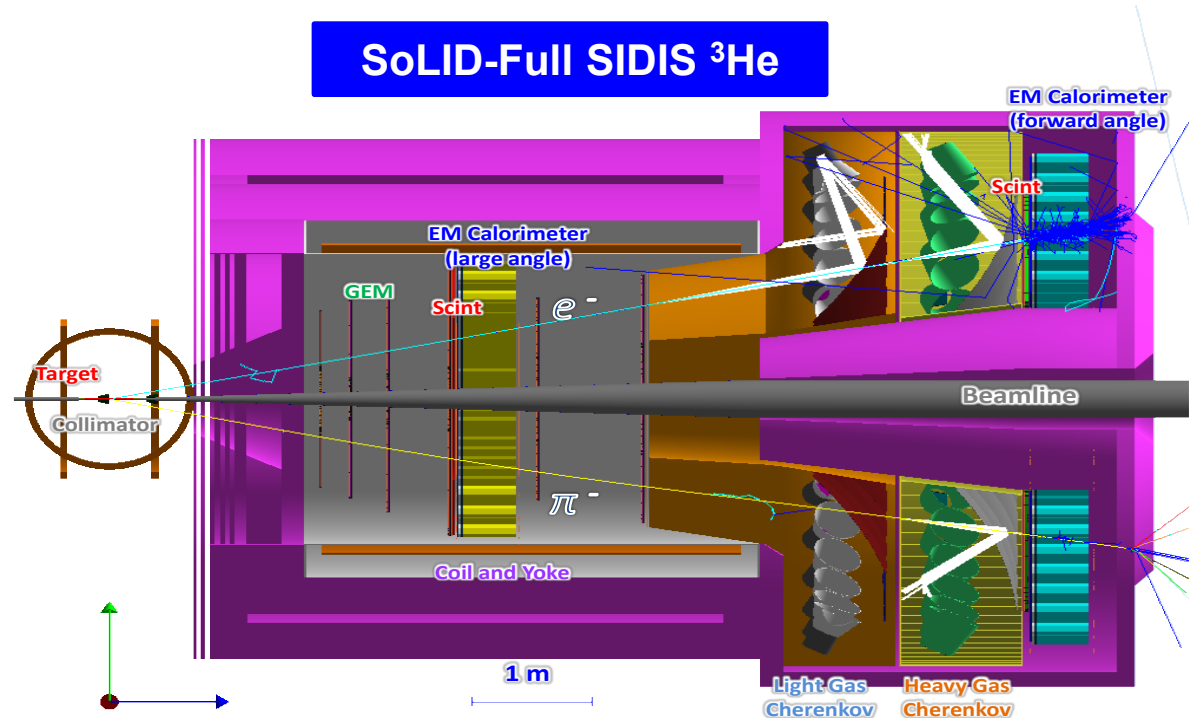


SoLID-Full SIDIS Physics Program

SIDIS: $e + p \rightarrow e' + \pi^{\pm} + X$

^3He target proposed to study neutrons

NH_3 (ammonium) target proposed to study protons



- A) SIDIS: (3) Transversely Polarized ^3He (n): Transversity, Sivers, Pretzelosity TMDs
Rating A Longitudinally Polarized ^3He (n): Worm-gear TMDs
Transversely Polarized NH_3 (p): Transversity, Sivers, Pretzelosity TMDs

B) Run group experiments: (8) approved for TMDs, GPDs, and Spin

SoLID-Full SIDIS: 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	$h_{1L}^\perp =$  - 
	T	$f_{1T}^\perp =$  -  Sivers	$g_{1T}^\perp =$  - 	$h_{1T} =$  -  Transversity $h_{1T}^\perp =$  -  Pretzelosity

Leading twist refers to leading power in cross-section expansion

SoLID-Full SIDIS: TMDs – confined motion inside the nucleon

Transversity

Transversely Polarized Nucleon TMDs

→ Nucleon Spin
→ Quark Spin

$$h_{1T} = \text{Diagram} \quad \text{---} \quad \text{Diagram} \quad \text{---} \quad \text{Diagram}$$

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

Relevant Vectors

$\mathbf{S}_T$: Nucleon Spin
 $\mathbf{s}_q$: Quark Spin
 $\mathbf{k}_\perp$: Quark Transverse Momentum
 $\mathbf{P}$: Virtual photon 3-momentum (defines z-direction)

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

Sivers

$$f_{1T}^\perp = \text{Diagram} \quad \text{---} \quad \text{Diagram} \quad \text{---} \quad \text{Diagram}$$

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

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

Pretzelosity

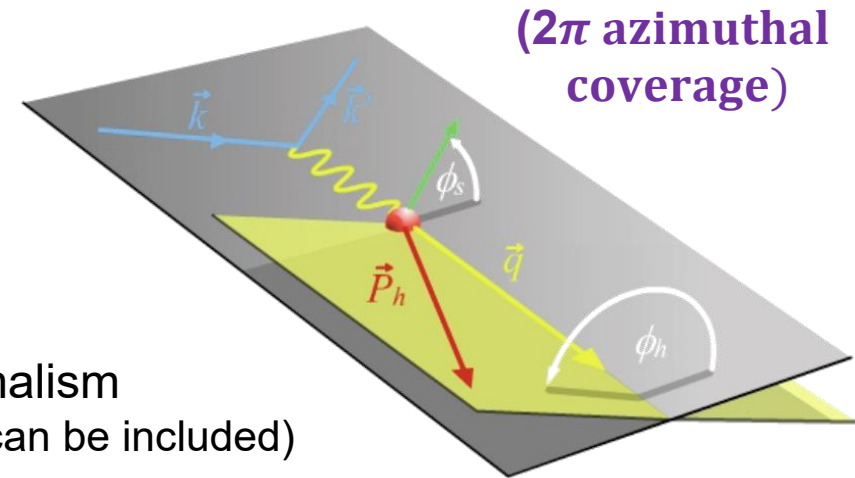
$$h_{1T}^\perp = \text{Diagram} \quad \text{---} \quad \text{Diagram} \quad \text{---} \quad \text{Diagram}$$

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

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

SoLID-Full SIDIS: SSAs – separation of the spin asymmetries

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



$$A_{UT}(\phi_h, \phi_S) = \frac{1}{P_{t,pol}} \frac{N^\uparrow - N^\downarrow}{N^\uparrow + N^\downarrow} \quad \text{Leading twist formalism (higher-twist terms can be included)}$$

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

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

Collins fragmentation function from e^+e^- collisions

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

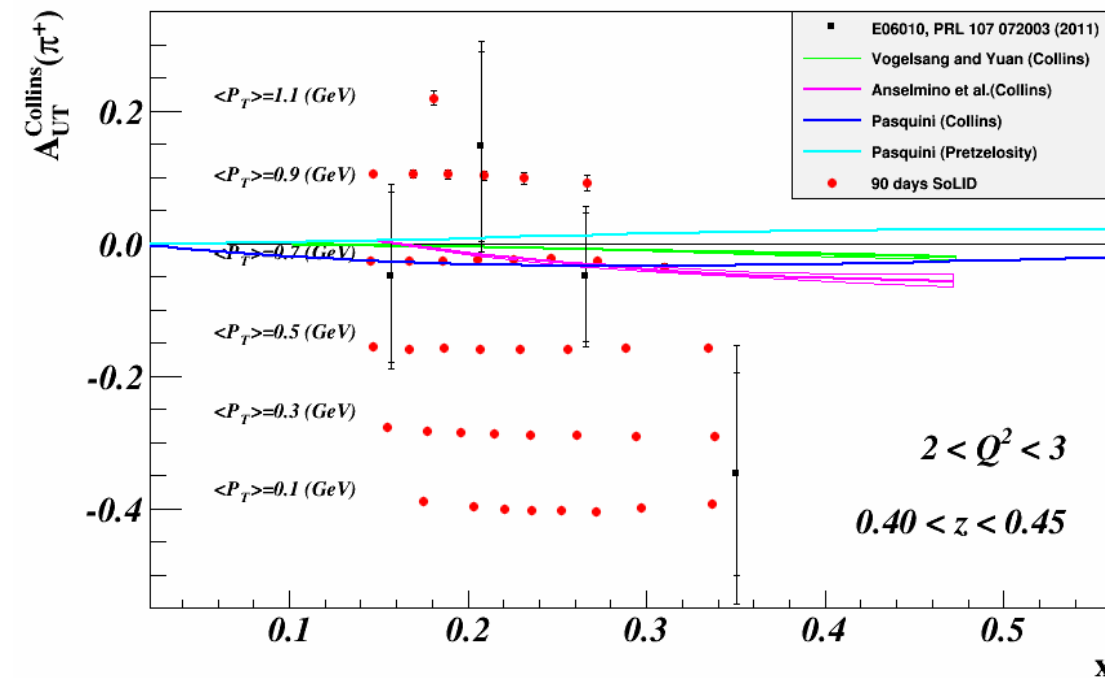
$$A_{UT}^{Sivers} \propto \langle \sin(\phi_h - \phi_S) \rangle_{UT} \propto f_{1T}^\perp \otimes D_1$$

Unpolarized fragmentation function

SoLID-Full SIDIS: SSAs – precision mapping in 4D

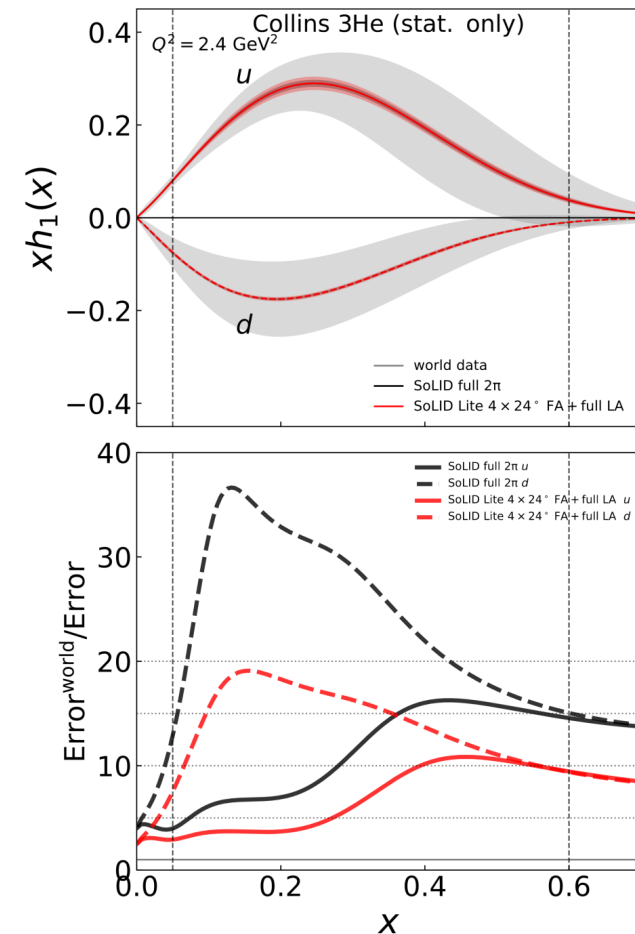
SIDIS program: Large acceptance, Full azimuthal coverage + High luminosity

- 4D mapping of asymmetries with precision
- Constrain models and forms of TMDs, Tensor charge, ...
- Lattice QCD, QCD dynamics



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

Transversity

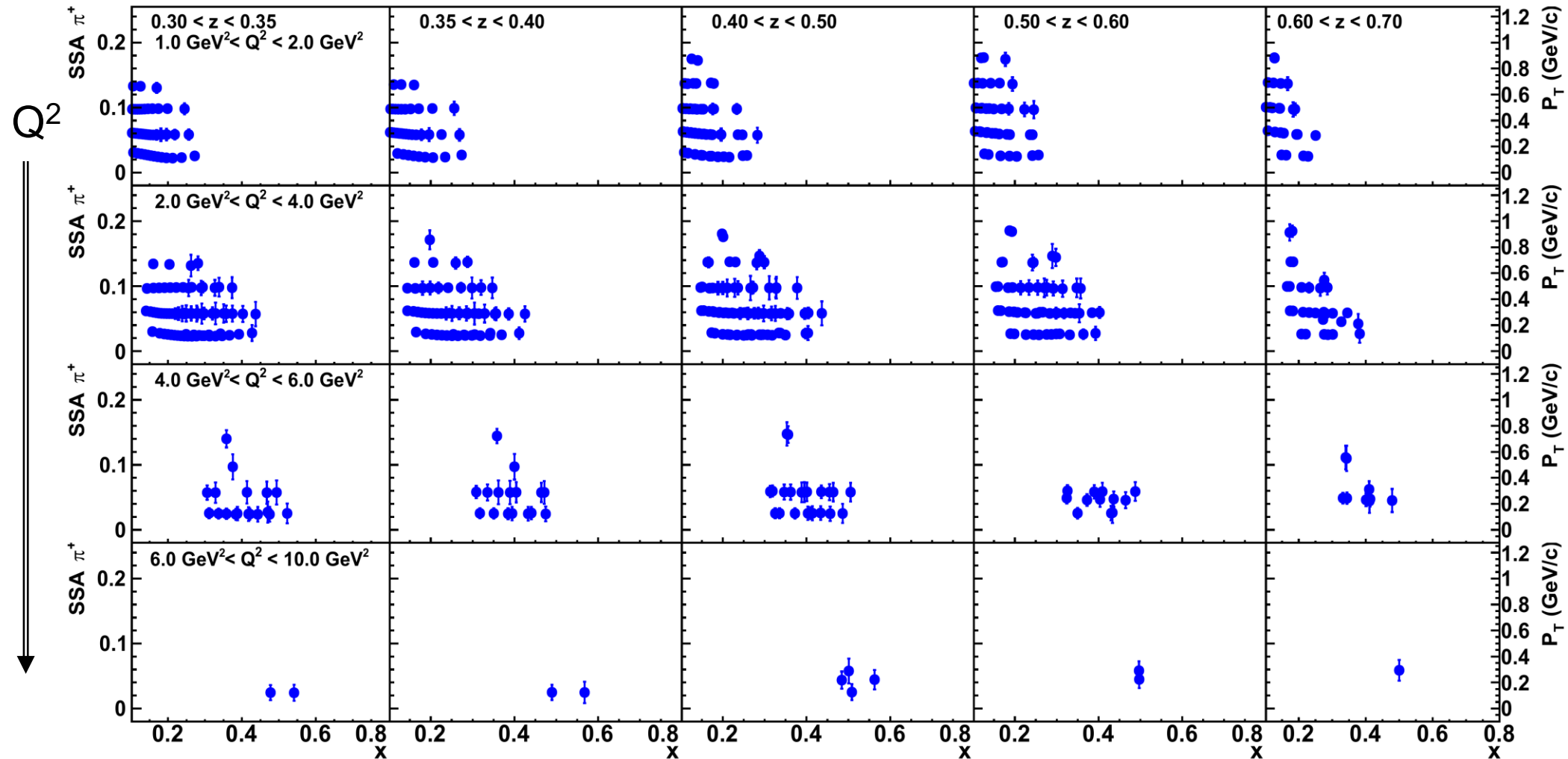


SoLID-Full SIDIS: SSAs – precision mapping in 4D

- Collins SSA uncertainties in 4D binning for π^+ , within all the phase-space coverage

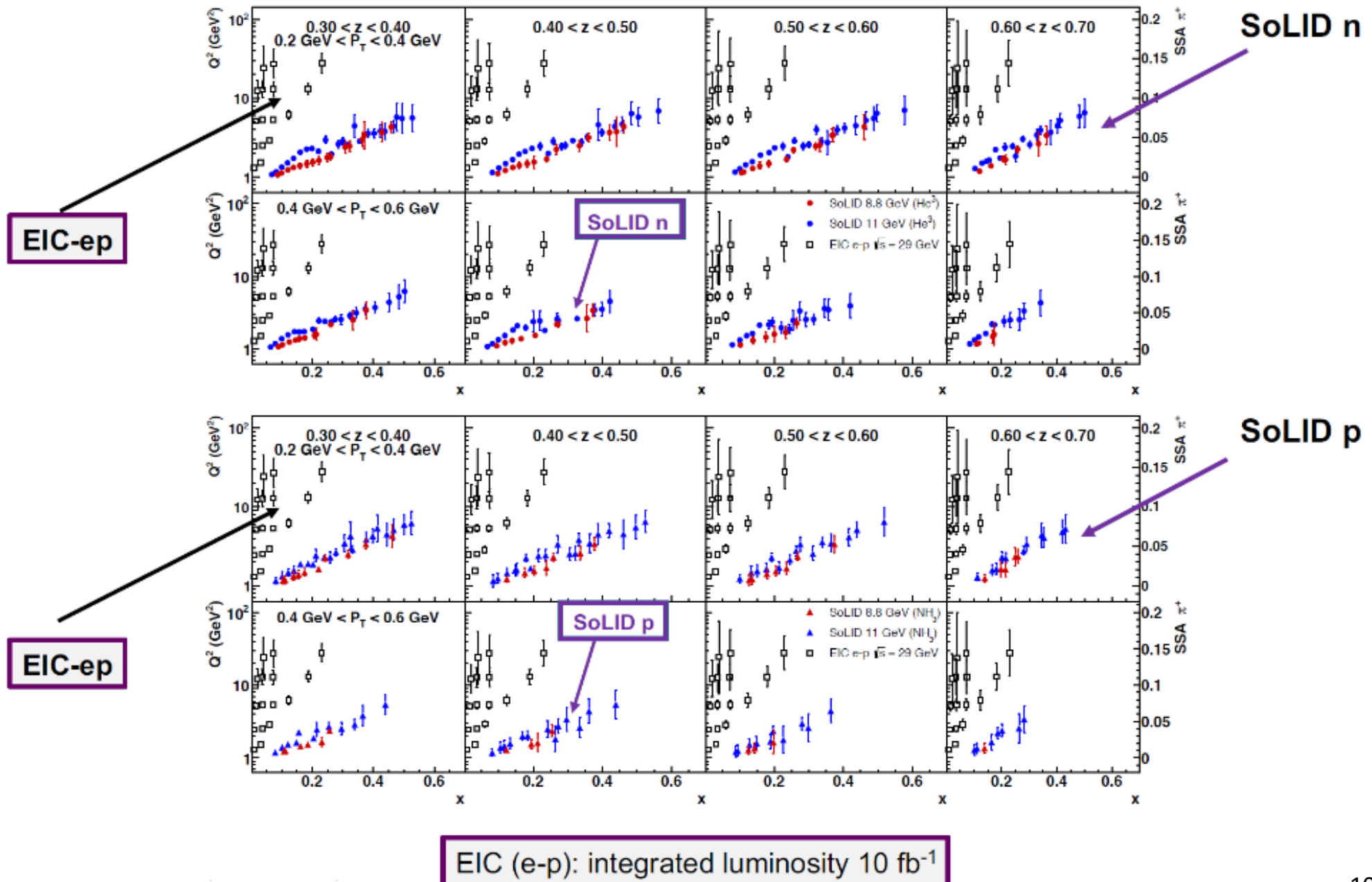
$z \longrightarrow$

^3He : • 11 GeV and 8.8 GeV



SoLID-Full SIDIS: SSAs – precision mapping in 4D

- EIC/SoLID: precision and complementary kinematic reach, e.g, for Collins SSA



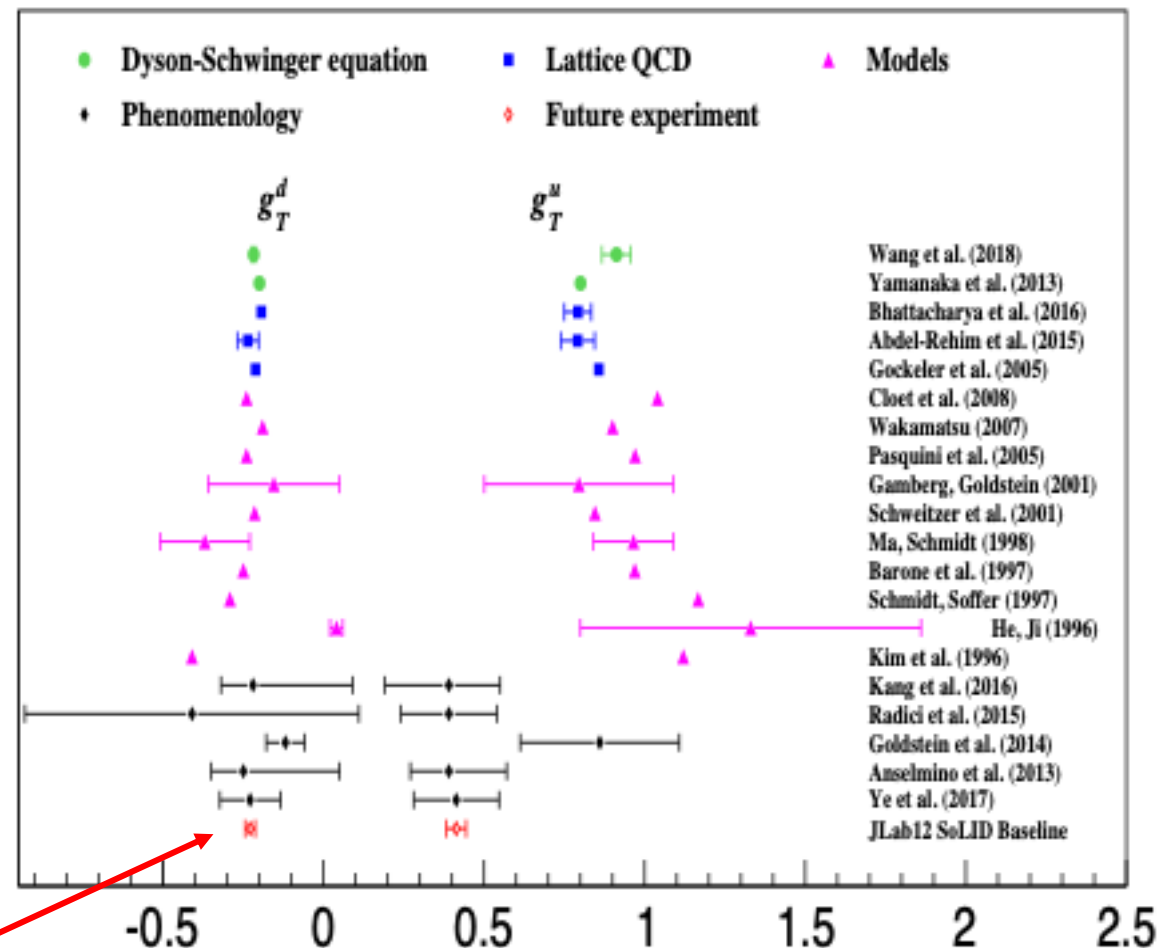
SoLID-Full SIDIS: SSAs – impact on tensor charge

Definition:

$$\langle P, S | \bar{\psi}_q i\sigma^{\mu\nu} \psi_q | P, S \rangle = g_T^q \bar{u}(P, S) i\sigma^{\mu\nu} u(P, S) \quad g_T^q = \int_0^1 [h_1^q(x) - h_1^{\bar{q}}(x)] dx$$

- A fundamental QCD quantity: matrix element of local operators
- Moment of transversity distribution
- Valence quark dominant
- Precision calculations available from lattice QCD
- Probe new physics combined with EDMs

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



SoLID-Full SIDIS Projection

Moving to SoLID-Lite SIDIS Physics Program

- **Original SoLID-Full:** Rich and vibrant science program to push intensity frontier limit for Cold QCD

Three pillars on 3D (TMDs/GPDs), PVDIS and J/ψ production

- Given current budget situation, DOE not likely to start new costly projects during next several years

→ SoLID as proposed will not happen in the foreseeable future

→ SoLID will adopt multi-stage approach

→ First stage: with minimal setup to run its J/ψ program

→ Other stages including SIDIS to come later

See Zein-Eddine
Meziani's slides!

- Now start with SoLID-Lite setup
- Three physics programs can still be included in SoLID-Lite within that staged approach

SoLID-Lite SIDIS Ideas and Recent Developments

- **SoLID-Full**

- operational with forward angle (FA) and large angle (LA) detectors

- **SoLID-Lite option (for ^3He)**

- Need 180° detector azimuthal symmetry to minimize systematic uncertainty

- Use 4 segments of 24° sectors in both FA and LA with $4\times$ luminosity

- Estimated to give one-third to one-fifth of full counts but with similar coverage

- **SoLID-Lite option (for NH_3)**

- No need of 180° detector symmetry because target transverse field breaks it

- 100 nA beam-current limit is target-operating constraint

- More study of possible reuse of ^3He setup

SoLID-Lite SIDIS: options with ^3He

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

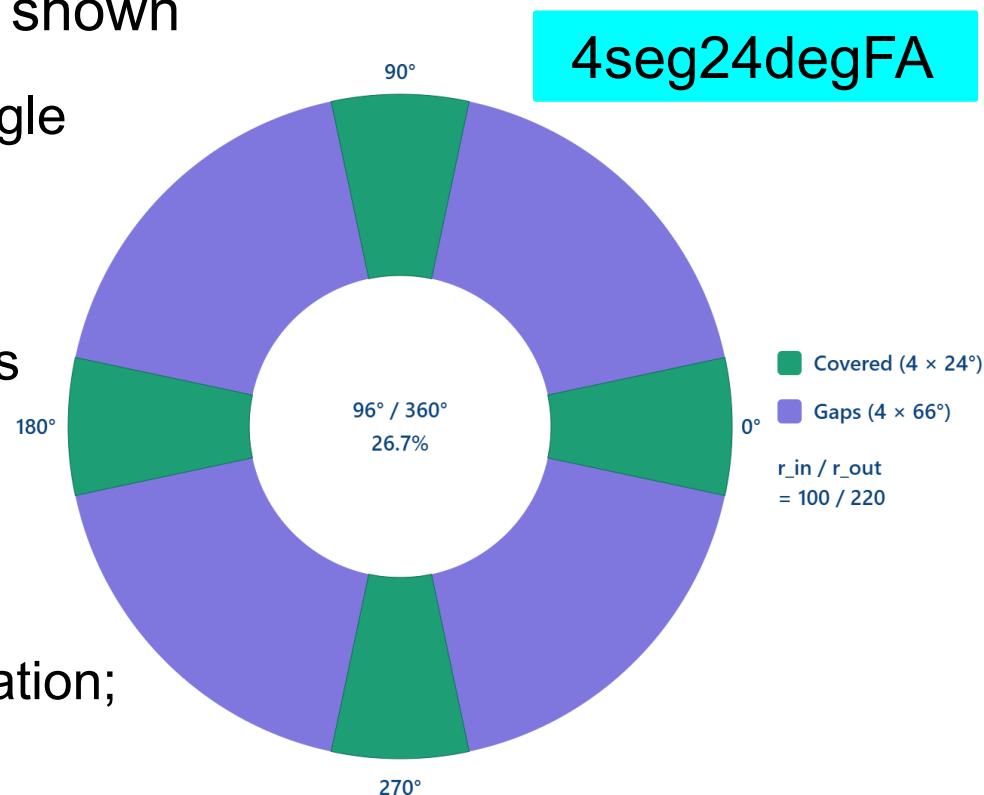
- FA to be critical to have hadron detection
- Specific ^3He 4seg24degFA configuration shown

→ 4 segments of 24° sectors in azimuthal angle for FA at $\phi = 0, 90^\circ, 180^\circ, 270^\circ$

→ 24° sectors being around beam, each containing two adjacent Cherenkov sectors with calorimeter modules behind them

→ π^+ and π^- have different acceptance in ϕ angle due to solenoid field; for now use equal acceptance as simplification; more realistic simulation needed later

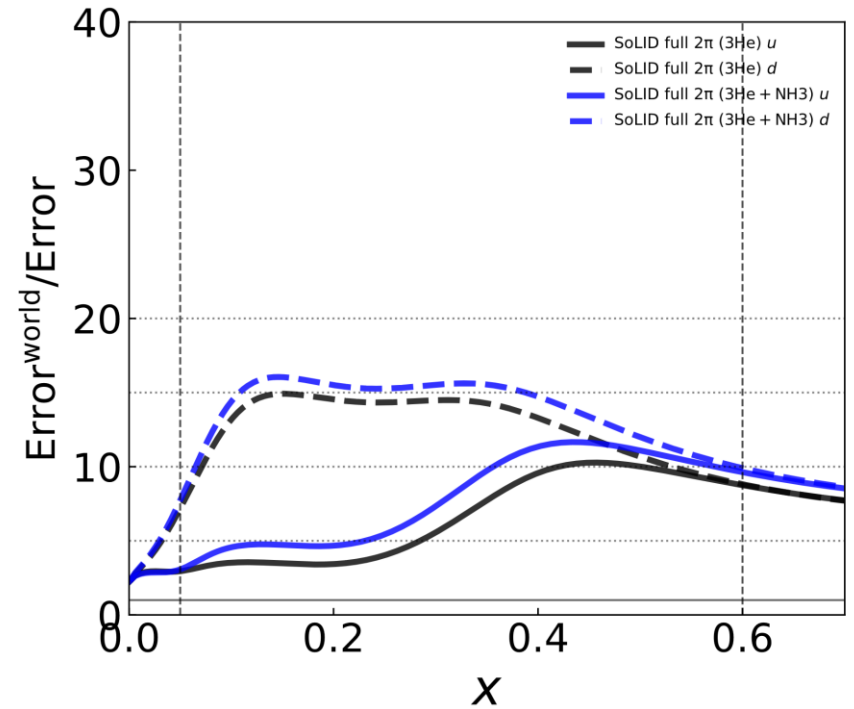
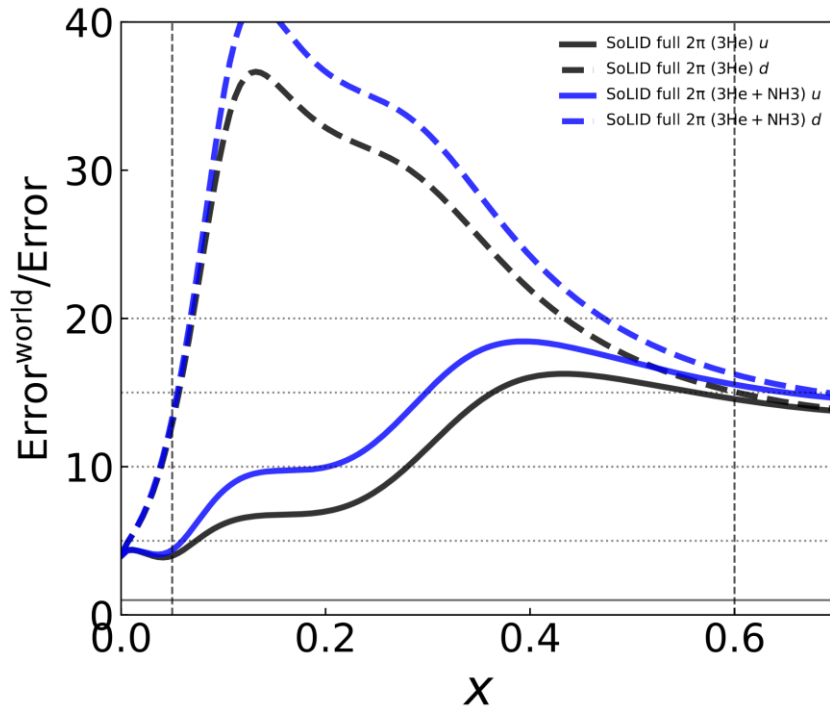
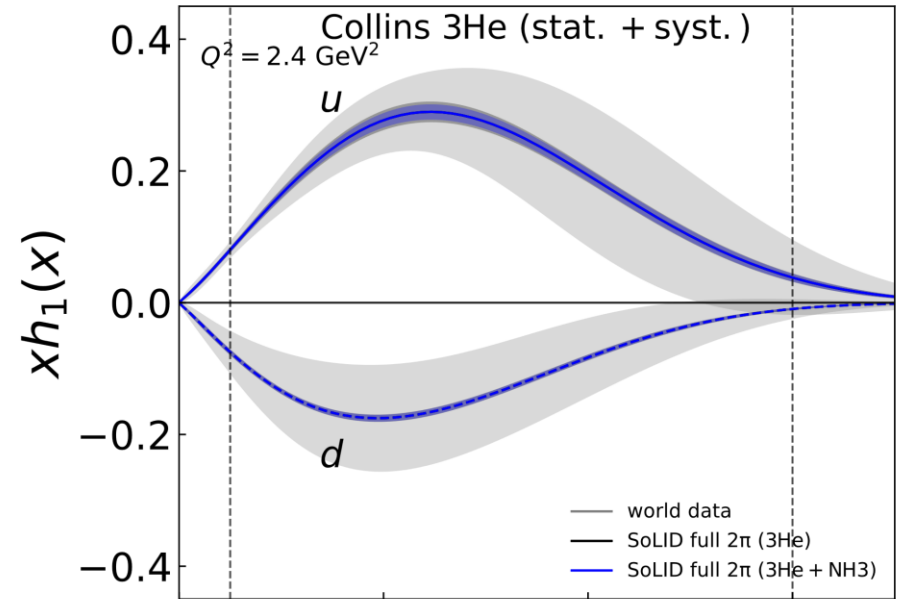
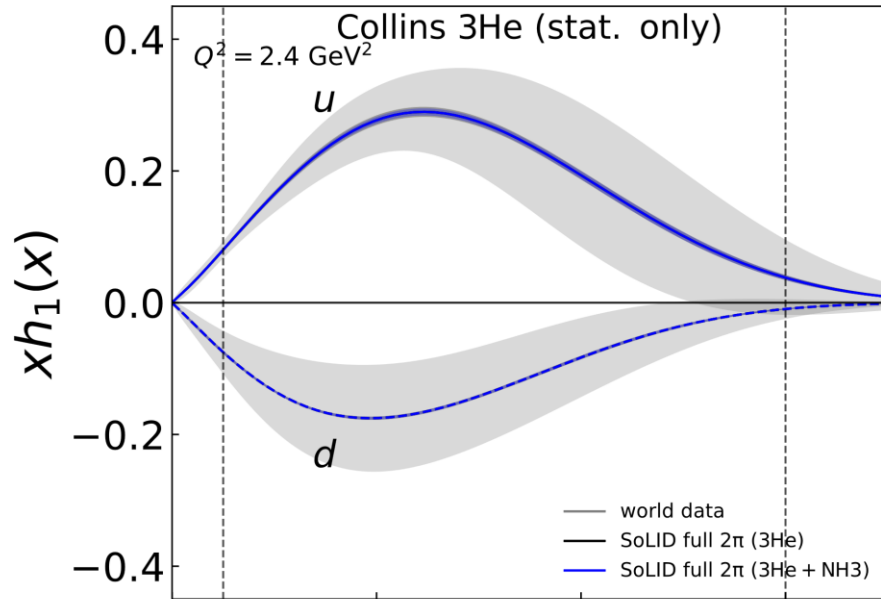
→ LA can also remain same as in SoLID-Full



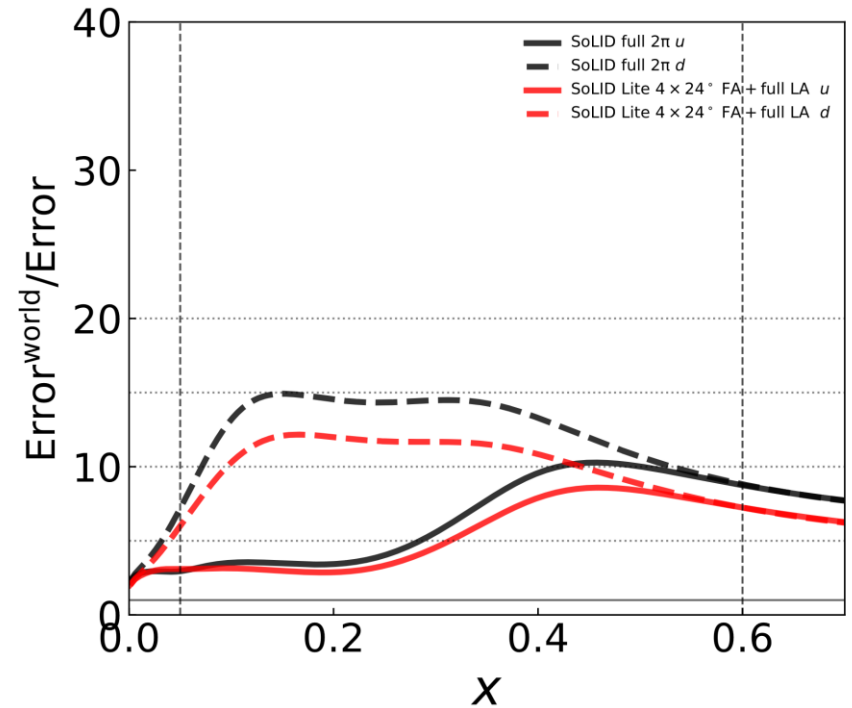
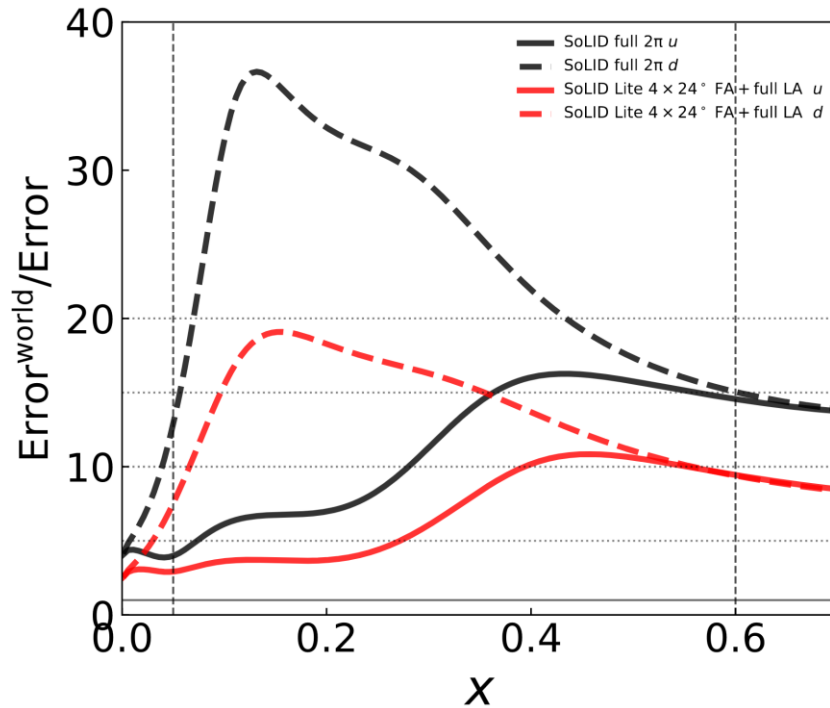
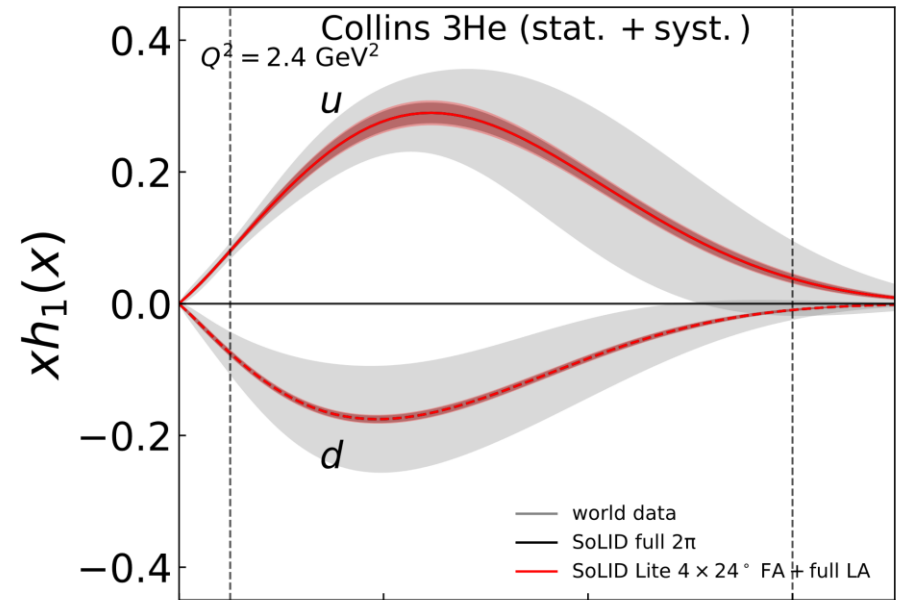
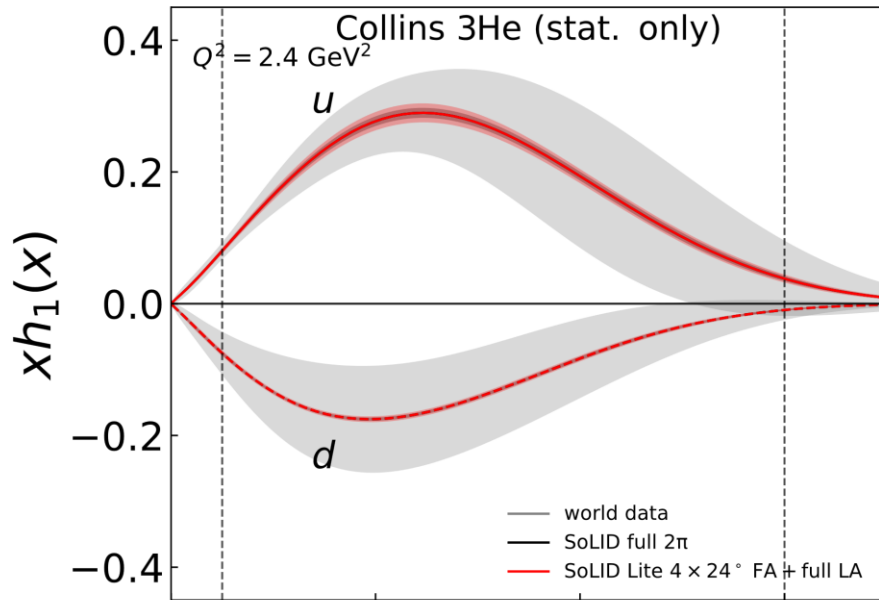
SoLID-Lite SIDIS: options with ^3He

- Various TMD comparisons shown in next several slides
- Increasing beam current and target length for SoLID-Lite to match SBS; it will have $4\times$ luminosity comparing to polarized SoLID-Full $10^{36}/\text{cm}^2/\text{s}$
- Comparing World, ^3He Full as well as ^3He Full + NH_3 Full TMD fitting uncertainties with same bins, including stat and syst uncertainties
- Comparing World, ^3He Full and ^3He Lite TMD fitting uncertainties with same bins, including stat and syst uncertainties
- Different binning giving similar results

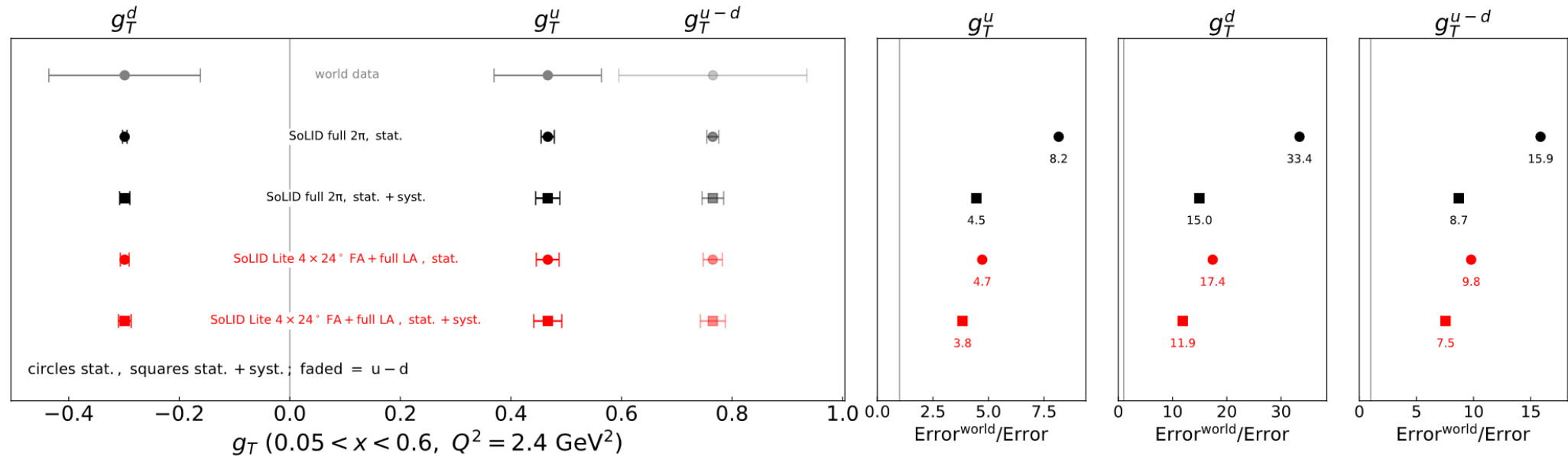
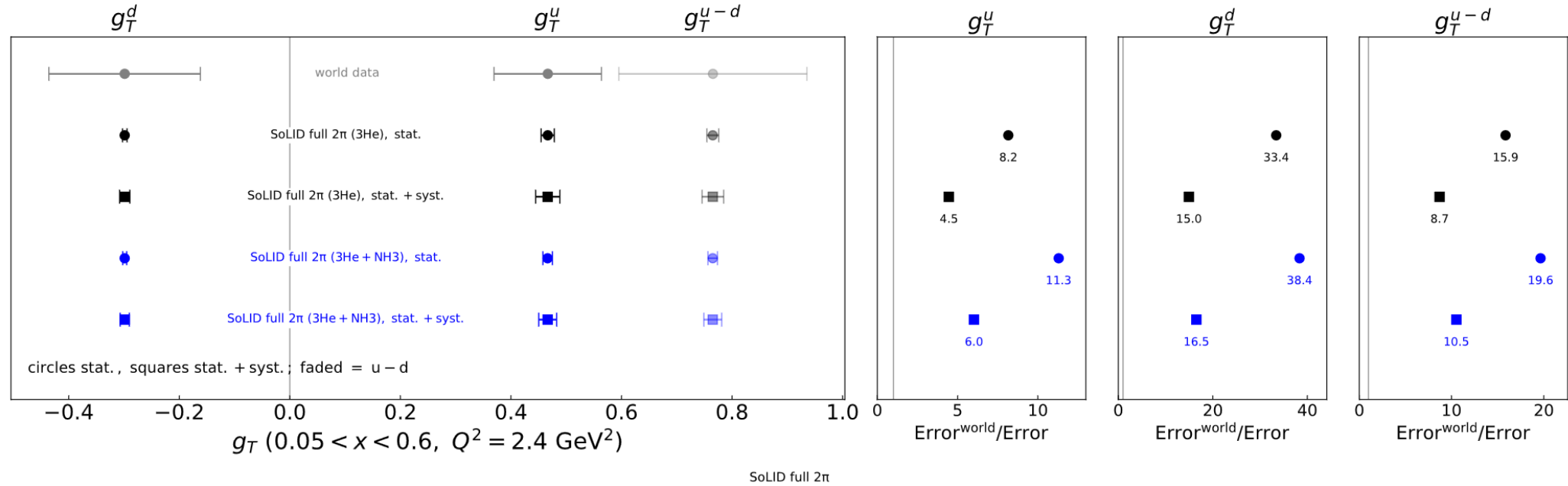
SIDIS-Lite Transversity: World, SoLID-Full ^3He , SoLID-Full $^3\text{He} + \text{NH}_3$



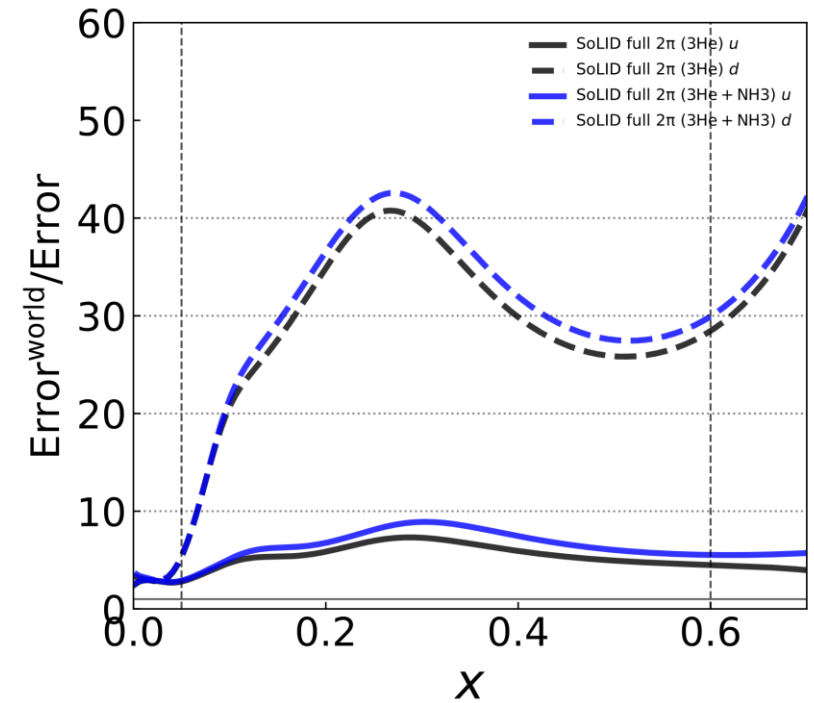
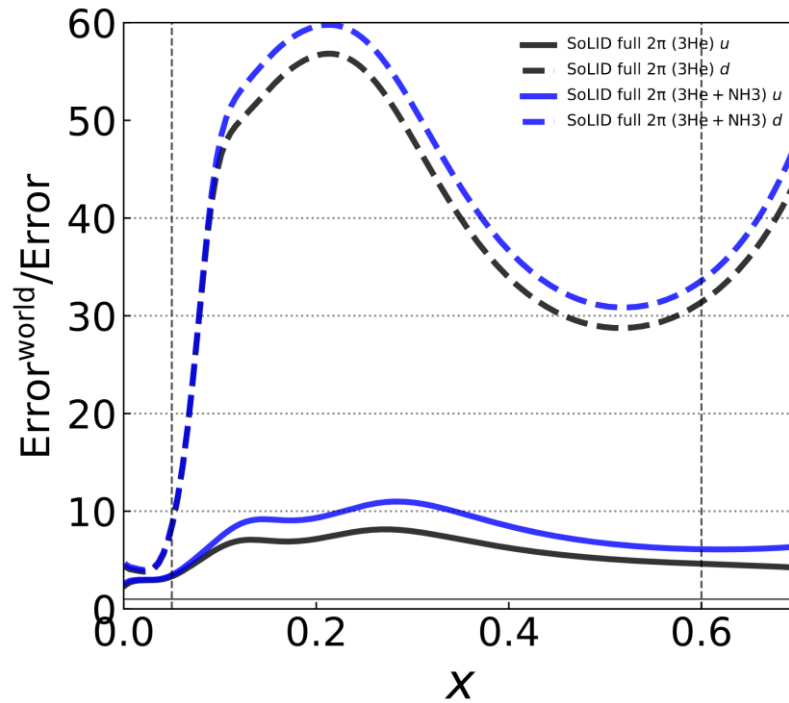
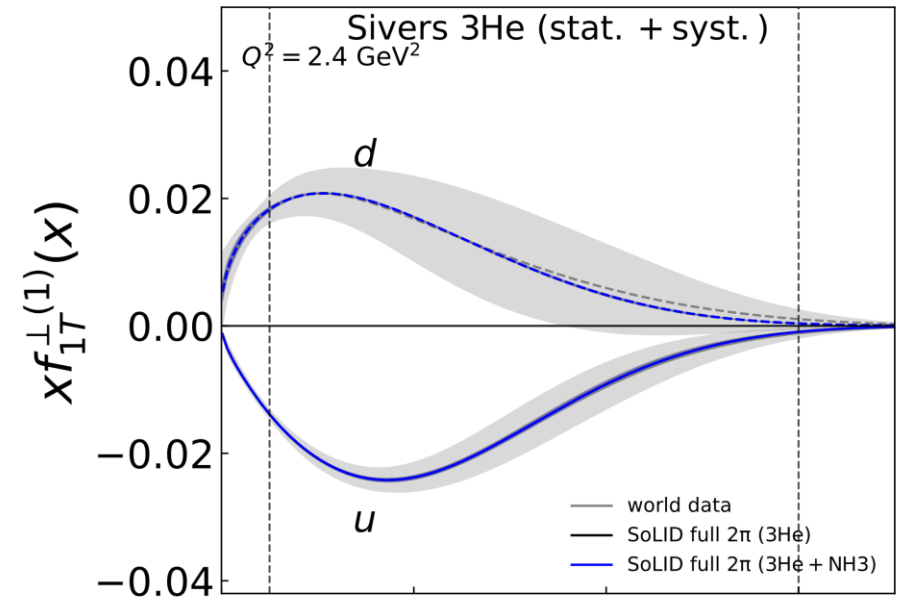
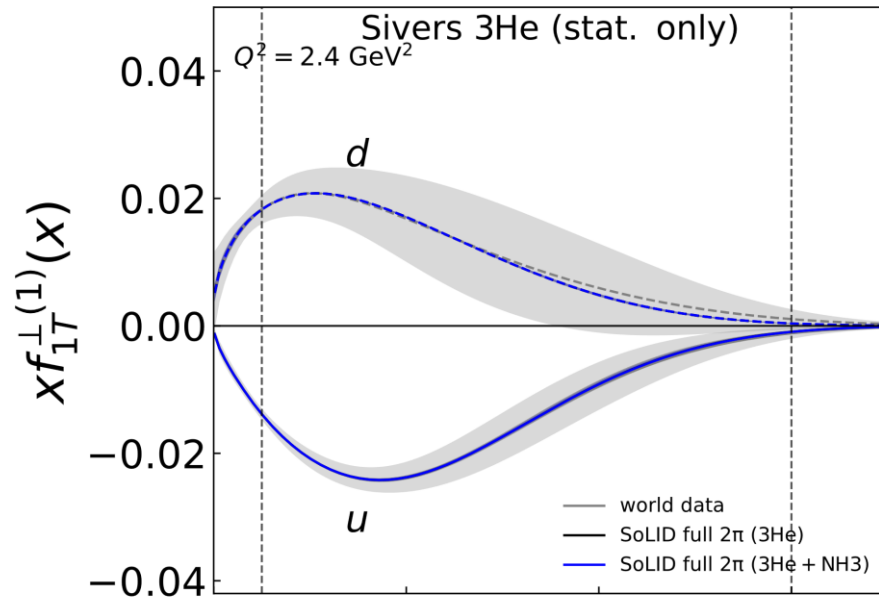
SIDIS-Lite Transversity: World, SoLID-Full ^3He , SoLID-Lite ^3He



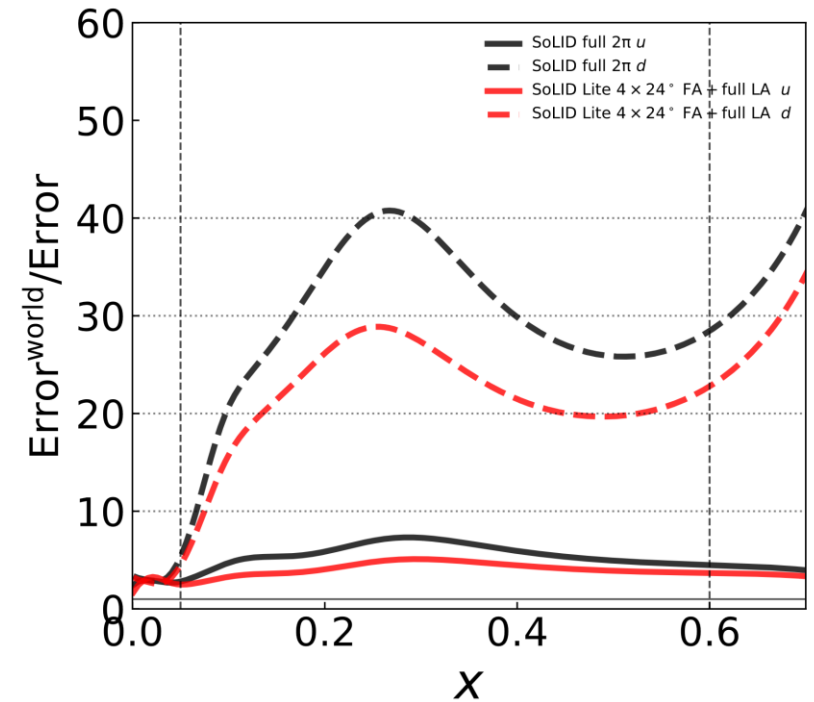
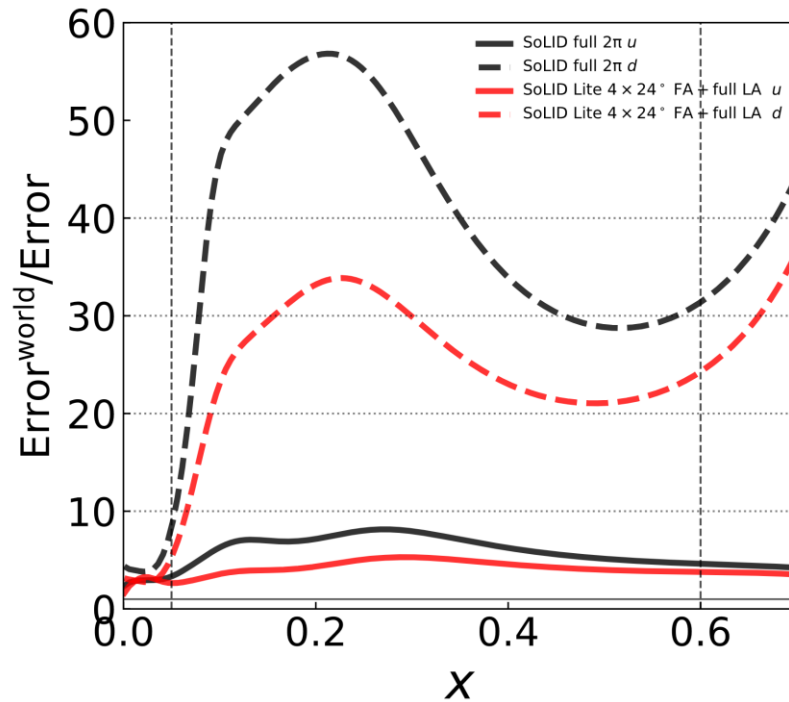
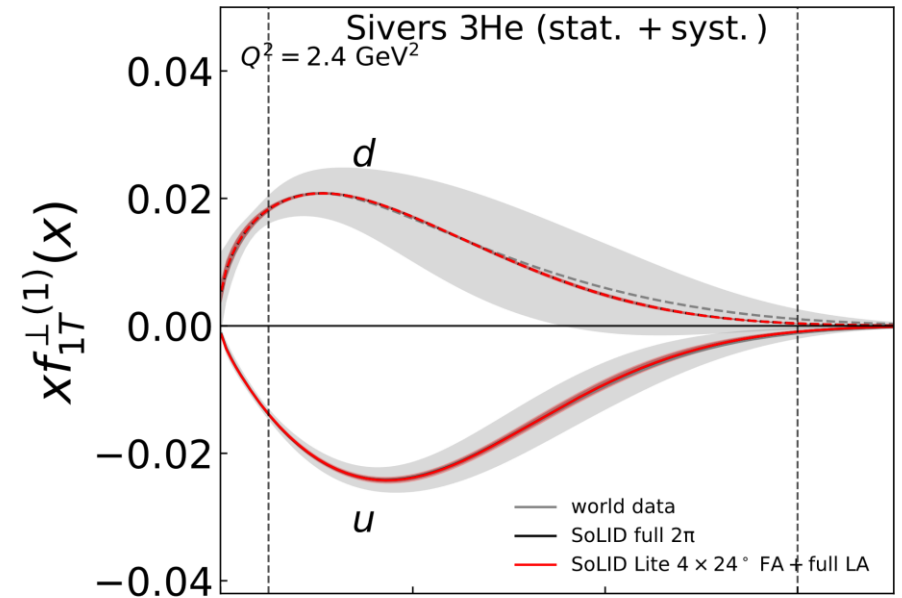
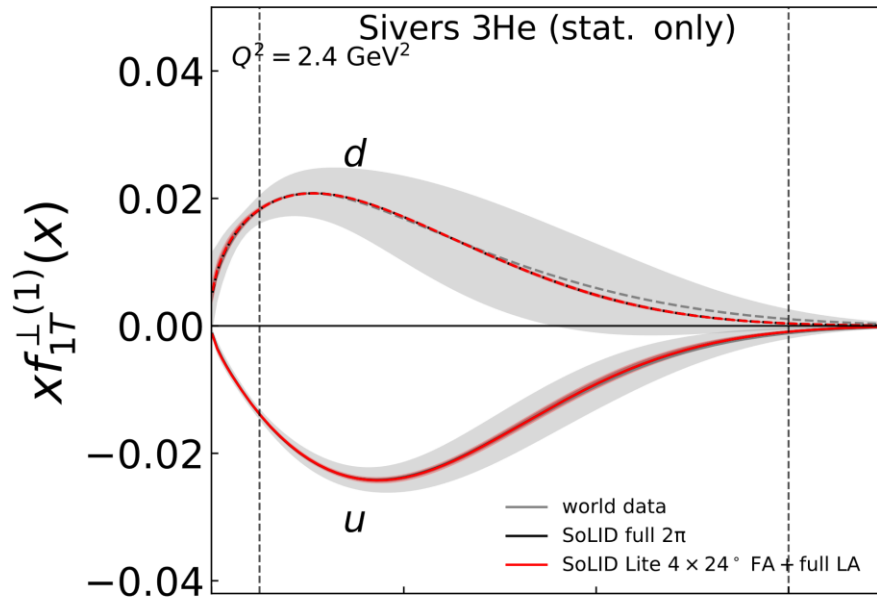
Tensor Charge: World, SoLID-Full ^3He , SoLID-Lite ^3He , SoLID-Full $^3\text{He} + \text{NH}_3$



SIDIS-Lite Sivers: World, SoLID-Full ^3He , SoLID-Full $^3\text{He} + \text{NH}_3$



SIDIS-Lite Sivers: World, SoLID-Full ^3He , SoLID-Lite ^3He



SoLID-Full SIDIS:

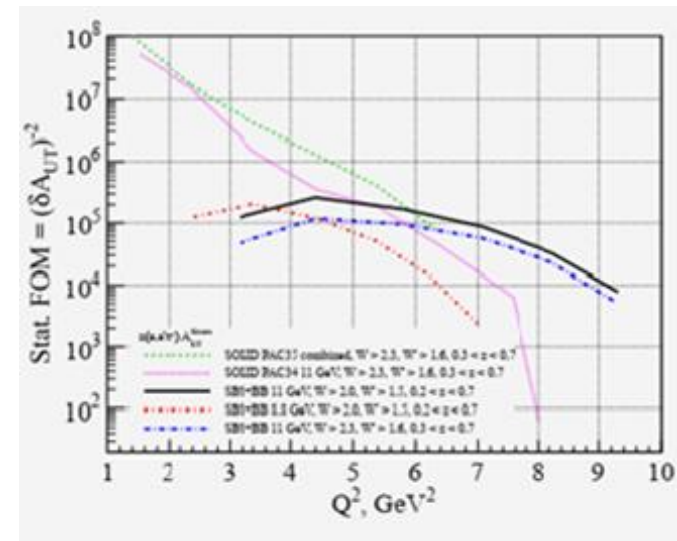
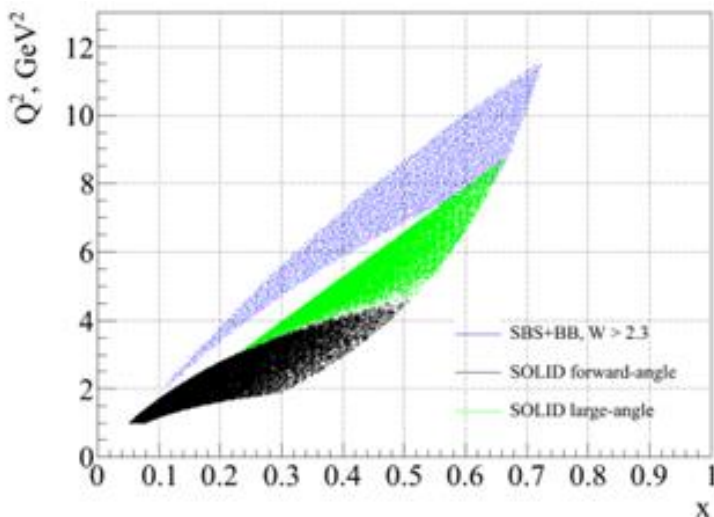
- Large acceptance device to handle very high luminosity and allow full exploitation of JLab 12 GeV potential for its SIDIS program as well

SoLID-Lite SIDIS and its main tradeoff:

- Core measurements of original SoLID-Full SIDIS program largely hold
- Keeping full LA coverage plus four FA sectors preserves much of accessible region, including valuable high- x coverage
- Lower detector cost but weakened features for statistical power and full azimuthal coverage
 - Tradeoff happening at expense of precision and detailed 4D mapping
 - Higher luminosity only partly compensates reduced acceptance
 - Separating angular asymmetries becomes more dependent on acceptance corrections

Backups

SoLID-Full and SBS Kinematics



Left: SoLID and E12-09-018 (SBS) comparison in terms of Q^2 vs x coverage at 11 GeV

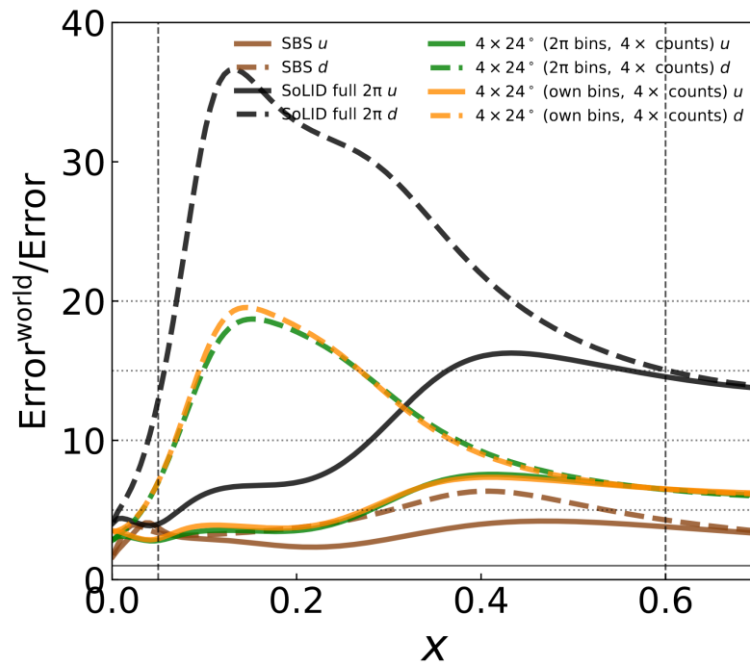
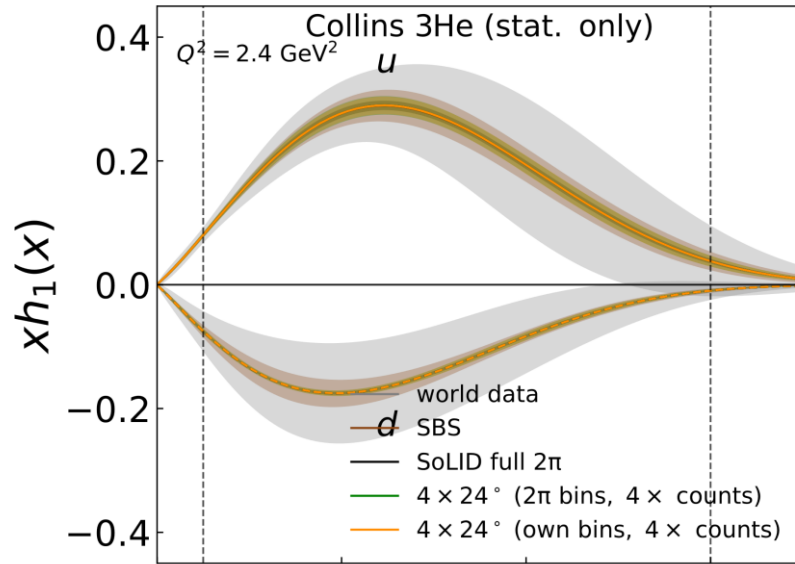
Right: SoLID and E12-09-018 (SBS) figure-of-merit comparisons as function of Q^2

- Beam time: SBS -- 40/20 day, SoLID -- 48/21 days, at 11 GeV / 8.8 GeV respectively
- Beam current: SBS -- 40 uA, SoLID -- 15 uA
- Target length: SBS -- 60 cm, SoLID -- 40 cm;
- Target pol in beam: SBS -- 60%, SoLID -- 60%

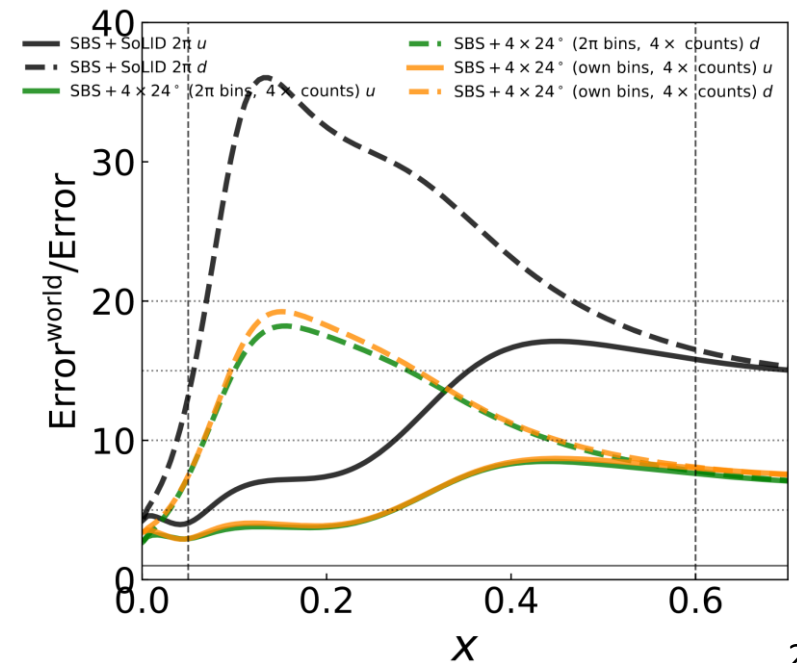
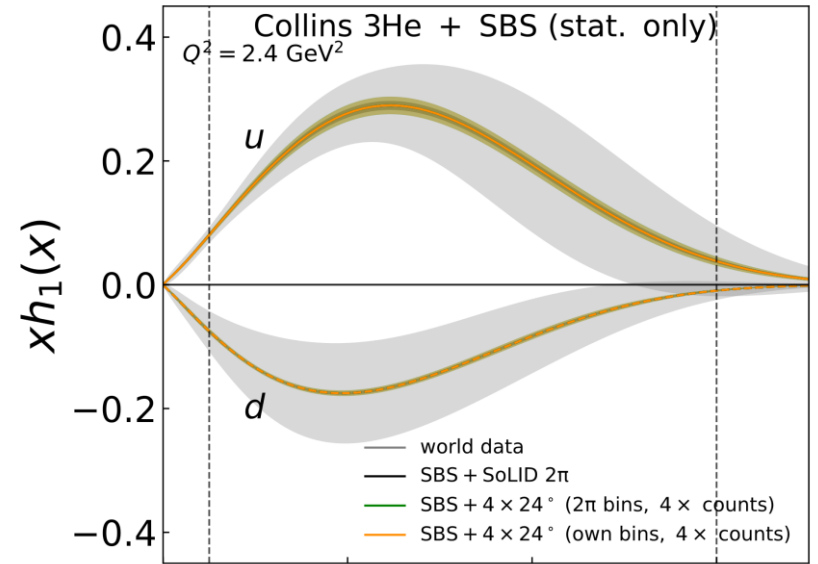
At same beam energy,
SoLID and SBS do not
overlap in Q^2 vs x

Transversity: World, SoLID-Full ^3He , SoLID-Lite ^3He , SBS, SoLID + SBS

Separated SoLID and SBS

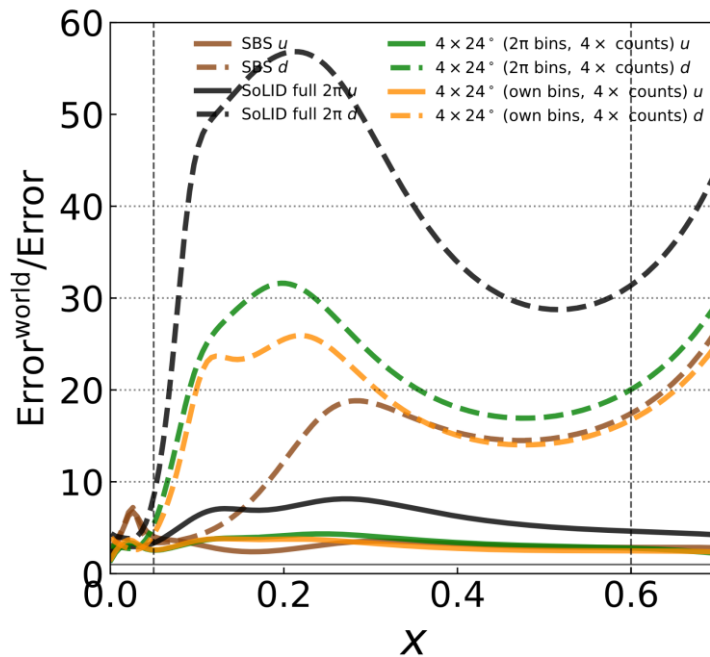
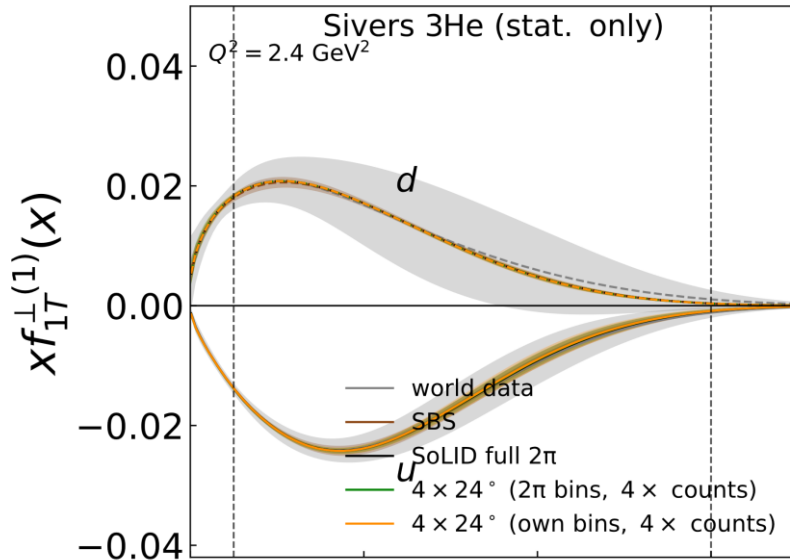


Combined SoLID and SBS

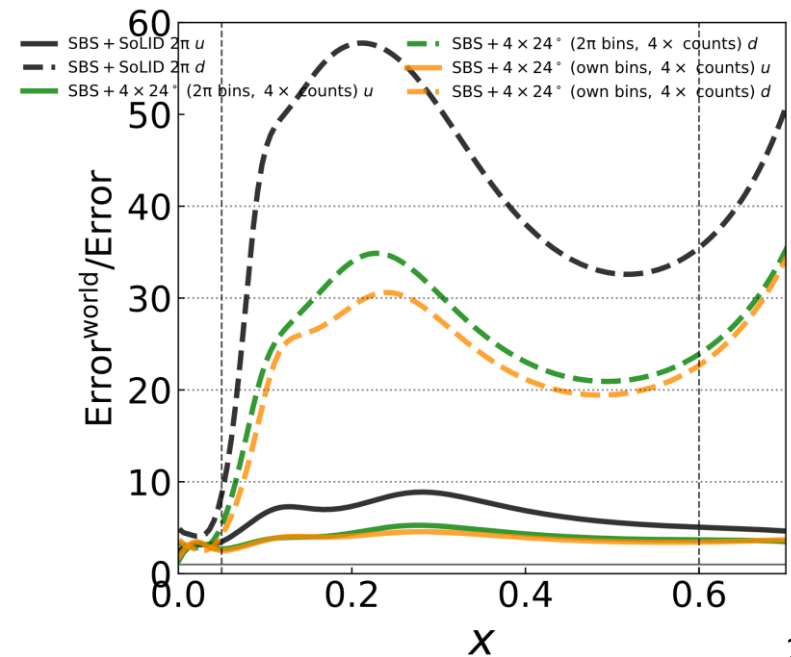
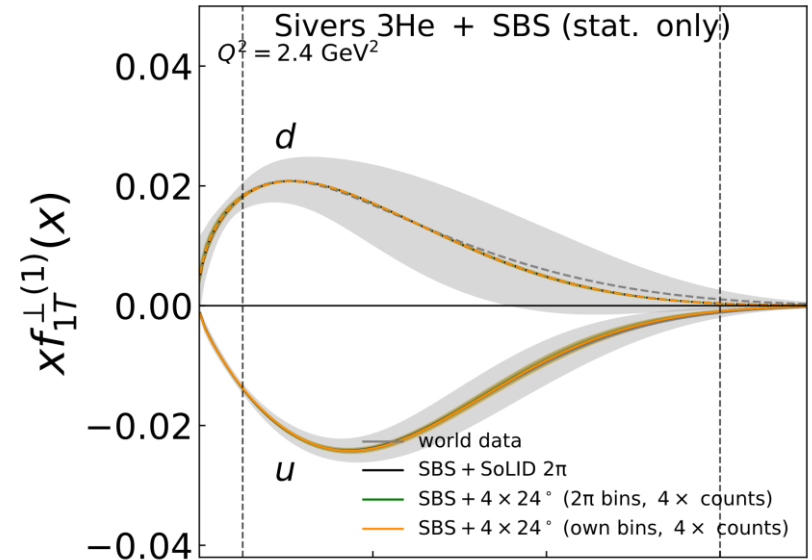


Sivers: World, SoLID-Full ^3He , SoLID-Lite ^3He , SBS, SoLID + SBS

Separated SoLID and SBS



Combined SoLID and SBS



Physics and pre-Project Development of SoLID

- **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-n (new phenomena), +
 - 1 C1 conditional approved with A rating (DDVCS)
 - 1 C2 conditional approval (PVEMC)
 - + 8 run-group experiments (3d/spin structure)

- **Pre-conceptual design, Pre-R&D and status**

- 2014: pCDR submitted to JLab with cost estimation, updated in 2017, 2019
 - Director's Reviews in 2015, 2019 and 2021

- 2015: LRP, highlighted, one of the MIEs recommended

- 2020: SoLID MIE (with updated pCDR/estimated cost) submitted to DOE

- 2021: DOE **Science Review for SoLID, positive feedback**

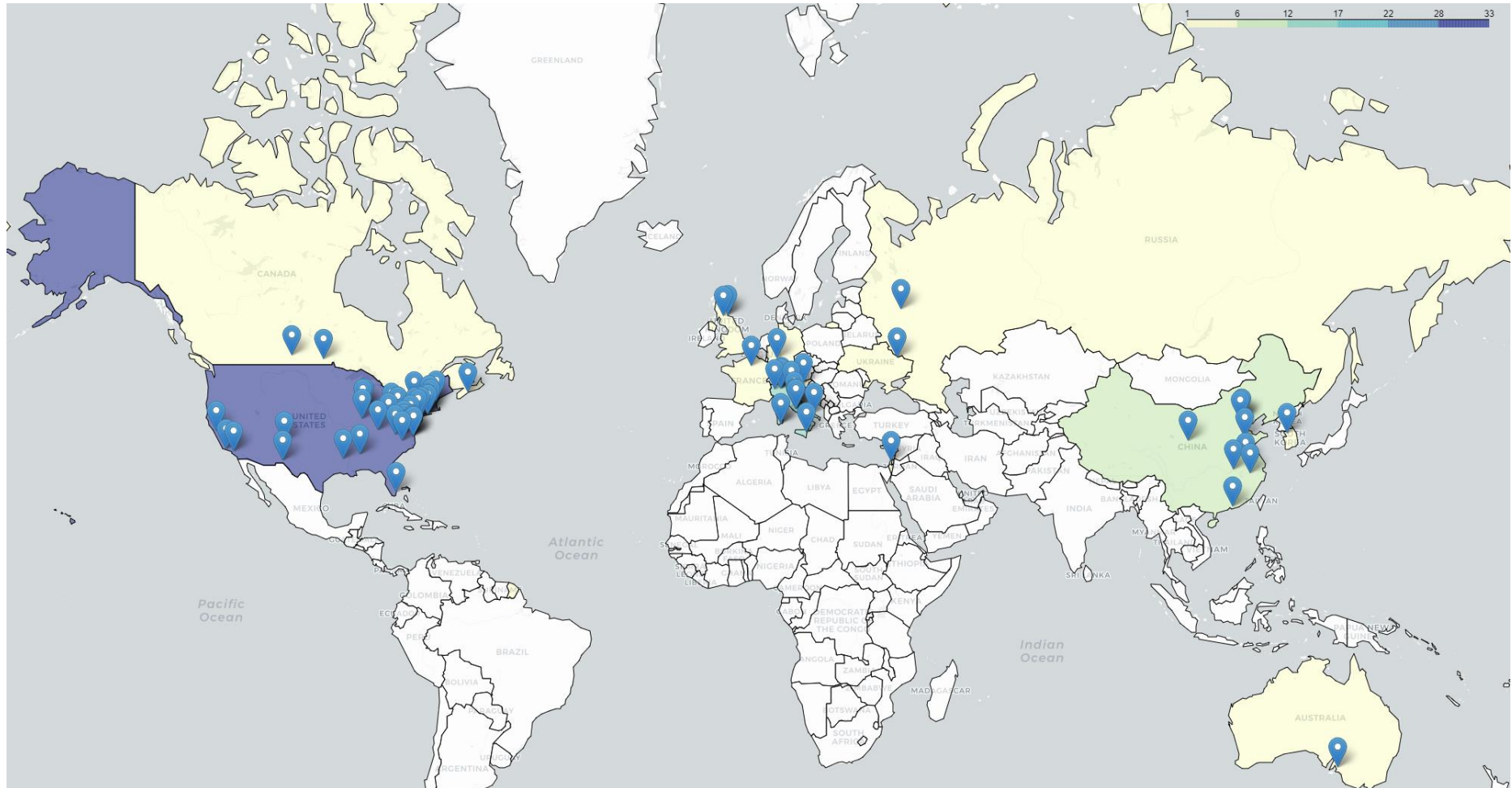
- 2023: Long Range Plan, highlighted prominently, one of the recommendations

- 2024: Facility Review: Ready to Launch

- 2020-2026: DOE funded/JLab supported pre-R&D activities

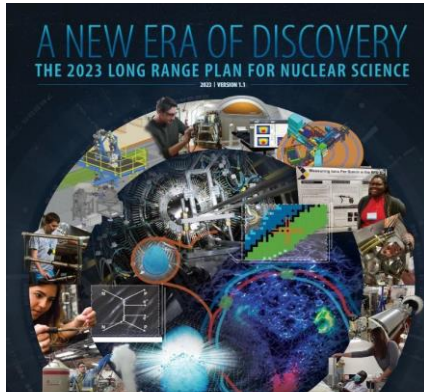
Strong Collaboration

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

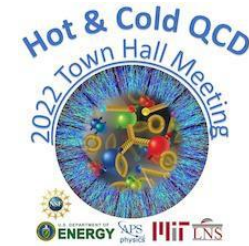


full list available at <https://solid.jlab.org/collaboration/full.html>

NSAC Long Range Plan & Community Strong Support



NSAC 2023 LRP Town Meetings – QCD



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 needs.

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.

Recommendation 1: Capitalizing on past investments

(Yes: 335; No: 3; No Answer: 4)

The highest priority for QCD research is to maintain U.S. world leadership in nuclear science for the next decade by capitalizing on past investments. Maintaining this leadership also requires recruitment and retention of a diverse and equitable workforce.

We recommend support for a healthy base theory program, full operation of the CEBAF 12-GeV and RHIC facilities, and maintaining U.S. leadership within the LHC heavy-ion program, along with other running facilities, including the valuable university-based laboratories, and the scientists involved in all these efforts.

This includes the following, unordered, programs:

- The 12-GeV CEBAF hosts a forefront program of using electrons to unfold the quark and gluon structure of visible matter and probe the Standard Model. We recommend executing the CEBAF 12-GeV program at full capability and capitalizing on the full intensity potential of CEBAF by the construction and deployment of the Solenoidal Large Intensity Device (SoLID).

Broad Impact of SoLID (even SoLID-Lite)

- Science Impact: valence-sea (SoLID) and sea-quark/gluon (EIC) regions required to fully unravel the 3-d structure of the nucleon and search for new physics
- Technologies: testing grounds for advanced detector, DAQ/electronics and computing technologies including AI/ML
- Workforce development critical for future success of nuclear physics including EIC
- STEM Workforce development for energy, medicine, national security and data science