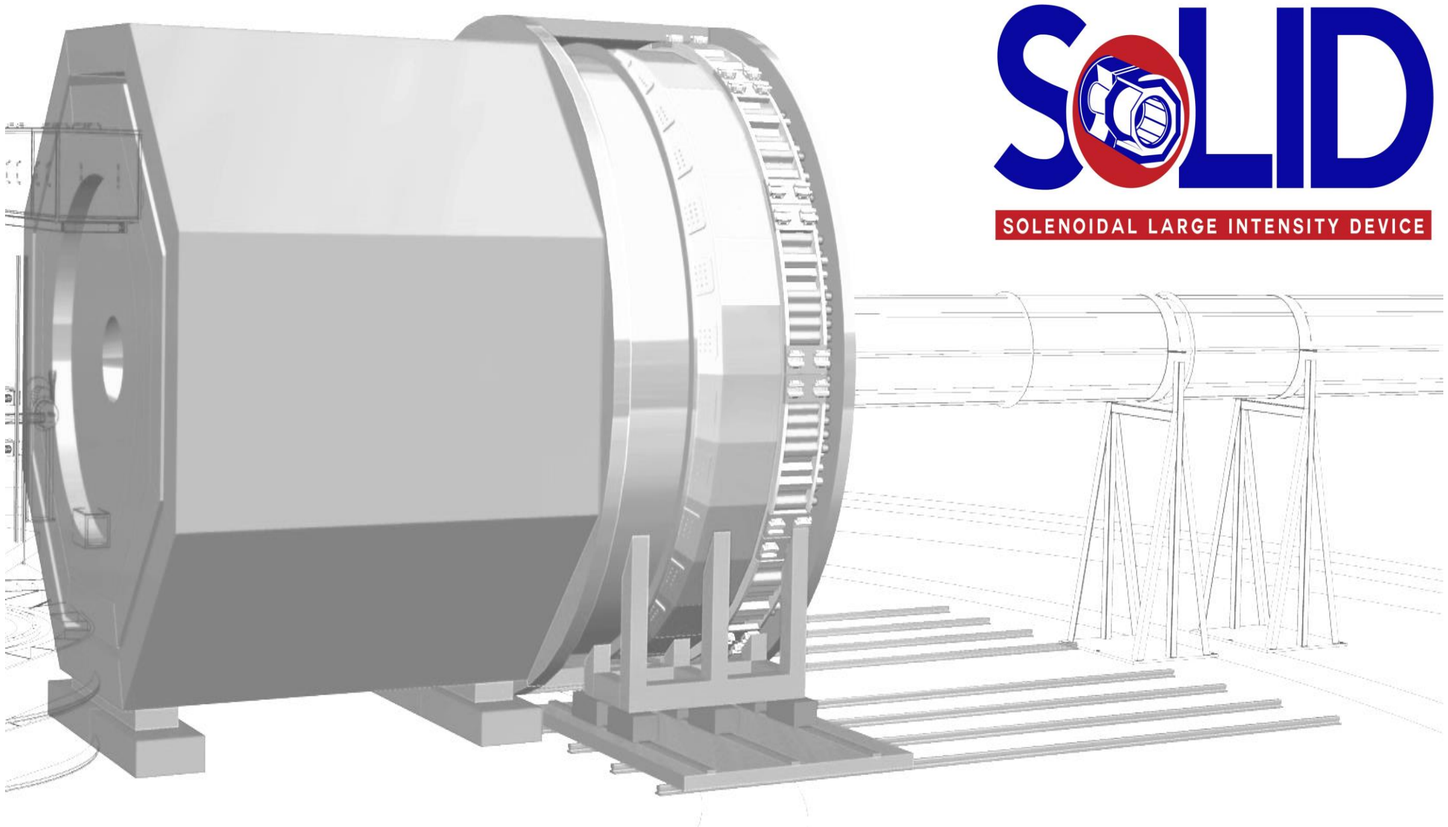
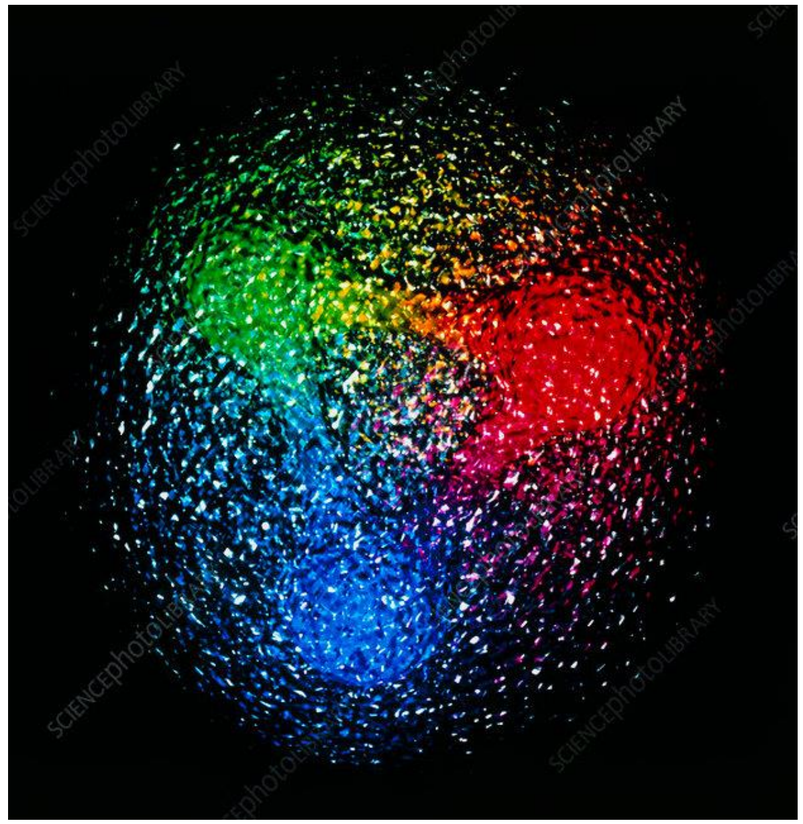
E12-10-006 Jeopardy Update to PAC50:
SoLID SIDIS Experiments with a Transversely Polarized ^{3}He Target



SoLID
SOLENOIDAL LARGE INTENSITY DEVICE



Vladimir Khachatryan
for the SoLID Collaboration

Physics Department
Duke University

SoLID Collaboration Meeting

Jefferson Lab
May 11-12, 2022

Outline

Some details on the SoLID SIDIS setup with a trans.-pol. ^{3}He (“n”) target	Reminder on three TMDs and three SSAs under consideration	Several results from the original proposal	**Recent updates**	Summary

- SoLID SIDIS setup with a transversely polarized ^{3}He target
  - *The setup and experimental details*

- Transverse-momentum-dependent parton distribution functions (TMDs) and target transverse single-spin asymmetries (SSAs)
  - *Three TMDs and three SSAs to be measured in E12-10-006*

- Several results from the original proposal
  - *Collins and Pretzelosity SSAs for π^+/π^-, as well as Sivers SSA for π^+/π^-*

- **Updates in recent years**
  - ***Complementarity to EIC***
  - ***Projections of Transversity TMD and Tensor Charge***
  - ***Projections of Sivers TMD***
  - ***Related run group experiments***

- *Summary*

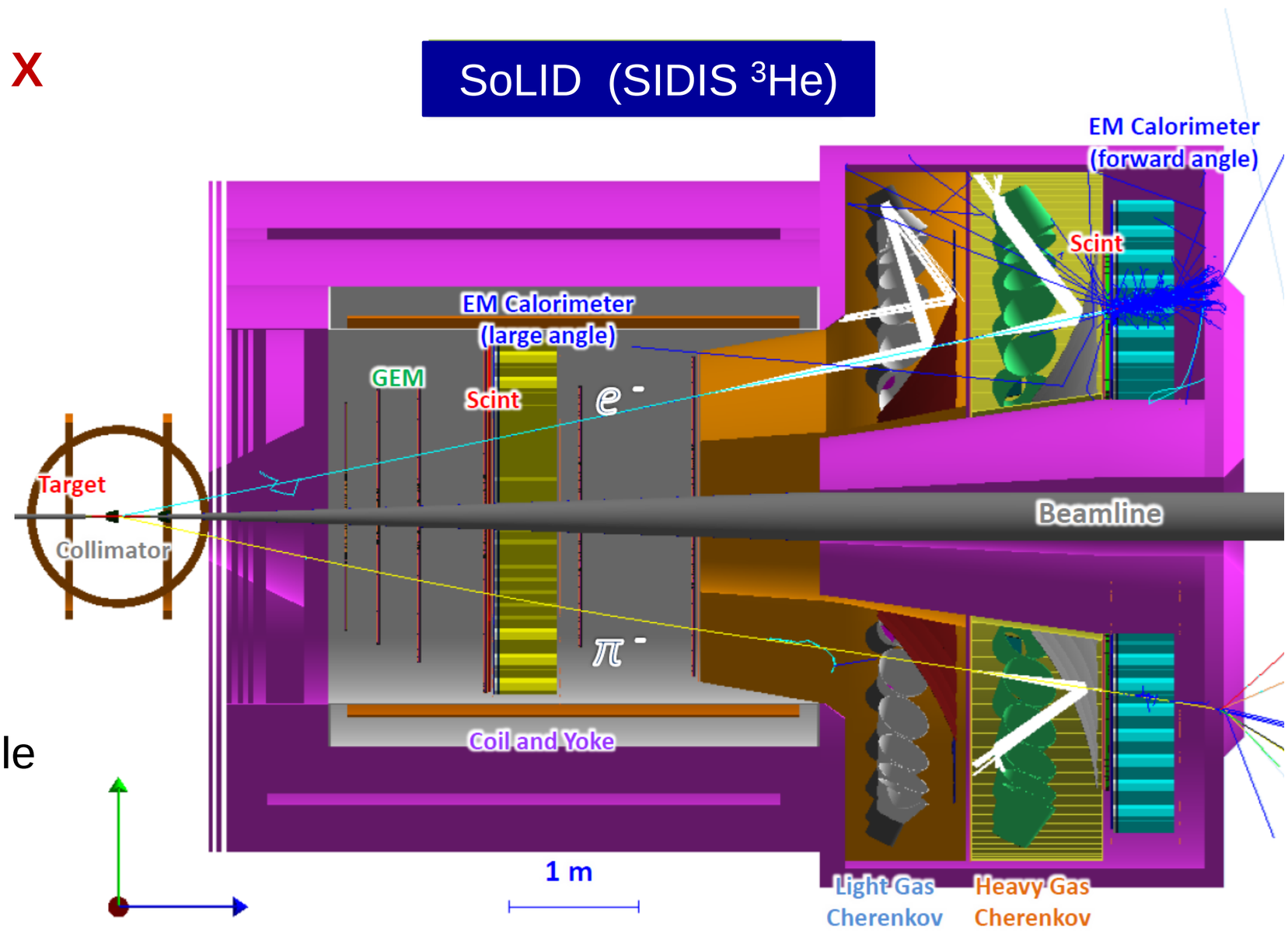
SoLID SIDIS setup with a transversely polarized ^{3}He ("neutron") target

E12-10-006: Single Spin Asymmetries on Transversely Polarized ^{3}He (neutron) @ 90 days

Rating A **Spokespersons: J.P. Chen, H. Gao (contact), J.C. Peng, X. Qian**

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

- Target:
  - *Length*: *40 cm*
  - *Polarization*: *~ 60%*
  - *Spin flip*: *≤ 20 mins*
  - *Polarimetry*: *~ 3%*
- GEM: 6 tracking chambers
- EM Calorimeter: Forward and Large angle
- SPD: Forward and Large angle
- LGC: 2 m long
- HGC: 1 m long



Experimental details for the E12-10-006 experiment

- Approved number of days: 90
- 69 days requested for the beam on the trans.-pol. ^{3}He target
- 10 days requested for a dedicated study of the x-z factorization with Hydrogen and Deuterium gas using a reference target cell
- 3 days requested with a longitudinal target polarization to study the systematics of potential A_{UL} contamination
- 8 days of overhead time requested for regular target annealing
- Major requirements: Radiation hardness, detector resolution, kaon contamination, DAQ
- Expected DAQ rates: $<$ 100 kHz
- Scattered electrons detected by both Forward-angle and Large-angle detectors; Produced pions detected by Forward-angle detectors only

Experimental details for the E12-10-006 experiment

- Momentum coverage: 1.0 - 7.0 GeV/c; Momentum resolution: $\sim$ 2%
- Polar angular coverage: 8 - 24 degree; Polar angular resolution: 2 mrad
- Azimuthal angular coverage: 2π; Azimuthal angular resolution: 6 mrad
- PID (e^-): detection efficiency $\geq$ 90%; pion contamination $<$ 1%
- PID ($\pi^\pm$): detection efficiency $\geq$ 90%; kaon contamination $<$ 1%
- Two beam energies: 11 GeV and 8.8 GeV
- Total luminosity: $3.74 \cdot 10^{36}\ cm^{-2}\ sec^{-1}$
- Beam polarimetry: $<$ 3%; Beam current: 15 μA, goes through 5 T magnetic field
- Many other details in ***SoLID (Solenoidal Large Intensity Device) Updated Preliminary Conceptual Design Report, https://solid.jlab.org/***

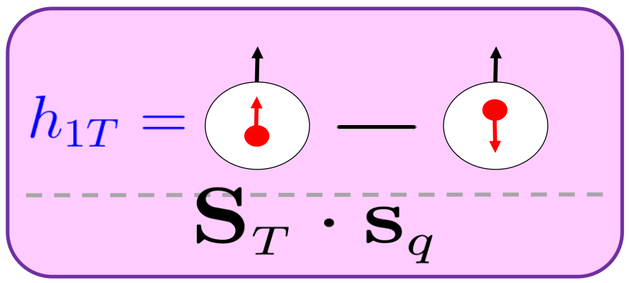
TMDs – confined motion inside the nucleon

Transversely Polarized Nucleon TMDs to be measured by SoLID

→ Nucleon Spin

→ Quark Spin

Transversity



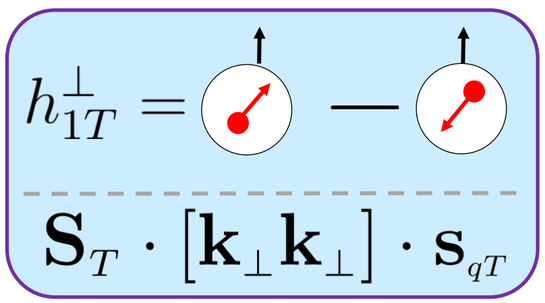
Relevant Vectors

- **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 electric dipole moment

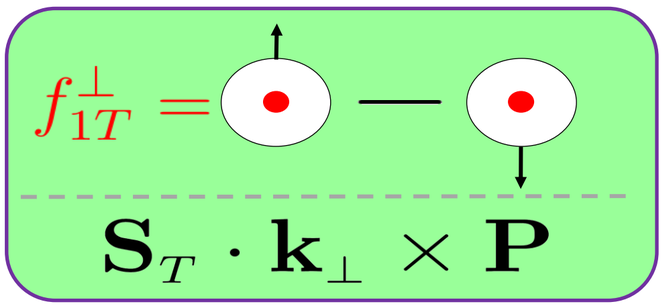
- Transversity → Tensor charge

Pretzelosity



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

Sivers

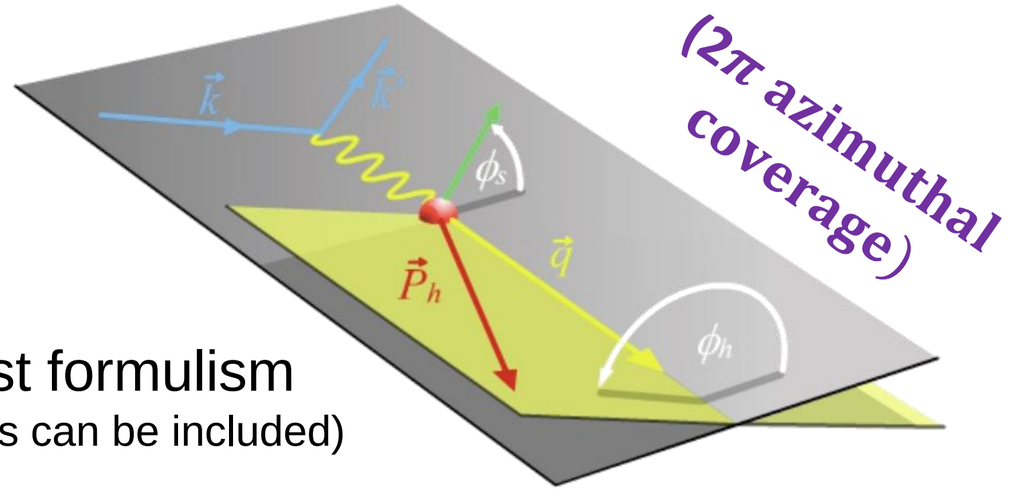


- Nucleon spin - quark orbital angular momentum (OAM) correlation
- Zero if no OAM (model dependence)

Separation of the transverse Collins / Sivers / Pretzelosity SSAs

SIDIS SSAs depend on 4-D variables (x, Q^2, z, P_T);

Small asymmetries demand **large acceptance** + **high luminosity** allowing for measuring asymmetries in 4-D binning with precision!



(2π azimuthal coverage)

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

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

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

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

Transverse SSAs in the SIDIS cross section

- Three transverse SSAs standing in the SIDIS differential cross section

$$\frac{d\sigma_{SIDIS}}{dx\,dy\,dz\,dP_T^2\,d\phi_h d\phi_S} = \frac{\alpha^2}{x\,y\,Q^2}\left(1-y+\frac{1}{2}y^2\right)F_{UU}(x,y,P_T^2)\times$$

Shown at leading order in 1/Q expansion

$$\times\Big\{1+\ \ldots\ + S_T\ \sin(\phi_h+\phi_S)\ p_1\ A_{UT}^{Collins}$$

$$+ S_T \sin(3\phi_h-\phi_S)\ p_1\ A_{UT}^{Pretzelosity}$$

S_T - transverse component of target-spin direction

$$+ S_T \sin(\phi_h-\phi_S)\ A_{UT}^{Sivers} + \ldots\Big\}$$

Totally 18 terms in leading and sub-leading order in 1/Q

S. Bastami, et al., JHEP 06, 007 (2019)

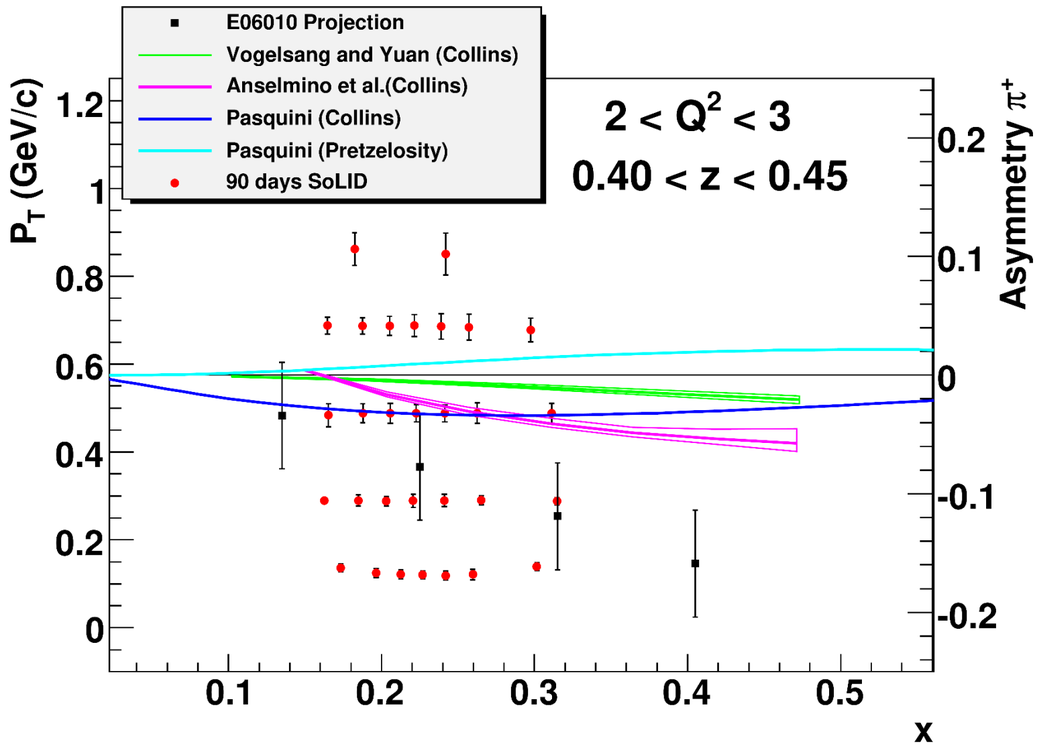
Nuclear physics questions to be addressed by SoLID SIDIS

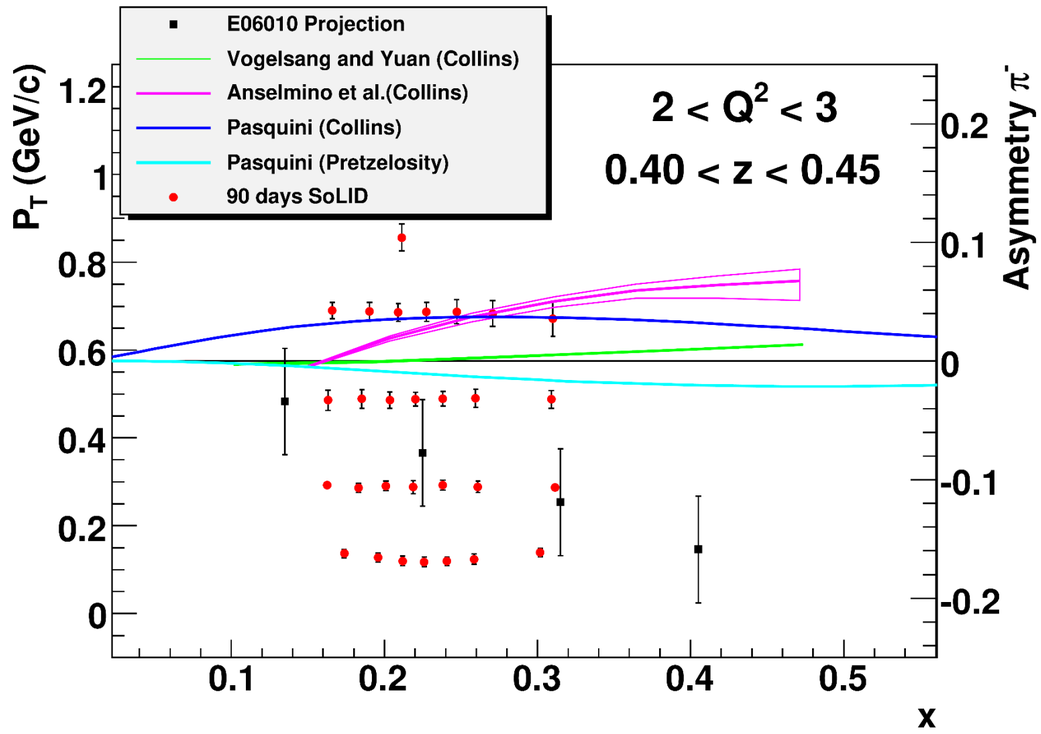
Nuclear physics critical problems to be addressed by the SoLID SIDIS program with both “neutron” and “proton” targets

- How to quantify the quark transverse motion inside the nucleon and observe spin-orbit correlations ?
  - *Sivers TMD*
- Is the confined motion in the transverse plane dependent on Bjorken x ?
  - *Sivers TMD*
- Is it possible to provide quantitative information on the quark OAM contribution to the nucleon spin ?
  - *Pretzelocity TMD and Sivers TMD*
- Are there clear signatures for relativity inside the nucleon ?
  - *Transversity TMD and Pretzelocity TMD*
- Is it possible to provide a high precision test for lattice QCD predictions ?
  - *Tensor charge from Transversity TMD*

Collins and Pretzelosity SSAs for π^+/π^- (original projections)

- SoLID SIDIS projections in a typical z and Q^2 bin for the π^+ Collins/Pretzelosity SSA measurements as a function of x, with different ranges of the hadron P_T labeled



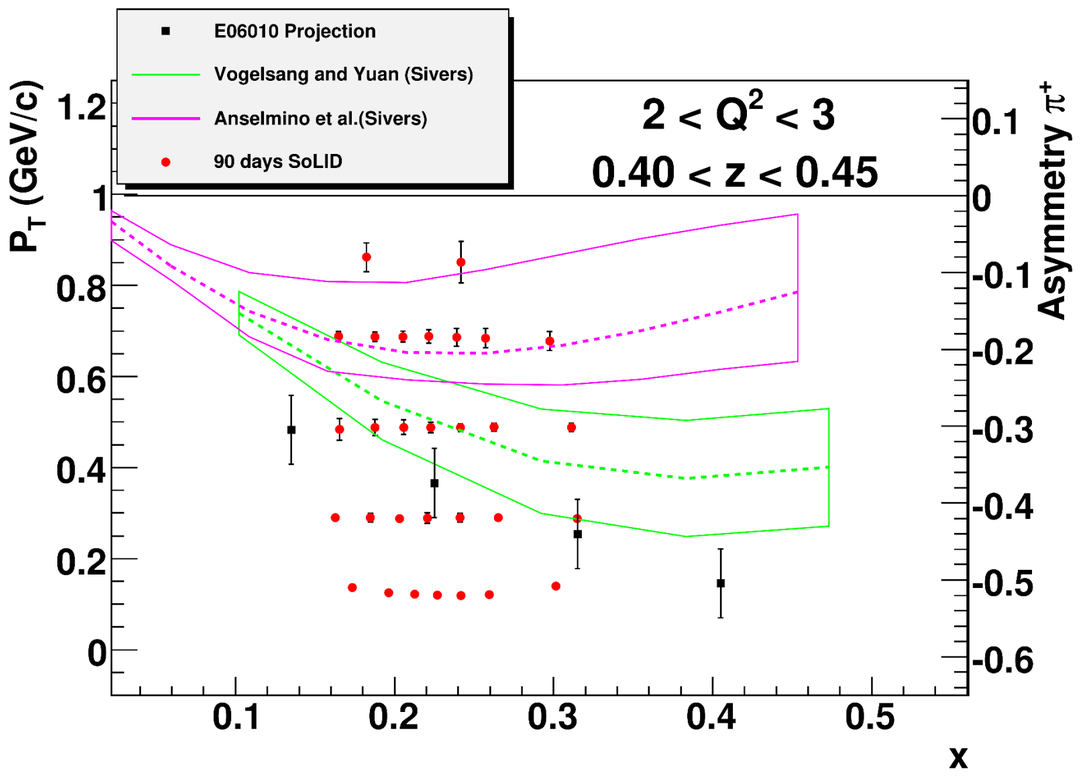


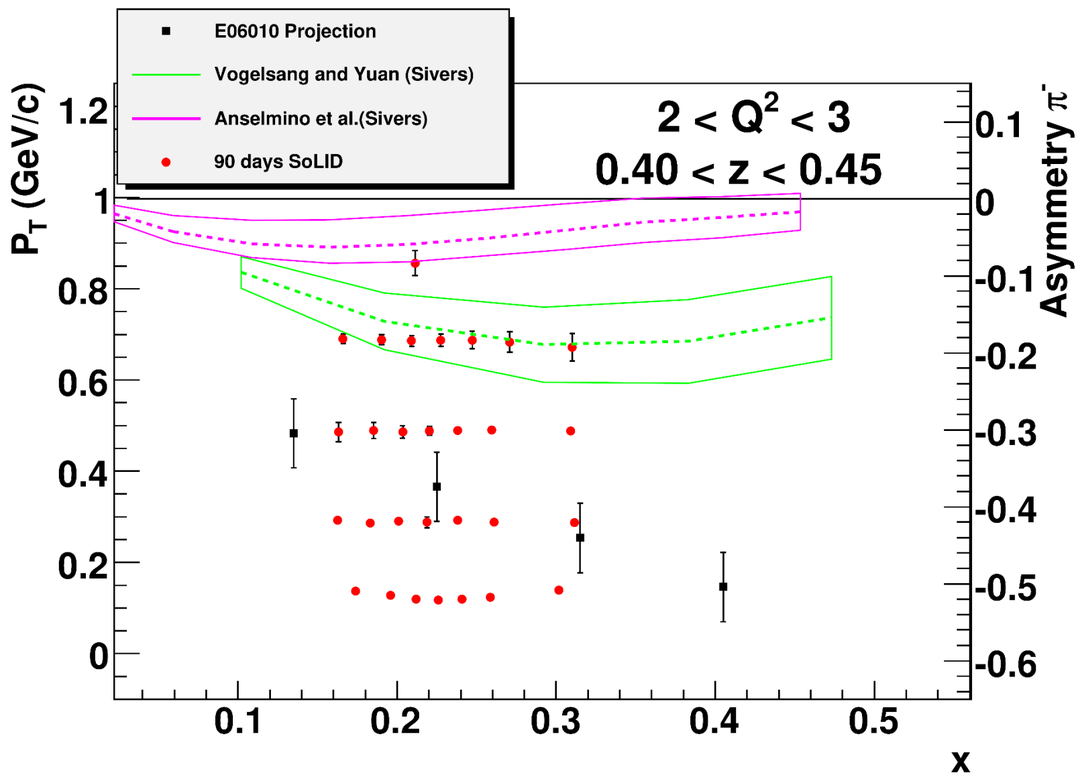
Theoretical predictions:

- W. Vogelsang and F. Yuan, Private communication (2009)
- M. Anselmino and A. Prokudin, Private communication (2009)
- B. Pasquini, et al., Private communication (2009)
- B. Pasquini, et al., PRD 79, 094012 (2009)

Sivers SSA for π^+/π^- (original projections)

- SoLID SIDIS projections in a typical z and Q^2 bin for the π^+/π^- Sivers SSA measurements as a function of x, with different ranges of the hadron P_T labeled



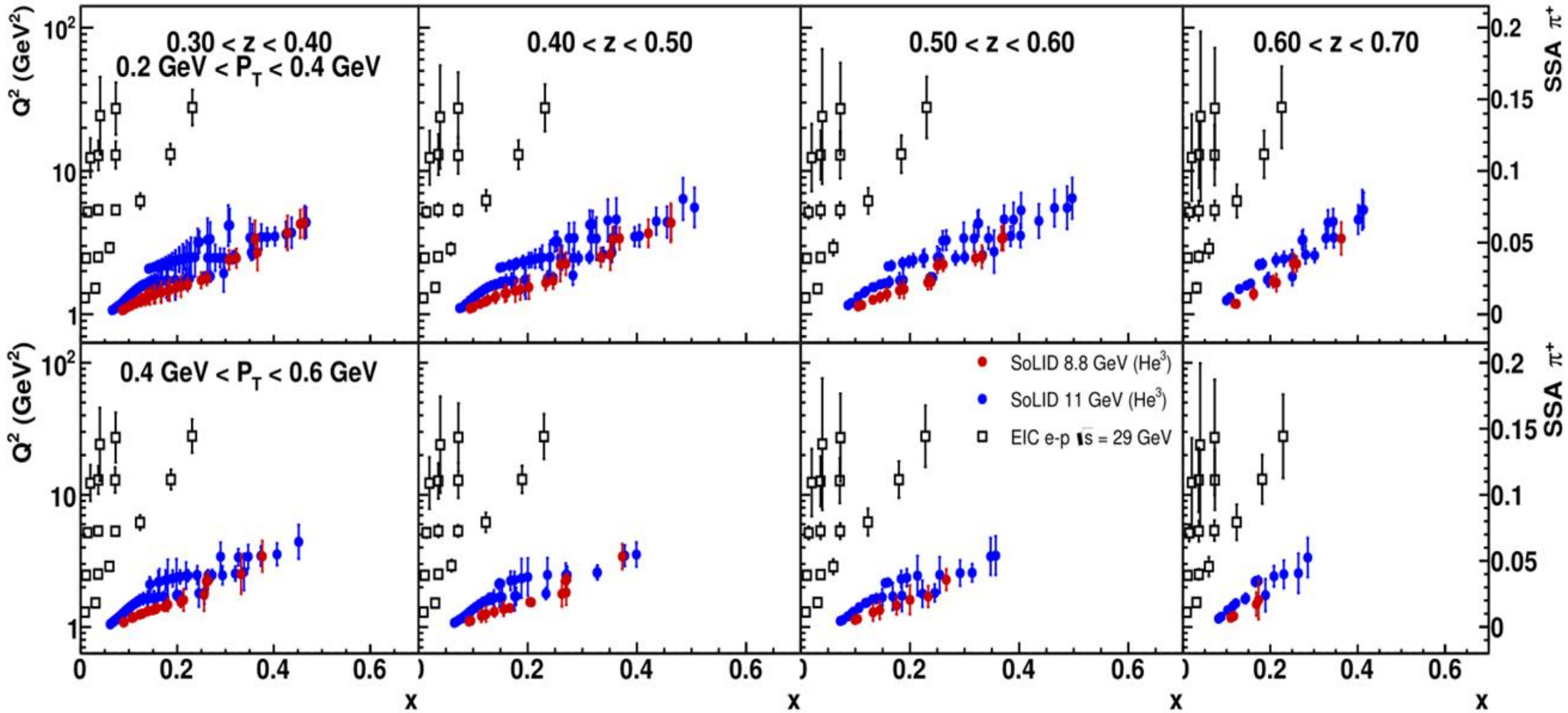


Theoretical predictions:

- W. Vogelsang and F. Yuan, Private communication (2009)
- M. Anselmino and A. Prokudin, Private communication (2009)

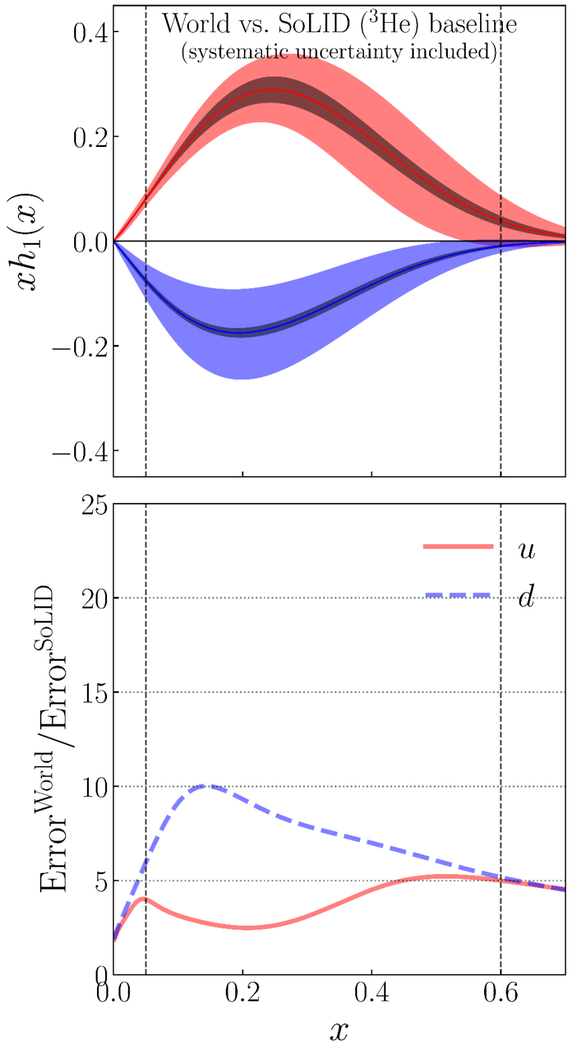
Transverse SSA projections: Complementarity to EIC

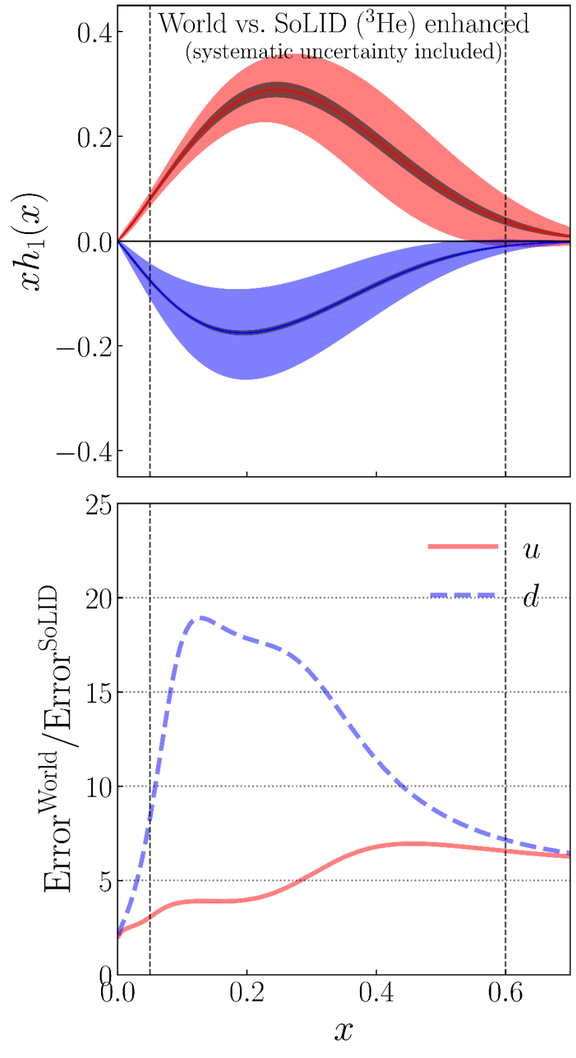
- SoLID SIDIS projections of A_{UT} in various 4-D bins at 11/8.8 GeV beam energies
- Projections at EIC kinematics for the same observable at 29 GeV center-of-mass energy
- SSA scale and uncertainties shown on the right-side axis of the figures
- SoLID and EIC projections synergistic towards each other,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

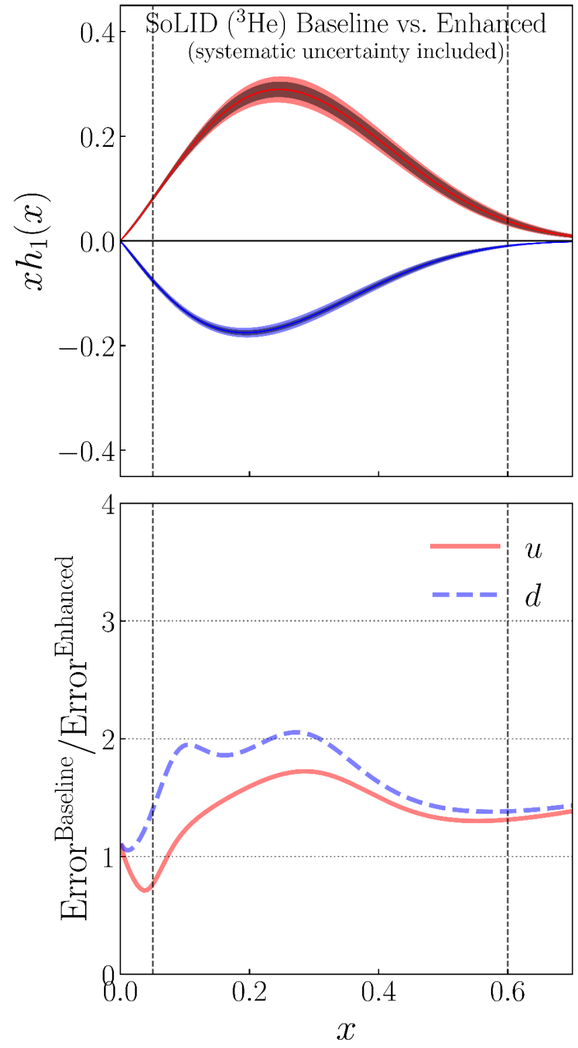


Transversity TMD projections

- Top figures: impact on the *u* and *d* quarks’ Transversity TMD extractions by the SoLID SIDIS program
- World: SIDIS data from COMPASS / HERMES, e^+e^- annihilation data from BELLE / BABAR / BESIII
- Bottom figures: ratios between the World and SoLID projected uncertainties shown in the top figures
- Monte Carlo method applied; the results obtained at $Q^2 = 2.4$ GeV^2

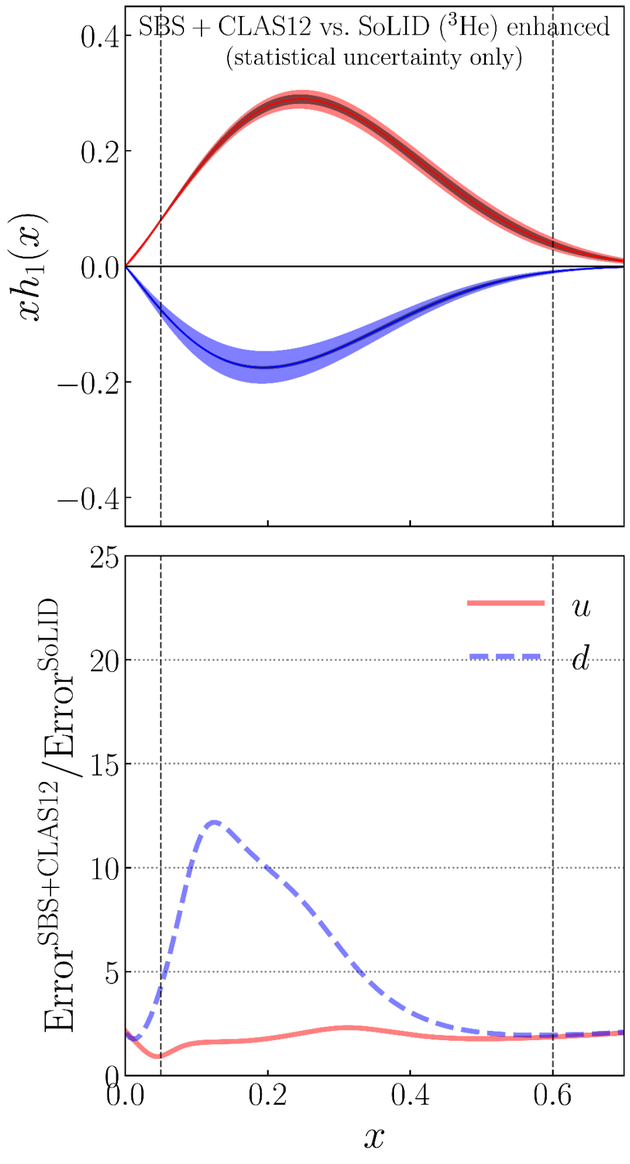




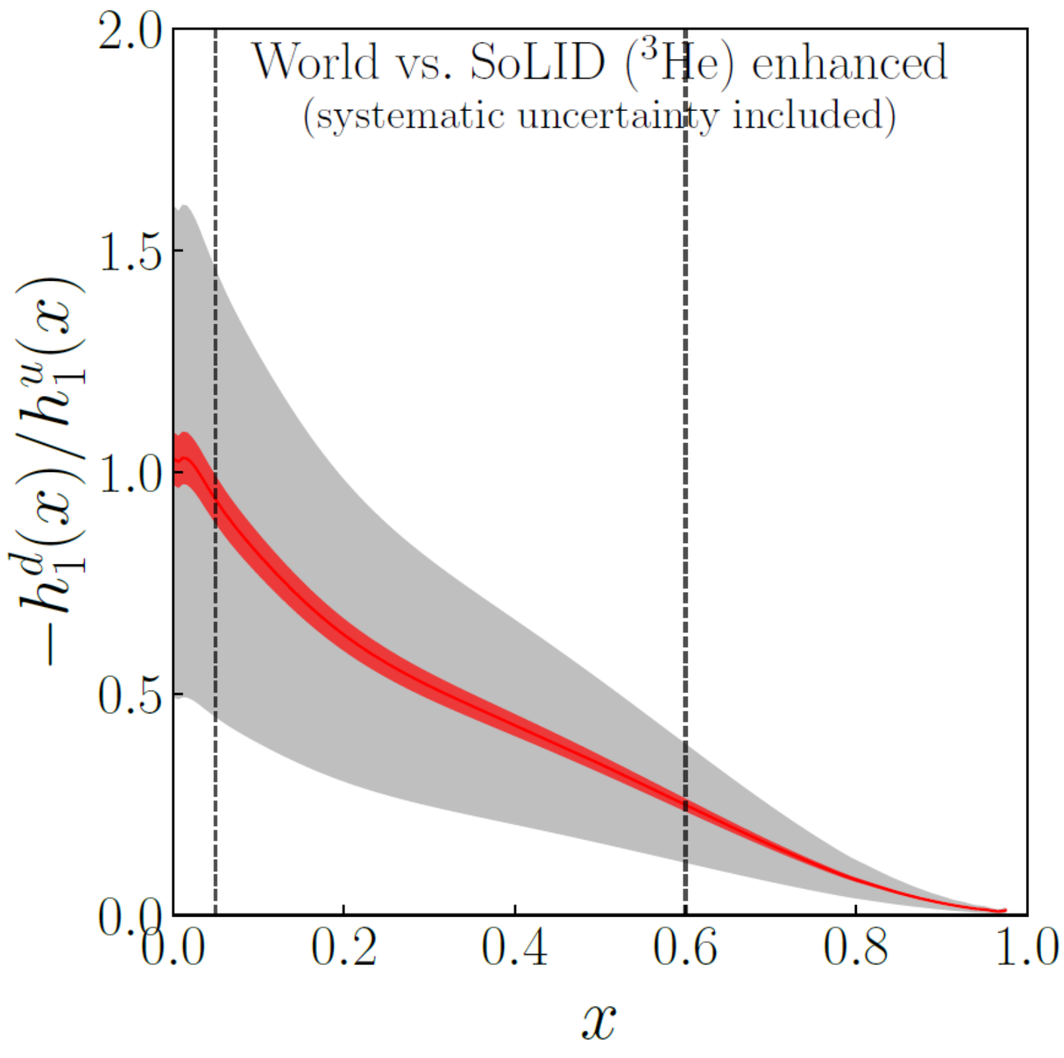


Transversity TMD projections

- Left figure: Same explanation as in the previous slide but compared to SBS+CLAS12 projections
- Region of x from 0.05 up to 0.6 measured by SoLID



- Right figure: ratio of the extracted *d* and *u* quarks’ Transversity compared to the World data
- The result obtained at $Q^2 = 2.4$ GeV^2



Tensor Charge projections

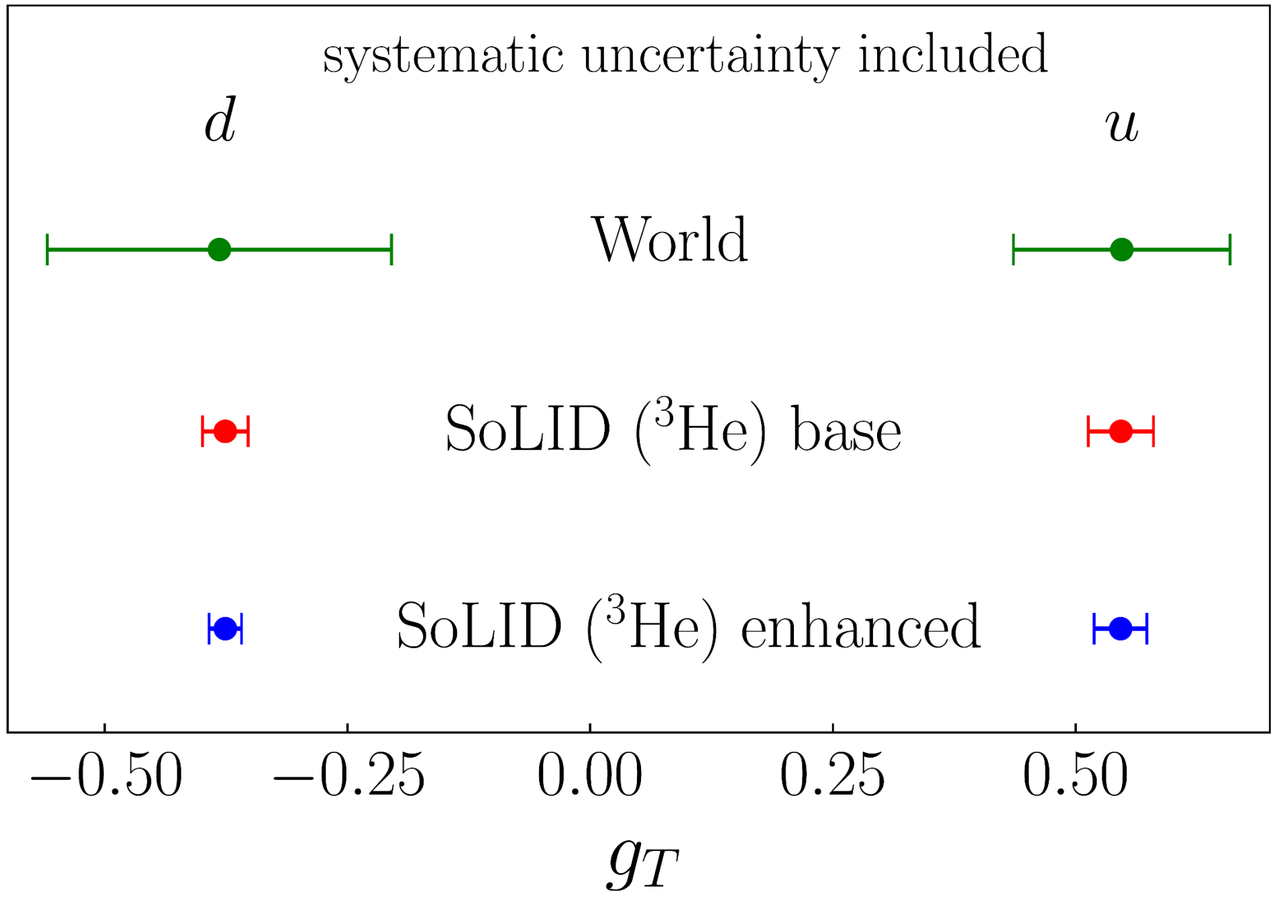
Tensor charge g_T:

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

<u>World data</u>

<u>SoLID projections</u>
from ^{3}He target at
11 / 8.8 GeV beams

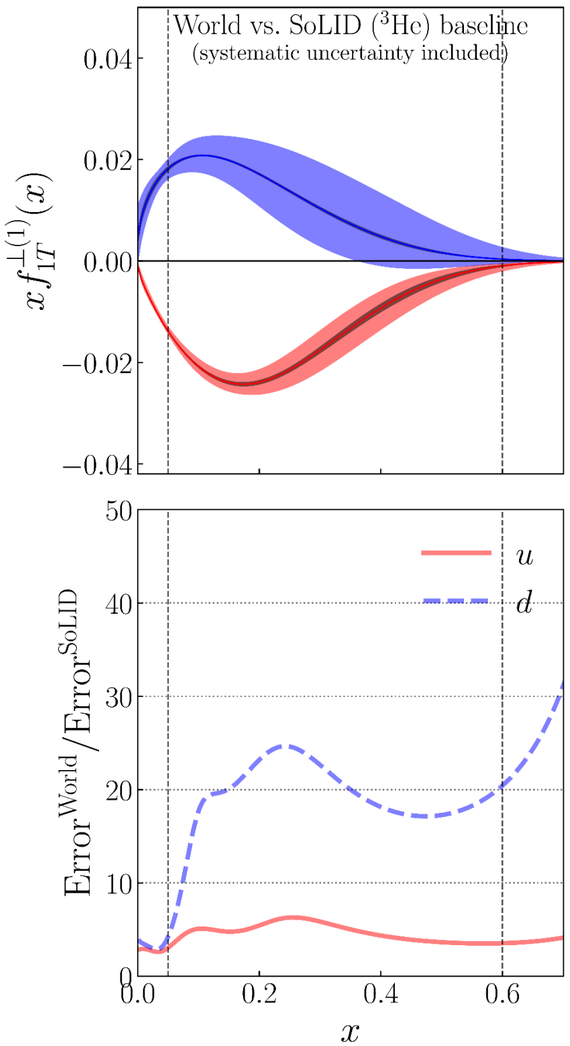
Statistical and systematic uncertainties included

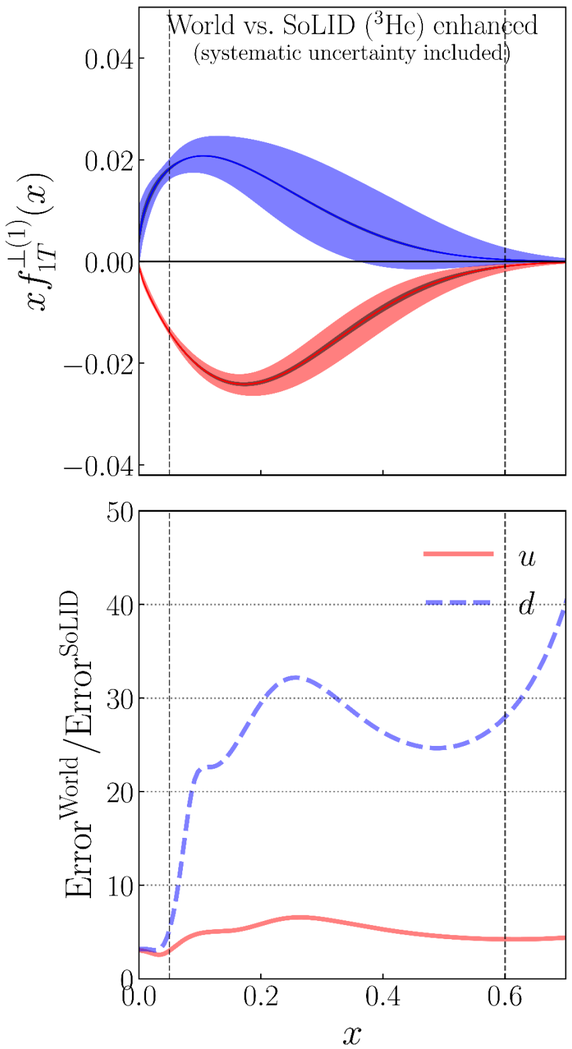


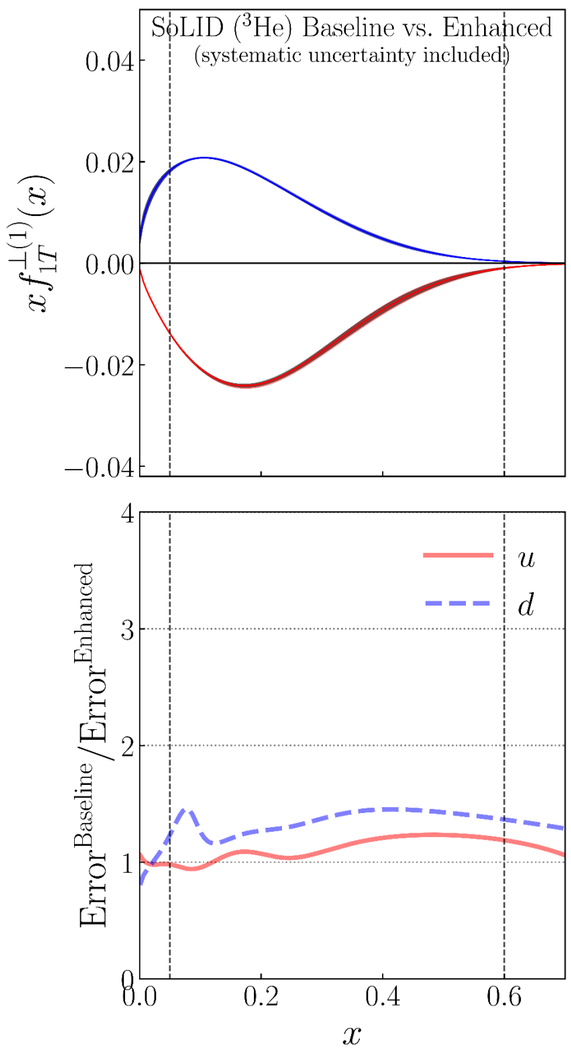
g_T Flavor separation	World data	SoLID baseline	SoLID enhanced baseline
u / *d* value	0.548 / -0.382	0.547 / -0.376	0.547 / -0.376
u / *d* error	0.112 / 0.177	0.034 / 0.023	0.027 / 0.017

Sivers TMD projections

- Top figures: impact on the *u* and *d* quarks’ Sivers TMD extractions by the SoLID SIDIS program
- World: SIDIS data from COMPASS / HERMES, e^+e^- annihilation data from BELLE / BABAR / BESIII
- Bottom figures: ratios between the World and SoLID projected uncertainties shown in the top figures
- Monte Carlo method applied; the results obtained at $Q^2 = 2.4$ GeV^2







E12-10-006 -- related run group experiments

Approved five Run Group Experiments

1. SIDIS Dihadron with Transversely Polarized ^{3}He target
   - *A study of transversity parton distribution using measurements of semi-inclusive electroproduction of two charged pions in the DIS region to be carried out*
   - *Will provide input data to extract the u and d transversity distributions in a model-independent way*
   - *Will be run in parallel with the experiment E12-10-006*

2. SIDIS in Kaon Production with Transversely Polarized NH_3 and ^{3}He targets
   - *Measurements of $K^{\pm}$ production in SIDIS using both the transversely polarized ^3He and NH_3 targets to be performed, to extract the $K^{\pm}$ Collins, Sivers and other TMD asymmetries*
   - *Will provide input data to determine the u, d and sea quarks’ TMDs*
   - *Will be run in parallel with the experiments E12-10-006 and E12-11-108*

3. Deep Exclusive Meson Production: Measurement of Deep Exclusive π^- Production using a Transversely Polarized ^{3}He Target and the SoLID Spectrometer
   - *Precision studies of GPDs with a deep exclusive π^- electroproduction*
   - *Measuring two specific transverse target single spin asymmetries related to four lowest-order GPDs*
   - *Will be run in parallel with the experiment E12-10-006*

E12-10-006 -- related run group experiments

4. A_y: Target Single Spin Asymmetry Measurements in the Inclusive Deep-Inelastic Reaction on Transversely Polarized Neutron (^{3}He) and Proton (NH_3) Targets using the SoLID Spectrometer
   - *Single spin asymmetry, A_y, to be obtained by scattering unpolarized electrons from a transversely polarized targets in the DIS region*
   - *Extract the two-photon exchange contribution in the absence of the typically dominant Born scattering contribution by measuring the azimuthal dependence of this asymmetry*
   - *Will be run in parallel with the experiments E12-10-006 and E12-11-108*

5. g_2^n and d_2^n: Measurement of Inclusive g_2^n and d_2^n with SoLID on a Polarized ^{3}He Target
   - *Precision measurements of the neutron structure function, $g_2(x, Q^2)$*
   - *Also, measure its moment, $d_2(Q^2)$, connected to the quark-gluon correlations within the nucleon*
   - *$d_2(Q^2)$, one of the cleanest observables to test the theoretical calculations from lattice QCD and various nucleon structure models*
   - *Will be run in parallel with the experiments E12-10-006 and E12-11-007*

Summary

- SoLID SIDIS program will be *unique* (valence quark region with high precision)
  - *Exploring the 3-D tomography of the nucleon in momentum space*
  - *Complementing the research of other key facilities, e.g., COMPASS, COMPASS-II, EIC*

- Impactful results to be obtained in the first three years of SoLID operations with ^{3}He and NH_3 trans.-pol. targets
  - *Measuring Transversity, Pretzelocity, and Sivers TMDs*
  - *Confronting the Lattice QCD predictions (e.g., tensor charge)*

- No less impactful results to be obtained with the SoLID SIDIS run group experiments based on using trans.-pol. and long.-pol ^{3}He targets, as well as NH_3 trans.-pol. target
  - *Enhancing our knowledge on light and sea quark TMD distributions inside the nucleon, quark–gluon interactions, GPDs, as well as having significant impact for discrimination among various parton model predictions for nucleon intermediate states*

Thank You !

Acknowledgement: Haiyan Gao, Zhiwen Zhao, Jian-Ping Chen, Tianbo Liu, Xiaqing Li, Ye Tian, and the entire SoLID collaboration.

Backups

Systematic uncertainty sources

➢ Systematic uncertainty sources and how we address them:

- *Raw asymmetry*: expect to 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 $\rightarrow$ translates to a 3% rel. syst. uncertainty of the SSA data

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

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

- *Radiative correction*: the effect is simulated with HAPRAD, at the QED one-loop level

- *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

➢ Average statistical uncertainties on the separated SSAs: $\sim 3.7 \cdot 10^{-3}$ (absolute) for 1400 bins

Systematic uncertainty budget

- The budget for the absolute and relative systematic uncertainties of the π^+/π^- Collins and Sivers SSAs

- The uncertainty sources are described on slide 12th

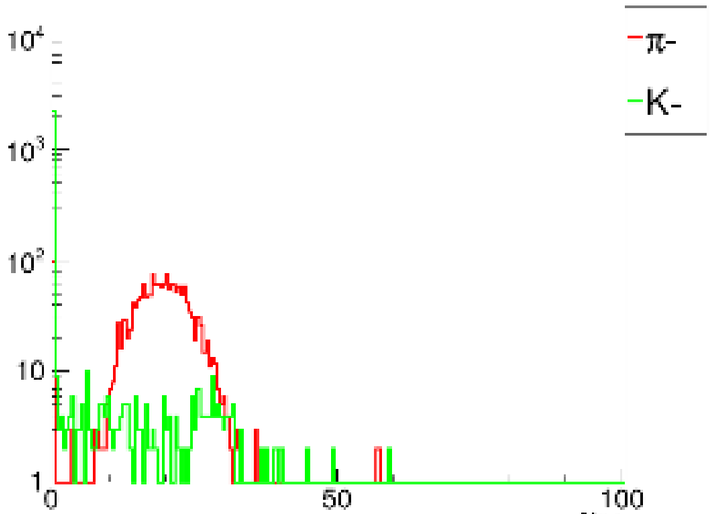
Source (Type): ^{3}He (E12-10-006)	Collins π^+	Collins π^-	Sivers π^+	Sivers π^-
Raw asymmetry (Abs.) Detector resolution (Abs.)	1.4×10^{-4} $< 10^{-4}$	1.4×10^{-4} $< 10^{-4}$	1.4×10^{-4} $< 10^{-4}$	1.4×10^{-4} $< 10^{-4}$
Target polarization (Rel.)	3% + 0.5%	3% + 0.5%	3% + 0.5%	3% + 0.5%
Random coincidence (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%

SoLID Sub-systems

- Coincidence detection of electrons and charged pions: good PID for electrons (LGC+EC); moderate PID for pions (HGC)
- DAQ rate: up to 100 KHz

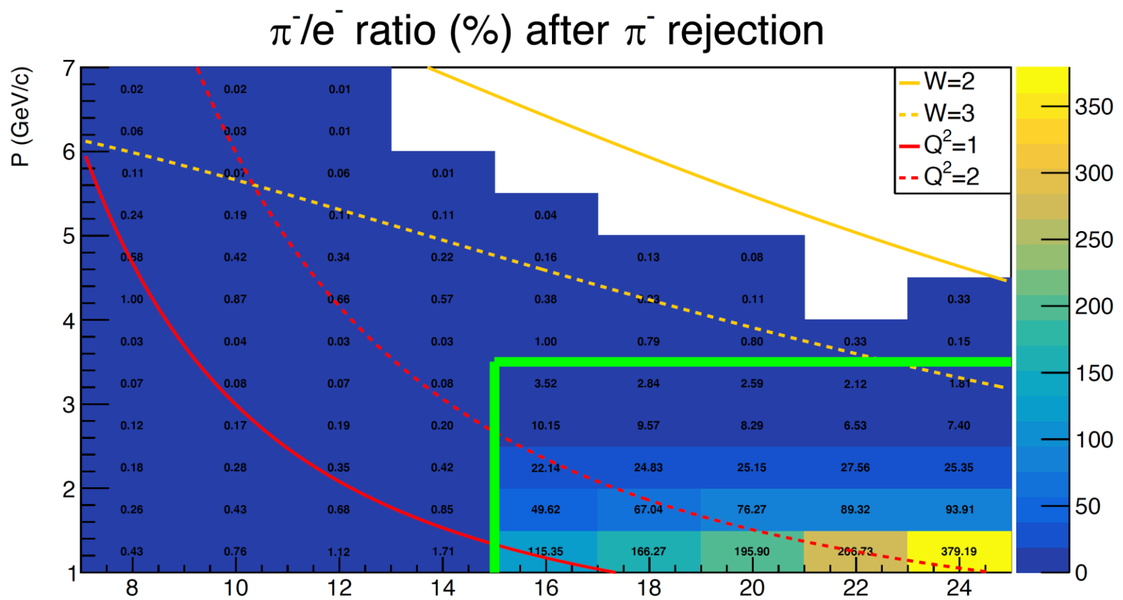
Combined light gas Cherenkov and Calorimeter detector performance

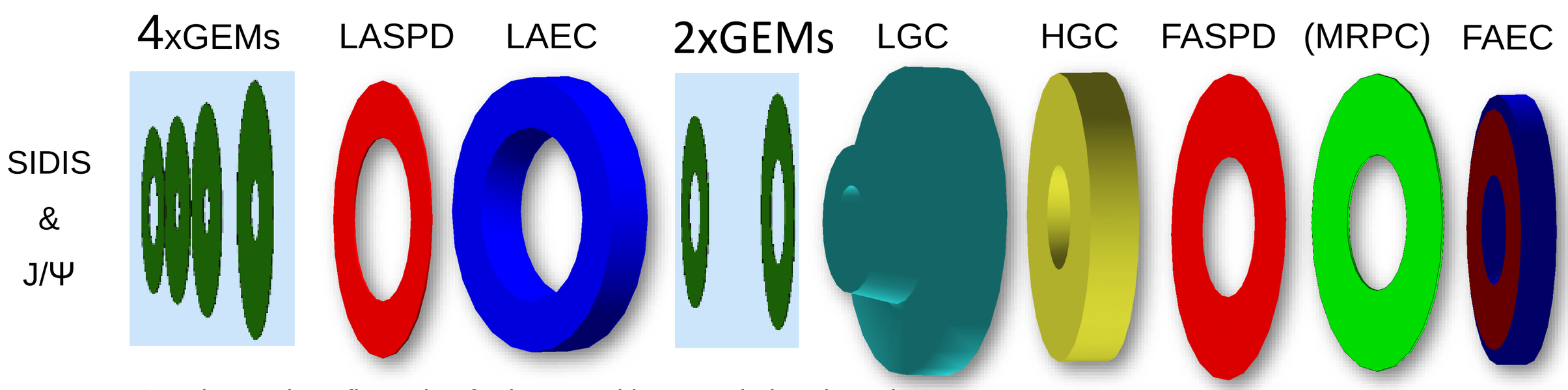
HGC performance at
2.5-3.0GeV, 8-9deg



π efficiency (~0.9)

K_{rej} ~10





MRPC: enhanced configuration for kaon and improved pion detection