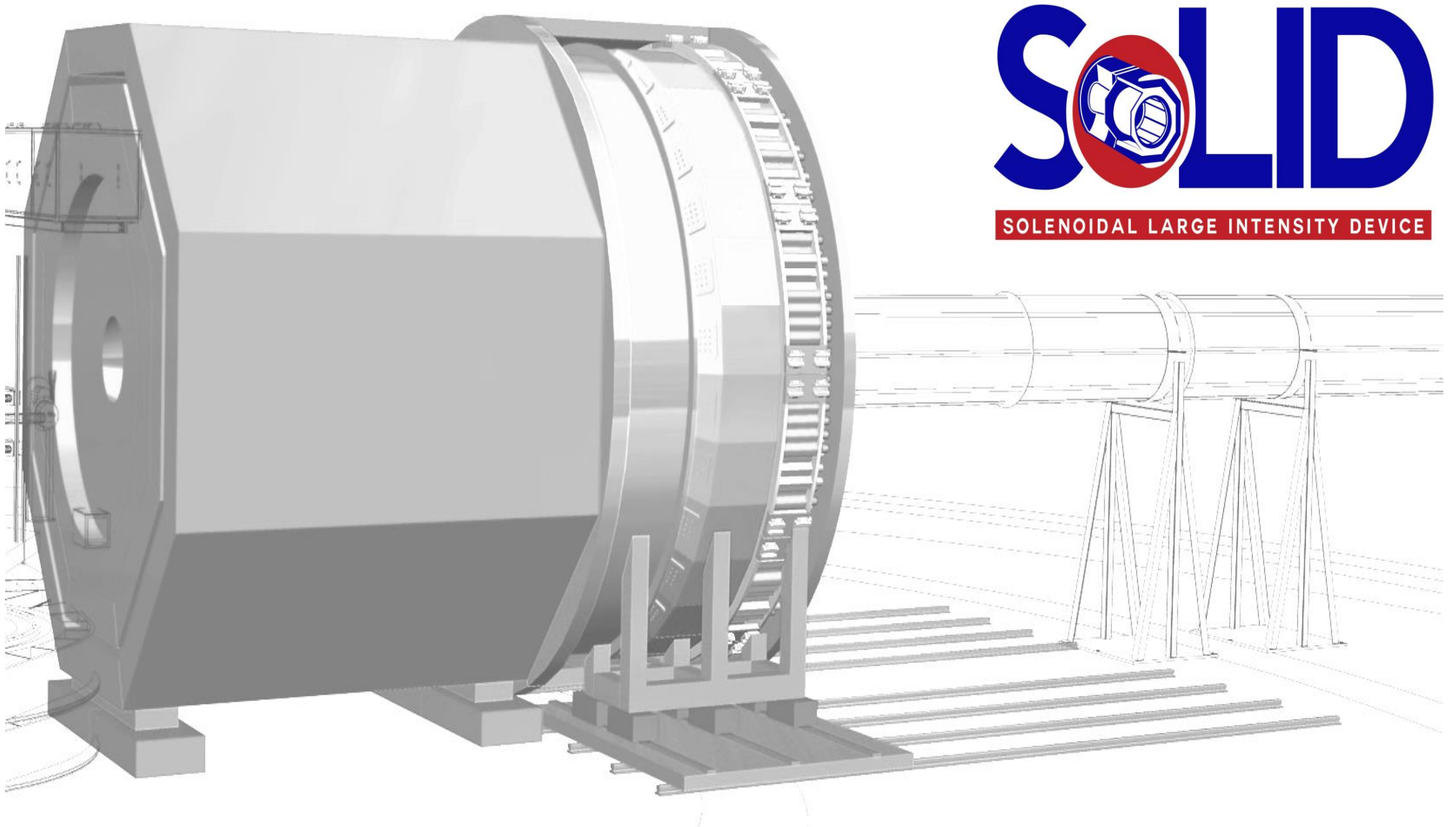
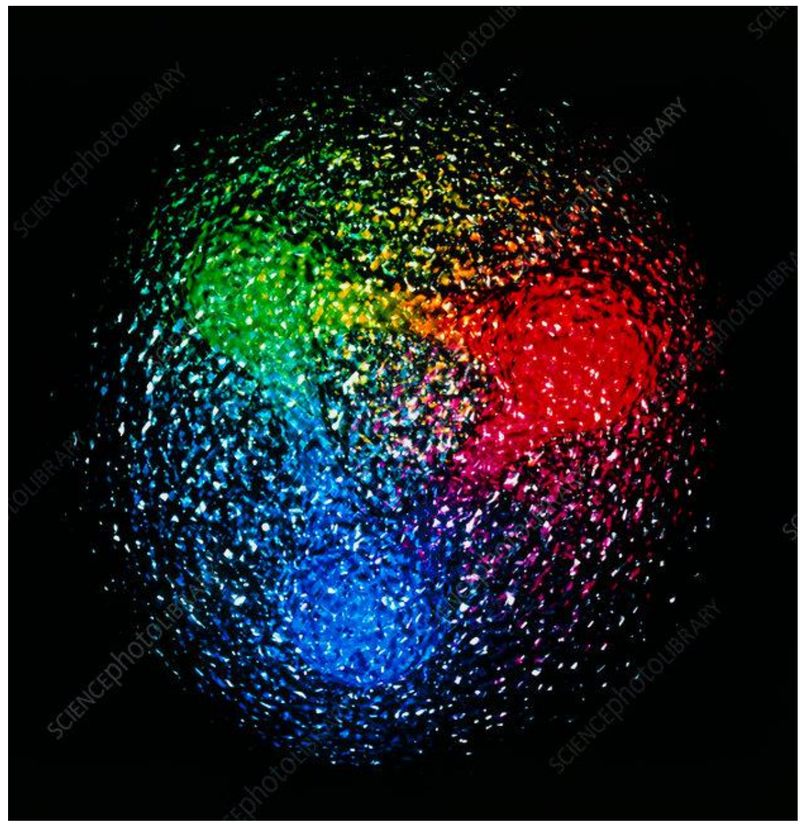
E12-11-108 Jeopardy Update to PAC50:
SoLID SIDIS Experiments with a Transversely Polarized NH_3 Target





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. NH_3 (“p”) 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 NH_3 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 E12-11-108*
- Several results from the original proposal
  - *Collins SSAs for π^+/π^-, as well as Pretzelosity and Sivers SSAs for π^+*
- **Updates in recent years**
  - ***Complementarity to EIC***
  - ***Projections of Transversity TMD and Tensor Charge***
  - ***Projections of Pretzelosity TMD***
  - ***Projections of Sivers TMD***
  - ***Related run group experiments***
- *Summary*

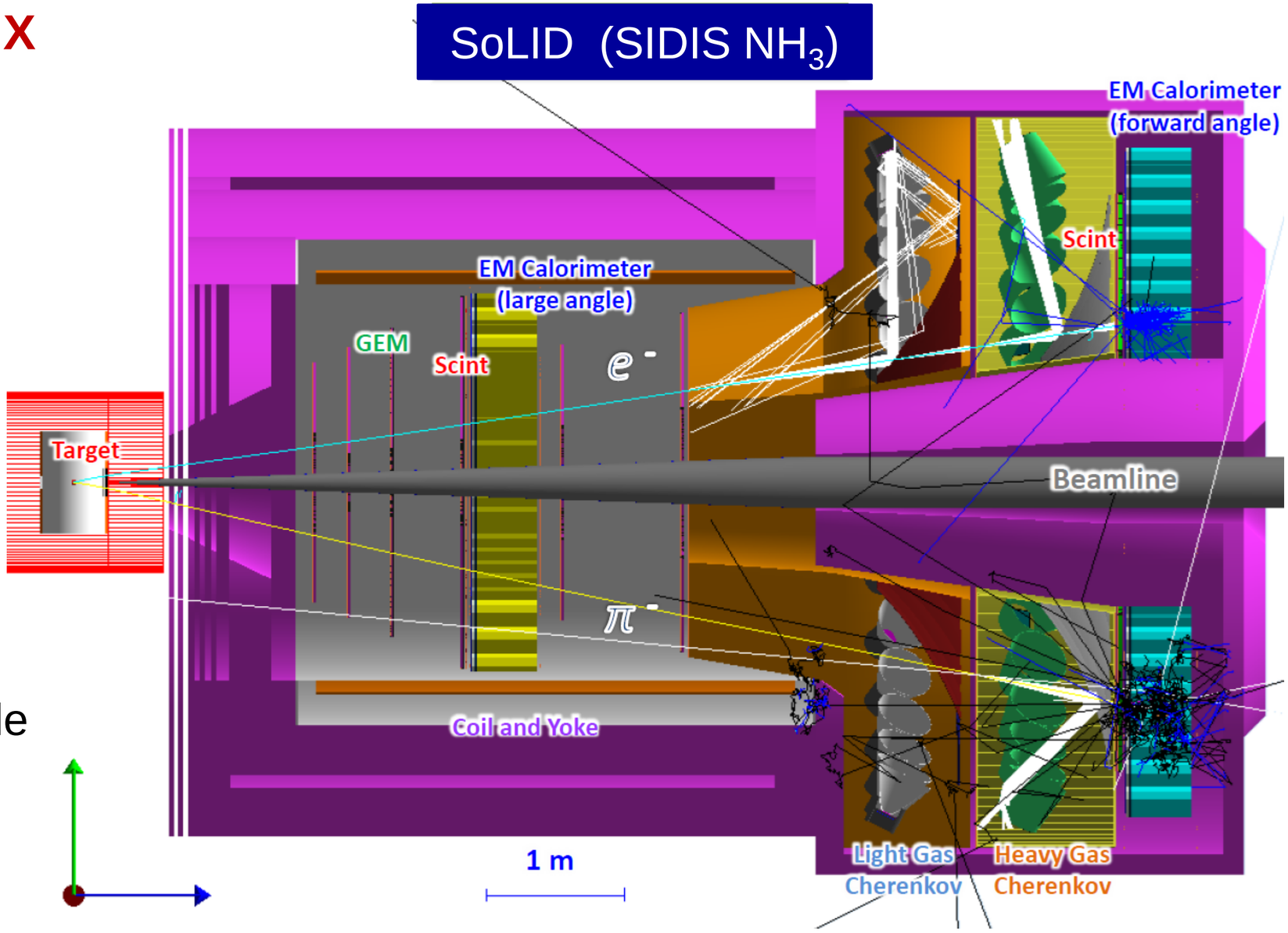
SoLID SIDIS setup with a transversely polarized NH_3 ("proton") target

E12-11-108: **Single Spin Asymmetries on Transversely Polarized NH_3 (proton) @ 120 days**

Rating A **Spokespersons: J.P. Chen, H. Gao (contact), X.M. Li, Z.-E. Meziani**

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

- Target:
  - *Length*: *3 cm*
  - *Polarization*: *~ 70%*
  - *Spin flip*: *≤ 4 hours*
  - *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 E12-11-108 experiment

- Approved number of days: 120

- 90 days requested for the beam on the trans.-pol. NH_3 target
  - *including 7.5 days for dilution measurements, optics, and detector calibrations*

- 4 days requested with a longitudinal target polarization to study the systematics of potential A_{UL} contamination

- 26 days of overhead time requested for regular target annealing

- Major requirements: target spin flip, kaon contamination, sheet-of-flame background shielding
  - *high-rate particles form a sheet-of-flame, due to the large magnetic field in the transverse direction*

- Expected DAQ rates: $<$ 100 kHz
  - *determined to be $\sim$ 79 kHz with the sheet-of-flame background*

- Scattered electrons detected by both Forward-angle and Large-angle detectors;
  Produced pions detected by Forward-angle detectors only

Experimental details for the E12-11-108 experiment

- Momentum coverage: 1.0 - 7.0 GeV/c; Momentum resolution: $\sim$ 3%
- Polar angular coverage: 8 - 24 degree; Polar angular resolution: 3 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: $5.95 \cdot 10^{35}\ cm^{-2}\ sec^{-1}$
- Beam polarimetry: $<$ 3%; Beam current: 100 nA, goes through 5 T magnetic field
- Many other details in ***SoLID (Solenoidal Large Intensity Device) Updated Preliminary Conceptual Design Report, https://solid.jlab.org/***

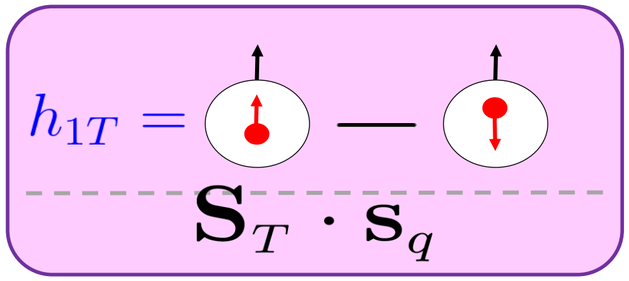
TMDs – confined motion inside the nucleon

Transversely Polarized Nucleon TMDs to be measured by SoLID

→ Nucleon Spin

→ Quark Spin

Transversity



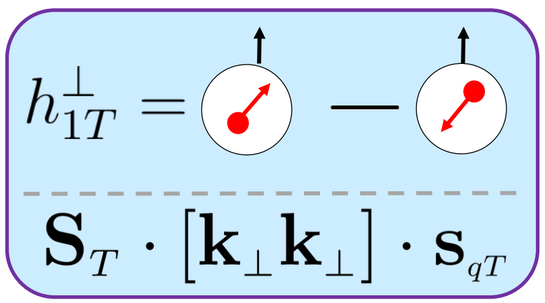
Relevant Vectors

- **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

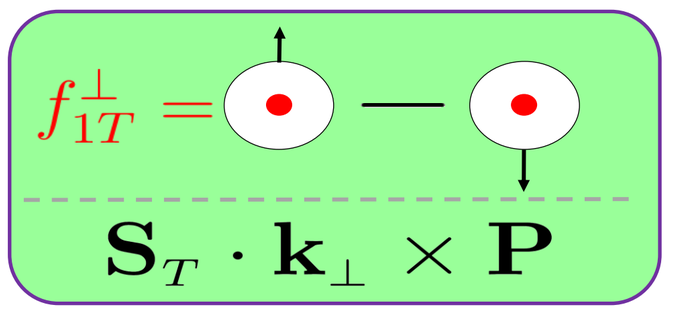
- Transversity → Tensor charge

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

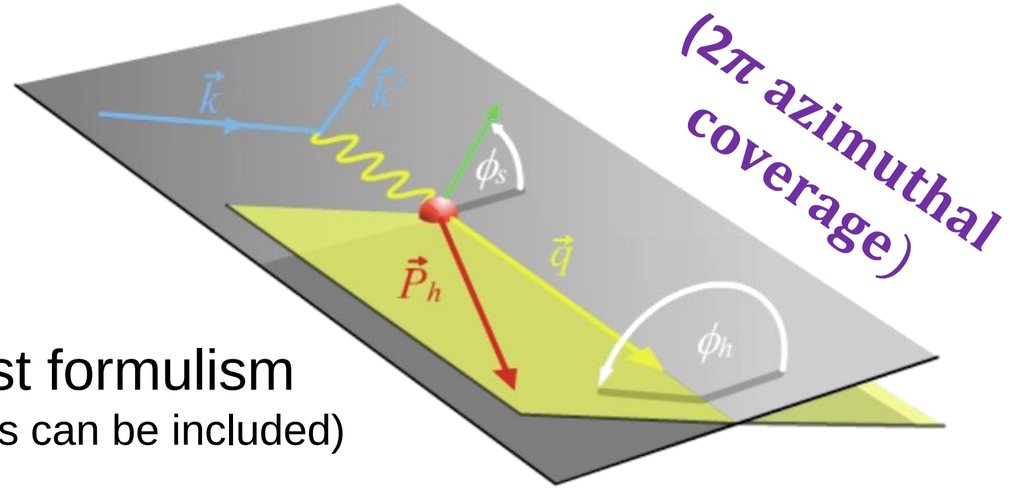


- Nucleon spin - quark orbital angular momentum (OAM) correlation
- Zero if no OAM (model dependence)

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)

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

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

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

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

Collins fragmentation function from e^+e^- collisions

Unpolarized fragmentation function

Transverse SSAs in the SIDIS cross section

- Three transverse SSAs standing in the SIDIS differential cross section

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

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

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

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

Shown at leading order in 1/Q expansion

S_T - transverse component of target-spin direction

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

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

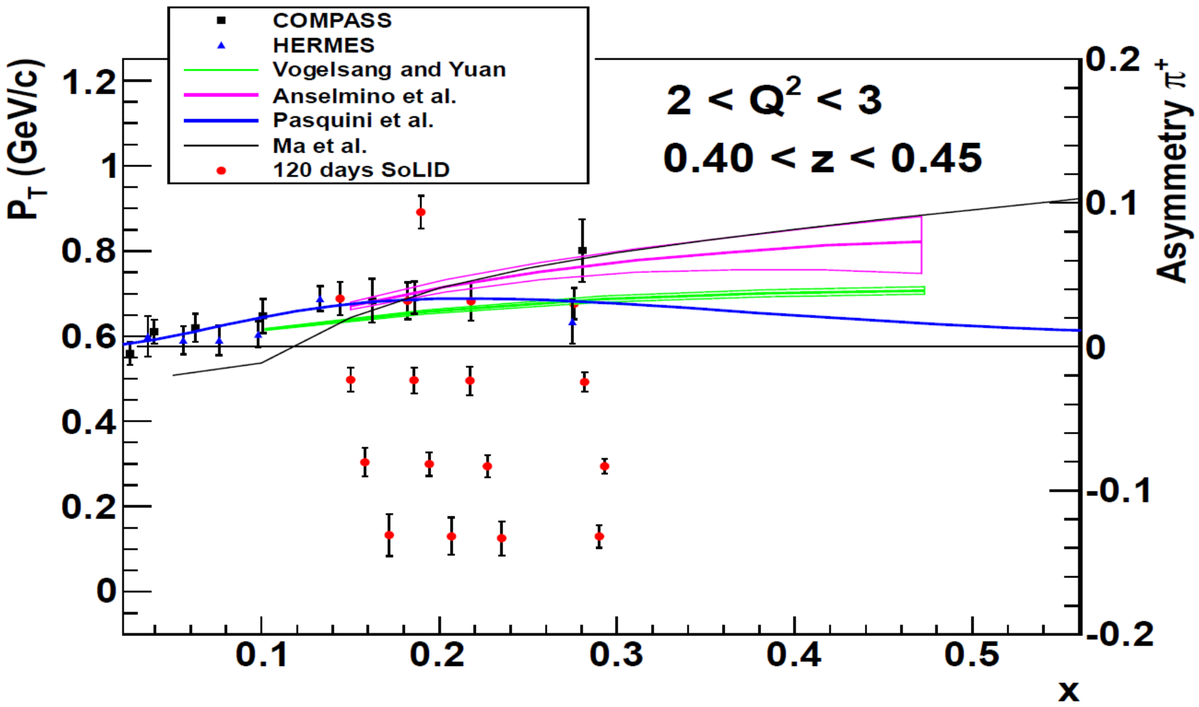
Nuclear physics questions to be addressed by SoLID SIDIS

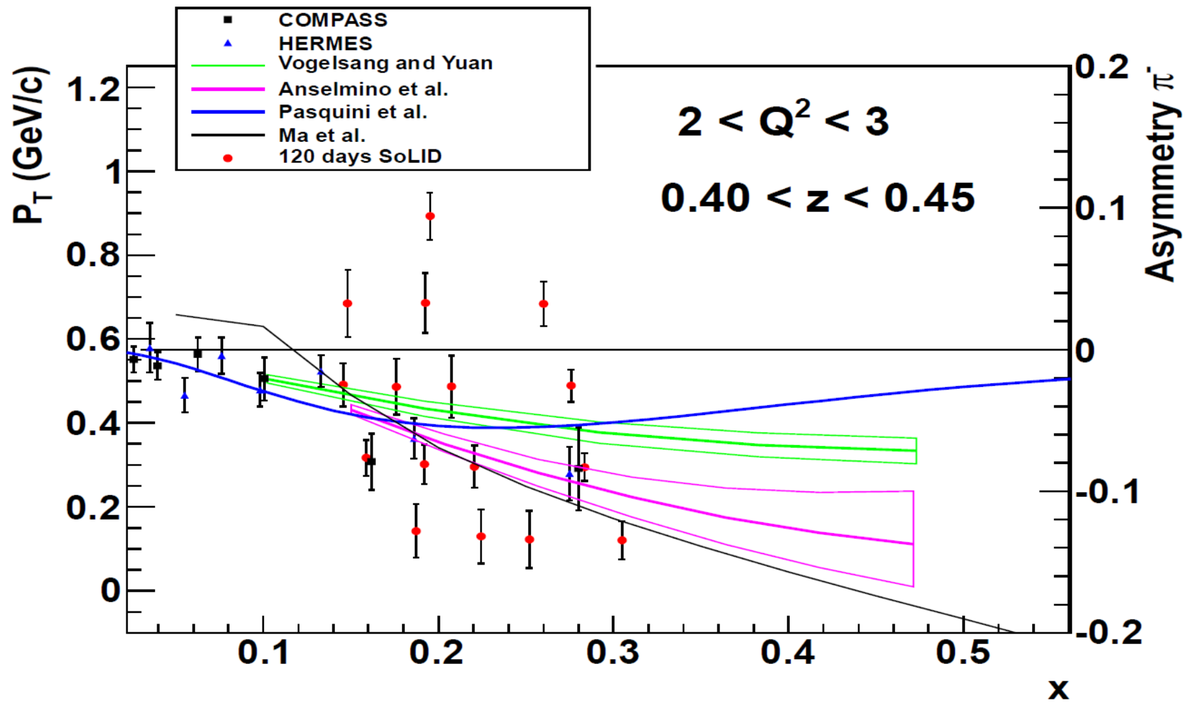
Nuclear physics critical problems to be addressed by the SoLID SIDIS program with both “neutron” and “proton” targets

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

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



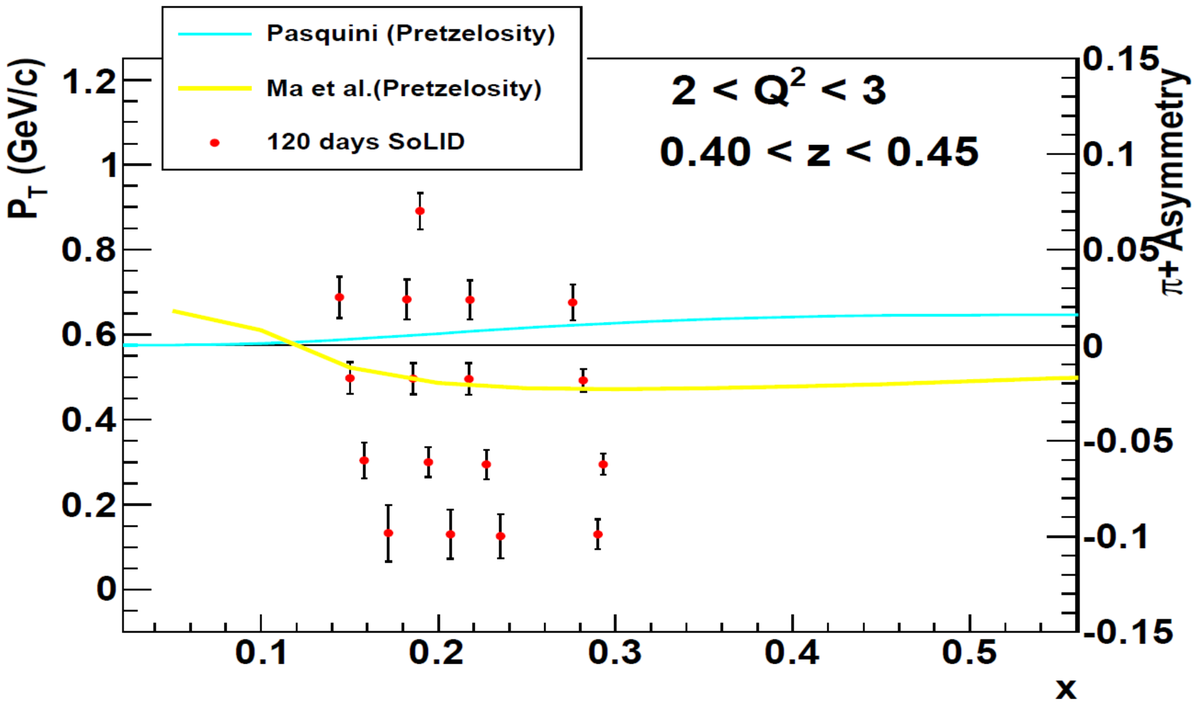


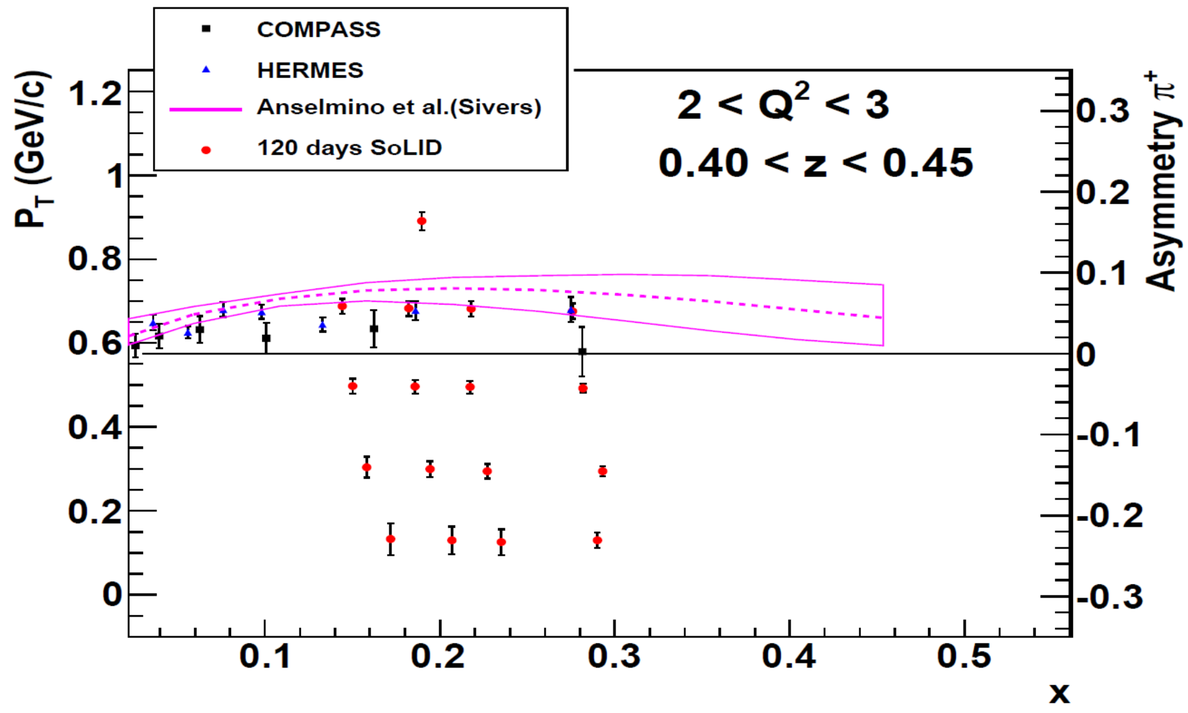
Theoretical predictions:

- W. Vogelsang and F. Yuan, Private communication (2011)
- M. Anselmino, et al., PRD 75, 054032 (2007)
- B. Pasquini, et al., PRD 78, 034025 (2008)
- J. She and B.-Q. Ma, PRD 83, 037502 (2011)

Pretzelosity and Sivers SSAs for π^+ (original projections)

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





Theoretical predictions:

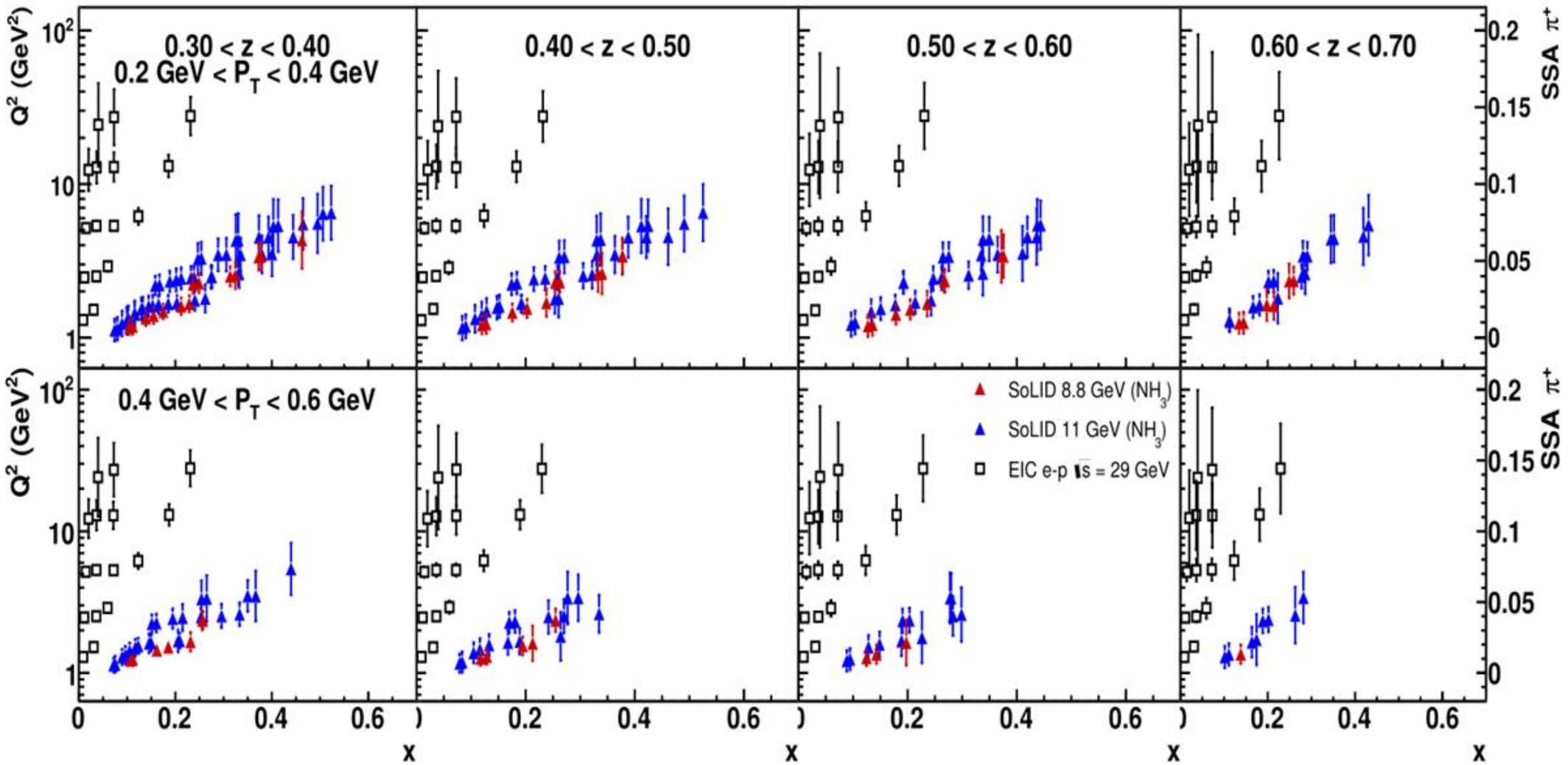
- B. Pasquini, et al., PRD 78, 034025 (2008)
- B.-Q. Ma, et. al, PRD 65, 034010 (2002)

Theoretical predictions:

- M. Anselmino, et al., PRD 72, 094007 (2005)
- M. Anselmino, et al., NPB Proc. Suppl. 191, 98 (2009)

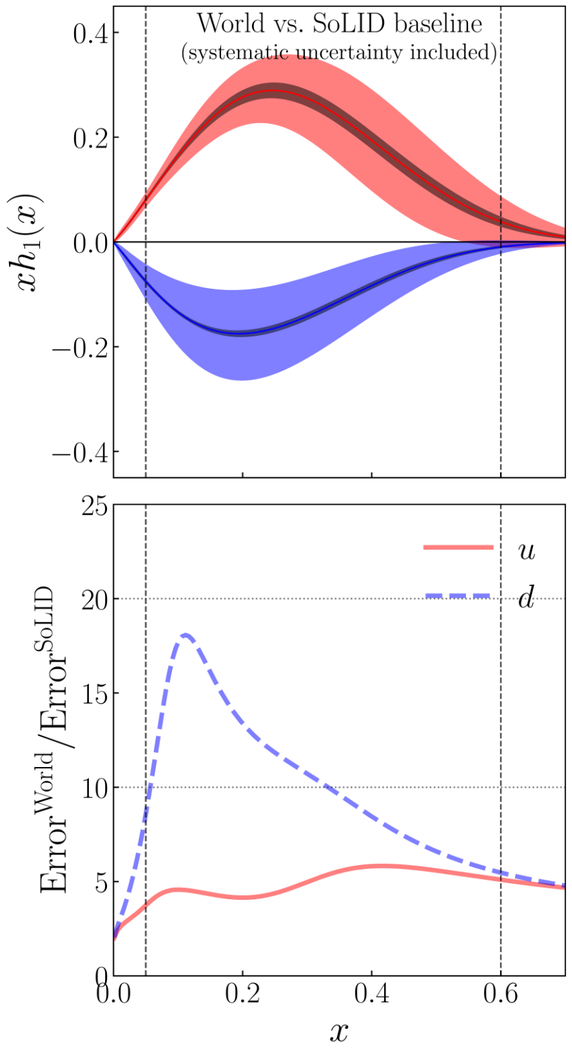
Transverse SSA projections: Complementarity to EIC

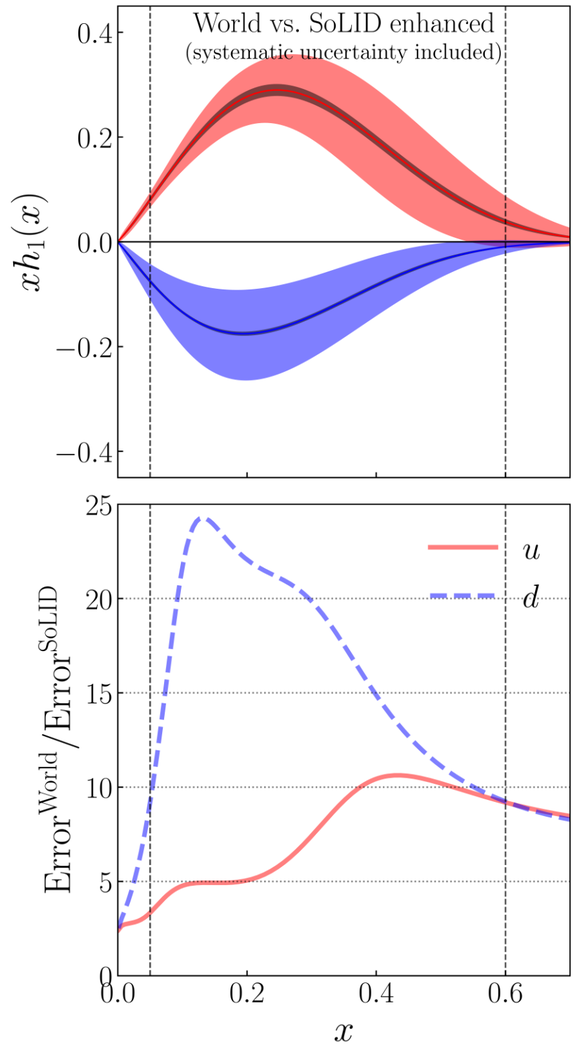
- SoLID SIDIS projections of A_{UT} in various 4-D bins at 11/8.8 GeV beam energies
- Projections at EIC kinematics for the same observable at 29 GeV center-of-mass energy
- SSA scale and uncertainties shown on the right-side axis of the figures
- SoLID and EIC projections synergistic towards each other,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

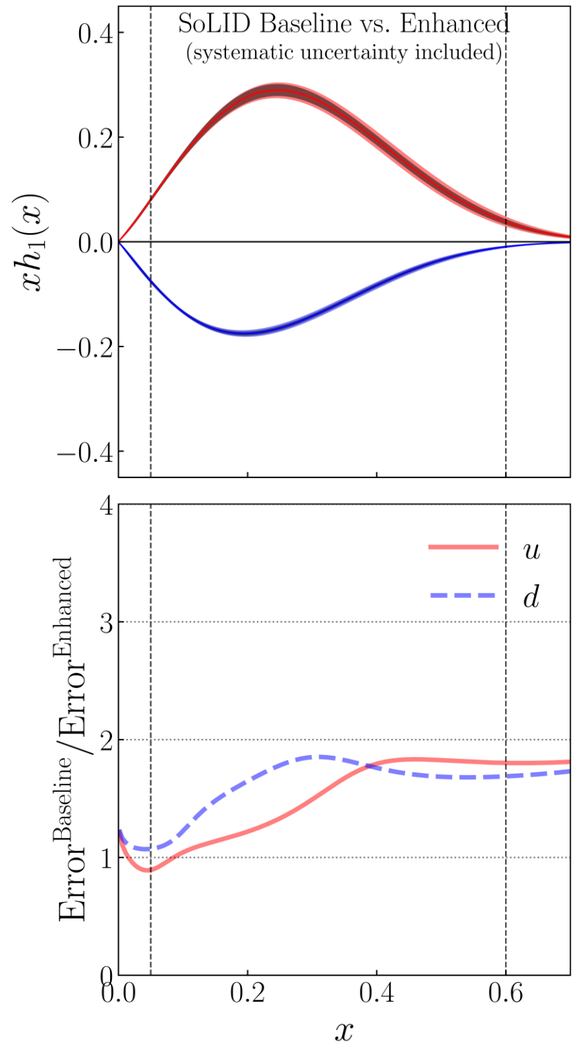


Transversity TMD projections (combined with the "neutron" results)

- 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 $Q^2 = 2.4\ GeV^2$

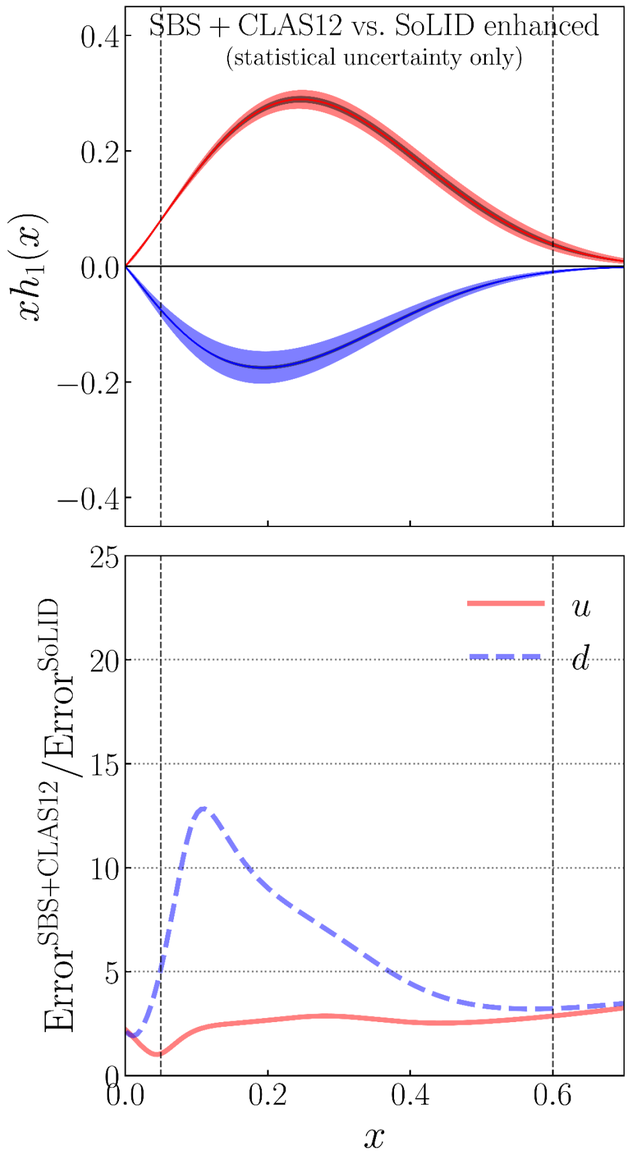




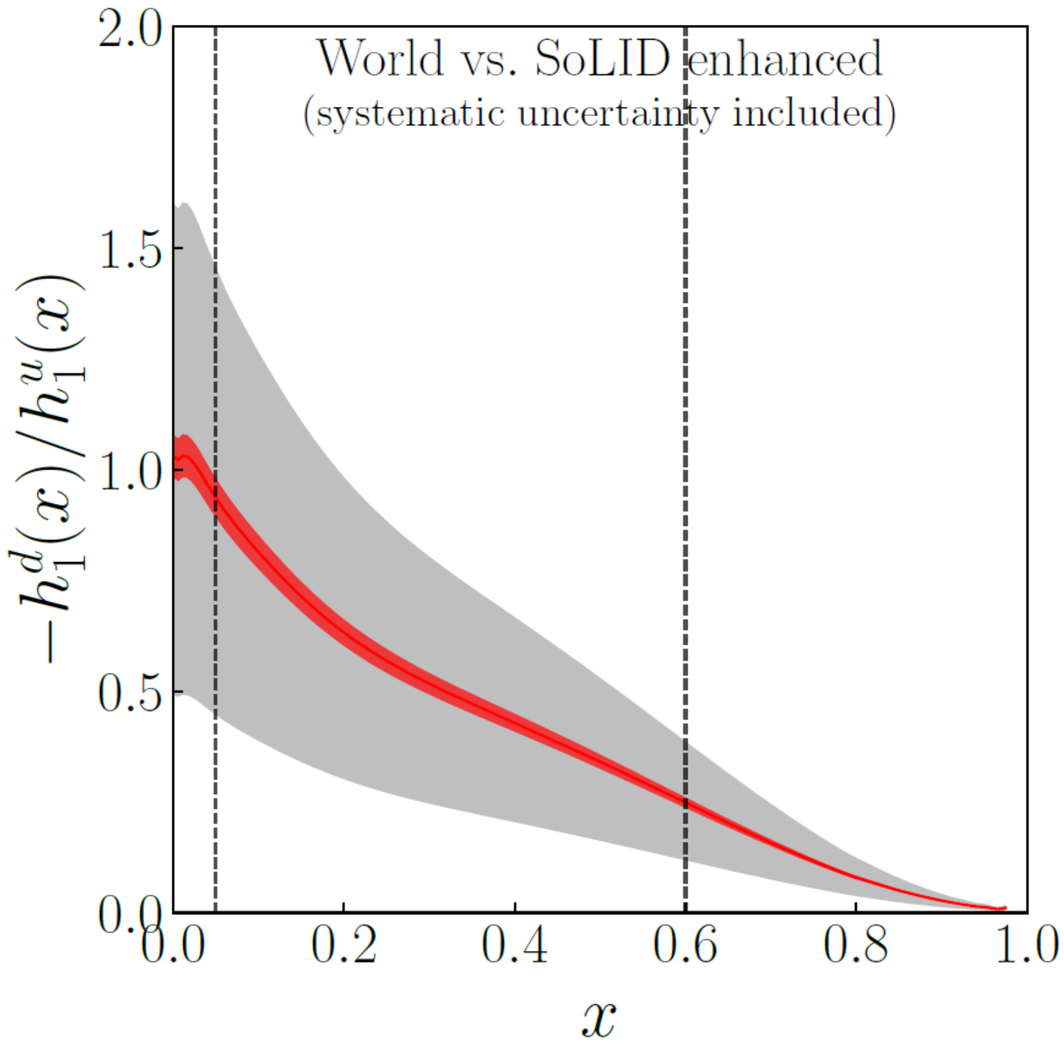


Transversity TMD projections (combined with the "neutron" results)

- 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 $Q^2 = 2.4\ \text{GeV}^2$



Tensor Charge projections (combined with the "neutron" results)

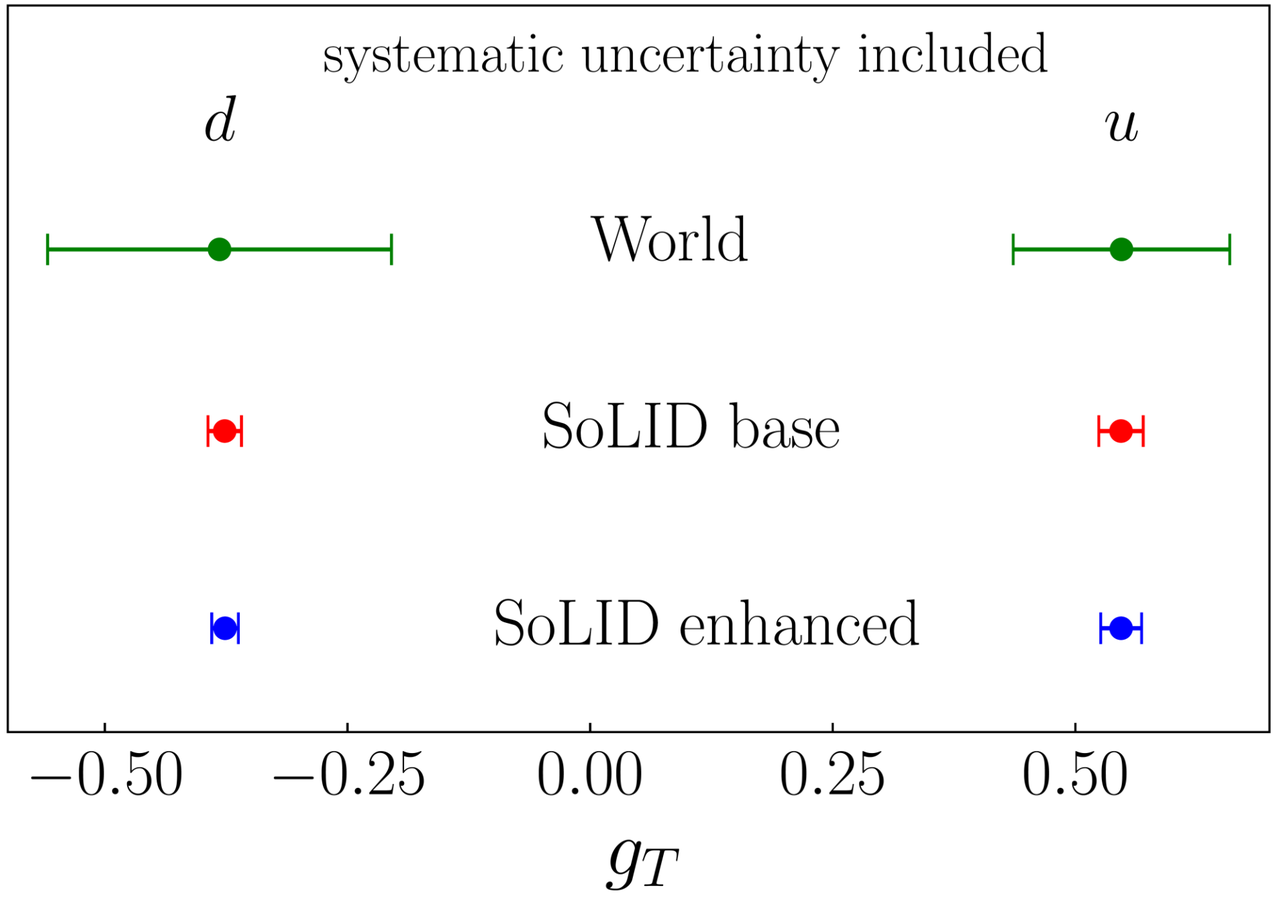
Tensor charge g_T:

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

<u>World data</u>

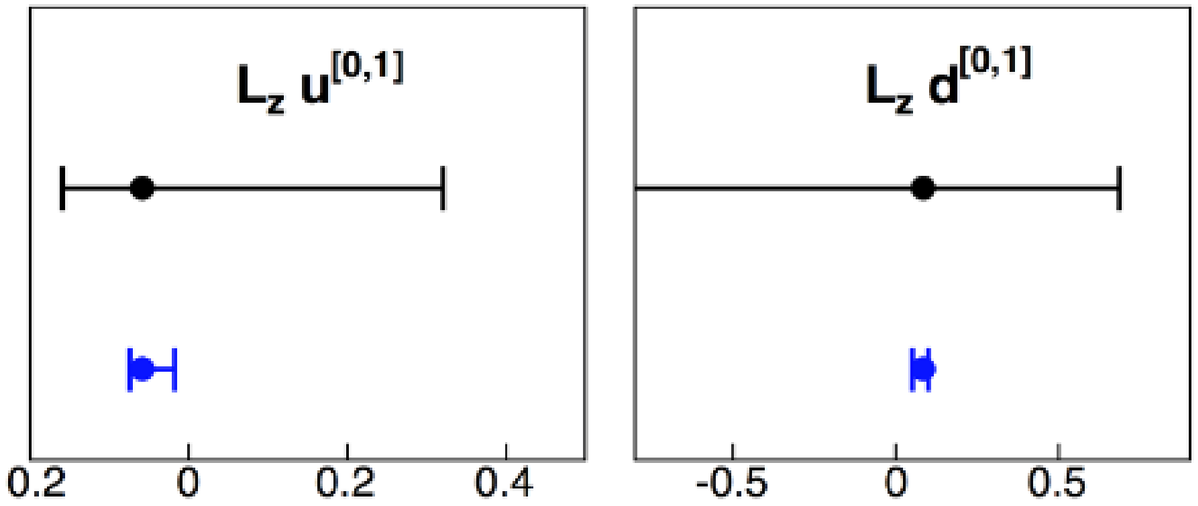
<u>SoLID projections</u> from both ^3He / NH_3 targets at 11 / 8.8 GeV beams

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	0.023 / 0.017	0.021 / 0.014

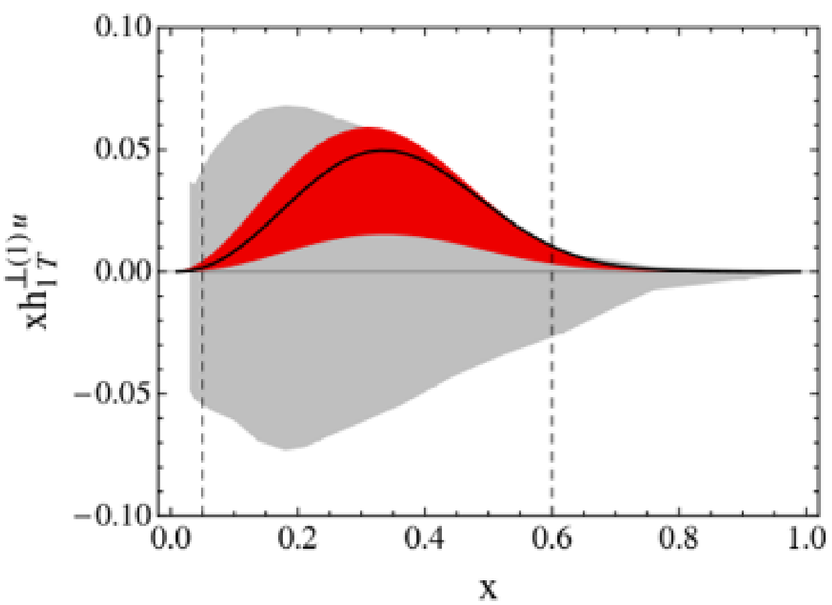
Pretzelosity TMD projections (combined with the "neutron" results)

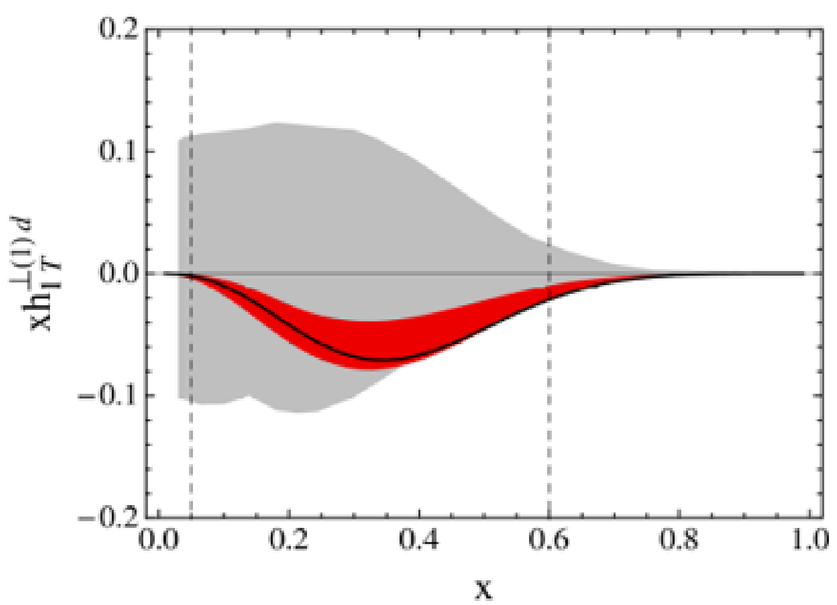


➢ The results obtained at $Q^2 = 2.4\ GeV^2$

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

- Relation of the Pretzelosity TMD distribution to the OAM of quarks
- Black points from Lefky and Prokudin; blue points from SoLID; the results obtained at $Q^2 = 2.4\ GeV^2$; integrated over the kinematic region of $0 < x < 1$





Parametrization by Lefky and Prokudin, PRD 91, 034010 (2015)

SoLID projections from transversely polarized "neutron" and "proton" targets

Sivers TMD projections (combined with the "neutron" results)

- 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
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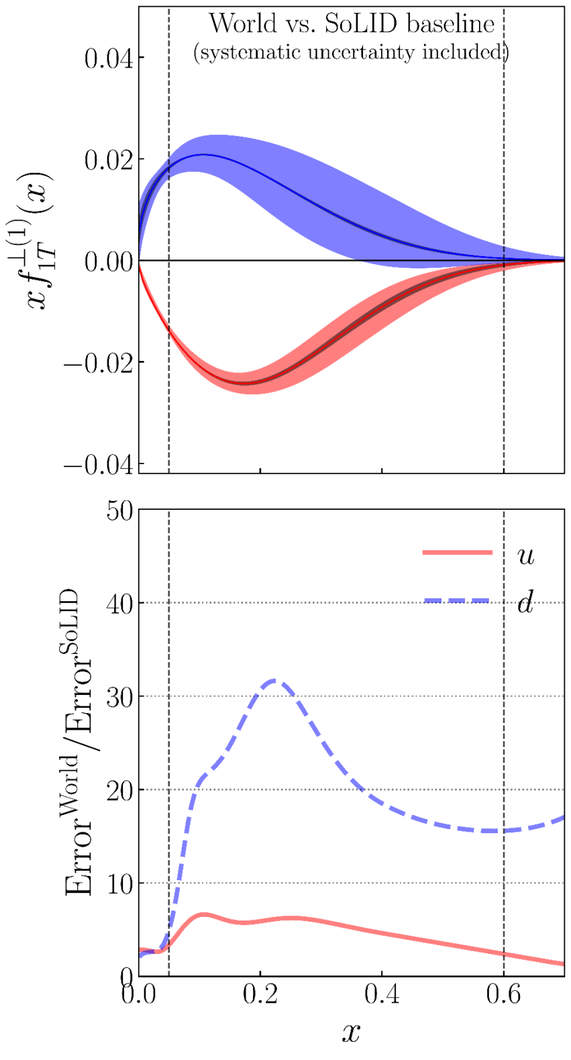
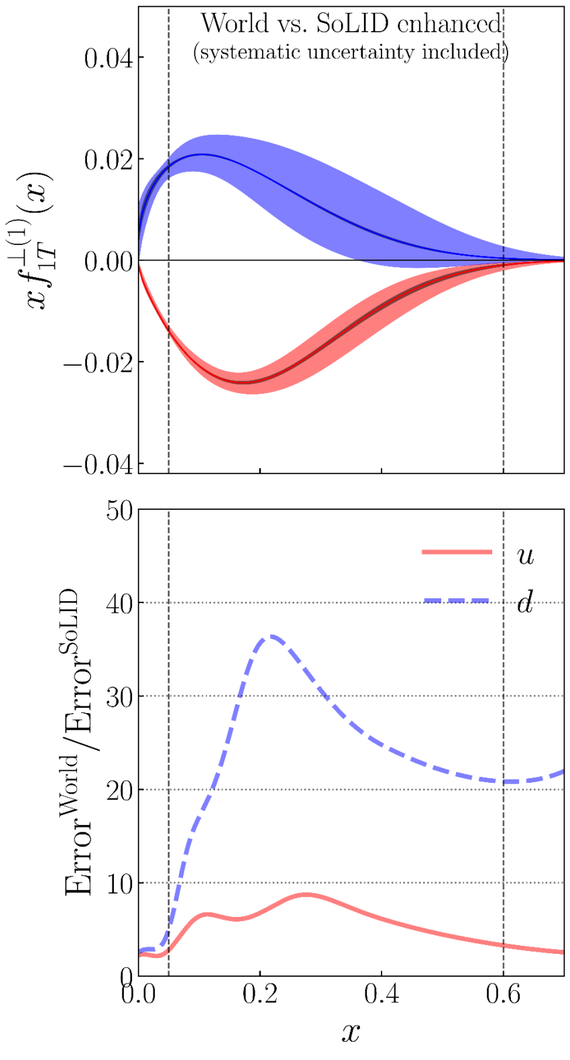
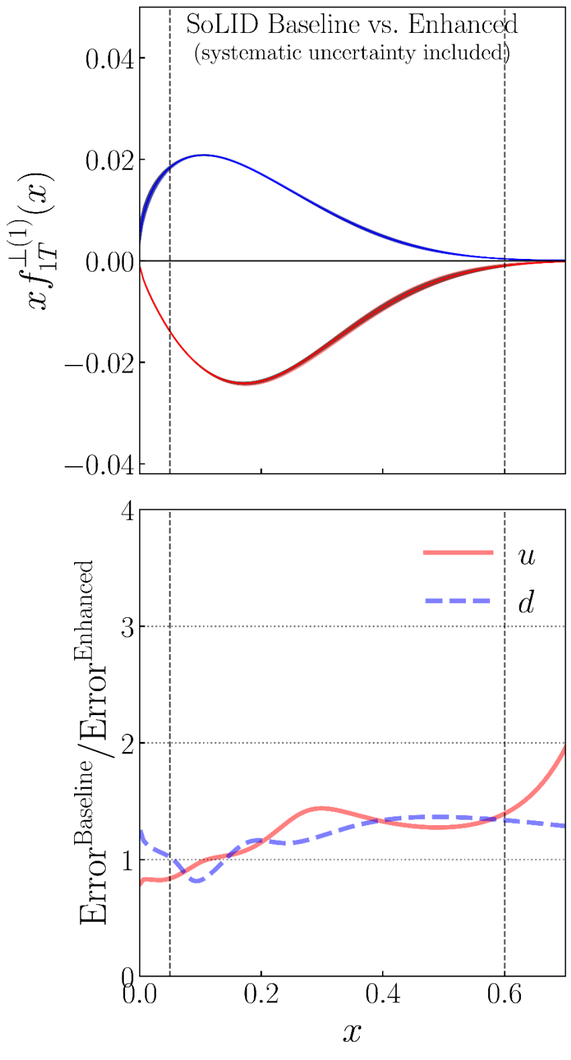
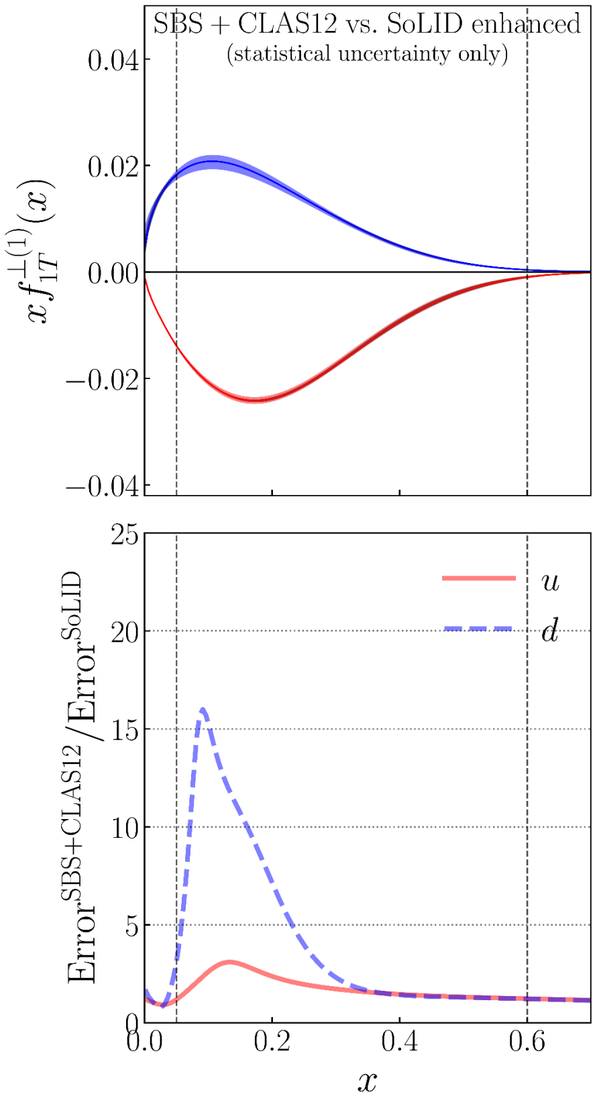


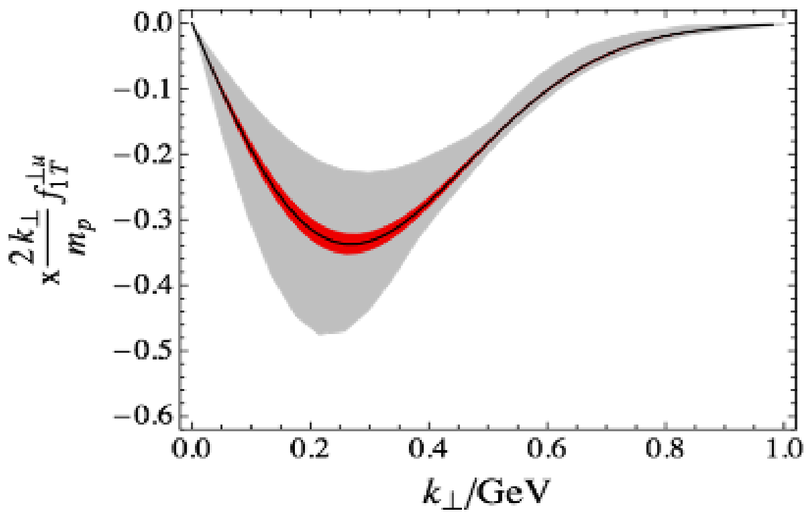


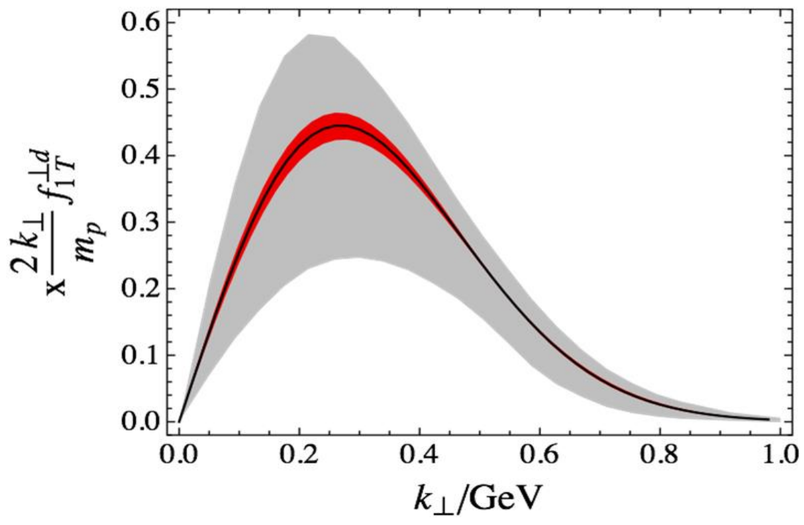


Sivers TMD projections (combined with the "neutron" results)

Same explanation as in the previous slide but compared to SBS+CLAS12 projections







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

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

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

Parametrization by M. Anselmino *et al.*, EPJ A 39, 89 (2009): based on HERMES and COMPASS pion and kaon production data

SoLID projections with transversely polarized "neutron" and "proton" targets

E12-11-108 -- related run group experiments

Approved two Run Group Experiments

1. SIDIS in Kaon Production with Transversely Polarized NH_3 and ^3He 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*

2. A_y: Target Single Spin Asymmetry Measurements in the Inclusive Deep-Inelastic Reaction on Transversely Polarized Neutron (^3He) 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*

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* (*see Backups*)
- Impactful results to be obtained in the first three years of SoLID operations with ^3He 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 ^3He targets, as well as NH_3 trans.-pol. target
  - *Enhancing our knowledge on light and sea quark TMD distributions inside the nucleon, 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

- *Dilution effects*: estimated based on target materials and characteristics

➢ Average statistical uncertainties on the separated SSAs: $\sim 1.4 \cdot 10^{-2}$ (absolute) for 674 bins

Systematic uncertainty budget

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

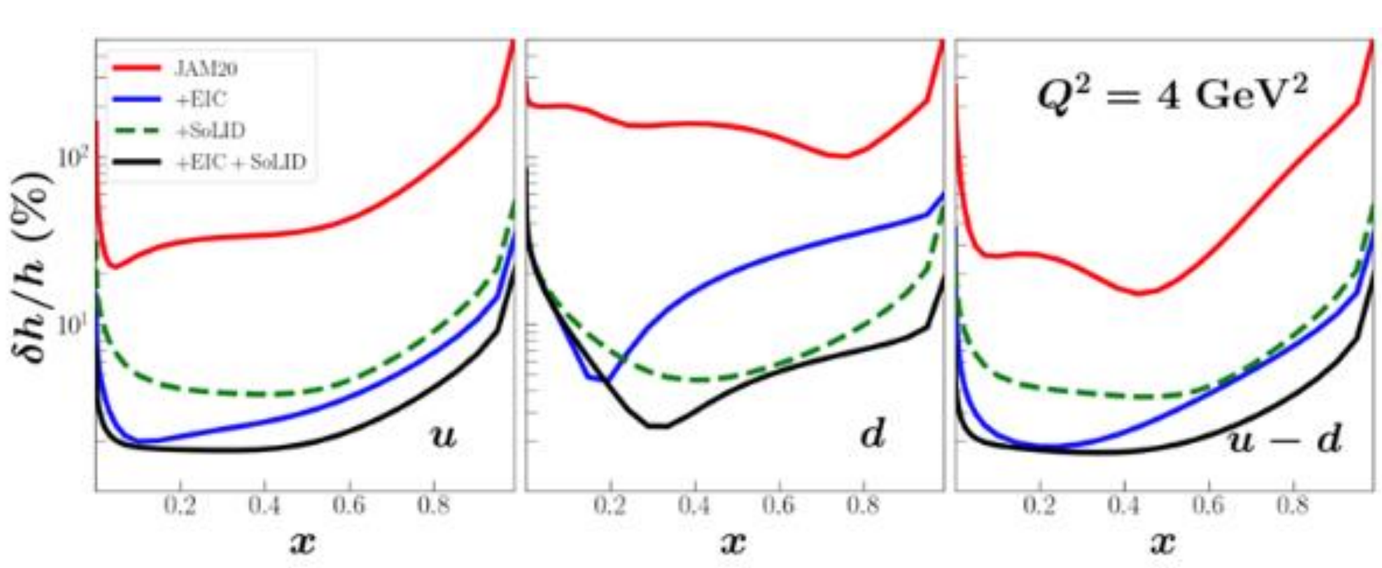
- The uncertainty sources are described on slide 12th

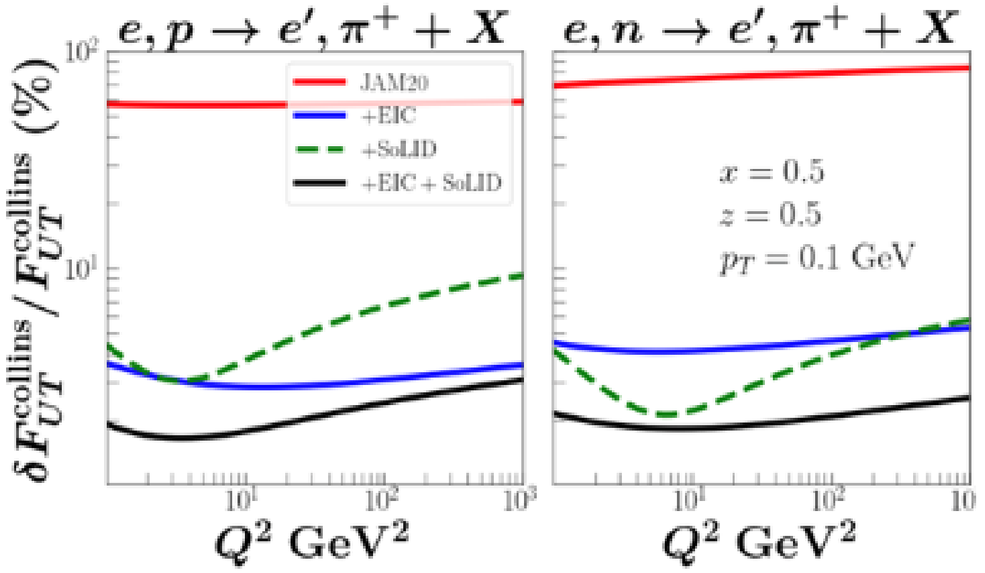
Source (Type): NH_3 (E12-11-108)	**Collins π^+**	**Collins π^-**	**Sivers π^+**	**Sivers π^-**
Raw asymmetry (Abs.) **Detector resolution (Abs.)**	**6.5×10^{-4}** **$< 10^{-4}$**	**6.5×10^{-4}** **$< 10^{-4}$**	**6.5×10^{-4}** **$< 10^{-4}$**	**6.5×10^{-4}** **$< 10^{-4}$**
Target polarization (Rel.)	**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%**

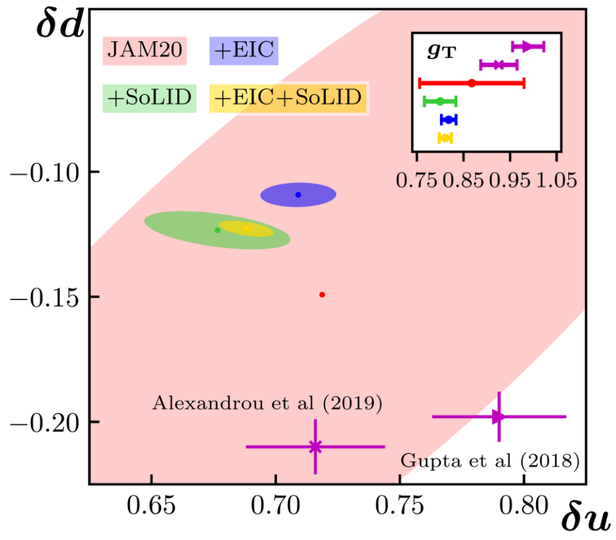
Transversity TMD projections (combined with the "neutron" results)

- Left three plots: the ratio of the Transversity error to its central value for *u*, *d*, and *u* − *d* as a function of x
- Right two plots: The ratio of the error of the Collins structure function to its central value as a function of Q^2

Nobuo Sato, Private communication; Gamberg, et al., PLB 816, 136255 (2021)







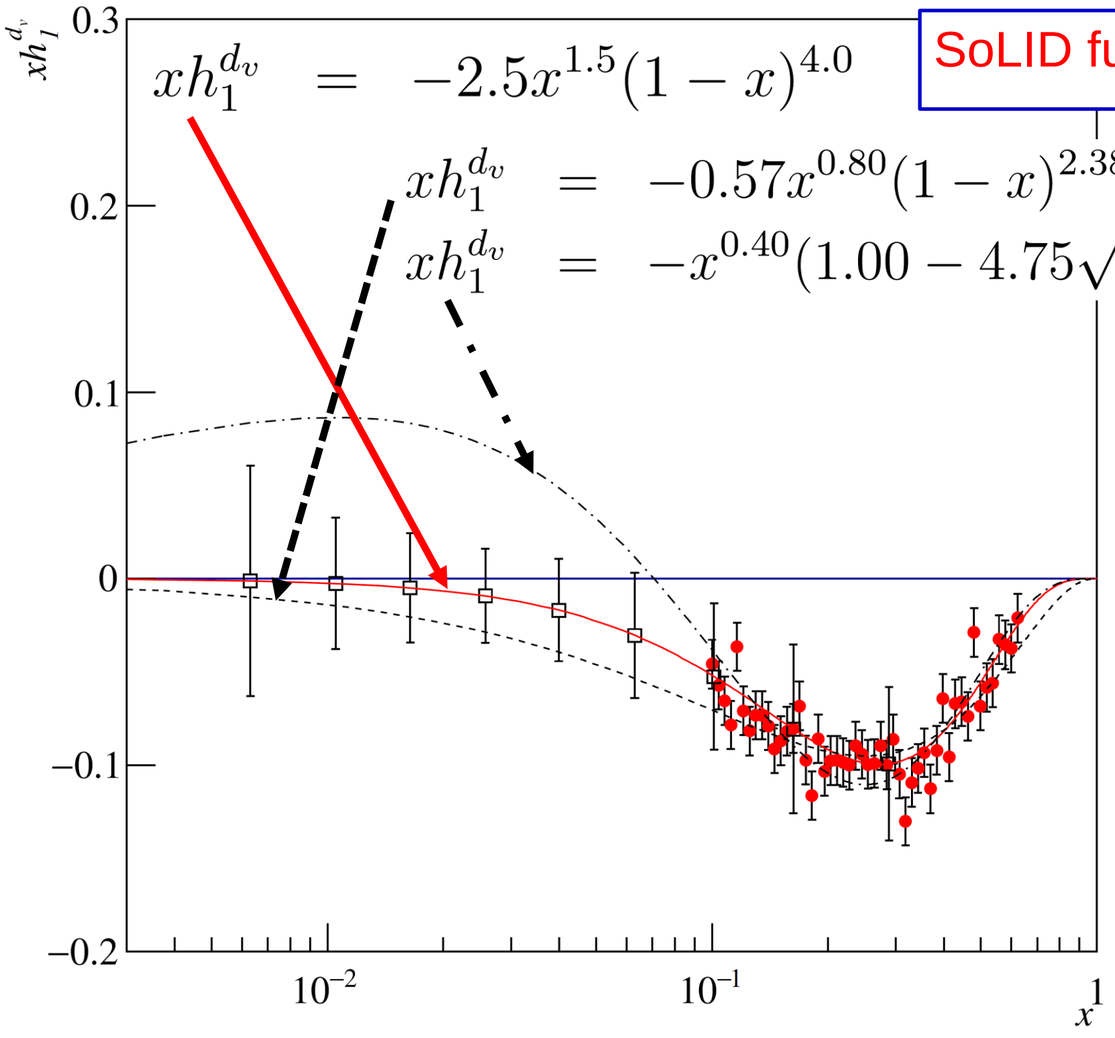
$$\langle \mathrm{P,S}|\overline{\psi}_q i\sigma^{\mu\nu}\psi_q|\mathrm{P,S}\rangle = g_T^q \overline{u}(\mathrm{P,S}) i\sigma^{\mu\nu} u(\mathrm{P,S})$$

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

- Extraction of the tensor charges for both EIC and SoLID projection data
- Figure from Gamberg, *et al.*, PLB 816, 136255 (2021)

Transversity TMD projections (combined with the "neutron" results)

- SoLID and COMPASS-II measurements to be **complementary**
- Assume no uncertainty due to Q^2 evolution and knowledge of the Collins functions
- Generate values for *d* quark transversity, assuming a parametric function that is used by SoLID
- Compare the generated SoLID data with two other functions used by COMPASS-II



SoLID function and **red projection points** in the region 0.06 < x < 0.6

COMPASS-II two functions

COMPASS-II **square projection points** overlayed on SoLID red curve in the region 0.008 < x < 0.21

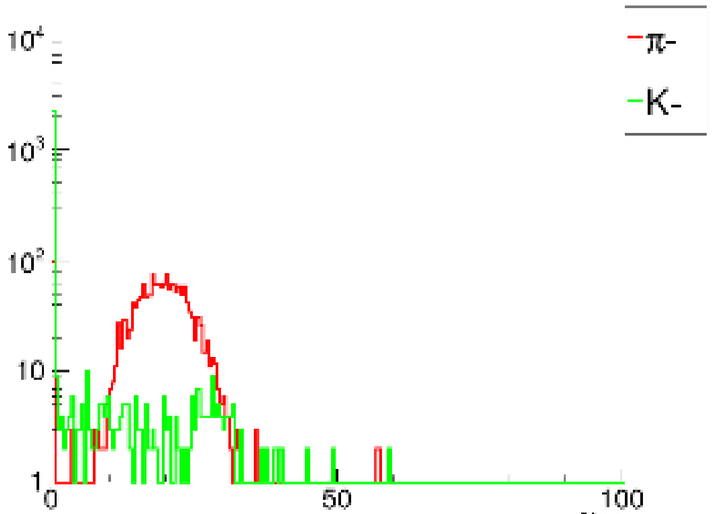
- At large x, SoLID will provide very accurate measurements for g_T
- At smaller x, the COMPASS-II data will provide a contribution to g_T with an uncertainty of ± 0.044
- Without having COMPASS-II data, tensor charge evaluation from only SoLID data will be affected by the error of the integration between 0 and 0.1, and the result will anyhow be model-dependent

The figure is from
d-Quark Transversity and Proton Radius: Addendum to the COMPASS-II Proposal

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

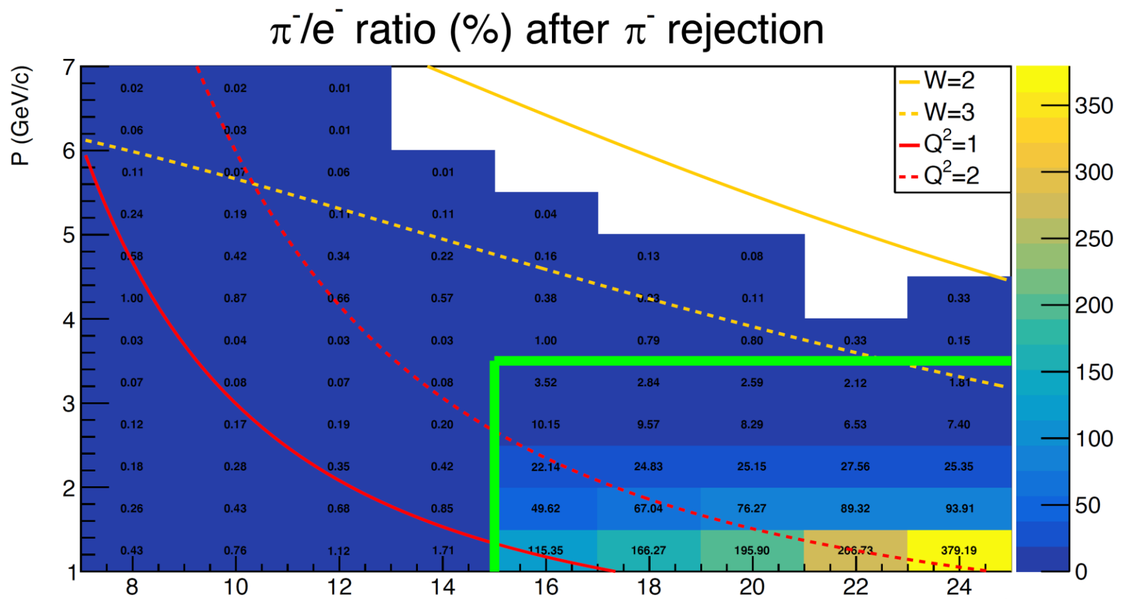
HGC performance at
2.5-3.0GeV, 8-9deg

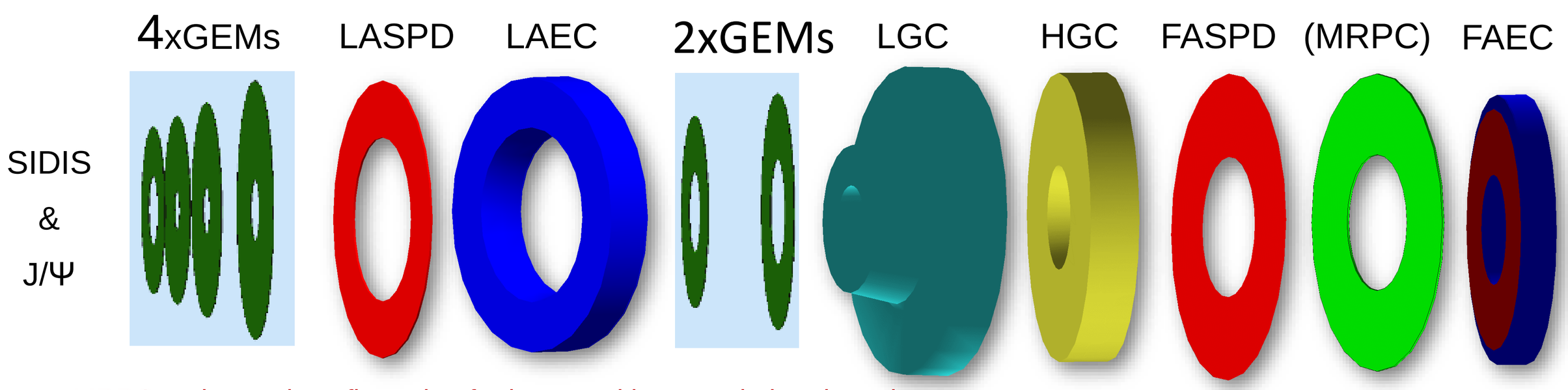


π efficiency (~0.9)

K_{rej} ~10

Combined light gas Cherenkov and Calorimeter detector performance





MRPC: enhanced configuration for kaon and improved pion detection