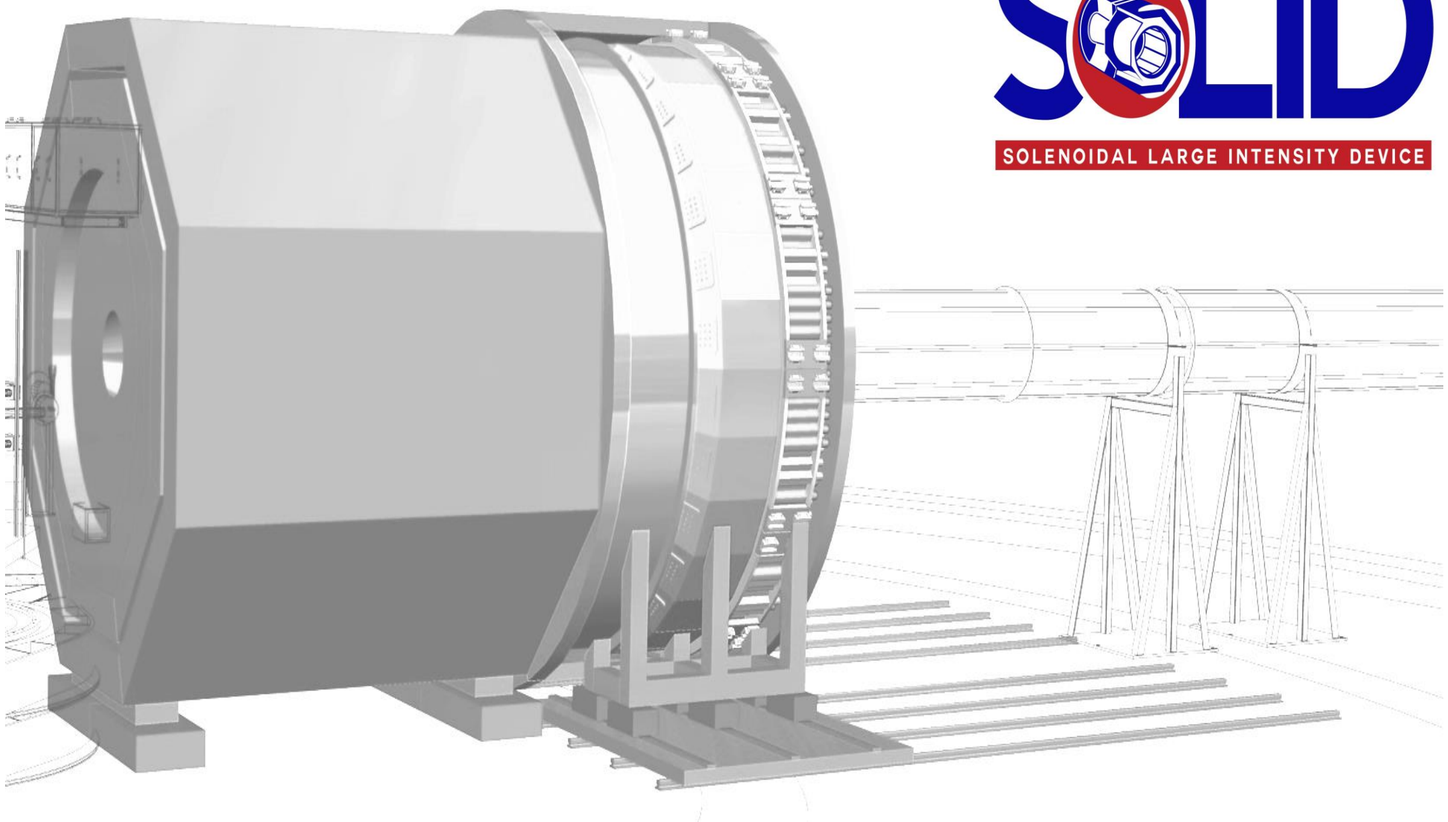
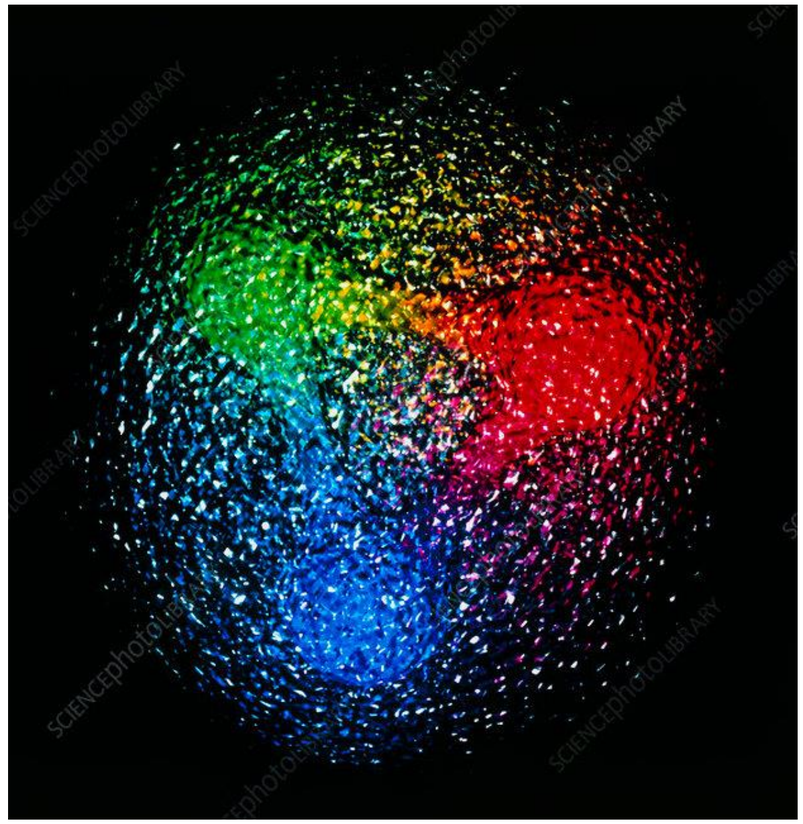
Target Single Spin Asymmetry in Semi-Inclusive Deep-Inelastic $(e,e'\pi^{\pm})$ *Reaction on a Transversely Polarized Proton Target*





Vladimir Khachatryan

Physics Department, Duke University

For E12-11-108 and SoLID Collaborations

JLab PAC50, July 11-15, 2022

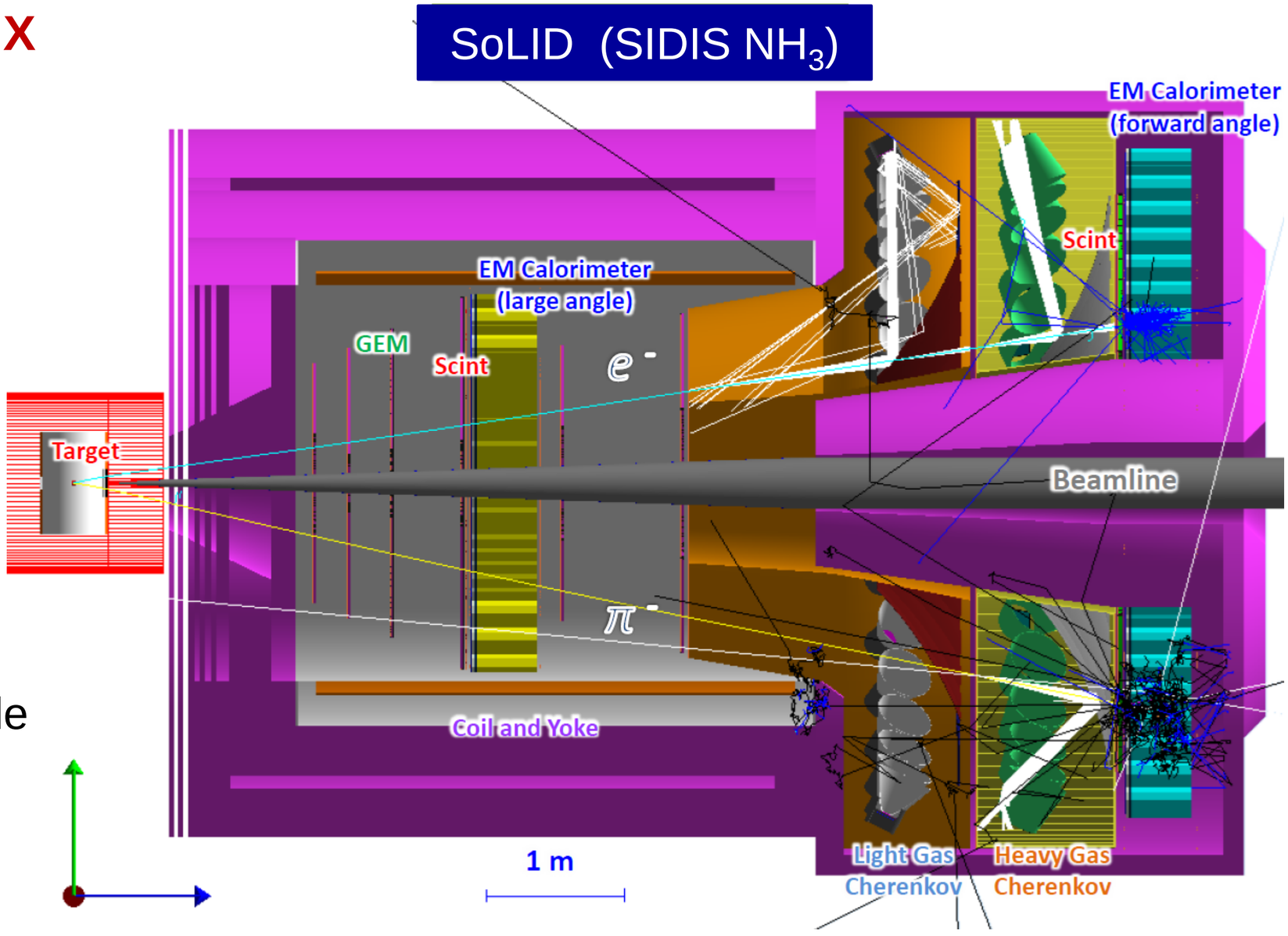
SoLID SIDIS setup with a transversely polarized NH_3 ("proton") target

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

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

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

- Beam:
  - *energy*: *8.8 GeV and 11 GeV*
  - *current*: *100 nA*
  - *polarization (not for SSA)*: *85%*
  - *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



Several details on the E12-11-108 experiment

- Approved number of days: 94 + 26 = **120**

- 90 days requested for the beam on the trans.-pol. NH_3 target
  - *55 days at 11 GeV, 27.5 days at 8.8 GeV*
  - *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

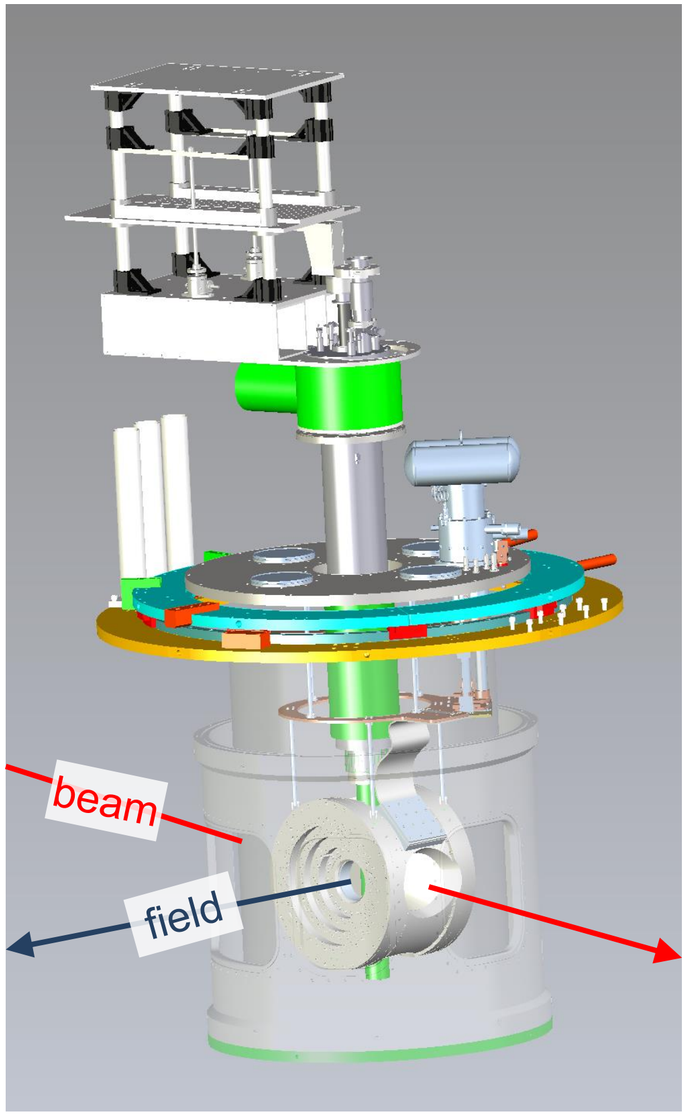
- 26 days of overhead time requested for regular target annealing
  - *no need for an electron beam*
  - *can be shared with other regular activities such as detector maintenance*

- Major requirements: target spin flip, kaon contamination, sheet-of-flame background handling

- Expected DAQ rates: < 100 kHz

NH_3 target characteristics and status

- Polarimetry: ~ 3%, spin flip: ≤ 4 hours, polarization: ~ 70%, thickness: 2.826 cm
- Polarized luminosity: $0.84 \cdot 10^{35}$ cm^{-2} sec^{-1}, total luminosity: $5.95 \cdot 10^{35}$ cm^{-2} sec^{-1}



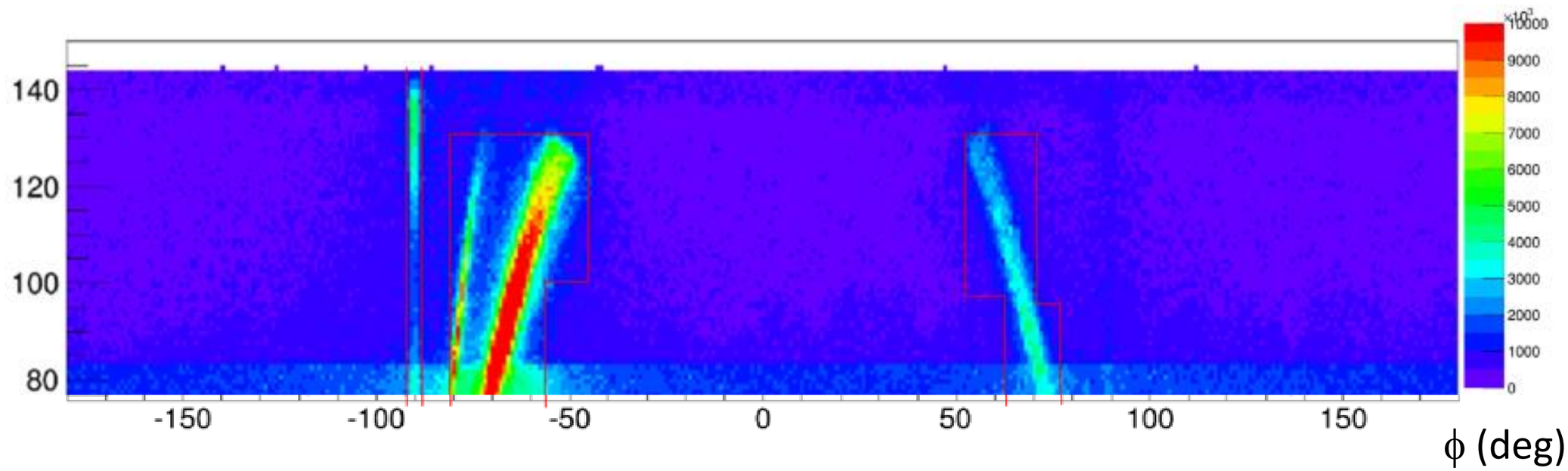
- NH_3 target polarized at 1K and 5T
- New superconducting solenoidal magnet with power-supply and cryogenic system
- Existing infrastructure from previous g2p/GEp experiments
  - *1 K refrigerator*, *vacuum chamber*, *microwaves*
- New JLab NMR system for polarization measurements
- New 12,000 m^3/h pumping system

SoLID requirement beyond transverse target:
restore beam line chicane as in g2p/Gep experiment – folded in as capital equipment for outyears (FY24-FY26)

Sheet-of-flame background

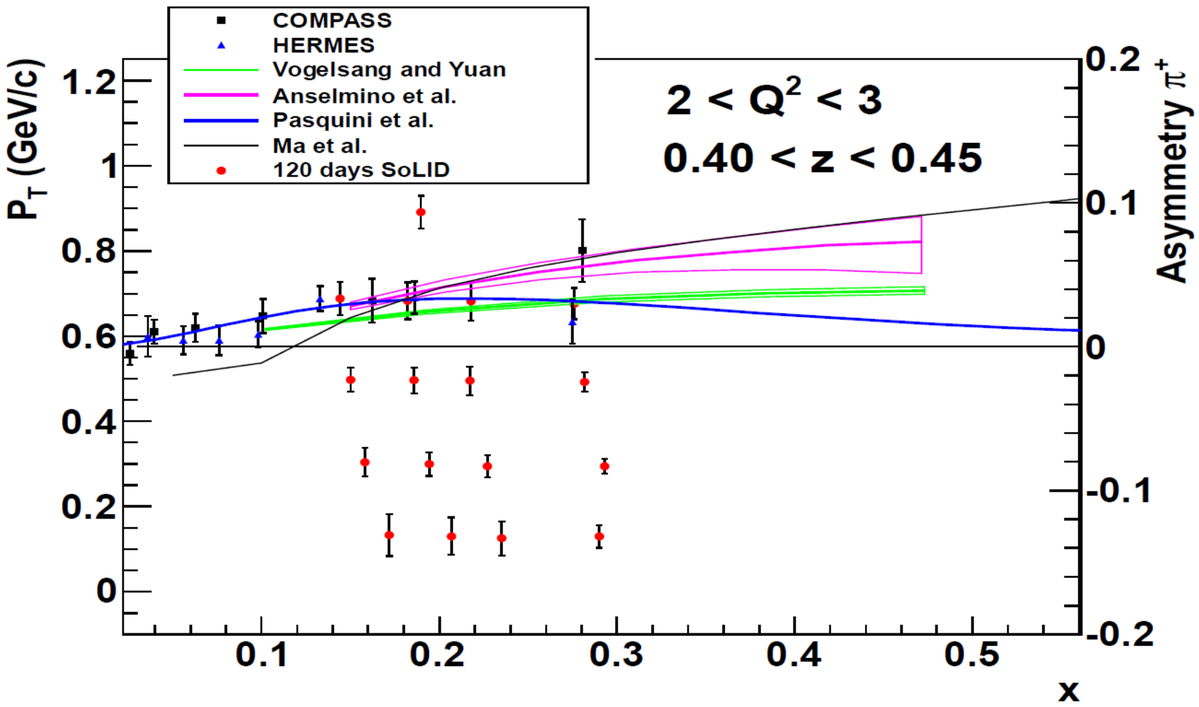
- High-rate particles form a sheet-of-flame type background, due to the large magnetic field in T direction
- Handle the SOF background properly to avoid damage to the entire SoLID apparatus
  - *turn off the high voltage*
- Determine the total trigger rate by using the combined trigger response
  - *from the forward-angle EC + LGC + SPD*
  - *from the large-angle EC + SPD*
- Current expected DAQ rate estimated to be ~ 79 kHz, less than required 100 kHz threshold

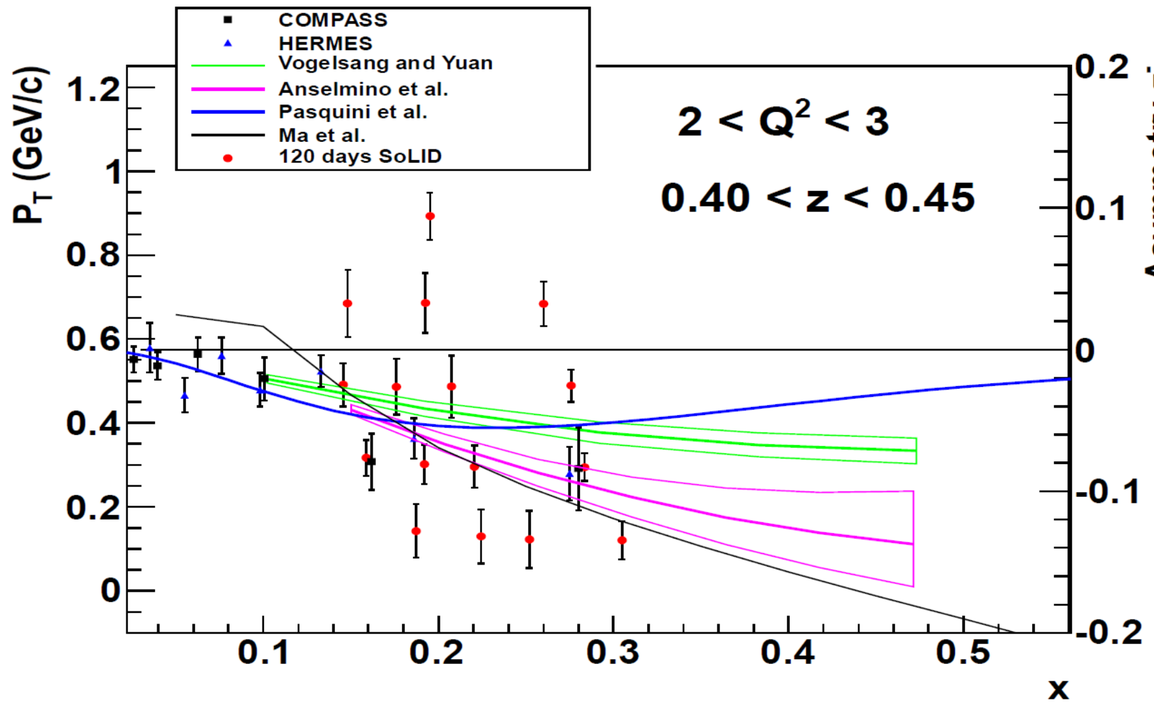
SOF example on LAEC



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





Good momentum and angular resolutions in 4-D binning over the kinematic variables (x, z, Q^2, P_T)

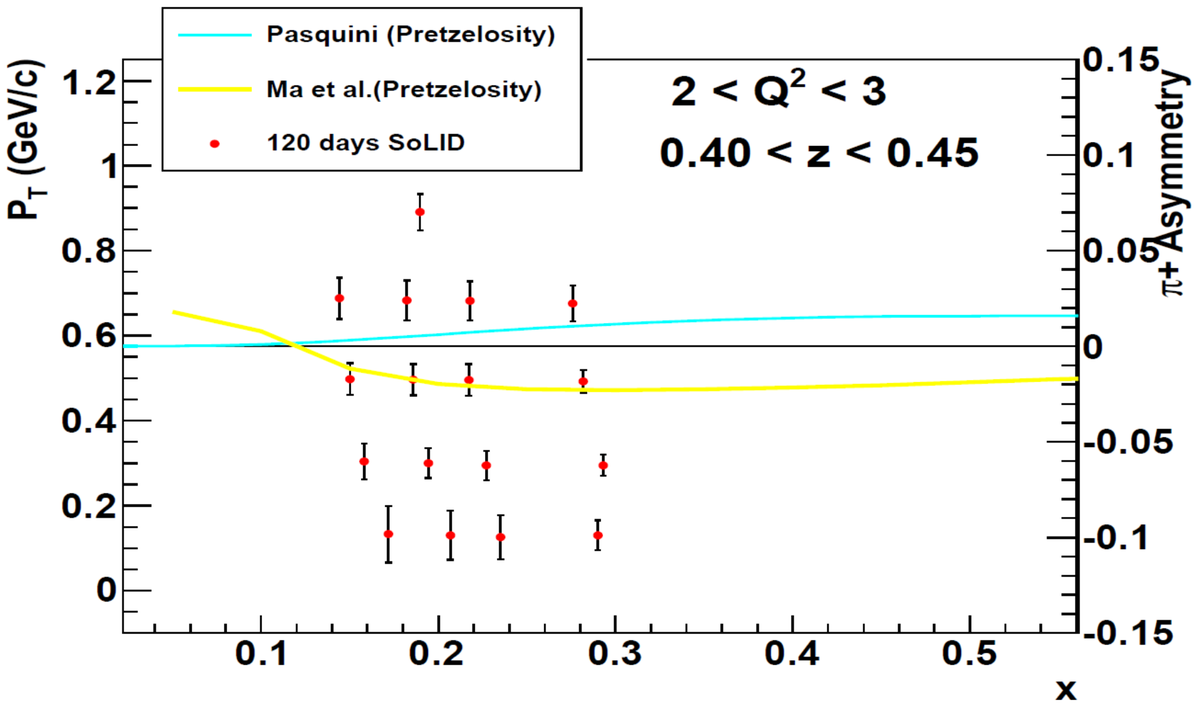
The theoretical curves are P_T integrated

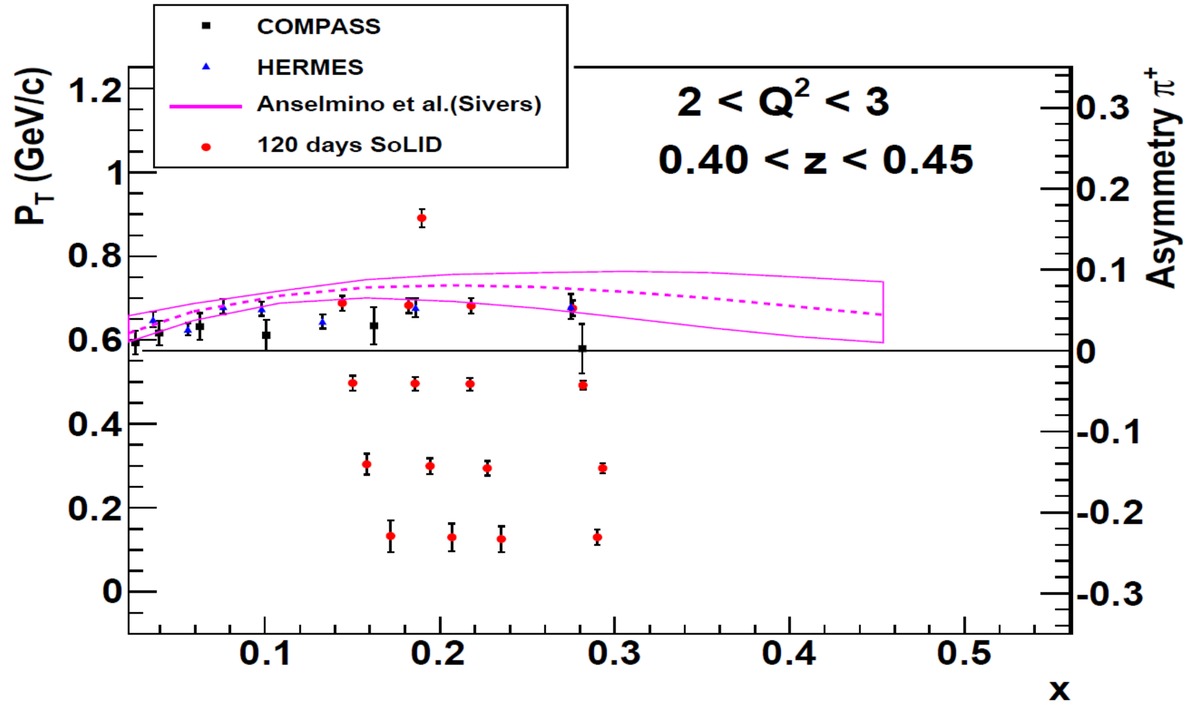
Theoretical predictions:

- W. Vogelsang and F. Yuan, PRD 72, 054028 (2005); PRD 79, 094010 (2009)
- 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:

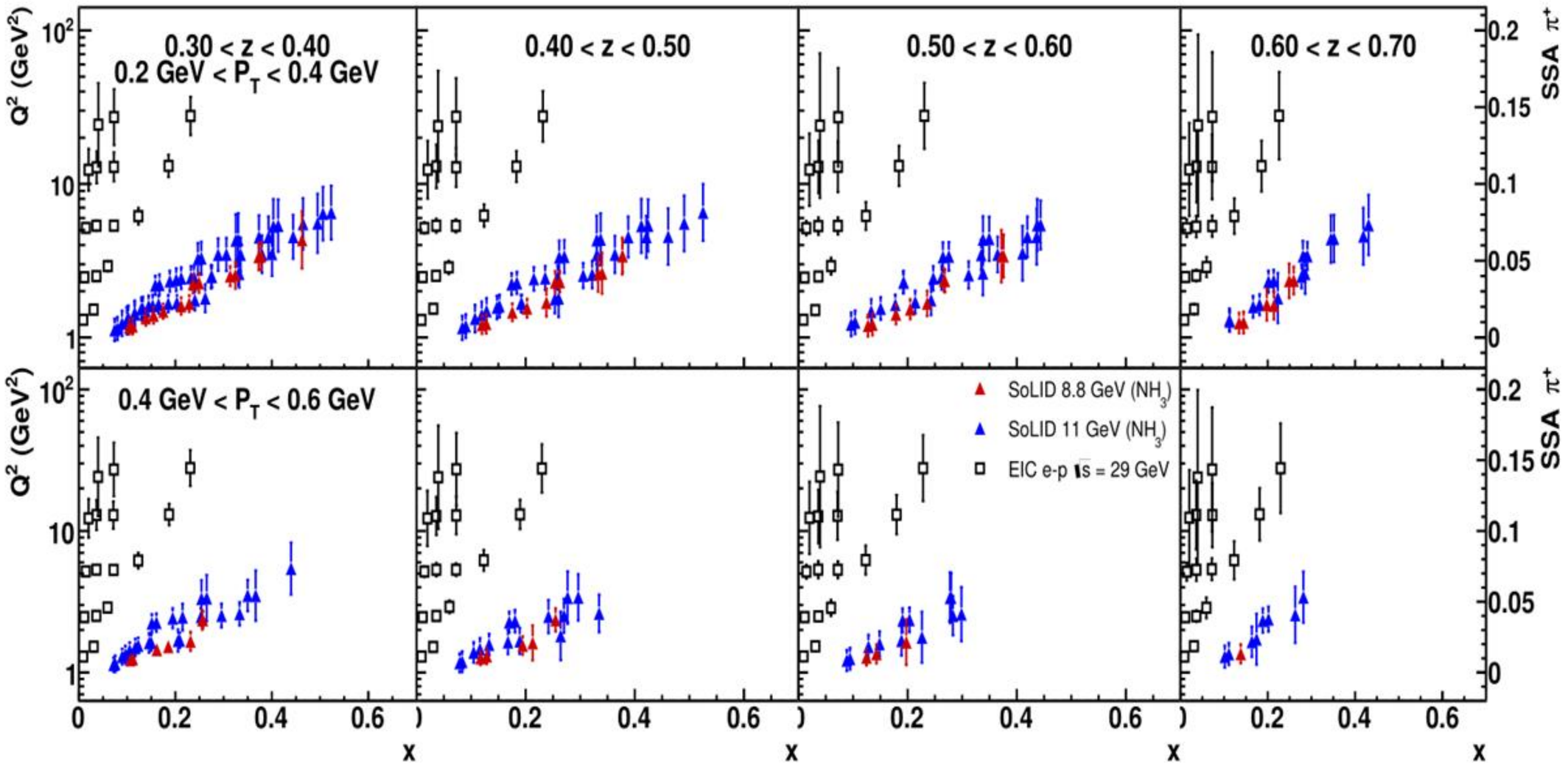
- B. Pasquini, et al., PRD 78, 034025 (2008)
- B.-Q. Ma, et. al, PRD 65, 034010 (2002)

Theoretical predictions:

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

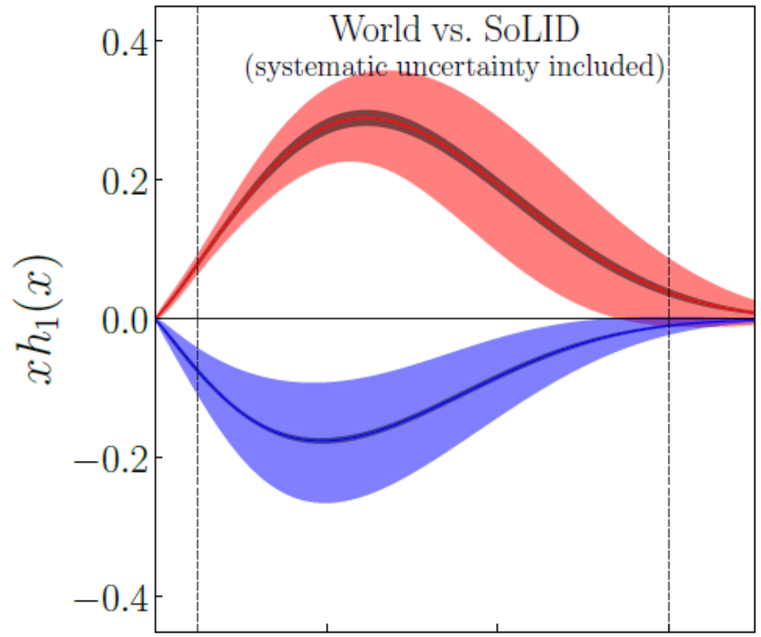
Transverse SSA projections: Complementarity to EIC

- 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 right two figures
- SoLID and EIC projections synergistic towards each other, by covering different x and Q^2 ranges

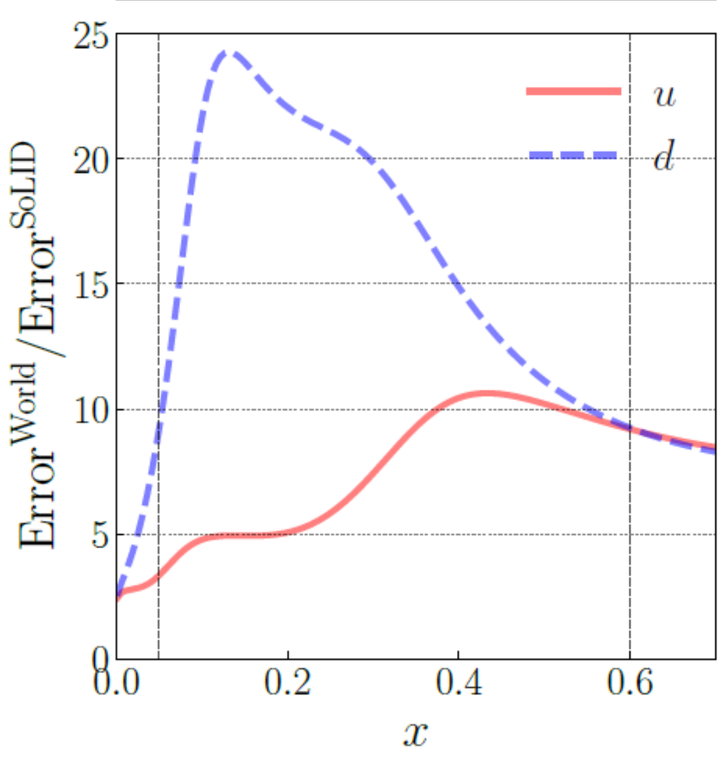


Transversity TMD projections (combined with the SoLID "neutron" results)

- Top figure: impact on the *u* and *d* quarks' **Transversity** TMD extractions by the SoLID SIDIS program
- Wide light-shaded uncertainty bands: our current knowledge coming from the global analysis of the World data
- Narrow dark-shaded uncertainty bands: SoLID projections

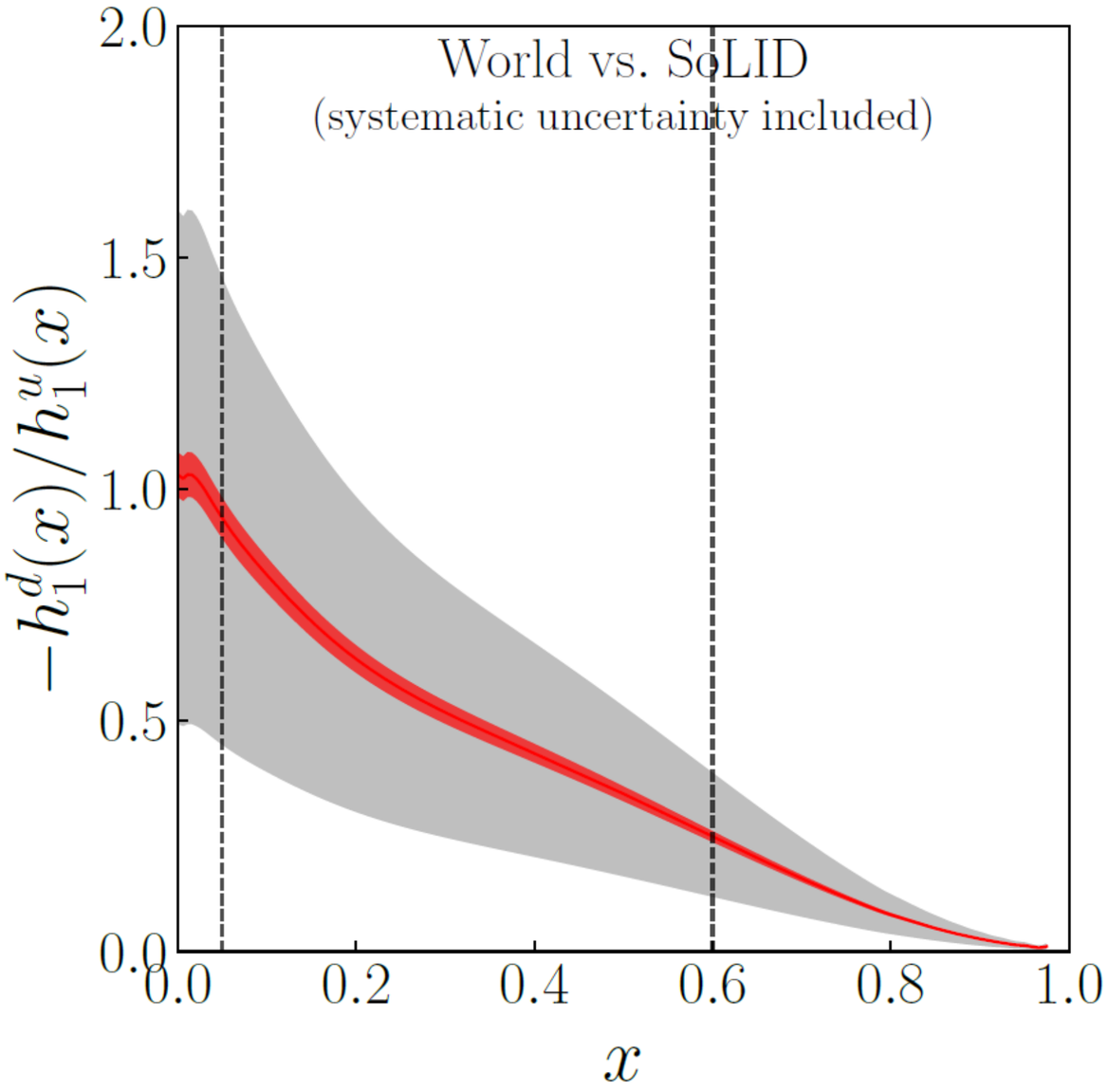


- World: SIDIS data from COMPASS / HERMES, and e^+e^- annihilation data from BELLE / BABAR / BESIII
- Bottom figure: uncertainty improvement manifested as a ratio between the World uncertainty band and the projected uncertainty band by SoLID
- Monte Carlo method applied; the results obtained at the scale of $Q^2 = 2.4\ GeV^2$



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

- Ratio of the SoLID-extracted *d* and *u* quarks' Transversity (red area) compared to that from the World data (gray area)
- Result obtained at the scale of $Q^2 = 2.4$ GeV^2 as in the figures of the previous slide
- Region of x from 0.05 up to 0.6 measured by SoLID
- World data keeps changing
- World data from the SoLID preCDR document as of 2019
  https://solid.jlab.org/experiments.html



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

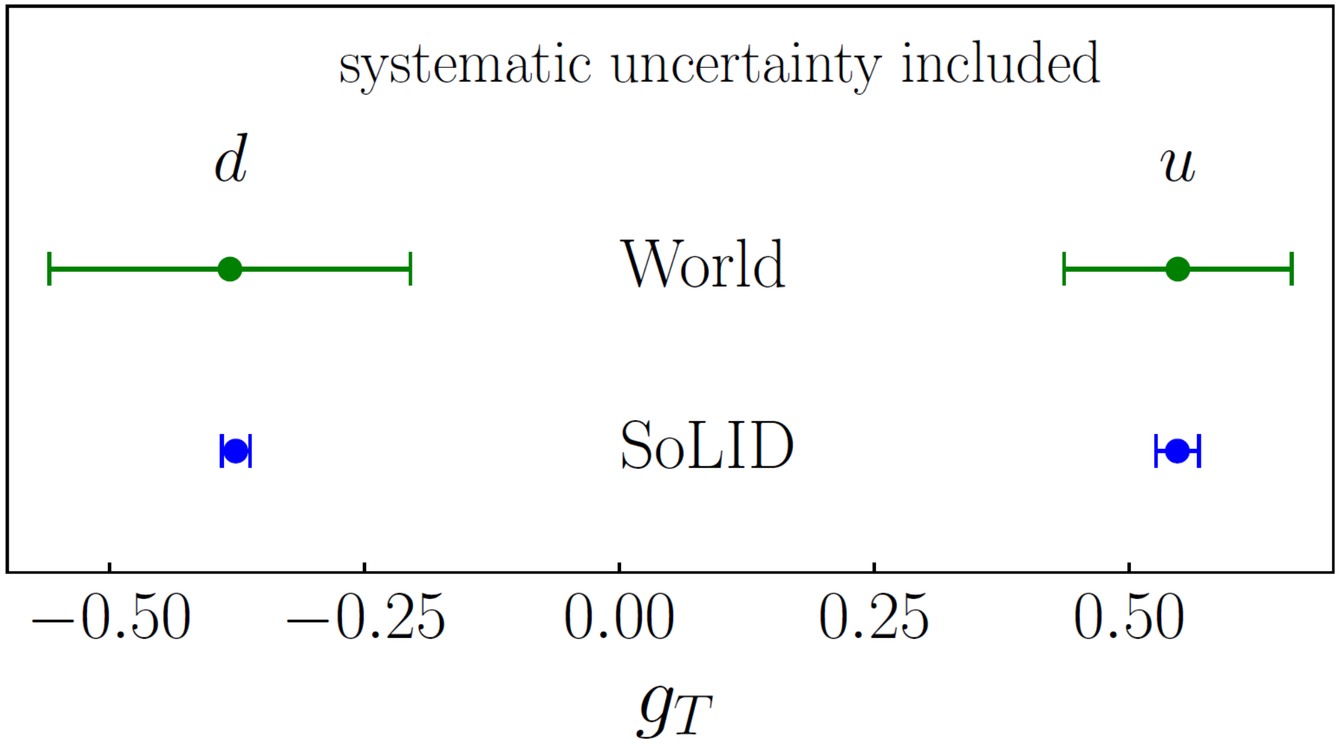
Tensor charge g_T:

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

<u>World data</u>

<u>SoLID projections</u>
in the figure and table
from both ^3He / NH_3 targets at 11 / 8.8 GeV beams

Statistical and systematic uncertainties included



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

Relation of Tensor Charge to Electric Diploe Moment

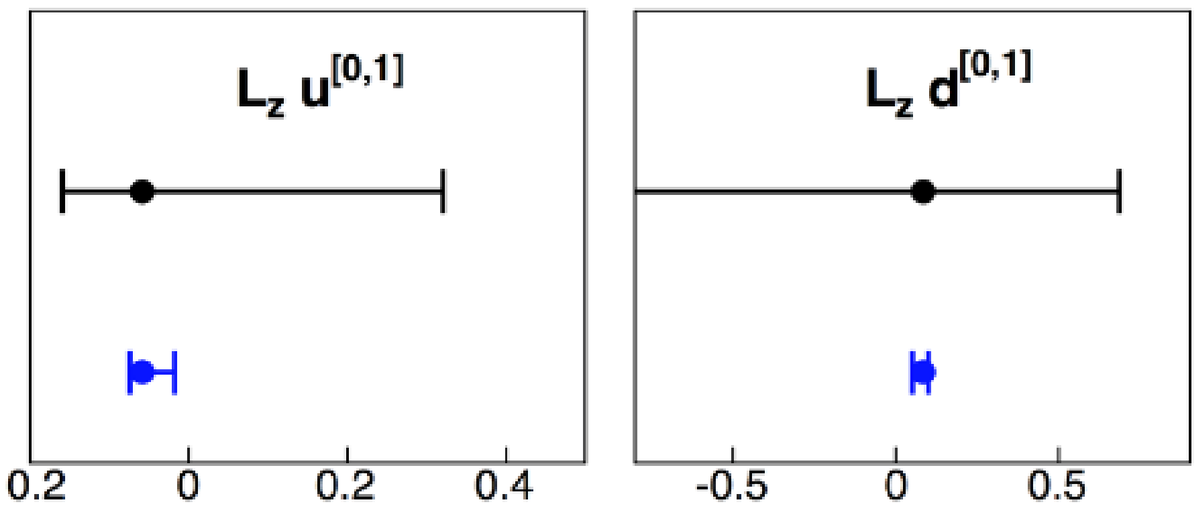
- Tensor Charge connected to neutron and proton electric dipole moments (EDMs)
  - *giving us a unique opportunity to test the Standard Model*
  - *search for new physics beyond the Standard Model*

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

- Use the current sensitivity of the neutron/proton EDM experiments and the existing precision of Tensor Charge extractions based on SoLID projections:
  H. Gao, T. Liu and Z. Zhao, PRD 97, 074018 (2018); Z. Ye et. al., PLB 767, 91 (2017)
  - *upper limit on u quark EDM is 1.27×10^{-24} e·cm*
  - *upper limit on d quark EDM is 1.17×10^{-24} e·cm*
  - *both EDMs determined at the scale of 4 GeV^2*
  - *estimated new physics scale probed by the current quark EDM limit to be about 1 TeV*

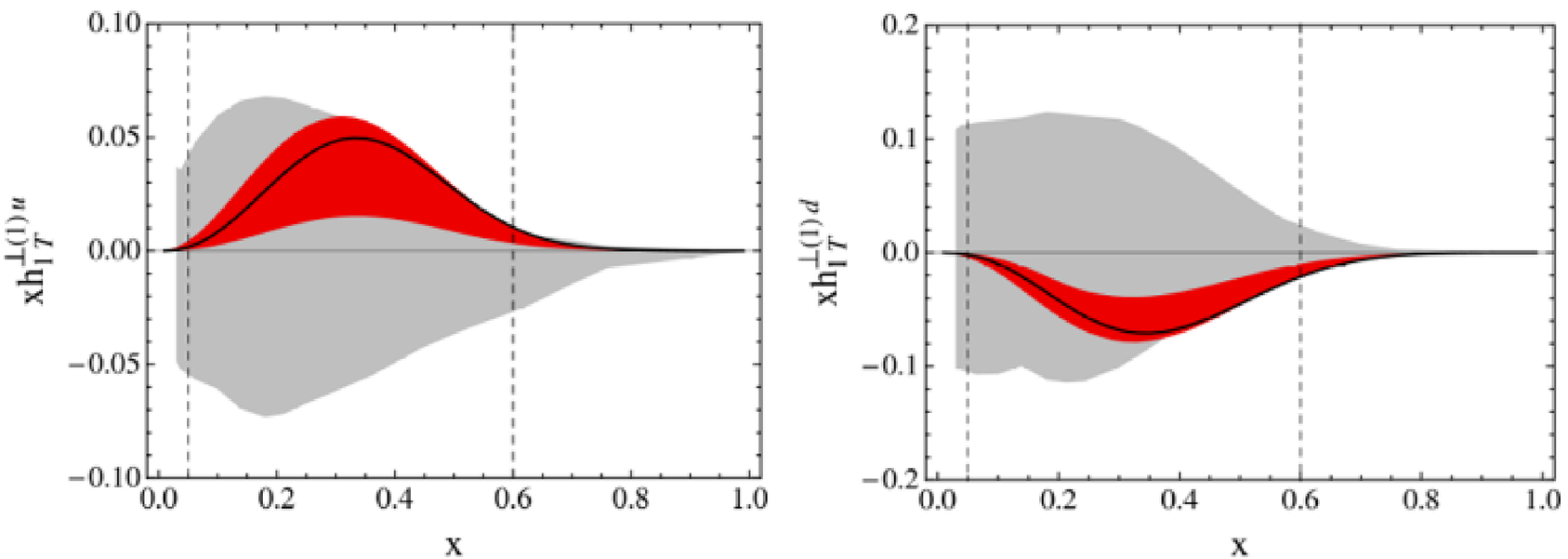
- Future precise measurements of Tensor Charge and the nucleon EDM
  - *reduce the upper limit on quark EDMs by about three orders of magnitude to the level of $\sim 10^{-27}$ e·cm*
  - *estimated new physics scale probed by the improved quark EDM limit to be about 30-40 TeV, beyond LHC energy scope*

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



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

- 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 SoLID "neutron" results)

- Top figure: impact on the *u* and *d* quarks' **Sivers** TMD extractions by the SoLID SIDIS program
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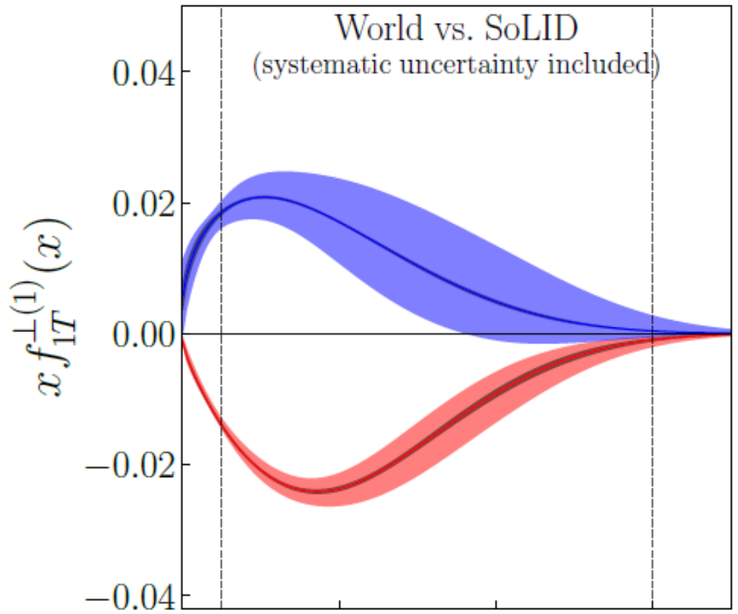

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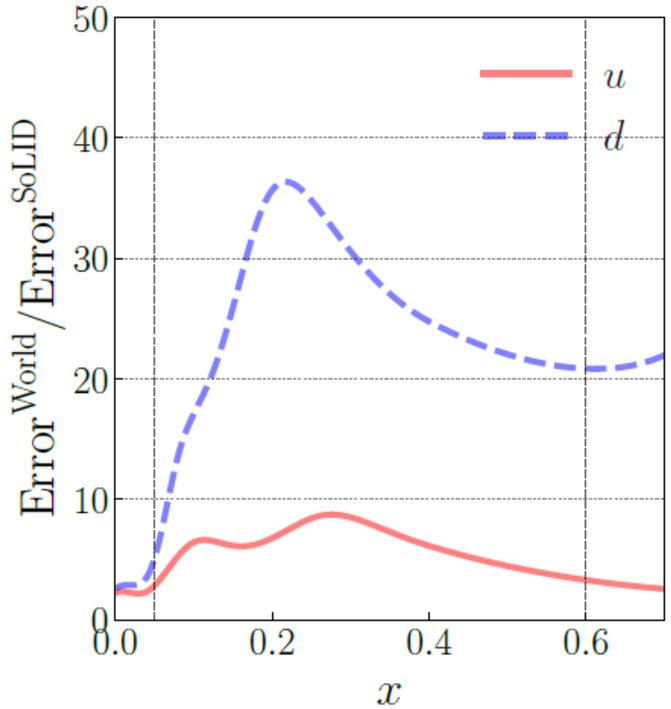
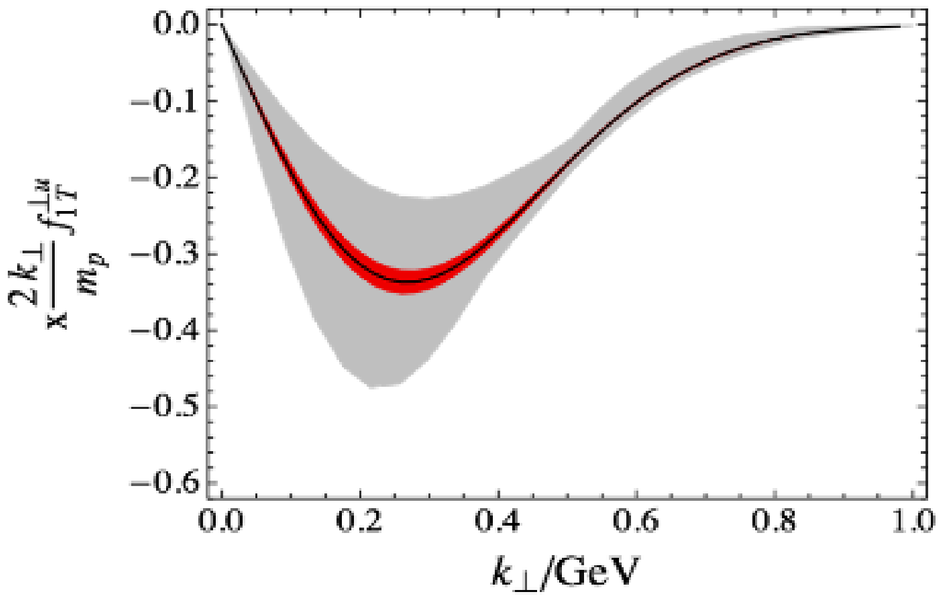
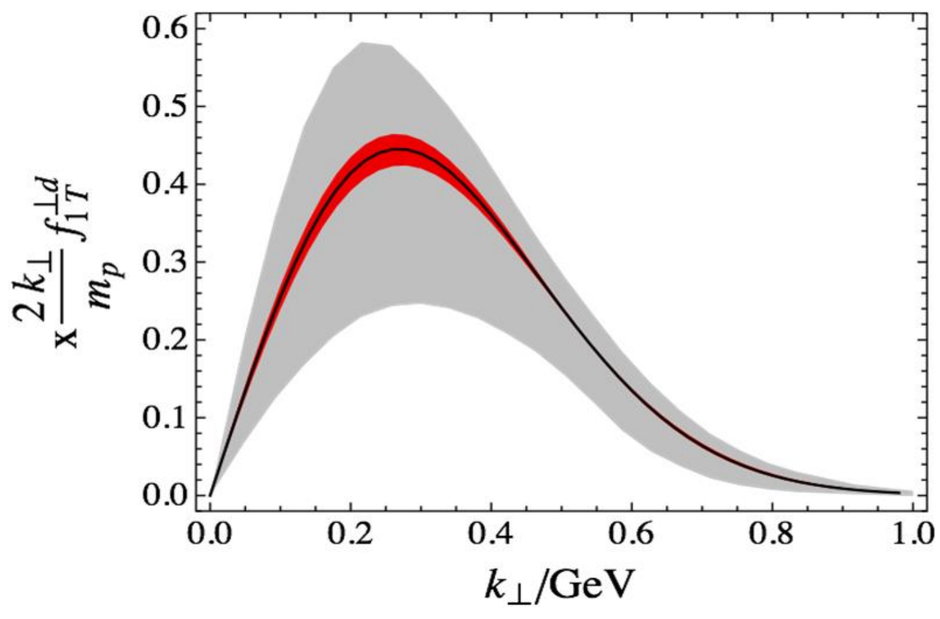


Sivers TMD projections (combined with the SoLID "neutron" results)





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

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

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

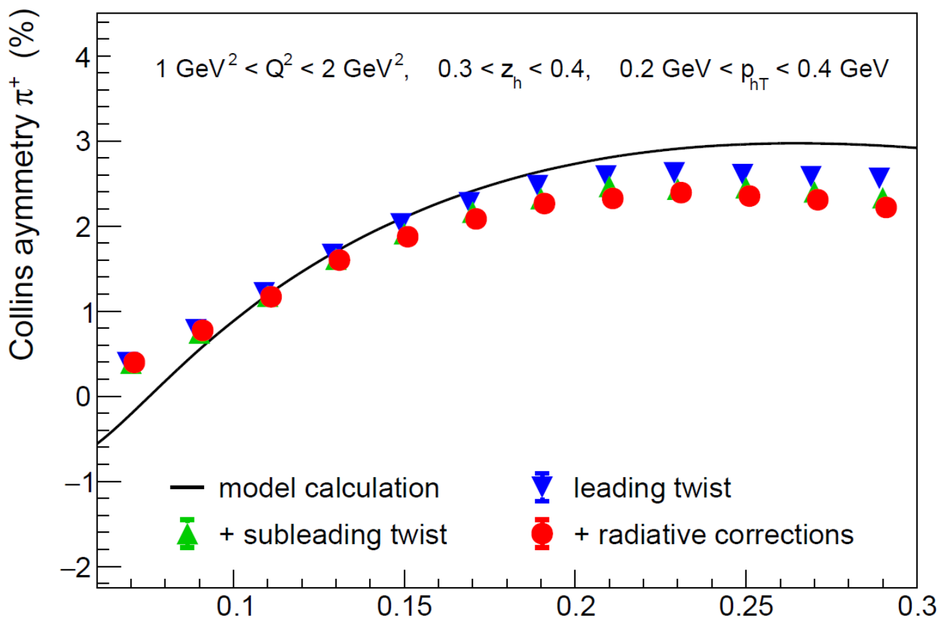
Parametrization by M. Anselmino *et al.*, EPJ A 39, 89 (2009): based on HERMES and COMPASS pion and kaon production data

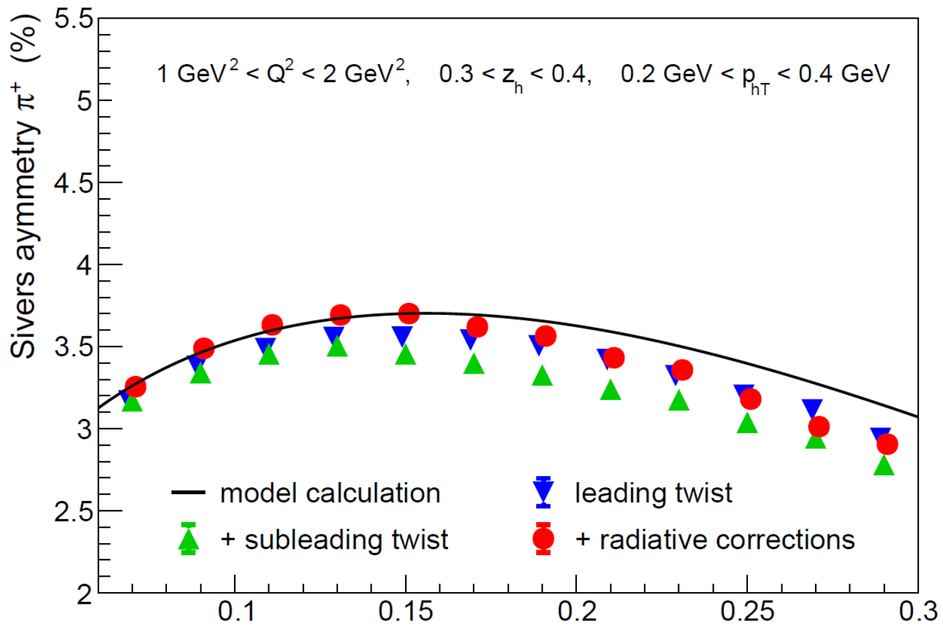
SoLID projections with transversely polarized "neutron" and "proton" targets

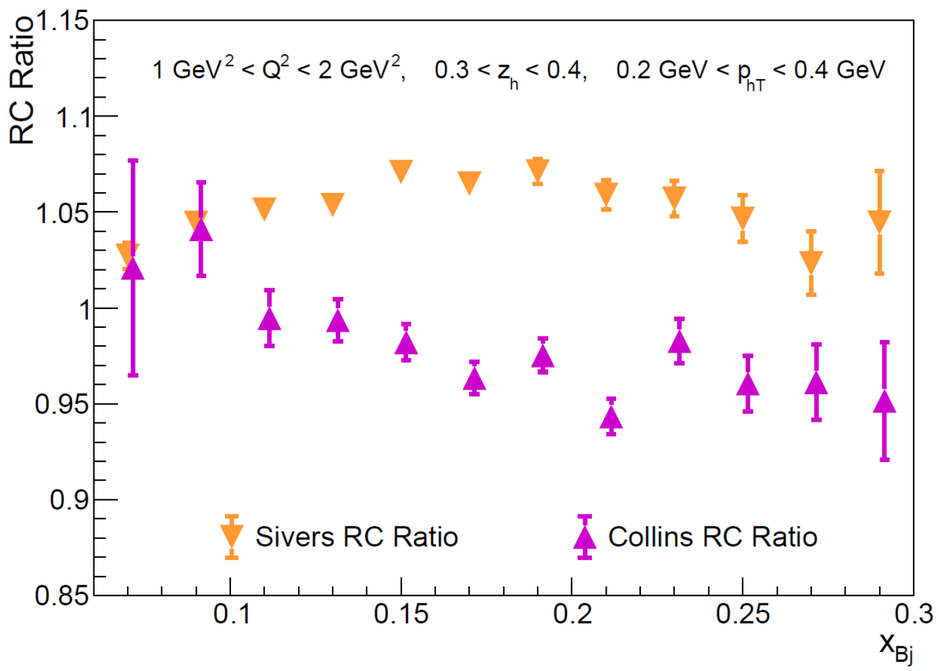
SIDIS event generator on radiative corrections

- Consider QED radiative corrections (RCs) to reliably extract TMDs from experimental data
- Momentum transfer and azimuthal angular modulation between leptonic and hadronic planes altered by radiative photons
- Non-trivial but traditional approach to SIDIS RCs: I. Akushevich and A. Ilychev, PRD100, (2019)
  - Lowest order RCs to SIDIS computed analytically beyond ultra-relativistic approximation
- Respective Monte-Carlo event generator created: https://github.com/duanebyer/sidis
  - Generates events for SIDIS six-fold cross sections computation
  - All eighteen SIDIS structure functions implemented in Gaussian and Wandzura-Wilczek type approximations: S. Bastami et. al., JHEP06, 007 (2019)
  - More fine tuning on the generator for running fully in the SoLID framework
- Examples of extracted Collins and Sivers asymmetries shown on the next slide

SIDIS event generator on radiative corrections







- Blue marker means $A_{UT}^{Collins}$ / A_{UT}^{Sivers} contribution
- Green marker means $A_{UT}^{Collins}$ / A_{UT}^{Sivers} + subleading
- Red marker means $A_{UT}^{Collins}$ / A_{UT}^{Sivers} + subleading + RCs

In the ratio plot shown on the left, red is divided by green, describing the Collins RC ratio and Sivers RC ratio

E12-11-108 -- related run group experiments

Approved two Run Group Experiments

1. SIDIS in Kaon Production with Transversely Polarized ^{3}He and NH_3 targets

   - *Measurements of $K^{\pm}$ production in SIDIS using both transversely polarized ^3He and NH_3 targets, 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 running 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 (^{3}He) and Proton (NH_3) Targets using the SoLID Spectrometer

   - *Single spin asymmetry, A_y, to be obtained by scattering of 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 running 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 at other key facilities, e.g., 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 both targets
  - *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*
- We have more confidence in delivering this Science after 10 years of experience and passing important reviews from the time of the original proton target proposal’s approval

Thank You !

Backups

SoLID magnet

- SoLID's magnet is the CLEO-II magnet
  - *solenoidal magnet with power-supply and cryogenic system*
  - *natural choice for SoLID that operates at high luminosity and has large acceptance*
  - *still requires some modifications to its design for use in the SoLID experiments*
  - *JLab-funded* (*Phase 1*) *test plan*: *static tests and a low current cold test to confirm the magnet condition*
  - *SoLID-funded* (*Phase 2*) *test plan*: *a full current test to be conducted after installation in Hall A*

- Uniform axial central field of 1.5 T
- Large inner space with a coil of 3.1 m diameter
- Coil length of 3.5 m
- Magnetic field uniformity ± 0.2 %

CLEO-II magnet at JLab

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 the HAPRAD program

- *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

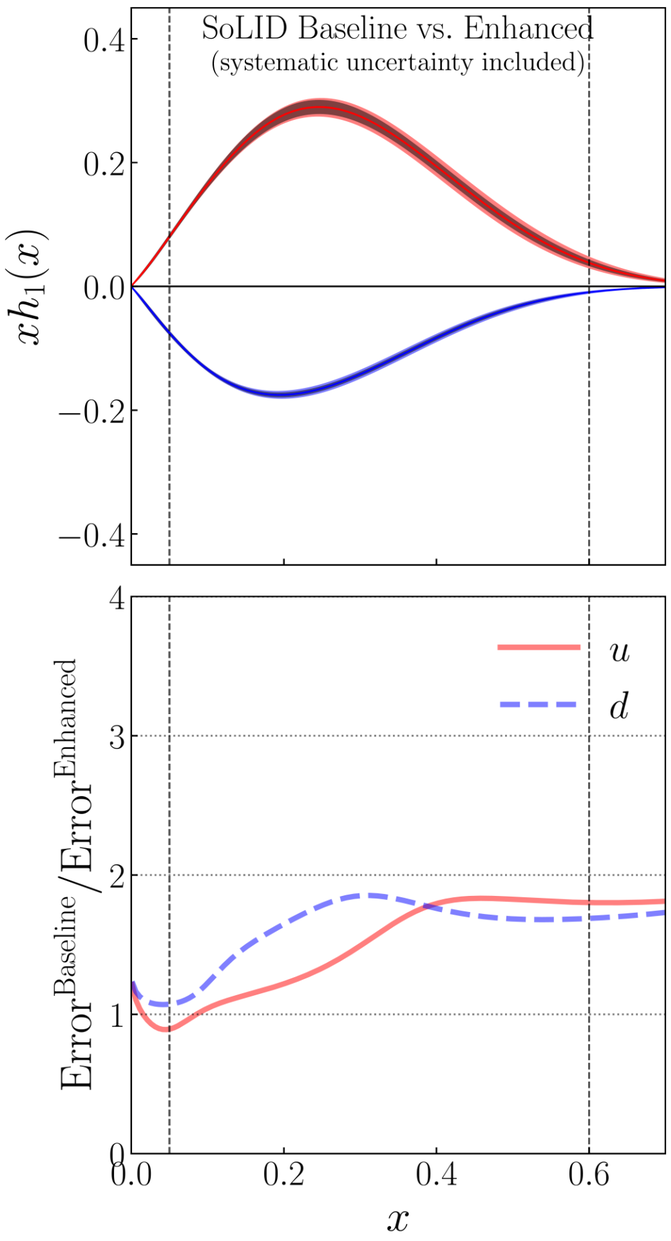
- The budget for the absolute and relative systematic uncertainties of the π^+/π^- Collins and Sivers SSAs

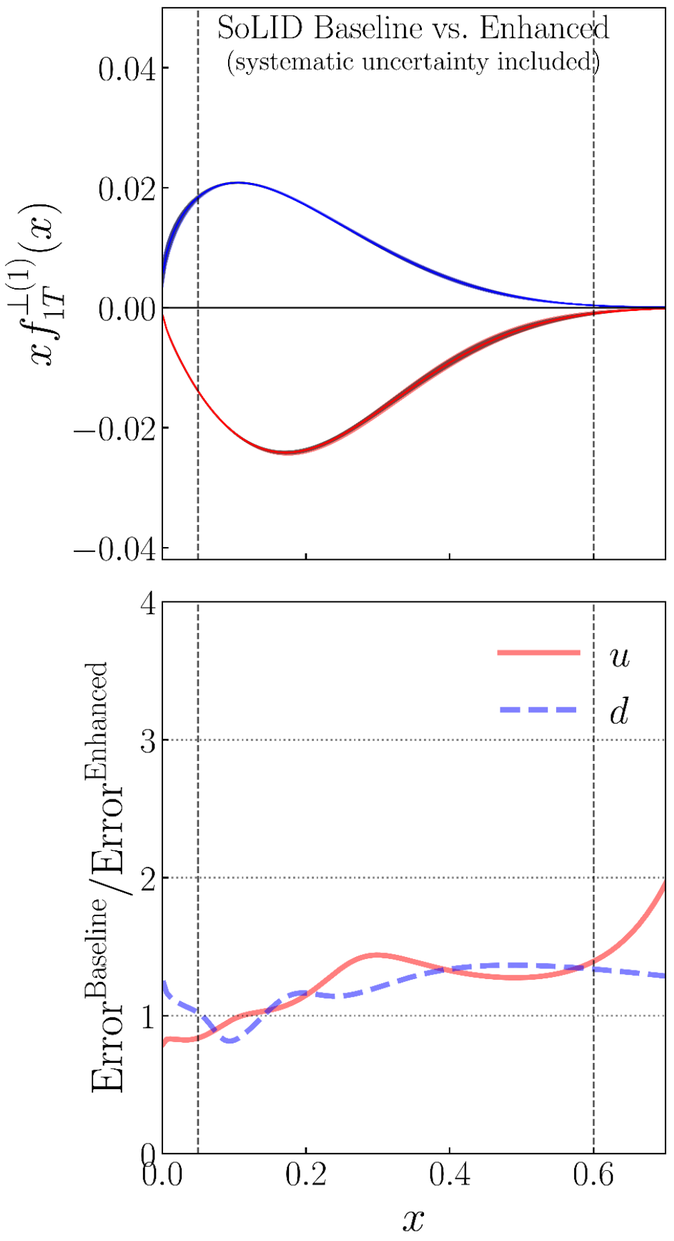
- The uncertainty sources described in the previous slide

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%**

Other projections (combined with the "neutron" results)

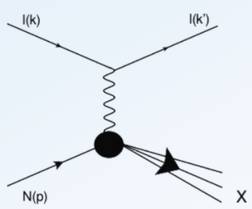
- SoLID projections using Baseline vs. Enhanced configurations (for Transversity and Sivers TMDs)

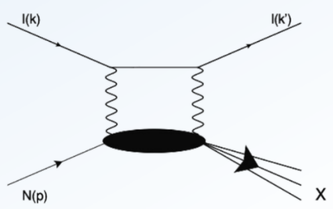


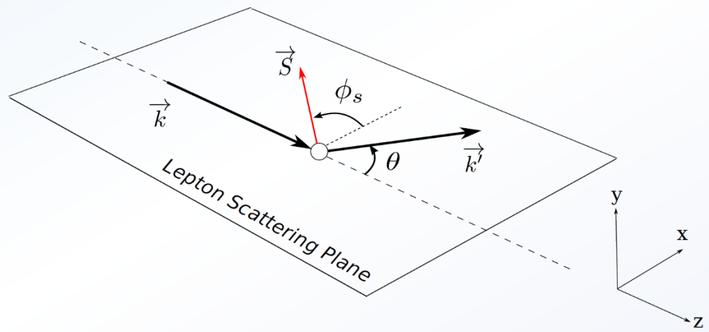


Measuring TPEX via Target Single Spin Asymmetry in DIS, proton & neutron, *T. Averett*, *W&M*

- A_y : target polarized perpendicular to the incident lepton momentum
- Inclusive DIS $N^{\uparrow}(e,e')X$
- Measure the ϕ_S dependence of the target SSA

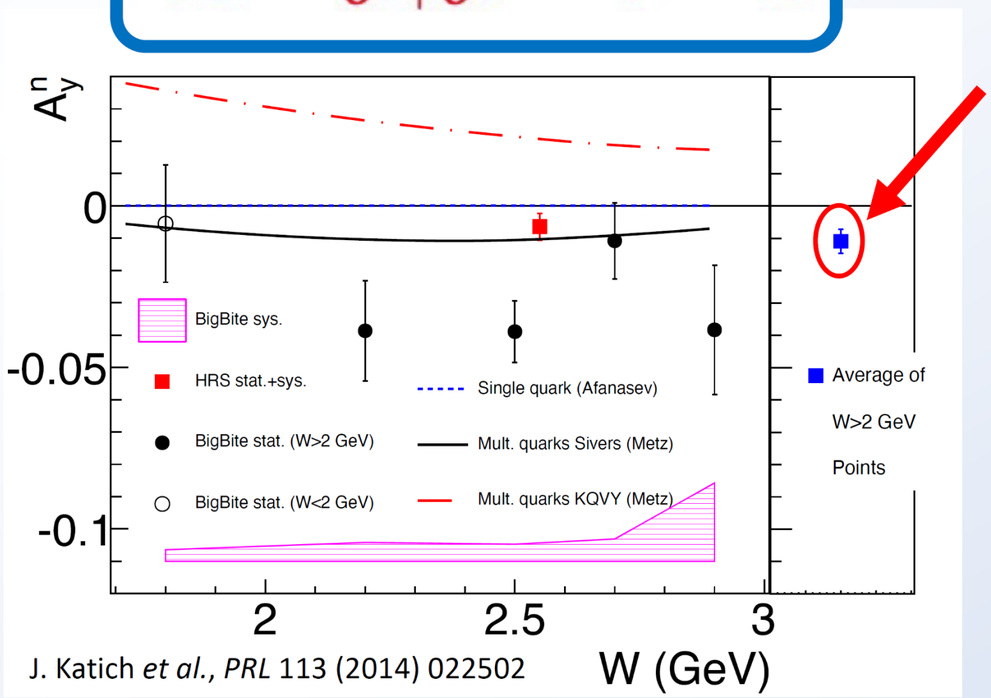






- **For G_e^p/G_M^p** Cross section $\sigma \propto \mathcal{M}_{1\gamma}^2 + \mathcal{R}e\{\mathcal{M}_{1\gamma} \times \mathcal{M}_{2\gamma}\}$
  → TPEX small relative to leading 1γ
- $A_y \propto \mathcal{I}m\{\mathcal{M}_{1\gamma} \times \mathcal{M}_{2\gamma}\}$
- For single photon exchange, $A_y = 0$ – Christ-Lee Theorem
- Can be non-zero with TPEX – *leading contribution*

$$A_{UT} = \frac{\sigma^{\uparrow} - \sigma^{\downarrow}}{\sigma^{\uparrow} + \sigma^{\downarrow}} = A_y \sin\phi_S$$



J. Katich *et al.*, *PRL* 113 (2014) 022502

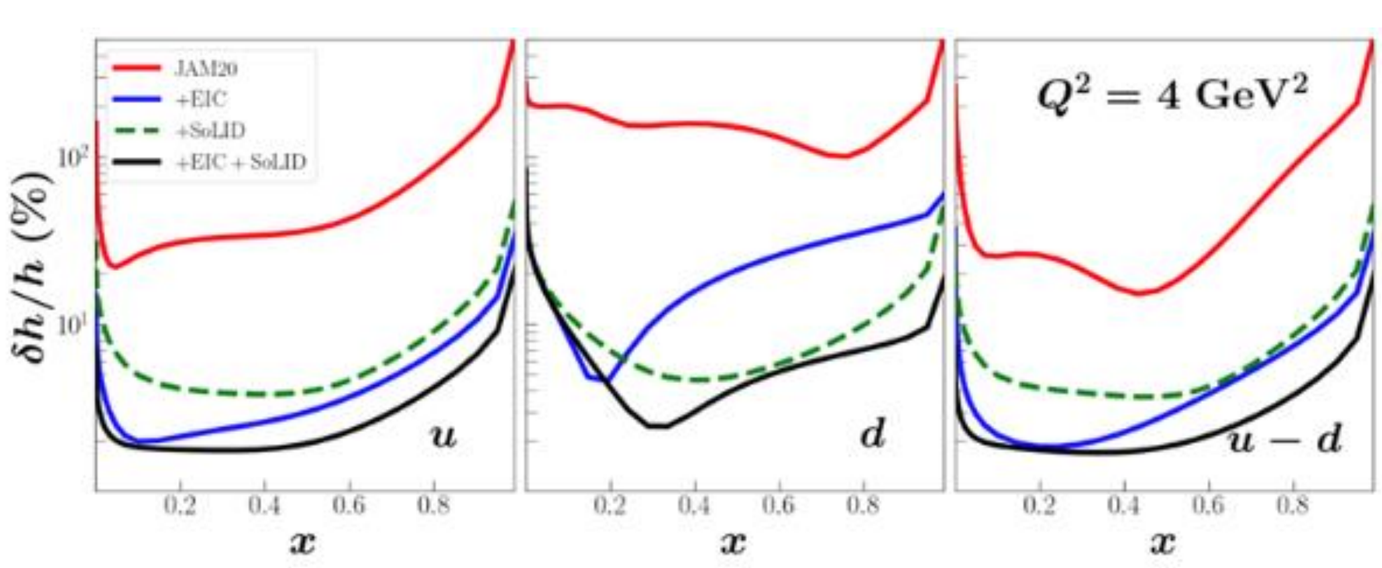
Primary issue: Neutron results agree with theory using Sivers input; disagree using Drell-Yan ($q\,\gamma q$) input (KQVY)

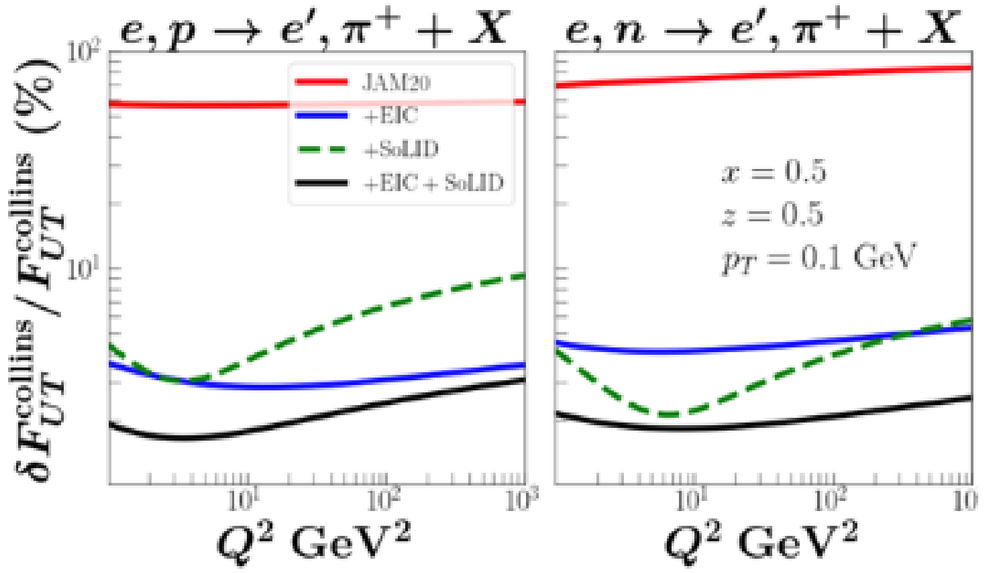
Metz et al., PRD 86 (2012) 094039,
"… it is of crucial importance to eventually settle what causes these asymmetries."

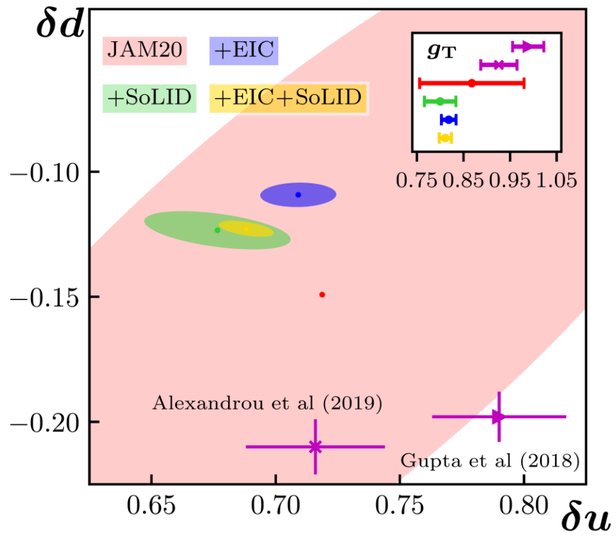
Transversity TMD projections (combined with the "neutron" results)

- 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)







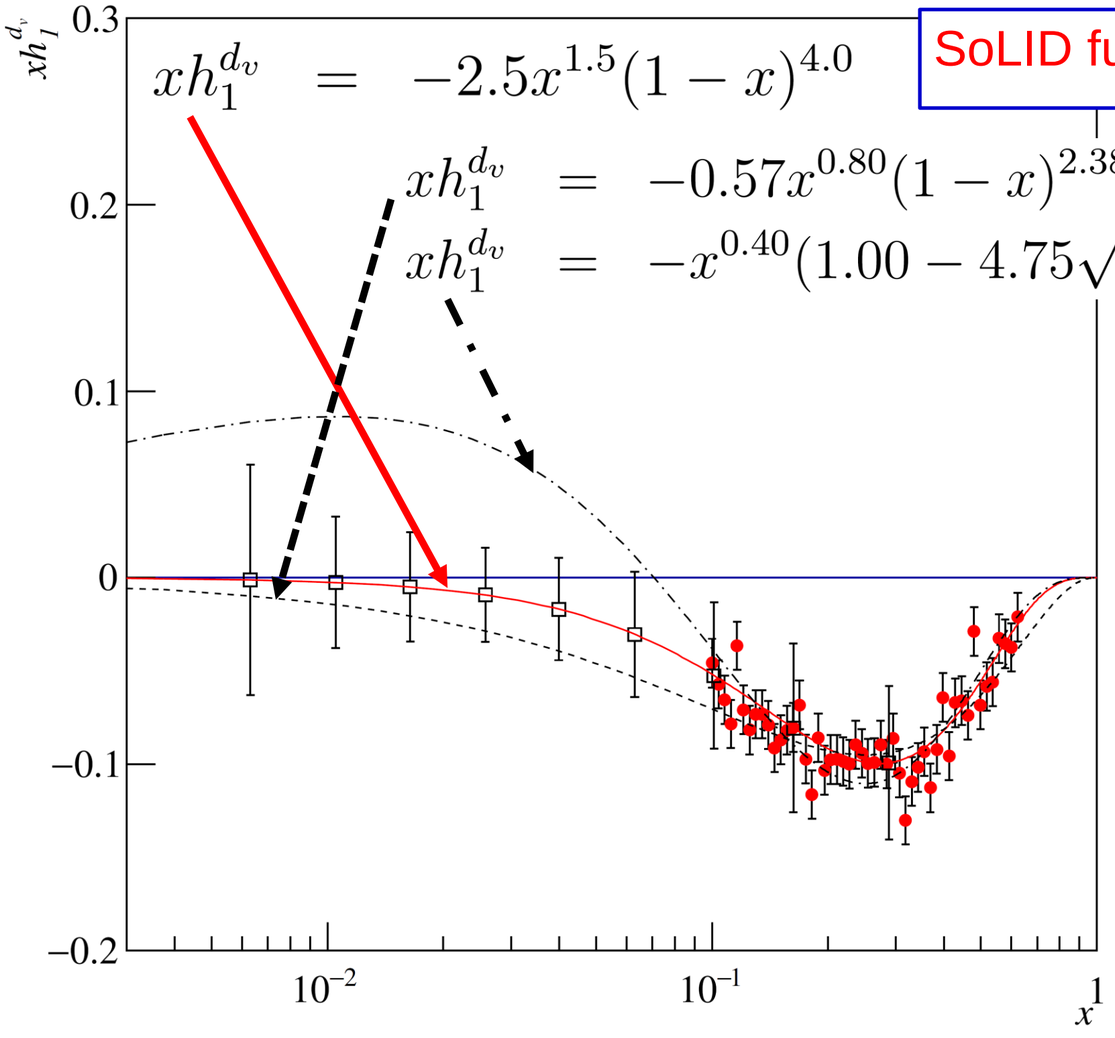
$$\langle \mathrm{P,S}|\overline{\psi}_q i\sigma^{\mu\nu}\psi_q|\mathrm{P,S}\rangle = g_T^q \overline{u}(\mathrm{P,S}) i\sigma^{\mu\nu} u(\mathrm{P,S})$$

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

- 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