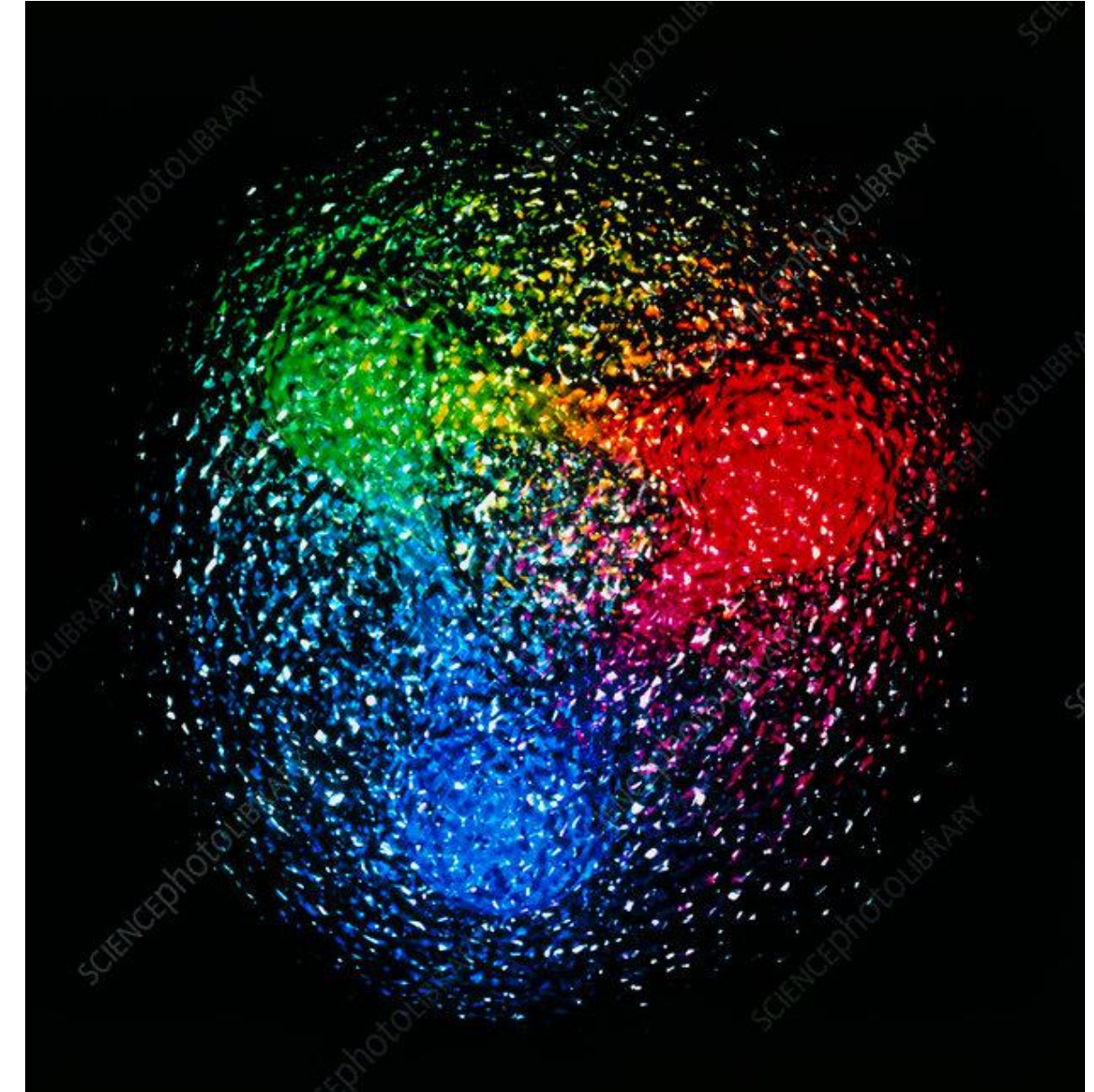
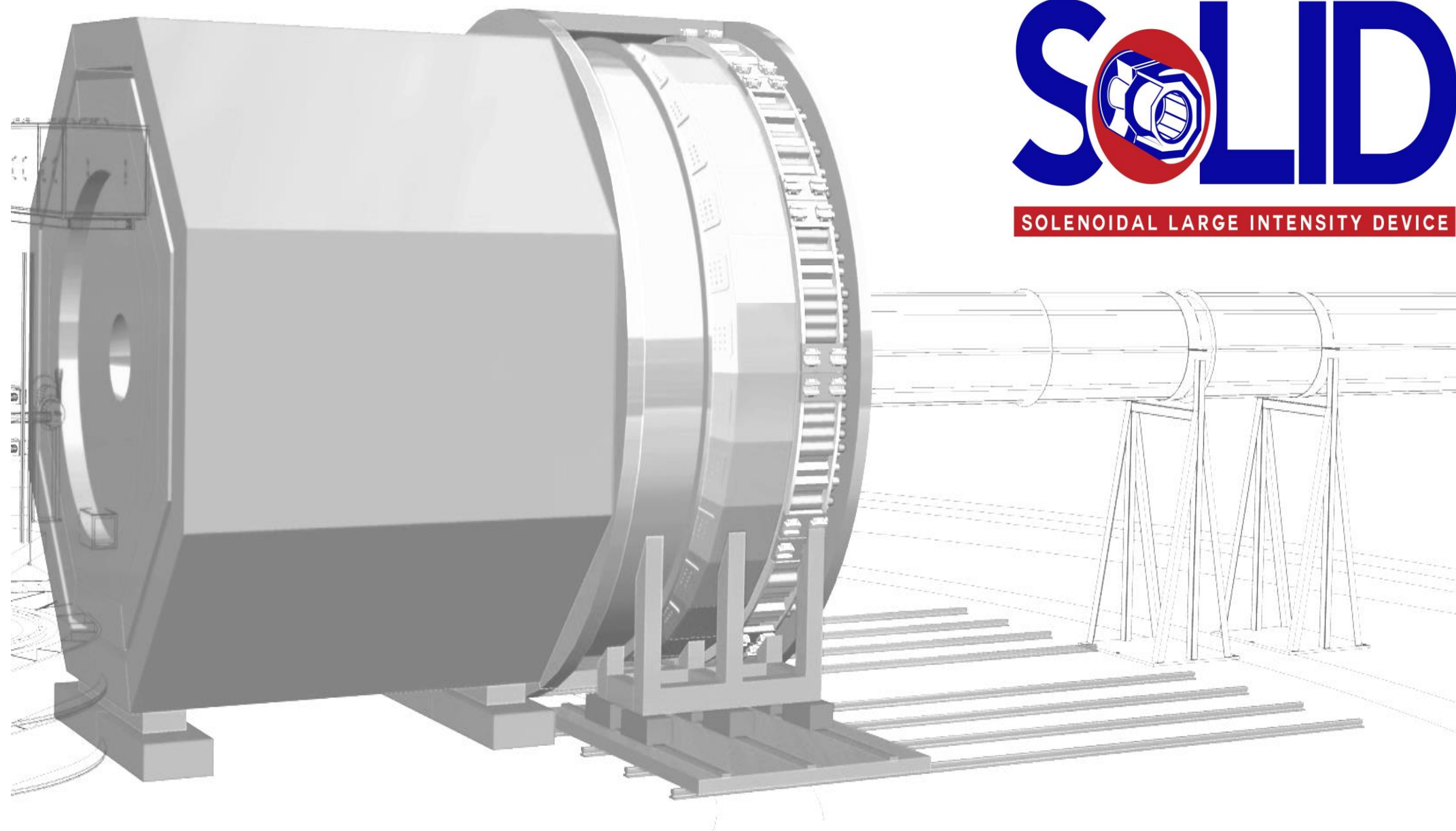


E12-11-108 Jeopardy Update to PAC50: SoLID SIDIS Experiments with a Transversely Polarized NH_3 Target



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
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- 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

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

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. Meiziani

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

➤ Target:

- Length: 3 cm
- Polarization: $\sim 70\%$
- Spin flip: ≤ 4 hours
- Polarimetry: $\sim 3\%$

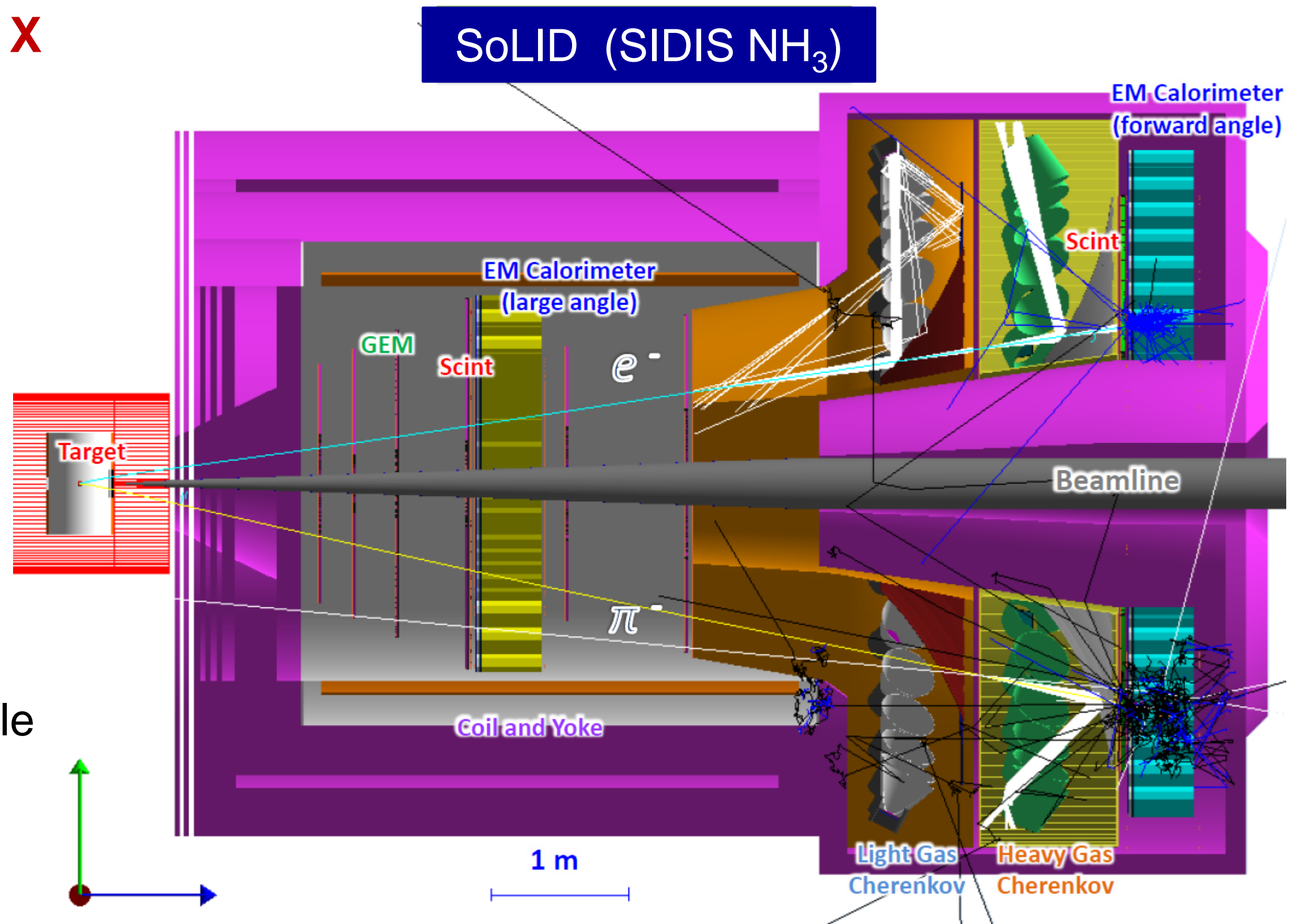
➤ GEM: 6 tracking chambers

➤ 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

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
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- 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 ~ 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



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
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- 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 (π^\pm): detection efficiency $\geq 90\%$; kaon contamination $< 1\%$
- Two beam energies: 11 GeV and 8.8 GeV
- Total luminosity: $5.95 \cdot 10^{35} \text{ cm}^{-2} \text{ sec}^{-1}$
- 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

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
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Transversely Polarized Nucleon TMDs to be measured by SoLID

 Nucleon Spin
 Quark Spin

Transversity

$h_{1T} =$ $\mathbf{S}_T \cdot \mathbf{S}_q$

- $h_{1T} (h_1) = g_1$ (no relativity)
- $h_{1T} \longrightarrow$ tensor charge (lattice QCD calculations)
- Connected to nucleon beta decay and electric dipole moment
- Transversity \longrightarrow Tensor charge

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)

Pretzelosity

The diagram illustrates the exchange interaction between two spins. It is enclosed in a light blue rounded rectangle. At the top, the expression $h_{1T}^\perp =$ is followed by two circles representing spins. Each circle contains a red dot and a red arrow. The left circle's arrow points up and to the right, while the right circle's arrow points down and to the right. Above each circle is a black arrow pointing straight up. A horizontal line connects the two circles. Below this diagram, a dashed horizontal line separates it from the mathematical expression $\mathbf{S}_T \cdot [\mathbf{k}_\perp \mathbf{k}_\perp] \cdot \mathbf{s}_{qT}$.

- 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

$f_{1T}^\perp =$


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

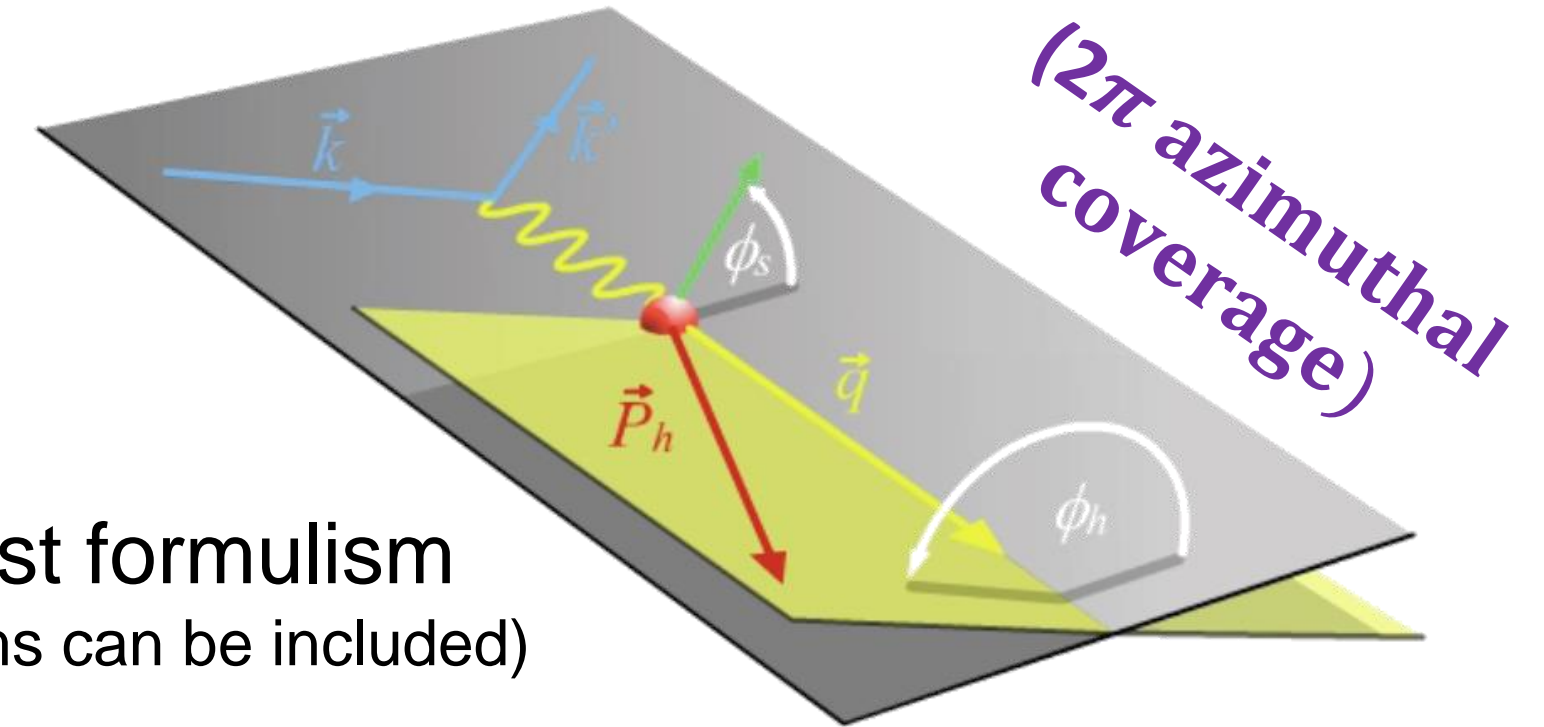
- Nucleon spin - quark orbital angular momentum (OAM) correlation
- Zero if no OAM (model dependence)

Separation of the transverse Collins / Sivers / Pretzelosity SSAs

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
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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!



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

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

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

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

Collins fragmentation function
from e^+e^- collisions

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

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

Unpolarized fragmentation function

Transverse SSAs in the SIDIS cross section

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
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- Three transverse SSAs standing in the SIDIS differential cross section

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

$$\times \left\{ 1 + \dots + S_T \sin(\phi_h + \phi_S) p_1 A_{UT}^{Collins} \right.$$

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

$$\left. + S_T \sin(\phi_h - \phi_S) A_{UT}^{Sivers} + \dots \right\}$$

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

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
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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 ?
 - *Pretzelosity TMD* and *Sivers TMD*
- Are there clear signatures for relativity inside the nucleon ?
 - *Transversity TMD* and *Pretzelosity 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)

Some details on the SoLID SIDIS setup with a trans.-pol. NH_3 ("p") target

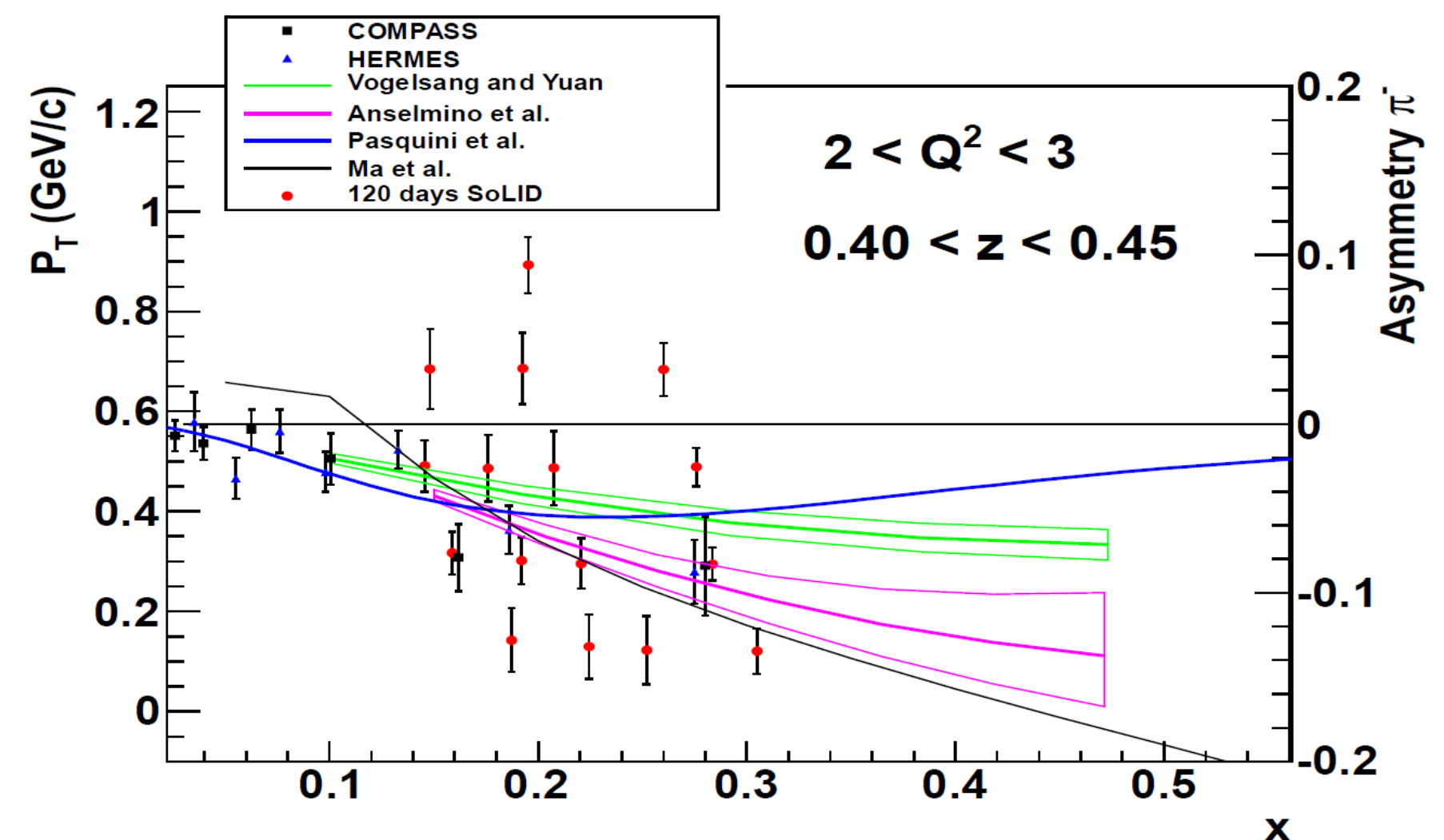
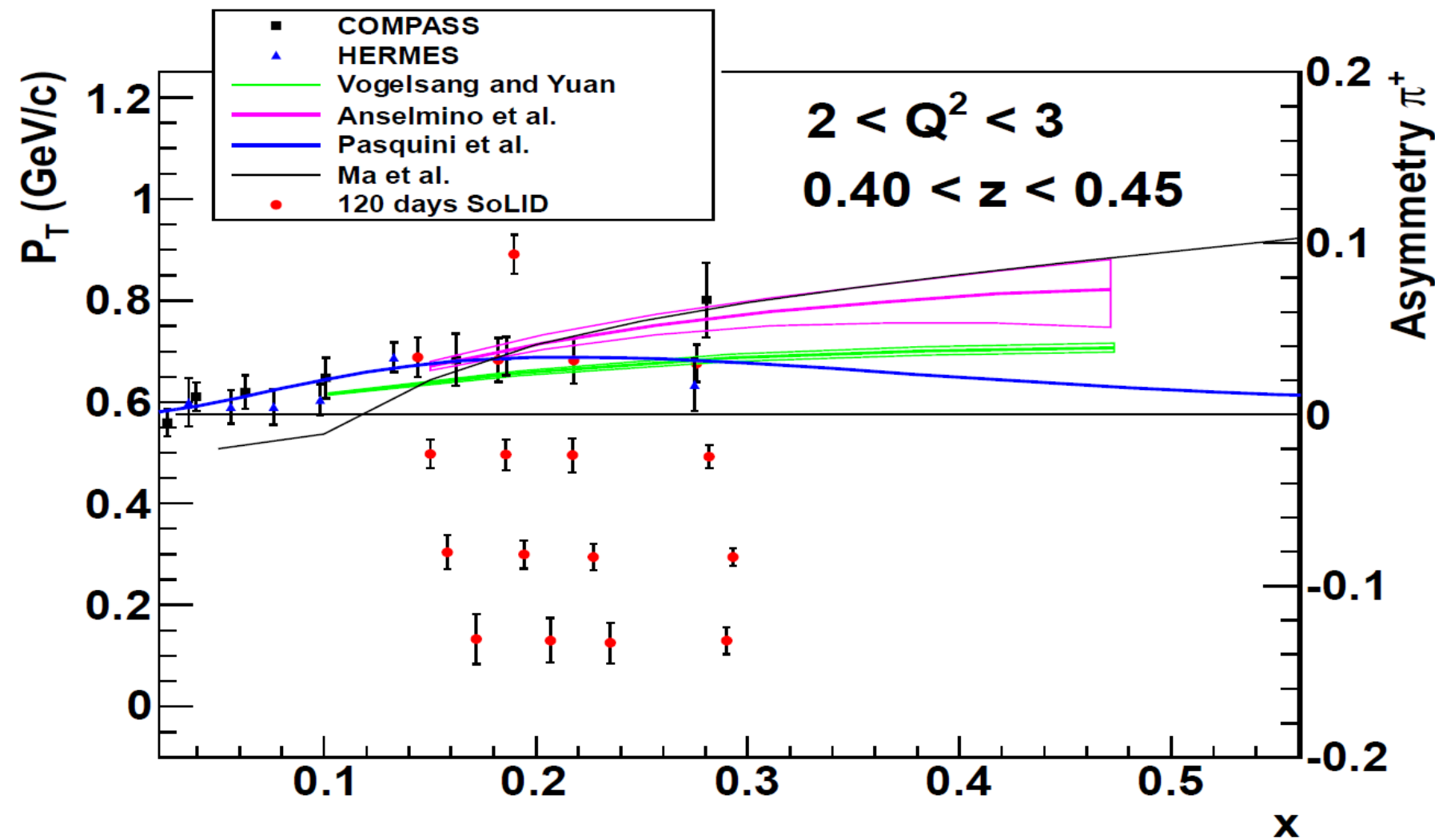
Reminder on three TMDs and three SSAs under consideration

Several results from the original proposal

Recent updates

Summary

- SoLID SIDIS 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)

Some details on the SoLID SIDIS setup with a trans.-pol. NH_3 ("p") target

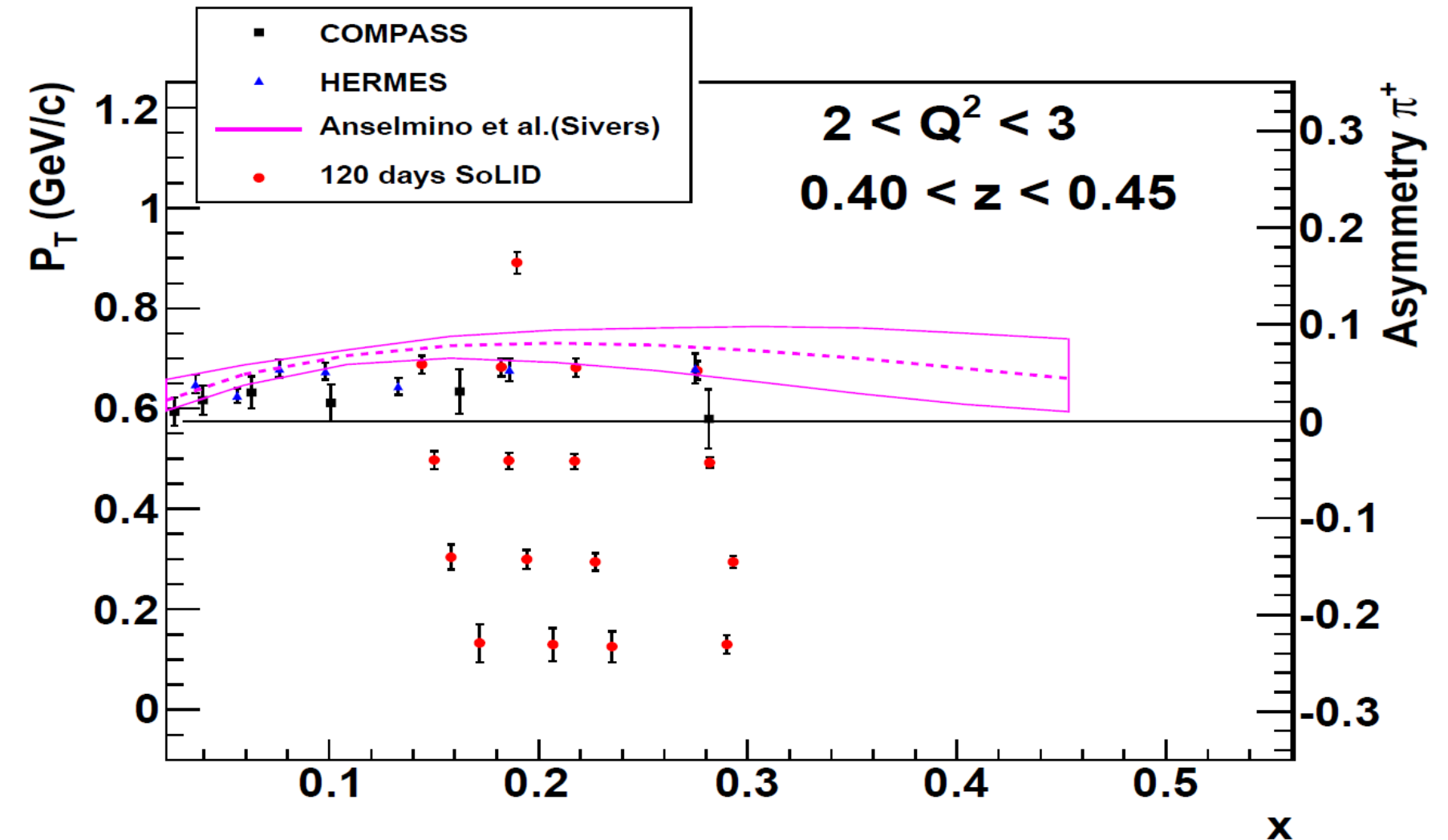
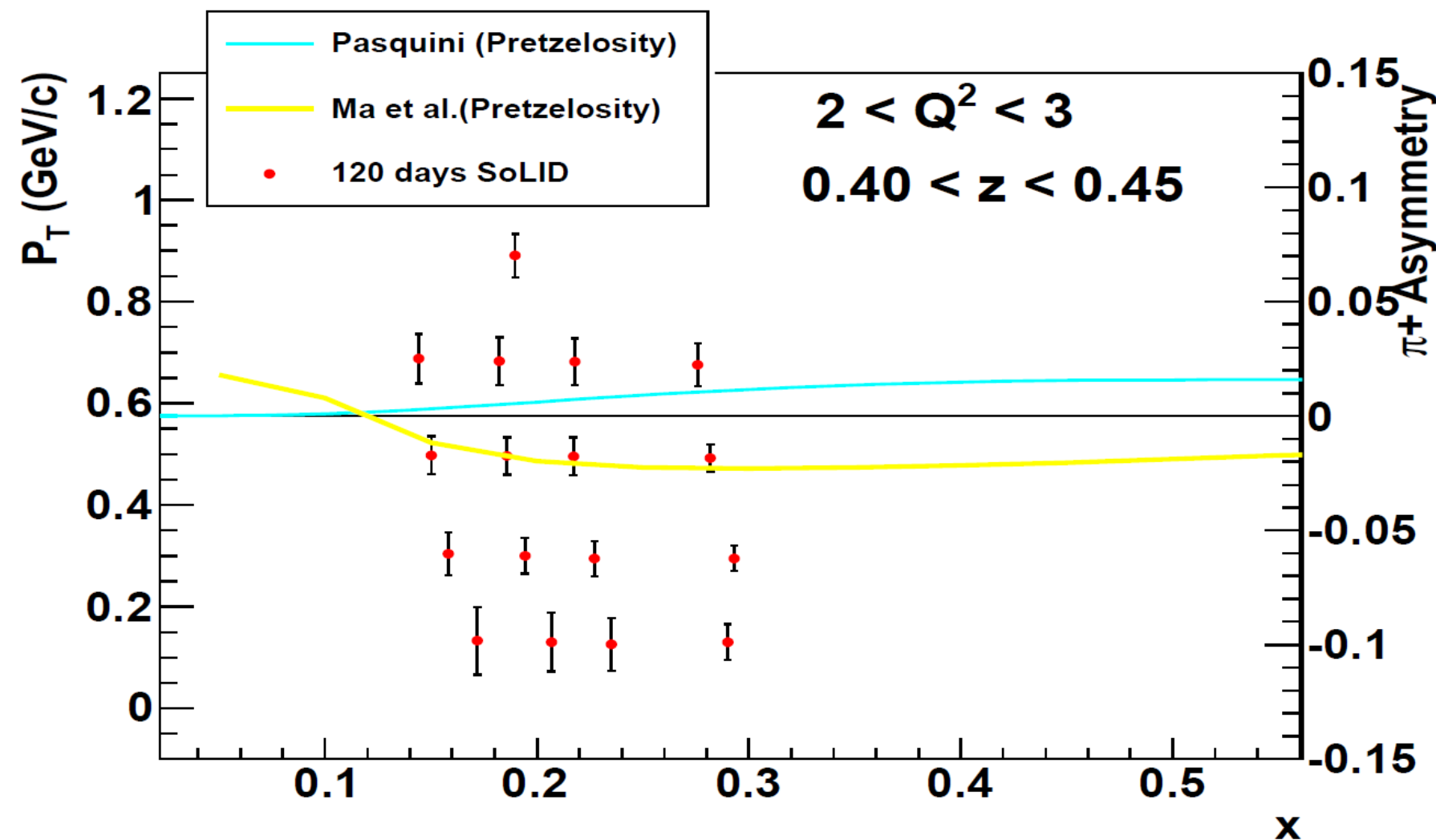
Reminder on three TMDs and three SSAs under consideration

Several results from the original proposal

Recent updates

Summary

- SoLID SIDIS 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)

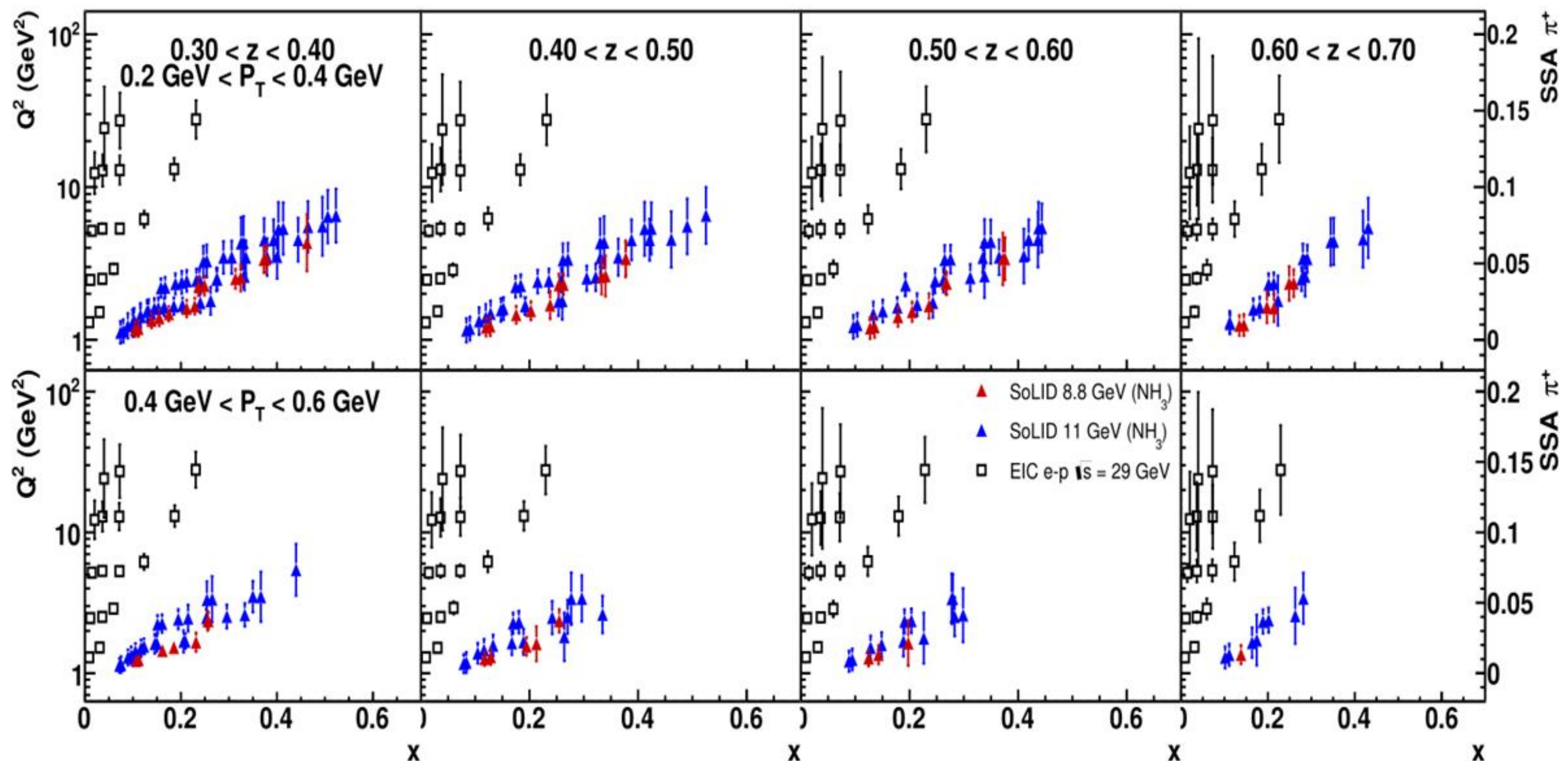
Theoretical predictions:

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

Transverse SSA projections: Complementarity to EIC

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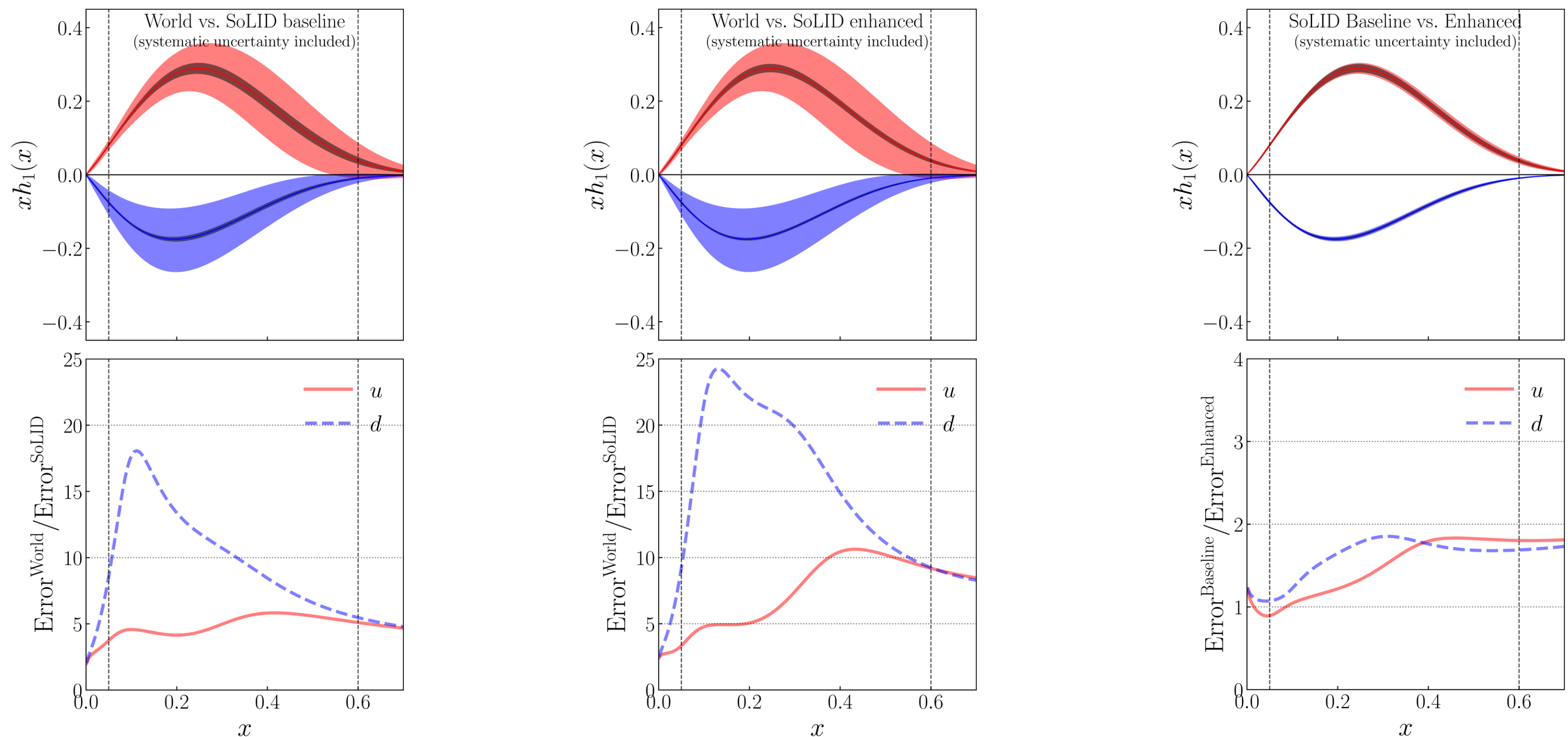
- SoLID SIDIS projections of A_{UT} in various 4-D bins at 11/8.8 GeV beam energies
- Projections at EIC kinematics for the same observable at 29 GeV center-of-mass energy
- SSA scale and uncertainties shown on the right-side axis of the figures
- SoLID and EIC projections synergistic towards each other,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



Transversity TMD projections (combined with the “neutron” results)

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



Transversity TMD projections (combined with the “neutron” results)

Some details on the SoLID SIDIS setup
with a trans.-pol. NH_3 (“p”) target

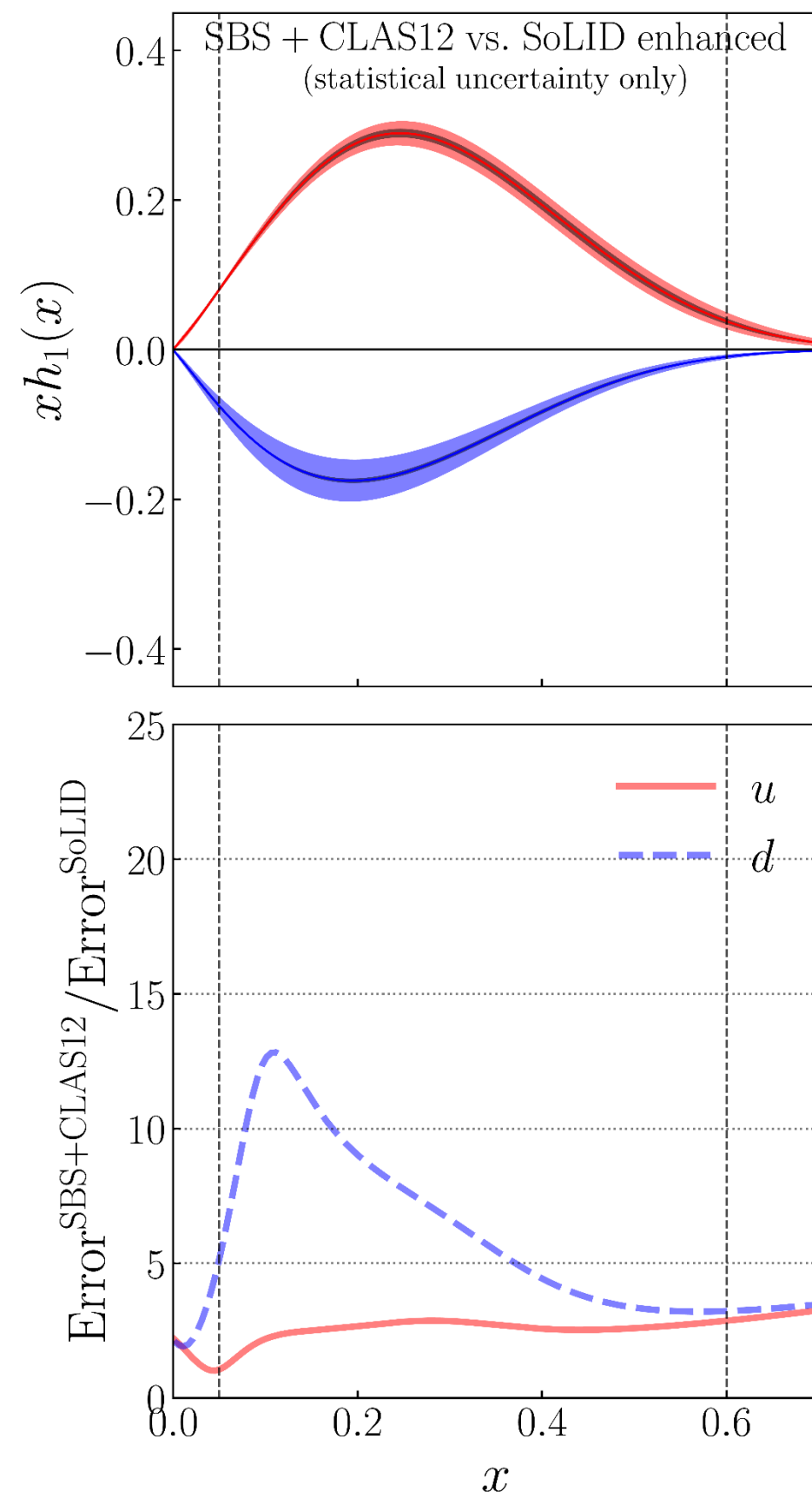
Reminder on three TMDs and
three SSAs under consideration

Several results from
the original proposal

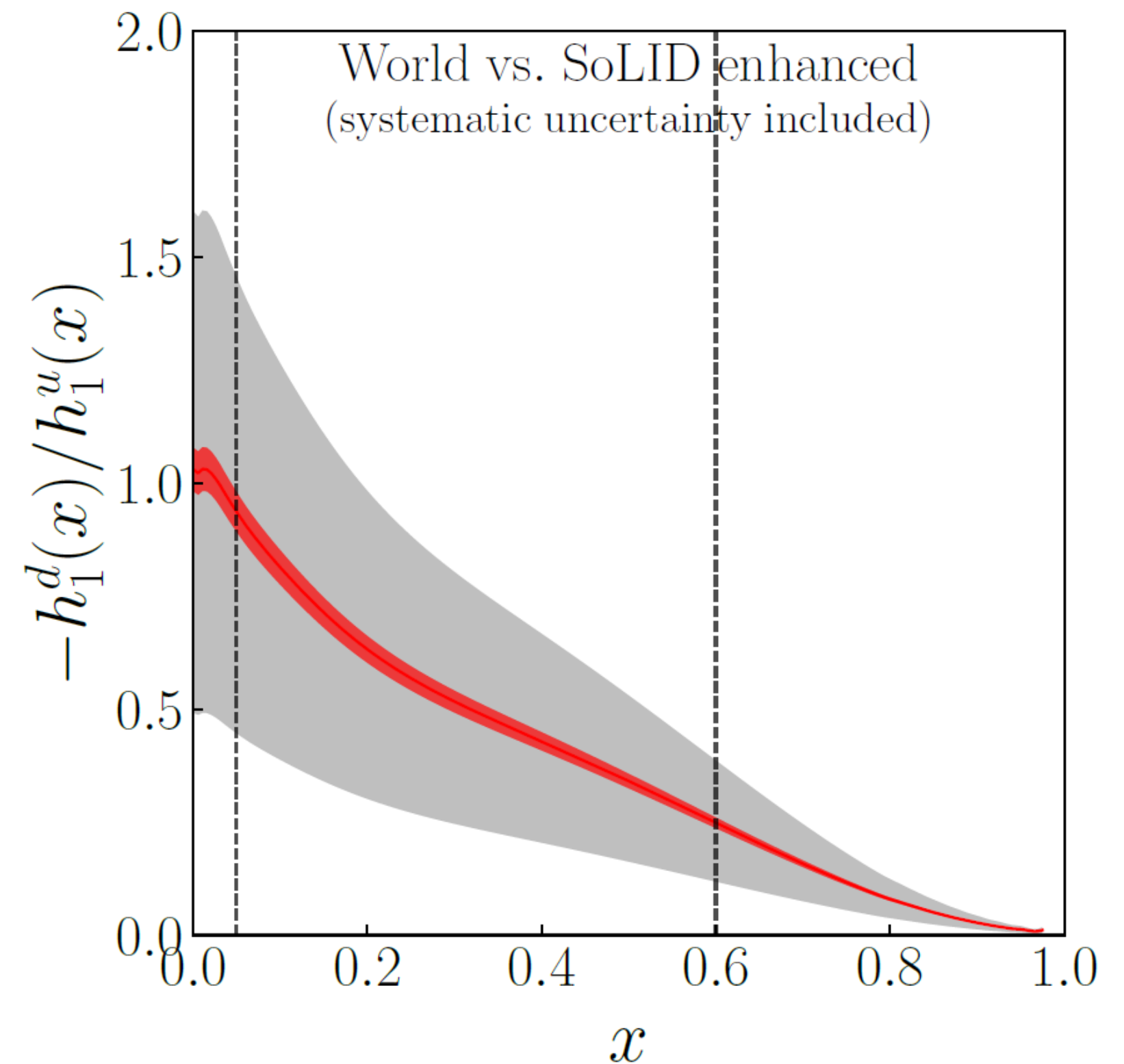
Recent updates

Summary

- 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)

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
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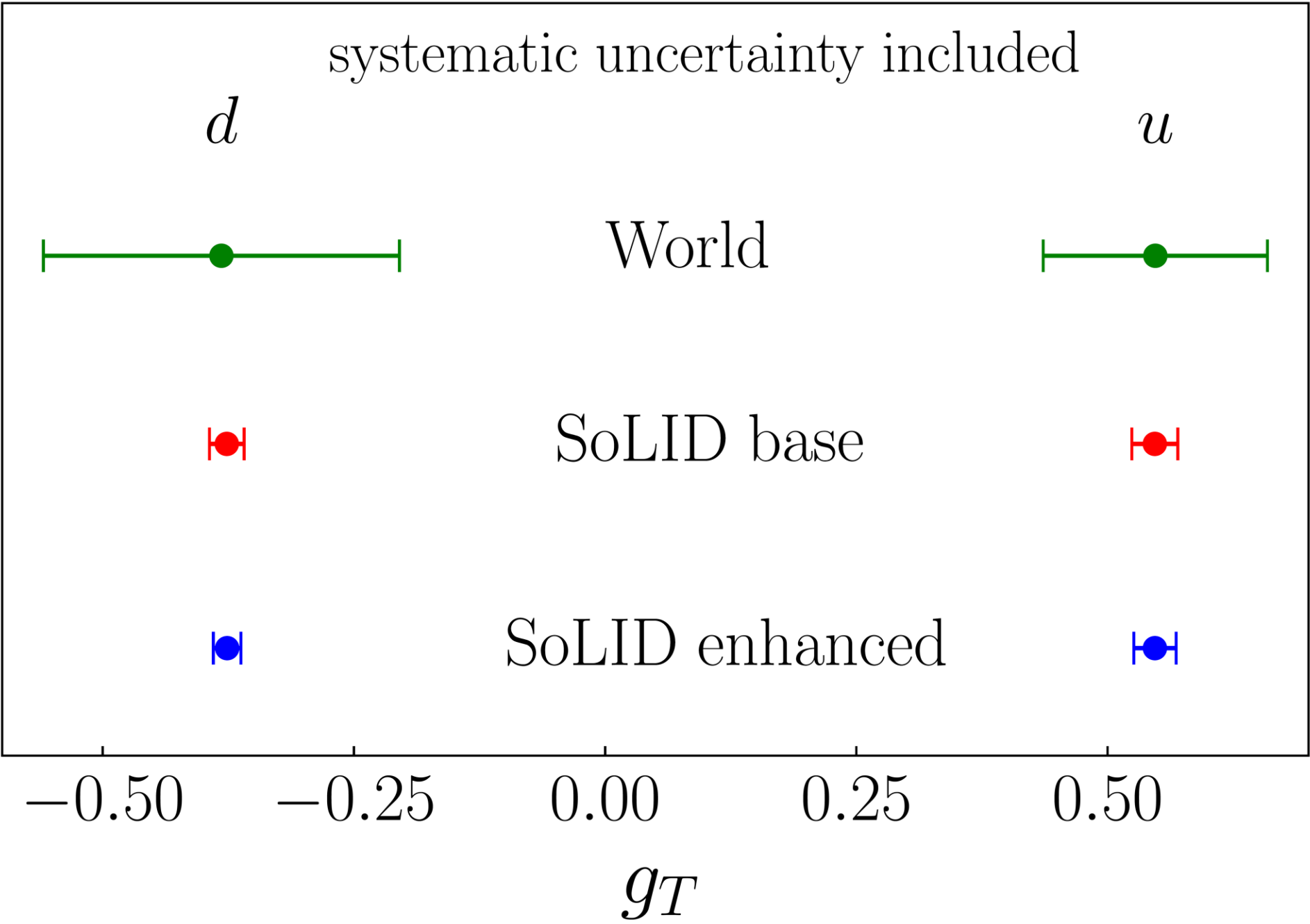
Tensor charge g_T :

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

World data

SoLID projections from both ³He / NH₃ 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)

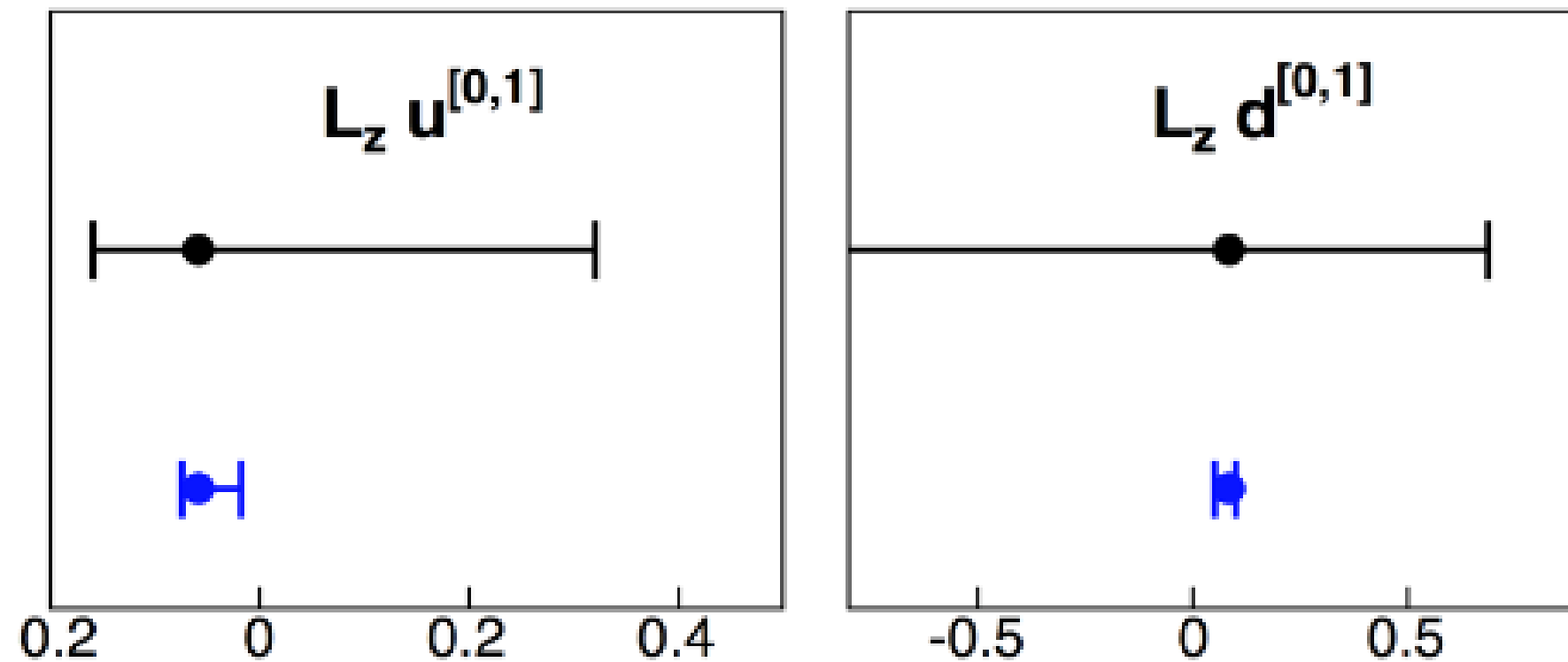
Some details on the SoLID SIDIS setup with a trans.-pol. NH_3 (“p”) target

Reminder on three TMDs and three SSAs under consideration

Several results from the original proposal

Recent updates

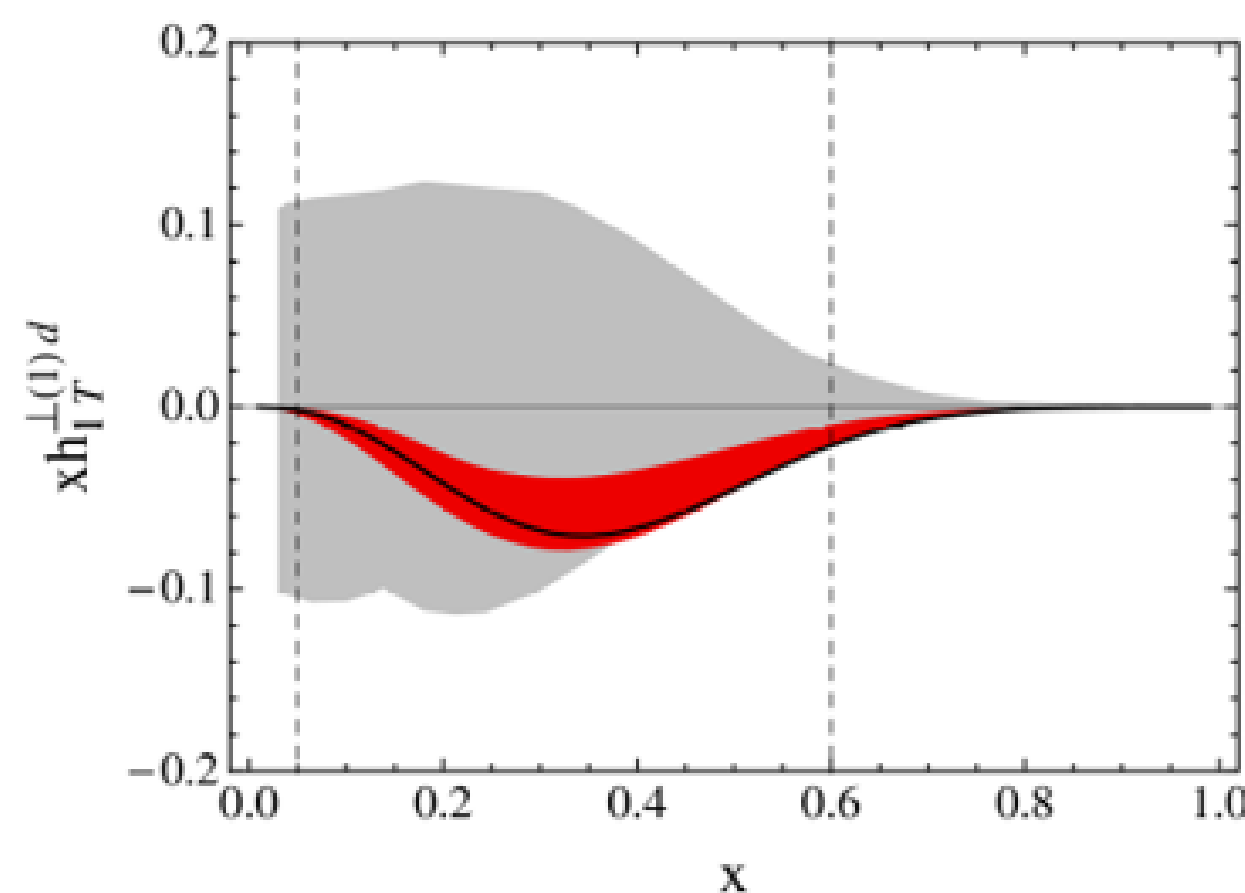
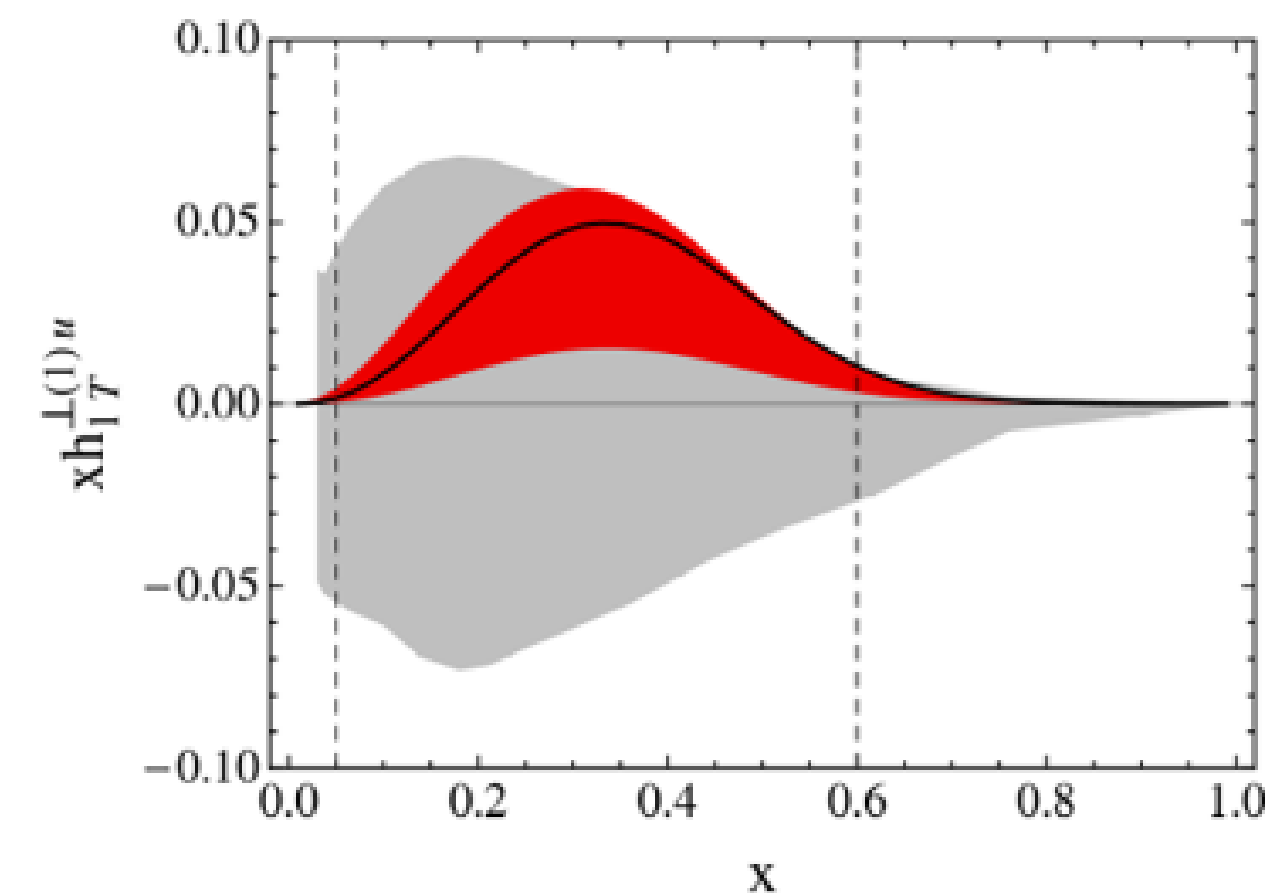
Summary



➤ The results obtained at $Q^2 = 2.4 \text{ GeV}^2$

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

- 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 $Q^2 = 2.4 \text{ GeV}^2$; integrated over the kinematic region of $0 < x < 1$

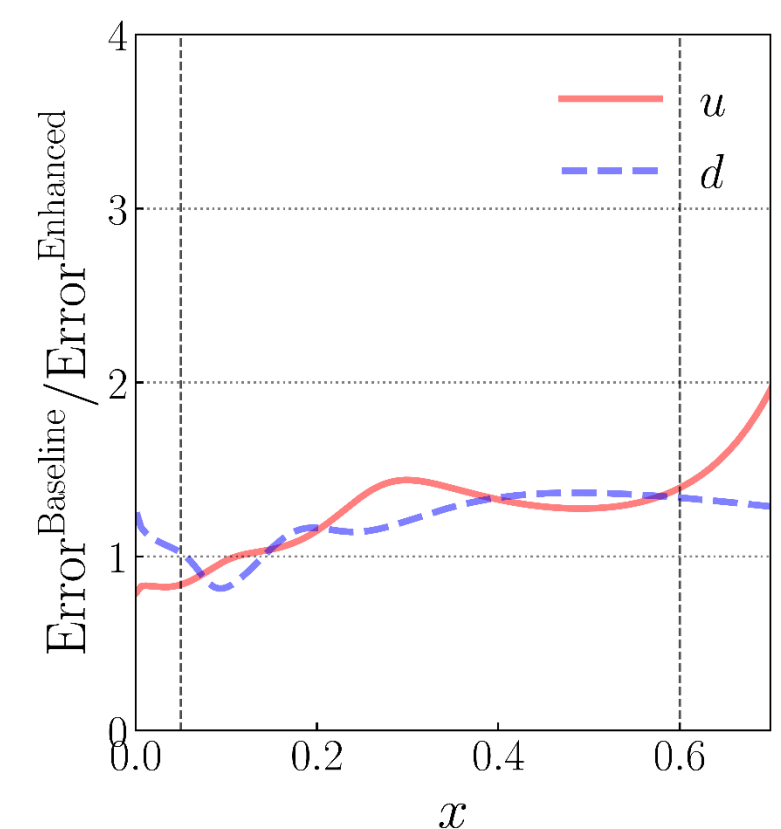
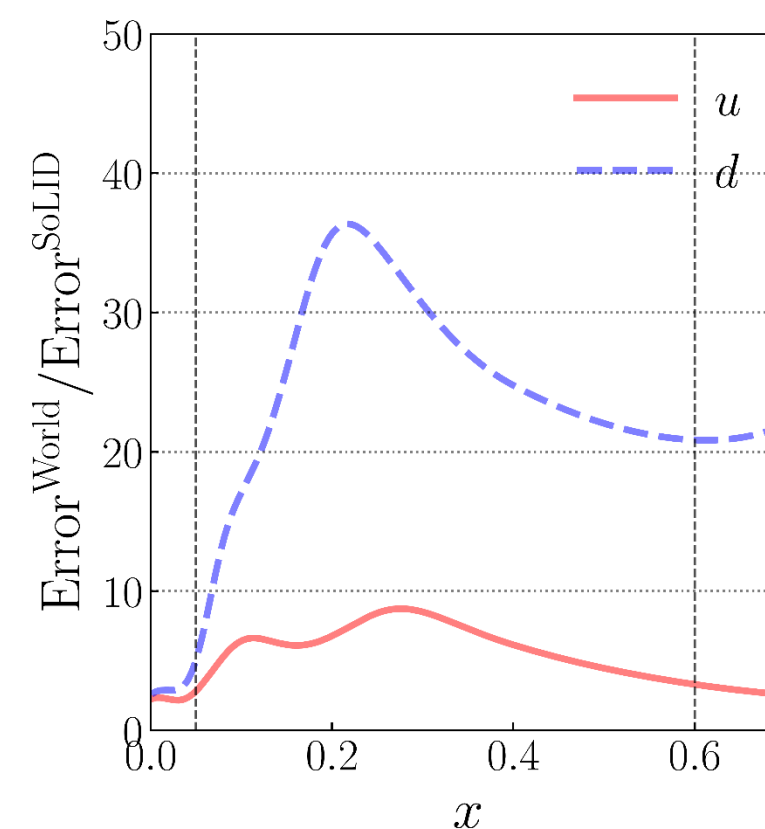
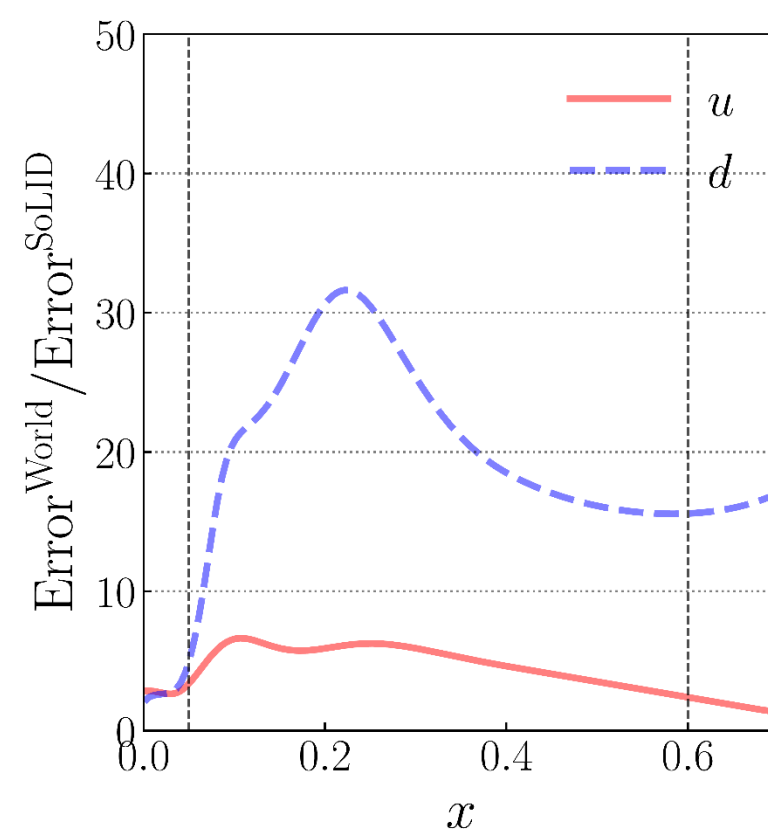
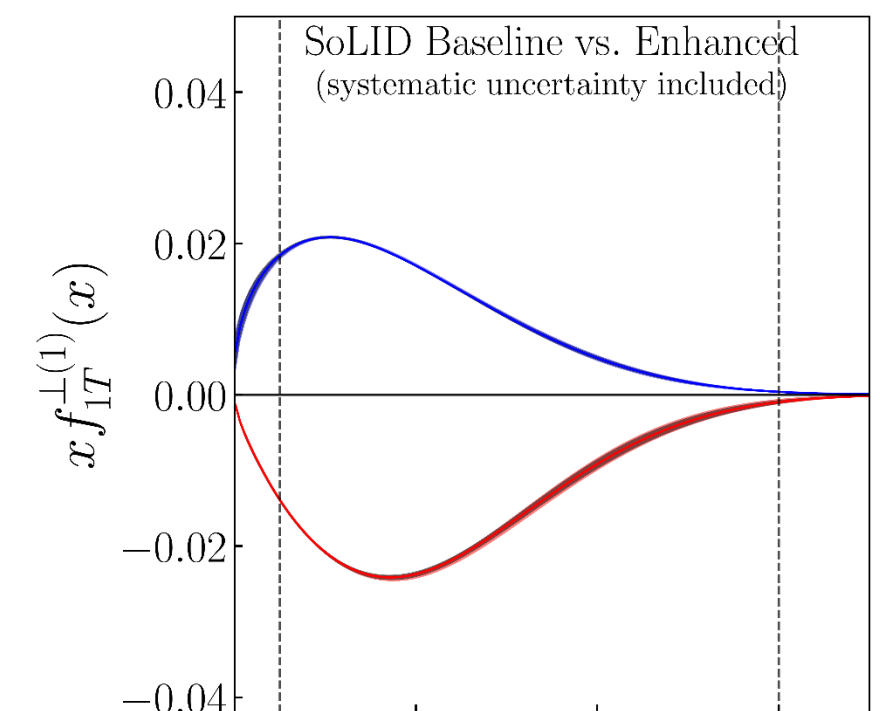
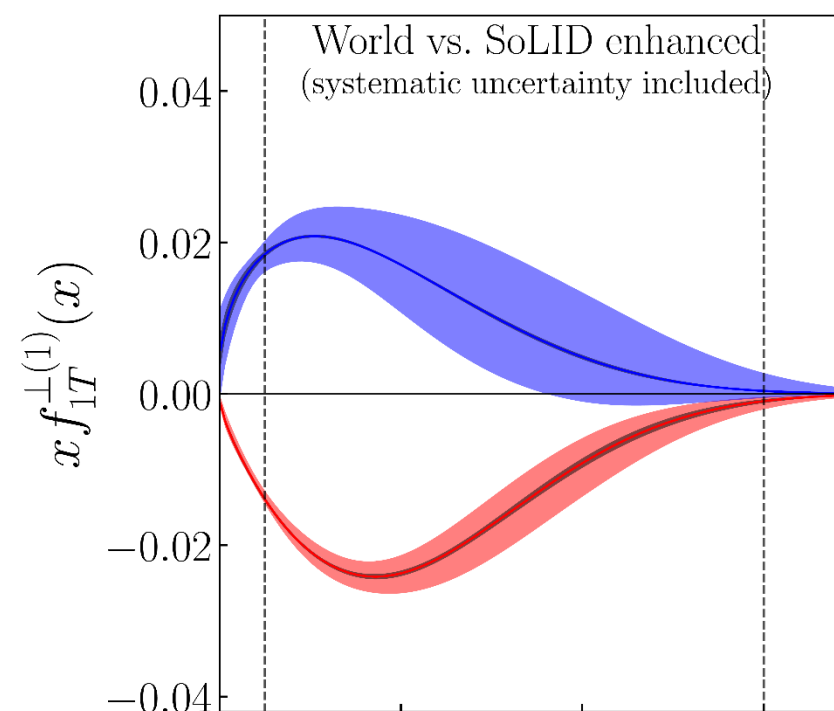
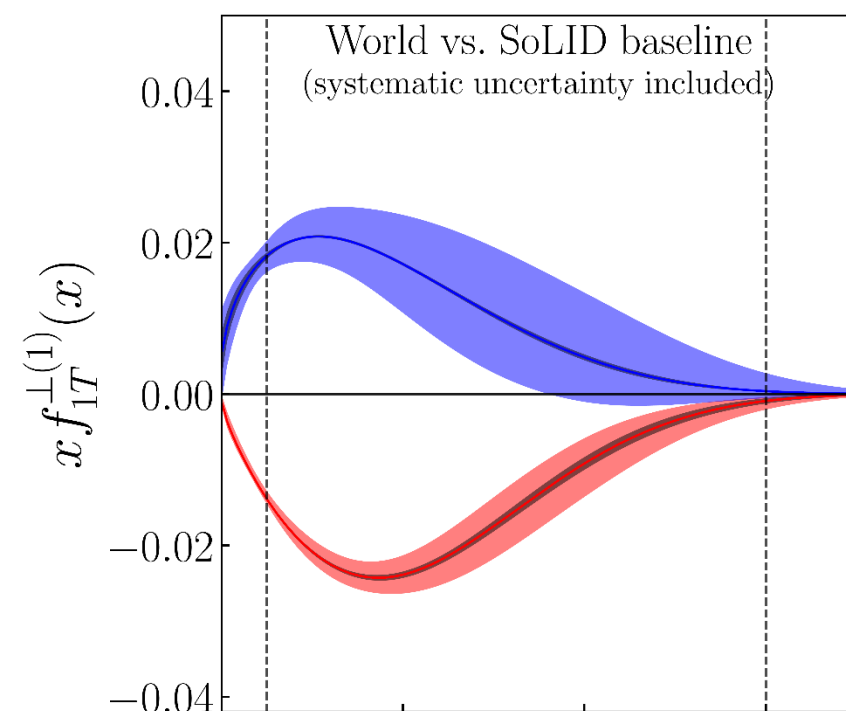


- Parametrization by Lefky and Prokudin, PRD 91, 034010 (2015)
- SoLID projections from transversely polarized “neutron” and “proton” targets

Sivers TMD projections (combined with the “neutron” results)

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
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- Top figures: impact on the u and d quarks’ Sivers TMD extractions by the SoLID SIDIS program
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Sivers TMD projections (combined with the “neutron” results)

Some details on the SoLID SIDIS setup with a trans.-pol. NH₃ (“p”) target

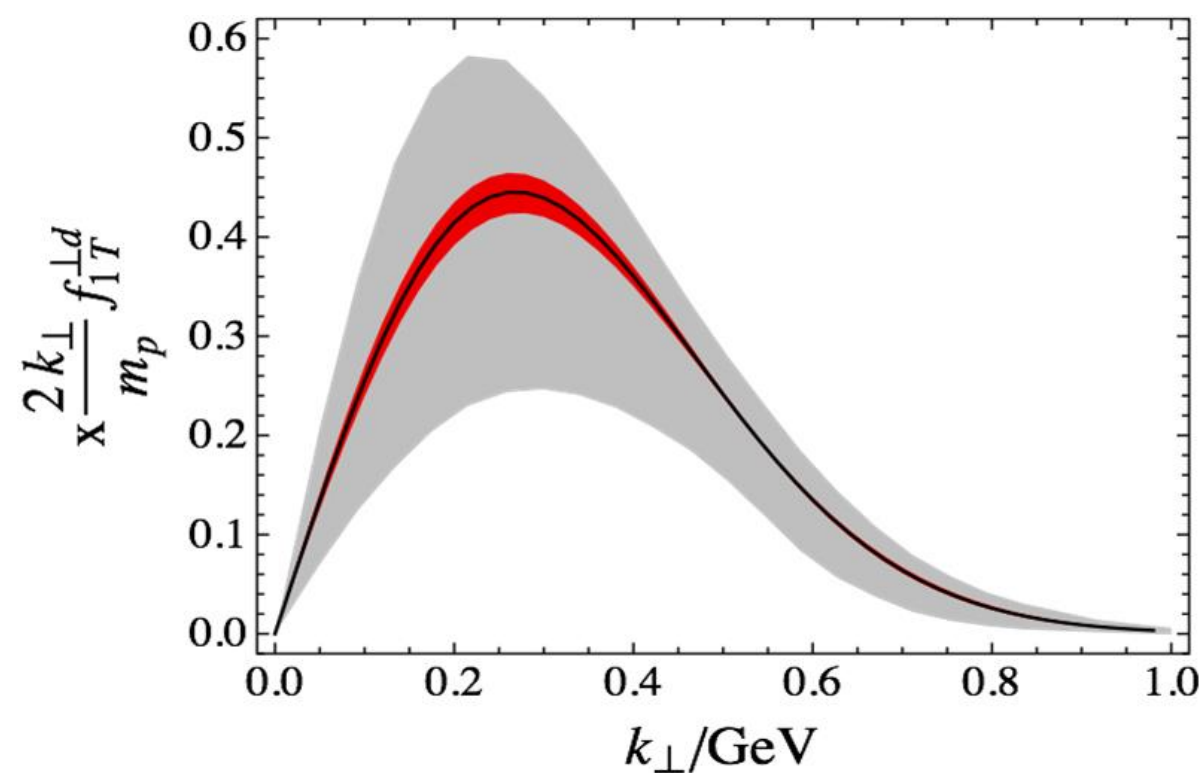
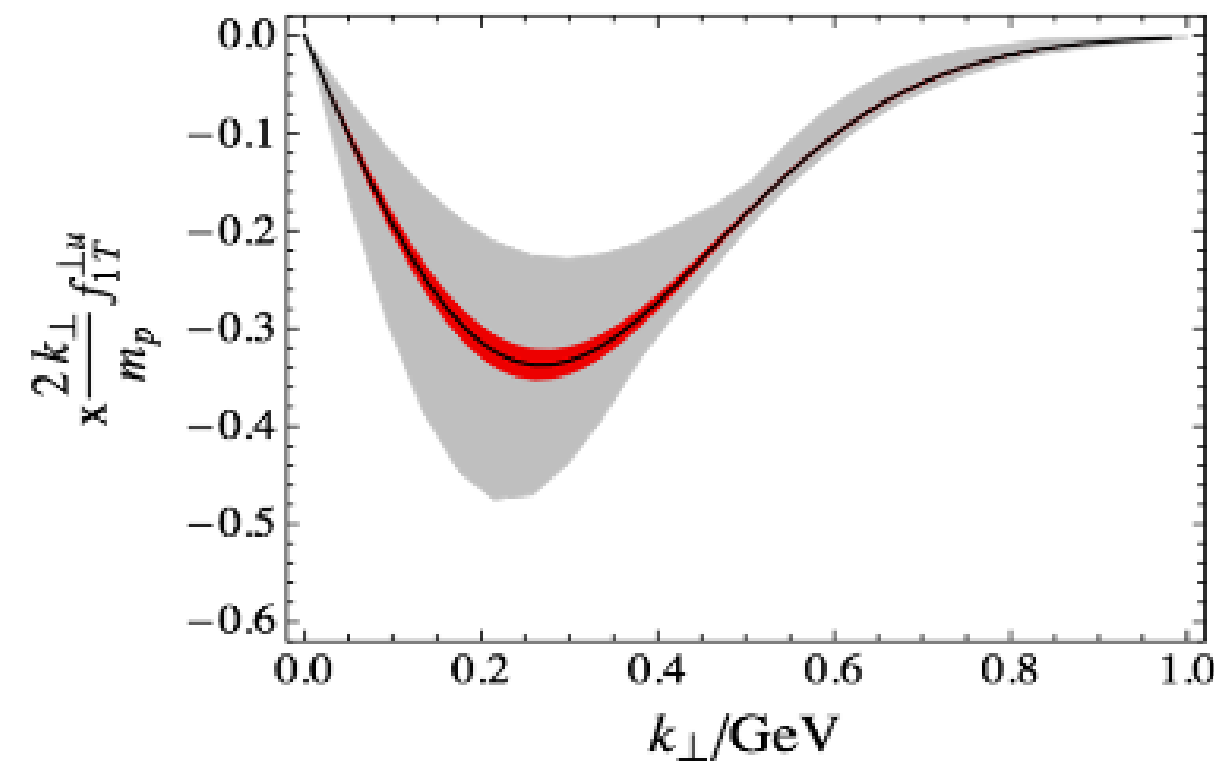
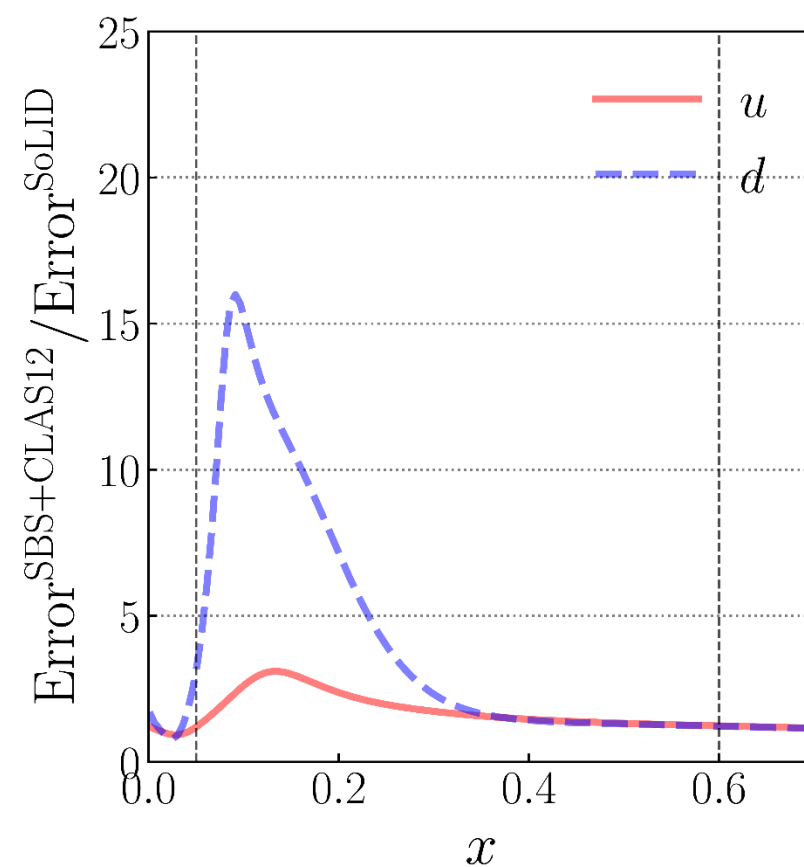
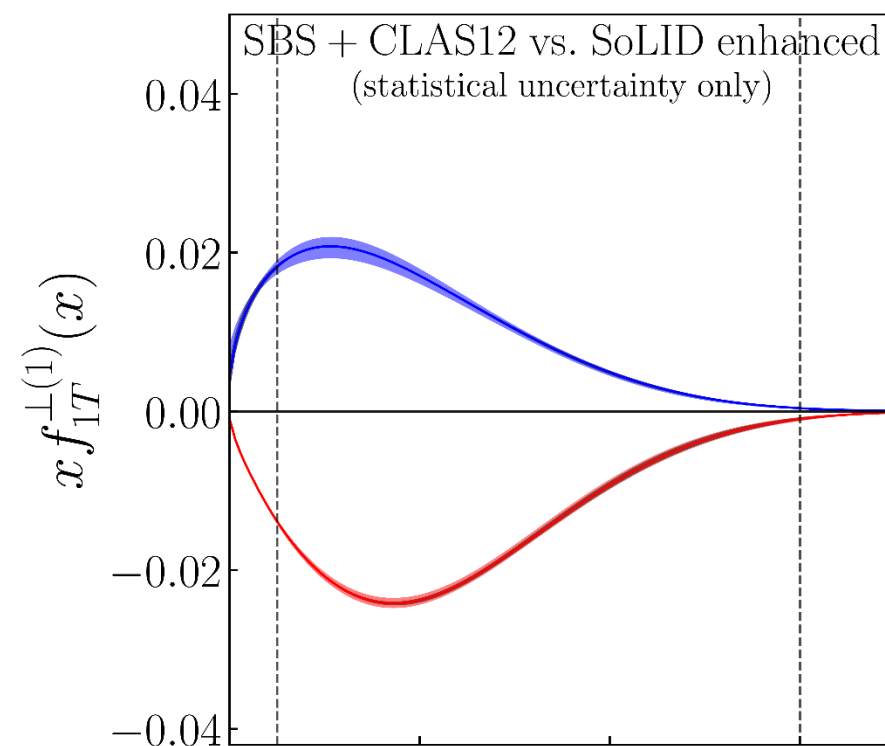
Reminder on three TMDs and three SSAs under consideration

Several results from the original proposal

Recent updates

Summary

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



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

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

$$\langle k_{\perp} \rangle^u$$

$$\langle k_{\perp} \rangle^d$$



$$96_{-28}^{+60} \text{ MeV}$$

$$-113_{-51}^{+45} \text{ MeV}$$



$$96_{-2.4}^{+2.8} \text{ MeV}$$

$$-113_{-1.7}^{+1.3} \text{ MeV}$$

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

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
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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

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
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- 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, Pretzelosity, 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
- *Diffraction 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

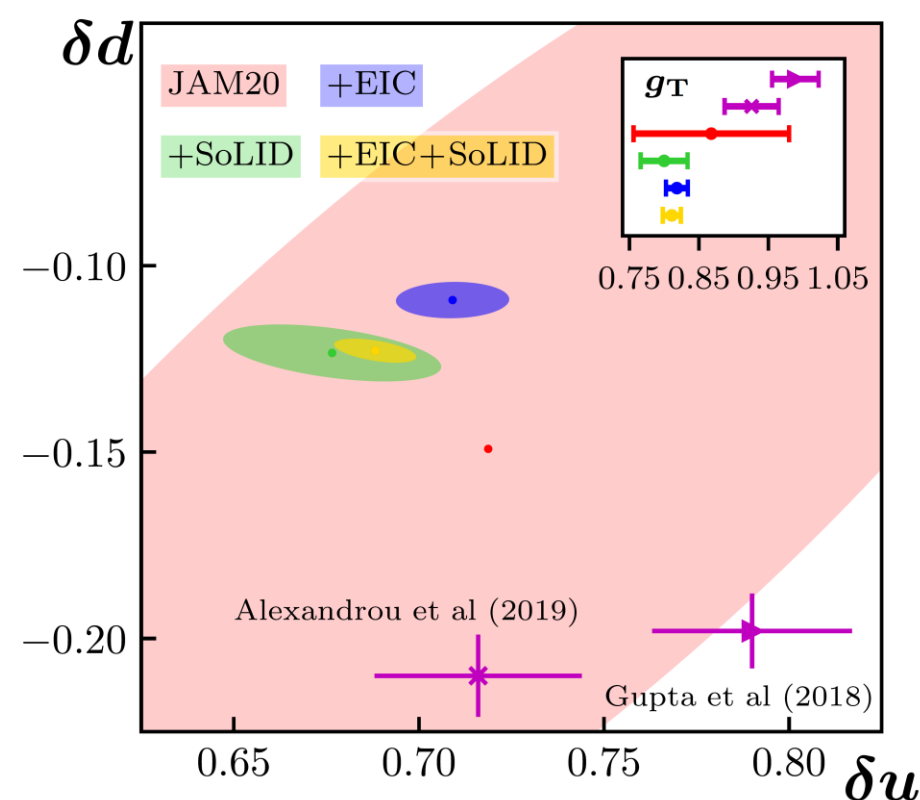
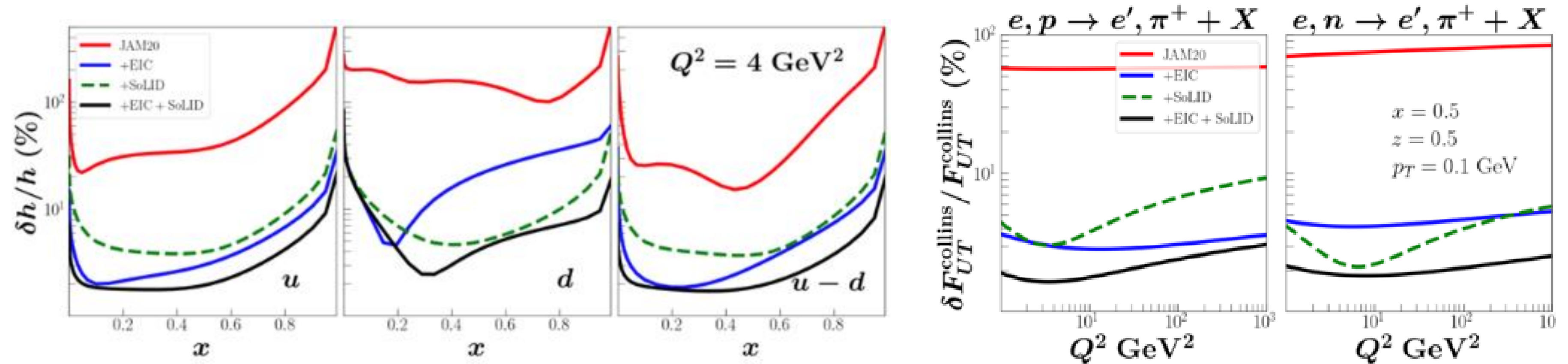
- The budget for the absolute and relative systematic uncertainties of the π^+/π^- Collins and Sivers SSAs
- The uncertainty sources described in the previous slide

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%
Diffraction 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)



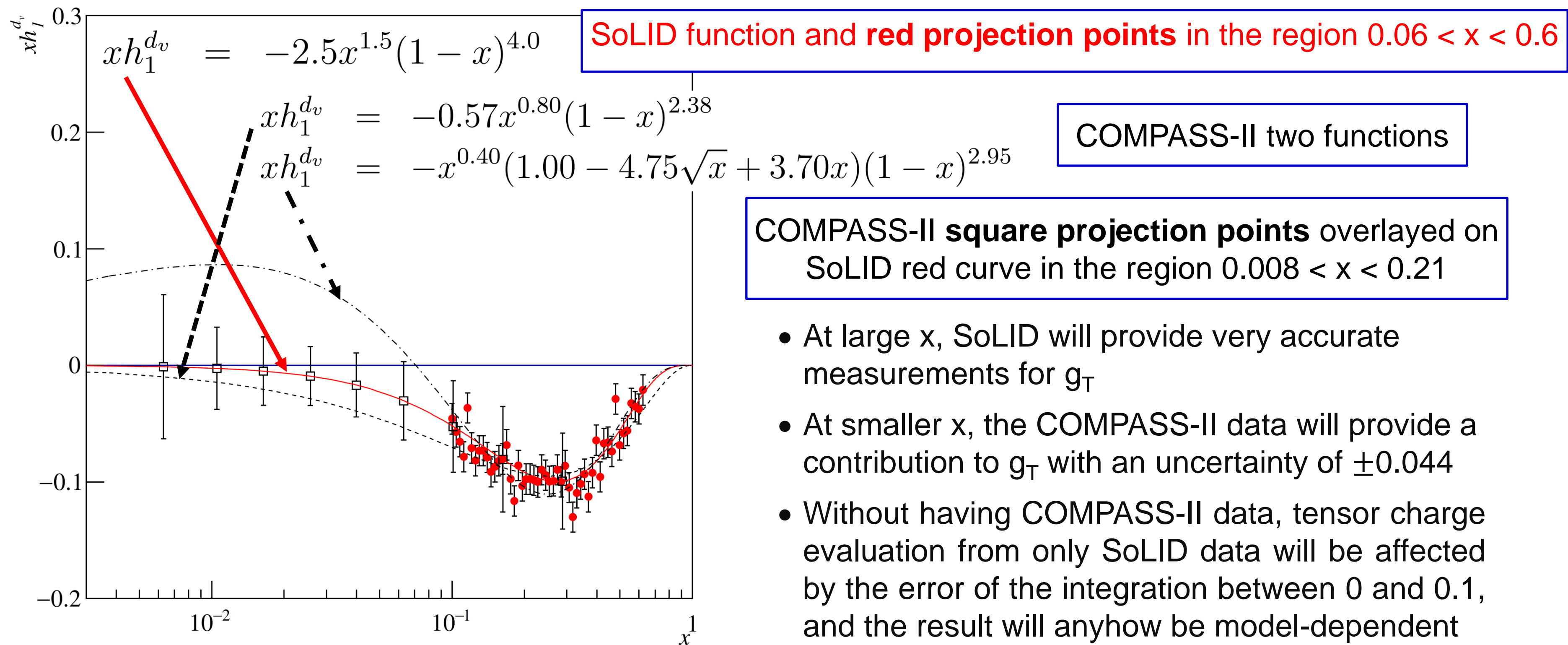
$$\langle P, S | \bar{\psi}_q i \sigma^{\mu\nu} \psi_q | P, S \rangle = g_T^q \bar{u}(P, S) i \sigma^{\mu\nu} u(P, S)$$

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

- 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



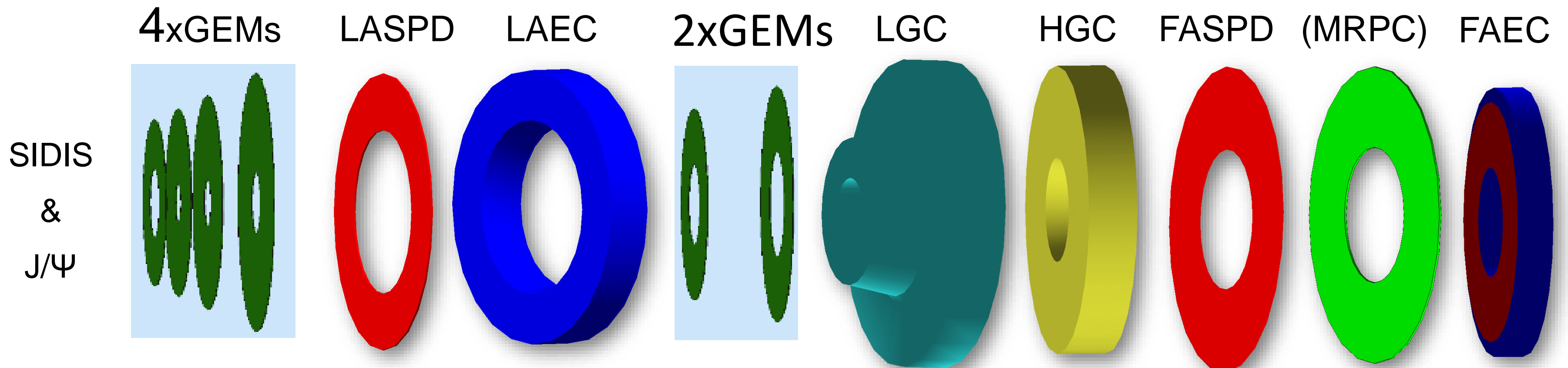
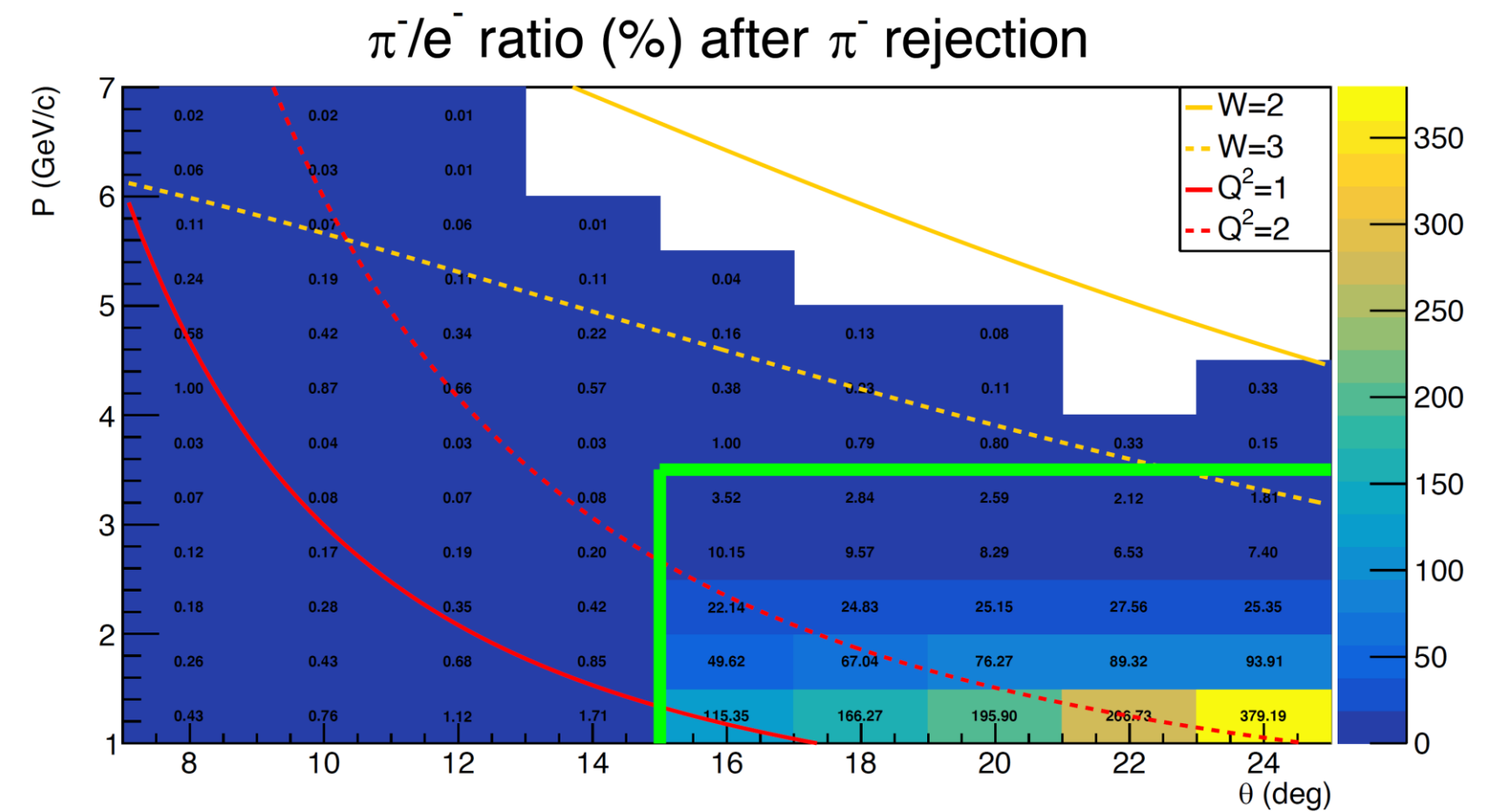
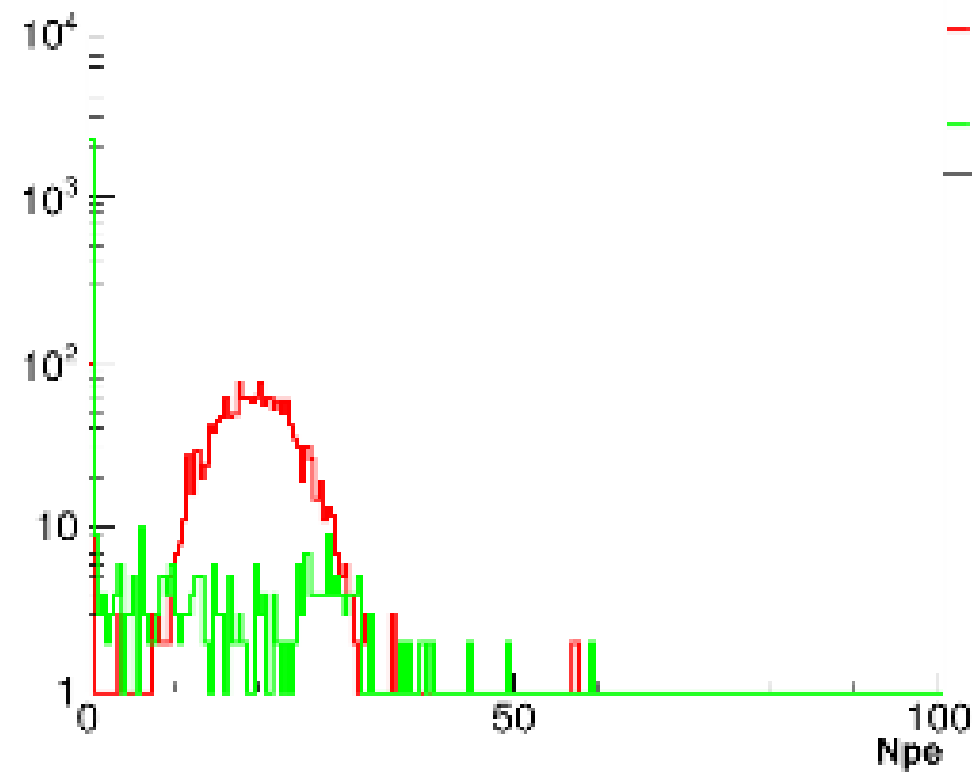
The figure is from
d-Quark Transversity and Proton Radius: Addendum to the COMPASS-II Proposal

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

Combined light gas Cherenkov and Calorimeter detector performance

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



MRPC: enhanced configuration for kaon and improved pion detection