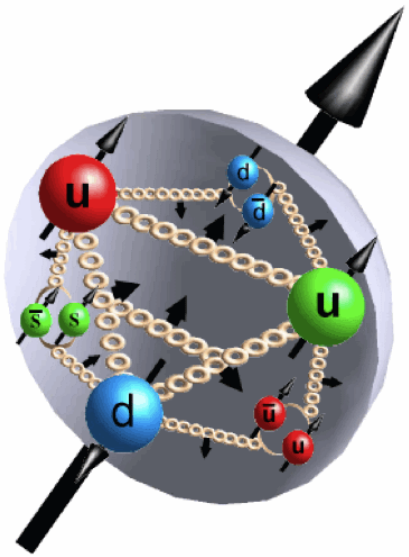
Study of TMDs with SoLID at 12-GeV Jefferson Lab

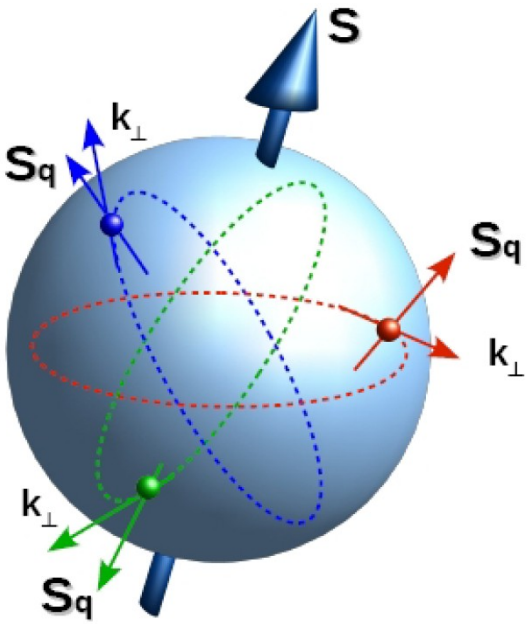


Kalyan Allada
Massachusetts Institute of Technology

DIS Workshop 2017, University of Birmingham, UK
4th April 2017

Spin and Intrinsic Transverse Momentum

We cannot learn about the spin structure of the nucleon without ***rigorously*** taking into account the transverse motion of the partons inside it !



Distribution and fragmentation functions depends on:

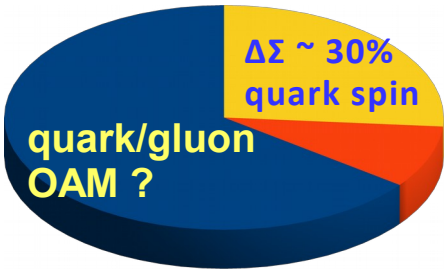
- lightcone momentum fraction
  (**x** for the distributions and **z** for the fragmentation)
- Q^2 (pQCD evolution)
- intrinsic transverse momentum of partons
  ($\mathbf{k_T}$ for the distrubutions and $\mathbf{p_T}$ for the fragmentation)

Open questions:

- How do TMD's depend on the intrinsic transverse momentum ?
  - Gaussian behaviour in the central region ...
  - Power law decrease at large transverse momentum…
- Does the partonic intrinsic transverse momentum $\mathbf{k_T}(\mathbf{p_T})$ depend on **x** (**z**) ?

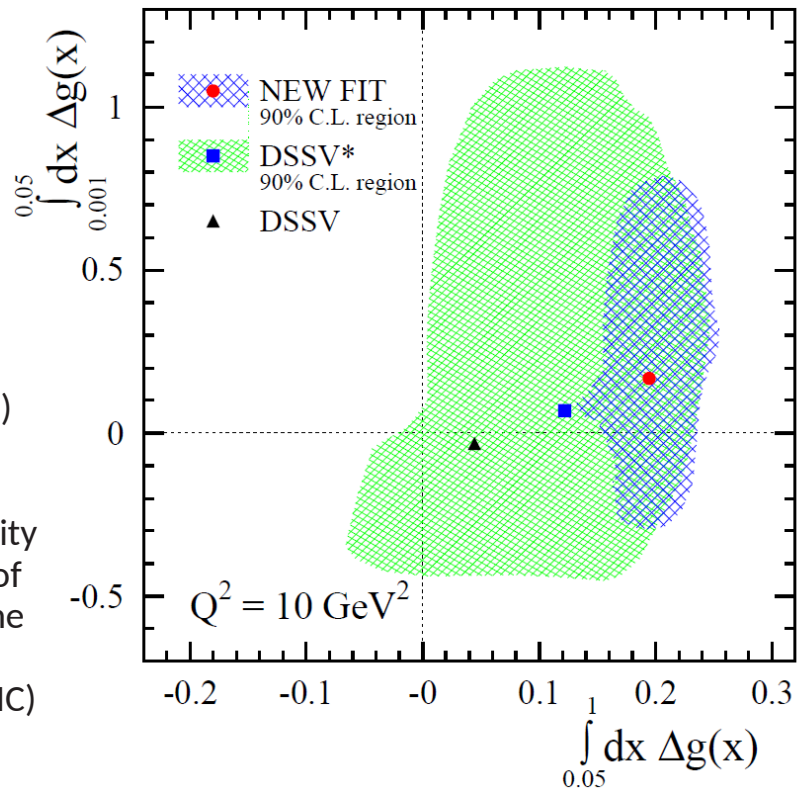
Nucleon Spin Puzzle

Nucleon spin: $$\frac{1}{2}=\frac{1}{2}\Delta\Sigma+\Delta G+\underbrace{L_q+L_g}_{\text{orbital angular momentum}}$$



ΔG ~ not small?

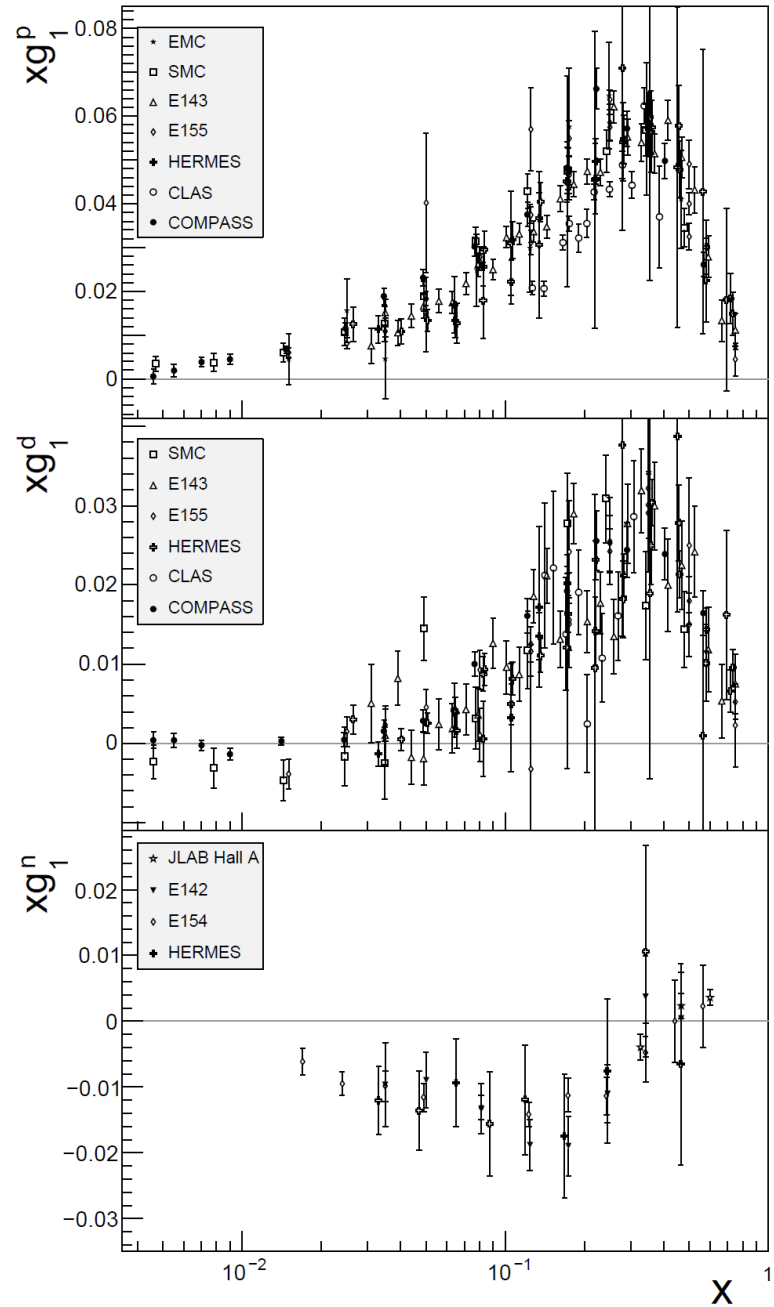
Gluon polarization



deFlorian, et al.,
PRL 113, 012001 (2014)

Global analysis of helicity PDFs – clear evidence of gluon polarization in the intermediate momentum scales (RHIC)

Polarized DIS data

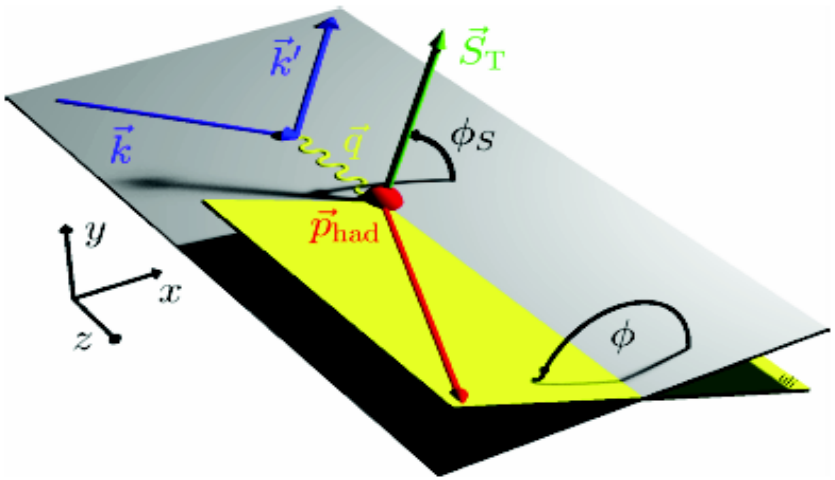


Structure functions from SIDIS

SIDIS differential cross section

18 structure functions $F(x, z, Q^2, P_T)$,

model independent (one photon exchange approximation)

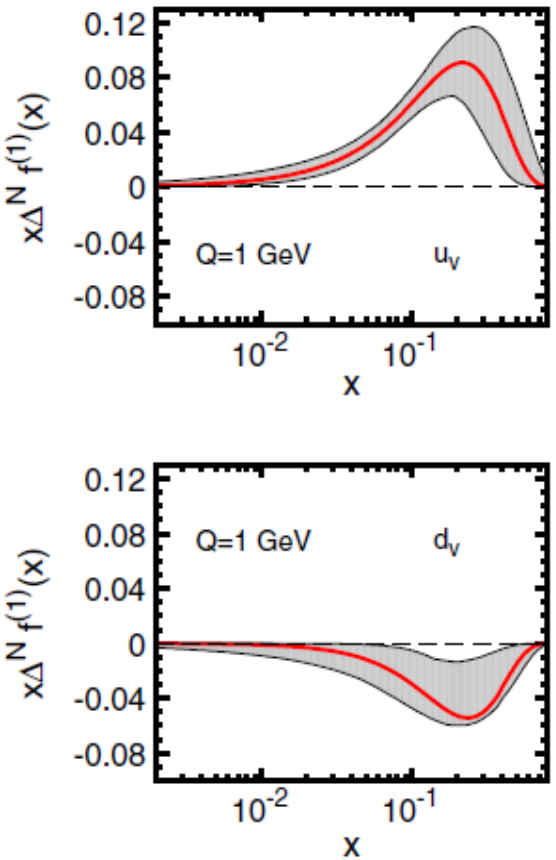


$$
\begin{aligned}
&\frac{d\sigma}{dx\,dy\,dz\,dP_T^2\,d\phi_h\,d\phi_S} \\
&= \frac{\alpha^2}{xyQ^2}\frac{y^2}{2(1-\epsilon)}\left(1+\frac{\gamma^2}{2x}\right) \\
&\times \Big\{ F_{UU,T} + \epsilon F_{UU,L} + \sqrt{2\epsilon(1+\epsilon)}F_{UU}^{\cos\phi_h}\cos\phi_h + \epsilon F_{UU}^{\cos 2\phi_h}\cos 2\phi_h + \lambda_e\sqrt{2\epsilon(1-\epsilon)}F_{LU}^{\sin\phi_h}\sin\phi_h \\
&+ S_L\left[\sqrt{2\epsilon(1+\epsilon)}F_{UL}^{\sin\phi_h}\sin\phi_h + \epsilon F_{UL}^{\sin 2\phi_h}\sin 2\phi_h\right] + \lambda_e S_L\left[\sqrt{1-\epsilon^2}F_{LL} + \sqrt{2\epsilon(1-\epsilon)}F_{LL}^{\cos\phi_h}\cos\phi_h\right] \\
&+ S_T\left[(F_{UT,T}^{\sin(\phi_h-\phi_S)} + \epsilon F_{UT,L}^{\sin(\phi_h-\phi_S)})\sin(\phi_h-\phi_S) + \epsilon F_{UT}^{\sin(\phi_h+\phi_S)}\sin(\phi_h+\phi_S) + \epsilon F_{UT}^{\sin(3\phi_h-\phi_S)}\sin(3\phi_h-\phi_S)\right. \\
&\qquad \left. + \sqrt{2\epsilon(1+\epsilon)}F_{UT}^{\sin\phi_S}\sin\phi_S + \sqrt{2\epsilon(1+\epsilon)}F_{UT}^{\sin(2\phi_h-\phi_S)}\sin(2\phi_h-\phi_S)\right] \\
&+ \lambda_e S_T\left[\sqrt{1-\epsilon^2}F_{LT}^{\cos(\phi_h-\phi_S)}\cos(\phi_h-\phi_S)\right. \\
&\qquad \left. + \sqrt{2\epsilon(1-\epsilon)}F_{LT}^{\cos\phi_S}\cos\phi_S + \sqrt{2\epsilon(1-\epsilon)}F_{LT}^{\cos(2\phi_h-\phi_S)}\cos(2\phi_h-\phi_S)\right]\Big\}
\end{aligned}
$$

In parton model, $F(x, z, Q^2, P_T)$s are expressed as the convolution of TMDs.

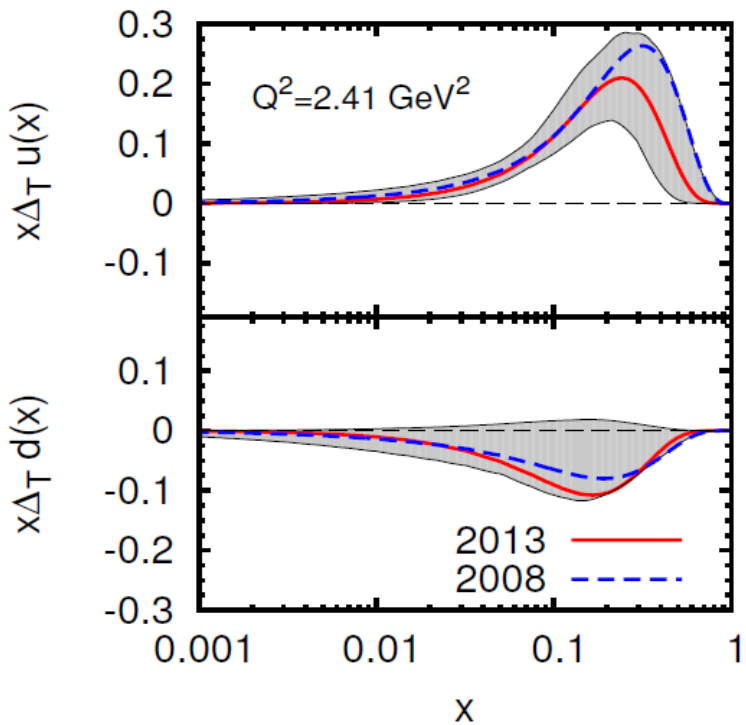
Present Status of TMD Extractions

SIVERS FUNCTION - TMD



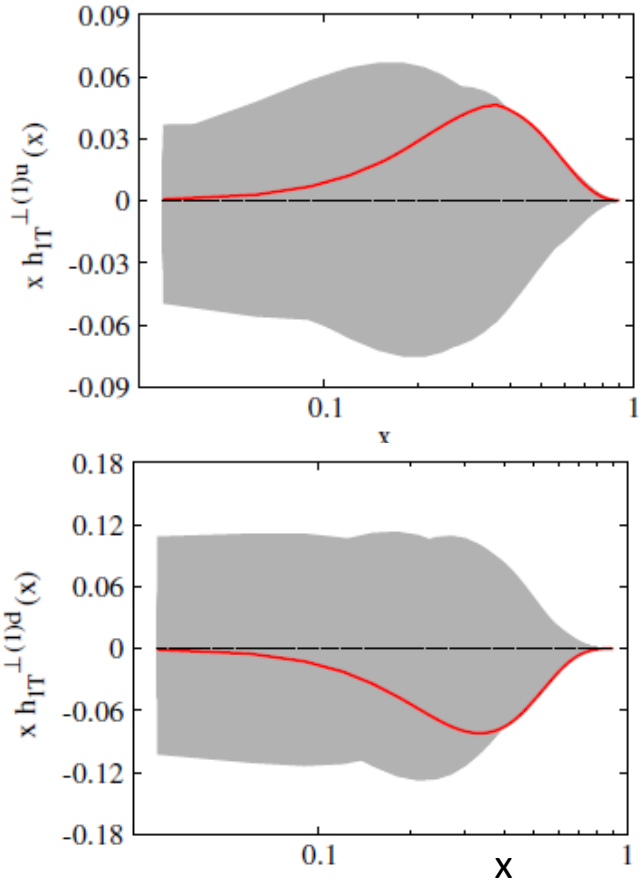
Anselmino et al.,
PRD 86, 014028 (2012)

Transversity



Anselmino et al.,
Phys. Rev. D 87, 094019

Pretzelosity



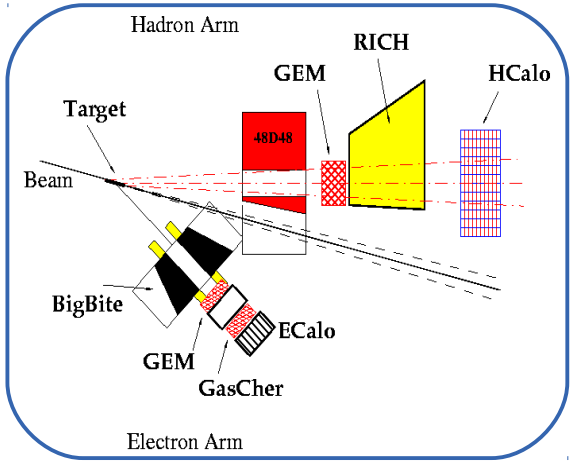
C. Lefky, A. Prokudin
PRD 91, 034010 (2015)

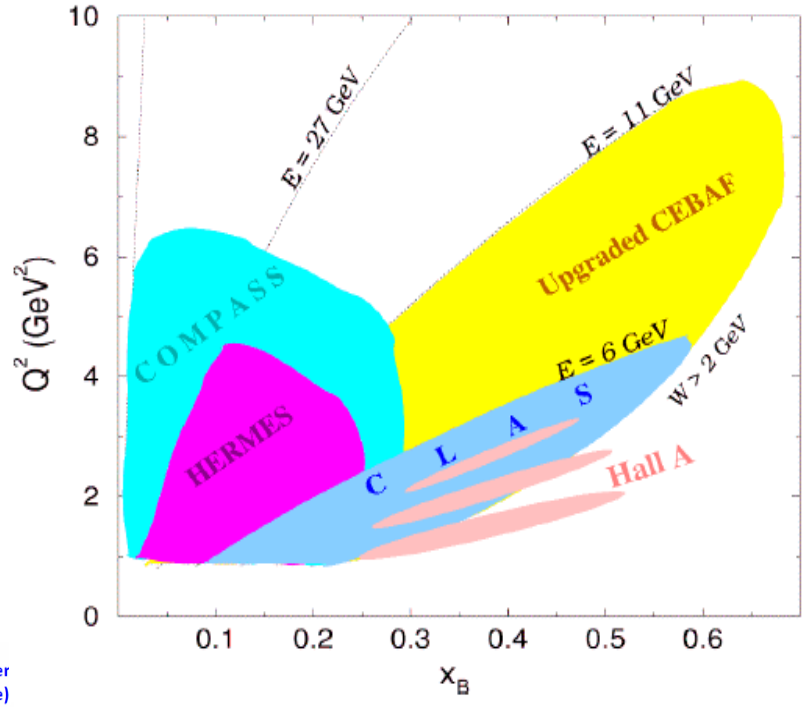
Transverse SSA data available from HERMES, COMPASS and JLab Hall A

Multi-Hall SIDIS Program at JLab

Hall A: Super BigBite

SIDIS with ^{3}He, high x, Q^2

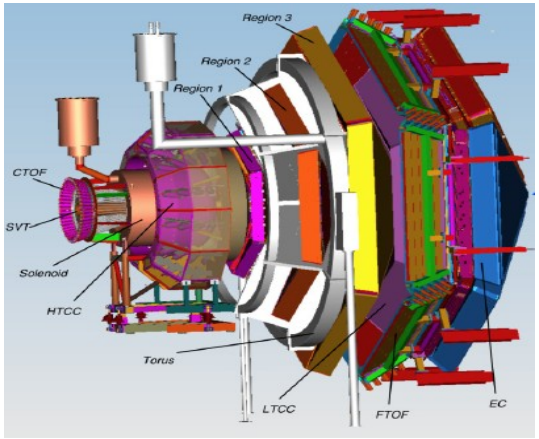




Hall B: CLAS12

SIDIS with polarized H/D

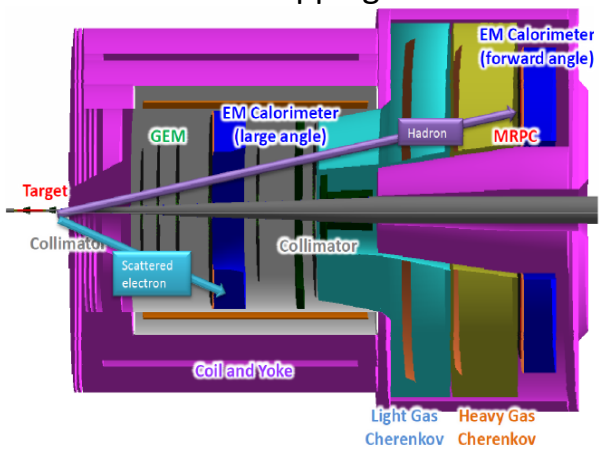
Comprehensive SIDIS program



Hall A: SoLID

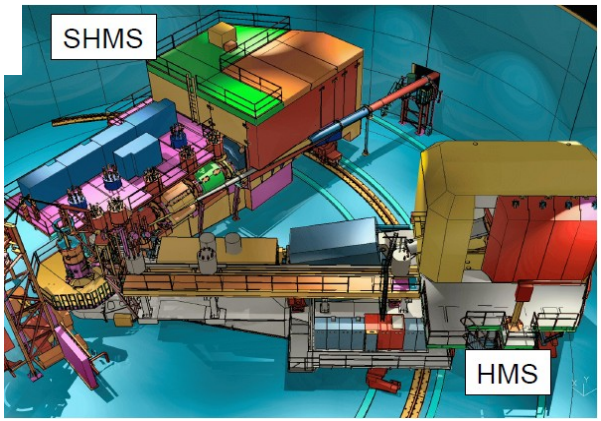
SIDIS with polarized ^{3}He/NH_3

Precision 4D mapping



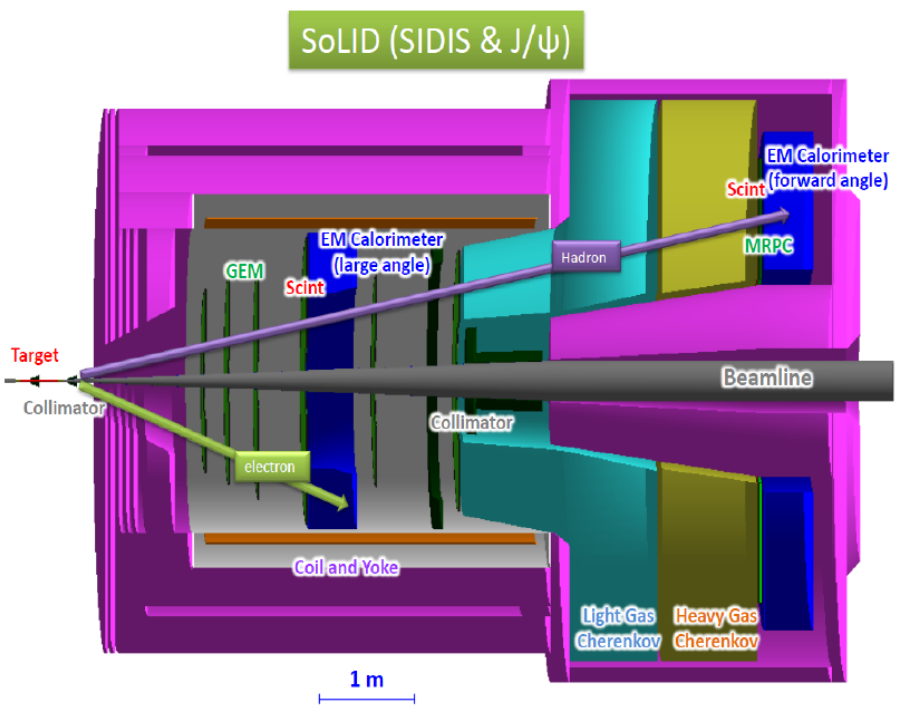
Hall C: SHMS

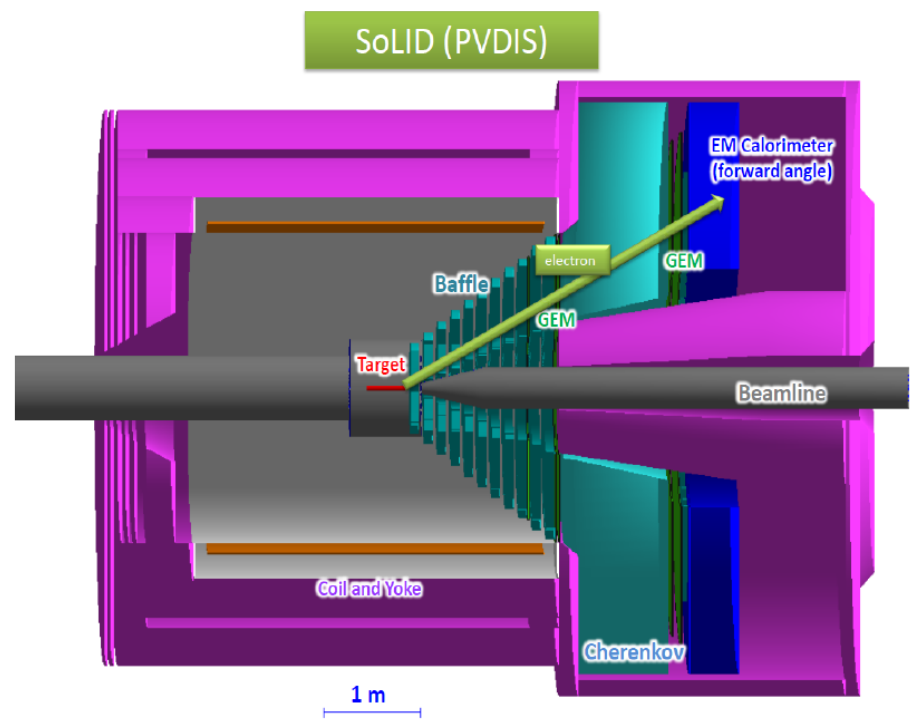
SIDIS with unpolarized H/D



Overview of SoLID

- Proposed to take full advantage of 12 GeV upgrade at JLab
  - A large acceptance detector which can handle high luminosity (10^{37} -10^{39}cm^{-2}s^{-1})
  - Modified CLEO-II magnet, modern detectors, latest data-acquisition technologies
- Five highly rated approved experiments:
  - Three SIDIS experiments, one PVDIS and one *J/ψ* production
- Large collaboration (250+ collaborators for 70+ institutes in 13 countries)
  - Major collaboration with Chinese institutes

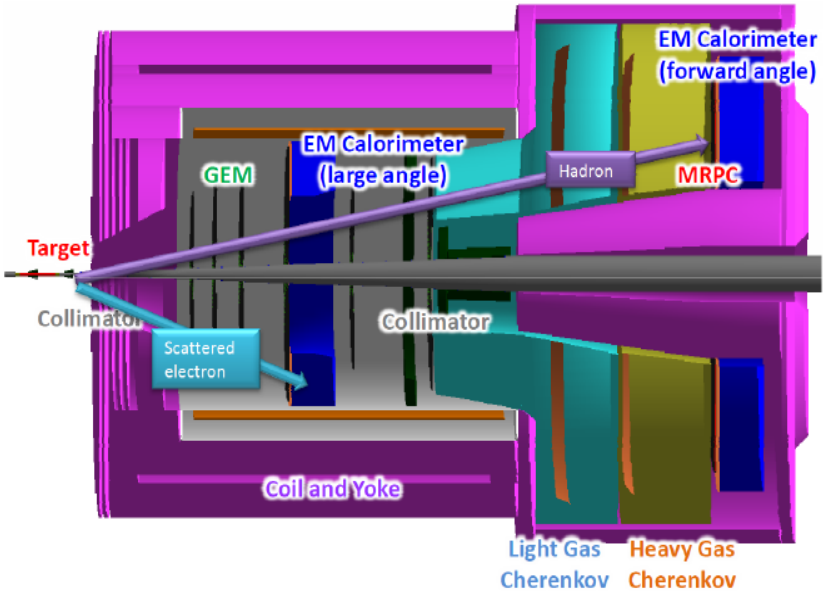




SoLID Spectrometer for SIDIS

- Longitudinal and transverse polarized targets
  - proton (NH_3) and neutron (^3He) targets
- Three approved Semi-inclusive DIS proposals:
  - SSA/DSA on longitudinal neutron (^3He) - E12-11-007
  - SSA on transverse neutron (^3He) - E12-10-006
  - SSA on transversely proton (NH_3) - E12-11-108
- Precision 4-D (x, Q^2, p_T, z) mapping of SSA/DSA
  - high luminosity($10^{36} cm^{-2} s^{-1}$) and larger acceptance
- Tensor charge, TMDs (Collins, Sivers, Pretzelosity...)
- Two run group experiments:
  - SSA in dihadron production and A_y (two photon-exchange)

Proposed design



Kinematic Coverage with SoLID

Wide phase space coverage – essential for 4D binning of SSA/DSA

- x_B = 0.05 – 0.68
- Q^2 = 1.0 – 9.0 GeV^2
- P_T = 0 – 1.5 GeV^2
- Z = 0.3 – 0.7
- W > 2.3 GeV

Forward acceptance:

$\phi = 2\pi$

$\theta = 8^o – 14^o$

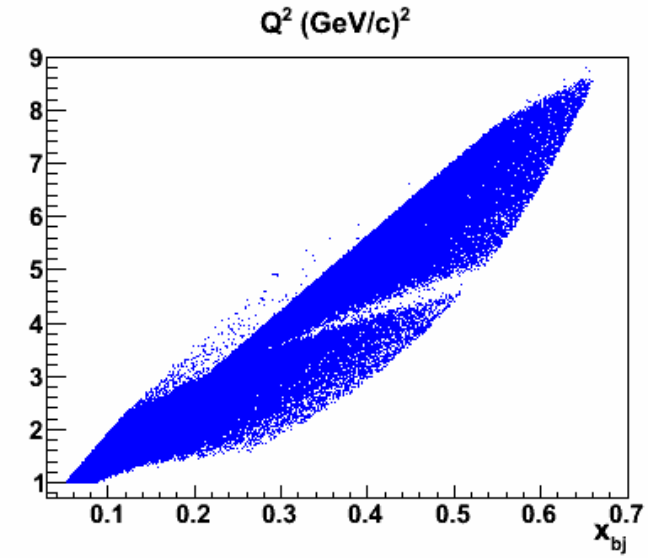
P : 1.0 – 7.0 GeV/c

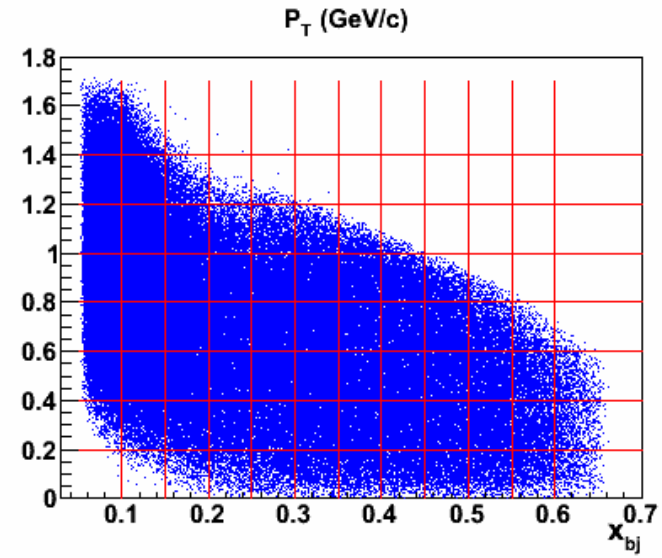
Large angle acceptance:

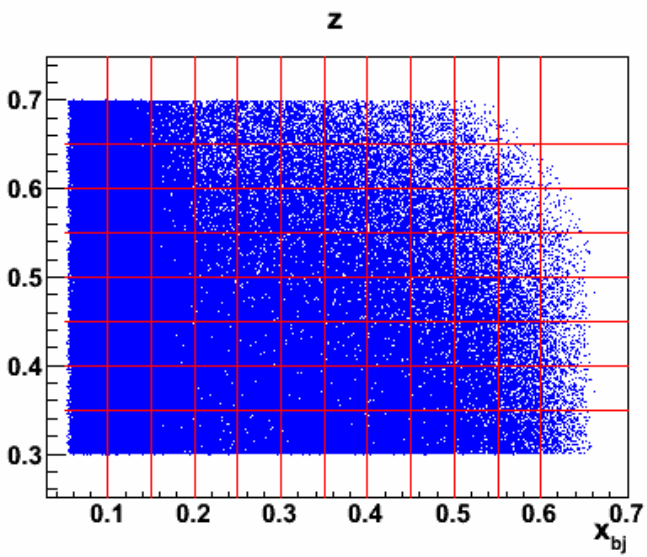
$\phi = 2\pi$

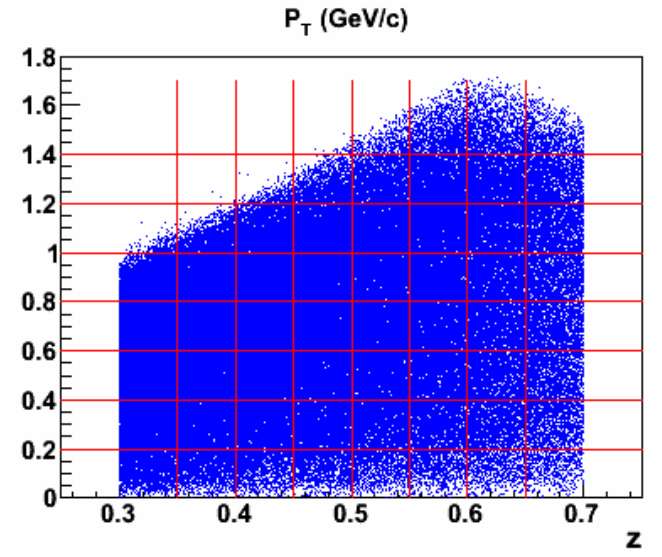
$\theta = 16^o – 24^o$

P : 3.5 – 7.0 GeV/c





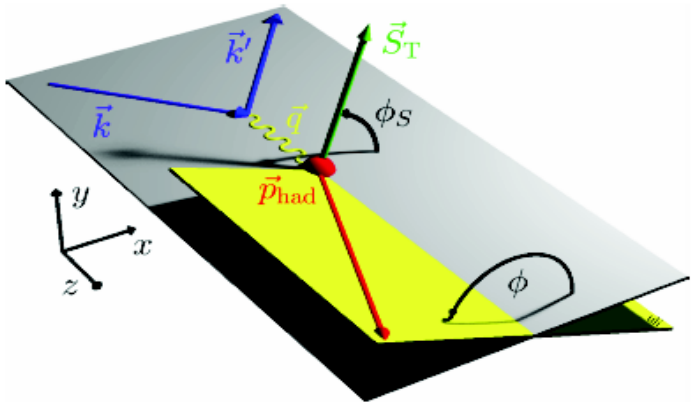




Target SSA Measurement using SoLID

Target SSA (used in 6 GeV experiment):

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



- Relative luminosity monitored using single particle triggers
- Target spin flip (every 10-20 mins for ^{3}He)

Target SSA definition for SoLID experiments:

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

- $N_1(\phi_h, \phi_s)$ and $N_1(\phi_h, \phi_s + \pi)$ taken at the same time
- Luminosity at different times cancels
- In first order, acceptance and detection efficiency cancels
- double cancellation due to spin-flip and full azimuthal coverage

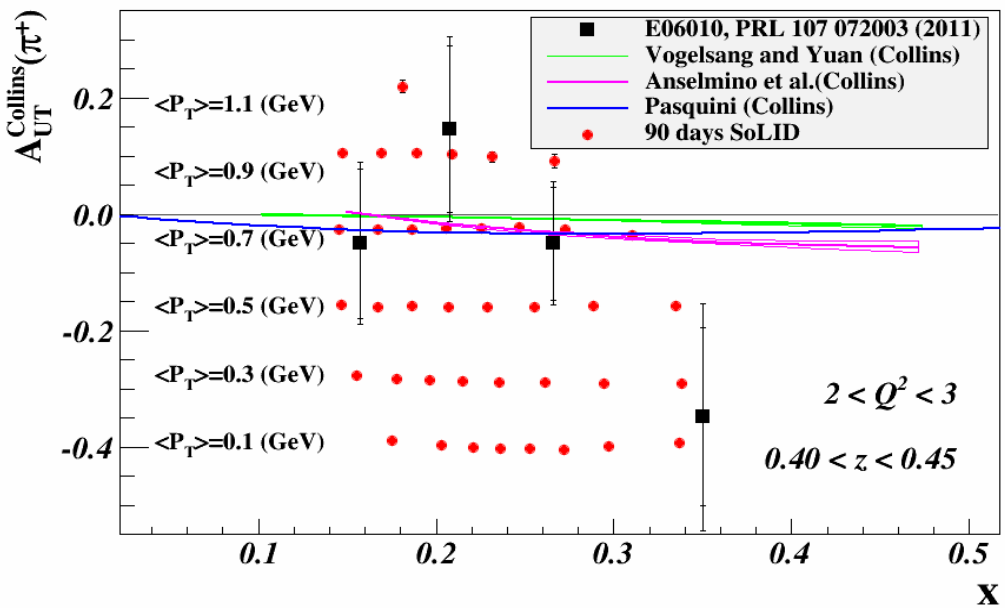
Unique advantage in reducing the systematics associated with detection efficiency, luminosity and acceptance effects

Expected Impact on Transversity

$$\sigma_{UT}^{SIDIS} \propto \sin(\phi_h + \phi_S)\, h_1 \otimes H_1^{\perp}$$

- Global fit to SIDIS and e+e- experimental data
- Covers wide region in x – important for transversity and tensor charge extraction
- Relatively large P_T range – important for testing TMD factorization approach

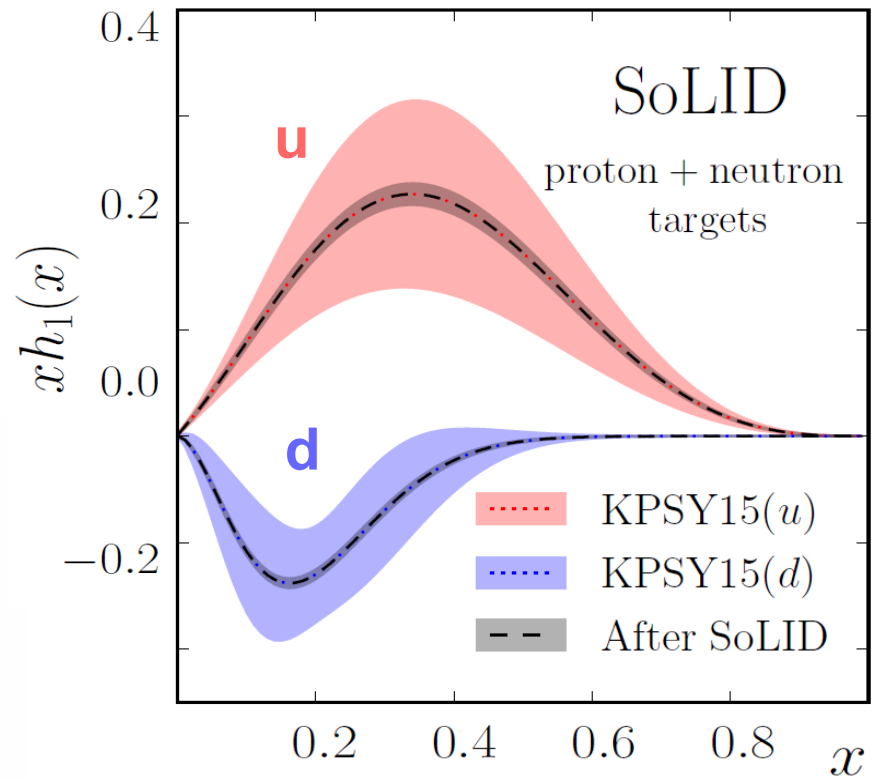
Collins Asymmetry (π^+)



P_T *vs.* x for one (Q^2, z) bin

Total > 1400 data points

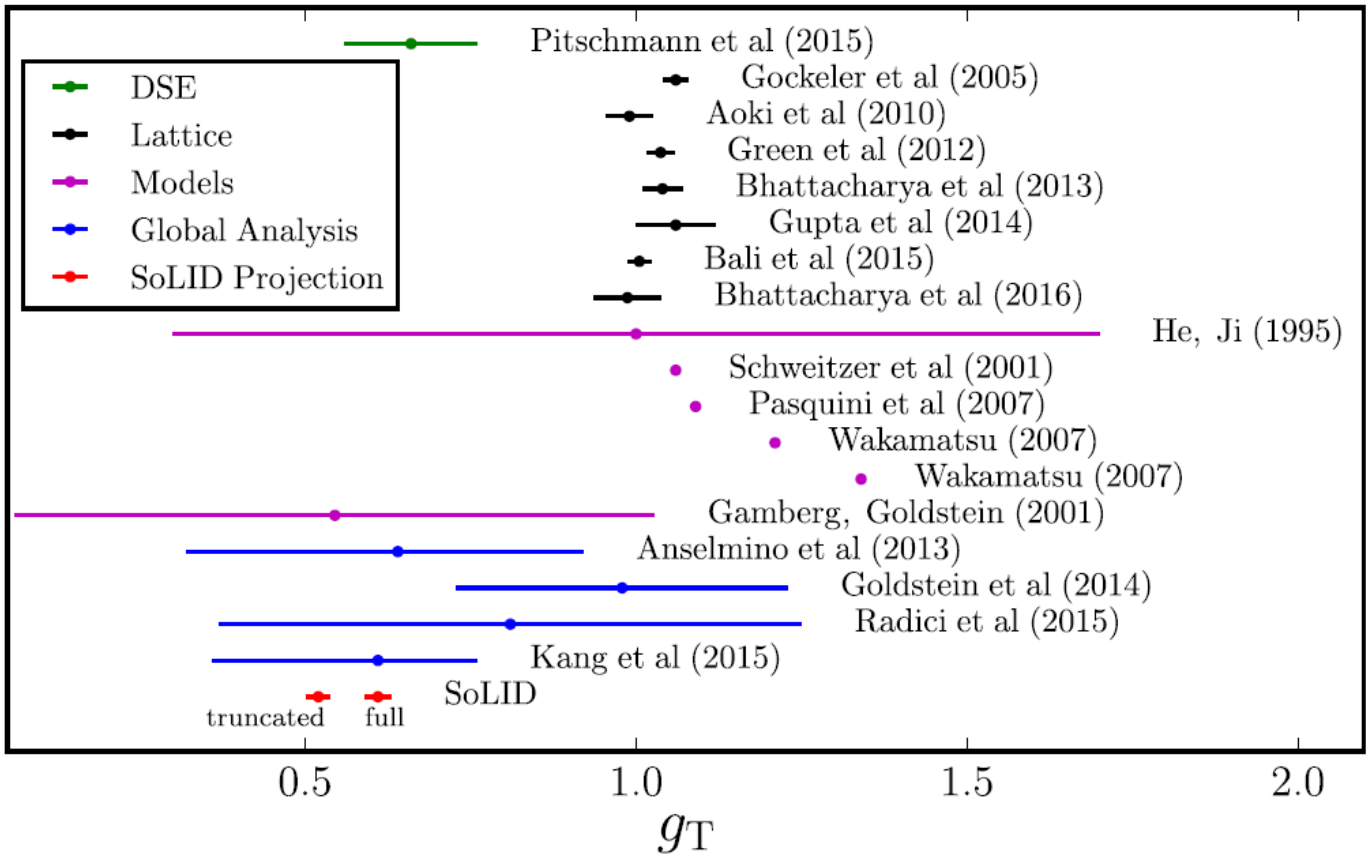
Transversity



Z. Ye, N. Sato et al., Phys. Lett. B 767C (2017)

Tensor Charge from SoLID

Isovector nucleon tensor charge $g_T = \delta u - \delta d$



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

Z. Ye, N. Sato et al., Phys. Lett. B 767C (2017)

- truncated range of x: 0.05 – 0.6
- assumption of a negligible contribution from sea quarks
- model dependent assumptions on the shape of underlying TMD distributions
- Q^2 evolution included

Tensor Charge and Neutron EDM

quark EDM (d_u, d_d) contribution to the nucleon EDM (d_p, d_n)

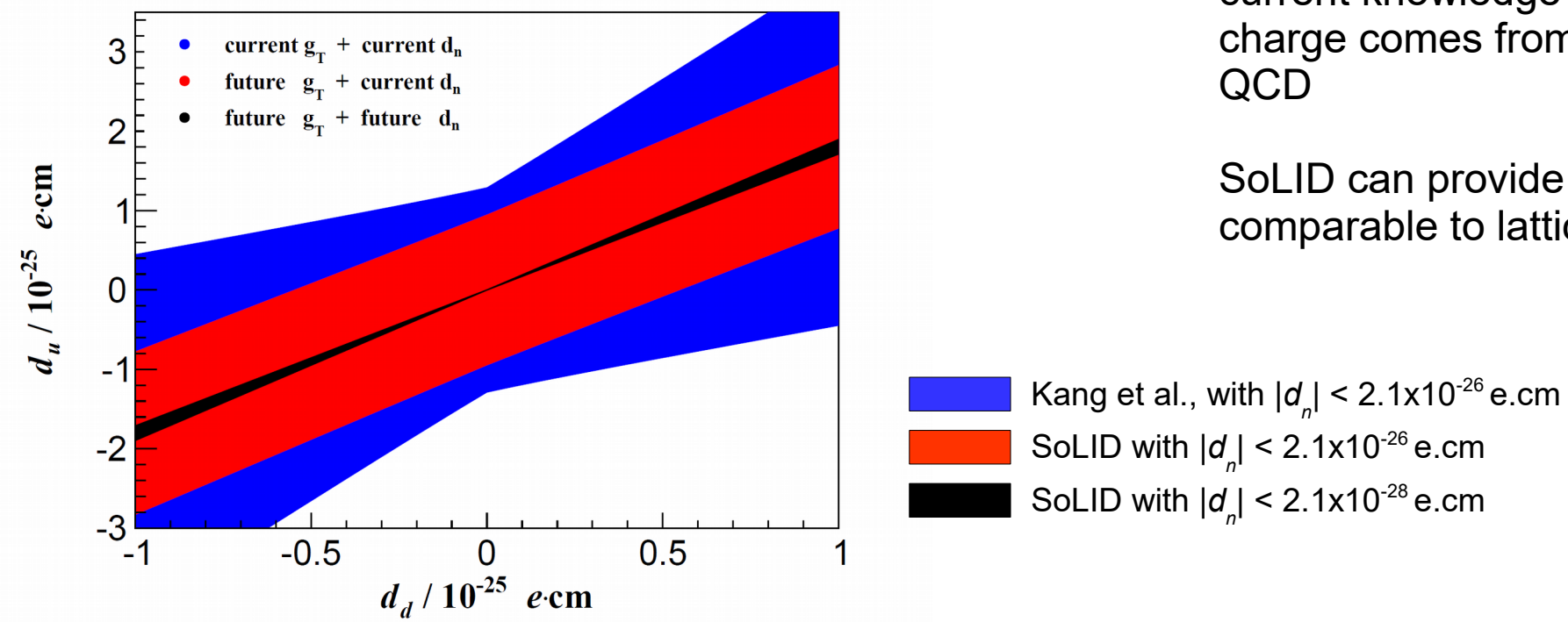
$$d_p = g_T^u\, d_u + g_T^d\, d_d,$$
$$d_n = g_T^d\, d_u + g_T^u\, d_d,$$

Bounds on d_u and d_d, assuming negligible strange quark contribution ($\delta_T s = 0$)

current knowledge of tensor charge comes from lattice QCD

SoLID can provide precision comparable to lattice QCD

Constraints on quark EDMs with the upper limits on nucleon EDMs and the tensor charge extraction



H. Gao, T. Liu et al., (arXiv:1704.00113)

Current neutron EDM limit $|d_n| < 2.1\times10^{-26}$ e.cm

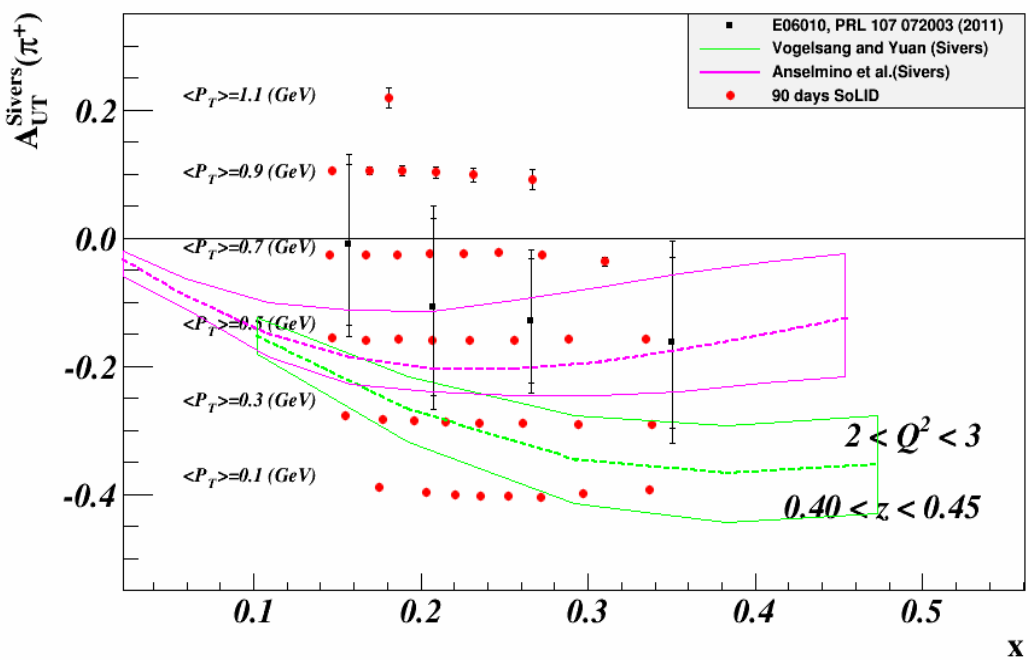
Sivers Asymmetry and Impact of SoLID

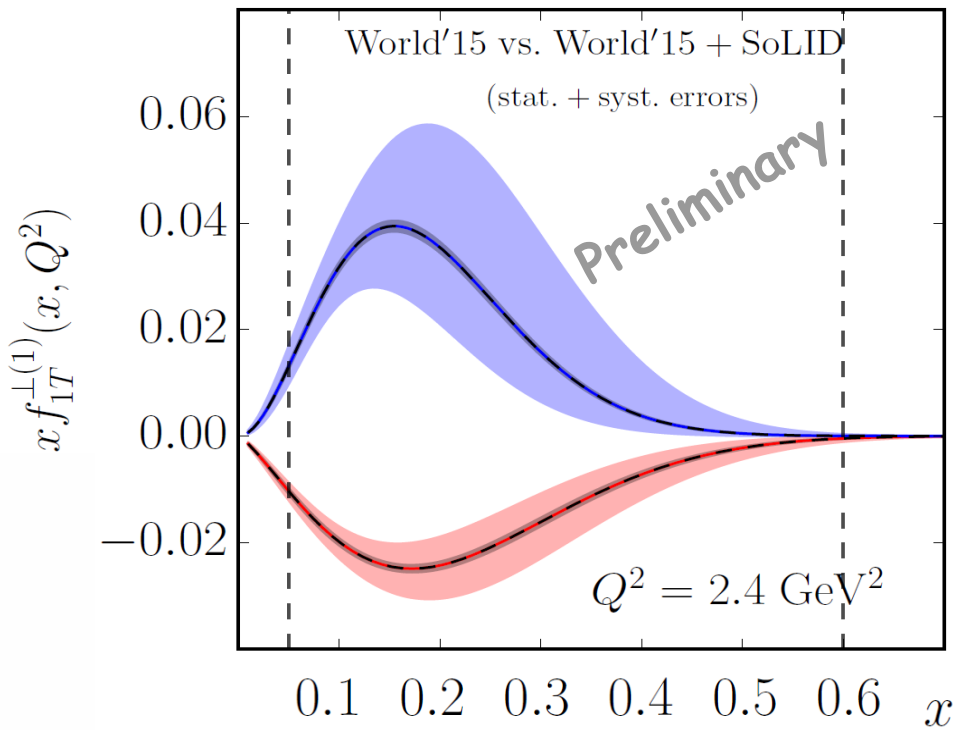
$$f_{q/p\uparrow}(x, \mathbf{k}_\perp) = f_1^q(x, k_\perp) - f_{1T}^{\perp q}(x, k_\perp)\frac{\hat{\mathbf{P}} \times \mathbf{k}_\perp \cdot \mathbf{S}}{M}$$

Sivers Asymmetry in SIDIS

$$A_{UT}^{\sin(\phi_h - \phi_S)} \sim f_{1T}^{\perp}(x, k_\perp) \bigotimes D_1(z, p_\perp)$$

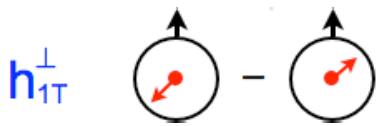
Sivers Asymmetry (π^+)





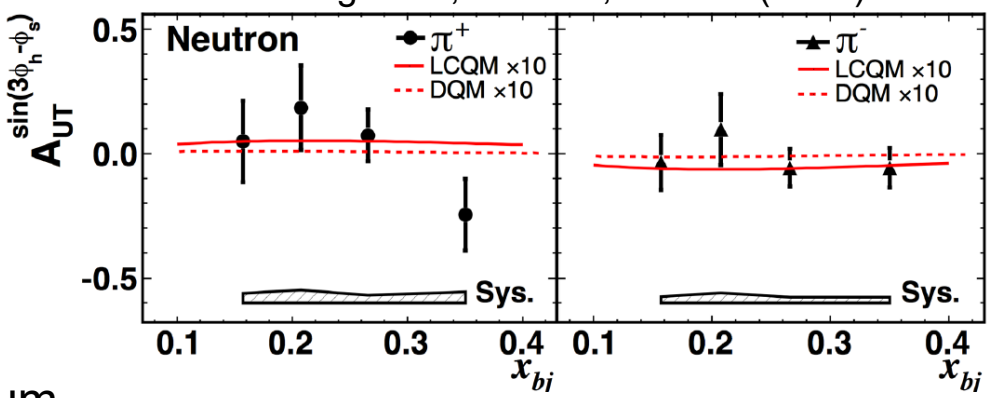
N. Sato, T. Liu, A. Prokudin et al.,
(In progress)

Pretzelosity



$$\sigma_{UT}^{SIDIS} \propto \sin(3\phi_h - \phi_S)\, h_{1T}^{\perp} \otimes H_1^{\perp}$$

JLab 6 GeV results:
Y. Zhang et al., PRC 90, 055209 (2014)

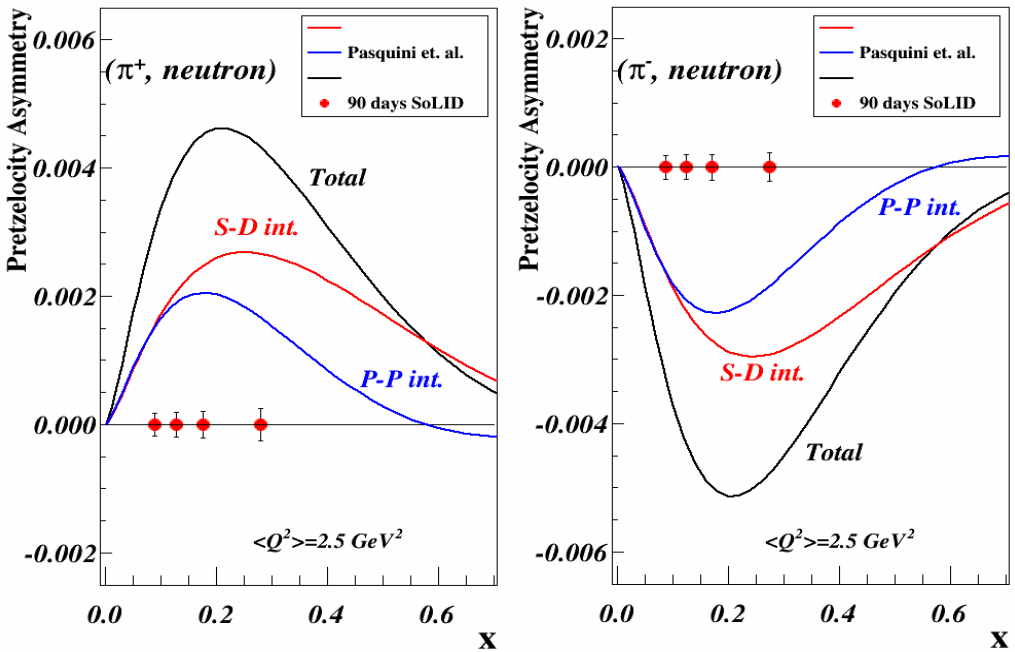


- Correlation between quark transverse momentum and transverse polarization of the nucleon
- Chiral odd, no gluon analogy
- Direct probe of relativistic effects
- Access to quark OAM though models

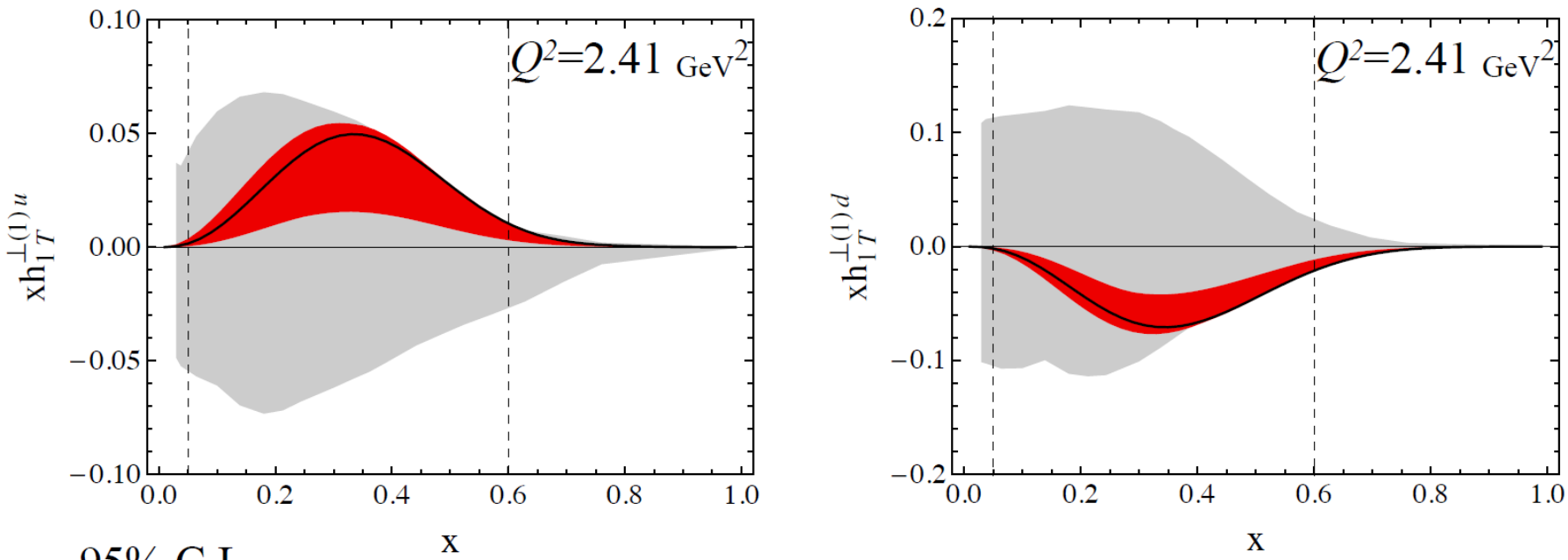
$$L_z^q = -\int \mathrm{d}x \mathrm{d}^2\mathbf{k}_\perp \frac{\mathbf{k}_\perp^2}{2M^2} h_{1T}^{\perp q}(x, k_\perp) = -\int \mathrm{d}x\, h_{1T}^{\perp(1)q}(x)$$

(model dependent)

SoLID SIDIS projections



Impact of SoLID on Pretzelosity



95% C.L.

parametrization by C. Lefky *et al.*, PR D 91, 034010 (2015).

SoLID projection with transversely polarized neutron and proton data.

C. Lefky, A. Prokudin PRD 91, 034010 (2015)
- A global fit to 175 data from COMPASS, HERMES, and JLab

Tianbo Liu (Duke)

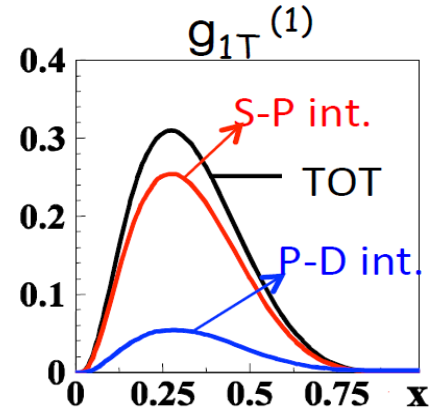
Summary

- TMDs provide very rich information of parton dynamics in the nucleon beyond the collinear picture
- High precision data in wide kinematic region is essential to study TMDs in SIDIS:
  - Clean extraction of TMDs, Q^2 evolution, P_T dependence, higher twist effects, current/target fragmentation regions, etc...
- Plans for high precision SIDIS measurements in Hall-A at 11 GeV using SoLID
  - Three fully approved SIDIS experiments
  - Transverse SSA on proton and neutron
- SoLID SIDIS data combined with high precision cross-section data from Hall C HMS+SHMS will allows us to perform a rigorous study of TMDs

Spare Slides

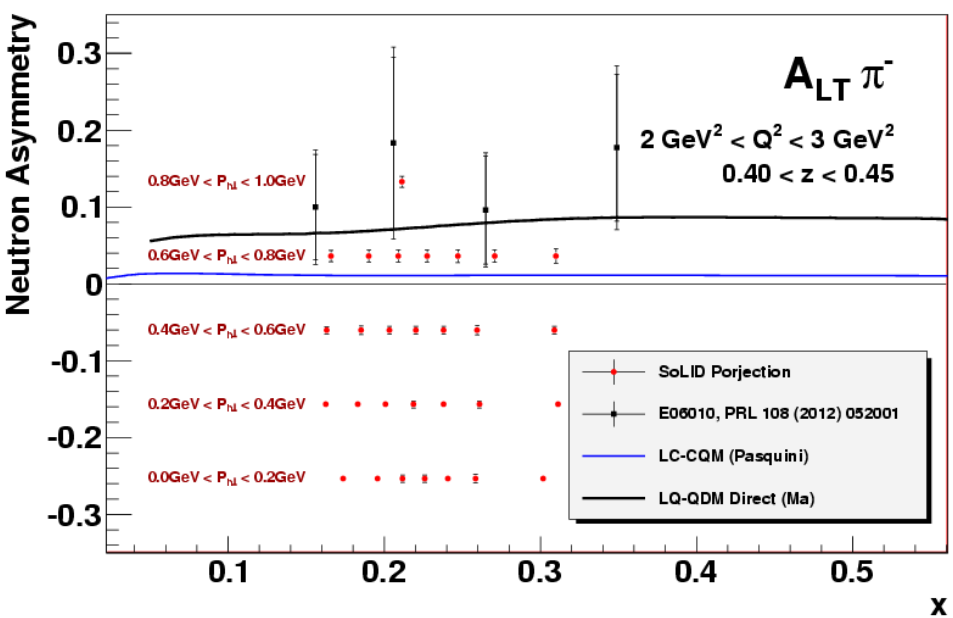
Worm-Gear Functions

- G1T and h1L
- Dominated by real part of interference between L=0 (S) and L=1 (P) states



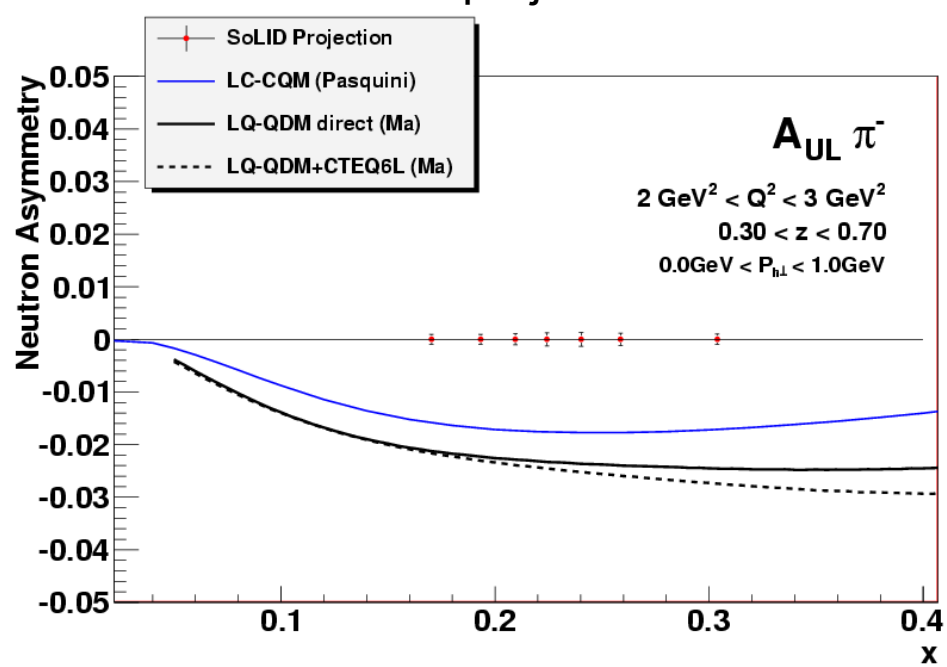
Light-Cone CQM by B. Pasquini
B.P., Cazzaniga, Boffi, PRD78, 2008

SoLID projections from neutron



$$A_{LT} \sim g_{1T}(x) D_1(z)$$

SoLID projections from neutron



$$A_{UL} \sim h_{1L}^{\perp}(x) \otimes H^{\perp}{}_1(z)$$

Extraction of neutron SSA from 3He – effect of FSI

$$A_n \simeq \frac{1}{p_n f_n}\left(A_3^{\rm exp} - 2p_p f_p\, A_p^{\rm exp}\right)$$

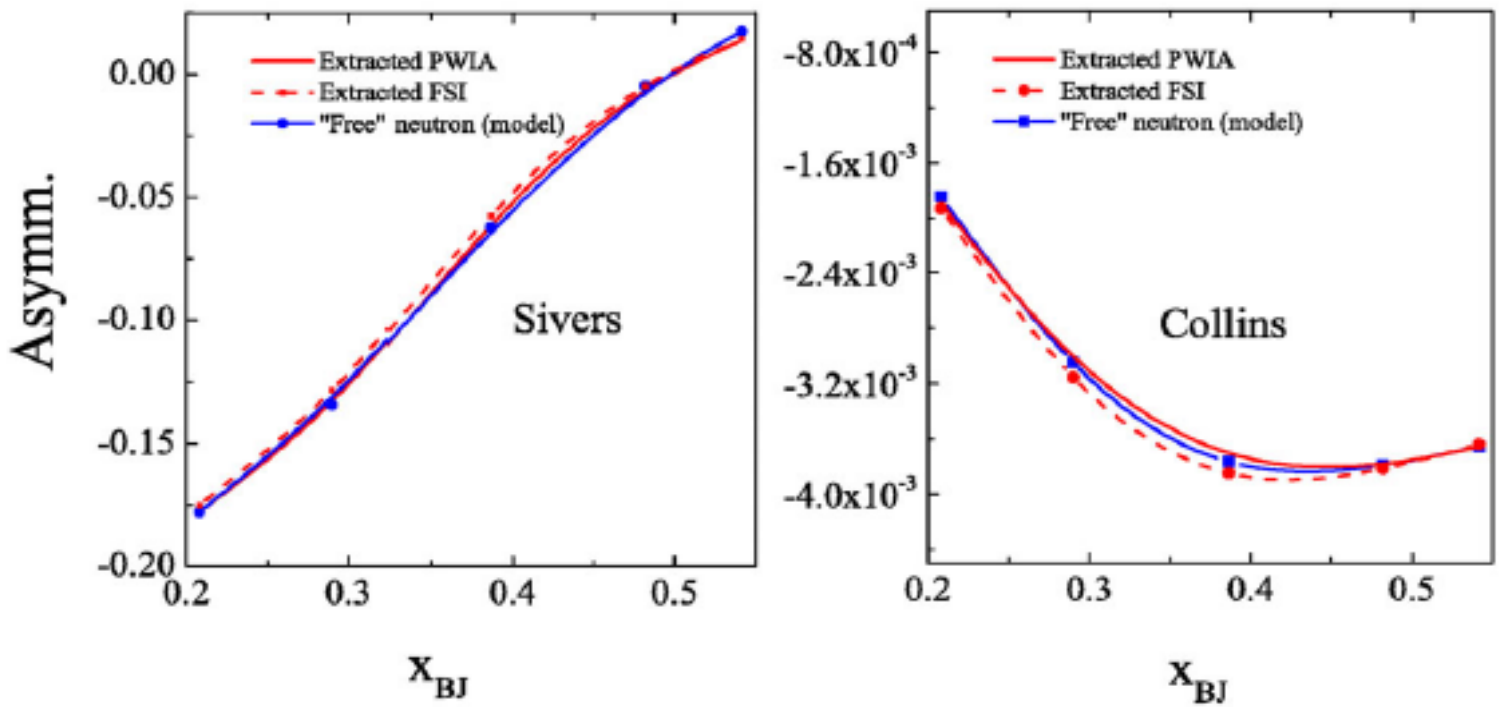


Fig. 13. Check of the extraction procedure, eq. (17), with and without FSI taken into account, for the Sivers (left) and Collins (right) SSAs, in the kinematics of [65].

Raphael Dupre and Sergio Scopetta
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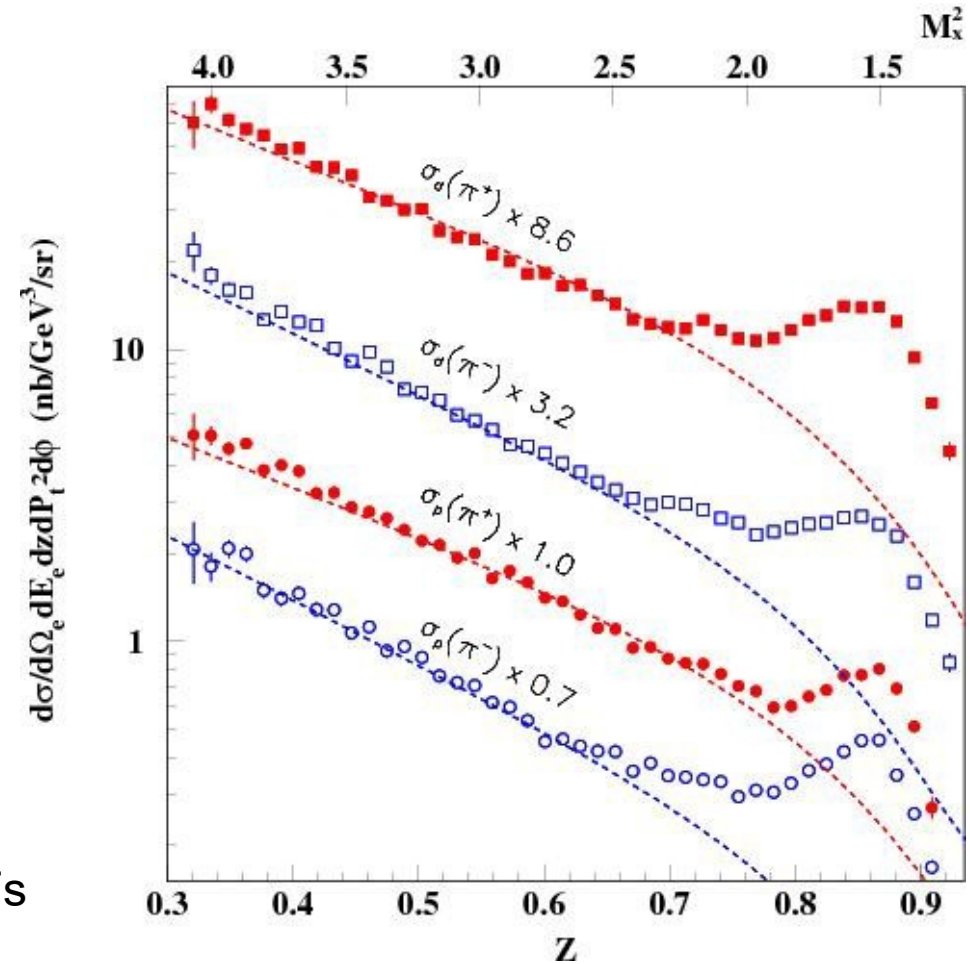
Hall C E00-108 Experiment: SIDIS Cross Section

e + p/d ⟶ e' + $\pi^{+/-}$ +X

$$\frac{\frac{d\sigma}{d\Omega_e dE_{e'} dz dp_T^2 d\phi}}{\frac{d\sigma}{d\Omega_e dE_{e'}}} = \frac{dN}{dz} b e^{-bp_T^2} \frac{1 + A\cos(\phi) + B\cos(2\phi)}{2\pi},$$

$$\frac{dN}{dz} \sim \sum_q e_q^2 q(x, Q^2) D_{q\to\pi}(z, Q^2)$$



Low energy semi-inclusive cross sections consistent with calculation using high energy parameters of frag. functions and CTEQ PDFs (for z<0.7 and M^2_x > ~2.5)