Hall-A Transversity Experiment

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Hall-A Postdoctoral Associate

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- PhD (Physics), University of Kentucky (2010)
  - Thesis: Hall-A neutron transversity experiment

- Hall-A Post-doctoral Associate
  - Analysis of Hall-A Transversity experiment data
  - Working on g2p experiment (currently taking data in Hall-A)
  - Co-spokesperson for 12 GeV proton transversity experiment in Hall-A

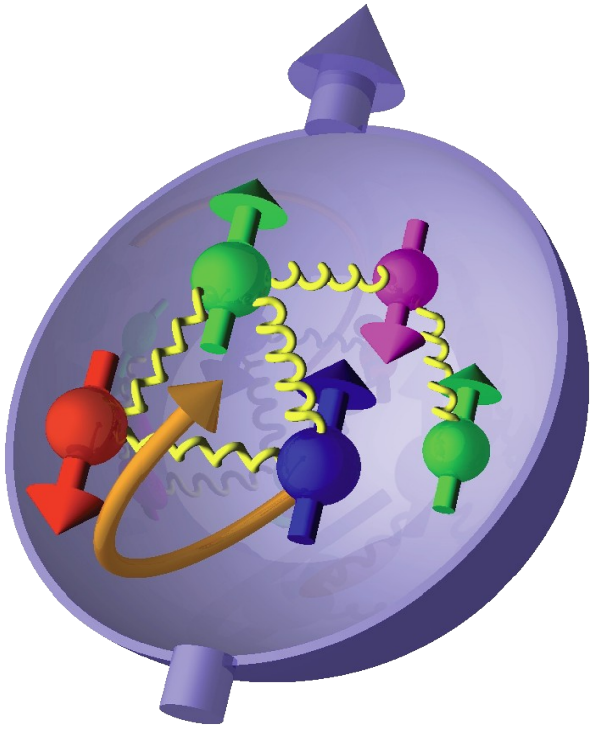
Outline

- Nucleon spin structure and transversity
- Semi-Inclusive DIS and TMDs
- 6 GeV transversity experiment in Hall-A
- Polarized SIDIS measurements using SoLID at 12 GeV

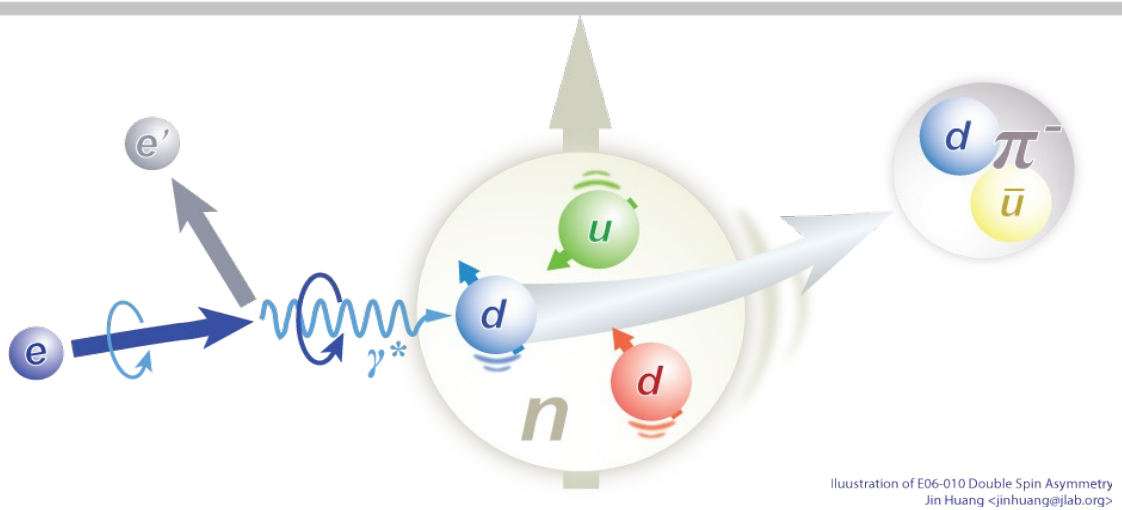
Nucleon Spin Structure

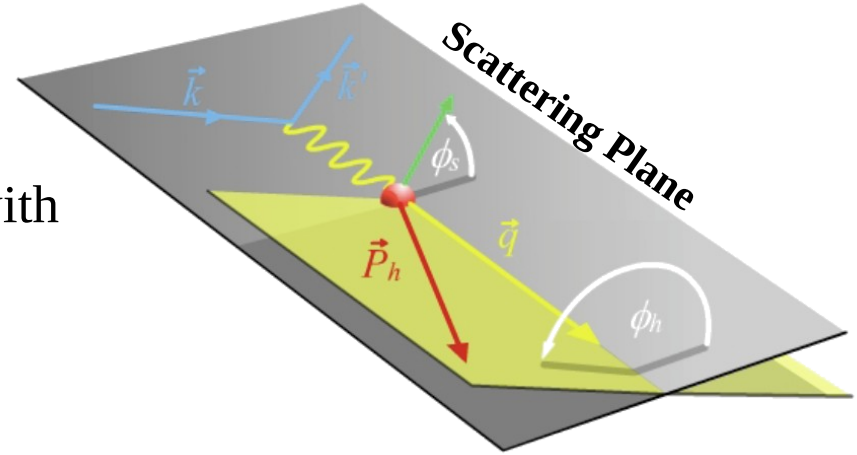
- Leading twist parton distribution functions:
  - Unpolarized: $f_1(x)$ (very well known)
  - Longitudinally polarized: $g_1(x)$ (well known)

  } Measured using DIS
  - Transversity: $h_1(x)$ (least known)
- Proton spin puzzle:
  - only ~30% from quark spin
- Orbital angular momentum plays important role
- Transverse Momentum Dependent PDFs
  - Quark transverse momentum($\mathbf{k}_T$) un-integrated
  - Semi-Inclusive DIS: Study TMDs and quark OAM



Semi-Inclusive Deep Inelastic Scattering





- Ideal tool to study TMDs
- Detect scattered electron in coincidence with hadron
- Flavor tagging via fragmentation function
- Single (SSA) and double (DSA) Spin Asymmetries

SIDIS Cross-section

A. Bacchetta *et al.*, arXive:hep-ph/0611265

$$
\begin{aligned}
&\frac{d\sigma}{dx\,dy\,d\phi_S\,dz\,d\phi_h\,dP_{h\perp}^2} \\
&= \frac{\alpha^2}{x\,y\,Q^2}\,\frac{y^2}{2\,(1-\varepsilon)}\Bigg\{ F_{UU,T} + \varepsilon\,F_{UU,L} + \sqrt{2\varepsilon(1+\varepsilon)}\,\cos\phi_h\,F_{UU}^{\cos\phi_h} + \varepsilon\cos(2\phi_h)\,F_{UU}^{\cos 2\phi_h} \\
&\quad + \lambda_e\sqrt{2\varepsilon(1-\varepsilon)}\,\sin\phi_h\,F_{LU}^{\sin\phi_h} + S_L\left[\sqrt{2\varepsilon(1+\varepsilon)}\,\sin\phi_h\,F_{UL}^{\sin\phi_h} + \varepsilon\sin(2\phi_h)\,F_{UL}^{\sin 2\phi_h}\right] \\
&\quad + S_L\,\lambda_e\left[\sqrt{1-\varepsilon^2}\,F_{LL} + \sqrt{2\varepsilon(1-\varepsilon)}\,\cos\phi_h\,F_{LL}^{\cos\phi_h}\right] \\
&\quad + S_T\Bigg[\sin(\phi_h-\phi_S)\left(F_{UT,T}^{\sin(\phi_h-\phi_S)} + \varepsilon\,F_{UT,L}^{\sin(\phi_h-\phi_S)}\right) + \varepsilon\,\sin(\phi_h+\phi_S)\,F_{UT}^{\sin(\phi_h+\phi_S)} \\
&\qquad + \varepsilon\,\sin(3\phi_h-\phi_S)\,F_{UT}^{\sin(3\phi_h-\phi_S)} + \sqrt{2\varepsilon(1+\varepsilon)}\,\sin\phi_S\,F_{UT}^{\sin\phi_S} \\
&\qquad + \sqrt{2\varepsilon(1+\varepsilon)}\,\sin(2\phi_h-\phi_S)\,F_{UT}^{\sin(2\phi_h-\phi_S)}\Bigg] + S_T\lambda_e\Bigg[\sqrt{1-\varepsilon^2}\,\cos(\phi_h-\phi_S)\,F_{LT}^{\cos(\phi_h-\phi_S)} \\
&\qquad + \sqrt{2\varepsilon(1-\varepsilon)}\,\cos\phi_S\,F_{LT}^{\cos\phi_S} + \sqrt{2\varepsilon(1-\varepsilon)}\,\cos(2\phi_h-\phi_S)\,F_{LT}^{\cos(2\phi_h-\phi_S)}\Bigg]\Bigg\}
\end{aligned}
$$

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&\qquad + \varepsilon\,\sin(3\phi_h-\phi_S)\,F_{UT}^{\sin(3\phi_h-\phi_S)} + \sqrt{2\varepsilon(1+\varepsilon)}\,\sin\phi_S\,F_{UT}^{\sin\phi_S} \\
&\qquad + \sqrt{2\varepsilon(1+\varepsilon)}\,\sin(2\phi_h-\phi_S)\,F_{UT}^{\sin(2\phi_h-\phi_S)}\Big] + S_T\,\lambda_e\Big[\sqrt{1-\varepsilon^2}\,\cos(\phi_h-\phi_S)\,F_{LT}^{\cos(\phi_h-\phi_S)} \\
&\qquad + \sqrt{2\varepsilon(1-\varepsilon)}\,\cos\phi_S\,F_{LT}^{\cos\phi_S} + \sqrt{2\varepsilon(1-\varepsilon)}\,\cos(2\phi_h-\phi_S)\,F_{LT}^{\cos(2\phi_h-\phi_S)}\Big]\Big\}
\end{aligned}
$$

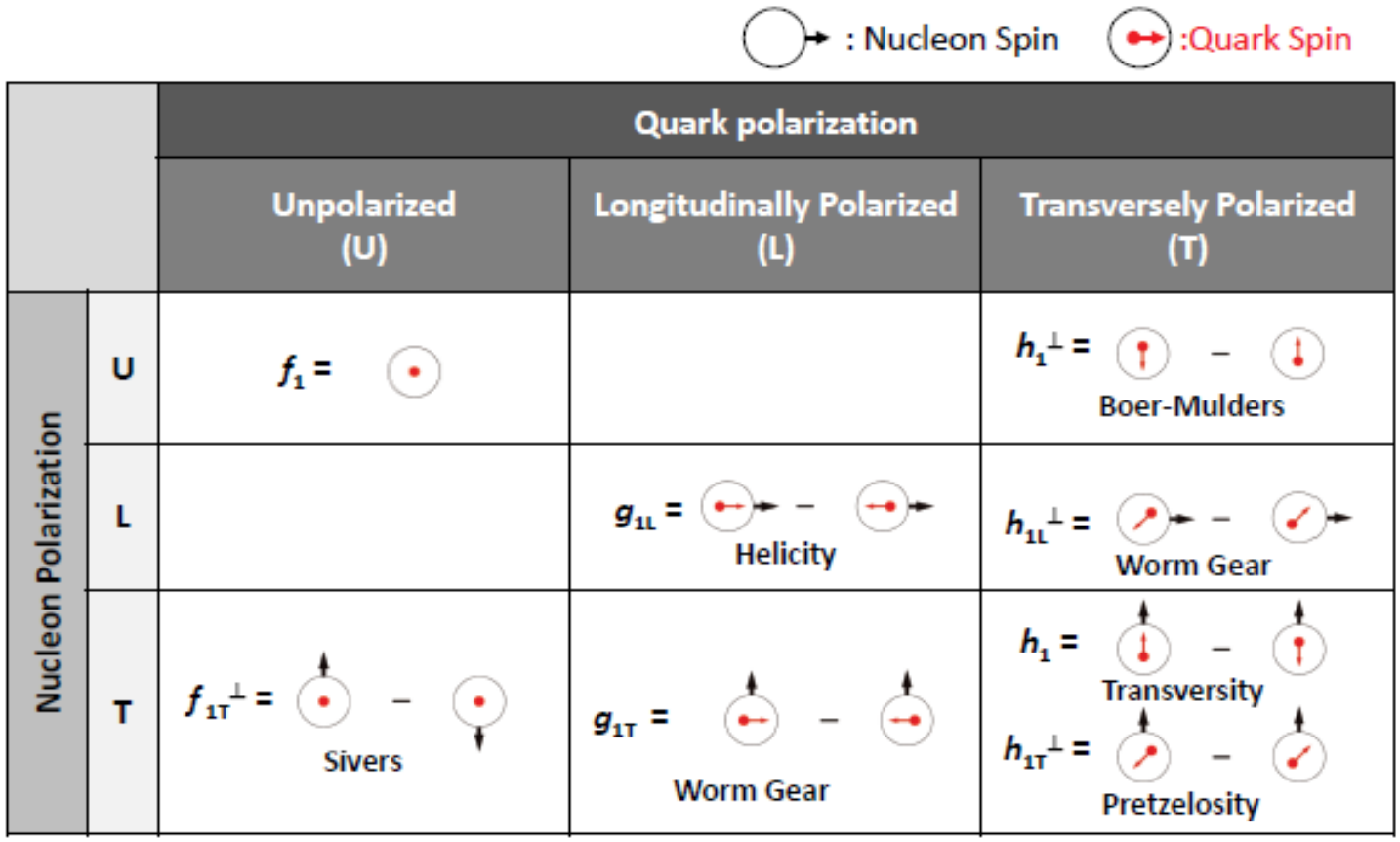
Collins

Sivers

Pretzelosity

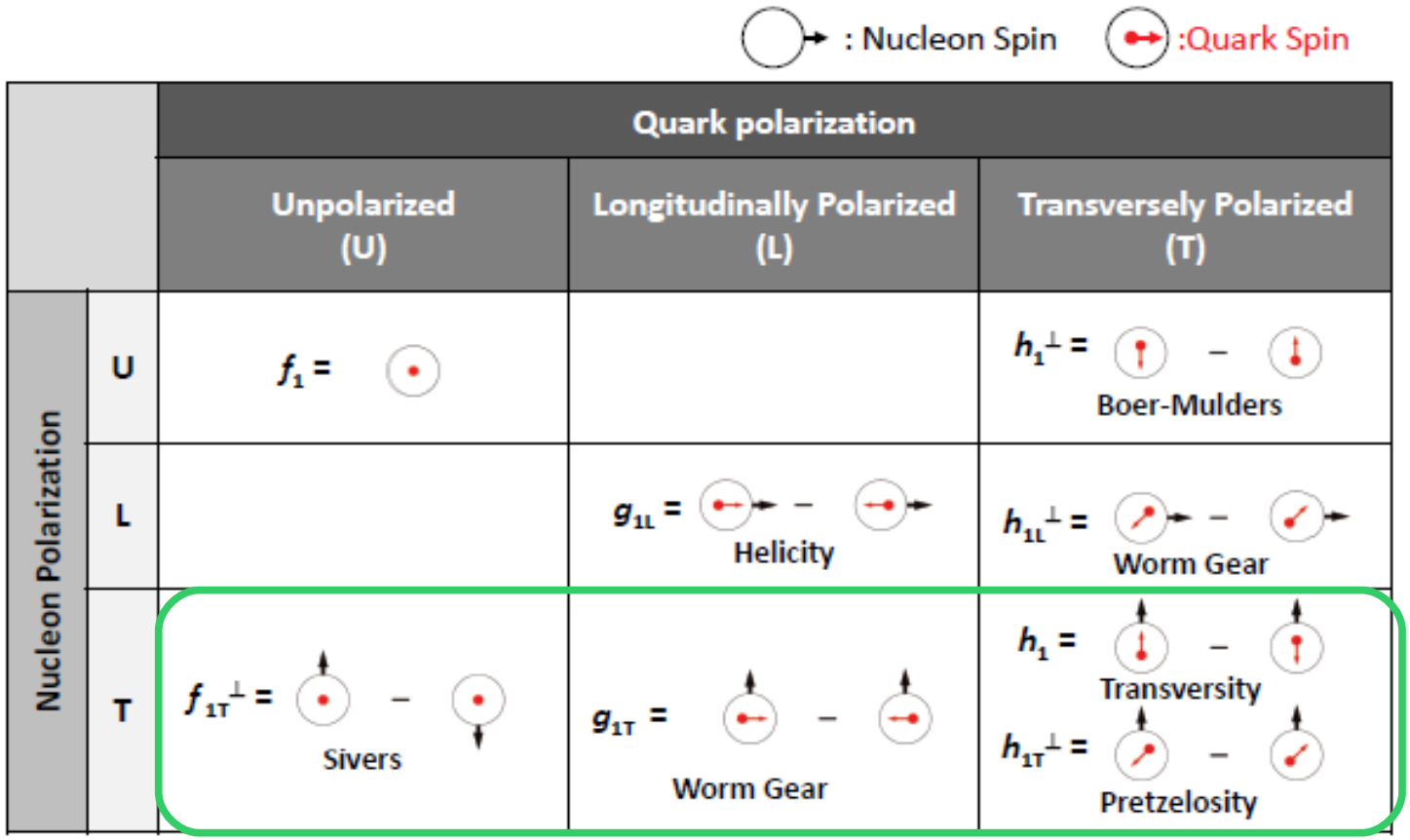
Worm-gear

Leading Twist Transverse Momentum Dependent PDFs



- f_1, g_{1L} and h_1 are $\mathbf{k}_T$ integrated PDFs
- Rest are $\mathbf{k}_T$ dependent PDFs

Leading Twist Transverse Momentum Dependent PDFs



Probed by E06-010
(6 GeV Transversity Expt.)

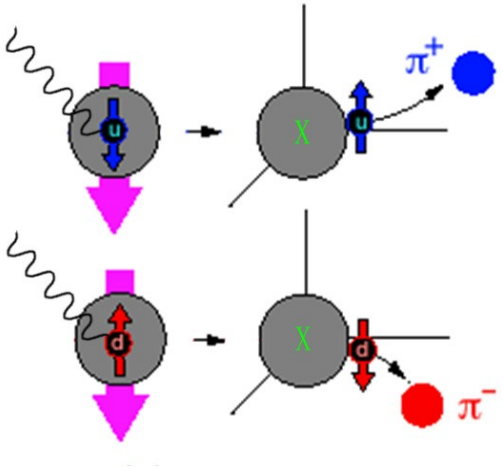
- f_1, g_{1L} and h_1 are $\mathbf{k}_T$ integrated PDFs
- Rest are $\mathbf{k}_T$ dependent PDFs

Collins and Sivers Effect

Collins Effect

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

Transversely polarized quark generates left-right asymmetry during fragmentation

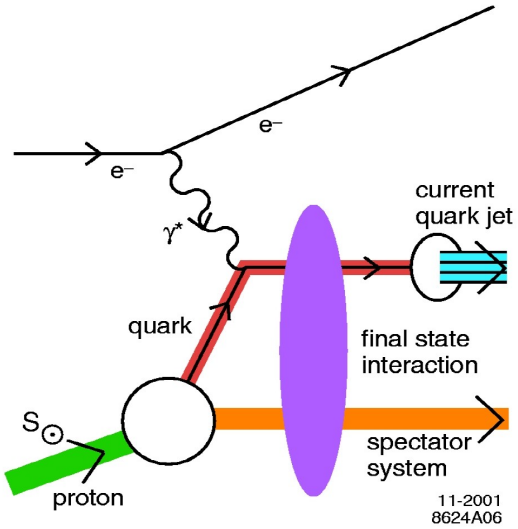


- Valence *x* behavior
- First moment gives nucleon tensor charge (calculable in LQCD)

Sivers Effect

$$\sigma_{UT}^{SIDIS} \propto \sin(\phi_h - \phi_S)\; f_{1T}^{\perp} \otimes D_1$$

Correlation between transverse spin of nucleon with transverse momentum of the quark



- Intrinsically asymmetric distribution of quarks (f_{1T})
- Observed via Final State Interaction (FSI)

Transverse Spin Observables

Separation of various terms using azimuthal angular dependence

- Collins Moment

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

- Sivers Moment

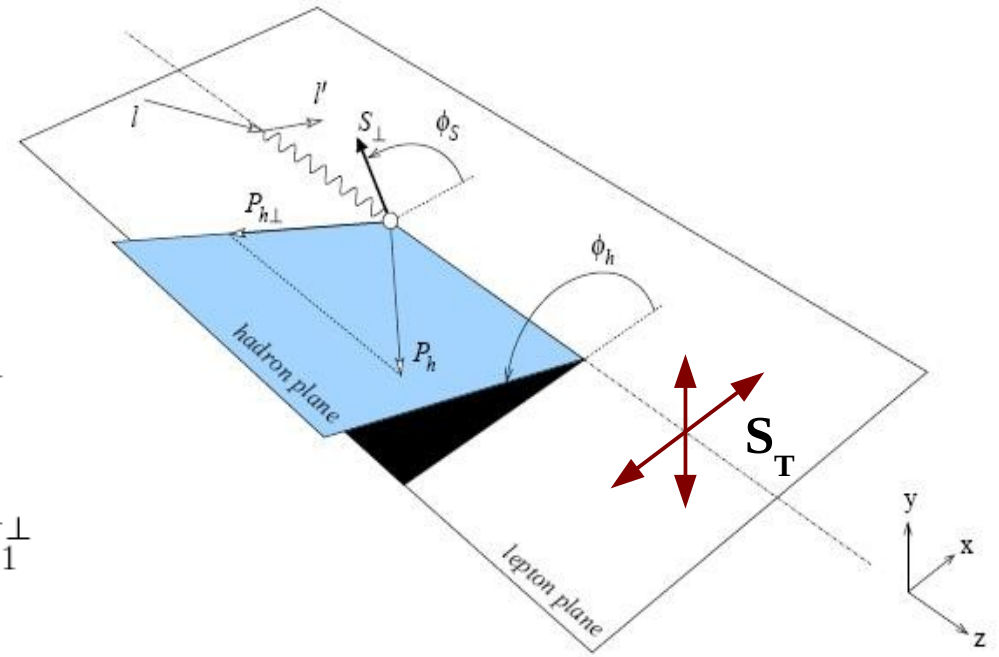
$$\sigma_{UT}^{SIDIS} \propto \sin(\phi_h - \phi_S)\; f_{1T}^{\perp} \otimes D_1$$

- Pretzelosity

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

- Worm-gear (DSA)

$$\sigma_{LT}^{SIDIS} \propto \cos(\phi_h - \phi_S)\; g_{1T} \otimes D_1$$



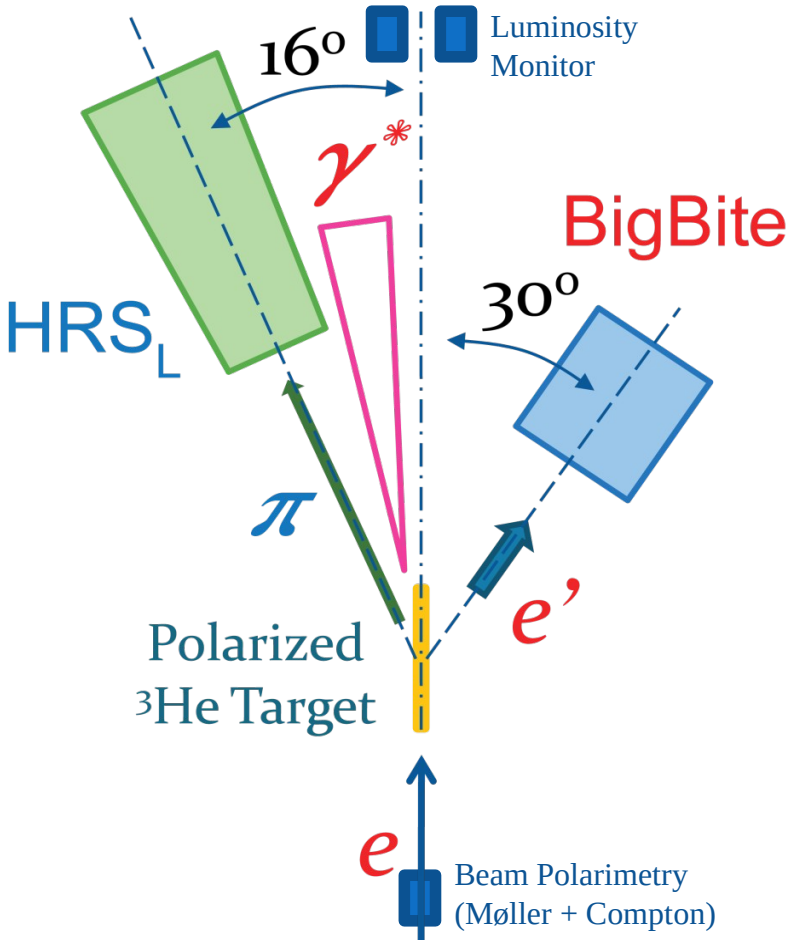
- Rotate target spin to increase angular coverage of ϕ_S
- Automatic target spin flip every 20min

6 GeV Transversity Experiment

- First measurement of SSA and DSA on transversely polarized ^{3}He target (effective neutron target)
- Run period: Oct 2008 – Feb 2009
- 7 PhD graduates
- Two PRL publications

  (working on other physics results)

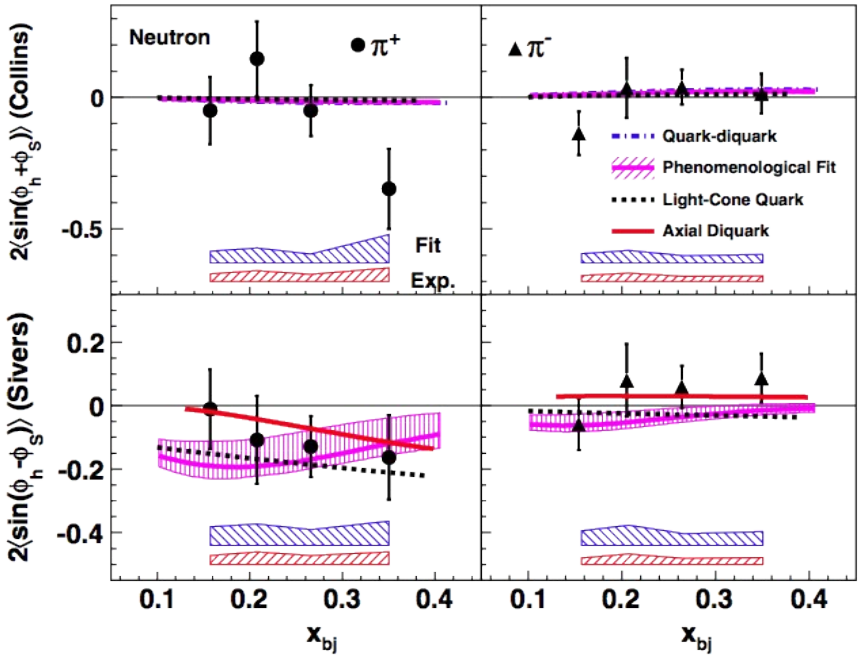
- Polarized ^{3}He target (P_{target} ~ 64%)
- Beam energy : 5.9 GeV
- BigBite at 30^0 as Electron Arm
  - **p_e = 0.8 – 2.2 GeV/c**
- HRSL at 16^0 as Hadron Arm
  - **p_h = 2.35 GeV/c**
- Target spin orientations: up-down and left-right (increase angular coverage)
- Automatic target spin-flip every 20 mins.



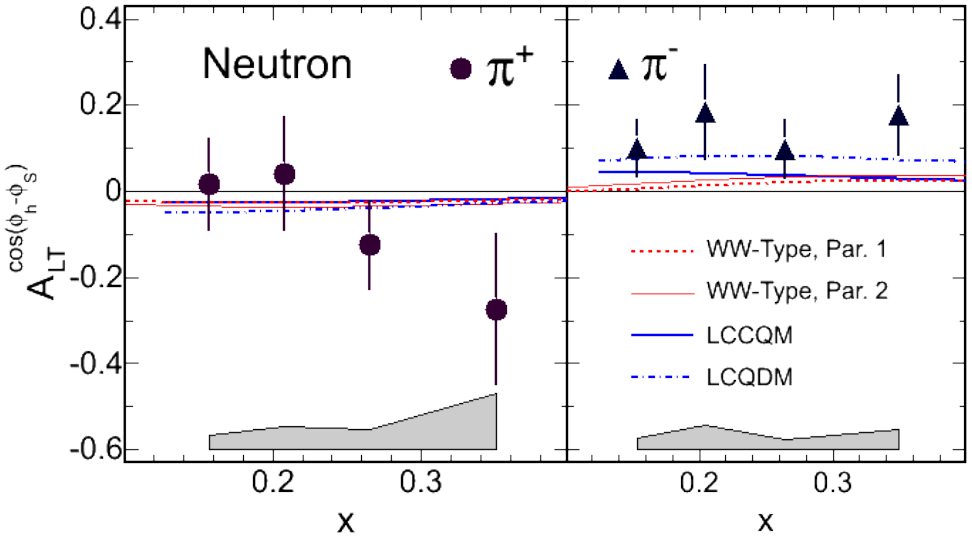
Results

- Collins and Sivers Moments:
  - π- moments consistent with zero
  - π^+ Sivers favor negative sign (positive for HERMES/COMPASS proton data)
- Neutron A_{LT}:
  - Consistent with model in sign
  - But suggest larger asymmetry

Phys. Rev. Lett. 107, 072003 (2011)



Phys. Rev. Lett. 108, 052001 (2012)



$\langle Q^2 \rangle \sim 2.0$ GeV^2

$\langle z \rangle = 0.5$

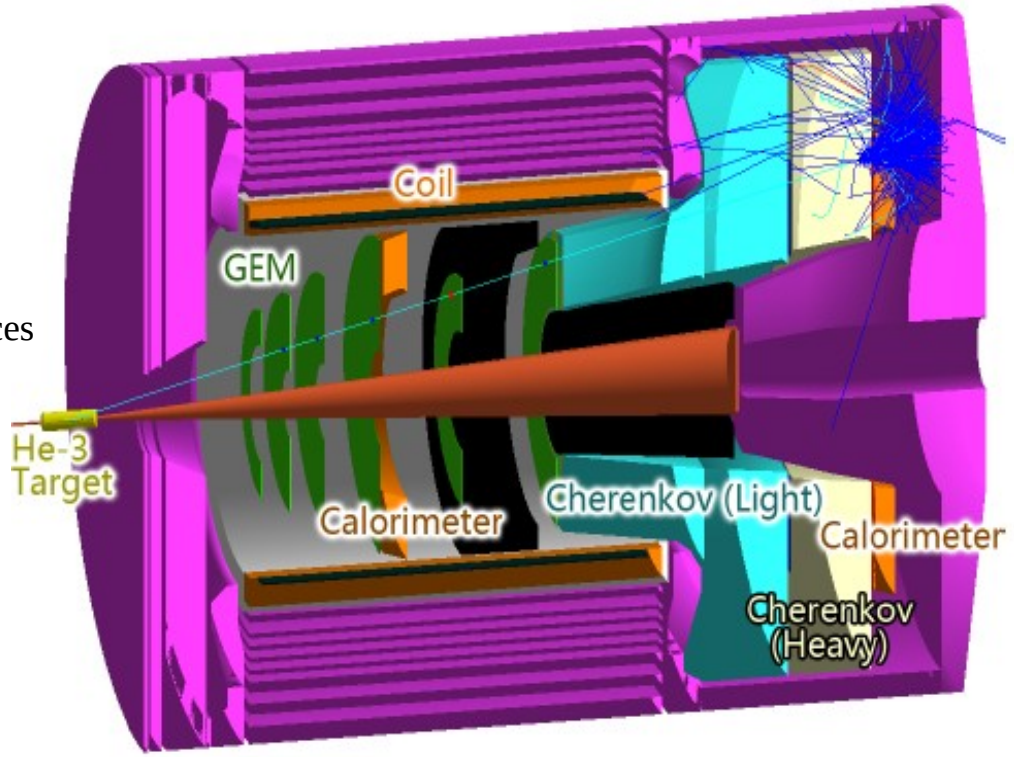
Future Measurements of Transversity

- Super BigBite in Hall-A
- SoLID Spectrometer in Hall-A
- CLAS 12 Polarized SIDIS program
- Projections with an EIC

SoLID - A New Device in Hall-A

Precision 4D (x,Q^2,z, P_T) mapping of single and double spin asymmetries using SIDIS on polarized neutron and proton targets

- Beam energy = 11 GeV and 8.8 GeV
- High Luminosities:
  - ^{3}He (neutron) : 10^{36} N/cm^2/s
  - NH_3 (proton) : 10^{35} N/cm^2/s
- Full azimuthal angle coverage
  - Crucial for 4D mapping of asymmetries Reduces systematics when extracting various moments
- Tracking with GEMs (6 GEM planes)
- Electron Identification:
  - EM calorimeter for large angle and high momentum
  - EM calorimeter and light gas Cerenkov for forward angle
- Pion identification:
  - Heavy Gas Cerenkov and TOF (Multi-Resistive Plate Chamber)



- Fast pipeline electronics for DAQ

Precision SIDIS Experiments at 12 GeV with SoLID and Transversely Polarized Target

- Approved SIDIS experiments with SoLID
  - **E12-10-006:** SSA and DSA measurement using transversely polarized ^{3}He target

    (Spokespersons: J.P.Chen, H. Gao, X. Jiang, J-C.Peng, X. Qian)
- Conditionally approved Experiment
  - **PR12-11-108:** SSA and DSA measurement using transversely polarized NH_3 target

    (Spokespersons: **K. Allada**, J.P. Chen, H. Gao, X. Li, Z.E. Meziani)

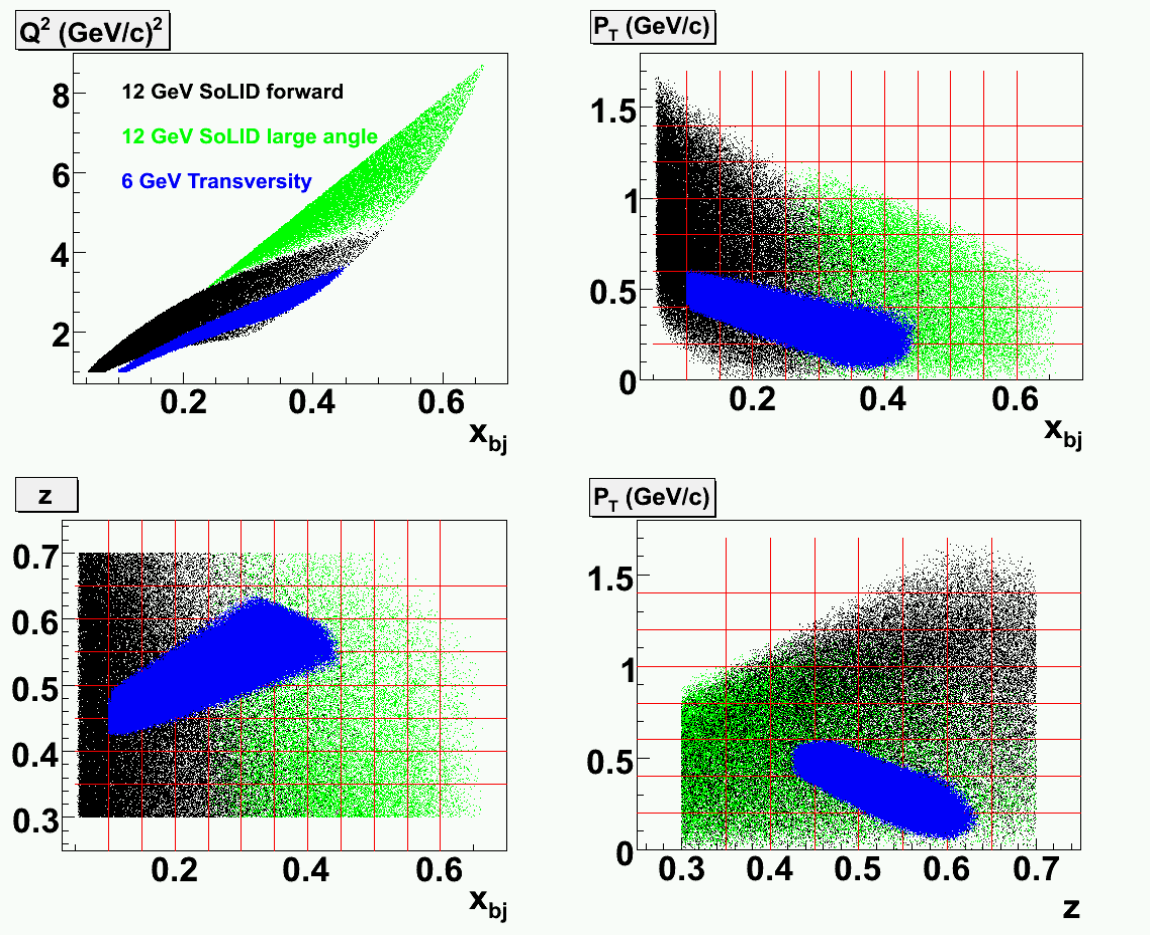
Other proposed measurements at JLab 12 GeV:

1. **Hall-A**: SIDIS using Super BigBite and transversely polarized ^{3}He target
2. **Hall-B**: SIDIS using CLAS12 and transversely polarized HD-Ice target

E06-010 vs 12 GeV SoLID Measurement

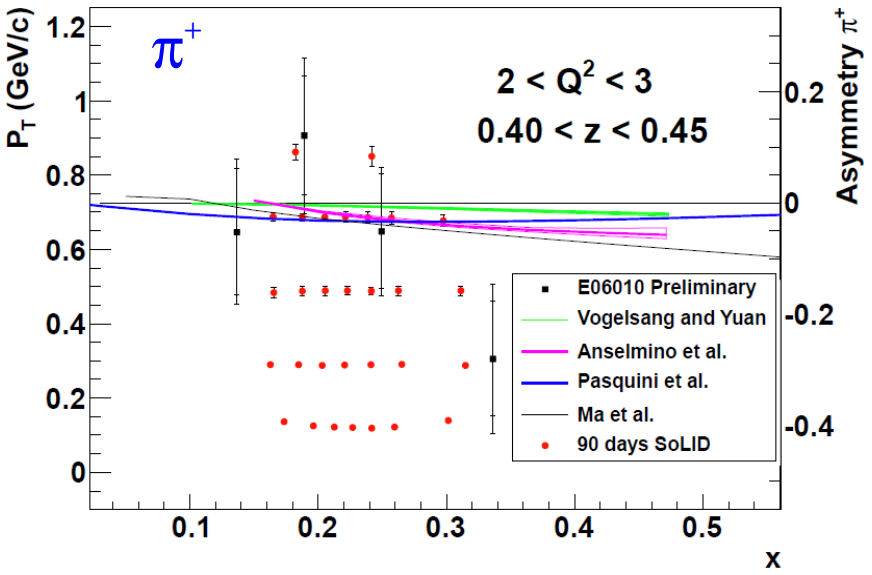
- 6 GeV vs 11 GeV kinematics
- Two regions in SoLID
  - Forward region (6.6° - 12°)
  - Large angle region (14.5° - 22°)
- Wider phase space coverage for proposed SoLID measurements
- Necessary for 4D binning of SSA/DSA in SIDIS

- x_B = 0.05 – 0.68
- Q^2 = 1.0 – 9.0 (GeV/c)^2
- P_T = 0 – 1.8 GeV/c
- z = 0.3 – 0.7
- W > 2.3 GeV



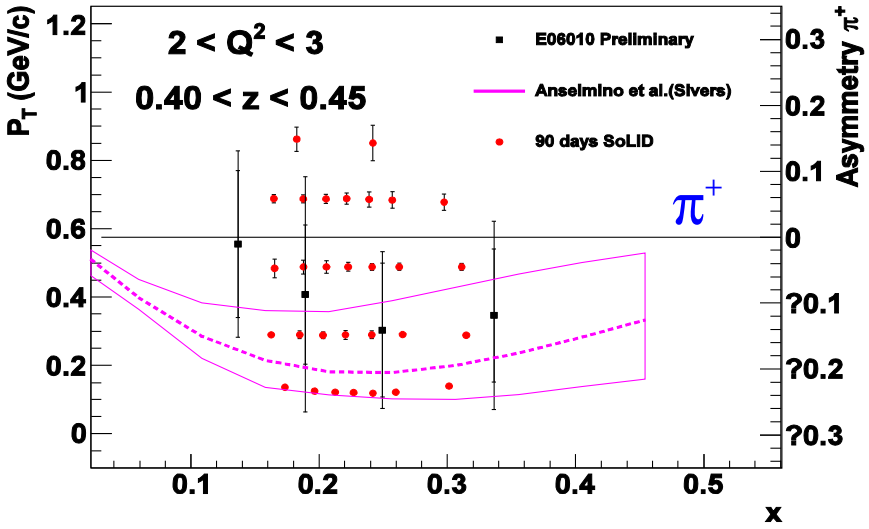
Projected Results

Collins Moment



- Moments in one bin of Q^2 and z
- Cover large x region
- Proton and neutron data
  - Constrains both u and d-quark tensor charge (test lattice QCD results)

Sivers Moment

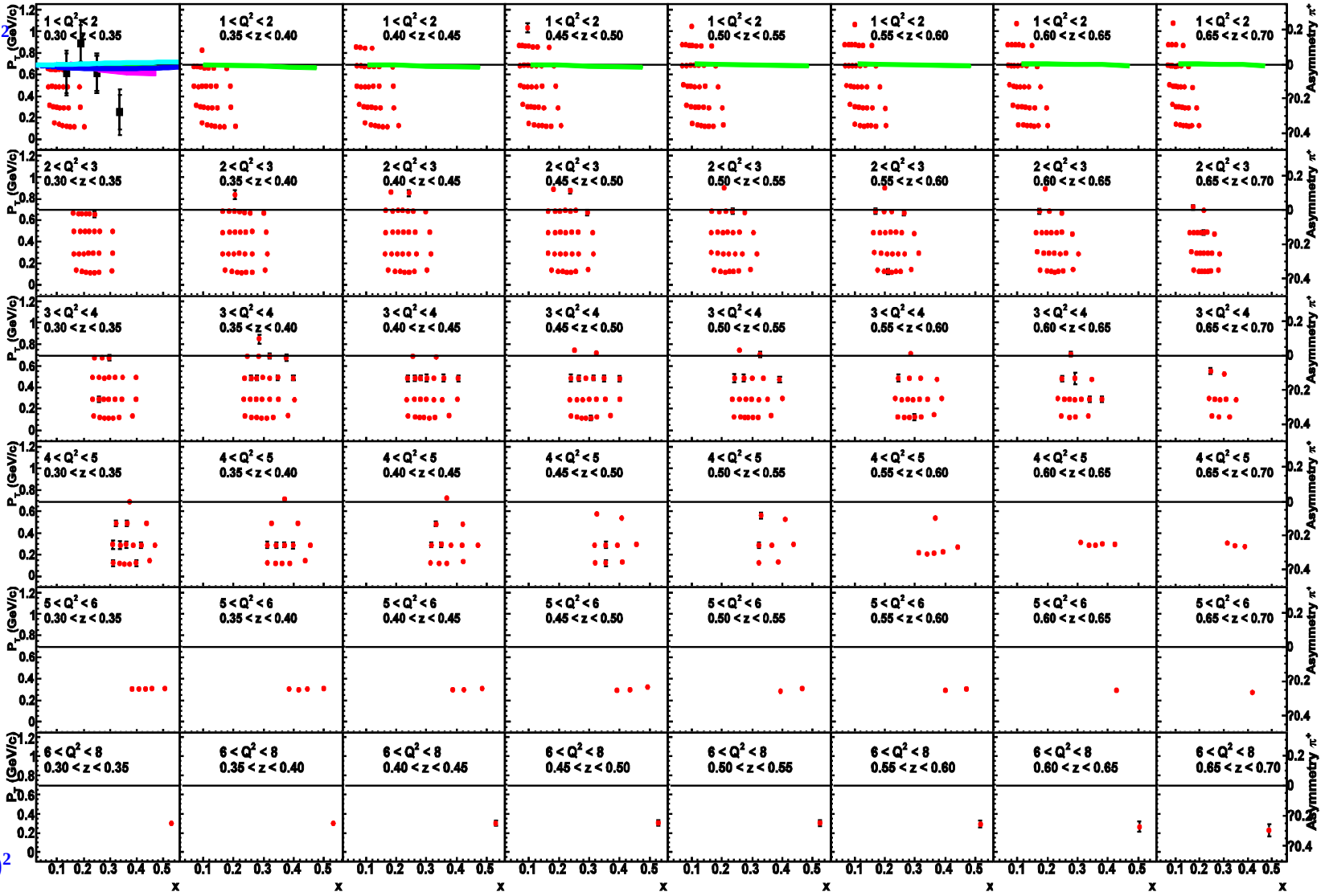


- Help precise extraction of Sivers DF
- QCD predicted sign reversal betwen SIDIS and Drell-Yan process (RHIC, FANL, etc..)

$$f_{1T}^{\perp q}\Big|_{SIDIS} = -f_{1T}^{\perp q}\Big|_{D-Y}$$

Multi-dimensional Binning

Q^2 = 1.0 (GeV/c)^2



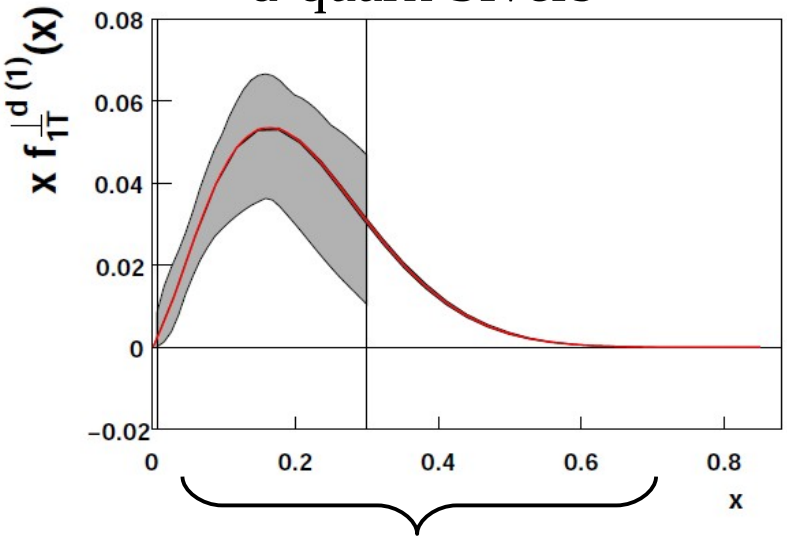
Q^2 = 8.0 (GeV/c)^2

Z = 0.3 → Z = 0.7

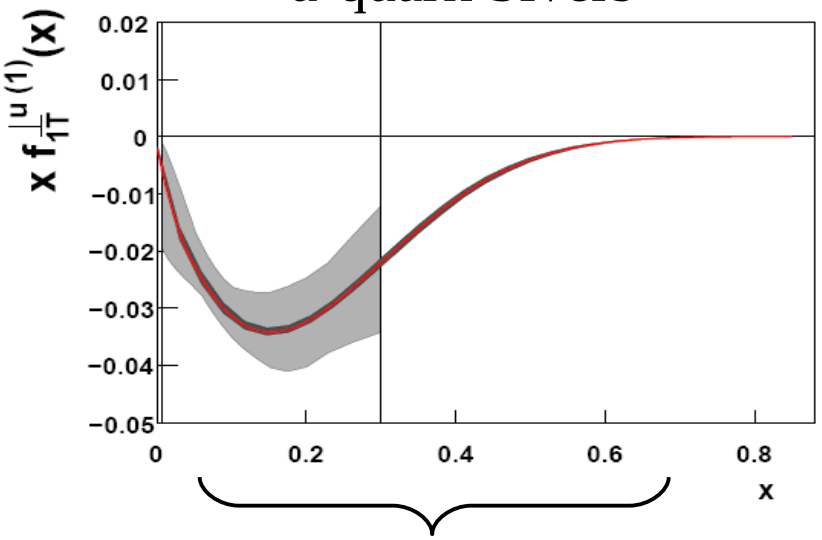
Impact of 12 GeV Measurement With SoLID

- Clean extraction of TMDs - precision comparable to longitudinal spin g_1
- Covers large x range – important for extracting transversity (and thus tensor charge)

d-quark Sivers



u-quark Sivers



A. Prokudin

- Only Sivers function is shown
- Current experimental uncertainties in large light grey band
- Projected uncertainties in dark grey band

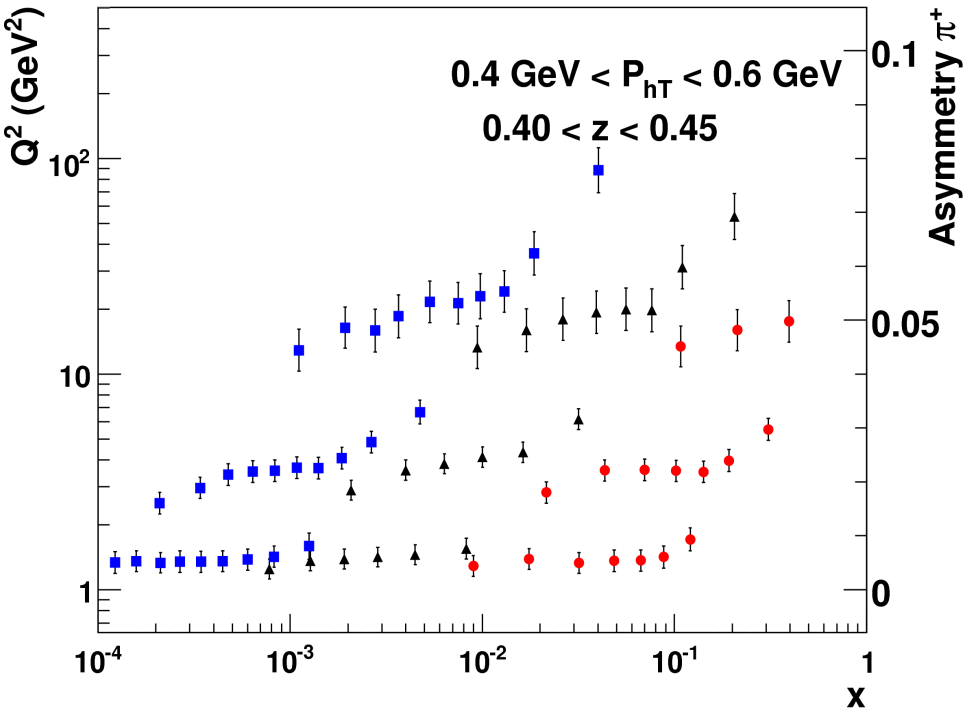
Projections with an EIC

Three Options:

- $\sqrt{s}$ = 140 GeV (20 X 250)
  50 GeV (11 X 60)
  15 GeV (3 X 20)
- Integrated Luminosity in each case :
  30 fb^{-1}
  (about 1 month running with $10^{34}/cm^2/s$)
- 0.8 > y > 0.05
- Polarization : 70 %
- Overall efficiency : 50%
- z : 12 bins, 0.2 – 0.8
- P_T : 5 bins, 0 – 1 GeV
- How important are sea quark TMDs ?

Projection of π^+ SSA on proton

1 out of 60 bins on (P_T,z)



Summary

- First measurement of Collins and Sivers moments (A_{UT}) on ^{3}He target
- First indication of non-zero A_{LT} with neutron target
- Foundation for future experiments at JLab 12 GeV
  - Precision mapping of A_{UT} and A_{LT} using SoLID in Hall-A
  - Comprehensive study of transverse spin and spin-orbit correlations
- A Future EIC can extend these measurements to much lower *x*
  - Important for the study of sea quark TMDs