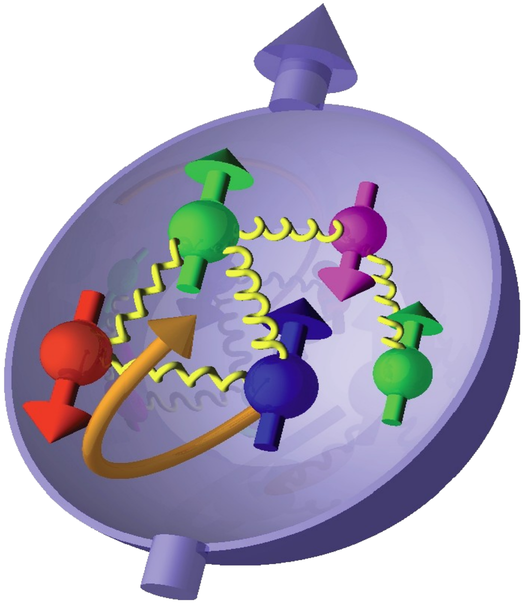
Semi-Inclusive DIS Experiments Using Transversely Polarized Targets in Hall-A



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MESON 2012, 5th June 2012
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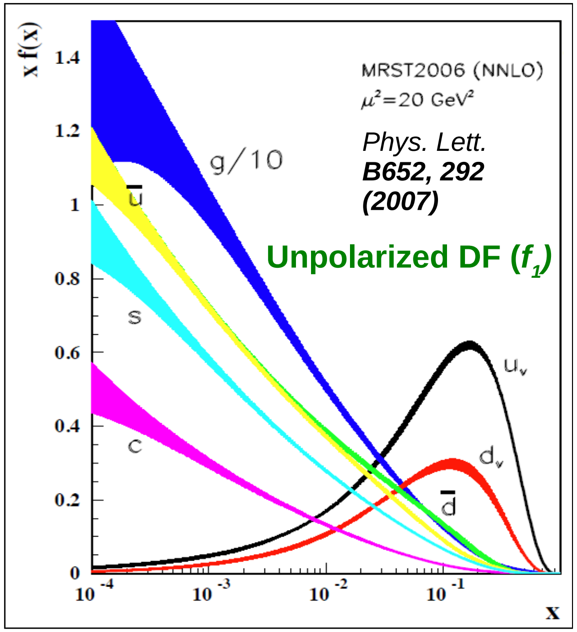
Outline

- Introduction to nucleon spin structure
- Transversity and Transverse Momentum Dependent (TMD) PDFs
- Experimental status of TMDs:
  - Data on Collins and Sivers moments
- E06-010 experiment in Hall-A using polarized ^{3}He target
- Future plans for SIDIS measurements in Hall-A at JLab 12 GeV

Nucleon Spin Structure

- Leading twist Parton Distribution Function
  - Unpolarized PDF : $f_1(x)$ (very well known)
  - Longitudinally polarized: $g_1(x)$ (well known)
  - Transversity: $h_1(x)$ (least known)

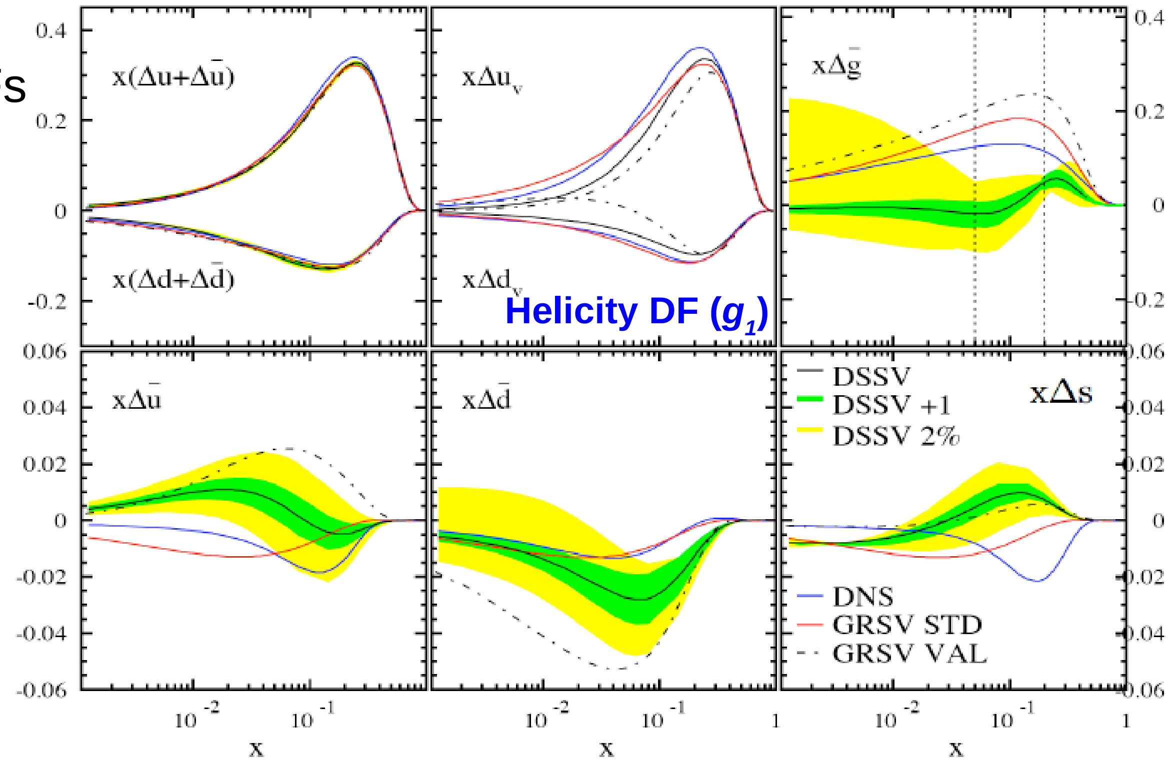
  Measured in DIS process



- Experimental efforts on transversity have recently begun
- First extraction of transversity DF (Anselmino *et al.*)
- Orbital angular momentum of quarks play important role in explaining nucleon spin

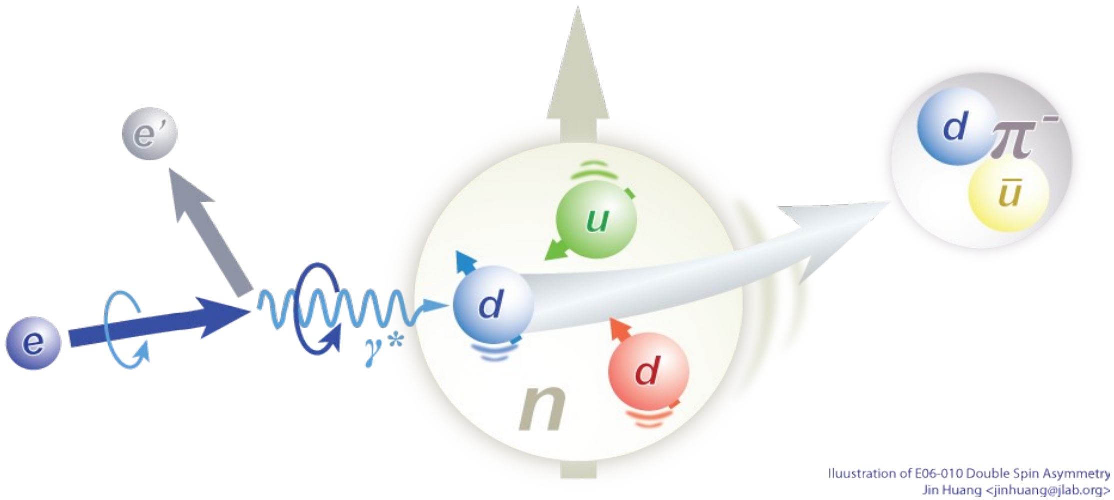
- Transverse Momentum Dependent PDFs
  - Both x_{bj} and k_T dependent
  - Accessible using Semi-Incluisve DIS

k_T : intrinsic transverse momentum of quarks

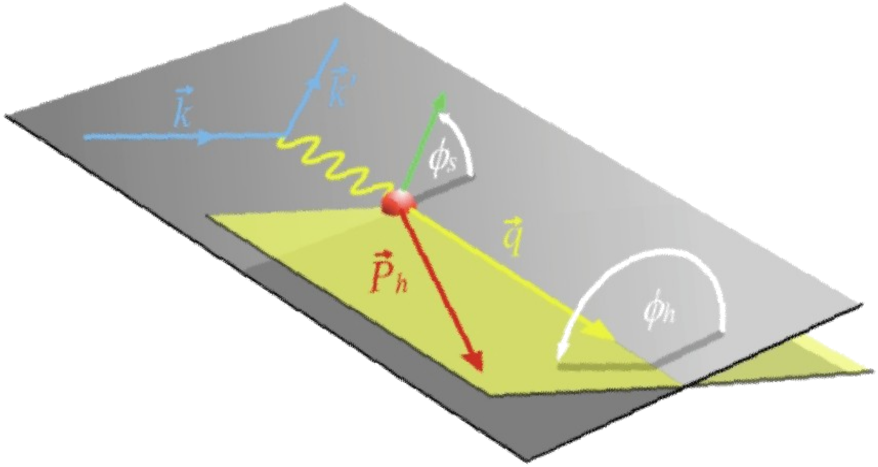


Semi-Inclusive Deep Inelastic Scattering

$$Q^2 = 4EE' \sin^2(\theta/2)$$
$$\nu = E - E'$$
$$x = Q^2/2M\nu$$
$$y = \nu/E$$
$$z = E_h/\nu$$



$$\sigma^{eN \to e'hX} \propto DF(x, k_T) \otimes FF(z, p_T)$$



- Detect scattered electron in coincidence with produced hadron
- Quark flavor tagging via fragmentation function
- Ideal tool to study TMDs

SIDIS Cross-section

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

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

SIDIS Cross-section

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&\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[\boxed{\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\,\boxed{\sin(\phi_h+\phi_S)}\,F_{UT}^{\sin(\phi_h+\phi_S)} \\
&\qquad + \varepsilon\,\boxed{\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}\,\boxed{\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}
$$

Collins

Sivers

Pretzelosity

Worm-gear

Accessible with transversely polarized target

Leading Twist Transverse Momentum Dependent PDFs

: Nucleon Spin :Quark Spin

		Quark polarization		
		Unpolarized (U)	Longitudinally Polarized (L)	Transversely Polarized (T)
Nucleon Polarization	U	$f_1 =$		$h_1^{\perp} = \quad - \quad$ Boer-Mulders
	L		$g_{1L} = \quad - \quad$ Helicity	$h_{1L}^{\perp} = \quad - \quad$ Worm Gear
	T	$f_{1T}^{\perp} = \quad - \quad$ Sivers	$g_{1T} = \quad - \quad$ Worm Gear	$h_1 = \quad - \quad$ Transversity $h_{1T}^{\perp} = \quad - \quad$ Pretzelosity

- f_1, g_{1L} and h_1 are integrated over quark transverse momentum (k_T)
- Rest are k_T dependent PDFs

Leading Twist Transverse Momentum Dependent PDFs

: Nucleon Spin :Quark Spin

		Quark polarization		
		Unpolarized (U)	Longitudinally Polarized (L)	Transversely Polarized (T)
Nucleon Polarization	U	f_1 =		$h_1^\perp$ = − Boer-Mulders
	L		g_{1L} = − Helicity	$h_{1L}^\perp$ = − Worm Gear
	T	$f_{1T}^\perp$ = − Sivers	g_{1T} = − Worm Gear	h_1 = − Transversity $h_{1T}^\perp$ = − Pretzelosity

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

- f_1, g_{1L} and h_1 are integrated over quark transverse momentum (k_T)
- Rest are k_T dependent PDFs

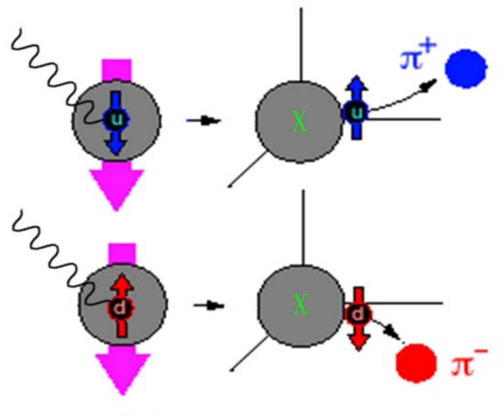
Transversity

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

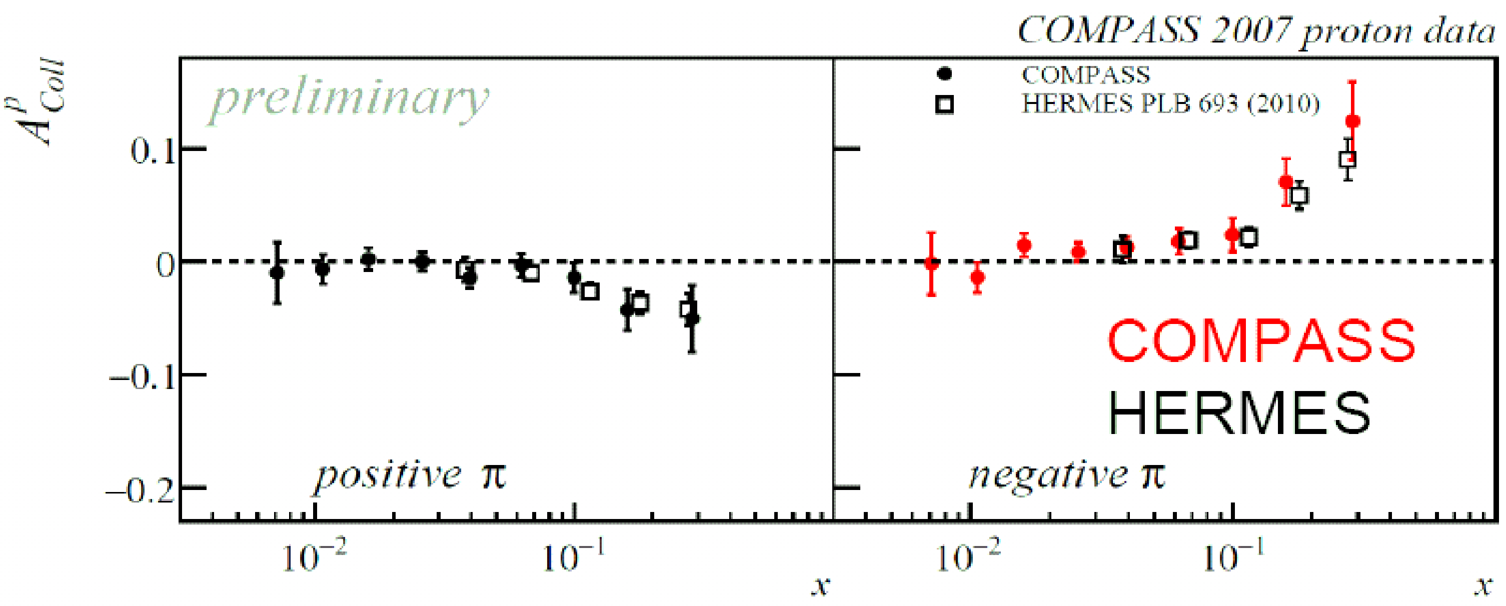
Transversely polarized quark generates left-right asymmetry during fragmentation

- Valence like behavior
- Related to quark tensor charge – a fundamental property (a benchmark test for Lattice QCD + models)
- Large and opposite signal for π^+ and π^- on proton
- Small (near-zero) asymmetries on deuteron
- Need precision data in high *x* region

Collins Effect



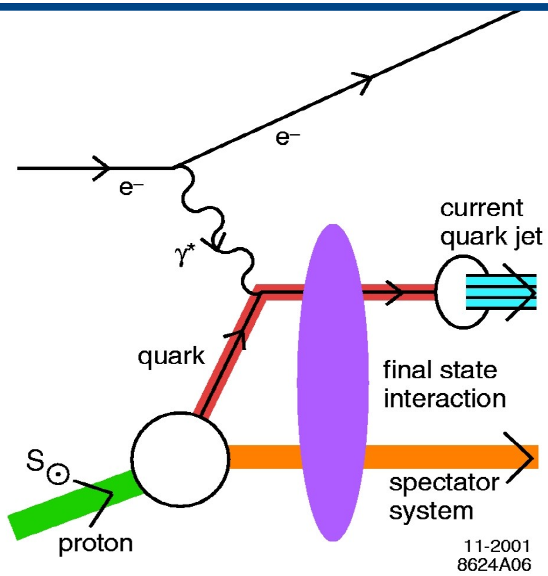
C. Schill, DIS2011 Workshop



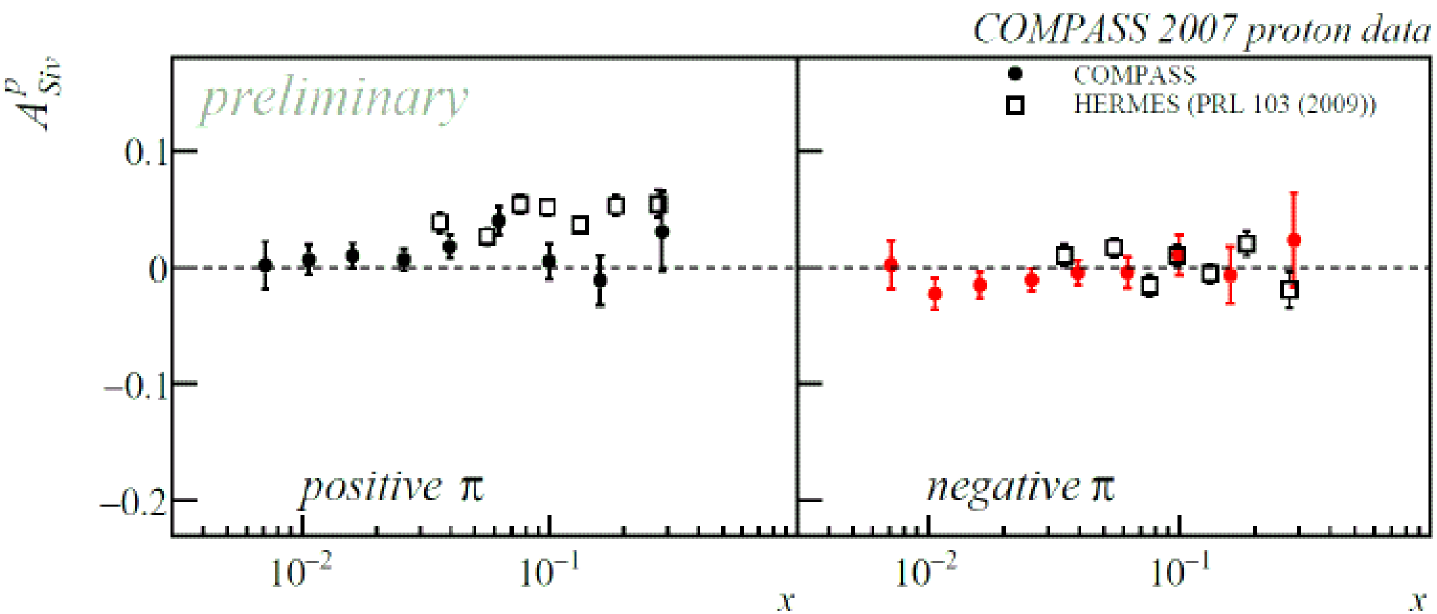
Sivers Function

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

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



- Require non-zero quark angular momentum
- SSA observed via final state interactions
- Clear non-zero signal for π^+ on proton
- Test an important QCD prediction: f_{1T} (SIDIS) = - f_{1T}(DY)
- Need high precision data in 4 dimensions (x,Q^2,z,P_T)



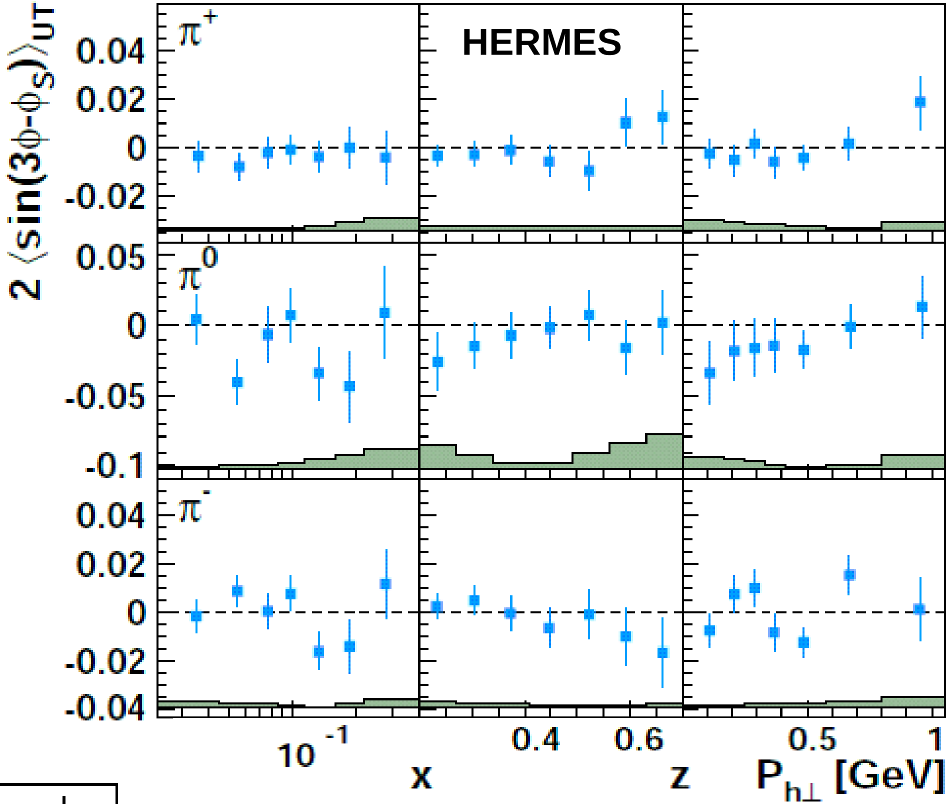
C. Schill, DIS2011 Workshop

Pretzelosity and Worm-gear Functions

- **Pretzelosity**
  - Direct probe of relativistic effects
  - No clear signal seen yet at both HERMES and COMPASS (limited precision)

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

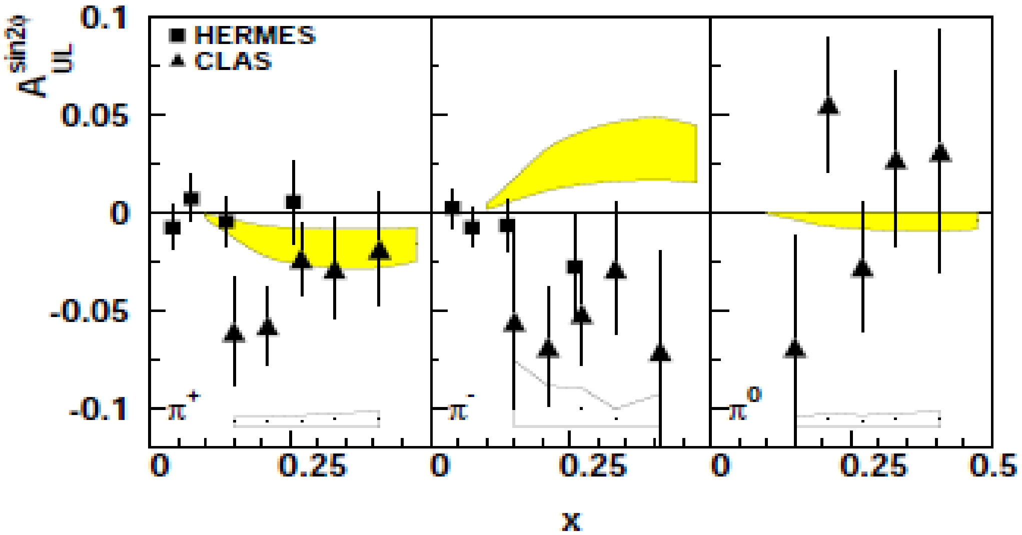
M. Diefenthaler's Dissertation (HERMES)



- **Worm-gear functions (g_{1T} and h_{1L})**
  - Related to spin-orbit correlations
  - A_{LT} and A_{UL} data from JLab, HERMES and COMPASS

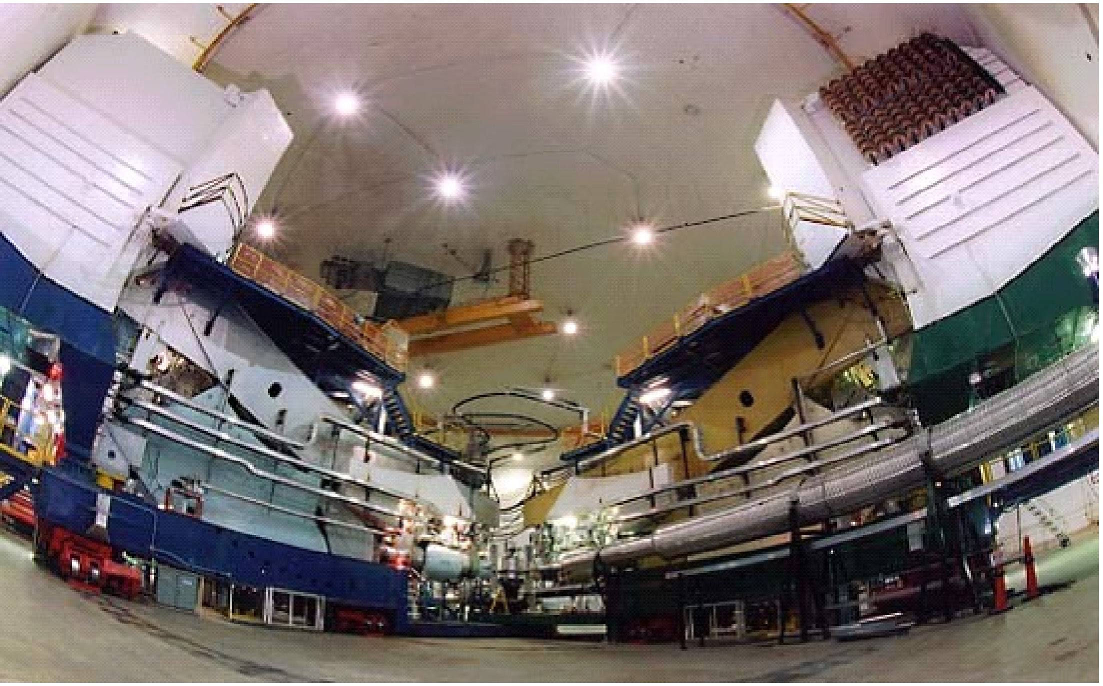
$$\sigma_{LT}^{SIDIS} \propto \cos(\phi_h - \phi_S)\ g_{1T} \otimes D_1$$

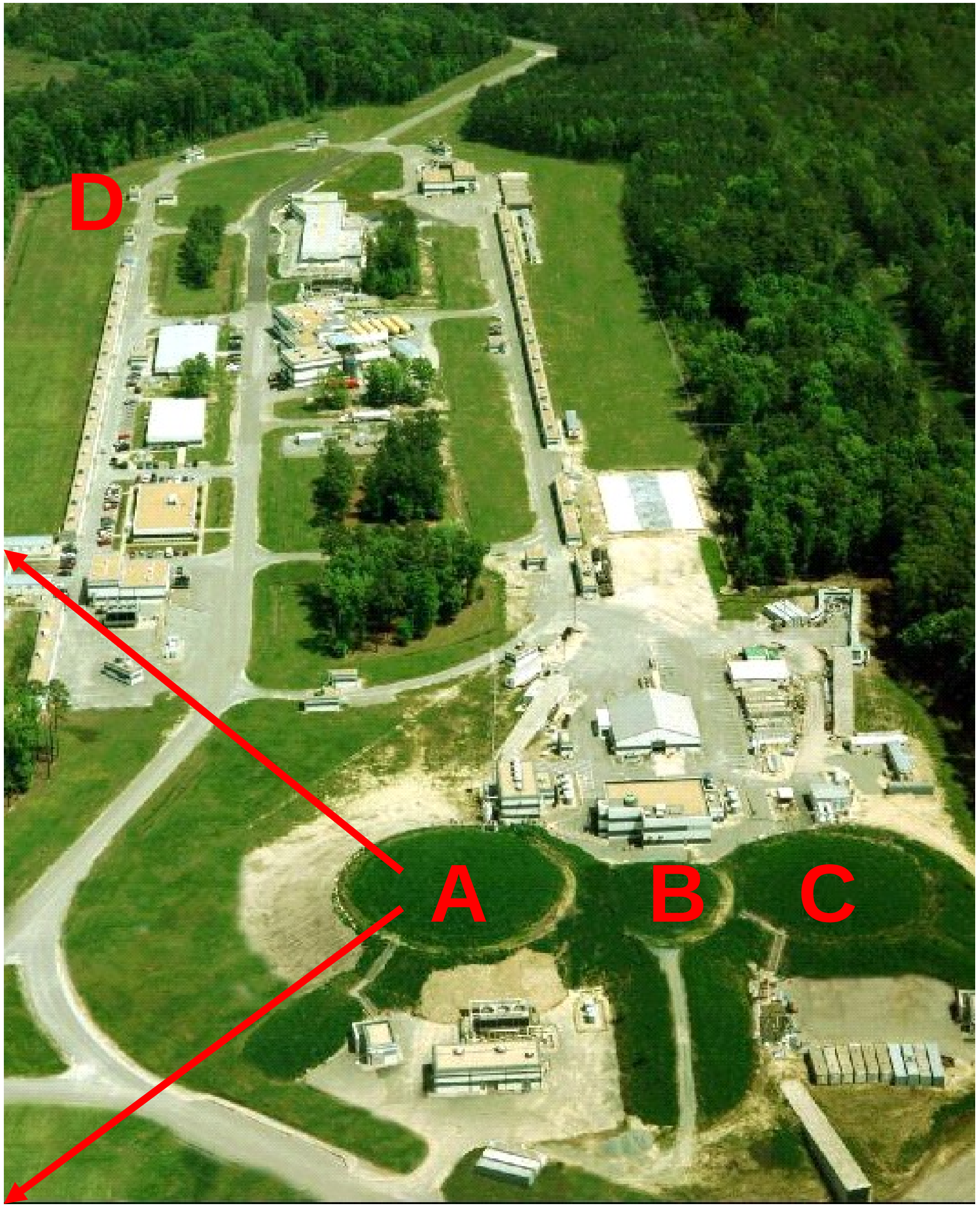
$$\sigma_{UL}^{SIDIS} \propto \sin(2\phi_h) h_{1L}^{\perp} \otimes H_1^{\perp}$$



Hall-A Transversity Experiment at Jefferson Lab

- First measurement of SSA and DSA on transversely Polarized ^3He target (neutron)
- Run period: Oct. 2008 – Feb. 2009
- 6 GeV electron beam
- Beam Polarization : ~85 %



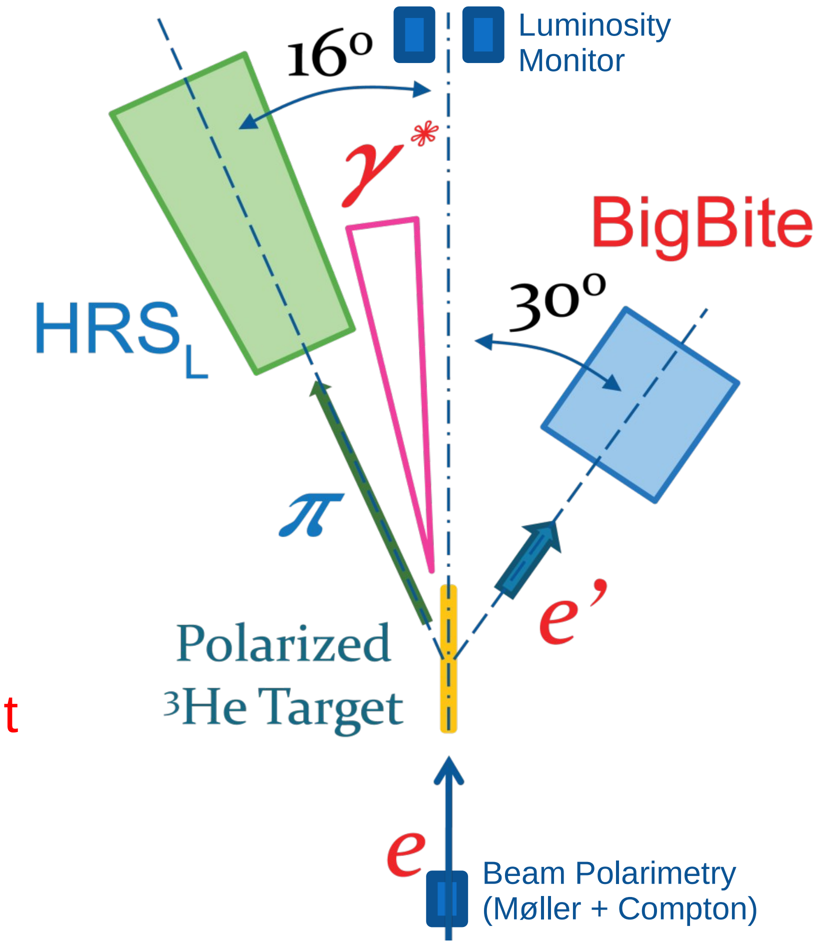


Experimental Setup

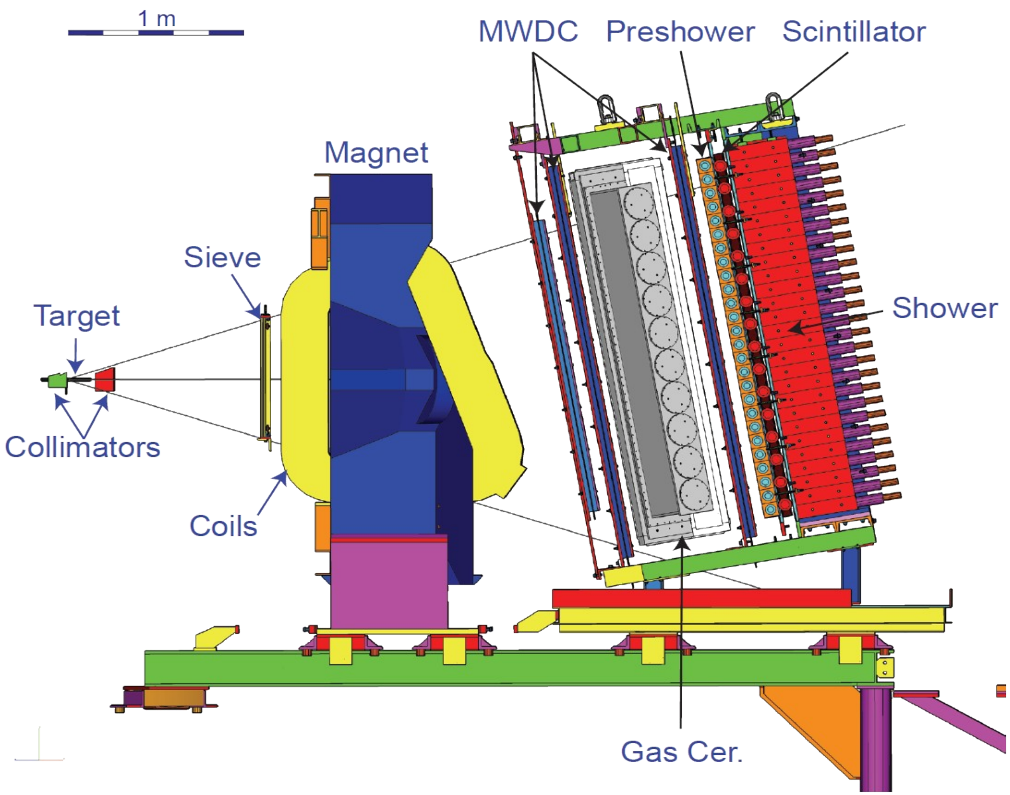
$$e + {}^3He^{\uparrow} \longrightarrow e' + h + X$$

$$h = \pi^{+/-}, K^{+/-}$$

- Polarized ^{3}He target ($P_{target} \sim 64\%$)
- 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
- Beam helicity flip at 30 Hz
- Target spin orientations: up-down and left-right
- Automatic target spin-flip every 20 mins.

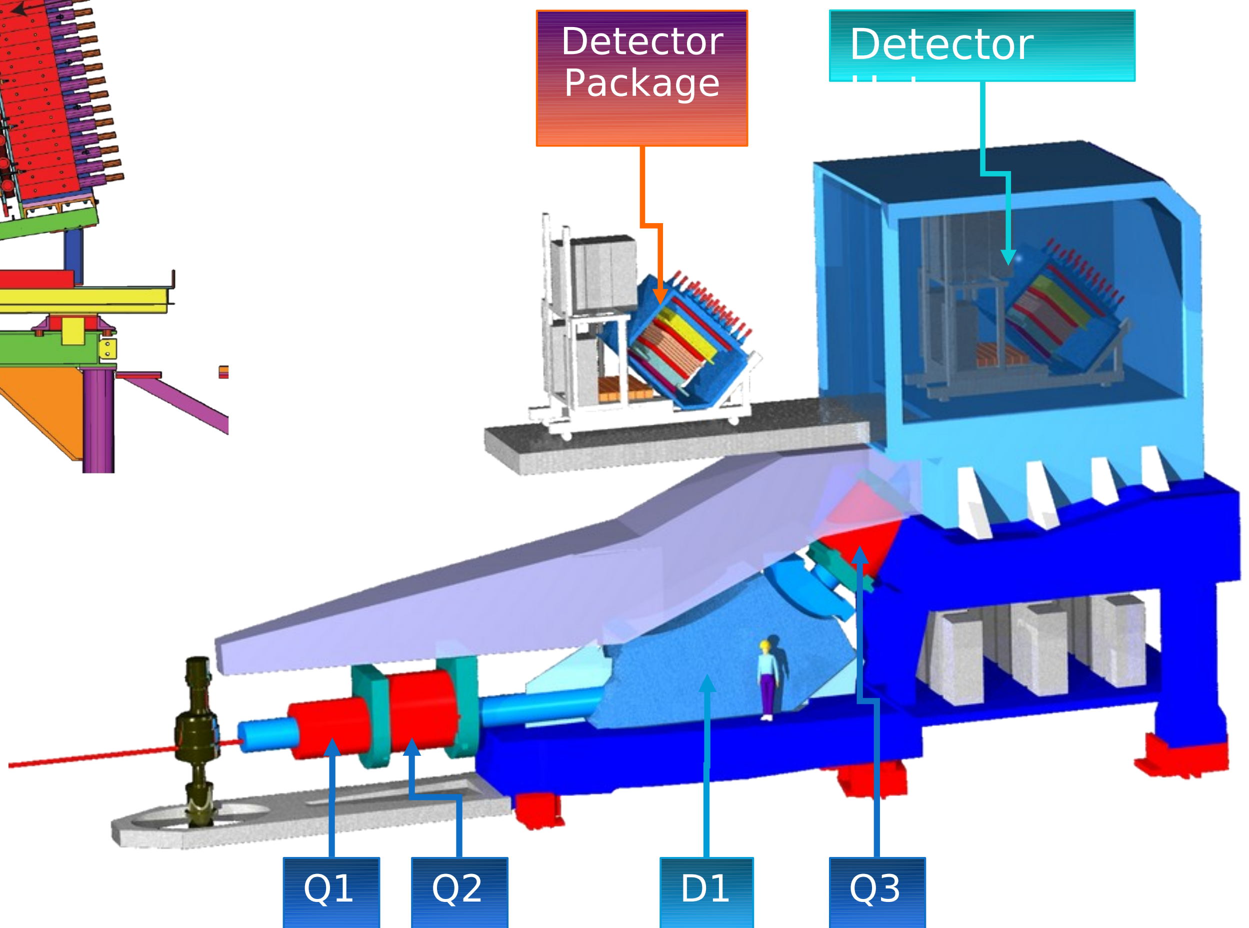


Spectrometers

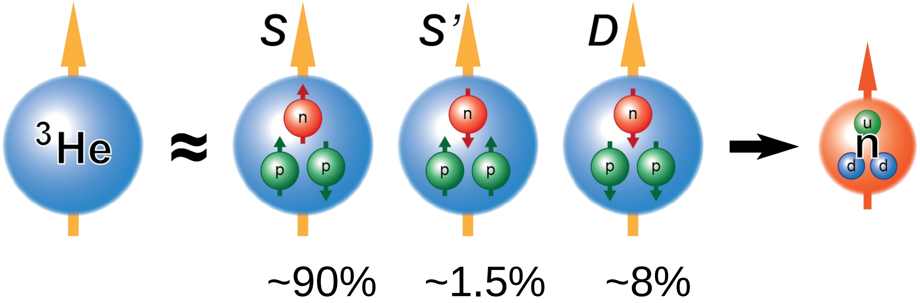


BigBite spectrometer (electron arm)

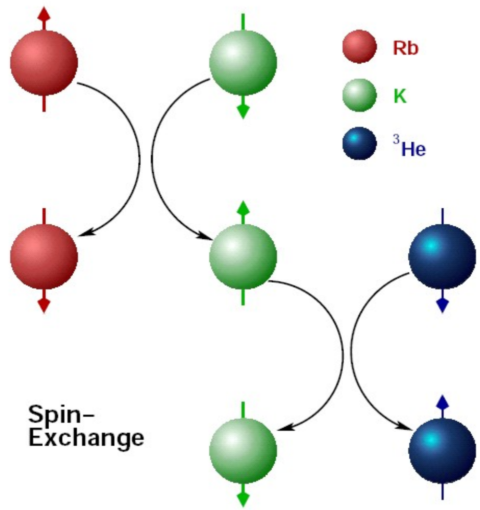
High Resolution Spectrometer (hadron arm)

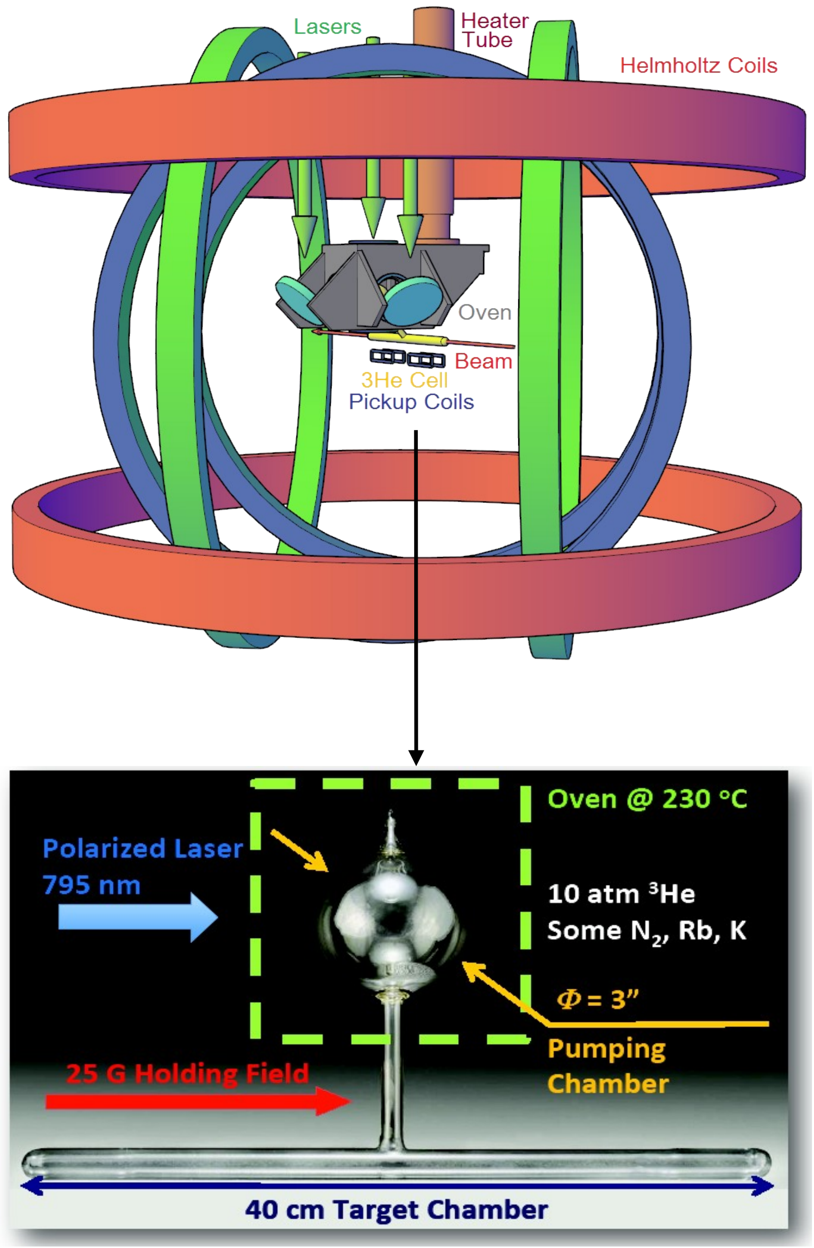


Polarized ^{3}He Target



- High Luminosity polarized target ($10^{36}/cm^2/s$)
- Fast spin-exchange with Rb-K hybrid cells
- Average polarization : ~64%
- Automatic spin-flip every 20 mins





Access to Transverse Spin Observables in SIDIS

Separate different moments through azimuthal angular dependence

- **Collins asymmetry:**

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

- **Sivers asymmetry:**

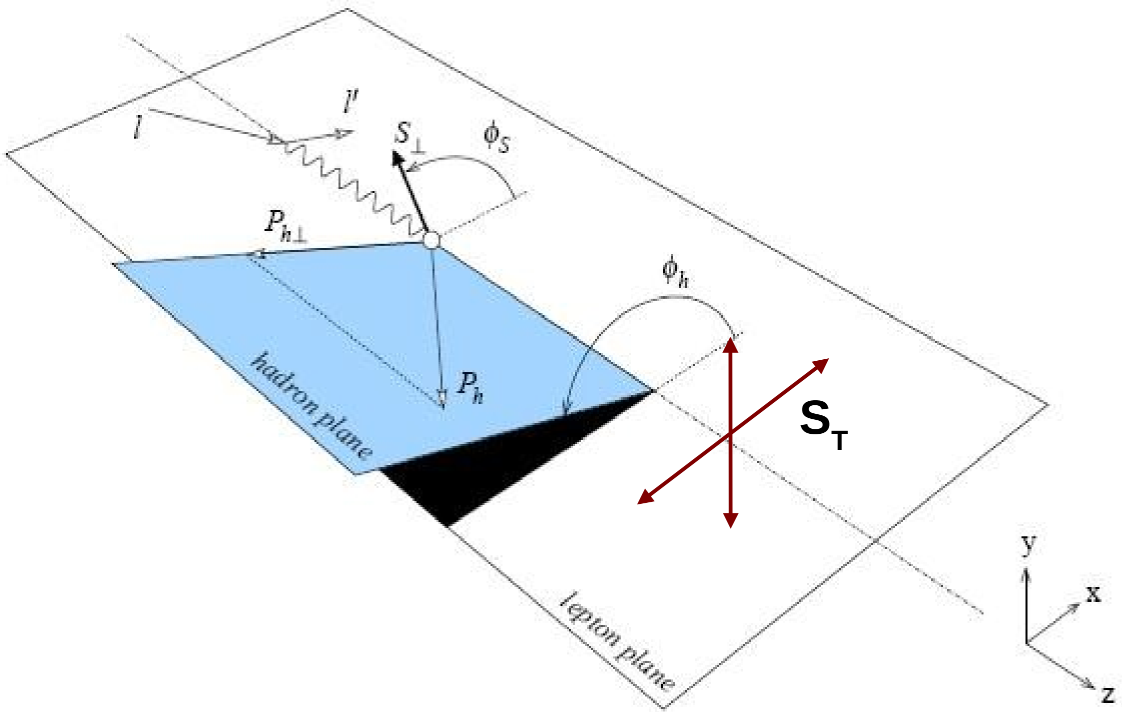
$$\sigma_{UT}^{SIDIS} \propto \sin(\phi_h - \phi_S)\ f_{1T}^{\perp} \otimes D_1$$

- **"Pretzelosity":**

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

- **Double-spin asymmetry:**
(long. polarized beam)

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

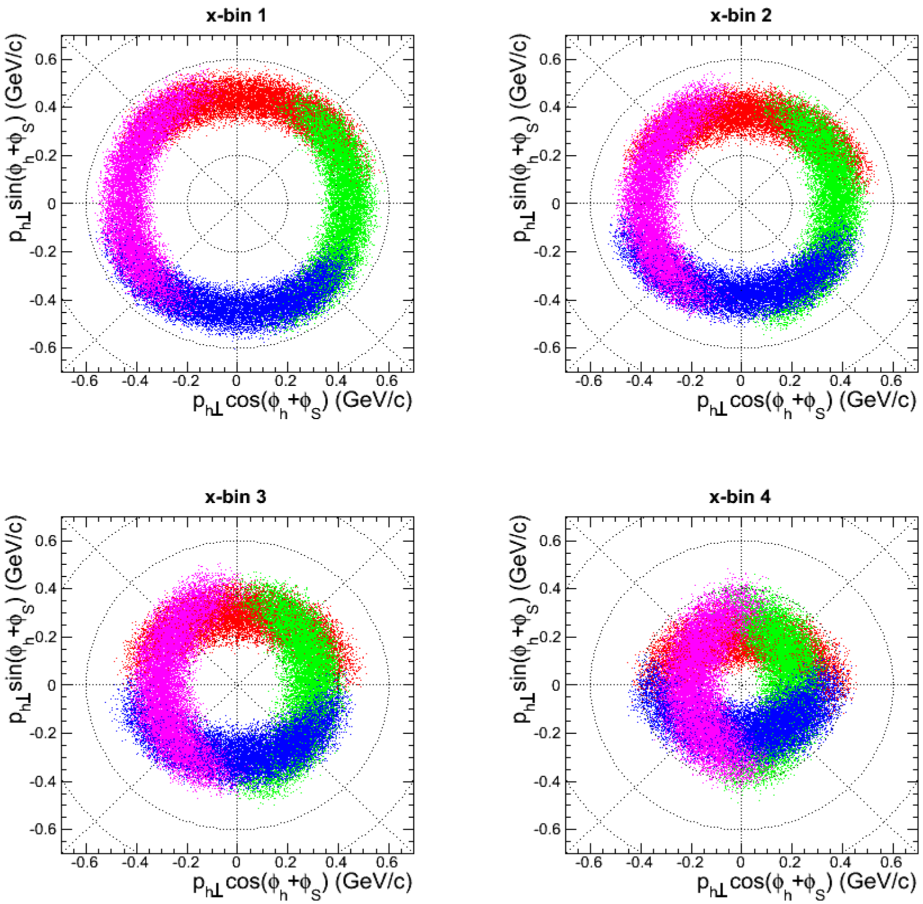


- Target spin orientations: up-down and left-right
(increase azimuthal angular coverage)
- Automatic target spin-flip every 20 mins
(keeps systematics due to target under control)

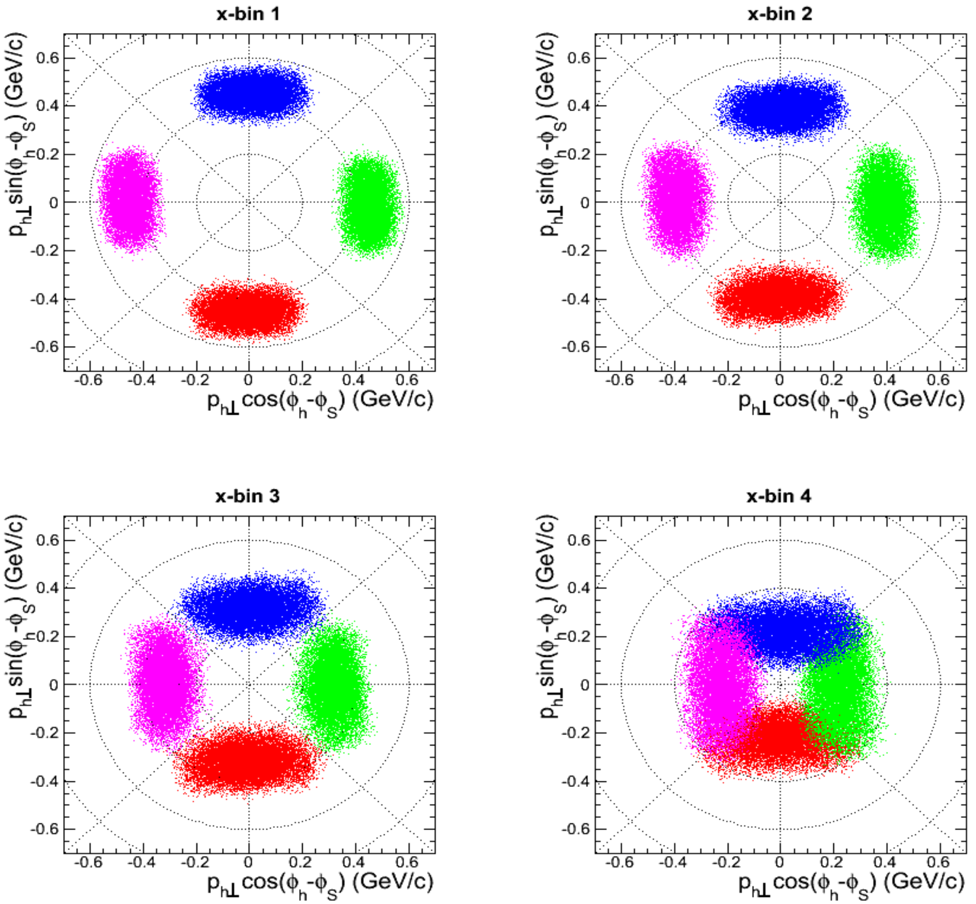
$$A_{UT}(\phi_h, \phi_S) = \frac{1}{P} \frac{N^{\uparrow} - N^{\downarrow}}{N^{\uparrow} + N^{\downarrow}}$$

Azimuthal Angular Coverage

Collins angle: $\phi_h + \phi_s$



Sivers angle: $\phi_h - \phi_s$

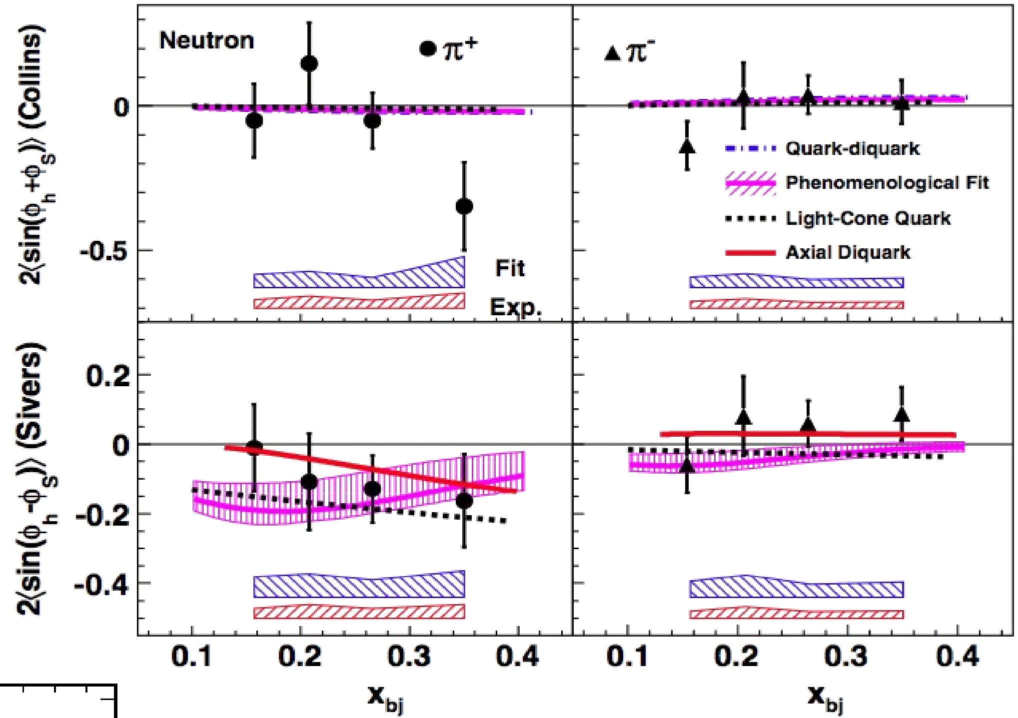


Different colors corresponds to different target spin states - left, right, up and down

Neutron 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

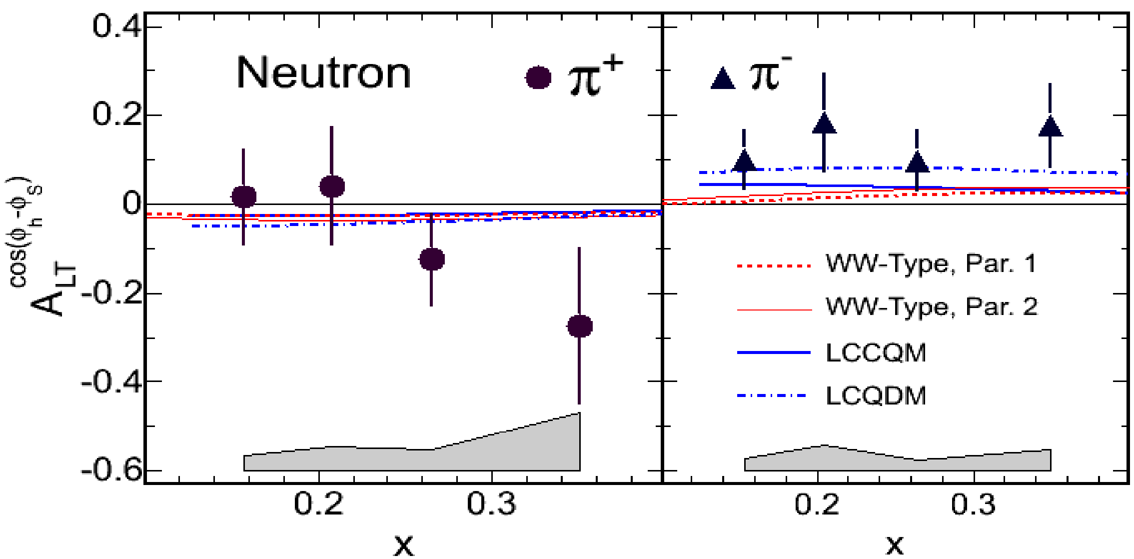
Phys. Rev. Lett. 107, 072003 (2011)



Single spin asymmetry

$<Q^2> \sim 2.0$ GeV^2
$<z> = 0.5$

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



Double spin asymmetry

World Data on Transverse SSA

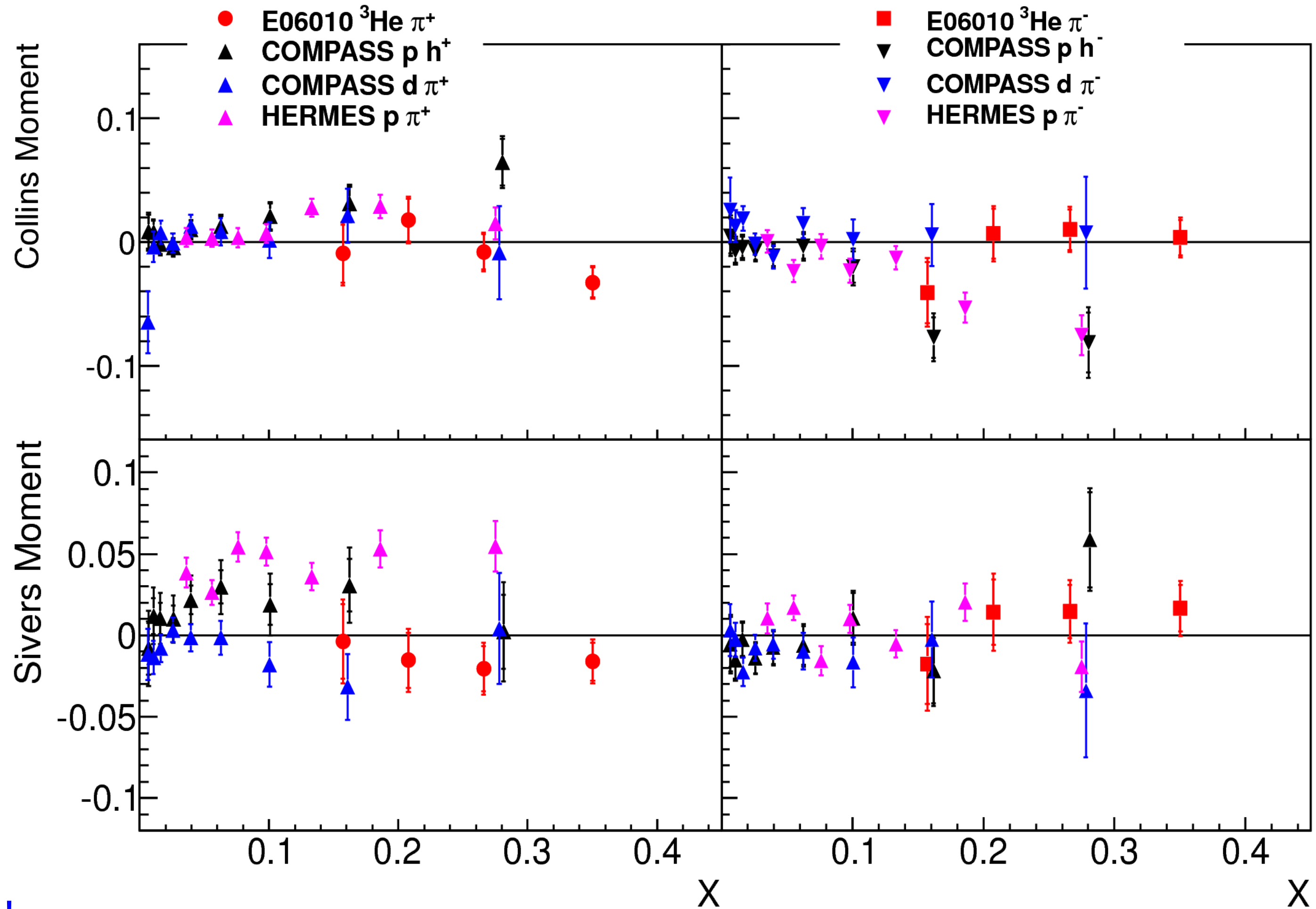
(proton, deuteron and ^{3}He targets)

Comparison of Hall-A ^{3}He results with world data on Collins and Sivers moments

JLab(E06-010)
Q^2 = 1.4 - 2.7 GeV^2

HERMES:
Q^2 = 1.3 - 6.2 GeV^2

COMPASS:
Q^2 = 1.3 – 20.2 GeV^2



- Higher *x* data is needed!
- Multi-dimensional binning is needed to fully understand these SSAs

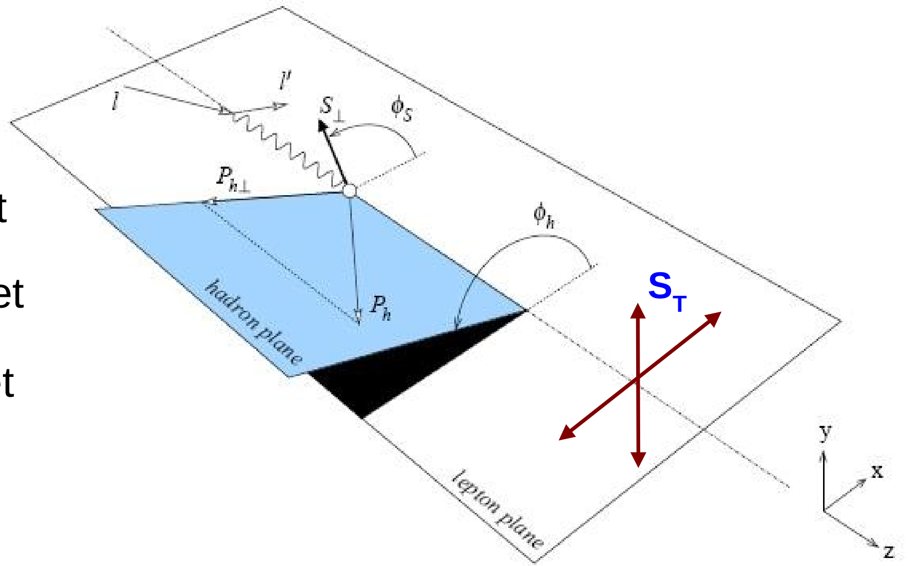
Future SIDIS Experiments in Hall-A

First generation of SIDIS with polarized targets gave interesting information about TMDs but severely limited in precision and/or kinematics

Our goal is to perform precision 4D (x,Q^2,z, P_T) mapping of single and double spin asymmetries using SIDIS on polarized neutron and proton targets

Proposed experiments with SoLID:

- SIDIS measurement using transversely polarized ^{3}He target
- SIDIS measurement using longitudinally polarized ^{3}He target
- SIDIS measurement using transversely polarized NH_3 target [conditionally approved]

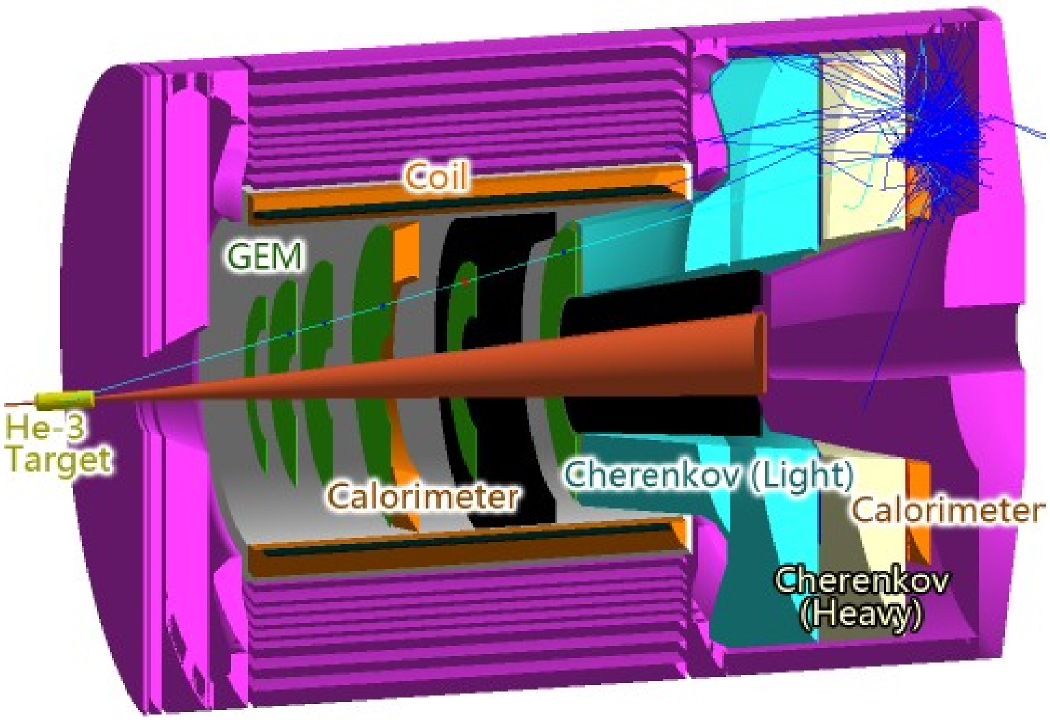


<u>Other complementary measurements proposed at JLab 12 GeV:</u>

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

SoLID: A New Device in Hall-A

- Beam energy = 11 GeV and 8.8 GeV
- Solenoid Magnet
- 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



SoLID-SIDIS Collaboration

Peking U., CalState-LA, CIAE, W&M, Duke, FIU, Hampton, Huangshan U., Cagliari U. and INFN, INFN-Bari and U. of Bari, INFN-Frascati, INFN-Pavia, Torino U. and INFN, JLab, JSI (Slovenia), Lanzhou U, LBNL, Longwood U, LANL, MIT, Miss. State, New Mexico, ODU, Penn State at Berks, Rutgers, Seoul Nat. U., St. Mary's, Syracuse, Tel Aviv, Temple U., Tsinghua U., UConn, Glasgow, UIUC, Kentucky, Maryland, UMass, New Hampshire, USTC, UVa, *Shangdong University, Huazhong Univ. of Science and Technology, Inst. of Modern Physics of CAS, ANL, INFN/Catania*

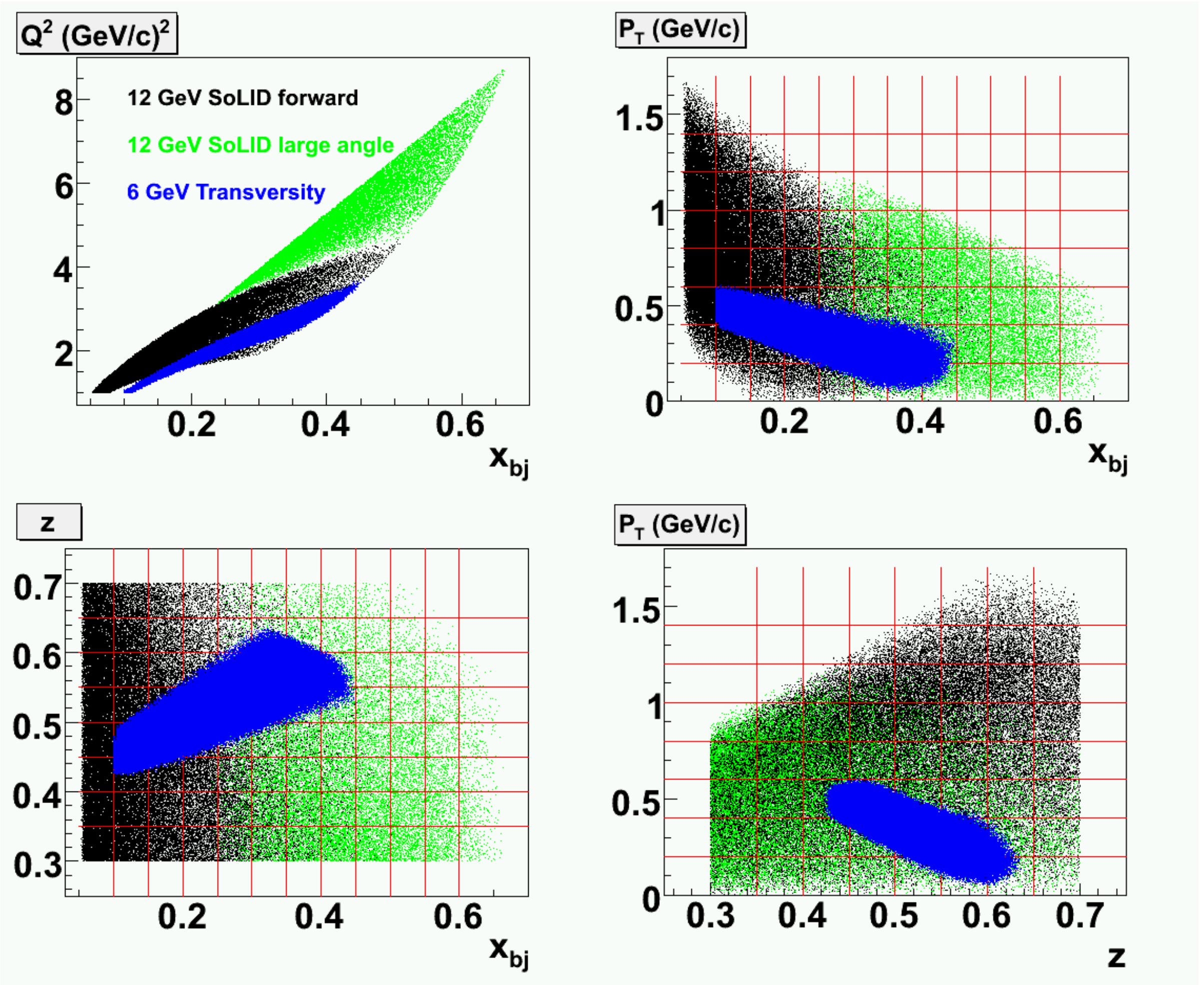
and the Hall A Collaboration

Strong theory support, Over 130 collaborators, 40 institutions,
8 countries, strong overlap with PVDIS Collaboration

Three A-rated experiments and one conditionally approved experiment
(Jefferson Lab PAC38)

Hall-A E06-010 vs SoLID Phase Space

- Hall-A 6 GeV Transversity Experiment covered limited phase space
- Proposed measurement with SoLID covers much wider phase space
- Multi-term fitting to extract various azimuthal moments related to TMDs

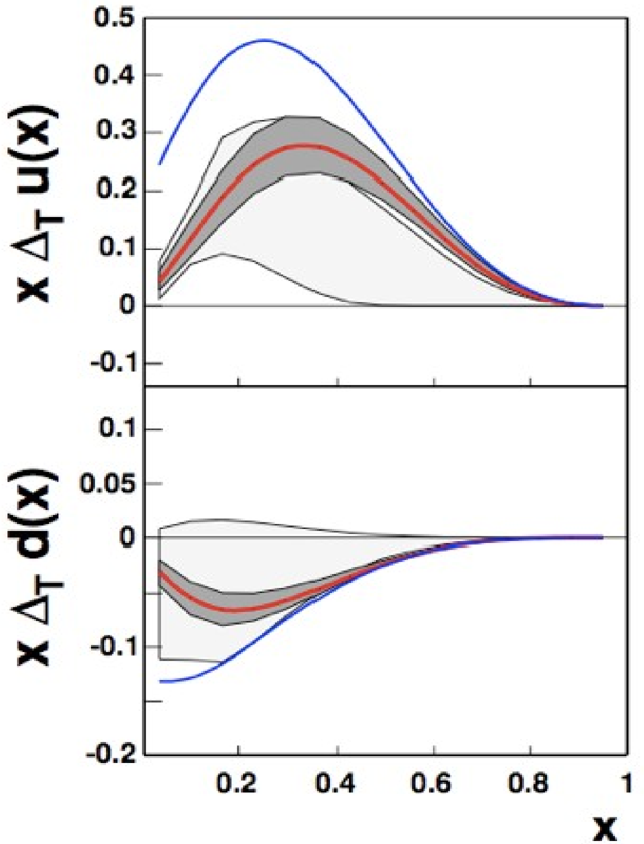


- $x_B = 0.05 – 0.68$
- $Q^2 = 1.0 – 9.0\ (GeV/c)^2$
- $P_T = 0 – 1.8$ GeV/c
- $z = 0.3 – 0.7$
- W > 2.3 GeV

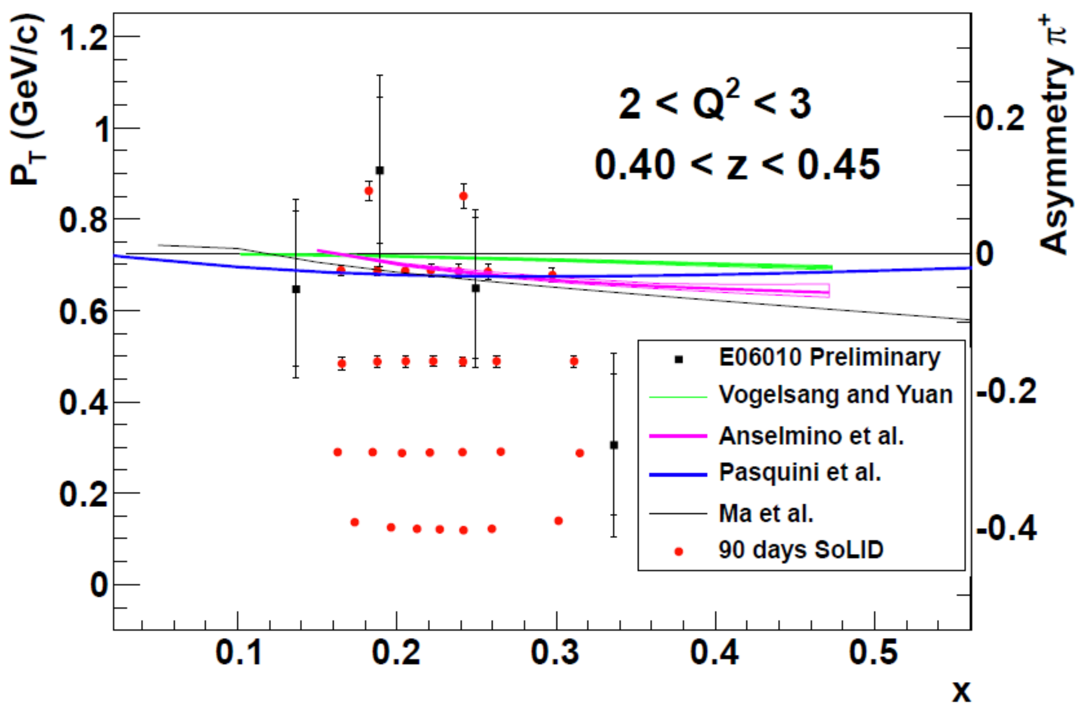
Collins Moment Projections

- Currently large errors on the theoretical fit for transversity
- Future measurements will provide precision data and extend x coverage
- Constraint u and d-quark tensor charge

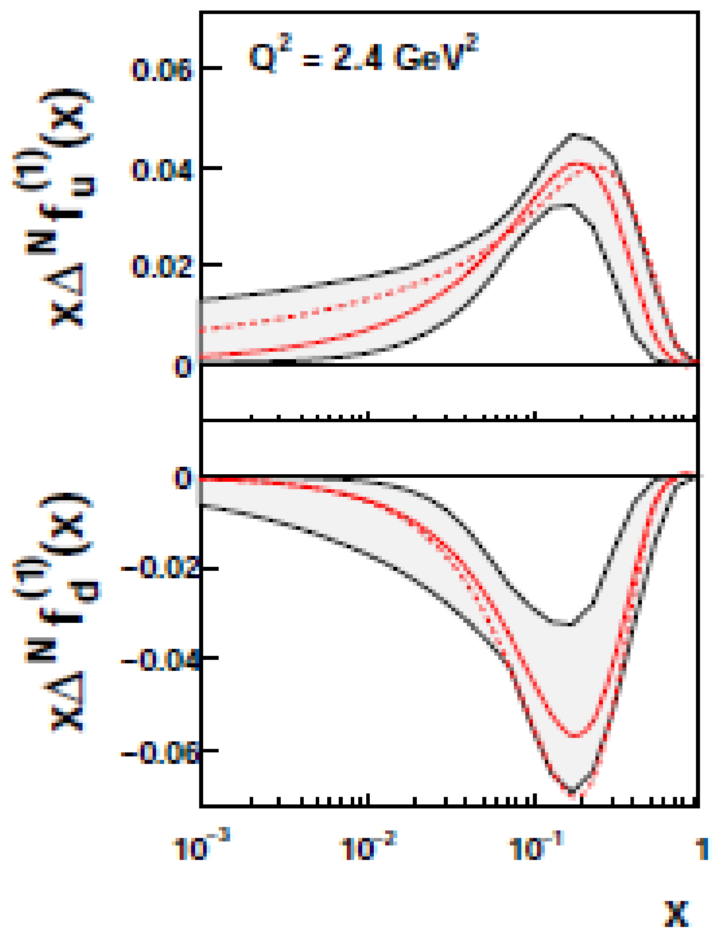
Current fit by Anselmino *et al.*



SoLID Projections in one bin of Q^2 and z



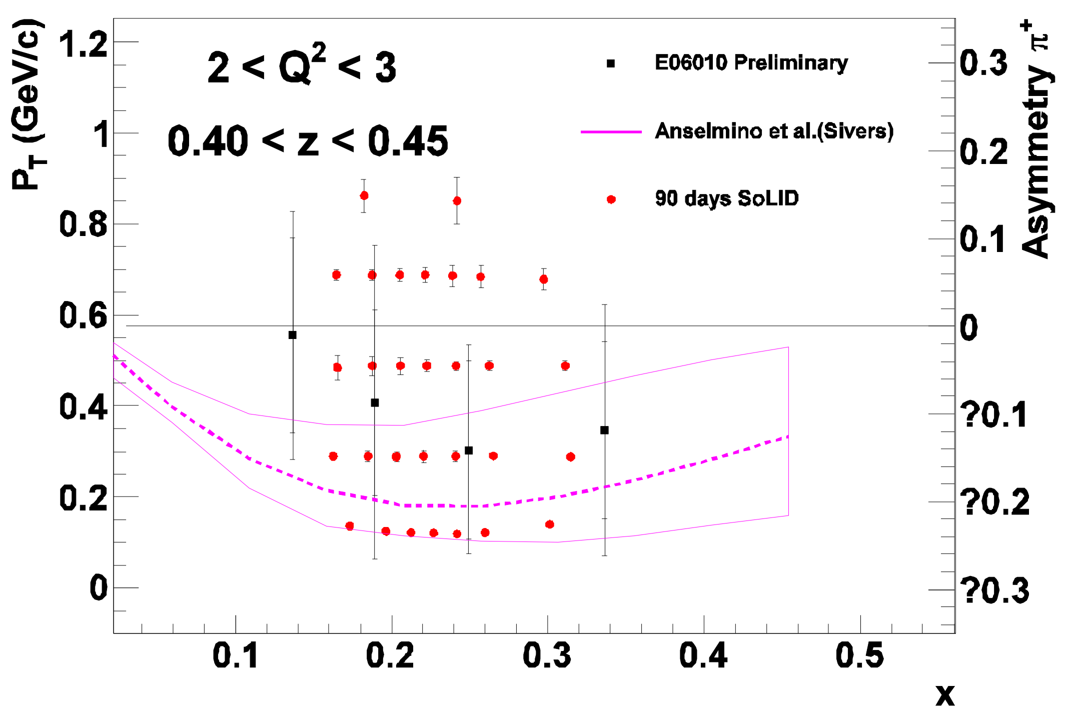
Sivers Moment Projections



Current fit by Anselmino *et al.*

- Large P_T coverage
  - Test various theoretical models of TMDs

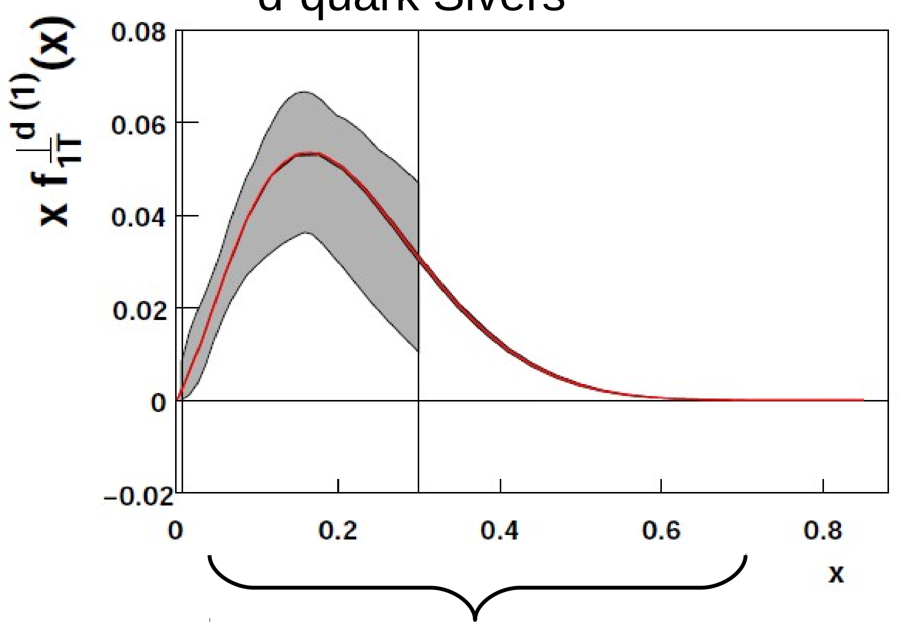
SoLID Projections in one bin of Q^2 and *z*



Impact on Extraction of TMDs

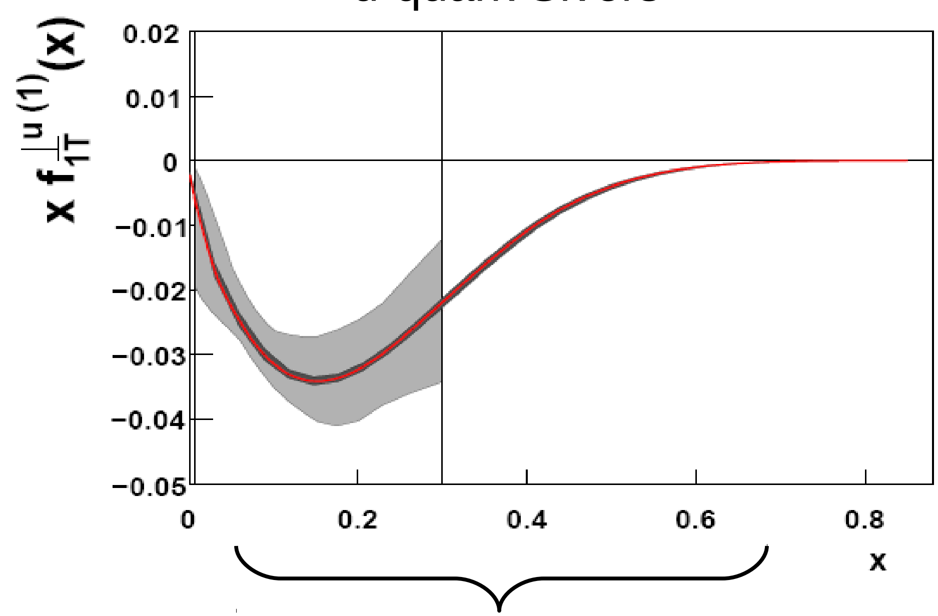
- Precision data : help understand the role of quark OAM in spin of the nucleon

d-quark Sivers



Region covered

u-quark Sivers

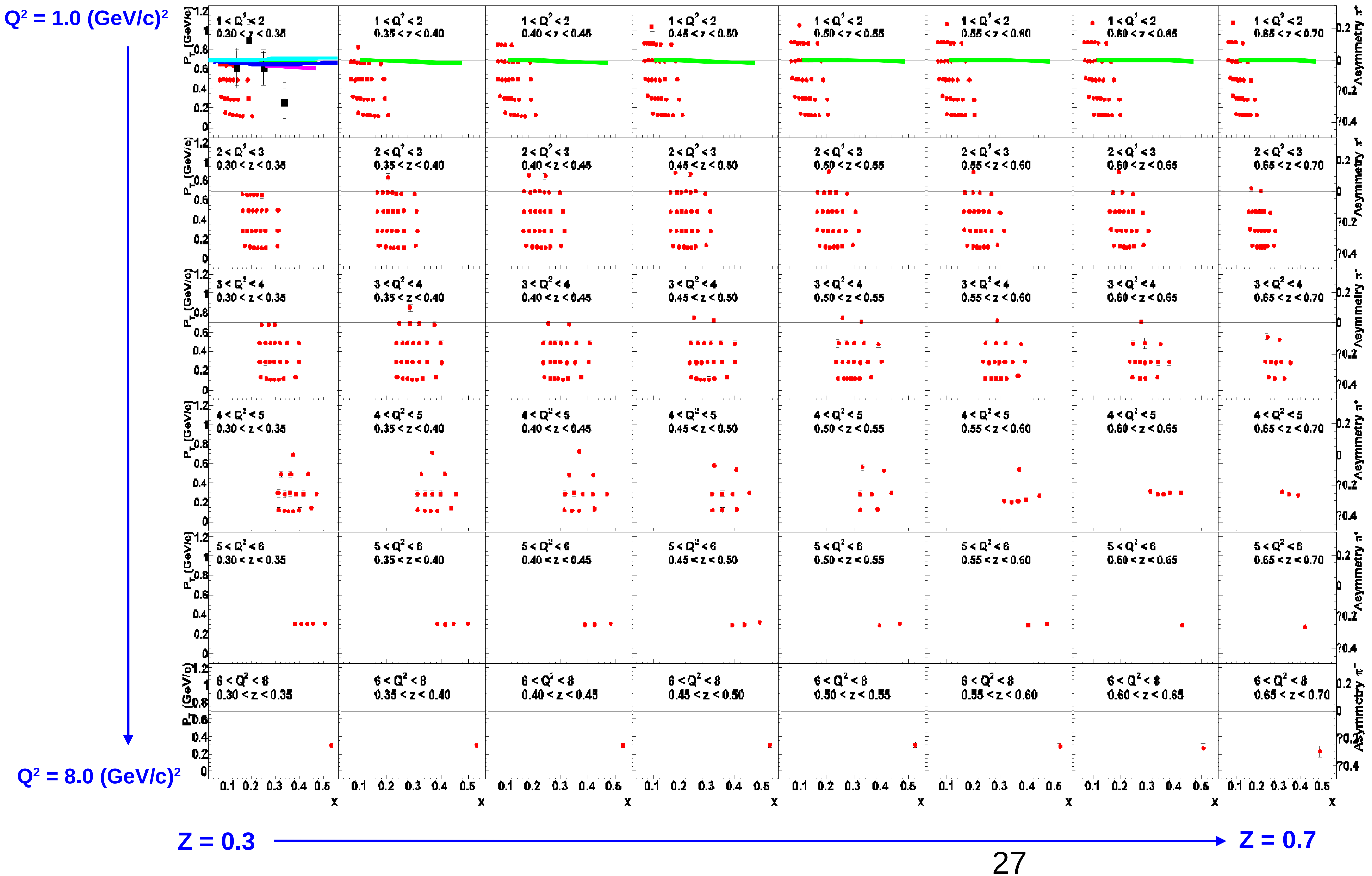


Region covered

A. Prokudin

- Only Sivers function is shown
- Similar precision can be achieved for transversity
- Current experimental uncertainties in large light grey band
- Projected uncertainties in dark grey band

Multi-dimensional Binning



Summary and Outlook

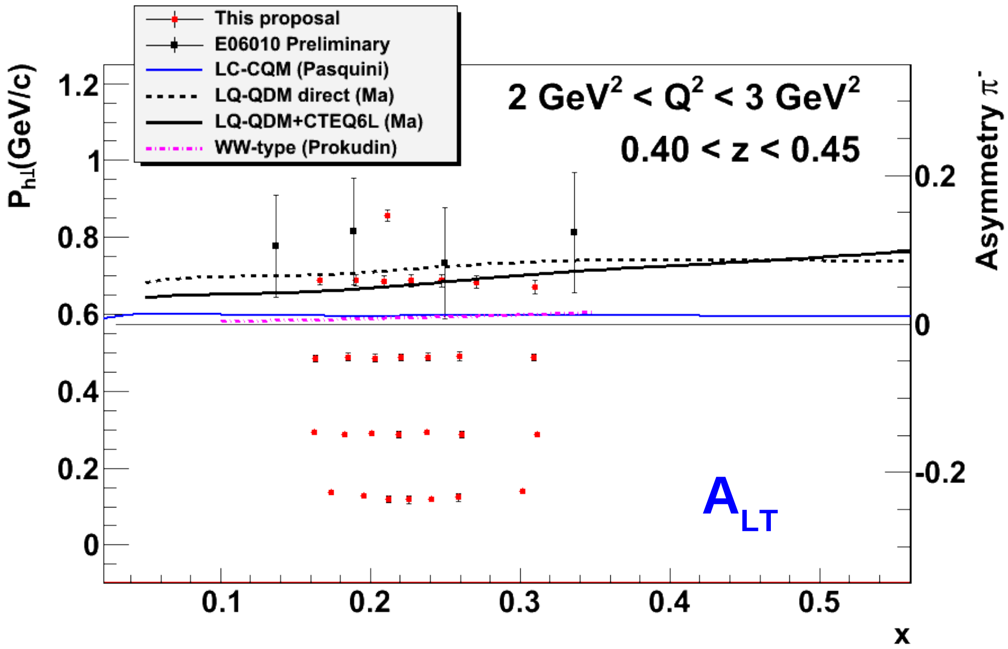
- First measurement of transverse SSA/DSA using polarized ^{3}He target
  - Negative favoring Sivers moment for π^+
  - First non-zero A_{LT} moment observed on neutron
- Study of TMDs with SIDIS - moving from exploration to precision measurement
  - Study spin-orbit corrections, P_T dependence, factorization, flavor dependence etc..
- SIDIS measurements at JLab 12 GeV with SoLID spectrometer in Hall-A
  - Full azimuthal coverage, high luminosities, large acceptance
  - Cover wide kinematic rage, provide multi-dimensional mapping of SSA and DSA
- Rich and complementary SIDIS program in Hall A/B/C at Jefferson Lab
  - Comprehensive view of TMDs and nucleon spin structure

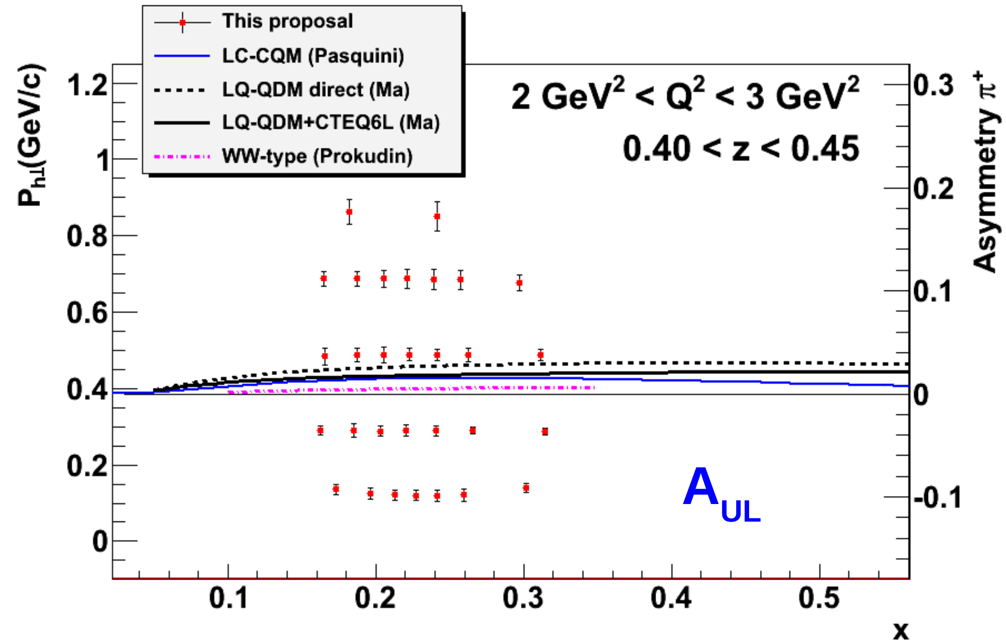
Spare Slides

Worm-gear Moment Projections

- Dominated by real part of interference between L=0 (s) and L=1 (p) states
  - Imaginary part -> Sivers effect
- First TMDs in Lattice calculations
  - arXiv:0908.1283, arXiv: 1011.1213
- No GPD correspondence

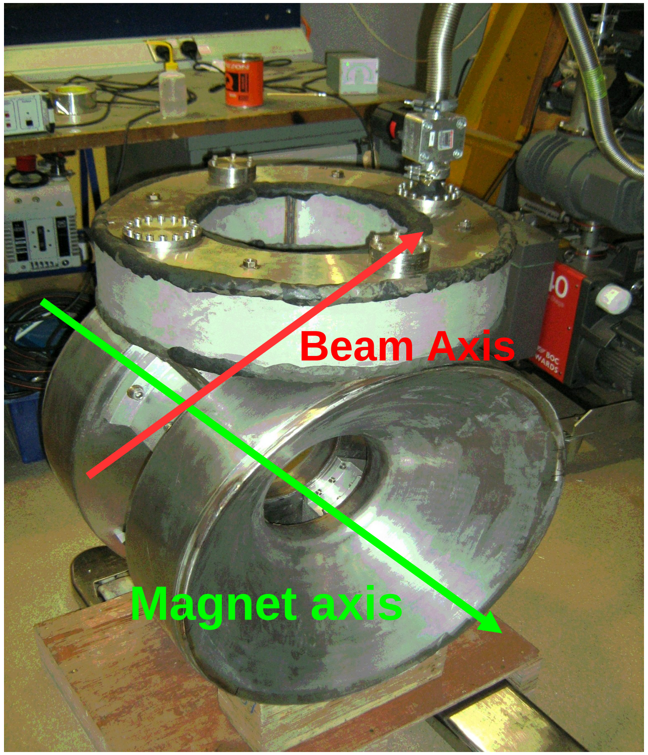
Projections for one bin of Q^2 and z



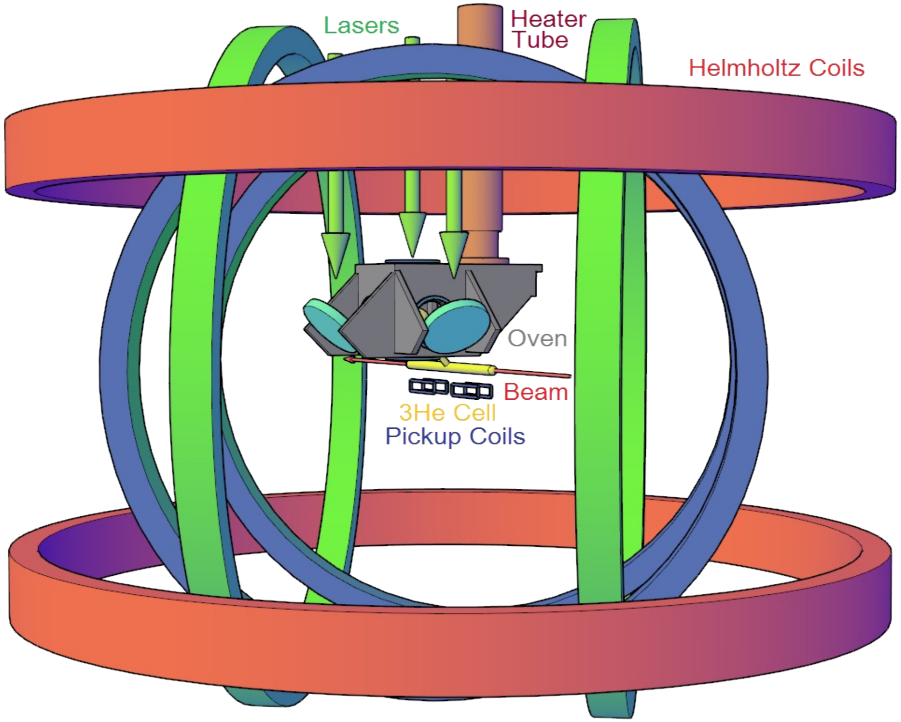


Polarized Targets

- Polarized solid NH_3 target (proton)
  - High in-beam polarization: ~90%
  - Spin-flip every ~2hrs
  - Spin direction: longitudinal and transverse
  - 5T superconducting magnet, 1K refrigerator
  - 3 cm long target



JLab/UVA polarized NH_3 target magnet



- Polarized ^{3}He gas target (neutron)
  - 40 cm long target
  - Rb-K hybrid spin-exchange
  - In-beam polarization: ~65%
  - Fast spin-flip (~ 20mins)
  - Spin direction: longitudinal and transverse

SoLID Collaboration

- CO_2 gas Cerenkov detector: Temple U.
- Heavy Gas Cerenkov: Temple U.
- EM Calorimeter : W&M, UMass, JLab, Rutgers, Syracuse
- GEM detectors: UVa, Miss State, W&M, Chinese Collaboration (CIAE, Huangshan U, PKU, LZU, Tsinghua, USTC), UKY, Korean Collaboration (Seoul National U)
- Scintillator: Chinese Collaboration, Duke
- MRPC: Tsinghua Univ., Duke
- Electronics: JLab
- DAQ: LANL, UVa and Jlab
- Magnet: JLab and UMass
- Simulation: JLab and Duke

Combined effort with Parity-violating DIS Collaboration to build this device

Preparing for Director's Review in Fall 2012