Transverse Spin Effects in the Nucleon: Recent Results from Hall-A

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JLab Pizza Seminar Series, 14th Nov 2012

Jefferson Lab
Thomas Jefferson National Accelerator Facility

Nucleon Structure From Inclusive DIS

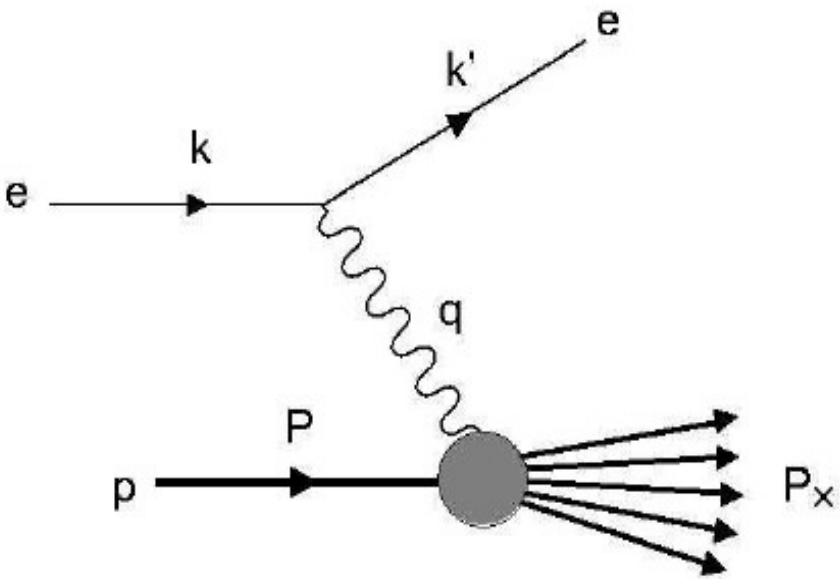
- Deep Inelastic Scattering (**DIS**) is an important tool to probe internal structure of the nucleon.
- Momentum transferred directly to the parton
- A complete understanding of both **quark momentum and spin structure** of the nucleon is required

$Q^2 = -q^2$: Negative squared of 4-momentum transfer

$x = Q^2/2M\nu$: Fraction of nucleon momentum carried by the struck quark (Bjorken scaling variable)

DIS: $Q^2 > 1.0$ GeV^2, W>2.0 GeV

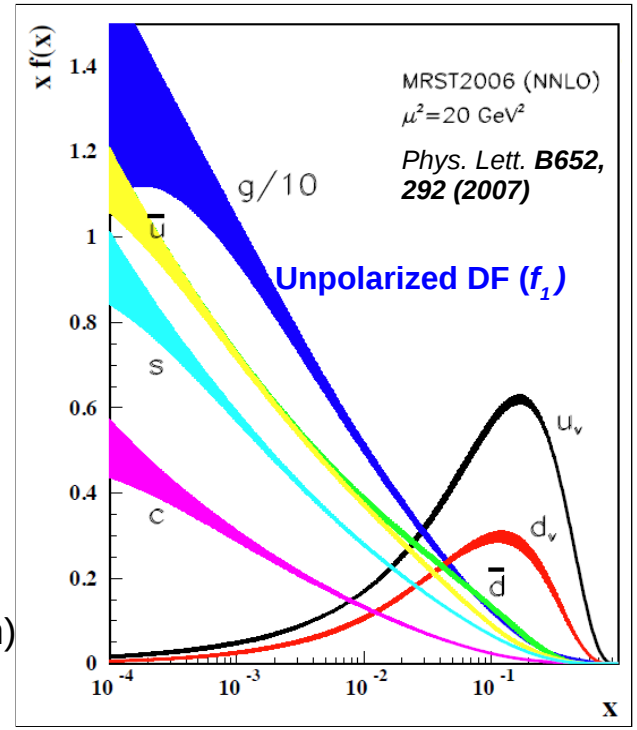
- In the leading twist, three parton distribution function (PDFs) describe the structure.

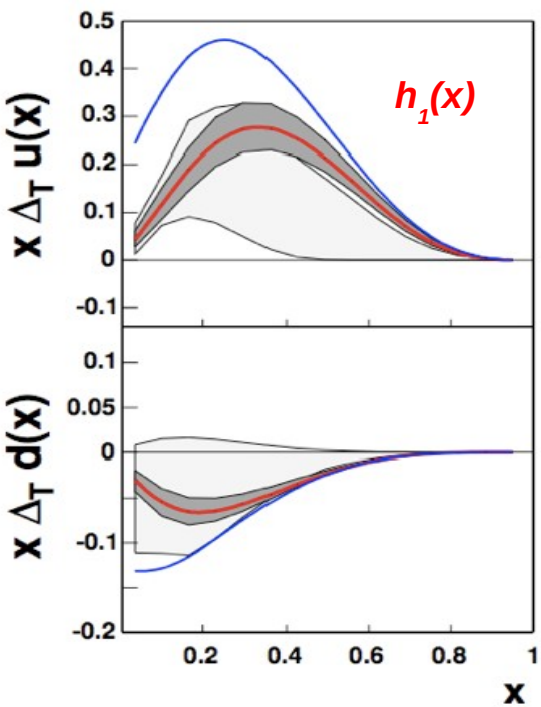


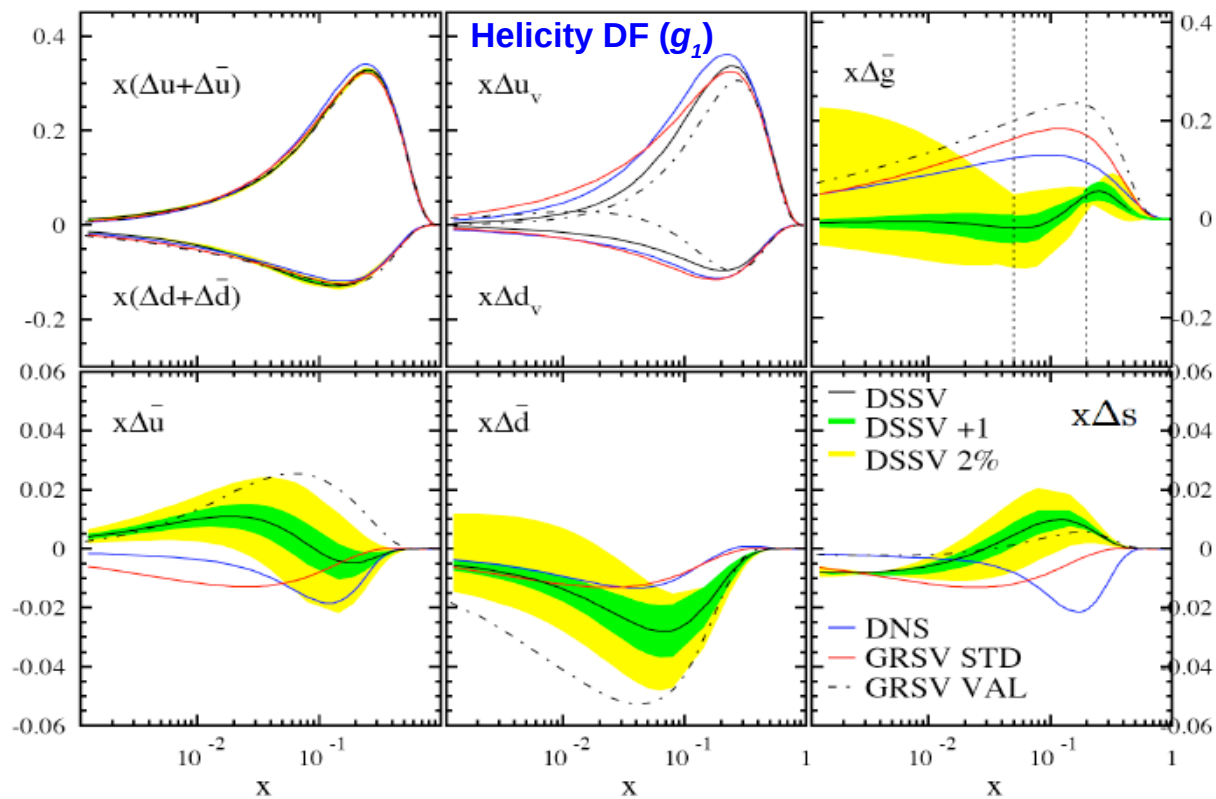
Inclusive DIS

Nucleon Spin Structure: Collinear PDFs

- Inclusive reactions probe both momentum and longitudinal spin structure
  - *eN -> e'X, pp -> hX*, etc ..
- Leading twist Parton Distribution Function
  - Momentum DF : $f_1(x)$ (very well known)
  - Helicity DF : $g_1(x)$ (well known)
  - Transversity DF: $h_1(x)$ (least known)
- First global extraction of transversity DF (Anselmino *et al., 2007*)
  - first moment of $h_1(x)$ = tensor charge (deformation of quark DF in the nucleon)
  - Lattice QCD calculations exist

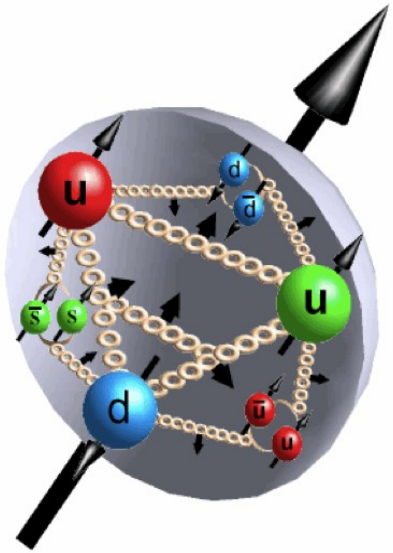




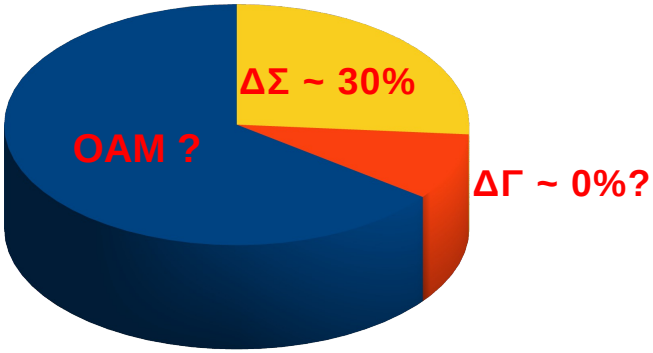


Nucleon Spin Structure: Non-collinear PDFs

- True picture of nucleon emerges in 3D!
- Transverse Momentum Dependent PDFs
  - Offers beyond collinear picture
  - Maps 3-d structure in momentum space
  - Links intrinsic parton motion, spin, and the nucleon spin
  - Provides access to OAM through spin-orbit correlations
  - Probes QCD dynamics - rich phenomena
- Contributions to nucleon spin:
  - Orbital angular momentum of quarks and gluons is important
- Semi-Inclusive DIS is an ideal tool to measure TMDs



Nucleon spin= ½



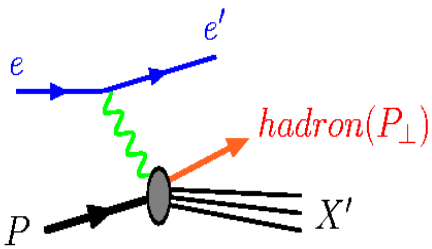
Unified Picture of the Nucleon

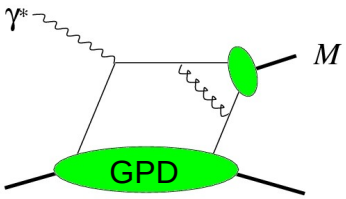
Wigner Distribution
W(x,r,p$_T$)

Probability to find a quark q in a nucleon P with a certain polarization at position **r** and with momentum **k**

$\int d^3 r$

$\int d^2 p_T$





Transverse Momentum Dependent PDF ***f(x,p$_T$)***

Generalized Parton Distributions
H(x,ξ,t)

$\int d^2 p_T$

$\int dx$

Ultimate goal:
To understand full phase-phase distribution of partons inside nucleon

PDF
f(x), g1(x) ...

Form Factors
GE, GM, ...

No simultaneous knowledge of position and momentum! $\Delta x \Delta p \geq \hbar/2$

This talk will focus on TMDs

SPIN EFFECTS IN THE INCLUSIVE REACTIONS $\pi^{\pm} + p(\uparrow) \rightarrow \pi^{\pm}$ + ANYTHING AT 8 GeV/c

L. DICK, A. GONIDEC, A. GSPONER and M. WERLEN
CERN, Geneva, Switzerland

C. CAVERZASIO, K. KURODA, A. MICHALOWICZ and M. POULET
IPN, Orsay, France

and

D. ASCHMAN, K. GREEN, P. PHIZACKLEA and G.L. SALMON
Oxford University, Oxford, England

The asymmetry in inclusive reactions of the type a + p(↑) → a + anything at 8 GeV/c (a = π^+, π^-, or p) have been measured at the CERN Proton Synchrotron using a polarized proton target. In the πp reactions and over a limited range of p_T ($0.17 \leq p_T \leq 0.36$) GeV/c the results indicate i) an asymmetry for $x = p^*_{\parallel}/p^*_{max} > 0.7$ which is mirror symmetric for the π^+ and π^- reactions; ii) an asymmetry compatible with zero for $0.3 < x < 0.7$.

Phys. Lett. B 57, 93 (1975)

Volume 57B, number 1 PHYSICS LETTERS 9 June 1975

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Single Spin Asymmetry

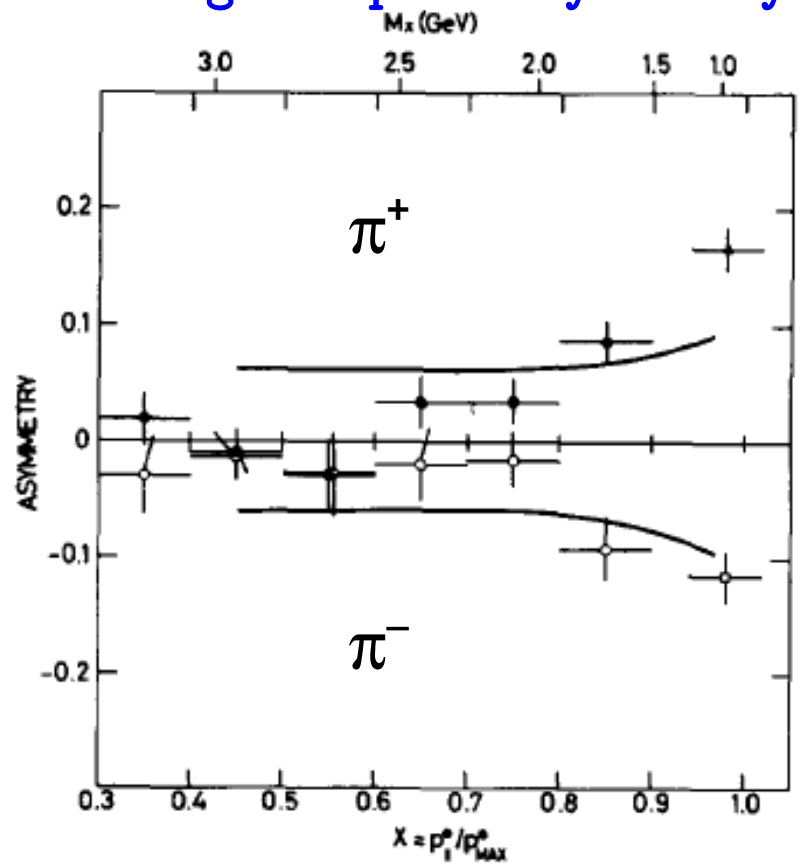


Fig. 3. Asymmetry data from this experiment. (●): $\pi^+ p \rightarrow \pi^+$; (○): $\pi^- p \rightarrow \pi^-$; (▲) and (□) "elastic points" in π^+, π^-.

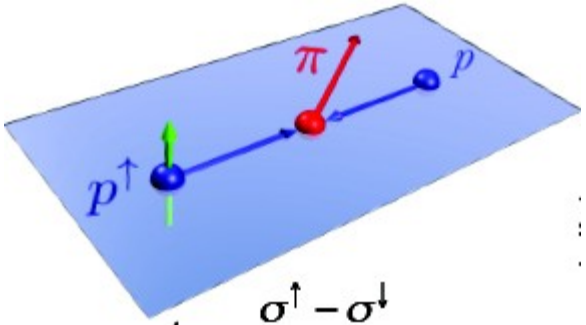
Earliest SSA data on transversely polarized nucleon that I could find!

E704 √s =20 GeV.

PLB 264 (1991) 462.

Analyzing power in inclusive π^+ and π^- production at high x_F with a 200 GeV polarized proton beam

FNAL E704 Collaboration



$$A_N = \frac{\sigma^\uparrow - \sigma^\downarrow}{\sigma^\uparrow + \sigma^\downarrow}$$

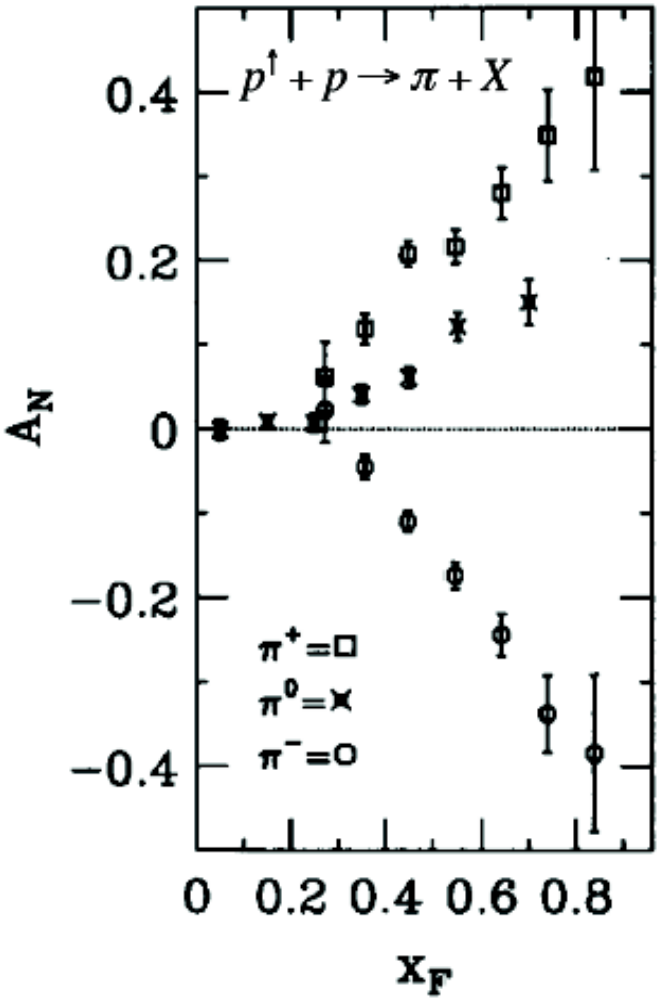
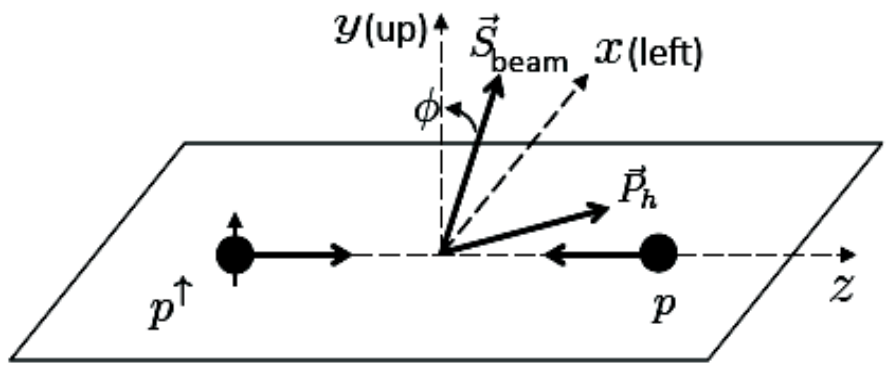


Fig. 4. A_N versus x_F for π^+, π^- and π^0 data.

$$A_N = -\frac{1}{P_B \cos\phi}\frac{N_\uparrow(\phi) - N_\downarrow(\phi)}{N_\uparrow(\phi) + N_\downarrow(\phi)},$$

ϕ is the azimuthal angle between the beam polarization direction and the normal to the $\pi^\pm$ production plane. $N_{\uparrow(\downarrow)}$ is the number of pions produced for beam spin tagged as positive (negative) normalized to the beam flux. P_B is the average beam polarization. The negative sign in front of the equation is due to the fact that the detection occurred to the right of the beam.



π^+ favors the left side of the polarized proton.

π^- favors the right side of the polarized proton.

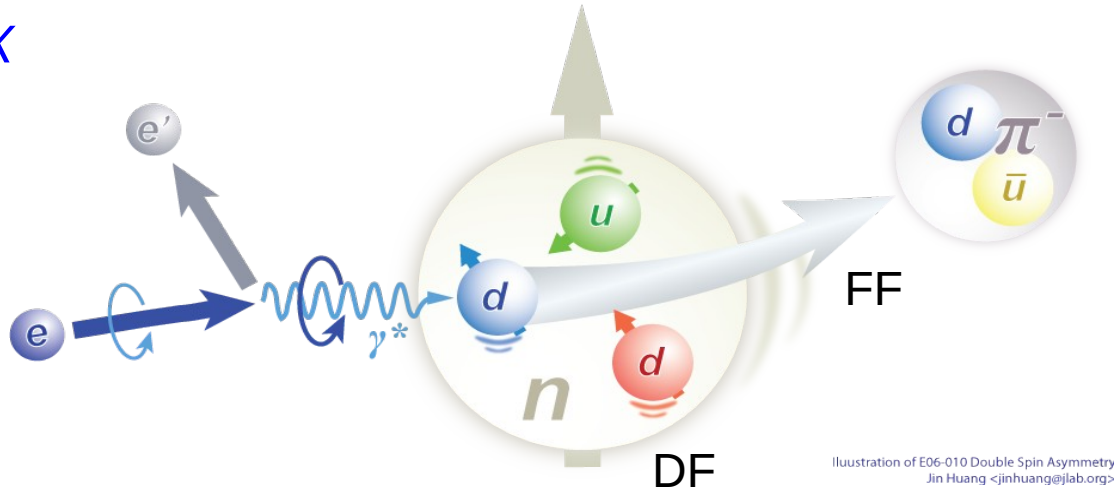
(slide from Xiaodong Jiang, LANL)

Semi-Inclusive DIS

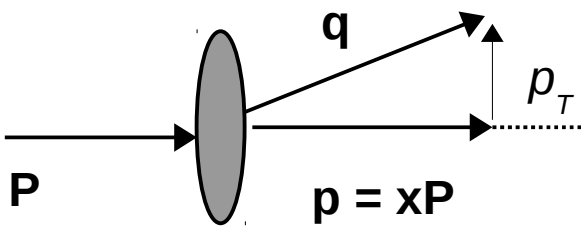
$e + N \longrightarrow e' + h + X$

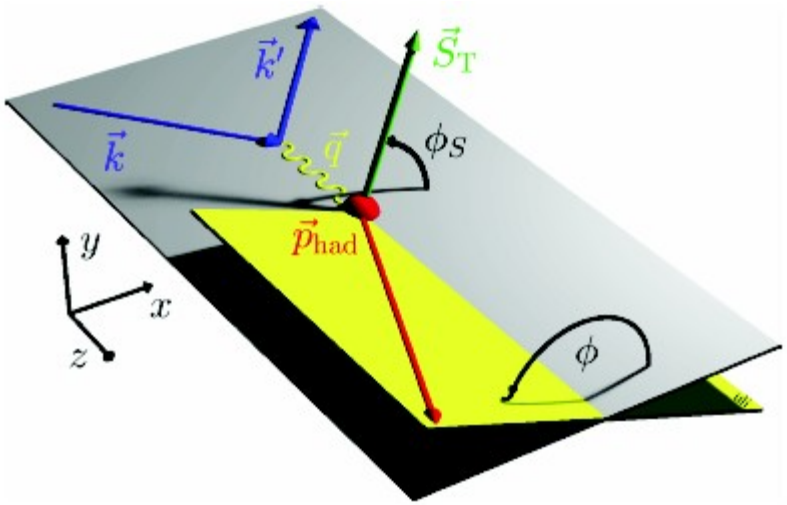
$$d\sigma \propto \sum_f e_f^2 \, DF \otimes FF$$

QCD factorization



- Ideal tool to study TMDs
- Flavor tagging via fragmentation function
- P_T of detected hadron gives access to transverse motion of in struck quark





P_T: transverse momentum of detected hadron

SIDIS cross section

18 structure functions

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

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

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&+ \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] \\
&+ 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] \\
&+ 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)} \\
&+ \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} \\
&+ \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)} \\
&+ \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

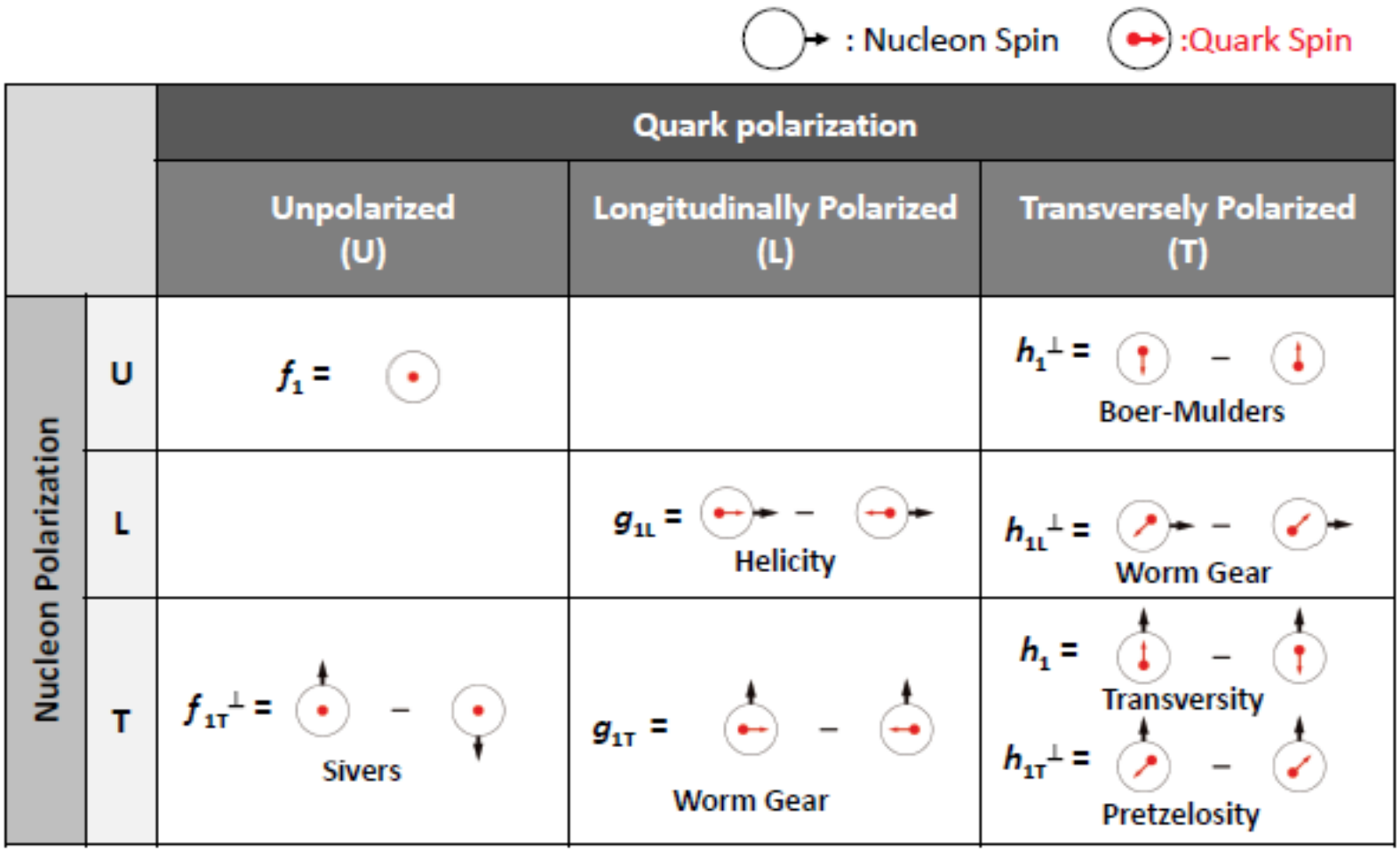
Sivers

Pretzelosity

Worm-gear

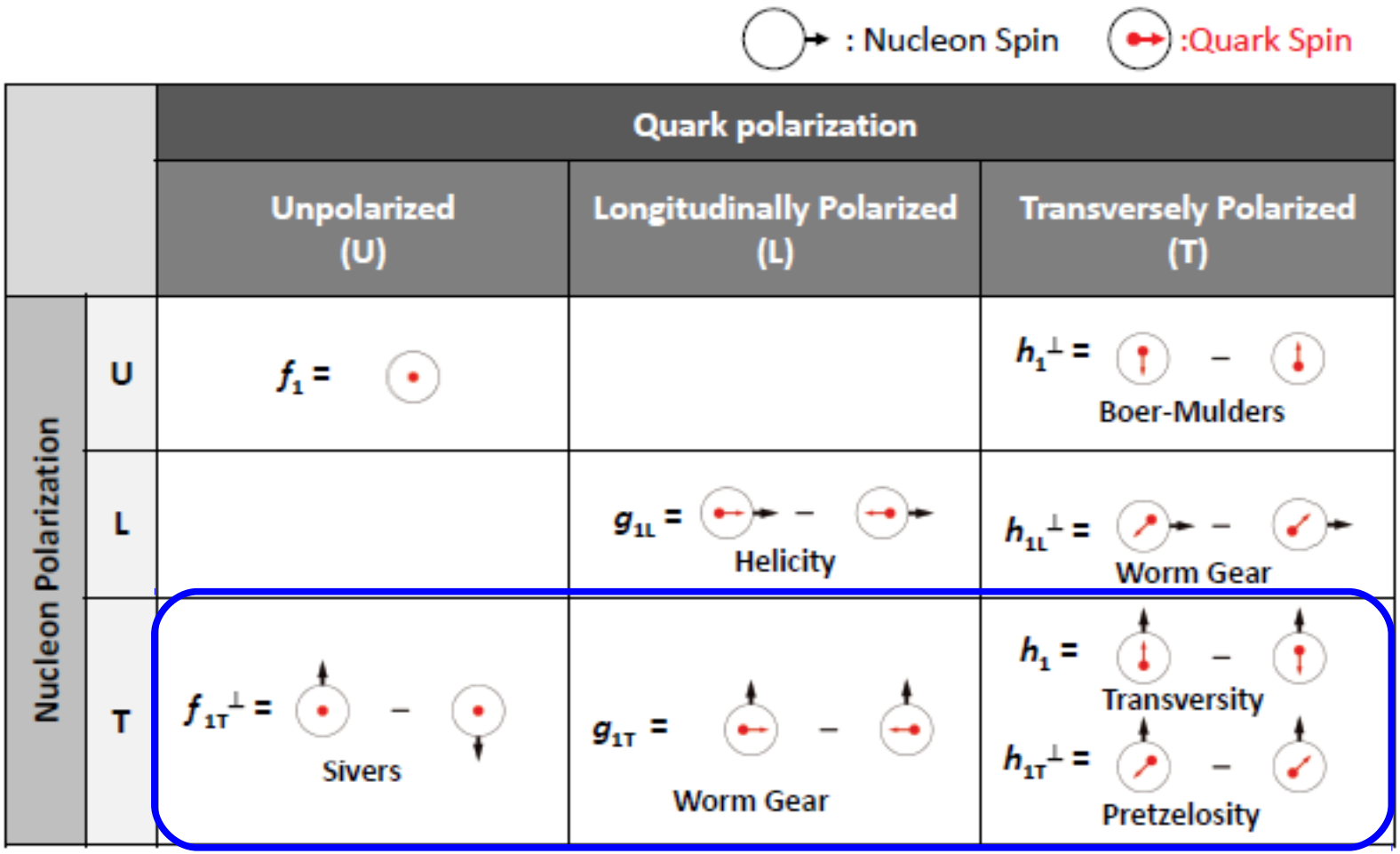
A. Bacchetta *et al.*, arXive:hep-ph/0611265

Leading Twist Transverse Momentum Dependent PDFs



- f_1, g_{1L} and h_1 collinear PDFs
- Rest are non-collinear (p_T dependent) PDFs

Leading Twist Transverse Momentum Dependent PDFs



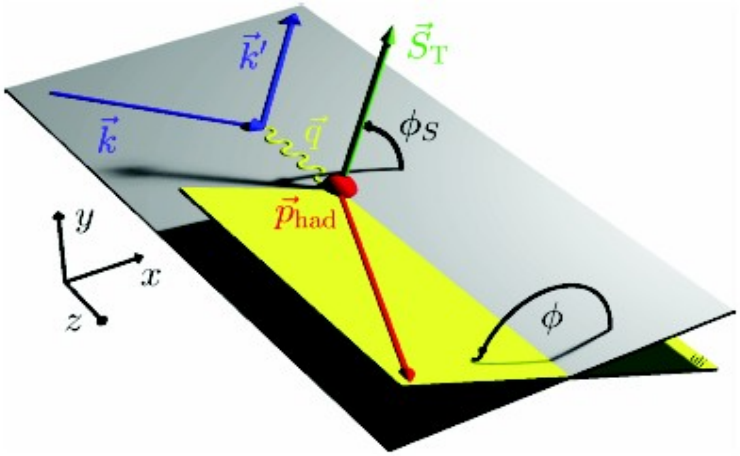
- f_1, g_{1L} and h_1 collinear PDFs
- Rest are non-collinear (p_T dependent) PDFs

Separation of Azimuthal Moments From SSA

$$A_{UT}(\varphi_h^l, \varphi_S^l) = \frac{1}{P}\frac{N^\uparrow - N^\downarrow}{N^\uparrow + N^\downarrow}$$

$$= A_{UT}^{Collins}\sin(\phi_h + \phi_S) + A_{UT}^{Sivers}\sin(\phi_h - \phi_S)$$

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



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

Collins frag. Func. from e^+e^- collisions

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

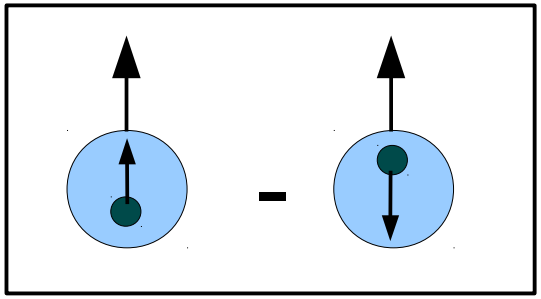
$$A_{UT}^{Pretzelosity} \propto \langle \sin(3\phi_h - \phi_S) \rangle_{UT} \propto h_{1T}^\perp \otimes H_1^\perp$$

SIDIS SSAs depend on 4-D variables (x, Q^2, z and P_T)

Large angular coverage and precision measurement of asymmetries in 4-D phase space is essential.

Transversity

- h1(x) is chiral-odd, need another chiral-odd object to observe
- Highly suppressed in inclusive DIS by $(\frac{m_q}{\sqrt{Q^2}})$
- Valence like behavior, do no mix with gluons
- Two Examples where is can be measured:



1. Drell-Yan : $\sigma^{p^\uparrow p^\uparrow \to l\bar{l}X} \propto \sum_q h_1^q \otimes \sigma^{q\bar{q}\to l\bar{l}} \otimes h_1^{\bar{q}}$

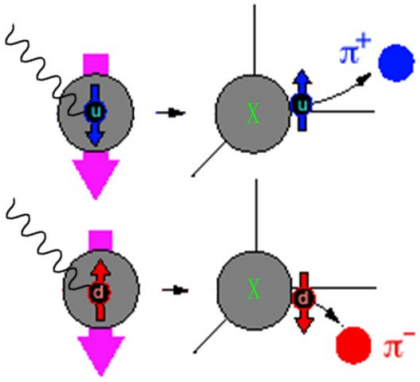
transversity

2. **Semi-Inclusive DIS** : $\sigma^{ep^\uparrow \to ehX} \propto \sum_q h_1^q \otimes \sigma^{eq\to eq} \otimes FF^{q\to h}$

Chiral-odd "Collins" fragmentation function

Collins Mechanism :

- Describes the fragmentation process
- Correlates quark's transverse spin and outgoing hadron's transverse momentum $\mathbf{S_q \cdot (k_q \times P_{h\perp})}$
- Produces left-right asymmetry in the direction of outgoing hadron



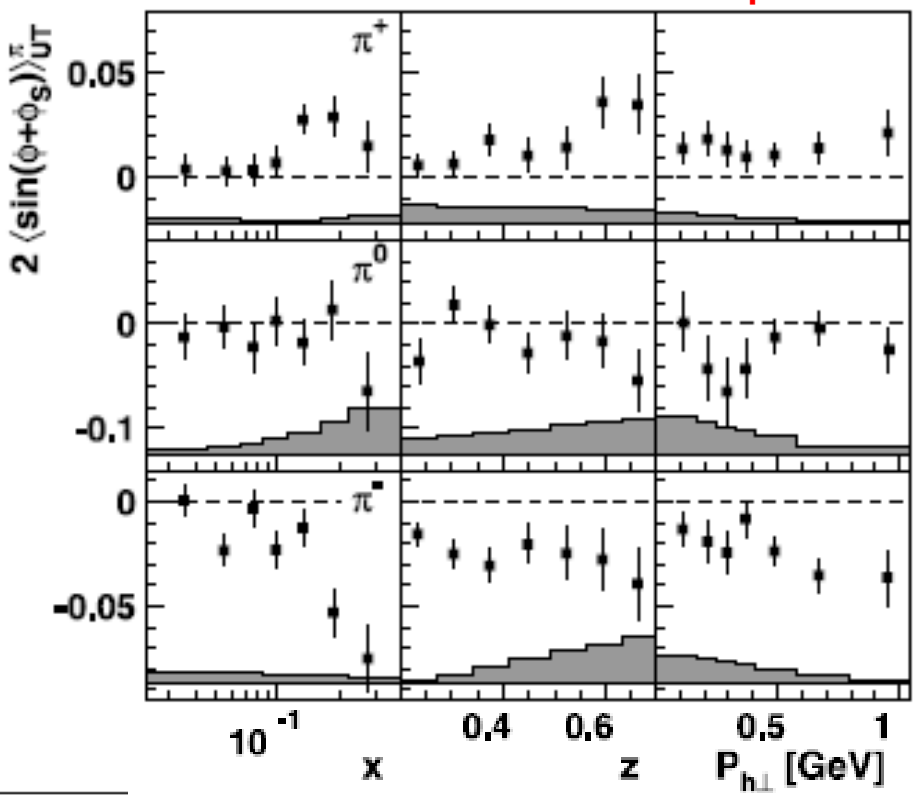
Collins Moments

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

$$A_{UT}^{Collins} = \frac{(1-y)}{(1-y+y^2/2)} \frac{\sum_q e_q^2 h_1^q(x) H_1^{\perp(1)q}(z)}{\sum_q e_q^2 f_1^q(x) D_1^q(z)}$$

- Non-zero amplitude for π^+ and π^-
- Opposite sign for $\pi^+ (u\bar{d})$ and $\pi^- (d\bar{u})$

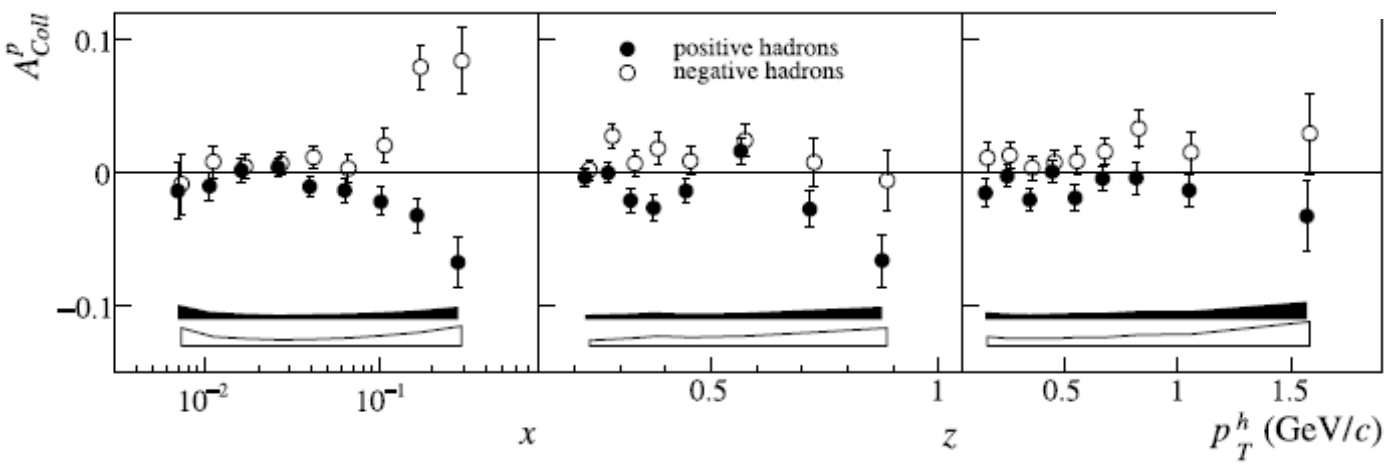
HERMES proton



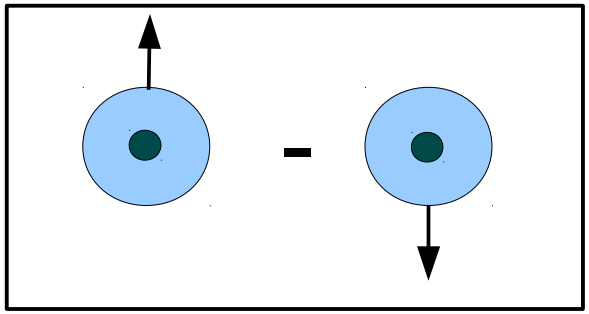
Phy. Lett. B 693 (2010) 11

COMPASS proton

Phy. Lett. B 692 (2010) 240

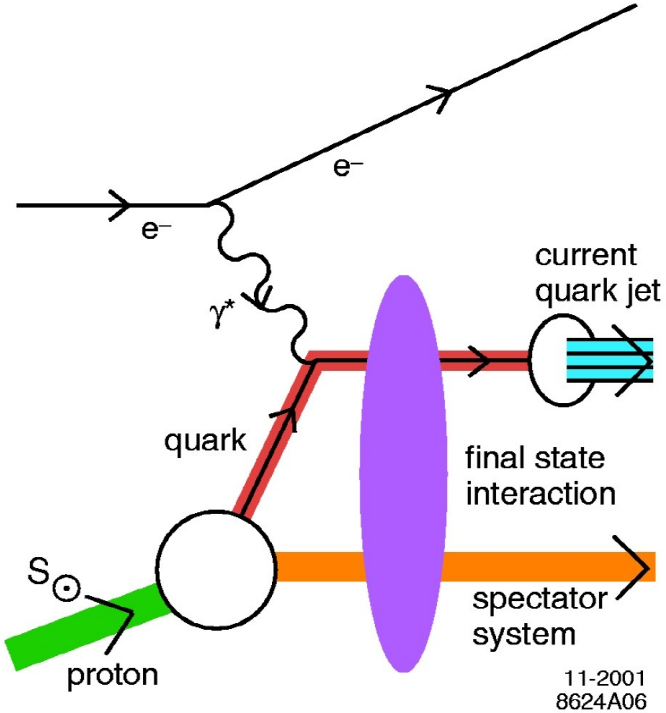


Sivers Distribution Function



$$\sigma^{ep^{\uparrow}\to ehX} \propto \sum_q f_{1T}^{\perp q} \otimes D_1^q$$

- Probability to find unpolarized quark with transverse momentum k_T in a tranversely polarized nucleon.
- Correlates transverse spin of nucleon with transverse momentum of unpolarized quark : $\mathbf{S_N \cdot (P \times k_T)}$
- Sensitive to angular momentum of quarks L_q
- Produces **left-right azimuthal asymmetry**
- Asymmetry caused by the attractive FSI (Brodsky, Hwang, Schmidt)
- Non-universal: f_{1T} (SIDIS) = - f_{1T}(DY)



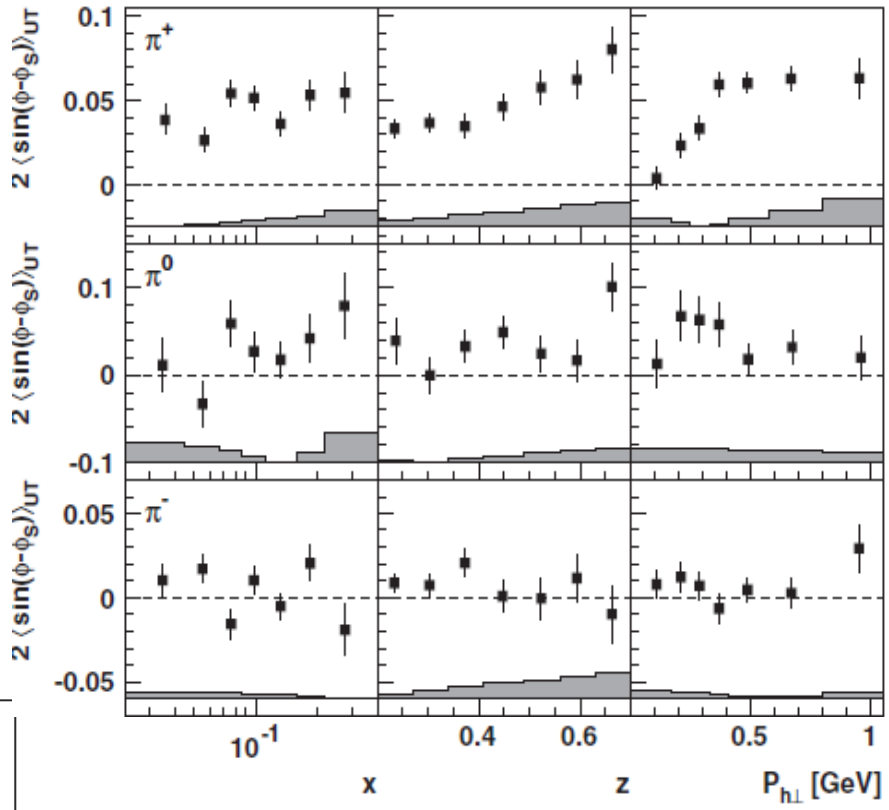
Sivers Moments

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

$$A_{UT}^{Sivers} = \frac{\sum_q e_q^2 f_{1T}^{\perp(1)q}(x) D_1^q(z)}{\sum_q e_q^2 f_1^q(x) D_1^q(z)}$$

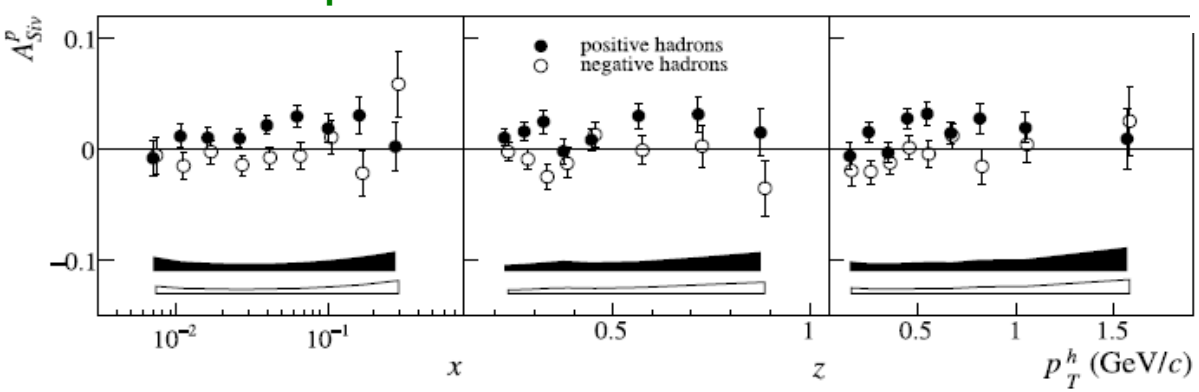
- Clear non-zero amplitude for π^+, but small for π^-

HERMES proton



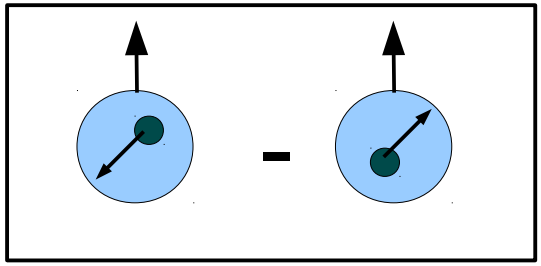
PRL 103, 152002 (2009)

COMPASS proton



Phy. Lett. B 692 (2010) 240

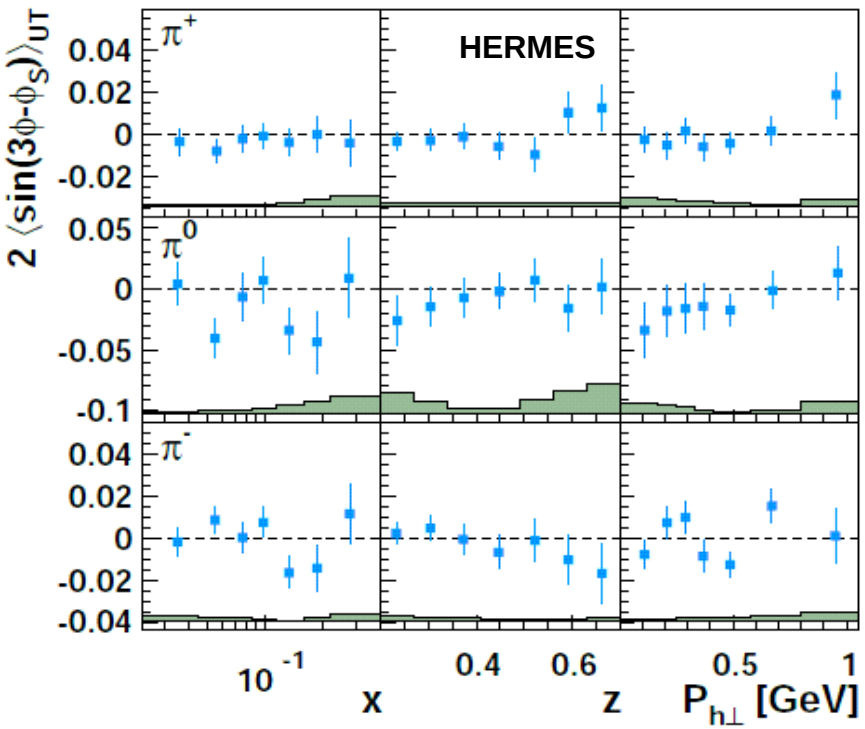
Pretzelosity



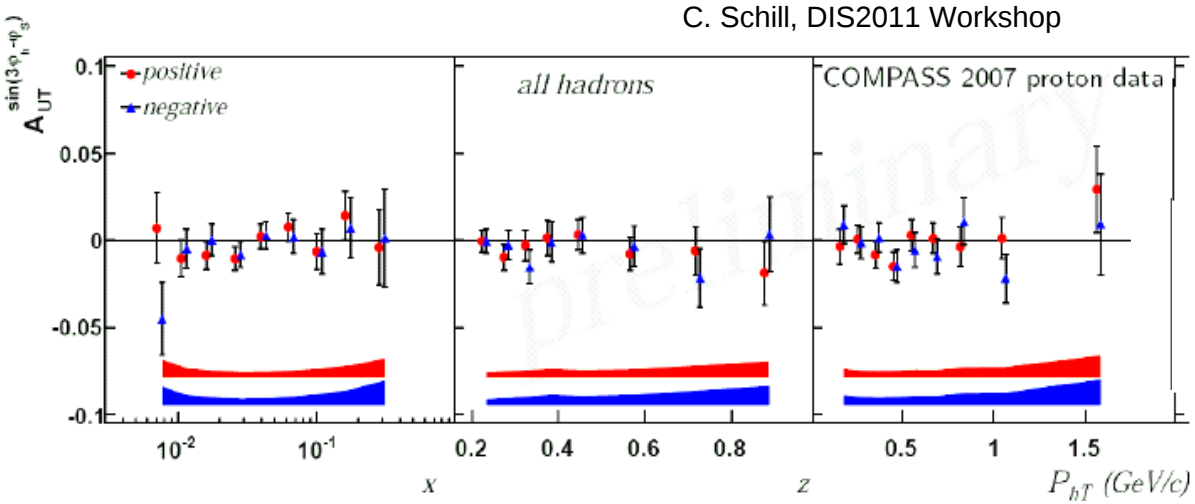
$$\sigma_{UT}^{SIDIS} \propto \sin(3\phi_h - \phi_S)\, h_{1T}^{\perp} \otimes H_1^{\perp}$$

- Correlation between transverse momentum and transverse polarization of the nucleon
- Direct probe of relativistic effects
- Access to quark OAM (model dependent)
- No clear signal seen yet, need high precision data

M. Diefenthaler's Dissertation (HERMES)

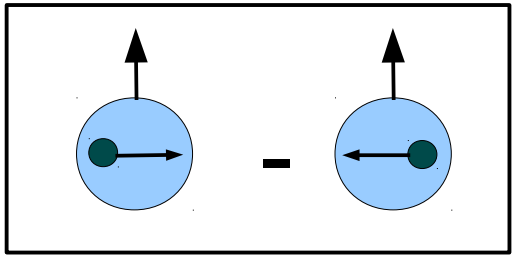


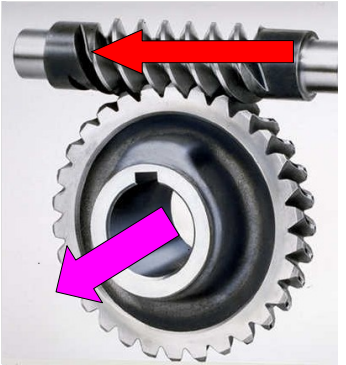
C. Schill, DIS2011 Workshop



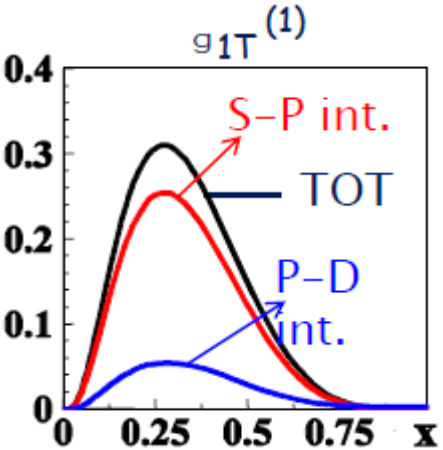
Worm-Gear Function

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



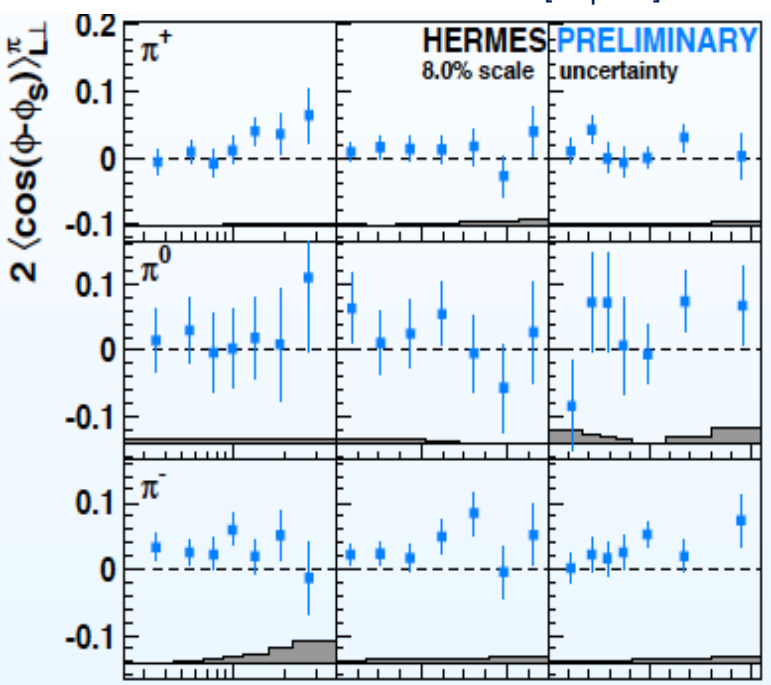


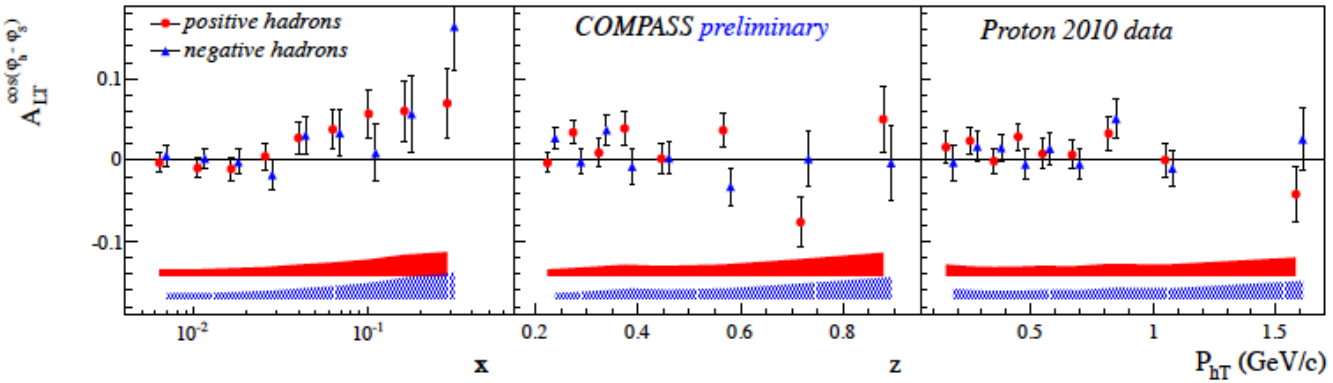
- Beam-target Double Spin Asymmetry (DSA) to measure A_{LT}
- Dominated by real part of interference between s and p wave
  - g_{1T} ~ Re[(L=0) x (L=1)]
    spin-orbit correlation
- Experimentally not very well explored



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

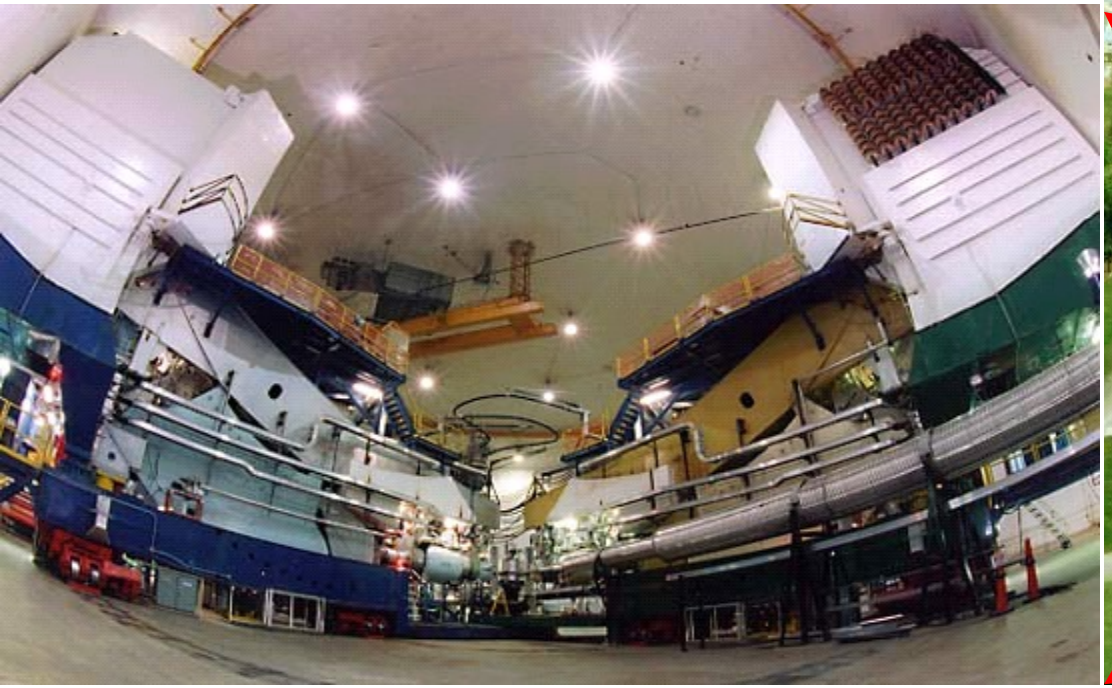
arXiv:1107.4227 [hep-ex]

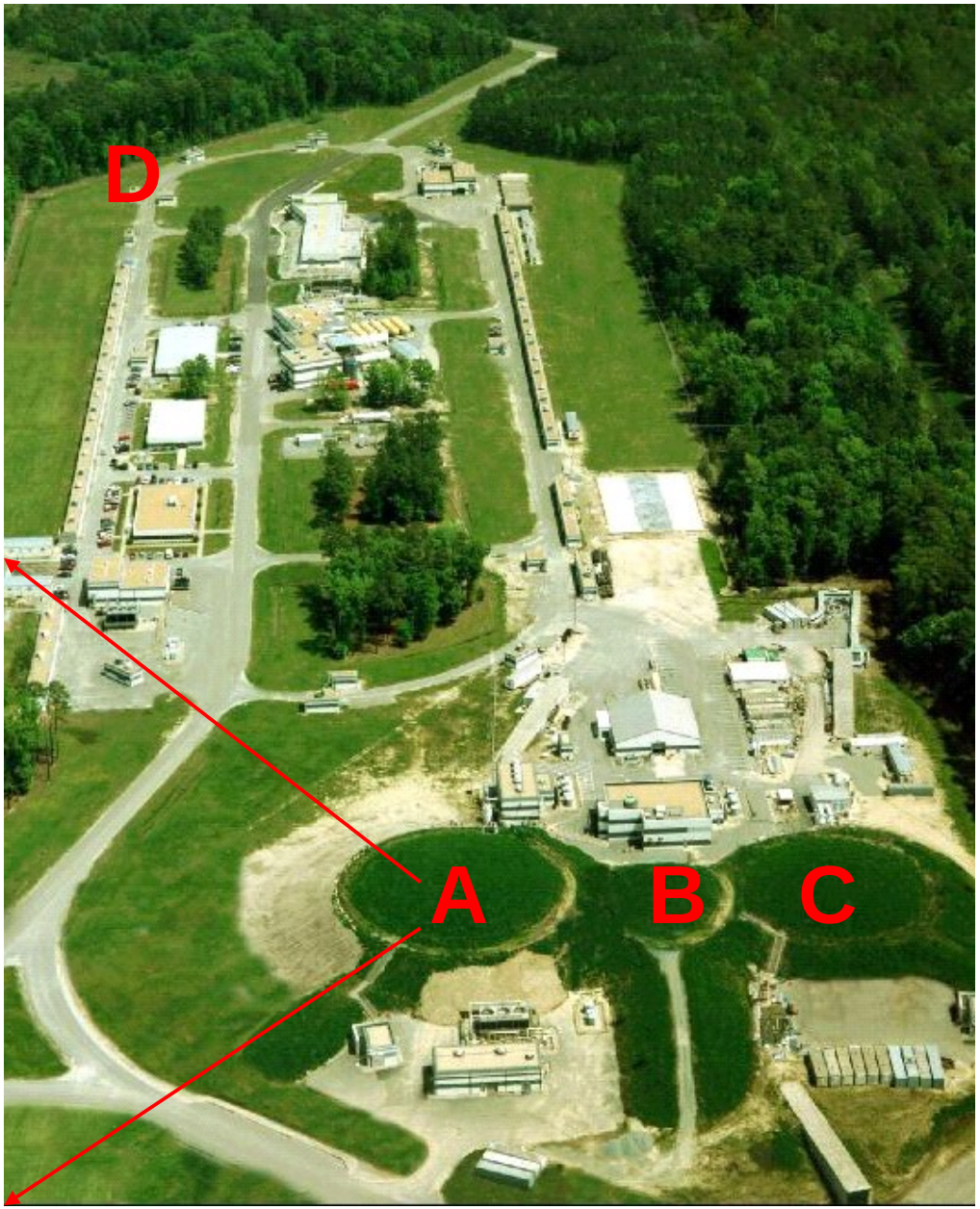




Hall-A Transversity Experiment at Jefferson Lab

- Run period: Oct. 2008 – Feb. 2009
- 6 GeV electron beam
- Beam Polarization : ~85 %



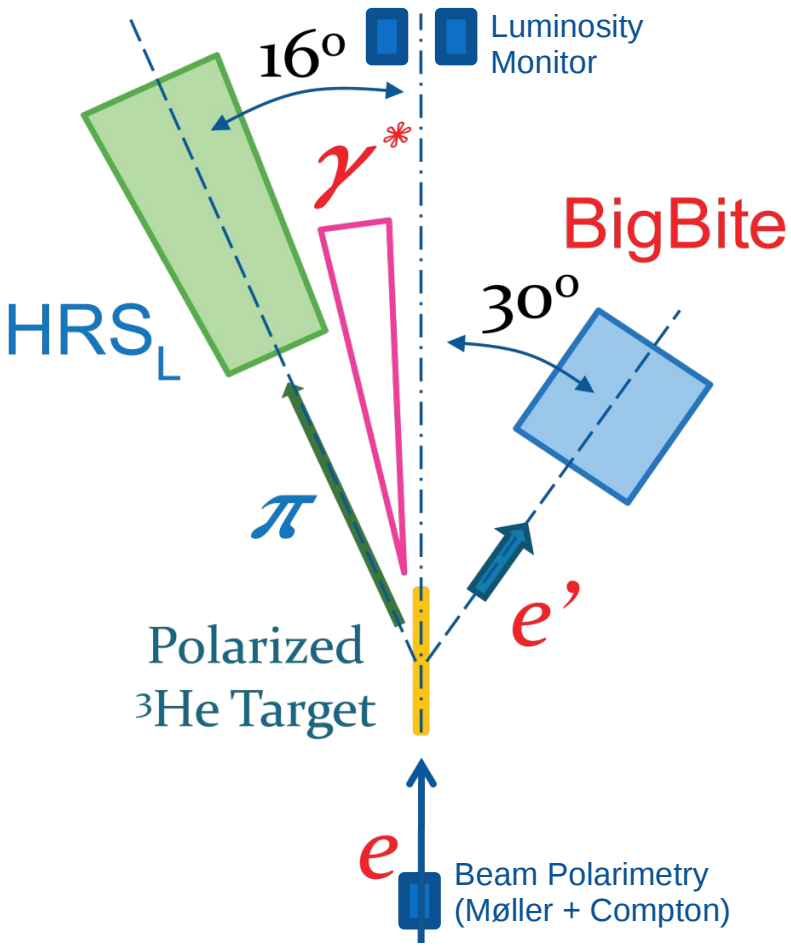


Experimental Setup

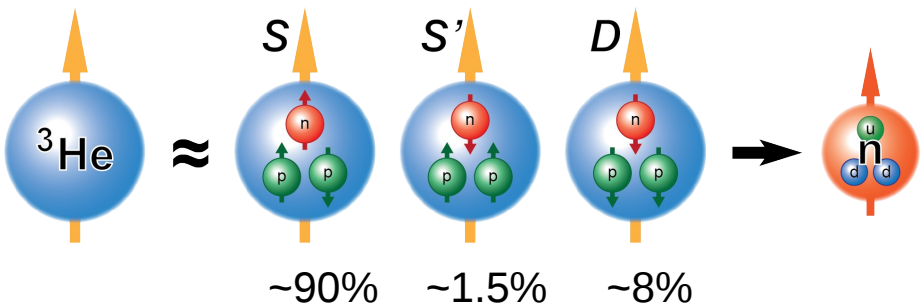
$$^{3}He^{\uparrow}\ (e,\ e'\ h\ )X$$

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

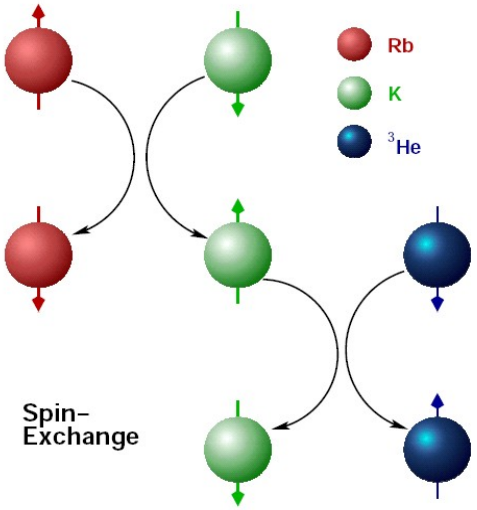
- Polarized ^{3}He target (P_{target}~ 64%)
- Beam energy : 5.9 GeV
- BigBite at 30^{0} as Electron Arm
  - ***p_e* = 0.8 – 2.2 GeV/c**
- HRSL at 16^{0} as Hadron Arm
  - ***p_h* = 2.35 GeV/c**
- Beam helicity flip at 30 Hz
- Target spin orientations: up-down and left-right (increase angular coverage)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

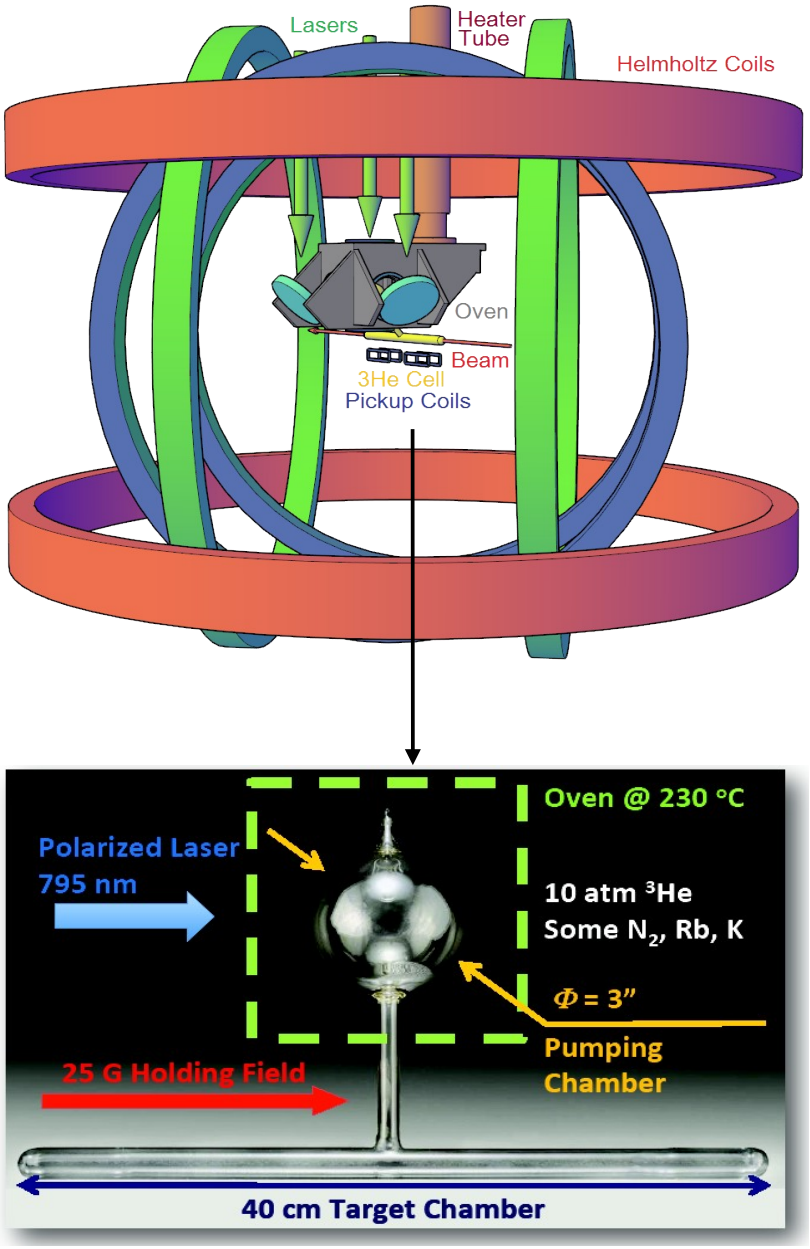


Polarized ^{3}He Target

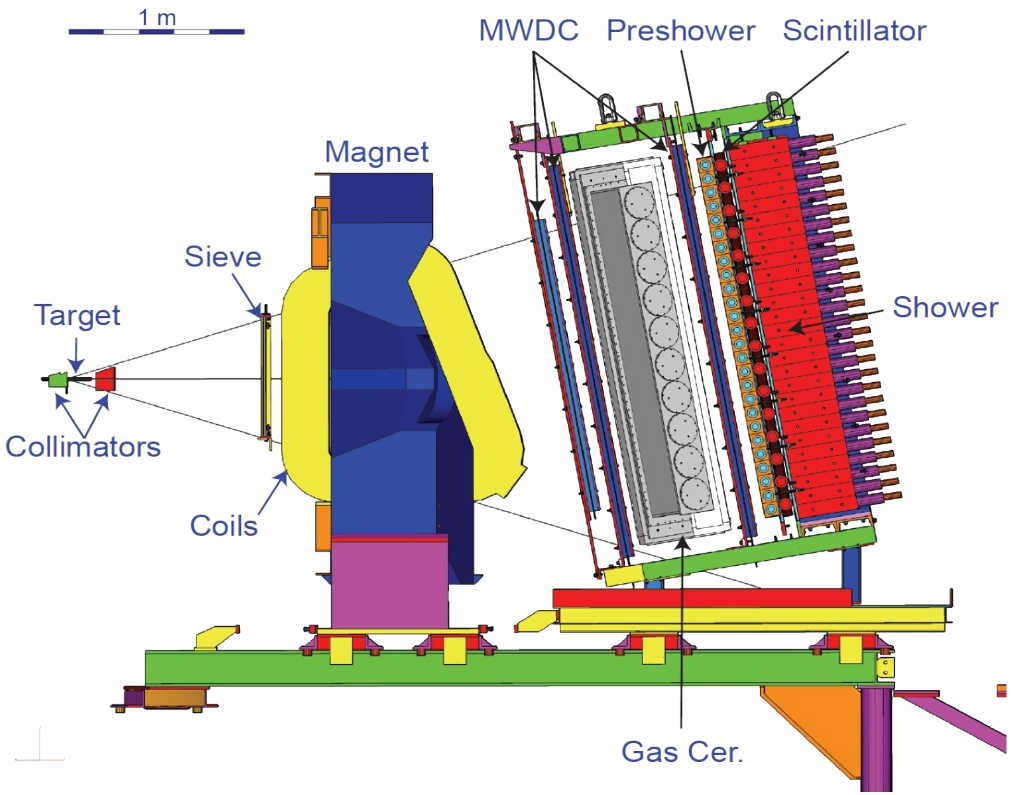


- High Luminosity polarized target (10^{36}/cm^2-s)
- Fast spin-exchange with Rb-K hybrid cells
- Average polarization : ~64%
- Automatic spin-flip every 20 mins



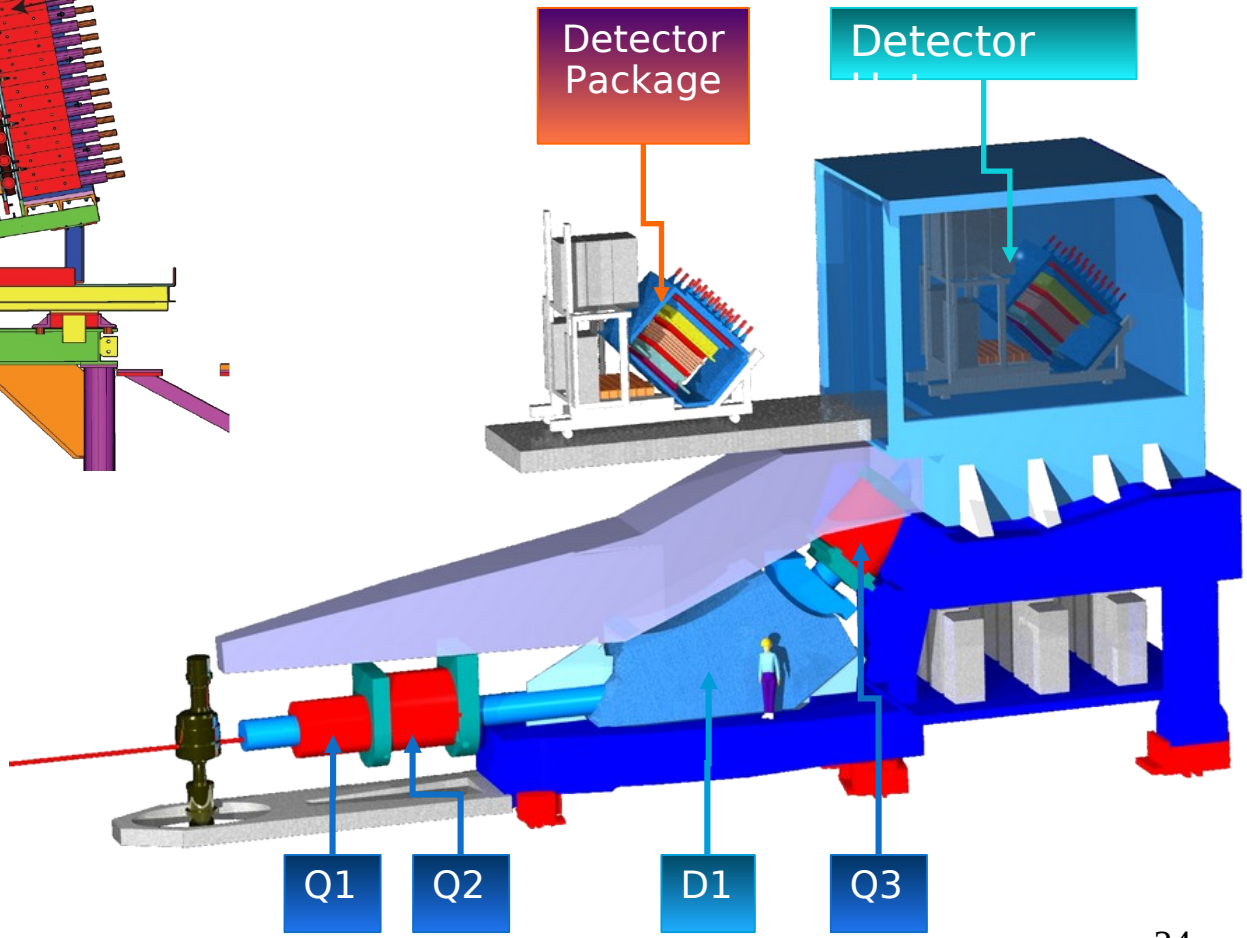


Spectrometers



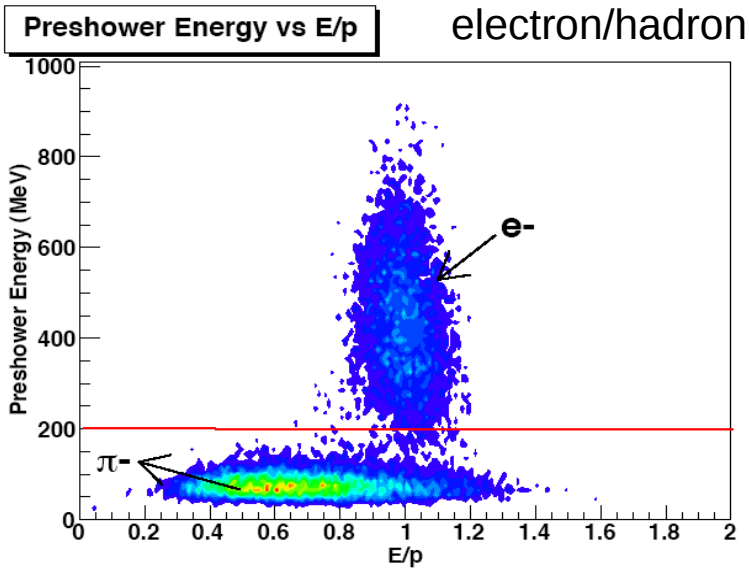
BigBite spectrometer (electon arm)

High Resolution Spectrometer (hadron arm)

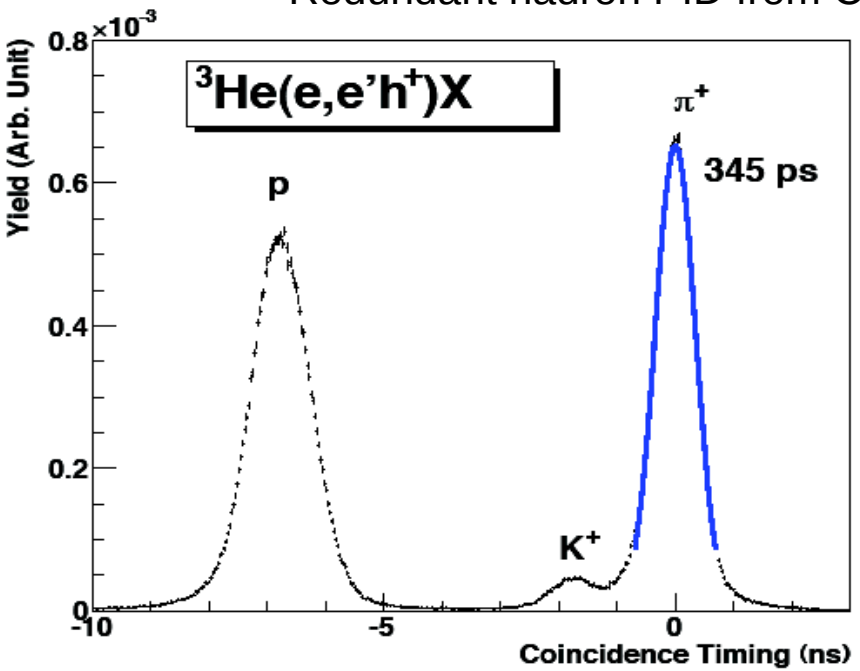


Data Analysis

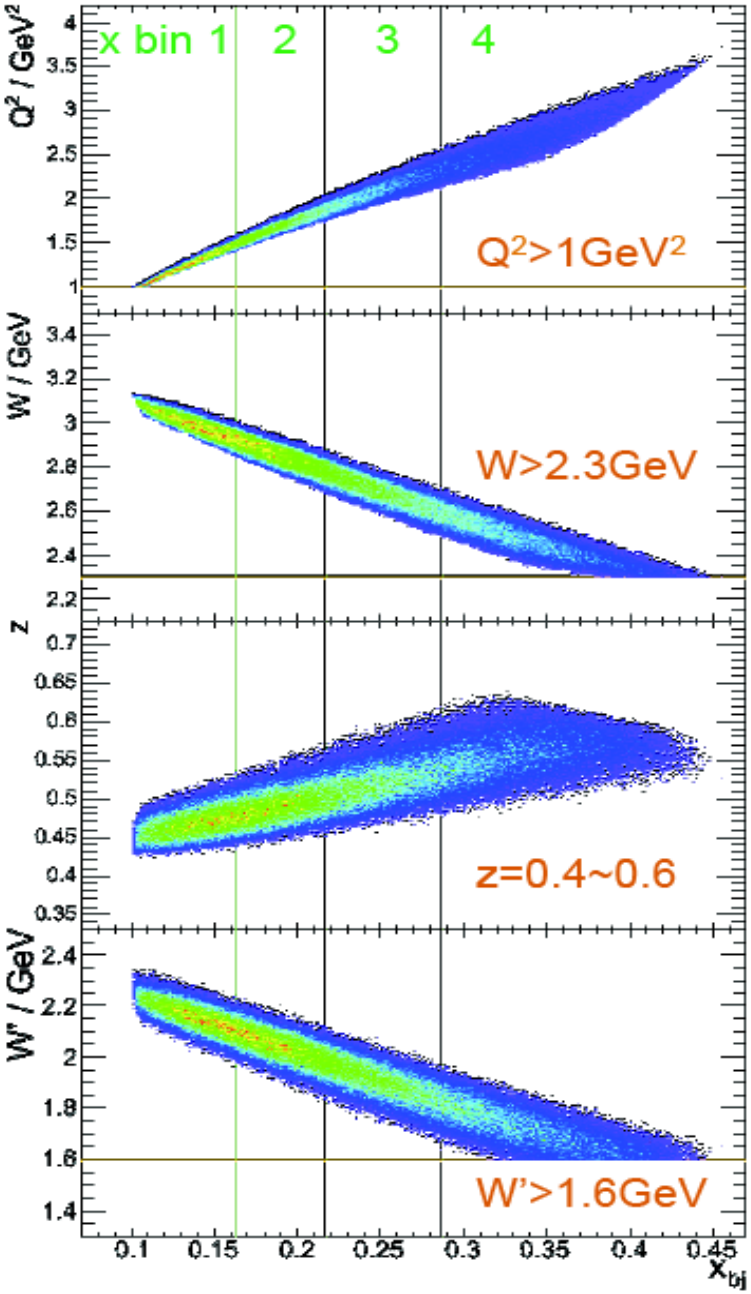
electron/hadron PID from BigBite



Redundant hadron PID from CToF



Kinematics Coverage



<Q^2>=2.0 GeV^2 <W>=2.8 GeV.
(HERMES: <Q^2>=2.4 GeV^2).

Access to Transverse SSA moments in SIDIS

Separate different effects through azimuthal angular dependence

- **Collins asymmetry:**

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

- **Sivers asymmetry:**

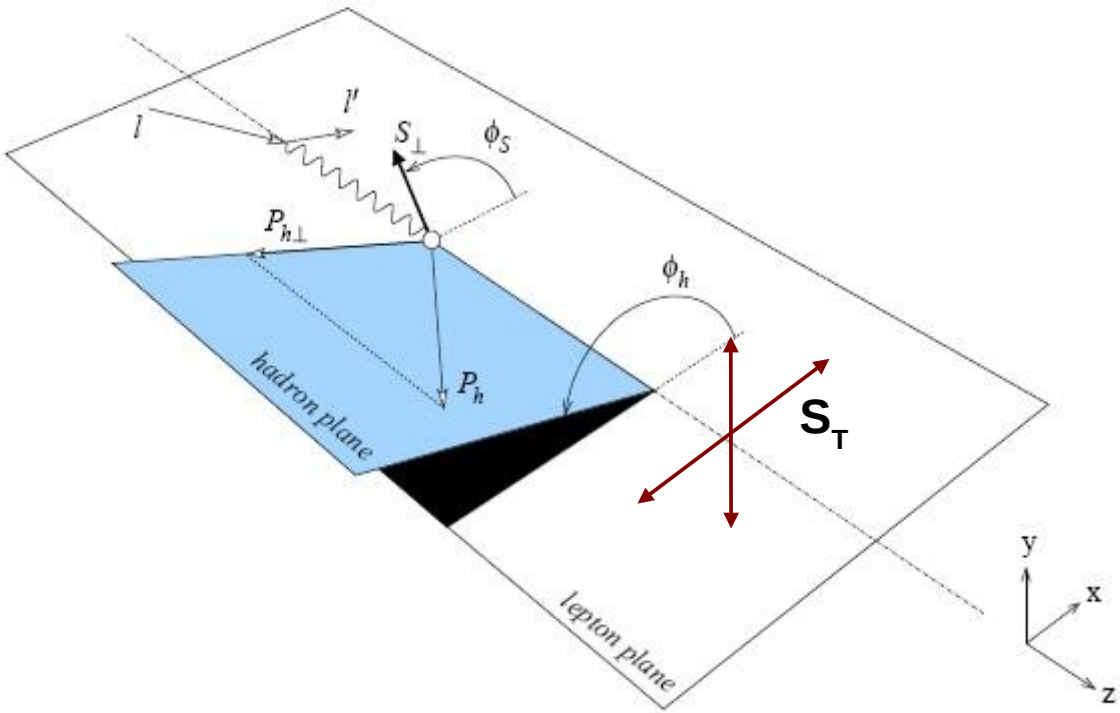
$$\sigma_{UT}^{SIDIS} \propto \sin(\phi_h - \phi_S)\ f_{1T}^{\perp} \otimes D_1$$

- **"Pretzelosity":**

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

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

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



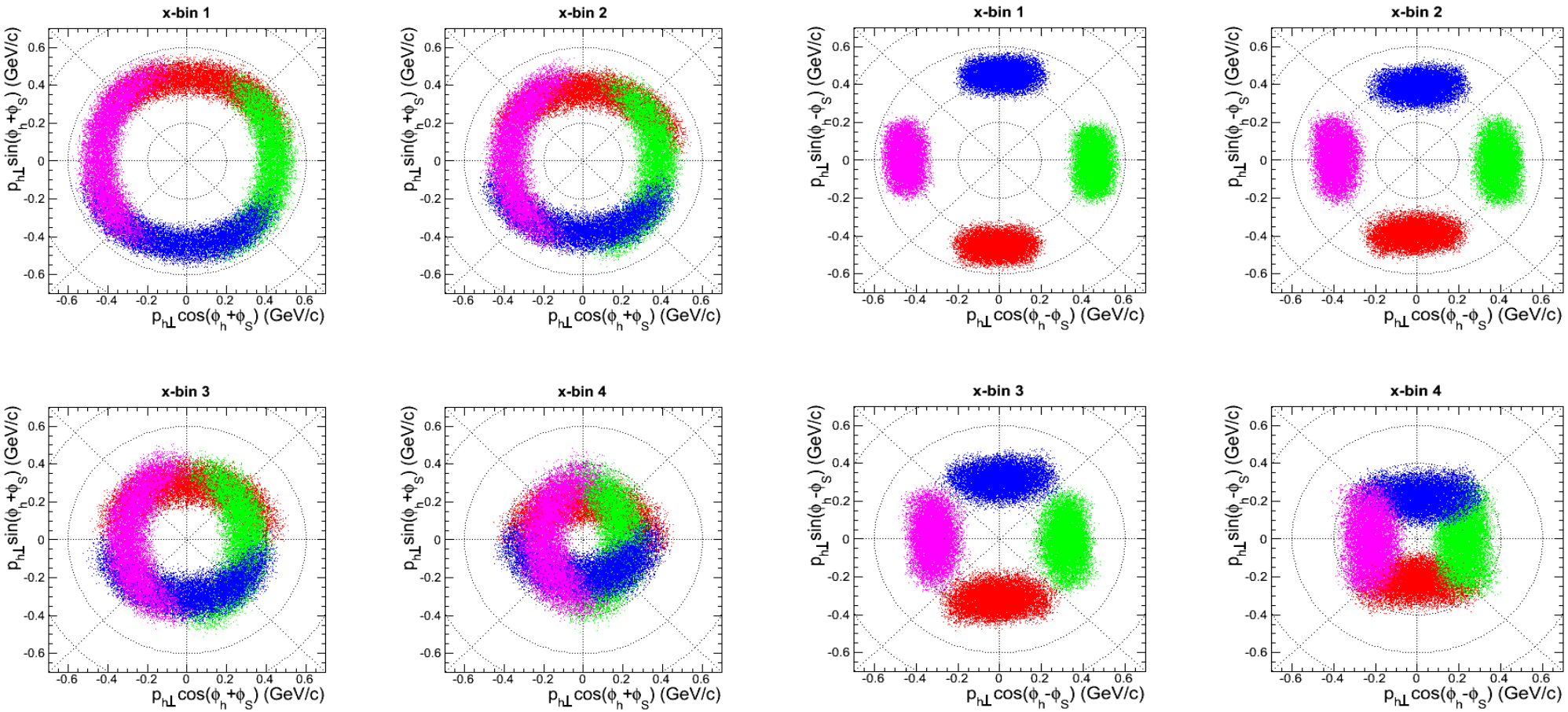
- Target spin orientations: up-down and left-right
(increase angular coverage)
- Automatic target spin-flip every 20 mins
(keeps systematics due to target under control)

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

Azimuthal Angular Coverage

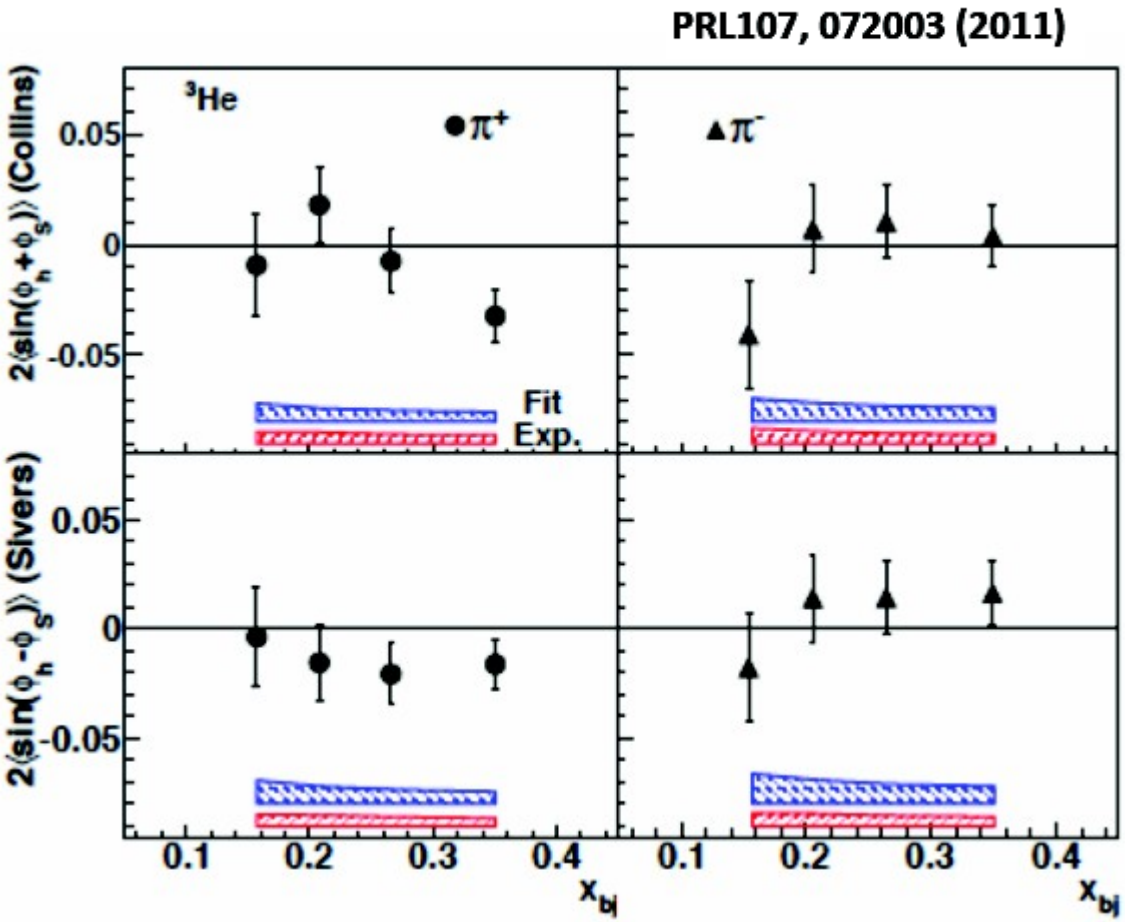
Collins angle: $\phi_h + \phi_s$

Sivers angle: $\phi_h - \phi_s$



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

E06-010: ^{3}He Target SSA Results



$$^3He^{\uparrow} = 0.865 \cdot n^{\uparrow} - 2 \times 0.028 \cdot p^{\uparrow}$$

^{3}He Collins asymmetry:

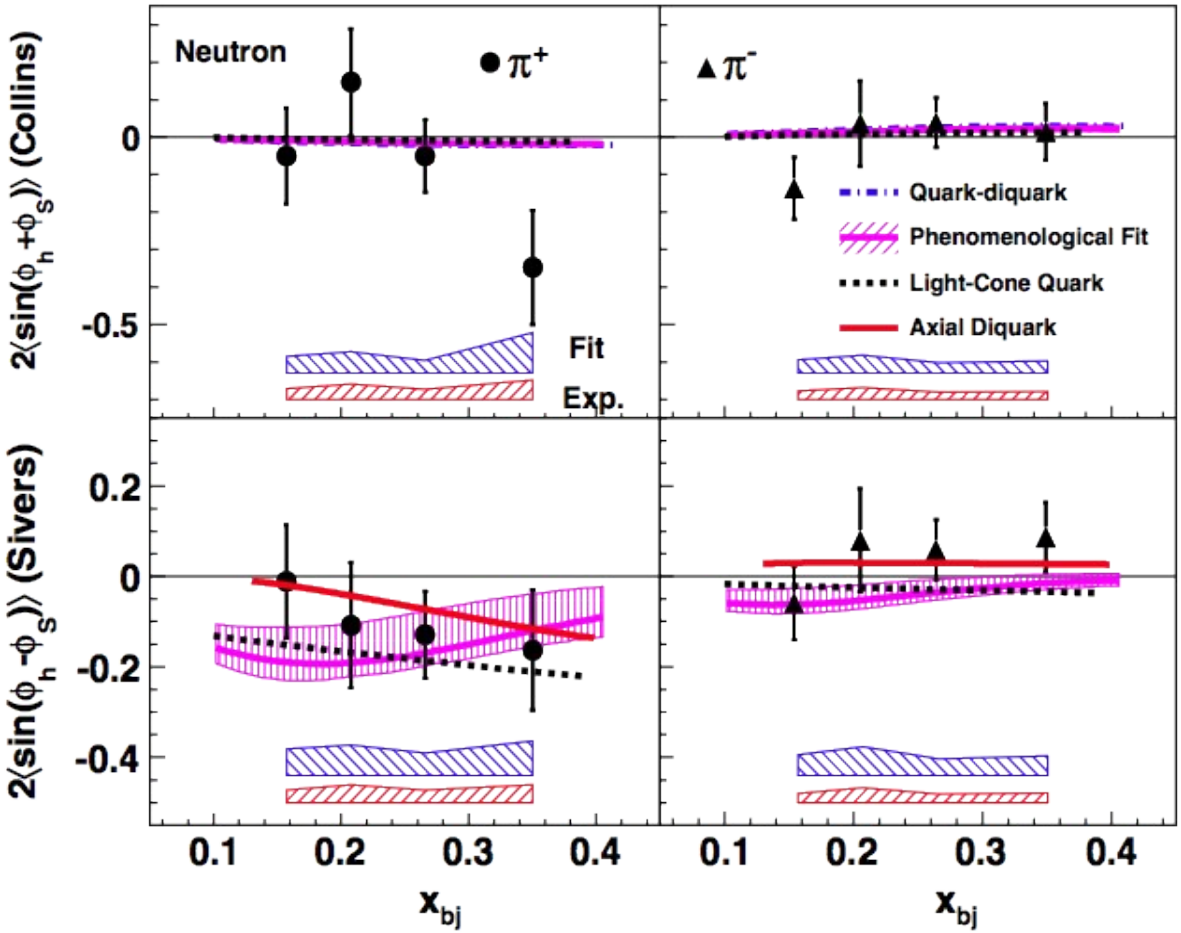
- Not very large

^{3}He Siver asymmetry:

- Negative for π^+
- Consistent with zero for π^-

E06-010: Neutron SSA Results

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



Collins Moment:

- Not very large, except x=0.35

Sivers Moment:

- Agree with global fit and light-cone quark model

$\langle Q^2 \rangle \sim 2.0$ GeV^2
$\langle z \rangle = 0.5$

Combined Data on TSSA in SIDIS

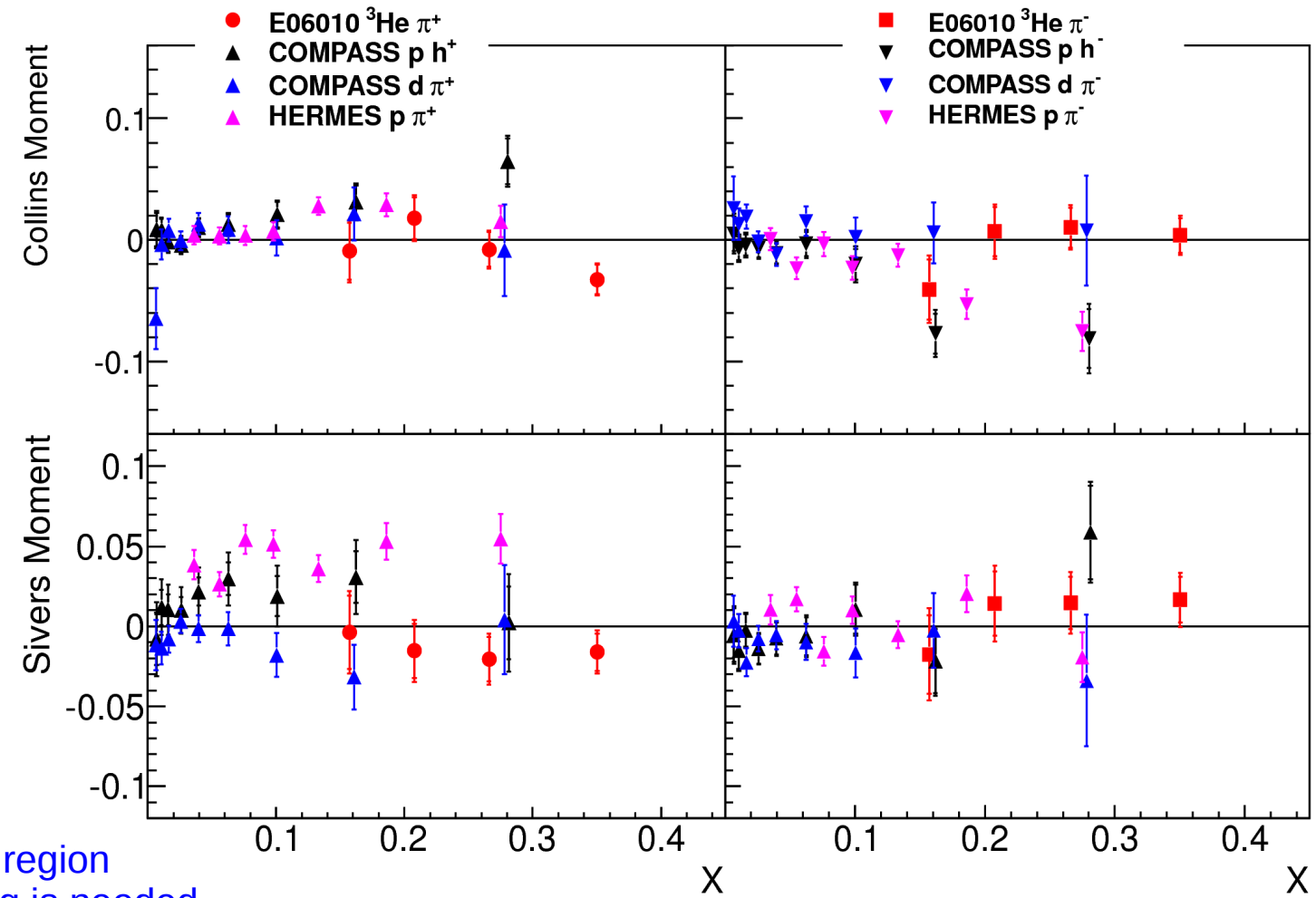
(proton, deuteron and ^{3}He targets)

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

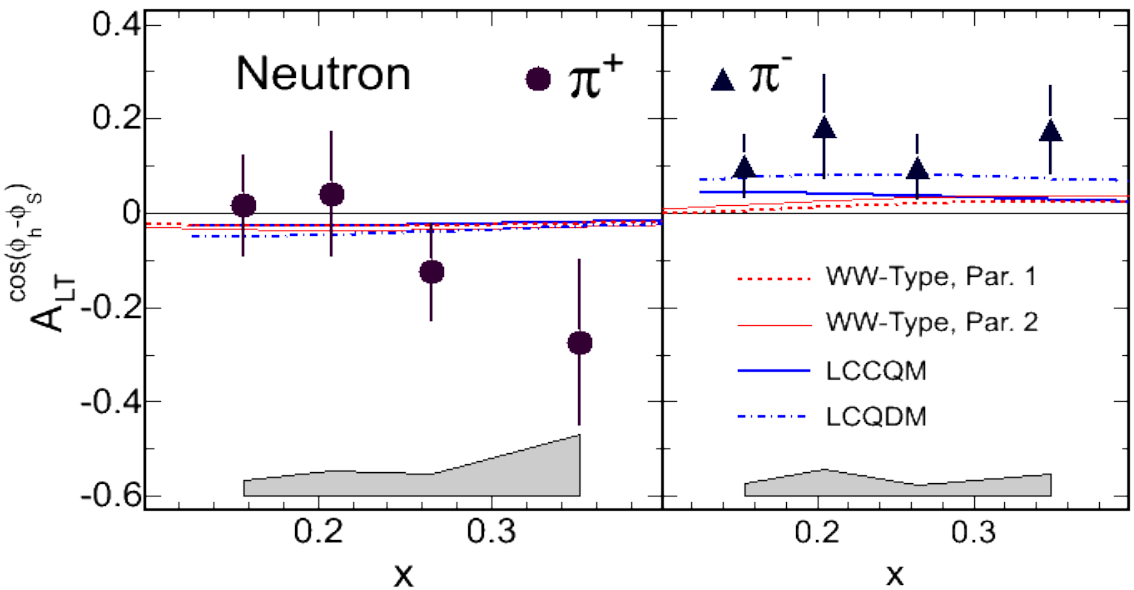


- Not much data at high *x* region
- Multi-dimensional binning is needed to fully understand these SSA

E06-010: Neutron Double-Spin Asymmetry Results

$$A_{LT} \propto \frac{g_{1T}^{\perp q}(x) \otimes D_{1q}^{h}(z)}{f_1^q(x) \otimes D_{1q}^{h}(z)}$$

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



- Non-zero A_{LT} is observed
- Consistent with model in sign
- Related to TMD $g_{1T}(x,k_T)$

Light-cone constituent quark model (LCCQM):

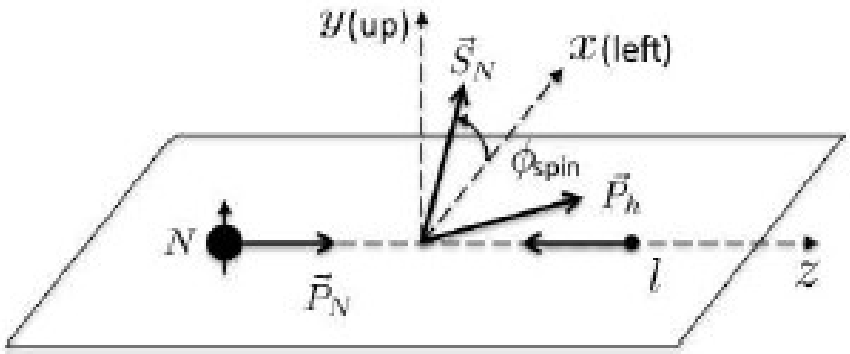
[16] B. Pasquini, S. Cazzaniga, and S. Boffi, Phys. Rev. **D78**, 034025 (2008).

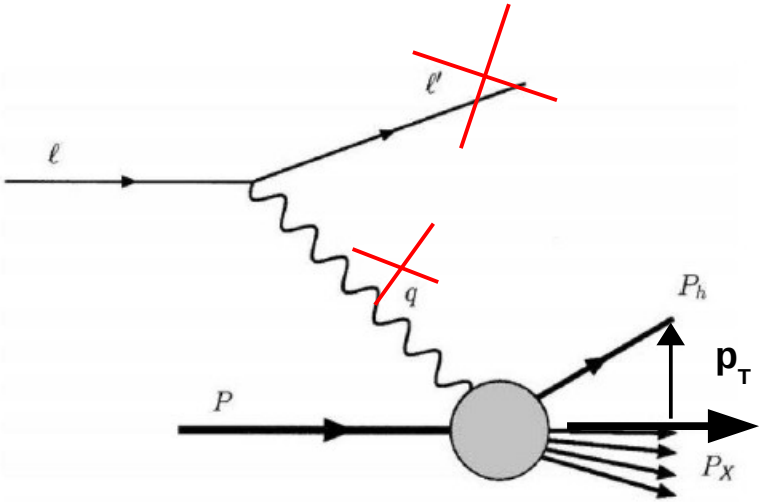
Light-cone quark-diquark model (LCQDM):

[21] J. Zhu and B.-Q. Ma, Phys. Lett. **B696**, 246 (2011).

Transverse SSA in Inclusive Hadron Electroproduction

$e + N^{\uparrow} \longrightarrow h^{+/-} + X \qquad (h = \pi^{+/-}, K^{+/-})$



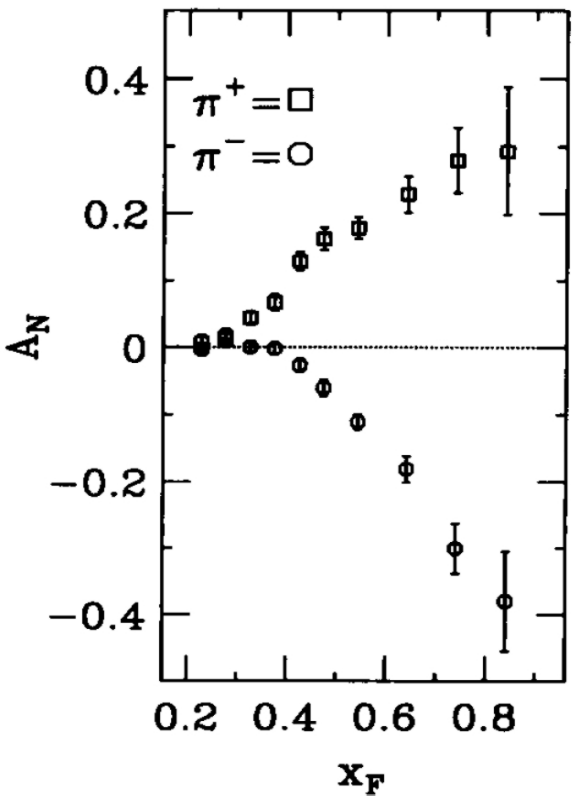


- Only one hadron is detected in the final state
- Final lepton remains undetected
- Only one scale in the process: transverse momentum of the outgoing hadron (p_T)
- Relevant kinematic variables:
  - p_T : Transverse momentum of hadron w.r.t to the incoming beam direction
  - $x_F \simeq 2p_L/\sqrt{s}$: p_L is the long. momentum of hadron
- Why a non-zero A_N is interesting?
  - Related to the same transverse spin effects seen in the SIDIS and p-p collisions (eg: Sivers and Collins effects convoluted)
  - Test validity of TMD factorization (at large p_T)
  - To help understand large A_N observed in p-p collisions in the TMD framework

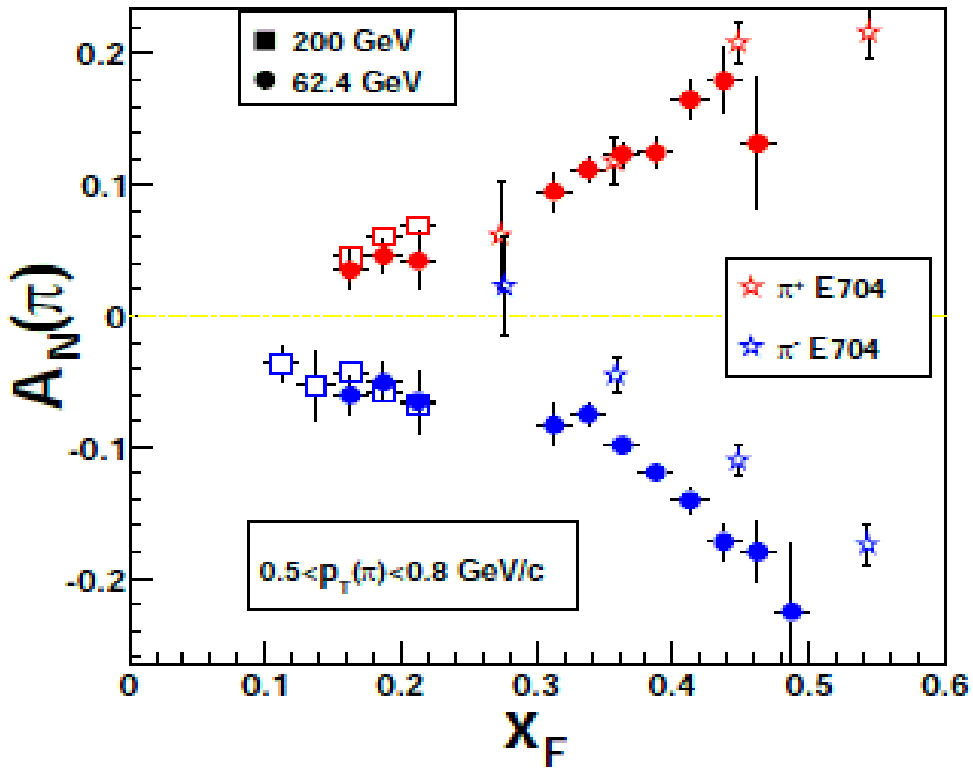
SSA in Hadronic Collisions

- Large non-zero asymmetries (A_N) observed in inclusive single-hadron production ($pp^{\uparrow} \rightarrow \pi X$)
- Moderate transverse momentum of hadron : *0.5 GeV < p_T < 2.0 GeV and 4.9 GeV < $\sqrt{s}$ < 200 GeV*
- Two approaches to explain large left-right asymmetry (A_N):
  - Using TMD distribution and fragmentation function (through mechanism such as Sivers effect)
  - Link between collinear parton dynamics and higher-twist quark gluon correlations

E704 $pp^{\uparrow} \rightarrow \pi X$ at $\sqrt{s} = 20\,GeV$
PLB 264, (1991) 462



BRAHMS $pp^{\uparrow} \rightarrow \pi X$
Prog. Part. Nuc. Phys. 65, 2 (2010) 267



Future Measurements

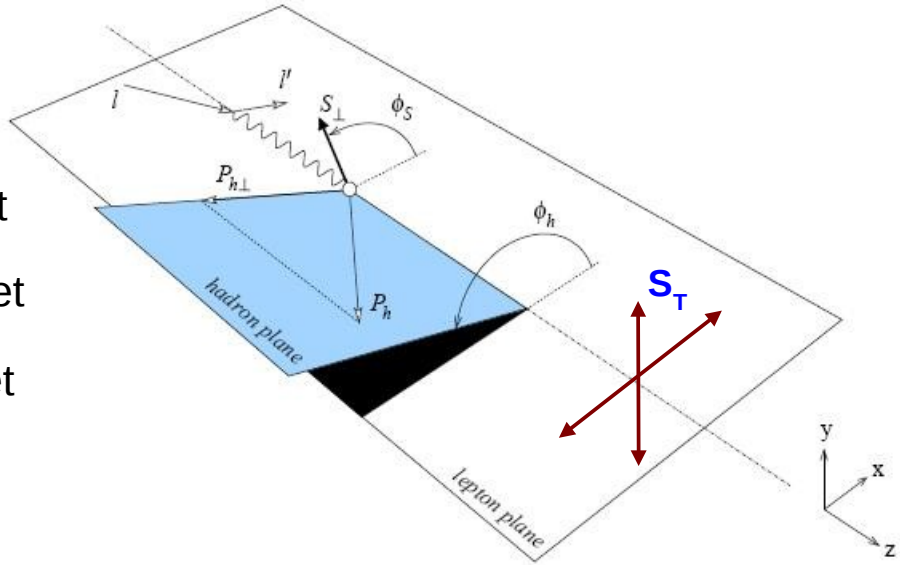
SoLID SIDIS Experiments in Hall-A

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

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

Approved 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

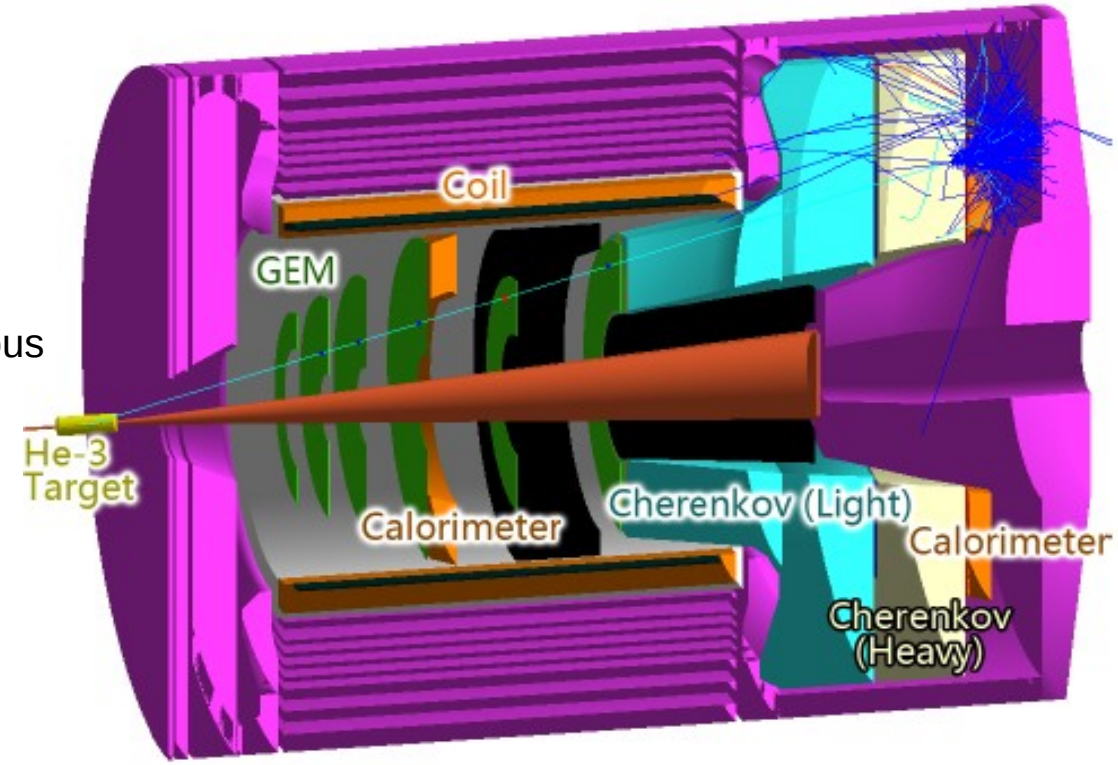


Other proposed measurements at JLab 12 GeV:

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

SoLID Configuration for SIDIS with ^{3}He and NH_3 Targets

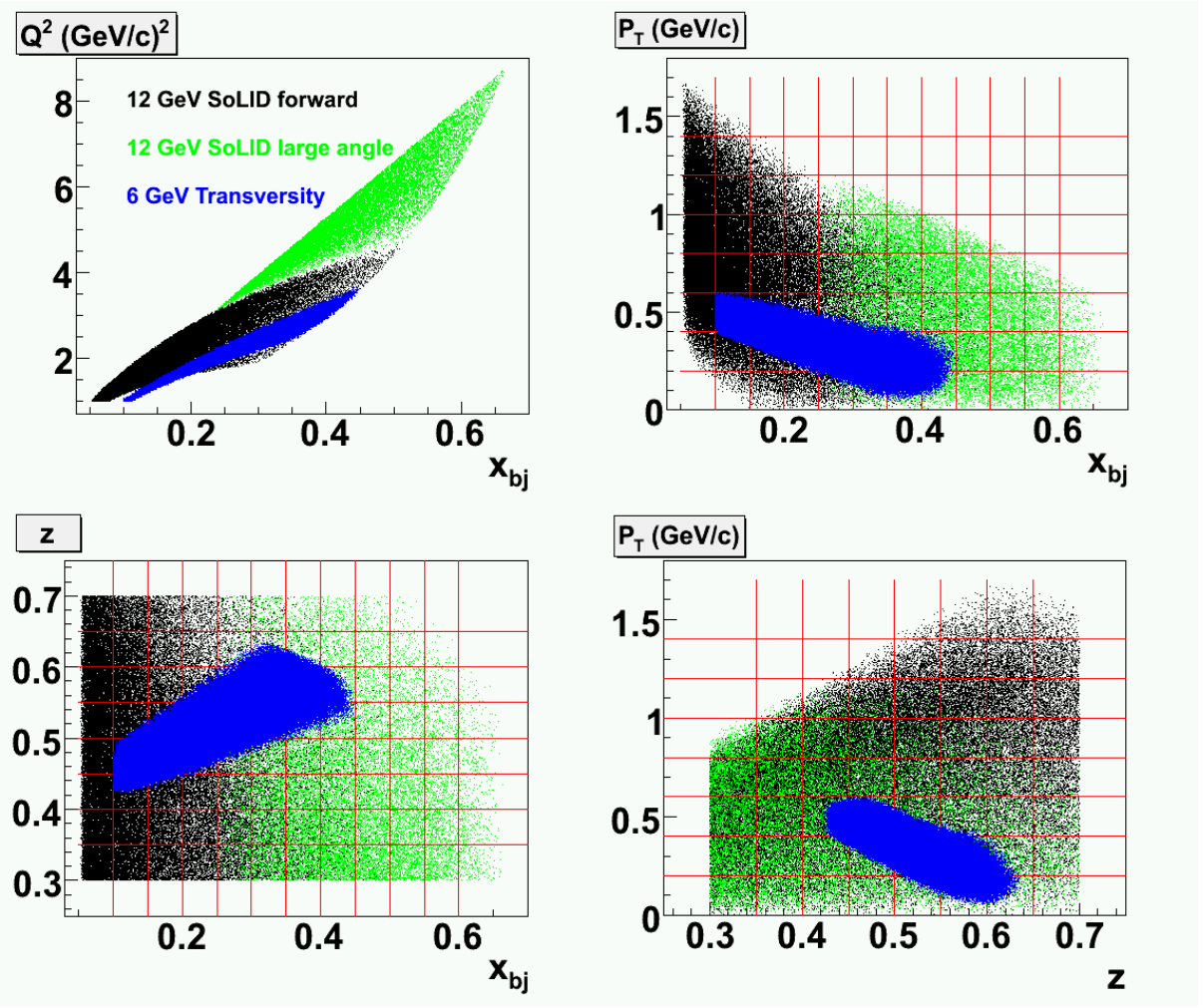
- Beam energy = 11 GeV and 8.8 GeV
- Solenoid Magnet (1.5 T field)
- Luminosities:
  - ^{3}He (neutron) : 10^{36} N/cm^2/s
  - NH_3 (proton) : 10^{35} N/cm^2/s
- Full azimuthal angle coverage
  - Crucial for 4D mapping of asymmetries
  - Reduces systematics when extracting various moments
- Tracking 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 Phase Space Coverage

- 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

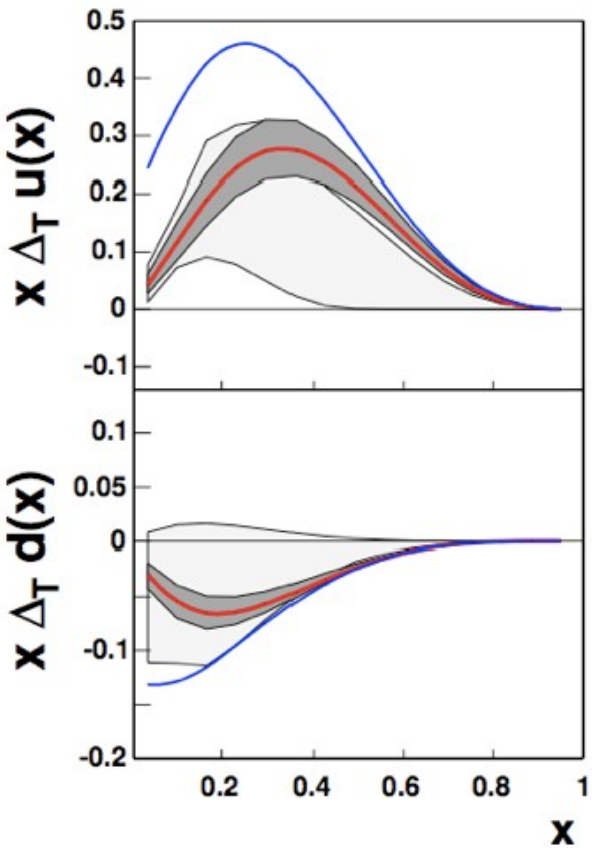


Collins Moment Projections

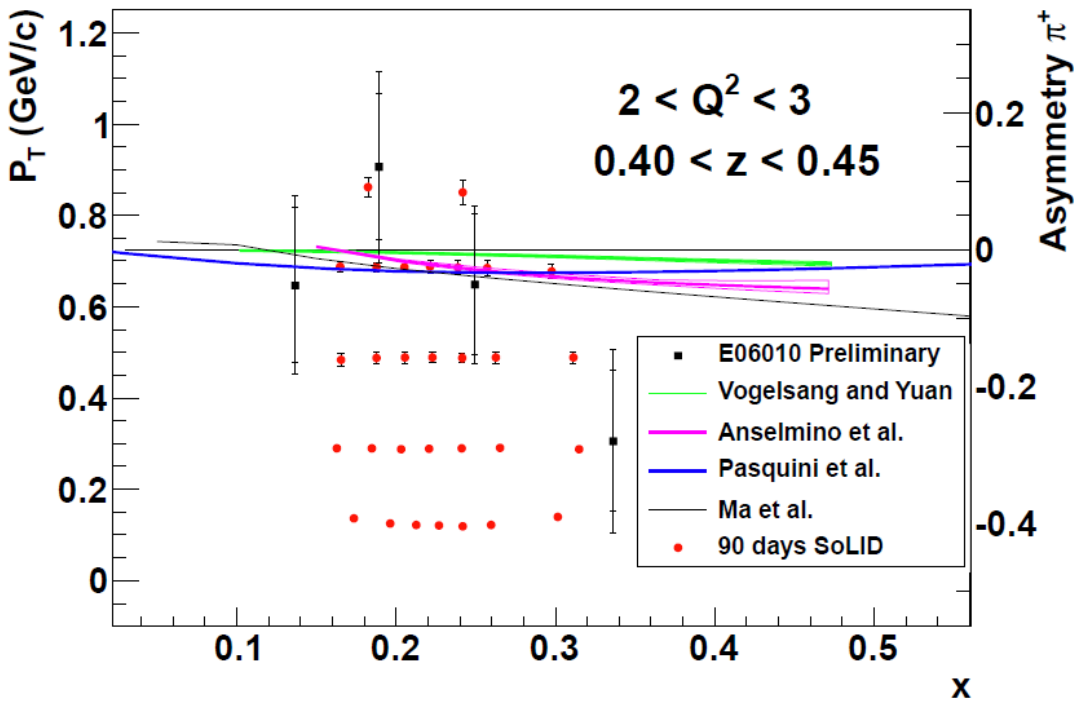
- Least known leading order PDF
- Cover large-x region
- Extract both u and d- quark tensor charge within 10% uncertainty

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

Current status of transversity



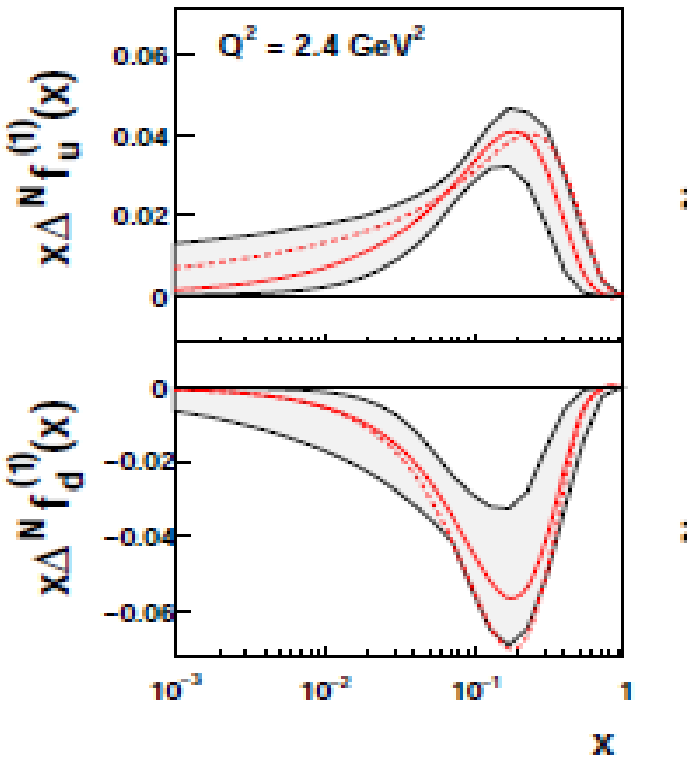
Projections for one bin of Q^2 and z



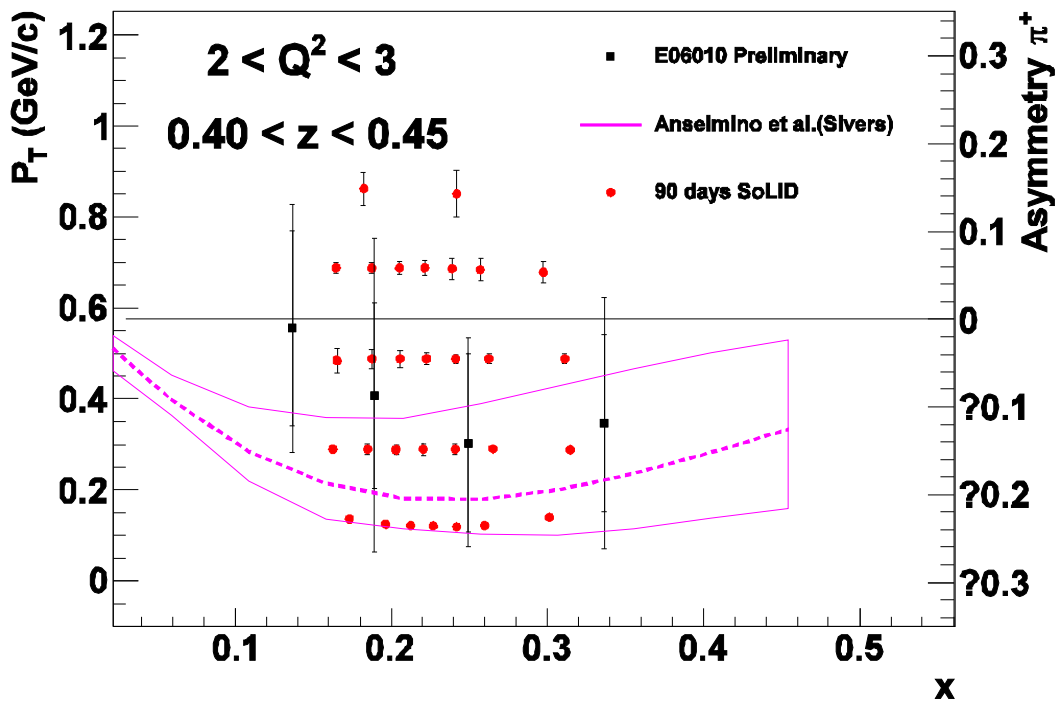
Sivers Moment Projections

- Relation between quark spin and OAM
- Test the QCD predicted sign reversal with Drell-Yan process $f_{1T}^{\perp q}\Big|_{SIDIS} = -f_{1T}^{\perp q}\Big|_{D-Y}$
- Test TMD factorization

Current status of Sivers function



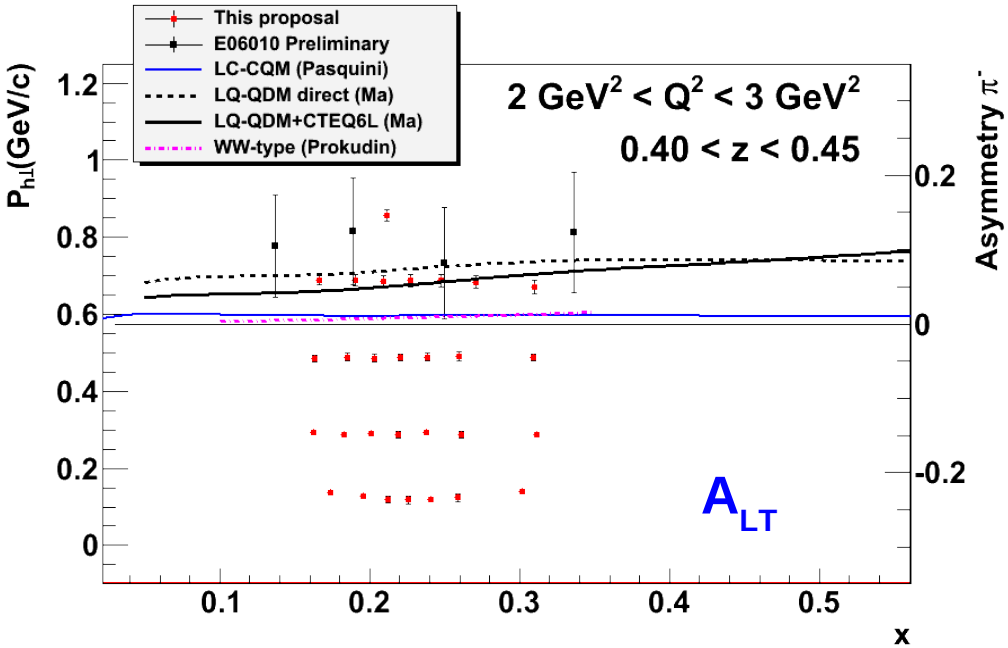
Projections for one bin of Q^2 and z

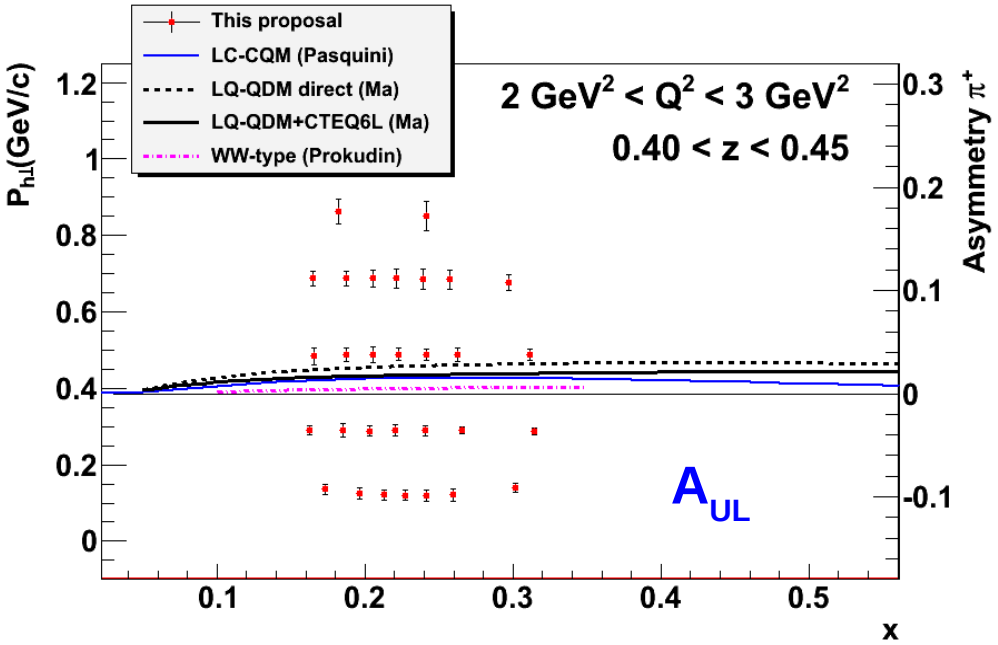


Worm-gear Moment Projections

- 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

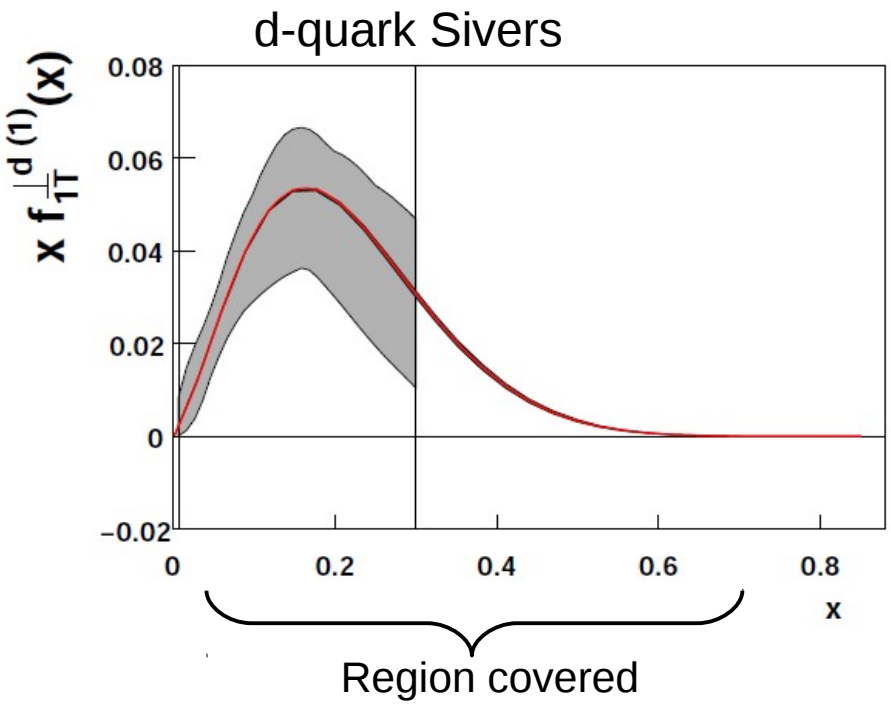
Projections for one bin of Q^2 and z

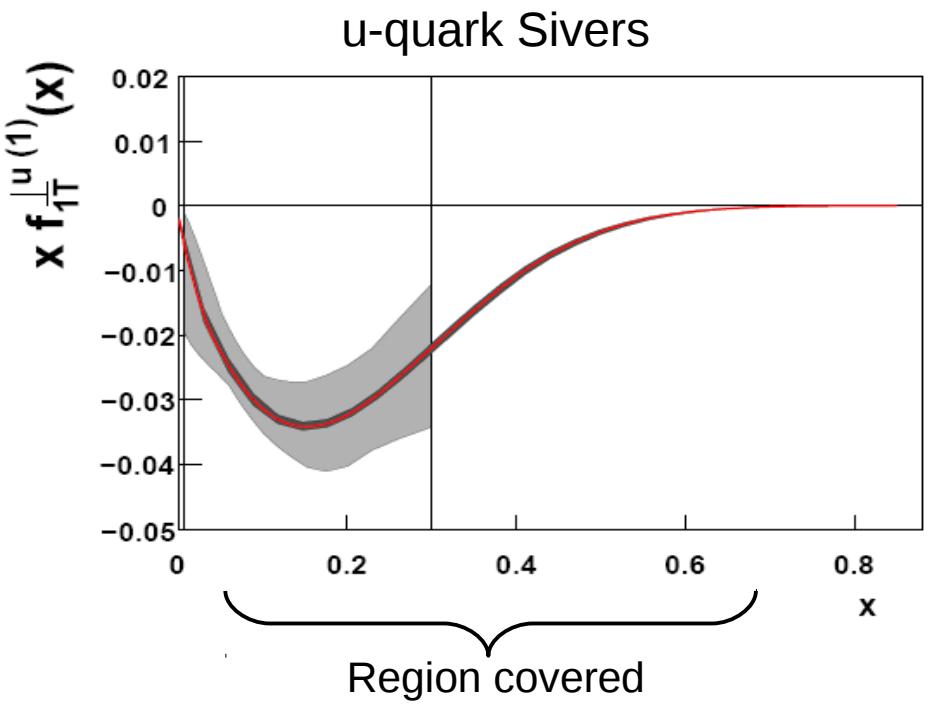




Impact on Extraction of TMDs

- Clean extraction of TMDs - precision comparable to longitudinal spin g_1
- Cover large *x* range to – important for extracting transversity DF



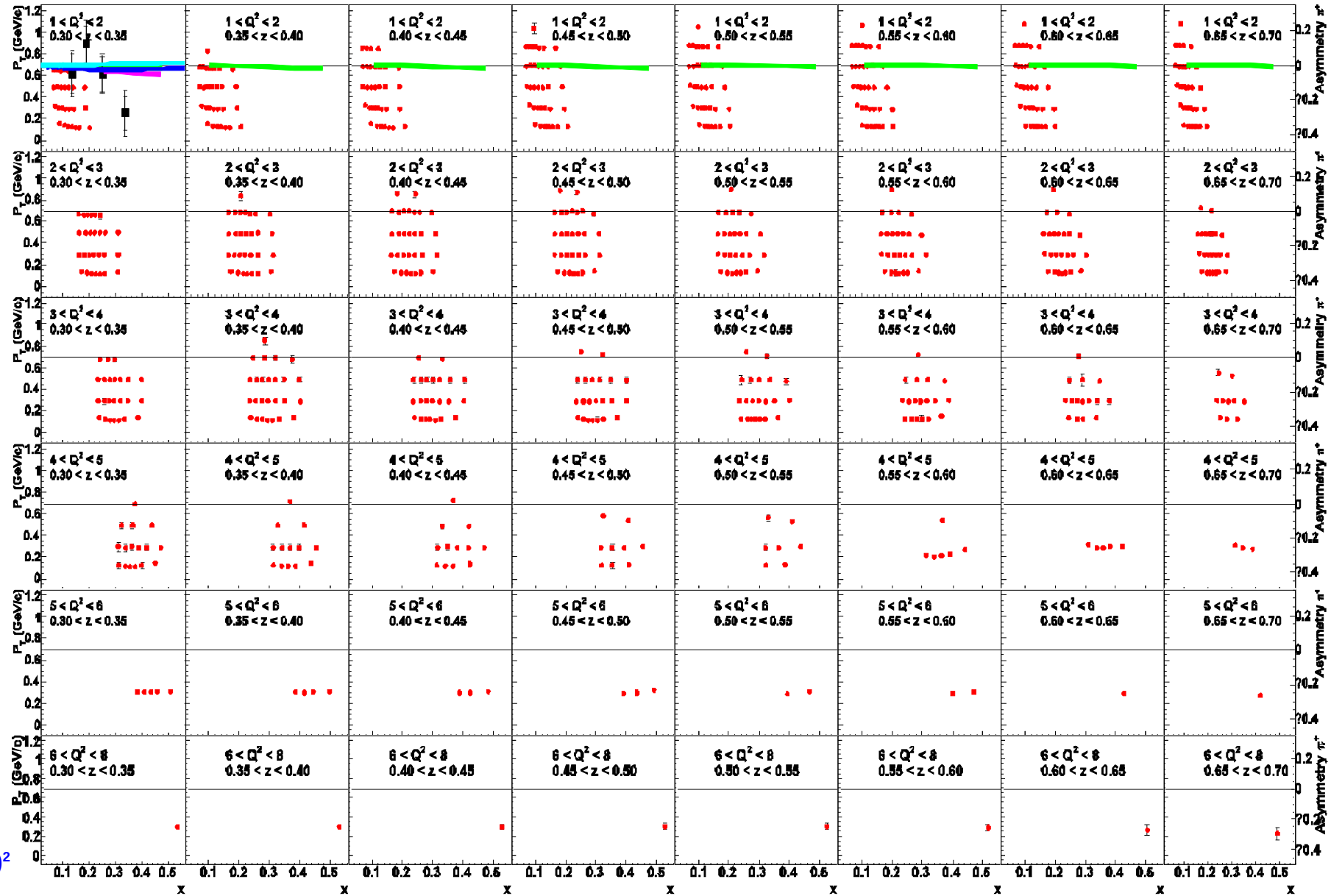


A. Prokudin

- Only Sivers function is shown
- Current experimental uncertainties in large light grey band
- Projected uncertainties in dark grey band
- Model uncertainties not included

Multi-dimensional Binning

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



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

Z = 0.3 → Z = 0.7

Summary

- TMDs provide very rich information of parton dynamics in the nucleon
  - 3D imaging of nucleon in momentum space
- Exploration of TMDs have just begun:
  - Several exploratory measurements done (HERMES, COMPASS, JLAB, RIHC-spin, etc..)
- First measurement of A_{UT} and A_{LT} and inclusive hadron A_N on ^{3}He (neutron) target
  - Non-zero A_{LT} observed for the first time
  - Negative sign for π^+ Sivers moments from A_{UT}
  - Clear non-zero and opposite sign A_N for π^+ and π^-, larger amplitude for K^+
- High precision experiments needed to study several issues
  - Clean extraction of TMDs, TMD evolution, sea-quark distribution, higher twist, etc..
- JLab 12 GeV experiments (Hall-A, B and C) will provide very precise data to help pin down these distributions
- Many exciting developments on theory/phenomenology front!