Experimental Study of Single Spin Asymmetries and TMDs

Jian-ping Chen , Jefferson Lab

QCD Evolution Workshop, JLab, May 6-10, 2013

- Recent SSA Results from JLab Hall A with a Transversely Polarized ^3He (n)
 - Collins/Sivers Asymmetries on π^+/π^- (published)
 - Worm-gear II Asymmetries on π^+/π^- (published)
- New Preliminary SSA Results from JLab Hall A with a Transversely polarized ^3He (n)
 - Collins/Sivers Asymmetries in K^+/K^-**
 - Pretzelosity Asymmetries on π^+/π^-**
 - Inclusive hadron SSA**
 - Inclusive electron SSA (DIS, QE)**
- TMD study at JLab 12 GeV in Hall A:
 - SoLID Program on SSA/TMDs: 3 Approved Experiments on ^3He and p**
 - New LOI on dihadron production**
- Long-term Future: TMDs study with Electron-Ion Colliders (EIC)
 - MEIC@ JLab and E-RHIC@BNL
 - A New Opportunity: an EIC in China (EIC@HIAF)**

Single Spin Asymmetries with A Transversely Polarized ^3He (n)

JLab Hall A E06-010

Leading-Twist TMD PDFs

		Quark polarization		
		Unpolarized (U)	Longitudinally Polarized (L)	Transversely Polarized (T)
Nucleon Polarization	U	$f_1 =$		$h_1^\perp =$ - <i>Boer-Mulders</i>
	L		$g_1 =$ - <i>Helicity</i>	$h_{1L}^\perp =$ - <i>Worm Gear</i>
	T	$f_{1T}^\perp =$ - <i>Sivers</i>	$g_{1T} =$ - <i>Worm Gear</i>	$h_1 =$ - <i>Transversity</i> $h_{1T}^\perp =$ - <i>Pretzelosity</i>

Nucleon Spin
Quark Spin

: Probed with transversely pol target
HERMES, COMPASS, JLab E06-010

Separation of Collins, Sivers and pretzelosity effects through angular dependence

$$\begin{aligned}
 A_{UT}(\varphi_h^l, \varphi_S^l) &= \frac{1}{P} \frac{N^\uparrow - N^\downarrow}{N^\uparrow + N^\downarrow} \\
 &= A_{UT}^{\text{Collins}} \sin(\phi_h + \phi_S) + A_{UT}^{\text{Sivers}} \sin(\phi_h - \phi_S) \\
 &\quad + A_{UT}^{\text{Pretzelosity}} \sin(3\phi_h - \phi_S)
 \end{aligned}$$

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

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

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

E06-010 Experiment

Spokespersons: Chen/Evaristo/Gao/Jiang/Peng

- **First measurement on n (^3He)**
- Polarized ^3He Target
- Polarized Electron Beam, 5.9 GeV
- BigBite at 30° as Electron Arm
 - $P_e = 0.7 \sim 2.2 \text{ GeV}/c$
- HRS_L at 16° as Hadron Arm
 - $P_h = 2.35 \text{ GeV}/c$
 - Excellent PID for $\pi/K/p$
- **7 PhD Thesis Students (All graduated)**
+ new students

Published Results (I) from JLab Hall A E06-010 with a Transversely Polarized ^3He (n)

Collins/Sivers Asymmetries on π^+/π^-

X. Qian et al., [PRL 107:072003\(2011\)](#)

³He Target Single-Spin Asymmetry in SIDIS

$$^3\text{He}^\uparrow(e, e'h), \quad h = \pi^+, \pi^-$$

³He Collins SSA small
Non-zero at highest x for π^+

³He Sivers SSA:
negative for π^+ ,

Blue band: model (fitting) uncertainties
Red band: other systematic uncertainties

Neutron Results with Polarized ^3He from JLab

Blue band: model (fitting) uncertainties

Red band: other systematic uncertainties

Collins

asymmetries are not large, except at $x=0.34$

Sivers

$\pi^+ (u\bar{d})$ negative

Published Results (II) from JLab Hall A E06-010 with a Transversely Polarized ^3He (n)

Worm-Gear II: Trans-helicity on π^+/π^-

J. Huang et al., *PRL*. 108, 052001 (2012).

Asymmetry A_{LT} Result

To leading twist:

$$A_{LT}^{\cos(\phi_h - \phi_s)} \propto F_{LT}^{\cos(\phi_h - \phi_s)} \propto g_{1T}^q \otimes D_{1q}^h$$

- $^3\text{He } A_{LT}$: Positive for π^-

Neutron A_{LT}^n Extraction

- $A_{LT}^{3\text{He}} = P_n \frac{\sigma_n}{\sigma^{3\text{He}}} A_{LT}^n + P_p \frac{2\sigma_p}{\sigma^{3\text{He}}} A_{LT}^p$ $\begin{cases} P_n = 0.86^{+0.036}_{-0.02} \\ P_p = -0.028^{+0.009}_{-0.004} \end{cases}$
 - Corrected for proton dilution, f_p
 - Predicted proton asymmetry contribution $< 1.5\%$ (π^+), 0.6% (π^-)

- $A_{LT}^n \propto g_{1T}^q \otimes D_{1q}^h$ *Trans-helicity*
 - Dominated by $L=0$ (S) and $L=1$ (P) interference
- Consist w/ model in signs, suggest larger asymmetry

Preliminary New Results (I) from JLab Hall A E06-010 with a Transversely Polarized ^3He (n)

Collins/Sivers Asymmetries on K^+/K^-

Analysis by Y. Zhao (USTC), Y. Wang (UIUC)

Kaon PID by Coincidence time of flight

Cross checked with RICH results

CT.K.t for positive run

K⁺/ π^+ ratio: ~5% K⁻/ π^- ratio: ~1%

Preliminary K⁺/K⁻ Collins and Sivers Asymmetries on ³He

Preliminary New Results (II) from JLab Hall A E06-010 with a Transversely Polarized ^3He (n)

Pretzelosity on π^+/π^-

Analysis by Y. Zhang (Lanzhou) and X. Qian (Caltech)

Pretzelosity on π^+/π^-

Pretzelosity Asymmetries, $A_{UT}\sin(\varphi_h - \varphi_s)$, in $^3\text{He}(e,e')$

With a transversely polarized target

For both π^+ and π^- , **consistent with zero** within uncertainties.

Extracted Results on Neutron

Extracted Pretzelosity Asymmetries, $A_{UT}\sin(\varphi_h - \varphi_s)$, on the neutron
For both π^+ and π^- , consistent with zero within uncertainties.

Preliminary Results

Preliminary New Results (III) from JLab Hall A E06-010 with a polarized ^3He (n)

Inclusive Electron SSA

Analysis by J. Katech(W&M), X. Qian (Caltech)

Inclusive Target Single Spin Asymmetry: DIS

$$A_y(Q^2) = \frac{\sigma^{\uparrow} - \sigma^{\downarrow}}{\sigma^{\uparrow} + \sigma^{\downarrow}}$$

- Unpolarized e^- beam incident on ^3He target polarized normal to the electron scattering plane.
- **However, $A_y=0$ at Born level,**
 → sensitive to physics at order α^2 ; **two-photon exchange.**

$$A_y \propto \frac{\text{Im}(T_{1\gamma} T_{2\gamma}^*)}{|T|^2}$$

- In DIS case: related to integral of Sivers
- Physics Importance discussed in [A. Metz](#) and [M. Schlegel's talks \(Tuesday\)](#)

Inclusive Target Single-Spin Asymmetry

SSA in $^3\text{He}(e,e')$

Vertically polarized target

Extracted neutron SSA

Vertically polarized target

Preliminary New Results from JLab Hall A E05-015 with a polarized ^3He (n)

Inclusive Electron SSA in Quasi-Elastic Scattering

Analysis by Y. Zhang (Rutgers), B. Zhao (W&M)

Inclusive Target Single Spin Asymmetry: QE

$$A_y(Q^2) = \frac{\sigma^{\uparrow} - \sigma^{\downarrow}}{\sigma^{\uparrow} + \sigma^{\downarrow}}$$

- Unpolarized e^- beam incident on ^3He target polarized normal to the electron scattering plane.
- **However, $A_y=0$ at Born level,**
 → sensitive to physics at order α^2 ; **two-photon exchange.**

$$A_y \propto \frac{\text{Im}(T_{1\gamma} T_{2\gamma}^*)}{|T|^2}$$

- (Q)Elastic: Calculable at large Q^2 using moments of GPD's
- Measurement of A_y at large Q^2 provides access to GPD's

Preliminary ^3He results at $Q^2=0.5$ and 1.0 GeV^2

$^3\text{He}(e,e') \quad A_y^{^3\text{He}}$

Data above is for helium-3

Prediction below is for $Q^2=1 \text{ GeV}^2$
Carlson et al.--Neutron

Preliminary New Results (IV) from JLab Hall A E06-010 with a transversely polarized ^3He (n)

Inclusive Hadron SSA

Analysis by K. Allada (JLab), Y. Zhao (USTC)

Inclusive Hadron Electroproduction

$$e + N^\uparrow \longrightarrow h + X \quad (h = \pi, K, p)$$

$$\sigma_{UT} \propto \vec{S}_N \cdot (\vec{l} \times \vec{P}_h) \propto \sin(\phi_S)$$

Why a non-zero A_N is interesting?

- Analogues to A_N in $pp^\uparrow \rightarrow hX$ collision
- Simpler than $pp^\uparrow \rightarrow hX$ due to only one quark channel
- Same transverse spin effects as SIDIS and p - p collisions (Sivers, Collins, twist-3)
- Clean test TMD formalism (at large $p_T \sim 1$ GeV or more)
- To help understand mechanism behind large A_N in $pp^\uparrow \rightarrow hX$ in the TMD framework

$$A_N(x_F, p_T) = A_{UT}^{\sin(\phi_S)}$$

Transverse SSA in Inclusive Hadron

$$\vec{S}_N \cdot (\vec{l} \times \vec{P}_h) = 0$$

$$A_{UT}^{\sin(\varphi_S)}(\varphi_S = 0)$$

$$A_{UT}^{\sin(\varphi_S)} = \frac{N^\uparrow - N^\downarrow}{N^\uparrow + N^\downarrow}$$

- Target spin flip every 20 minutes
- Acceptance effects cancels
- Overall systematic check with A_N at $\phi_S = 0$
 - False asymmetry $< 0.1\%$

E06-010: Inclusive Hadron SSA (A_N)

$$\vec{S}_N \cdot (\vec{l} \times \vec{P}_h) \neq 0$$

$$A_{UT}^{\sin(\varphi_S)}(\varphi_S = 90^\circ)$$

- Clear non-zero target SSA
- Opposite sign for π^+ and π^-

E06-010: Inclusive Hadron SSA (A_N)

$$\vec{S}_N \cdot (\vec{l} \times \vec{P}_h) \neq 0$$

$$A_{UT}^{\sin(\varphi_S)}(\varphi_S = 90^\circ)$$

- Clear non-zero target SSA
- Opposite sign for π^+ and π^-
- A_N at low p_T not very well understood

Future: TMD study with SoLID at 12 GeV JLab Hall A

Precision 4-D mapping of Collins/Sivers/Pretzelosity
Worm-Gear I/II
with Polarized ^3He (Neutron) and Proton

JLab 12 GeV Era: Precision Study of *TMDs*

- From exploration to **precision** study with 12 GeV JLab
- Transversity: fundamental *PDFs*, tensor charge
- *TMDs*: 3-d momentum structure of the nucleon
- → Quark orbital angular momentum
- **Multi-dimensional** mapping of *TMDs*
 - 4-d ($x, z, P_{\perp}, Q^2$)
 - Multi-facilities, global effort
- Precision → high statistics
 - **high luminosity and large acceptance**

SoLID for SIDIS/PVDIS with 12 GeV JLab

- Exciting physics program:
 - Five approved experiments:
 - three SIDIS “A rated”, one PVDIS “A rated”, one J/Psi “A- rated”
- International collaboration: eight countries and 50+ institutions

- CLEOII Magnet
- GEMs for tracking
- Cherenkov and EM Calorimeter for electron PID
- Heavy Gas Cherenkov and MRPC (TOF) for pion PID

E12-10-006/E12-11-108, Both Approved with “A” Rating
Mapping of Collins(Sivers) Asymmetries with SoLID

- Both π^+ and π^-
- Precision Map in region
 $x(0.05-0.65)$
 $z(0.3-0.7)$
 $Q^2(1-8)$
 $P_T(0-1.6)$
- $<10\%$ d quark tensor charge

Map Collins and Sivers asymmetries in 4-D (x, z, Q^2, P_T)

Expected Improvement: Sivers Function

$$f_{1T}^{\perp} = \text{spin up} - \text{spin down}$$

- Significant Improvement in the valence quark (high- x) region
- Illustrated in a model fit (from A. Prokudin)

E12-11-107: Worm-gear functions (“A’ rating:)

Spokespersons: Chen/Huang/Qiang/Yan

- Dominated by **real** part of interference between **L=0 (S)** and **L=1 (P)** states
- **No** GPD correspondence
- Lattice QCD -> Dipole Shift in mom. space.
- Model Calculations -> $h_{1L}^\perp = ? -g_{1T}$.

$$h_{1L}^\perp = \begin{array}{c} \text{Diagram 1} \\ \text{Diagram 2} \end{array} \quad \begin{array}{c} \text{Diagram 3} \\ \text{Diagram 4} \end{array}$$

$$g_{1T} = \begin{array}{c} \text{Diagram 5} \\ \text{Diagram 6} \end{array} \quad \begin{array}{c} \text{Diagram 7} \\ \text{Diagram 8} \end{array}$$

Longi-transversity
Trans-helicity

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

$$A_{UL} \sim h_{1L}^\perp(x)H_1^\perp(z)$$

Future: TMD study with SoLID at 12 GeV JLab Hall A

New Letter Of Intent: Dihadron Production

Measure Transversity via Dihadron with SoLID

Lol submitted to Jlab PAC 40, [J. Zhang, A. Courtoy, et al.](#)

- Precision dihadron ($\pi^+\pi^-$) production on a transversely polarized ^3He (n)
- Extract transversity on neutron
- Provide crucial inputs for flavor separation of transversity

talk by M.Radici

Projected Statistics error for one ($M_{\pi\pi}, z_{\pi\pi}$) bin, integrated over all y and Q^2 .

Projected Statistics Error

- Hall A, SoLID program
- Polarized ^3He target, ($\sim 60\%$ polarization)
- Lumi= 10^{36} (n)/s/cm 2
- Wide x_b and Q^2 coverages
- Bin central values labeled on axes
- 4-d ($x_b, Q^2, Z_{\pi^+\pi^-}, M_{\pi^+\pi^-}$) mapping
- Z scale (color) represent stat. error

Summary on SoLID TMD Program

- Unprecedented precision 4-d mapping of SSA
 - Collins, Sivers, Pretzelosity and Worm-Gear
- Both polarized ^3He (n) and polarized proton with SoLID
- Study factorization with x and z -dependences
- Study P_T dependence
- Combining with the world data
 - extract transversity and fragmentation functions for both u and d quarks
 - determine tensor charge
 - study TMDs for both valence and sea quarks
 - learn quark orbital motion and quark orbital angular momentum
 - study Q^2 evolution
- Global efforts (experimentalists and theorists), global analysis
 - much better understanding of multi-d nucleon structure and QCD
- **Long-term future: EIC to map sea and gluon SSAs**

Long-term Future: TMD study with EIC

MEIC@JLab and E-RHIC@BNL

New Opportunity: EIC in China

Image the Transverse Momentum of the Quarks

Only a small subset of the (x, Q^2) landscape has been mapped here.

An EIC with good luminosity & high transverse polarization is the optimal tool to study this!

Exact k_T distribution presently essentially unknown!

Electron Ion Colliders on the World Map

Lepton-Nucleon Facilities

EIC@HIAF: $e(3\text{GeV}) + p(12\text{GeV})$, both polarized, $L(\text{max})=10^{33}\text{cm}^2/\text{s}$

High Intensity Accelerator Facility (One Option)

Slide courtesy of Xurong Chen

Design Goal

$$L \sim 10^{33} \text{ 1/cm}^2\text{s}$$

	Electron	proton
Energy	3.0GeV	12GeV
n [particle/bunch 10^{10}]	30	4.0
I_b [bunch current mA]	25	3.0
I [total current A]	4.0	0.6

EIC@HIAF Kinematic Coverage Comparison with JLab 12 GeV

$e(3\text{GeV}) + p(12\text{GeV})$, both polarized, $L(\text{max})=10^{33}\text{cm}^2/\text{s}$

EIC@HIAF:

- study sea quarks ($x > 0.01$)
- deep exclusive scattering at $Q^2 > 5-10$
- higher Q^2 in valence region
- range in Q^2 allows study gluons

Timeline:

Funding Approved for HIAF
EIC under design/discussion
Construction 2014-2019

plot courtesy of Xurong Chen

Science Goals

The Science of eRHIC/MEIC

Goal: Explore and Understand QCD:

Map the spin and spatial structure of quarks and gluons in nucleons

Discover the collective effects of gluons in atomic nuclei

(role of gluons in nuclei & onset of saturation)

Emerging Themes:

Understand the emergence of hadronic matter from quarks and gluons & EW

The Science of EIC@HIAF

One Main Goal: Explore Hadron Structure

Map the spin-flavor, multi-d spatial/momentum structure of valence & sea quarks

TMD Study and other Programs at EIC@HIAF

- Unique opportunity for TMD in “sea quark” region
reach $x \sim 0.01$ (JLab12 mainly valence quark region, reach $x \sim 0.1$)
- Significant increase in Q^2 range for valence region
energy reach $Q^2 \sim 40 \text{ GeV}^2$ at $x \sim 0.4$ (JLab12, $Q^2 < 10$)
- Significant increase in P_T range
reach $>1 \text{ GeV}$? (TMD/co-linear overlap region) (JLab12, reach $<1 \text{ GeV}$)
- Other Physics Programs:
 - Nucleon spin-flavor structure (polarized sea, Δs)
 - 3-d Structure: GPDs (DVMP, pion/Kaon)
 - e-A to study hadronization
 - Pion/Kaon structure functions?

.....

2nd Conference on QCD and Hadron Physics:

<http://qcd2013.csp.escience.cn/dct/page/1>

Whitepaper on EIC@China is being worked on:

need inputs and help from international community

Summary

- SSA and TMD study have been exciting and fruitful
 - Recent and Preliminary Results from JLab Hall A with a transversely polarized ^3He (n) target
 - Collins/Sivers asymmetries for $\pi^+/\pi^-/K^+/K^-$
 - Pretzelosity on π^+/π^-
 - SSA: inclusive hadron
 - SSA: inclusive electron DIS
 - SSA: inclusive electron (Quasi)Elastic
 - Planned SoLID program with JLab12
 - Precision 4-d mapping of TMD asymmetries
 - EIC@HIAF opens up a new window
 - Exciting new opportunities
- Precision experimental data + development in TMD theory (QCD evolution...)+...
- lead to breakthrough in understanding QCD?