SIDIS results from Hall A

7th Workshop on Hadron Physics in China and Opportunities Worldwide, Aug 4, 2015

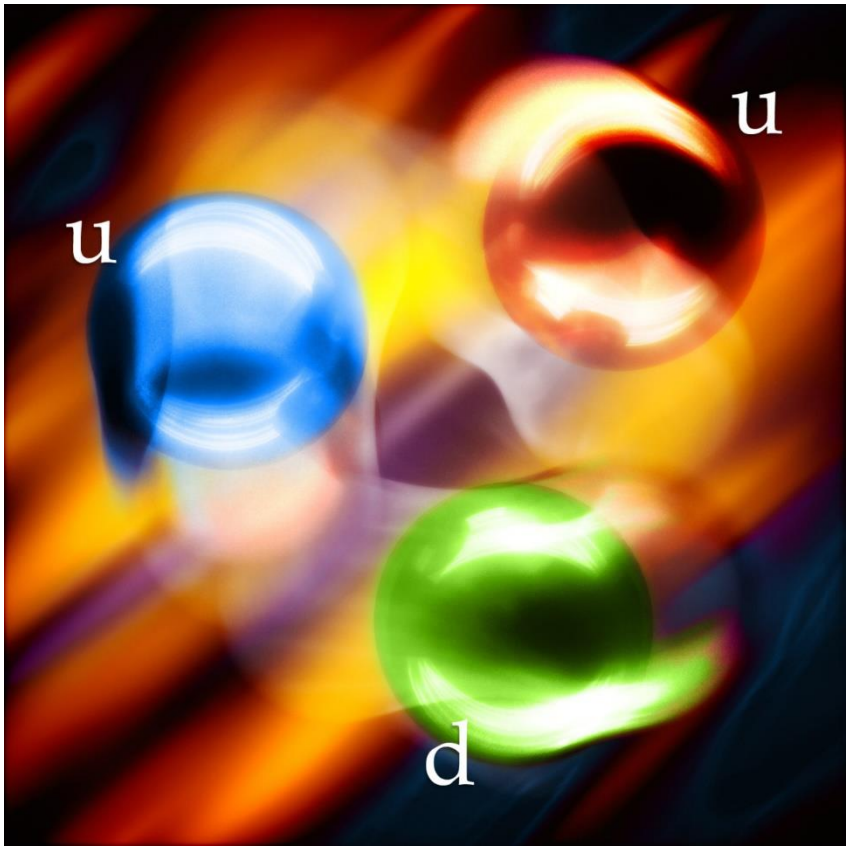
Xuefei Yan

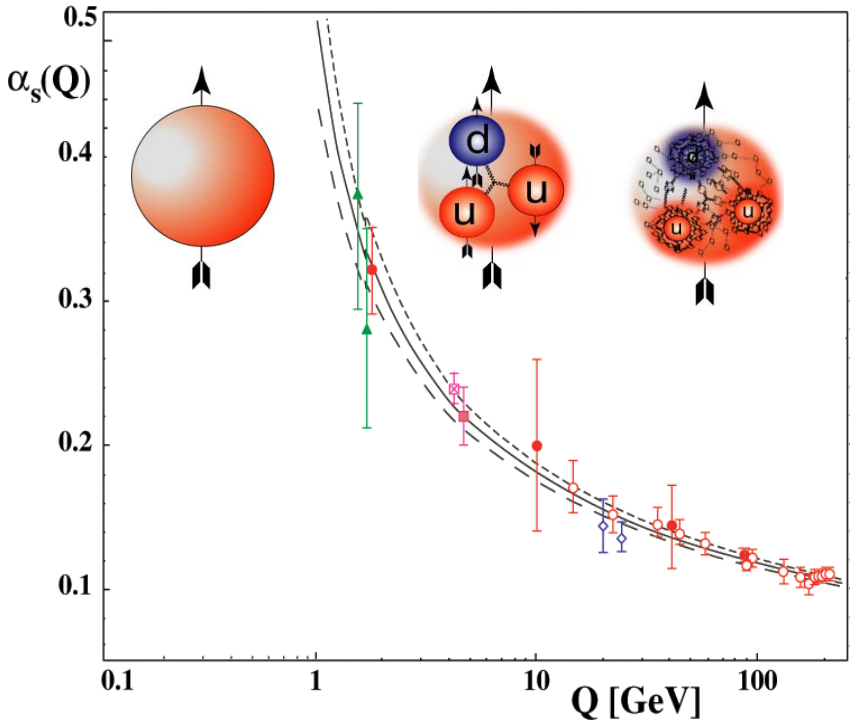
Duke University

Durham, NC, U.S.A.

Duke UNIVERSITY

QCD: still unsolved in non-perturbative region

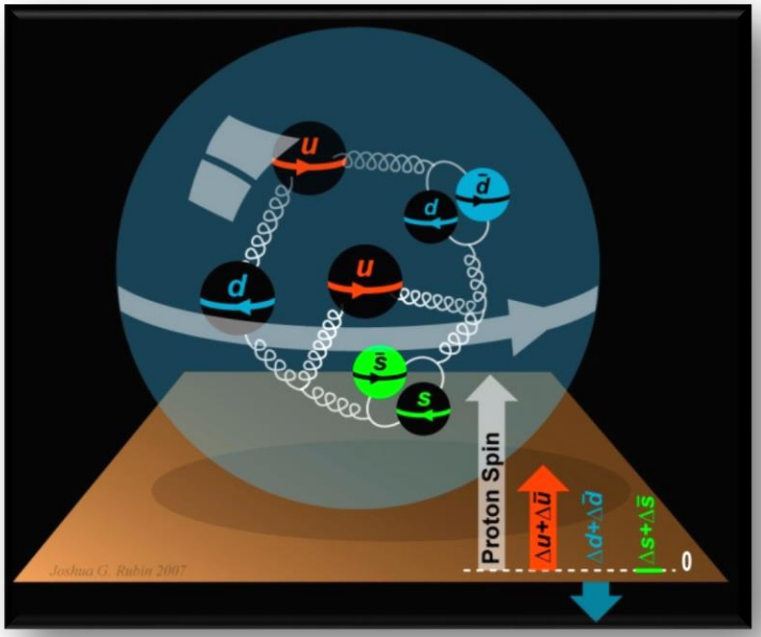




Confinement to asymptotic freedom

- *2004 Nobel prize for QCD: theory of strong interaction*
- *Confinement/non-perturbative regime: one of top challenges in physics*
- *Nucleon structure: one of the most active areas*

The Incomplete Nucleon: Spin Puzzle



$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma(\mu) + L_q(\mu) + J_g(\mu)$$

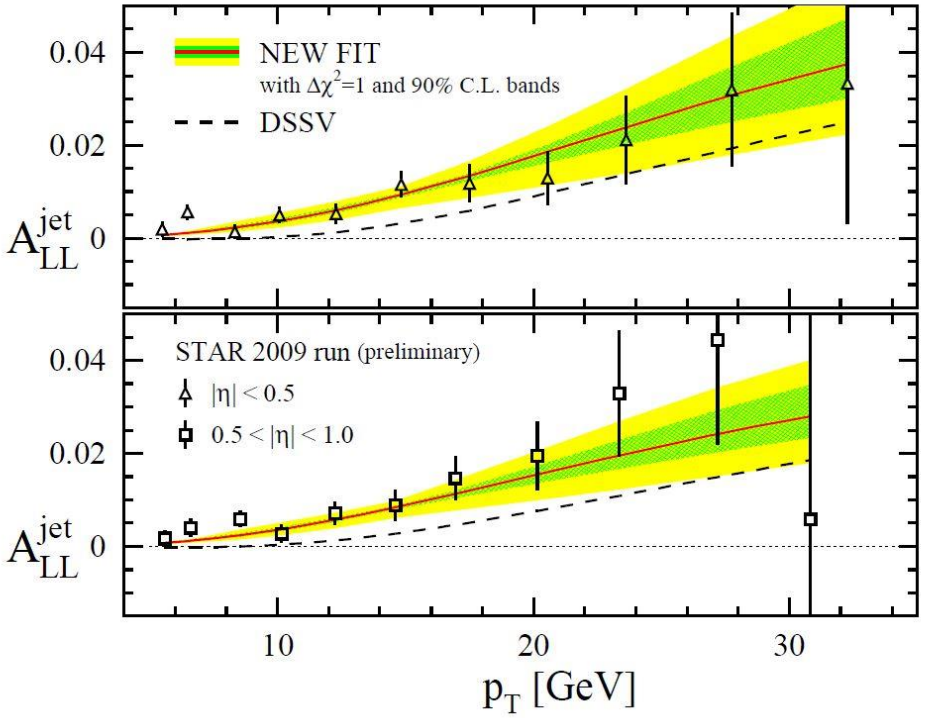
[X. Ji, 1997]

Jaffe-Manohar 1990
Chen *et al.* 2008
Wakamatsu 2009,2010

- DIS → $\Delta\Sigma \cong 0.30$
- RHIC + DIS → Δg not small
- → L_q

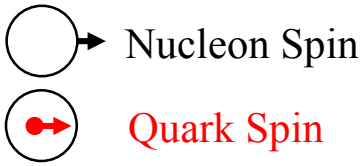
Orbital angular momentum of quarks gluons is important
Understanding of spin-orbit correlation (atomic hydrogen, topological insulator

How to access OAM?



PRL 113, 012001 (2014)

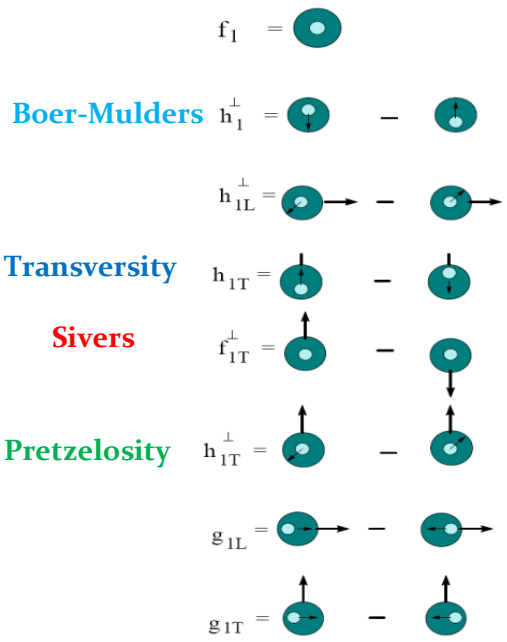
Leading-Twist TMD PDFs



Nucleon Polarization	Quark polarization: Unpolarized (U)	Quark polarization: Longitudinally Polarized (L)	Quark polarization: Transversely Polarized (T)
U	f_1		$h_1^\perp$ – **Boer-Mulders**
L		g_1 – **Helicity**	$h_{1L}^\perp$ – **Long-Transversity**
T	$f_{1T}^\perp$ – **Sivers**	g_{1T} – **Trans-Helicity**	h_1 – **Transversity**; $h_{1T}^\perp$ – **Pretzelosity**

Access Parton Distributions through Semi-Inclusive DIS

$$\frac{d\sigma}{dxdyd\phi_S dzd\phi_h dP_{h\perp}^2} = \frac{\alpha^2}{xyQ^2}\frac{y^2}{2(1-\varepsilon)}\cdot$$



$$\{F_{UU,T} + \ldots$$
$$+ \varepsilon\cos(2\phi_h)\cdot F_{UU}^{\cos(2\phi_h)} + \ldots$$

Unpolarized

$$+ S_L[\varepsilon\sin(2\phi_h)\cdot F_{UL}^{\sin(2\phi_h)} + \ldots]$$
$$+ S_T[\varepsilon\sin(\phi_h+\phi_S)\cdot F_{UT}^{\sin(\phi_h+\phi_S)}$$
$$+ \sin(\phi_h-\phi_S)\cdot(F_{UL}^{\sin(\phi_h-\phi_S)} + \ldots)$$
$$+ \varepsilon\sin(3\phi_h-\phi_S)\cdot F_{UT}^{\sin(3\phi_h-\phi_S)} + \ldots]$$

Polarized Target

$$+ S_L\lambda_e[\sqrt{1-\varepsilon^2}\cdot F_{LL} + \ldots]$$
$$+ S_T\lambda_e[\sqrt{1-\varepsilon^2}\cos(\phi_h-\phi_S)\cdot F_{LT}^{\cos(\phi_h-\phi_S)} + \ldots]\}$$

Polarized Beam and Target

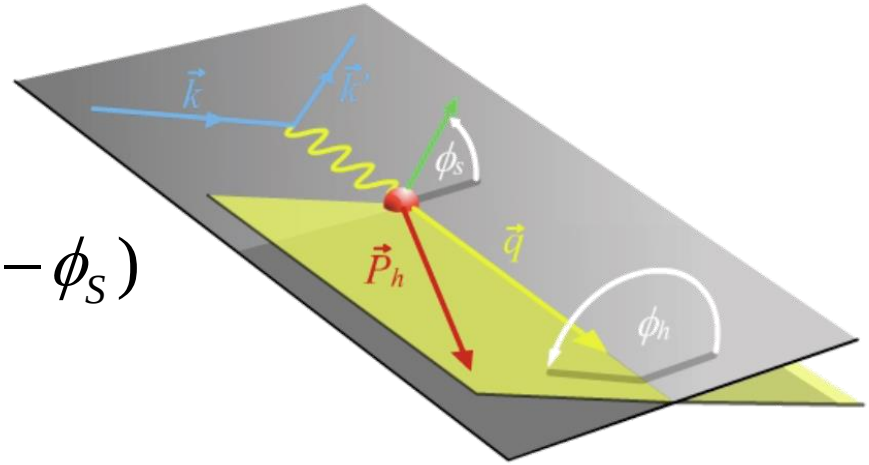
S_L, S_T: Target Polarization; λ_e: Beam Polarization

Separation of Collins, Sivers and pretzelocity effects through angular dependence

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

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

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



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

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

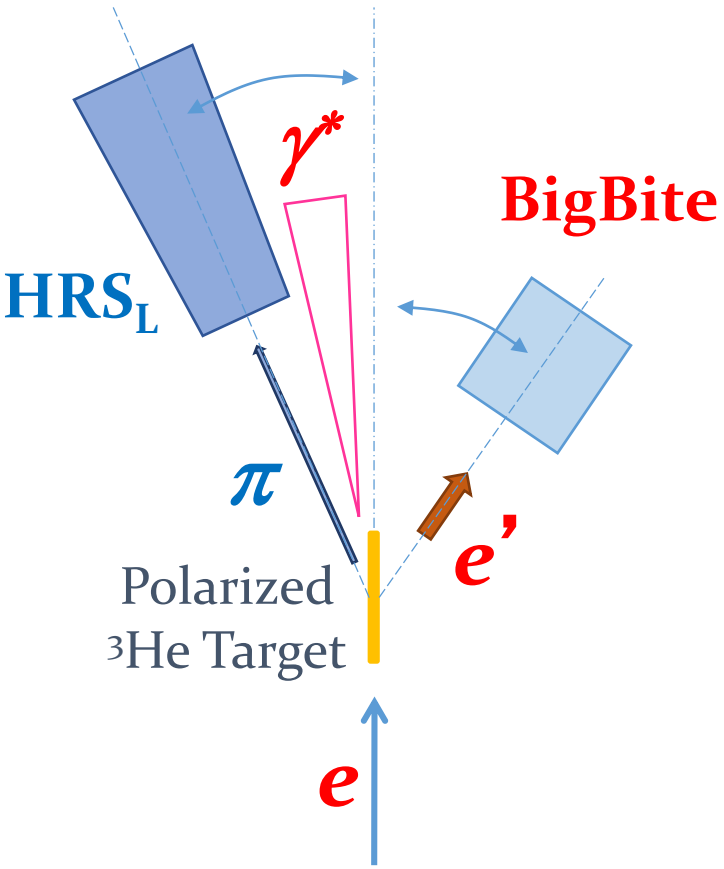
$$A_{UT}^{Sivers} \propto \langle \sin(\phi_h - \phi_S) \rangle_{UT} \propto f_{1T}^{\perp} \otimes D_1$$

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

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.

E06-010: experimental configuration

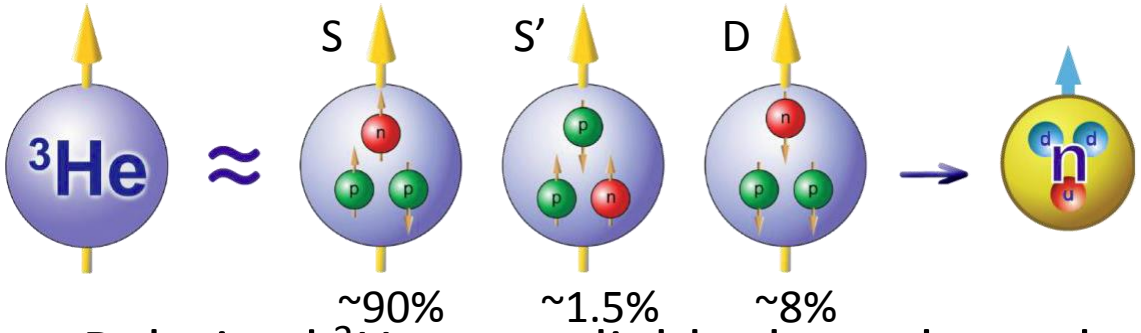


- ***First*** **neutron** data in SIDIS **SSA&DSA**
  - Similar Q^2 as HERMES experiment
- Preliminary results on SIDIS **unpolarized cross section**

- Electron beam: E = 5.9 GeV
  - High luminosity L ~ 10^{36} $cm^{-2}s^{-1}$
  - 40 cm transversely polarized ^{3}He target
  - Average beam current 12 uA (max: 15 uA as in proposal)

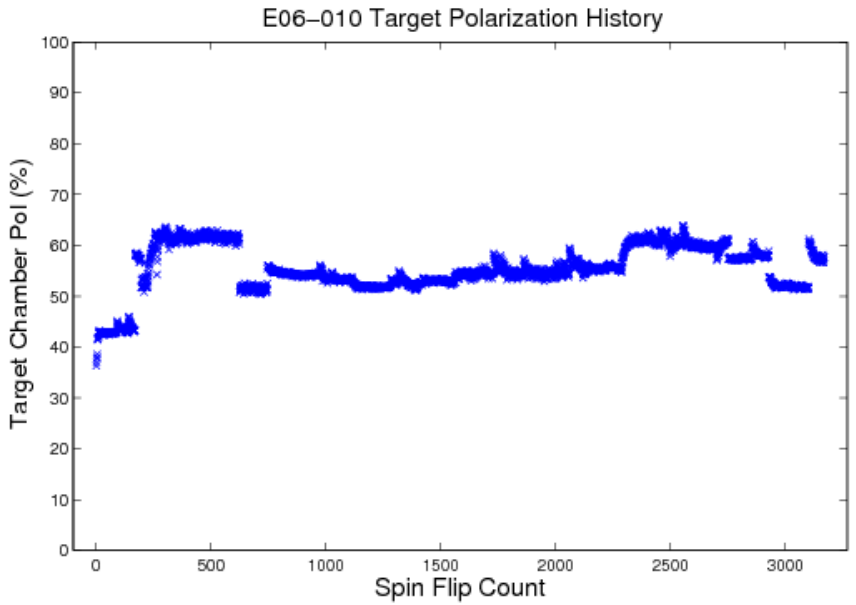
- BigBite at 30° as **electron** arm:
  P_e = 0.6 ~ 2.5 GeV/c
- HRSL at 16° as **hadron** arm:
  P_h = 2.35 GeV/c

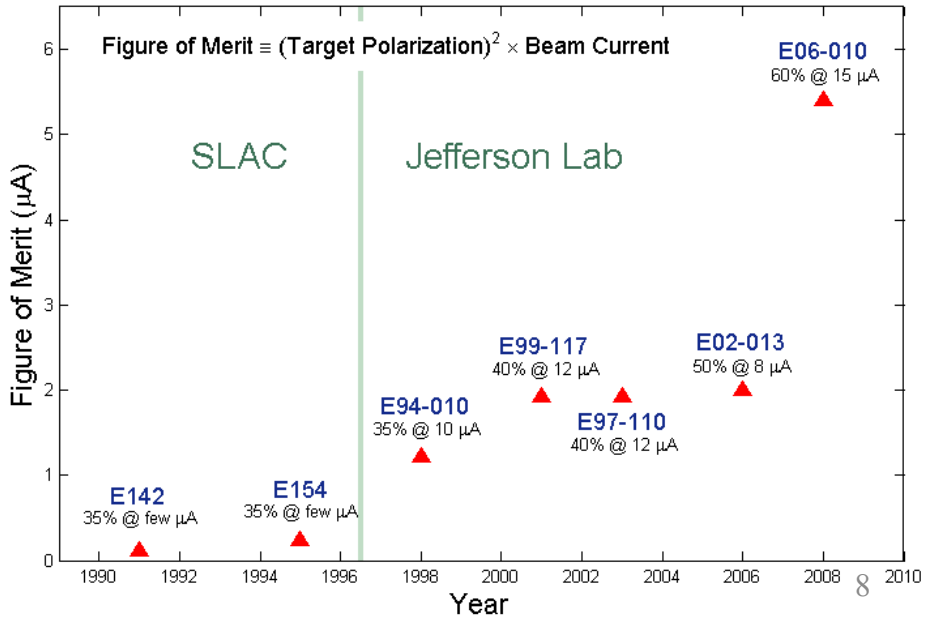
^{3}He Target



Effective Polarized Neutron Target!

- Polarized ^{3}He ran reliably throughout the experiment, and the following three experiments.
- Reached **55%-60%** polarization with 15 μA beam and 20 minute spin flip! **A NEW RECORD!**



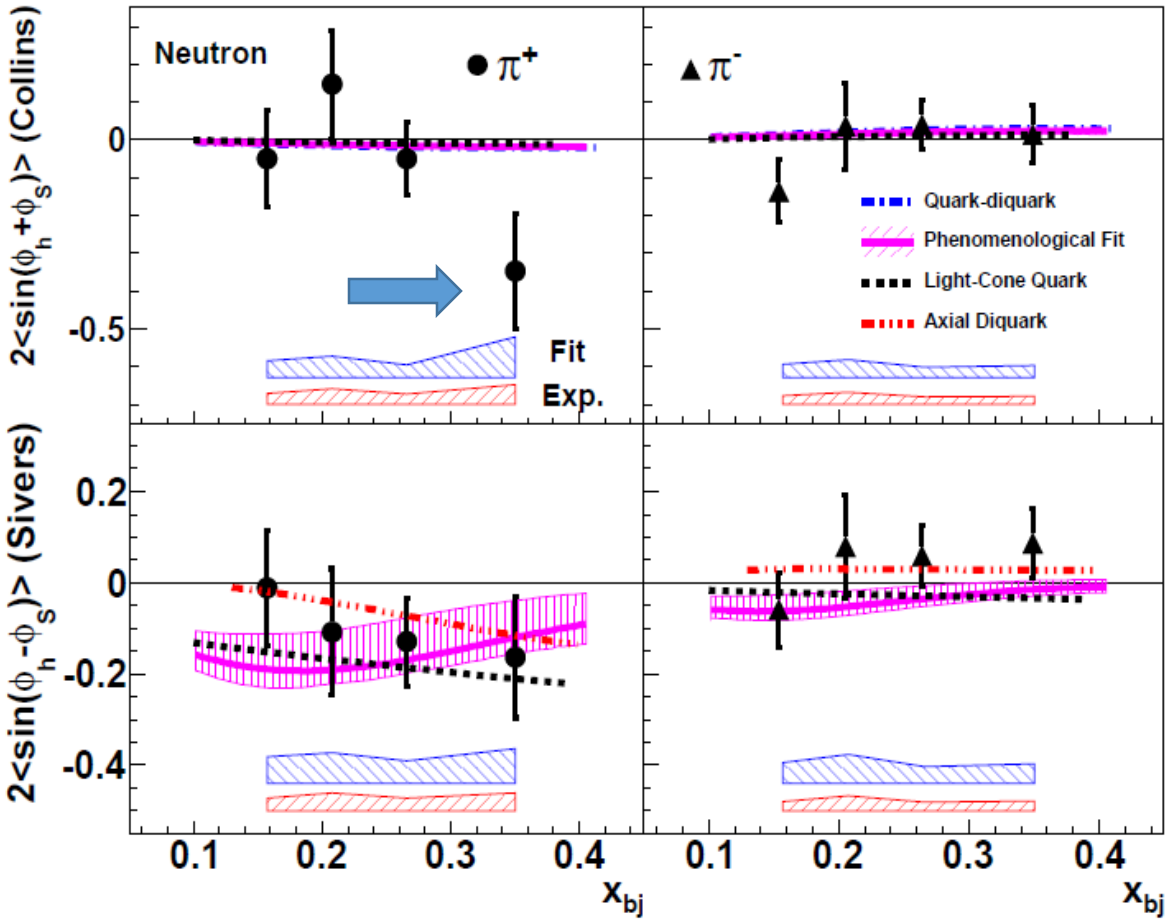


Results on Neutron

- Sizable Collins π^+ asymmetries at x=0.34?
  - Sign of violation of Soffer's inequality?
  - **Data are limited by stat. Needs more precise data!**

- Negative Sivers π^+ Asymmetry
  - Consistent with HERMES/COMPASS

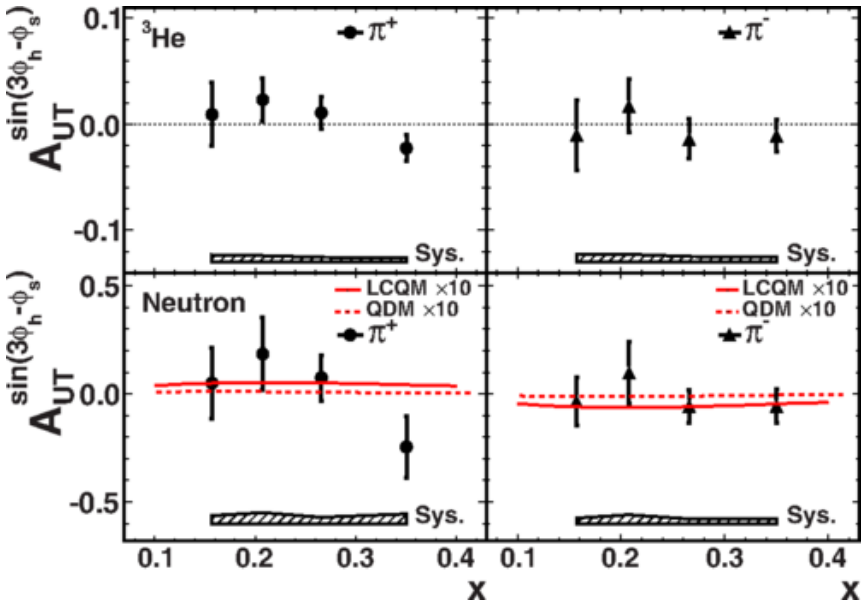
  - **demonstration of negative d quark Sivers function.**



Model (fitting) uncertainties shown in blue band.
Experimental systematic uncertainties: red band
X. Qian *et al*, Phys. Rev. Lett. 107, 072003 (2011)

Results on ^{3}He and neutron

- Pretzelosity TMD ($h_{1T}^{\perp}$) intuitively related to quark OAM
- Non-zero $h_{1T}^{\perp}$ is direct consequence of relativistic nature of quark motion [H. Avakian et al. Phys. Rev. D 81, 074035 (2010), C. Lorce' et al., Phys. Lett. B 710, 486 (2011)]



- Pretzelosity asymmetries consistent with 0 (within experimental uncertainties)

Experimental Pretzelosity asymmetries

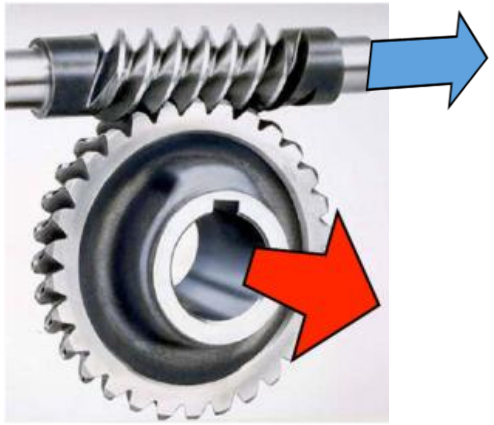
- Top plots for SSAs of ^{3}He
- Bottom plots for SSAs of neutron

Y. Zhang et al. Phys. Rev. C 90, 055209 (2014)

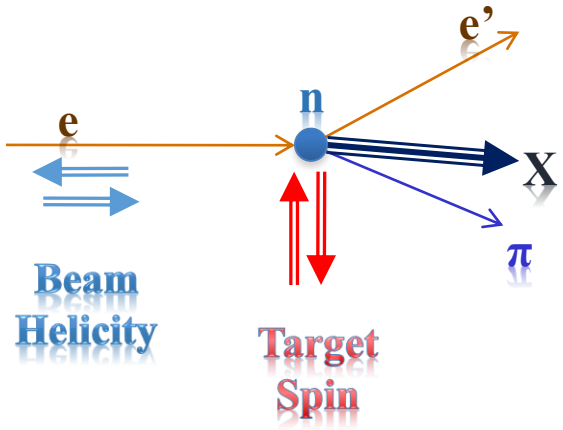
- Large coverage of of transverse momentum of produced hadrons ($P_{h\perp}$) and higher statistical precision necessary [J. She et al., Phys. Rev. D 79, 054008 (2009)] to observe non-zero Pretzelosity asymmetry

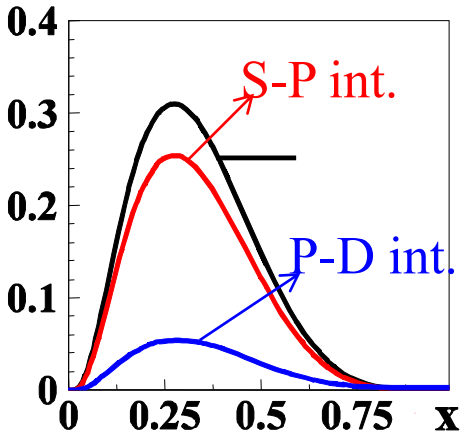
Double Spin Asymmetry: g_{1T}

- $A_{LT}^{\cos(\phi_h - \phi_s)} \propto g_{1T}^q \otimes D_{1q}^h$
  - Leading twist TMD PDFs
  - T-even, Chiral-even
- Dominated by real part of interference between L=0 (S) and L=1 (P) states
  - Imaginary part -> Sivers effect
- First TMDs in Pioneer Lattice calculation
  - arXiv:0908.1283 [hep-lat], Europhys.Lett.88:61001,2009
  - arXiv:1011.1213 [hep-lat] , Phys.Rev.D83:094507,2011



g_{1T} 



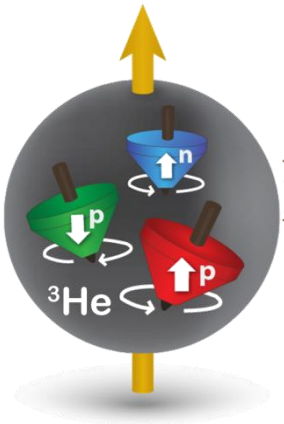


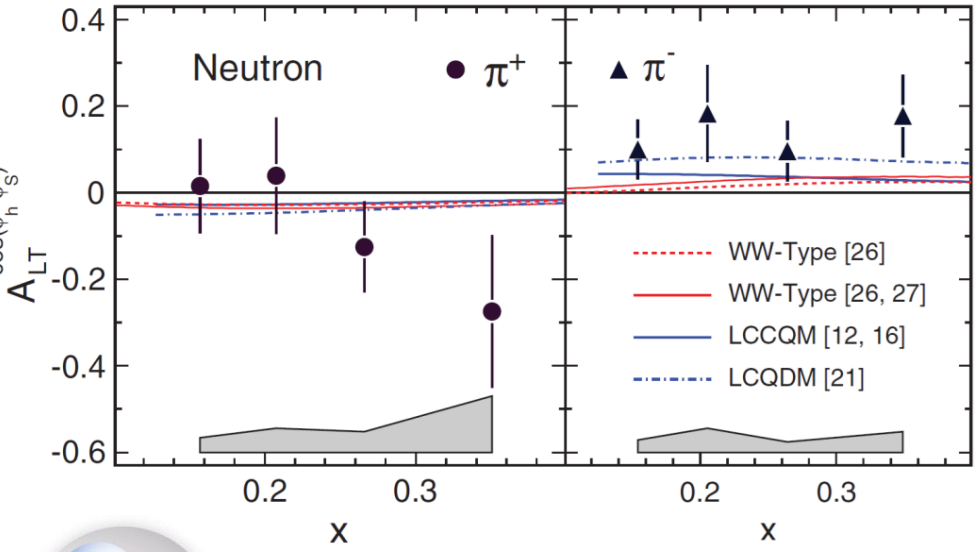
Light-Cone CQM by B. Pasquini, et al. Mod. Phys. Lett. A 24 2903 (2009)

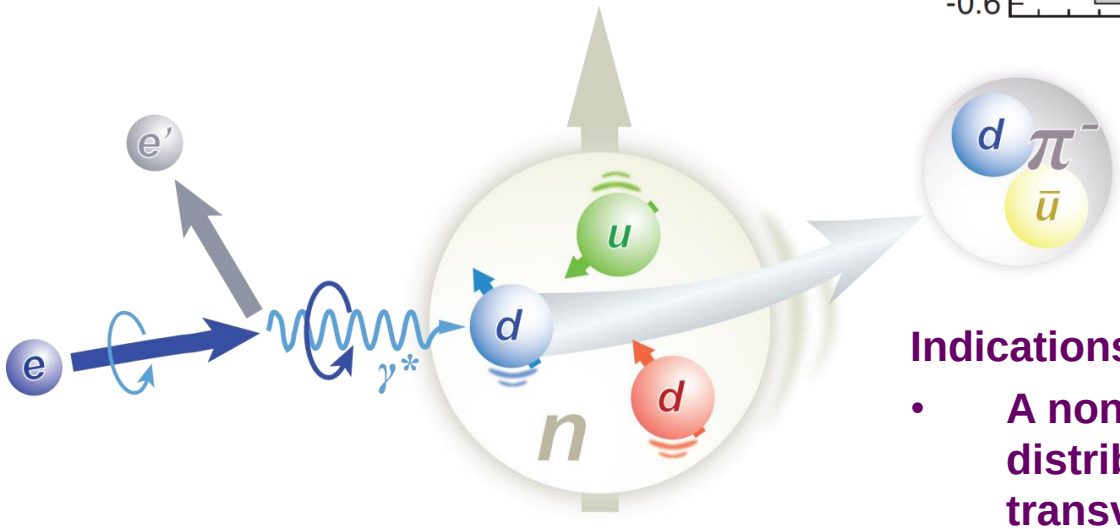
New Observable Reveals Interesting Behaviors of Quarks

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

Target:
polarized ^{3}He => polarized neutron







First measurement of A_{LT}

beam-target double-spin asymmetry

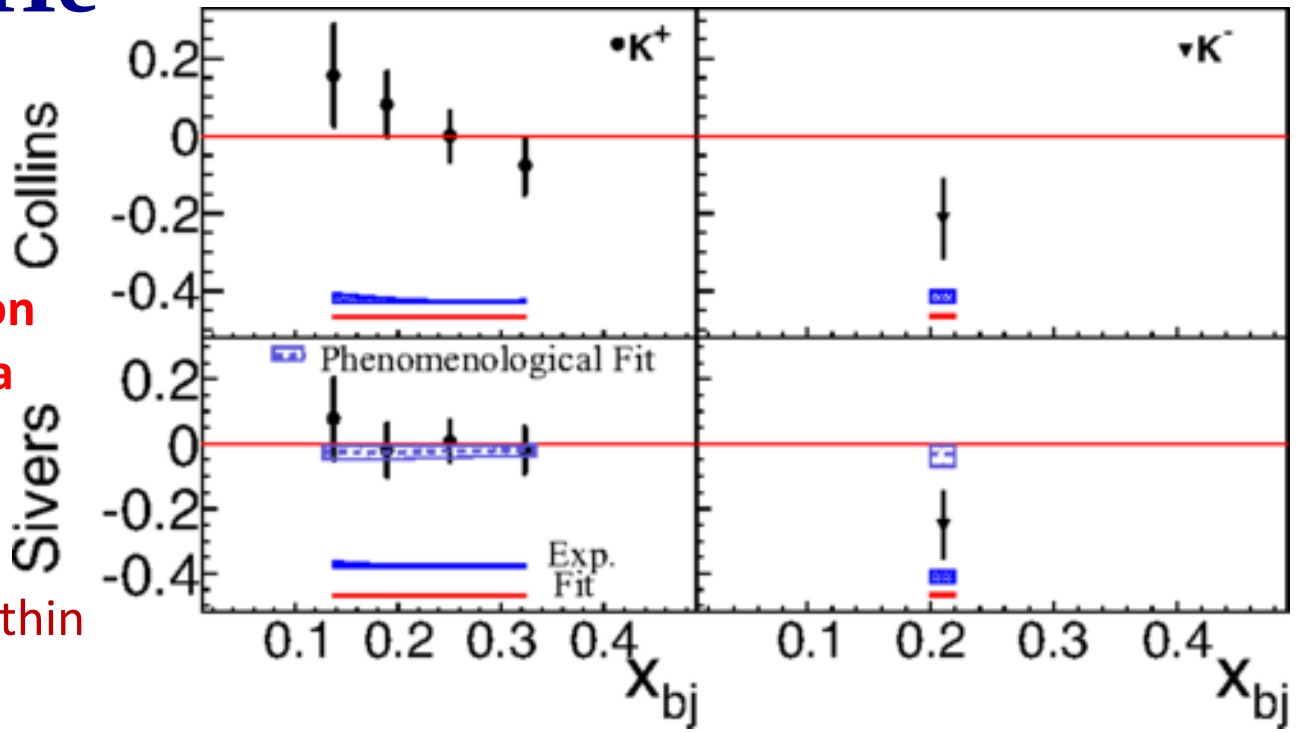
Indications:

- **A non-vanishing quark "transversal helicity" distribution, reveals alignment of quark spin transverse to neutron spin direction**
- **Quark orbital motions**

J. Huang et al., PRL108, 052001 (2012)

Results on ^{3}He

- Negative Collins & Sivers K^- Asymmetry
  - **Sivers moment: 2σ away from prediction based on world data**
- Sivers & Collins K^+ Asymmetry
  - Consistent with 0 within stat uncertainty
  - **Data limited by stat**
  - Sivers moment: Consistent with prediction based on world data
  - Further study of quark flavor dependence of Sivers and Transversity



- Previous SIDIS results from HERMES and COMPASS with proton and deuteron target showed Transversity and Sivers have dependence on quark flavor [A. Airapetian et al., Phys. Rev. Lett. 103, 152002 (2009), A. Airapetian et al., Phys. Lett. B 693, 11 (2010), M. Alekseev et al., Phys. Lett. B 692, 240 (2010), M. Alekseev et al., Phys. Lett. B 673, 127 (2009)]

Y. X. Zhao et al. Phys. Rev. C 90, 055201 (2014)

Unpolarized differential cross section of Semi-Inclusive DIS

$$\frac{d\sigma}{dxdyd\phi_S dz d\phi_h dP_{h\perp}^2} = \frac{\alpha^2}{xyQ^2}\frac{y^2}{2(1-\epsilon)} \cdot \{F_{UU,T} + \epsilon \cdot F_{UU,L}$$

$$+\sqrt{2\epsilon(1-\epsilon)}\cos\phi_h \cdot \boldsymbol{F_{UU}^{cos\phi_h}}$$ Twist-2 Cahn effect: $\cos\phi_h$ dependence

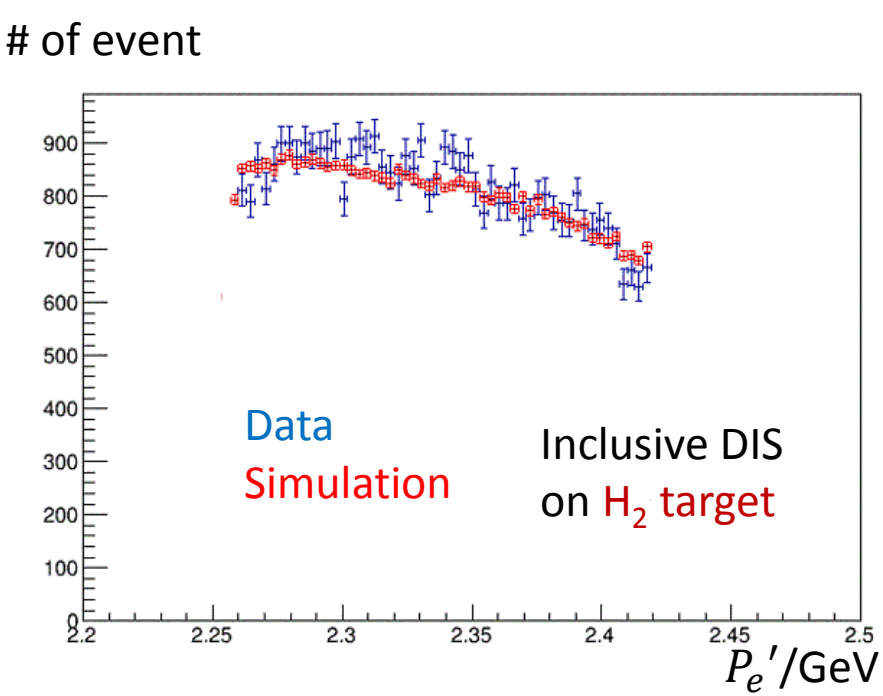
$$+\epsilon\cos(2\phi_h) \cdot \boldsymbol{F_{UU}^{\cos(2\phi_h)}}\}$$ Boer-Mulders & twist-4 Cahn : $\cos(2\phi_h)$ dependence

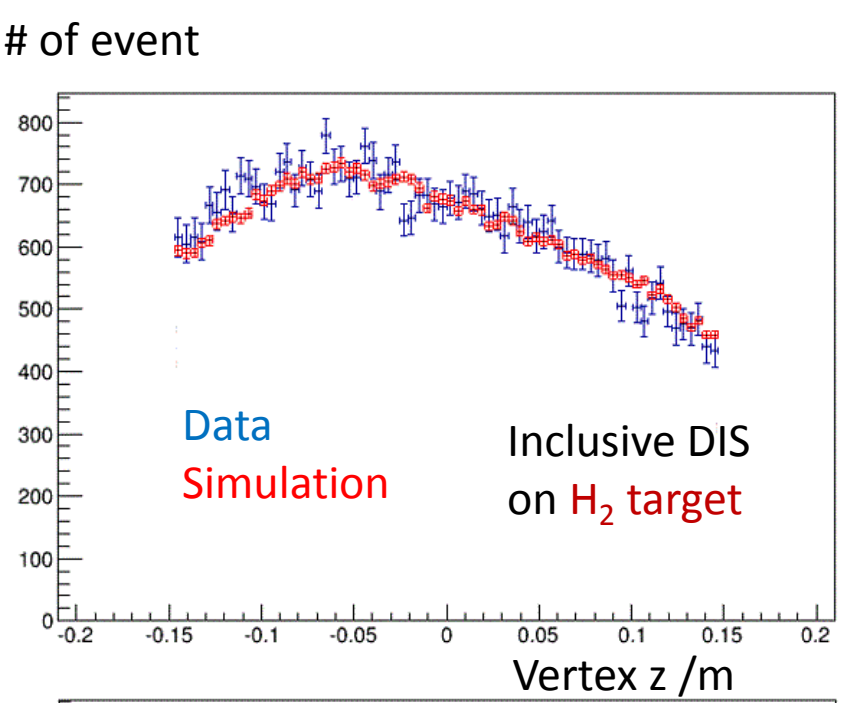
- Twist-2 and 4 Cahn effect $\propto f_1 \otimes D_1$
  - Non-zero Cahn effect **solely require non-zero quark transverse momentum**
  - Related to quarks' **intrinsic transverse momentum distribution**
- Boer-Mulders effect $\propto h_1^\perp \otimes H_1^\perp$
  - Boer-Mulders TMD PDF: transversely polarized quarks in unpolarized nucleon
- Twist-4 Cahn effect could have similar size of contribution to $\langle\cos(2\phi_h)\rangle$ as Boer-Mulders [Phys. Rev. D. 81:114026 (2010) based on HERMES/COMPASS results]

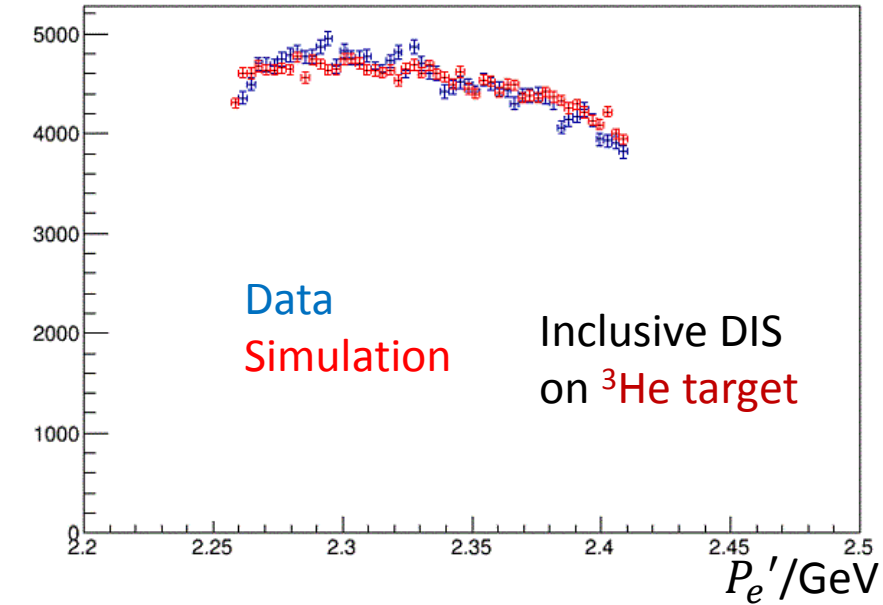
Unpolarized differential cross section

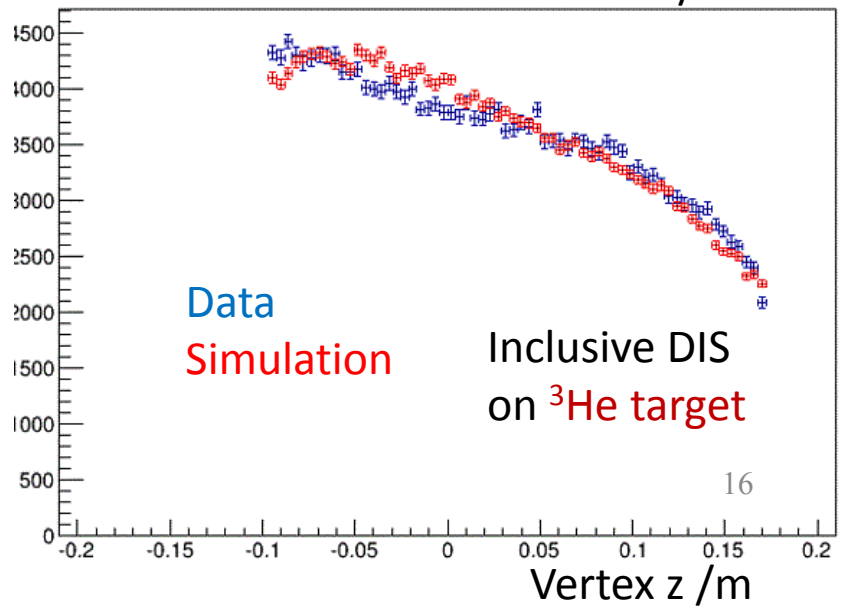
- Combine data with different target and beam polarizations for unpolarized cross section analysis
  - Radiative correction for unpolarized process
- Detector models in simulation for description of experimental acceptance
  - Simulation vs. data in HRS and BigBite detector individually: inclusive DIS and elastic e-p processes
- Updated efficiency and contamination study with higher precision than SSA & DSA analysis

HRS simulation vs. data



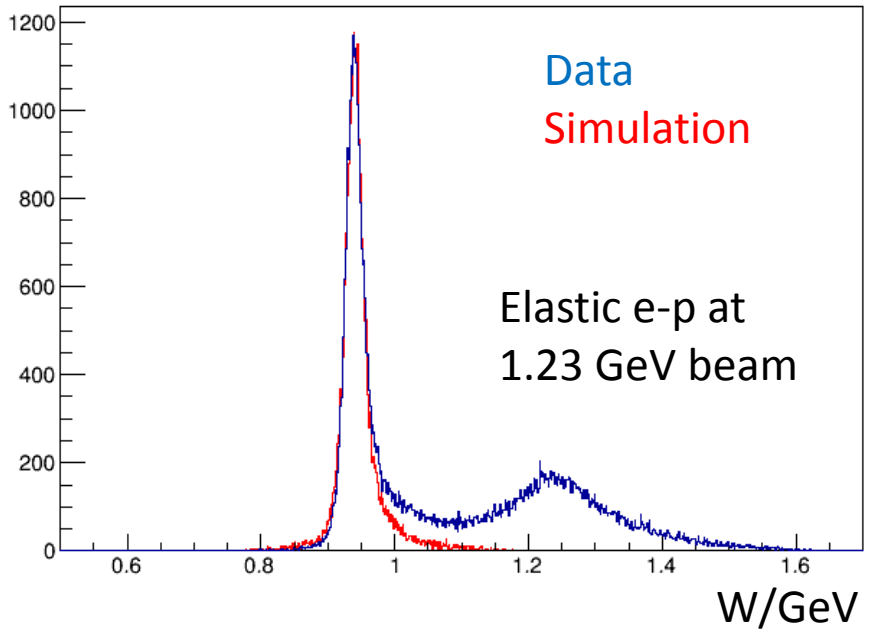




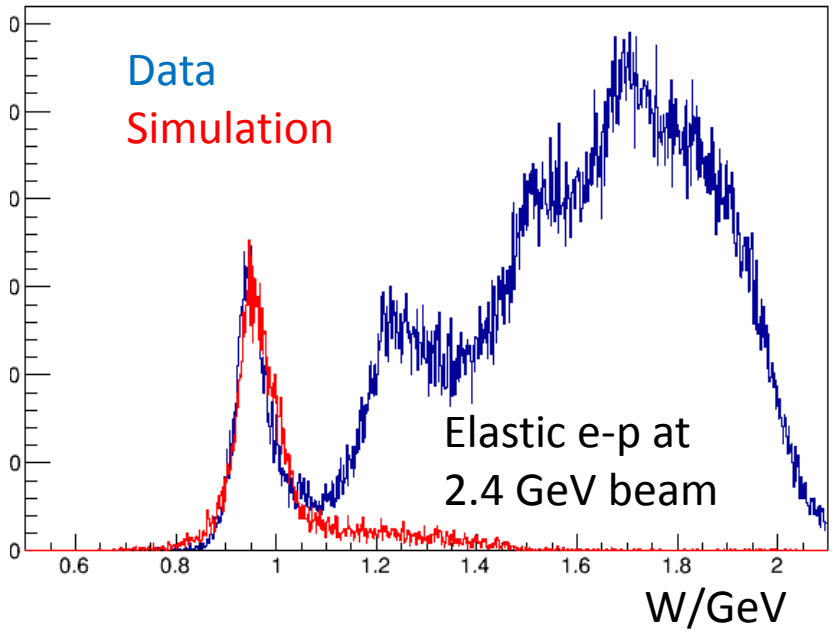


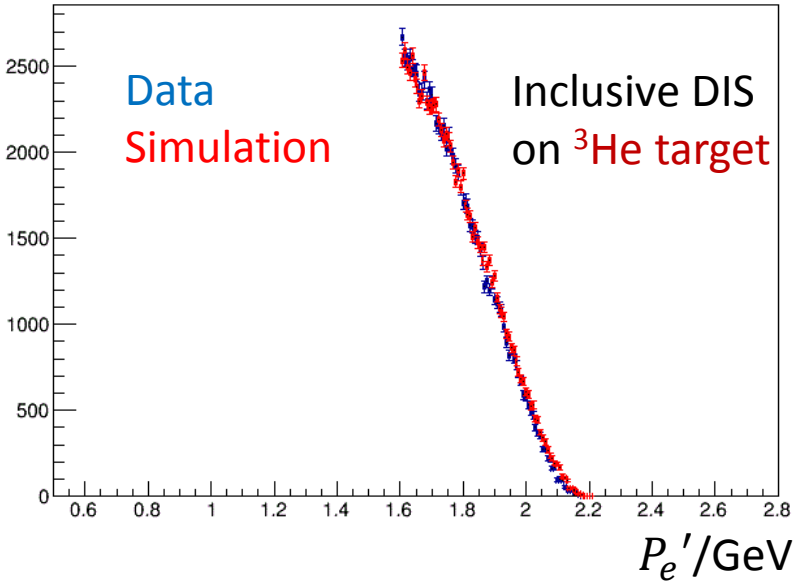
BigBite simulation vs. data

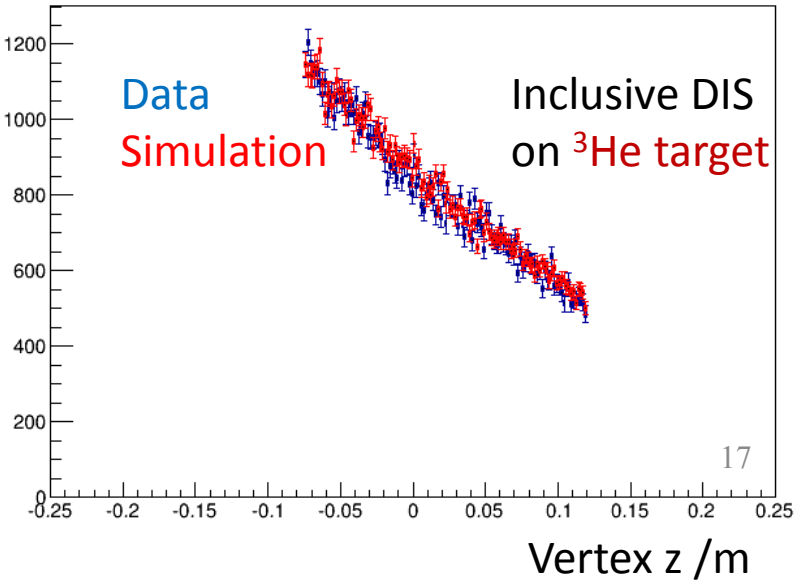
of event



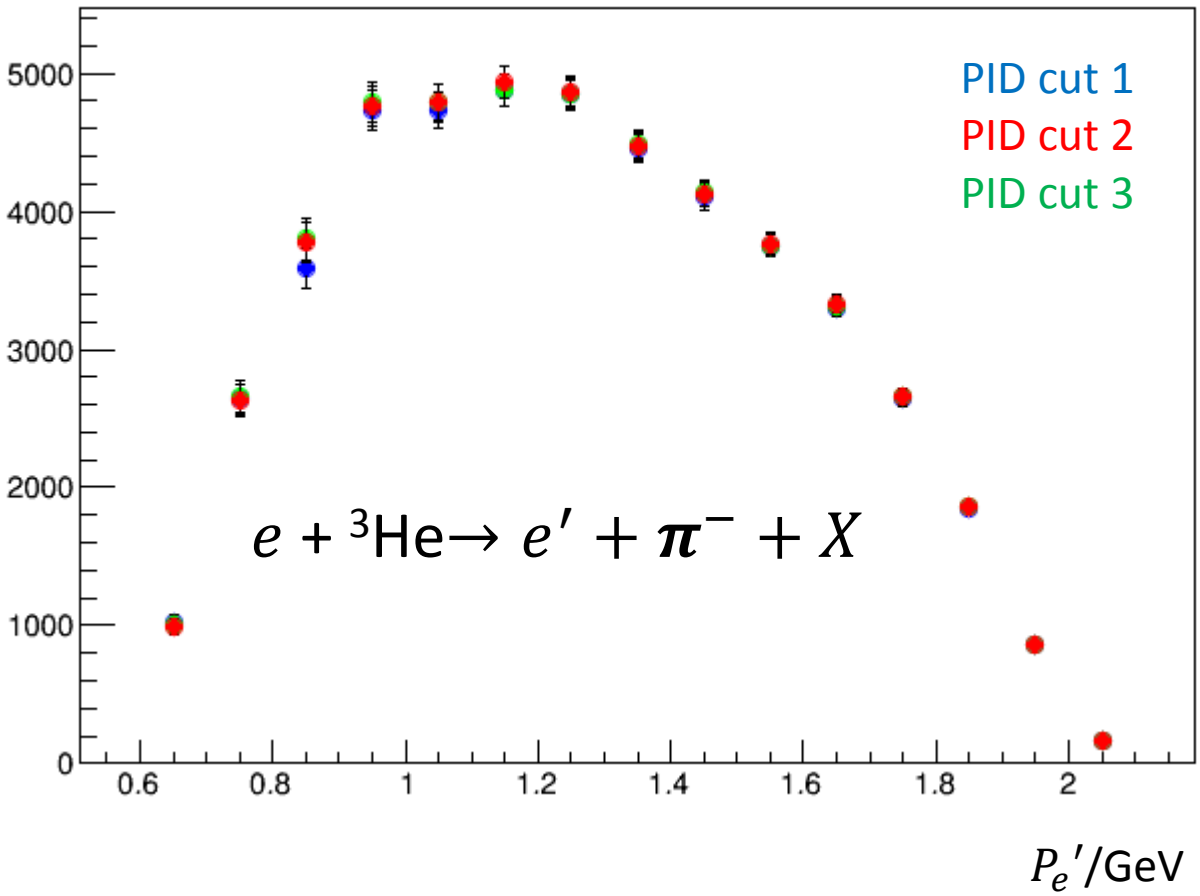
# of event







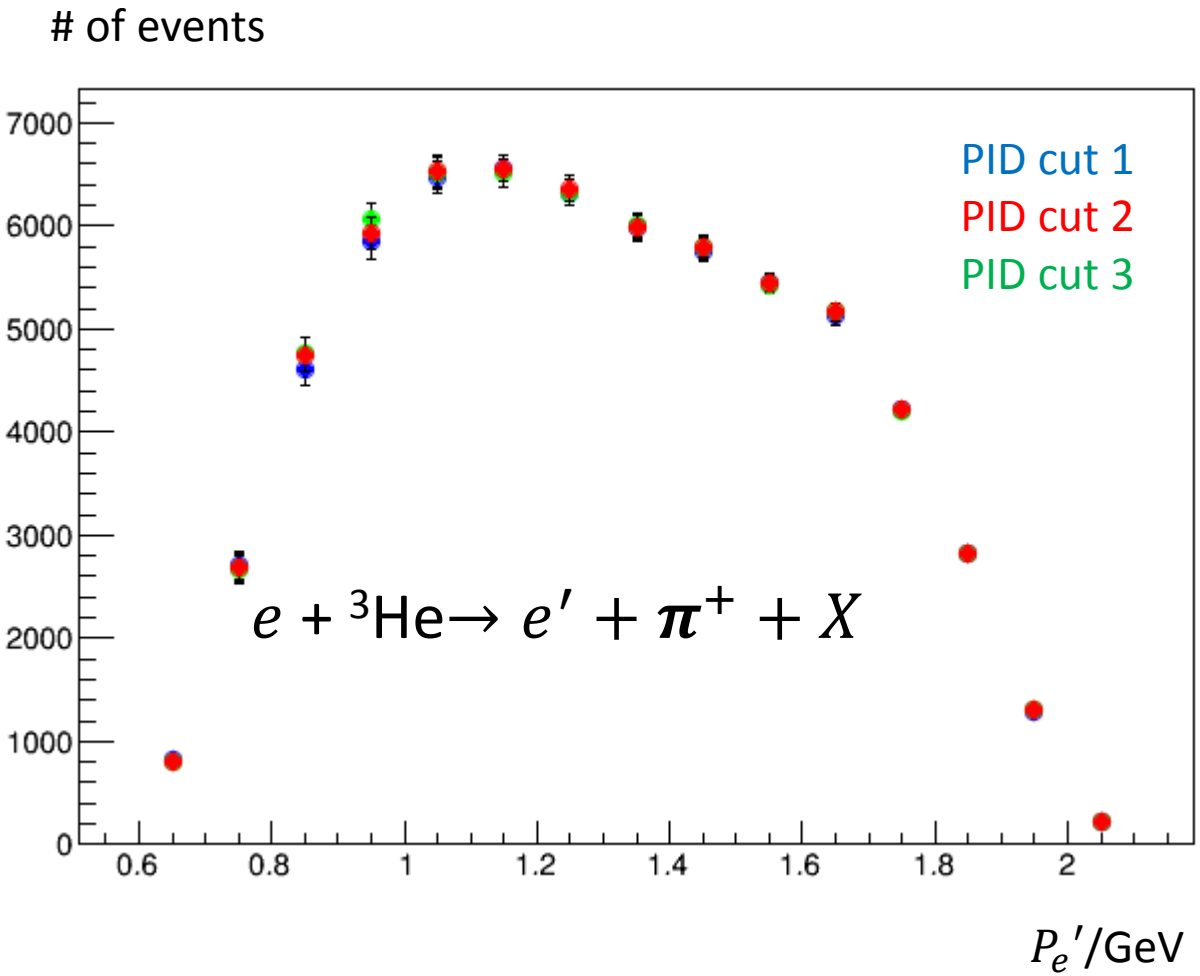
Data with efficiency/contamination correction in SIDIS channel



- PID cut 1-3: lower π^- contamination & higher loss of e' in BigBite
- Consistency: data under 3 different PID cuts, corrected by related contamination and efficiency, respectively

- SIDIS channel: $e + {}^3\mathrm{He} \rightarrow e' + \pi^- + X$
  - e' detected by BigBite
  - π^- detected by HRS

Data with efficiency/contamination correction in SIDIS channel



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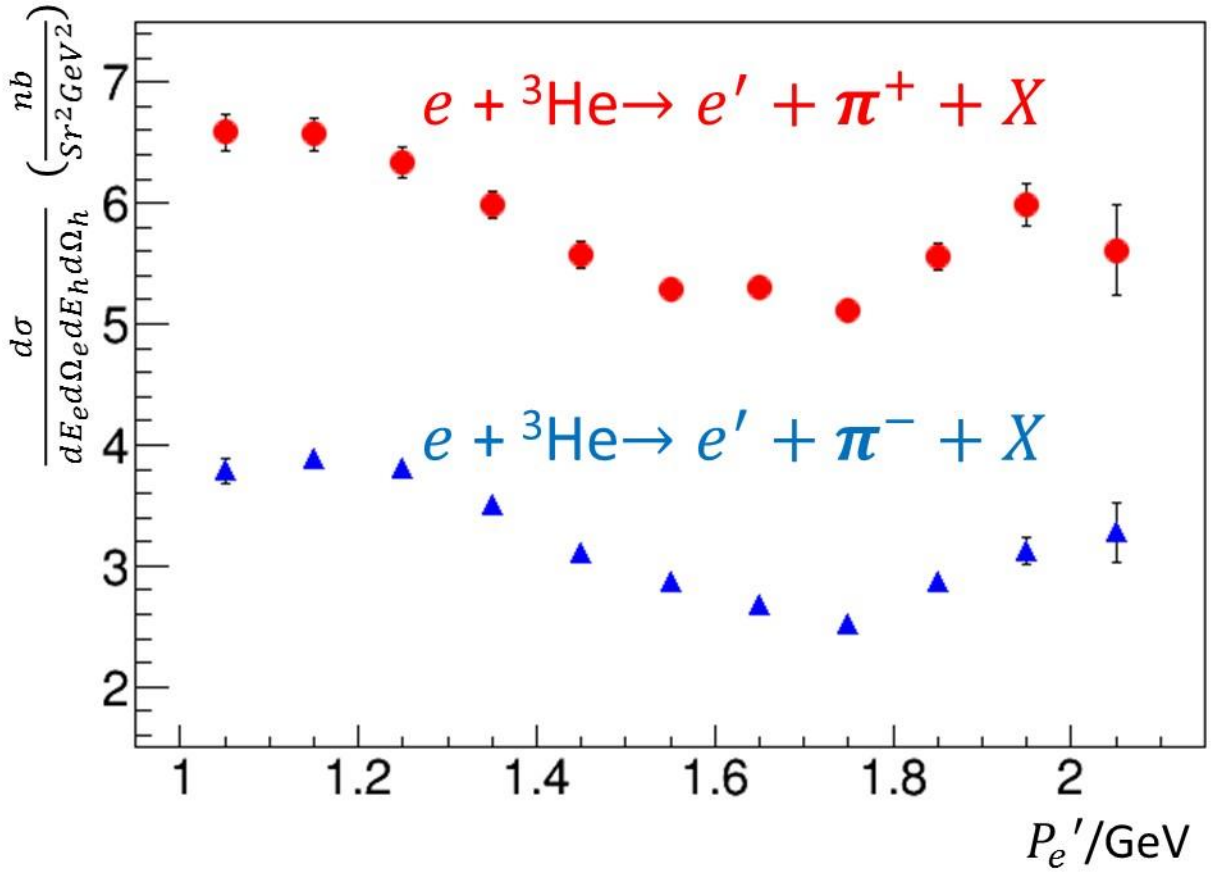
Preliminary results



- Data corrected for efficiency & contamination
- N_2 background subtracted
- Acceptance, radiative correction & $\pi^{\pm}$ decay effect: SIDIS simulation

- Additional systematic uncertainties to be added
- P_e' < 1 GeV: large uncertainties in photon-induced-*e* & trigger efficiency
  - On-going improvements

- Cross section to be binned in other variables (x_{bj}, z_h, Q^2, ϕ_h, etc.) for physics of interest

Summary

- SIDIS results from JLab experiment E06-010 explored SSA and DSA: Sivers, Collins, Pretzelosity, Trans-Helicity, etc.
  - Future experiments with larger coverage of kinematics and higher statistics: exploration to precision (SoLID & JLab 12 GeV upgrade)
- Unpolarized SIDIS differential cross section from E06-010: Boer-Mulders and Cahn effect (& more physics)

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