Studies of Nucleon Transverse Spin and TMDs at JLab

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Pacific-Spin2015, Taipei, October 8, 2015

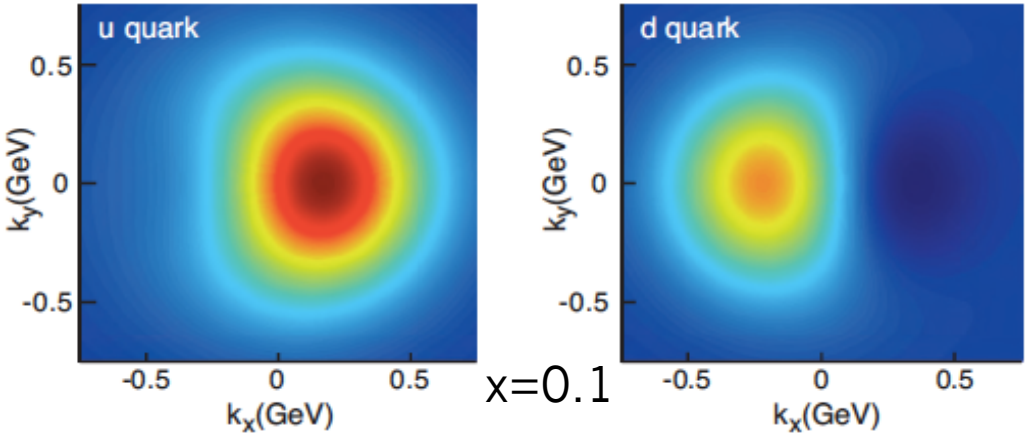
- Introduction
- Transverse Spin (Transversity) and Tensor Charge
- TMDs and Orbital Angular Momentum: Worm-Gear, Pretzelosity, Sivers
- Single Spin Asymmetries from Inclusive Reactions

  Inclusive hadron productions

  Inclusive electron: 2-photon exchange to probe nucleon
- TMD Study with JLab12 : **SoLID Program** and CLAS12
- Summary

Introduction

Transverse Spin and TMDs



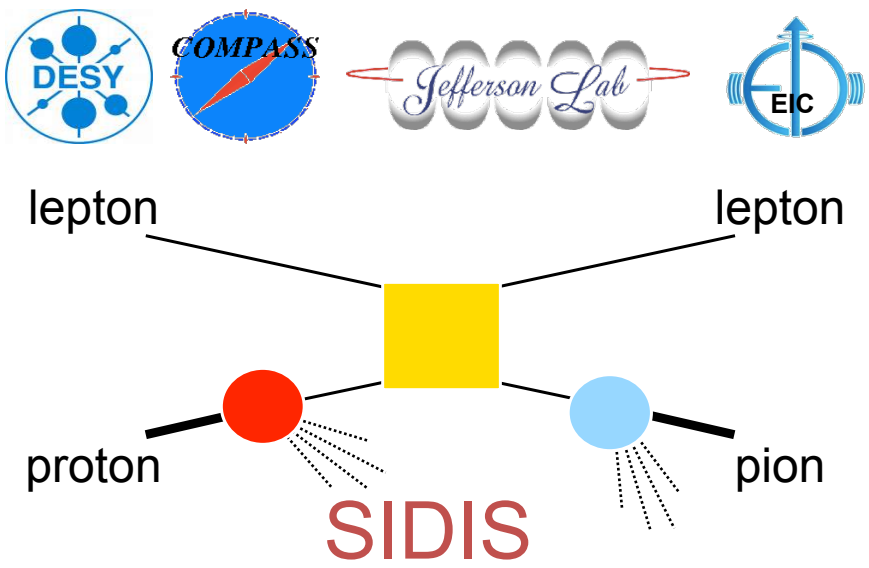
Leading-Twist TMD PDFs

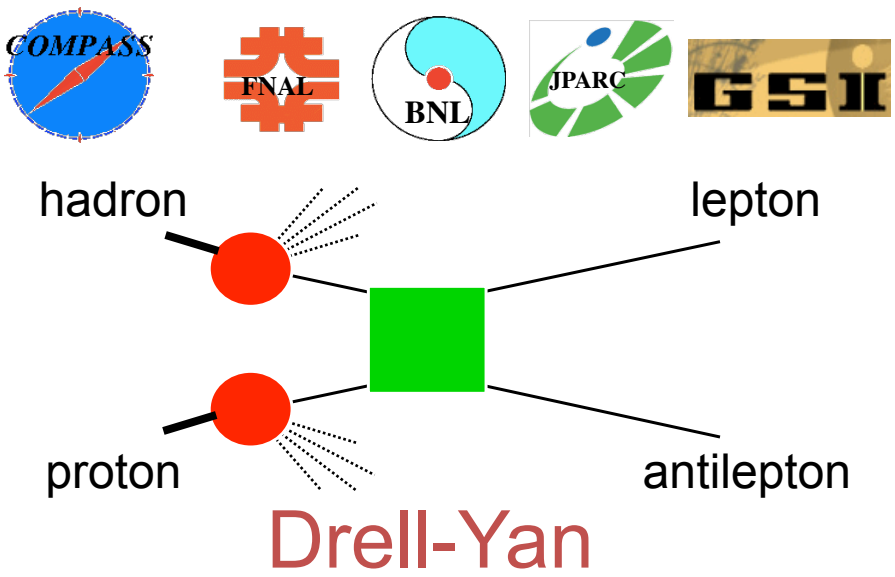
Nucleon Spin

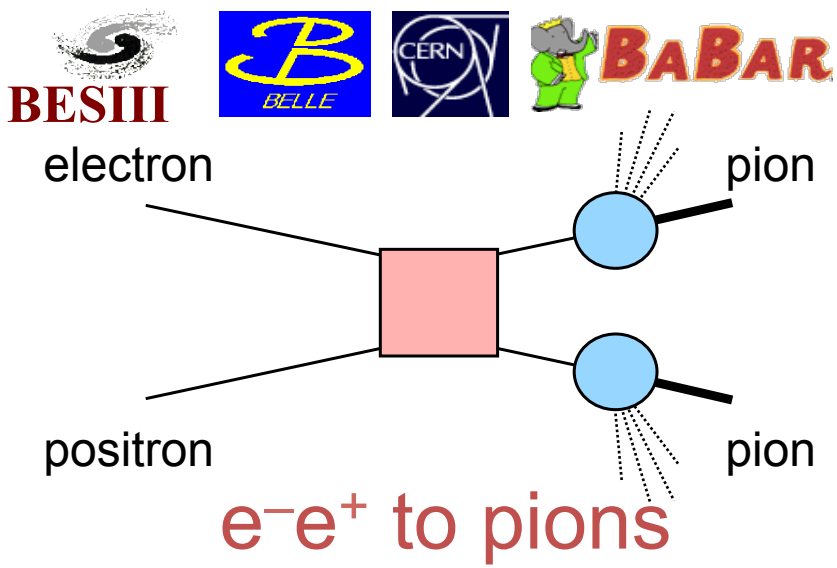
Quark Spin

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

Access TMDs through Hard Processes







Partonic scattering amplitude

Fragmentation amplitude

Distribution amplitude

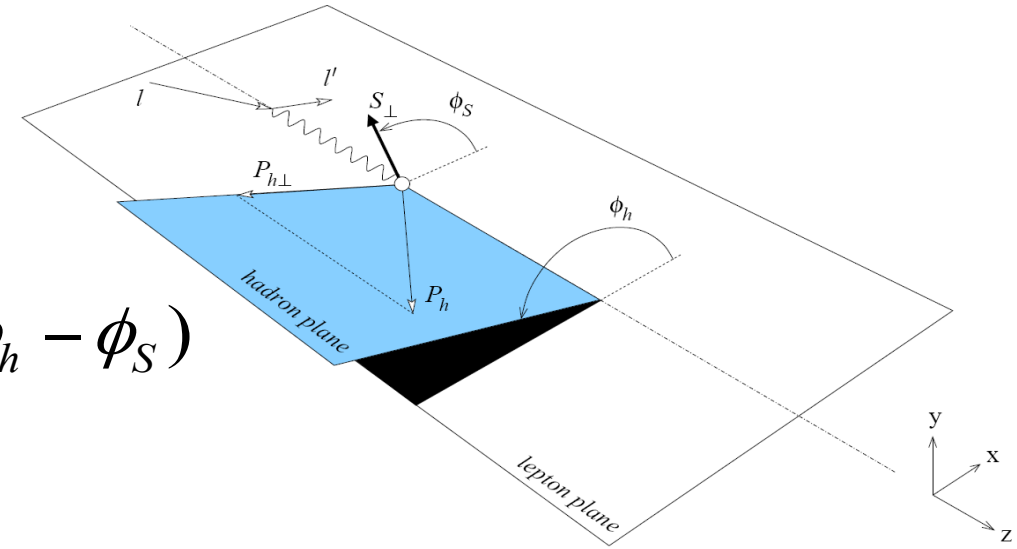
$$f_{1T}^{\perp q}(\mathrm{SIDIS}) = -f_{1T}^{\perp q}(\mathrm{DY})$$

SIDIS: Separation of Collins, Sivers and pretzelocity Asymmetries through Angular Dependence

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

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

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



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

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

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

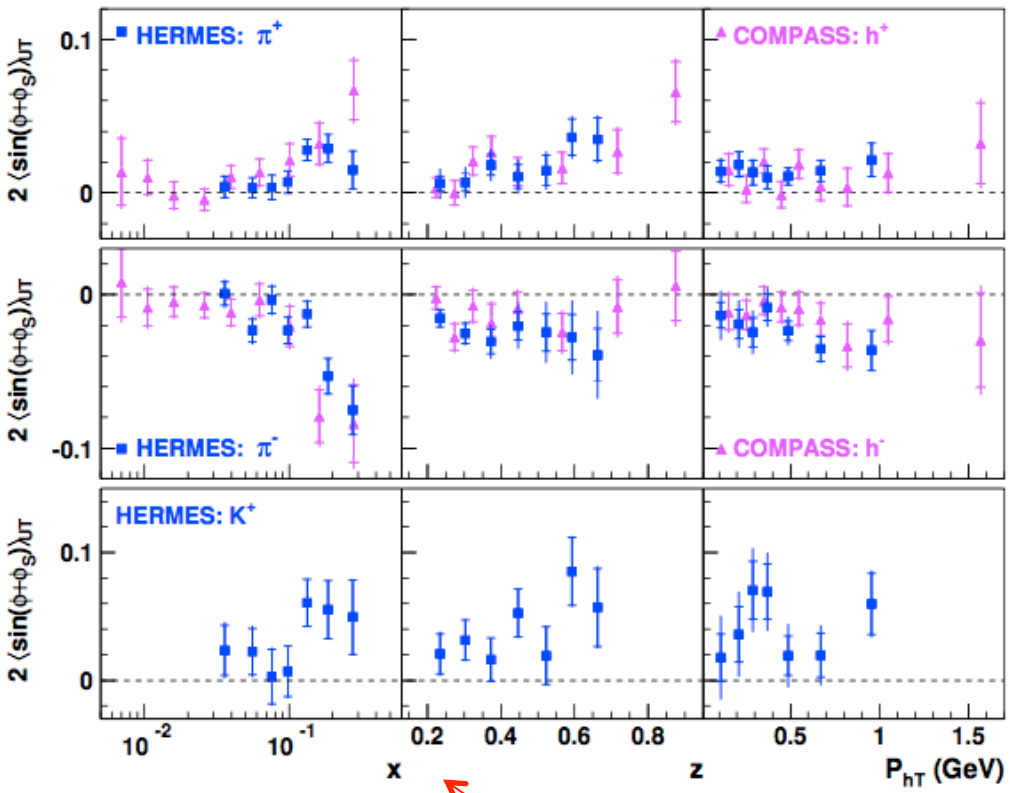
Transverse Spin (Transversity)

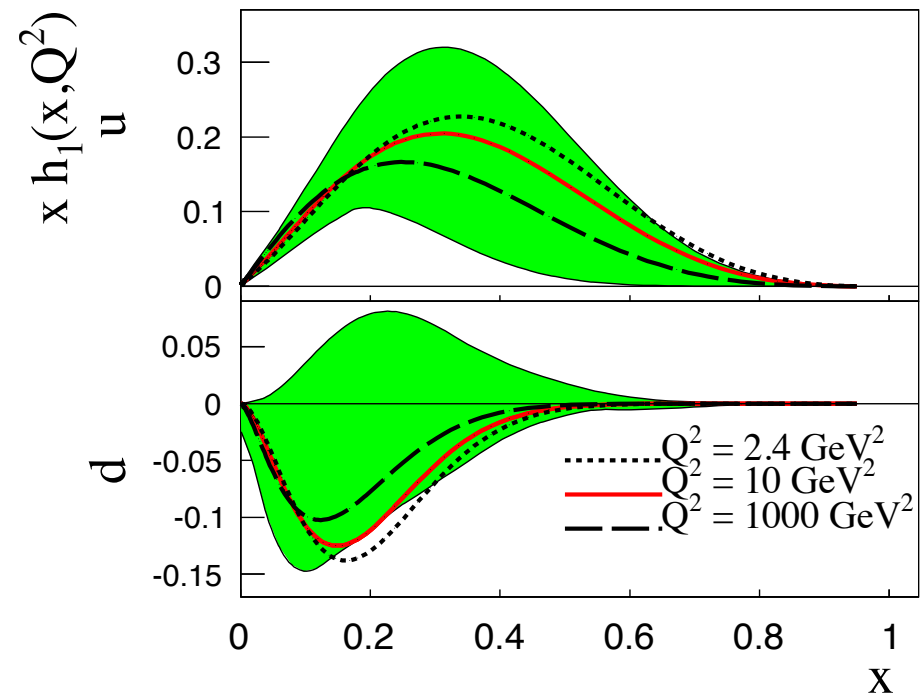
h_1

Transversity

and Tensor Charge

HERMES/COMPASS: *Collin Asymmetries and Extraction of Transversity*



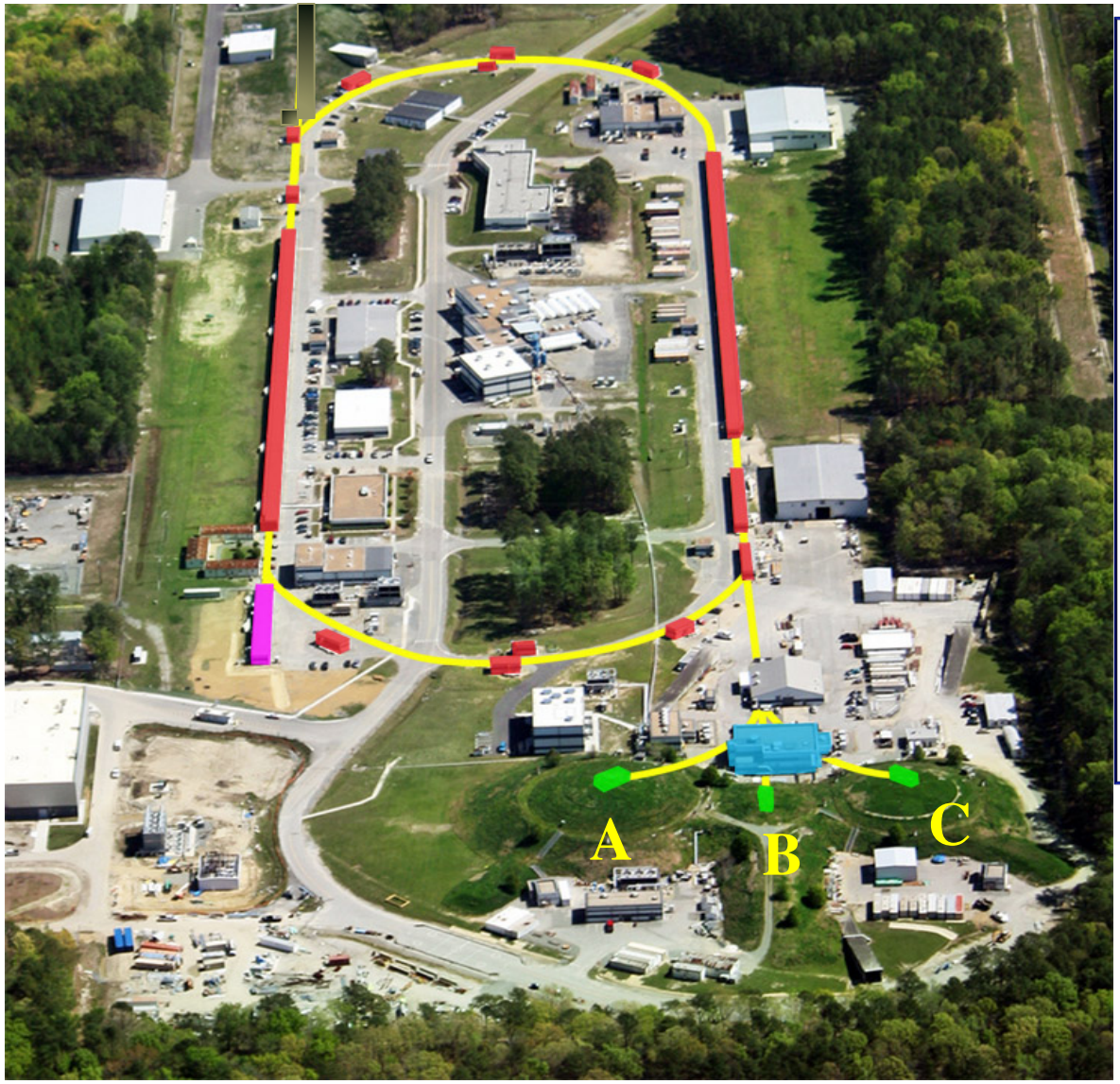


Also Sivers and other TMDs.

N \ q	U	L	T
U	f_1		$h_1^\perp$
L		g_1	$h_{1L}^\perp$
T	$f_{1T}^\perp$	g_{1T}	h_1 $h_{1T}^\perp$

Z. Kang, *et al.*
arXiv:1505.05589 (2015)

Jefferson Lab at a Glance (12 GeV now!)



CEBAF

- **High-intensity** electron accelerator based on **CW SRF** technology
- **I_{max} = 200 μA**
- **Pol_{max} = 90%**
- **E_{max} = 6 GeV: 1995-2012**
- **Energy Upgrading to 12 GeV (2012-now)**
- **12 GeV data taking started**

- **~ 1400** Active Users
- Produces **~1/3** of US PhDs in Nuclear Physics

JLab 6 GeV Experiment E06-010

$$^3He^{\uparrow}(\vec{e},e'\pi^{\pm})X$$

$$^3He^{\uparrow}(\vec{e},e'K^{\pm})X$$

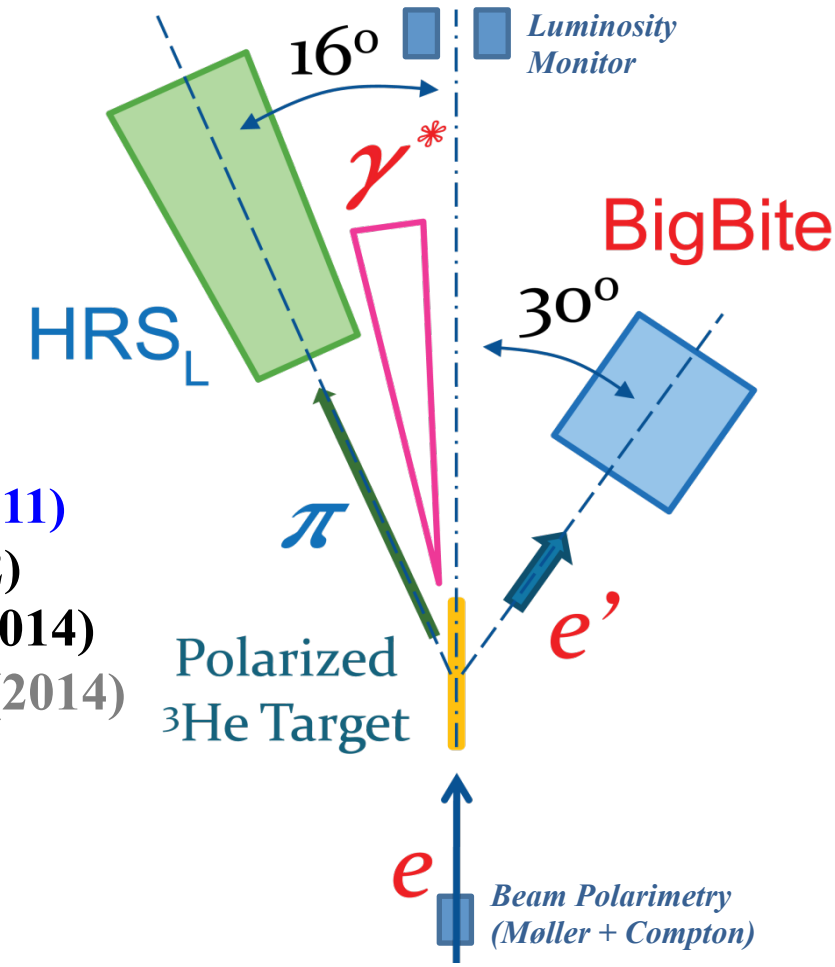
Spokespersons: J. P. Chen, E. Cisbani, H. Gao, X. Jiang and J. C. Peng

7 PhD Thesis Students (graduated) + 2 new students

- **First measurement on n (^{3}He)**
- Transversely Polarized ^{3}He Target
- Polarized Electron Beam, 5.9 GeV

- **Results published in 7 PRL/PRC papers:**

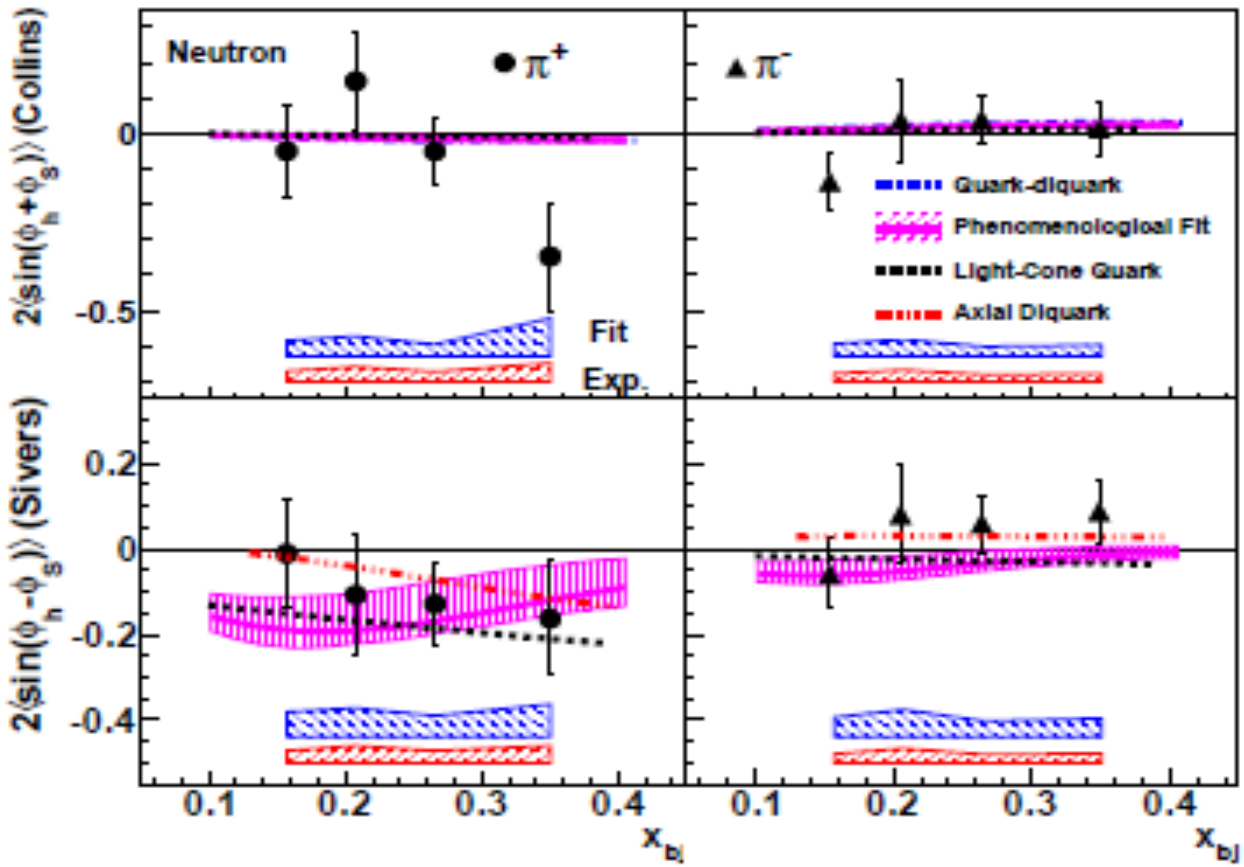
✓ **π^{+-} Collins/Sivers asymmetries: PRL 107:072003(2011)**
✓ **π^{+-} worm-gear asymmetries: PRL 108, 052001 (2012)**
✓ **π^{+-} pretzelosity asymmetries: PRC 90 5, 055209(2014)**
✓ **K^{+-} Collins/Sivers asymmetries:PRC 90 5, 05520 (2014)**
✓ **Inclusive hadron SSA: PRC 89, 042201 (2014)**
✓ **Inclusive electron SSA: PRL 113, 022502 (2014)**
✓ **Inclusive hadron DSA: PRC 92, 015207 (2015)**



^{3}He (n) Target Single-Spin Asymmetry in SIDIS

JLab E06-010 collaboration, X. Qian at al., **PRL 107:072003(2011)**

$$n^{\uparrow}(e,e'h), h = \pi^+, \pi^-$$



neutron Collins SSA small
Non-zero at highest x for π+

N \ q	U	L	T
U	f_1		$h_1^{\perp}$
L		g_1	$h_{1L}^{\perp}$
T	$f_{1T}^{\perp}$	g_{1T}	h_1 $h_{1T}^{\perp}$

neutron Sivers SSA:
negative for π^+,
Agree with Torino Fit

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

Precision Study of TMDs: JLab 12 GeV, EIC

- Explorations: HERMES, COMPASS, RHIC-spin, JLab6,…
- From exploration to precision study

  JLab12: valence region; EIC: sea and gluons
- Transversity: fundamental *PDF*s, tensor charge
- *TMD*s: 3-d momentum structure of the nucleon

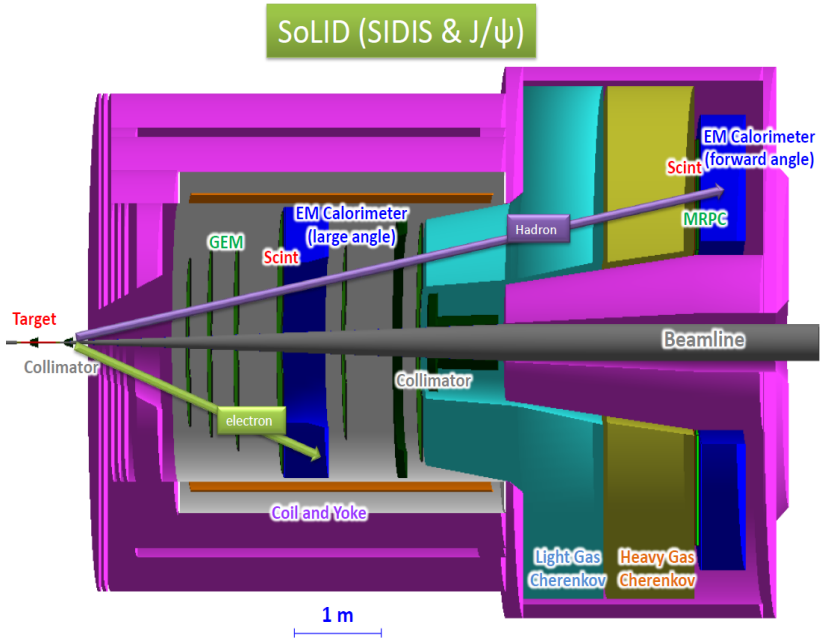
  → information on quark orbital angular momentum

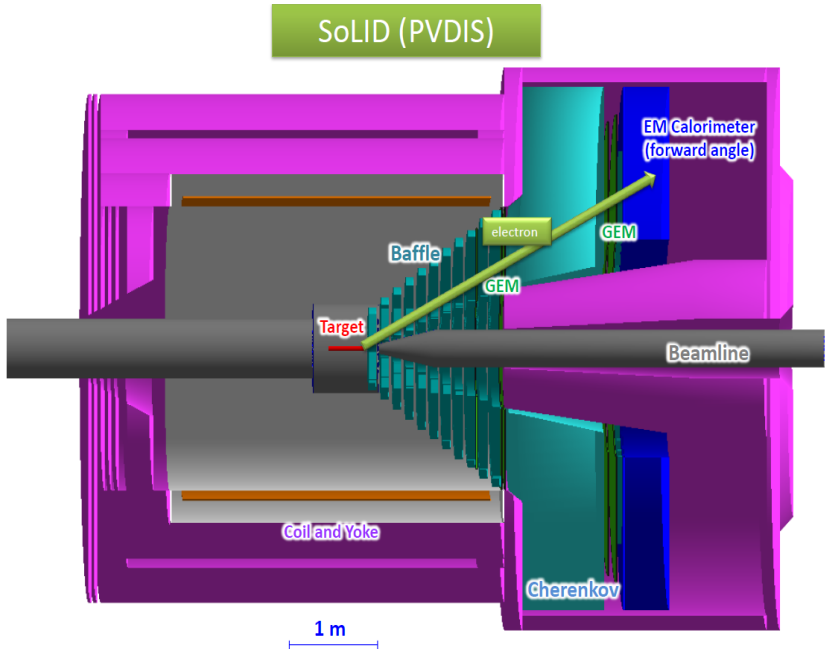
  → information on QCD dynamics
- Multi-dimensional mapping of *TMD*s
- Precision → high statistics
  - high luminosity and large acceptance

Overview of SoLID

Solenoidal **L**arge **I**ntensity **D**evice

- **Full exploitation of JLab 12 GeV Upgrade**
  → A **Large Acceptance** Detector **AND** Can Handle **High Luminosity** (10^{37}-10^{39})
  Take advantage of latest development in detectors , data acquisitions and simulations
  Reach ultimate precision for SIDIS (TMDs), PVDIS in high-*x* region and threshold J/ψ
- **5 highly rated experiments approved**
  Three SIDIS experiments, one PVDIS, one J/ψ production (+ 3 run group experiments)
- **Strong collaboration** (250+ collaborators from 70+ institutes, 13 countries)
  Significant international contributions (Chinese collaboration)

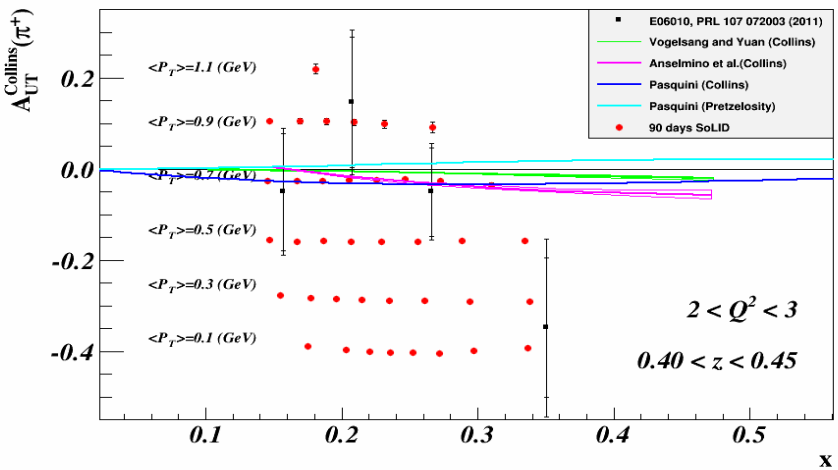




Transversity and Tensor Charge

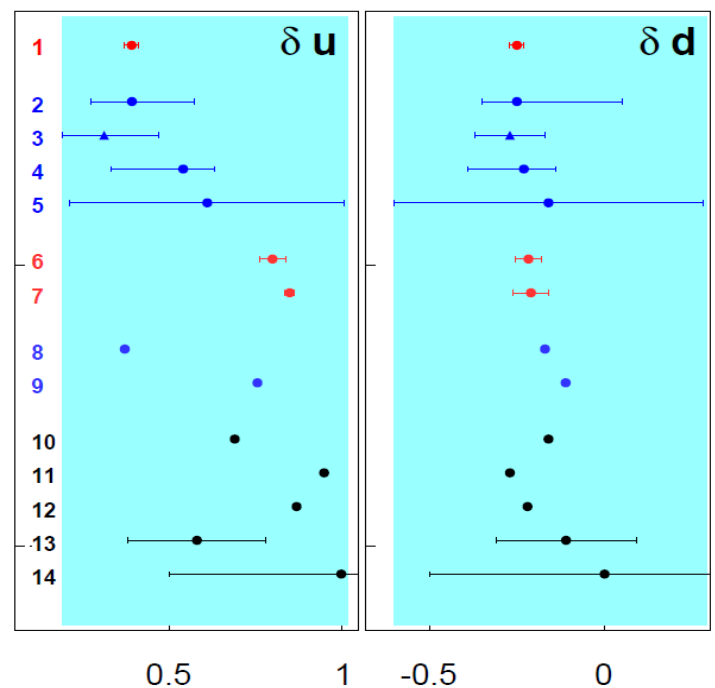
- Collins Asymmetries ~ Transversity (x) Collin Function
- **Transversity**: chiral-odd, not couple to gluons, **valence behavior**, largely unknown
- **Tensor charge (0th moment of transversity): fundamental property**
  Lattice QCD, Bound-State QCD (Dyson-Schwinger) , Light-cone Quark Models, …
- **SoLID** with **trans polarized n & p** → determination of tensor charges for **d & u**
- **Inputs to other physics: ex. EDM** $\tilde{d}_n = \tilde{d}_u \delta_T d + \tilde{d}_d \delta_T u.$

Collins Asymmetries



P_T vs. x for one (Q^2, z) bin
Total > 1400 data points

Tensor Charges



SoLID projections

Extractions from existing data

LQCD

DSE

Models

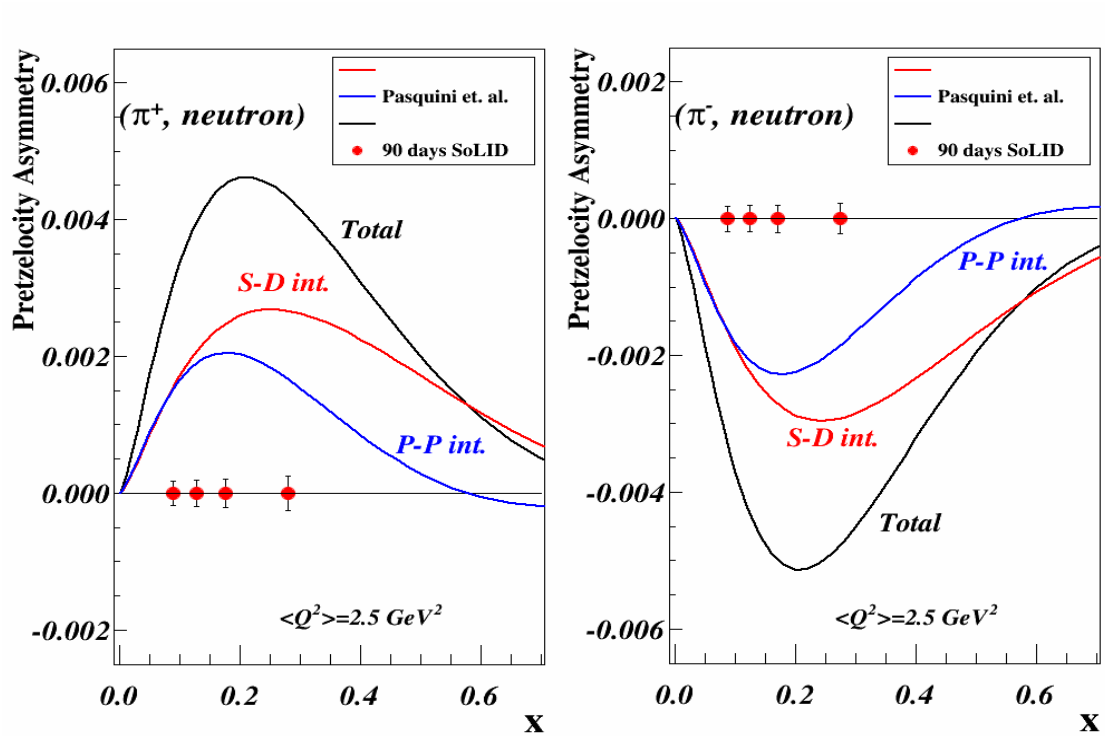
- *Projections with a model*
- *There are un-measured regions*
- *QCD evolutions being worked*

TMDs and Orbital Angular Momentum

Worm-Gear, Pretzelosity, Sivers

TMDs: Access Quark Orbital Angular Momentum

- TMDs : Correlations of transverse motion with quark spin and orbital motion
- **Without OAM, off-diagonal TMDs=0**,
  no direct model-independent relation to the OAM in spin sum rule yet
- Sivers Function: QCD lensing effects
- In a large class of models, such as light-cone quark models
  Pretzelosity: ΔL=2 (L=0 and L=2 interference , L=1 and -1 interference)
  Worm-Gear: ΔL=1 (L=0 and L=1 interference)
- **SoLID with trans polarized n/p → quantitative knowledge of OAM**



SoLID Projections
Pretzelosity

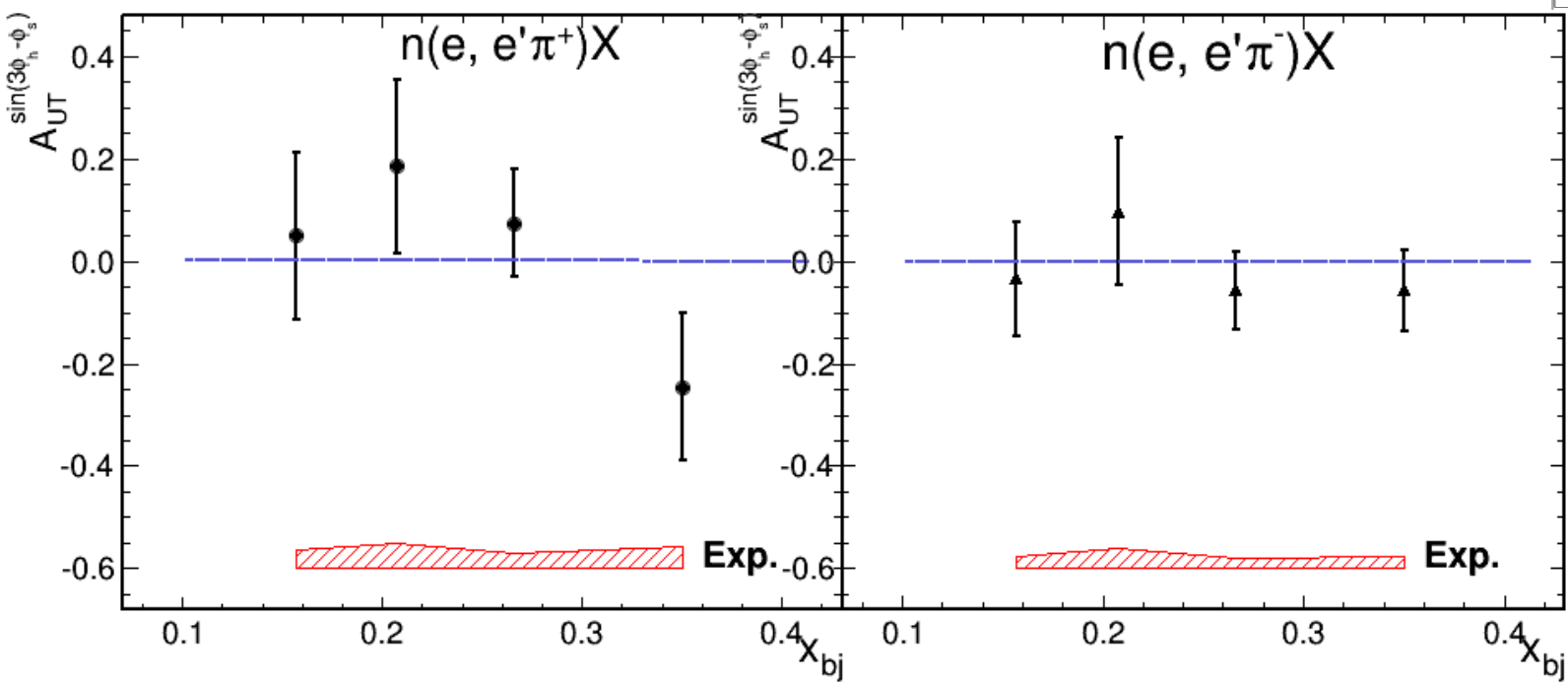
Pretzelosity Results on Neutron

(from E06-010)

Y. Zhang, et al., PRC 90 5, 055209(2014)

N \ q	U	L	T
U	f_1		$h_1^\perp$
L		g_1	$h_{1L}^\perp$
T	$f_{1T}^\perp$	g_{1T}	h_1 $h_{1T}^\perp$

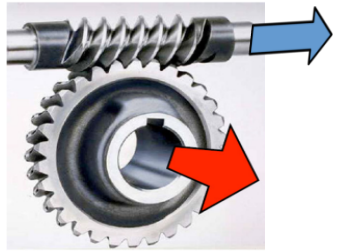
Extracted Pretzelosity Asymmetries



In models, directly related to OAM, L=0 and L=2 interference

Asymmetry A_{LT} Result from E06-010

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



Worm-Gear
Trans helicity

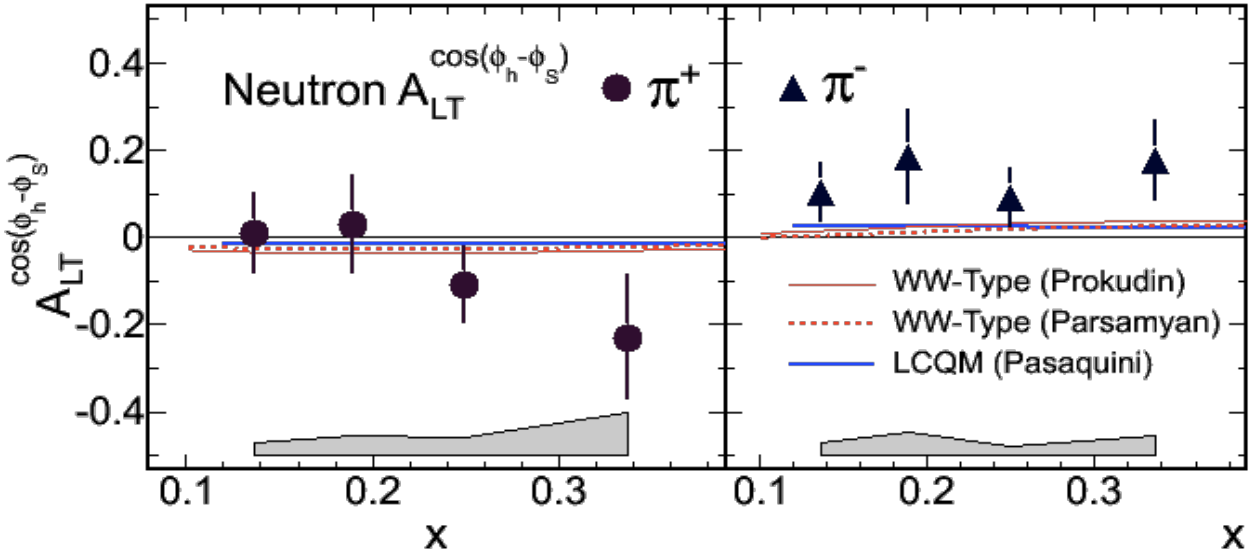
To leading twist:

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

Dominated by L=0 (S) and L=1 (P) interference

N \ q	U	L	T
U	f_1		$h_1^{\perp}$
L		g_1	$h_{1L}^{\perp}$
T	$f_{1T}^{\perp}$	g_{1T}	h_1 $h_{1T}^{\perp}$

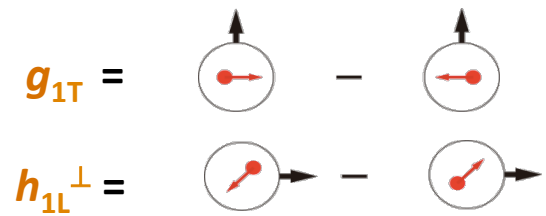
- **neutron A_{LT}: Positive for π-**
- **Consist w/ model in signs, suggest larger asymmetry**

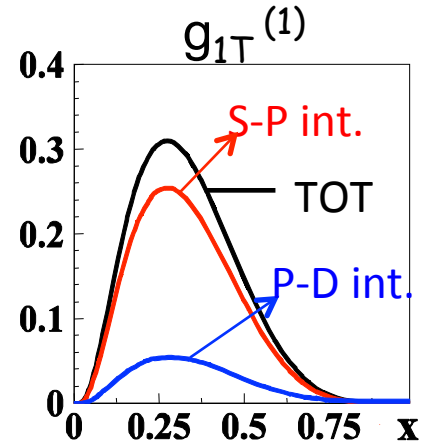


Worm-gear Functions

SoLID Projections

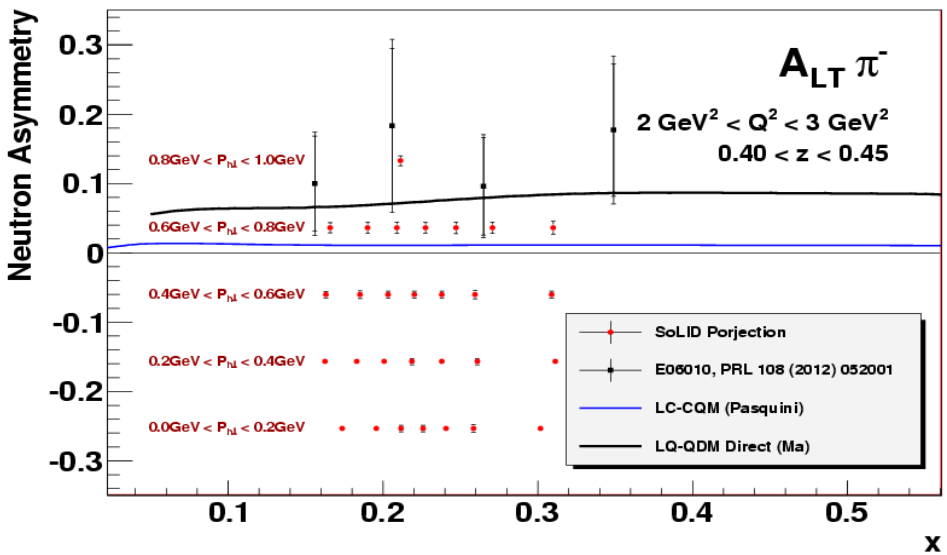
- Dominated by real part of interference between **L=0 (S) and L=1 (P) states**
- No GPD correspondence
- Exploratory lattice QCD calculation:
  Ph. Hägler et al, EPL 88, 61001 (2009)

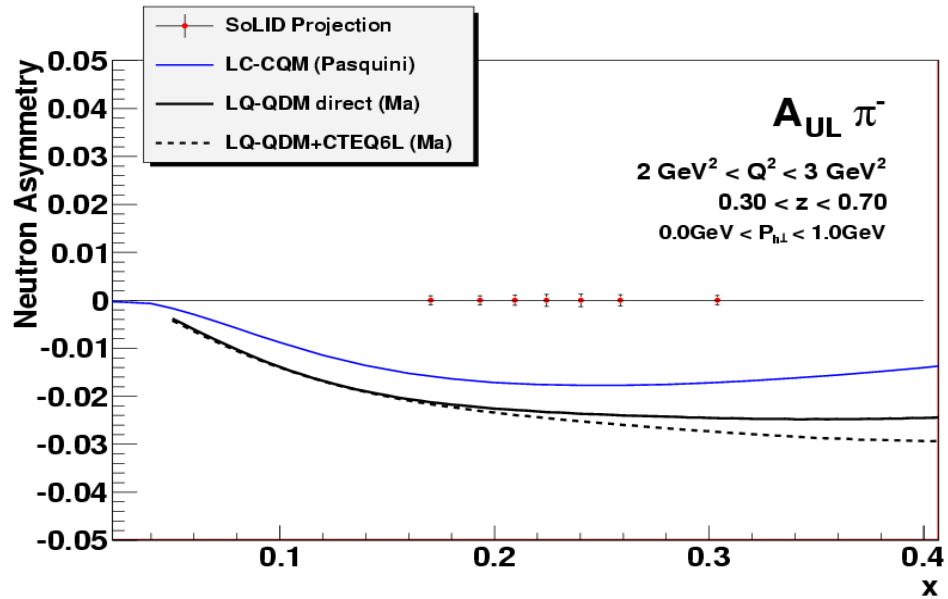




Light-Cone CQM by B. Pasquini
B.P., Cazzaniga, Boffi, PRD78, 2008

SoLID Neutron Projections,





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

$$A_{UL} \sim h_{1L}^{\perp}(x) \otimes H^{\perp}{}_1(z)$$

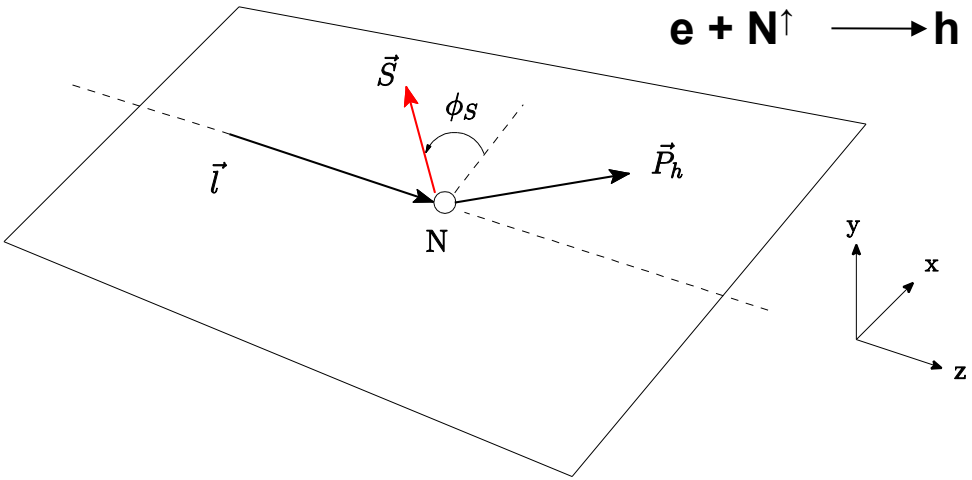
Single Spin Asymmetries in Inclusive Reactions

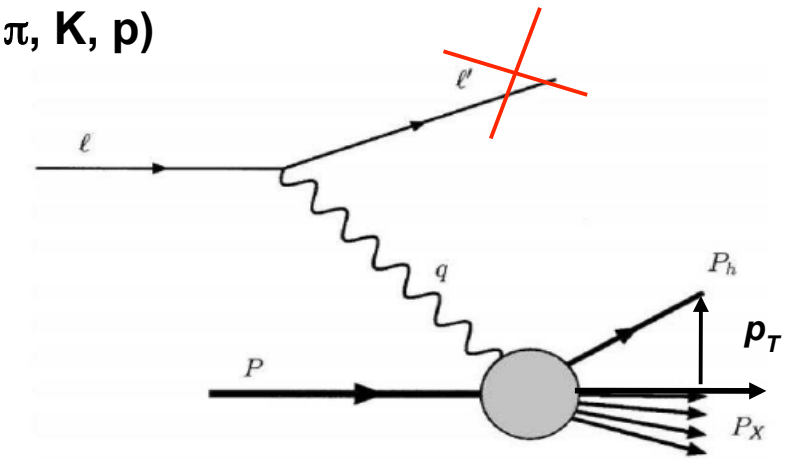
Inclusive Hadron Productions

Single Electron : 2-photon Exchange

Inclusive Hadron Electroproduction

e + N↑ ⟶ h + X (h = π, K, p)





$$\sigma_{UT} \propto \vec{S}_N \cdot \left(\vec{l} \, x \vec{P}_h\right) \propto \sin(\varphi_S)$$

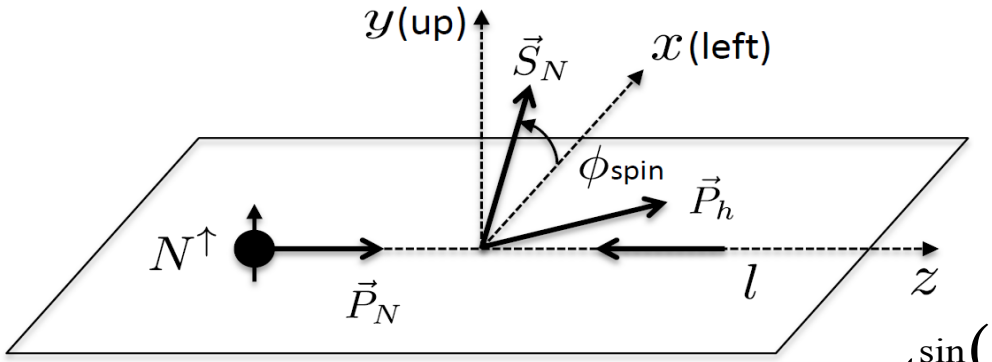
$$A_N(x_F, p_T) = A_{UT}^{\sin(\varphi_S)}$$

Why a non-zero A_N is interesting?

- Analogues to A_N in $pp^{\uparrow} \to hX$ collision
- Simpler than $pp^{\uparrow} \to hX$ due to only one quark channel
- Transverse spin effects related SIDIS and *p-p* collisions (Sivers, Collins, twist-3)
- Test TMD formalism (at large p_T ~ 1 GeV or more)

E06-010: Inclusive Hadron SSA (A_N)

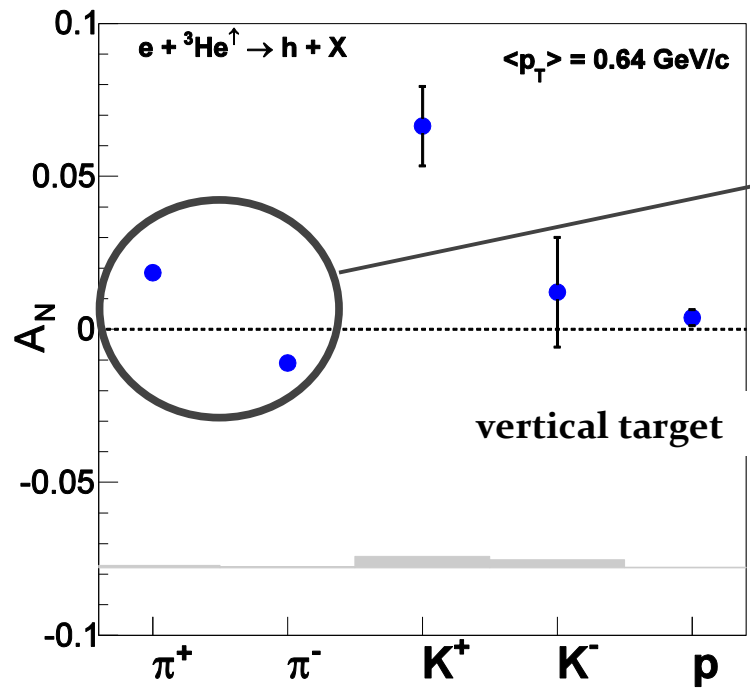
K. Allda *et al.*, PRC 89, 042201 (2014)

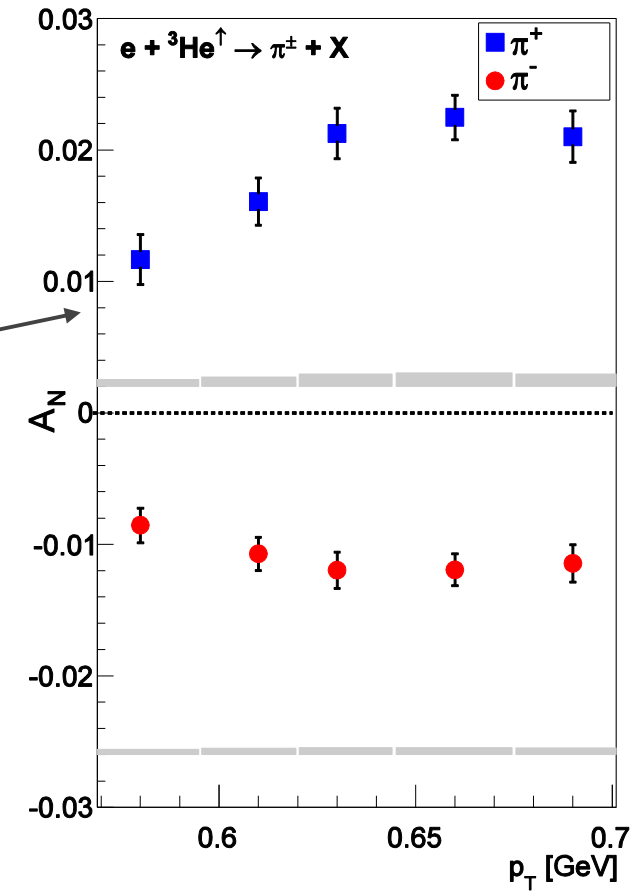


$$\vec{S}_N \cdot \left(\vec{l} \, x \vec{P}_h\right) \neq 0$$

$$A_{UT}^{\sin(\varphi_S)}\left(\varphi_S = 90^0\right)$$

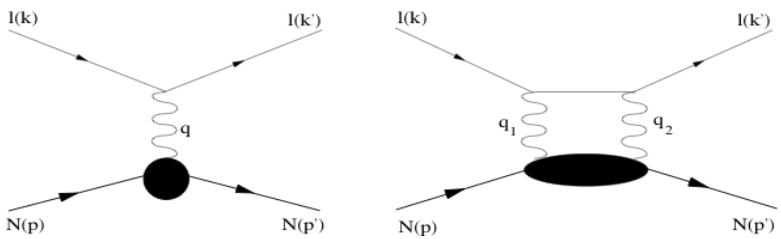
- Clear non-zero target SSA
- Opposite sign for π^+ and π^-
- Large for K^+
- Results consistent with predictions based on Sivers mechanism (valid at high p_T)

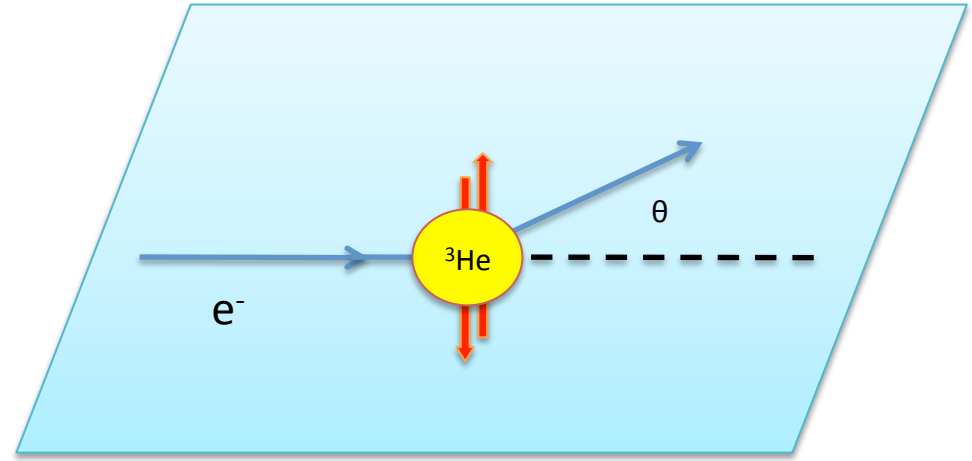




Inclusive Single Normal Target Spin Asymmetry

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





- Unpolarized e^- beam incident on ^{3}He 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.

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

- In DIS case: related to integral of Sivers
- Physics Importance discussed in A. Metz's paper

Jefferson Lab
Thomas Jefferson National Accelerator Facility

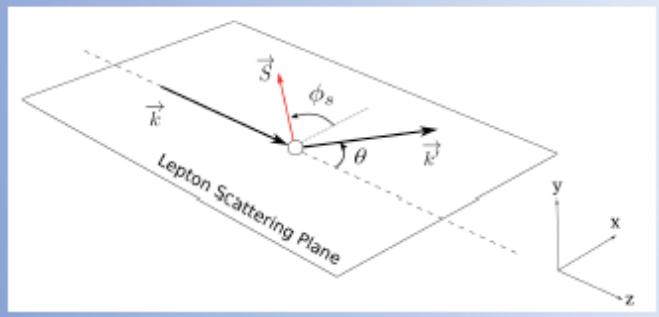
U.S. DEPARTMENT OF ENERGY | Office of Science

First Observation of a Non-Zero Target-Normal Single-Spin Asymmetry

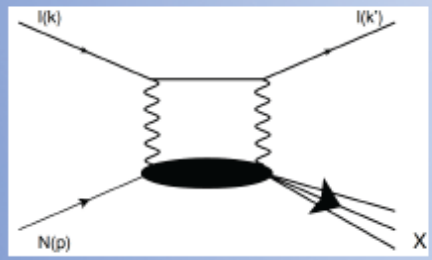
Jefferson Lab E07-013, Hall A, Polarized ^{3}He Collaboration,

J. Katich *et al.*, Phys. Rev. Lett. **113**, 022502 (2014)

- Un-polarized electrons, transversely polarized target, inclusive DIS reaction $^3\mathrm{He}^{\uparrow}(e,e')X$
- No Born contribution due to time-reversal invariance
- Direct access to nucleon dynamics through two-photon processes
- Parton model predictions $A_y^n \approx 10^{-2}$ to 10^{-4}, sign not known
- Predictions have opposite signs using input from SIDIS vs. hadron-hadron collisions

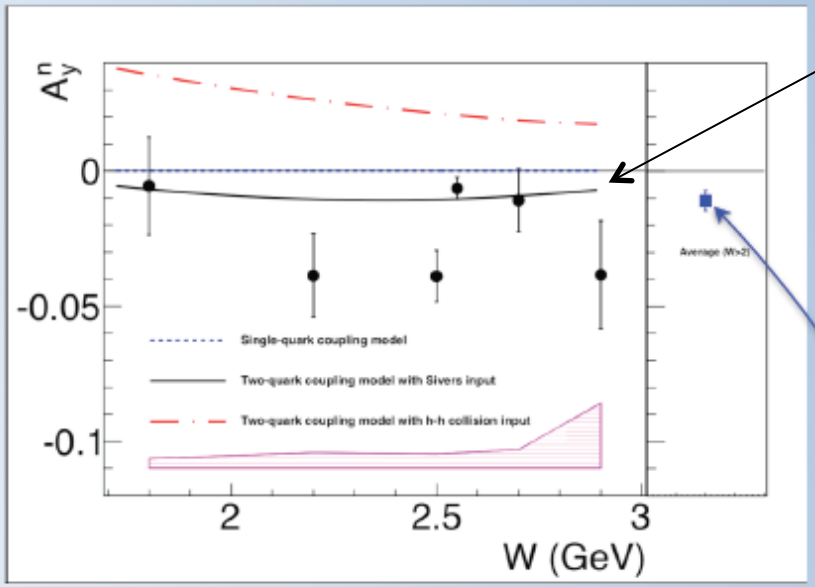


$$A_{UT}(\phi_S) = \frac{d\sigma(\phi_S) - d\sigma(\phi_S+\pi)}{d\sigma(\phi_S) + d\sigma(\phi_S+\pi)} = A_y \sin\phi_S$$



- Two-photon exchange asymmetry
  - -- zero for non-interacting quarks
  - -- non-zero with qgq, qγq correlations

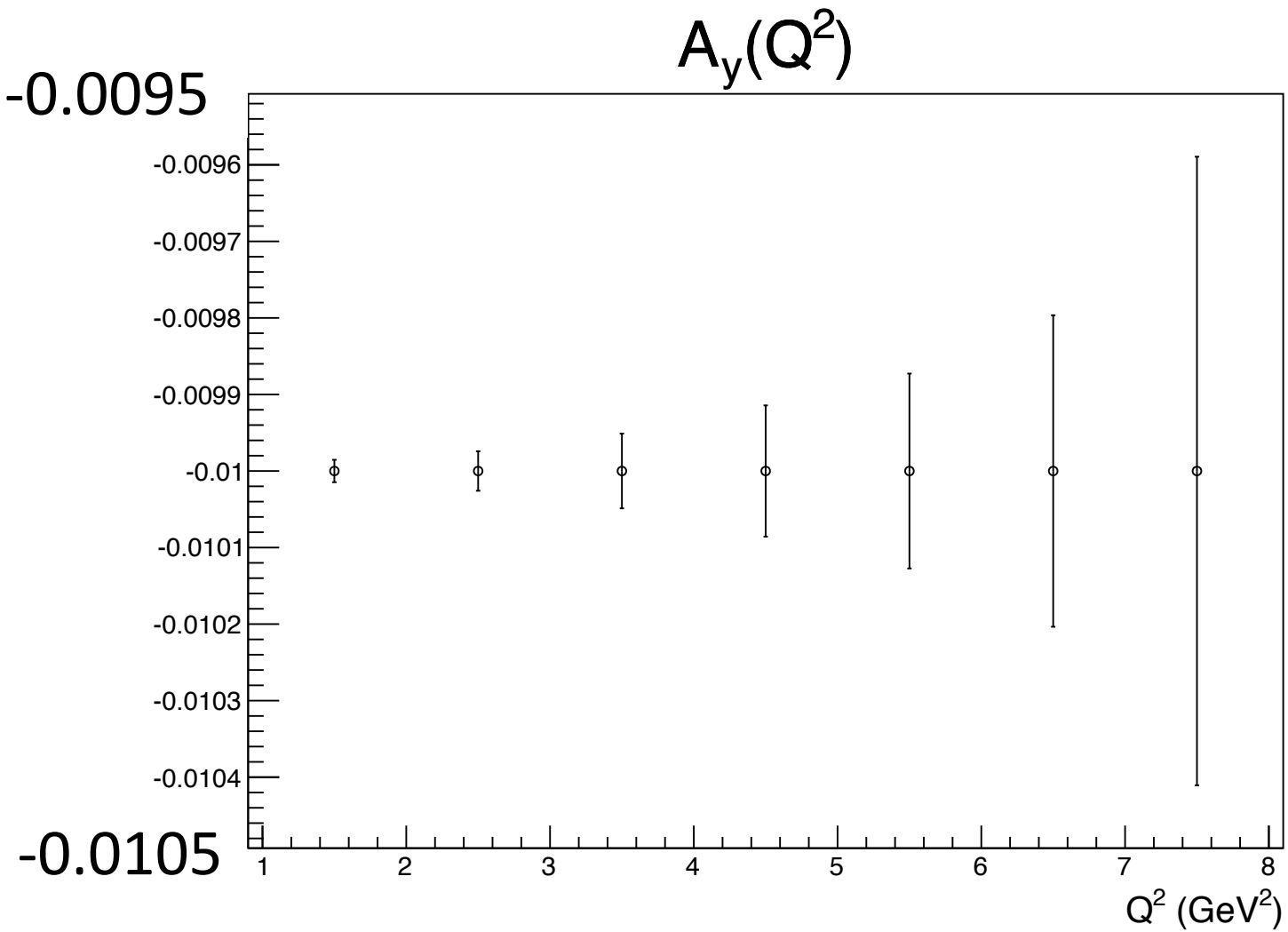
A. Metz



- First measurement of target single-spin asymmetry for neutrons
- First non-zero measurement (3σ) of target single-spin asymmetry
- Consistent with model using SIDIS Sivers input
- Result: $A_y^n = (-1.09 \pm 0.38) \times 10^{-2}$ ($W > 2$ GeV)

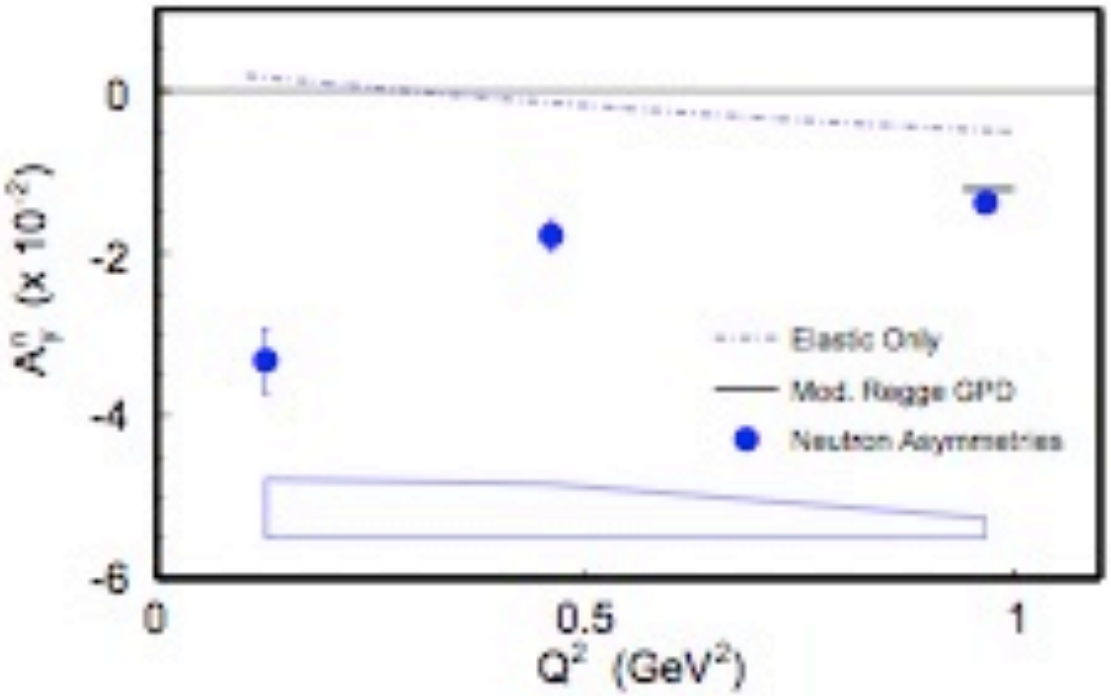
Inclusive Target Normal Single Spin Asymmetry

SoLID Projections

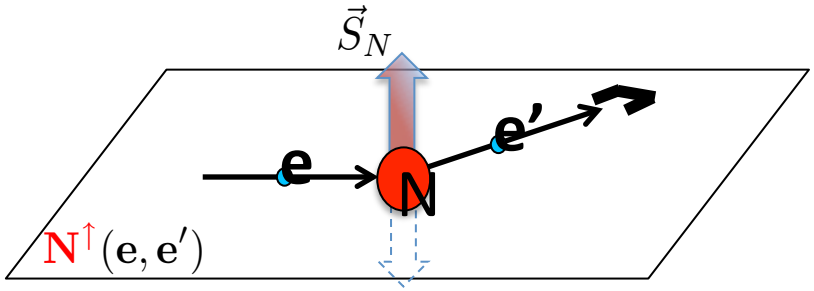


Experiment E05-015 @ Jefferson Lab Hall A

Target Single-Spin Asymmetry in QE $\mathbf{N}^{\uparrow}(\mathbf{e},\mathbf{e}')$



Y.-W. Zhang *et al* Phy. Rev. Lett. (2015).
Just got accepted



$$A_y \propto (\vec{e} \times \vec{e'}) \cdot \vec{S}_N$$

$$A_y \equiv 0 \text{ under } 1\gamma \text{ exchange}$$

$$A_y \neq 0 \text{ with } 1\gamma \otimes 2\gamma \text{ interference}$$

- Time-Reversal Odd observable.
- Non-zero A_y has never been measured.
- New observable for nucleon structure, **provides access to the moments of nucleon's Generalized-Parton-Distributions (GPDs).**

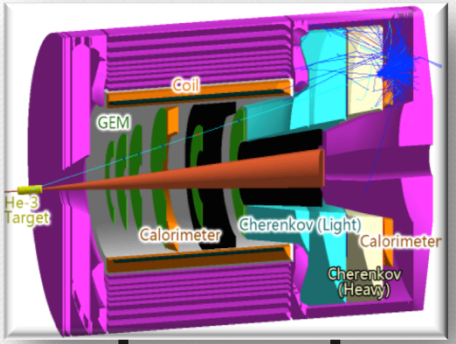
- The last experiment was in 1970, set an upper limit of 1~2%. T. Powell *et al*, PRL 753, **24** (1970).
- **First observation of a non-zero target single-spin asymmetry in this reaction**
- Jefferson Lab E05-015: Y.-W. Zhang Ph.D. thesis, Rutgers Univ. (2013).
  Co-Spokespersons: T. Averett (W&M), J.-P. Chen (JLab) and X. Jiang (LANL).

More on Planned TMD Studies with JLab 12

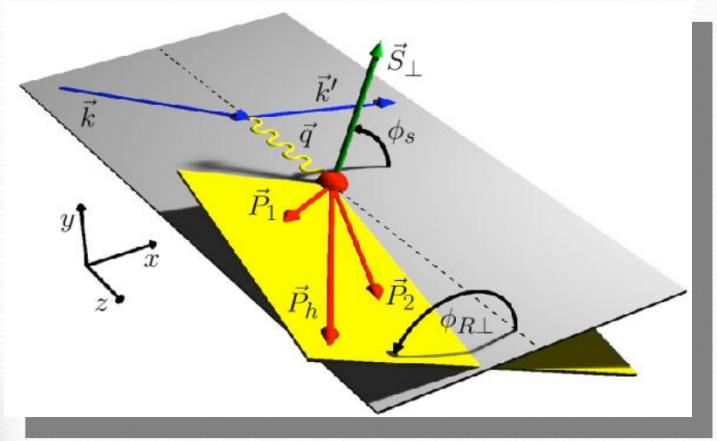
Multi-Hall Program, SoLID

JLab 12: Multi-Halls TMD Program

Hall A/SOLID
High Lumi and acceptance – 4D

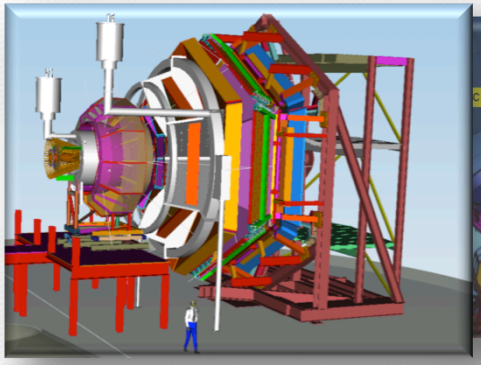


^{3}He, NH_3



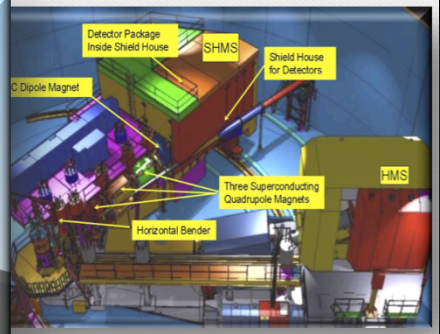
N \ q	U	L	T
U	f_1		$h_1^\perp$
L		g_1	$h_{1L}^\perp$
T	$f_{1T}^\perp$	g_{1T}	h_1 $h_{1T}^\perp$

Hall B/CLAS12
General survey, medium luminosity



H_2/D_2, NH_3/ND_3, HD

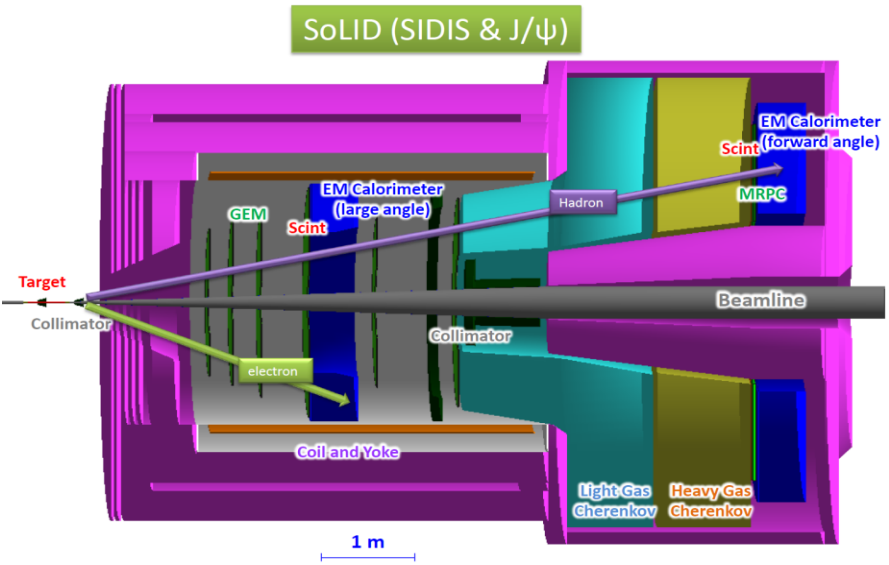
Hall C/SHMS
L-T studies, precise π^+/π^- ratios



H_2 D_2

Hall A/SBS
High x - Q^2, 2-3D

SoLID-Spin: SIDIS on ^{3}He/Proton @ 11 GeV

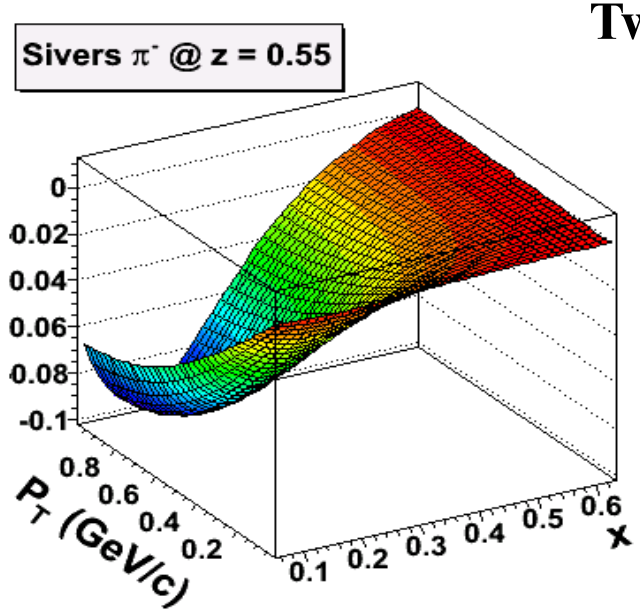


E12-10-006: Single Spin Asymmetry on Transverse ^{3}He, **rating A**

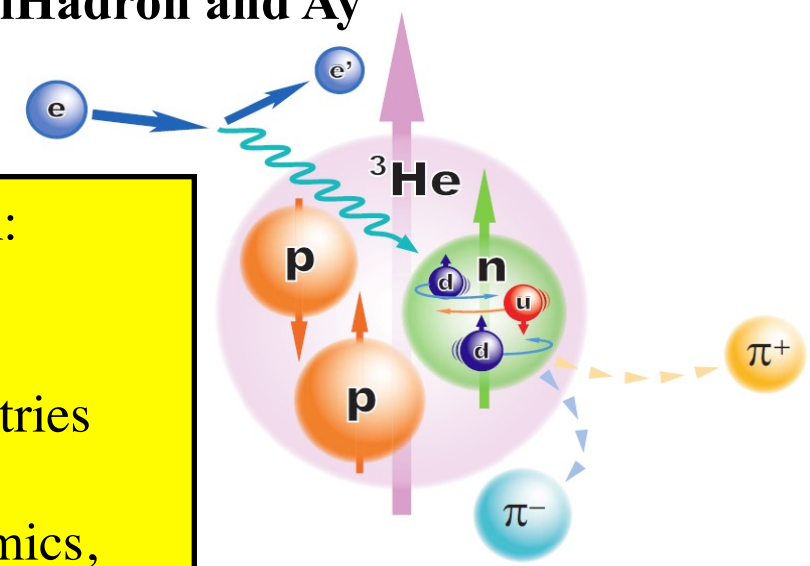
E12-11-007: Single and Double Spin Asymmetries on ^{3}He, **rating A**

E12-11-108: Single and Double Spin Asymmetries on Transverse Proton, **rating A**

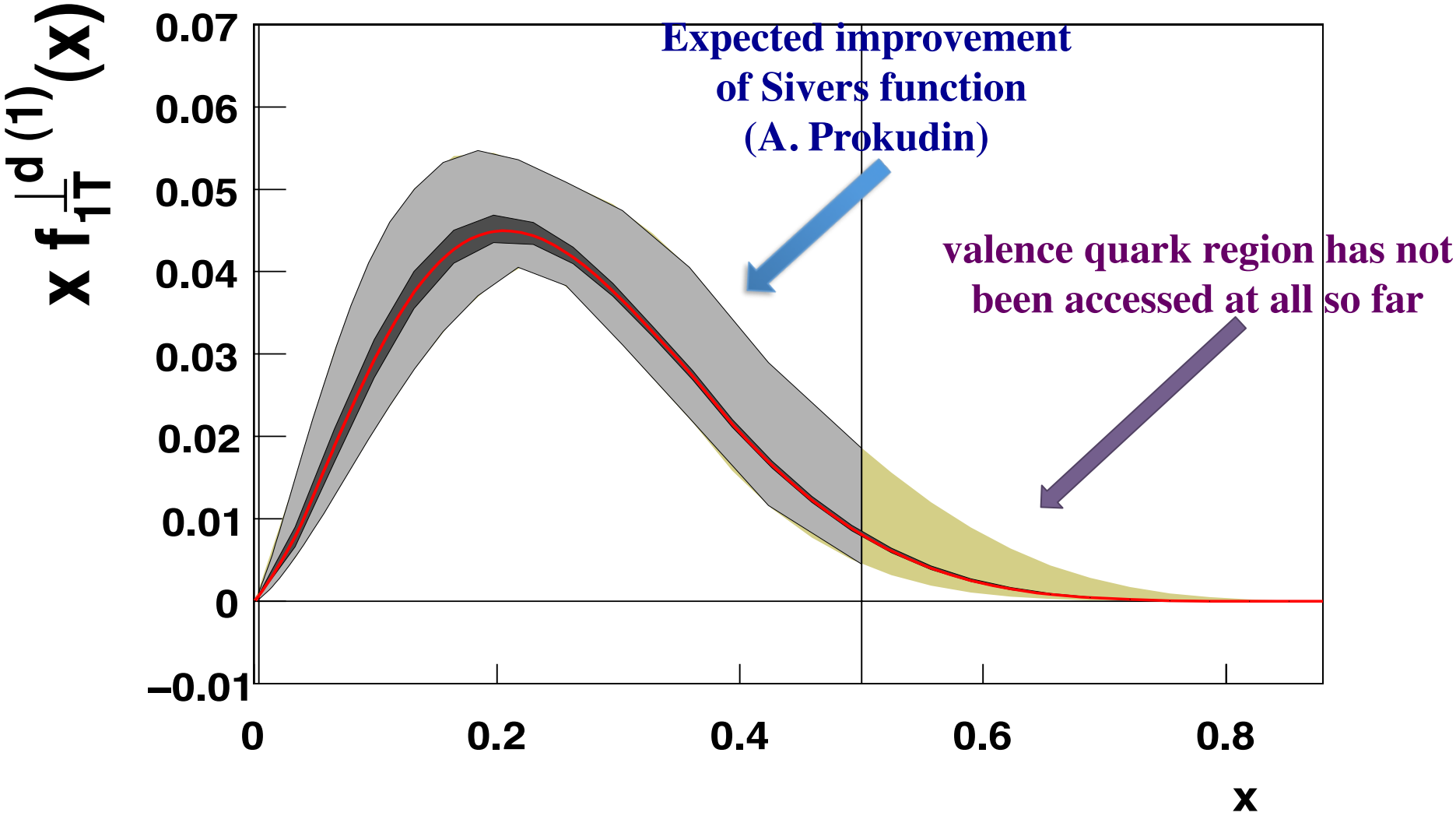
Two run group experiments DiHadron and Ay



Key of SoLID-Spin program:
Large Acceptance
+ High Luminosity
→ **4-D** mapping of asymmetries
→ Tensor charge, TMDs …
→Lattice QCD, QCD Dynamics, Models.

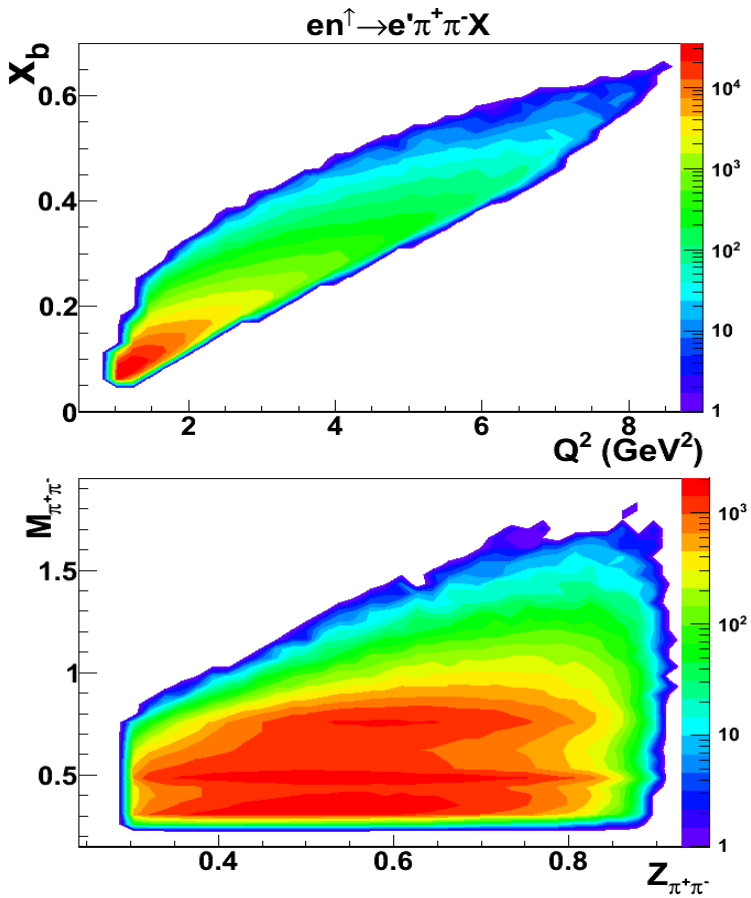


Projected Sivers Function

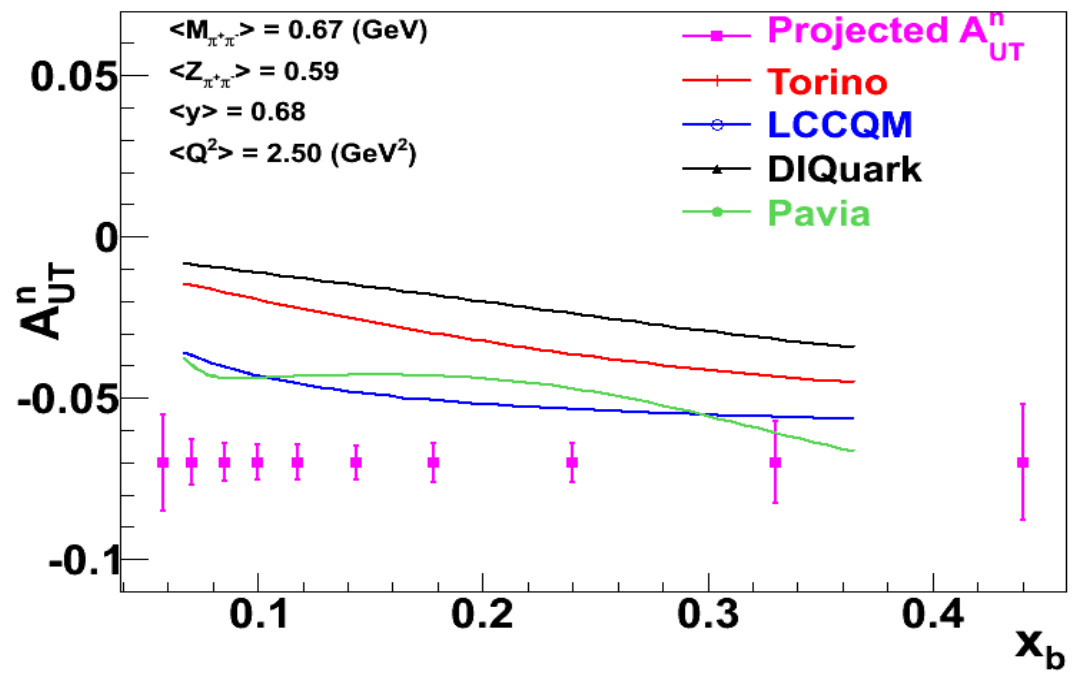


Measure Transversity via Dihadron with SoLID

- Precision dihadron (π+/π-) production on a transversely polarized ^{3}He (n)
- Extract transversity on neutron
- Provide crucial inputs for flavor separation of transversity



Wide x_b and Q^2 coverages



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

SoLID Timeline and Status

- 2010-2012 Five SoLID experiments approved by PAC with high rating
  3 SIDIS with polarized ^{3}He/p target, 1 PVDIS, 1 threshold J/ψ
- 2014-2015: three run-group proposals approved: Dihadron, Ay, TCS; LOI DDVCS
- 2013: **CLEO-II magnet formally requested and agreed**
- 2014: Site visits, plan transportation to JLab (now-2017)

2010-2014: Progress

- Spectrometer magnet, modifications
- Detailed simulations
- Detector pre-R&D
- DAQ

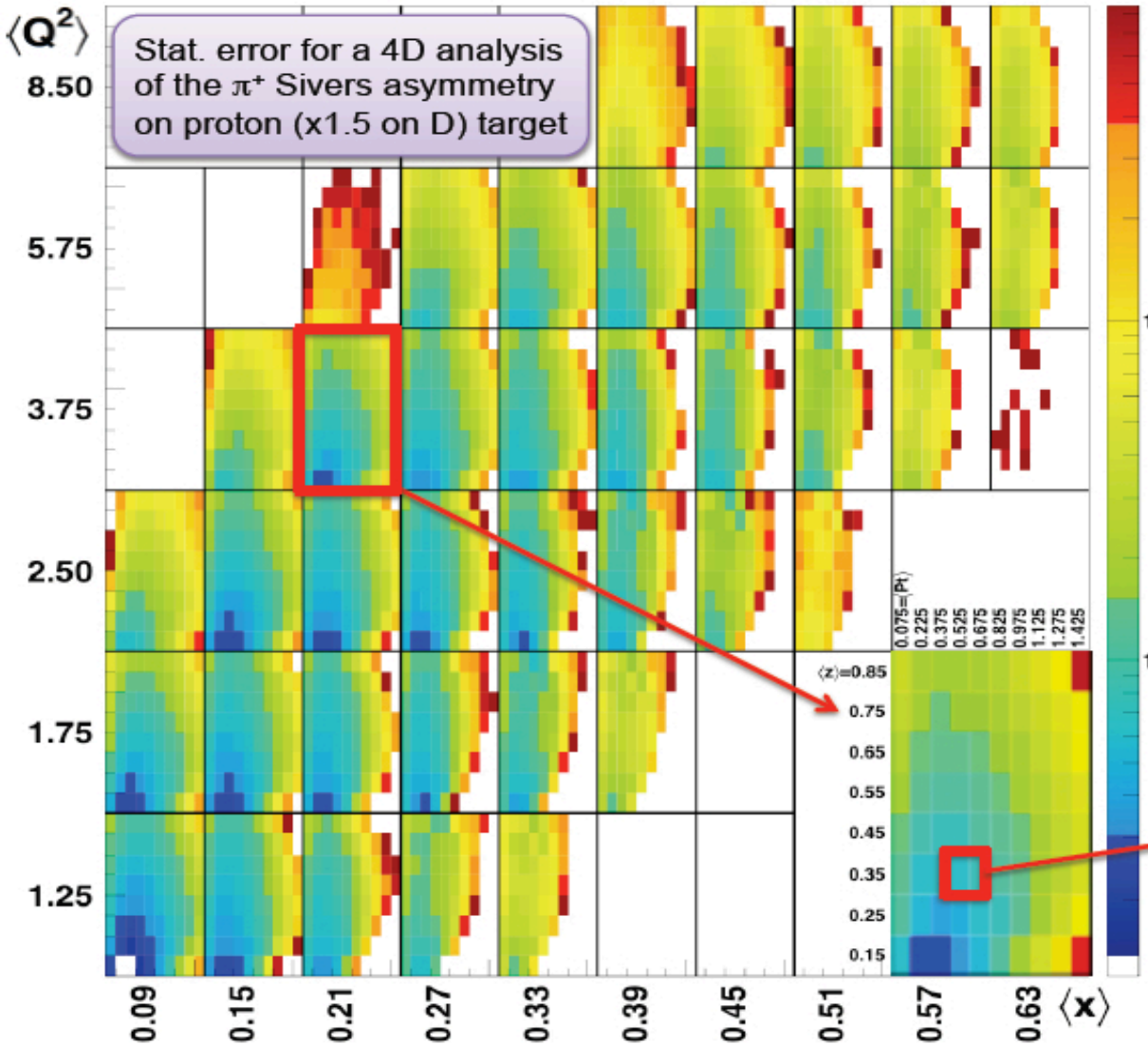
✓ 2014: **pre-CDR submitted**

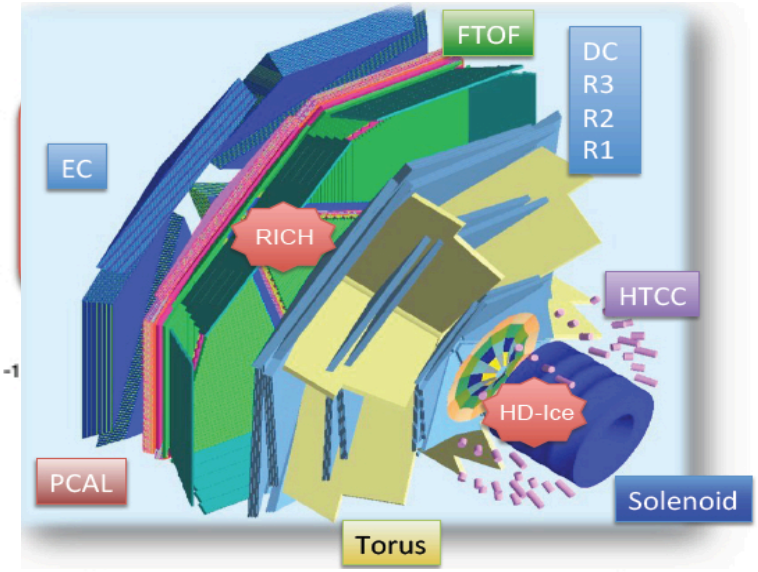
✓ 2015: **Director's Review**

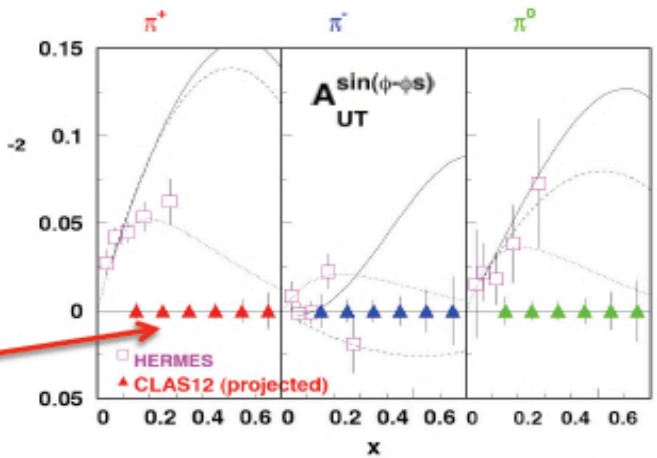
Next:

- **Pre-R&D, full simulation, pCDR → TDR**
- **MIE proposal**
- **DOE Science Review: soon**
- **Construction: starting 2018?**
- **Experiment starting: 2022?**

CLAS12 A_{UT} with transverse proton target







Curves from hep-ph/0507266 and hep-ph/0507181

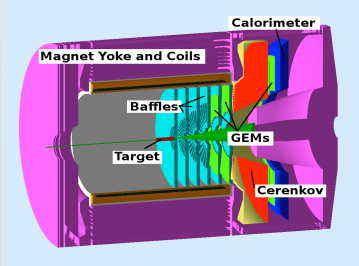
Summary

- Transverse Spin, Tensor Charge
- TMDs and Access Quark OAM
- Single Spin Asymmetries in Inclusive Reactions
- Highlights of JLab 6 GeV Results with Polarized neutron/3He
- TMD @ JLab 12 GeV: **SoLID** Program, CLAS12 and …

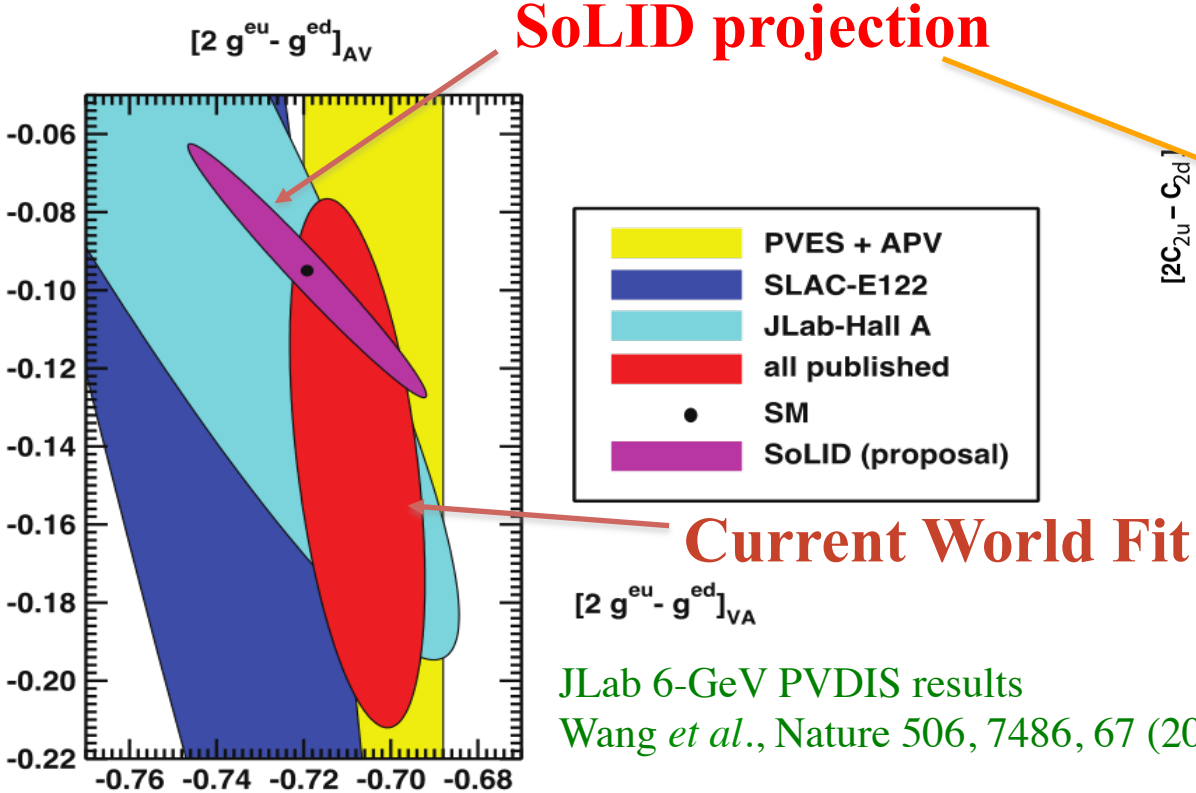
  Precision Multi-dimensional Mapping

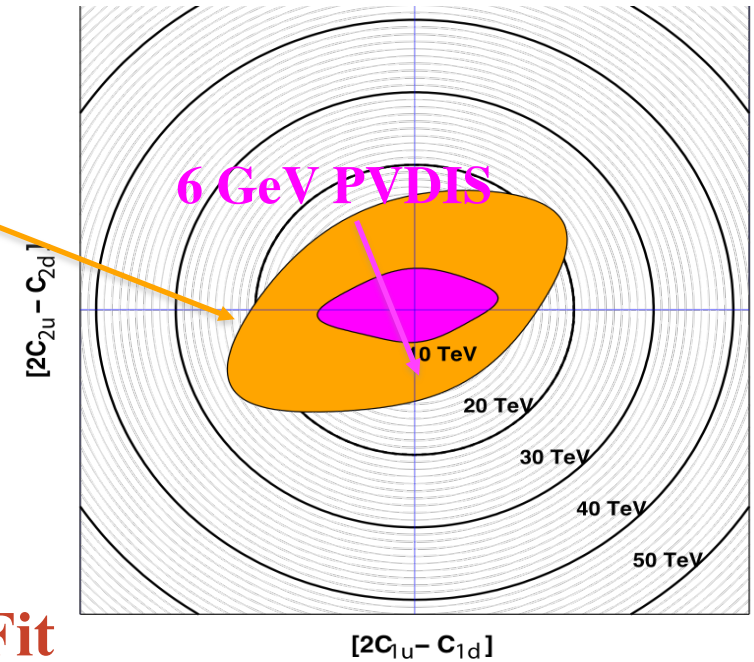
→ **Understanding nucleon spin, 3-d structure, QCD dynamics and more**

Extra: Other SoLID Programs



Parity Violation with SoLID





$g^2=4\pi$

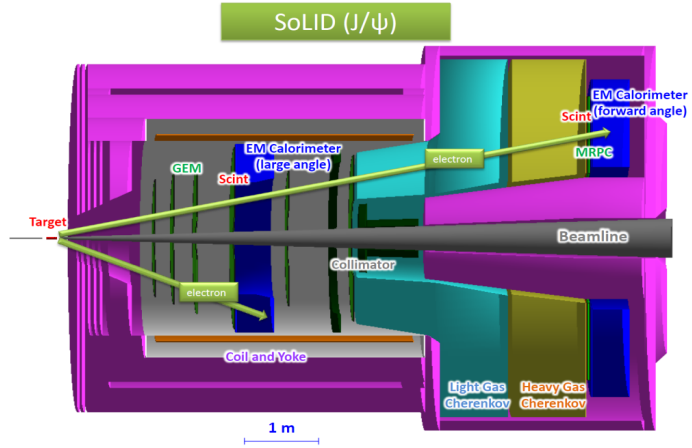
JLab 6-GeV PVDIS results
Wang *et al.*, Nature 506, 7486, 67 (2014)

Qweak and SOLID will expand sensitivity that will match high luminosity LHC reach with complementary chiral and flavor combinations

SoLID ~ 10 times improvement over 6 GeV result

- High Luminosity on LD2 and LH2
- Better than 1% errors for small bins over large range kinematics
- Test of Standard Model
- Quark structure:
  - charge symmetry violation
  - quark-gluon correlations
  - d/u at large-x

J/ψ @ SoLID



Threshold J/Ψ production, probing strong color field in the nucleon, QCD trace anomaly (important to proton mass budget)

$$e\,p \rightarrow e'\,p'\,J/\psi(e^-\,e^+)$$
$$\gamma\,p \rightarrow p'\,J/\psi(e^-\,e^+)$$

Imaginary part: related to the total cross section through optical theorem

Real part: contains the conformal (trace) anomaly