A New Polarized Proton Target for Semi-inclusive DIS and Polarized Drell-Yan Measurements

Xiaodong Jiang, Los Alamos National Laboratory.

Sept. 2nd, 2011 @Transversity-2011 Workshop

- **Results of JLab Transversity Experiment (E06-010):**
  - **Target single-spin asymmetry A_{UT}**
  - **Beam-target double-spin asymmetry A_{LT}**
  - **Target single-spin asymmetry: inclusive and quasi-elastic scattering.**
- **New SIDIS experiments planned in Hall-A.**
- **A new polarized proton(NH_3) target for high luminosity experiments.**
  - **requirements of SIDIS at JLab Hall A.**
  - **also fits for a Drell-Yan experiment at Fermi Lab.**
  - **technical challenges and practical solutions.**
- **Projections for a polarized target Drell-Yan experiment at Fermi Lab.**

In collaboration with: Ming Liu (LANL), Don Crabb (UVa), Jian-Ping Chen (JLab).
and take slides from: Andrew Puckett (LANL), Xin Qian (Caltech), Kalyan Allada (JLab), Yi Qiang (JLab).

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Work supported by: DOE Office of Science, Medium Energy Nuclear Physics.

Jefferson Lab E06-010 Collaboration

Institutions

CMU, Cal-State LA, Duke, Florida International, Hampton, UIUC, JLab, Kharkov, Kentucky, Kent State, Kyungpook National South Korea, LANL, Lanzhou Univ. China, Longwood Univ. UMass, Mississippi State, MIT, UNH, ODU, Rutgers, Syracuse, Temple, UVa, William & Mary, Univ. Sciences & Tech China, Inst. of Atomic Energy China, Seoul National South Korea, Glasgow, INFN Roma and Univ. Bari Italy, Univ. Blaise Pascal France, Univ. of Ljubljana Slovenia, Yerevan Physics Institute Armenia.

Collaboration Members

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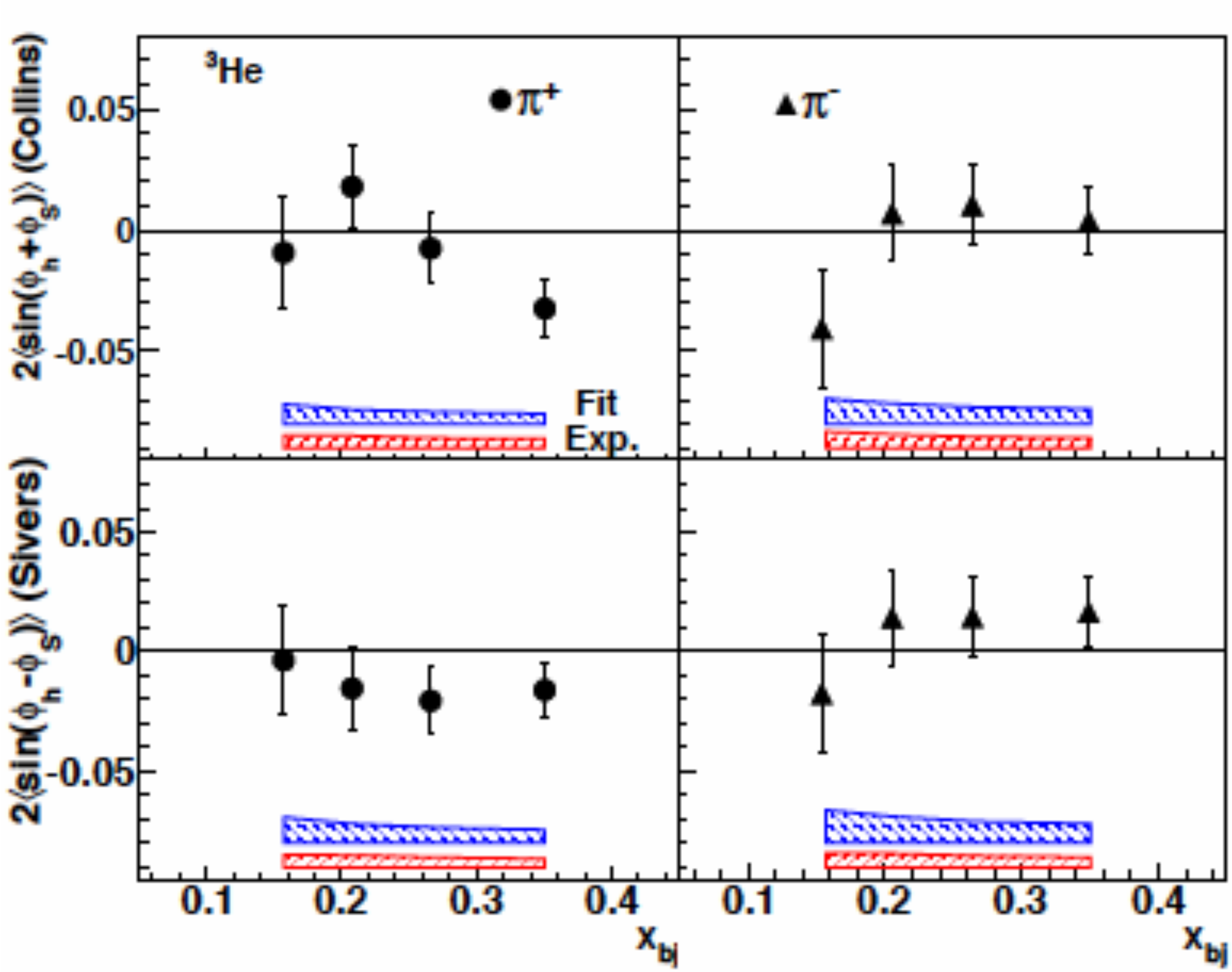
- 7 Ph.D. thesis: C. Dutta (Kentucky, 2010), J. Huang (MIT), K. Allada (Kentucky, 2010), J. Katich (W&M, 2010), X. Qian (Duke, 2010), Y. Wang (UIUC, 2011), Y. Zhang (Lanzhou U.)

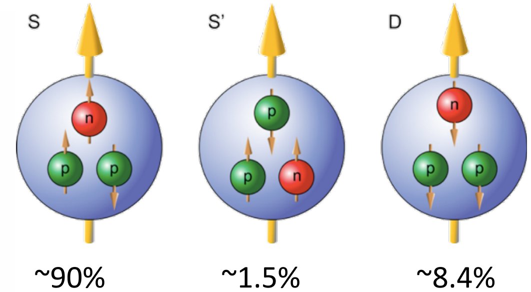
Results of target single-spin asymmetry (arXiv:1106.0363 and on PRL).
Results of beam-target double-spin asymmetry (arXiv:1108.0489).

JLab E06-010: ^{3}He Target Single-Spin Asymmetry in semi-Inclusive DIS

PRL107, 072003 (2011)



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

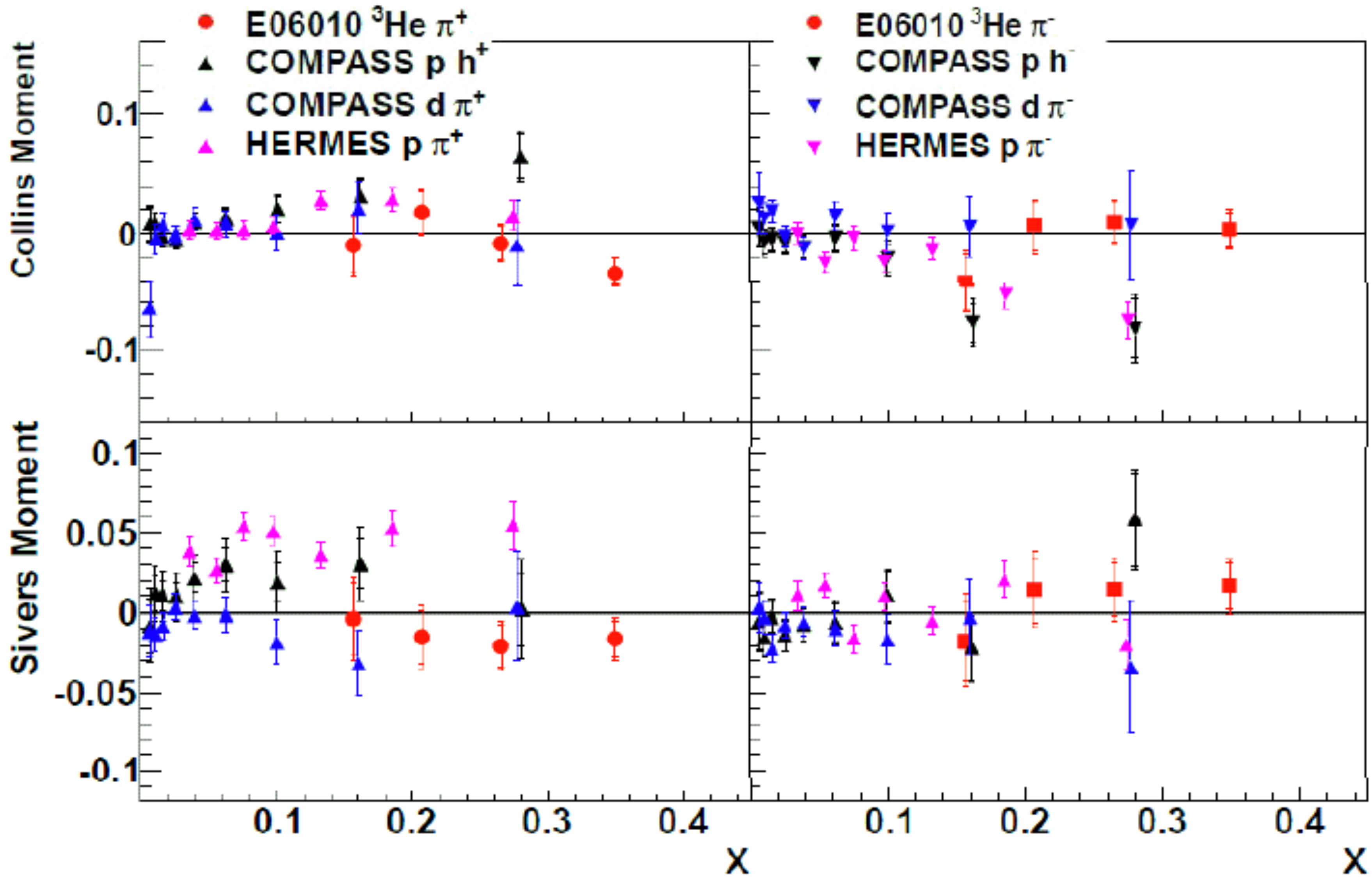


$$^3He^{\uparrow} = 0.865 \cdot n^{\uparrow} - 2 \times 0.028 \cdot p^{\uparrow}$$

^{3}He Collins SSA:
not large (as expected).

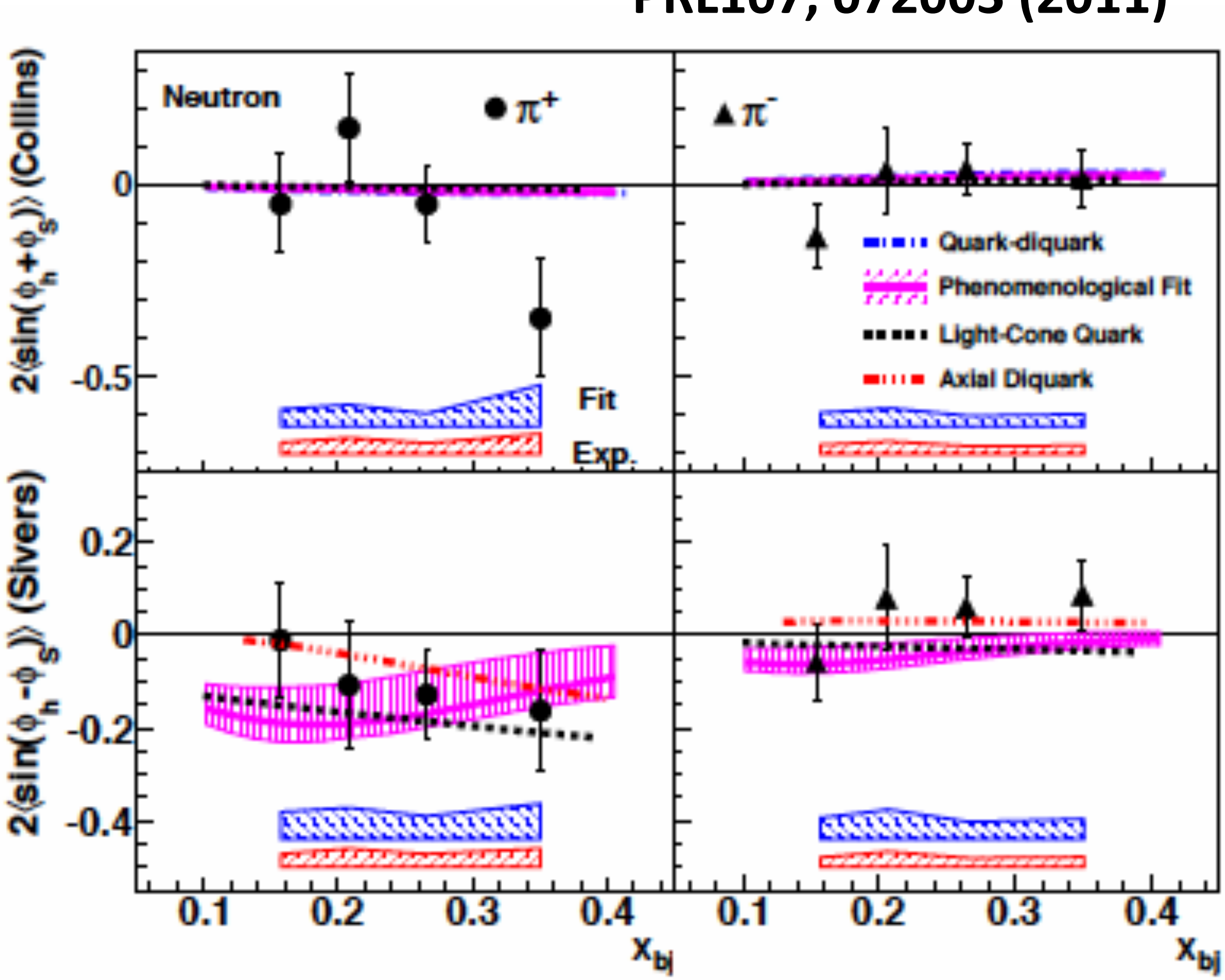
^{3}He Sivers SSA:
negative sign for π^+,
consistent with zero for π^-

Published World Data on SSA: (p, d, ^3He)



Neutron Single-Spin Asymmetry

PRL107, 072003 (2011)



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

Collins

asymmetries are not large, except at x=0.35

Sivers

agree with global fit, and light-cone quark model.

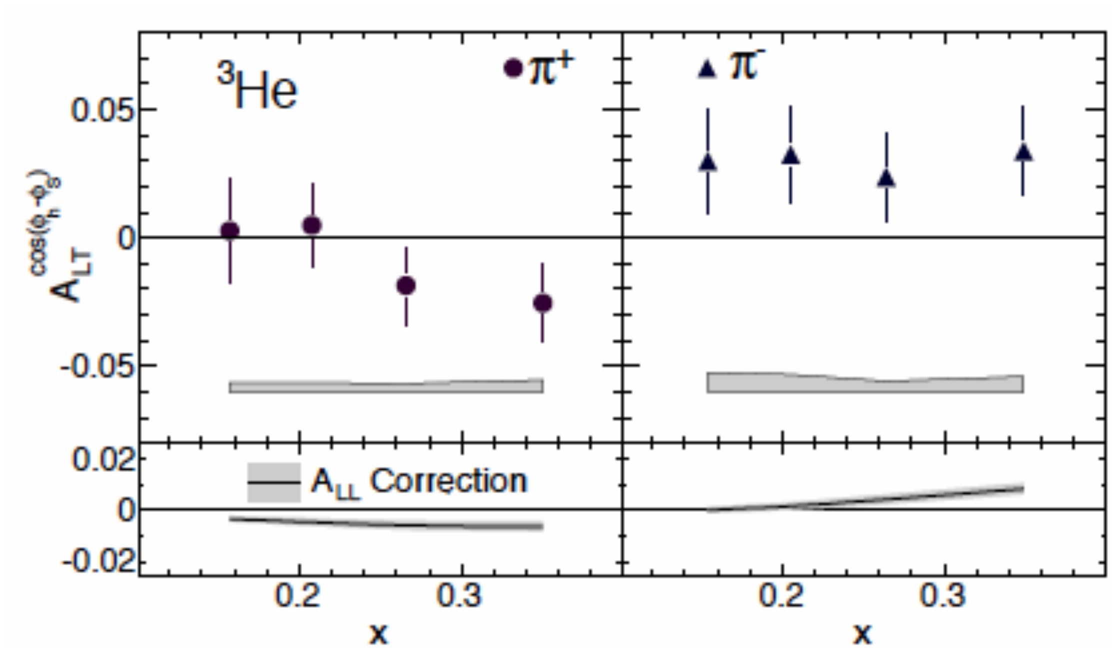
$\pi^+ \, (u\bar{d})$ favors negative.
u-quark in neutron favors negative, by SU(2):

d-quark in proton favors negative.

^{3}He double-spin asymmetry A_{LT}

arXiv:1108.0489

Quark TMD g_{1T}: longitudinal quark polarization in a transversely polarized nucleon. (“Transversal Helicity”)



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

- observation of a none-zero A_{LT}.
- Relate to quark TMD $g_{1T}(x, k_T)$.
- The real part of quark wave function interference, “twin-brother” of Sivers.

Ph.D. thesis of J. Huang (MIT Oct. 2011).

$$\sigma_n^{\pi+} \propto 4d \cdot D_1^{fav} + u \cdot D_1^{unfav} \qquad \sigma_n^{\pi-} \propto 4d \cdot D_1^{unfav} + u \cdot D_1^{fav}$$

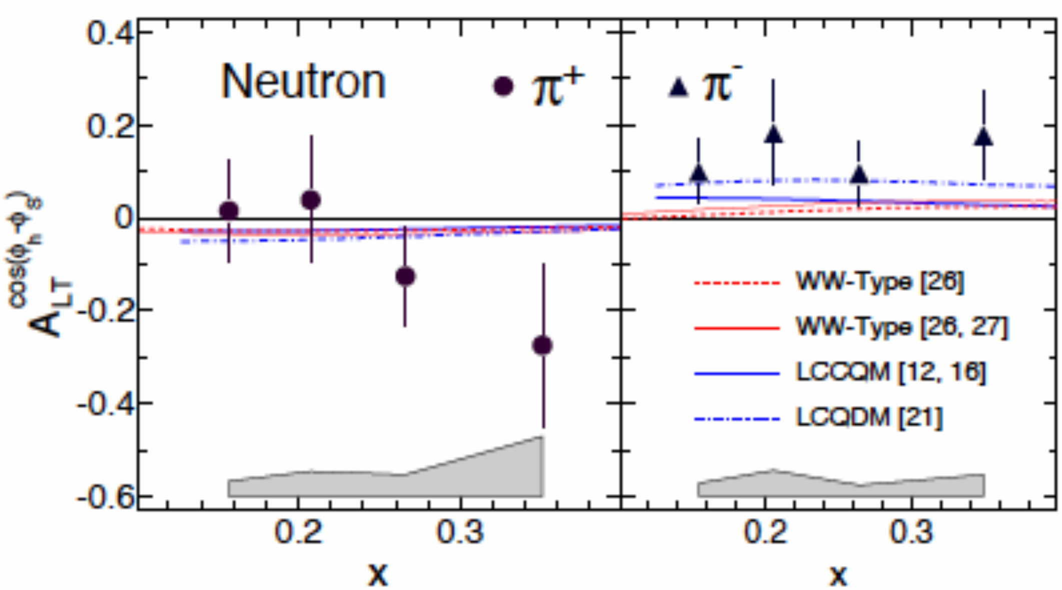
down-quark’s $g_{1T}(x)$ is rather small at low-x, negative at high-x.
up-quark’s $g_{1T}(x)$ is not small, positive in sign.

➔ **A_{LT} on proton should be noticeable.**

Neutron Double-Spin Asymmetry

arXiv:1108.0489

- $A_{LT} \propto g_{1T} \otimes D_1$
- Consist with models in sign



Light-cone constituent quark model (LCCQM):

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

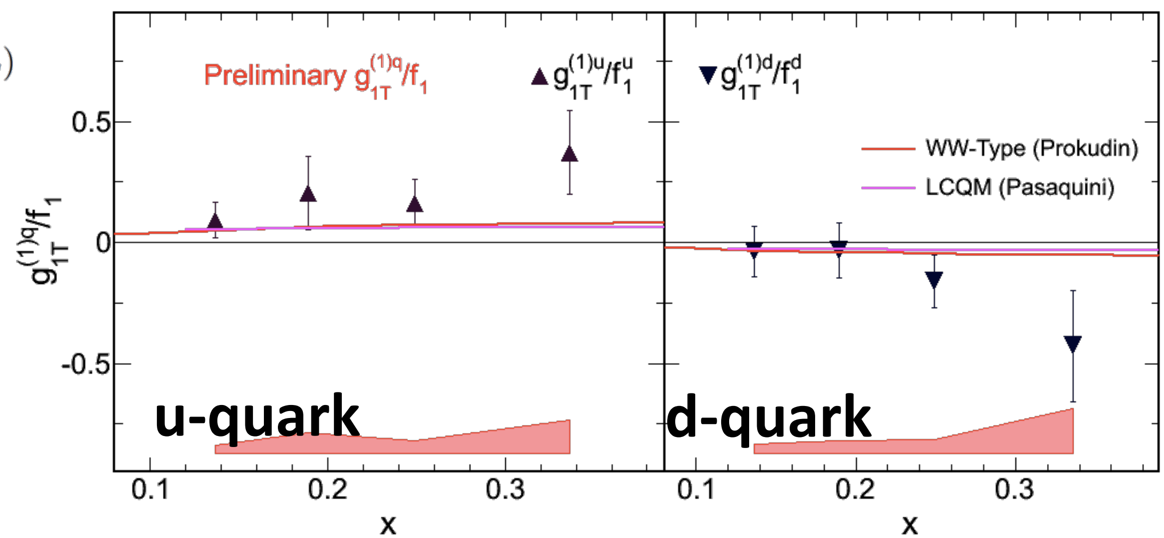
Light-cone quark-diquark model (LCQDM):

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

Naïve extraction of quark g_{1T}/f_1

- Extract TMD ratio g_{1T}/f_1 , with assumptions
  - TMD interpretation of the asymmetry
  - Gaussian p_T dependence
    - $<p_T^2>(f_1)=0.25\text{GeV}^2$, $<K_T^2>(D_1)=0.2\text{GeV}^2$, $<p_T^2>(g_{1T})=0.1\text{GeV}^2$
  - Anti-quark contribution is negligible
  - FF ratio D+/D- follows arXiv:1103.1649
- Compare to model: suggest a larger effect @ higher-x

$$g_{1T}^{(1)q}(x) \equiv \int d^2\boldsymbol{p}_T \frac{p_T^2}{2M^2} g_{1T}^q(x, p_T^2)$$



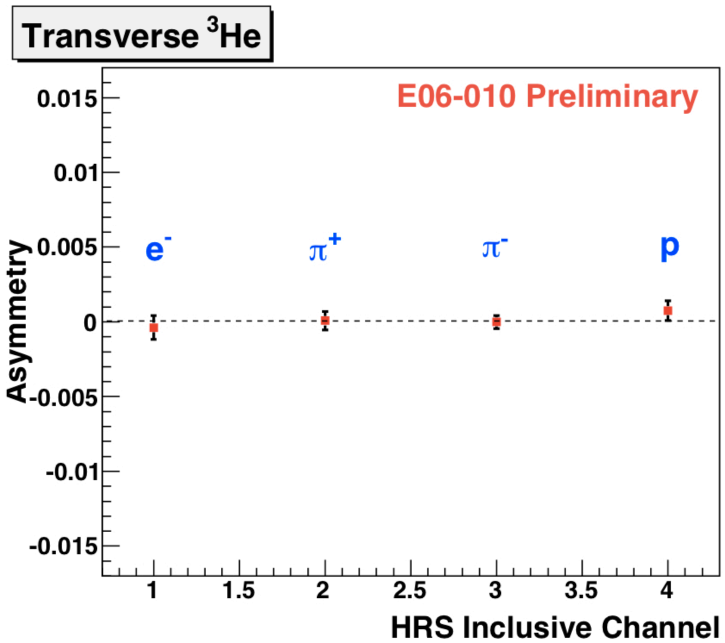
Target Single-Spin Asymmetry

A left-right asymmetry which always:

- involves a helicity flip.
- needs two more vectors in addition to spin. Naïve T-Odd.
- relates to the imaginary piece of interference amplitudes. Need a phase difference.

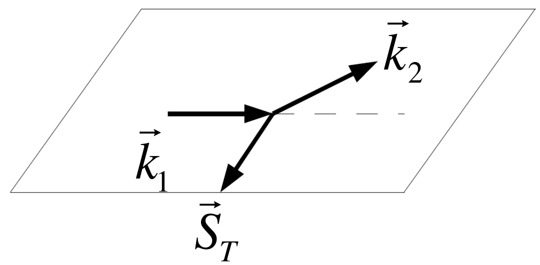
$$A_N \propto (\vec{k}_1 \times \vec{k}_2) \bullet \vec{S}$$

^{3}He Target Single-Spin Asymmetry: Inclusive Channels

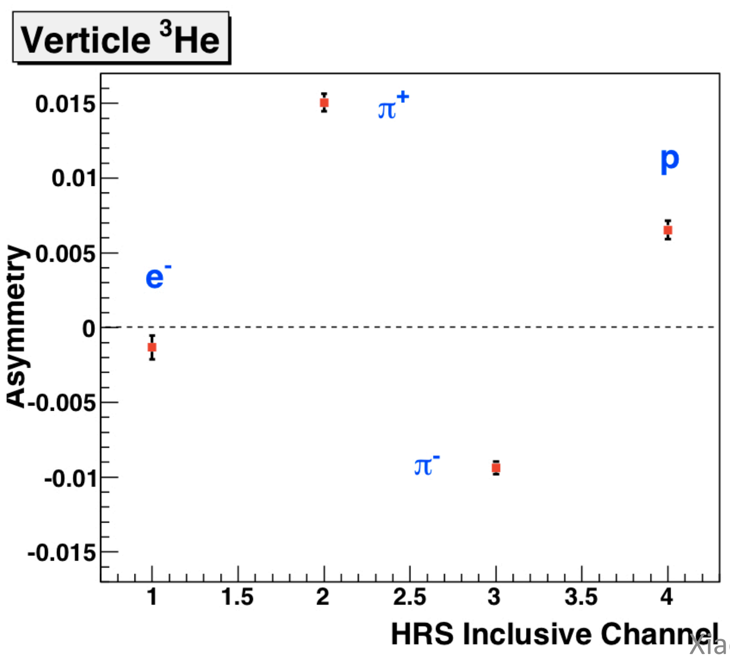


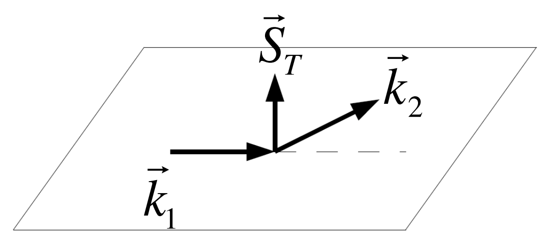
E_0=5.9 GeV, P_T=0.6 GeV/c.

K. Allada
Univ. of Kentucky
2010.



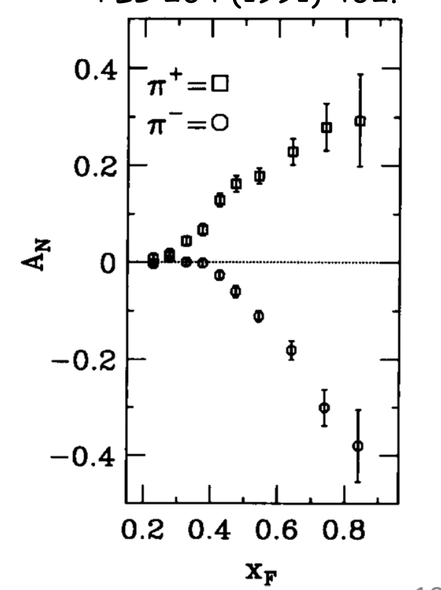
$$(\vec{k}_1 \times \vec{k}_2) \bullet \vec{S}_T = 0$$





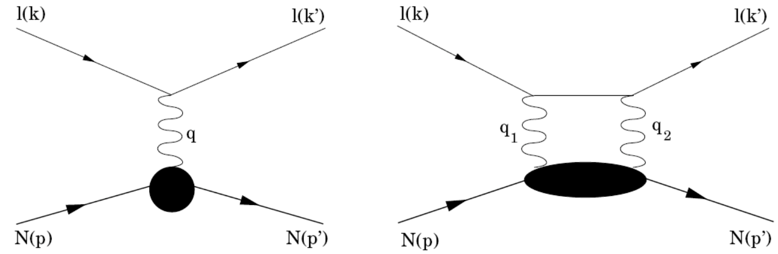
$$(\vec{k}_1 \times \vec{k}_2) \bullet \vec{S}_T \neq 0$$

Recall in $pp^\uparrow \to \pi X$
FNAL-E704: $\sqrt{s}$ =20 GeV.
PLB 264 (1991) 462.



Clear non-zero target SSA.
False asymmetry < 0.001.

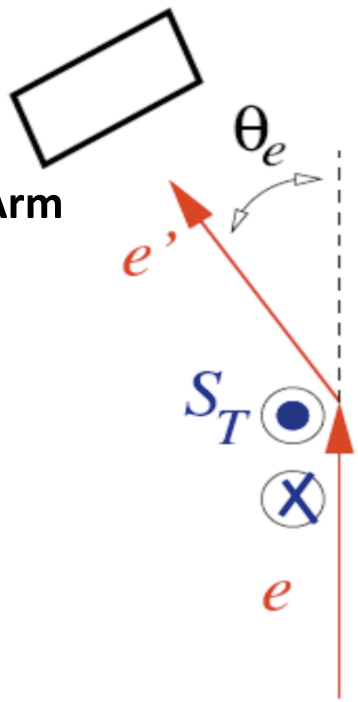
Target Single-Spin Asymmetry in inclusive ^{3}He↑(e,e') scattering (Quasi-Elastic)



A_y arises from interference of one- and two-photon exchange, provides access to moments of GPDs Ê and Ĥ.

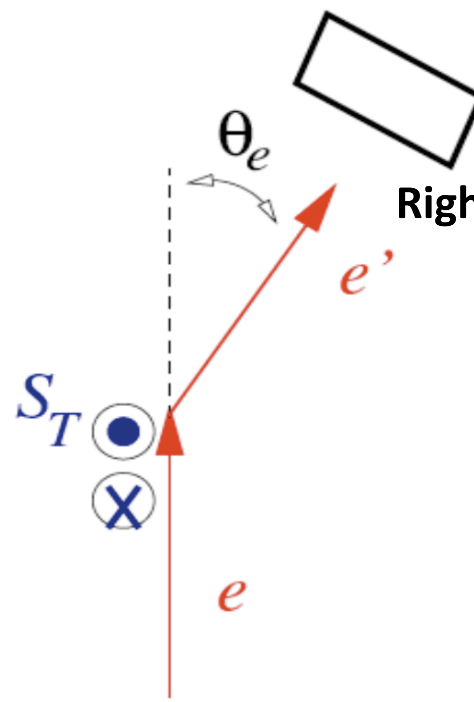
Two independent measurements.
Real physics asymmetry should flip sign.

Left Arm



$$A_y = \frac{N_\uparrow - N_\downarrow \cdot \frac{\mathcal{L}_\uparrow}{\mathcal{L}_\downarrow}}{N_\uparrow + N_\downarrow \cdot \frac{\mathcal{L}_\uparrow}{\mathcal{L}_\downarrow}}$$

Right Arm

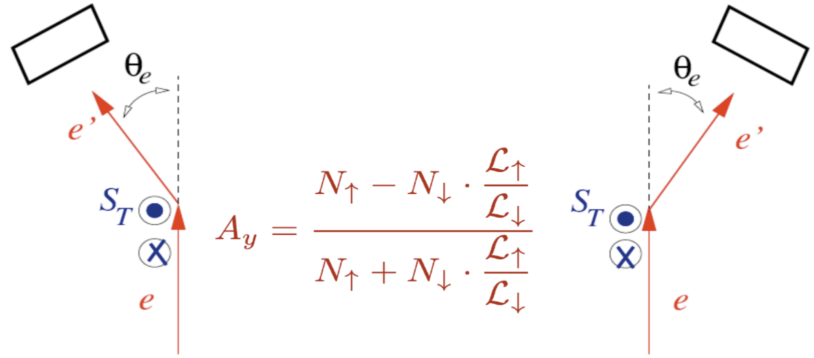


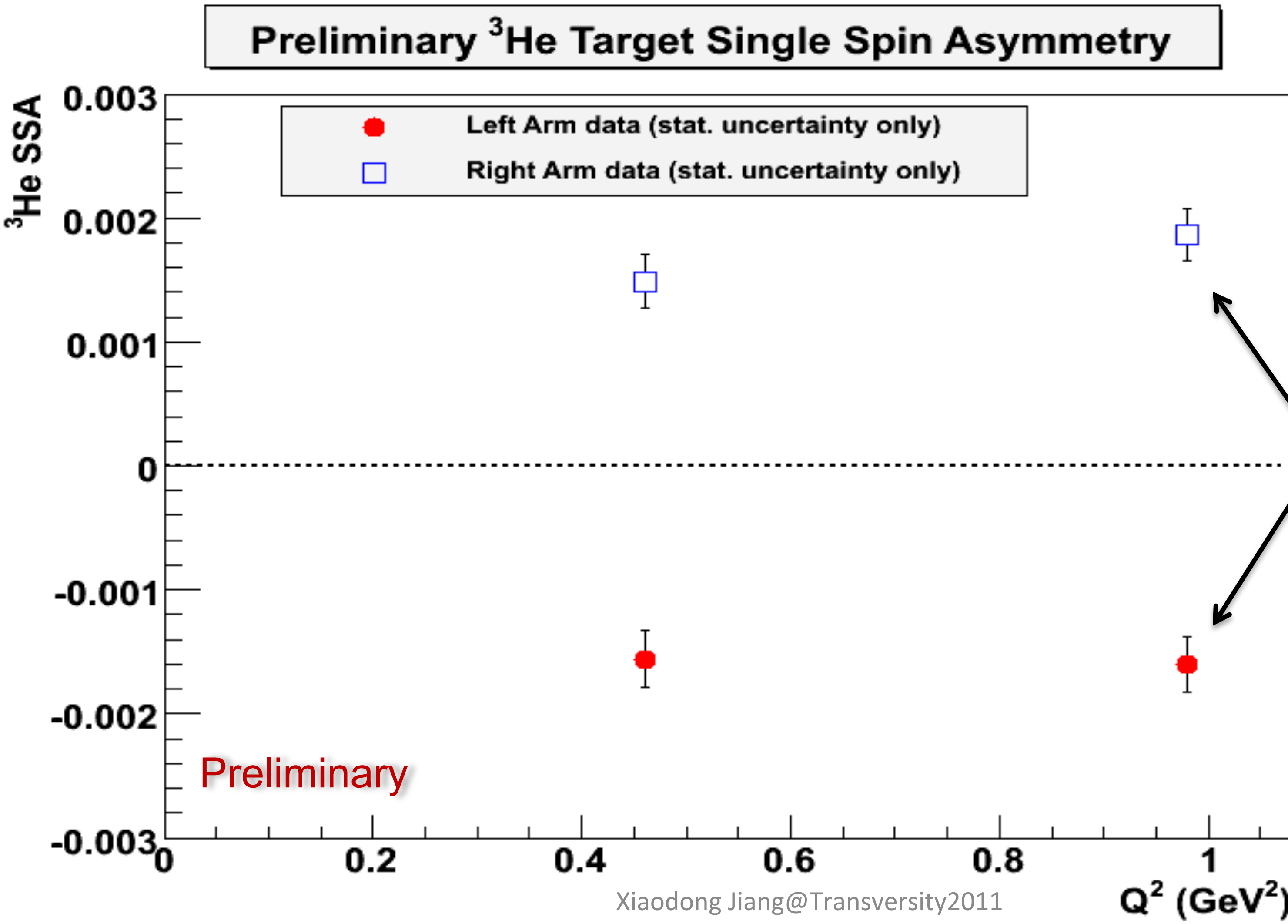
$$(\vec{e} \times \vec{e}\,') \bullet \vec{S}_T > 0$$

$$(\vec{e} \times \vec{e}\,') \bullet \vec{S}_T < 0$$

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

Q^2 = 0.46 and 0.98 GeV^2





Physics SSA flip signs between left-arm and right-arm.

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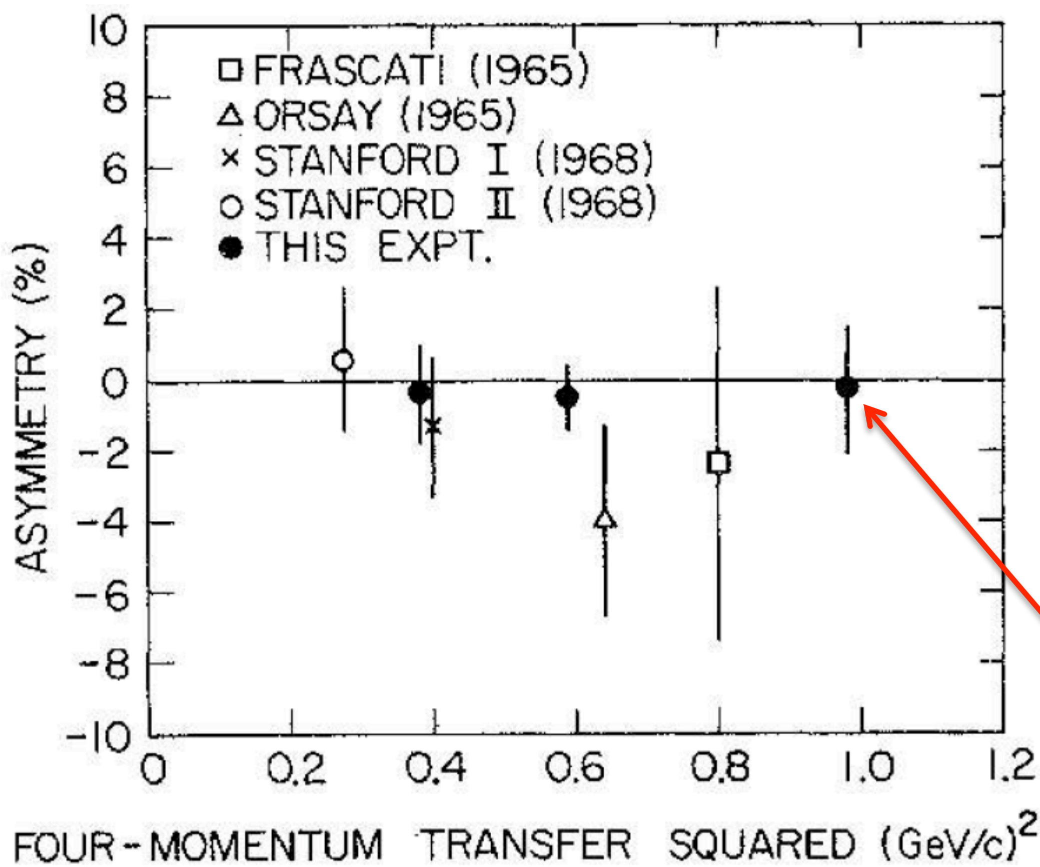
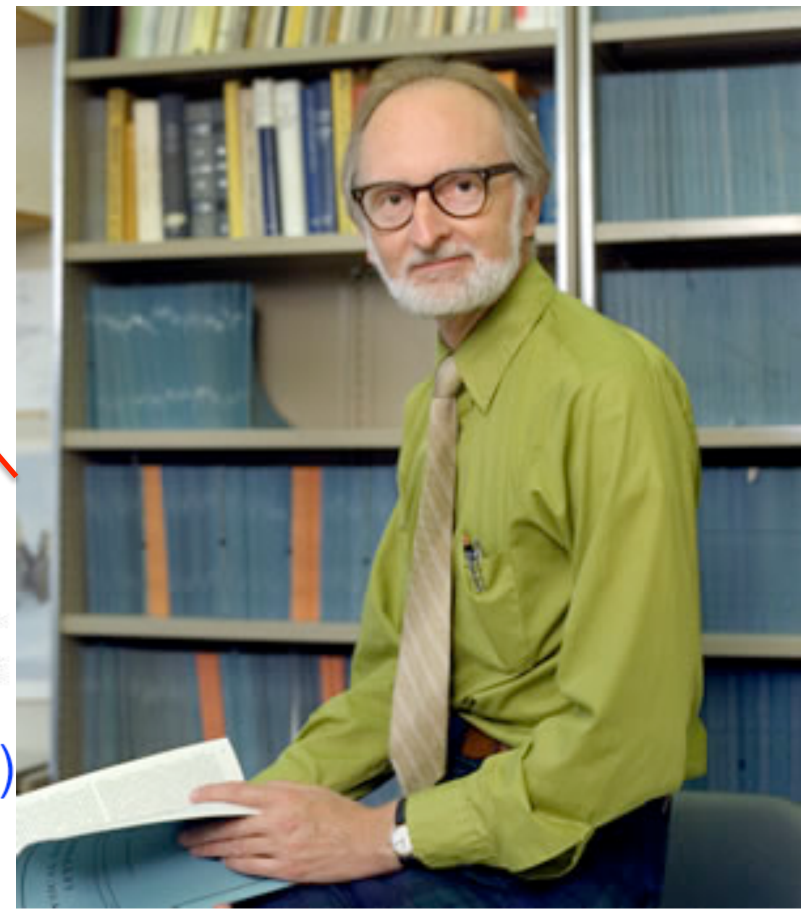
A non-vanishing inclusive A_y has never been observed



SLAC, T. Powell *et al.*, PRL **24**, 753 (1970)

The last effort was made at Stanford in 1969, black dots. Set an upper limit: A_y<2% for proton.



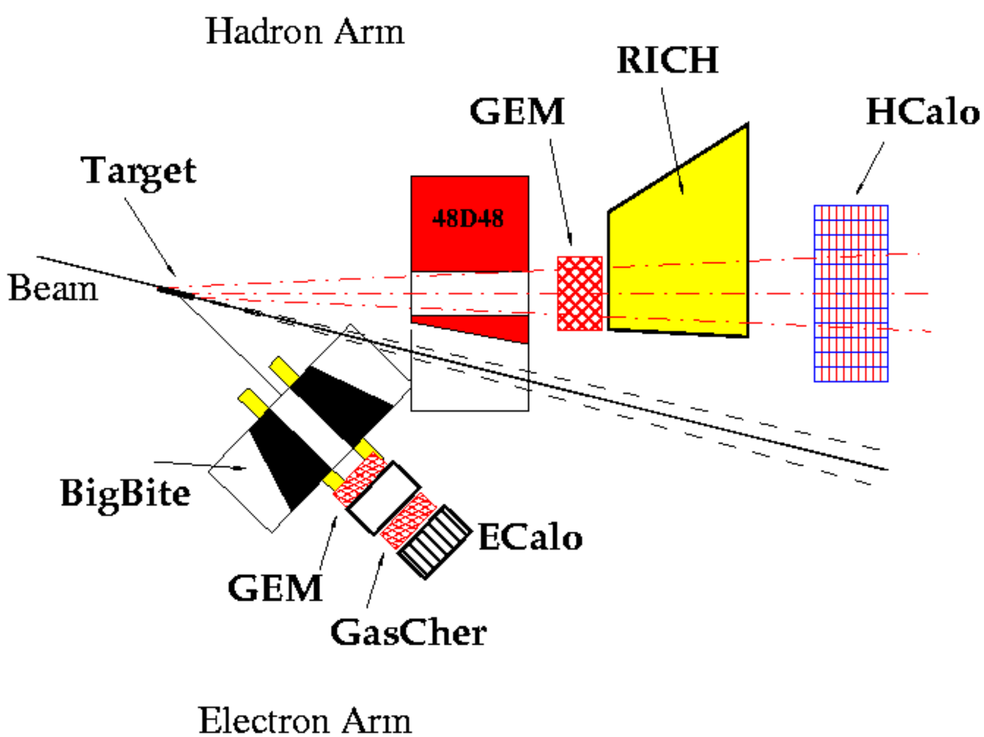
Owen Chamberlain (1920-2006)
Nobel physics 1959.

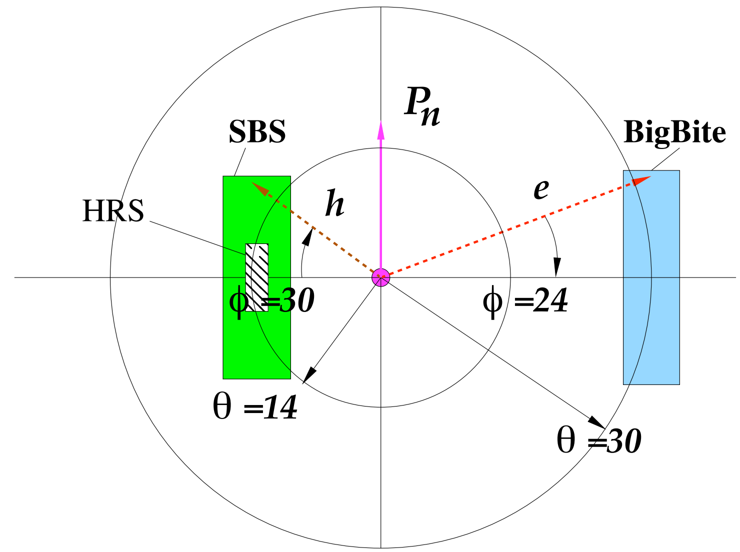
New SIDIS Experiments with JLab-12 GeV in Hall A

- Polarized neutron (^{3}He) transverse
  - Two magnetic spectrometer: Bigbite+Super_BigBite.
  - Large acceptance spectrometer (SoLID).
- Polarized neutron (^{3}He) longitudinal with SoLID.
- Polarized proton (NH_3) with SoLID.
  - Design considerations for a new polarized proton (NH_3) target.

Neutron (^3He) Transversity with BigBite + Super BigBite
(E12-09-018 approved with A^- rating, 64 days of beam)

E12-09-018: Layout

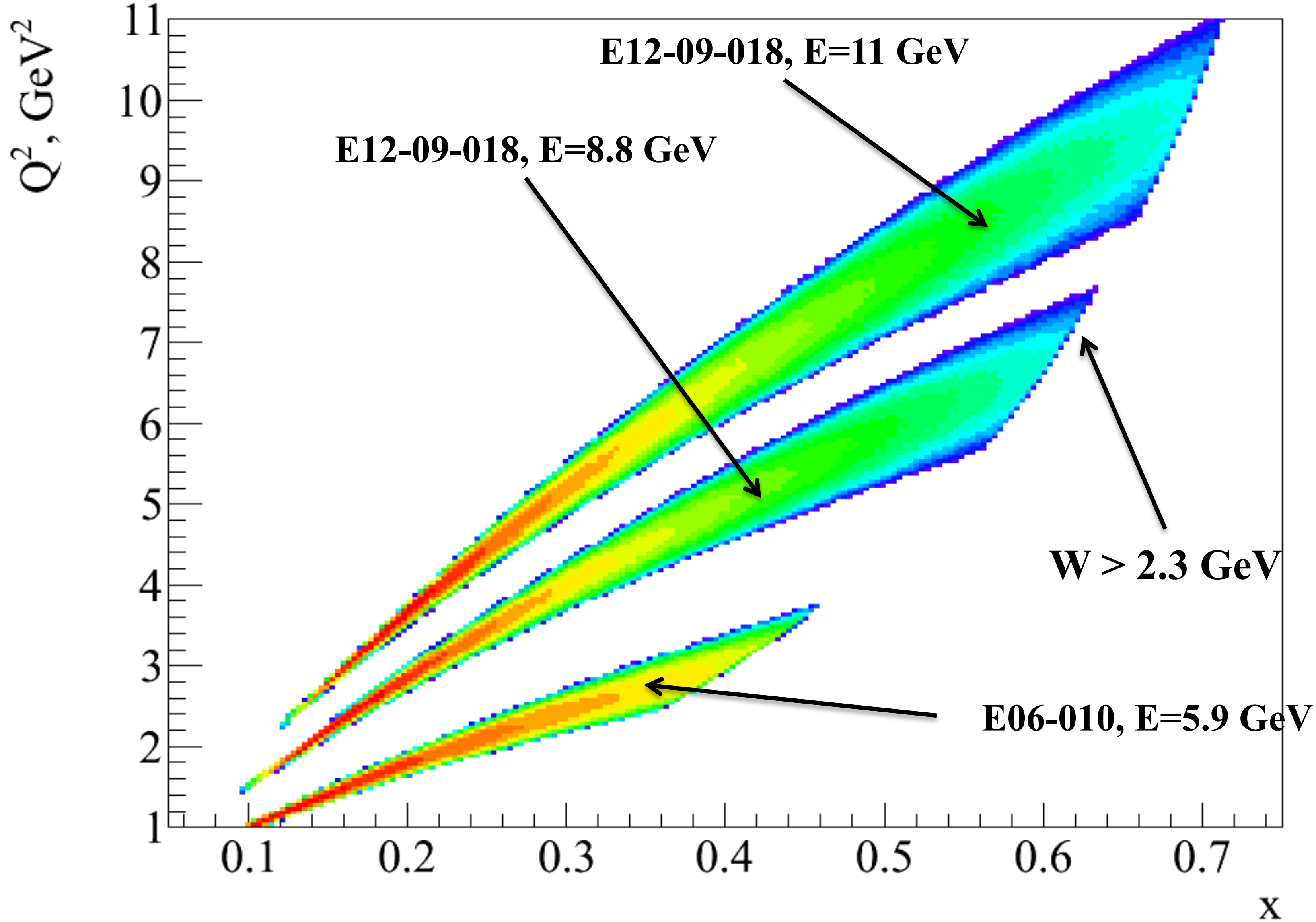




Angular coverage viewed along beam

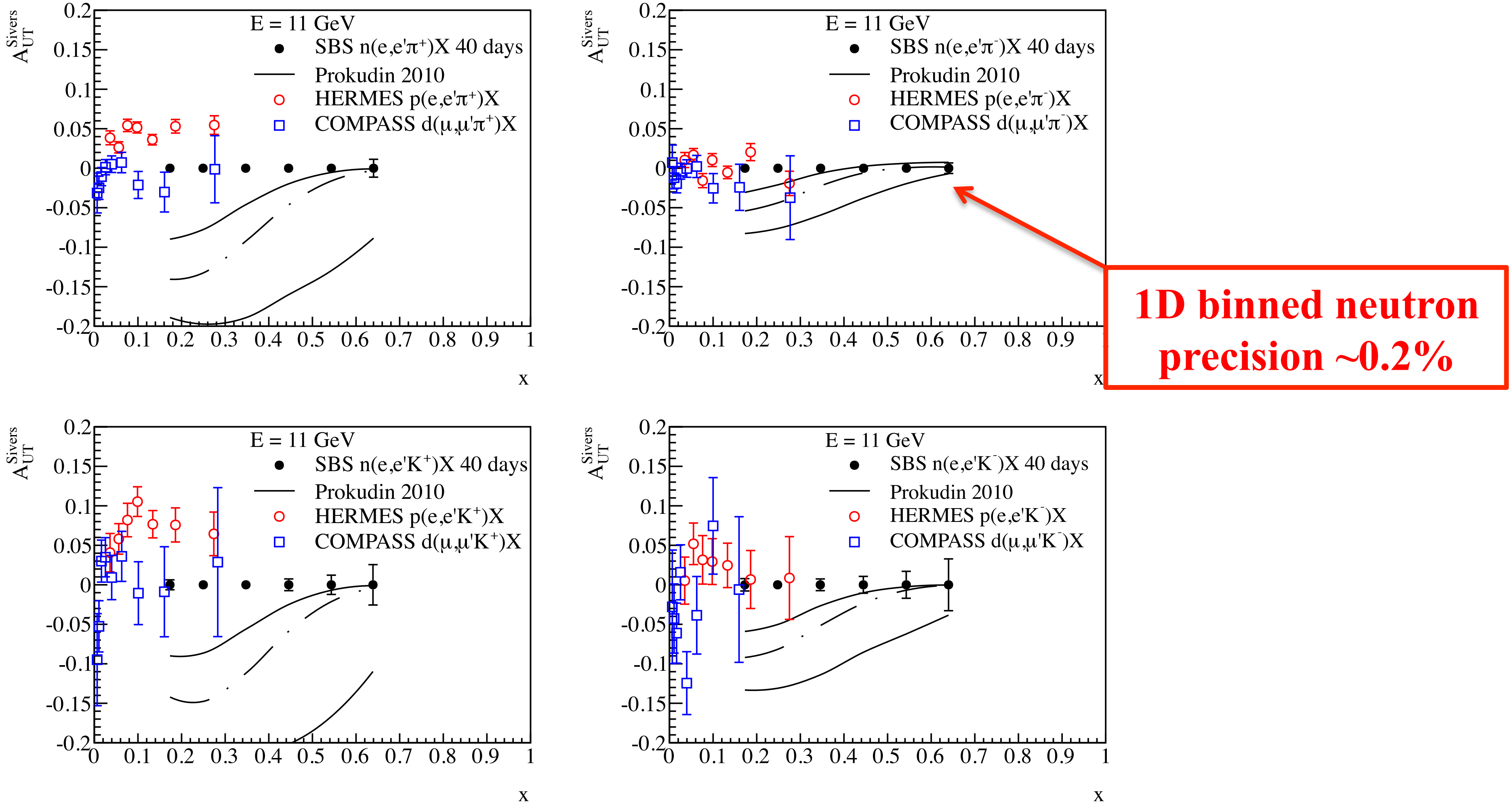
- Electron arm (BigBite) at 30° and hadron arm (SBS) at 14°
- Both arms: large solid angle and large momentum bite.
- Upgraded high-luminosity ^{3}He target, 60 cm long; target spin can be oriented in any transverse direction, we will use 8, sufficient to cover the full azimuthal phase space
- ***10X larger angular acceptance compared to E06-010, 20X larger useful momentum acceptance, ~4X higher useful luminosity → ~800X greater FOM***

SBS nSIDIS Q^2-x Coverage



Expected Precision

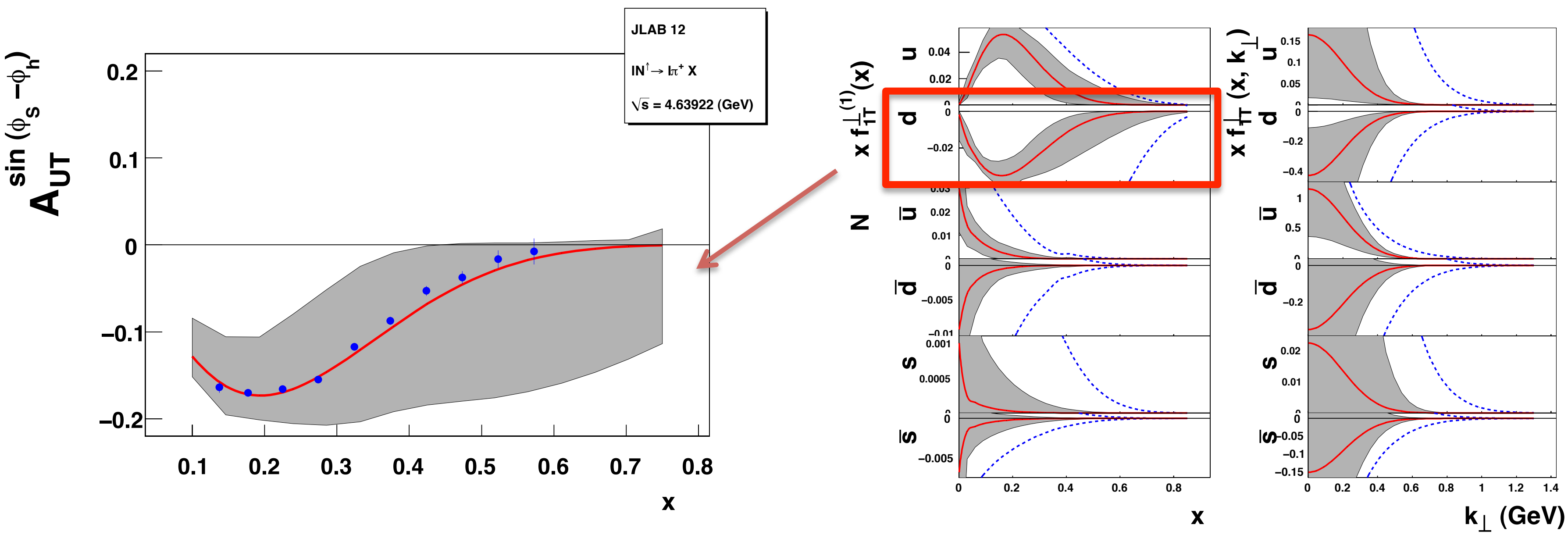
π± , K± Sivers compared to HERMES, COMPASS, theory fit



• E12-09-018 will achieve statistical FOM for the neutron ~100X of HERMES proton data and ~1000X of E06-010 neutron data.

• Kaon and neutral pion data will aid flavor decomposition.

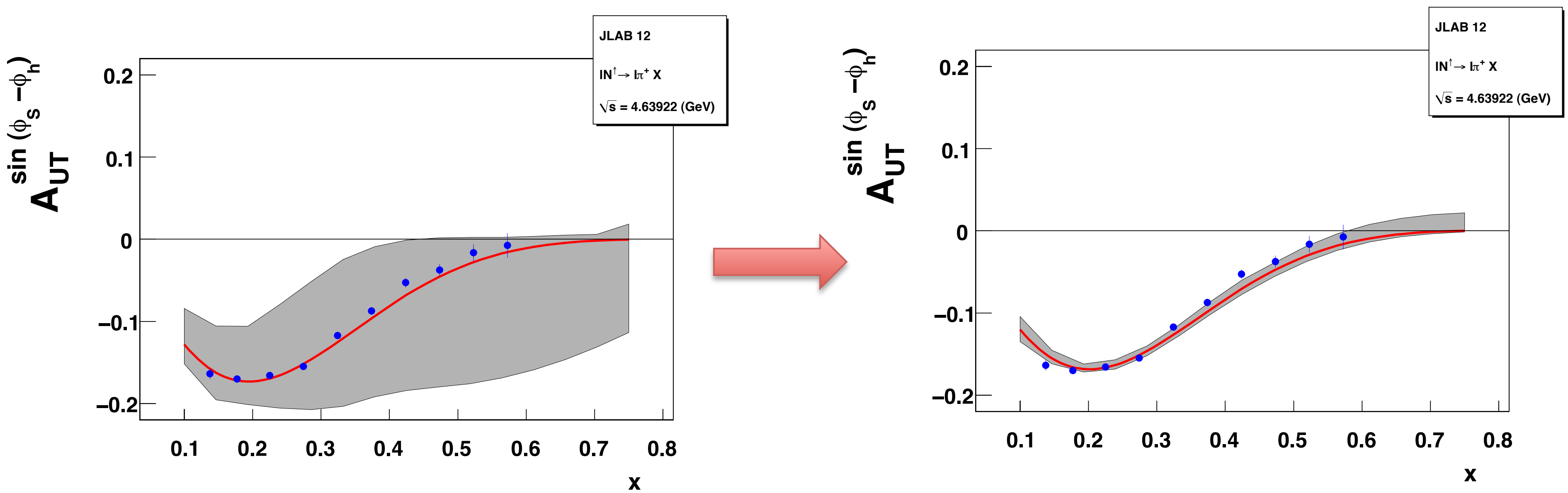
Shrink the Sivers Function Error Corridors



• A. Prokudin: example global fit with E12-09-018 pseudo-data, π^+ Sivers moments at E = 11 GeV, ½ of projected statistics.

• at least 5X shrinking of n(e,e' π^+)X Sivers A_{UT} band

Shrink the Sivers Function Error Corridors



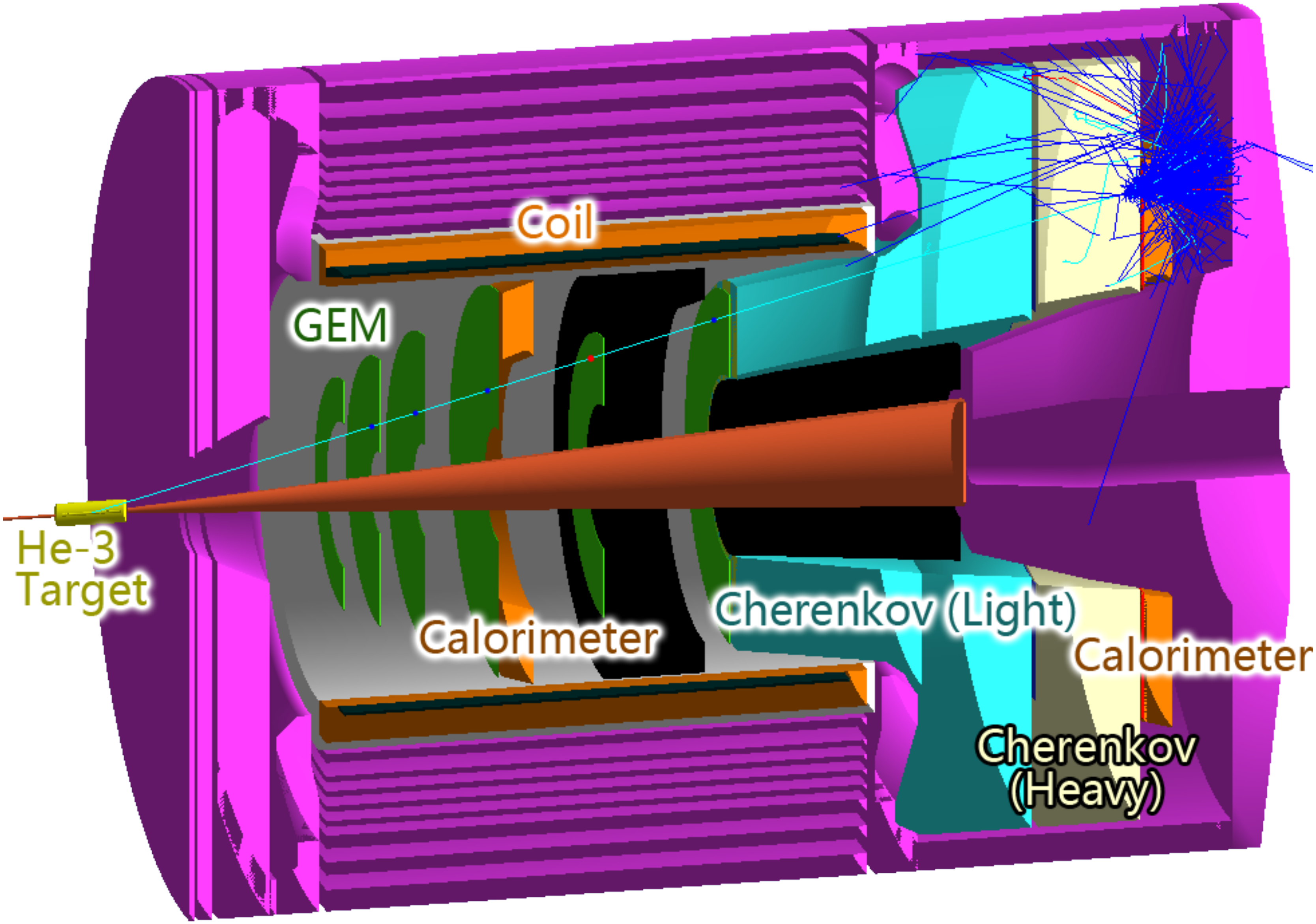
- A. Prokudin: example global fit with E12-09-018 pseudo-data, π^+ Sivers moments at E = 11 GeV, ½ of projected statistics.
- at least 5X shrinking of n(e,e' π^+)X Sivers A_{UT} band

First Jlab-12 GeV beam in Hall A: Oct. 2013.
E12-09-018 can be ready by mid-2014.

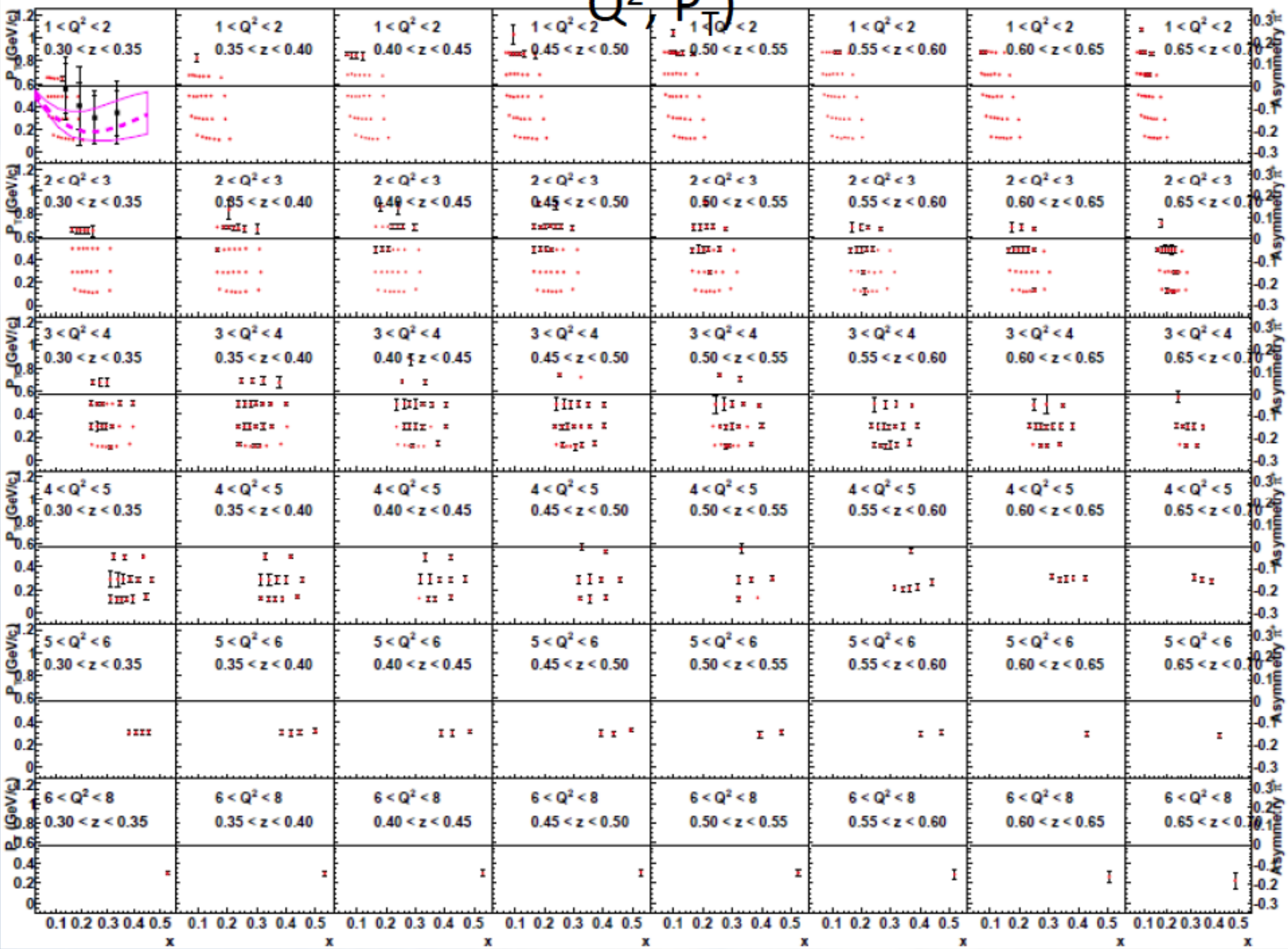
Of course,

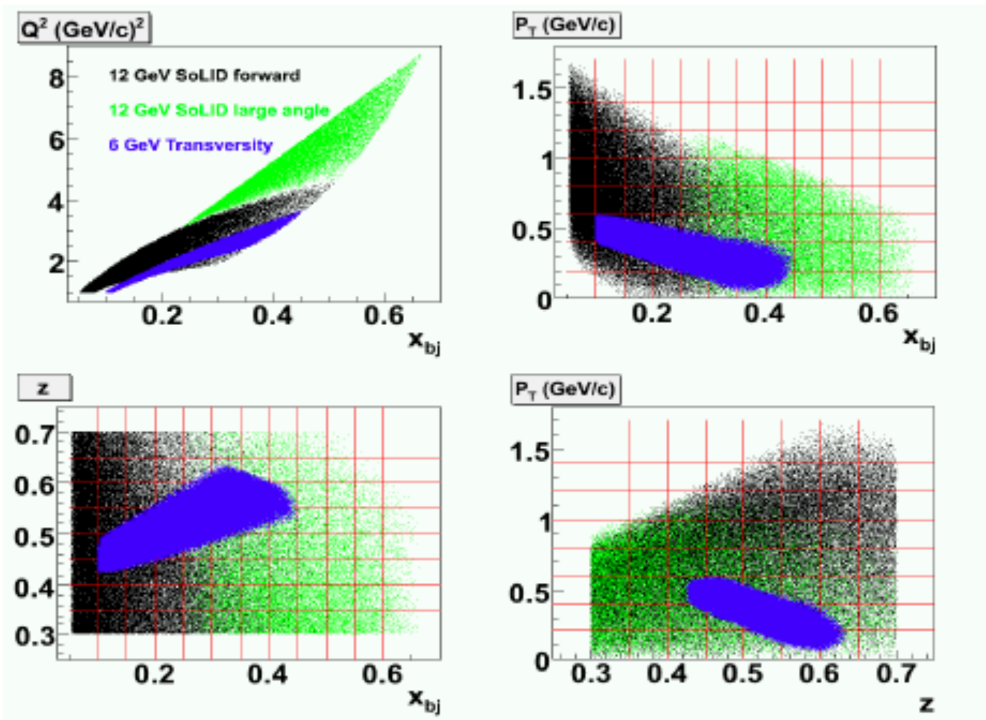
our goal is to pin down SSA in a multi-dimensional space of (x, Q^2, z, p_T) with a large acceptance spectrometer which can take a high luminosity, for polarized neutron and proton targets.

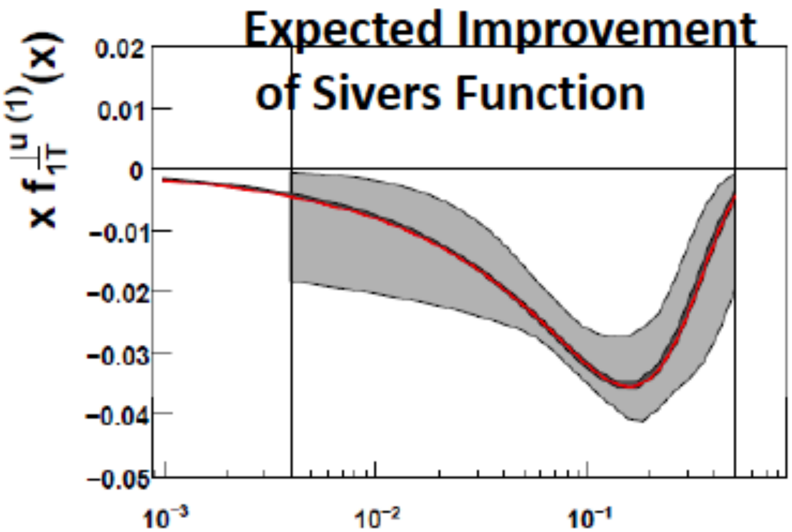
SoLID in Hall A : conceptual design



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



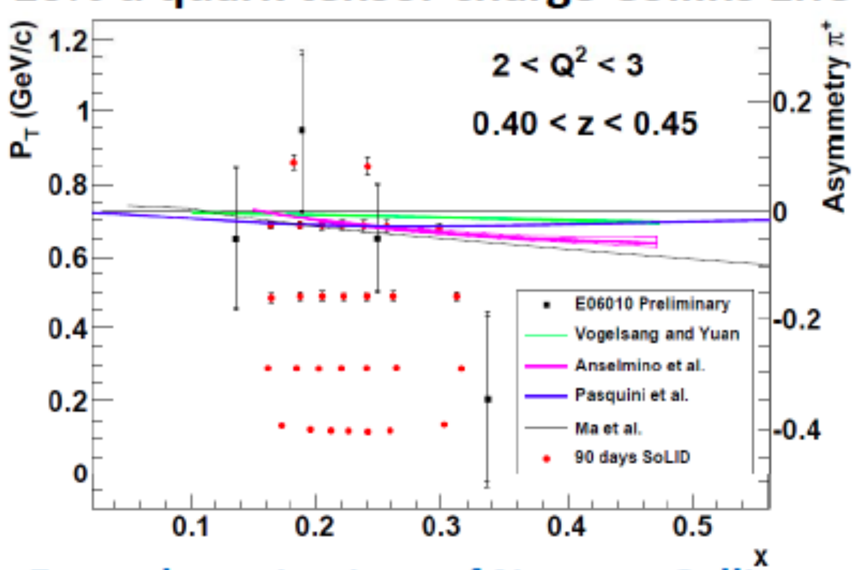




$$A_{UT}^{Collins} \propto \langle \sin(\phi_h + \phi_s) \rangle \propto h_{1T} \otimes^x H_1^\perp$$

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

10% d quark tensor charge Collins Effect



Example projections of Neutron Collins moments, 1/48 bins in z vs. Q^2.

Sys.: 0.1% (abs.) + ~6% (rel.) + Nuclear Effect/FSI

50 days @ 11 GeV + 22 days @ 8.8 GeV + 10 days on H/D (Dilution, FSI, Mechanism) + 8 days calibration

= 90 days!

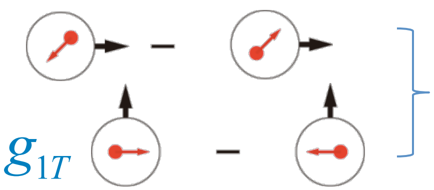
(E12-10-006 approved with A rating)

These data will provide ultimate precision mapping of Neutron SSA in the valence region

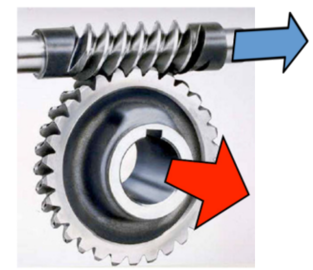
E12-11-007: SIDIS using Longitudinally Pol. ^{3}He and SoLID

(approved with A rating, 35 days additional beam)

- **Semi-Inclusive DIS $\pi^{\pm}$ production**
  - **Longitudinally Pol. ^{3}He target** effective pol. neutron target, achieved world-best performance
  - **SoLID** large symmetric acceptance detector, high statistics and better angular modulation separation
- **Extraction of novel TMDs**
  - $A_{UL}(\sin(2\phi_h)) \to h_{1L}^{\perp}$
  - $A_{LT}(\cos(\phi_h - \phi_S)) \to g_{1T}$



WORM-GEAR distributions, interference of OAMs: Re $[(L=0)_q \times (L=1)_q]$



  - $A_{LL} \to g_{1L}$

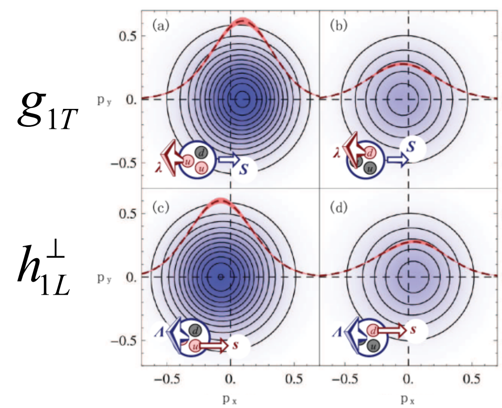
p_T dependent helicity distribution

- **Many predictions available**
  - First Lattice QCD calculation
  - Light-cone quark model and others
- **No GPD Correspondence**
  - Genuine sign of intrinsic transverse motion
- **Links to Collinear PDFs**

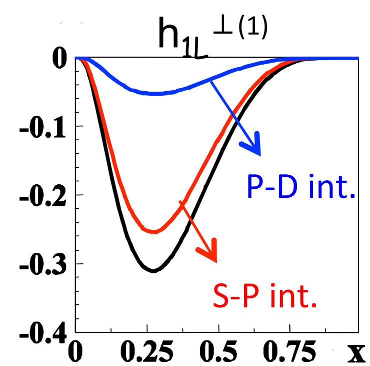
$$h_{1L}^{\perp q(1)}(x) \overset{WW-type}{\approx} -x^2 \int_x^1 \frac{dy}{y^2} \cdot h_1^q(y)$$

$$g_{1T}^{q(1)}(x) \overset{WW-type}{\approx} x \int_x^1 \frac{dy}{y} \cdot g_1^q(y)$$

hep-ph/0603194



Lattice QCD, arXiv:0908.1283



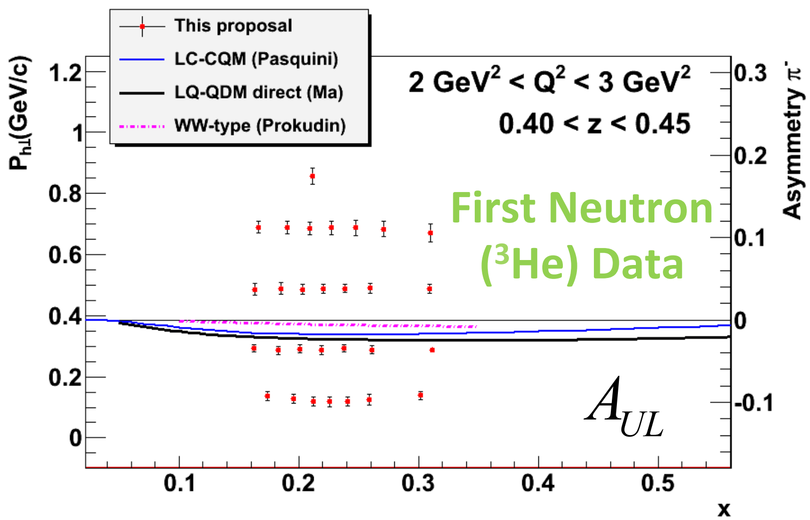
Light-Cone CQM, arXiv:0806.2298

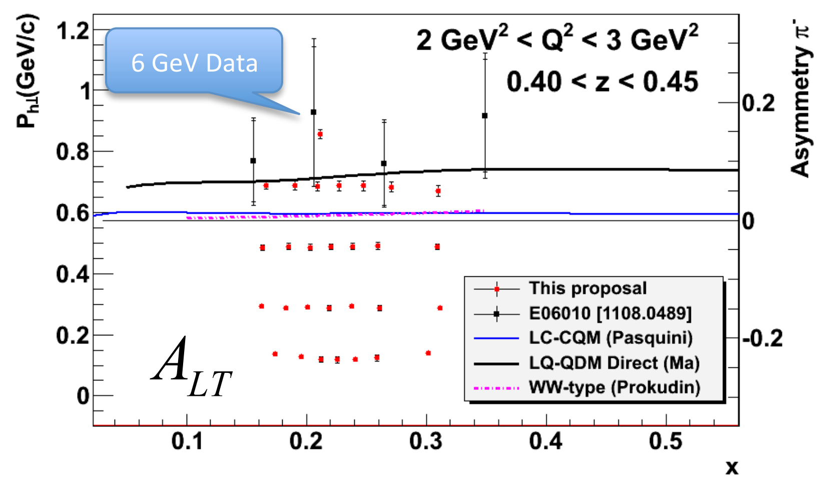
E12-11-007 Projections

4-D mapping of azimuthal asymmetries

- ***35 PAC days on longitudinally pol. ^{3}He target (8.8 & 11 GeV)***

- ***High statistics and excellent systematic uncertainty***
  - **>1000 4-D bins** for A_{LL}, A_{UL} or A_{LT} with $\pi^{\pm}$ together, **1 of 48 Z-Q^2 panels** of π^- shown here
  - Neutron asymmetries: $\delta A_{stat.} \approx 0.5\%$ (absolute)
  - Large symmetric acceptance together with spin flips: $\delta A_{sys.}/A \approx 7\%$ (relative)



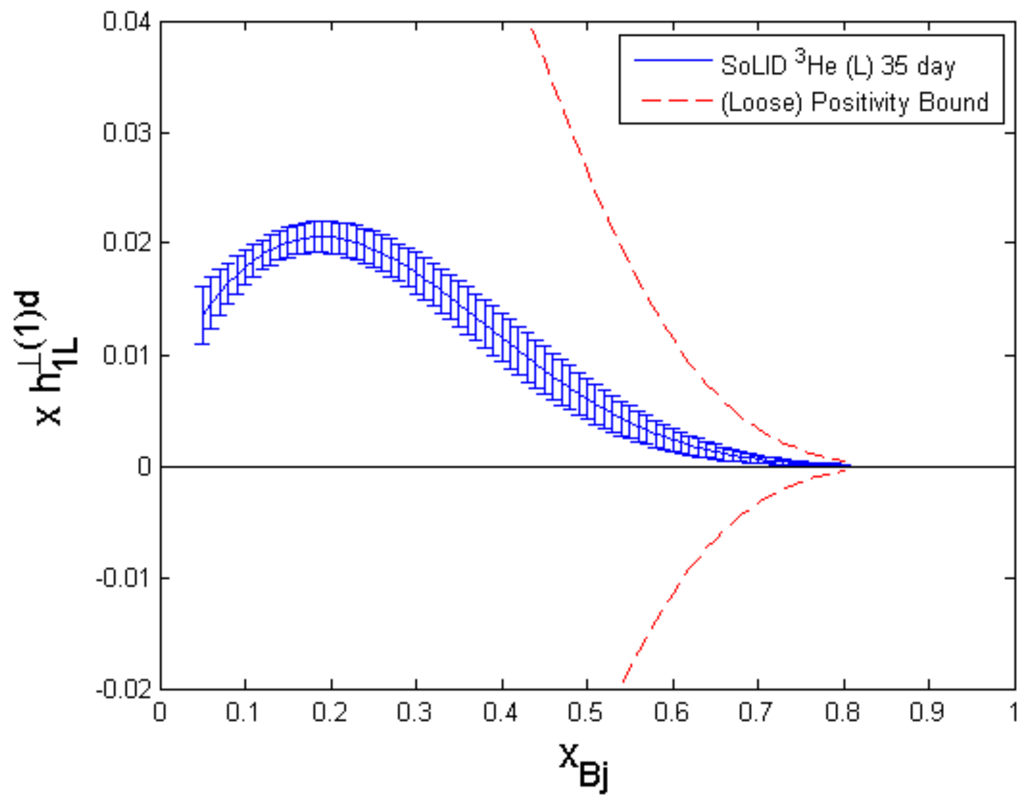


- ***Test TMD relations at matching kinematics***
  - $g_{1T} \approx -h_{1L}^{\perp}$ suggested by a large class of models based on geometrical symmetry, also supported by lattice calculations
  - Test of WW relations, provides a constraint on Transversity

E12-11-007 : Projection of h_{1L}

$A_{UL} \sim h_{1L}\ H_1$

(assume $H_1 \sim 0.15\ D_1$)



C12-11-108:

Target Single Spin Asymmetry in SIDIS *(e, e'$\pi^{\pm}$)* Reaction on a Transversely Polarized Proton Target and SoLID

(Conditionally approved pending on magnet design.)

- Based on an existing JLab polarized NH_3 target system (3cm cell).
- Plan to build a new superconducting magnet with larger opening to access high-x kinematics.
- Conditionally approved pending on the magnet design.

Requested for 120 days of JLab beam.

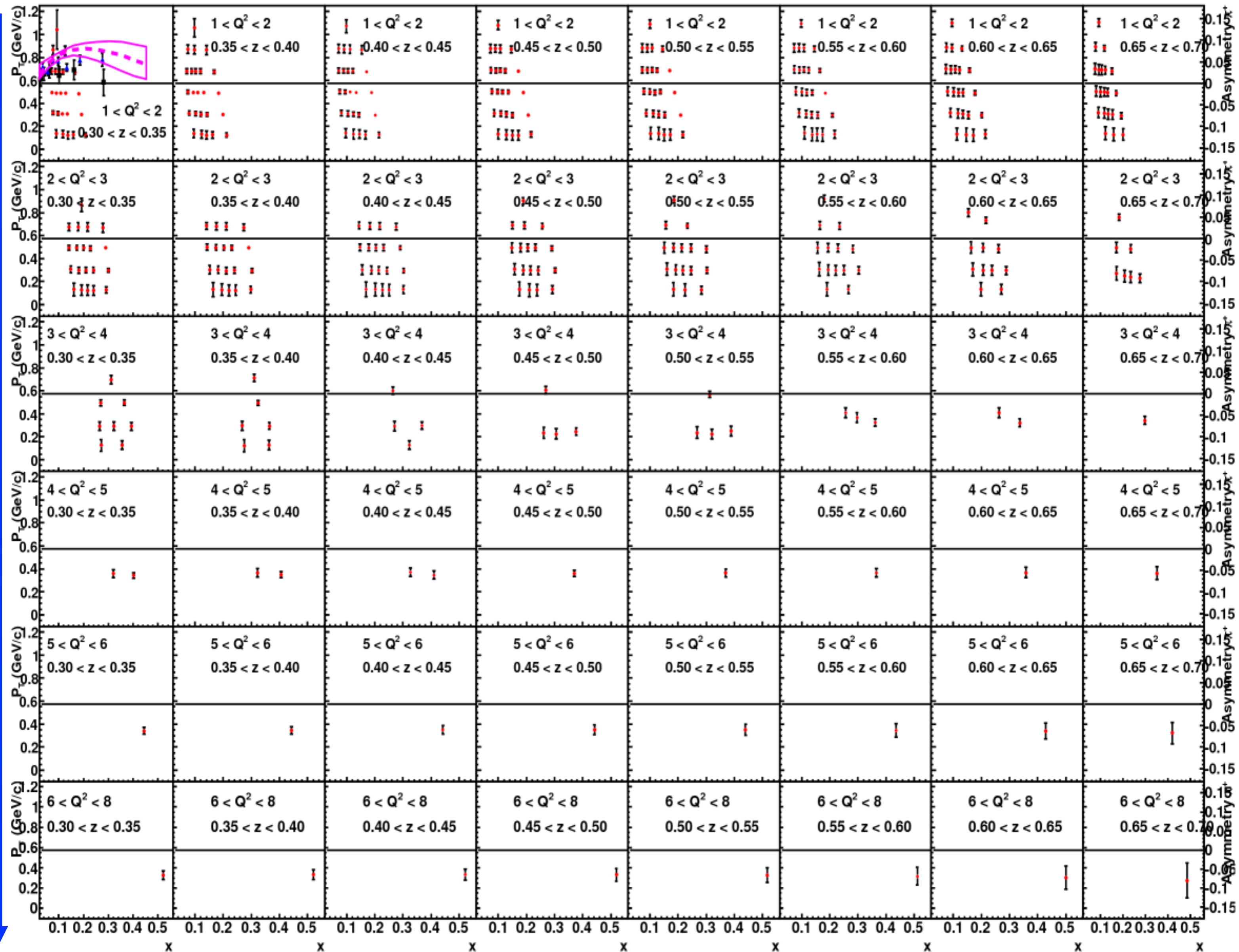
- A new design of a high luminosity transversely polarized NH_3 target system could improve statistics by ~4x (or reduce the running time to 1/4).

A_{UT} Projections (π^+ Sivers)

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

Multi-dimensional binning in
x, Q^2, p_T, z

(674 bins in total)



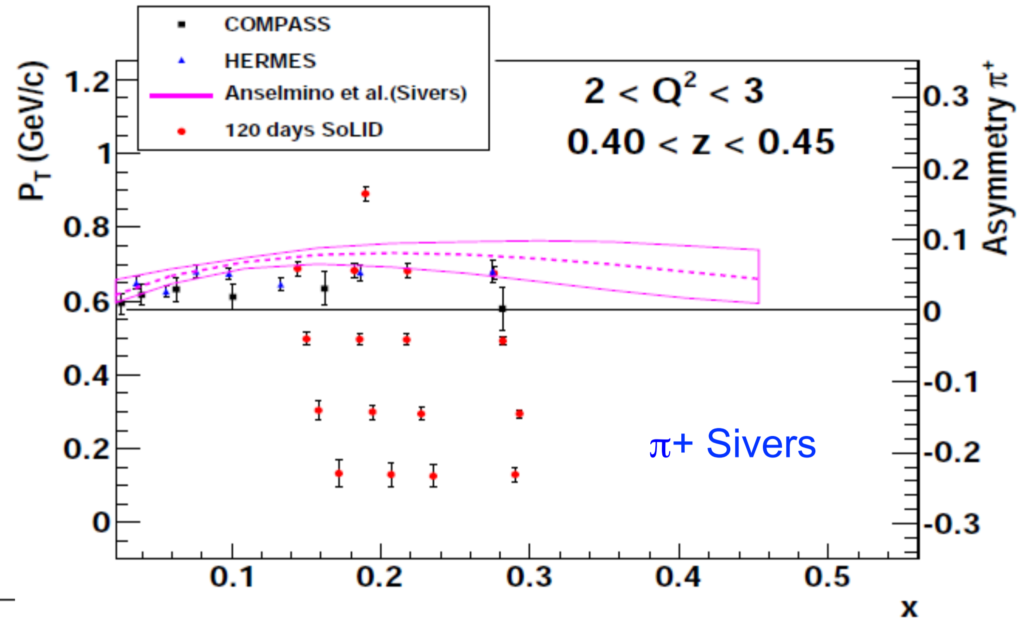
$Q^2 = 8$ (GeV/c)^2

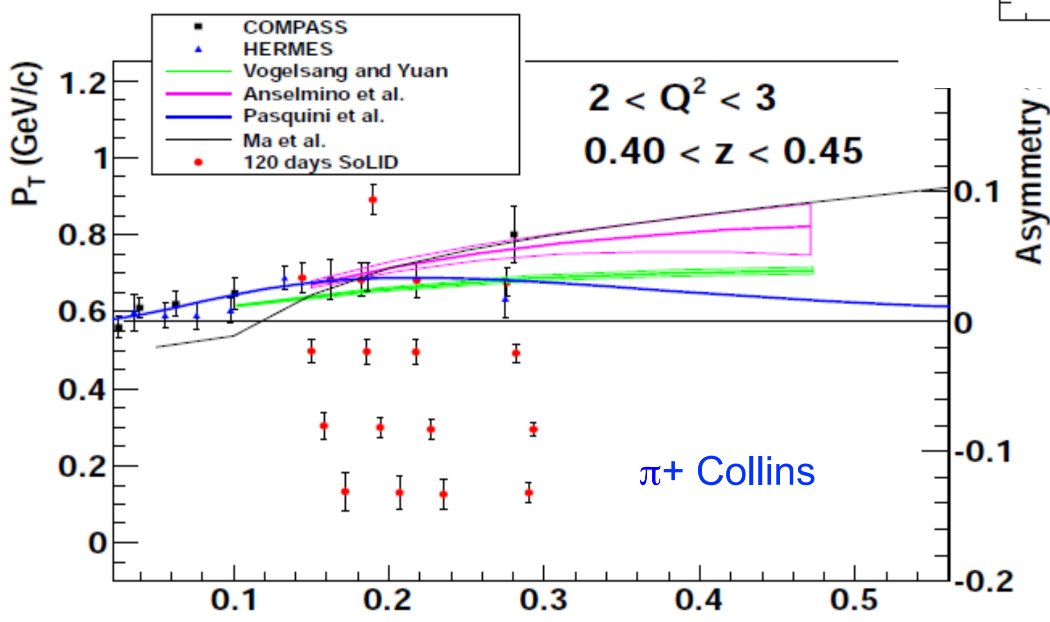
z = 0.3

z = 0.7

C12-11-108:
Proton A_{UT} Projections

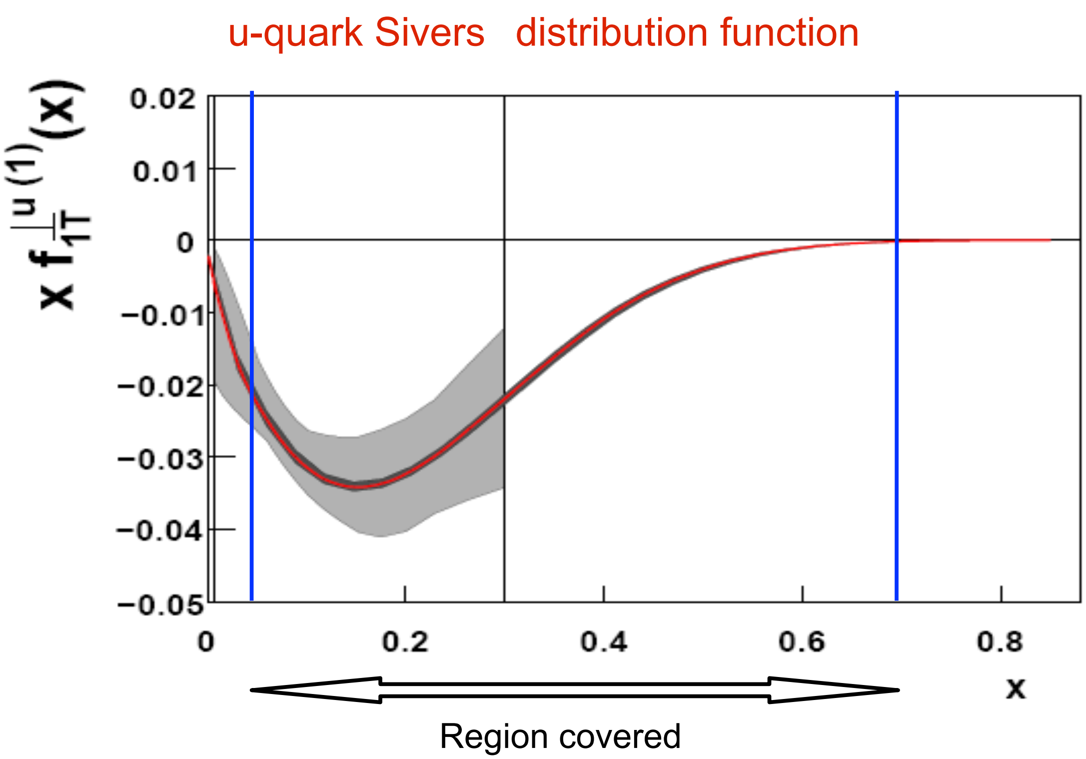
- Projections for one out of 48 panels in Q^2 and z





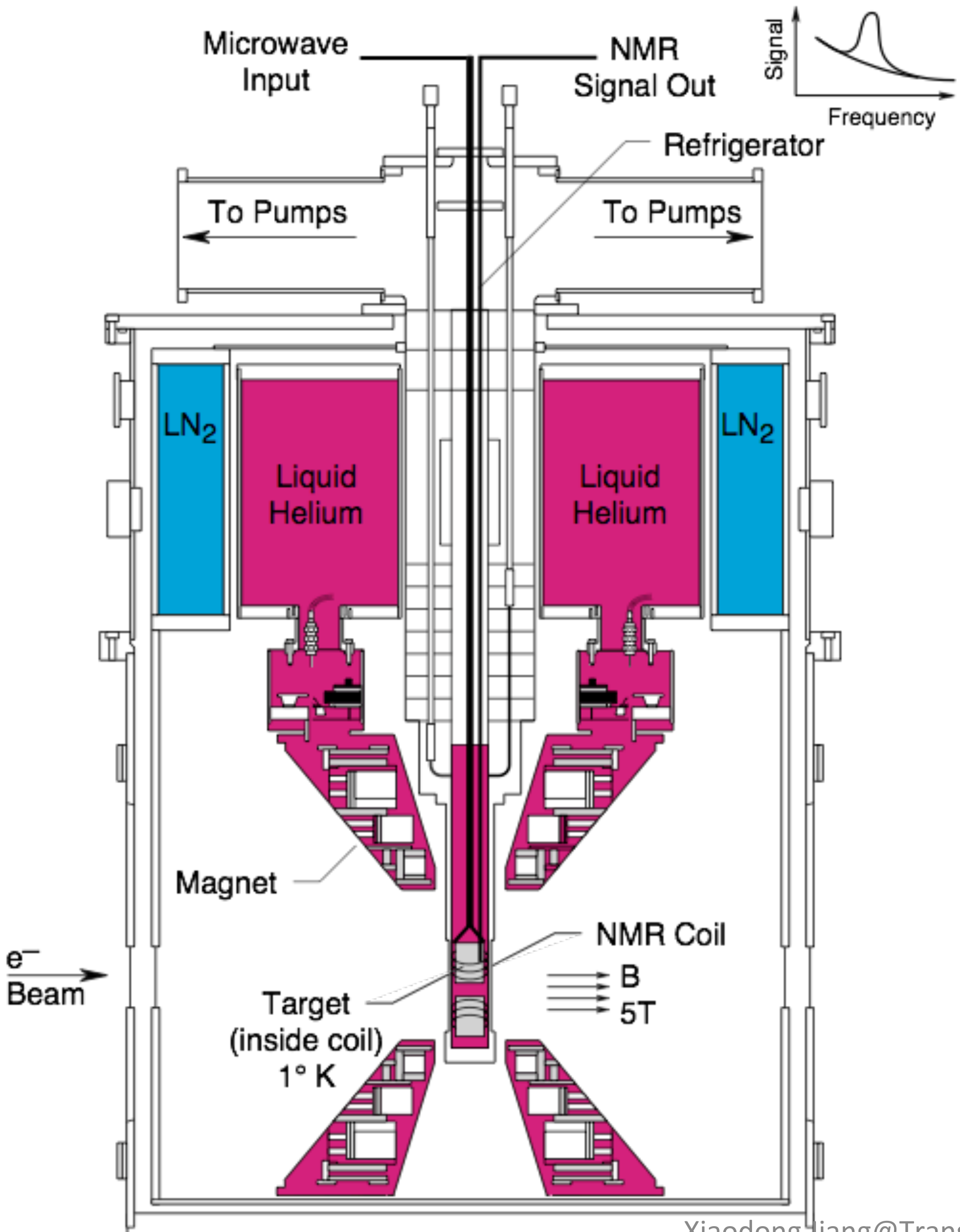
Impact

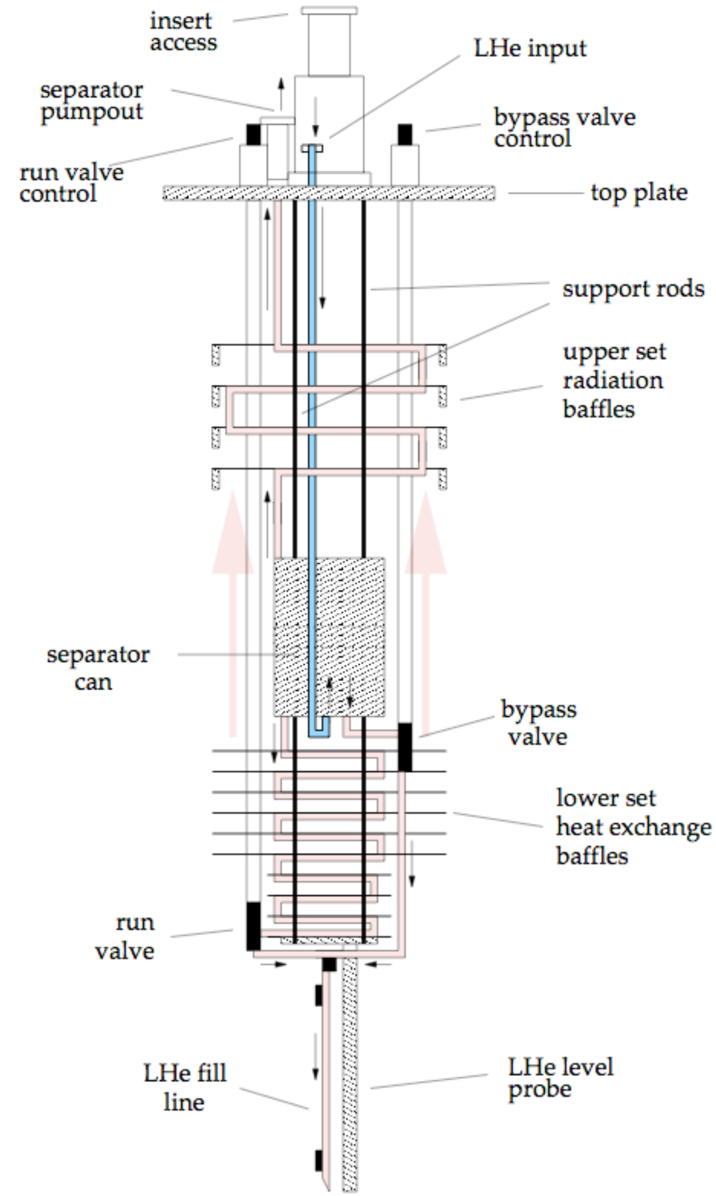
Impact of this measurement on u-quark Sivers distribution function



A. Prokudin

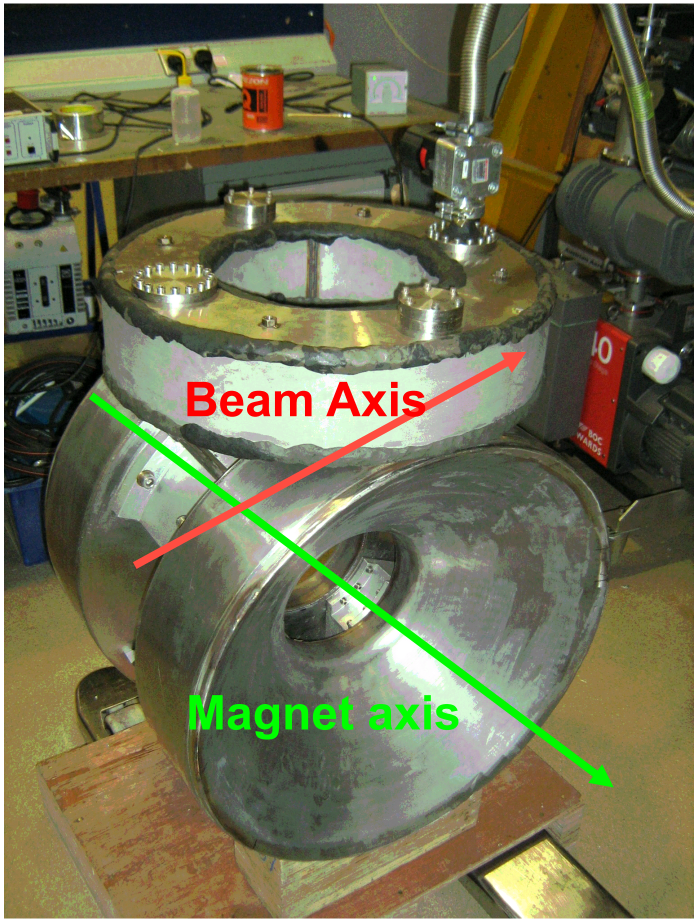
JLab Existing NH_3 Target





Existing JLab Polarized NH_3 Target

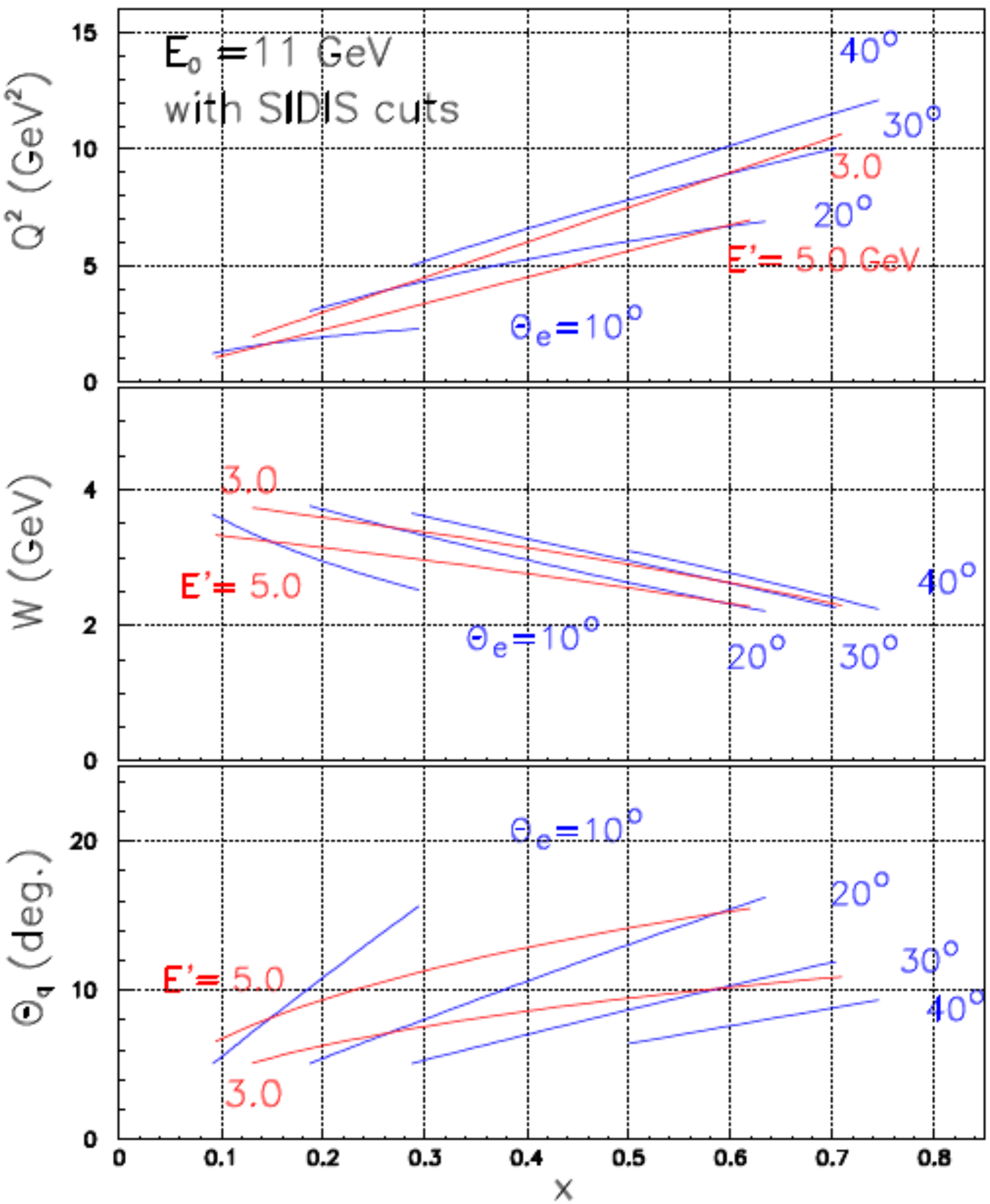
- JLab polarized target, built in early 90s at ~$0.7M, used in many experiments (SLAC, JLab Hall C). Planned for Hall A g2p experiment in Fall 2011.
  - 3cm NH_3 cell at 1K
  - 5 Tesla superconducting magnet
  - Dynamic Nuclear Polarization(DNP)
  - Target magnet designed for longitudinal
    - Opening of +/- 45 deg in long. direction
    - Opening of +/- 17 deg in transverse direction



Current JLab polarized target magnet

Need to access ~30° to cover high-x and high Q^2 kinematics at JLab-12 GeV.

Large angle →high-x@high-Q²



For 11 GeV:

Blue: constant θ_e lines.

Red: constant E' lines.

with all SIDIS cuts:

$Q^2 > 1.0$ GeV^2
$W > 2.0$ GeV

$y < 0.85$
$\theta_q > 5.0°$

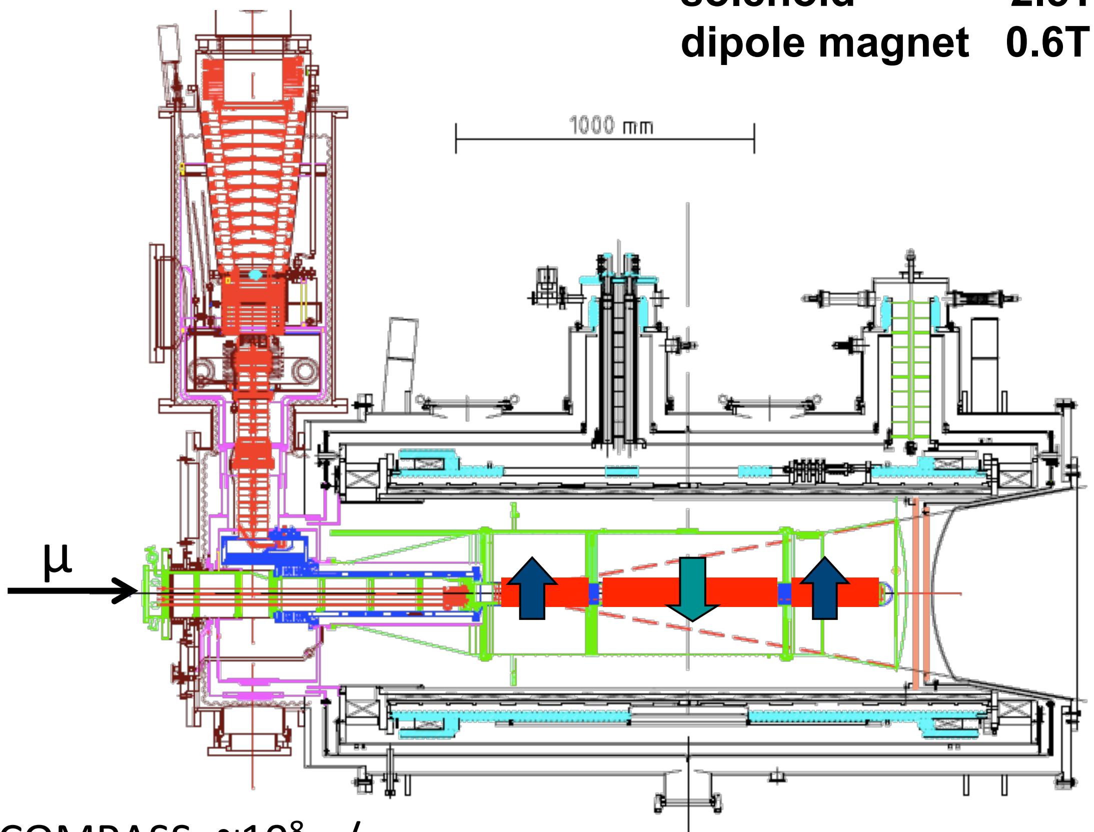
@ $z_h = 0.5$:
$p_h > 2.0$ GeV/c
$W'_K > 1.55$ GeV
($\Rightarrow W'_\pi > 1.63$ GeV)

we would love to have …

the polarized target system (>2005)

^3He – ^4He dilution refrigerator (T~50mK)

solenoid 2.5T
dipole magnet 0.6T



acceptance ± 180 mrad

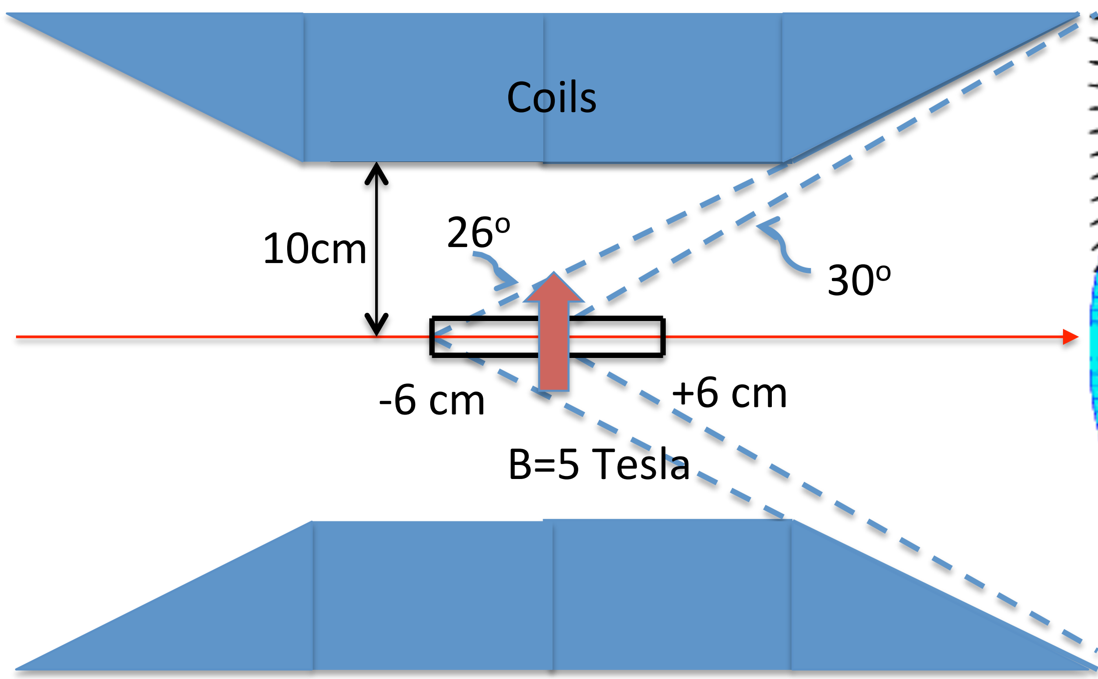
3 target cells
30, 60, and 30 cm long

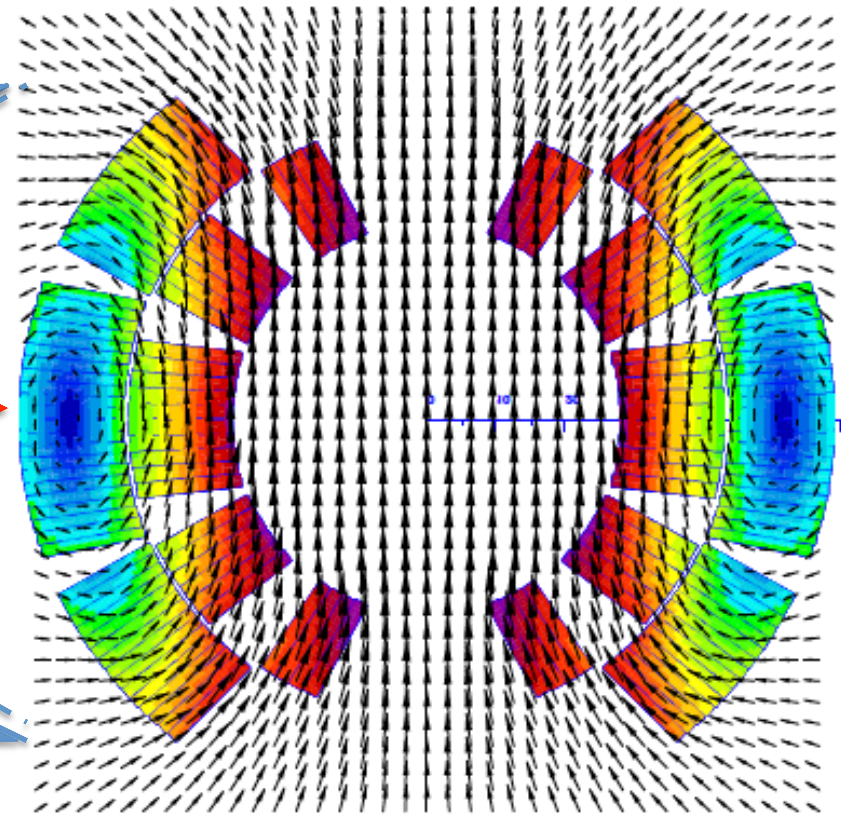
opposite polarisation

	d (^6LiD)	p (NH_3)
polarization	50%	90%
dilution factor	40%	16%

COMPASS: ~10^8 μ/s
JLab (80nA): ~$5x10^{11}$ e/s
E906 average: ~$1.5x10^{11}$ p/s

Illustration of a New Target Dipole Magnet





- a 5 Tesla superconducting dipole. B*dl ≈2.5 T•m pre-bend 11 GeV/c beam by 3.9°
- nominal target area: 12.0cm x R2.0cm with $\delta B/B<10^{-4}$.
- target insert: horizontal from upstream.
- separated vacuum for magnet bore and target insert.
- symmetric around beam. No side access.
- magnet and cryostat to rotate ±45° around beam.

Costs Estimation:

- Magnet:$0.5M.
- Cryostats:$0.25M
- Target RF tubes: $0.40 M
- pumps: ~$0.4M

Total cost: ~$2.0 M over 3 years.

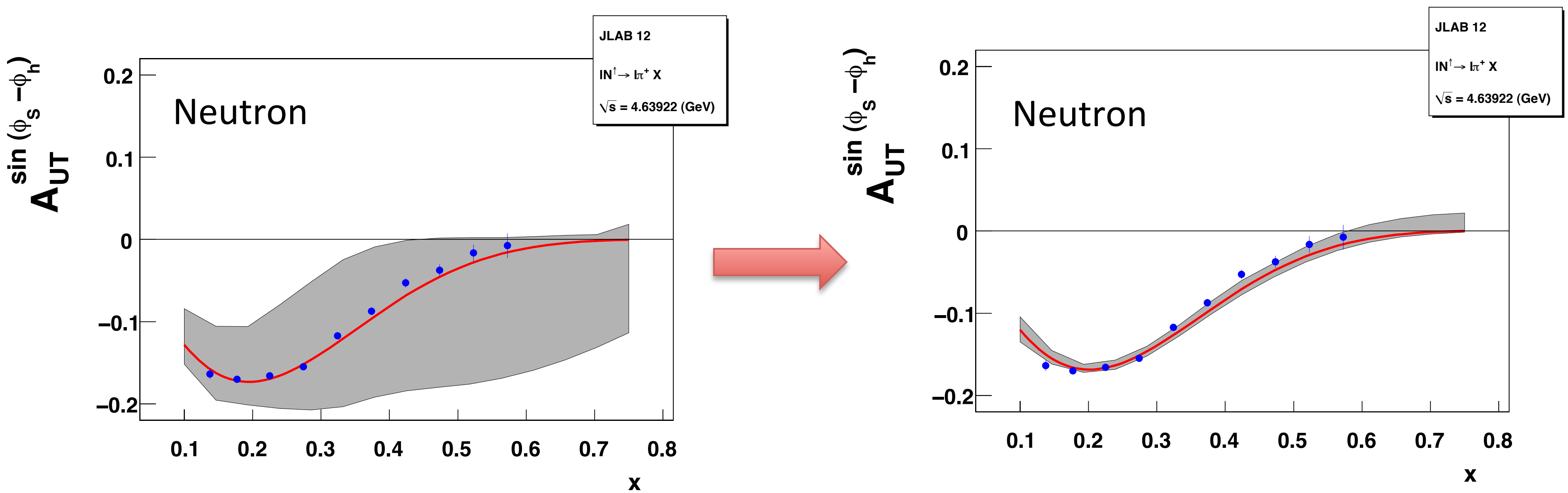
12 months of design.

24 months of manufacture/tests

A New Transversely Polarized NH_3 Target for JLab SIDIS

	NH_3
Target Length (cm): t	2×5.0 (or 12.0)
Density (g/cm^3): ρ	0.917
Packing Factor: κ	0.55
Average Polarization in beam: P_T	0.80
Dilution factor: f	0.176
e-beam max. current (nA): I (or take ~4x proton flux of E906)	80.0
Luminosity at JLab L_{eN} ($cm^{-2}s^{-1}$):	$1.5x10^{36}$
Luminosity at E906 L_{pN} ($cm^{-2}s^{-1}$):	$\sim 3.0x10^{35}$
Refrigerator cooling power (Watt): (~4x existing JLab target).	4.0
FOM(p): $\rho t \bullet \kappa \bullet I \bullet (P_T \bullet f)^2$	

With such a proton target, 80 days of running can obtain proton SSA with 2x statistic uncertainties of that of E12-09-018 (neutron).



proton uncertainties = 2x neutron uncertainties

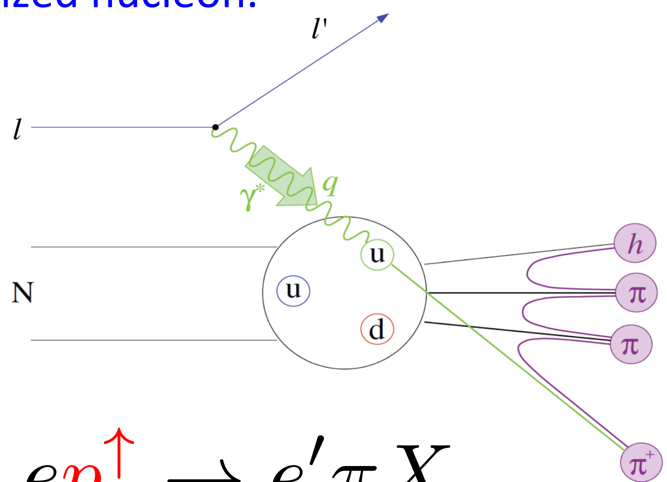
… to constrain u-quark Sivers function at high-x.

First Jlab-12 GeV beam in Hall A: Oct. 2013.
E12-09-018 can be ready by mid-2014.

The same target design could also fit for a Drell-Yan experiment at Fermi Lab

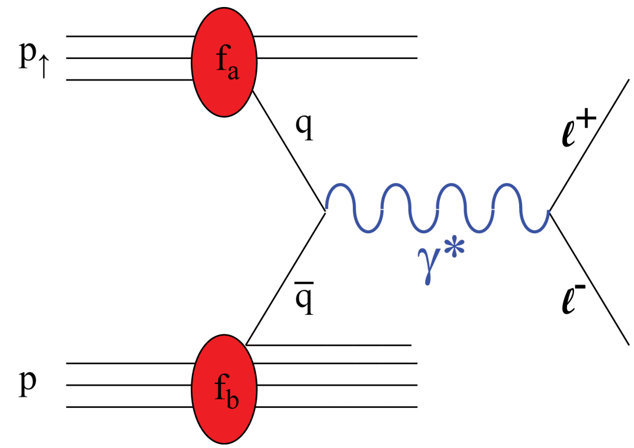
Quark Sivers Distributions can be Accessed through Two Types of Experiments, but with a Difference in Sign

Left-right asymmetry in semi-inclusive deep inelastic scattering (SIDIS) on a polarized nucleon.



$$e p^{\uparrow} \rightarrow e' \pi X$$

Left-right asymmetry in Drell-Yan di-muon pair production (DY) on a polarized nucleon.



$$p p^{\uparrow} \rightarrow \mu^{+} \mu^{-} X$$

The same quark Sivers distribution shows up in both processes, but with an opposite sign.
[J. Collins, PLB536, 43 (2002). S. Brodsky, NPB642, 344 (2002)].

$$f_{1T}^{\perp q} \mid_{SIDIS} = - f_{1T}^{\perp q} \mid_{DY}$$

A Critical Test of Fundamental QCD Predictions

- Possible outcomes:
  - If confirmed: first major triumph of QCD in hadron spin physics: validation of color gauge formalism and QCD factorization
  - If confirmed the sign change, but not the magnitude:
    Sub-leading contributions play x-dependent role ?
    Significant flaws in our current understanding of QCD processes ?
  - If no sign change:
    fundamental flaws in our understating of QCD and it applicability to strong interaction phenomena, could lead to a new theoretical breakthrough

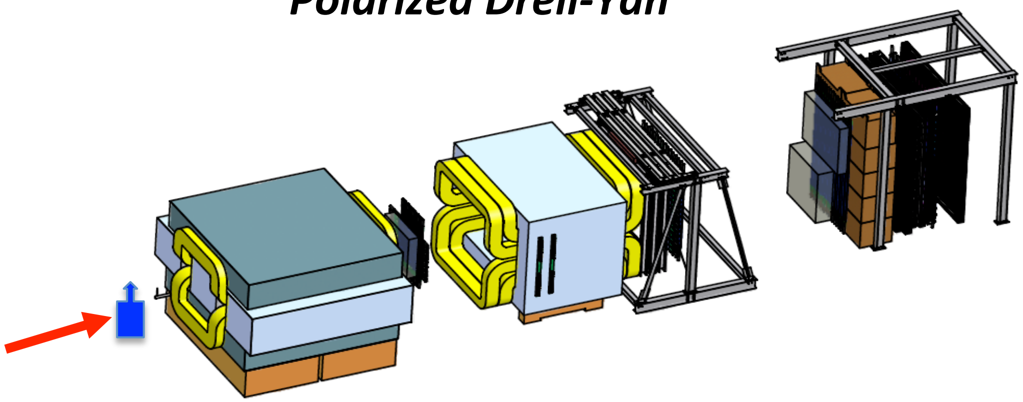
A consensus reached through several D-Y workshops (BNL-2011, Santa Fe-2010, CERN-2010).

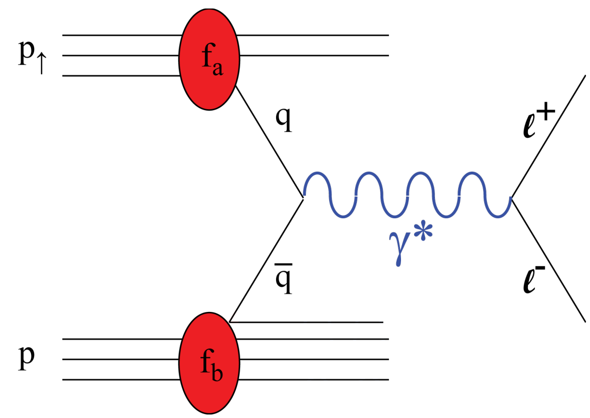
DOE Milestone HP13: "Test unique QCD predictions for relations between single-spin phenomena in p-p scattering and those observed in deep-inelastic scattering".

A Possible Polarized Target Drell-Yan Measurement at Fermi Lab

Take advantage of the E906 Drell-Yan Exp. @Fermilab

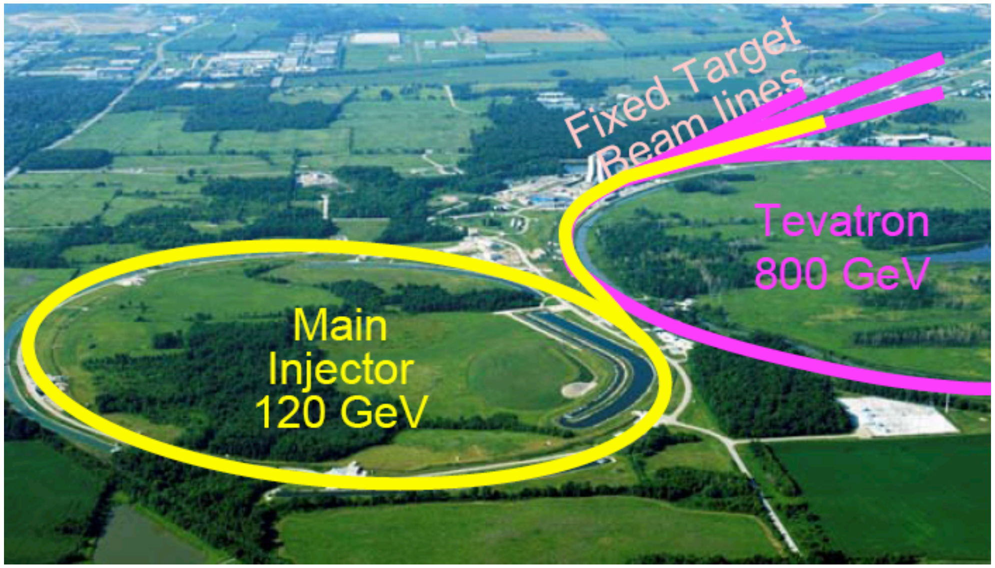
Polarized Drell-Yan

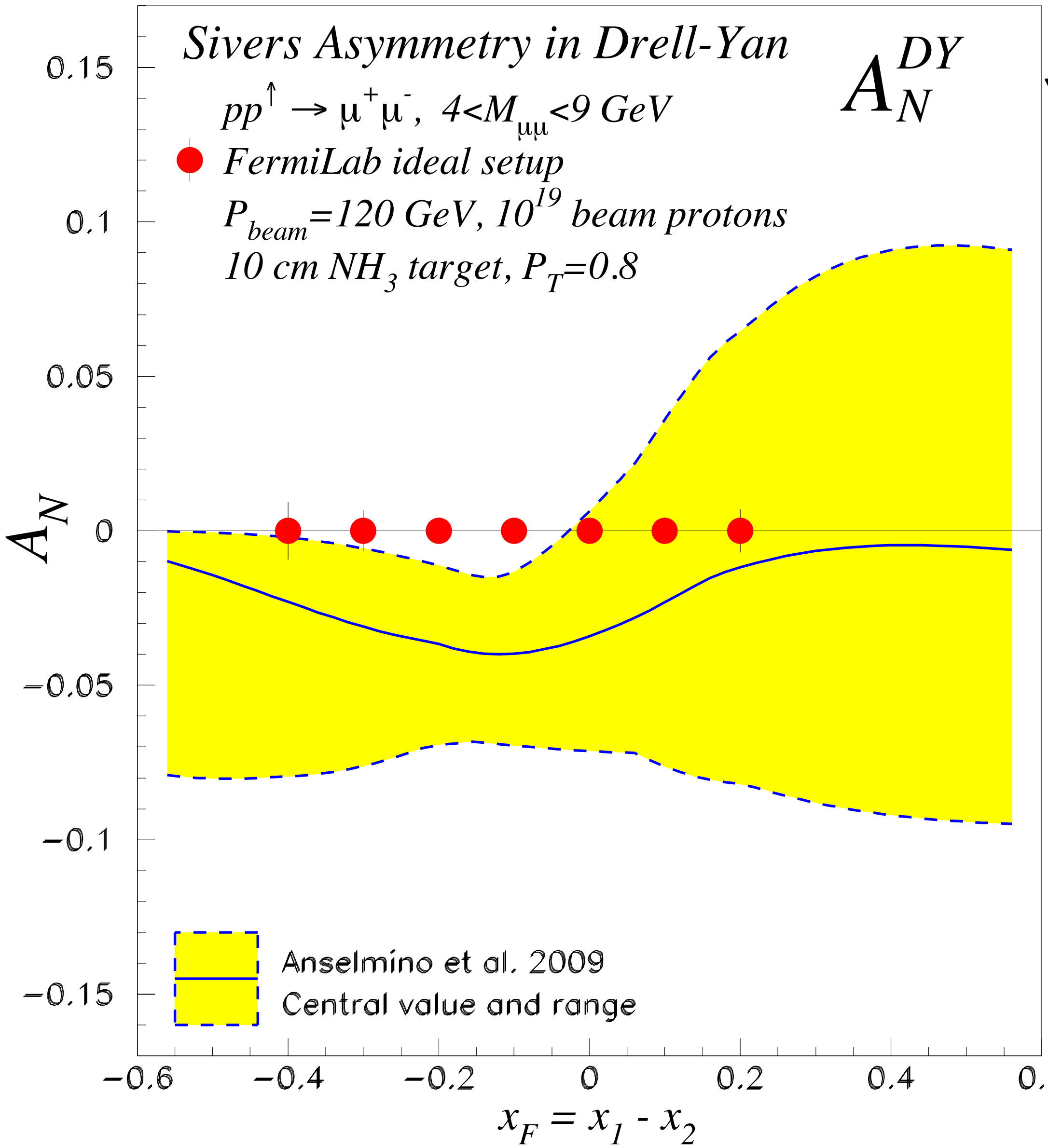




Drell-Yan Transverse Single Spin Asymmetry:

- Polarized proton (NH_3) target 12 cm long.
- Unpolarized 120 GeV proton beam from the Main Injector





A Possible Polarized Target Drell-Yan Measurement at Fermilab

Estimated statistical uncertainties of 3-year running at FNAL following E906

- A new 12 cm long transversely polarized NH_3 target. P_T=0.80.
- A "re-designed" spectrometer with large angle coverage to cover x_F<0.

- A precise measurement on quark Sivers distributions.
- A direct test of QCD prediction of Sivers distribution sign change.
- **The first measurement of sea quark Sivers distributions.**

Expecting the first polarized Drell-Yan result by ~2015

- p+p Drell-Yan: AnDY, PHENIX and STAR@RHIC (2013-2015).
- π^{-}p Drell-Yan @COMPASS (2013-2015).

+ many others in the planning stage …

It is extremely urgent for JLab to produce a high precision SSA data set on a polarized proton target by ~2015:

- to pin down the Sivers asymmetry observed.
- map out p_t dependence of SSA (a sign change from low- to high-p_t ?)
- map out x-dependence of SSA (a node around x=0.4 ?)
- and Q^2 dependence (?).

… and to shape the physics goals for EIC .

Summary

- "Neutron Transversity" experiment (E06-010):
  - Final results on SSA and DSA. More inclusive SSA results to come.
  - Four follow-up experiments approved in Hall A for JLab-12 GeV.
- Testing the Sivers function sign change between SIDIS and Drell-Yan processes, with a high precision, becomes "the most important task" of spin experiments.
- **It is extremely urgent for JLab to produce a high precision SSA data set on a polarized proton target by ~2015.**
- **It is extremely urgent to plan for a high precision polarized Drell-Yan experiment to start as soon as possible (~2015 ?).**

A common technical bottleneck is the design of a high luminosity polarized proton (NH_3) target, we outlined a conceptual design of such a target system, fit for both SIDIS and DY:

- Operate at 1K with a 5 Tesla dipole magnetic. 12 cm target length, $\pm 30^o$ front opening cone.
- Take 80nA electron beam (4x E906 proton flux).
- Magnet and cryostat be able to rotate $\pm 45^o$ around the nominal field direction.

A high luminosity polarized proton target, plus a polarized proton beam at FNAL, will dramatically advance our knowledge of nucleon's structure and the bonds that prevent them from broking apart.

Backup Slides

Semi-Inclusive Deep-Inelastic Scattering on a Neutron

Neutron

Proton:	u	u	d	Notation: $d = u_n$			
e_q^2:	$\frac{4}{9}$	$\frac{4}{9}$	$\frac{1}{9}$				
Neutron:	d_n	d_n	u_n	$\Rightarrow$	u	u	d
e_q^2:	$\frac{1}{9}$	$\frac{1}{9}$	$\frac{4}{9}$		$\frac{1}{9}$	$\frac{1}{9}$	$\frac{4}{9}$

Charged pion

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

$$D^{fav} = D_u^{\pi^+} = D_d^{\pi^-} \qquad D^{unfav} = D_u^{\pi^-} = D_d^{\pi^+}$$

$$\sigma_n^{\pi^+} \propto 4d \cdot D^{fav} + u \cdot D^{unfav} \qquad \sigma_n^{\pi^-} \propto 4d \cdot D^{unfav} + u \cdot D^{fav}$$

$n(e, e'\pi^+)$ is sensitive to d-quark. $n(e, e'\pi^-)$ is more sensitive to u-quark.