Recent Results of Target Single-Spin Asymmetry Measurements from Jefferson Lab Hall A

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- Introduction: target single-spin asymmetry (SSA)
  (in parity conserving interactions).
- Results of JLab polarized ^{3}He target SSA measurements:
  - Semi-inclusive deep-inelastic scattering channels (E06-010)
    - Target single-spin asymmetry A_{UT} , Collins and Sivers SSA on neutron.
  - Inclusive channels (E06-010, E05-015, E07-013)
    - Target SSA: inclusive hadron production channels.
    - Target SSA: inclusive ^{3}He(e,e') quasi-elastic scattering.
    - Target SSA: inclusive ^{3}He(e,e') deep inelastic-elastic scattering.
- New SIDIS experiments planned in Hall-A for JLab-12 GeV.

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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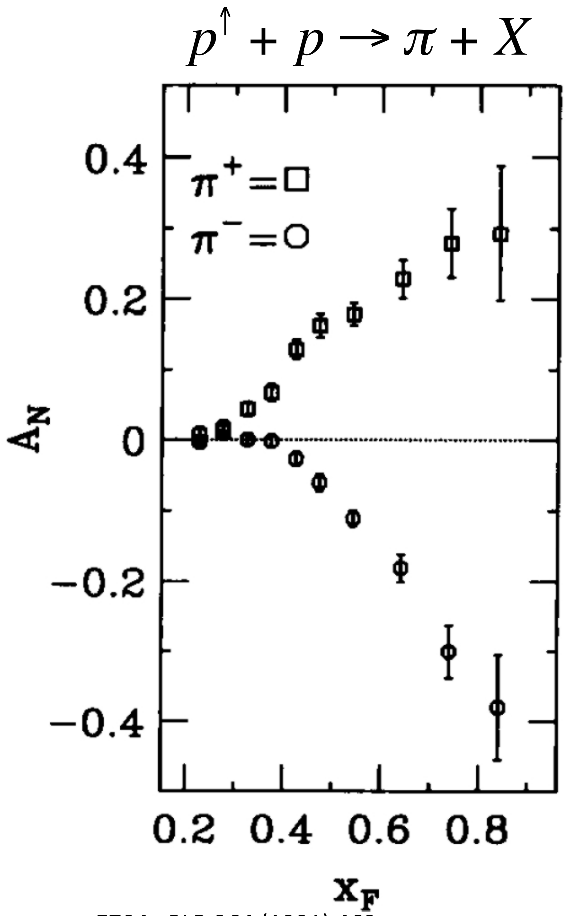
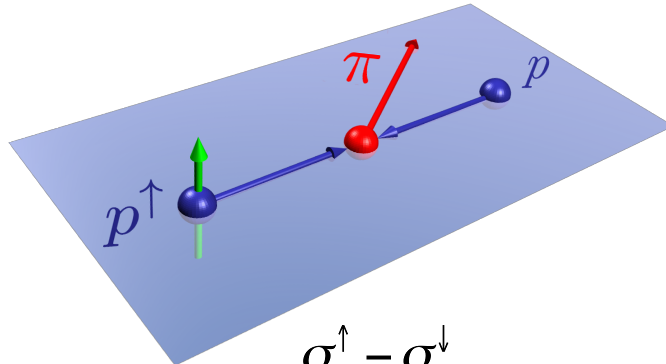
- 8 Ph.D. thesis: C. Dutta (Kentucky, 2010), J. Huang (MIT), K. Allada (Kentucky, 2010), J. Katich (W&M, 2010), X. Qian (Duke, 2010), Y. Wang (UIUC, 2011), Y. Zhang (Lanzhou U. 2012), Y.-W. Zhang(Rutgers, 2013).

Introduction: single-spin asymmetry in $p\, p^{\uparrow} \rightarrow \pi X$



E704: PLB 264 (1991) 462.



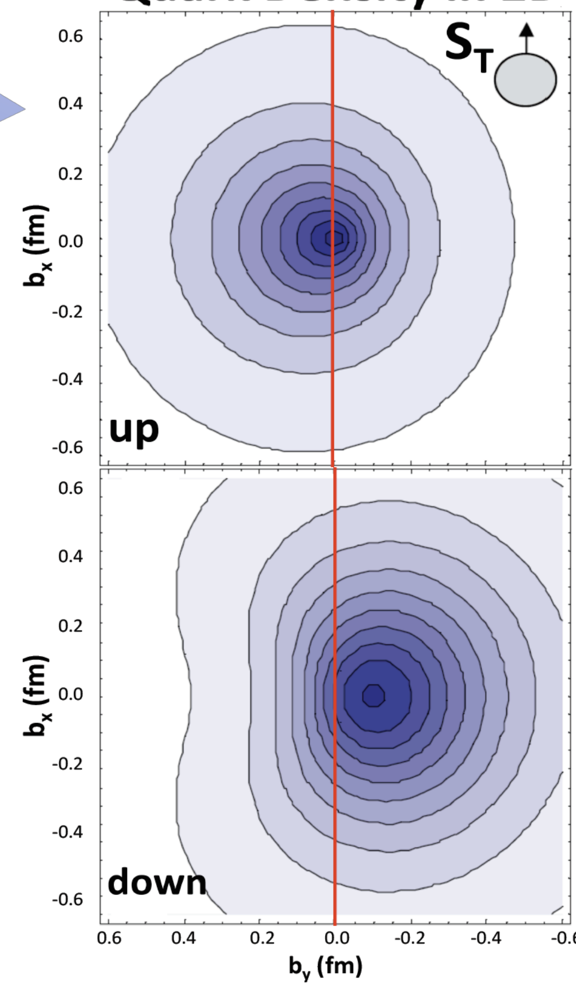
$$A_N = \frac{\sigma^{\uparrow} - \sigma^{\downarrow}}{\sigma^{\uparrow} + \sigma^{\downarrow}}$$

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

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

One possible explanation (Sivers effect): quark transvers motion generates a left-right bias.

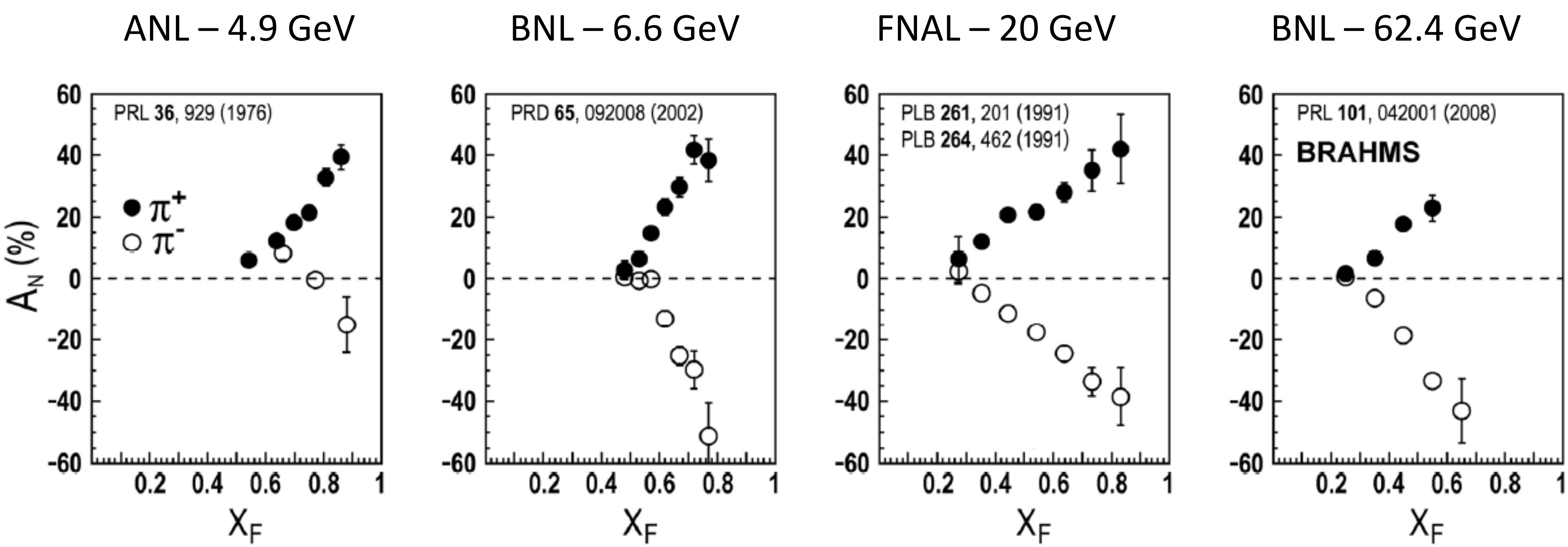
Quark Density in 2D



Lattice QCD PRL98:222001,2007.

Quarks in a transversely polarized nucleon can tell left-right, up-quarks favor left, down-quarks favor right.

Single-Spin Asymmetry in $p\, p^{\uparrow} \rightarrow \pi X$



SSA does not disappear at a higher energy.
Similar size SSA persists at √s=200, 500 GeV (BRAHMS, PHENIX and STAR)

Nature has produced large left-right asymmetries

- ~15% of this type of crab are left-handed, left-right asymmetry of

  A=-70%

(Parity Conserving) Single-Spin Asymmetry

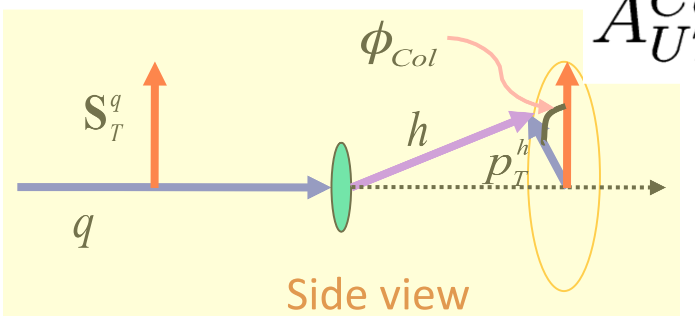
A left-right asymmetry which always:

- 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.

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

How could a quark tell left from right ?

- Collins: a transversely polarized quark generates left-right asymmetry during fragmentation.



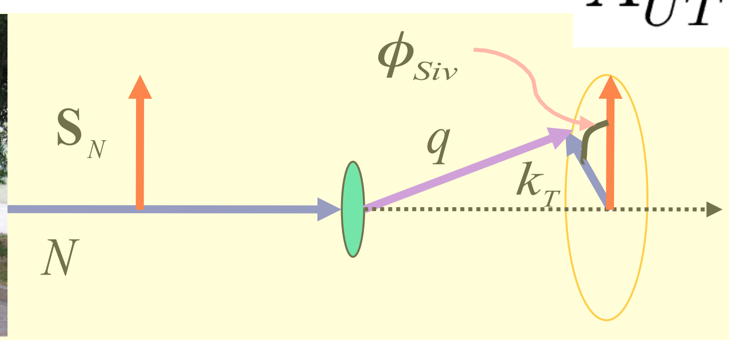
$$A_{UT}^{Collins} \propto \delta q(x) \otimes H_{1q}^{\perp h}(z, P_{h\perp}^2)$$

Transversity

T-Odd fragmentation function

- Sivers: quark-distribution is left-right asymmetric in a transversely polarized nucleon due to quark's transverse motion.

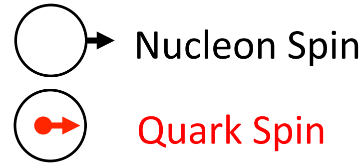
$$A_{UT}^{Sivers} \propto f_{1T}^{\perp q}(x) \otimes D_{1q}^{h}(z, P_{h\perp}^2)$$



T-Odd quark distribution

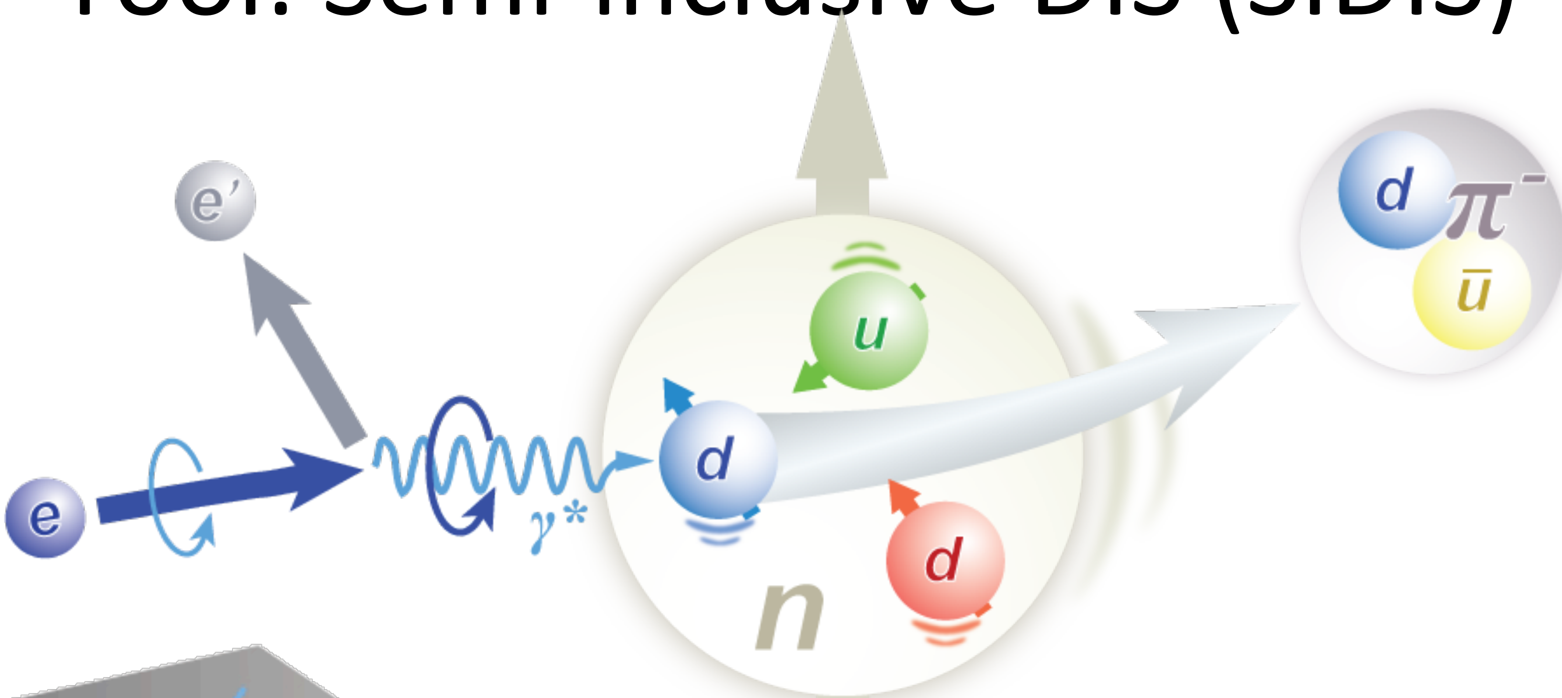
Regular fragmentation function

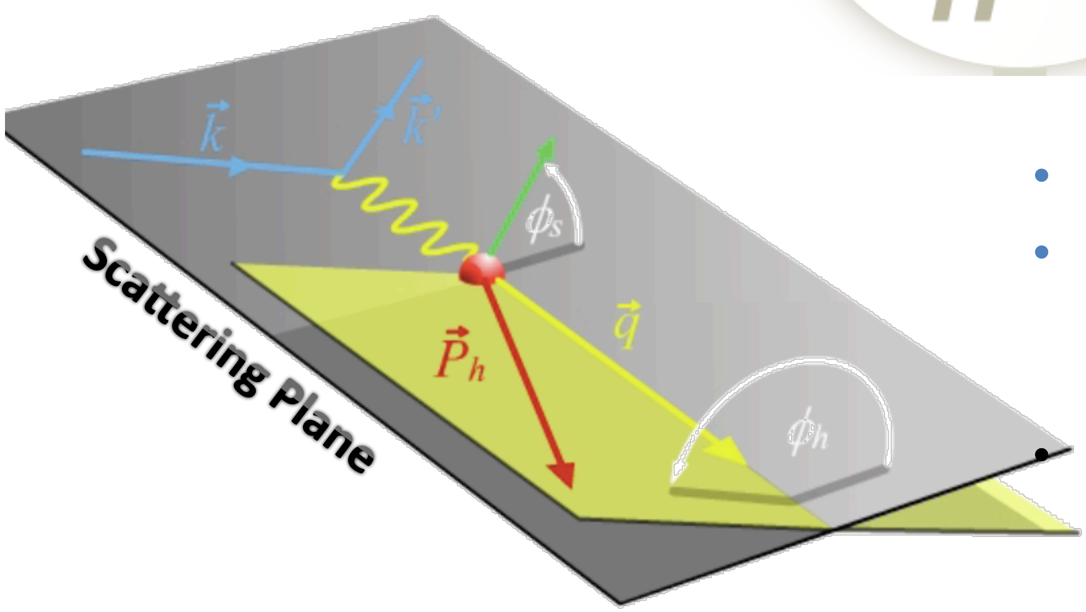
Leading-Twist TMD PDFs



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

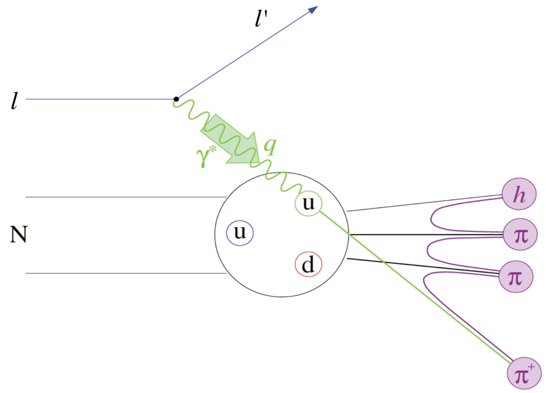
Tool: Semi-inclusive DIS (SIDIS)

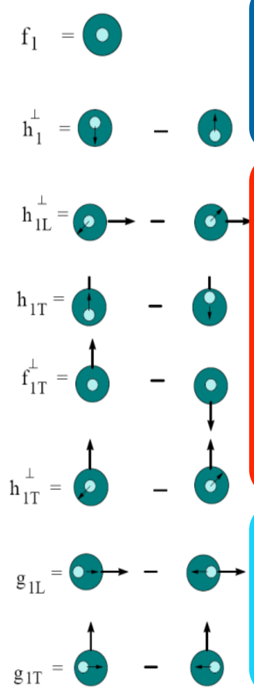




- Gold mine for TMDs
- Access all eight leading-twist TMDs through spin-comb. & azimuthal-modulations
- Tagging quark flavor/kinematics

Access TMDs through semi-inclusive DIS





Boer-Mulder

Transversity/ Collins

Sivers

Pretzelosity

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

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

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

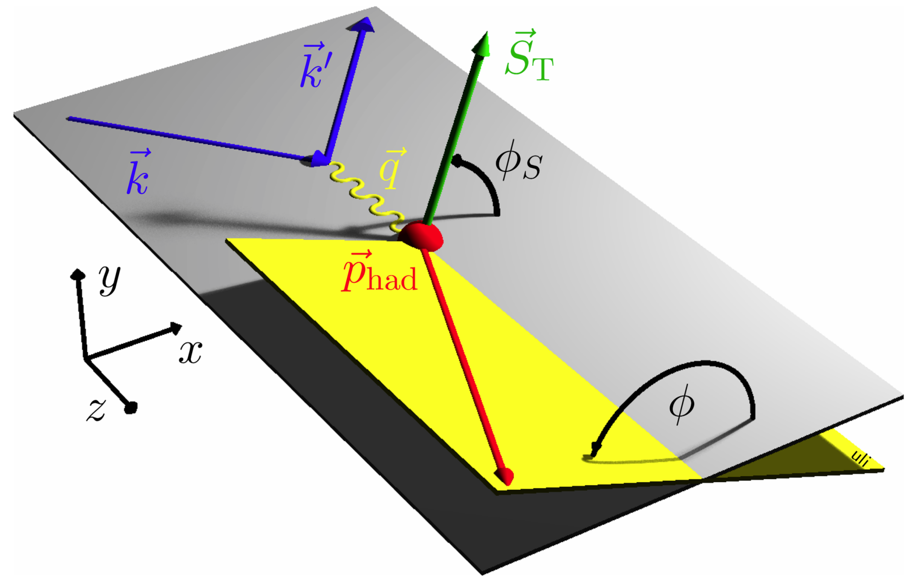
$$+S_L\lambda_e[\sqrt{1-\varepsilon^2}\cdot F_{LL} + \ldots]$$
$$+S_T\lambda_e[\sqrt{1-\varepsilon^2}\cos(\phi_h-\phi_S)\cdot F_{LT}^{\cos(\phi_h-\phi_S)} + \ldots]\}$$

Polarized Beam and Target

S_L, S_T: Target Polarization; λ_e: Beam Polarization

Collins and Sivers effects can be separated in semi-inclusive deep-inelastic scattering experiments

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



$$\begin{aligned}\sigma_{UT} \quad \propto \quad & S_T(1-y)\frac{P_{h\perp}}{zM_h}\sin(\phi_h^\ell + \phi_S^\ell)\cdot\sum e_q^2\, h_1^q(x)\otimes H_{1q}^{\perp h}(z, P_{h\perp}^2) \\ + \quad & S_T(1-y+\frac{y^2}{2})\frac{P_{h\perp}}{zM_N}\sin(\phi_h^\ell - \phi_S^\ell)\cdot\sum e_q^2\, f_{1T}^{\perp q}(x)\otimes D_{1q}^h(z_h, P_{h\perp}^2)\end{aligned}$$

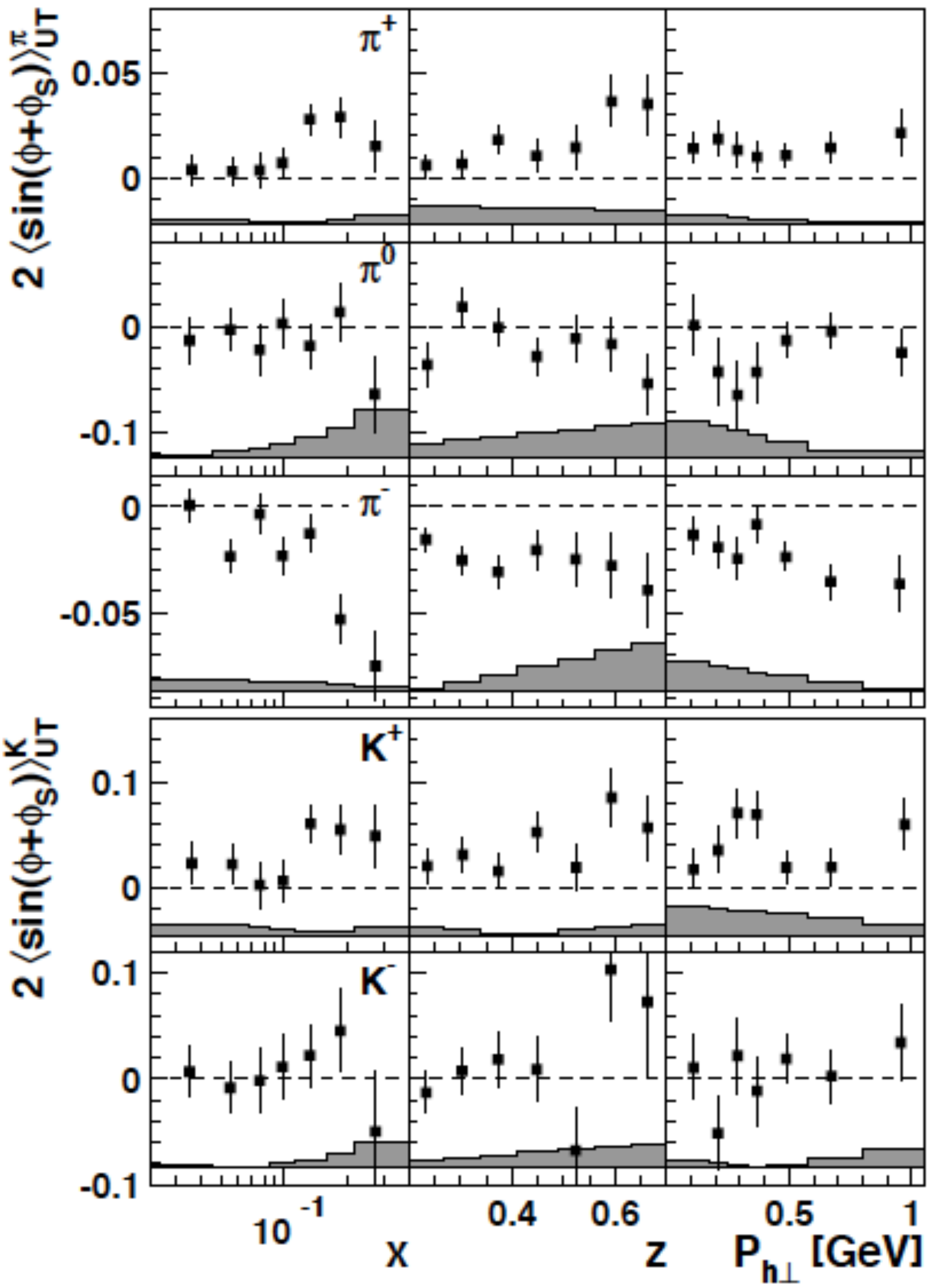
Collins effect (linked with transversity h_1) and Sivers effect (linked with T-Odd distribution f_{1T}) can be separate through the angular dependence of the asymmetries.

Recent data of semi-inclusive DIS.

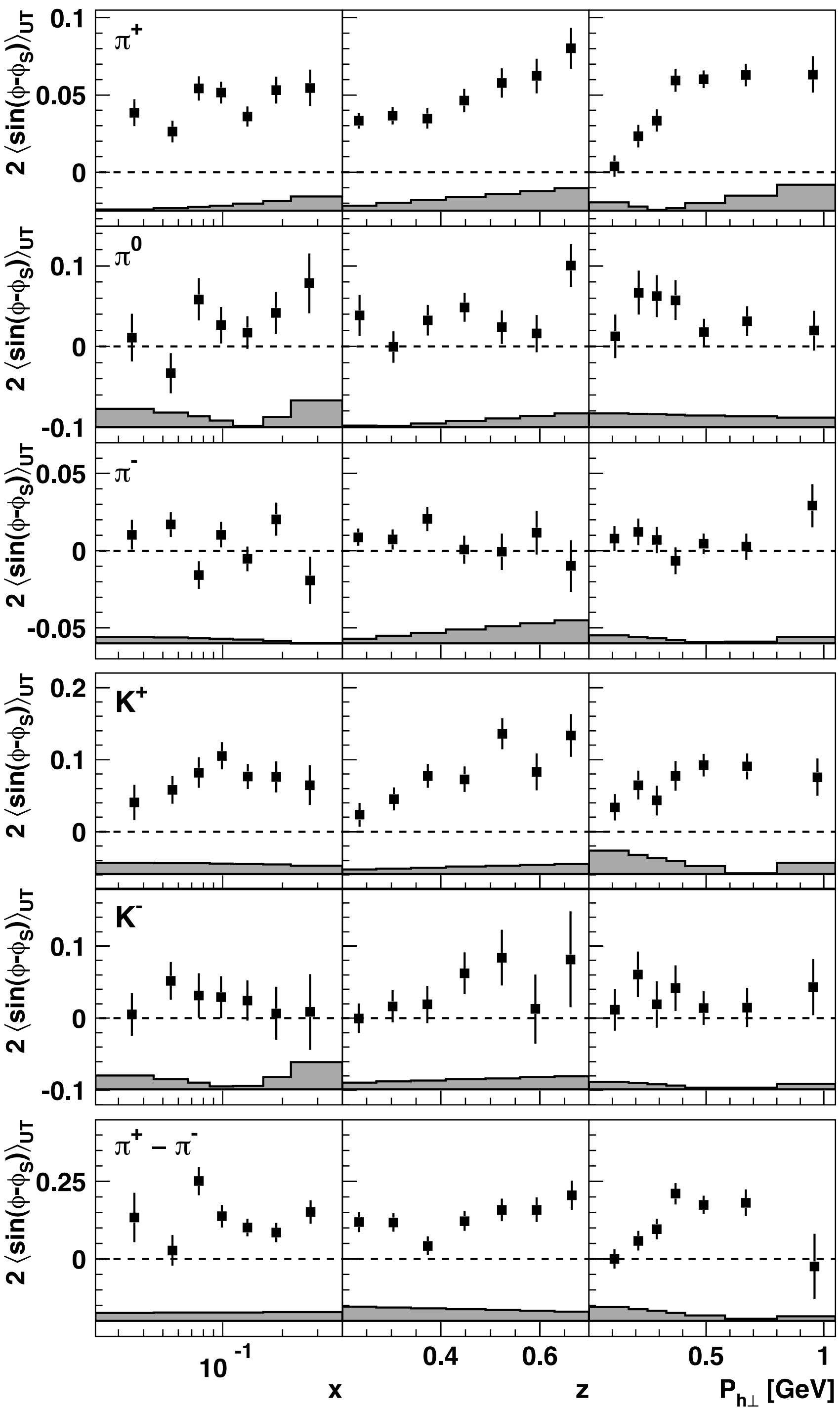
Target single-spin asymmetries in semi-inclusive deep-inelastic scattering: $A_N = \frac{\sigma^{\uparrow} - \sigma^{\downarrow}}{\sigma^{\uparrow} + \sigma^{\downarrow}}$

- **HERMES@DESY: p(e, e' $\pi^{+/-}$)X 2002-2005**
- **COMPASS@CERN:**
  D(μ, μ' $h^{+/-}$)X 2002-2004
  p(μ, μ' $h^{+/-}$)X 2006-2007 and 2010.
- **Jefferson Lab: n(e, e'$\pi^{+/-}$)X.**

See A. Prokudin's talk on Wednesday.



HERMES:
Collins moments
on a proton target



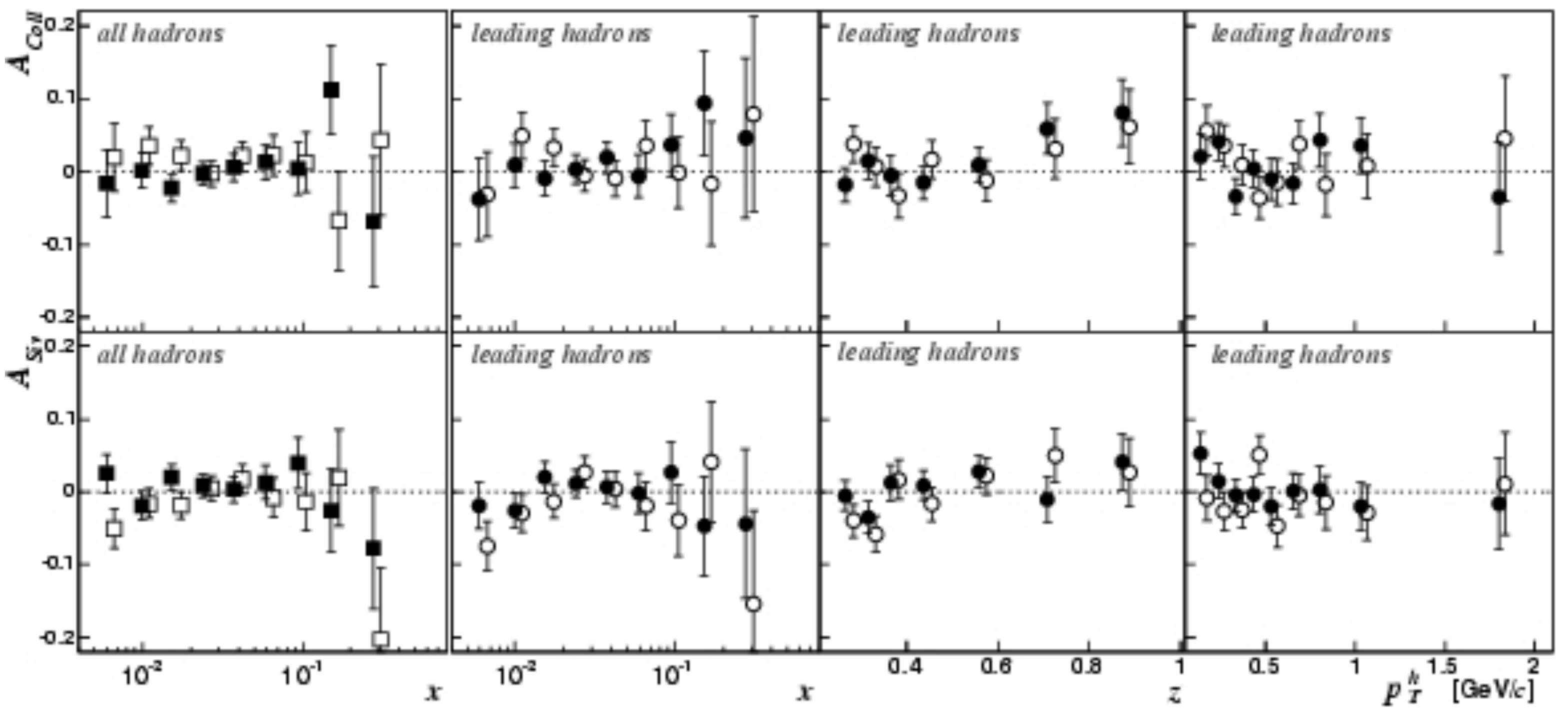
Hermes Proton: Sivers Asymmetry

$$\sigma(\phi,\phi_S) = \sigma_{UU}\{1 + 2\langle\cos\phi\rangle_{UU}\cos\phi + 2\langle\cos 2\phi\rangle_{UU}\cos 2\phi$$

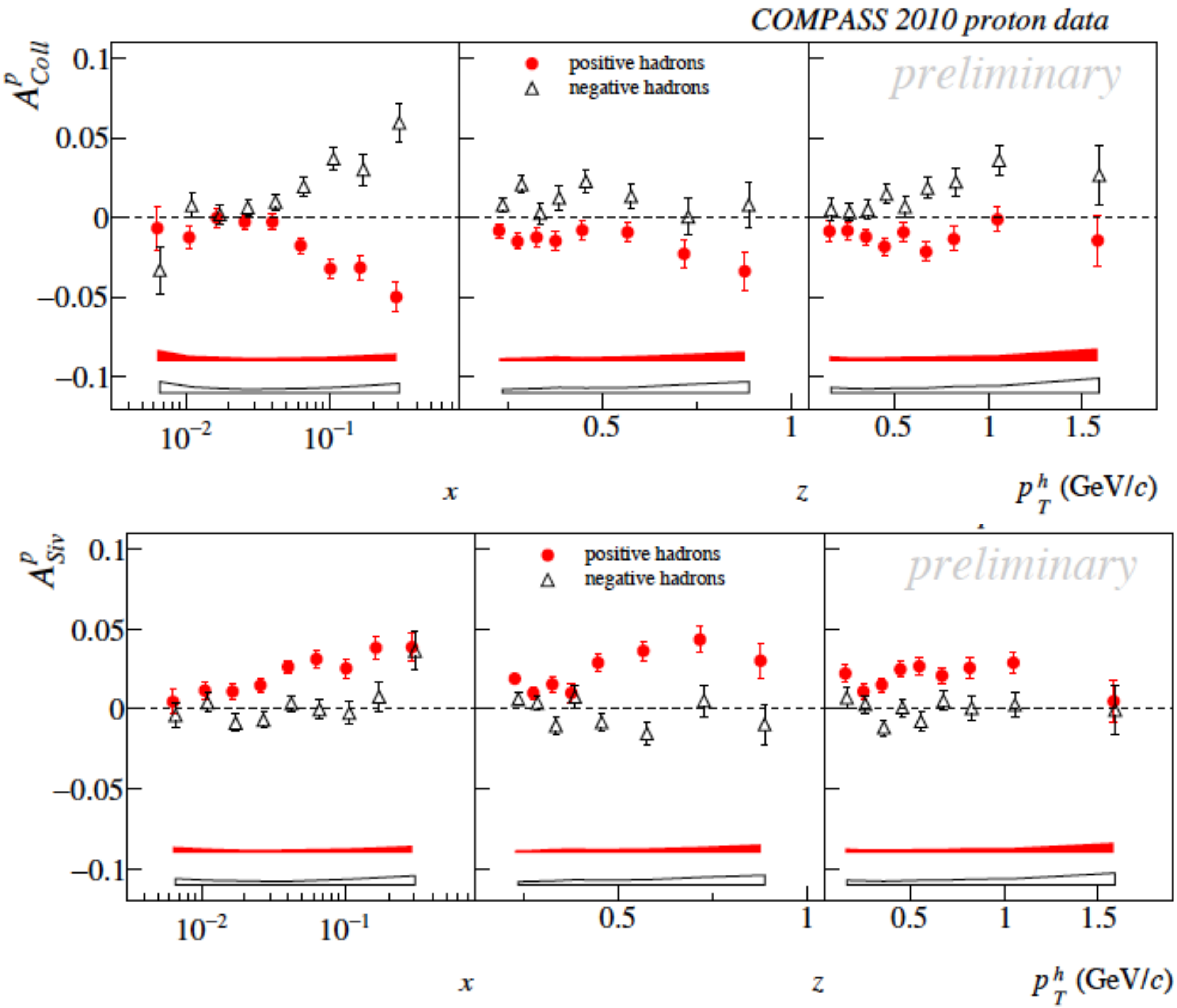
$$+|S_T|[2\langle\sin(\phi-\phi_S)\rangle_{UT}\sin(\phi-\phi_S) + 2\langle\sin(\phi+\phi_S)\rangle_{UT}\sin(\phi+\phi_S) + \ldots]\}$$

$$2\langle\sin(\phi-\phi_S)\rangle_{UT} = -\frac{\sum_q e_q^2 f_{1T}^{\perp,q}(x,p_T^2)\otimes D_1^q(z,k_T^2)}{\sum_q e_q^2 f^q(x)\otimes D_1^q(z)}$$

COMPASS-2006: small A_{UT} on deuteron (p+n)



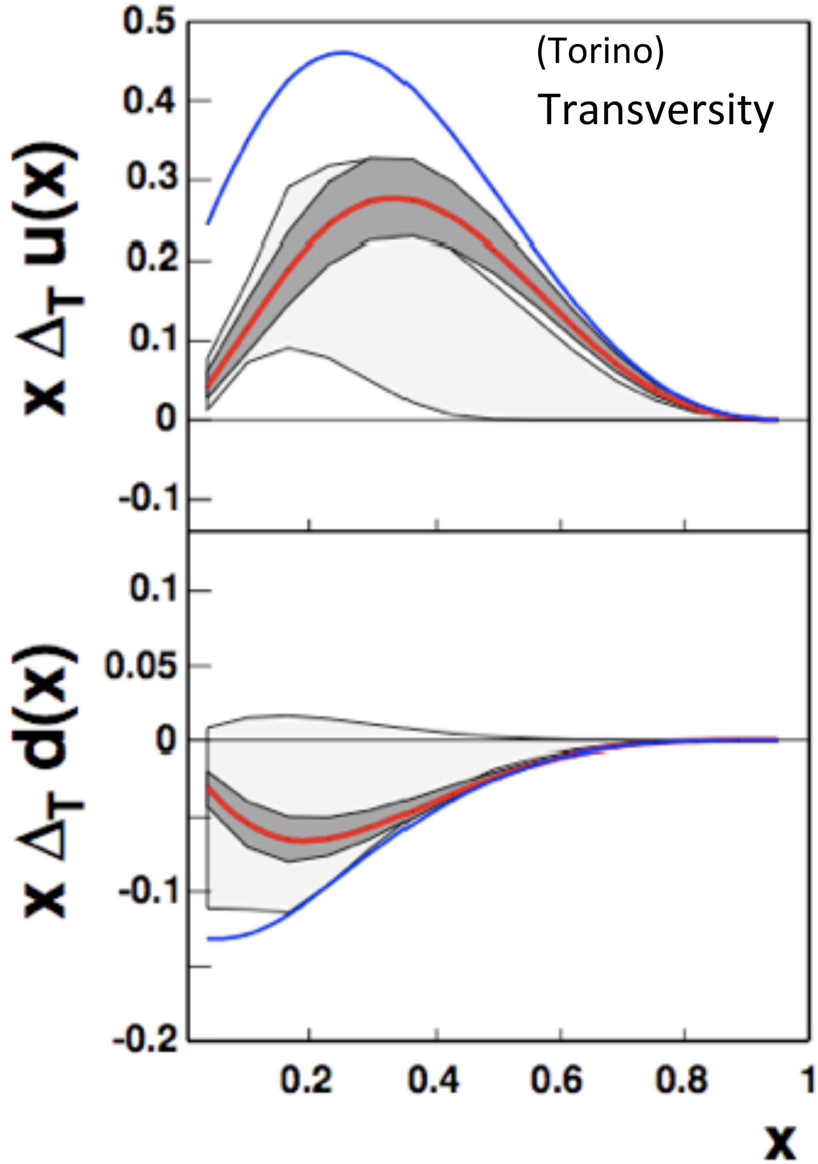
- Neutron SSA must have strong flavor dependence, in both Collins and Sivers.
- d-quark makes a large and opposite contribution compared to u-quark.



COMPASS 2010 proton data
preliminary
positive hadrons
negative hadrons
A^p_{Coll}
A^p_{Siv}
0.1
0.05
0
−0.05
−0.1
10^{-2}
10^{-1}
0.5
1
1.5
x
z
p^h_T (GeV/c)

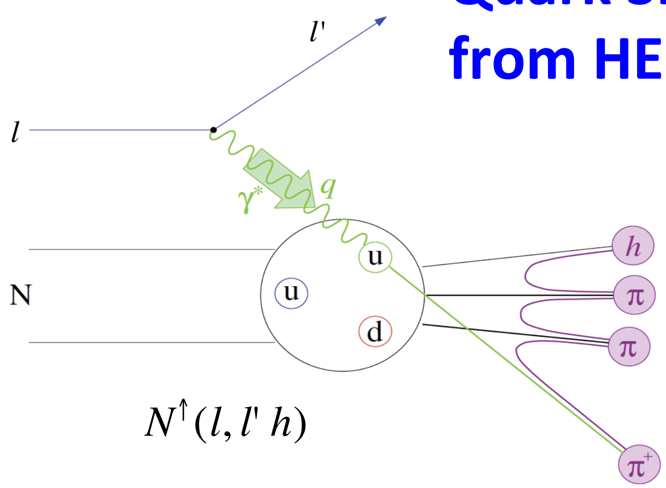
The first gimps of quark transversity:

fit of existing data to obtain quark transversity distributions

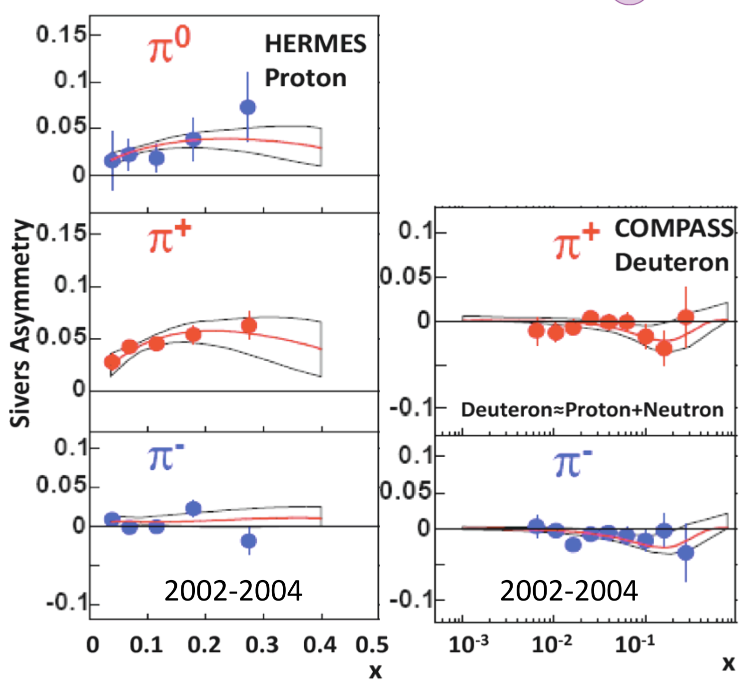


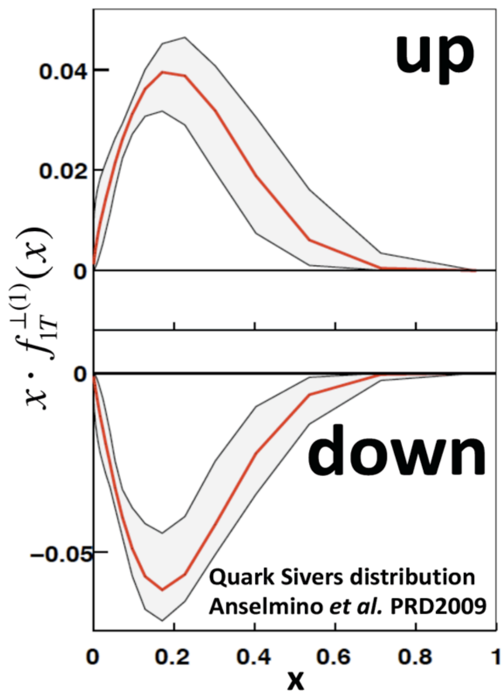
From Collins asymmetry of semi-inclusive DIS, and correlation asymmetry in $e^+e^- \rightarrow \pi^+\pi^-$

Quark Sivers distributions
from HERMES Proton and COMPASS Deutron data



$N^{\uparrow}(l, l'\, h)$





up-quarks favor left (L_u>0),

down-quarks favor right (L_d<0).

Semi-Inclusive Deep-Inelastic Scattering on a Neutron

Neutron

Proton:	u	u	d				
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:	$\frac{1}{9}$	$\frac{1}{9}$	$\frac{4}{9}$		$\frac{1}{9}$	$\frac{1}{9}$	$\frac{4}{9}$

Notation: $d = u_n$

Charged pion

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

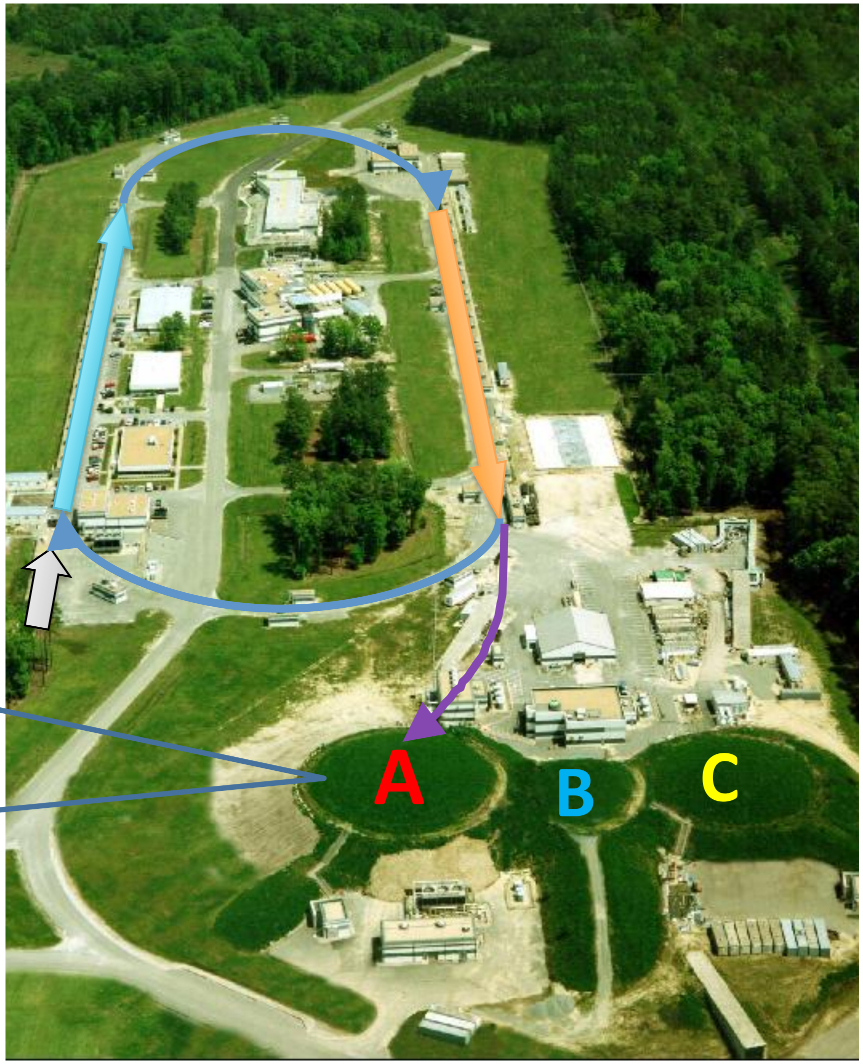
$$D^{fav} = D_u^{\pi^+} = D_d^{\pi^-} \qquad D^{unfav} = D_u^{\pi^-} = D_d^{\pi^+}$$

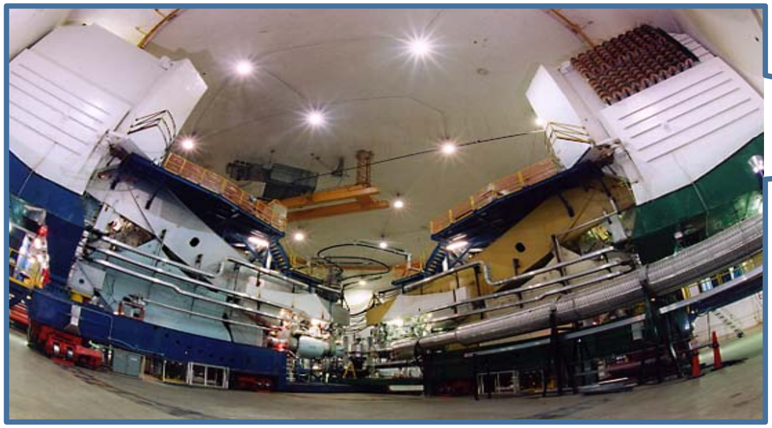
$$\sigma_n^{\pi^+} \propto 4d \cdot D^{fav} + u \cdot D^{unfav} \qquad \sigma_n^{\pi^-} \propto 4d \cdot D^{unfav} + u \cdot D^{fav}$$

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

Experiment E06-010 @JLab-6 GeV

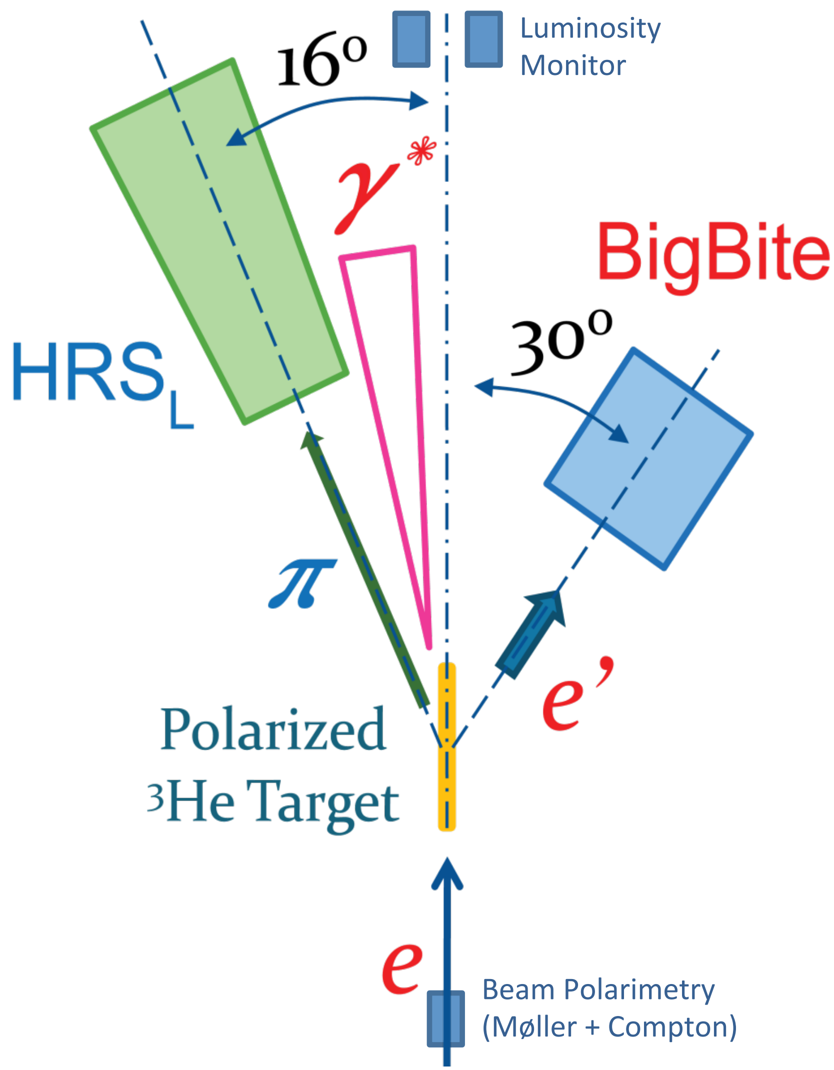
- Linear accelerator provides continuous polarized electron beam
  - E_{beam} = 6 GeV
  - P_{beam} = 85%

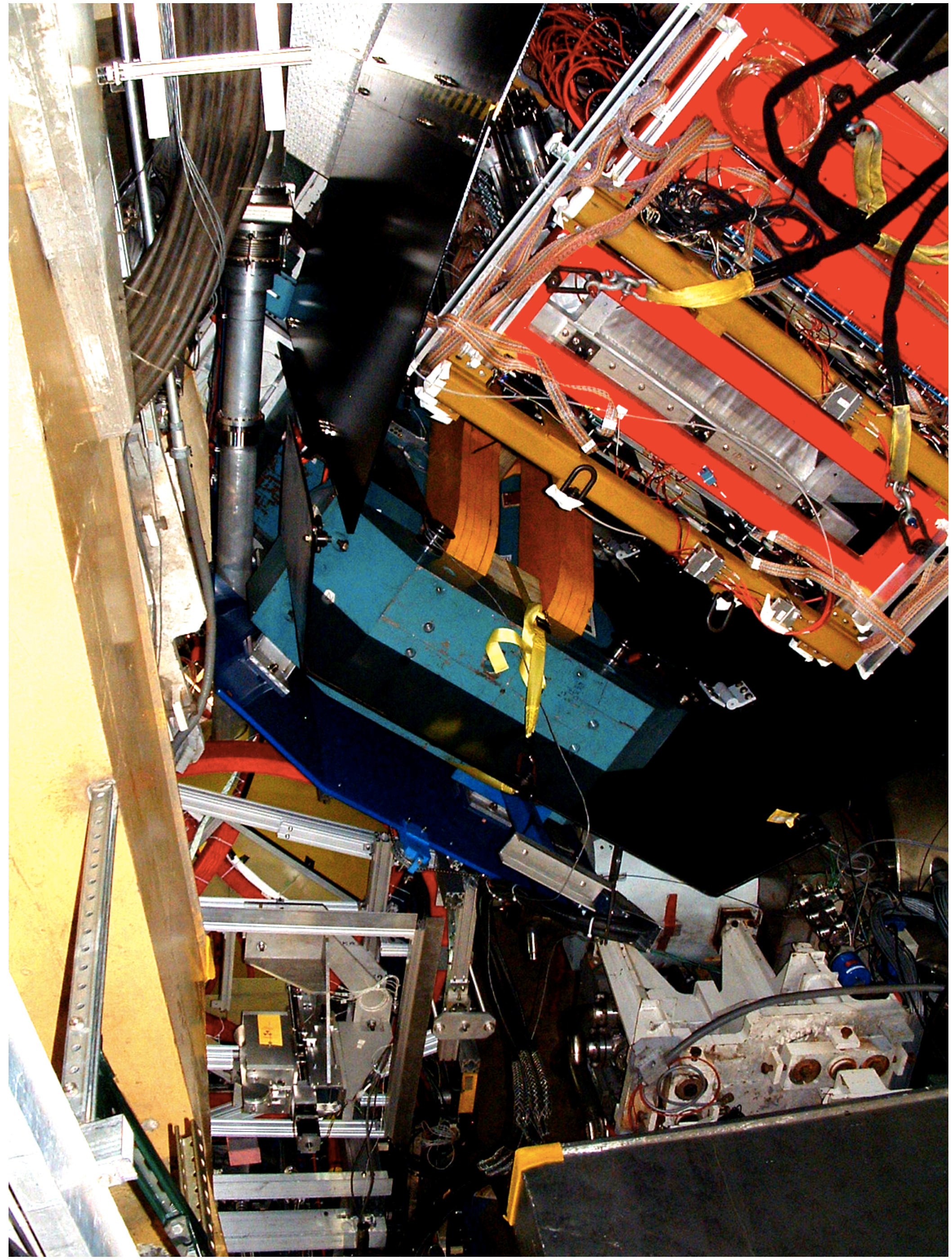




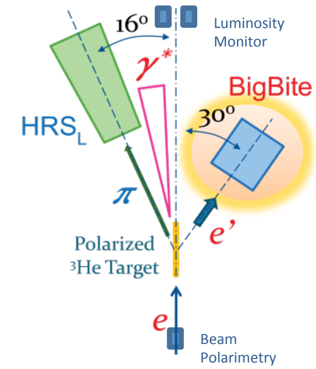
$$^{3}\mathrm{He}^{\uparrow}(e,e'h)$$

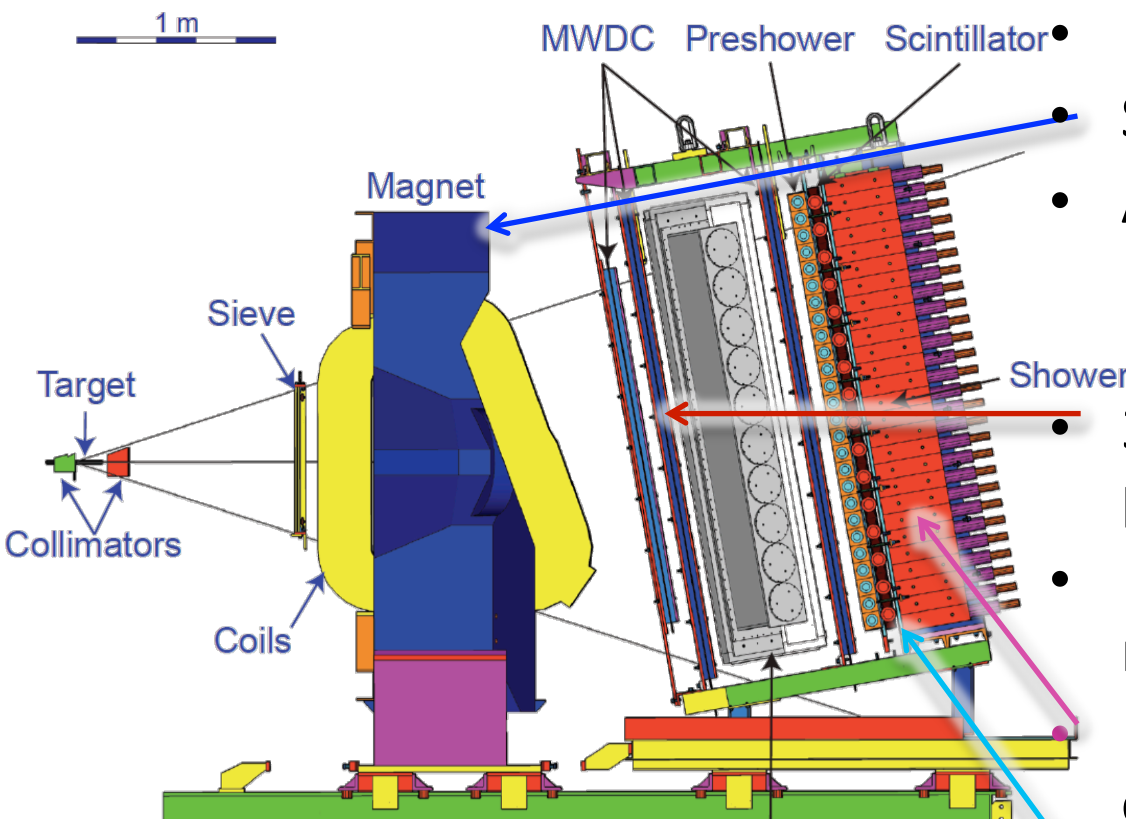
$$h=\pi^{+/-},K^{+/-}$$





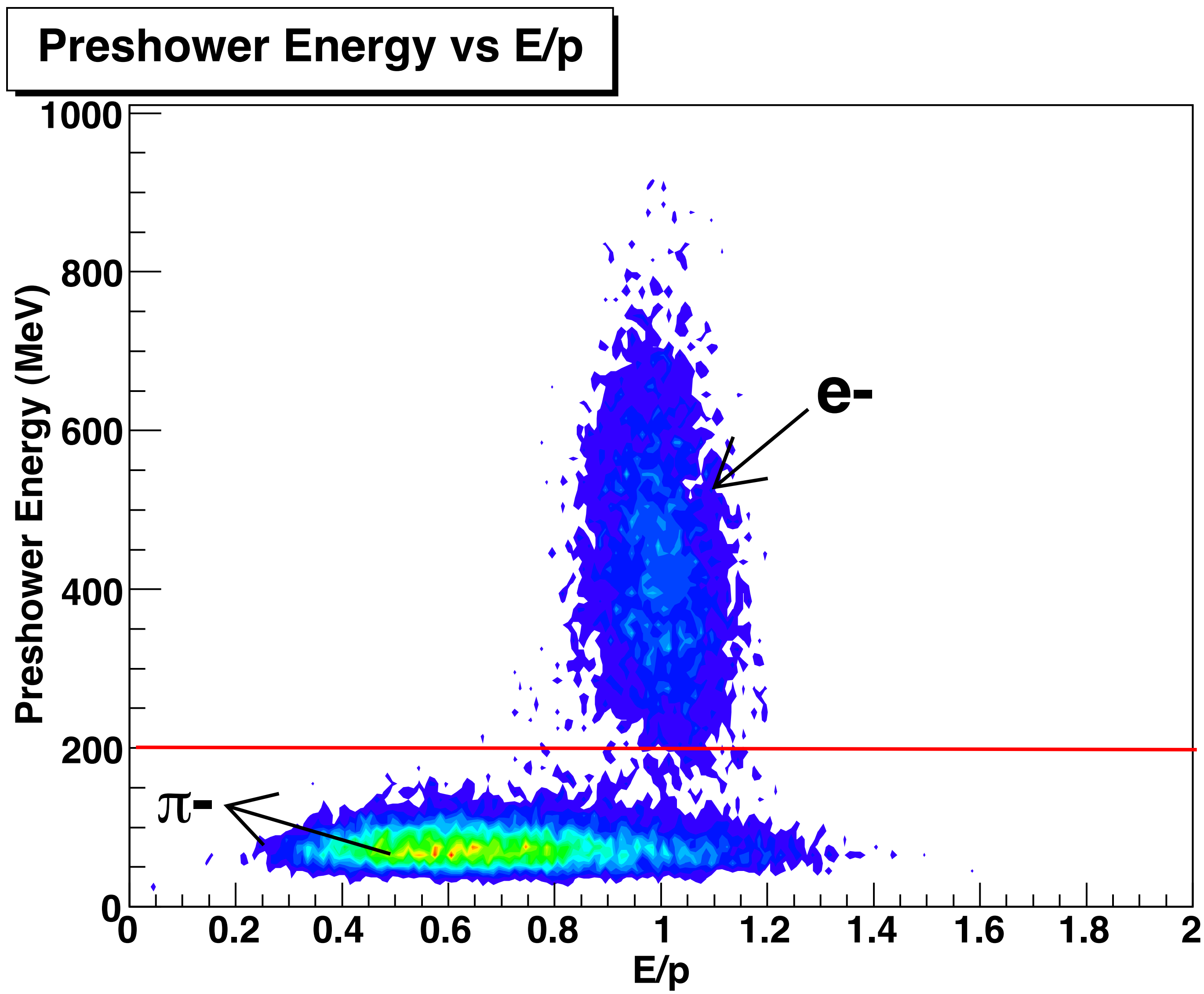
BigBite Spectrometer

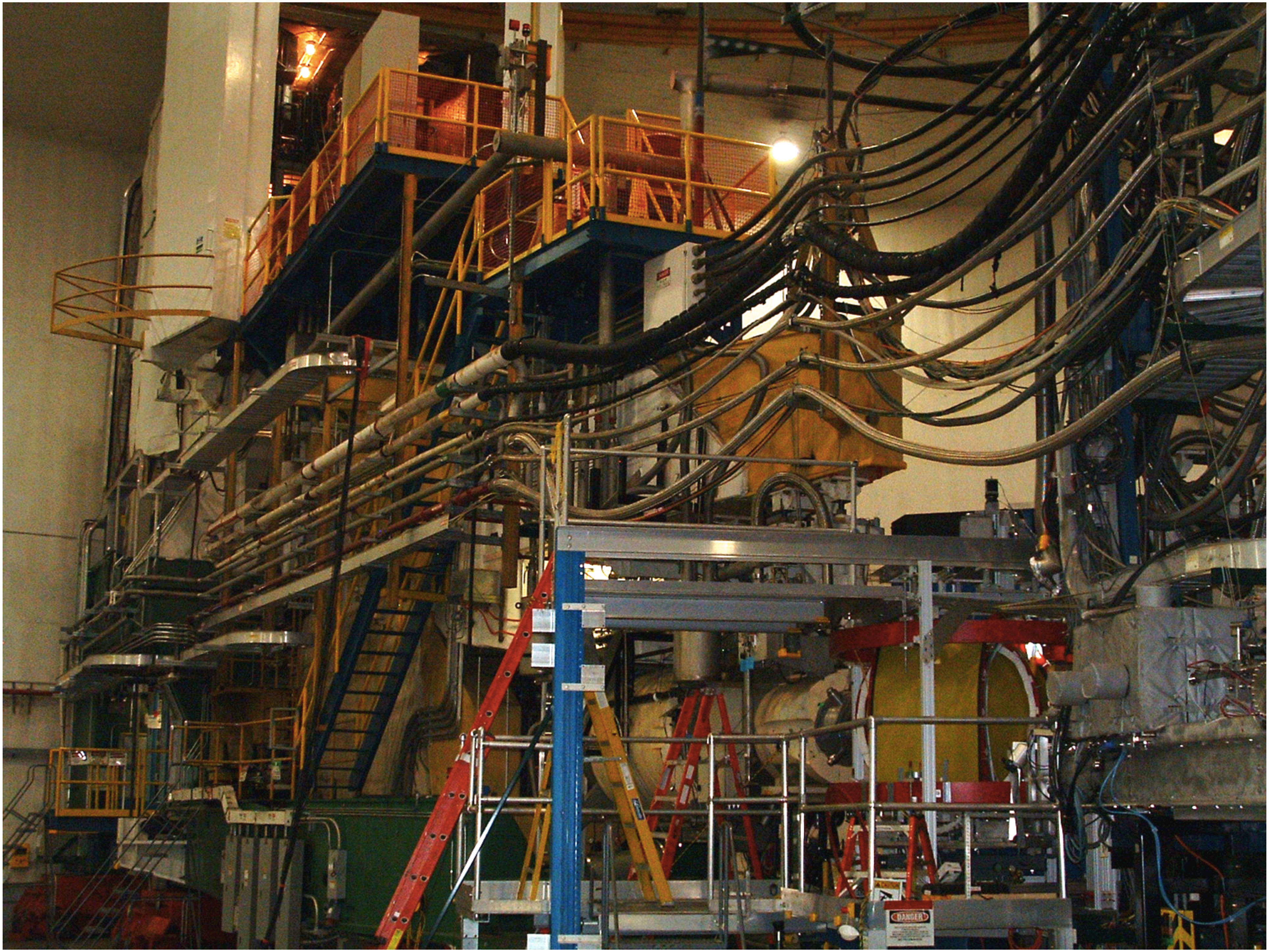




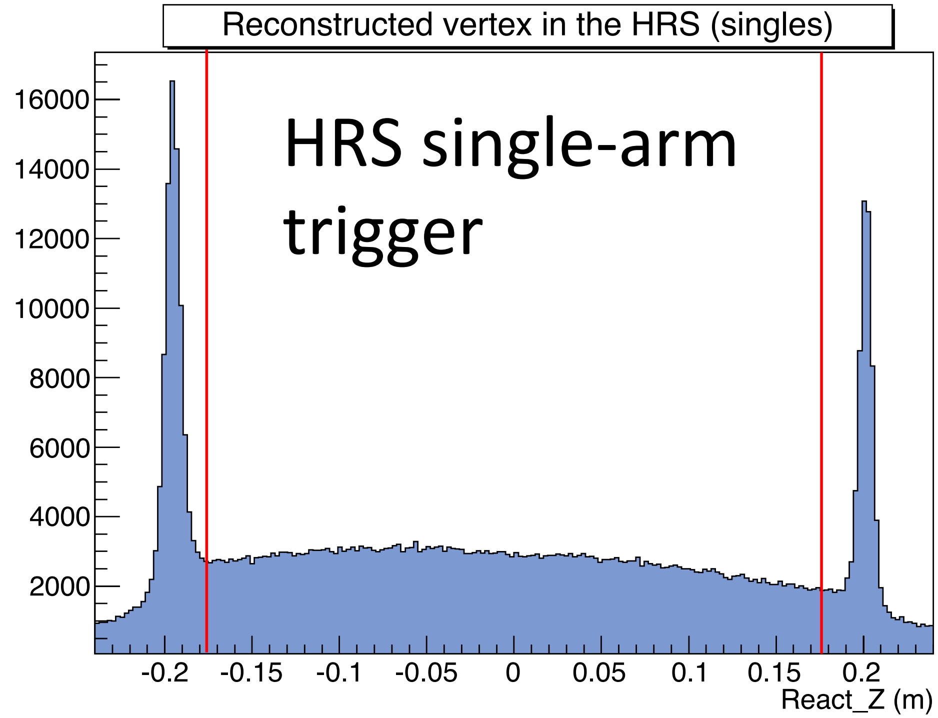
- Detects electrons
- Single dipole magnet
- A "big bite" of acceptance
  - $\Delta\Omega$ = 64 msr
  - P : 0.6 ~ 2.2 GeV/c
- 3 wire chambers: 18 planes for precise tracking
- Bipolar momentum reconstruction
- Pre-shower and shower for electron PID
- Scintillator for coincidence with left HRS

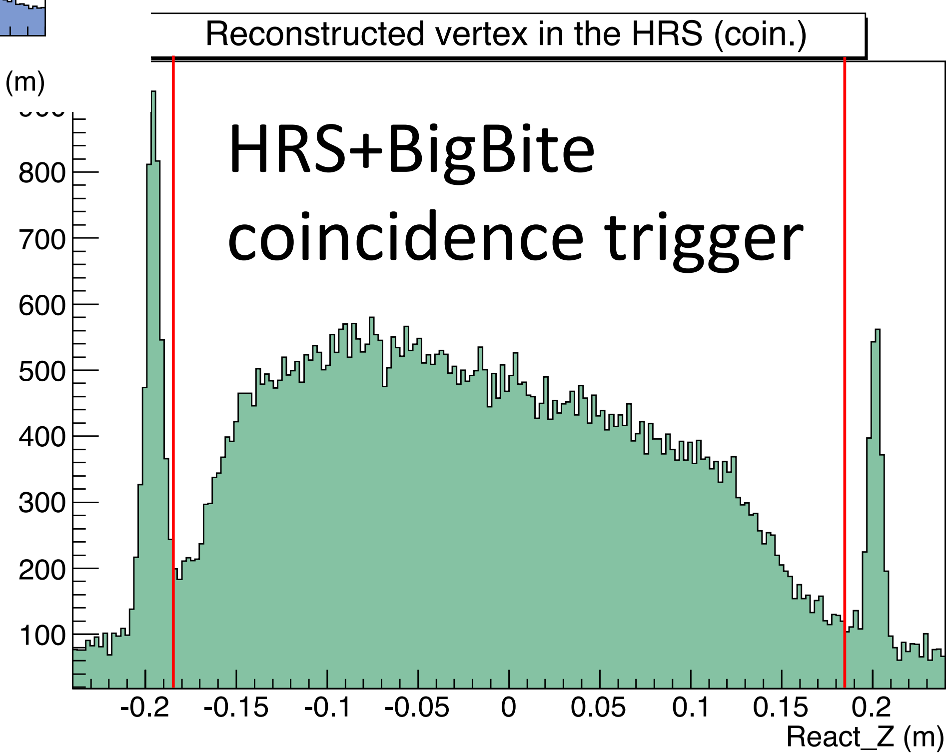
BigBite: e-Arm Particle Identification




DANGER

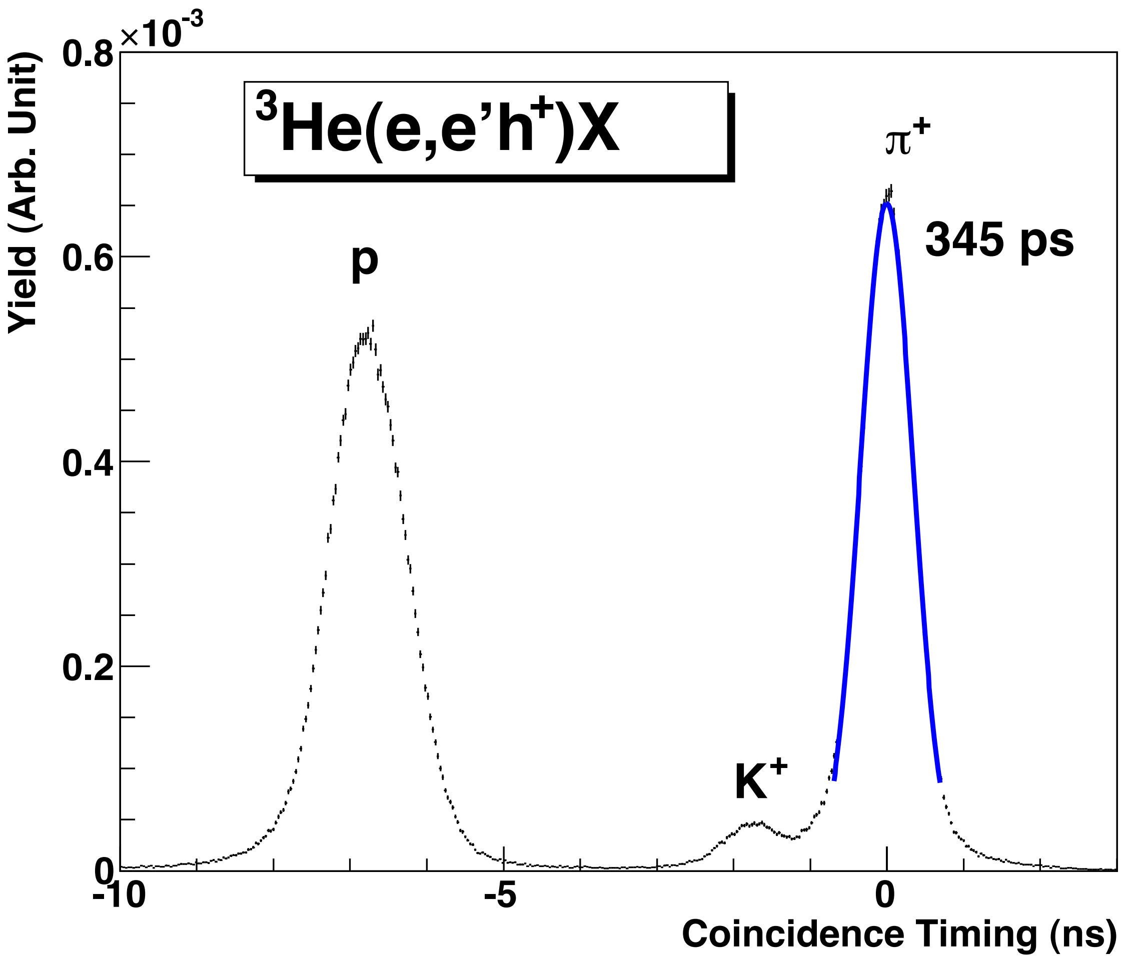
Target cell viewed from HRS



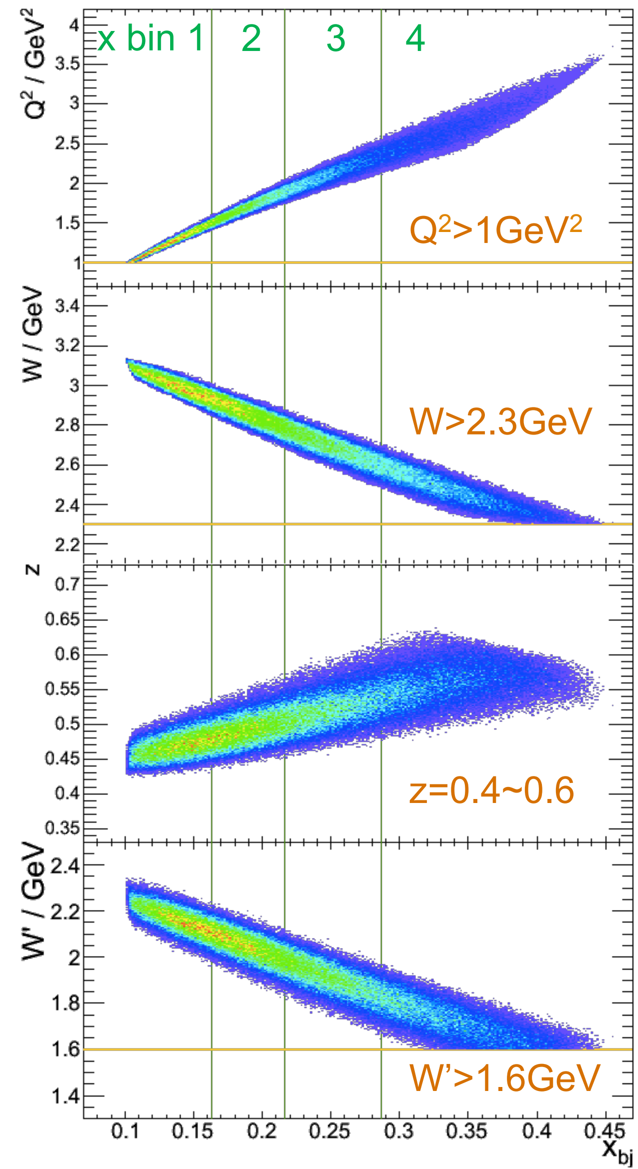


Coincidence time-of-flight as redundant particle identification

in addition to the HRS_L standard PID detector cuts.

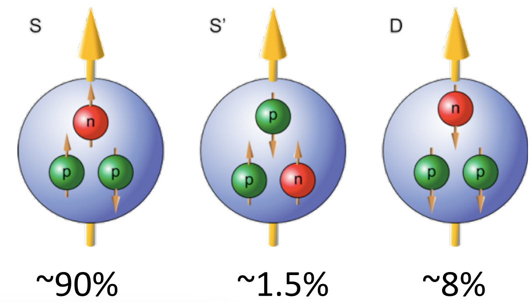


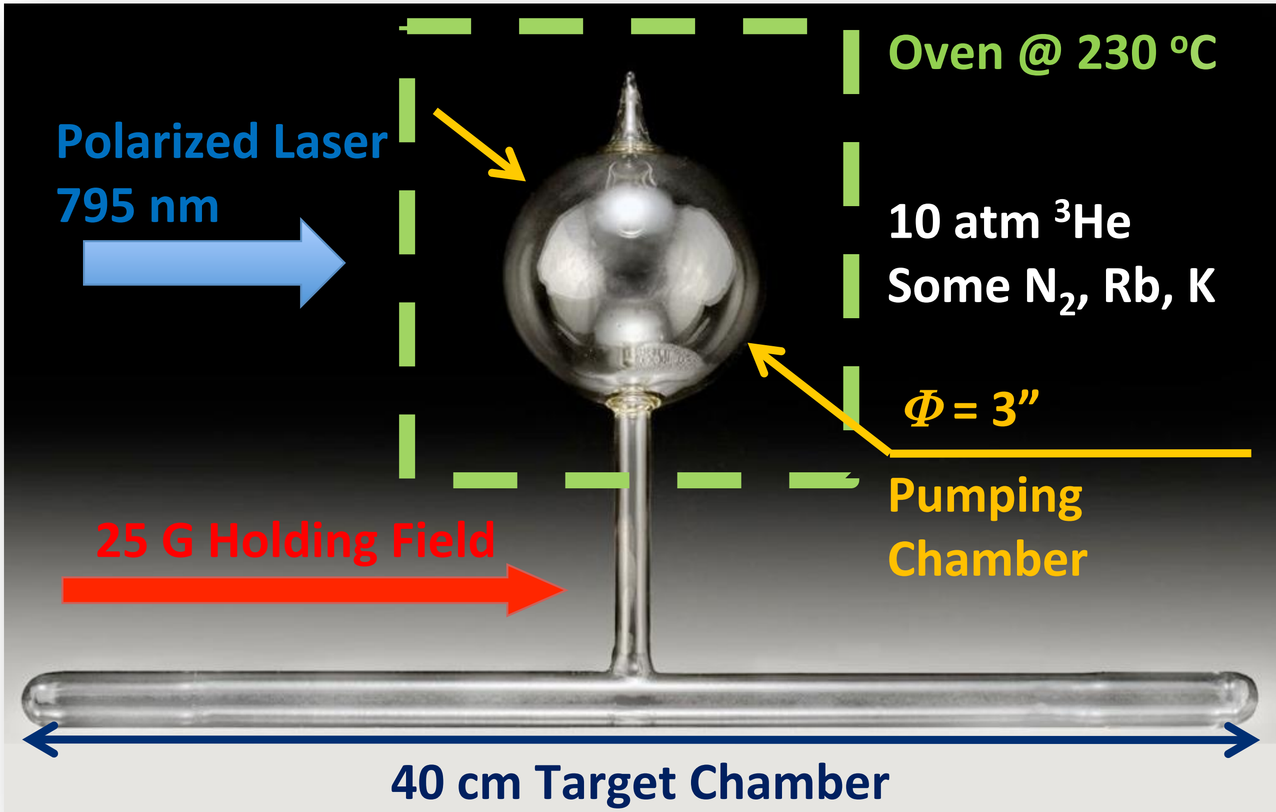
Kinematics Coverage



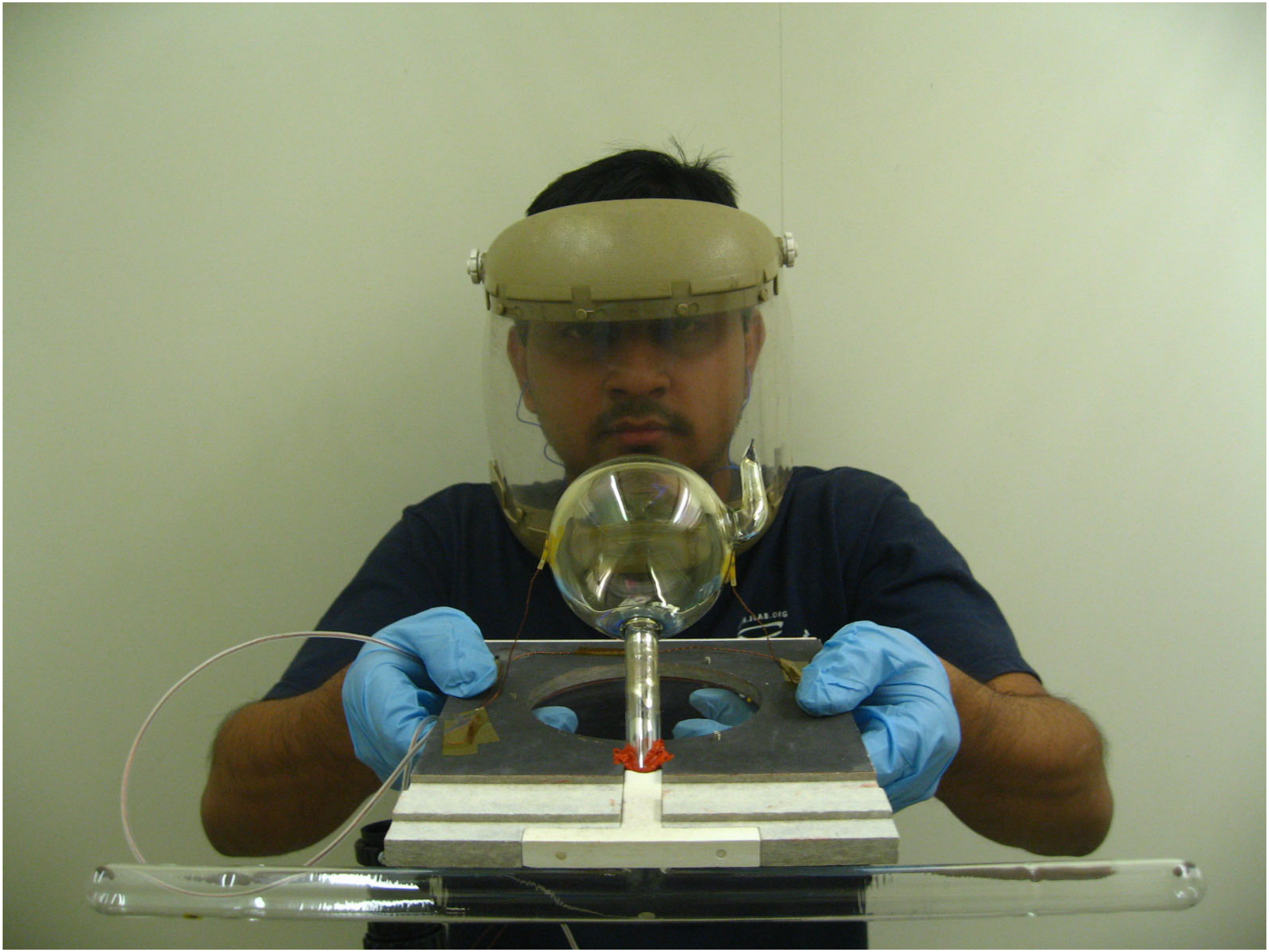
<Q^2>=2.0 GeV^2 <W>=2.8 GeV.
(HERMES: <Q^2>=2.4 GeV^2).

Polarized ^{3}He Gas Target

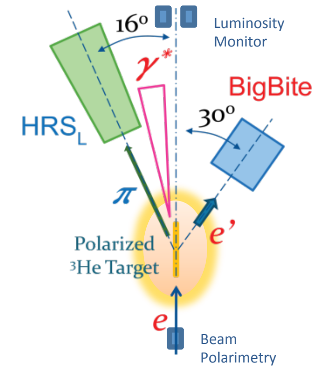




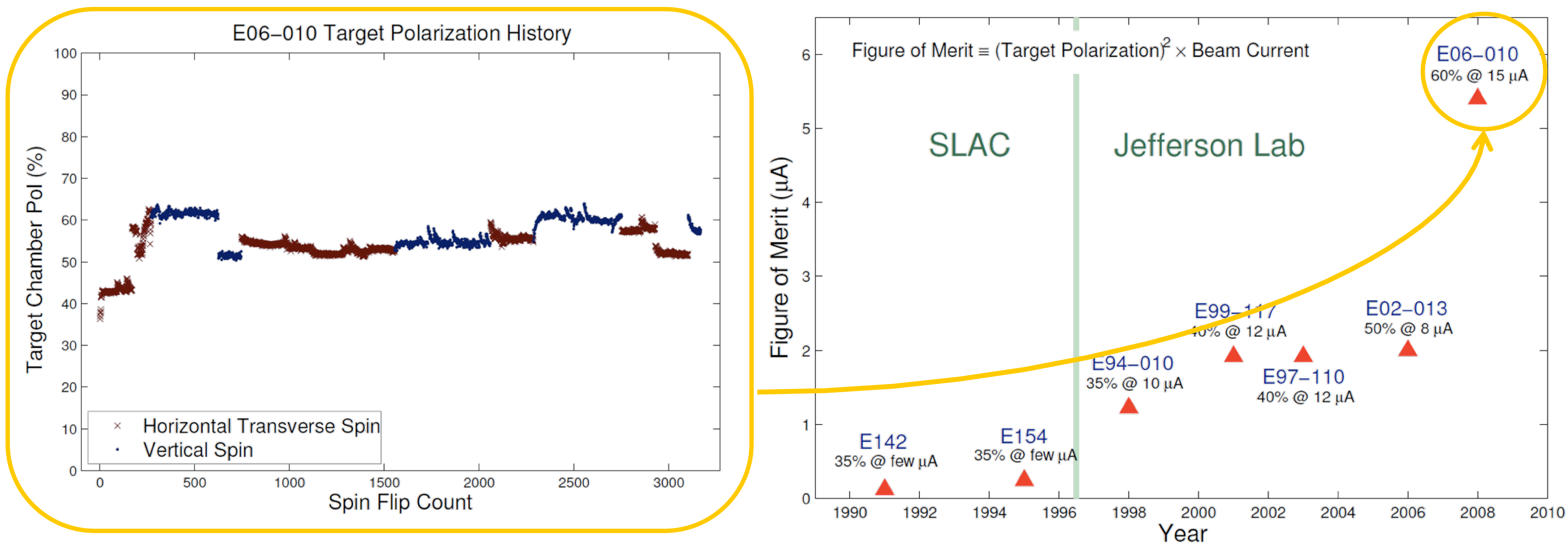
- 10 atm ^{3}He, Rb/K alkali mixture
- Luminosity with 15 μA electron beam
  - $\boldsymbol{L}(n) = 10^{36}$ cm^2/s

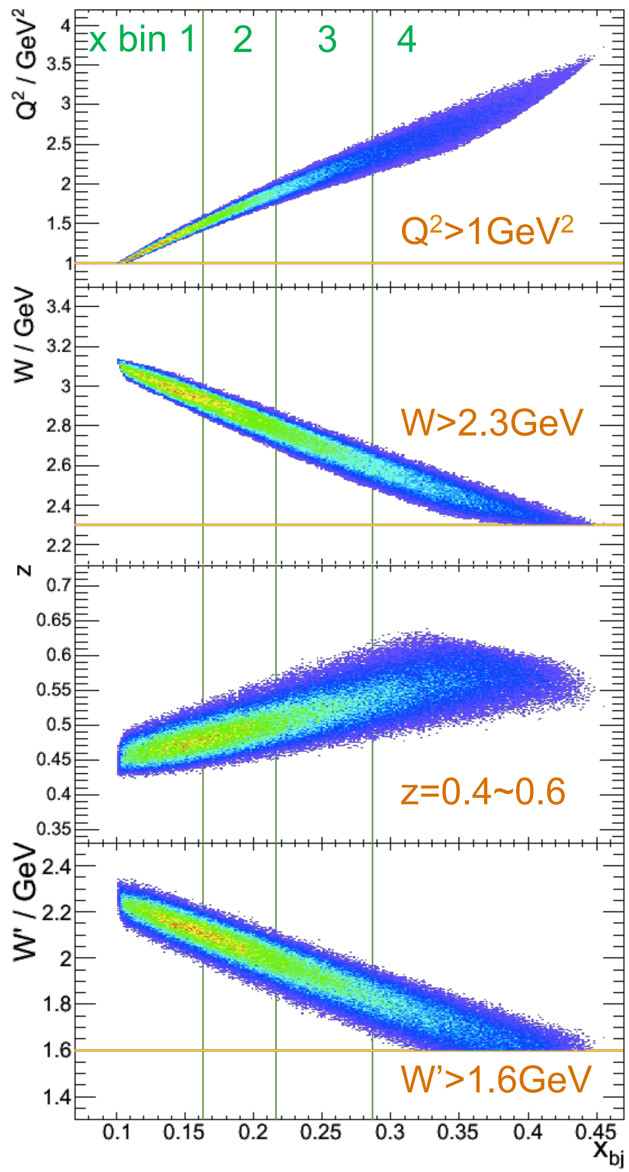


Performance of ^{3}He Target

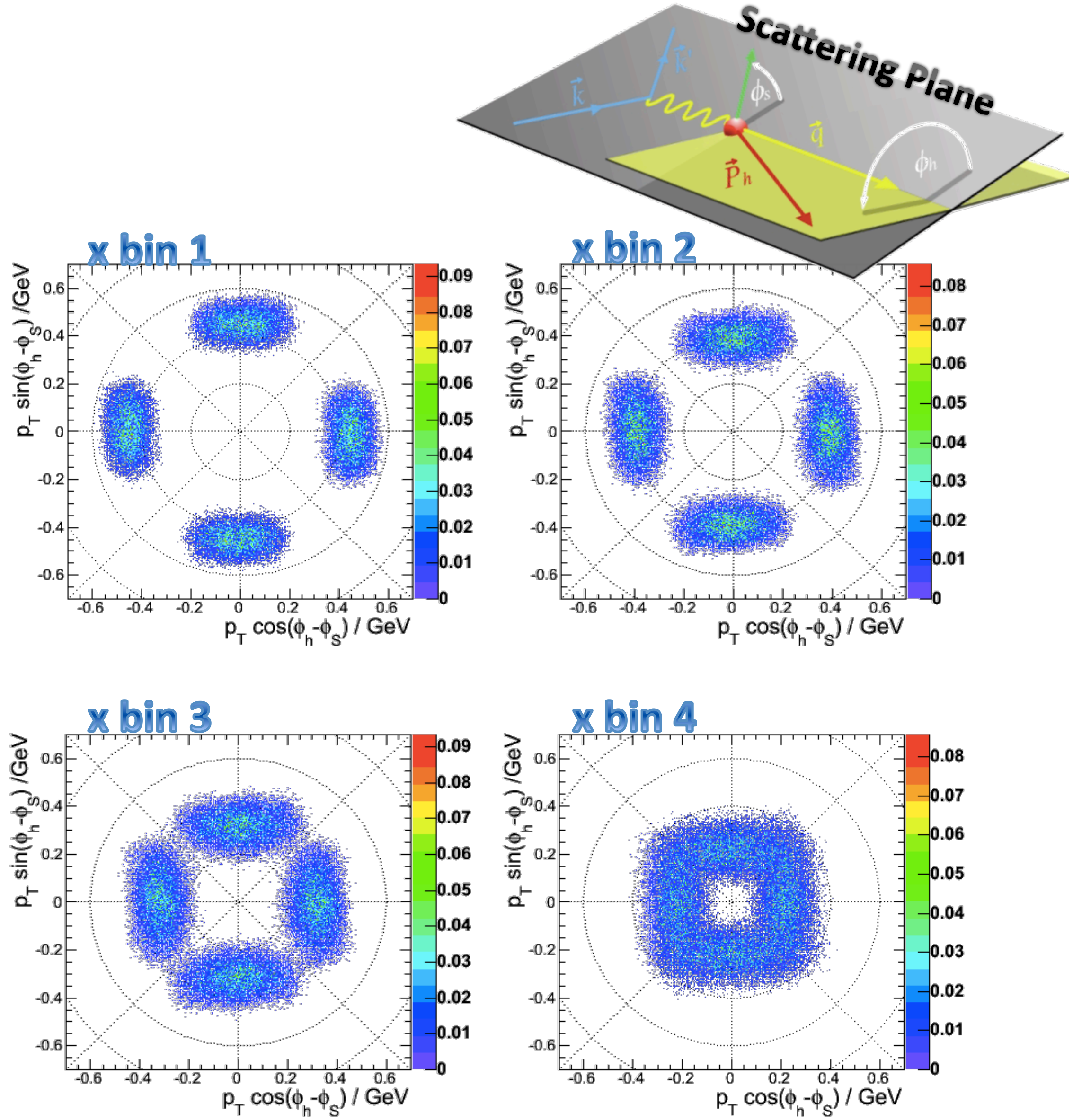


- High luminosity: $\boldsymbol{L}(n) = 10^{36}$ cm^{-2} s^{-1}
- Record high 50-65% polarization in beam with automatic spin flip / 20min
- <P> = 55.4% ± 0.4% (stat. per spin state) ± 2.7 % (sys.)





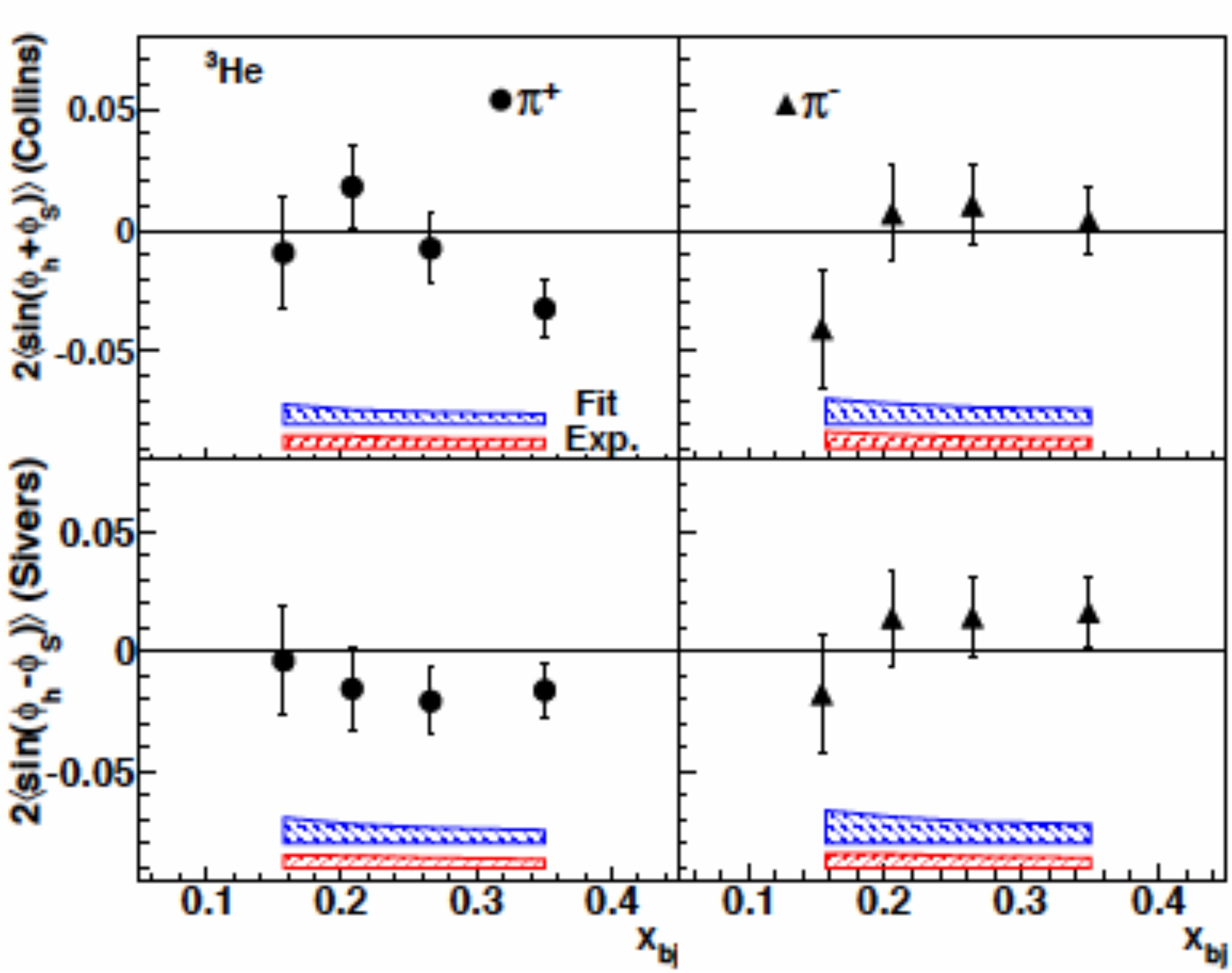
Kinematics coverage



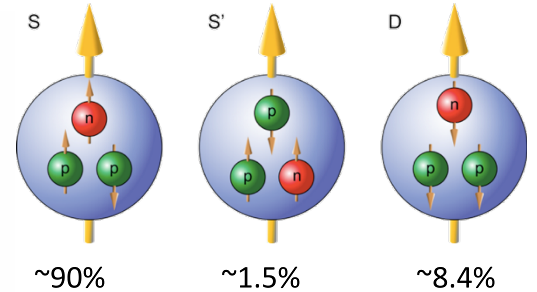
p_T & ϕ_h- ϕ_S coverage

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

PRL107, 072003 (2011)



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



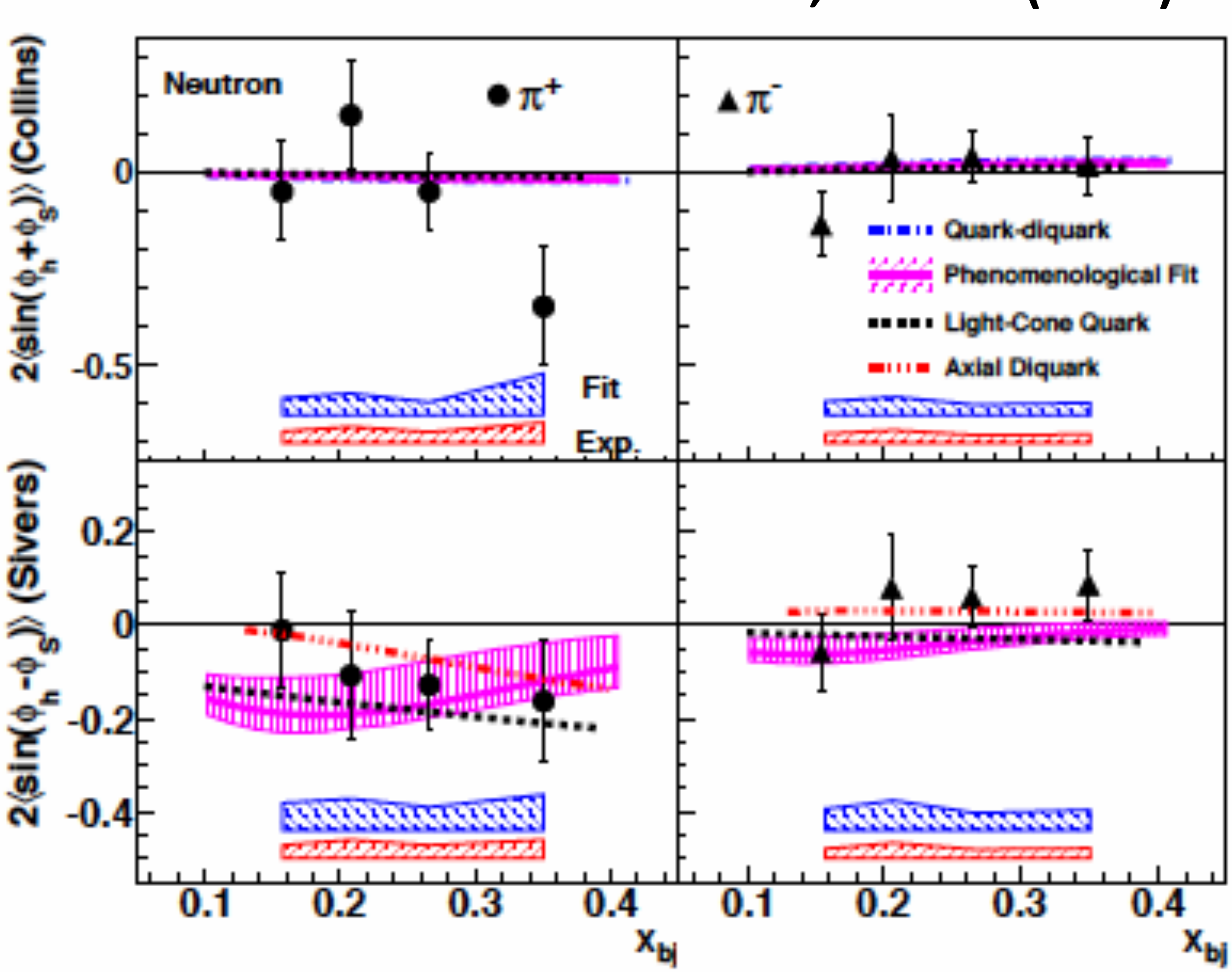
$$^3He^{\uparrow} = 0.865 \cdot n^{\uparrow} - 2 \times 0.028 \cdot p^{\uparrow}$$

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

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

Neutron Single-Spin Asymmetry

PRL107, 072003 (2011)



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

Collins

asymmetries are not large, except at x=0.35

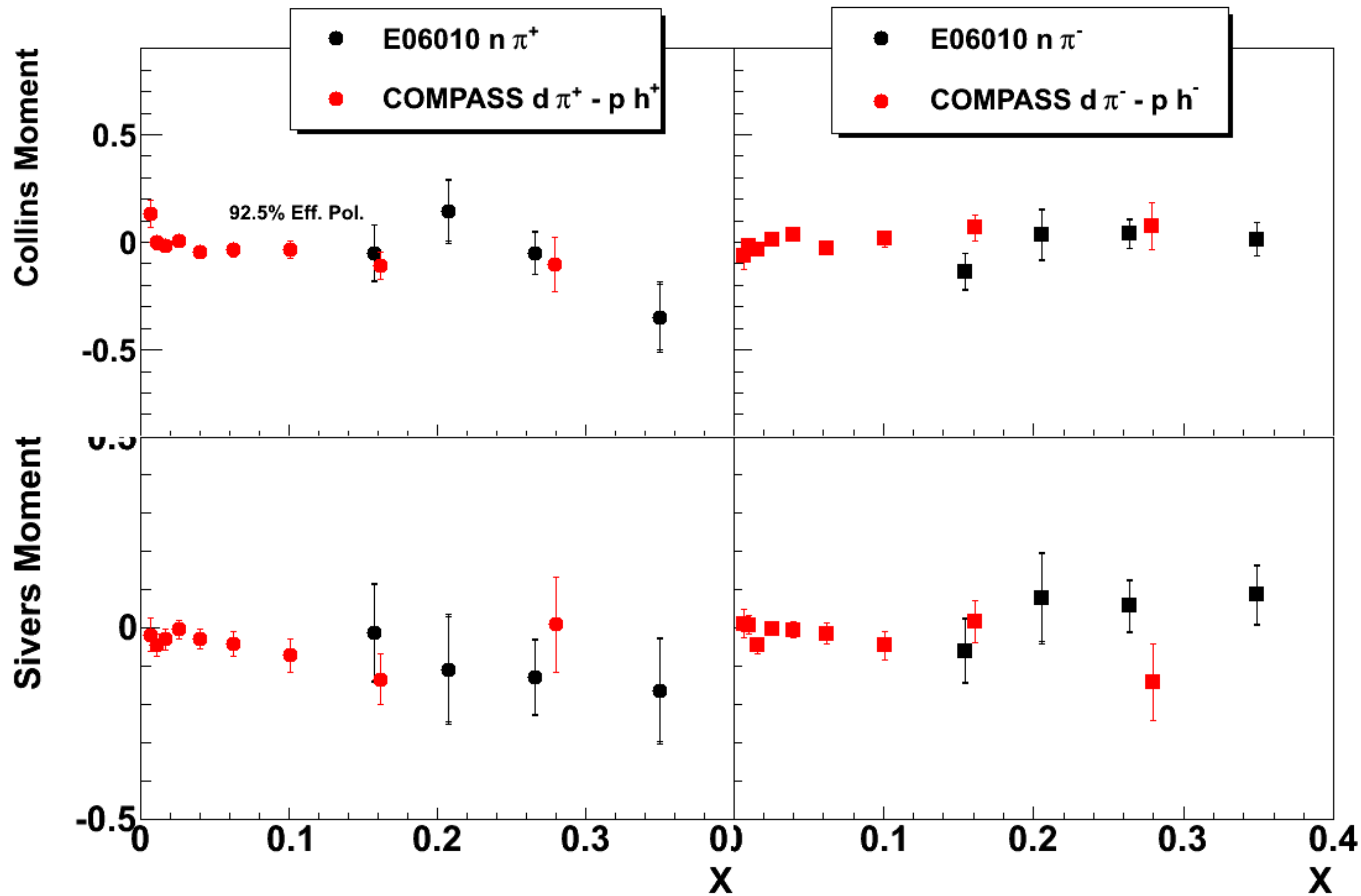
Sivers

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.

Best Measurements on Neutron at High x



Q: **can quarks tell the difference between left and right ?**

A: Yes. Quarks' transverse spin and transverse motion generate left-right biases.

Q: Would sea quarks and valence quarks behave in the same way ?

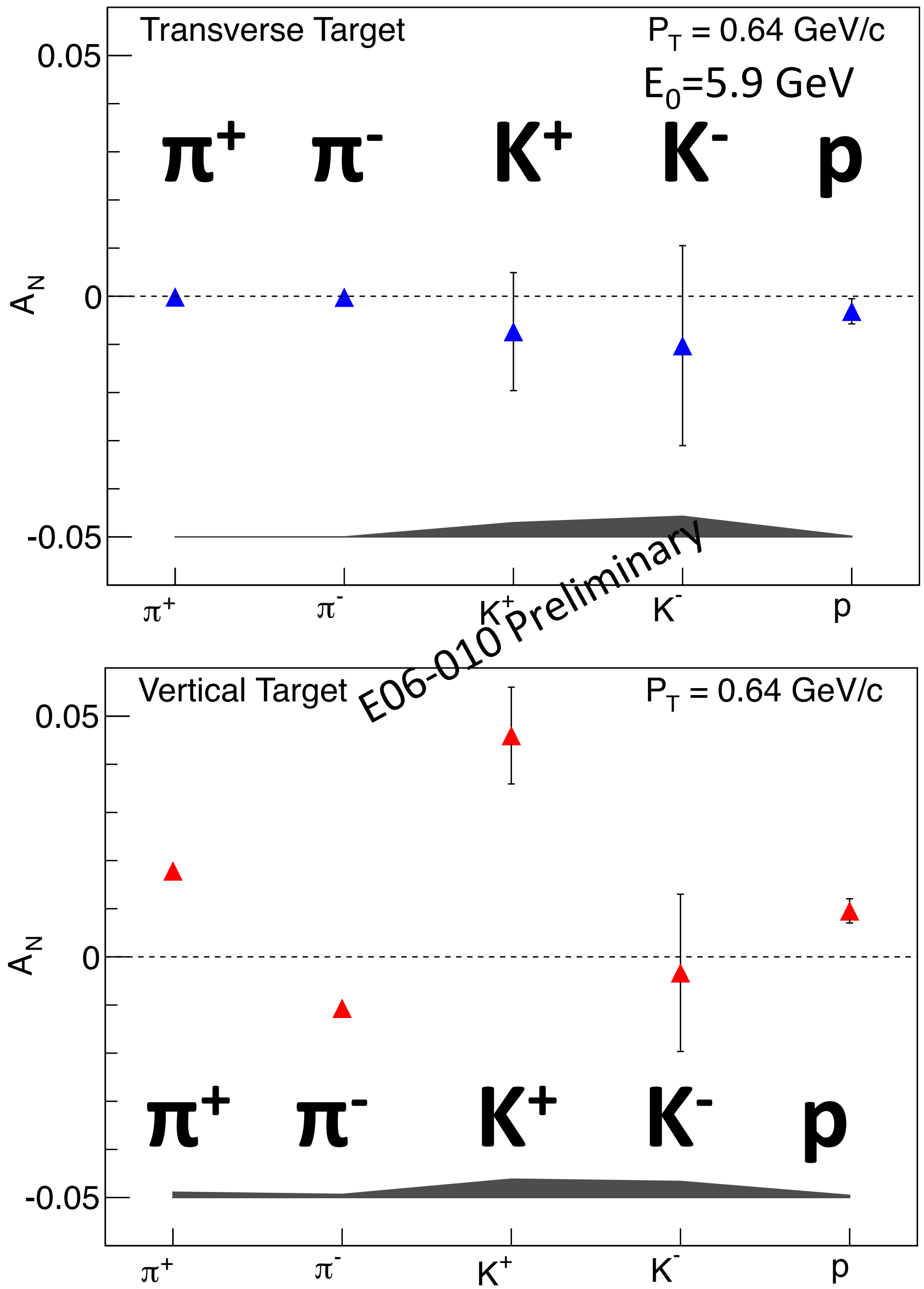
Q: Can gluons tell left from right ?

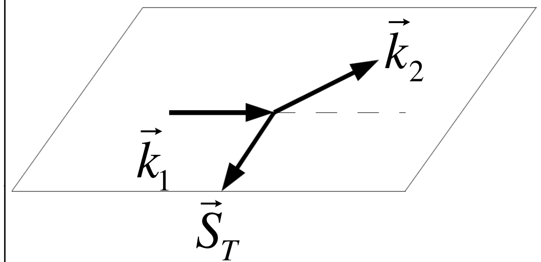
Can hadrons produced in a hard scattering tell left-right ?

$$N^{\uparrow}(e, h)X$$

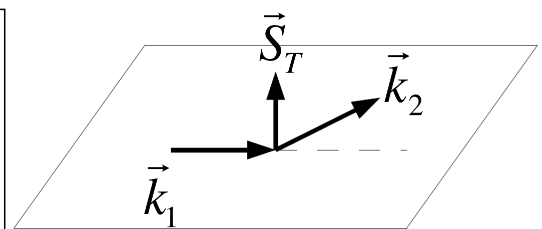
^{3}He Target SSA: Inclusive Hadron Production Channels

$N^{\uparrow}(e, h)X$



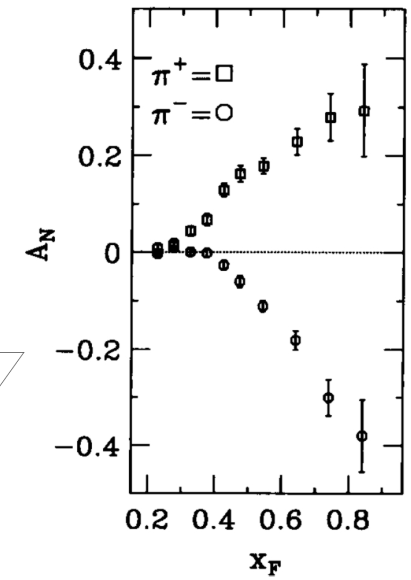


$$(\vec{k}_1 \times \vec{k}_2) \bullet \vec{S}_T = 0$$



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

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

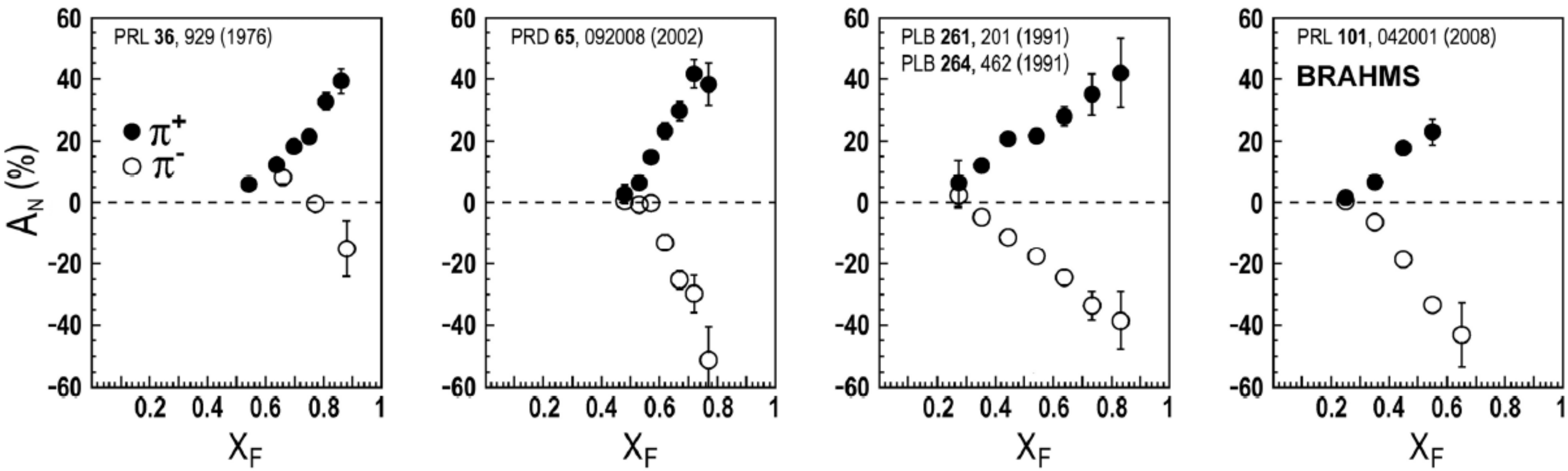


Hadrons produced from hard scattering have left-right bias.

… and recall that

Single-Spin Asymmetry in $p\, p^{\uparrow} \to \pi X$

ANL – 4.9 GeV | BNL – 6.6 GeV | FNAL – 20 GeV | BNL – 62.4 GeV



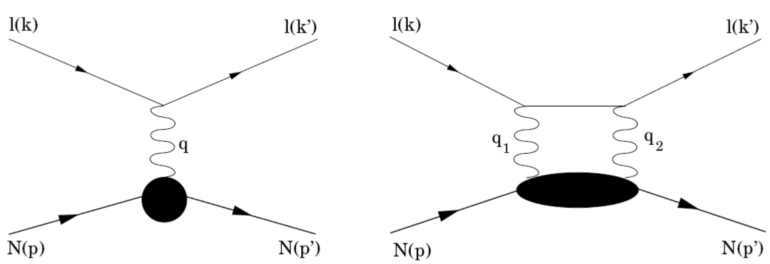
$N^{\uparrow}(e, h)X$: would such SSA persist at a higher energy, such as at EIC ?

Can electrons tell left-right in elastic scattering on a nucleon ?

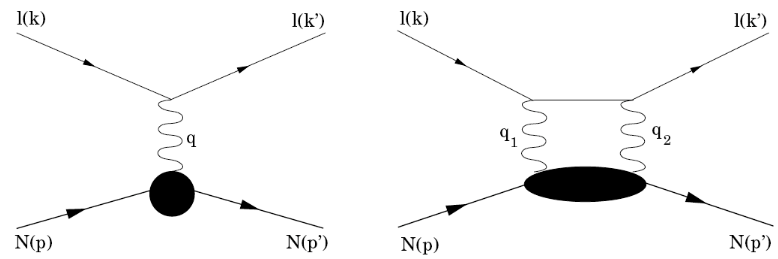
$$N^{\uparrow}(e, e')N$$

Not allowed, if only one-photon exchange, no imaginary piece in the scattering amplitude.

Yes, from interference of one- and two-photon exchange amplitudes.

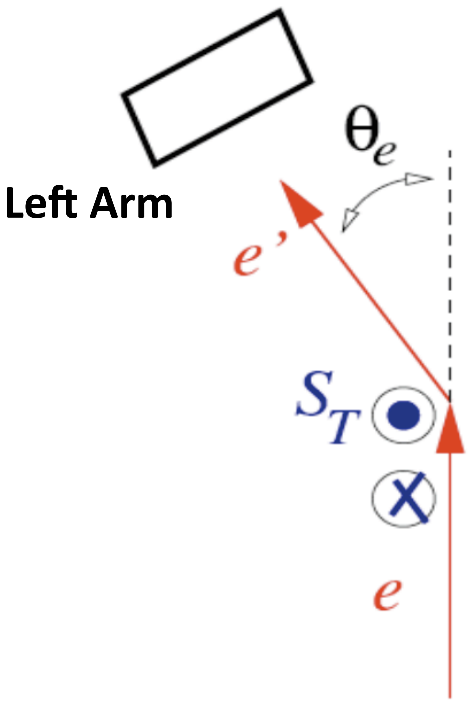


Target Single-Spin Asymmetry in inclusive $^3He^{\uparrow}(e,e')$ scattering (Quasi-Elastic)

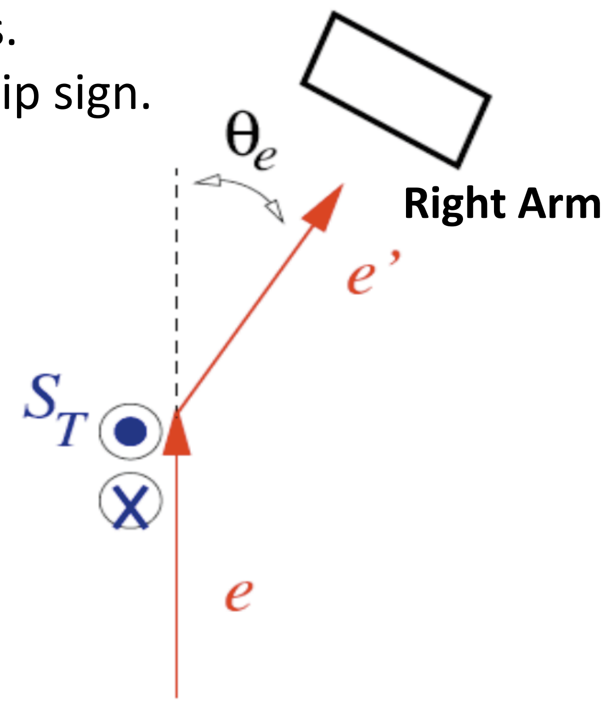


A_y arises from interference of one- and two-photon exchange, provides access to weighted moments of GPD E and H.

Two independent measurements.
Real physics asymmetry should flip sign.



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

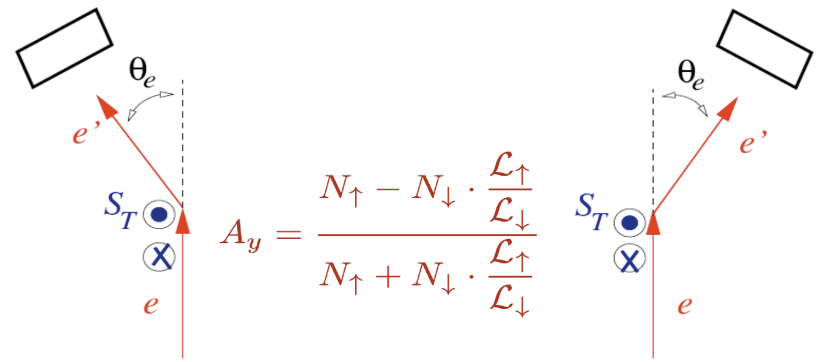


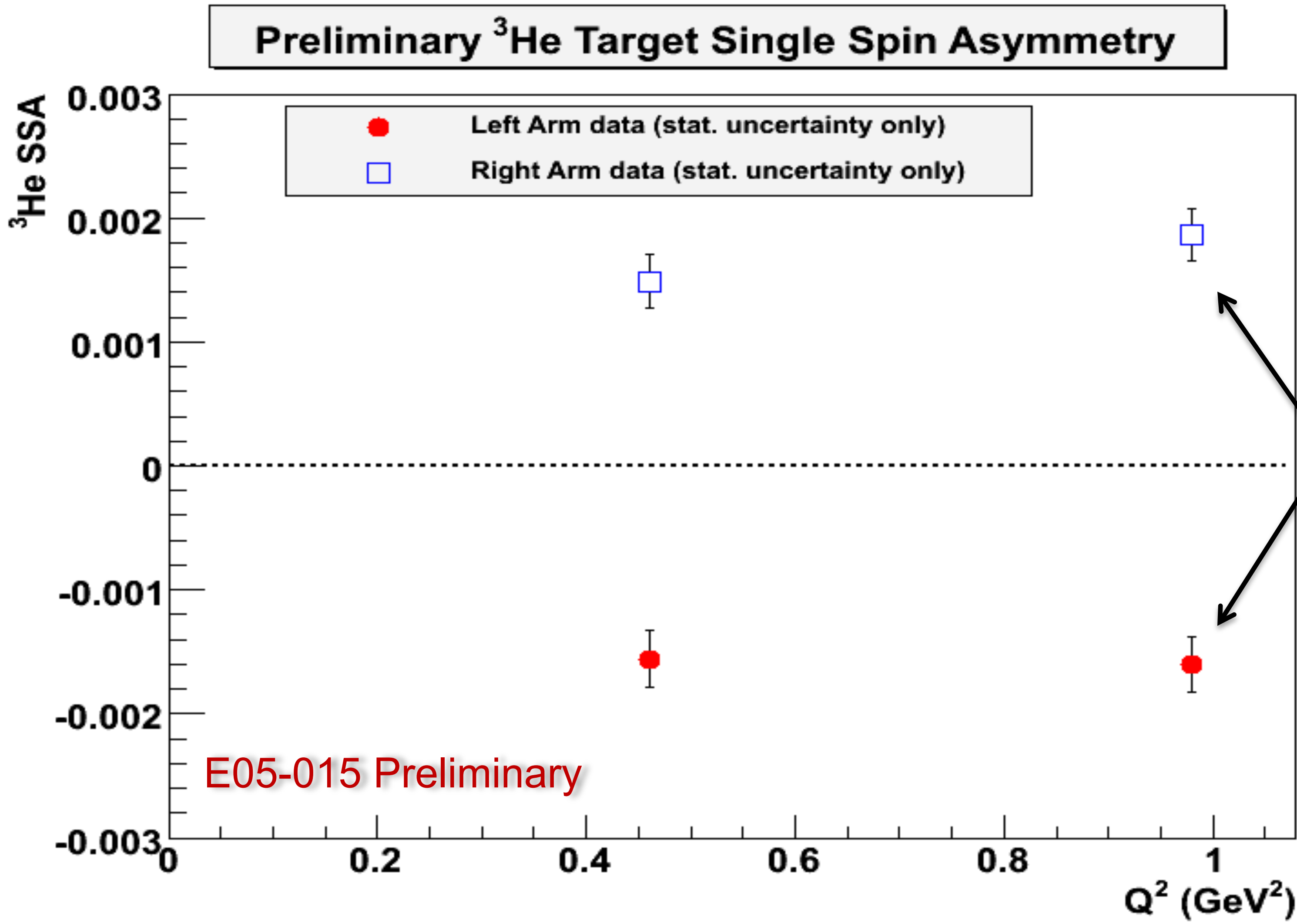
$$(\vec{e} \times \vec{e}\,') \bullet \vec{S}_T > 0$$

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

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

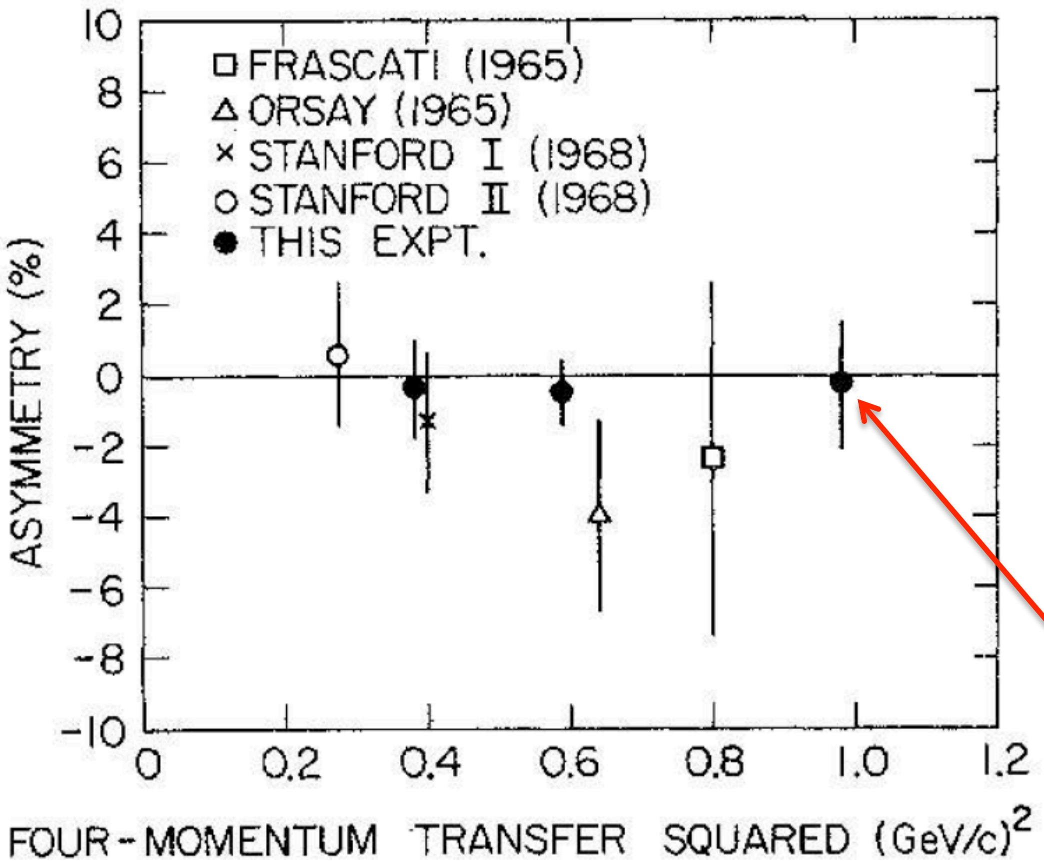
Q^2 = 0.46 and 0.98 GeV^2 W≈M_N





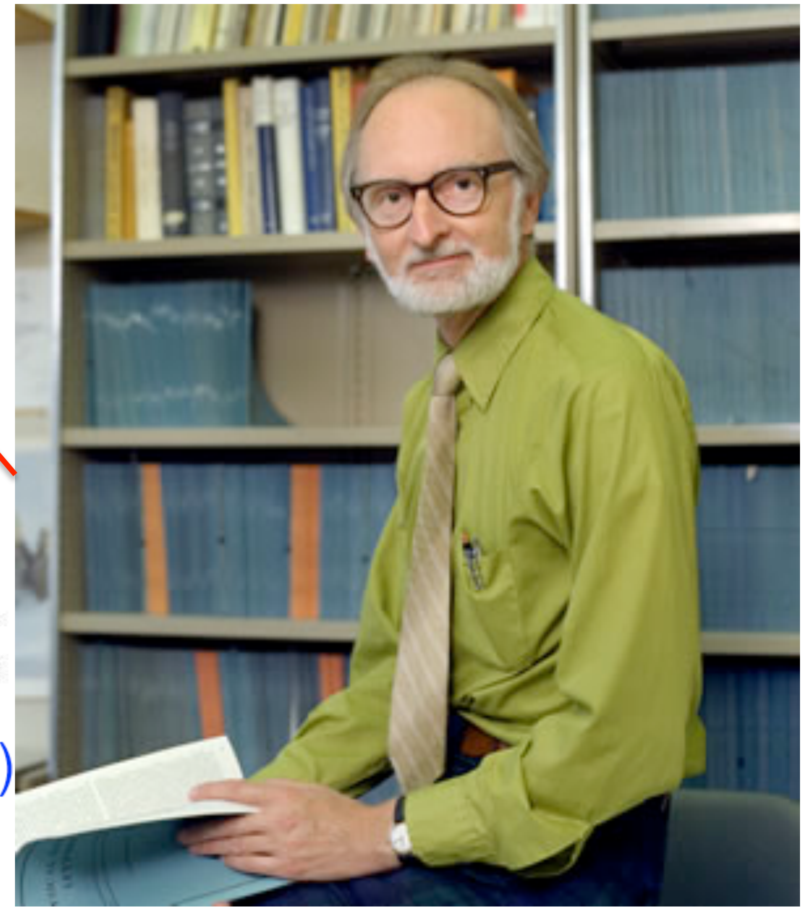
Physics SSA flip signs between two independent measurements.

A non-vanishing inclusive A_y has never been observed



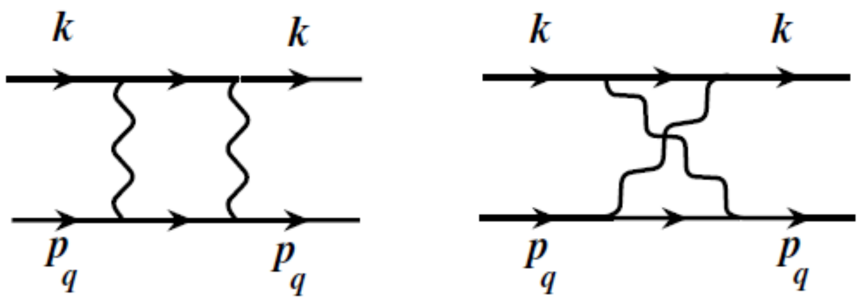
SLAC, T. Powell *et al.*, PRL **24**, 753 (1970)

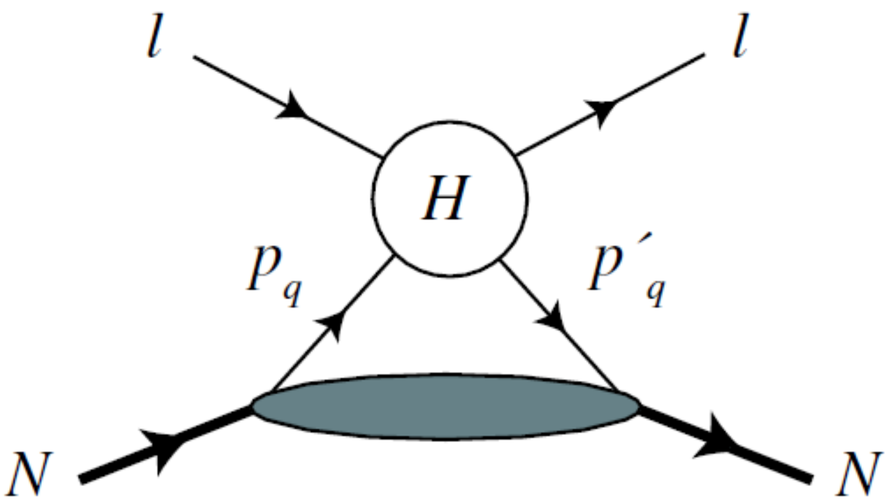
The last effort was made at Stanford in 1969, black dots. Set an upper limit: A_y<2% for proton.



Owen Chamberlain (1920-2006)
Nobel physics 1959.

A_N in GPD framework—handbag mechanism





Afanasev *et al* PRD72, 013008 (2005).

- Two-photon exchange occurs at the parton level in eq → eq box diagram
- Parton process embedded in the nucleon via GPDs:

$$A_n = \sqrt{\frac{2\varepsilon(1+\varepsilon)}{\tau}} \frac{1}{\sigma_R} \left\{ G_E I(A) - \sqrt{\frac{1+\varepsilon}{2\varepsilon}} G_M I(B) \right\},$$

$$A \equiv \int_{-1}^{1} \frac{dx}{x} \frac{[(\hat{s}-\hat{u})\tilde{f}_1^{\text{hard}} - \hat{s}\,\hat{u}\,\tilde{f}_3]}{(s-u)} \sum_q e_q^2 (H^q + E^q),$$

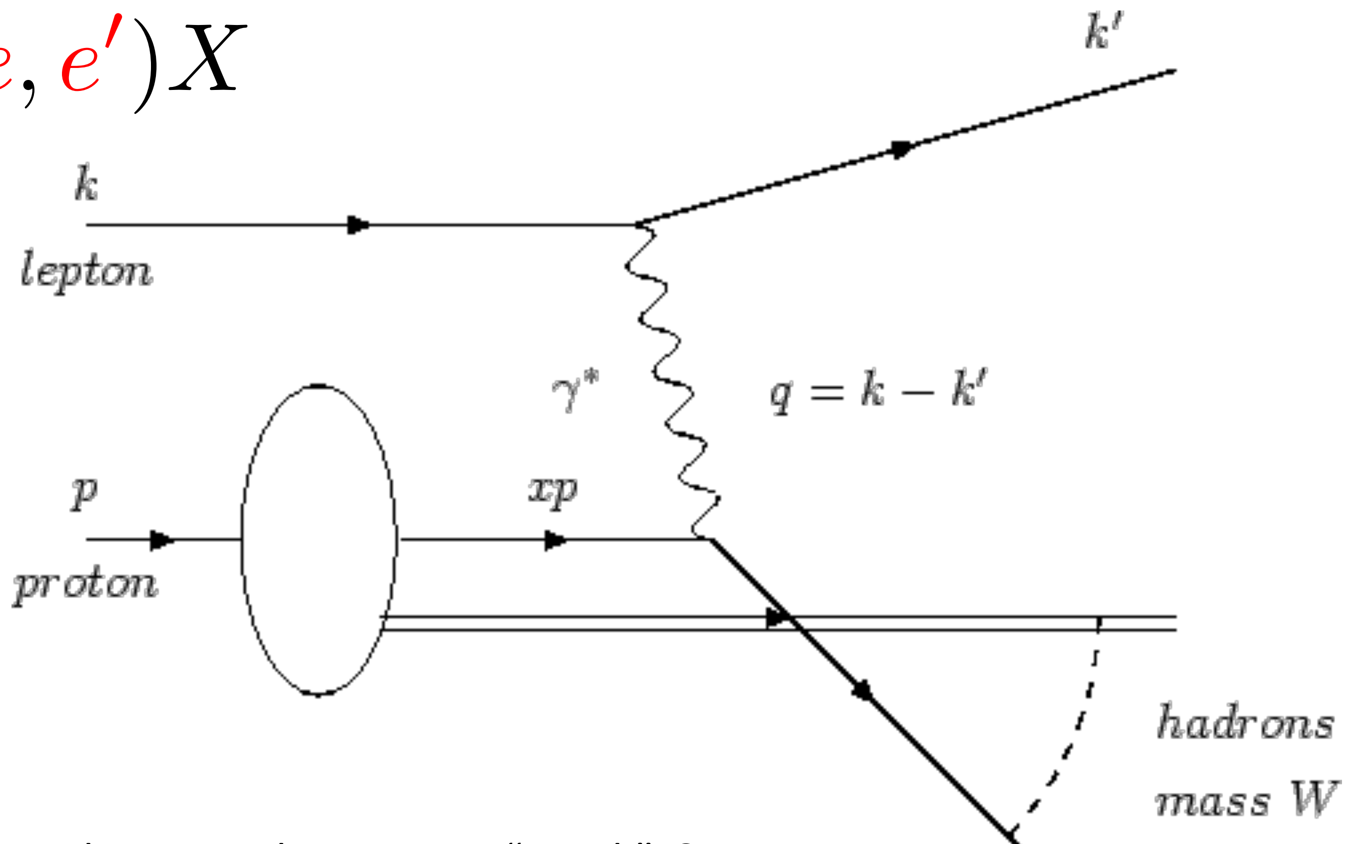
$$B \equiv \int_{-1}^{1} \frac{dx}{x} \frac{[(\hat{s}-\hat{u})\tilde{f}_1^{\text{hard}} - \hat{s}\,\hat{u}\,\tilde{f}_3]}{(s-u)} \sum_q e_q^2 (H^q - \tau E^q),$$

at a high Q^2 …

SSA as a probe to access the (weighted) moments of GPDs.

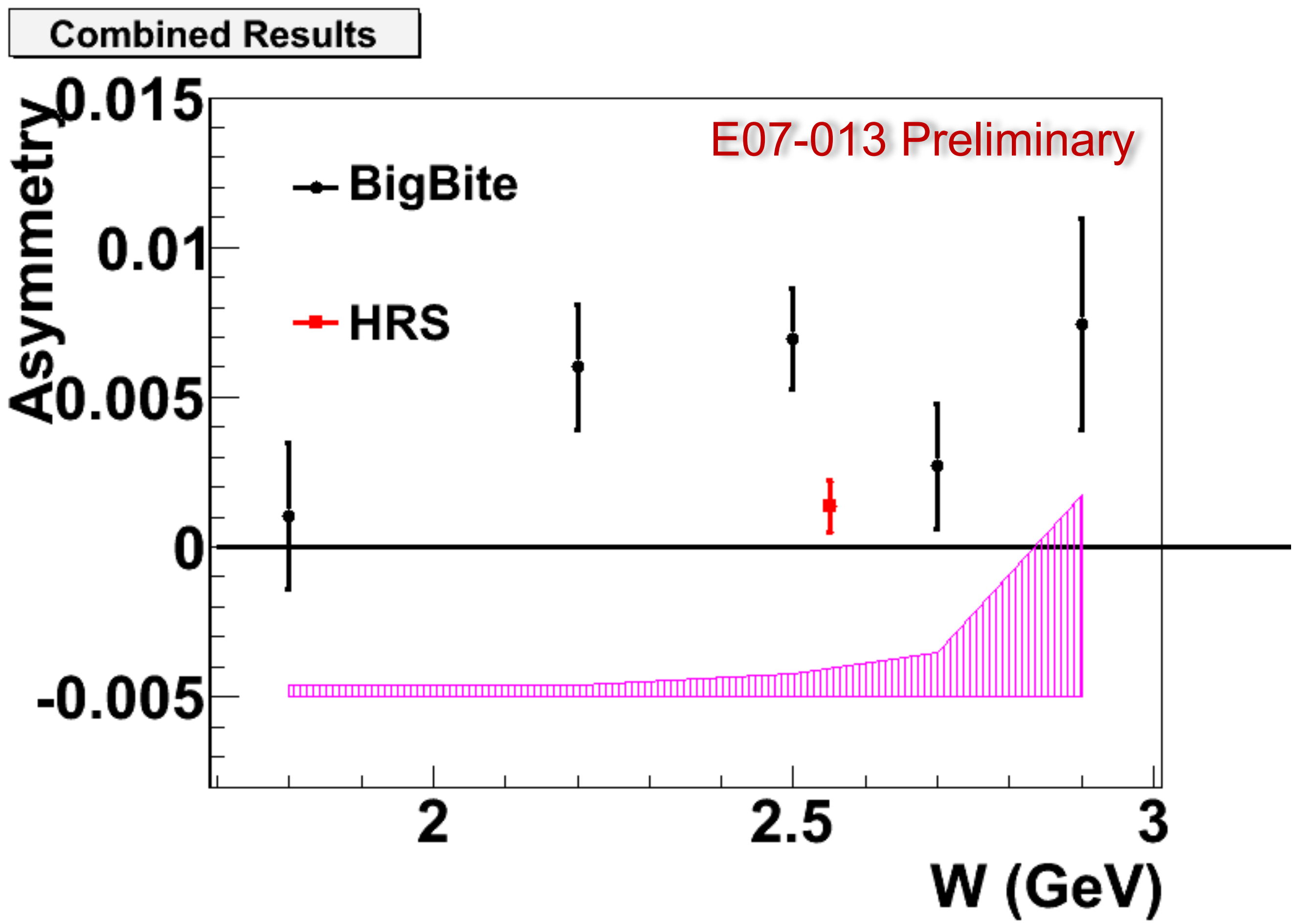
Can electrons tell left-right in deep inelastic scattering on a "quark" ?

$$N^{\uparrow}(e, e')X$$



Requires two-photon exchange on a "quark" ?
(a helicity flip on a "quark" ?)

$^3He^{\uparrow}(e, e')X$ Inclusive SSA at DIS Kinematics



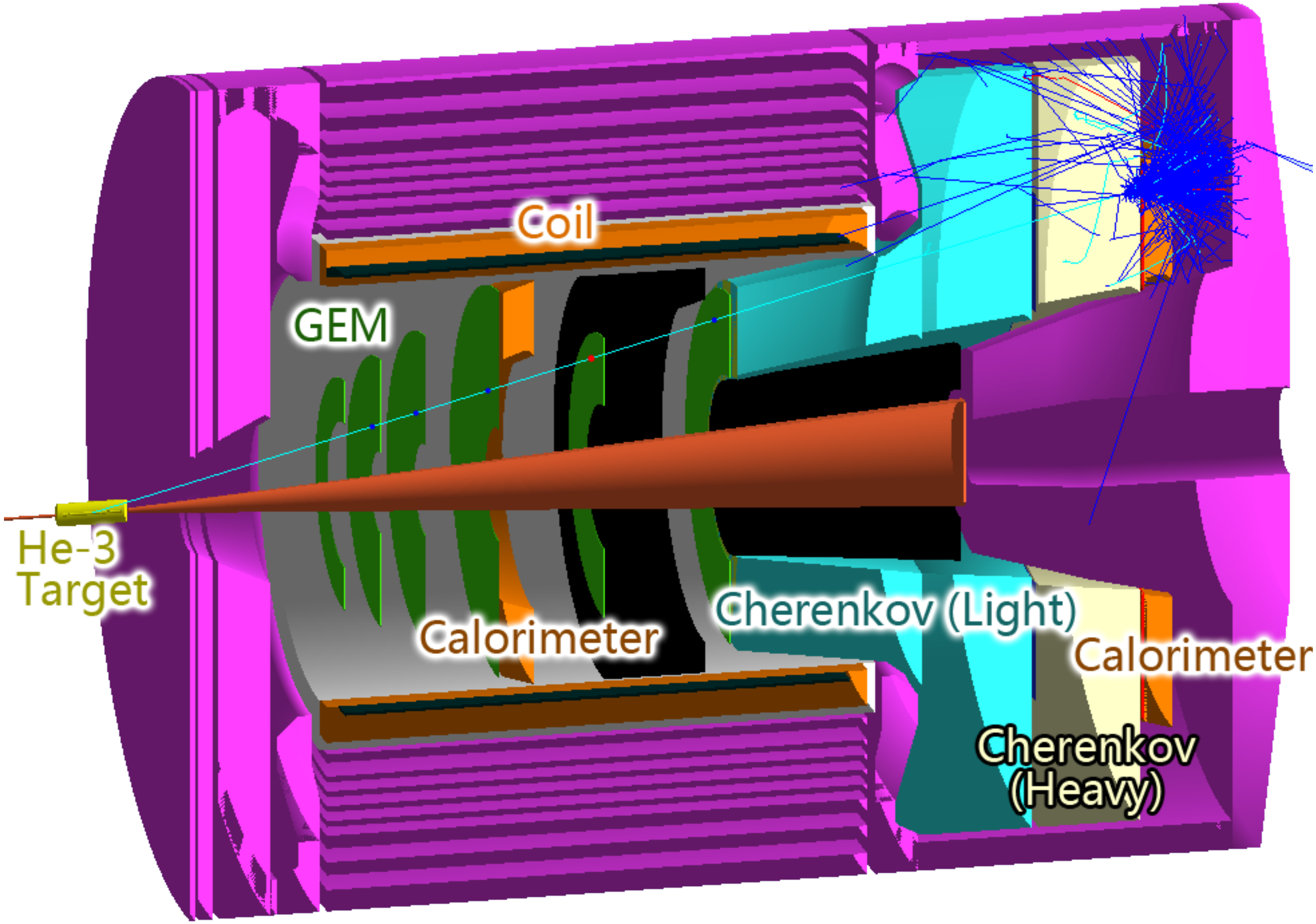
A slight "hint" of non-vanishing SSA, not conclusive.

New SIDIS Experiments with JLab-12 GeV in Hall A

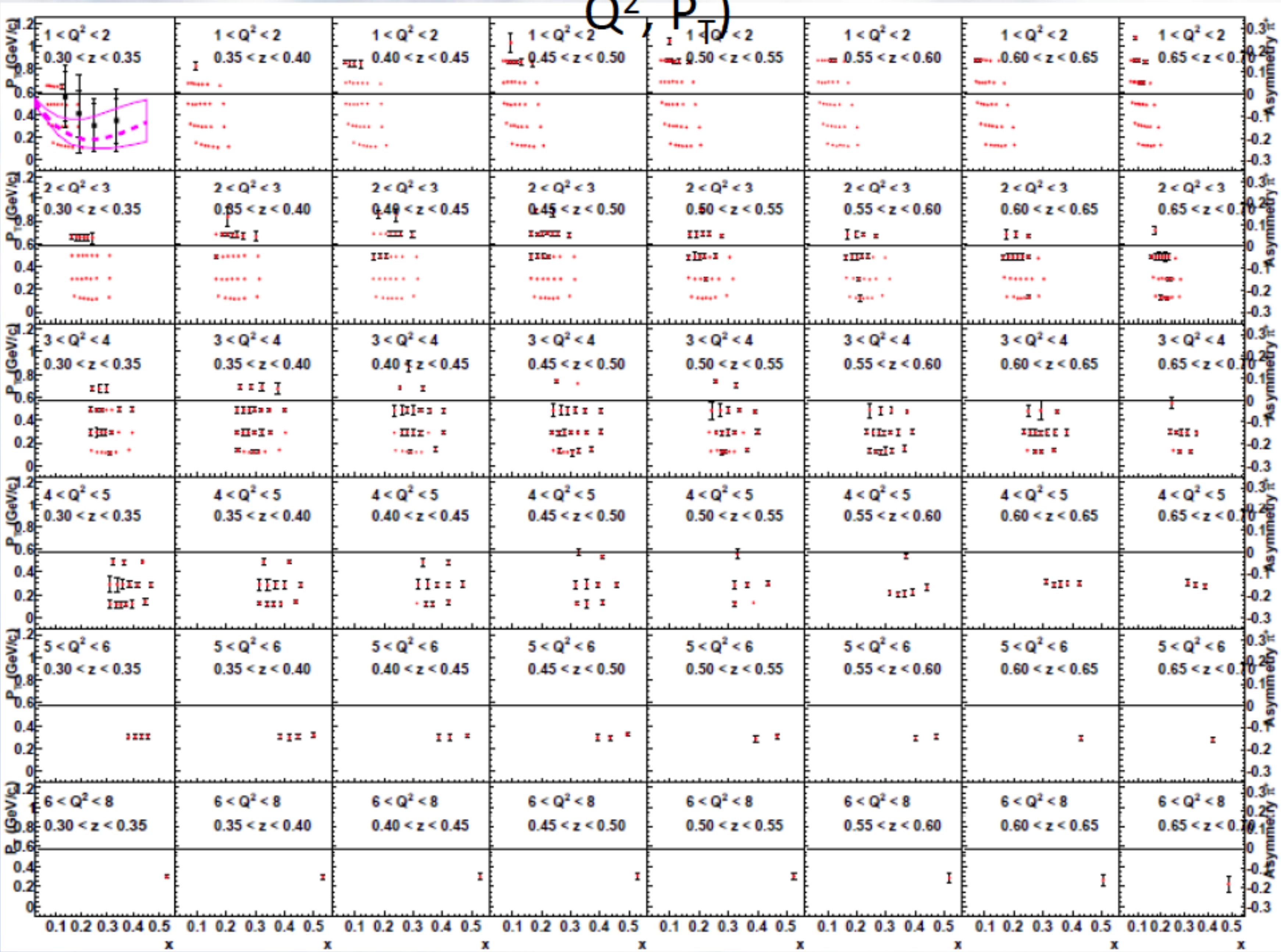
- Polarized neutron (^{3}He) transverse
  - Two magnetic spectrometer: Bigbite+Super_BigBite.
  - Large acceptance spectrometer (SoLID).
- Polarized neutron (^{3}He) longitudinal with SoLID.
- Polarized proton (NH_3) with SoLID.

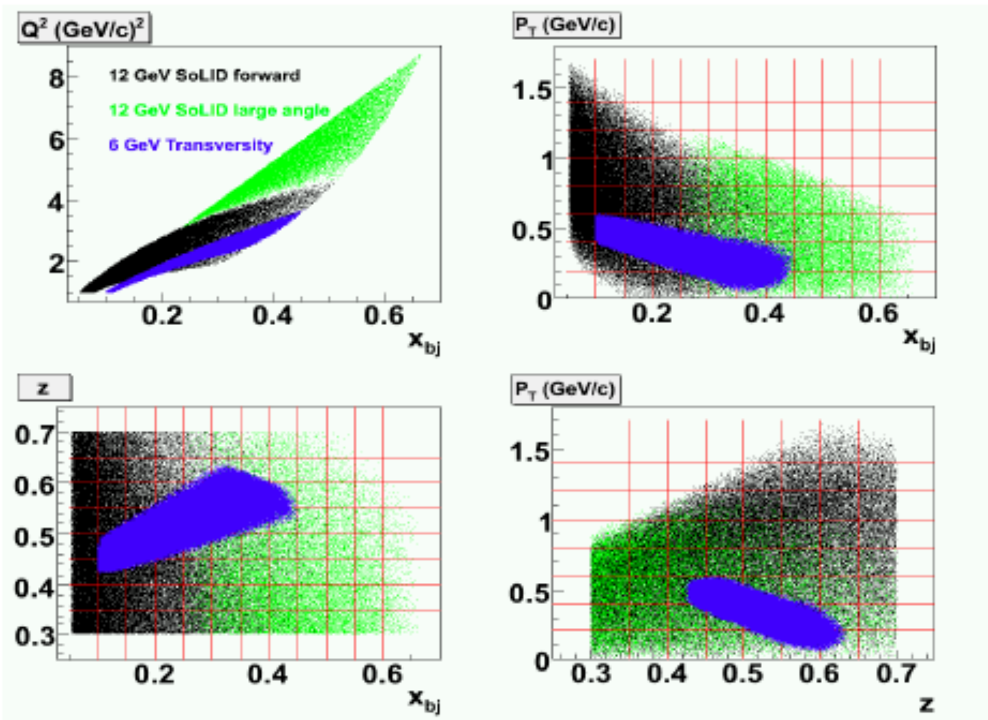
Our goal is to pin down SSA in a multi-dimensional space of (x, Q^2, z, p_T) with a large acceptance spectrometer which can take a high luminosity, for polarized neutron (^3He) and proton (NH_3) targets.

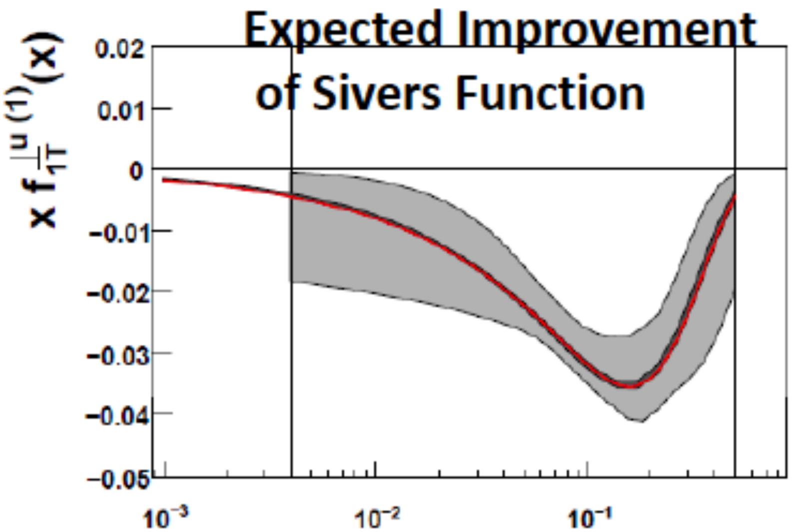
SoLID in Hall A : conceptual design



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



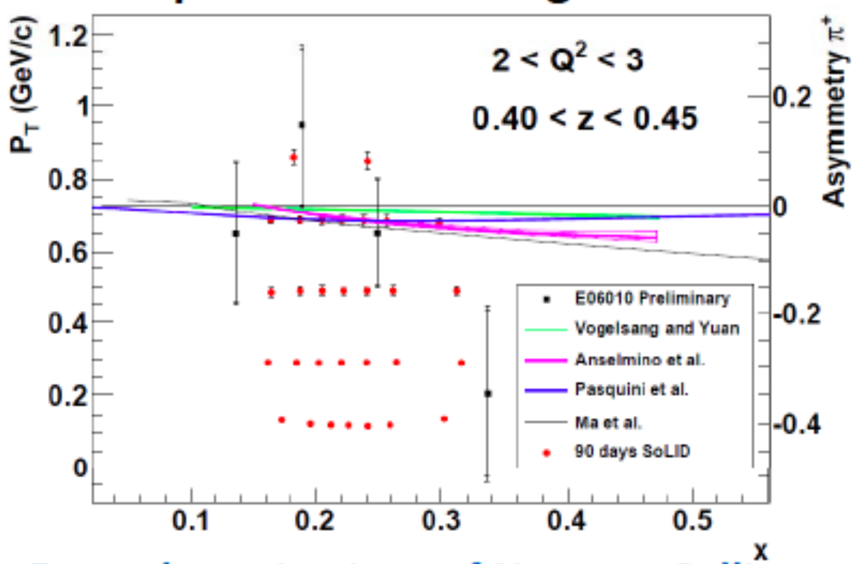




$$A_{UT}^{Collins} \propto \langle \sin(\phi_h + \phi_s) \rangle \propto h_{1T} \otimes^{x} H_1^{\perp}$$

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

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

Summary

- **Semi-inclusive deep-inelastic scattering channels.**
  - **Target single-spin asymmetry A_{UT}**
  - **small Collins SSA, Negative π+ Sivers SSA on neutron .**
- **Inclusive channels**
  - **"large" SSA observed in inclusive hadron production channels.**
  - **"large" SSA observed in inclusive ^{3}He(e,e') quasi-elastic scattering.**
  - **a "hint" of SSA in inclusive ^{3}He(e,e') deep inelastic-elastic scattering.**

Many new SIDIS experiments planned in Hall-A for JLab-12 GeV upgrade.

On a transversely polarized nucleon, through parity conserving interactions,

Yes, hadrons produced in a hard scattering can tell left-right.

Yes, electrons can tell left-right in elastic scattering on a nucleon.

Electrons might be able to tell left-right in deep inelastic scattering on a "quark".

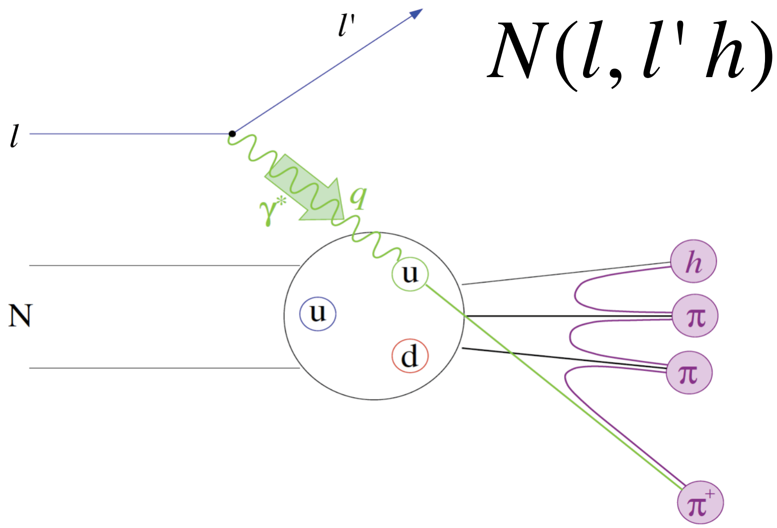
Backup Slides

Details of Kinematics

E_0(GeV)	E'(GeV)	θ_{spec} (Deg)	Q^2 (GeV^2)	|q| (GeV)	θ_q (Deg)
1.25	1.22	17	0.13	0.359	71
2.43	2.18	17	0.46	0.681	62
3.61	3.09	17	0.98	0.988	54

(Q^2=0.13 point was not plotted.)

Semi-Inclusive Deep-Inelastic Scattering to access quark information



$$N^{\pi^{\pm}}(x,z) \propto \sum_i e_i^2 \left[q_i(x)\, D_{q_i}^{\pi^{\pm}}(z) \,+\, \overline{q}_i(x)\, D_{\overline{q}_i}^{\pi^{\pm}}(z) \right]$$

Parton model interpretation.

Hall-C E00-008
E=5.479 GeV.

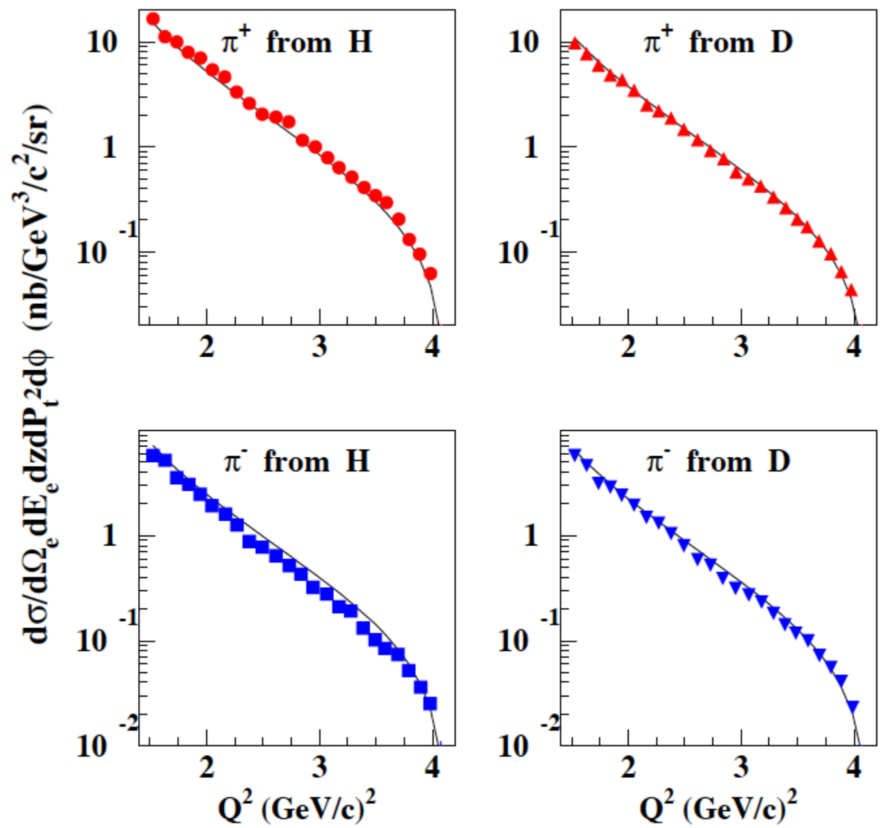


FIG. 10: (Color online) The ^{1,2}H(e,e$'\pi^{\pm}$)X cross sections at fixed values of $x = 0.40$ and $z = 0.55$, as a function of Q^2. The solid curves are the simple quark-parton model calculations following a high-energy factorized description. Solid symbols are data after events from coherent ρ production are subtracted (see text).