Transverse Spin Experiments

Xiaodong Jiang, Los Alamos National Laboratory.

- Introduction: quarks can tell the difference between left and right in a transversely polarized nucleon.
- Quark transversity and Sivers distributions - transverse single spin asymmetries in p+p and semi-inclusive DIS.

  Collins effect: transversely polarized quarks generate left-right bias in fragmentation.

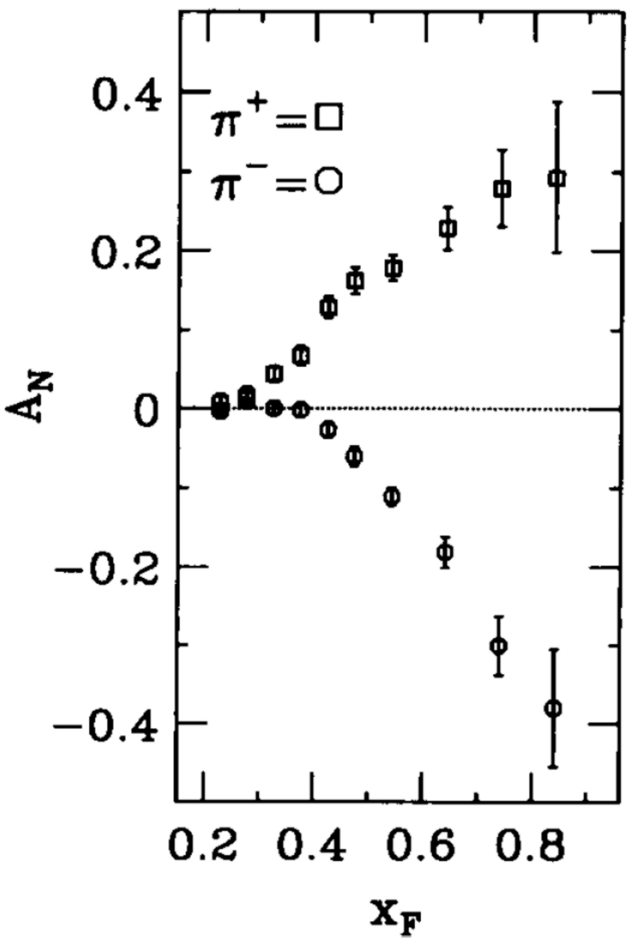
  Sivers effect: quarks' transverse motion generate left-right bias in "effective" density.
- HERMES and COMAPSS results of SIDIS target single-spin asymmetry.
  - HERMES proton published results.
  - COMPASS deuteron published results.
  - COMPASS proton data update.
- **JLab Hall A "Neutron Transversity" Experiment (E06-010).**
- Upcoming transverse spin experiments at JLab-12 GeV.
- Fixed polarized target Drell-Yan experiments.

Los Alamos NATIONAL LABORATORY EST. 1943

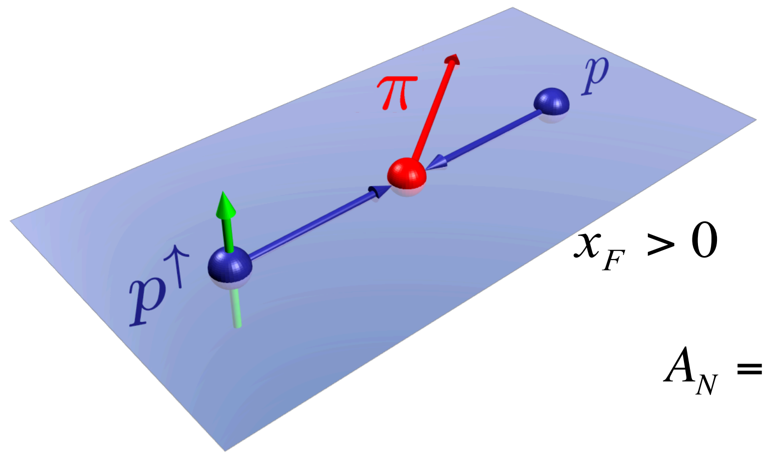
Nature has produced large left-right asymmetries

- about 15% of this type of crab are left-handed, left-right asymmetry of A=-70%

Quarks can tell left-right in $p\,p^{\uparrow} \rightarrow \pi X$



FNAL-E704: √s =20 GeV. PLB 264 (1991) 462.



$x_F > 0$

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

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

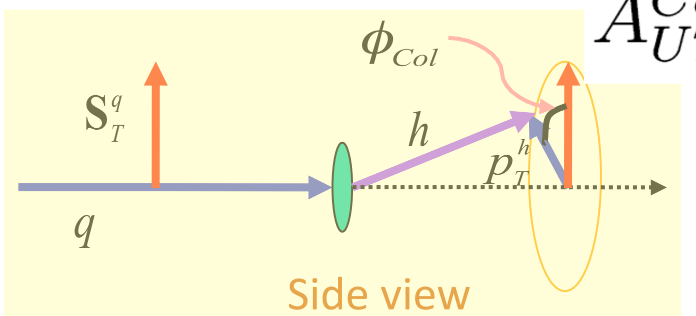
$\pi^-\ (d\bar{u})$ favors right

One explanation (Sivers effect):
quark's angular motion generates a left-right density difference.

up-quarks favor left (L_u>0), down-quarks favor right (L_d<0).

How could a quark tell left from right ?

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

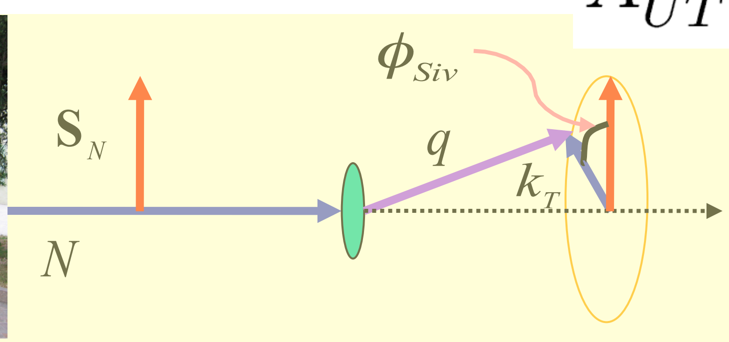


$$A_{UT}^{Collins} \propto \delta q(x) \otimes H_{1q}^{\perp h}(z, P_{h\perp}^2)$$

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 Transverse Momentum Dependent Parton Distributions (TMDs)

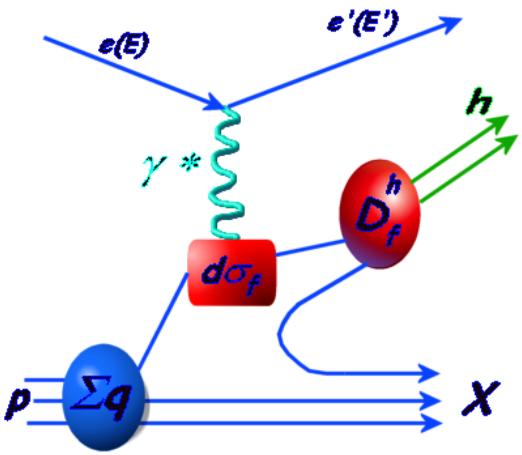
→ Nucleon Spin
→ Quark Spin

		Quark polarization		
		Un-Polarized	**Longitudinally Polarized**	**Transversely Polarized**
Nucleon Polarization	U	$f_1 =$		$h_1^{\perp} =$ − **Boer-Mulder**
	L		$g_1 =$ − **Helicity**	$h_{1L}^{\perp} =$ −
	T	$f_{1T}^{\perp} =$ − **Sivers**	$g_{1T}^{\perp} =$ −	$h_{1T} =$ − **Transversity** $h_{1T}^{\perp} =$ − **Pretzelosity**

to access quark transversity distributions …

- Transversity distribution is chiral--odd, not accessible through inclusive deep-inelastic scattering. Need to be combined with another chiral-odd object, i.e. Collins fragmentation function.

Through target single spin asymmetry in semi-inclusive DIS.
J.C. Collins, NPB 396, 161(1993).

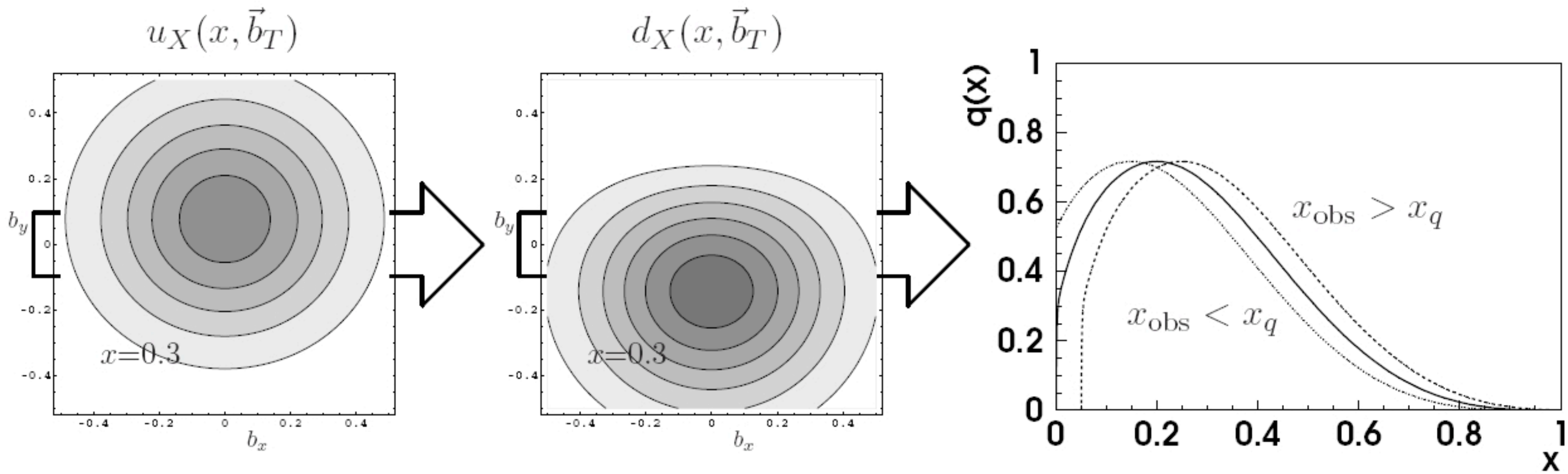


$$A_{UT}^{Collins}(x,z) \propto \frac{\sum_q e_q^2\, \delta q(x) \otimes H_{1q}^{\perp h}(z, P_{h\perp}^2)}{\sum_q e_q^2\, q(x) \otimes D_{1q}^{h}(z, P_{h\perp}^2)}$$

Collins frag. fun. can be accessed in e^+e^- collisions (BELLE experiment at KEK).

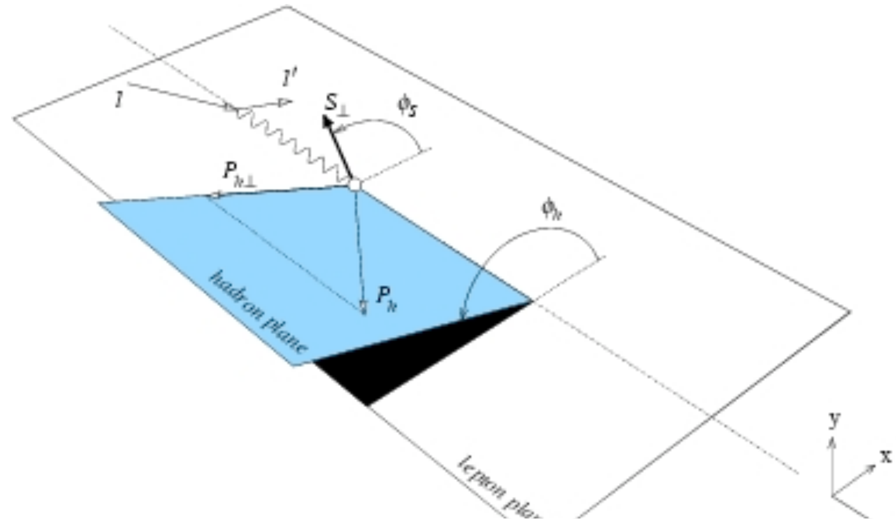
Sivers: with transverse motion, quarks on one side of the nucleon are moving towards the probe while on the other side are moving away from the probe.

Left and right are different.



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

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

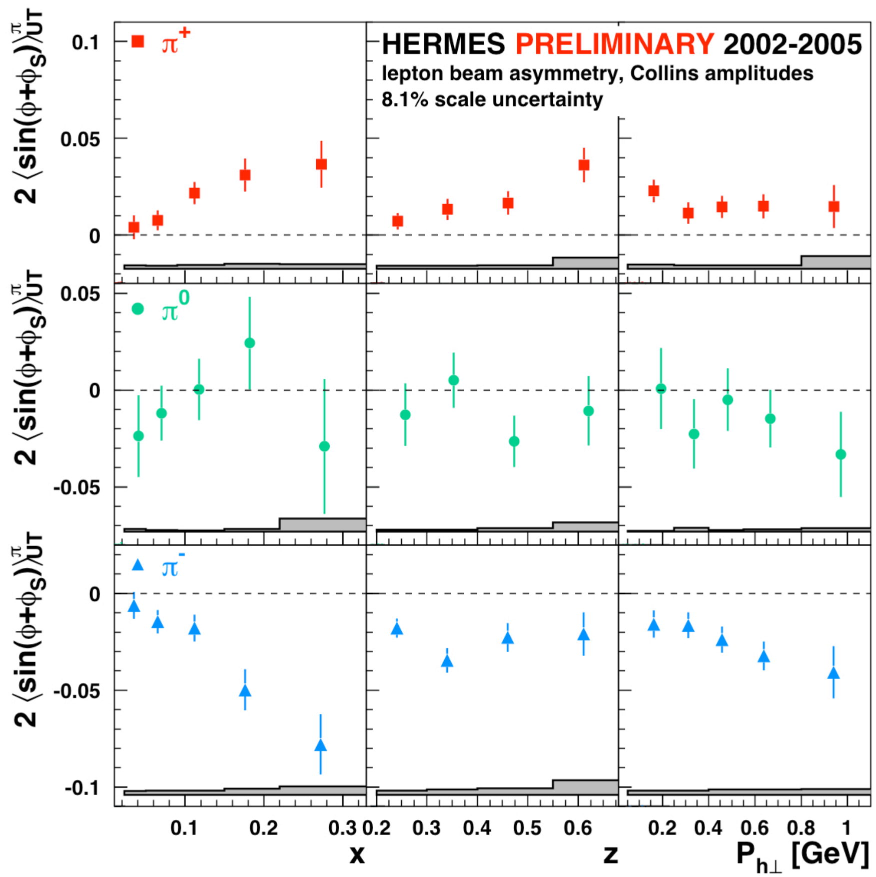


$$\begin{aligned} \sigma_{UT} \quad \propto \quad & S_T(1-y)\frac{P_{h\perp}}{zM_h}\,\sin(\phi_h^\ell + \phi_S^\ell)\cdot \sum e_q^2\, h_1^q(x) \otimes H_{1q}^{\perp h}(z, P_{h\perp}^2) \\ + \quad & S_T(1-y+\frac{y^2}{2})\frac{P_{h\perp}}{zM_N}\,\sin(\phi_h^\ell - \phi_S^\ell)\cdot \sum e_q^2\, f_{1T}^{\perp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

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.

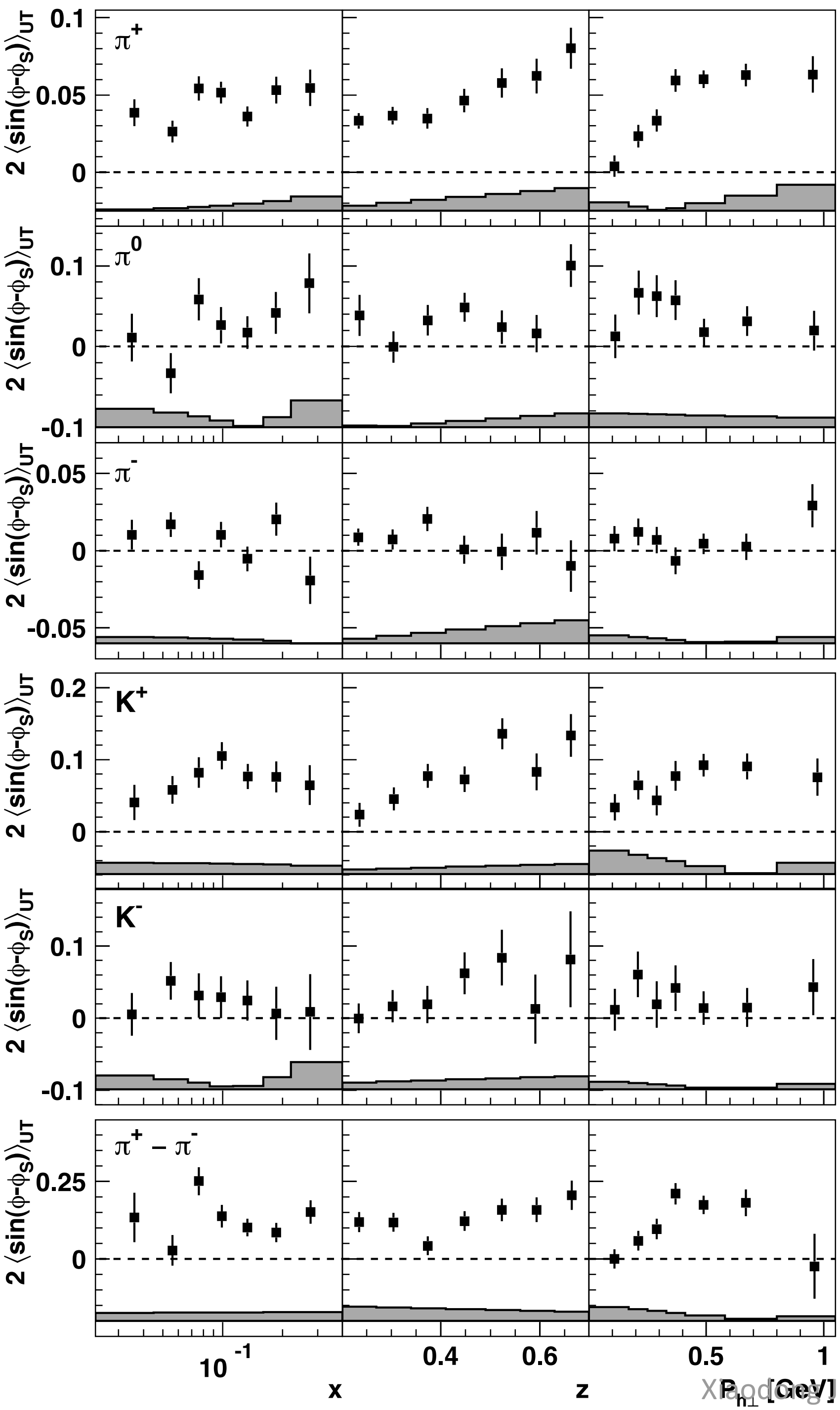
HERMES: non-vanishing Collins A_{UT} on proton

Collins



- Collins asymmetries are strongly dependent on the hadron flavor.

Hermes Proton: Sivers Asymmetry

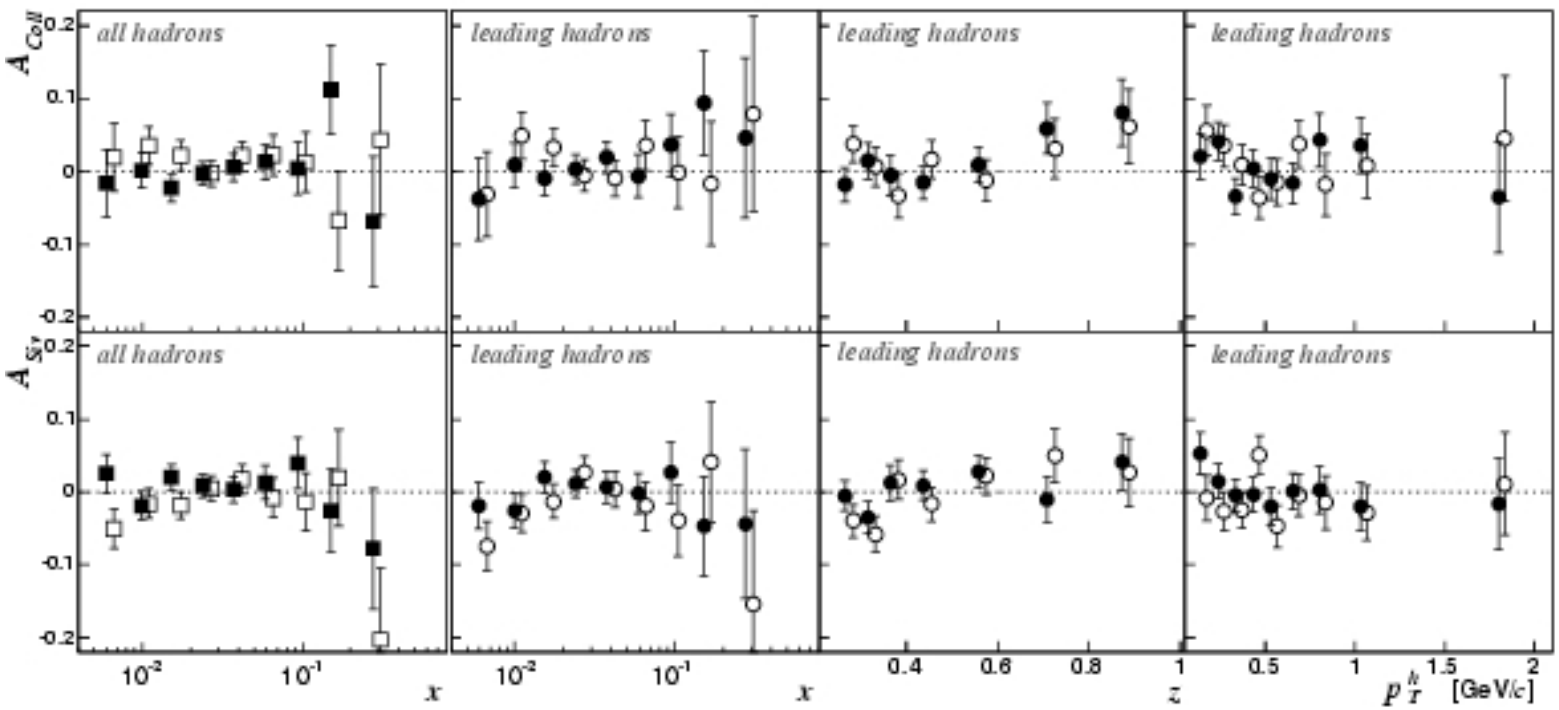


$$\sigma(\phi,\phi_S) = \sigma_{UU}\{1 + 2\langle\cos\phi\rangle_{UU}\cos\phi + 2\langle\cos 2\phi\rangle_{UU}\cos 2\phi$$

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

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

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.

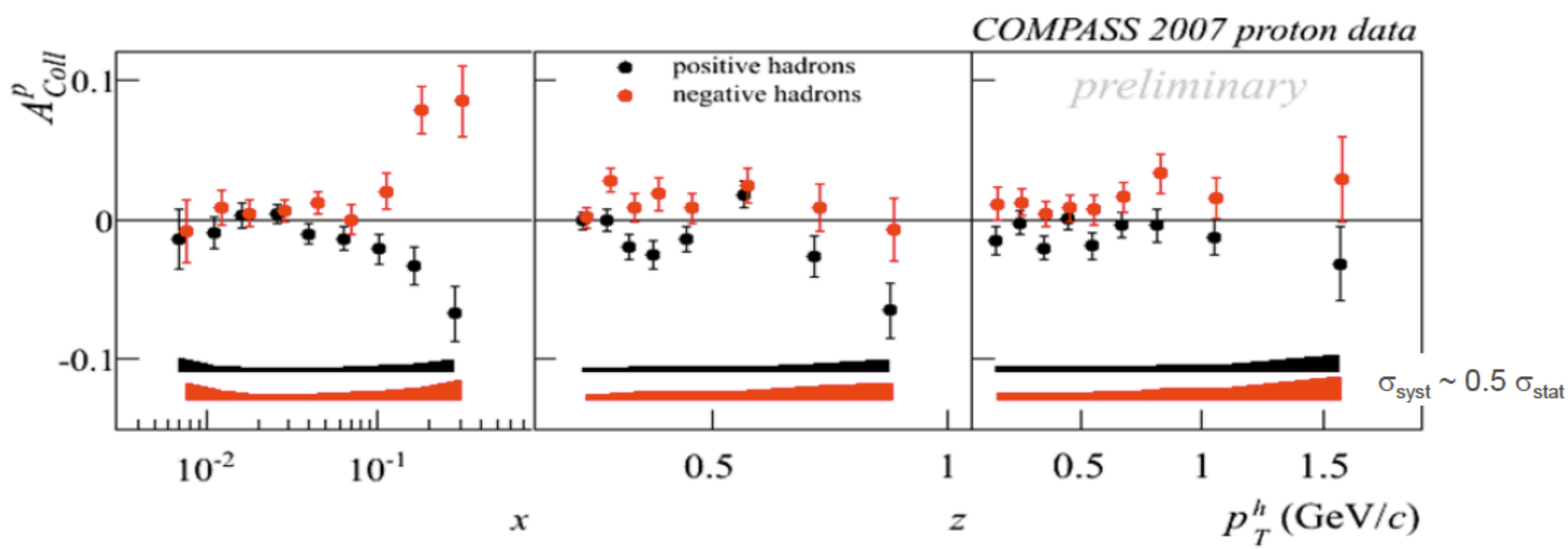
At DIS-2010

Collins asymmetry – proton data

COMPASS proton results from 2007 run

the analysis is over and the paper almost ready to be sent

new results very much the same as presented at DIS 2009



- **at small x, the asymmetries are compatible with zero**
- **large signal in the valence region**
  of opposite sign for positive and negative hadrons

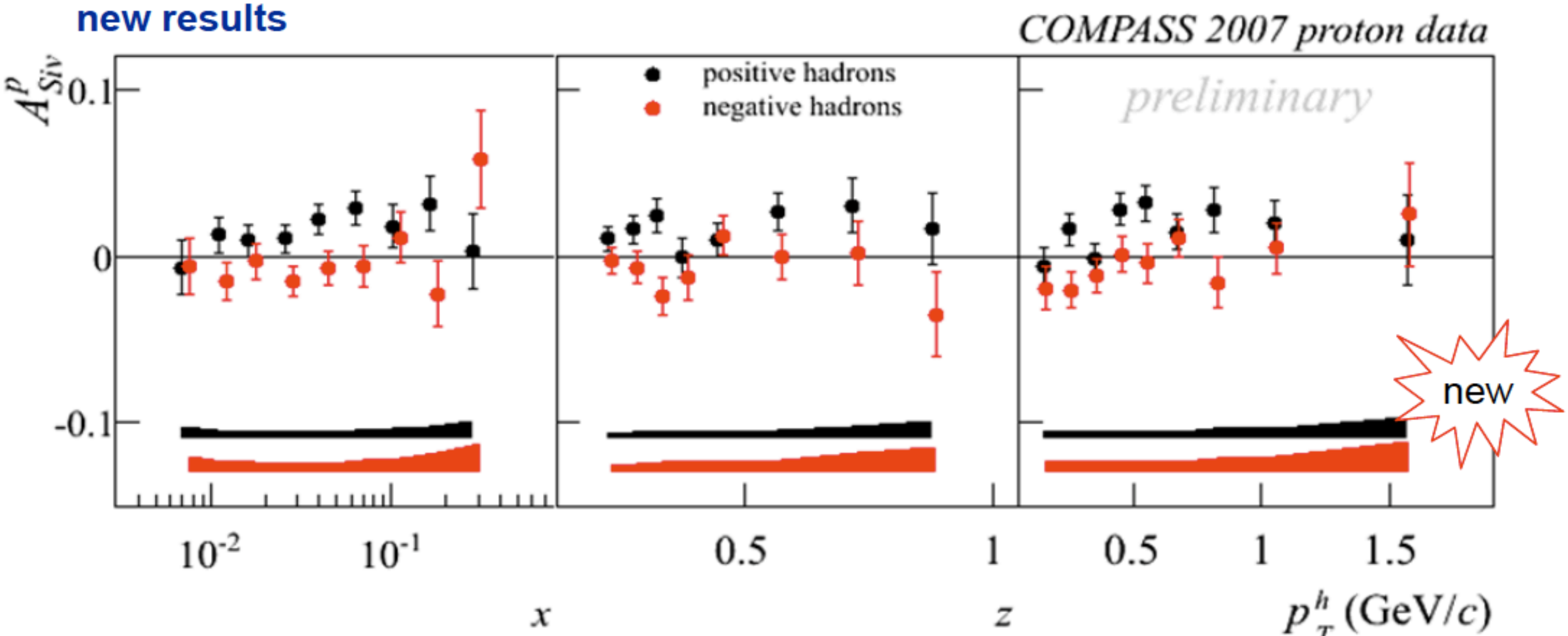
same sign and
~ strength as HERMES

At DIS-2010

Sivers asymmetry – proton data

the analysis of the 2007 data is over

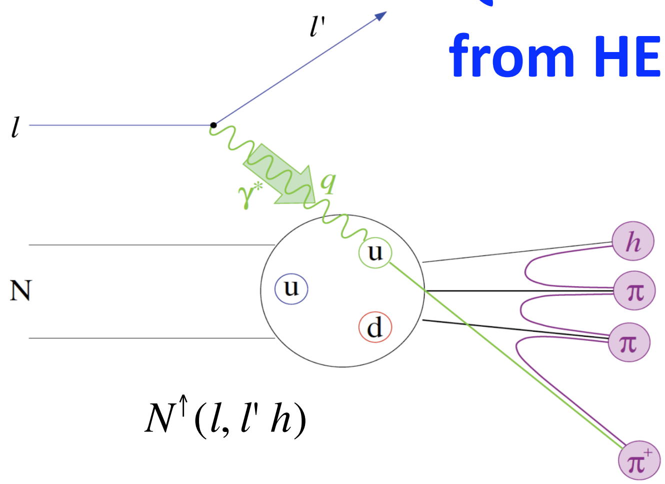
new results



evidence for a positive signal for h^+,
which extends to small x, in the region not measured before

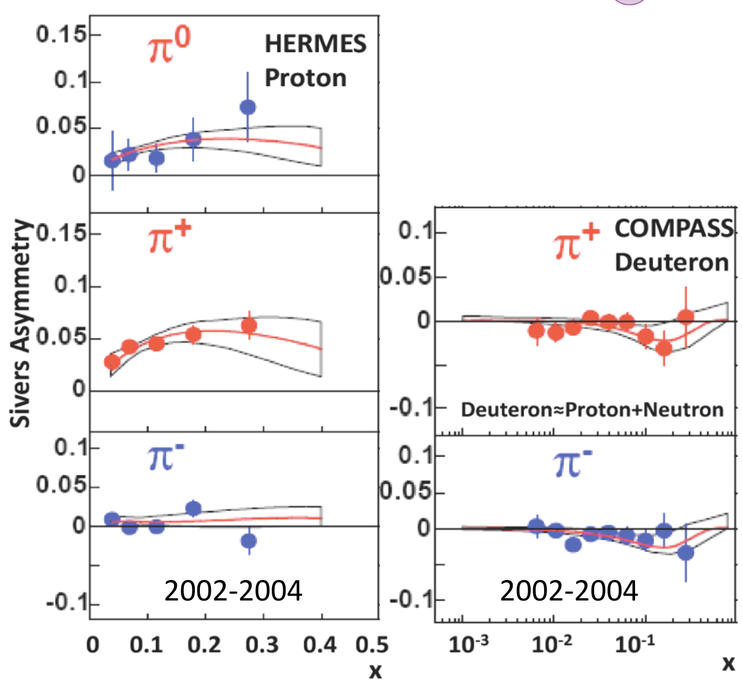
New COMPASS proton run scheduled for 2010-2011.

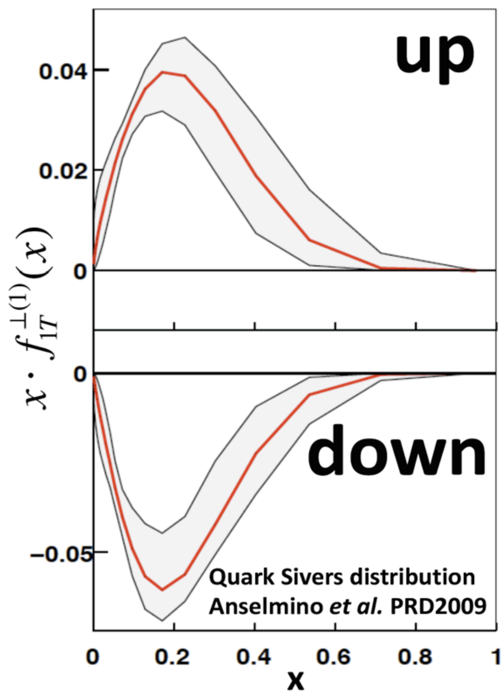
Quark Sivers distributions from HERMES Proton and COMPASS Deutron data



Forbidden before 2002 quark Sivers distribution $f_{1T}^{\perp q}(x,\ k_T)$

- Naive T-odd, not allowed for collinear quarks. Transverse Mom. Dep. parton distributions (TMDs).
- Imaginary piece of interference L_q=0 ✖ L_q=1 quark wave functions.
- Gauge invariance of QCD requires Sivers function to flip sign between semi-inclusive DIS and Drell-Yan.

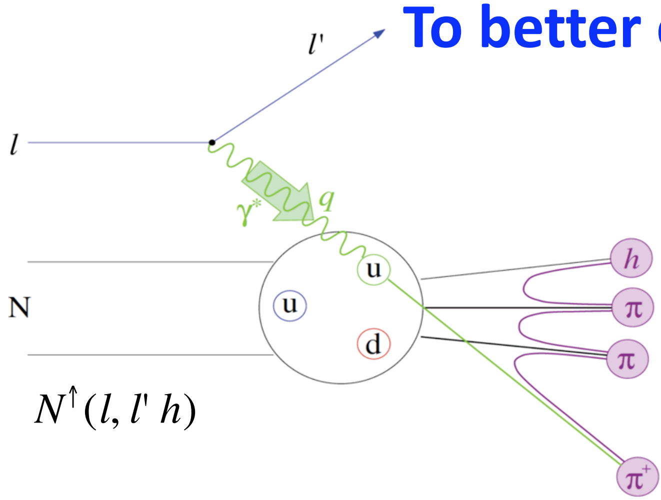




up-quarks favor left (L_u>0),

down-quarks favor right (L_d<0).

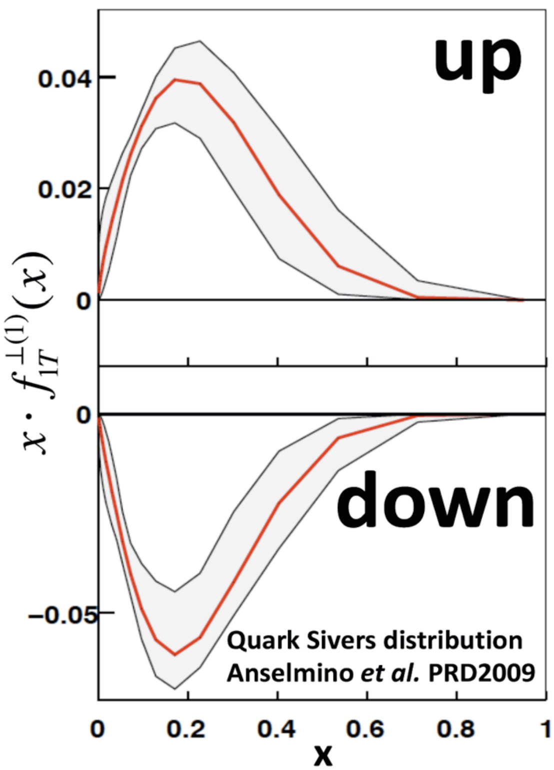
To better constrain quark Sivers distributions …

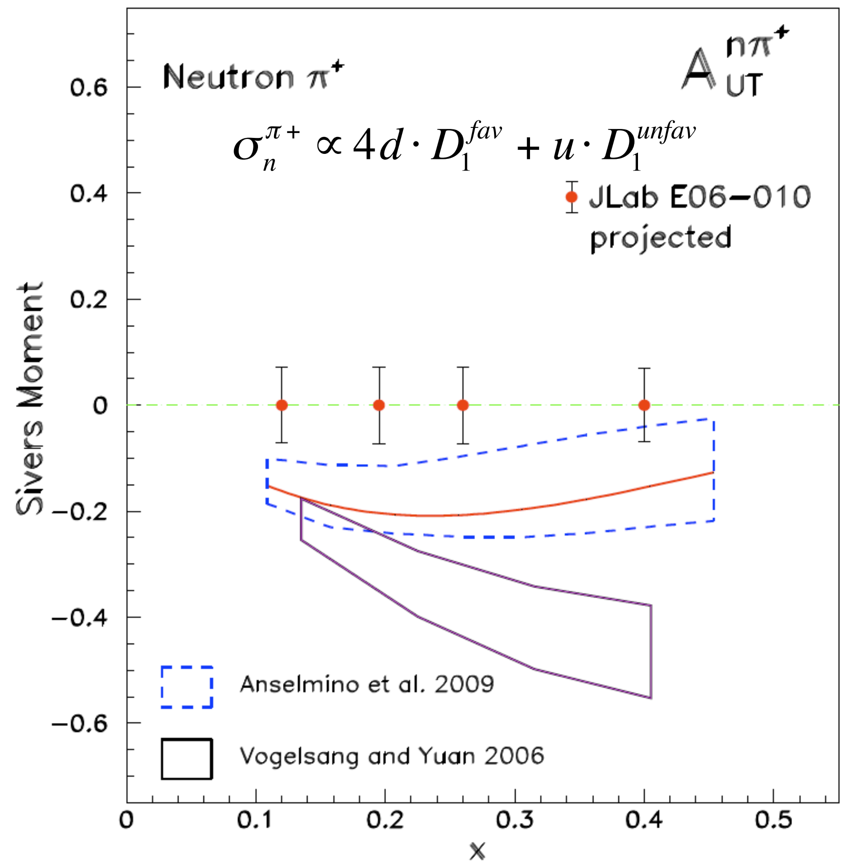


Target single spin asymmetry in semi-inclusive DIS

- Proton: HERMES 2002-2004.
  COMPASS 2006-2007, 2010-2011.
- Deuteron: COMPASS 2002-2004.
- **Neutron (^{3}He): JLab E06-010, Oct. 2008-Feb.2009.**

Existing data do not constrain d-quark Sivers well





Semi-Inclusive DIS 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

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

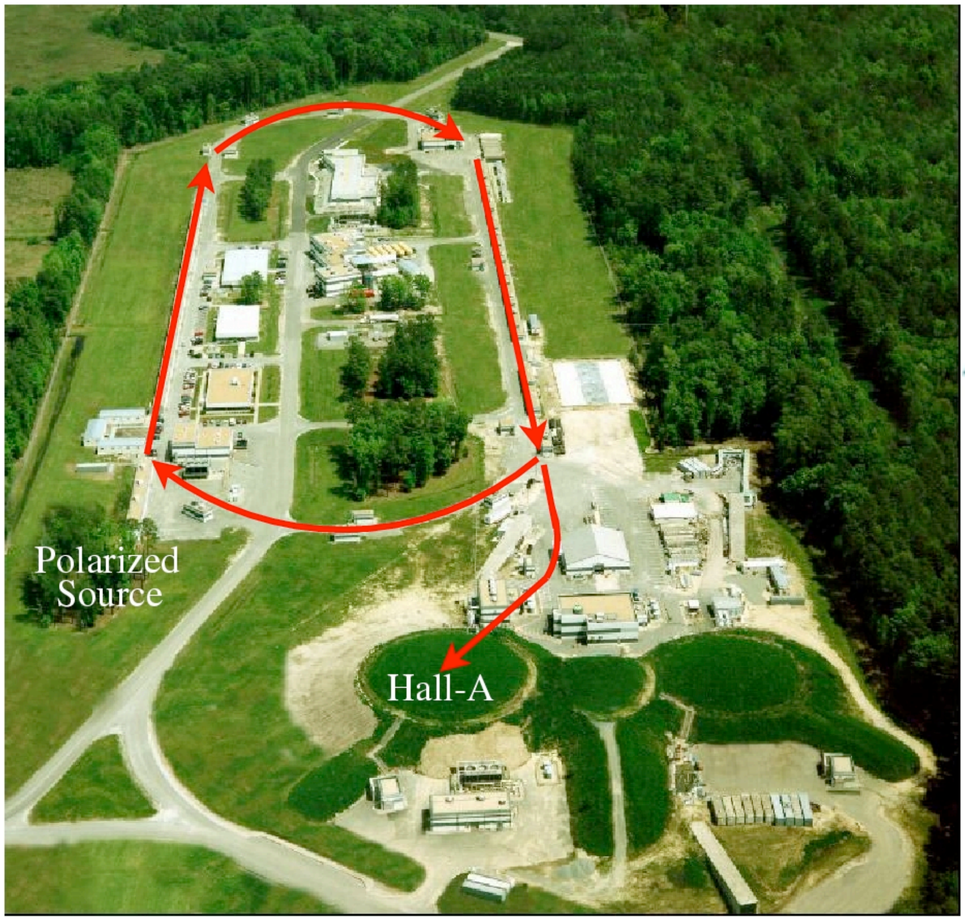
$$D^{fav} = D_u^{\pi^+} = D_d^{\pi^-} \qquad D^{unfav} = D_u^{\pi^-} = D_d^{\pi^+}$$

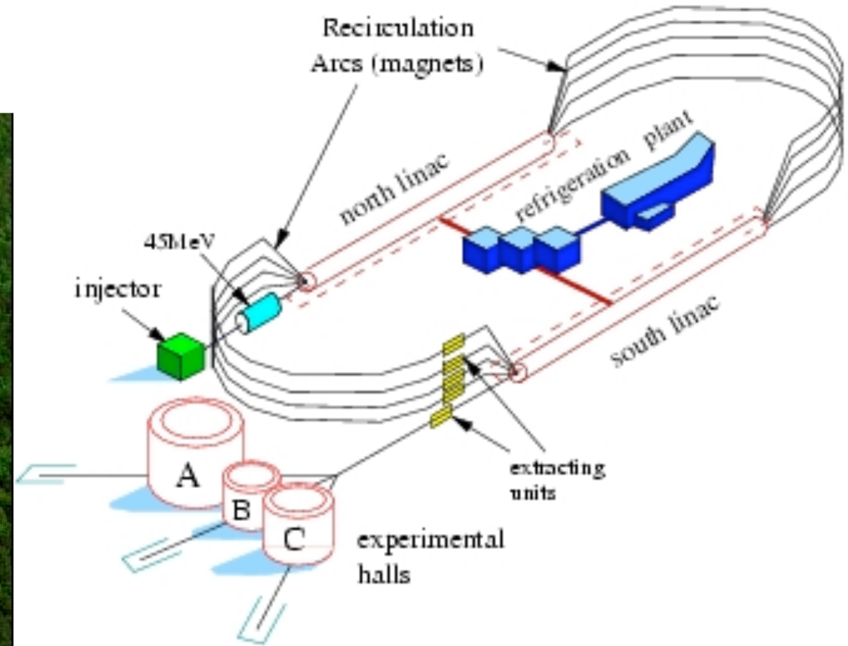
$$\sigma_n^{\pi^+} \propto 4d \cdot D^{fav} + u \cdot D^{unfav} \qquad \sigma_n^{\pi^-} \propto 4d \cdot D^{unfav} + u \cdot D^{fav}$$

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

Thomas Jefferson National Accelerator Facility

Newport News, Virginia.





- 6 GeV polarized electron beam now, will upgrade to 12 GeV in 2013.
- Continuous beam to three experiment halls.

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.

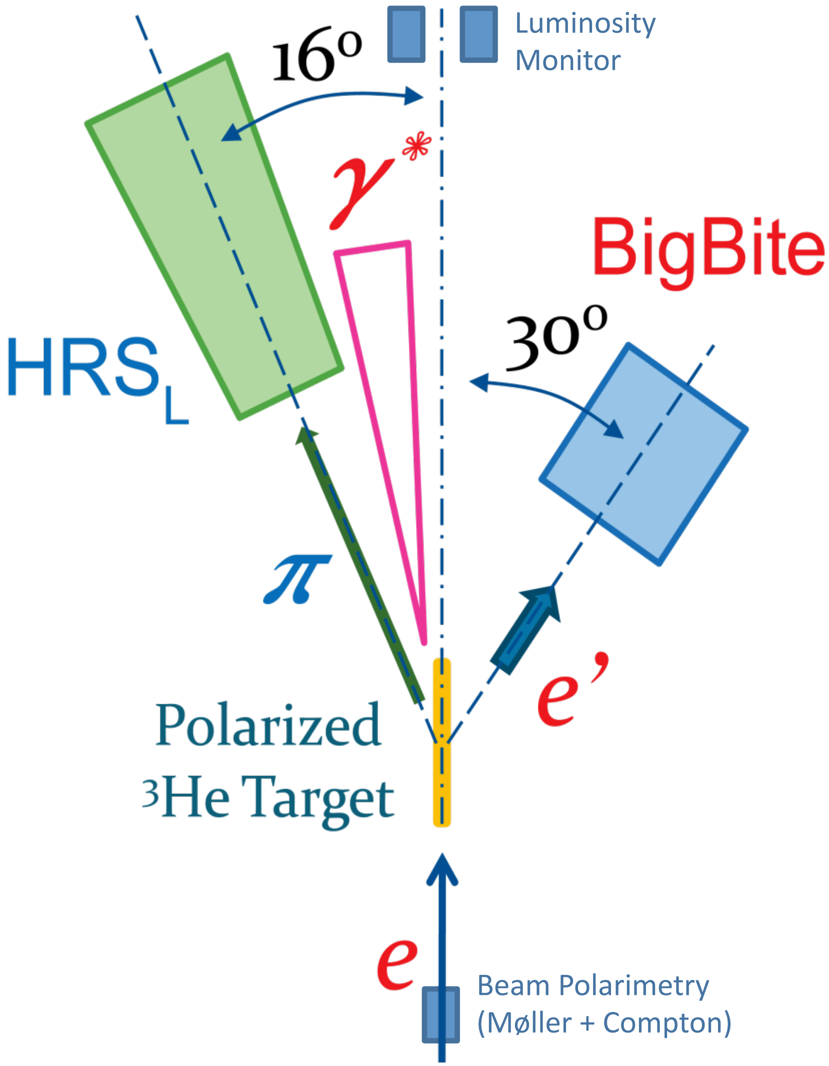
Collaboration members

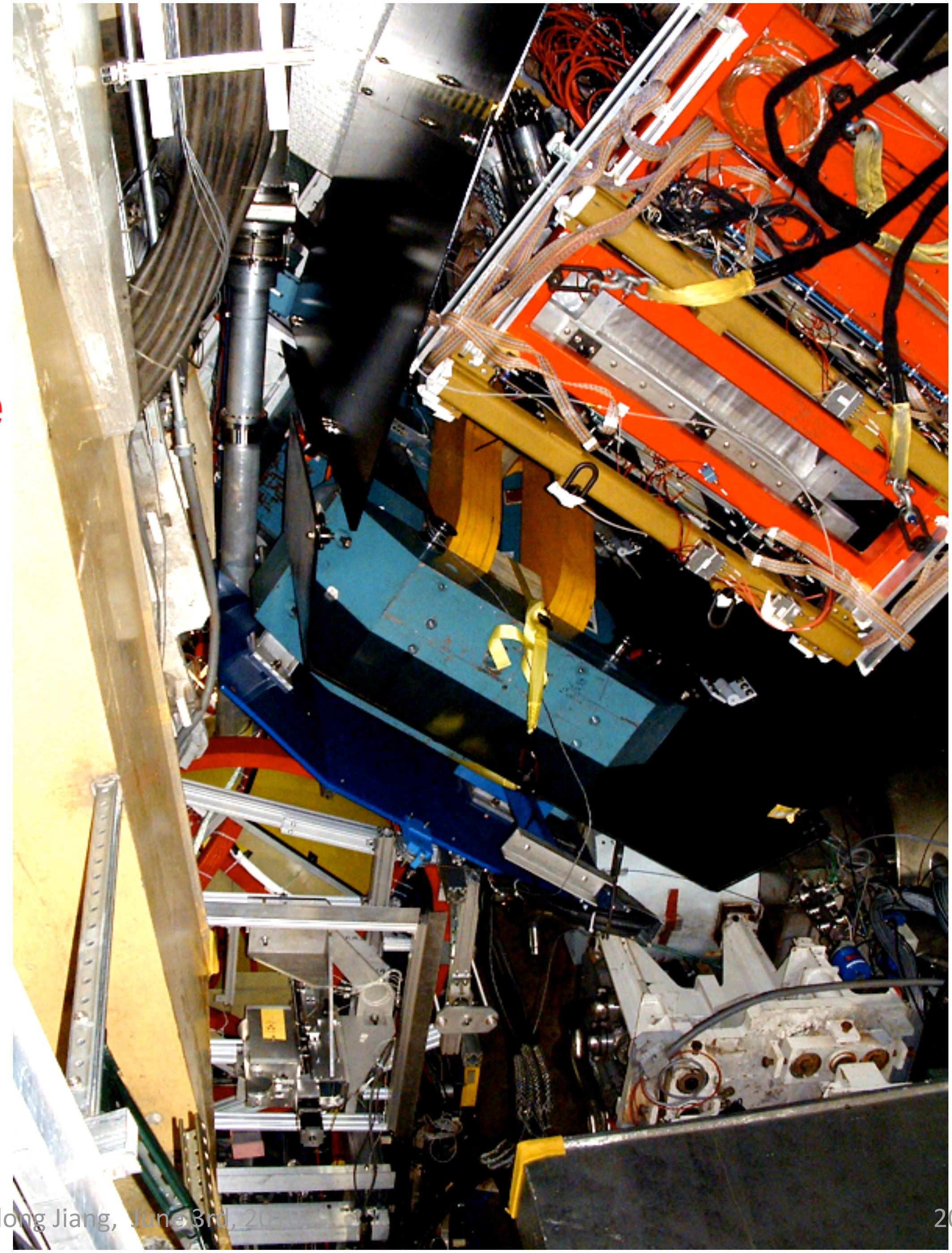
K. Allada, K. Aniol, J.R.M. Annand, T. Averett, F. Benmokhtar, W. Bertozzi, P.C. Bradshaw, P. Bosted, A. Camsonne, M. Canan, G.D. Cates, C. Chen, , **J.-P. Chen** (Co-SP), W. Chen, K. Chirapatpimol, E. Chudakov, , **E. Cisbani**(Co-SP), J. C. Cornejo, F. Cusanno, M. Dalton, W. Deconinck, C. de Jager, R. De Leo, X. Deng, A. Deur, H. Ding, **C. Dutta**, C. Dutta, D. Dutta, L. El Fassi, S. Frullani, **H. Gao**(Co-SP), F. Garibaldi, D. Gaskell, S. Gilad, R. Gilman, O. Glamazdin, S. Golge, L. Guo, D. Hamilton, O. Hansen, D.W. Higinbotham, T. Holmstrom, **J. Huang**, M. Huang, H. Ibrahim, M. Iodice, **X. Jiang** (Co-SP), G. Jin, M. Jones, J. Katich, A. Kelleher, A. Kolarkar, W. Korsch, J.J. LeRose, X. Li, Y. Li, R. Lindgren, N. Liyanage, E. Long, H.-J. Lu, D.J. Margaziotis, P. Markowitz, S. Marrone, D. McNulty, Z.-E. Meziani, R. Michaels, B. Moffit, C. Munoz Camacho, S. Nanda, A. Narayan, V. Nelyubin, B. Norum, Y. Oh, M. Osipenko, D. Parno, , **J. C. Peng**(Co-SP), S. K. Phillips, M. Posik, A. Puckett, **X. Qian**, Y. Qiang, A. Rakhman, R. Ransome, S. Riordan, A. Saha, B. Sawatzky,E. Schulte, A. Shahinyan, M. Shabestari, S. Sirca, S. Stepanyan, R. Subedi, V. Sulkosky, L.-G. Tang, A. Tobias, G.M. Urciuoli, I. Vilardi, K. Wang, **Y. Wang**, B. Wojtsekhowski, X. Yan, H. Yao, Y. Ye, Z. Ye, L. Yuan, X. Zhan, **Y. Zhang**, Y.-W. Zhang, B. Zhao, X. Zheng, L. Zhu, X. Zhu, X. Zong.

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

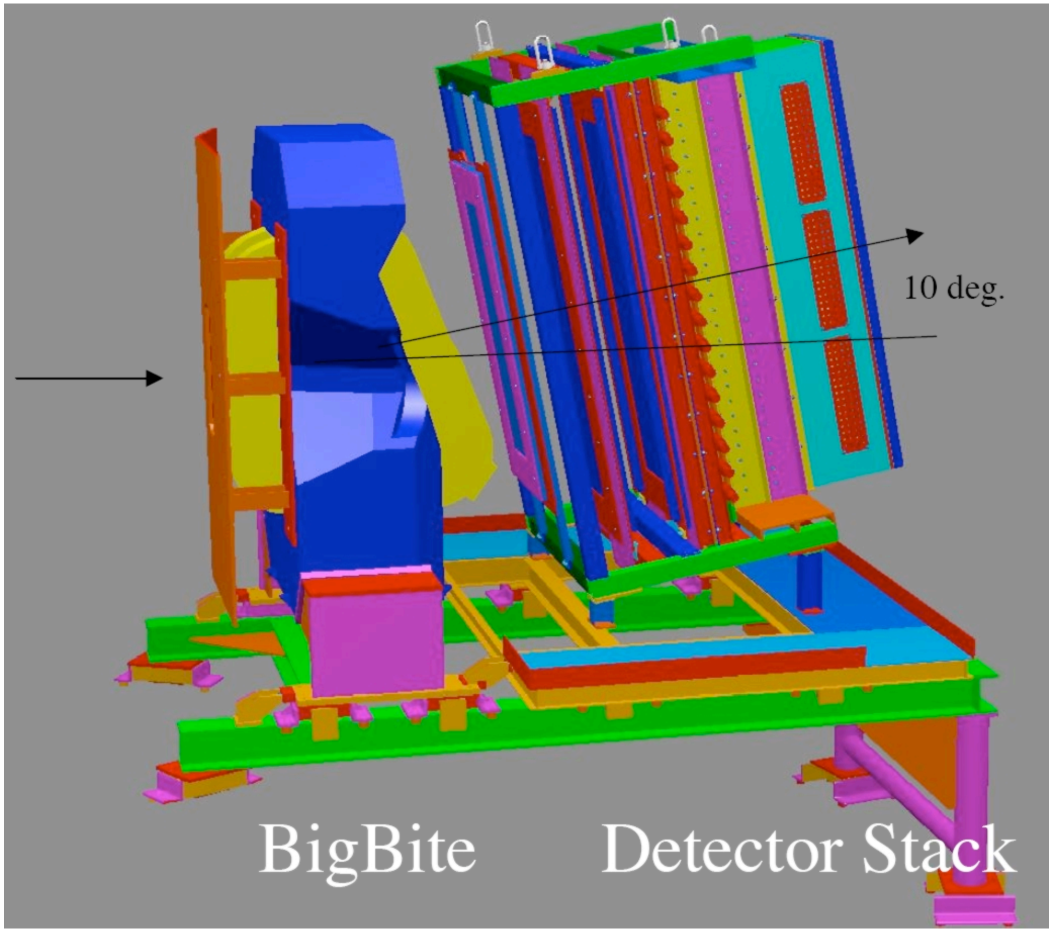
$$^{3}\mathrm{He}^{\uparrow}(e,e'h)$$

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

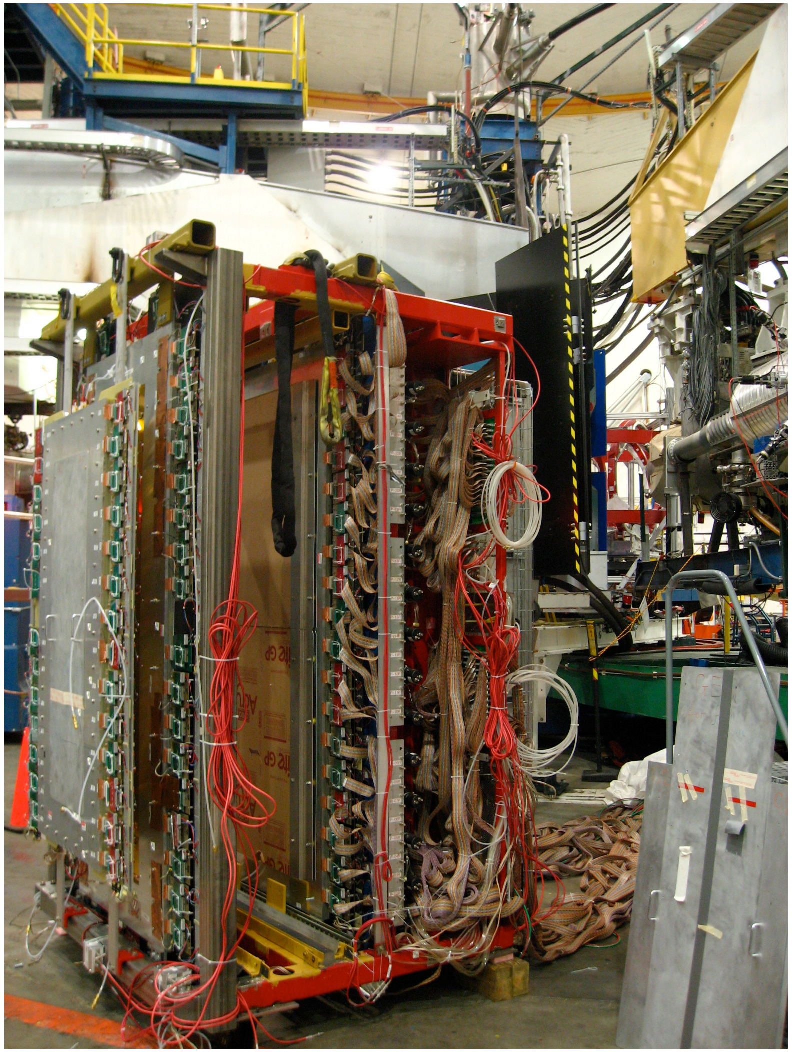




BigBite Spectrometer as the electron-Arm of the Coincidence



Measure a particle's trajectory for momentum reconstruction.

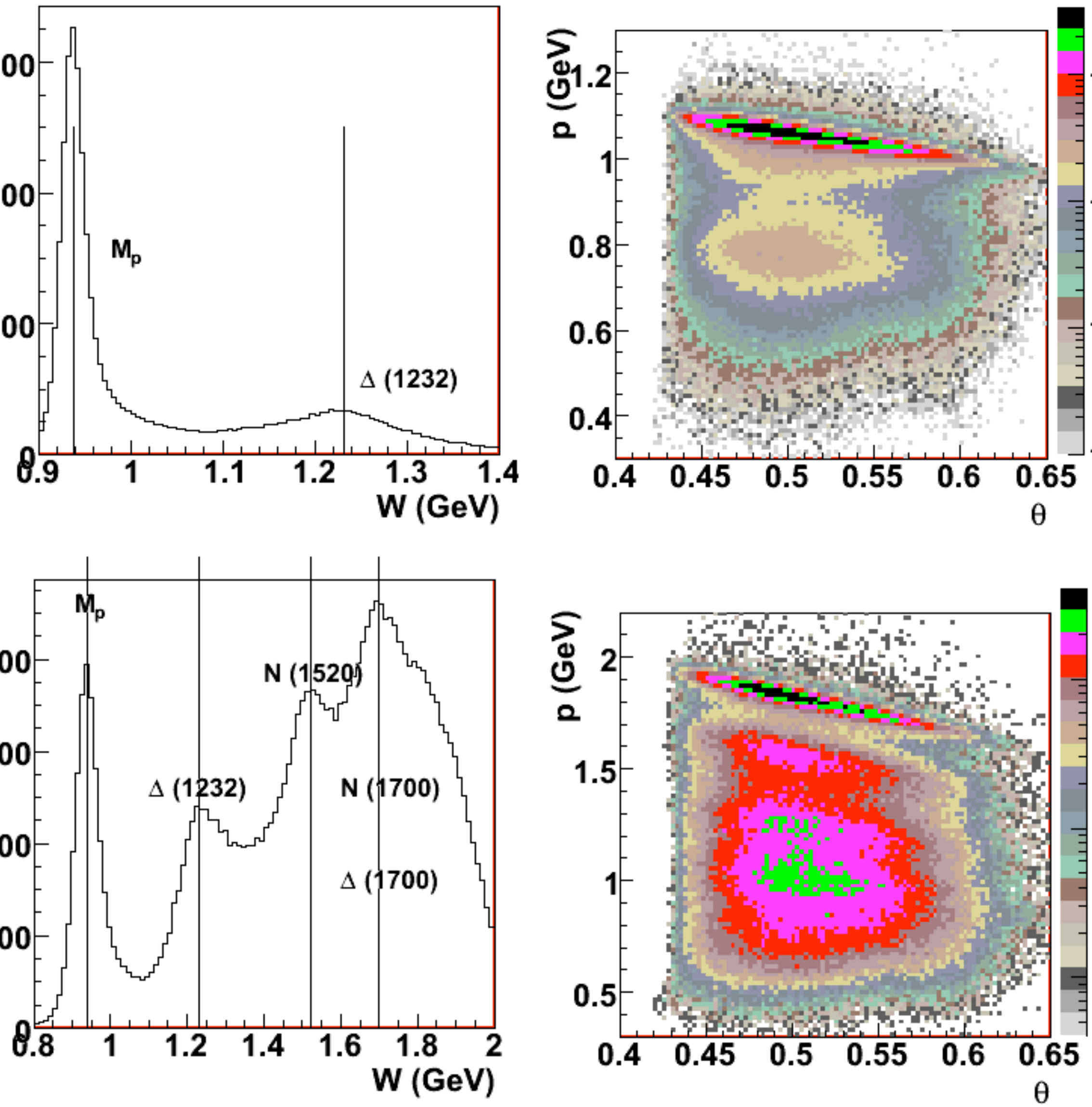


A 1.2 Tesla dipole magnet, 3 drift chambers,
a threshold gas Cherenkov detector,
a pre-shower+scintillator+shower package.

BigBite Optics Calibration, momentum

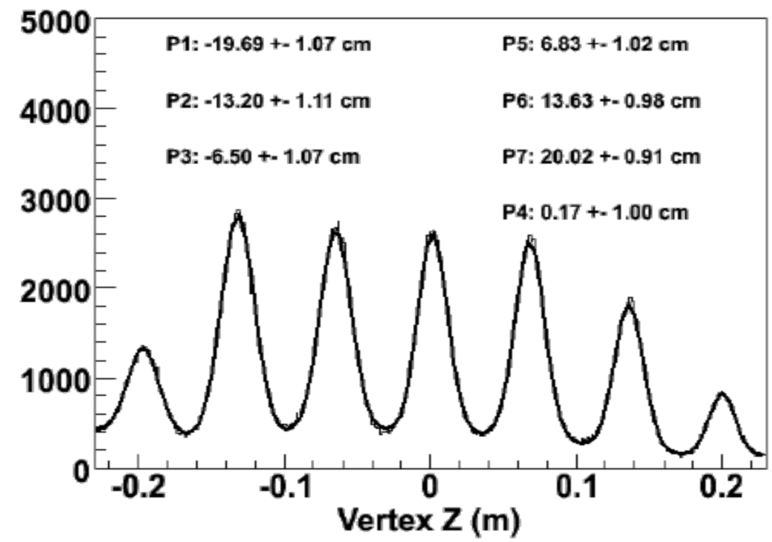
1st pass beam, E':1-1.2 GeV
p<1 GeV, calibrated with Δ
2nd pass beam, E': 1.7-1.9 GeV
1.7>p>1.2 Checked with
resonance states

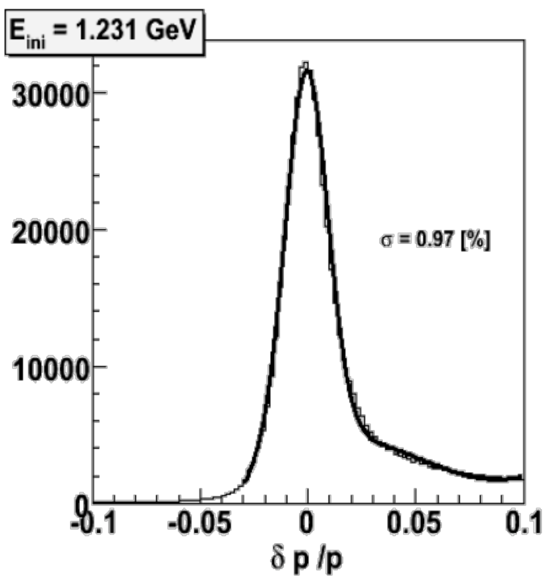
Elastic H, Elastic He3

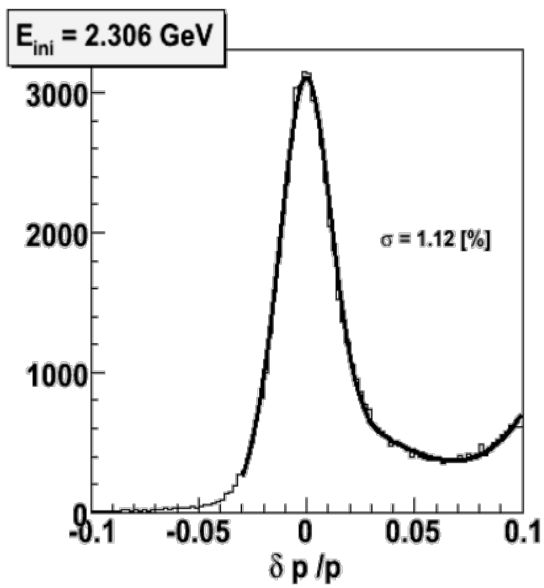


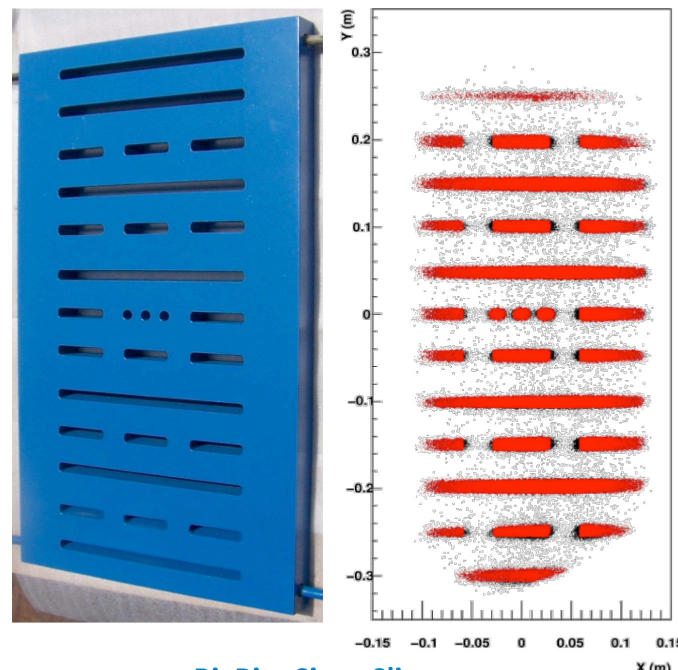
BigBite Optics Calibration

- Optics for both negative and positive charged particles have been done
- Wire Chamber Spatial Resolution: 180 μm
- Vertex Resolution: 1 cm
- Angular Resolution: ~ 10 mrad
- Momentum Resolution: 1%

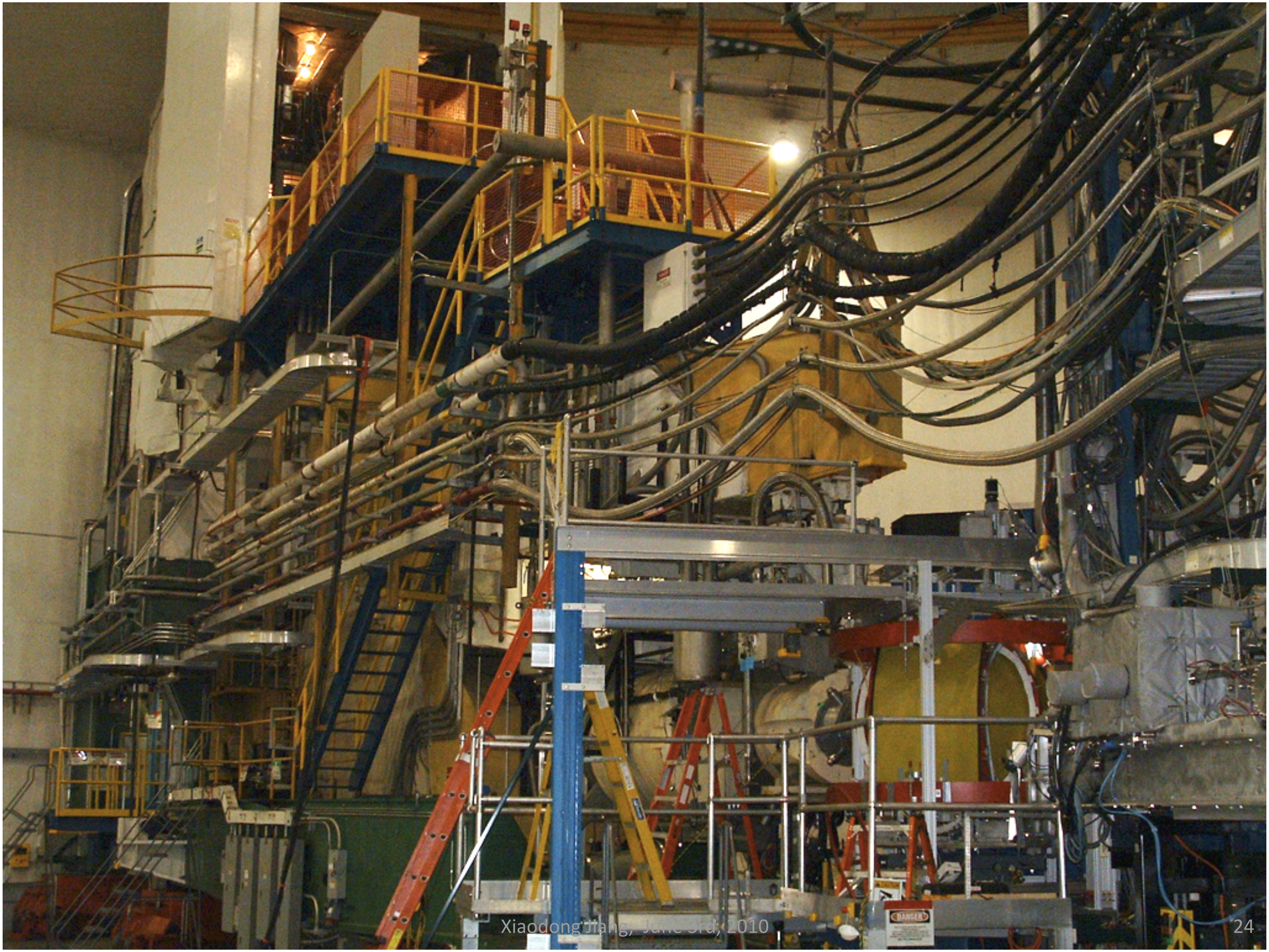








BigBite Sieve Slit

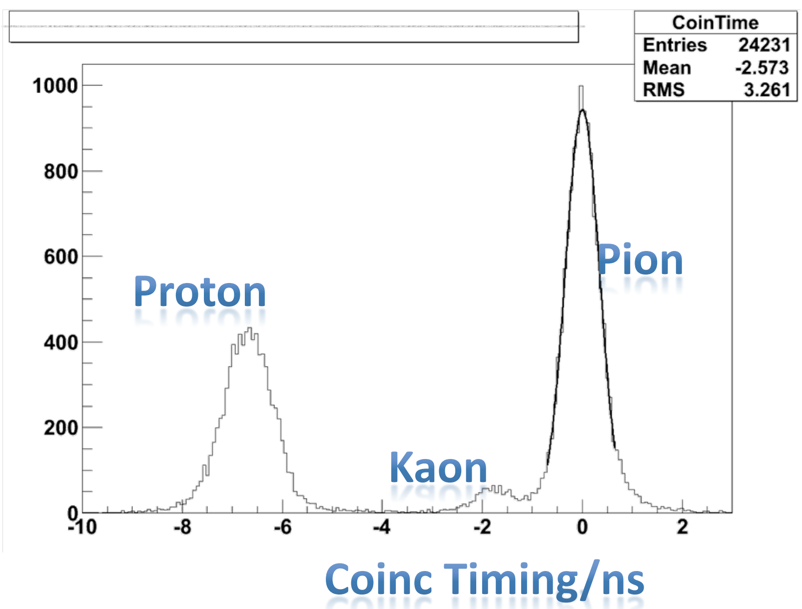


In addition to the HRS_L standard PID detectors …

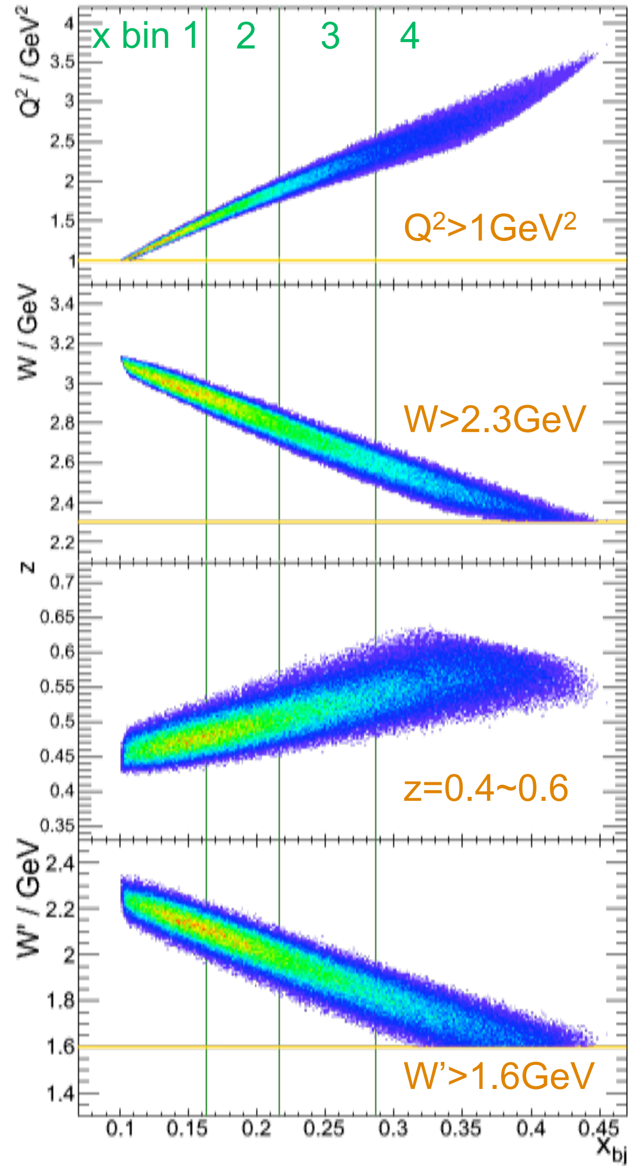
Coincidence time-of-flight as redundant particle identification

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

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

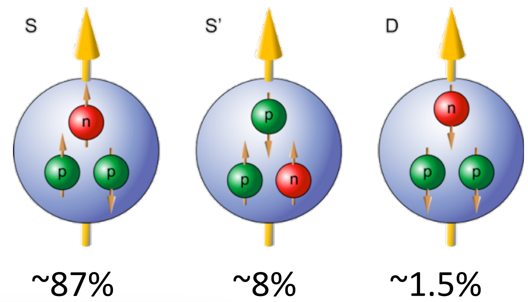


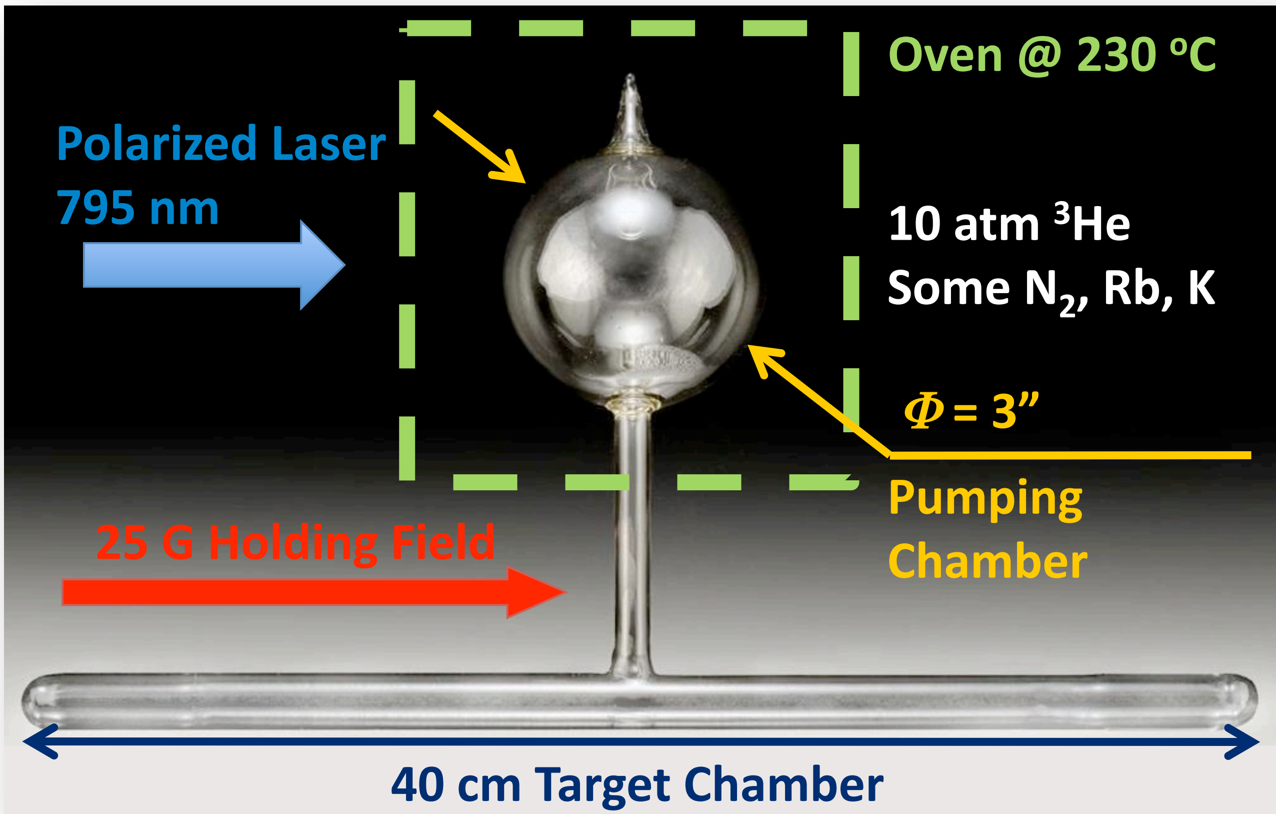
Kinematics Coverage



$\langle Q^2\rangle$=2.0 GeV^2 $\langle W\rangle$=2.8 GeV.
(HERMES: $\langle Q^2\rangle$=2.4 GeV^2).

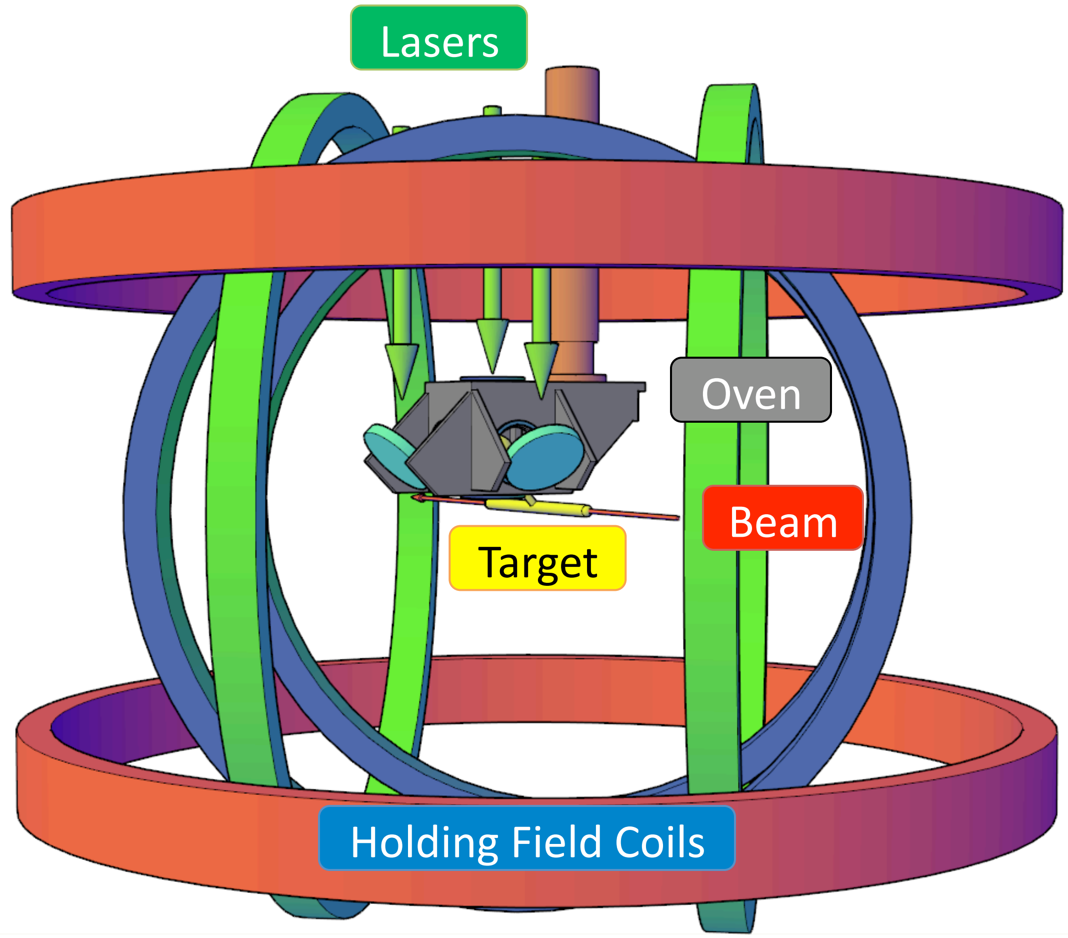
Polarized ^{3}He Gas Target





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

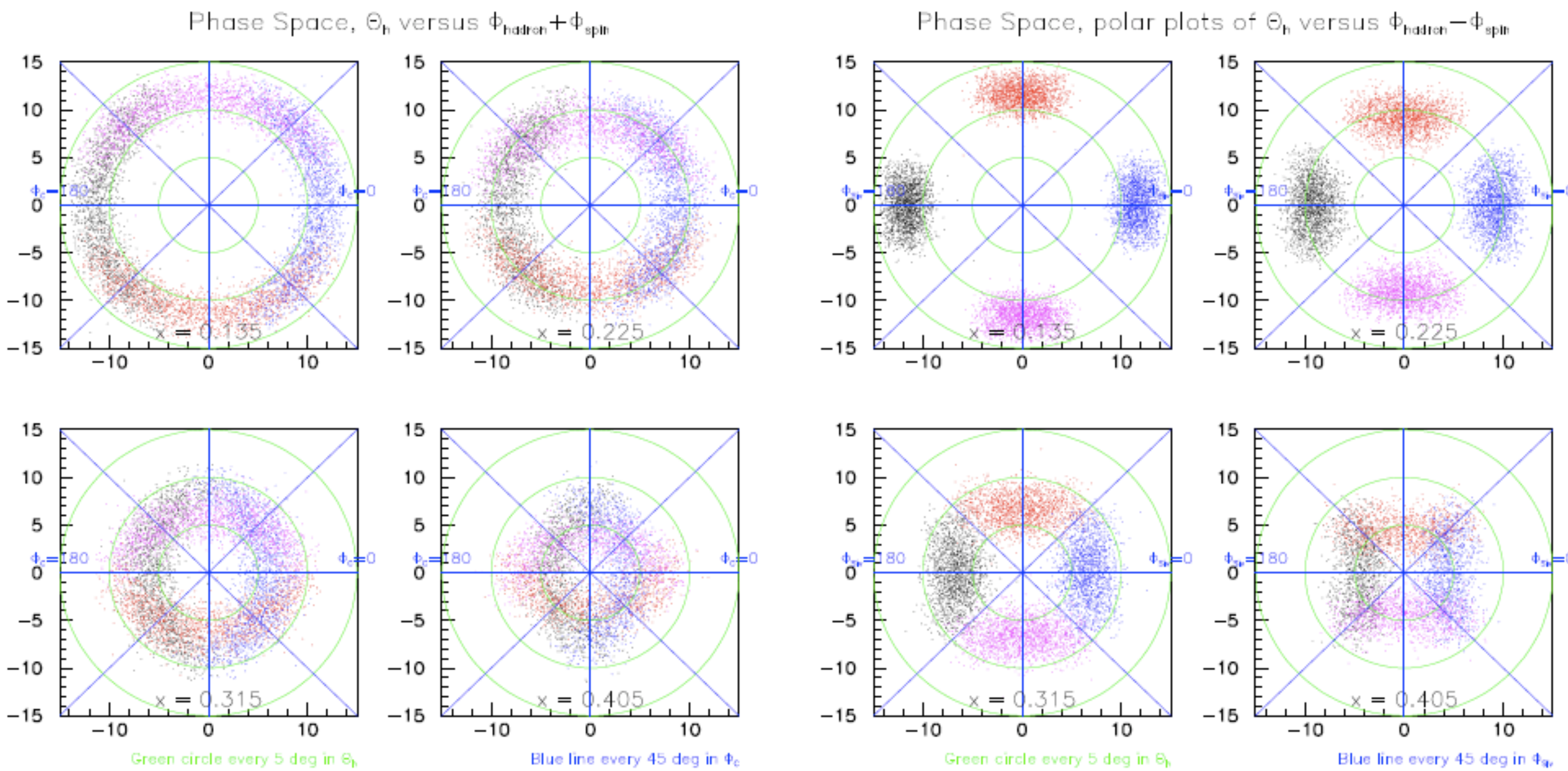
Target System



- 3D Holding Field.
- Automatic spin flip every **20** minutes using Adiabatic Fast Passage (AFP).
- Average polarization 60%.

For E06-010, four target spin configurations:
vertical up-down
Transverse left-right

$$\phi_{Collins} = \phi_h + \phi_S \textbf{ and } \phi_{Sivers} = \phi_h - \phi_S$$



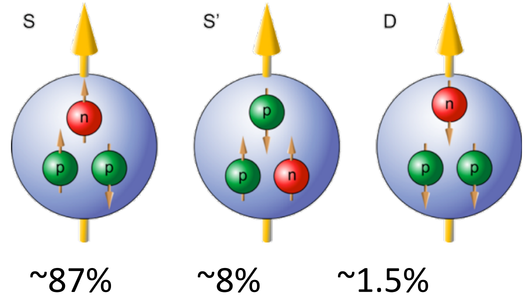
E06-010 Data Analysis

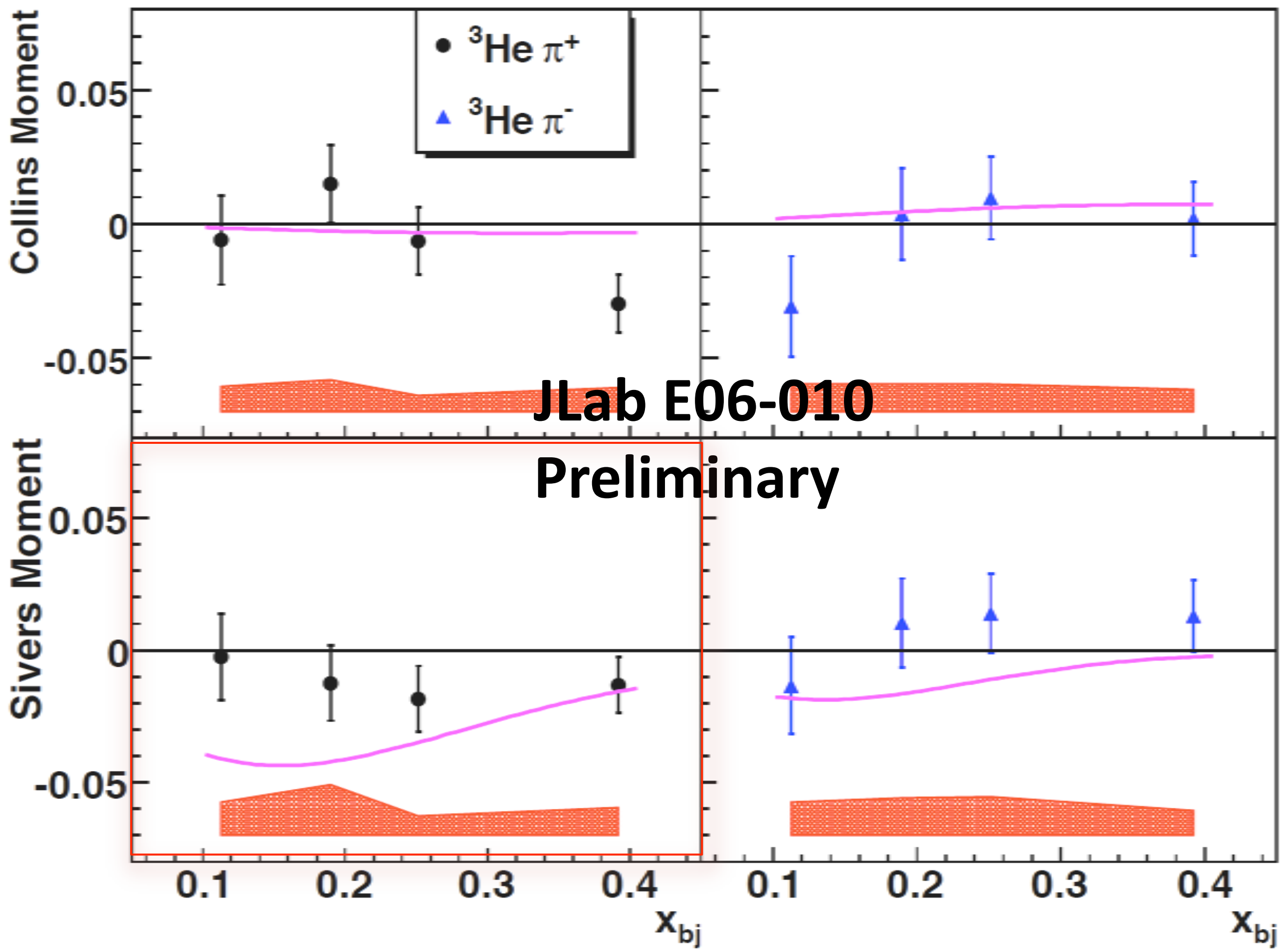
- **Two analysis teams cross check results**
  - **Red Team**: Maximum Likelihood Method
  - **Blue Team**: Local Pair-Angular Bin-Fit Method
  - Asymmetry results are consistent
- Radiative corrections and estimation of systematic uncertainties are in progress

^{3}He Target Single-Spin Asymmetry in SIDIS: JLab E06-010

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

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





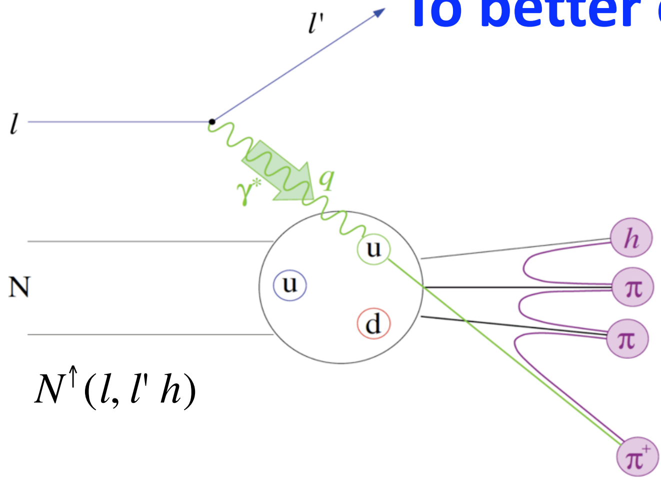
To extract information on neutron, one would assume:

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

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

^{3}He Sivers SSA are smaller than expected (Vogelsong and Yuan 2006), follow the trend of Anselmino et al. 2009.

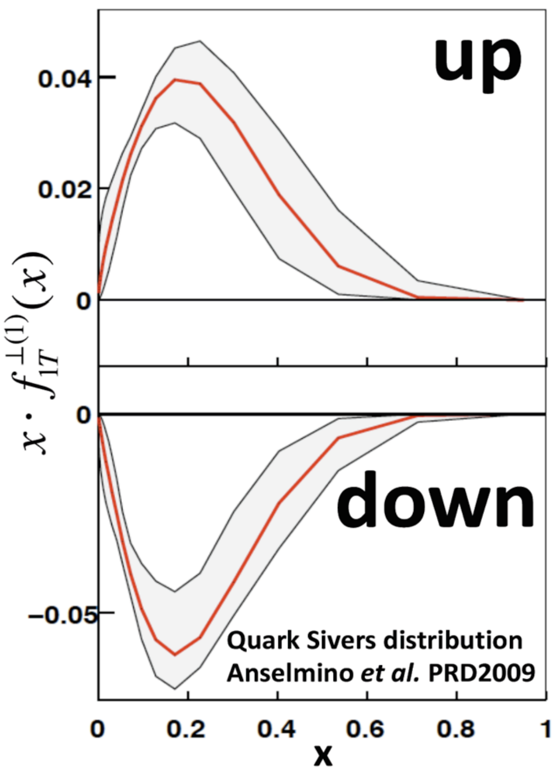
To better constrain quark Sivers distributions …

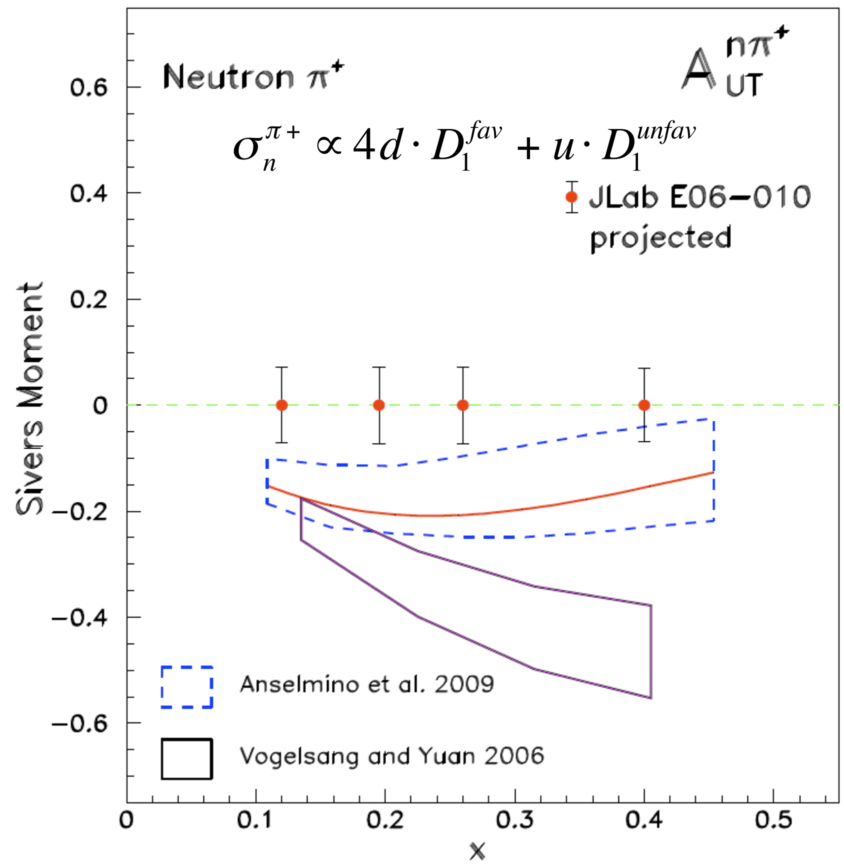


Target single spin asymmetry in semi-inclusive DIS

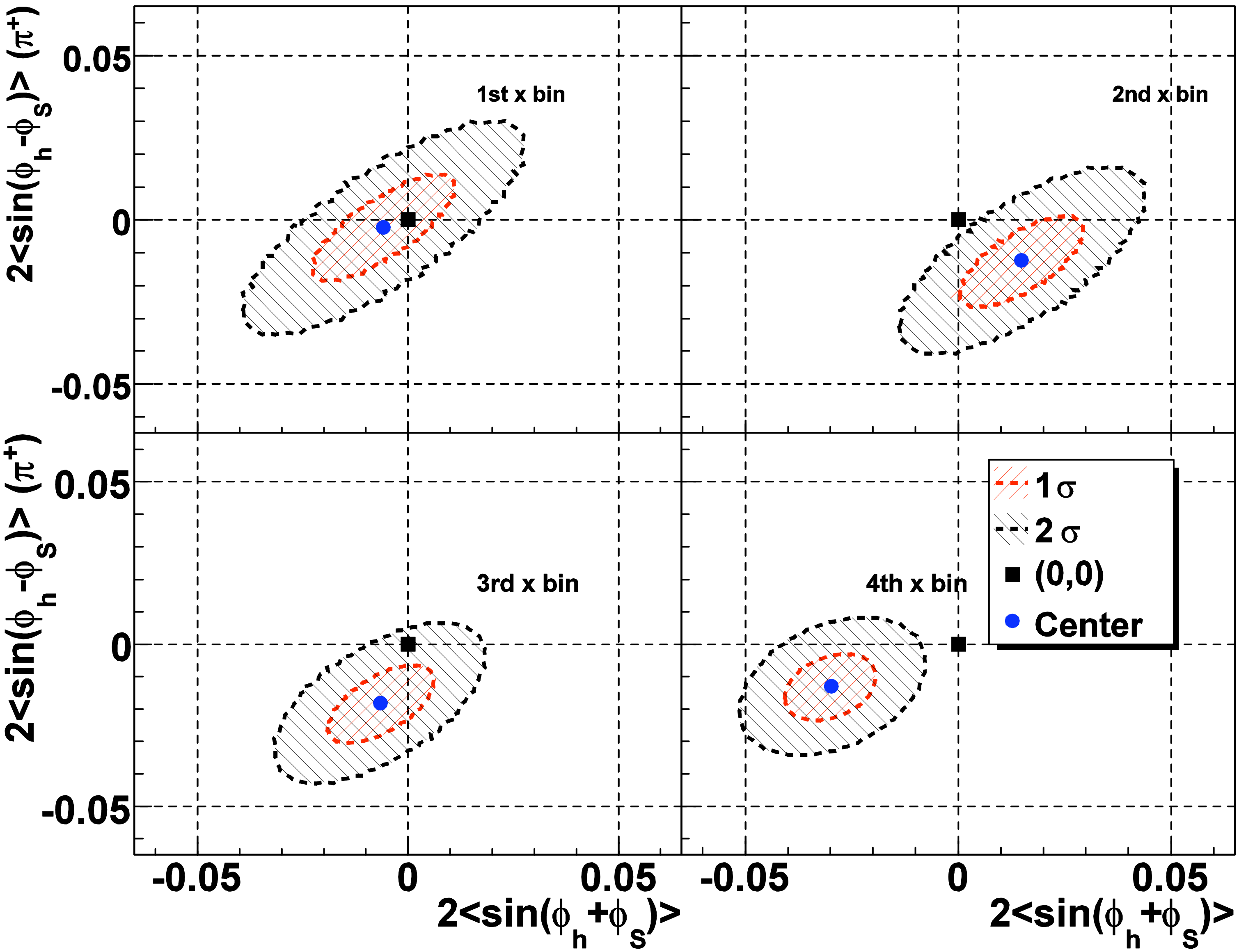
- Proton: HERMES 2002-2004.
  COMPASS 2006-2007, 2010-2011.
- Deuteron: COMPASS 2002-2004.
- **Neutron (^{3}He): JLab E06-010, Oct. 2008-Feb.2009.**

Existing data do not constrain d-quark Sivers well

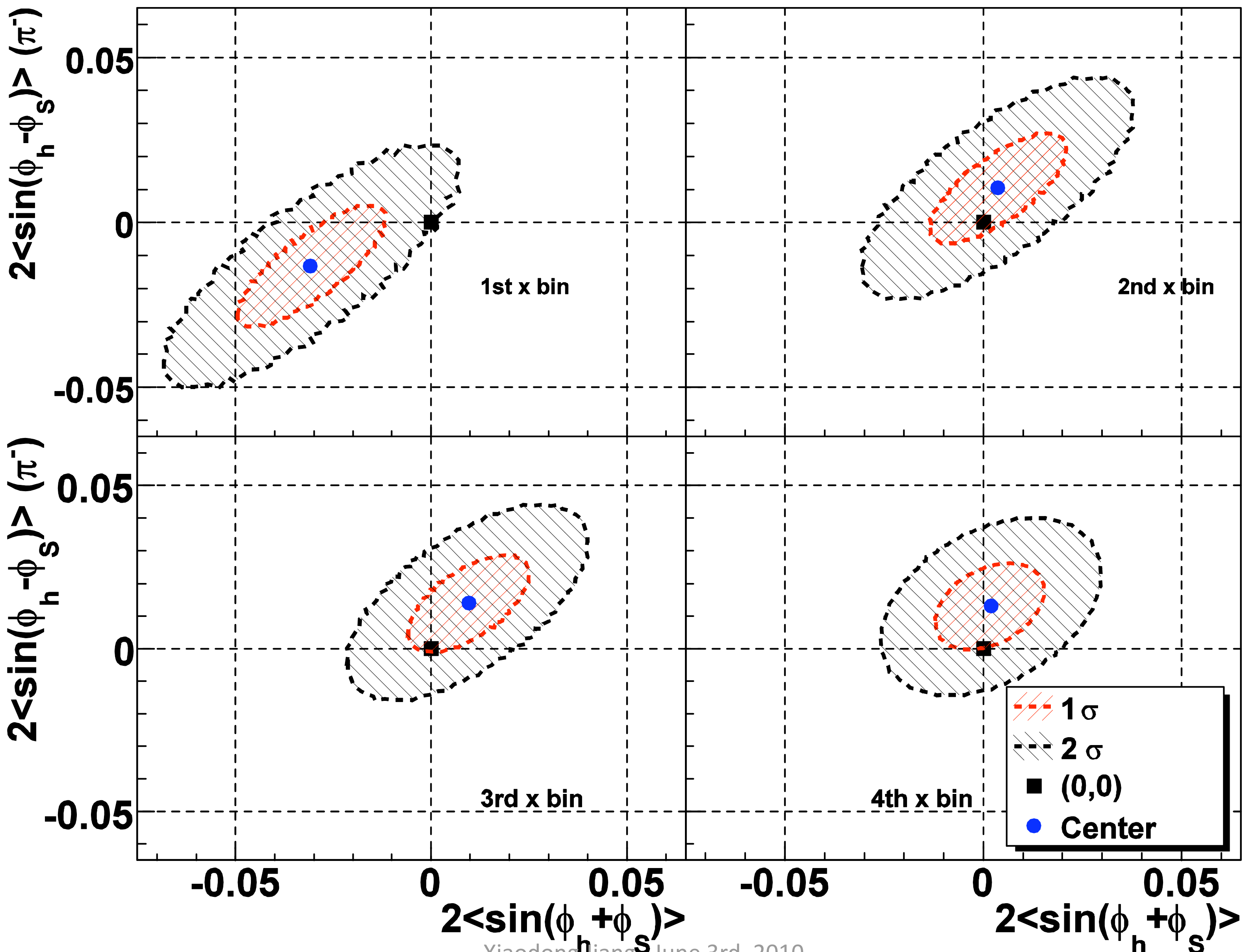




Statistical uncertainties are correlated between Collins and Sivers asymmetries on ^{3}He (π^{+})

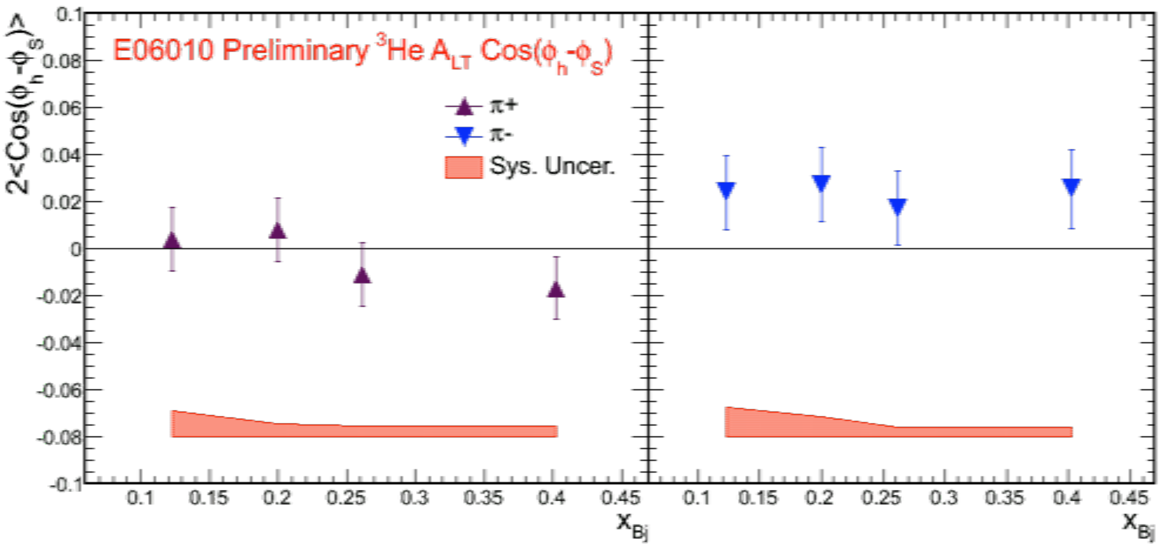


^3He (π^-)



2<sin(φh-φS)> (π-)
0.05
0
-0.05
1st x bin
2nd x bin
3rd x bin
4th x bin
1 σ
2 σ
(0,0)
Center
-0.05
0
0.05
2<sin(φh+φS)>

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



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

- First observation of a none-zero A_{LT}.
- First measurement on neutron(^{3}He).
- Relate to quark TMD $g_{1T}(x, k_T)$.
- The real part of quark L=0✖L=1 interference, "twin-brother" of Sivers.

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

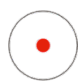
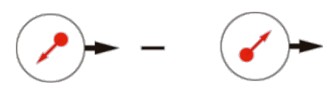
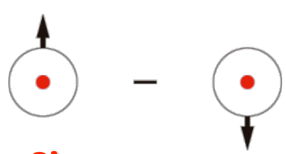
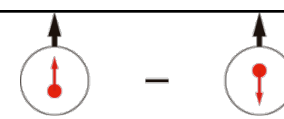
$$\sigma_n^{\pi+} \propto 4d \cdot D_1^{fav} + u \cdot D_1^{unfav} \qquad \sigma_n^{\pi-} \propto 4d \cdot D_1^{unfav} + u \cdot D_1^{fav}$$

down-quark's $g_{1T}(x)$ is rather small.
up-quark's $g_{1T}(x)$ is not small.

A_{LT} on proton should be noticeable (?)

Leading Twist Transverse Momentum Dependent Parton Distributions (TMDs)

→ Nucleon Spin
→ Quark Spin

		Quark polarization		
		Un-Polarized	Longitudinally Polarized	Transversely Polarized
Nucleon Polarization	U	$f_1 =$ 		$h_1^{\perp} =$  **Boer-Mulder**
	L		$g_1 =$  **Helicity**	$h_{1L}^{\perp} =$ 
	T	$f_{1T}^{\perp} =$  **Sivers**	$g_{1T}^{\perp} =$ 	$h_{1T} =$  **Transversity** $h_{1T}^{\perp} =$  **Pretzelosity**

SSA on pol. ^{3}He in the 11 GeV era in Hall A

Measure Transversity / Sivers / Pretzelosity and more

- **SIDIS on π and K** (conditionally approved, 01/2009)
  - G. Cates, E. Cisbani, G.B. Franklin, B. Wojtsekhowski
  - Similar layout of the 6GeV experiment at higher luminosity and acceptance
    - HRS replaced by a new large acceptance spectrometer (SBS), improved target
  - 2D binning on the relevant variables: x, $P_\perp$ and z, for both hadrons and Q^2 dependence
  - High x valence region (with overlap to HERMES, COMPASS, JLab6 data)

- **SoLID-Transversity experiment** (approved, 01/2010)
  - J.-P. Chen, H. Gao, X. Jiang, J.-C. Peng, and X. Qian
  - "2π"-angular coverage
    - Use a large acceptance solenoid magnet
  - Precision measurement in 4D phase space (x, z, $P_\perp$ and Q^2)
  - Better systematic control due to the 2π geometry
  - Extended phase space coverage

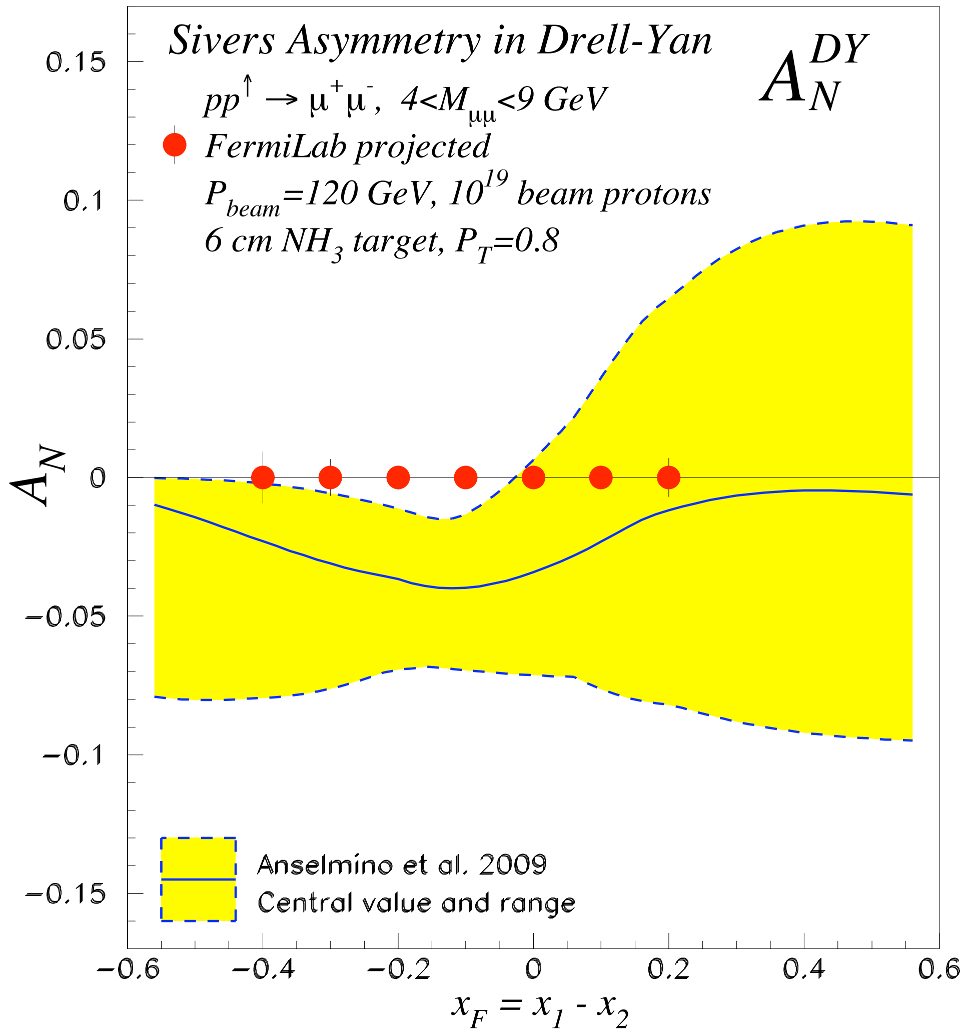
Transverse Spin Experiments

- JLab-6 GeV transverse spin experiments
  - "Neutron Transversity" (E06-010) completed.
  - Both Collins and Sivers single-spin asymmetries on ^{3}He are not large.
  - First observation of non-zero A_{LT} (^{3}He), $g_{1T}(x)$ is none-zero.
- JLab-12 GeV
  - Two pol. ^{3}He experiments approved in Hall A.
  - Letter-of-Intend for for polarized proton in Hall B.
    HD target test scheduled for 2011.

New COMPASS proton target run 2010-2011.

Should COMPASS confirm the proton Sivers results (of HERMES), the next step will be a polarized Drell-Yan experiment to verify "the sign flip" of the Sivers distribution.

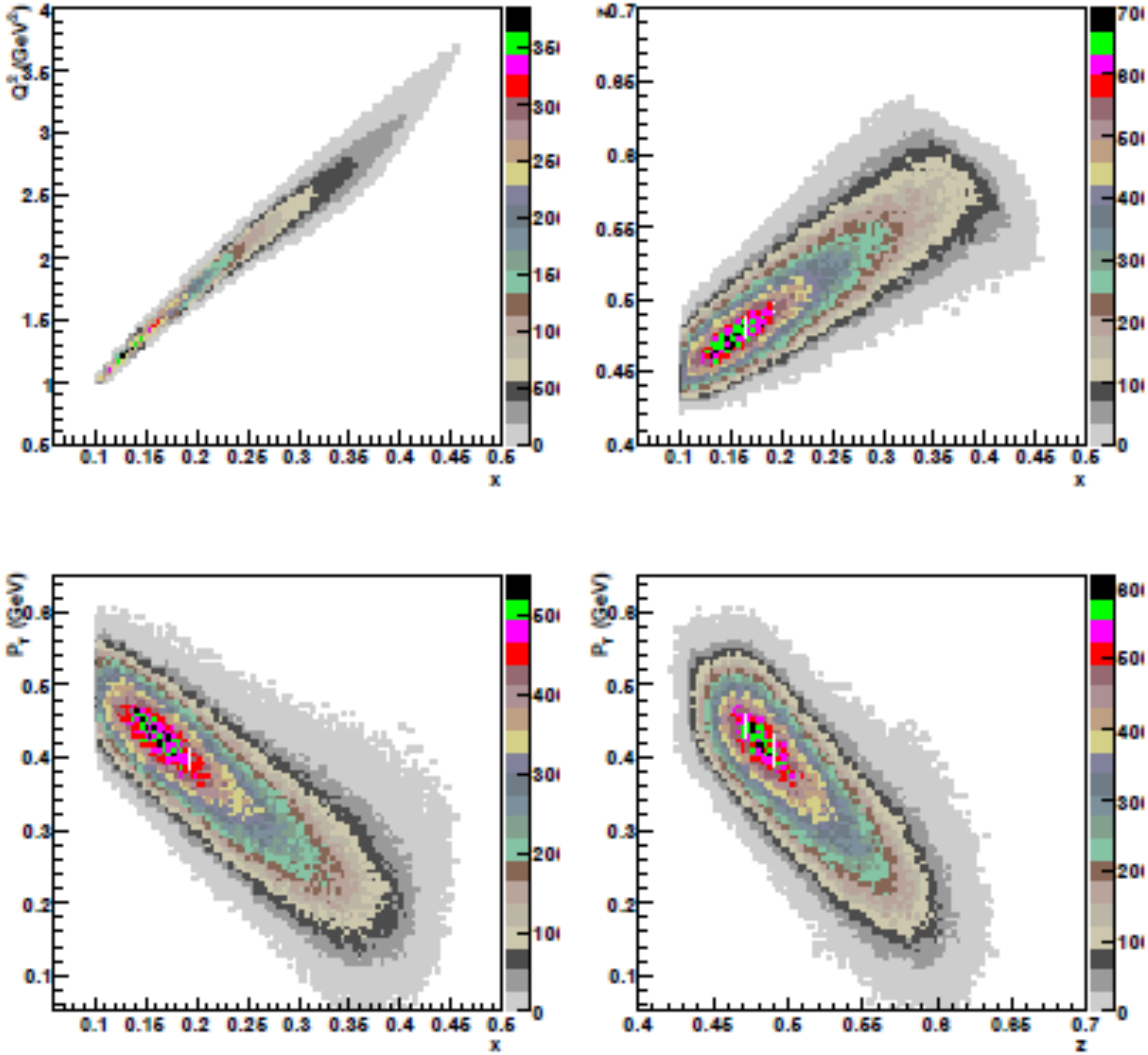
NSAC Milestone 2010-2015: HP13 "Test unique QCD predictions for relations between single-spin phenomena in p-p scattering and those observed in deep-inelastic scattering".



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

- A new 6 cm long vertically polarized NH_3 target. P_T=0.80.
- Frequent target spin flip to reduce systematic uncertainties.

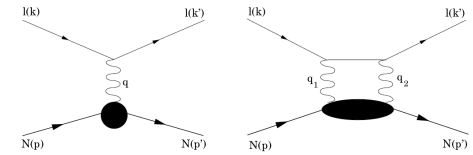
Backup Slides for MENU_2010



x
x
P_T (GeV)
x
P_T (GeV)
z

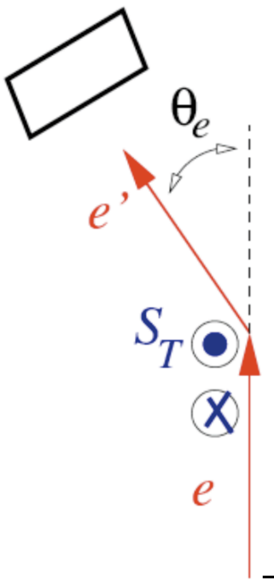
A_y (E05-015): Target Single-Spin Asymmetry in Quasi-Elastic ^{3}He↑(e,e')

(Run in May 2009, JLab Hall A. Jiang: co-spokesperson)

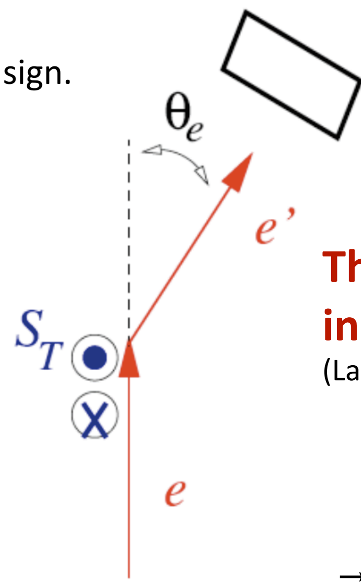


A_y arises from interference of one- and two-photon exchange, provides access to moments of GPDs.

Two independent measurements.
Real physics asymmetry should flip sign.



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



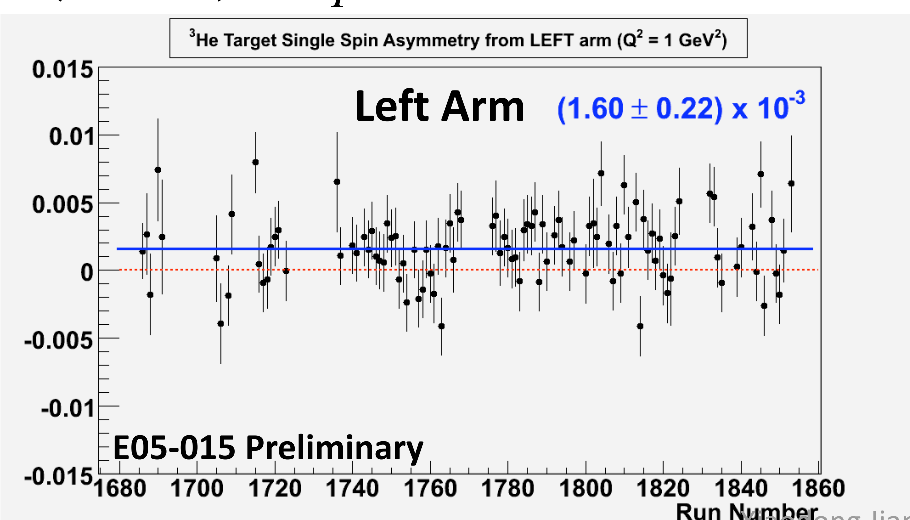
$(\vec{e} \times \vec{e}\,') \bullet \vec{S}_T > 0$

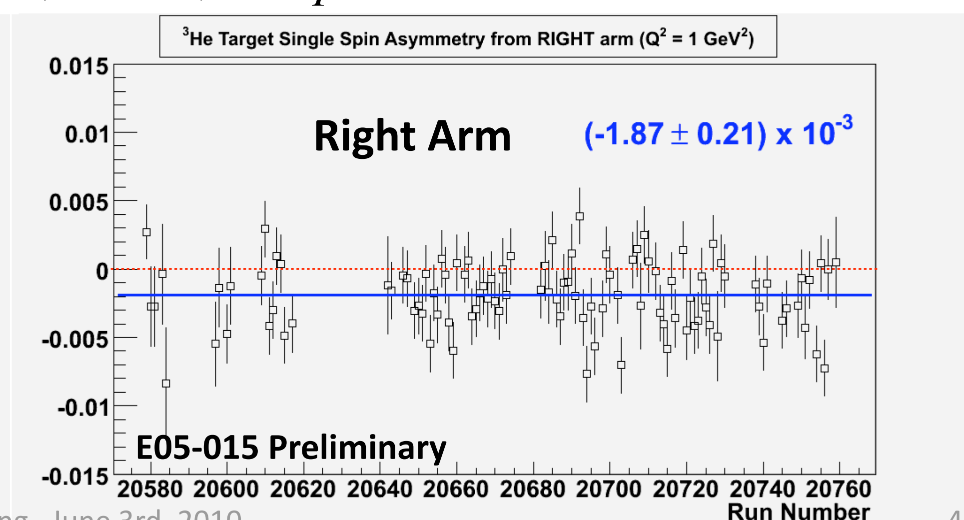
$(\vec{e} \times \vec{e}\,') \bullet \vec{S}_T < 0$

The first target SSA signal in inclusive scattering !

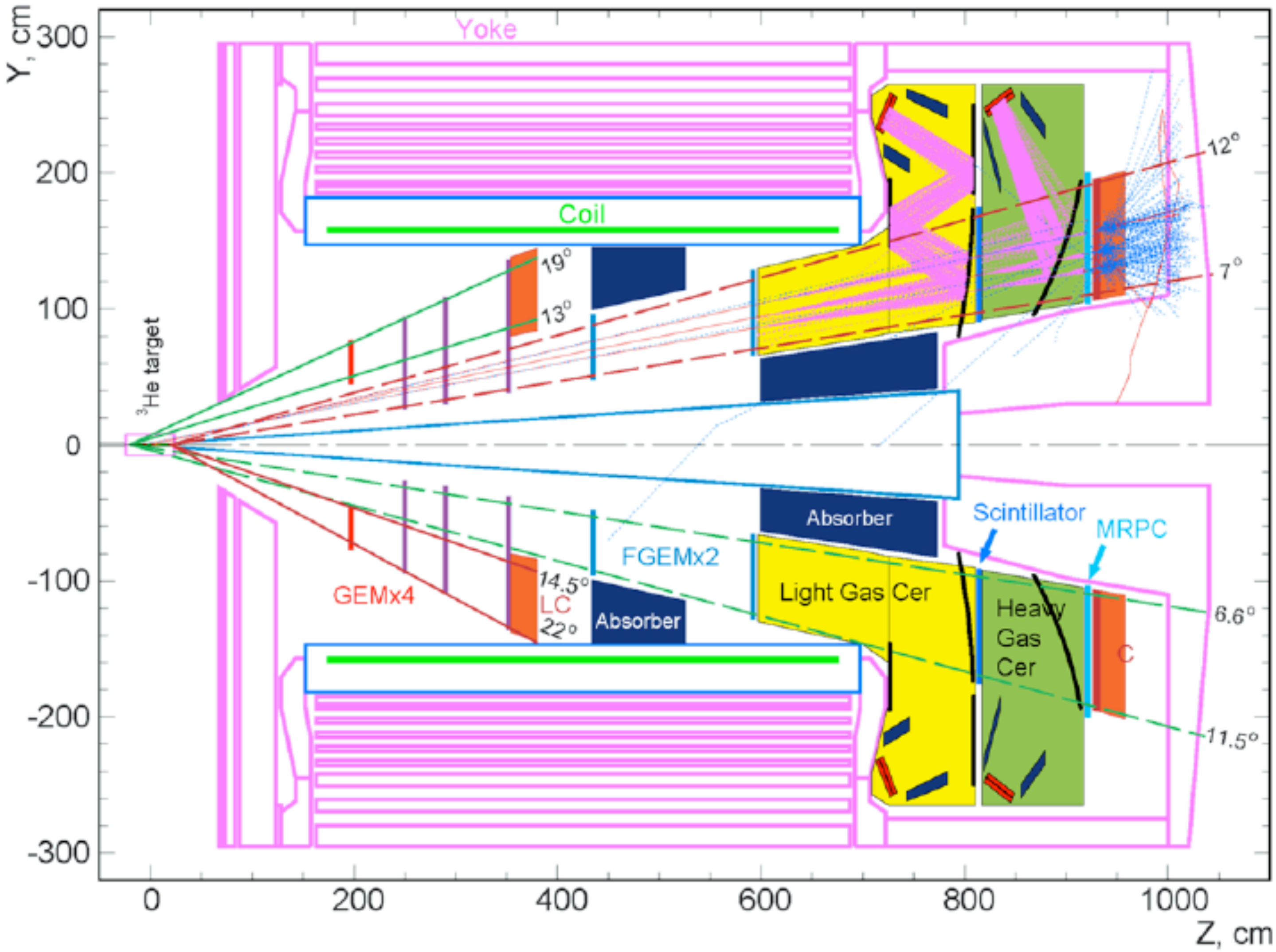
(Last effort in 1969 led by Owen Chamberlain)

Left Arm (%)	Right Arm (%)
0.160 ± 0.022	**- 0.187** ± 0.021





SoLID: experimental setup



from JLab-PAC35 / X. Qian