Transversity Experiments

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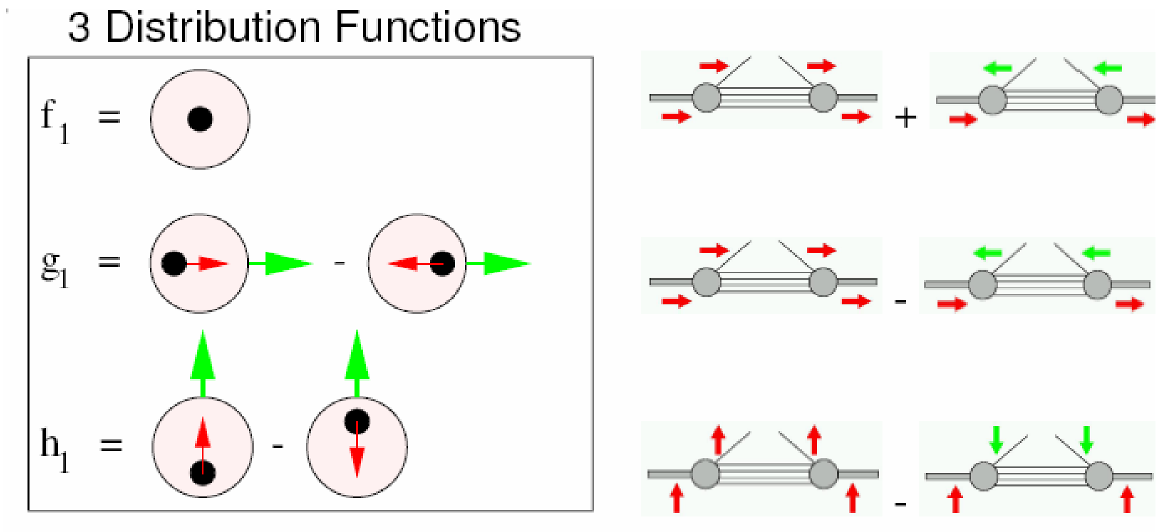
2007 JLab Users Group Meeting, June 18-20, 2007

- Physics and experimental probes for transversity
- Current experimental status on transversity and other related distribution and fragmentation functions
- Future prospects of transversity experiments at JLab

WHY Transversity ?

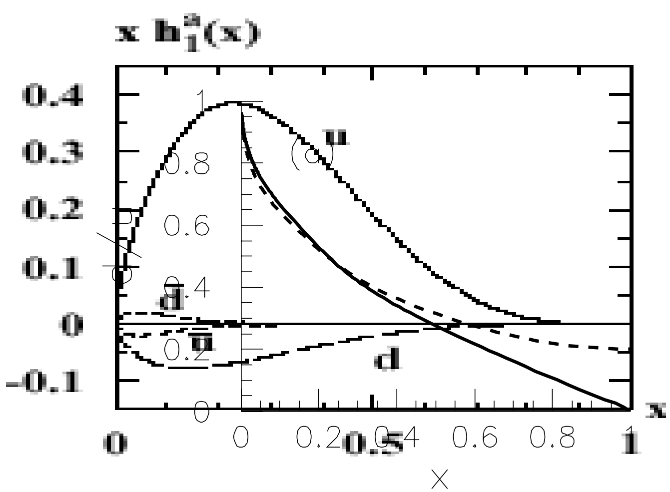


- Remaining frontier of k_T – independent distribution functions
- Connections to many novel k_T – dependent distribution and fragmentation functions
- Major experimental challenges to measure transversity. Opportunities for lepton and hadron beams.
- Active interaction between theory and experiment

Transversity

- Some characteristics of transversity:
  - $\delta q(x) = \Delta q(x)$ for non-relativistic quarks
  - δq and gluons do not mix → Q^2-evolution for δq and Δq are different
  - Chiral-odd → not accessible in inclusive DIS

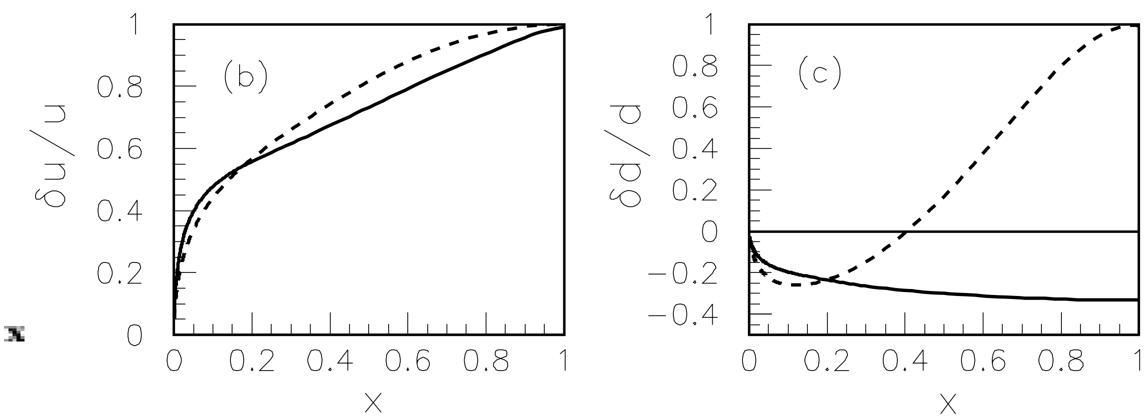
Chiral-quark soliton model



Similar to helicity distributions

hep-ph/0101300

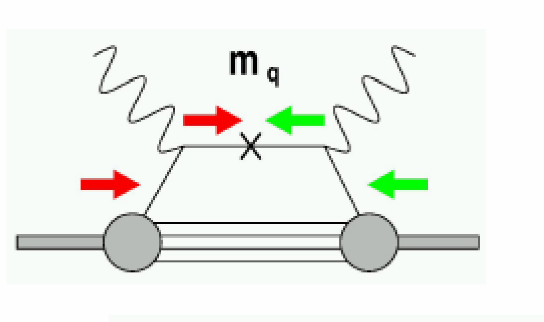
Quark – diquark model (solid) and pQCD-based model (dashed)



B. –Q. Ma, I. Schmidt and J. –J. Yang,

PRD 65, 034010 (2002)

How to measure transversity?



- Chiral-odd → not accessible in DIS
- Require another chiral-odd object (either parton distribution function or fragmentation function)

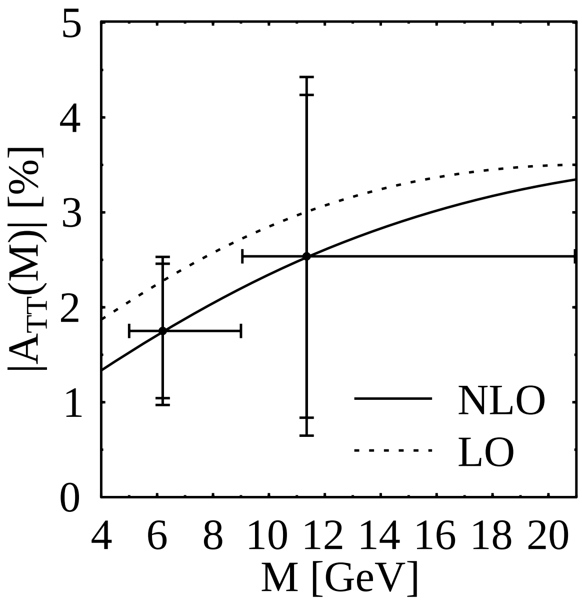
- Transversely Polarized Drell-Yan (transversity in both hadrons)
- Semi-Inclusive DIS (transversity plus fragmentation function)
  - Single-hadron (Collins fragmentation function)
  - Two hadrons (Interference fragmentation function)
  - Vector meson polarization
  - Λ - polarization

Polarized Drell-Yan in p-p collision (RHIC-spin)

Transverse double-spin asymmetry for Drell-Yan

$$A_{TT} = \hat{a}_{TT} \frac{\sum_q e_q^2 h_1^q(x_1, M^2) h_1^{\bar{q}}(x_2, M^2)}{\sum_q e_q^2 q(x_1, M^2) \bar{q}(x_2, M^2)}$$

- Well understood reaction mechanism. Clear interpretation
- An unique method to extract sea-quark transversity
- Small effect due to the expected small sea quark transversity

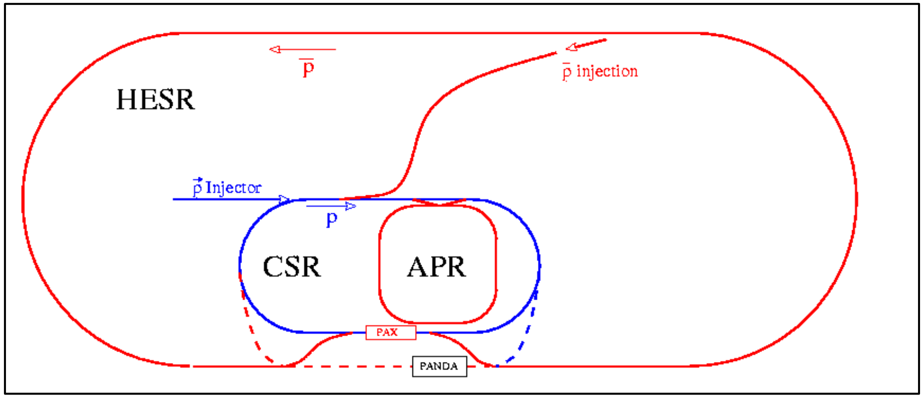


PHENIX, $s^{1/2}$=200GeV, 320 pb^{-1}

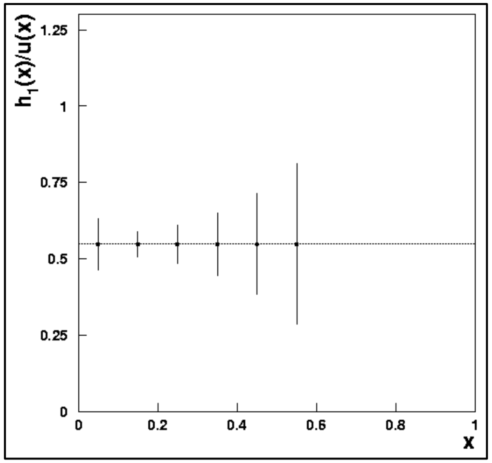
hep-ph/9902250

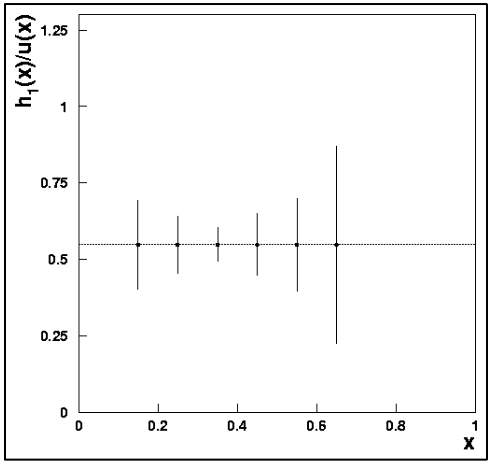
Transversely polarized Drell-Yan in $\bar{p}$ - p collision

FAIR
Polarized
Antiproton
eXperiment
(PAX)



DIS2005
talk by
Lenisa
(AIP 792
(2005))





Collider:

$L=2\times10^{30}\ cm^{-2}s^{-1}$

Fixed target:

$L=2.7\times10^{31}\ cm^{-2}s^{-1}$

Phase I: 2013-2017, Phase II: 2018 -

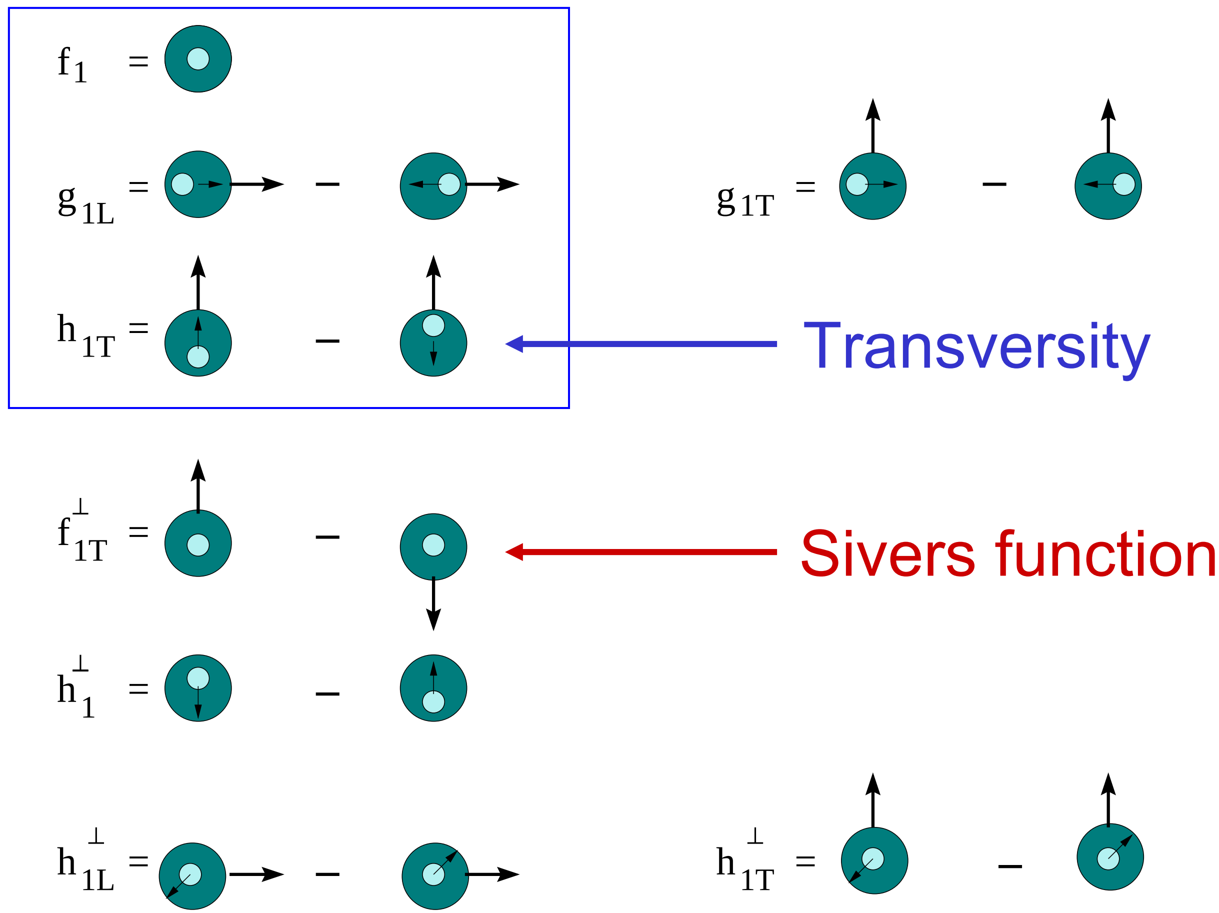
Semi-inclusive DIS can access all leading-twist quark distributions

Leading-Twist Quark Distributions

(A total of eight distributions)

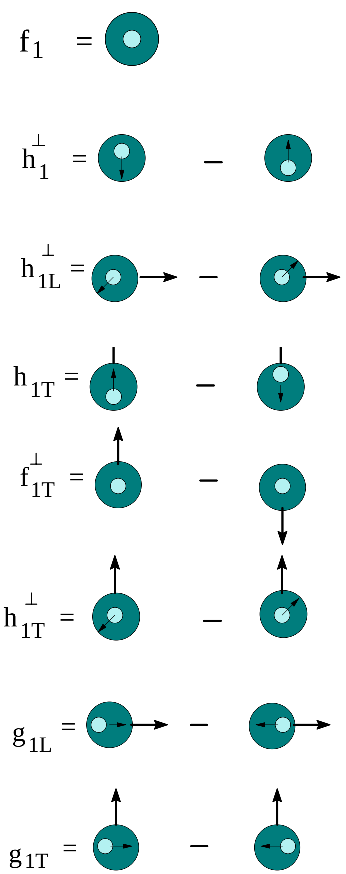
Three have no k_T dependence

The other five are transverse momentum (k_T) dependent (TMD)



All Eight Quark Distributions Are Probed in Semi-Inclusive DIS

$$d^6\sigma = \frac{4\pi\alpha^2 sx}{Q^4}\times$$



Transversity

Sivers

Unpolarized

$$\{[1+(1-y)^2]\sum_{q,\bar{q}} e_q^2 f_1^q(x) D_1^q(z,P_{h\perp}^2)$$

$$+(1-y)\frac{P_{h\perp}^2}{4z^2 M_N M_h}\cos(2\phi_h^l)\sum_{q,\bar{q}} e_q^2 h_1^{\perp(1)q}(x) H_1^{\perp q}(z,P_{h\perp}^2)$$

Polarized target

$$-|S_L|(1-y)\frac{P_{h\perp}^2}{4z^2 M_N M_h}\sin(2\phi_h^l)\sum_{q,\bar{q}} e_q^2 h_{1L}^{\perp(1)q}(x) H_1^{\perp q}(z,P_{h\perp}^2)$$

$$+|S_T|(1-y)\frac{P_{h\perp}}{zM_h}\sin(\phi_h^l+\phi_S^l)\sum_{q,\bar{q}} e_q^2 h_1^q(x) H_1^{\perp q}(z,P_{h\perp}^2)$$

$$+|S_T|(1-y+\frac{1}{2}y^2)\frac{P_{h\perp}}{zM_N}\sin(\phi_h^l-\phi_S^l)\sum_{q,\bar{q}} e_q^2 f_{1T}^{\perp(1)q}(x) D_1^q(z,P_{h\perp}^2)$$

$$+|S_T|(1-y)\frac{P_{h\perp}^3}{6z^3 M_N^2 M_h}\sin(3\phi_h^l-\phi_S^l)\sum_{q,\bar{q}} e_q^2 h_{1T}^{\perp(2)q}(x) H_1^{\perp q}(z,P_{h\perp}^2)$$

Polarzied beam and target

$$+\lambda_e|S_L|y(1-\frac{1}{2}y)\sum_{q,\bar{q}} e_q^2 g_1^q(x) D_1^q(z,P_{h\perp}^2)$$

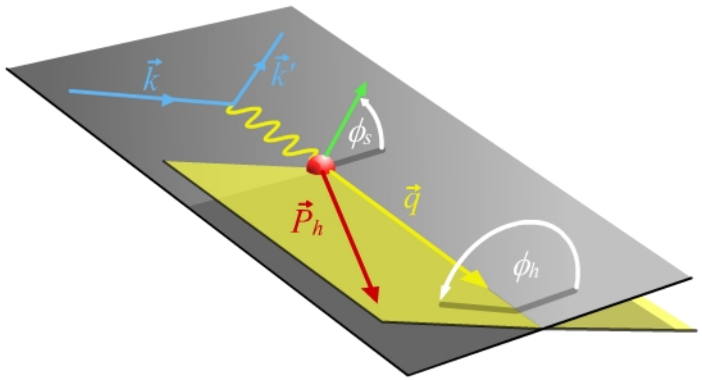
$$+\lambda_e|S_T|y(1-\frac{1}{2}y)\frac{P_{h\perp}}{zM_N}\cos(\phi_h^l-\phi_S^l)\sum_{q,\bar{q}} e_q^2 g_{1T}^{(1)q}(x) D_1^q(z,P_{h\perp}^2)\}$$

S_L and S_T: Target Polarizations; λe: Beam Polarization

Observation of Single-Spin Azimuthal Asymmetry

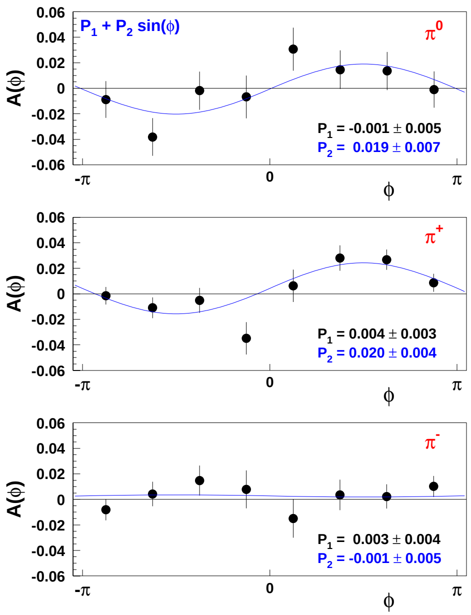
$ep \rightarrow e'\pi x$

Longitudinally polarized target



$\langle S_T \rangle \sim 0.15$

HERMES



Origins of the azimuthal asymmetry ?

Collins effect: Correlation between the quark's transverse spin with pion's transverse momentum in the fragmentation process.

Sivers effect: Correlation between the transverse spin of the proton with the quark's transverse momentum.

Other higher twist effects could also contribute.

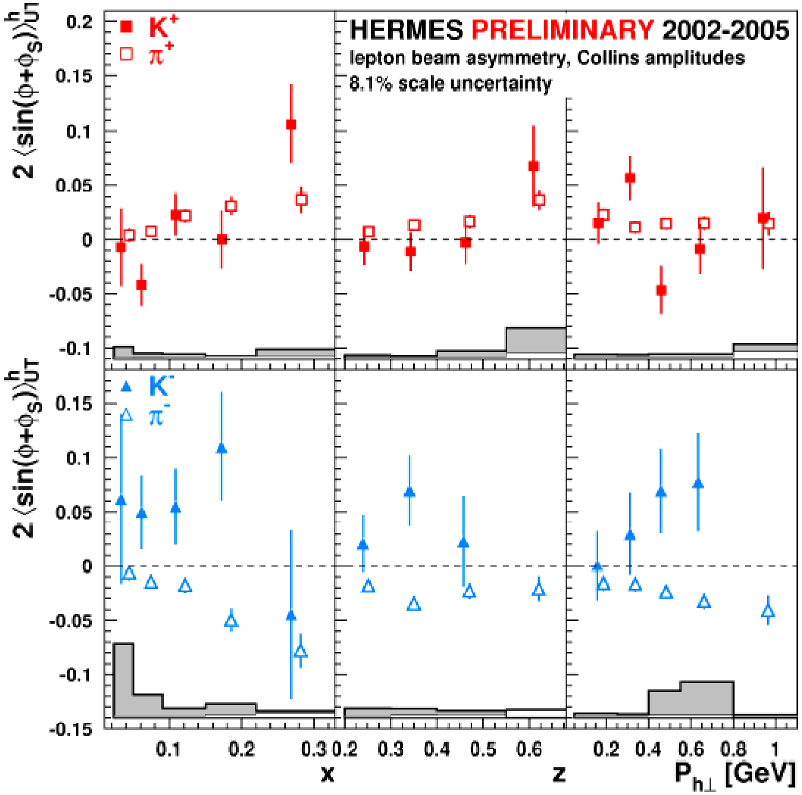
$A_{UT}^{\sin(\phi)}$ from transv. pol. H target

Simultaneous fit to $\sin(\phi + \phi_s)$ and $\sin(\phi - \phi_s)$

"Collins" amplitude :

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

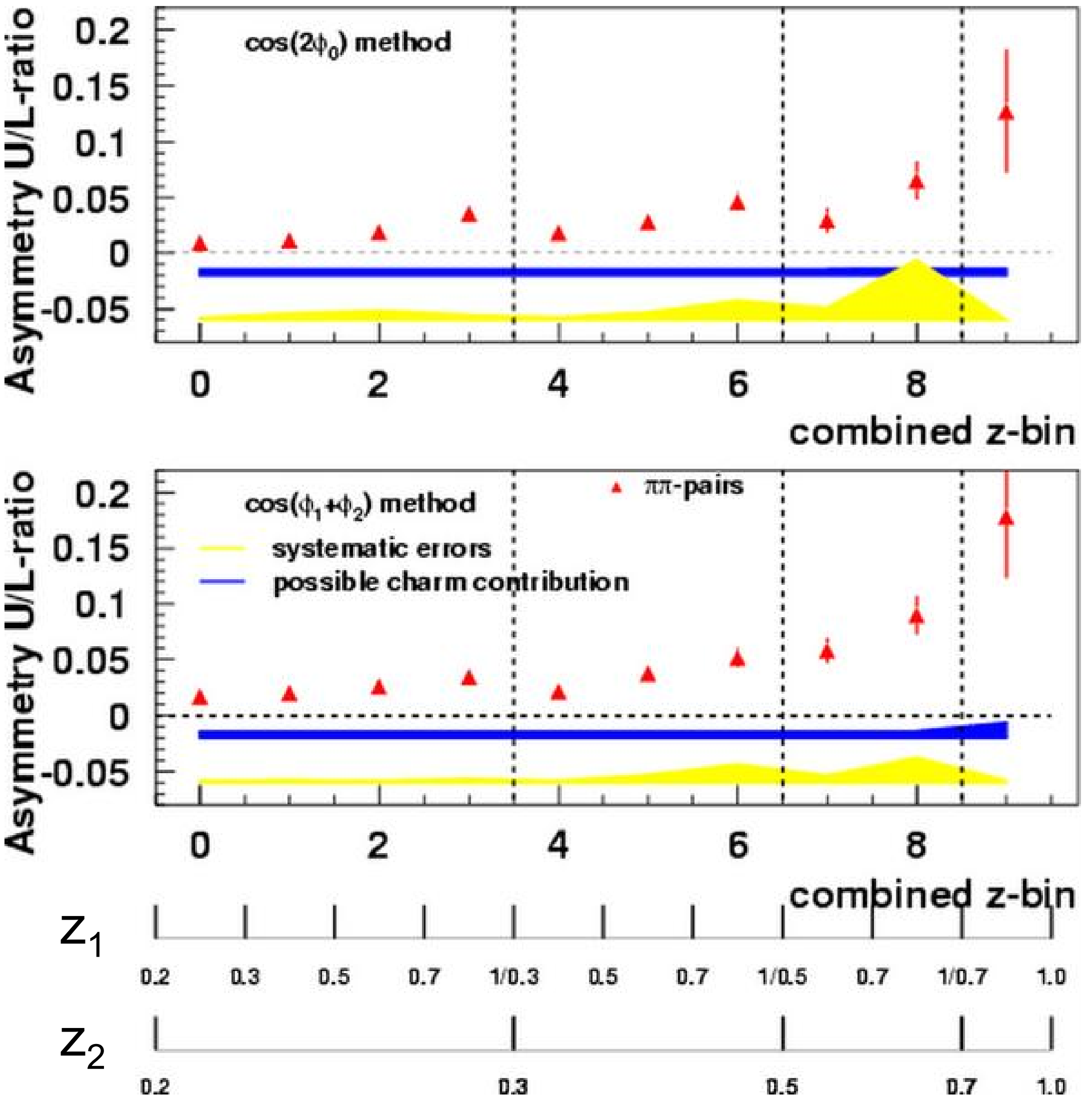
(Van der Nat, May 2007)



- Product of $h_1(x) H_1^{\perp}(z)$ is non-zero
- A surprising flavor dependence : $H_1^{\perp,\, unfavored} / H_1^{\perp,\, favored} \approx -1$
- Extraction of $h_1(x)$ requires an independent measurement of Collins function $H_1^{\perp}(z)$

Collins functions from Belle

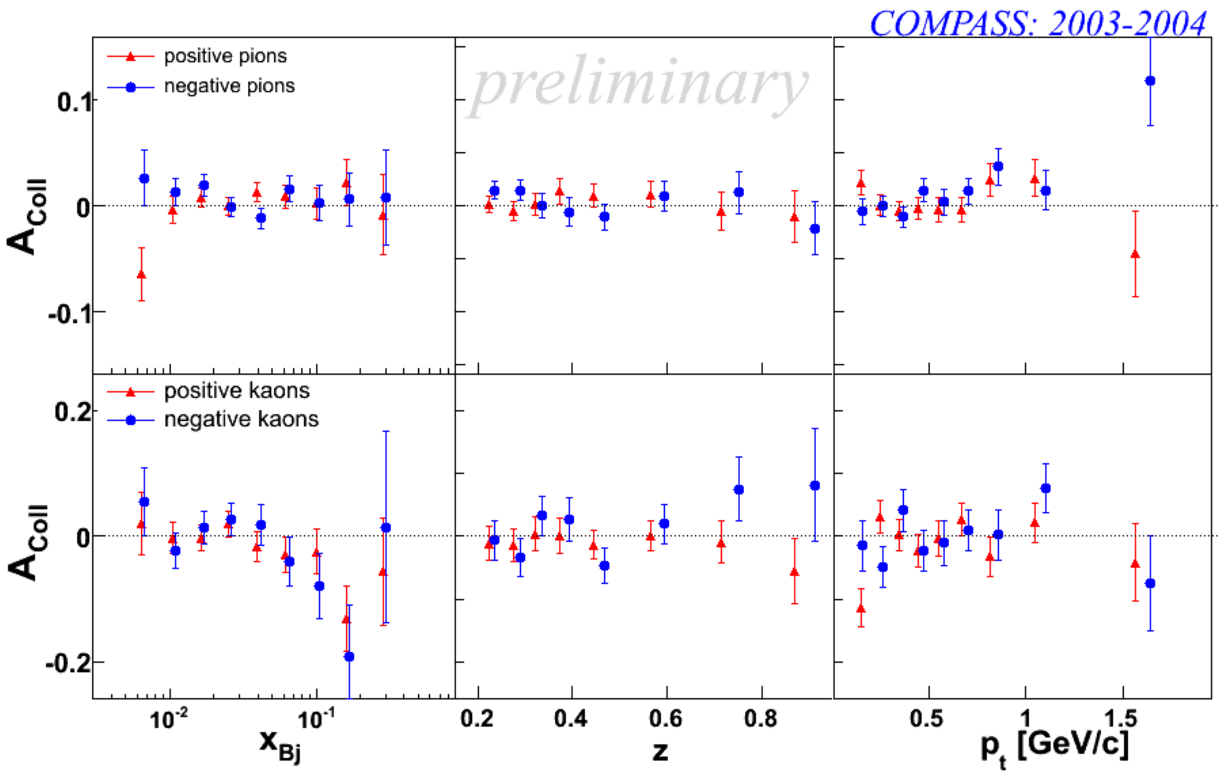
$e^+e^- \to \pi\pi x$ (cos 2ϕ correlation between pions)



- Significant non-zero asymmetries
- Rising behaviour vs. z
- First direct measurement of the Collins function

hep-ex/0507063

Collins asymmetry from COMPASS



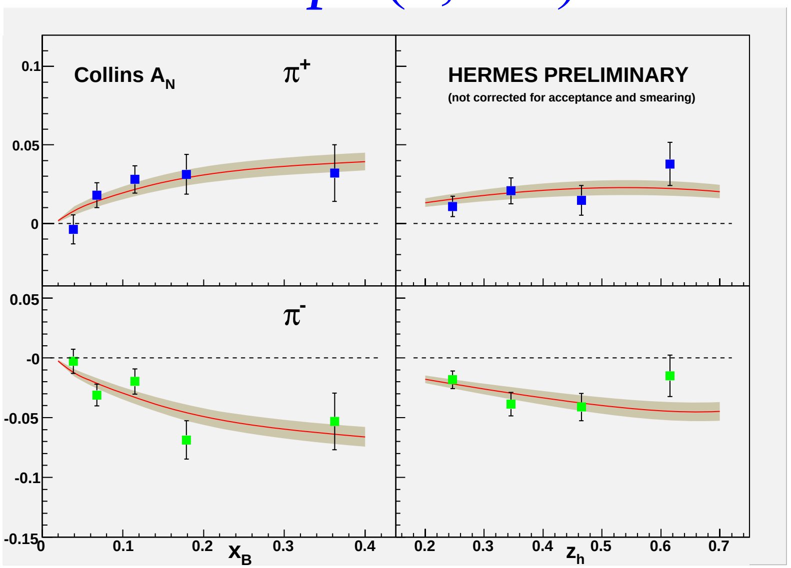
- Transversely polarized ^{6}LiD target
- 160 GeV/c muon beam
- Cover smaller *x*
- Consistent with 0 !
- Cancellation between p and n ?

DIS 2007, Bressan

Extraction of Collins functions from the Collins asymmetry measurements

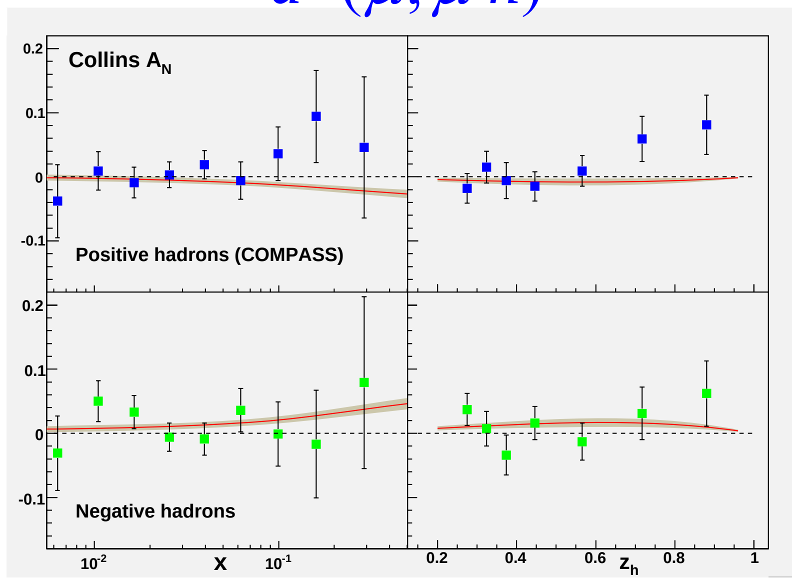
Fits to the Hermes data

$$p^{\uparrow}(e, e'\pi)$$



"Prediction" of the Compass data

$$d^{\uparrow}(\mu, \mu' h)$$



Assuming $H_1^{\perp, fav}(z) = C_{fav} z(1-z) D_1^{fav}(z); \quad H_1^{\perp, unfav}(z) = C_{unfav} z(1-z) D_1^{fav}(z)$

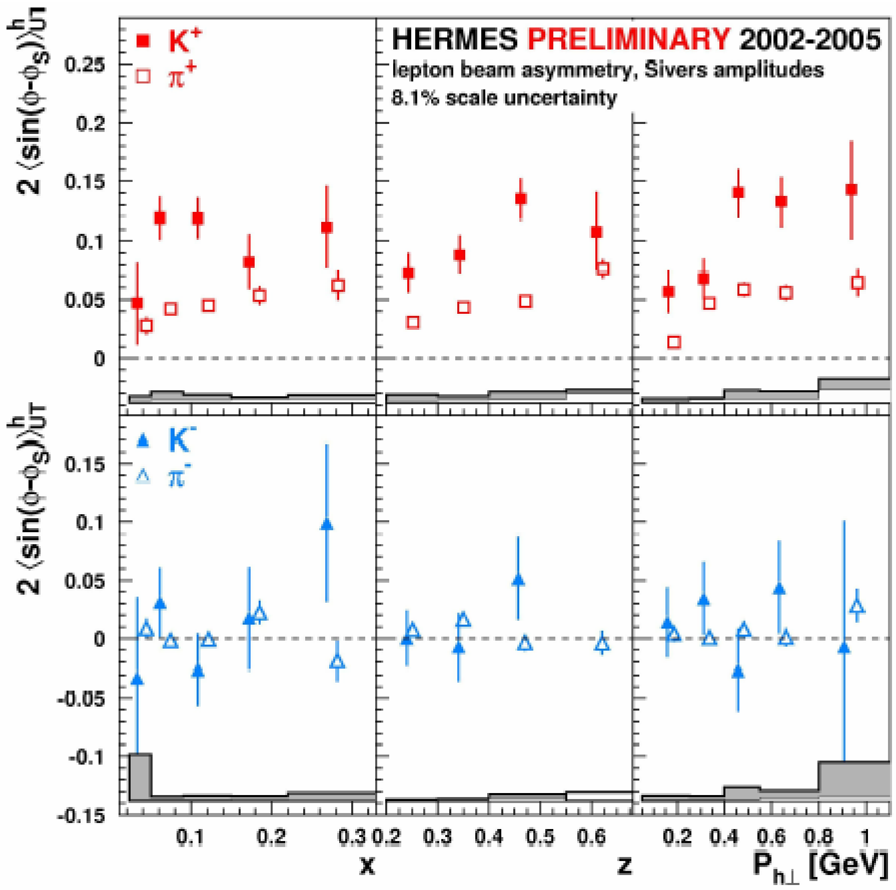
$$C_{fav} = -0.29 \pm 0.04, \quad C_{unfav} = 0.33 \pm 0.04$$

(Vogelsang and Yuan, hep-ph/0507266)

$$H_1^{\perp, unfavored} / H_1^{\perp, favored} \approx -1$$

Sivers amplitudes from Hermes

"Sivers" amplitude : $\langle \sin(\phi - \phi_S) \rangle_{UT} \propto f_{1T}^{\perp} \otimes D_1$



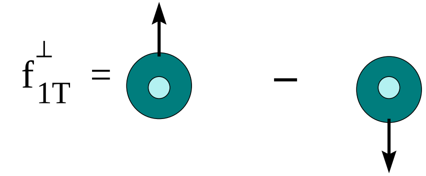
- significantly positive amplitudes for π^+ and K^+ ,which indicates:
  - non-zero L_z^q
  - existence naive T-odd distribution functions

- K^+ amplitude > π^+ amplitude: influence of anti-quarks

- π^- and K^- consistent with zero

(Van der Nat, May 2007)

Sivers Function



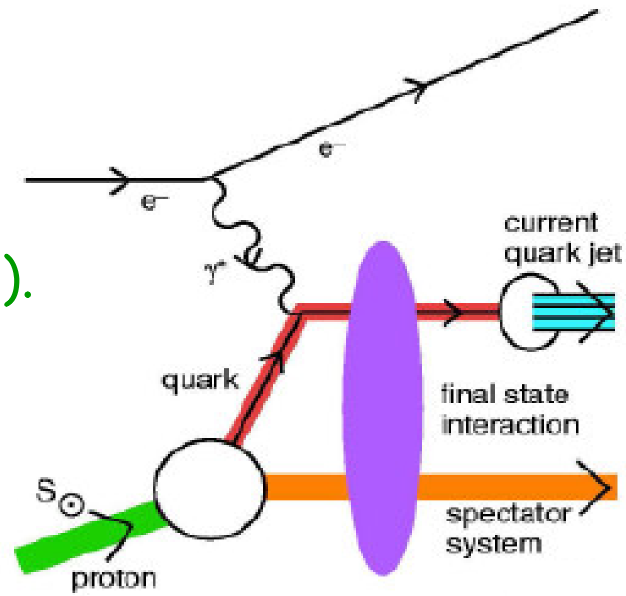
- On the basis of time reversal arguments:

$$f_{1T}^{\perp}(x,p_T^2)=0$$

Collins, NPB396, 161(1993)

- Final-state interaction from gluon exchange between the quark and the spectator lead to nonzero Sivers function.

Brodsky, Hwang & Schmidt, PLB530, 99(2002).



- Final-state interaction can be reproduced by a prescription of the light-cone singularities or an extra gauge link at the spatial infinity for the parton distributions.

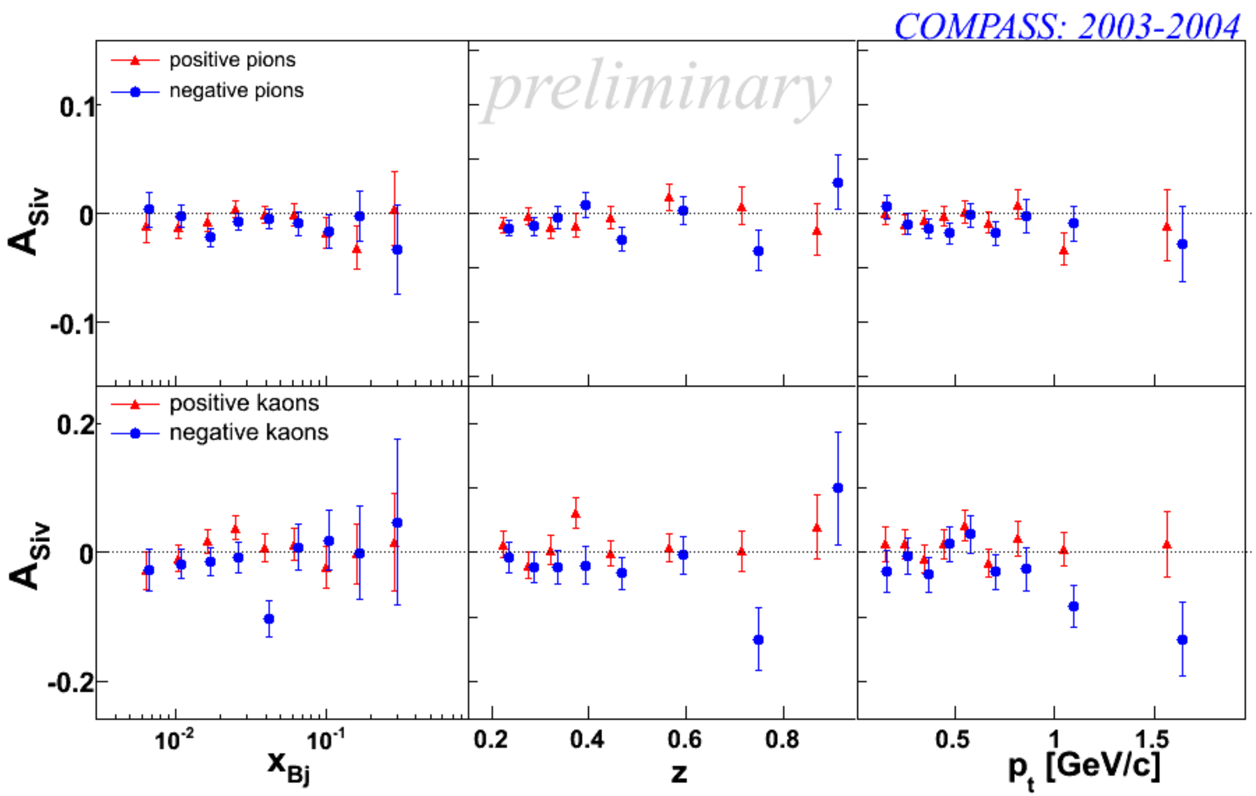
Ji & Yuan, PLB543,66(2002).

- Add final state interaction to the time reversal arguments:

$$f_{1T}^{\perp}(x,p_T^2)_{SIDIS}=-f_{1T}^{\perp}(x,p_T^2)_{DY}$$

Collins, PLB536, 43(2002)

Sivers asymmetry from COMPASS

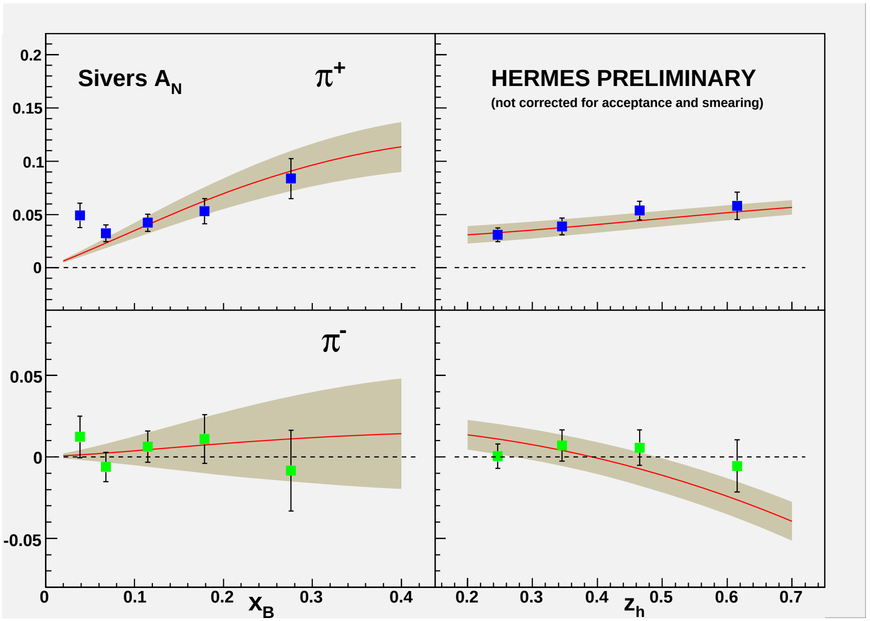


- Transversely polarized ^{6}LiD target
- 160 GeV/c muon beam
- Cover smaller *x*
- Consistent with 0 !
- Cancellation between p and n ?

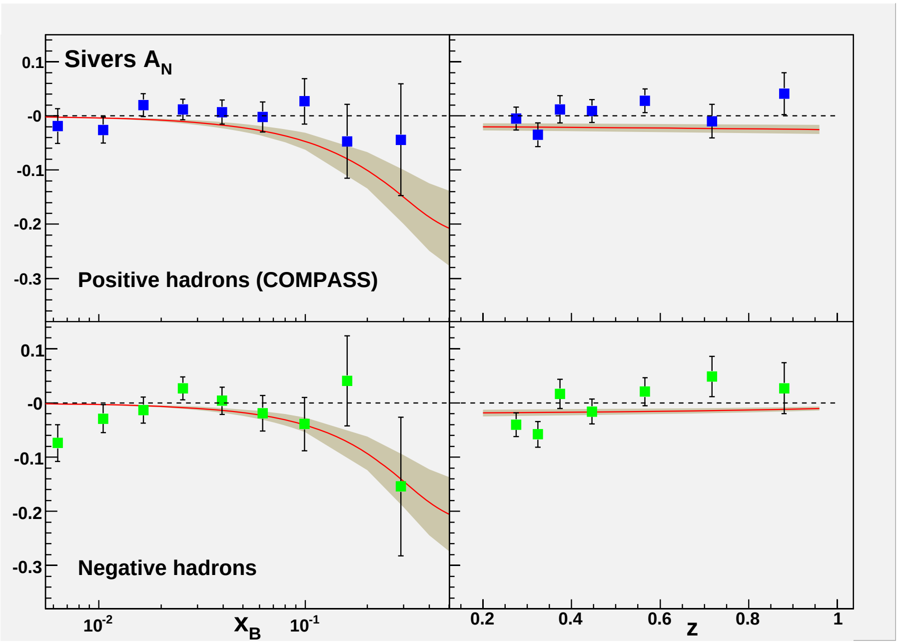
DIS 2007, Bressan

Extraction of Sivers functions from the Sivers moment measurements

Fits to the Hermes data



"Prediction" of the Compass data



$$\text{Assuming} \quad f_{1T}^{\perp,u}(x) = S_u\, x(1-x)u(x); \qquad f_{1T}^{\perp,d}(x) = S_d\, x(1-x)u(x)$$

$$S_u = -0.81 \pm 0.07, \quad S_d = 1.86 \pm 0.28$$

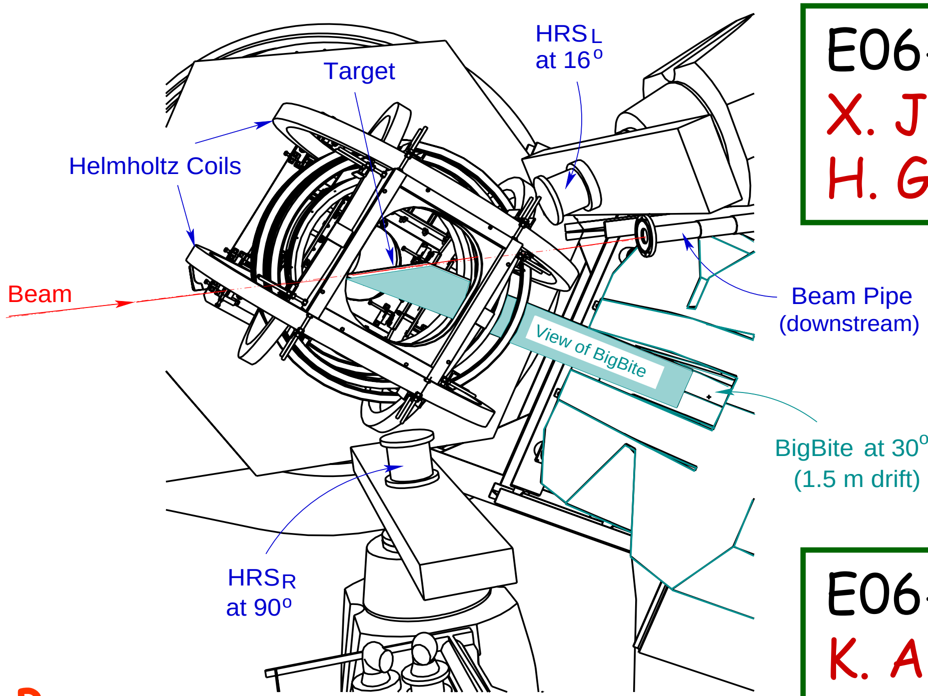
(Vogelsang and Yuan, hep-ph/0507266)

Striking flavor dependence of the Sivers function

Opportunities at JLab for transversity experiments

- High-intensity CW electron beam
- High-density polarized ^{3}He target which could be polarized transversely
- Probe valence-quark region similar to HERMES kinematics, providing complimentary information on transversely polarized neutron
- An independent test of the striking flavor structures of Collins and Sivers functions observed at HERMES/COMPASS

$^3He^{\uparrow}(e,e'\pi^{+/-})x$ at JLab Hall A

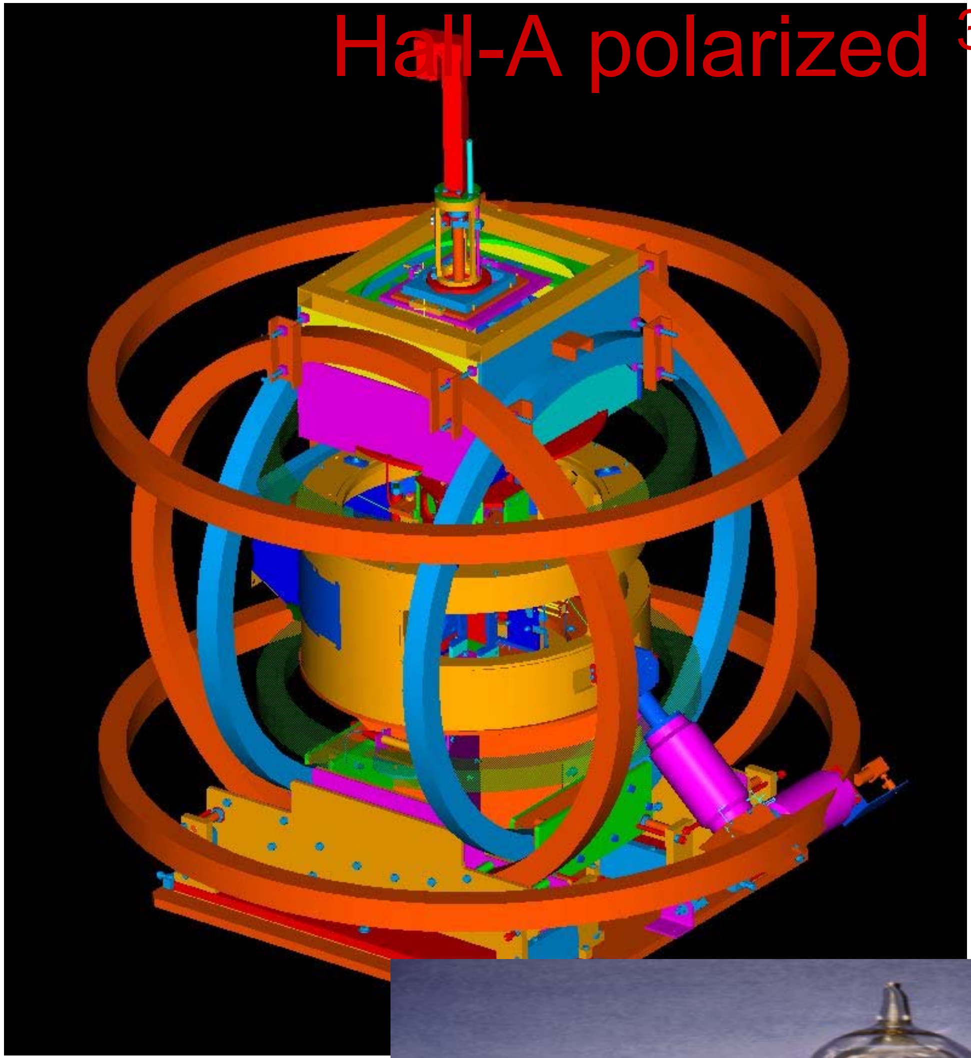


E06-010/06-011 Spokespersons:
X. Jiang, J.P. Chen, E. Cisbani, H. Gao, J.C. Peng

E06-010/06-011 thesis students:
K. Allada, C. Dutta, X. Qian, M. Shabestari, Y. Wang.

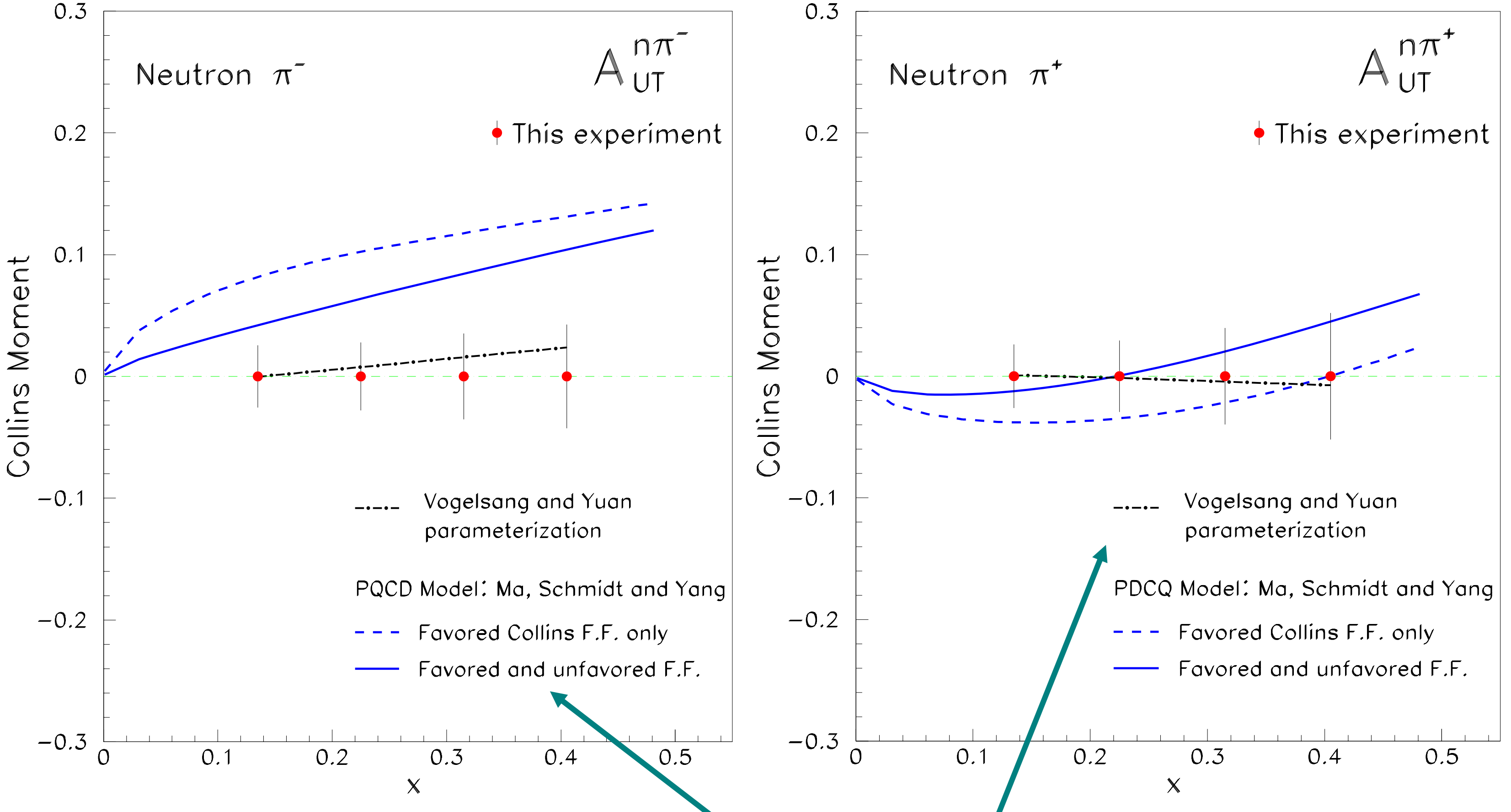
- Beam
  - 6 GeV, 15 μA e^- beam
- Target
  - Optically pumped Rb-K spin-exchange ^3He target, 50 mg/cm^2, ~42% polarization, transversely polarized with tunable direction
- Electron detection
  - BigBite spectrometer, Solid angle = 60 msr, $\theta_{Lab} = 30^0$
- Charged pion/kaon detection
  - HRS spectrometer, $\theta_{Lab} = -16^0$

Hall-A polarized ^{3}He target



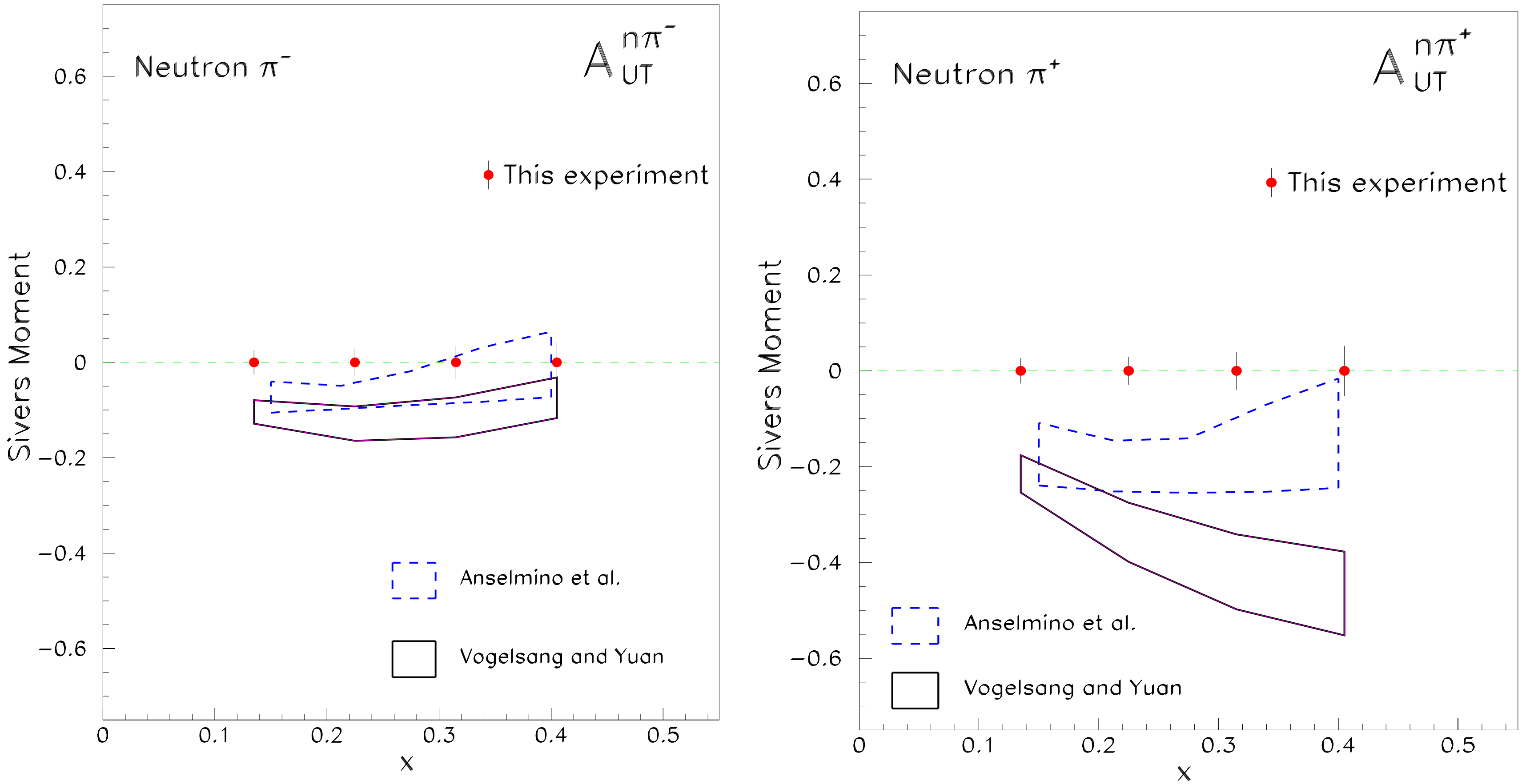
- 40-cm long Rb-K spin-exchange hybrid cell at 10 atm with beam current of 15 μA
- 42% target polarization with spin-flip frequency of 20 minutes
- A third set of Helmholtz coils will be added, together with the laser optics, to allow for vertical polarization of the ^{3}He target

Predictions of Collins asymmetry on neutron



It can separate the predictions before and after HERMES transverse data.

Predictions of Sivers asymmetry on neutron

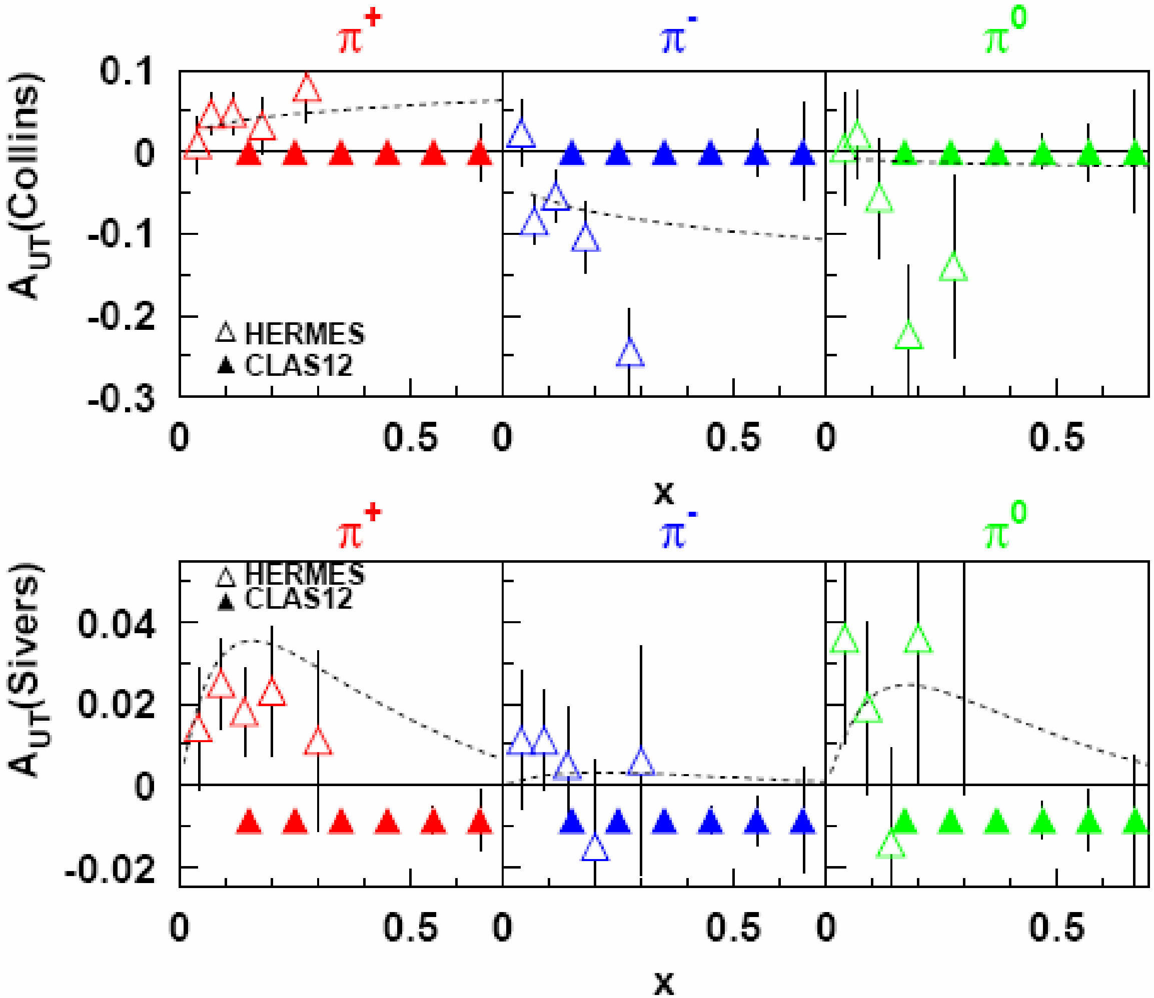


It can even separate the predictions constrained by HERMES data.

Expect to run in 2008

Transversity measurements at JLab 12 GeV upgrade

Projected sensitivity at CLAS12

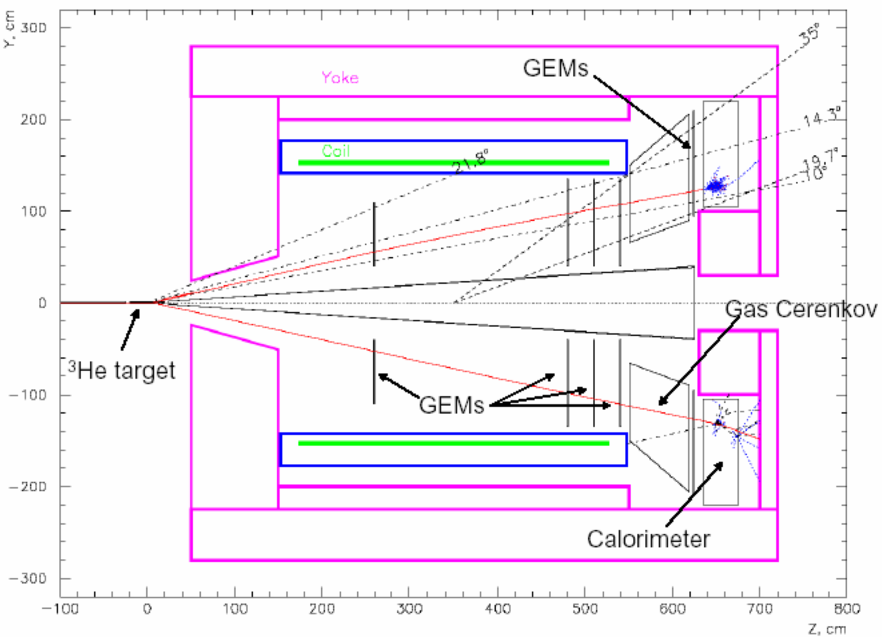


Transversity with Solenoid

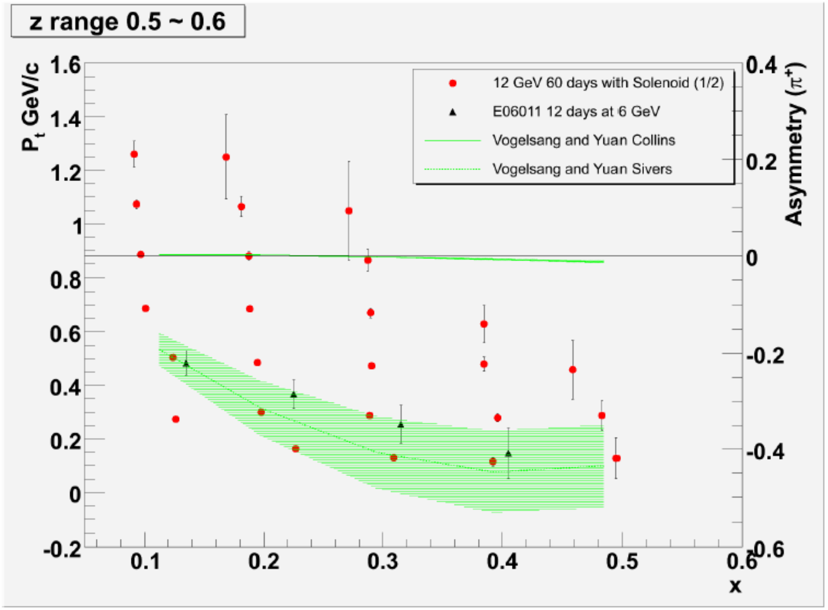
J.P. Chen, E. Cisbani, E. Chudakov, X. Jiang,
J.C. Peng, X. Qian, L.Y. Zhu

Haiyan Gao
Duke University/TUNL
Dec 14, 2006

Solenoid detector for SIDIS



Projections for Collins and Sivers Asymmetry (π^+)



Cos2Φ Dependence in Unpolarized Semi-inclusive DIS and Drell-Yan

Large cos2Φ dependences have been observed in π – induced Drell-Yan

This azimuthal dependence could arise from a product of K_T-dependent distribution function $h_1^\perp$ (Boer-Mulders function)

(Boer, hep-ph/9902255; Boer, Brodsky, Hwang, hep-ph/0211110, and Gamberg et al.)

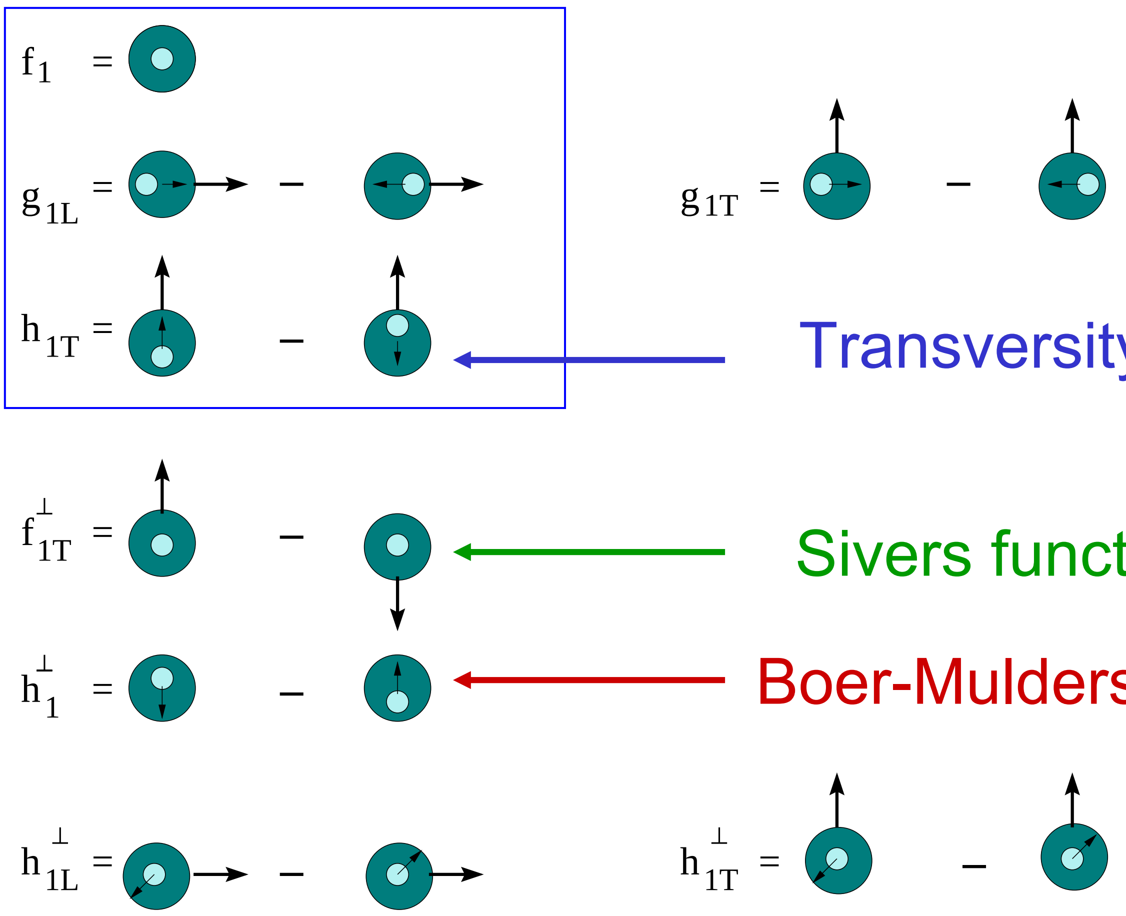
In quark-diquark model, $h_1^\perp$ is identical to Sivers function. It represents the correlation between quark's transverse spin and transverse momentum

Semi-inclusive DIS can access all leading-twist quark distributions

Leading-Twist Quark Distributions

(A total of eight distributions)

Three have no k_T dependence



Transversity

Sivers function

Boer-Mulders function

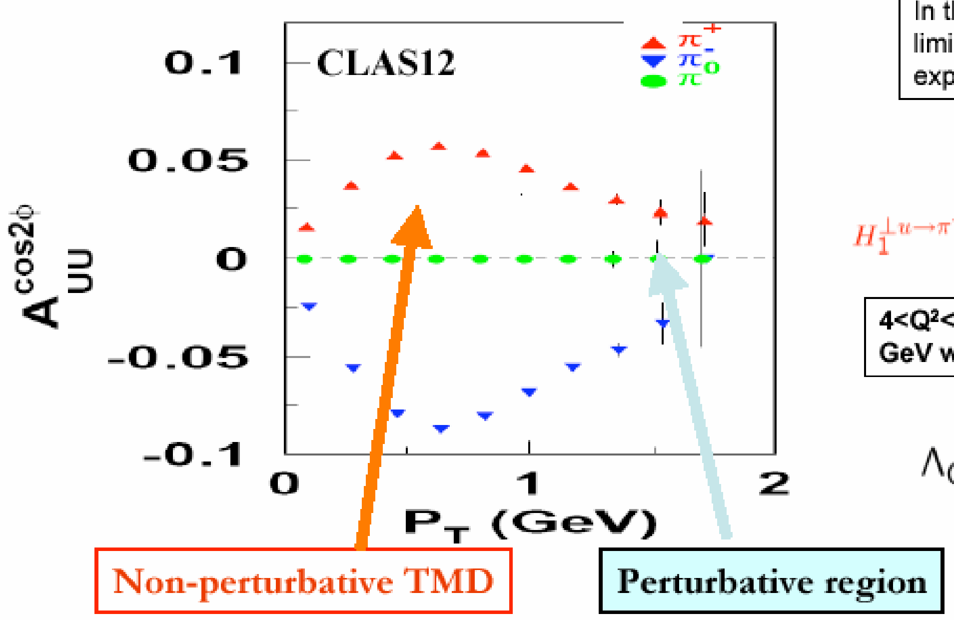
The other five are transverse momentum (k_T) dependent (TMD)

JLab PR12-06-112

Spokespersons: H. Avakian, Z.-E. Meziani, B. Seitz, K. Joo

Boer-Mulders Asymmetry: P_T-dependence

$$A_{UU}^{\cos 2\phi} \propto h_1^{\perp} H_1^{\perp}$$



In the perturbative limit $1/P_T^2$ behavior expected (F.Yuan)

$$H_1^{\perp u \to \pi^+} \approx -H_1^{\perp u \to \pi^-}$$

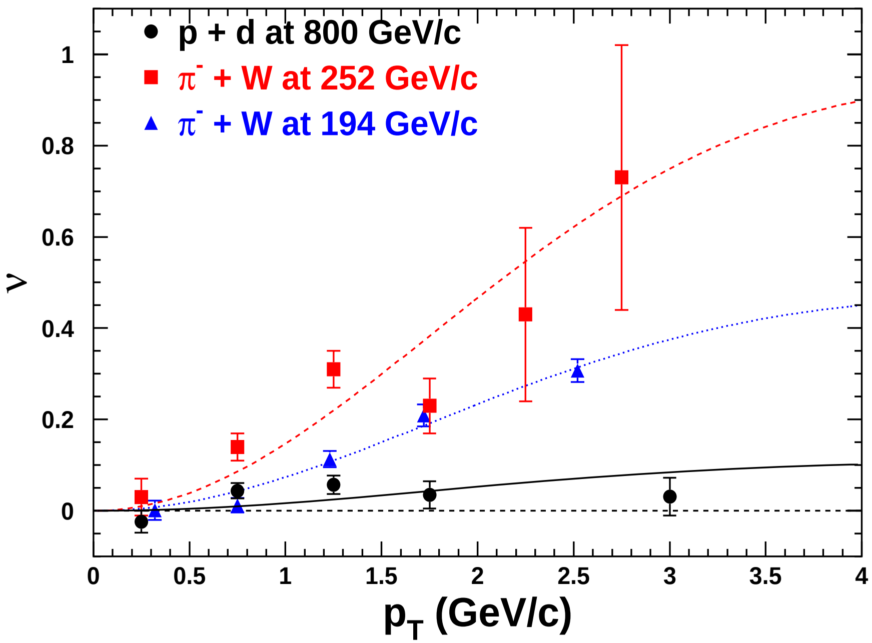
$4<Q^2<5$ (2000h @ 11 GeV with 10^{35}sec^{-1}cm^{-2})

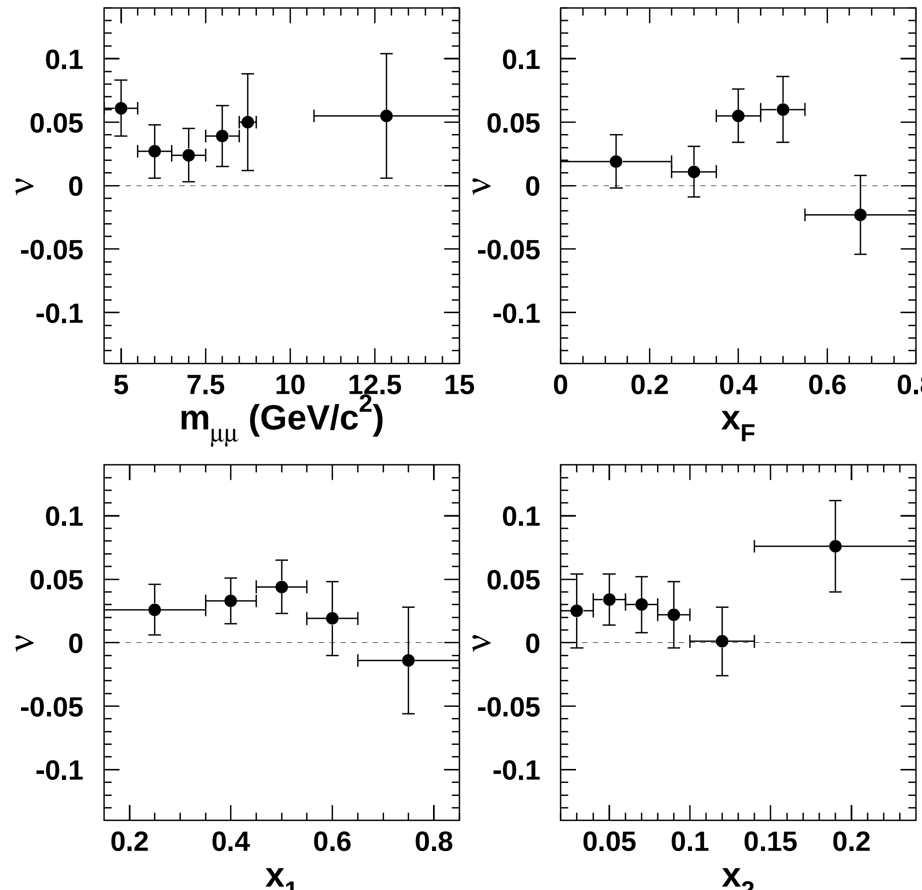
$$\Lambda_{QCD} \ll P_T \ll Q$$

P_T-dependence of azimuthal moments allows studies of transition from non-perturbative to perturbative description (Unified theory by Ji et al).

Azimuthal cos2Φ Distribution in p+d Drell-Yan

L.Y. Zhu, J.C. Peng, P. Reimer et al., hep-ex/0609005.





With Boer-Mulders function $h_1^\perp$:

$\nu(\pi^- W \rightarrow \mu^+\mu^- X) \sim$ valence $h_1^\perp(\pi)$ * valence $h_1^\perp(p)$

$\nu(pd \rightarrow \mu^+\mu^- X) \sim$ valence $h_1^\perp(p)$ * sea $h_1^\perp(p)$

Summary

- There has been much recent interest and progress on the study of transversity and novel transverse-momentum dependent parton distribution functions and fragmentation functions.
- The first transversity measurements at JLab will start soon at Hall-A using polarized ^{3}He target.
- A rich program of Semi-inclusive DIS experiments will be pursued at the 12 GeV JLab upgrade.