JLab results: TMD measurements

M. Aghasyan

Aug 30, 2011

Transversity 2011 *Veli Lošinj (Croatia)*

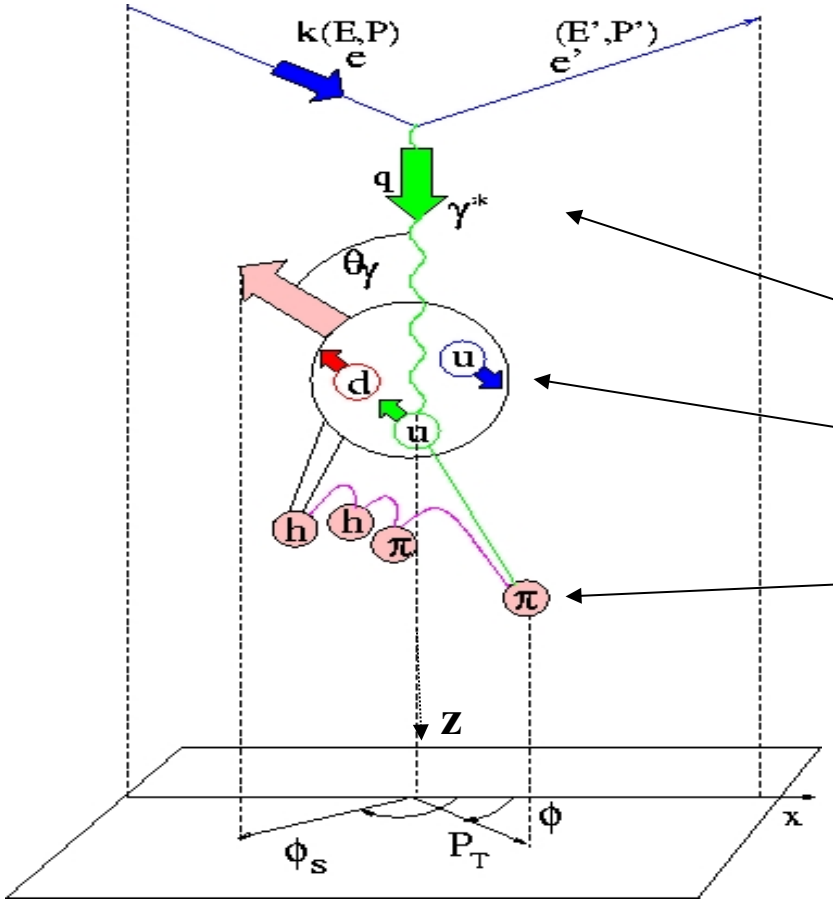
INFN Istituto Nazionale di Fisica Nucleare

Jefferson Lab

Outline

- Physics motivation
- Unpolarized and polarized target data.
  - Single Spin asymmetries
  - Double Spin asymmetries
- TMD extraction
- Summary

SIDIS kinematical plane and observables



$$\nu = (qP)/M$$
$$Q^2 = (k - k')^2$$
$$y = (qP)/(kP)$$
$$x = Q^2/2(qP)$$
$$z = (qP_h)/(qP)$$

P_b, P_t { **U** unpolarized; **L** long.polarized; **T** trans.polarized

Transverse spin effects are observable as correlations of transverse spin and transverse momentum of quarks.

SIDIS cross section

$$\frac{d\sigma}{dx\,dy\,d\psi\,dz\,d\phi_h\,dP_{h\perp}^2} =$$

$$\frac{\alpha^2}{xyQ^2}\frac{y^2}{2\,(1-\varepsilon)}\left(1+\frac{\gamma^2}{2x}\right)\Big\{F_{UU,T}+\varepsilon F_{UU,L}+\sqrt{2\varepsilon(1+\varepsilon)}\,\cos\phi_h\,F_{UU}^{\cos\phi_h}$$

$$+\varepsilon\cos(2\phi_h)\,F_{UU}^{\cos 2\phi_h}+\lambda_e\sqrt{2\varepsilon(1-\varepsilon)}\,\sin\phi_h\,F_{LU}^{\sin\phi_h}$$

$$+S_\parallel\Big[\sqrt{2\varepsilon(1+\varepsilon)}\,\sin\phi_h\,F_{UL}^{\sin\phi_h}+\varepsilon\sin(2\phi_h)\,F_{UL}^{\sin 2\phi_h}\Big]$$

$$+S_\parallel\lambda_e\Big[\sqrt{1-\varepsilon^2}\,F_{LL}+\sqrt{2\varepsilon(1-\varepsilon)}\,\cos\phi_h\,F_{LL}^{\cos\phi_h}\Big]$$

$$+|\boldsymbol{S}_\perp|\Big[\sin(\phi_h-\phi_S)\Big(F_{UT,T}^{\sin(\phi_h-\phi_S)}+\varepsilon\,F_{UT,L}^{\sin(\phi_h-\phi_S)}\Big)$$

$$+\varepsilon\,\sin(\phi_h+\phi_S)\,F_{UT}^{\sin(\phi_h+\phi_S)}+\varepsilon\,\sin(3\phi_h-\phi_S)\,F_{UT}^{\sin(3\phi_h-\phi_S)}$$

$$+\sqrt{2\varepsilon(1+\varepsilon)}\,\sin\phi_S\,F_{UT}^{\sin\phi_S}+\sqrt{2\varepsilon(1+\varepsilon)}\,\sin(2\phi_h-\phi_S)\,F_{UT}^{\sin(2\phi_h-\phi_S)}\Big]$$

$$+|\boldsymbol{S}_\perp|\lambda_e\Big[\sqrt{1-\varepsilon^2}\,\cos(\phi_h-\phi_S)\,F_{LT}^{\cos(\phi_h-\phi_S)}+\sqrt{2\varepsilon(1-\varepsilon)}\,\cos\phi_S\,F_{LT}^{\cos\phi_S}$$

$$+\sqrt{2\varepsilon(1-\varepsilon)}\,\cos(2\phi_h-\phi_S)\,F_{LT}^{\cos(2\phi_h-\phi_S)}\Big]\Big\},$$

Bacchetta et al., JHEP 0702:093,2007

Unpol. target ✓

Long. Pol. target ✓

Trans. Pol. Target

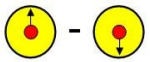
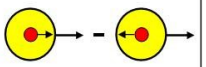
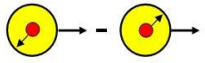
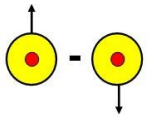
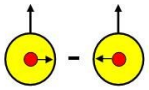
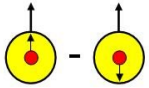
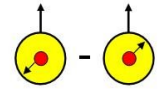
Experiment in preparation (CLAS)
Transversely polarized ^{3}He (E06-010/011) and proton/ deuterium targets (E08-015) Hall A

18 structure functions !!

Nucleon TMDs

$$d\sigma^h \propto \sum f^{H\to q}(x, k_T) \otimes \mathrm{d}\sigma_q(y) \otimes D^{q\to h}(z, p_\perp)$$

leading twist TMDs

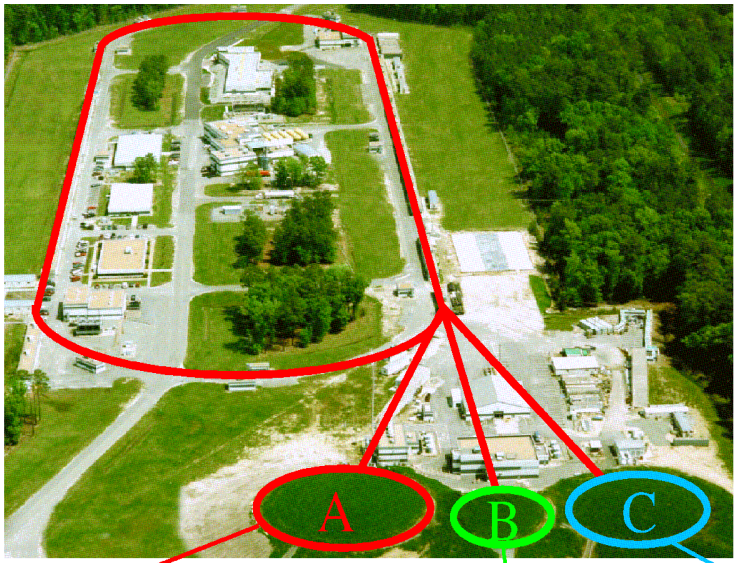
		quark		
		U	**L**	**T**
nucleon	**U**	**f1** 		$h_1^\perp$ 
	L		**g1** 	$h_{1L}^\perp$ 
	T	$f_{1T}^\perp$ 	$g_{1T}^\perp$ 	**h1**  $h_{1T}^\perp$ 

+ Higher twist distribution functions

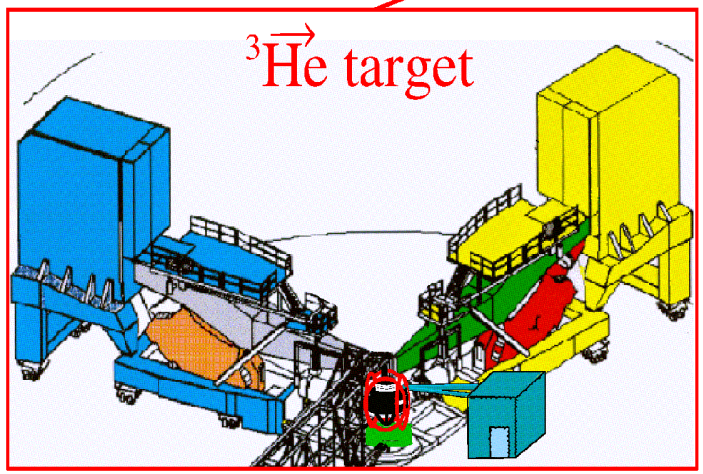
N/q	U	L	T
U	$f^\perp$	$g^\perp$	$h, \mathbf{e}$
L	$f_L^\perp$	$g_L^\perp$	$\mathbf{h_L}, e_L$
T	$f_T, f_T^\perp$	$\mathbf{g_T}, g_T^\perp$	$h_T, e_T, h_T^\perp, e_T^\perp$

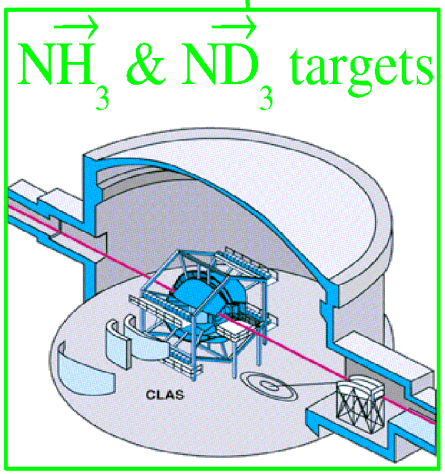
Jefferson Lab Experimental Halls

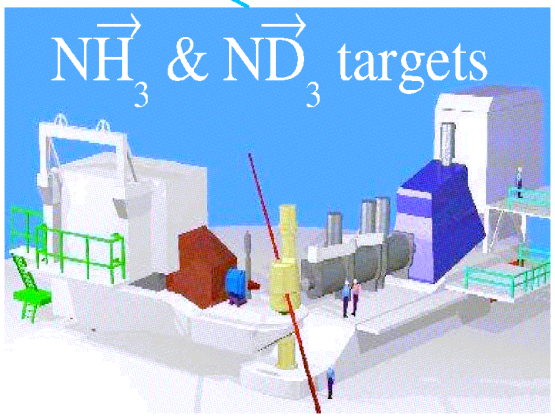
6 GeV polarized
electron beam
Pol=85%, 180μA



Will be upgraded to
12 GeV by ~2014







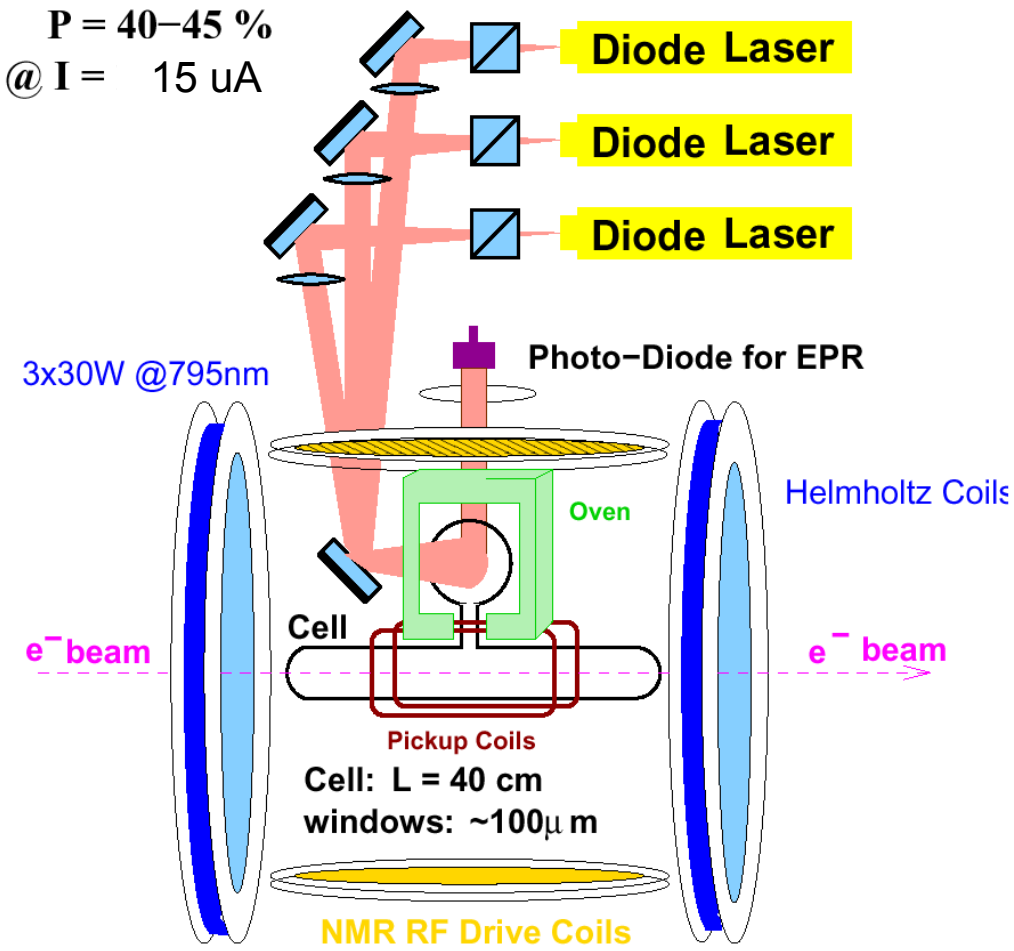
HallA: two HRS'

Hall B:CLAS

Hall C: HMS+SOS

Hall A

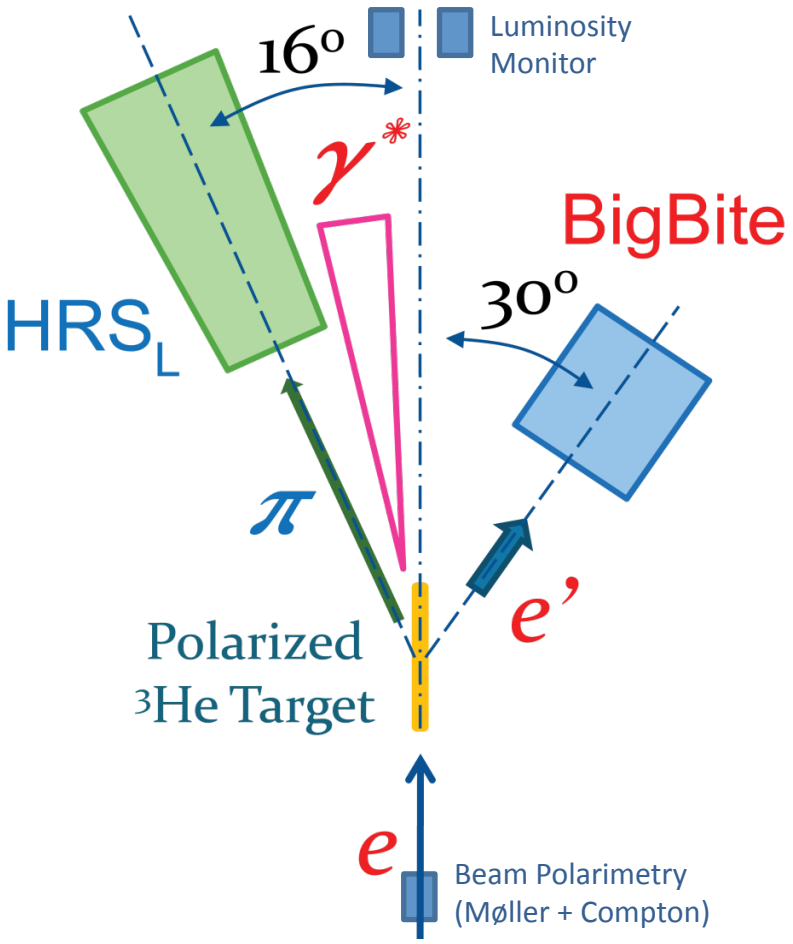
JLab Polarized ^{3}He Target



- ✓longitudinal, transverse
- ✓Luminosity=10^{36} (1/s) (highest in the world)
- ✓High in-beam polarization ~ 60%
- ✓Effective polarized neutron target

E06-010 Experiment $^3He^{\uparrow}(\vec{e},e'\pi^{\pm})X$

- **First measurement on n (^{3}He)**
- Polarized ^{3}He Target
- Polarized Electron Beam, 5.9 GeV
  - ~80% Polarization
  - Fast Flipping at 30Hz
- BigBite at 30º as Electron Arm
  - P_e = 0.7 ~ 2.2 GeV/c
- HRS_L at 16º as Hadron Arm
  - P_h = 2.35 GeV/c
  - Excellent PID for π/K/p
- **7 PhD Thesis Students (5 graduated)**

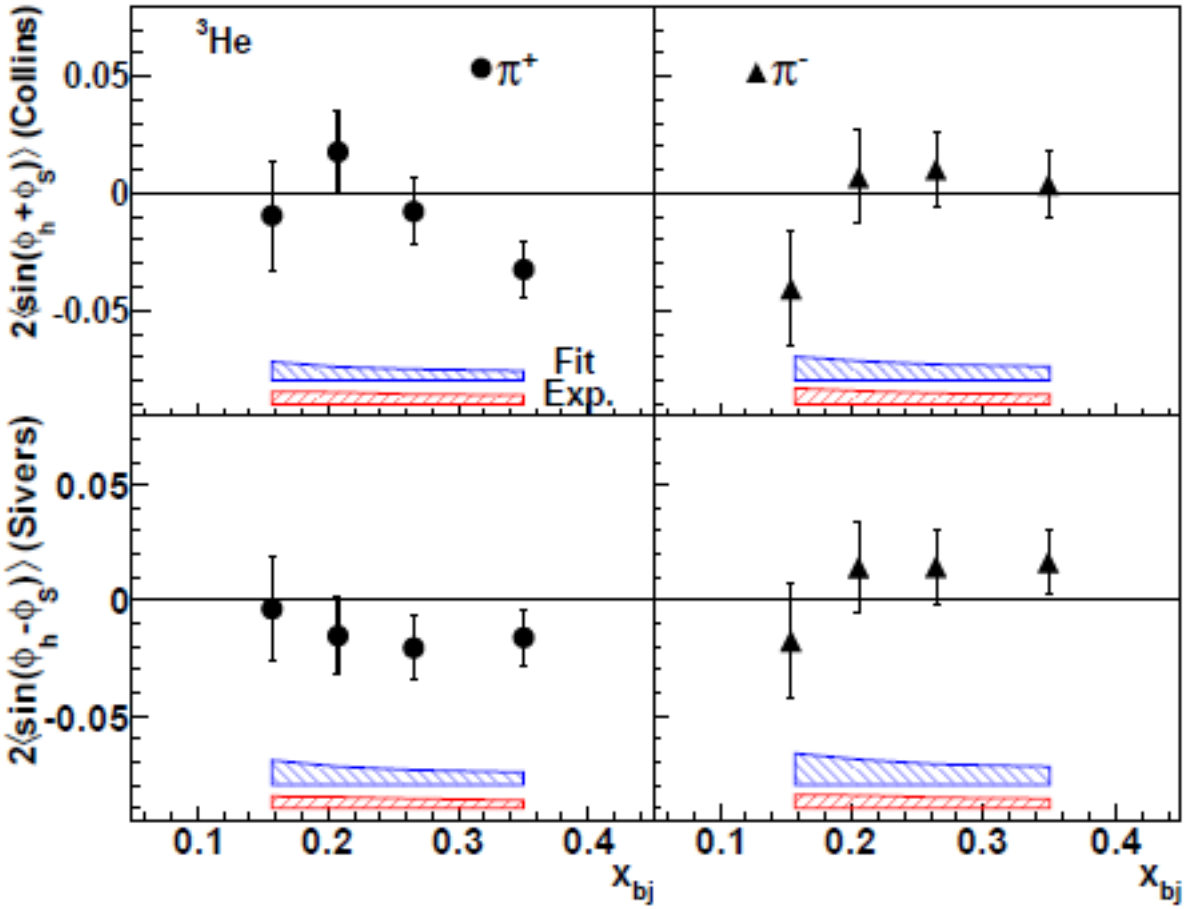


Slides from Jian-Ping Chen

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

arXiv: 1106.0363, submitted to PRL

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

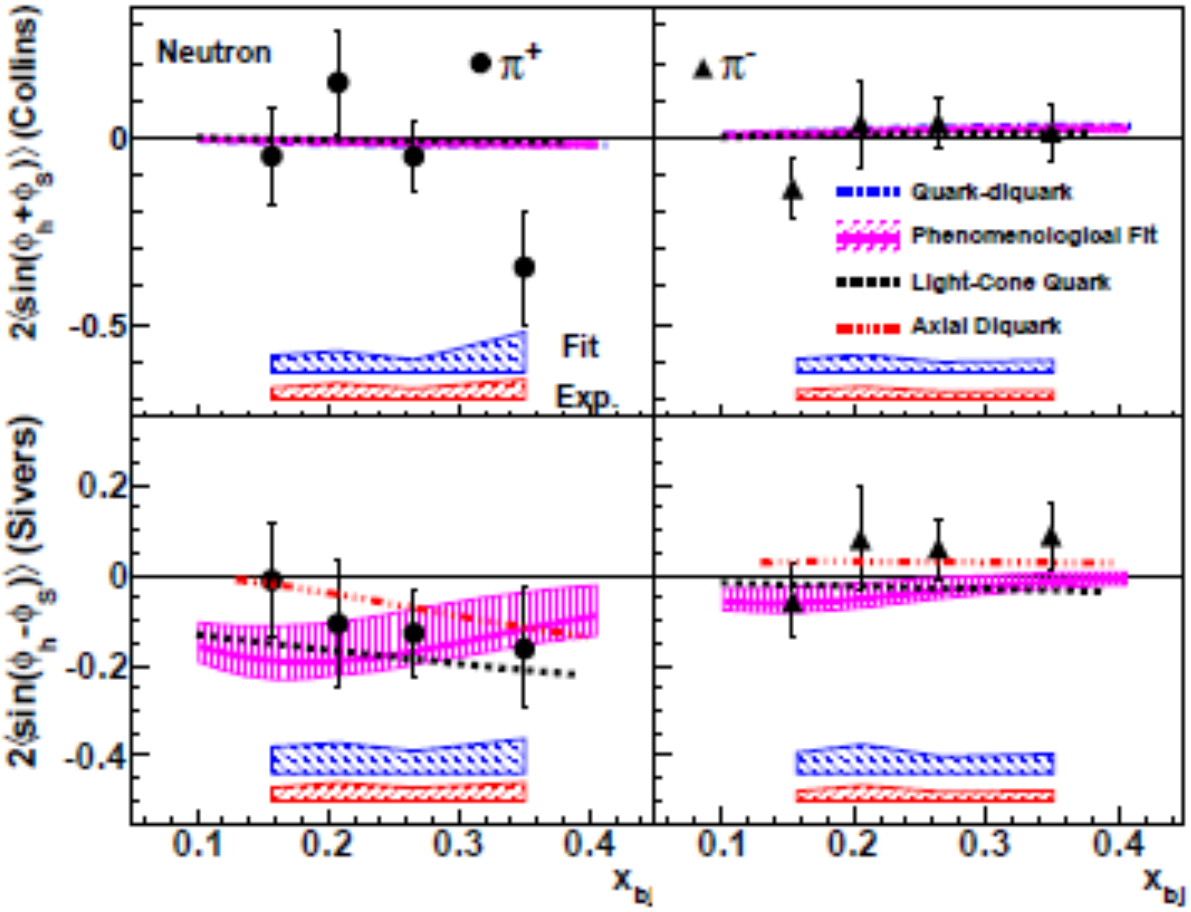


^{3}He Collins SSA small
Non-zero at highest x for π^+

^{3}He Sivers SSA:
negative for π^+,

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

Results on Neutron



Collins asymmetries are not large, except at x=0.34

Sivers

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

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

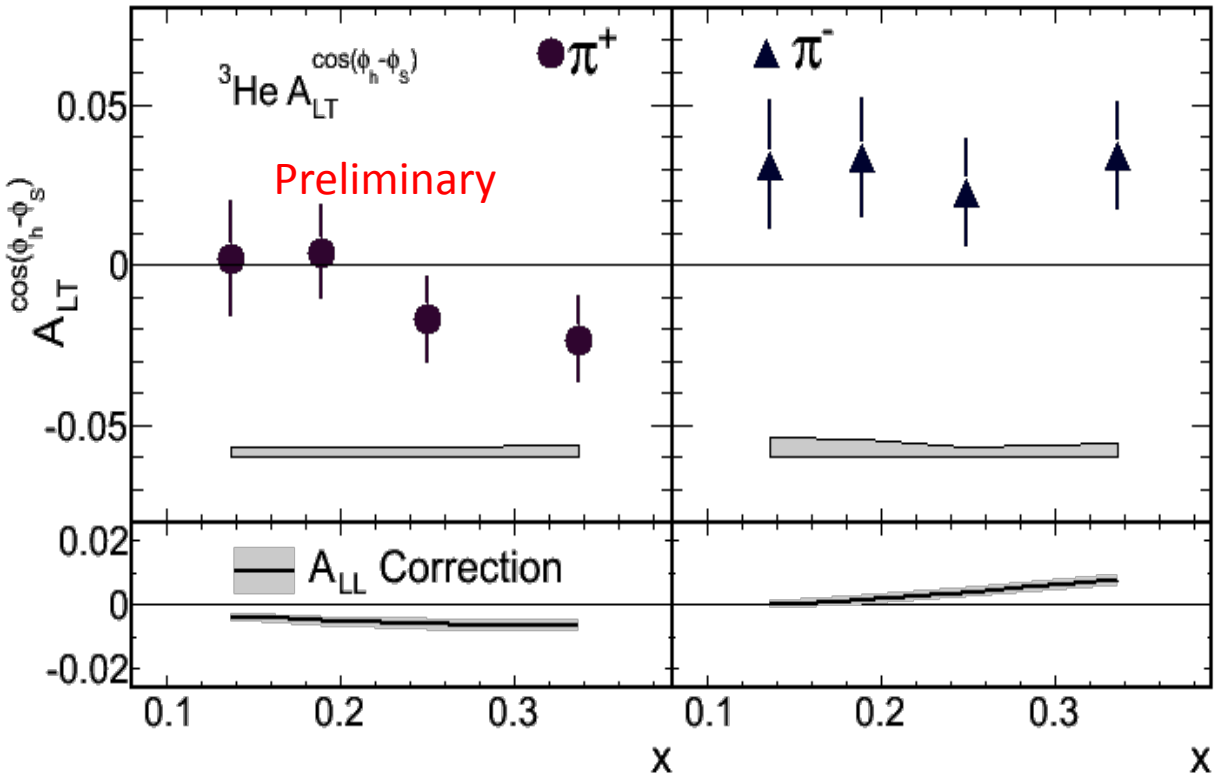
Asymmetry A_{LT} Result

To leading twist:

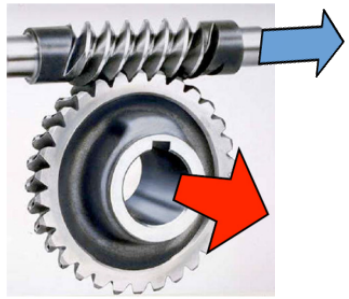
$$A_{\mathrm{LT}}^{\cos(\phi_h-\phi_s)} \propto F_{LT}^{\cos(\phi_h-\phi_s)} \propto g_{1T}^{q} \otimes D_{1q}^{h}$$

- **^{3}He A_{LT}**

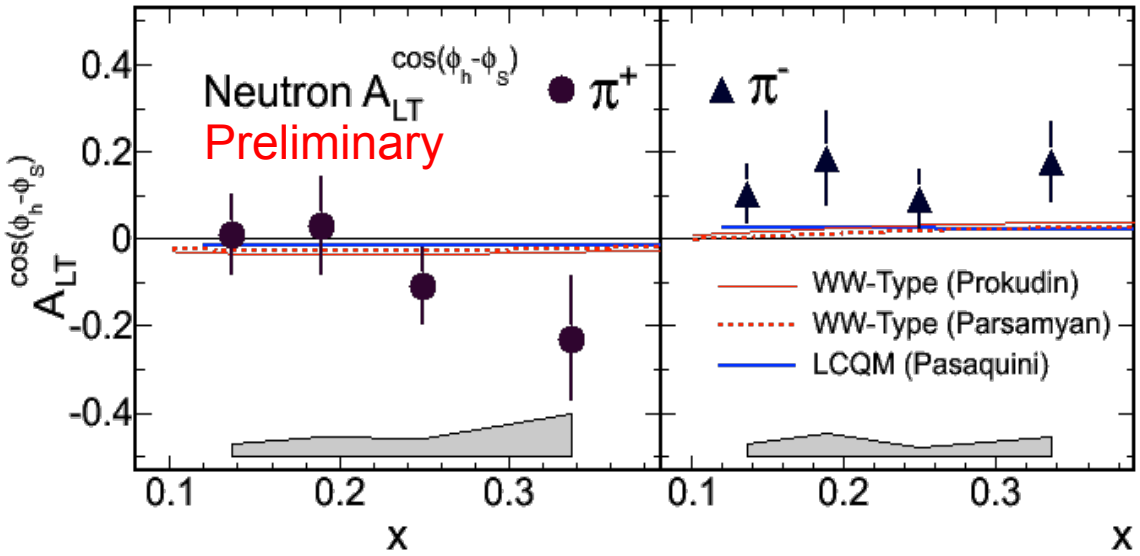
  Positive for π-



Neutron A_{LT} Extraction

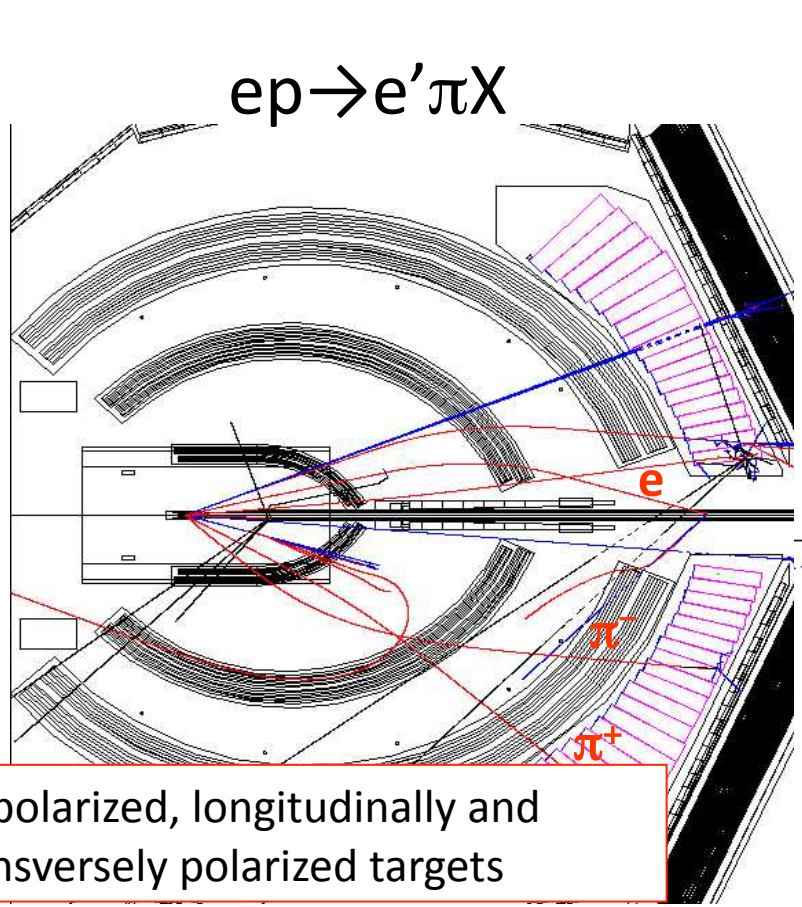


- $A_{LT}^{^3\mathrm{He}} = P_n \frac{\sigma_n}{\sigma_{^3\mathrm{He}}} A_{LT}^n + P_p \frac{2\sigma_p}{\sigma_{^3\mathrm{He}}} A_{LT}^p$ $\quad \begin{cases} P_n = 0.86^{+0.036}_{-0.02} \\ P_p = -0.028^{+0.009}_{-0.004} \end{cases}$
  - Corrected for proton dilution, f_p
  - Predicted proton asymmetry contribution < 1.5% (π^+), 0.6% (π^-)
- $A_{\mathrm{LT}}^n \propto g_{1T}^q \otimes D_{1q}^h$
  - Dominated by L=0 (S) and L=1 (P) interference
- Consist w/ model in signs, suggest larger asymmetry

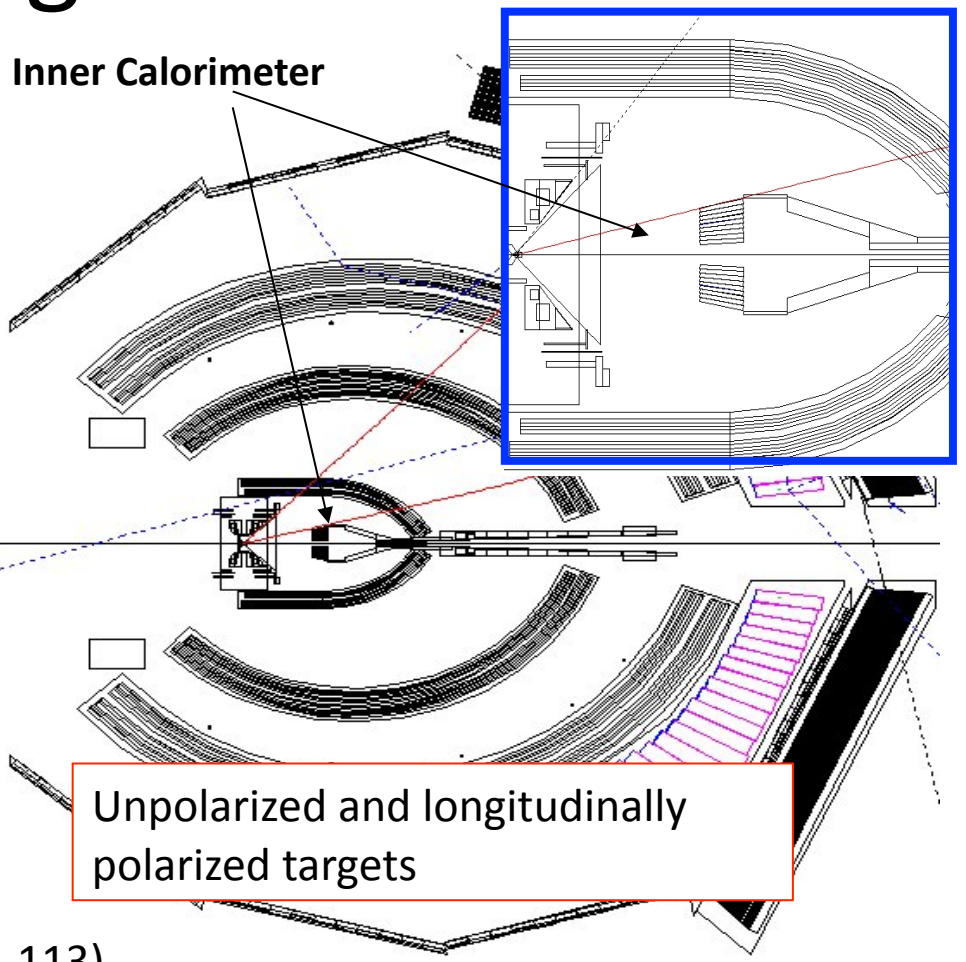


Hall B

CLAS configurations



Unpolarized, longitudinally and transversely polarized targets

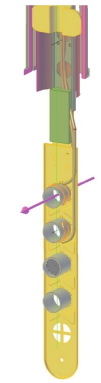


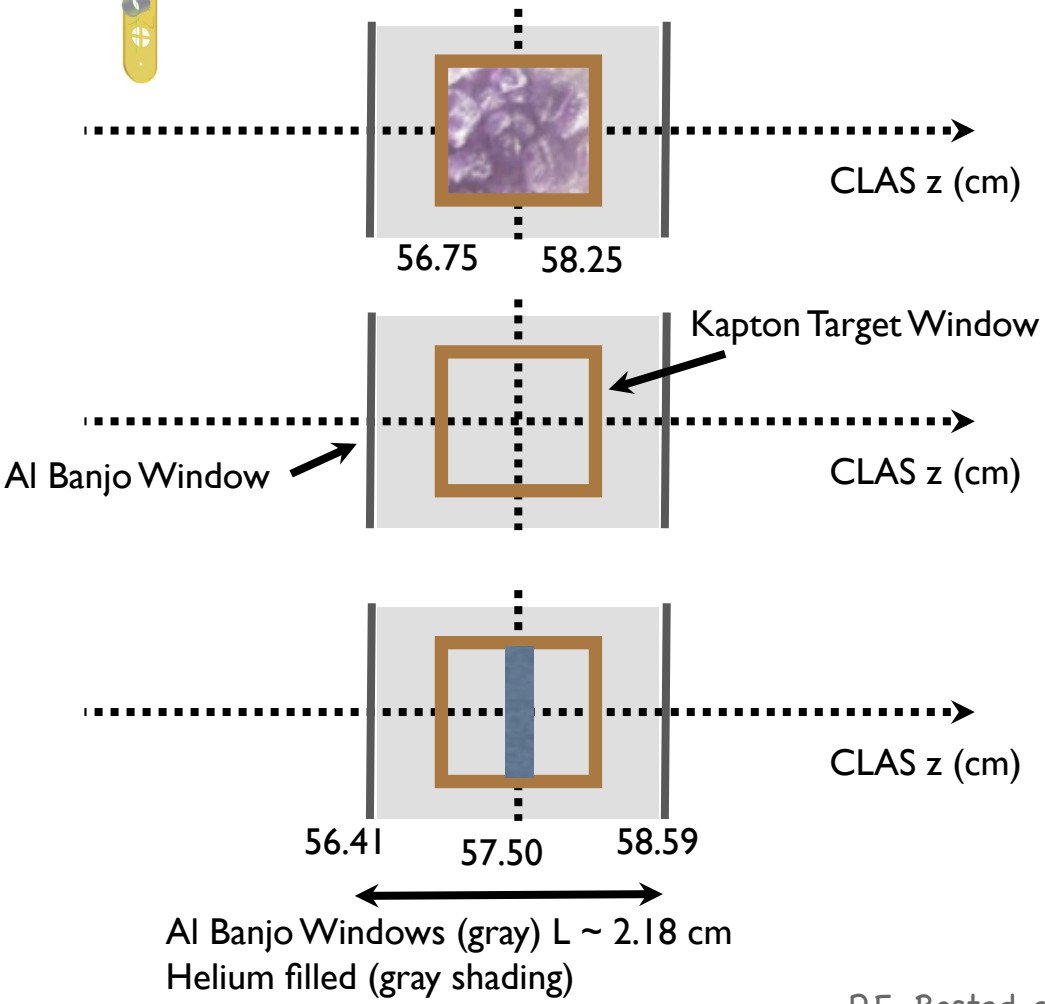
Unpolarized and longitudinally polarized targets

1) Polarized NH3/ND3 (no IC, ~5 days E05-113)
2) Unpolarized H (with IC ~ 60 days)
3) Polarized NH3/ND3 with IC 60 days
   10% of data on carbon
4) Polarized HD-Ice (no IC, 25 days)

- **Polarizations:**
- **Beam: ~80%**
- **NH3 proton 80%, ND3 ~30%**
- **HD (H-75%,D-25%)**

Dilution factor for NH3/ ND3





$$\sigma = \frac{\sigma_p + \sigma_n}{2} \qquad n \approx \sum_i \rho_i \sigma_i$$

$$n_C \approx A_C \sigma$$

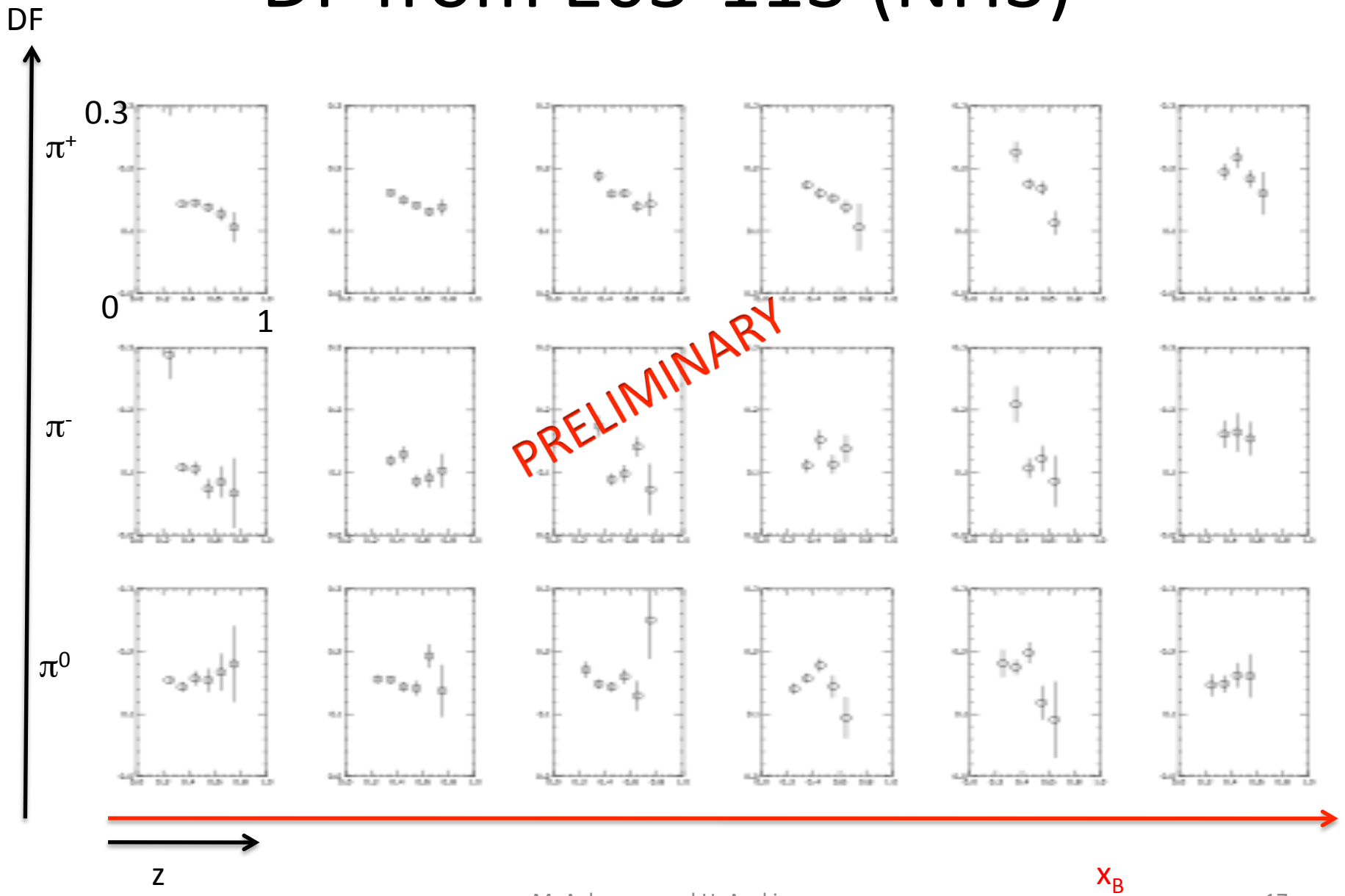
$$n_{NH_3} \approx A_{NH_3}\sigma + B_{NH_3}\sigma_p$$

$$f_{DF} = \frac{B_{NH_3}\sigma_p}{A_{NH_3}\sigma + B_{NH_3}\sigma_p}$$

A and B hold density information for all materials in the carbon and ammonia targets

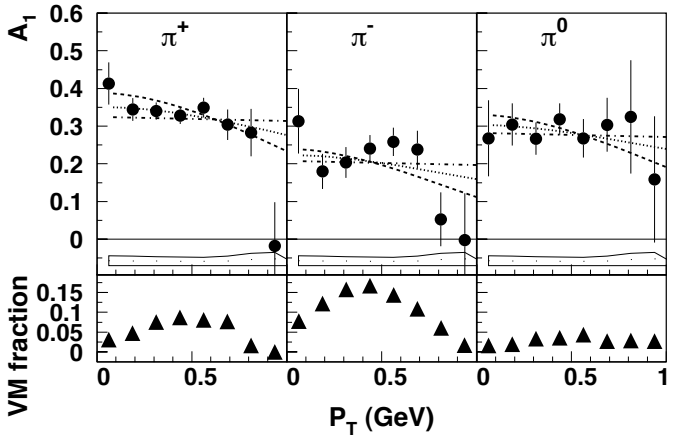
P.E. Bosted and M.E. Christy Phys Rev. C 77, 065206 (2008)

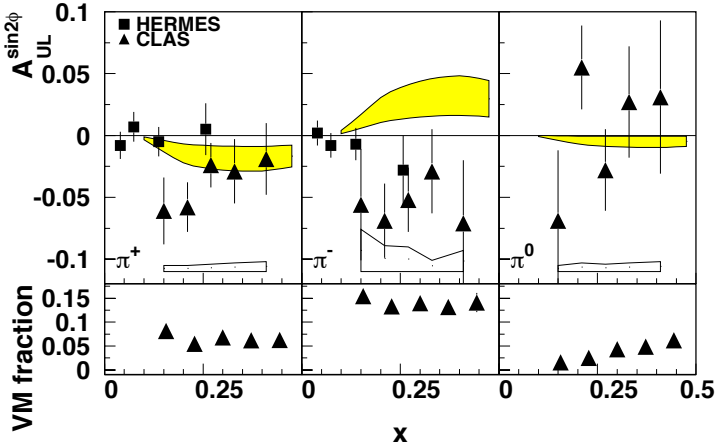
DF from E05-113 (NH3)

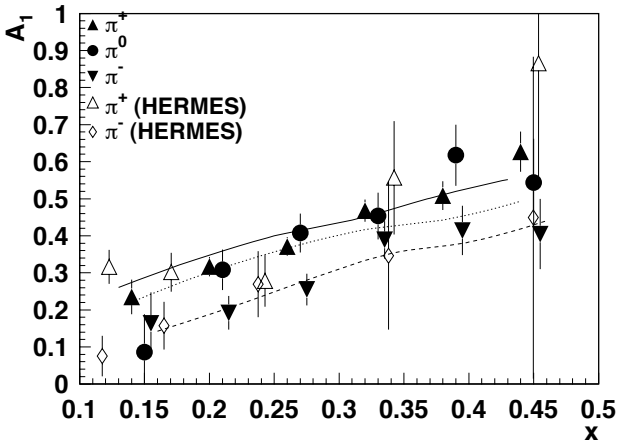


Longitudinally polarized NH3 target E05-113

Avakian PRL105 (2010)







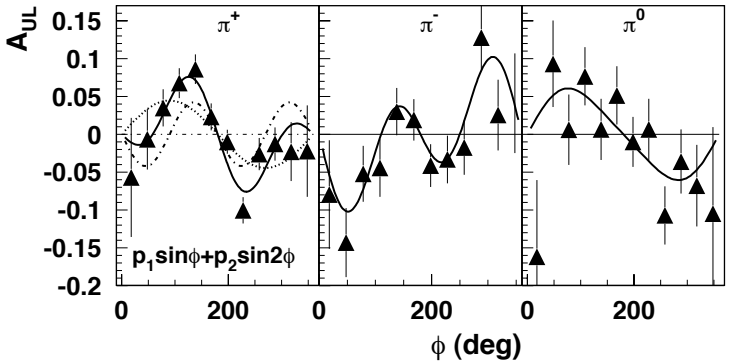
CLAS and HERMES g1 are consistent.

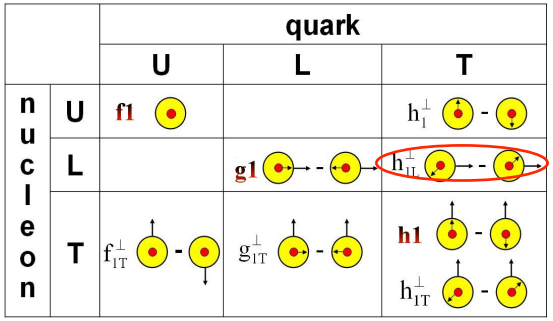
The sin2φ moment of the π^+ at large x_B is dominated by *u*-quarks, therefore with additional input from other experiments can provide a first glimpse of twist 2 $h_{1L}^{\perp}$ function

CLAS data suggests that width of g_1 is less than the width of f_1

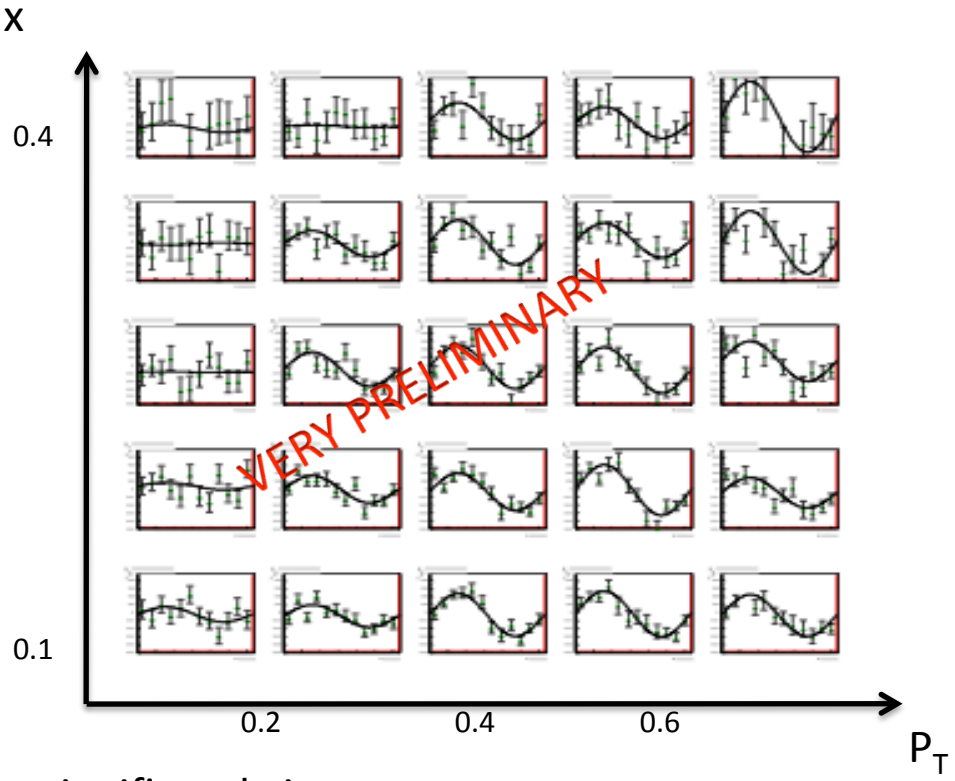
New data

Avakian PRL105 (2010)





New data for π^0
S. Jawalkar



New data with IC for positive pions significantly improves statistical errors and allows **more than one dimensional** extraction of A_{UL} an A_{LL}.

Extraction of kinematic dependences of TMD

Boer, Gamberg, Musch &Prokudin arXiv:1107.5294

$$2\pi \int_0^{\frac{\pi}{2}} d\phi_h \int_0^{\infty} d|\mathbf{P}_{h\perp}||\mathbf{P}_{h\perp}|J_0(|\mathbf{P}_{h\perp}||\mathbf{b}_T|) \left[\frac{d\sigma}{dx_B dy d\phi_S dz_h d\phi_h}|\mathbf{P}_\perp d|\mathbf{P}_{h\perp}|\right]$$
$$= \frac{\alpha^2}{yQ^2}\frac{y^2}{(1-\epsilon)}(1+\frac{\gamma^2}{2x_B})\sum_\alpha e_\alpha^2 \left\{\tilde{f}_1^a(x,z^2\mathbf{b}_T^2) + S_\parallel \lambda_e \sqrt{1-\epsilon^2}\tilde{g}_1^a(x,z^2\mathbf{b}_T^2)\right\}\tilde{D}_1^a(z\mathbf{b}_T^2)$$

$$\Delta u(x,b_T)/u(x,b_T) = \frac{S_\pi^{pol+} - S_\pi^{pol-}}{S_\pi^{unp+} + S_\pi^{unp-}}$$

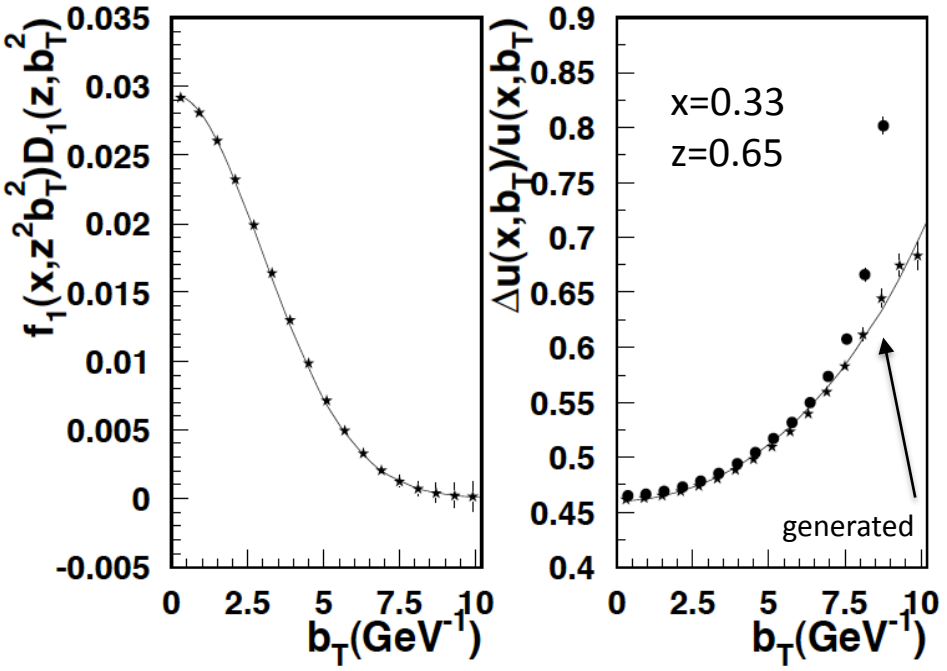
$$S_\pi^{unp\pm}(x_i,z_i,b_{Tj}) = \sum_{i=1}^{N_\pi^+/N_\pi^-} J_0(b_{Tj}P_{Ti})/\eta/A(x_i,y_i)$$

acceptance

$$S_\pi^{pol\pm}(x_i,z_i,b_{Tj}) = \sum_{i=1}^{N_\pi^+/N_\pi^-} J_0(b_{Tj}P_{Ti})/\eta/A(x_i,y_i)/\sqrt{1-\varepsilon}$$

$$A(x,y) = \frac{\alpha^2}{x_B y Q^2}\frac{y^2}{(1-\varepsilon)}\left(1+\frac{\gamma^2}{2x_B}\right)$$

J_0 = Bessel function $\quad \tilde{f}_1, \tilde{D}_1$ = TMDs Fourier transf.

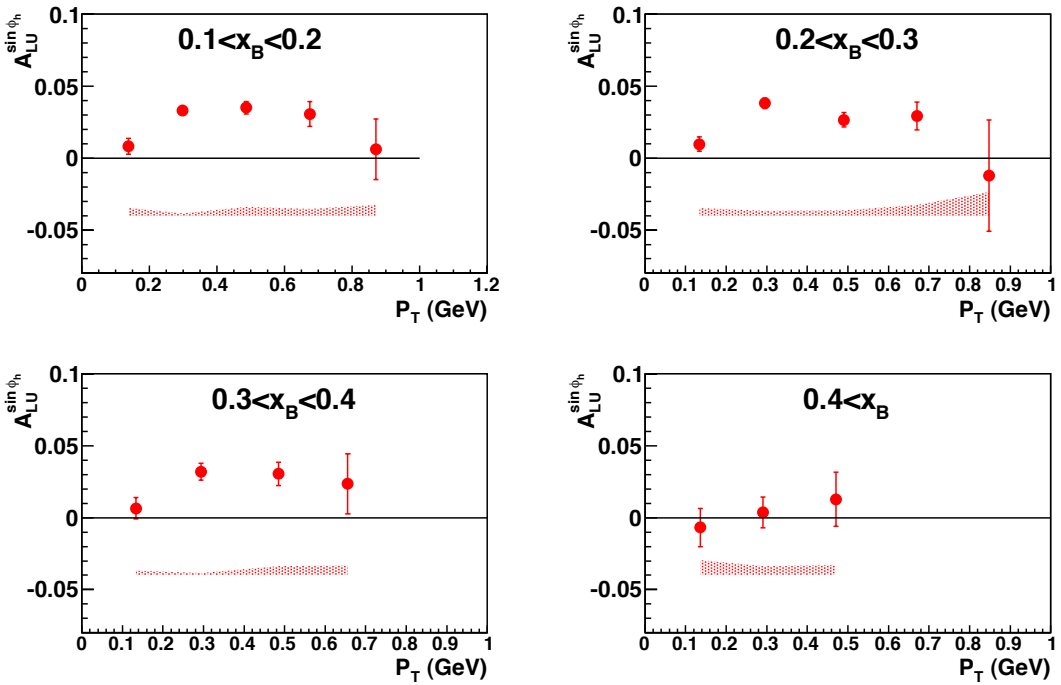


- The formalism in **b_T-space** avoids convolutions → easier to **perform a model independent analysis**
- The transformation depends on the parameter **$|b_T|$**
- Wide P_T range required for the extraction of b_T dependences for all relevant range of b_T (up to 2 fm)

After acceptance correction (stars) the b_T-dependence of the $\Delta u/u$ ratio has been recovered in a wide range of b_T

Beam Spin Asymmetry of π^0

$$F_{LU}^{\sin(\phi_h)} = \frac{2M}{Q} \times \int d^2\boldsymbol{p_T} d^2\boldsymbol{k_T}\, \delta^{(2)}\left(\boldsymbol{p_T} - \frac{\boldsymbol{P_T}}{z} - \boldsymbol{k_T}\right) \left\{ \frac{\hat{\boldsymbol{P}}_{\boldsymbol{T}} \cdot \boldsymbol{p_T}}{M} \left[\frac{M_h}{M}\, h_1^{\perp} \frac{\tilde{E}}{z} + x_B\, g^{\perp} D_1 \right] - \frac{\hat{\boldsymbol{P}}_{\boldsymbol{T}} \cdot \boldsymbol{k_T}}{M_h} \left[\frac{M_h}{M}\, f_1 \frac{\tilde{G}^{\perp}}{z} + x_B\, e H_1^{\perp} \right] \right\}.$$



First time: A_{LU} two dimensional mapping for 0.4<z<0.7

leading twist TMDs

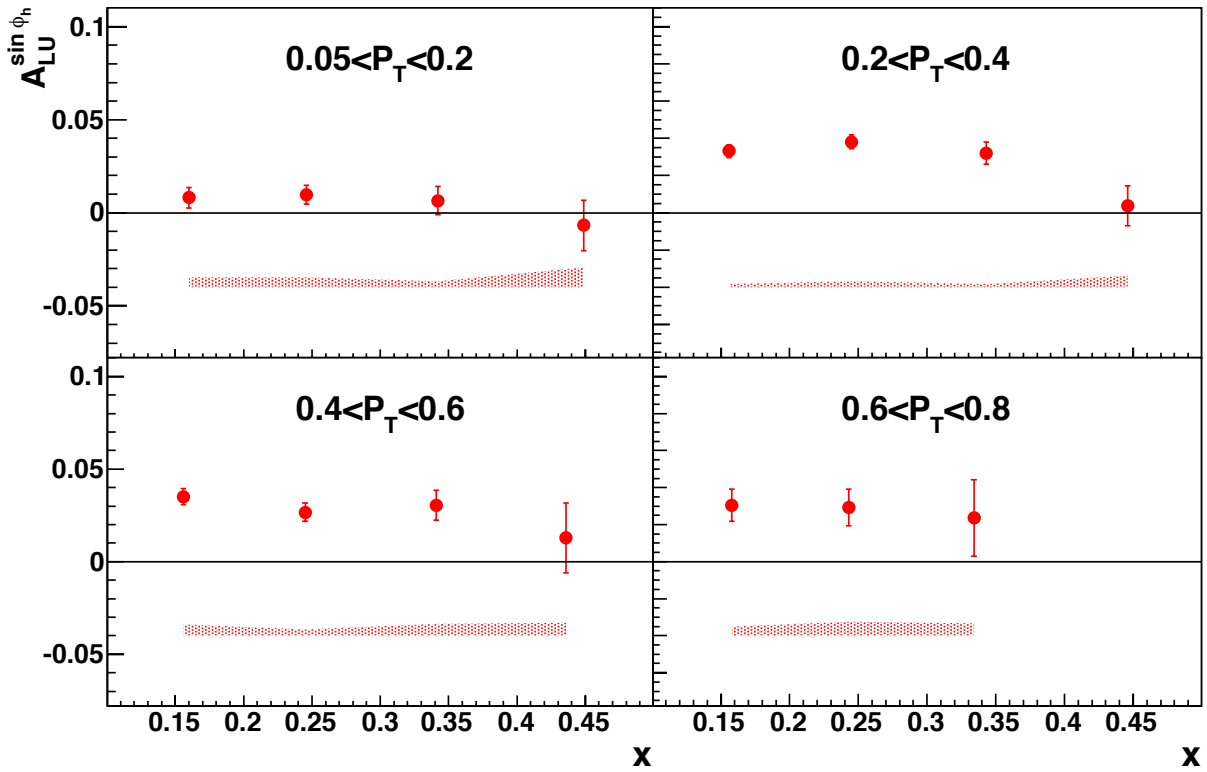
nucleon \ quark	U	L	T
U	f1		$h_1^{\perp}$
L		g1	$h_{1L}^{\perp}$
T	$f_{1T}^{\perp}$	$g_{1T}^{\perp}$	h1, $h_{1T}^{\perp}$

Higher twist TMDs

N/q	U	L	T
U	$f^{\perp}$	$g^{\perp}$	h, e
L	$f_L^{\perp}$	$g_L^{\perp}$	$\mathbf{h_L}, e_L$
T	$f_T, f_T^{\perp}$	$\mathbf{g_T}, g_T^{\perp}$	$h_T, e_T, h_T^{\perp}, e_T^{\perp}$

Beam Spin Asymmetry of π^0

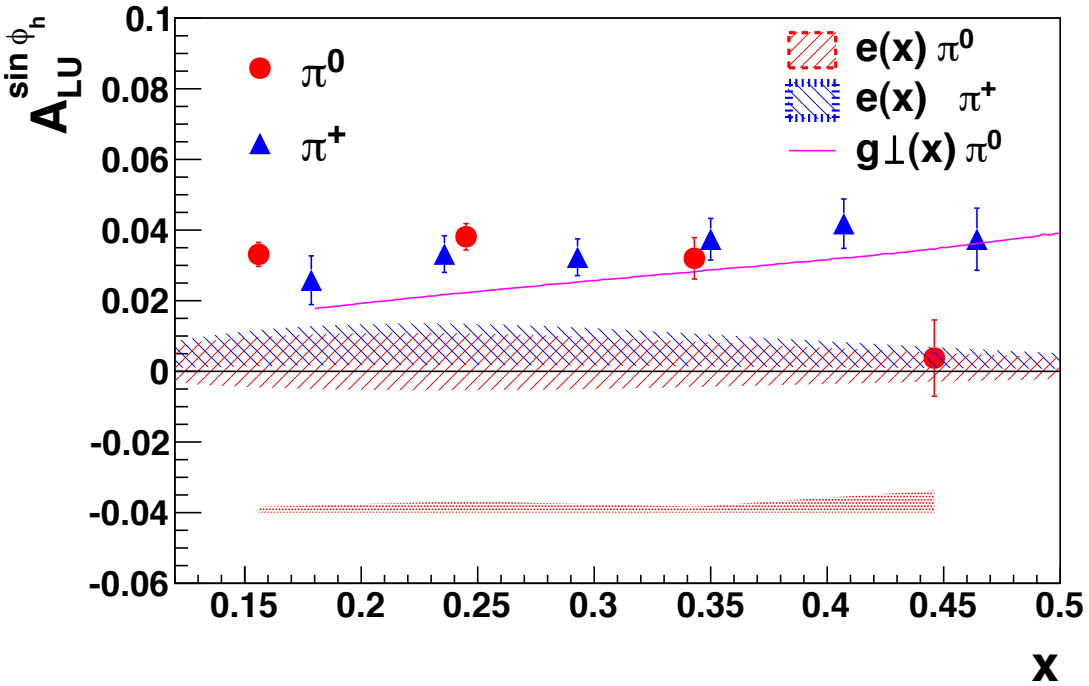
$$F_{LU}^{\sin(\phi_h)} = \frac{2M}{Q} \times \int d^2\boldsymbol{p_T} d^2\boldsymbol{k_T}\, \delta^{(2)}\left(\boldsymbol{p_T} - \frac{\boldsymbol{P_T}}{z} - \boldsymbol{k_T}\right)$$
$$\left\{ \frac{\hat{\boldsymbol{P}}_{\boldsymbol{T}} \cdot \boldsymbol{p_T}}{M} \left[\frac{M_h}{M}\, h_1^{\perp} \frac{\tilde{E}}{z} + x_B\, g^{\perp} D_1 \right] - \right.$$
$$\left. \frac{\hat{\boldsymbol{P}}_{\boldsymbol{T}} \cdot \boldsymbol{k_T}}{M_h} \left[\frac{M_h}{M}\, f_1 \frac{\tilde{G^{\perp}}}{z} + x_B\, e H_1^{\perp} \right] \right\}.$$



For fixed P_T *x* dependence is flat.

Models and Data

$$F_{LU}^{\sin(\phi_h)} = \frac{2M}{Q} \times \int d^2\boldsymbol{p_T} d^2\boldsymbol{k_T}\, \delta^{(2)}\left(\boldsymbol{p_T} - \frac{\boldsymbol{P_T}}{z} - \boldsymbol{k_T}\right) \left\{ \frac{\hat{\boldsymbol{P}}_{\boldsymbol{T}} \cdot \boldsymbol{p_T}}{M} \left[\frac{M_h}{M}\, h_1^{\perp} \frac{\tilde{E}}{z} + x_B\, g^{\perp} D_1 \right] - \frac{\hat{\boldsymbol{P}}_{\boldsymbol{T}} \cdot \boldsymbol{k_T}}{M_h} \left[\frac{M_h}{M}\, f_1 \frac{\tilde{G^{\perp}}}{z} + x_B\, e H_1^{\perp} \right] \right\}.$$



$$\int_0^{2\pi} d\phi_h \sin\phi_h \int_0^{\infty} d|\mathbf{P_{h\perp}}||\mathbf{P_{h\perp}}| \frac{2J_1(|\mathbf{P_{h\perp}}||\mathbf{b_T}|)}{zM_h|\mathbf{b_T}|} \left[\frac{d\sigma}{dxdydzd\phi_h|\mathbf{P_{h\perp}}|d|\mathbf{P_{h\perp}}|} \right]$$

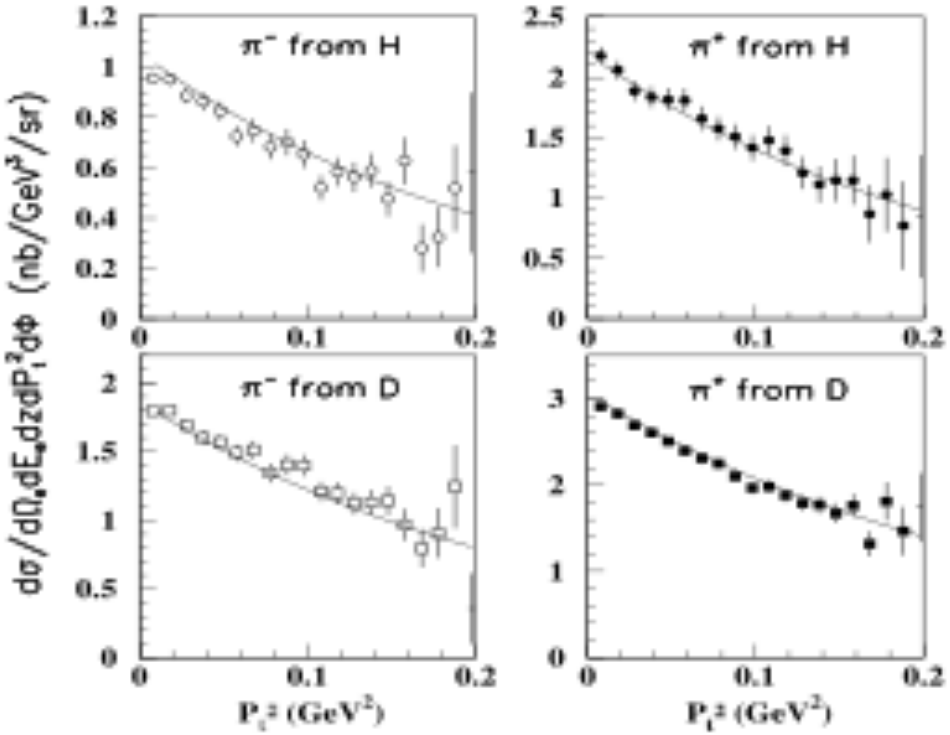
P. Schweitzer PRD67 (2003), PRD73 (2006)

$$\sum_a e_a^2 \tilde{g}^{\perp(1)a}(x, z^2 b_T^2) \tilde{D}_1^a(z, b_T^2) + \ldots$$

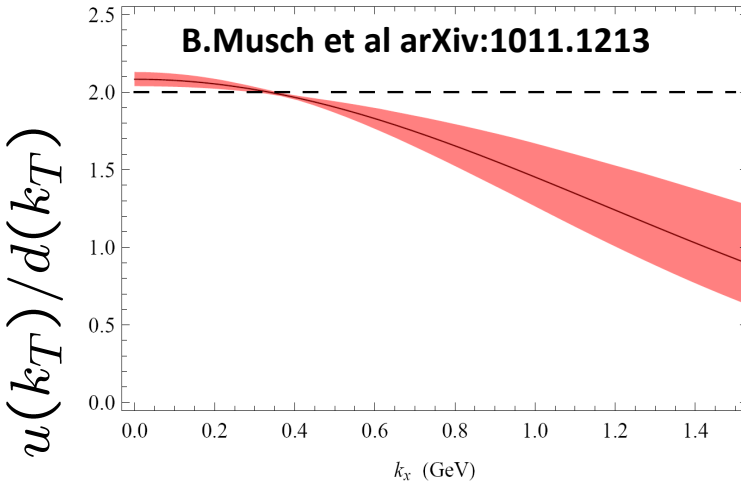
Hall C

Cross sections for semi-inclusive charged pions (p/D data)

arXiv:0709.3020v3



The P_t^2 dependence of differential cross-sections per nucleus for charged pions production on hydrogen and deuterium targets at <z>=0.55, <x>=0.32



The P_t dependence from the deuteron is found to be slightly weaker than from the proton.

There is an indication that the initial transverse momenta width of d quarks is larger than for u quarks and the transverse momentum width of the favored fragmentation function is larger than the unfavored one.

Summary

Variety of SIDIS measurements with polarized and un-polarized targets performed at JLAB at 6 GeV polarized beam.

- P_t dependence of double spin asymmetries.
- Neutron transversity/TMD measurement
- Kinematic dependences of SSA with longitudinally polarized target (A_{LU}, A_{UL} and A_{LL} of $\pi^{0/+/-}$ in multidimensional bins is coming).
- Kinematic dependences of SSA with longitudinally polarized beam and un-polarized target.

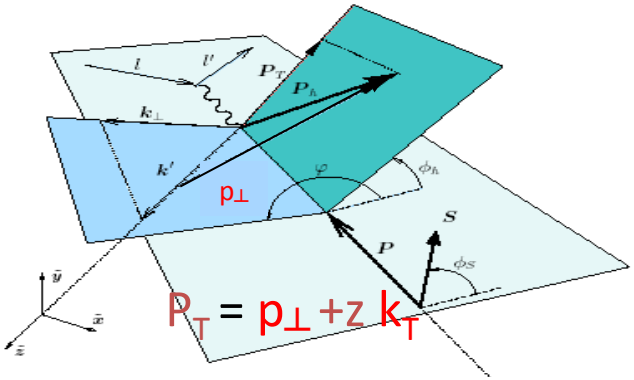
The k_T-dependent TMD flavor decomposition procedure, based on the Bessel weighting technique, has been tested using the new dedicated SIDIS MC, allowing simulation in 8D ($x,y,z,\phi,\phi_S,p_T,\lambda,h$).

FAST-MC for CLAS12

SIDIS MC in 8D ($x,y,z,\phi,\phi_S,p_T,\lambda,\pi$)

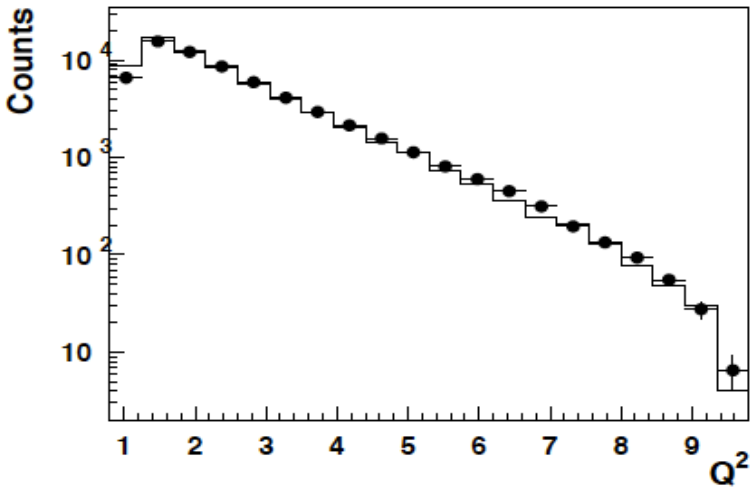
Simple model with 10% difference between f1 (0.2GeV^2) and g1 widths with a fixed width for D1 (0.14GeV^2)

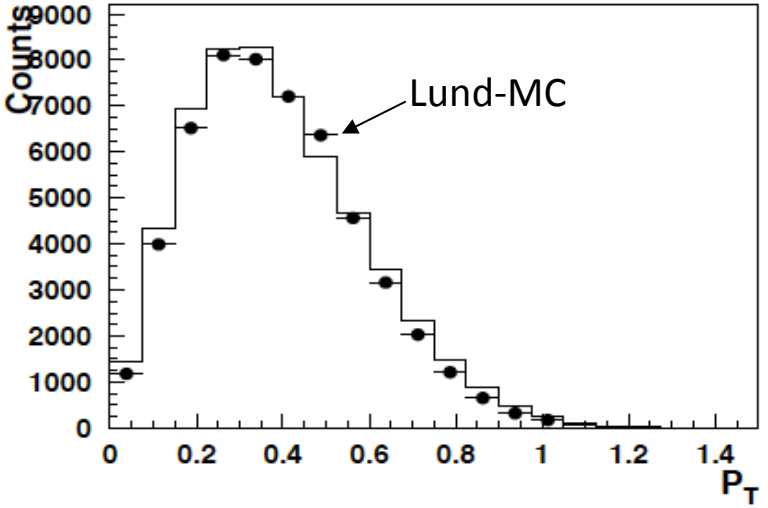
$$f_q(x,k_\perp) = f_q(x)\,\frac{1}{\pi\langle k_\perp^2\rangle}\,e^{-k_\perp^2/\langle k_\perp^2\rangle}$$



CLAS12 acceptance & resolutions

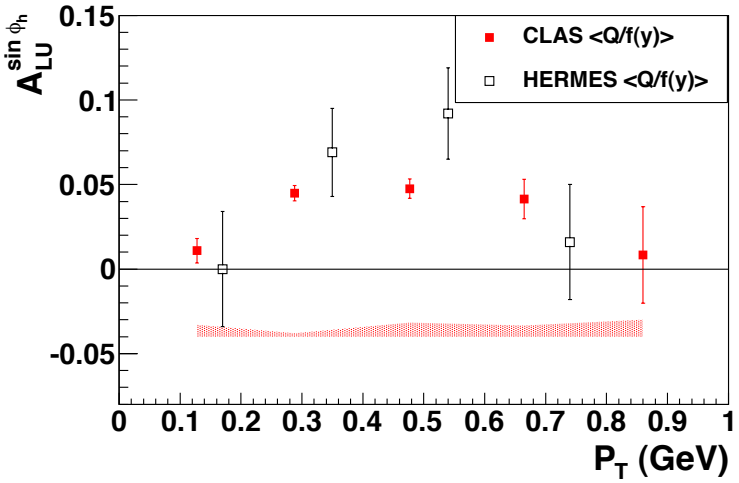
Events in CLAS12

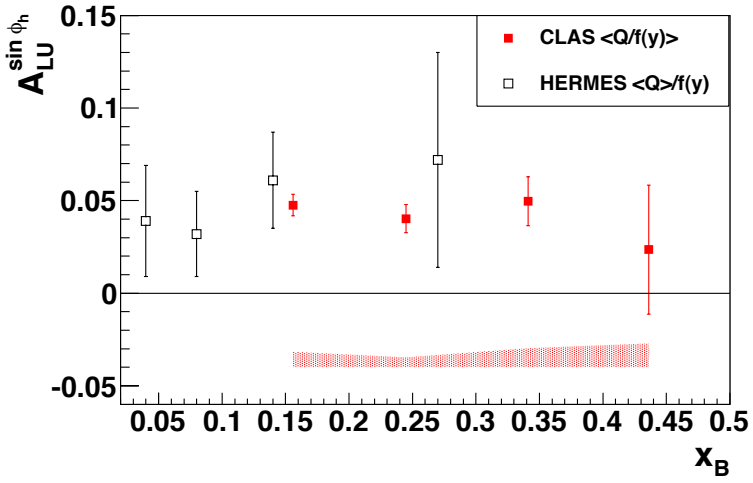




Reasonable agreement of kinematic distributions with realistic LUND simulation

Beam Spin asymmetry of π^0



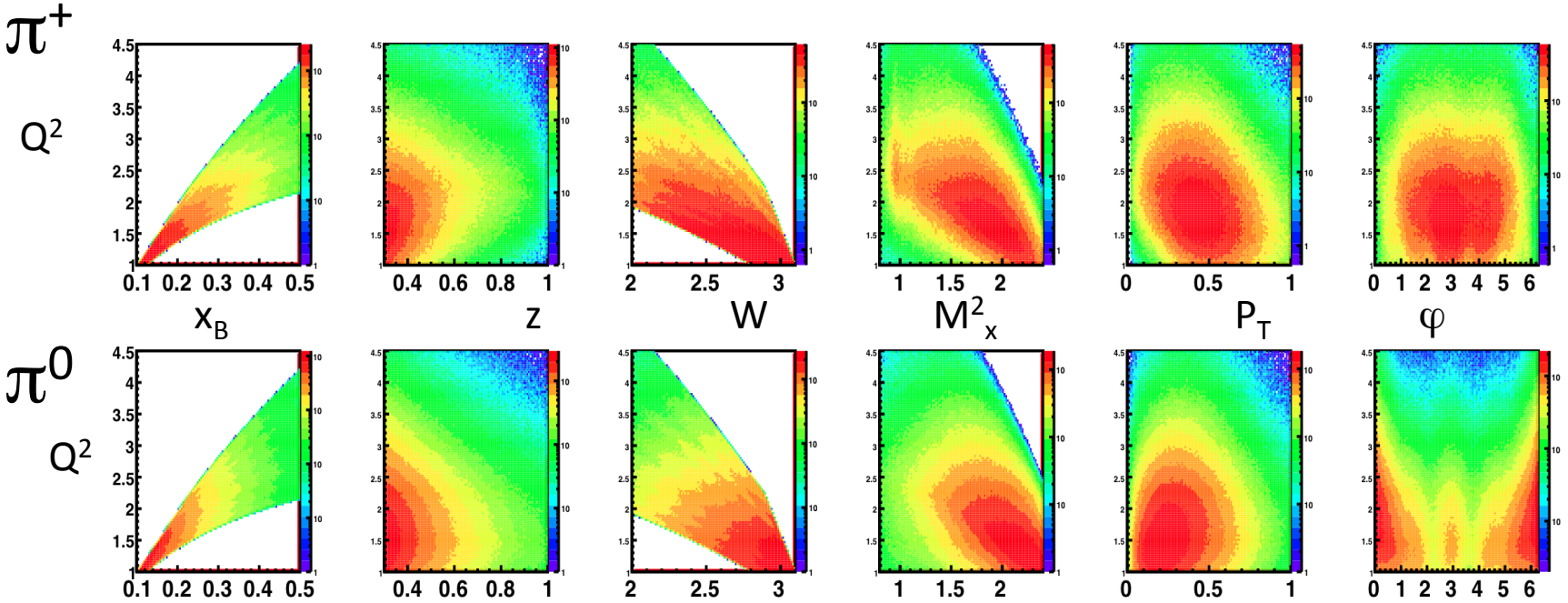


E01-113 experiment results on A_{LU} extends the x_B range and improves uncertainties.

SIDIS kinematic coverage with IC

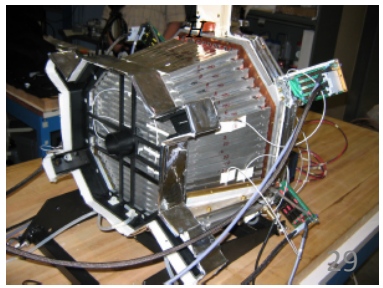
Scattering of 5.9 GeV electrons off unpolarized and polarized proton and deuteron targets

- **DIS kinematics,**
  $Q^2>1$ GeV^2, $W^2>4$ GeV^2, $M_x^2>2$ GeV^2

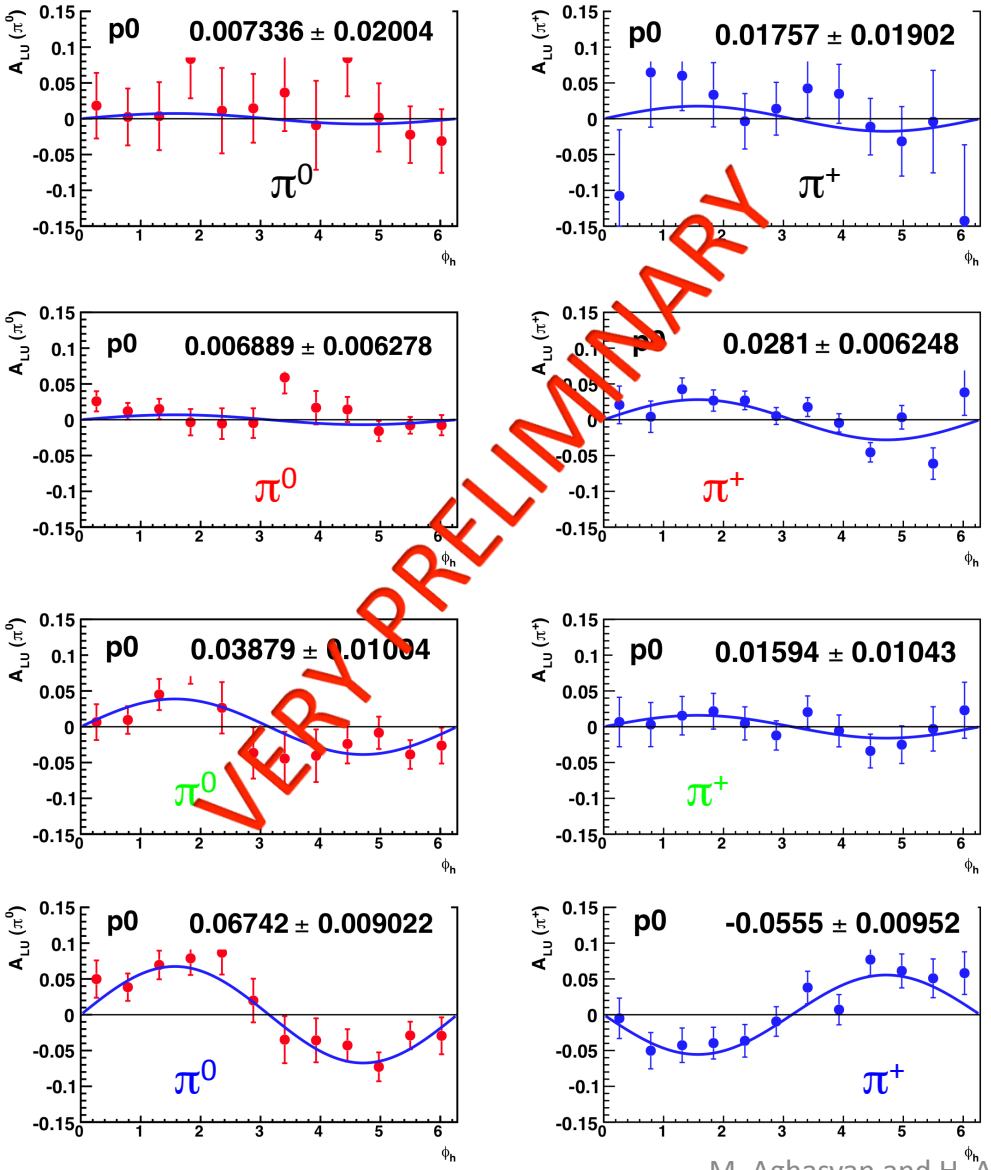


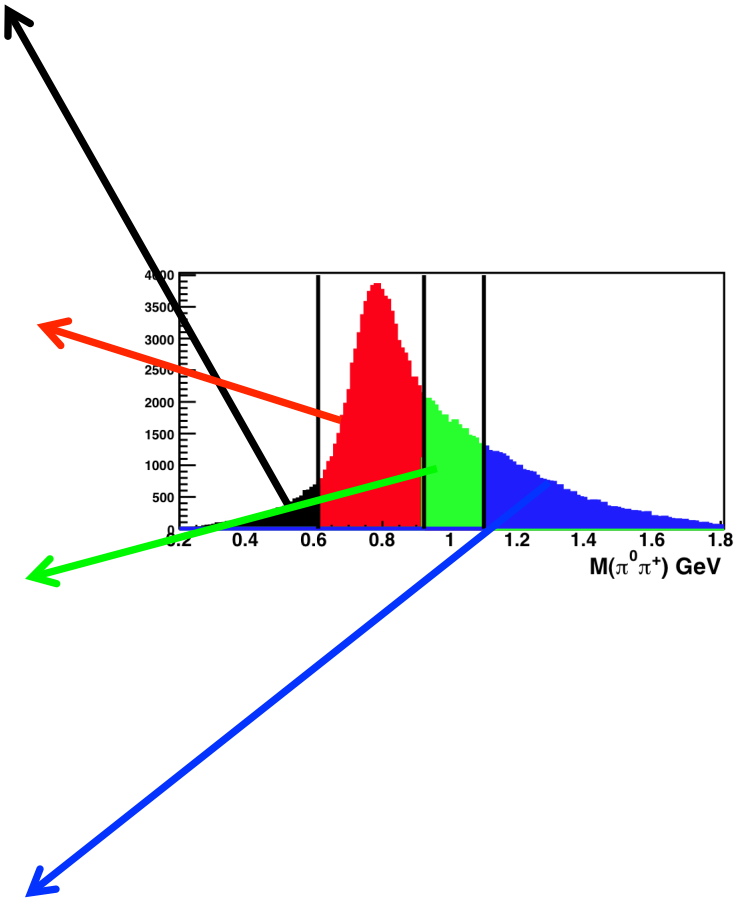
2009 data

CLAS provides a wide kinematical coverage



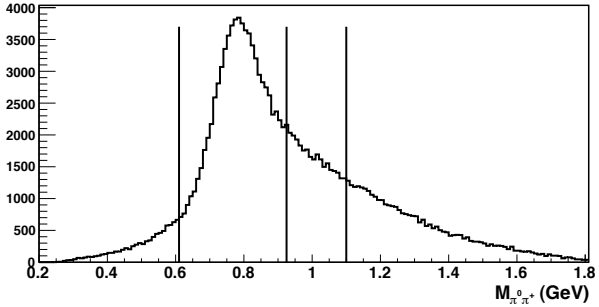
Exclusive $\pi^0\pi^+$ on proton

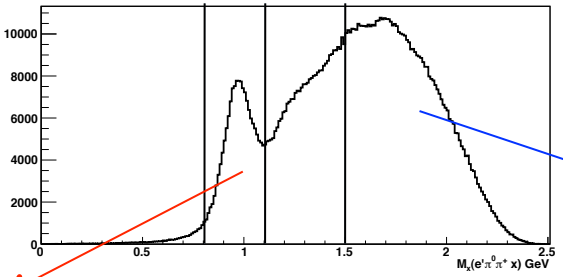




$\pi^0\pi^+$ pairs

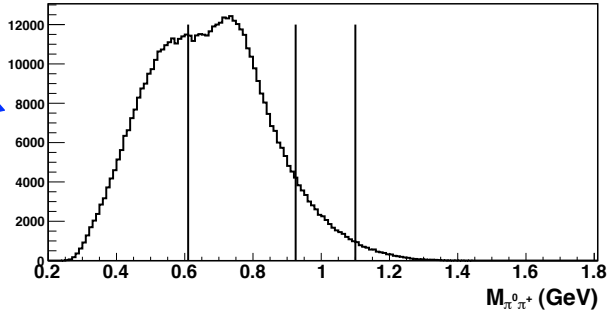
M ($\pi^+\pi^0$) GeV

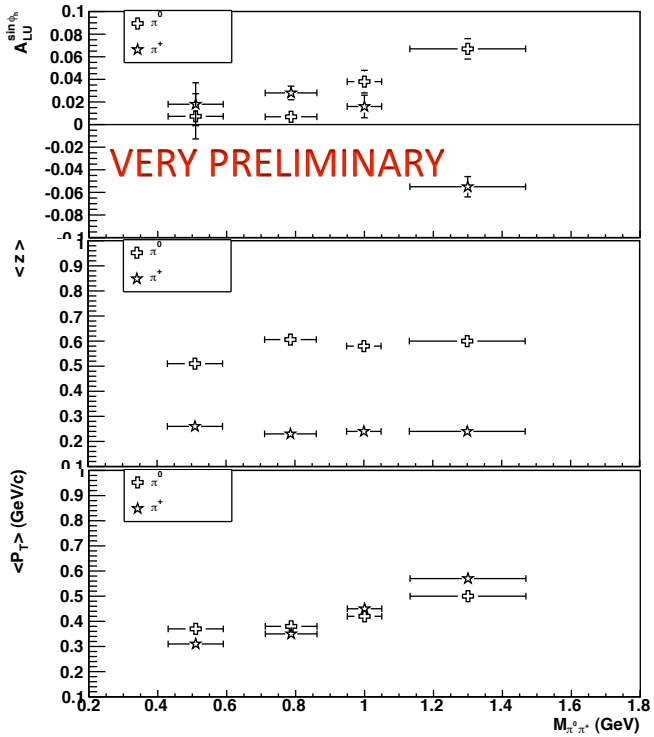




$M_x(ep->e\pi^+\pi^0 x)$ GeV

M ($\pi^+\pi^0$) GeV





Any asymmetry extraction should be done for each z, P_T, x_B, y bin!

Error bars are only Statistical.