# Studies of Spin-Orbit Correlations at JLab

M. Aghasyan, H. Avakian
(for the CLAS Collaboration)

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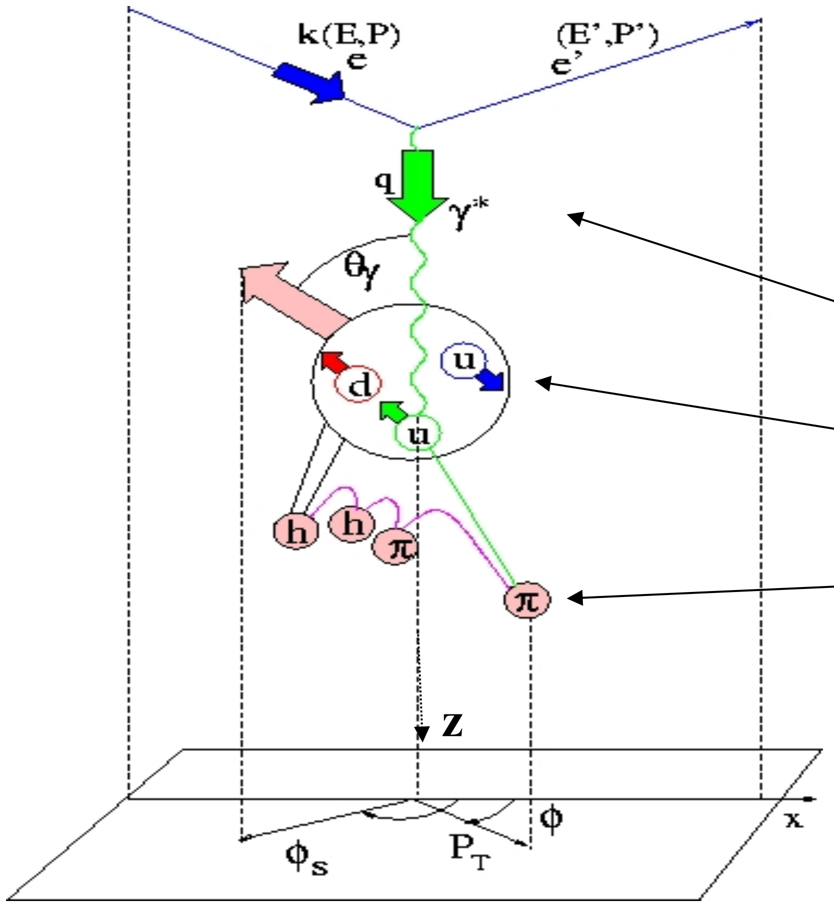
# Outline

- Physics motivation
- Unpolarized and longitudinally polarized target data.
  - Single Spin asymmetries
  - Double Spin asymmetries
- Studies of $A_{LU}$ from dihadrons
- 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

$$\frac{d\sigma}{dx\,dy\,d\psi\,dz\,d\phi_h\,dP_{h\perp}^2} = \frac{\alpha^2}{xyQ^2}\,\frac{y^2}{2\,(1-\varepsilon)}\left(1+\frac{\gamma^2}{2x}\right)\Big\{F_{UU,T} + \varepsilon F_{UU,L} + \sqrt{2\,\varepsilon(1+\varepsilon)}\,\cos\phi_h\,F_{UU}^{\cos\phi_h}$$
$$+\,\varepsilon\cos(2\phi_h)\,F_{UU}^{\cos 2\phi_h} + \lambda_e\,\sqrt{2\,\varepsilon(1-\varepsilon)}\,\sin\phi_h\,F_{LU}^{\sin\phi_h}$$
$$+\,S_\parallel\left[\sqrt{2\,\varepsilon(1+\varepsilon)}\,\sin\phi_h\,F_{UL}^{\sin\phi_h} + \varepsilon\sin(2\phi_h)\,F_{UL}^{\sin 2\phi_h}\right]$$
$$+\,S_\parallel\lambda_e\left[\sqrt{1-\varepsilon^2}\,F_{LL} + \sqrt{2\,\varepsilon(1-\varepsilon)}\,\cos\phi_h\,F_{LL}^{\cos\phi_h}\right]$$
$$+\,|\boldsymbol{S}_\perp|\Big[\sin(\phi_h-\phi_S)\left(F_{UT,T}^{\sin(\phi_h-\phi_S)} + \varepsilon\,F_{UT,L}^{\sin(\phi_h-\phi_S)}\right)$$
$$+\,\varepsilon\,\sin(\phi_h+\phi_S)\,F_{UT}^{\sin(\phi_h+\phi_S)} + \varepsilon\,\sin(3\phi_h-\phi_S)\,F_{UT}^{\sin(3\phi_h-\phi_S)}$$
$$+\,\sqrt{2\,\varepsilon(1+\varepsilon)}\,\sin\phi_S\,F_{UT}^{\sin\phi_S} + \sqrt{2\,\varepsilon(1+\varepsilon)}\,\sin(2\phi_h-\phi_S)\,F_{UT}^{\sin(2\phi_h-\phi_S)}\Big]$$
$$+\,|\boldsymbol{S}_\perp|\lambda_e\Big[\sqrt{1-\varepsilon^2}\,\cos(\phi_h-\phi_S)\,F_{LT}^{\cos(\phi_h-\phi_S)} + \sqrt{2\,\varepsilon(1-\varepsilon)}\,\cos\phi_S\,F_{LT}^{\cos\phi_S}$$
$$+\,\sqrt{2\,\varepsilon(1-\varepsilon)}\,\cos(2\phi_h-\phi_S)\,F_{LT}^{\cos(2\phi_h-\phi_S)}\Big]\Big\},$$

Unpol. target ✓

Long. Pol. target ✓

Trans. Pol. Target

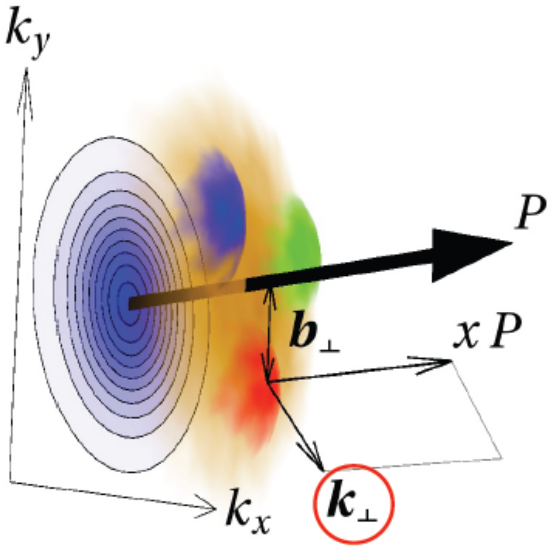
Experiment in preparation (CLAS)

**18 structure functions !!**

Bacchetta et al., JHEP 0702:093,2007

# Transverse Momentum Dependent (TMD) Distributions

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

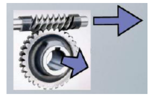


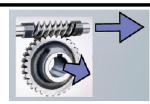

| N \ q | U | L | T |
|---|---|---|---|
| U | $f_1$ | | $h_1^\perp$ |
| L | | $g_1$ | $h_{1L}^\perp$ |
| T | $f_{1T}^\perp$ | $g_{1T}$ | $h_1$ $h_{1T}^\perp$ |

Boer-Mulders ($h_1^\perp$)

Sivers ($f_{1T}^\perp$)

pretzelosity ($h_{1T}^\perp$)





Transverse Momentum Distributions (TMDs) of partons describe the distribution of quarks and gluons in a nucleon with respect to x and the intrinsic transverse momentum $k_T$ carried by the quarks

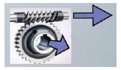
# Nucleon TMDs

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

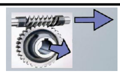
leading twist TMDs

| N \ q | U | L | T |
|---|---|---|---|
| U | $f_1$ | | $h_1^\perp$ |
| L | | $g_1$ | $h_{1L}^\perp$ |
| T | $f_{1T}^\perp$ | $g_{1T}$ | $h_1$ $h_{1T}^\perp$ |

← Boer-Mulde



↑ Sivers



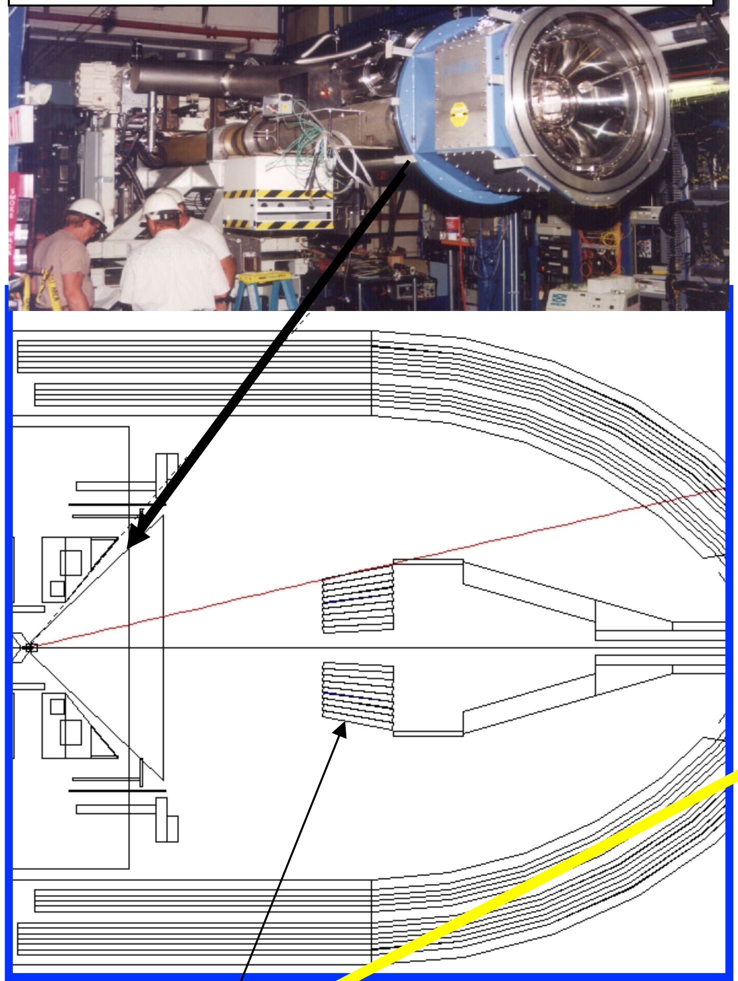
↑ pretzelosity

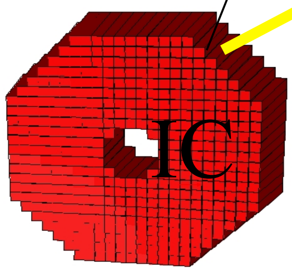
+ Higher twist distribution functions

| 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 | $f_T, f_T^\perp$ | $\mathbf{g_T}, g_T^\perp$ | $h_T, e_T, h_T^\perp, e_T^\perp$ |

# Experimental configuration

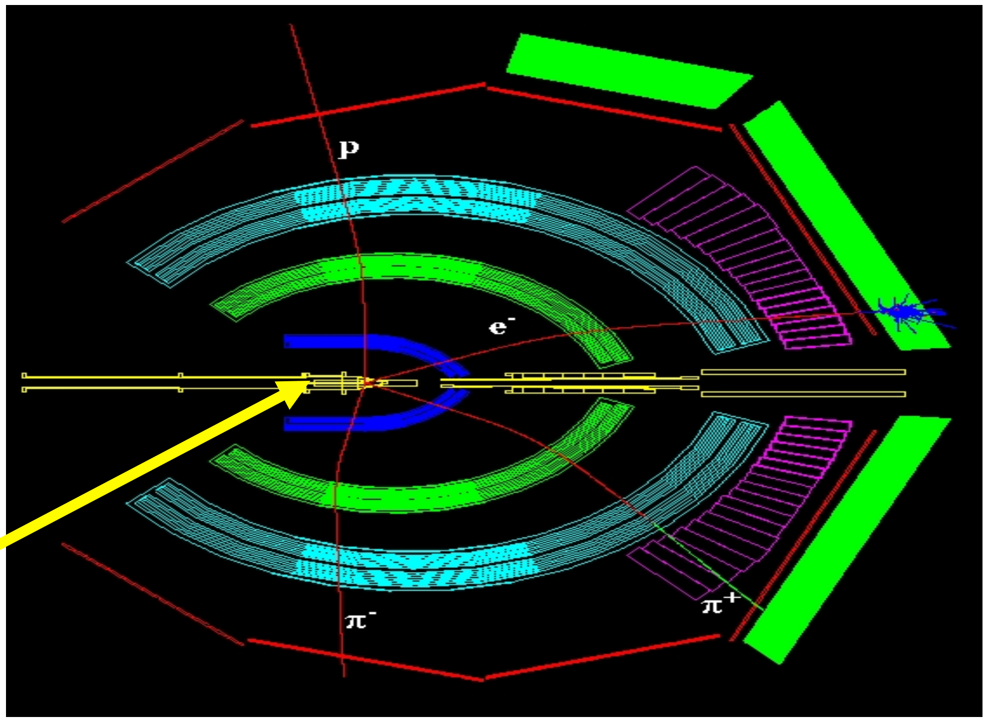
**Polarized target (NH3/ND3)**






Inner Calorimeter (424 $PbWO_4$ crystals) to detect high energy photons at forward lab angles.

Pol. $N\vec{H}_3$, $N\vec{D}_3$ targets $\langle P_H \rangle$ =0.75-0.8, $\langle P_D \rangle$=0.3
Longitudinal polarization



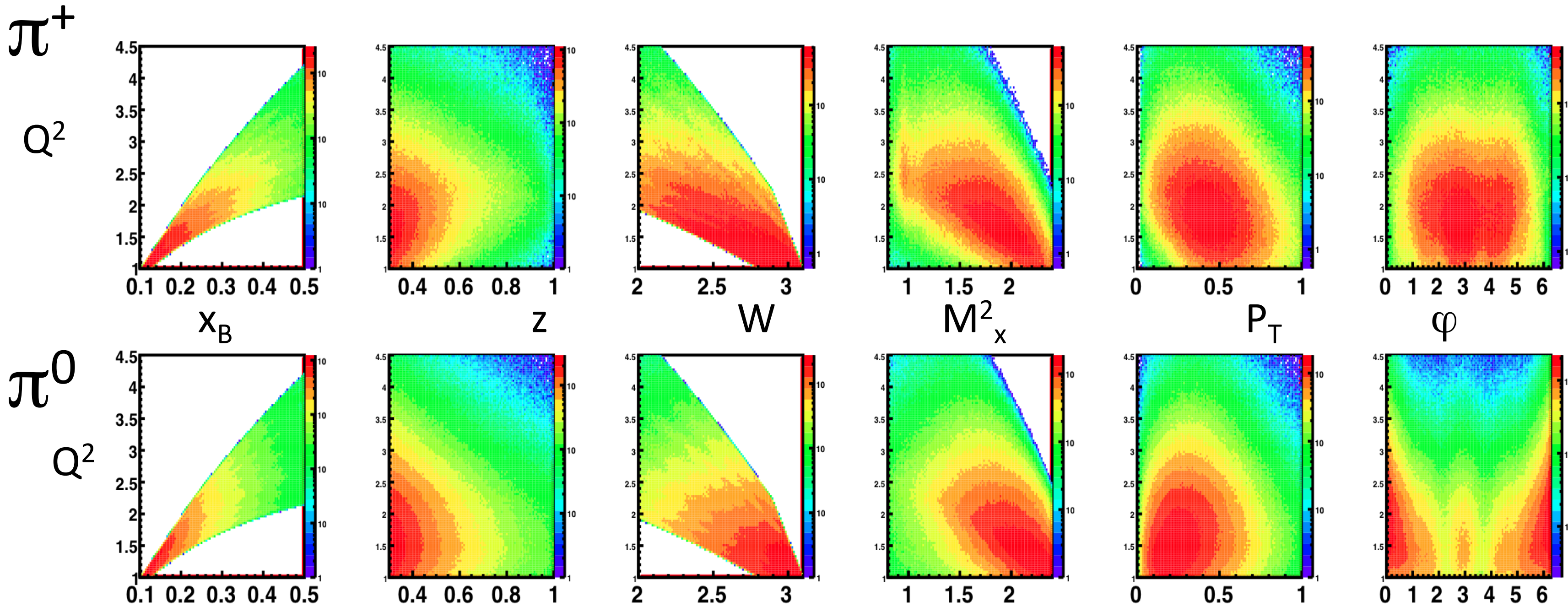

Experimental configuration for **unpolarized/long.polarized** target

$ep \rightarrow e'\pi X$

# SIDIS kinematic coverage with IC

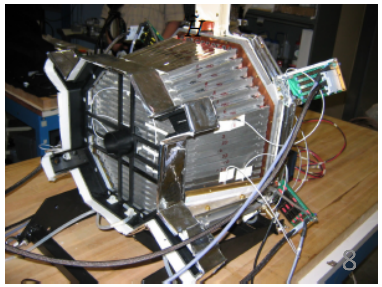
Scattering of 5.9 GeV electrons off unpolarized and polarized proton and deuteron targets

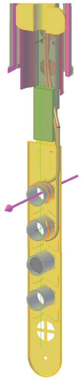
- **DIS kinematics,**
  **$Q^2>1$ GeV$^2$, $W^2>4$ GeV$^2$, $M_x^2>2$ GeV$^2$**



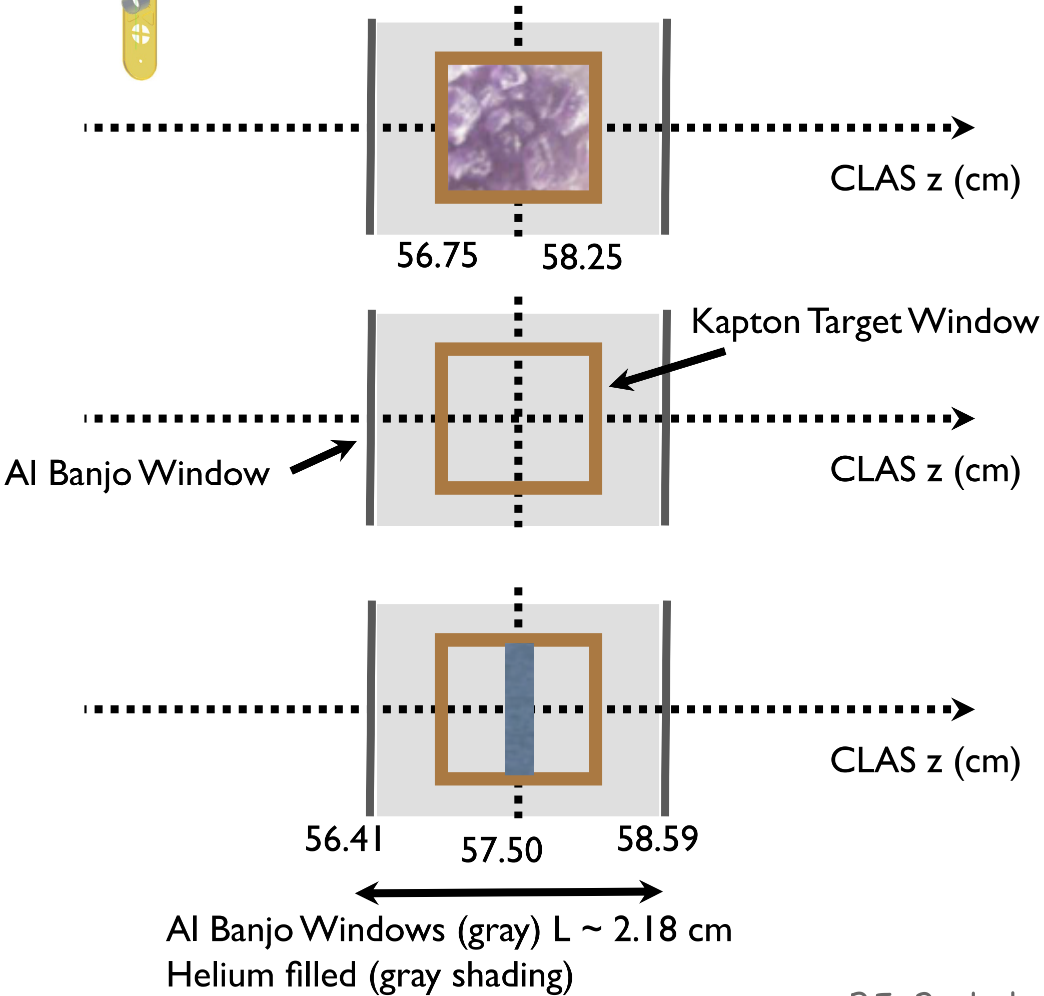

2009 data

CLAS provides a wide kinematical coverage





# Dilution factor for NH3/ ND3




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

$$n_C \approx A_C \sigma$$

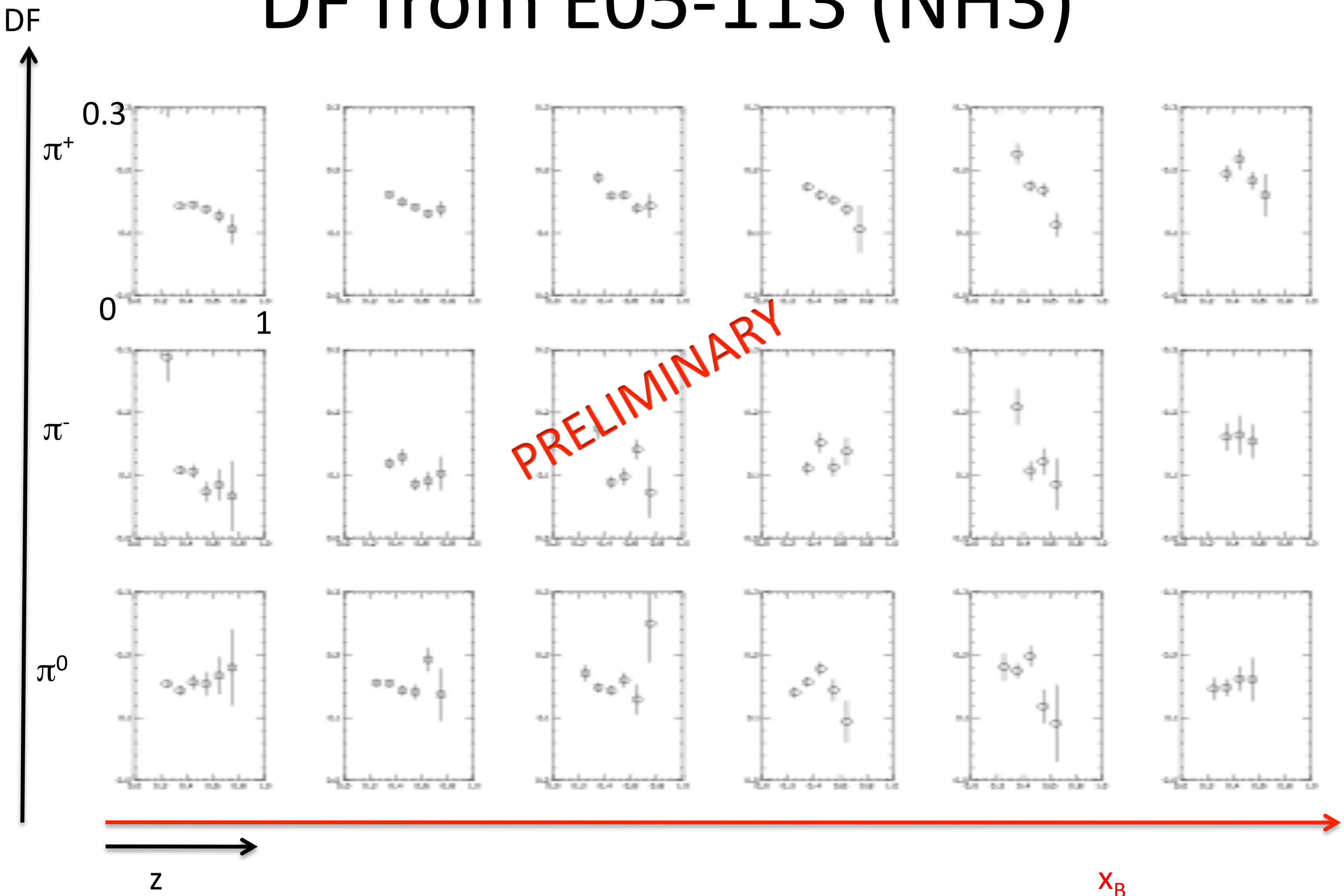
$$n_{NH_3} \approx A_{NH_3}\sigma + B_{NH_3}\sigma_p$$

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

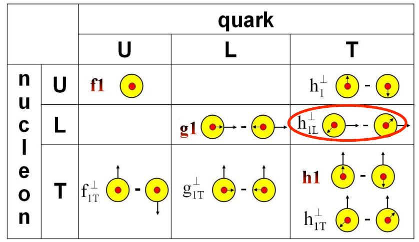
A and B hold density information for all materials in the carbon and ammonia targets

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

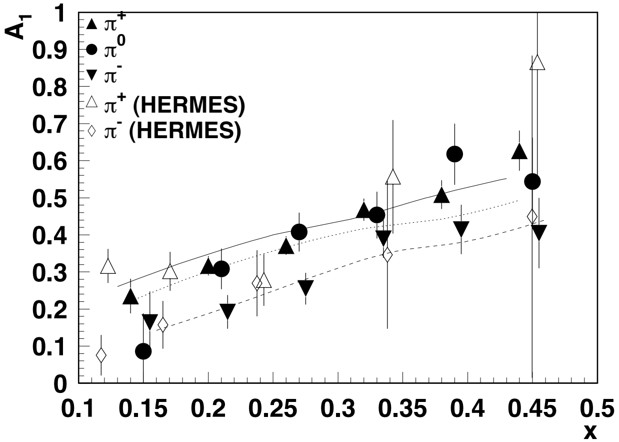
# DF from E05-113 (NH3)



# Longitudinally polarized NH3 target
# E05-113

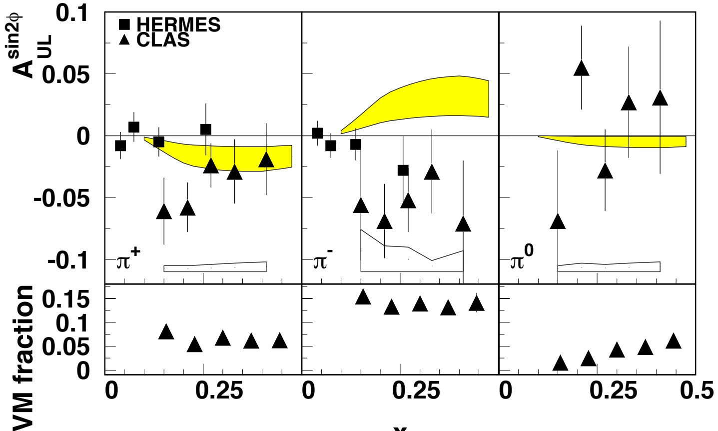



Avakian PRL105 (2010)




CLAS and HERMES g1 are consistent.

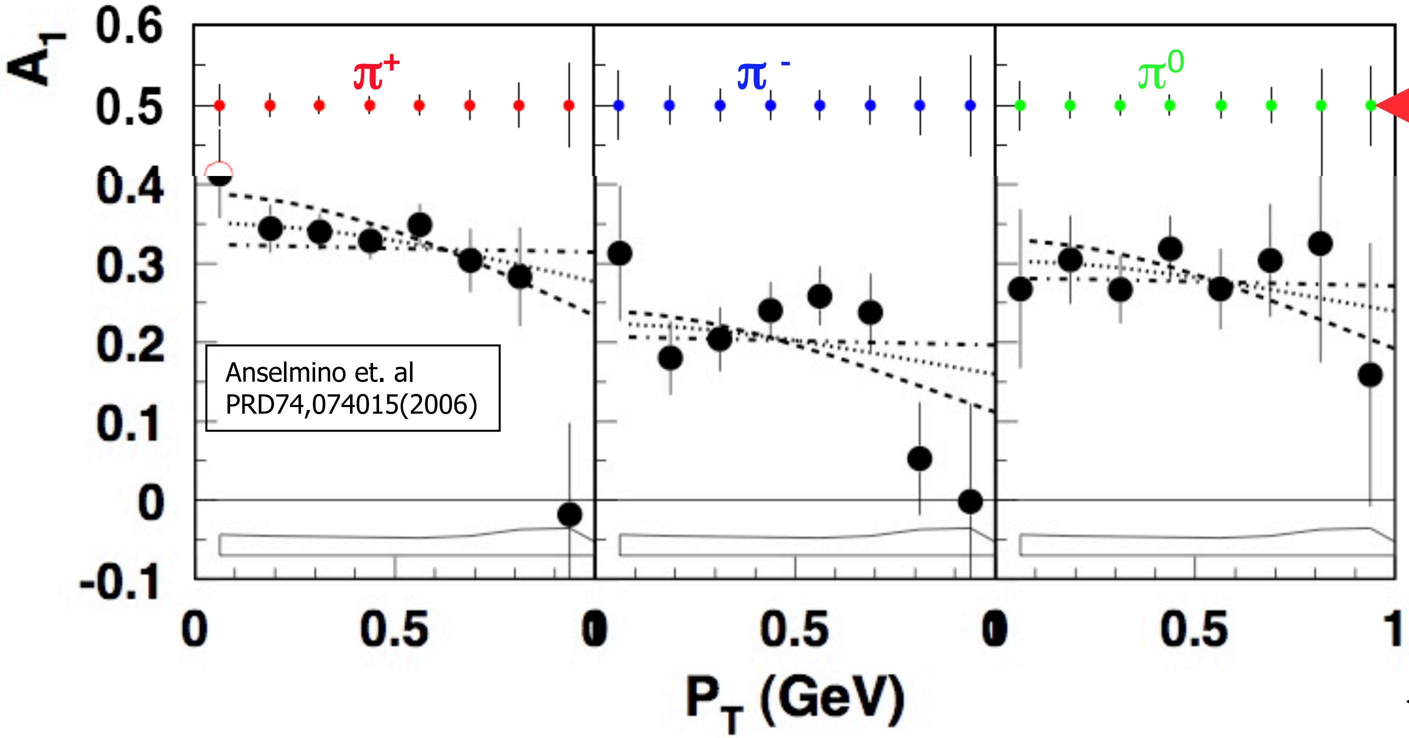
Kotzinian-Mulders Asymmetries




The sin2$\varphi$ moment of the $\pi^+$ 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

H. Avakian et al.
PRL105 (2010)

# Longitudinal pol. target: $A_1$-$P_T$ dependence




Projected results for Exp. E05-113

$$A_1(\pi) \propto \frac{\sum_q e_q^2 g_1^q(x) D_1^{q\to\pi}(z)}{\sum_q e_q^2 f_1^q(x) D_1^{q\to\pi}(z)}$$

$$f_1^q(x,k_T) = f_1(x)\frac{1}{\pi\mu_0^2}\exp\left(-\frac{k_T^2}{\mu_0^2}\right)$$

$$g_1^q(x,k_T) = g_1(x)\frac{1}{\pi\mu_2^2}\exp\left(-\frac{k_T^2}{\mu_2^2}\right)$$

$$< P_T^2(z) >= z^2\mu_{0/2}^2 + \mu_D^2$$

Different width of TMDs of quarks with different flavor and polarizations

$$R = \frac{k_\perp width\, dist(g_1)}{k_\perp width\, dist(f_1)}$$

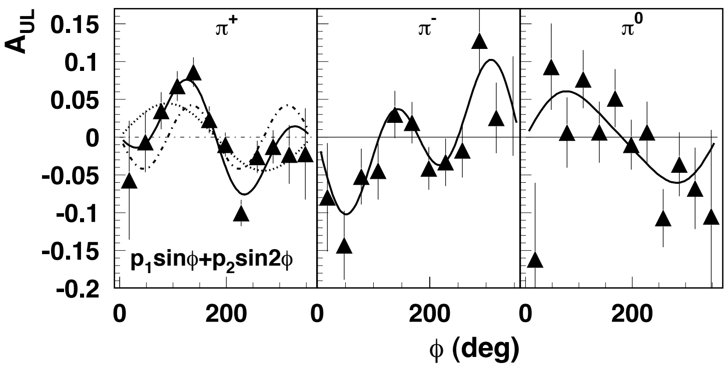
- – – – R=0.40
- ........... R=0.68
- – · – · R=1.0

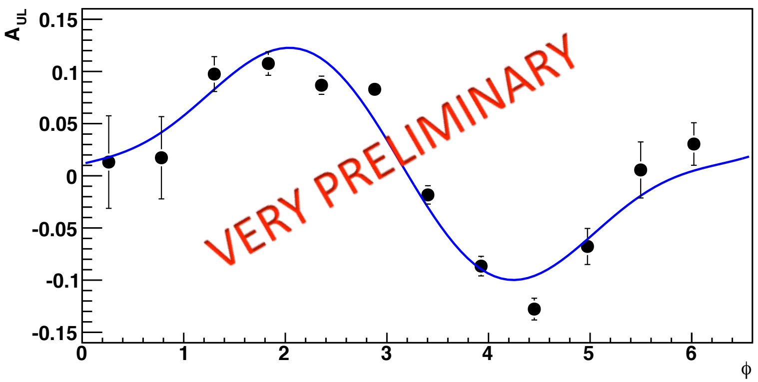
$f_1$=0.25 GeV$^2$

- Data shows slight preference for R< 1
- New experiment with 10 times more data will study the $P_T$-dependence for different quark helicities and flavors **for bins in x**

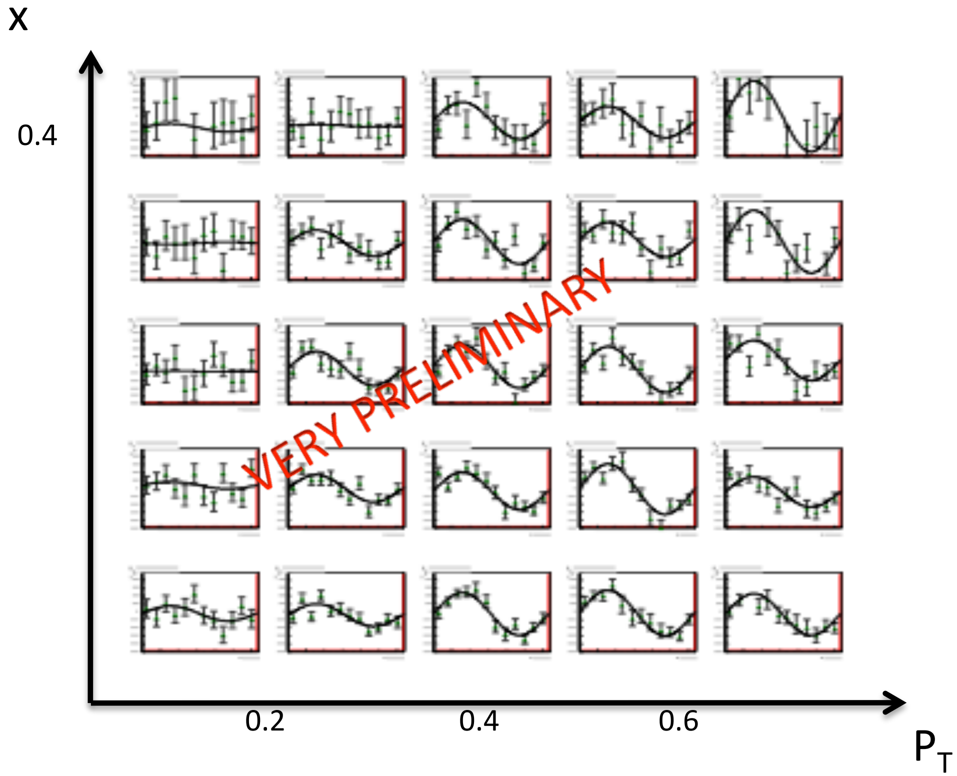
# New data

Avakian et al. PRL105 (2010)



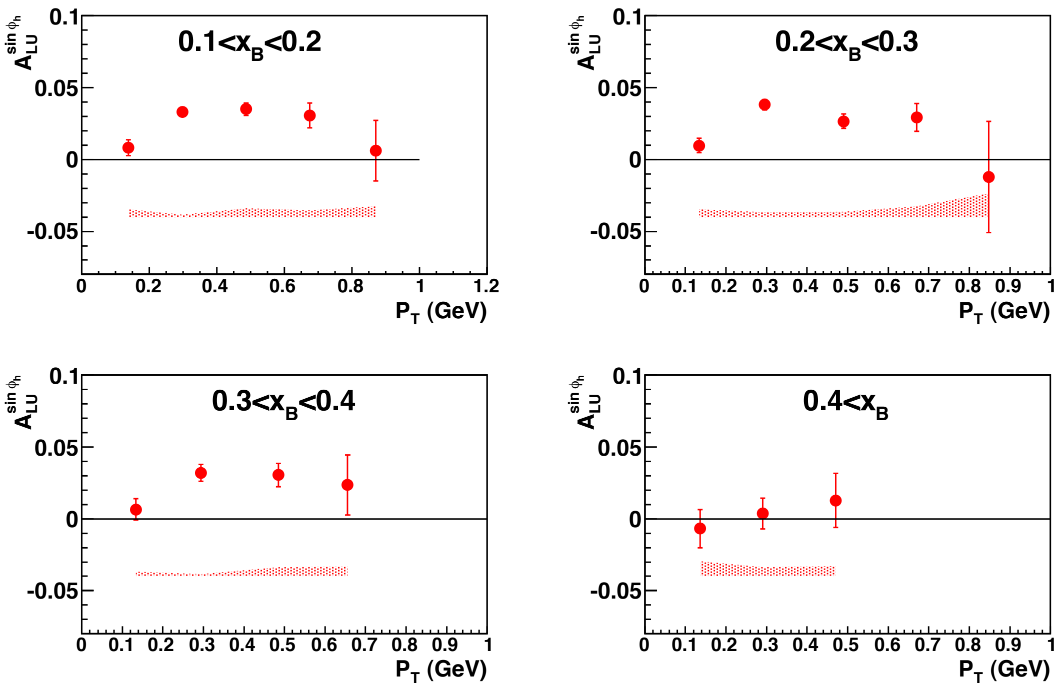

New data for $\pi^0$
S. Jawalkar




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

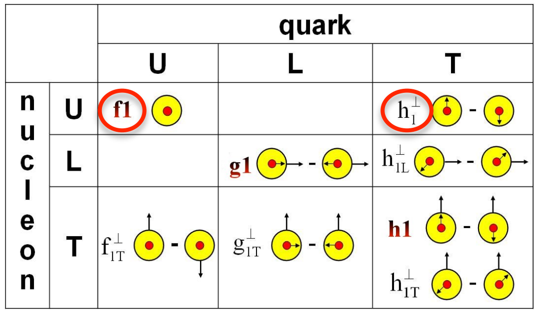
# Beam Spin Asymmetry of $\pi^0$

**arXiv:1106.2293**




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

leading twist TMDs




Higher twist TMDs

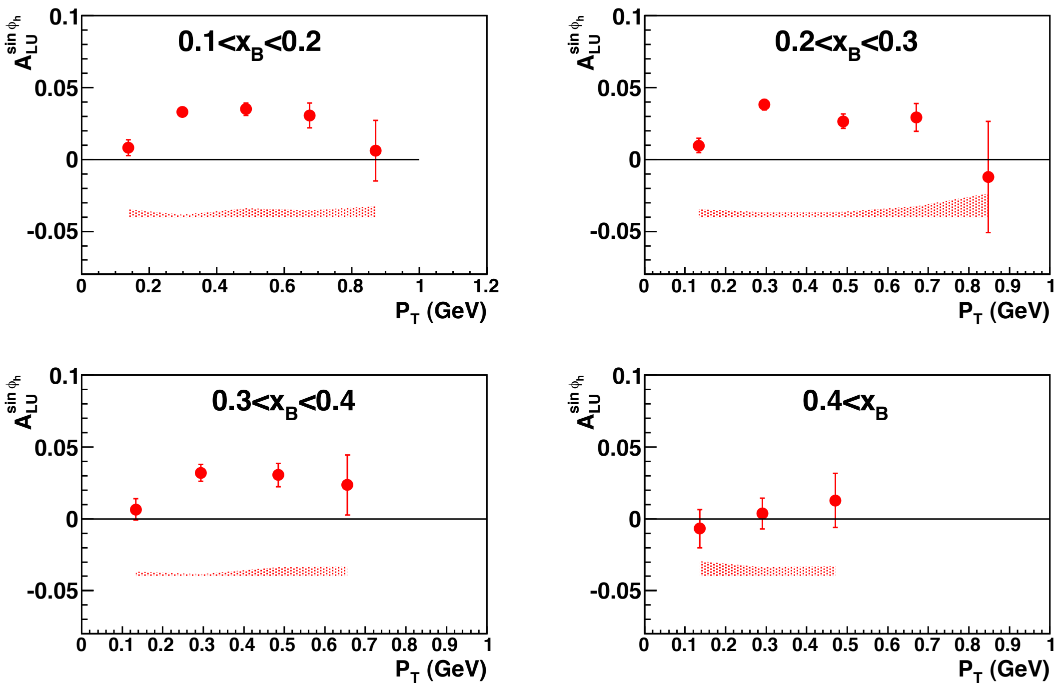
| N/q | U | L | T |
|---|---|---|---|
| U | $f^\perp$ | $g^\perp$ | $h, e$ |
| L | $f_L^\perp$ | $g_L^\perp$ | $h_L, e_L$ |
| T | $f_T, f_T^\perp$ | $g_T, g_T^\perp$ | $h_T, e_T, h_T^\perp, e_T^\perp$ |

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

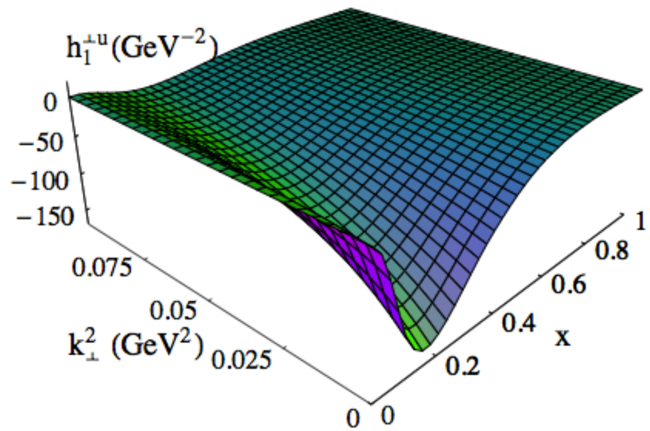
# Beam Spin Asymmetry of $\pi^0$

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

**arXiv:1106.2293**




Pasquini and Yuan,
Phys.Rev.D81:114013,2010

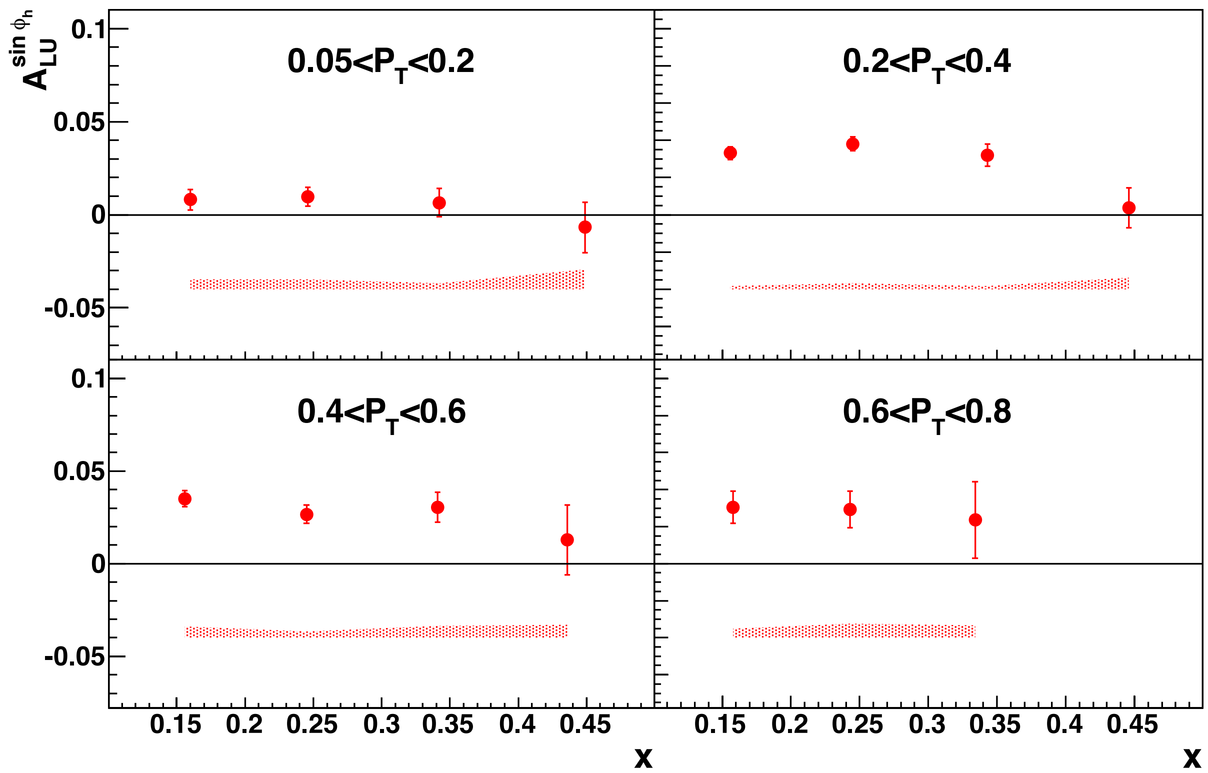



First time: $A_{LU}$ two dimensional mapping for 0.4<z<0.7

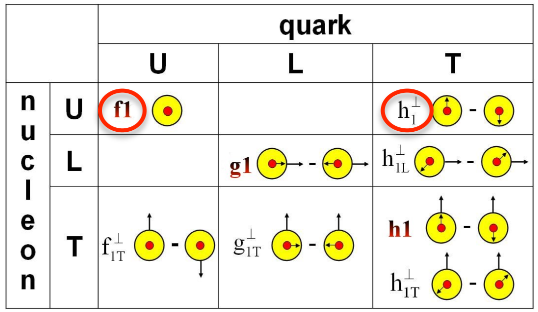
# Beam Spin Asymmetry of $\pi^0$

$$F_{LU}^{\sin(\phi_h)} = \frac{2M}{Q}\times\int d^2\boldsymbol{p_T}\, d^2\boldsymbol{k_T}\,\delta^{(2)}\left(\boldsymbol{p_T}-\frac{\boldsymbol{P_T}}{z}-\boldsymbol{k_T}\right)\left\{\frac{\hat{\boldsymbol{P}}_{\boldsymbol{T}}\cdot\boldsymbol{p_T}}{M}\left[\frac{M_h}{M}h_1^\perp\frac{\tilde{E}}{z}+x_B\, g^\perp D_1\right]-\frac{\hat{\boldsymbol{P}}_{\boldsymbol{T}}\cdot\boldsymbol{k_T}}{M_h}\left[\frac{M_h}{M}f_1\frac{\tilde{G}^\perp}{z}+x_B\, eH_1^\perp\right]\right\}.$$

arXiv:1106.2293




leading twist TMDs



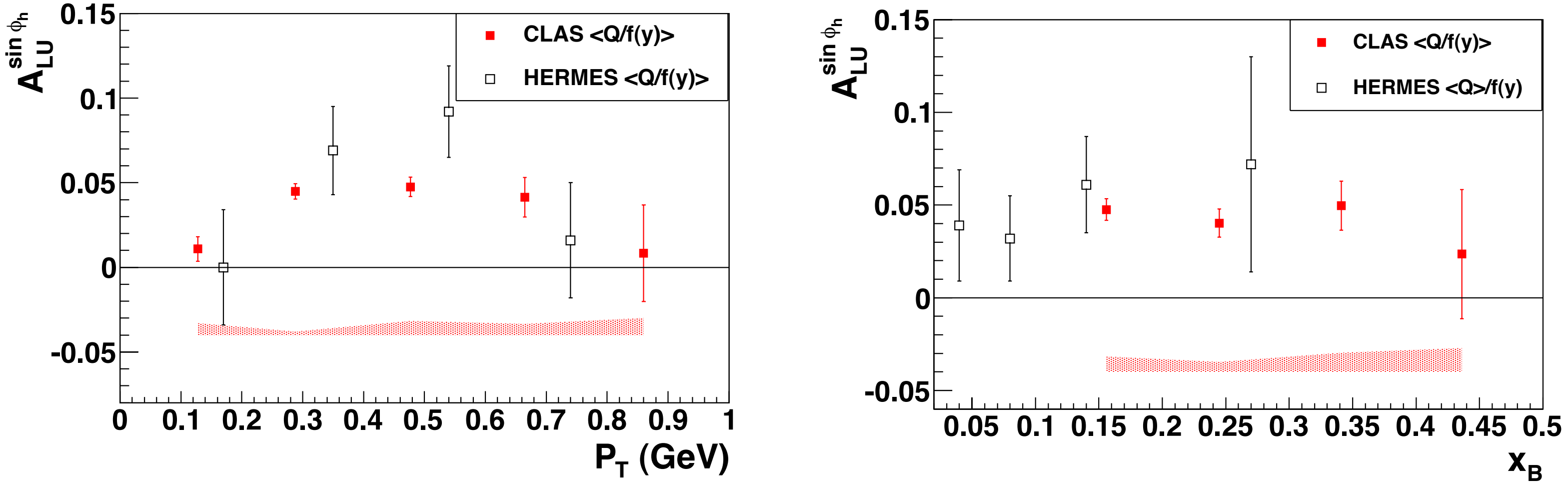

Higher twist TMDs

| 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 | $f_T, f_T^\perp$ | $\mathbf{g_T}, g_T^\perp$ | $h_T, e_T, h_T^\perp, e_T^\perp$ |

For fixed $P_T$ *x* dependence is flat.

# Beam Spin asymmetry of $\pi^0$

**arXiv:1106.2293**



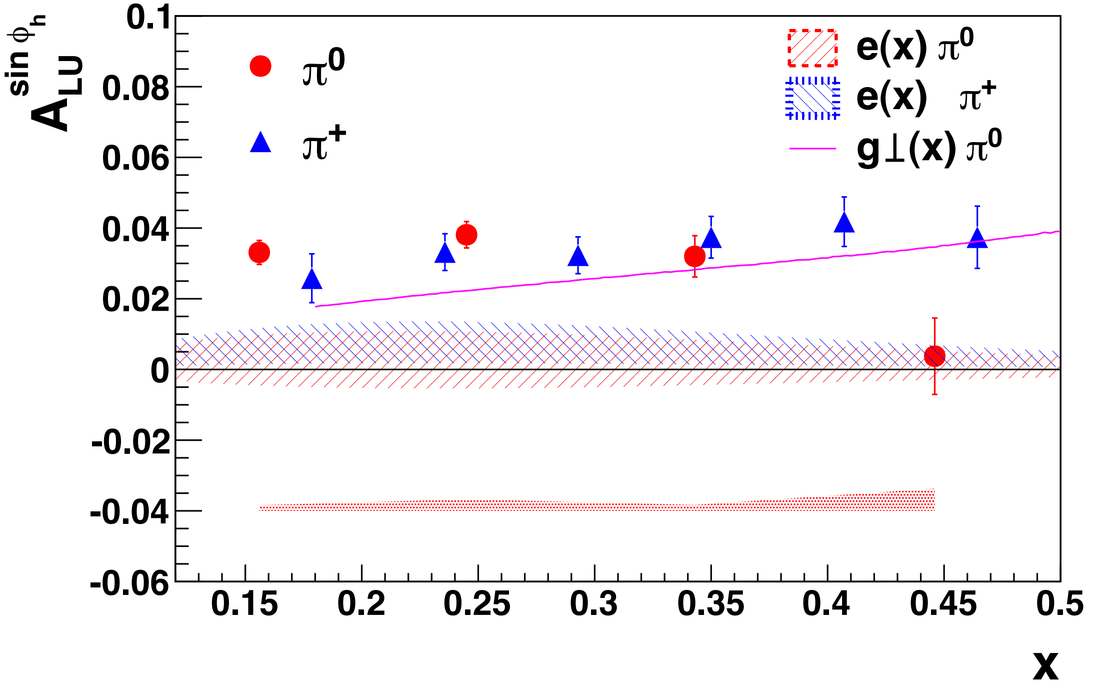

E01-113 experiment results on $A_{LU}$ extends the $x_B$ range and improves uncertainties.

# Models and Data

$$F_{LU}^{\sin(\phi_h)} = \frac{2M}{Q} \times \int d^2\boldsymbol{p_T} d^2\boldsymbol{k_T}\, \delta^{(2)}\Big(\boldsymbol{p_T} - \frac{\boldsymbol{P_T}}{z} - \boldsymbol{k_T}\Big)$$

$$\Big\{ \frac{\hat{\boldsymbol{P}}_{\boldsymbol{T}} \cdot \boldsymbol{p_T}}{M} \Big[ \frac{M_h}{M}\, h_1^{\perp} \frac{\tilde{E}}{z} + x_B\, g^{\perp} D_1 \Big] -$$

$$\frac{\hat{\boldsymbol{P}}_{\boldsymbol{T}} \cdot \boldsymbol{k_T}}{M_h} \Big[ \frac{M_h}{M}\, f_1 \frac{\tilde{G^{\perp}}}{z} + x_B\, e H_1^{\perp} \Big] \Big\}.$$




P. Schweitzer PRD67 (2003), PRD73 (2006), L. Gamberg- private communication

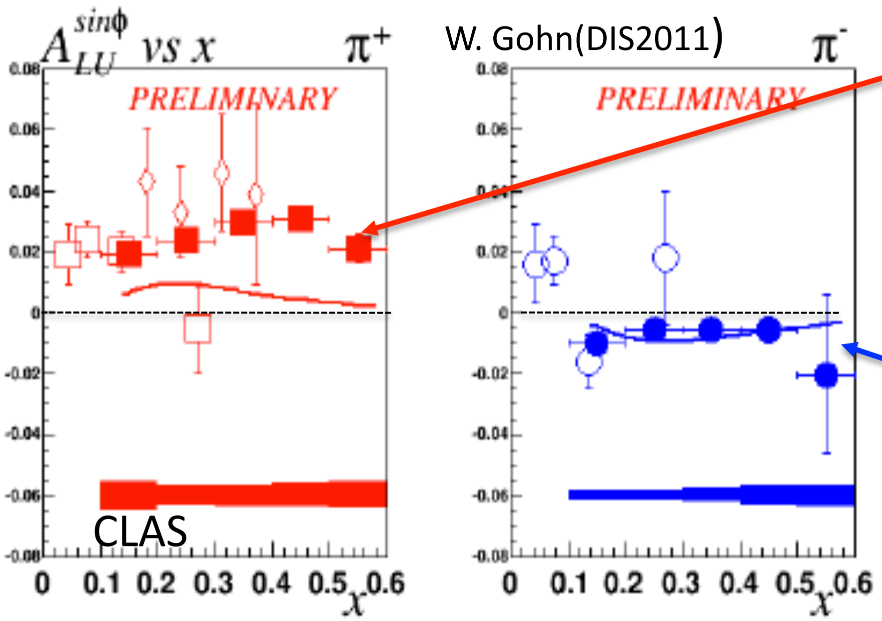
# HT-distributions in SIDIS

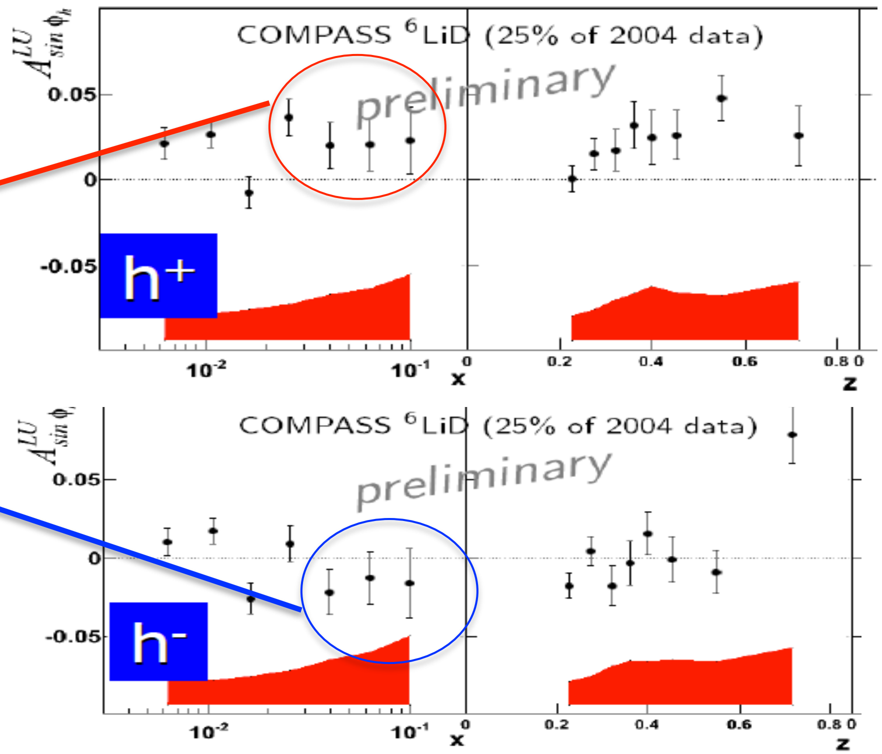
HT function related to force on the quark. Burkardt (2008),Qiu(2011)

C.Schill(DIS2011)

HT SSAs comparable at JLab and COMPASS

W. Gohn(DIS2011)

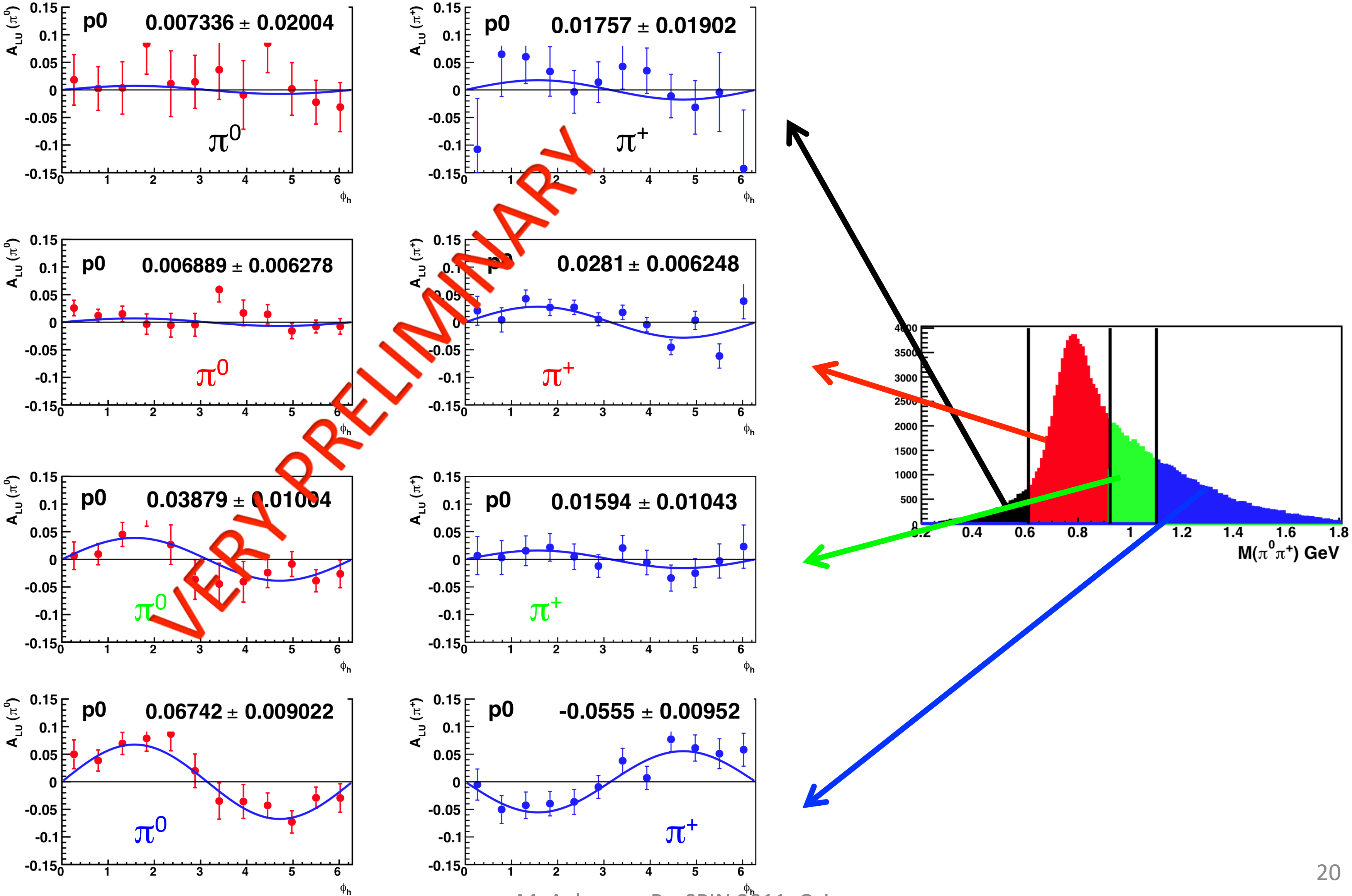



Factorization of higher twists in SIDIS not proved

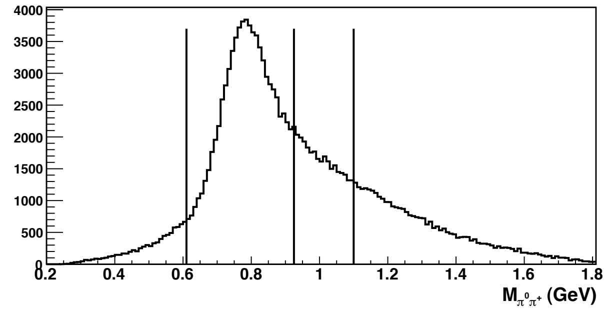
To study HT pdfs with dihadron SIDIS (replace $H_1^{\perp}$ with Interference FF PRD69 (2004) )

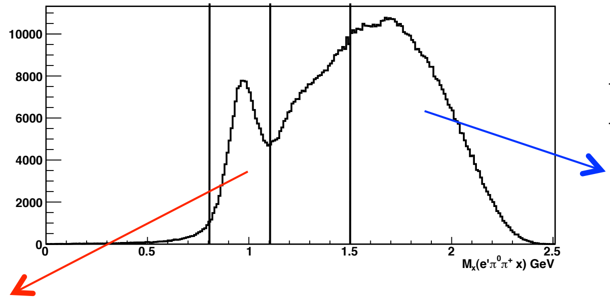
# Exclusive $\pi^0\pi^+$ on proton



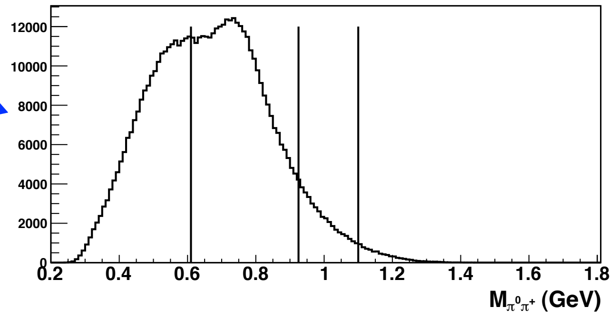
# $\pi^0\pi^+$ pairs

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

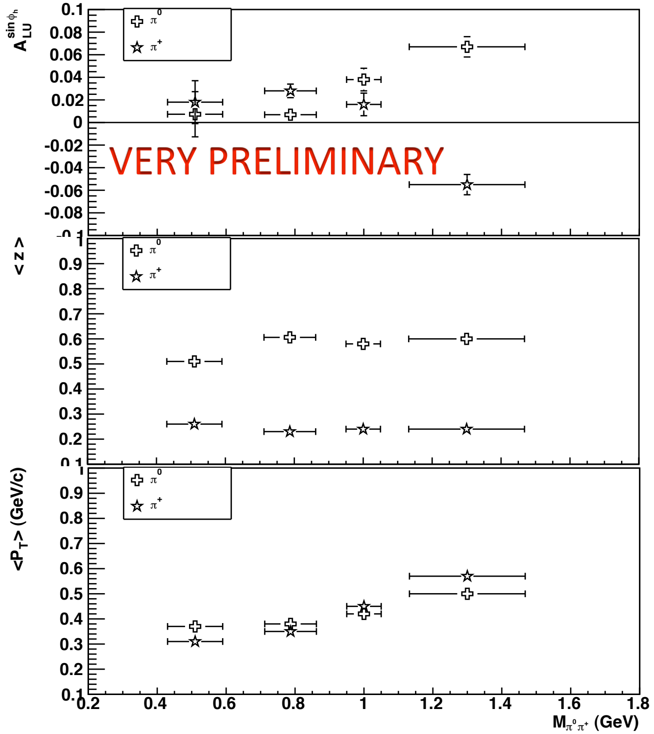



M $(\pi^+\pi^0)$ GeV



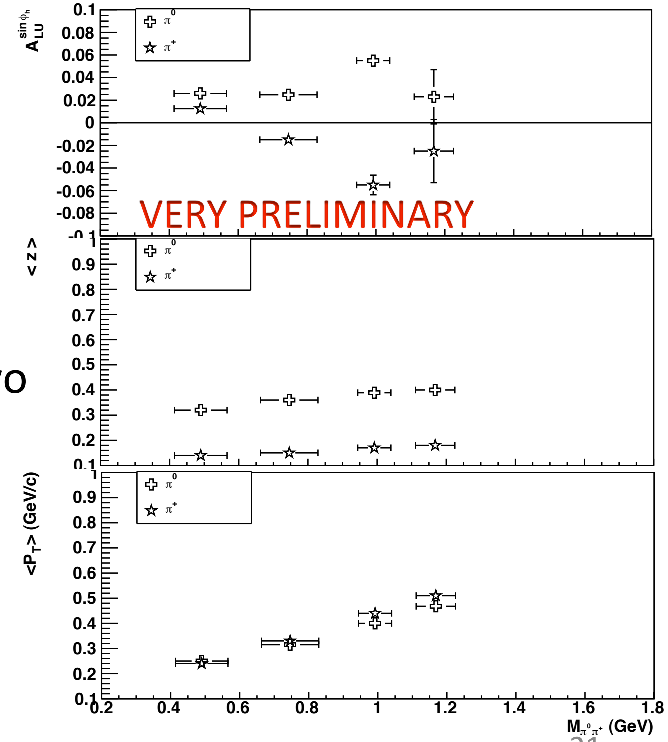

$M_x(ep\text{->}e\pi^+\pi^0\ x)$ GeV




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

Strong single pion $A_{LU}$ dependence vs mass of two pions

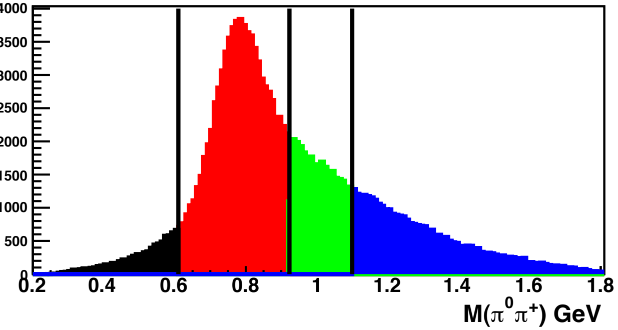
Or strong single pion $A_{LU}$ dependence
vs $x_B/P_T/z$ of single pions?



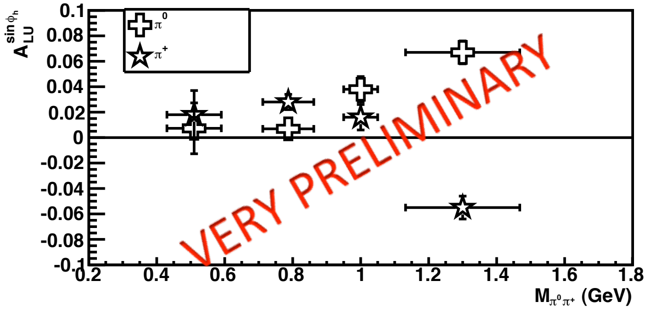
# Summary

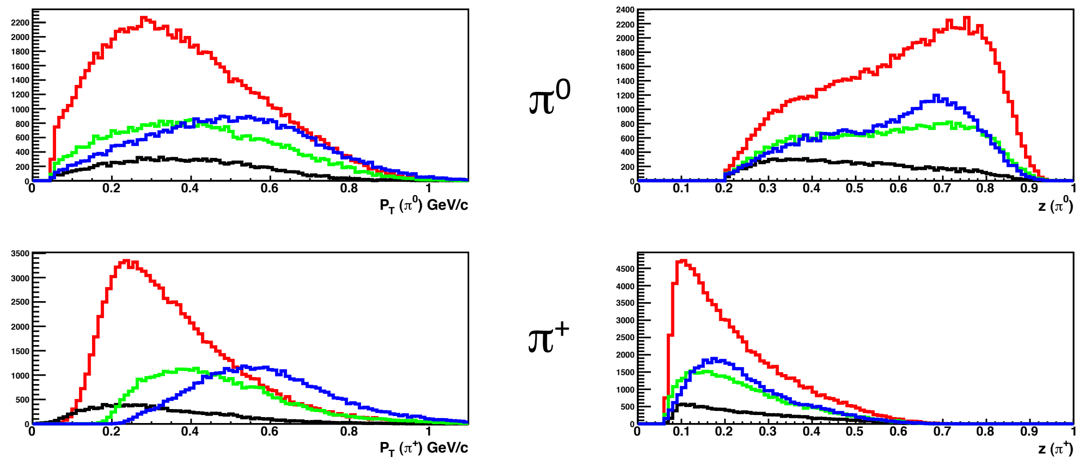
- ALU of $\pi^0$ in multidimensional bins.
- ALU, AUL and ALL of $\pi^{0/+/-}$ in multidimensional bins is coming.
- The data consistent with factorization (no x /z-dependence observed in single and double spin asymmetry measurements).
- Measured asymmetries (<sin$\phi$>, <sin2$\phi$>, …), provide access to new transverse momentum dependent distribution and fragmentation functions.
- Measured spin and azimuthal asymmetries are in agreement with theory predictions and measurements at higher energies.
- Measurements of azimuthal dependences of double and single spin asymmetries in SIDIS indicate that there are significant correlations between spin and transverse distribution of quarks.
- Sizable higher twist asymmetries measured in SIDIS indicate the quark-gluon correlations may be significant at moderate $Q^2$.

# Exclusive $\pi^+\pi^0$ $A_{LU}$ for any $\pi^0$




Strong single pion $A_{LU}$ dependence
vs mass of two pions?




**Or strong single pion $A_{LU}$ dependence**
**vs $x_B/P_T/z$ of single pions?**

**$P_T$** **z**

# HERMES BSA

**Phys.Lett.B648:164-170,2007**.
e-Print: **hep-ex/0612059**

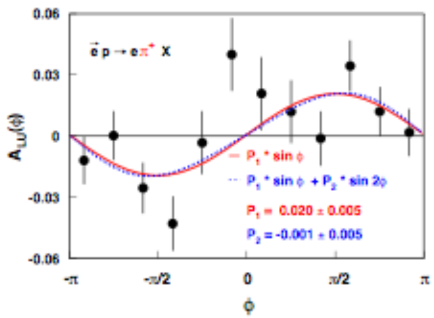



FIG. 2: Beam SSA as a function of $\phi$ for $\pi^+$ electroproduction at mid-$z$ range. The solid curve represents a $\sin\phi$ fit, and the dashed one includes also the $\sin 2\phi$ harmonic. Only statistical errors are shown.

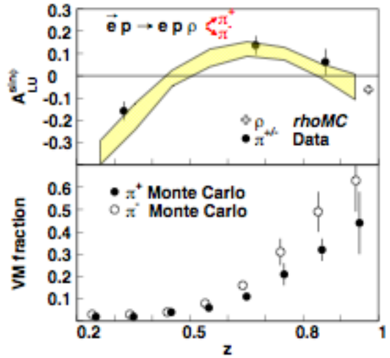



FIG. 4: Top panel: amplitude $A_{LU}^{\sin\phi}$ for $\pi^+$ mesons originating from $\rho^0$ meson decays, obtained with Monte Carlo (band) and data (full circles). The open cross displays the asymmetry for the $\rho^0$ itself (Monte Carlo). Bottom panel: the fraction of pions in the SIDIS sample originating from VM decays.

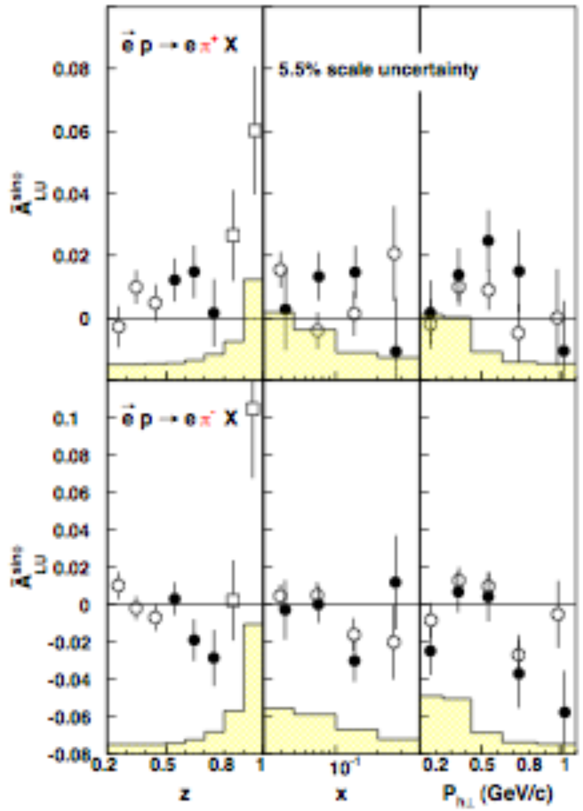



FIG. 5: Dependence of $\tilde{A}_{LU}^{\sin\phi}$ on $z$, $x$ and $P_{h\perp}$ for charged pions. The contribution from VM decays has been determined from a Monte-Carlo simulation and subsequently subtracted from the asymmetries. The measurement of the $x$ and $P_{h\perp}$ dependences is made separately for low $(0.2 < z < 0.5)$ and middle $(0.5 < z < 0.8)$ $z$-ranges (indicated by open and full circles, respectively). The error band indicates the uncertainties from PYTHIA and RHOMC.

What about $\rho^+ \to \pi^+\pi^0$ ?
According to MC VM contribution is less than 5%.
What do I have in data?