Studies of Spin-Orbit Correlations at JLab

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

1 October

SPIN 2010, Jülich, Germany

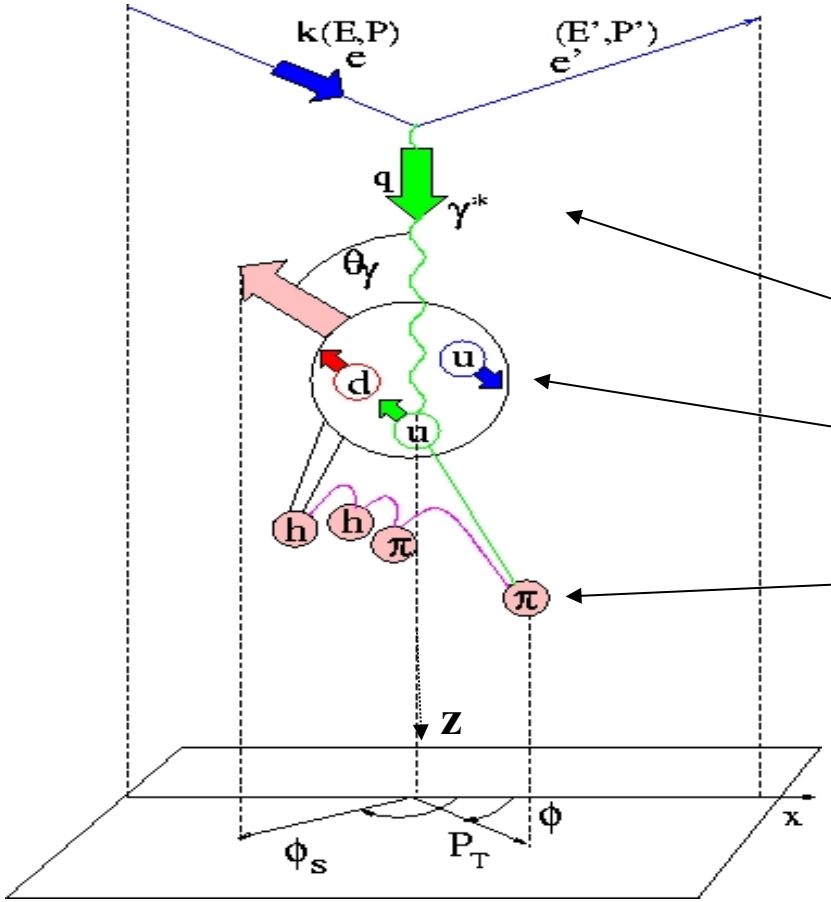
INFN Istituto Nazionale di Fisica Nucleare

Jefferson Lab

Outline

- Physics motivation
- Unpolarized and longitudinally polarized target data.
  - Single Spin asymmetries
  - Double Spin asymmetries
- Future studies of PDFs at CLAS at 6
- 12 GeV update
- 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

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

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)

18 structure functions !!

Bacchetta et al., JHEP 0702:093,2007

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

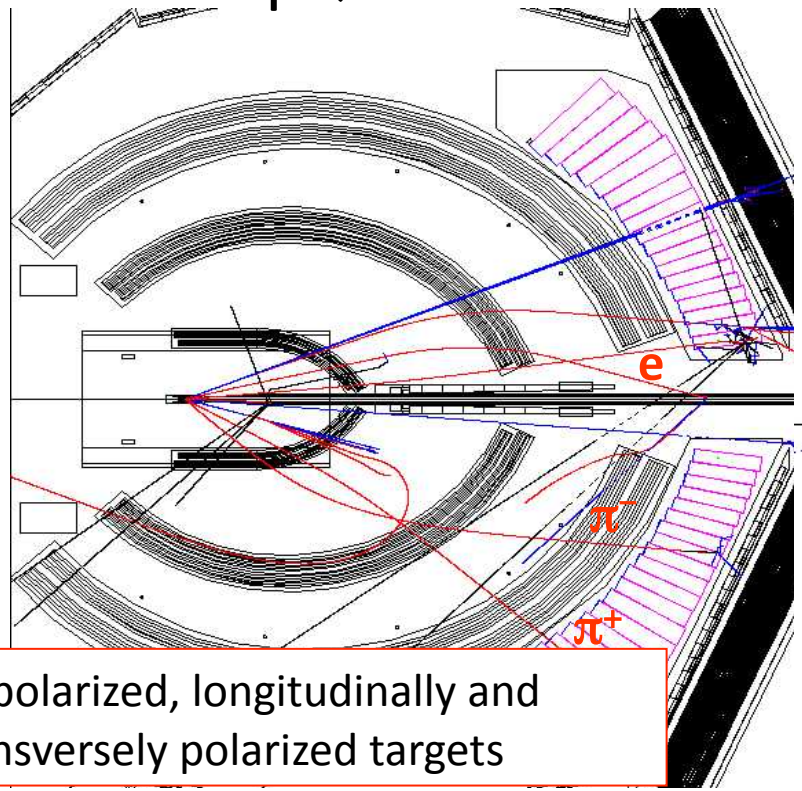
		quark		
		U	L	T
nucleon	U	f1		$h_1^\perp$
	L		g1	$h_{1L}^\perp$
	T	$f_{1T}^\perp$	$g_{1T}^\perp$	h1 $h_{1T}^\perp$

+ Higher twist distribution functions

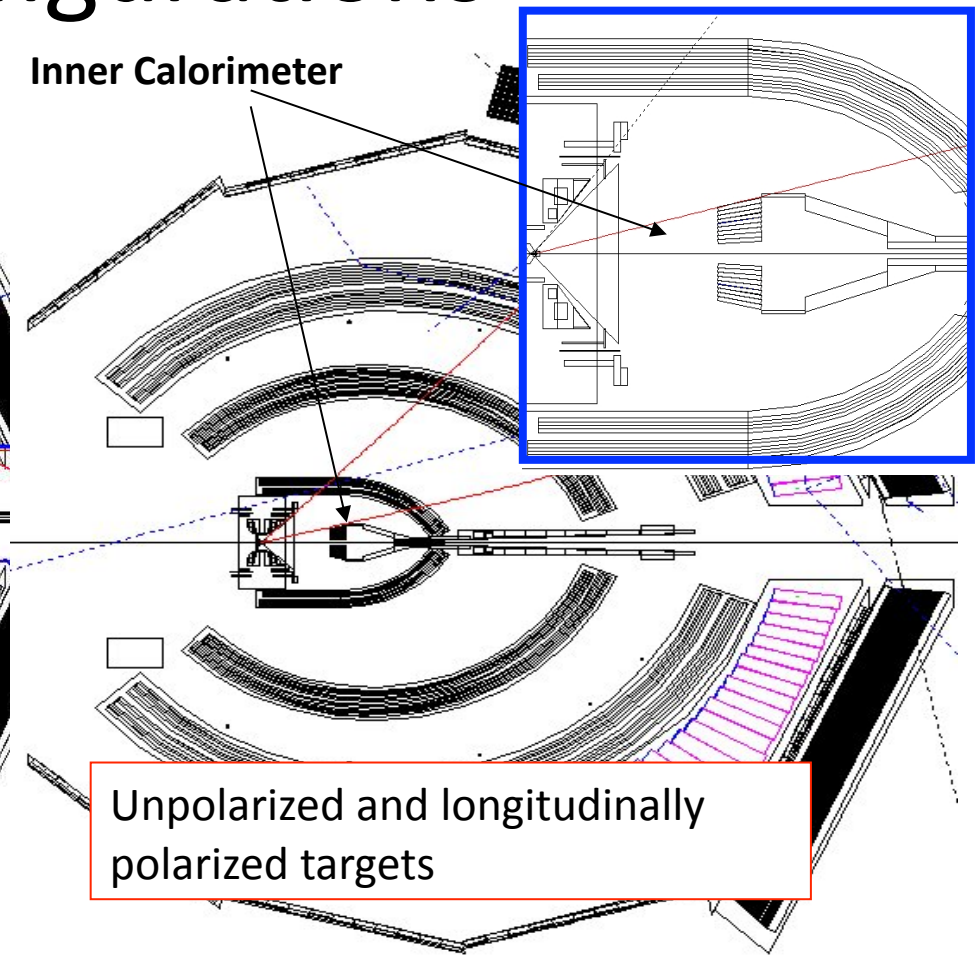
N/q	U	L	T
U	$f^\perp$	$g^\perp$	$h, \mathbf{e}$
L	$f_L^\perp$	$g_L^\perp$	$\mathbf{h_L}, e_L$
T	$f_T, f_T^\perp$	$\mathbf{g_T}, g_T^\perp$	$h_T, e_T, h_T^\perp, e_T^\perp$

CLAS configurations

$ep \rightarrow e'\pi X$



Unpolarized, longitudinally and transversely polarized targets



Unpolarized and longitudinally polarized targets

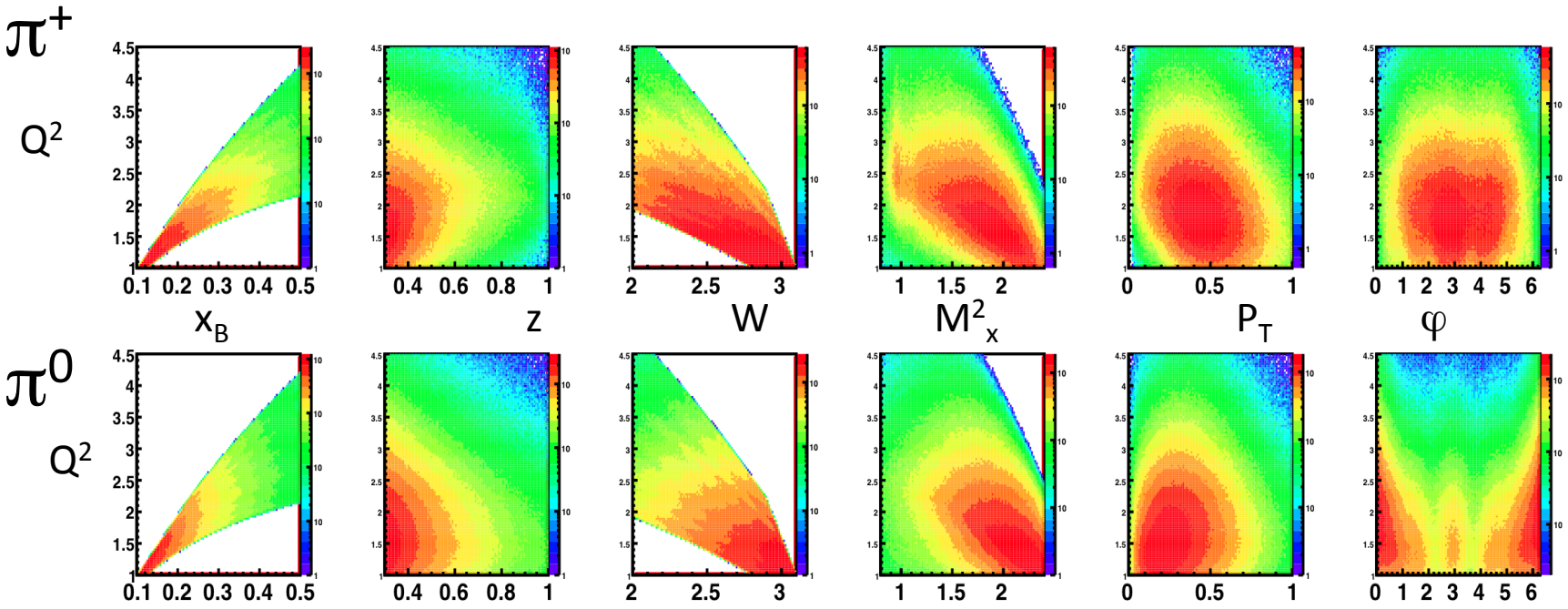
1) Polarized NH3/ND3 (no IC, ~5 days)
2) Unpolarized H (with IC ~ 60 days)
3) Polarized NH3/ND3 with IC 60 days
   10% of data on carbon
4) Polarized HD-Ice (no IC, 25 days)

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

SIDIS kinematic coverage with IC

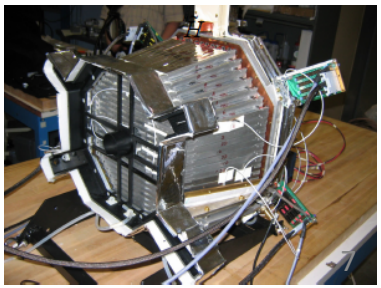
Scattering of 5.9 GeV electrons off unpolarized and polarized proton and deuteron targets

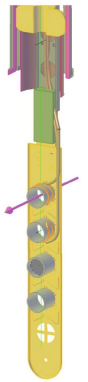
- **DIS kinematics,**
  Q^2>1 GeV^2, W^2>4 GeV^2, M_x^2>2 GeV^2



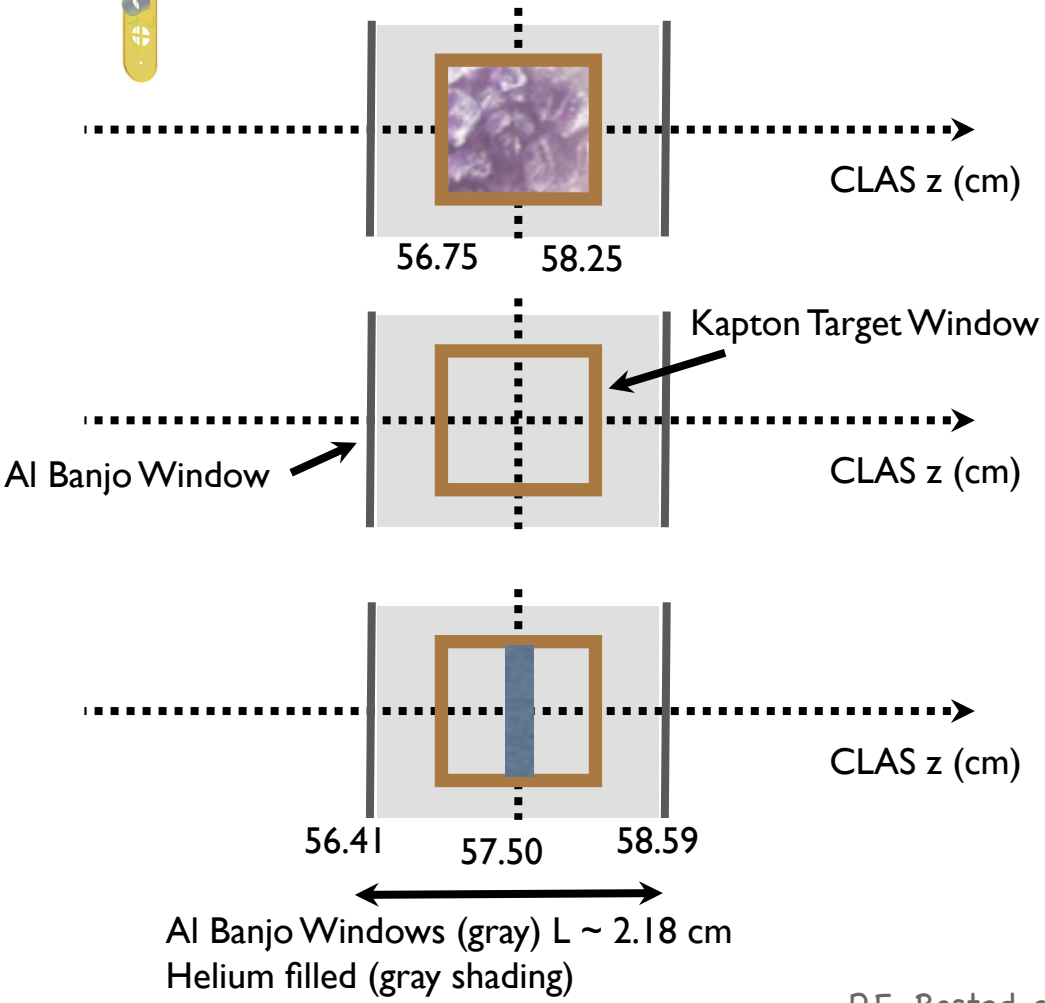
2009 data

CLAS provides a wide kinematical coverage





Dilution factor for NH3/ ND3



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

$$n_C \approx A_C \sigma$$

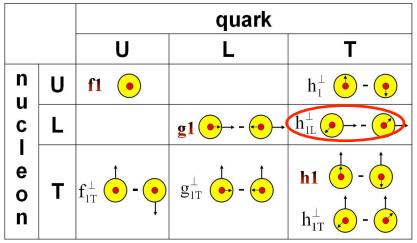
$$n_{NH_3} \approx A_{NH_3}\sigma + B_{NH_3}\sigma_p$$

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

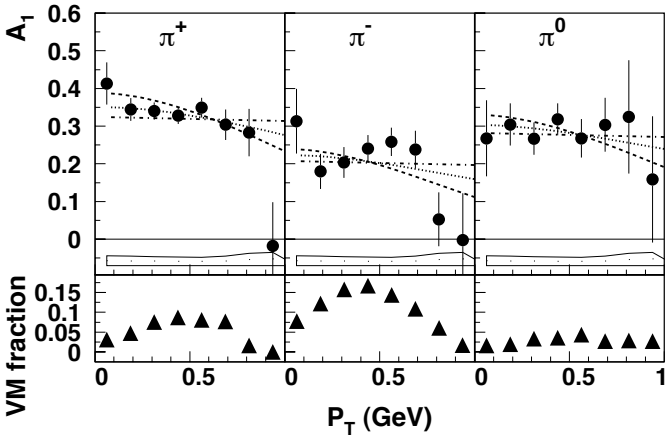
A and B hold density information for all materials in the carbon and ammonia targets

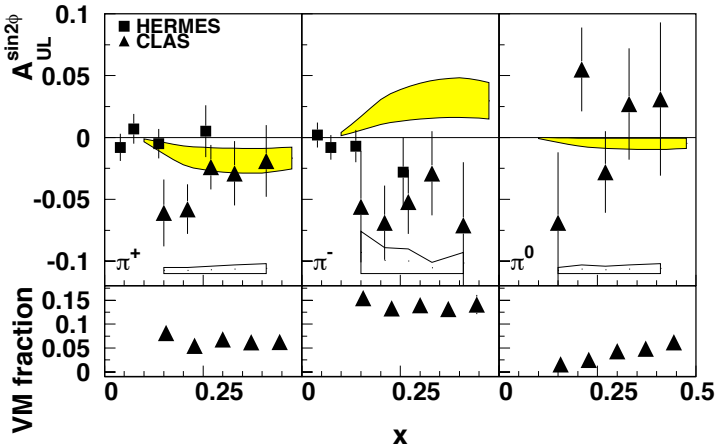
P.E. Bosted and M.E. Christy Phys Rev. C 77, 065206 (2008)

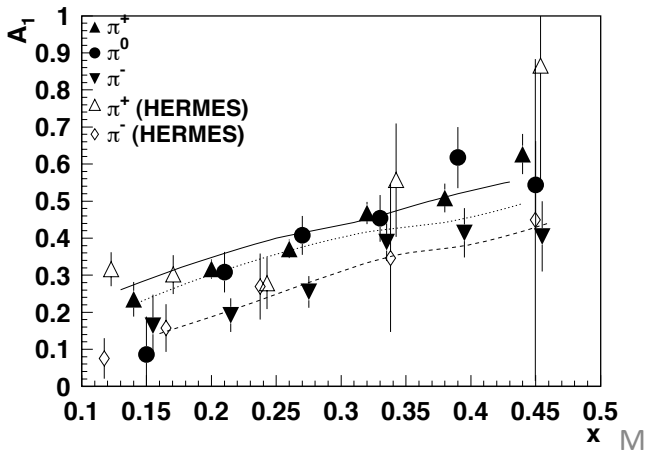
Longitudinally polarized NH3 target E05-113



arXiv:1003.4549

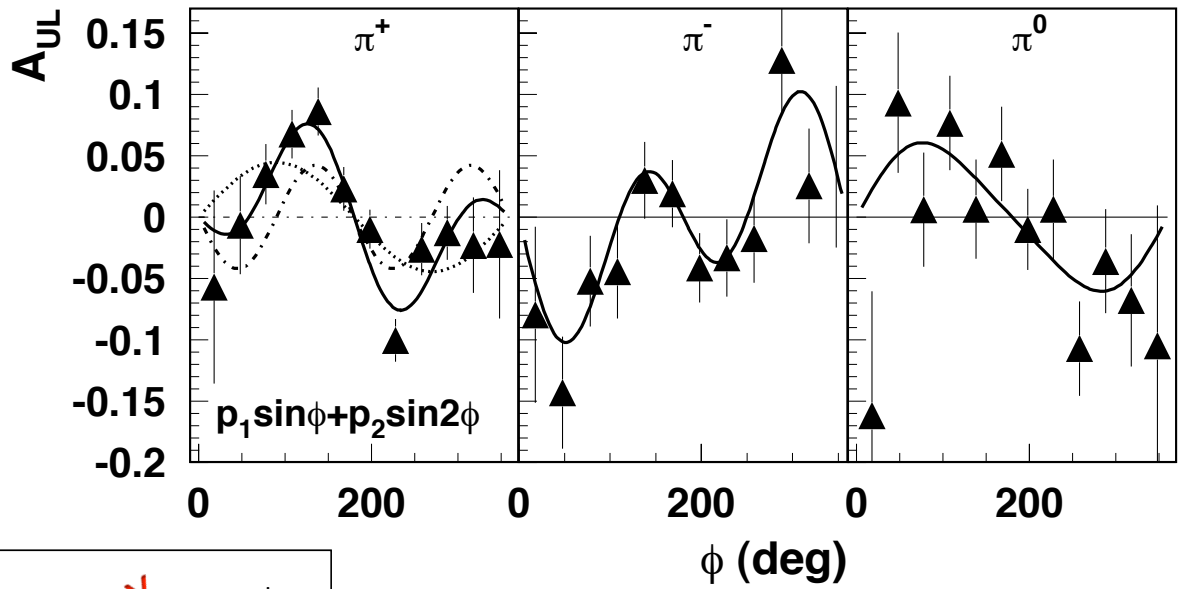


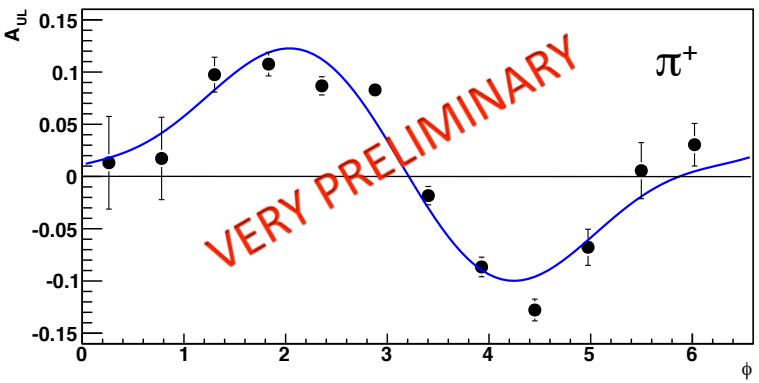




The sin2φ moment of the π^+ at large x_B is dominated by *u*-quarks, therefore with additional input from other experiments can provide a first glimpse of twist 2 $h_{1L}^{\perp}$ function

New data

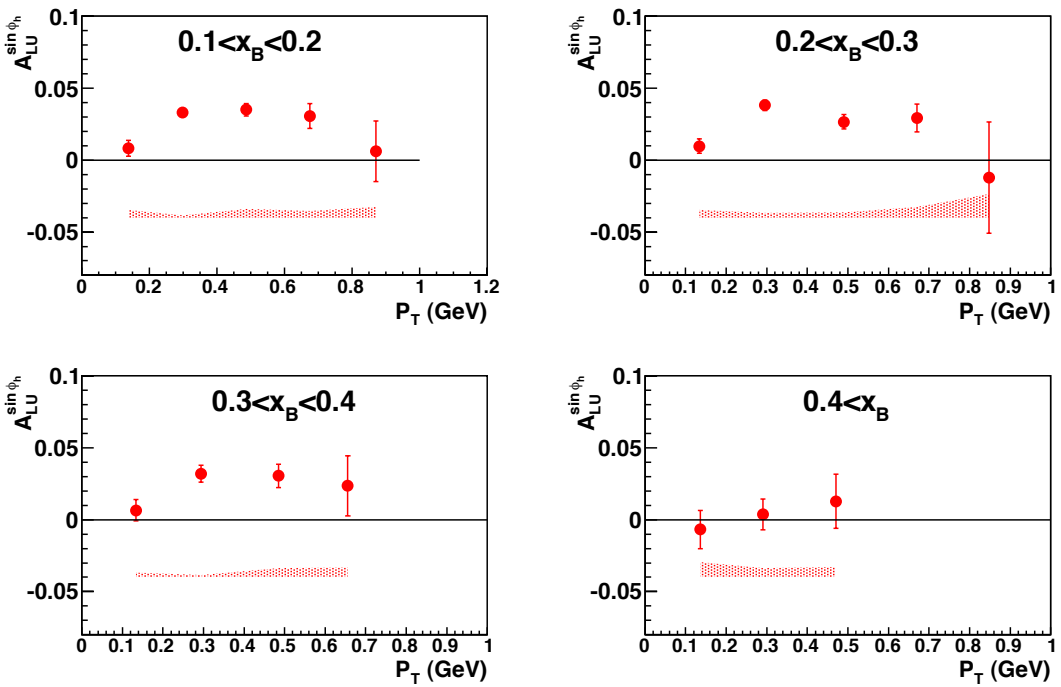




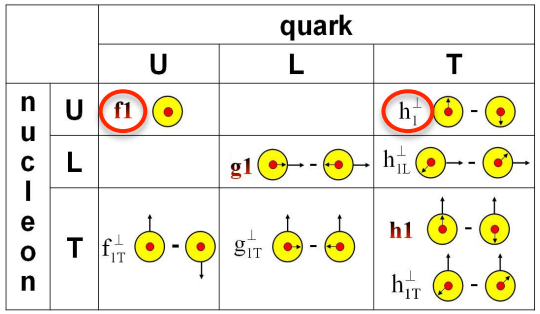
Only 10% of new data with IC for positive pions significantly improves statistical errors and will allow **<u>more than one dimensional</u>** extraction of A_{UL} an A_{LL}.

Beam Spin Asymmetry of π^0

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



leading twist TMDs



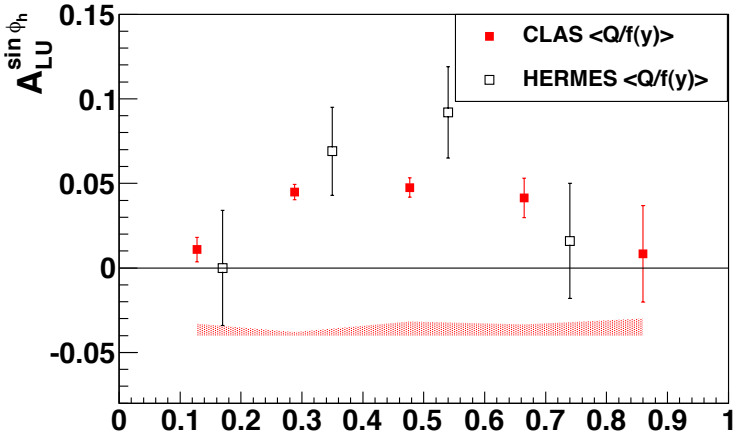
Higher twist TMDs

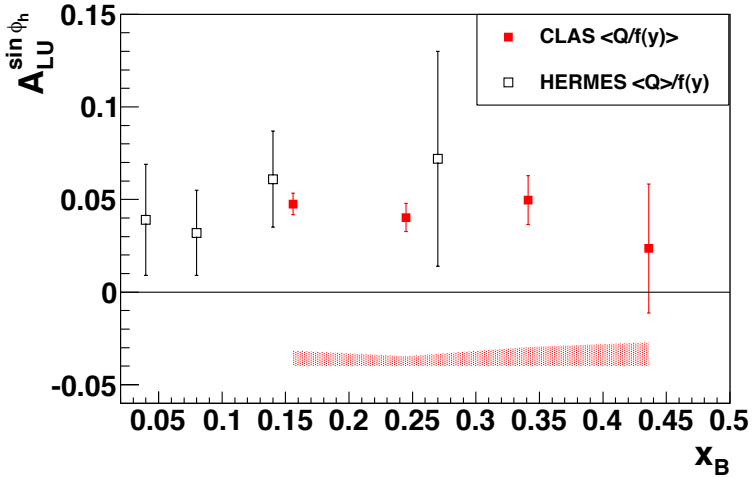
N/q	U	L	T
U	$f^{\perp}$	$g^{\perp}$	h, e
L	$f_L^{\perp}$	$g_L^{\perp}$	$\mathbf{h_L}, e_L$
T	$f_T, f_T^{\perp}$	$\mathbf{g_T}, g_T^{\perp}$	$h_T, e_T, h_T^{\perp}, e_T^{\perp}$

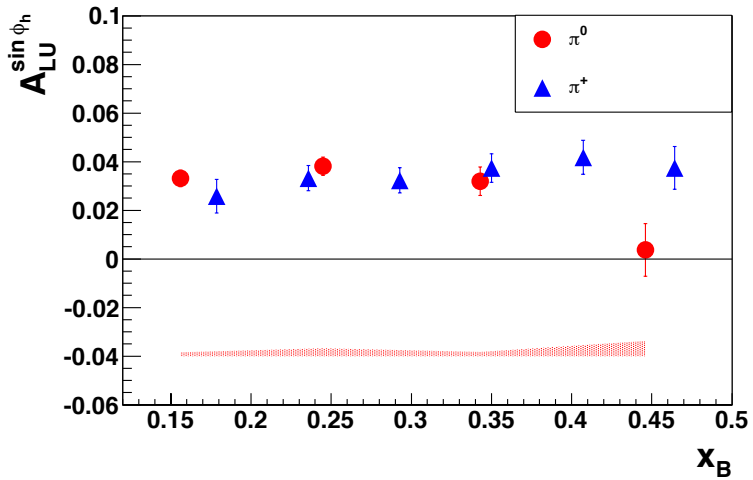
First time: A_{LU} two dimensional mapping for 0.4<z<0.7

Theory impute is needed!

Beam Spin asymmetry of π^0







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

HERMES BSA

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

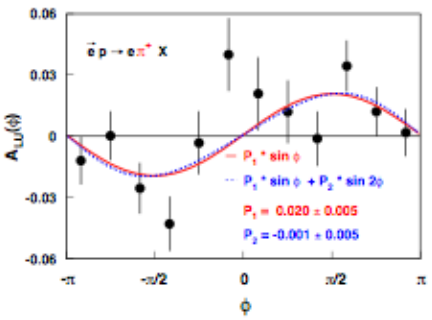


FIG. 2: Beam SSA as a function of ϕ for π^+ electroproduction at mid-z range. The solid curve represents a $\sin\phi$ fit, and the dashed one includes also the $\sin 2\phi$ harmonic. Only statistical errors are shown.

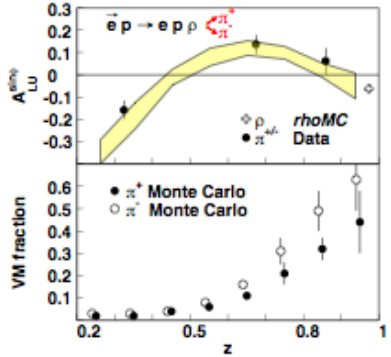


FIG. 4: Top panel: amplitude $A_{LU}^{\sin\phi}$ for π^+ mesons originating from ρ^0 meson decays, obtained with Monte Carlo (band) and data (full circles). The open cross displays the asymmetry for the ρ^0 itself (Monte Carlo). Bottom panel: the fraction of pions in the SIDIS sample originating from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

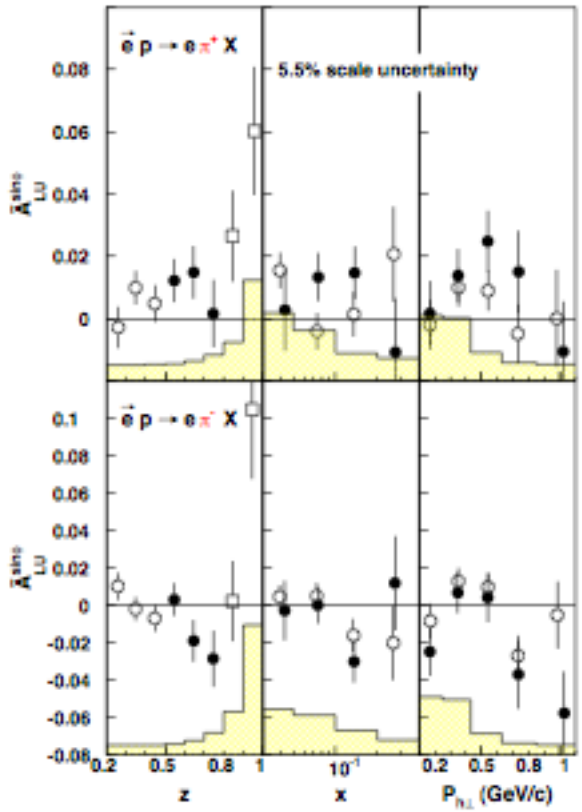
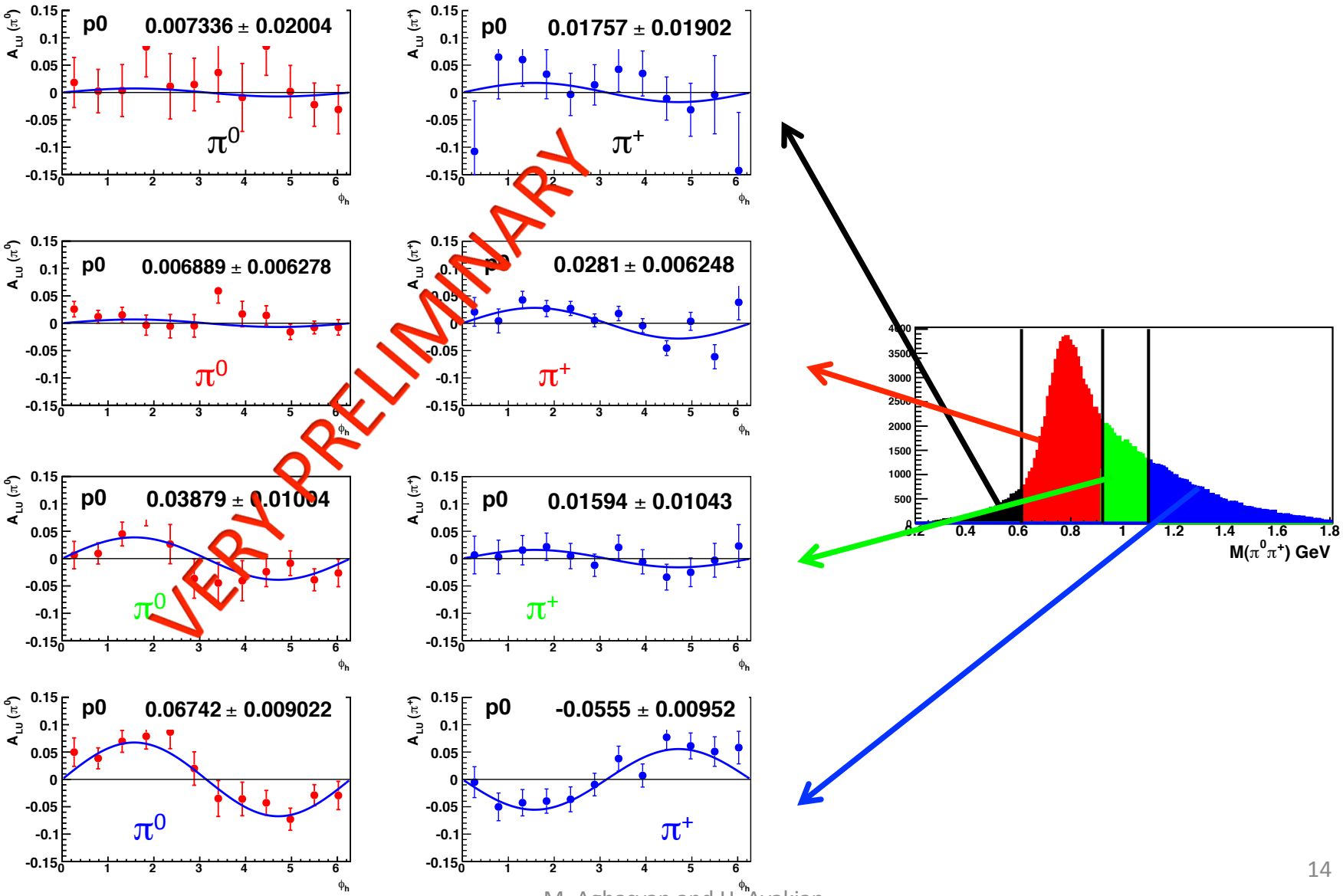


FIG. 5: Dependence of $\tilde{A}_{LU}^{\sin\phi}$ on z, x and $P_{h\perp}$ for charged pions. The contribution from VM decays has been determined from a Monte-Carlo simulation and subsequently subtracted from the asymmetries. The measurement of the x and $P_{h\perp}$ dependences is made separately for 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?

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



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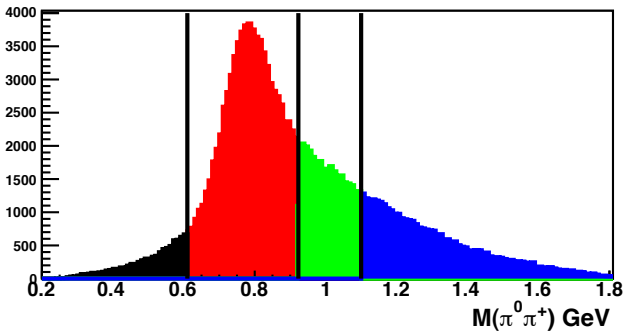
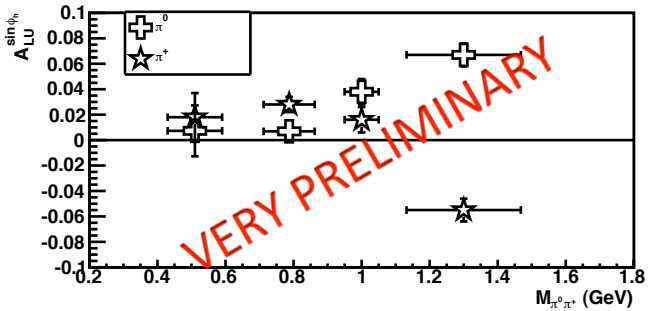
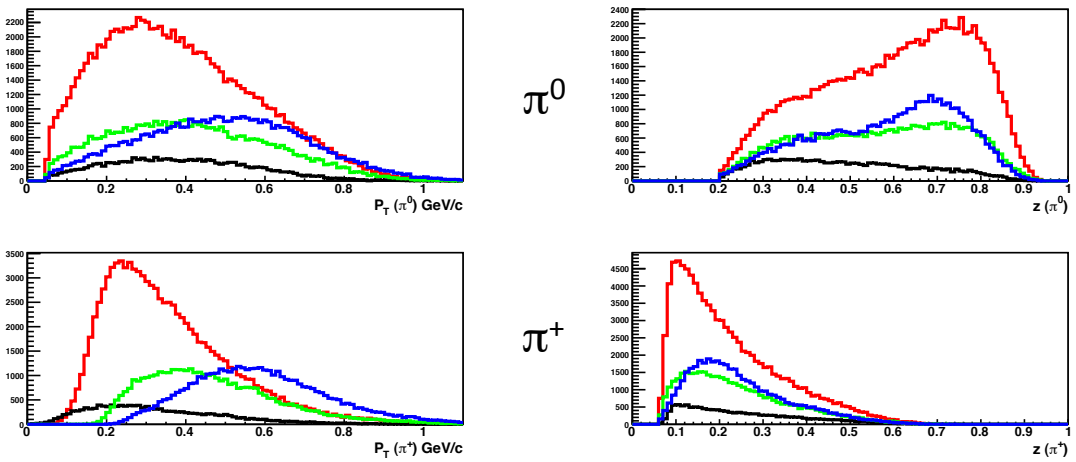
Exclusive $\pi^+\pi^0$ A_{LU} for any π^0



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



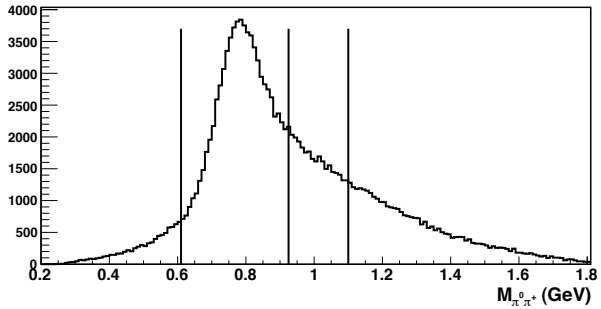
Or strong single pion A_{LU} dependence vs $x_B/P_T/z$ of single pions?

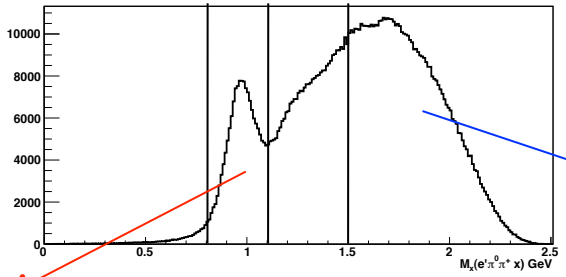


P_T **z**

$\pi^0\pi^+$ pairs

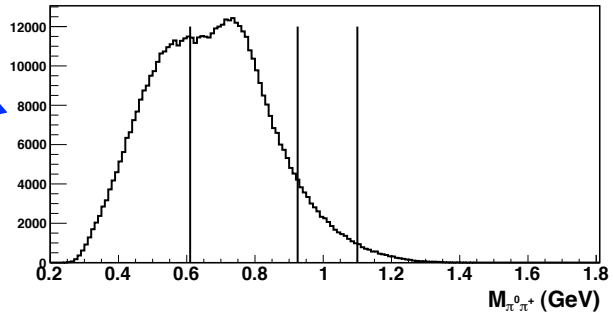
M ($\pi^+\pi^0$) GeV

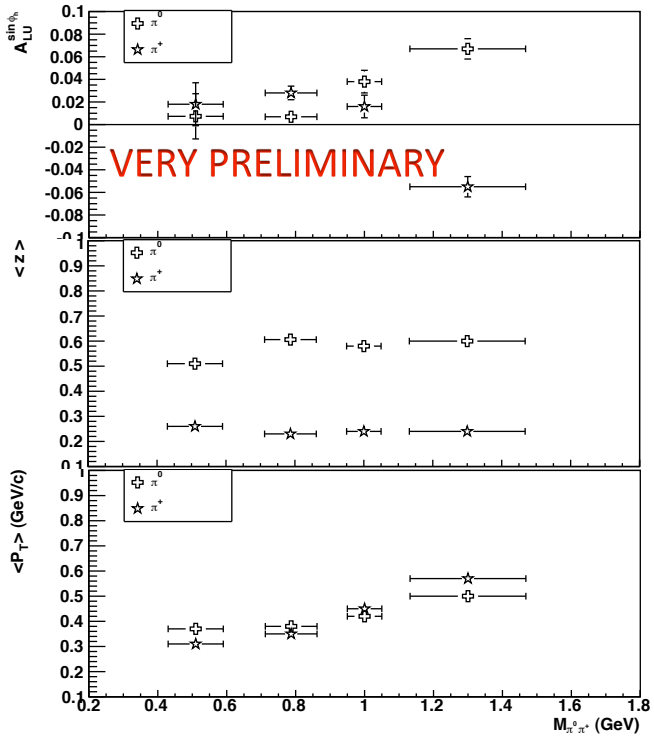




$M_x(ep\text{->}e\pi^+\pi^0\ x)$ GeV

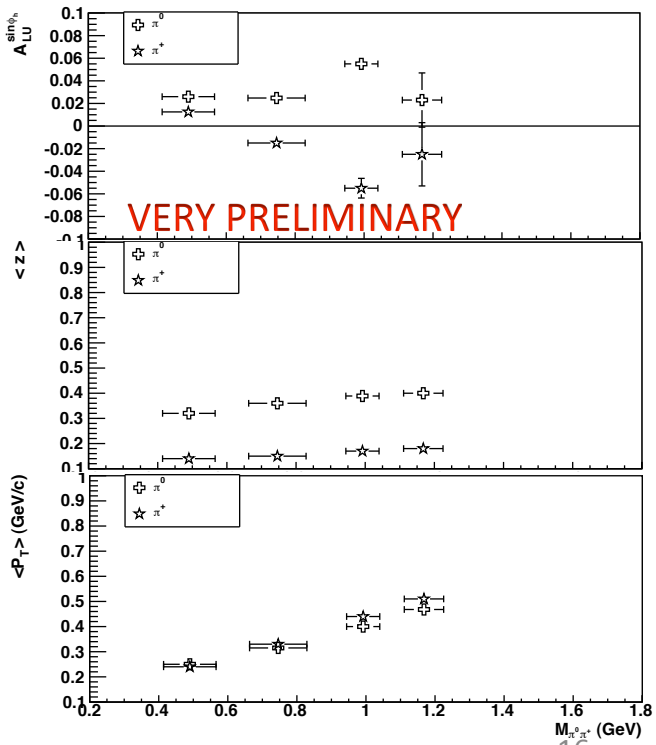
M ($\pi^+\pi^0$) GeV





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

Error bars are only Statistical.



SIDIS with Jlab at 6 GeV

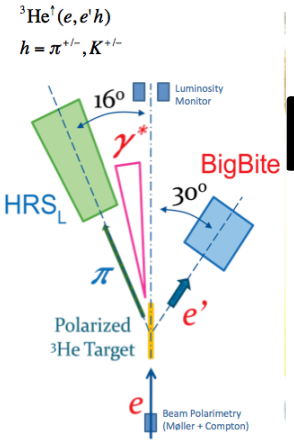
- Inclusive g1p
- Inclusive g1d
- SIDIS A_{UL} & A_{LL} for pions on proton
- SIDIS A_{UL} & A_{LL} for pions on deuteron
- SIDIS A_{UL} & A_{LL} for kaons
- SIDIS pion pairs
- Modifications of azimuthal moments in nuclei

Transversely polarized HD-ice target

- **Target used by LEGS at BNL with photon beam**
  - Small field ($\int Bdl \sim 0.005\text{-}0.05Tm$)
  - Small dilution factor
  - Less radiation length
  - Less nuclear background
  - Wider acceptance

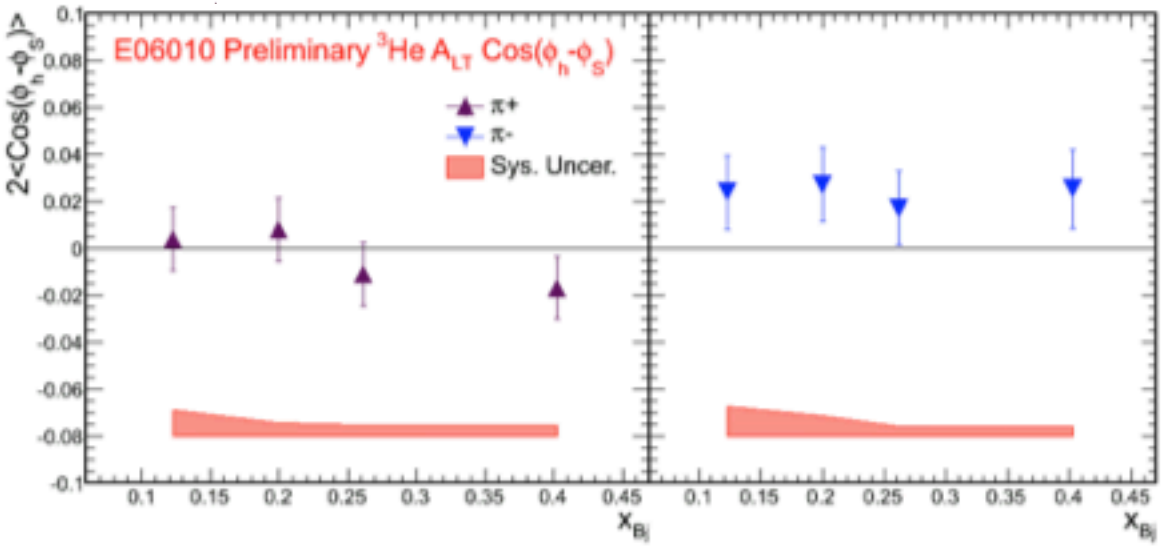
Need to demonstrate that the target can remain polarized for long periods with an electron beam with currents of order of 1-2 nA

- **The target is now at Jlab and all equipment moved to the new HDice lab**
  - Currently installing dilution refrigerators
  - Parallel development of new in-beam cryostat
  - **Installation ~ February 2011**
  - **Test with electrons ~ May 2011**



Preliminary results from Hall A

^{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 (?)

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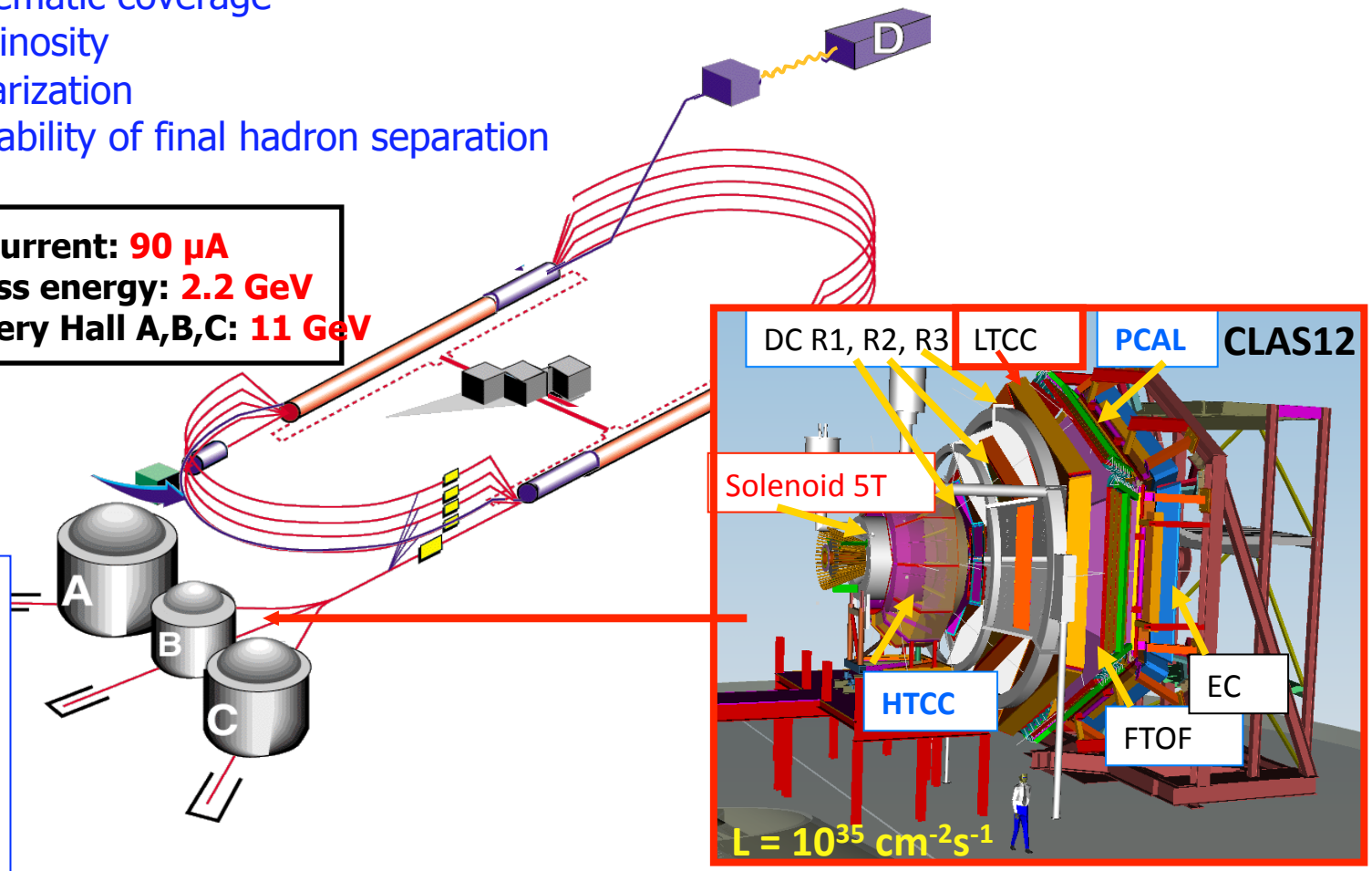
CLAS at 12 GeV

A new generation of experiments is necessary to fully exploit the properties of TMDs, with

- wide kinematic coverage
- high luminosity
- high polarization
- high capability of final hadron separation

Beam Current: 90 μA
Max Pass energy: 2.2 GeV
Max Enery Hall A,B,C: 11 GeV



May 2012

6 GeV Accelerator Shutdown starts

May 2013

Accelerator Commissioning starts

2013-2015

Pre-Ops (beam commissioning)

TMDs with 12 GeV in Hall B

PAC approved experiments

E12-06-112: **Pion** SIDIS
E12-09-008: **Kaon** SIDIS

E12-07-107: **Pion** SIDIS
E12-09-009: **Kaon** SIDIS

LOI12-06-108: **Pion** SIDIS
LOI12-09-004: **Kaon** SIDIS

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

- Complete program of TMDs studies for pions and kaons
- Kaon measurements crucial for a better understanding of the TMDs “kaon puzzle”
- Kaon SIDIS program requires an upgrade of the CLAS12 detector.

Summary

- ALU of π^0 in multidimensional bins.
- CLAS longitudinally polarized NH3 and ND3 target data provides superior sample of events allowing detailed studies of single and double spin asymmetries using multidimensional bins.

- Measurements of spin and azimuthal asymmetries with unpolarized, longitudinally polarized and transversely polarized targets in semi-inclusive processes at Hall-A/B :

- Measure TMDs of partons in the valence region
- Provide detailed info on partonic spin-orbit correlations
- Study quark-gluon correlations (HT)
- Study nuclear modification of 3D PDFs

- JLab12 will significantly increase the luminosity, kinematical coverage and particle identification capabilities of Hall-A/B