Spin and Azimuthal Asymmetries at JLAB

H. Avakian *)

Jefferson Lab

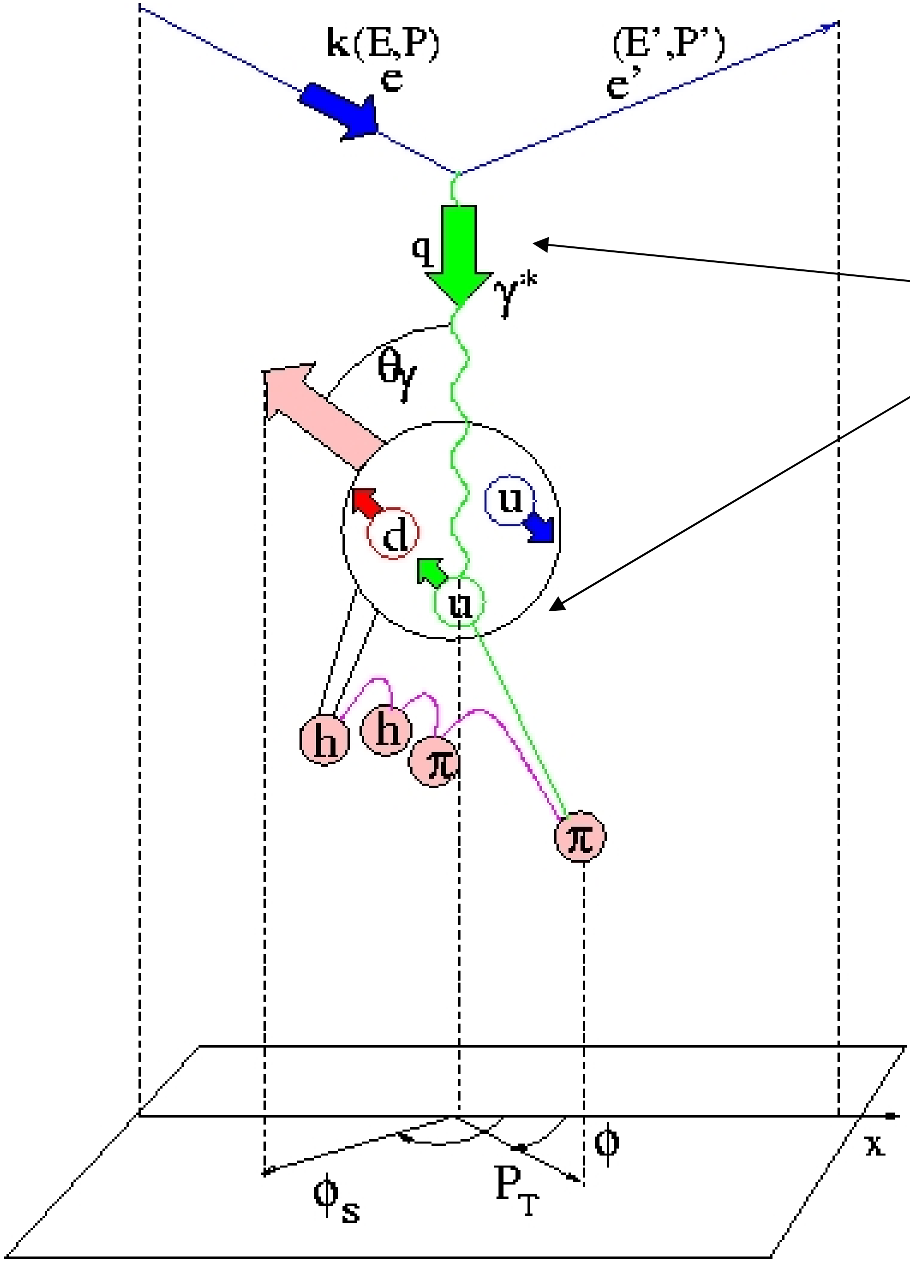
Single-Spin Asymmetries Workshop, BNL June 1-3, 2005

*) in collaboration with P.Bosted, V. Burkert and L. Elouadrhiri

Outline

- Introduction
- SSA in target fragmentation
- Transverse momentum of quarks in SIDIS
  - azimuthal asymmetries
- Double spin asymmetries
- SSA in SIDIS
  - beam single-spin asymmetries
  - target single-spin asymmetries
- SSA in hard exclusive processes
  - DVCS
  - DVMP
- Summary

Polarized Semi-Inclusive DIS

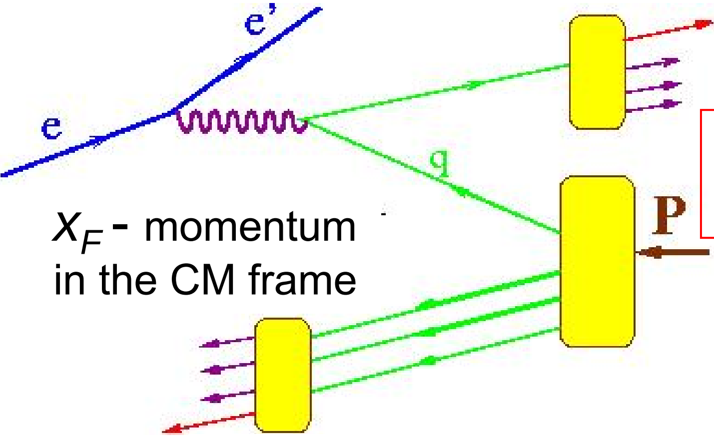


Cross section defined by scale variables **x,y,z**

$$
\begin{aligned}
x &= Q^2/2ME_\gamma \\
y &= E_\gamma/E \\
z &= E_h/E_\gamma \\
\sin\theta_\gamma &\approx \frac{2Mx}{Q}\sqrt{1-y} \\
\sin\phi &= \frac{[\vec{q}\times\vec{k}]\vec{P}_\perp}{|\vec{q}\times\vec{k}||P_\perp|}
\end{aligned}
$$

Hadron-Parton transition: by distribution function $f_1^u(x)$: probability to find a **u**-quark with a momentum fraction **x**

Parton-Hadron transition: by fragmentation function $D_{1u}^{\pi+}(z)$: probability for a **u**-quark to produce a π^+ with a momentum fraction **z**



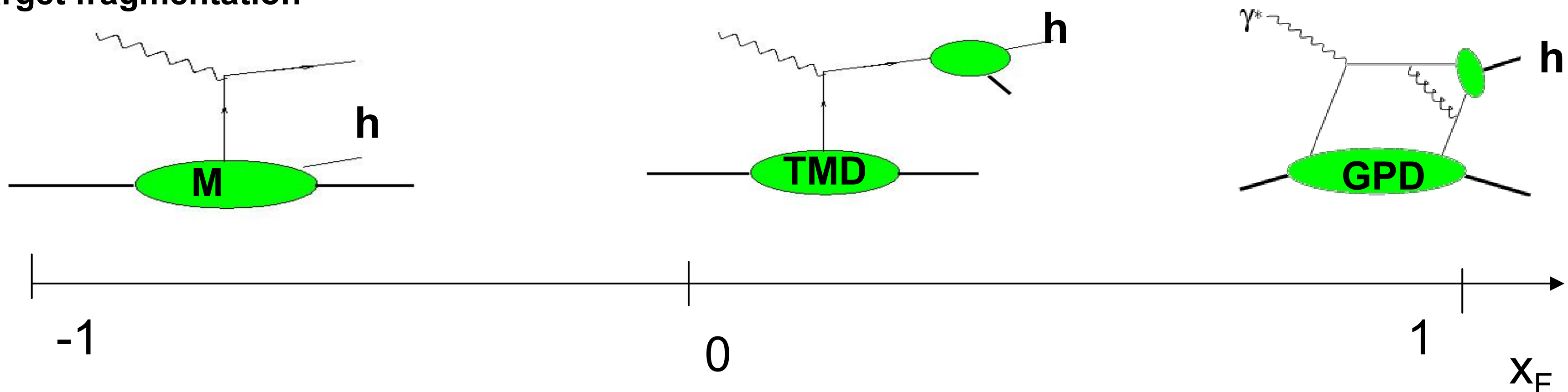
x_F - momentum in the CM frame

x_F>0 (current fragmentation)

Single pion production in hard scattering

Current fragmentation

Target fragmentation



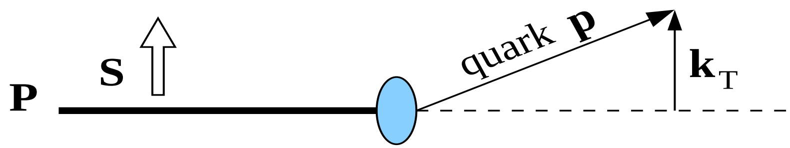
Fracture Functions

k_T-dependent PDFs

Generalized PDFs

Wide kinematic coverage of large acceptance detectors allows studies of hadronization both in the target and current fragmentation regions

Transverse momentum of quarks



- k_T – **crucial for orbital momentum and spin structure studies**
  - –lead to SSA in hard scattering processes
- k_T – **lead to 3 dimensional description**
  - –lead to introduction of k_T dependent/u PDFs
- k_T - **important for cross section description (important also for exclusive production)**
  - P_T distributions of hadrons in DIS
  - exclusive photon production (DVCS)
  - hard exclusive vector meson x-section
  - pp $\rightarrow \pi^0$X (E704,RHIC) x-sections

To study orbital motion of quarks in semi-inclusive DIS measurements in a wide range of **P_T, ϕ and ϕ_S** are required.

SIDIS ($\gamma^*p\text{->}\pi X$) x-section at leading twist:

TMD PDFs

$$\frac{d\sigma}{dx\,dy\,dz_h\,d^2\vec{P}_{h\perp}} = \frac{4\pi\alpha_{\rm em}^2 s}{Q^4}\Big[(1-y+y^2/2)xF_{UU}^{(1)}$$ → f_1

$$-(1-y)x\cos(2\phi_h)F_{UU}^{(2)}$$ → $h^{\perp}_1$

$$+\lambda_\ell\lambda y(1-y/2)xF_{LL}$$ → g_1

$$+\lambda(1-y)x\sin(2\phi_h)F_{UL}$$ $h^{\perp}_{1L}$

$$+|S_\perp|(1-y+y^2/2)x\sin(\phi_h-\phi_S)F_{UT}^{(1)}$$ → $f^{\perp}_{1T}$

$$+\lambda_\ell|S_\perp|y(1-y/2)x\cos(\phi_h-\phi_S)F_{LT}$$ g_{1T}

$$+|S_\perp|(1-y)x\sin(\phi_h+\phi_S)F_{UT}^{(2)}$$ → h_1

$$+\ \tfrac{1}{2}|S_\perp|(1-y)x\sin(3\phi_h-\phi_S)F_{UT}^{(3)}\Big]$$ $h^{\perp}_{1T}$

T-odd

Unpolarized target
Longitudinally pol.
Transversely pol.

k_T-even | k_T-odd

Studies of PDFs require <u>three</u> experiments

The structure functions depend on Q^2, x_B, z, P_{hT}

- ➢Factorization of k_T-dependent PDFs proven at low P_T of hadrons (Ji et al.)
- ➢Universality of k_T-dependent distribution and fragmentation functions proven (Collins,Mets…)

Spin-Azimuthal Asymmetries

Spin asymmetries + azimuthal dependence ⟶ new class of DIS measurements **Spin-Azimuthal Asymmetries:**

Significant progress made recently in studies of Single-Spin Azimuthal Asymmetries (SSA) in electroproduction with longitudinally polarized target (HERMES,CLAS), transversely polarized target (SMC,HERMES,COMPASS), and polarized beam (CLAS,HERMES).

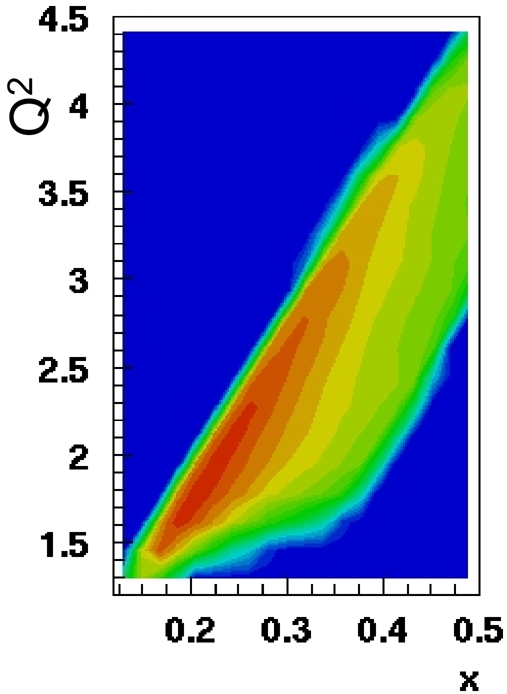
- SSA are sensitive to the orbital momentum of quarks.
- provide a window to the physics of partonic final and initial state interactions
- model calculations indicate that SSA are not affected significantly by a wide range of corrections.
- Good agreement in SSAs measured in a wide energy range in electroproduction and **pp** scattering.

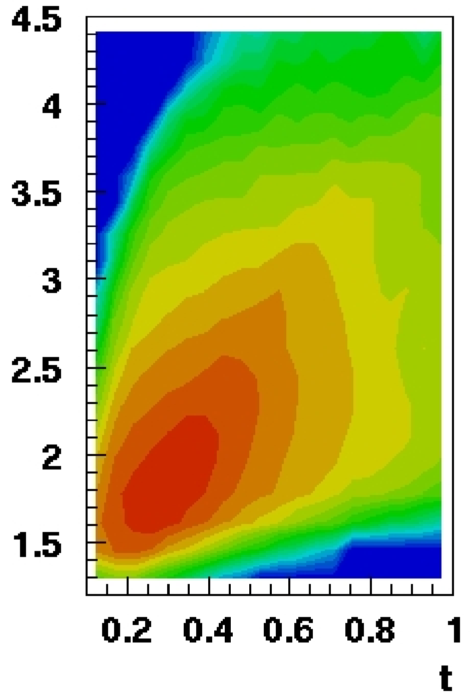
SSAs: stable observable over a wide beam energy and **Q^2** range

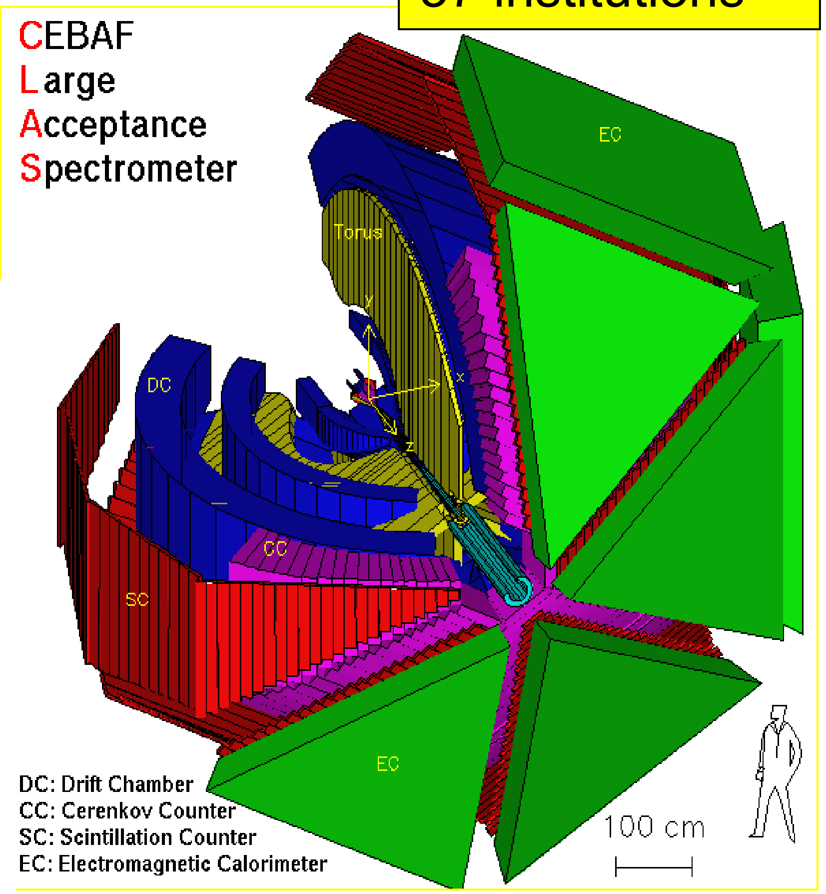
The CLAS Detector

- High luminosity, polarized CW beam
- Wide physics acceptance, including exclusive, semi-inclusive processes, current and target fragmentation
- Wide geometric acceptance, allowing detection of multi-particle final states

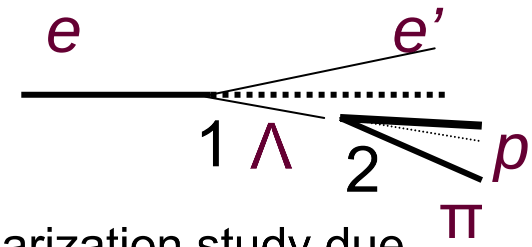
~ 200 physicists
37 institutions



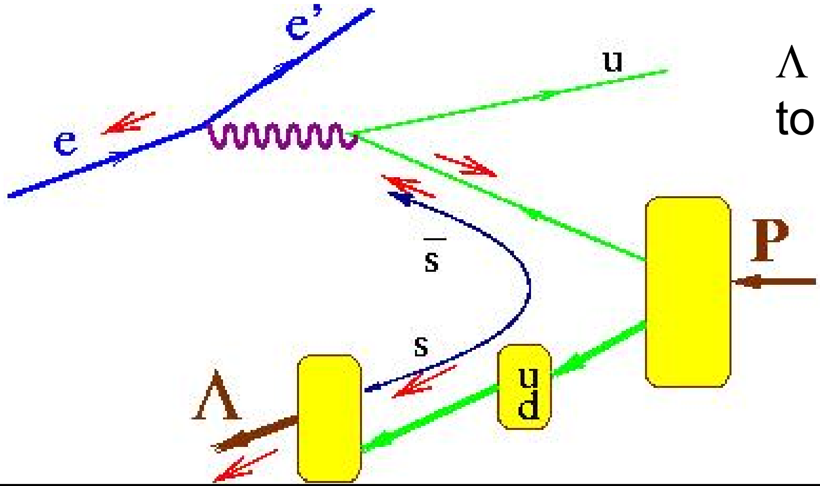




Λ in target fragmentation



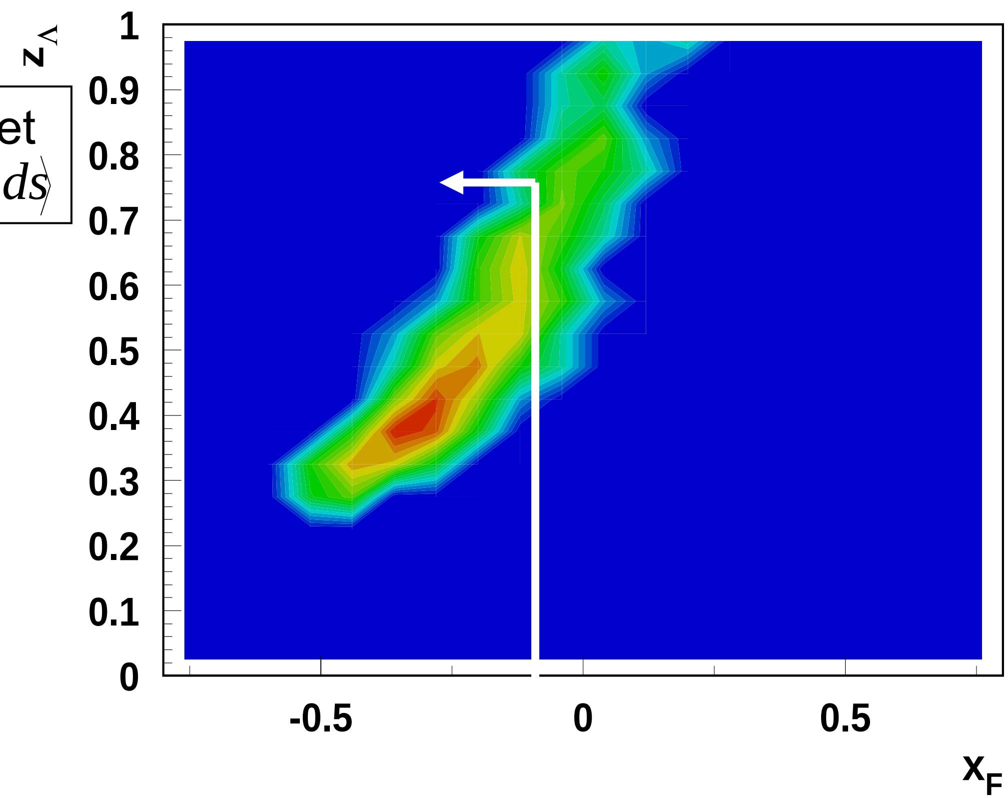
Λ – unique tool for polarization study due to self-analyzing parity violating decay



Accessing polarized PDFs with unpolarized target!

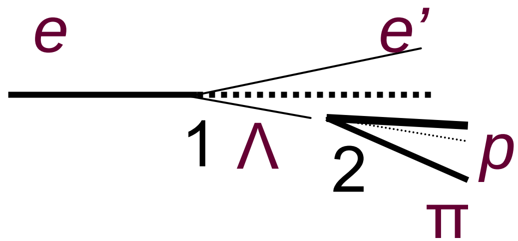
(ud)-diquark is a spin and isospin singlet
s-quark carries whole spin of Λ $|\Lambda\rangle = |uds\rangle$

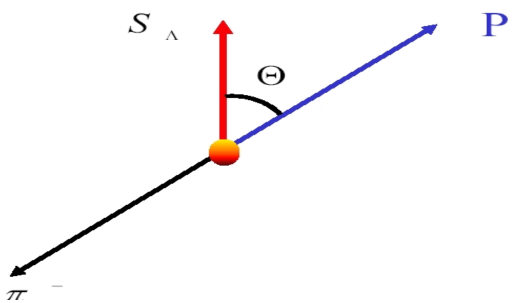
Λs accessible in CLAS (even at large **z**) are mainly in the TFR region and can provide information on contribution of strange sea to proton spin



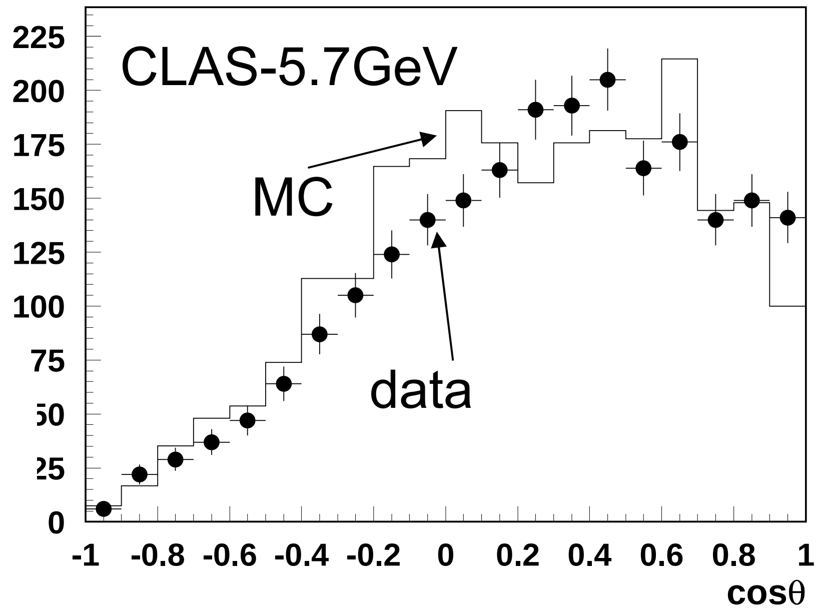
W.Melnitchouk and A.W.Thomas ‘96
J.Ellis, D.Kharzeev, A. Kotzinian ‘96

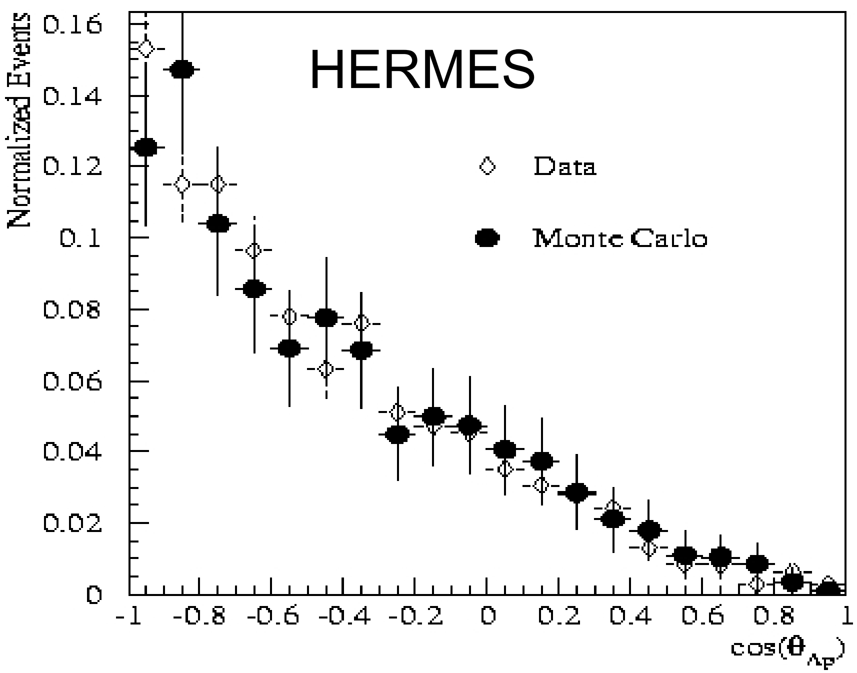
Λs in target fragmentation





$$\frac{d\sigma}{d\theta} = \sigma_0 A(\cos\theta)\left(1 + \alpha P_\Lambda \cos\theta\right)$$

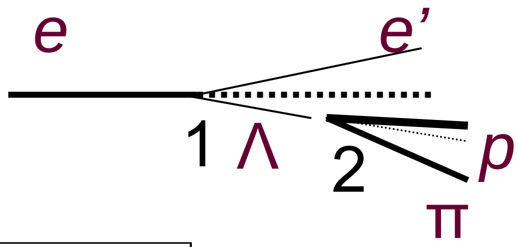


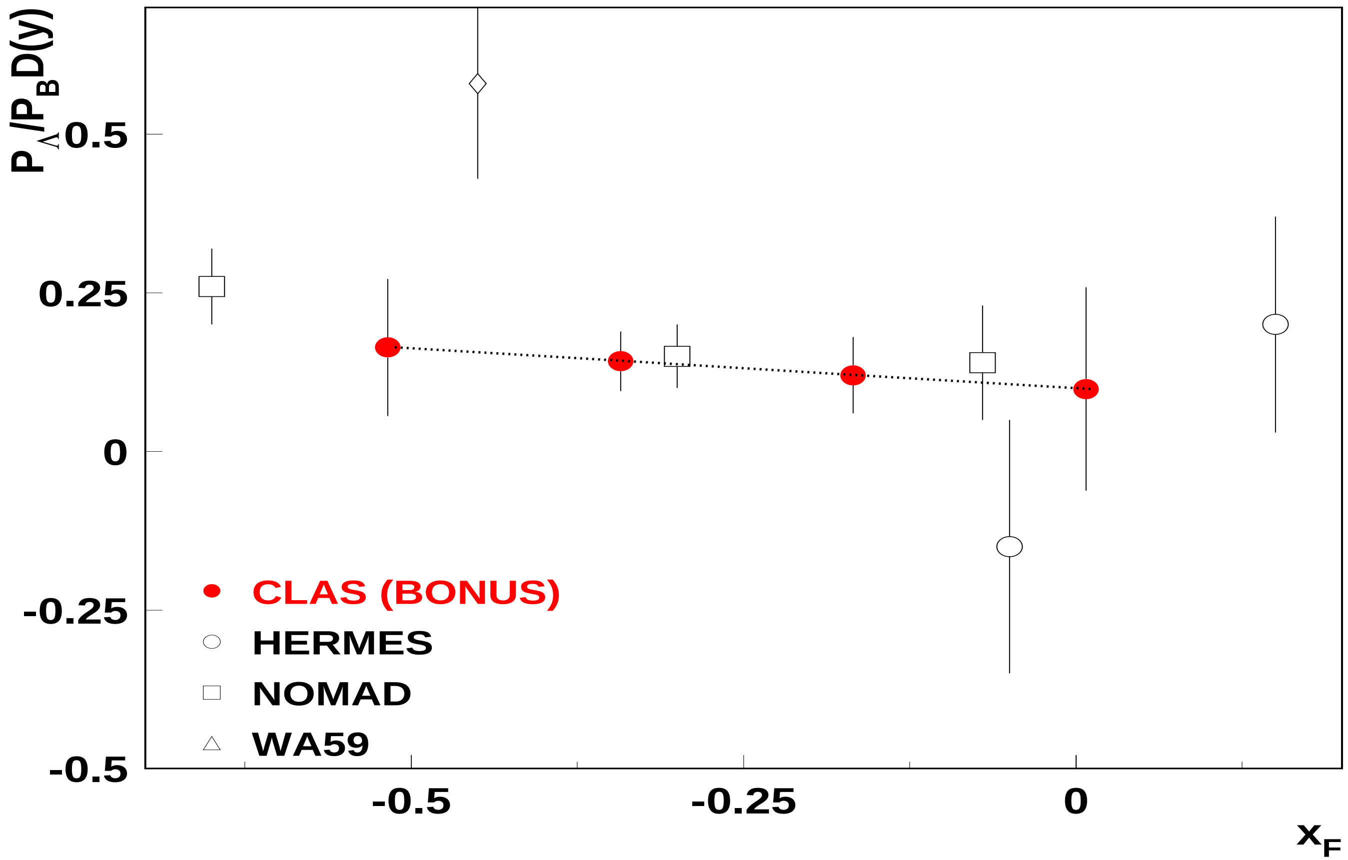


Presence of large cosθ from acceptance require:

1) Detailed MC simulation **OR**
2) Spin asymmetry measurement to cancel the acceptance contribution

Λs in target fragmentation

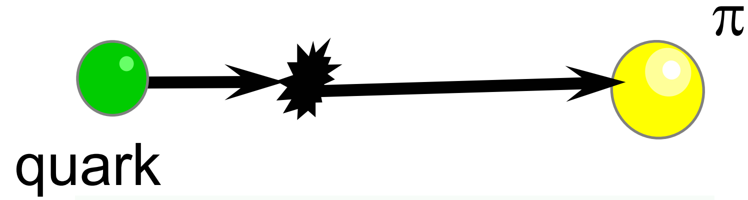




6

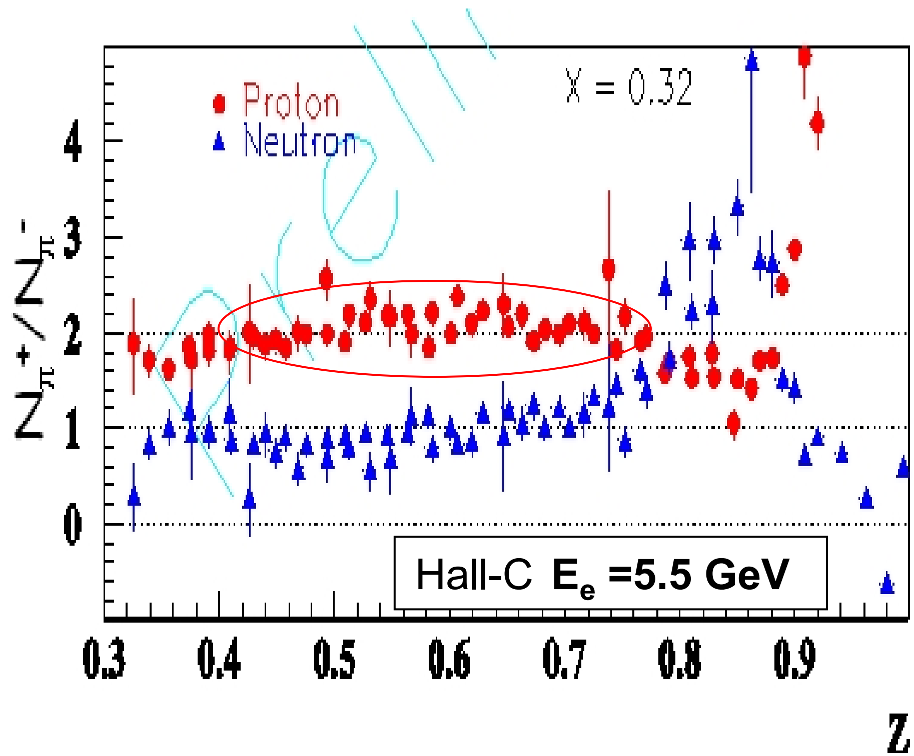
Projections for Lambda polarization for 5.75 GeV (25days) with neutron target (**predictions for 5.75 GeV from Ellis et al.**)

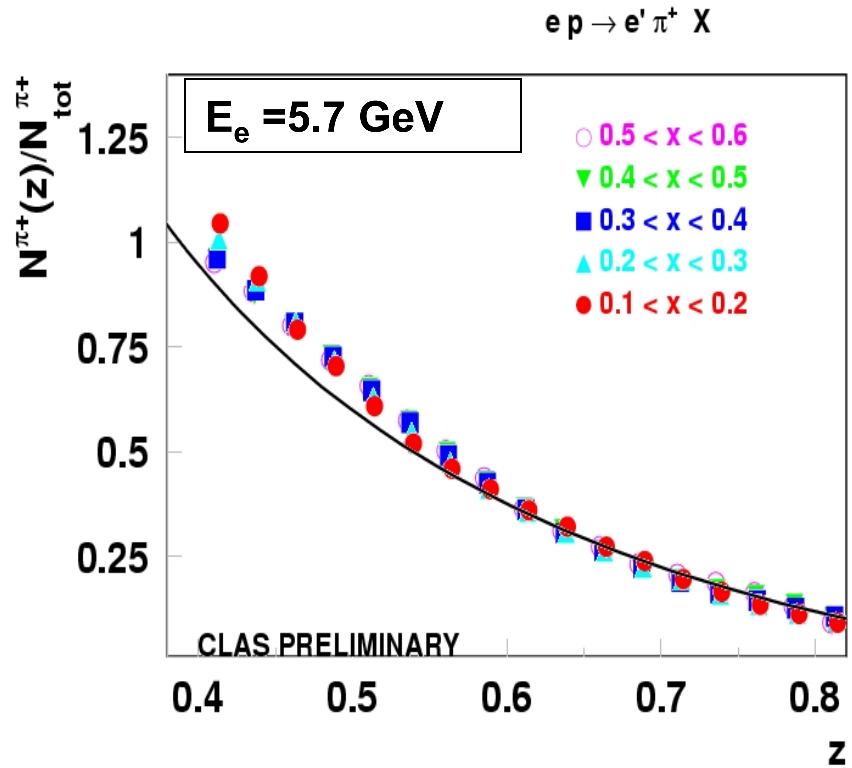
Collinear Fragmentation



The only fragmentation function at leading twist for pions in eN→e'πX is $D_1(z)$

$$\sum e_q^2\, q(x)\, D_{q\rightarrow M}(z)$$





No significant variation observed in π+/π– ratio and in z distributions of π+ for different **x** ranges (0.4<z<0.7, M_X>1.5)

Azimuthal Asymmetries in SIDIS

- Gluon bremsstrahlung (Georgi & Politzer, Mendez 1978) at z→1

$$-\frac{\alpha_s}{2}\sqrt{1-z}\,\frac{(2-y)\sqrt{1-y}}{1+(1-y)^2}$$

- Intrinsic transverse momentum of partons (Cahn 1978)

$$-4\left(\frac{P_\perp^2}{Q^2}\right)^{\frac{1}{2}}\frac{a^2 z}{b^2+z^2a^2}\,\frac{(2-y)\sqrt{1-y}}{1+(1-y)^2}$$

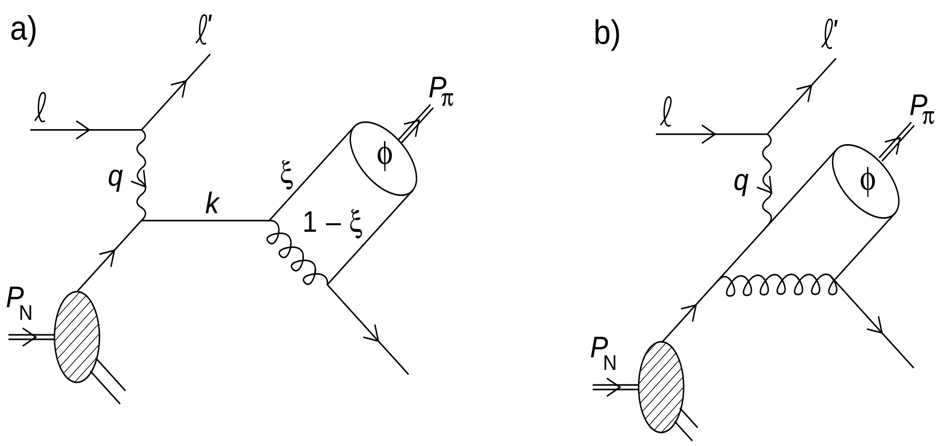
- Higher twists (Berger 1980, Brandenburg et al 1995)

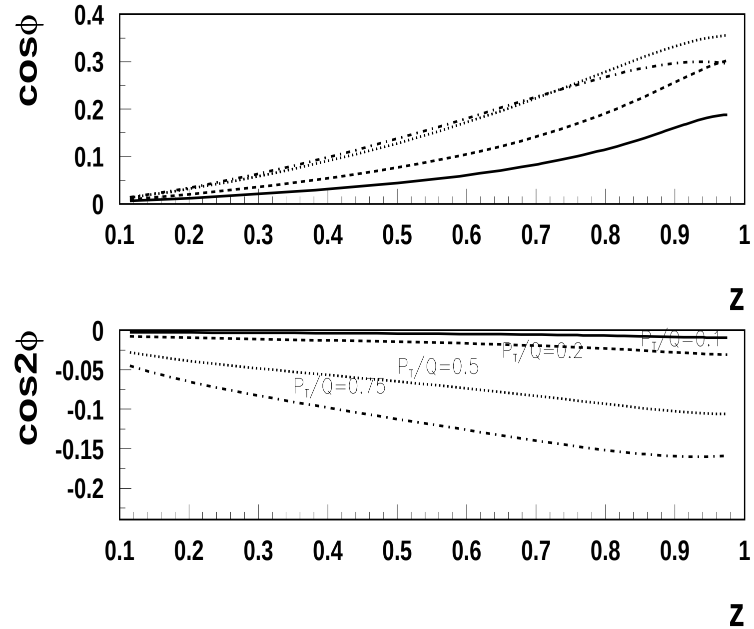
$$2\left(\frac{P_\perp^2}{Q^2}\right)^{\frac{1}{2}}\frac{1}{3(1-z)}\,\frac{(2-y)\sqrt{1-y}}{1+(1-y)^2}$$

The DIS data from EMC (1987) and Fermilab (1993) are most consistent with intrinsic parton transverse momentum squared, k_T^2 of ~ 0.25 GeV^2

Azimuthal Asymmetries in semi-exclusive limit

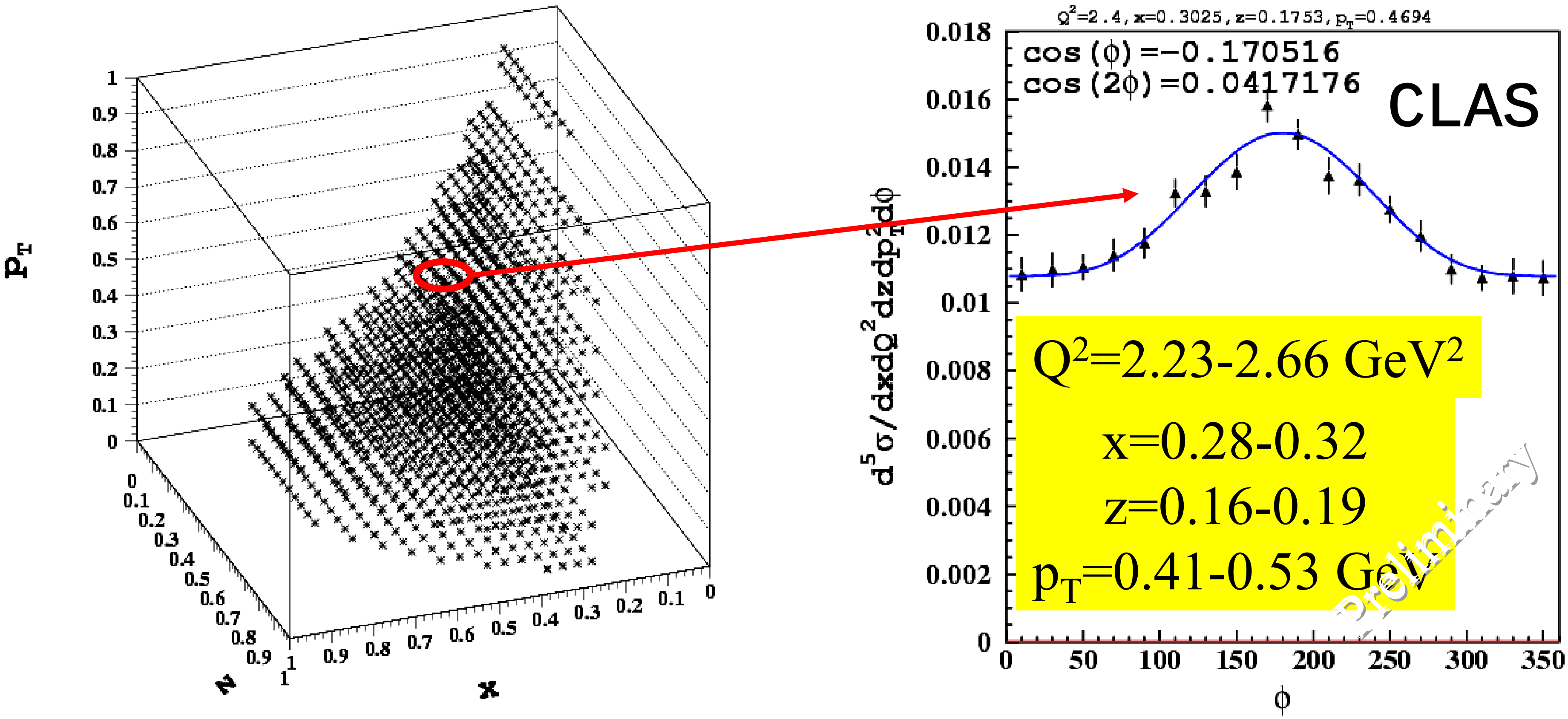
- Higher twists (Berger 1980, Brandenburg et al 1995) $z \to 1$ dominant contribution $u + e^- \to e^- \pi^+ d$





Dominant contribution to meson wave function is the perturbative one gluon exchange and approach is valid at factor ~3 lower Q^2 than in case of hard exclusive scattering (Afanasev & Carlson 1997)

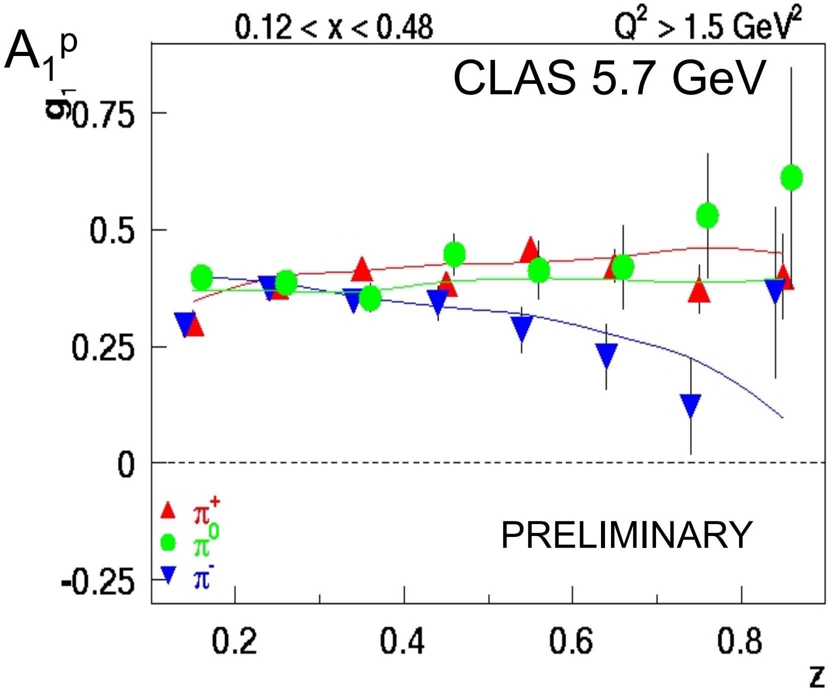
Azimuthal asymmetries at CLAS

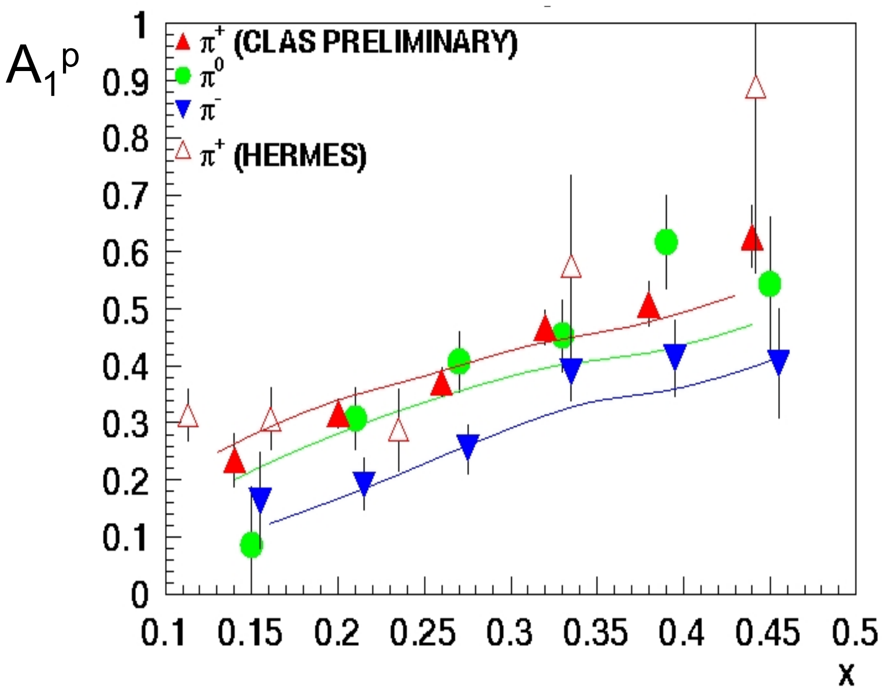


- Unpolarized Semi-inclusive electroproduction of π^+ measured.
- Complete <u>5-dimensional cross sections</u> were extracted.
- Direct separation of different structure functions.

A_1^p f-kinematic dependence for $\pi^{+/-/0}$

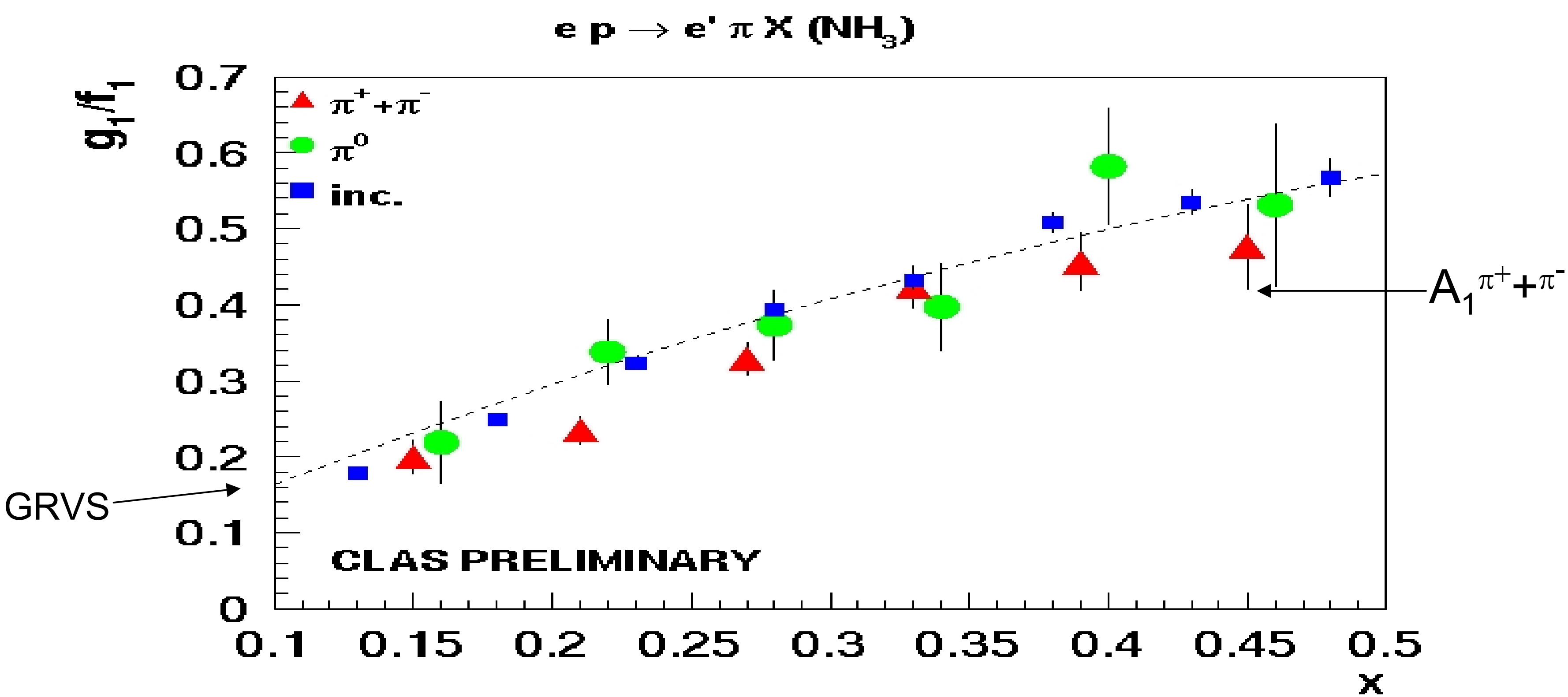
$$A_1^p \approx \frac{1}{P_B P_T f D_{LL}(y)} \frac{N^{+-} - N^{++}}{N^{+-} + N^{++}}$$





- No significant z-dependence of A_1 in the range $0.4<z<0.7$ ($\pi^+\pi^0$)
- **x** dependence of CLAS $\mathbf{A_1^p}$ (A_2=0) consistent with HERMES data at x3 higher Q^2 and with PEPSI (LUND)MC.

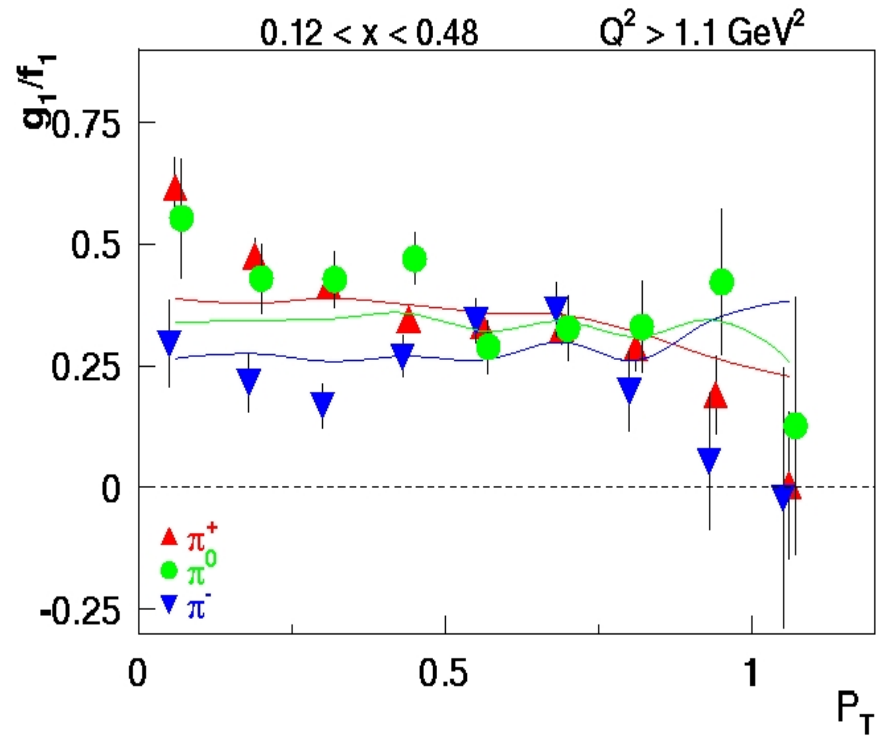
SIDIS: factorization studies



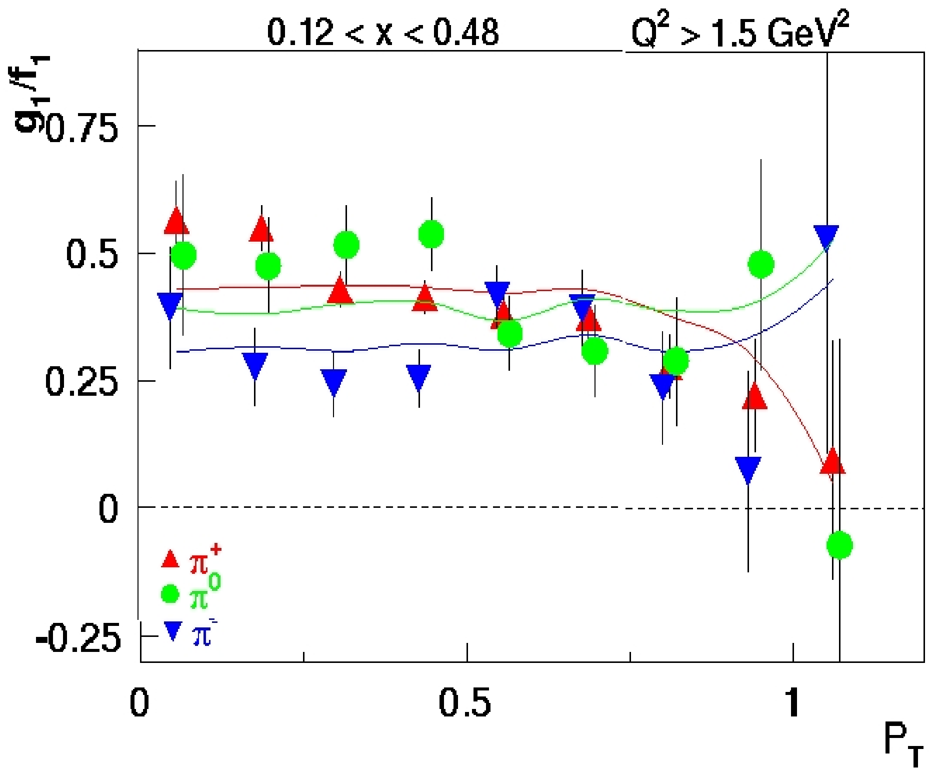
- **A_1** inclusive, from $\pi^+\pi^-$ sum and π^0 are consistent (in range 0.4<z<0.7)
- **A_1^p** dependence can serve an important check of HT effects and applicability of simple partonic description.
- There is an indication that **A_1^p** of $\pi^+ + \pi^-$ is lower than inclusive at large z.

g_1/f_1 for $\pi^{+/-/0}$: PT-dependence

EG2000



PEPSI-MC



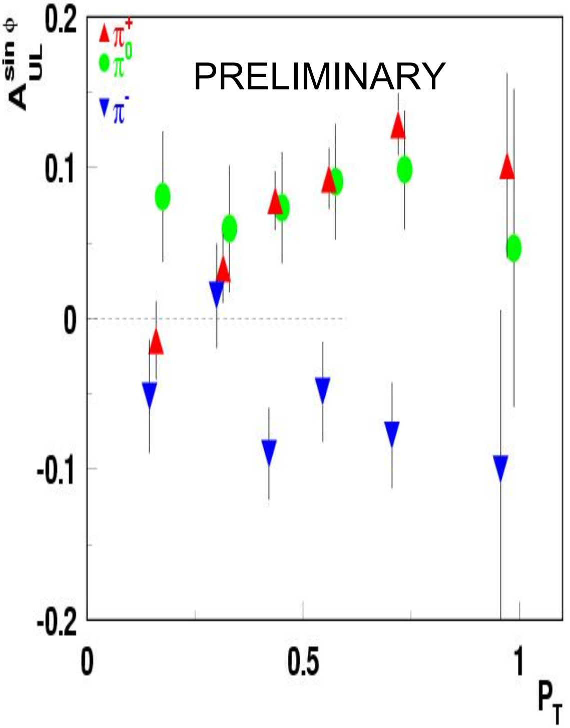
Data consistent with PEPSI-MC

Asymmetries from k_T-odd ($f_1^{\perp}$, $h_1^{\perp}$, g_T..) and k_T-even (g_1) distribution functions are expected to have a very different behavior (F.Yuan)

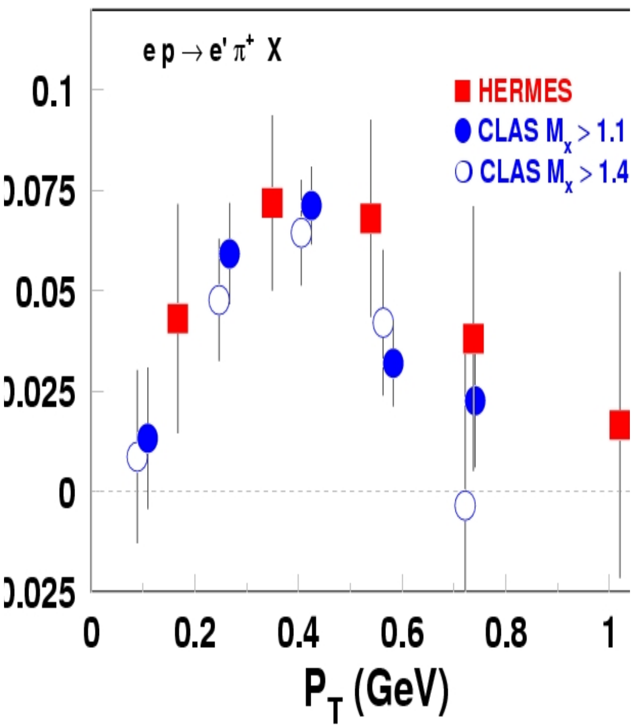
SSA: P_T-dependence of sinϕ moment

$\sigma^{\sin\phi}_{LU(UL)} \sim F_{LU(UL)} \sim 1/Q$ (Twist-3)

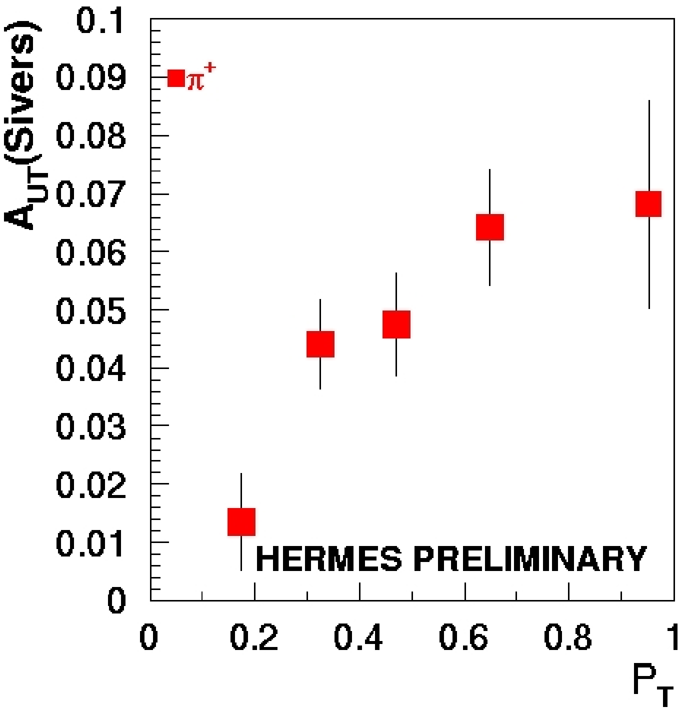
A_{UL} (CLAS @5.7 GeV)



A_{LU} CLAS @4.3 GeV



A_{UT} HERMES @27.5 GeV



Beam and target SSA for π+ are consistent with increase with P_T

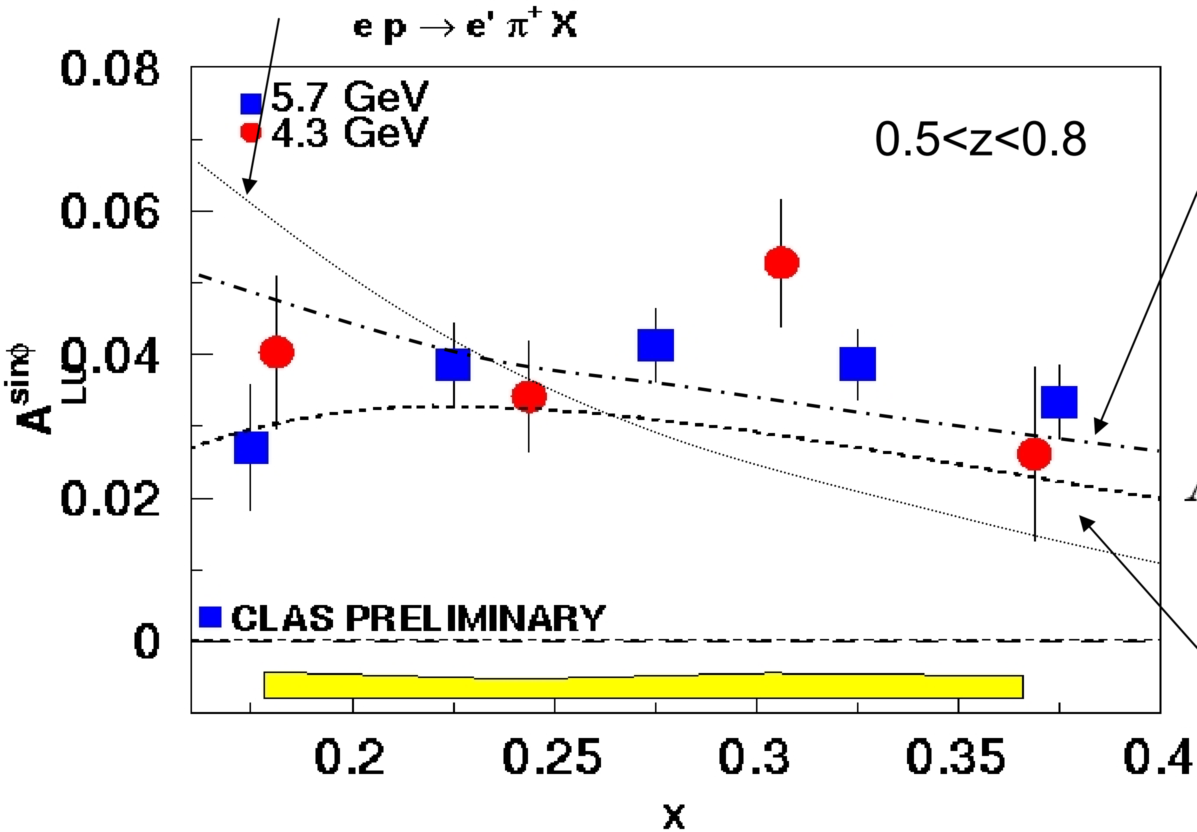
A_{LU}: x-dependence

$$A_{LU}^{AC} \propto g^{\perp(1)}(x) D_1(z)$$

Photon Sivers Effect Afanasev & Carlson, Metz & Schlegel

$$A_{LU}^{Sivers} \propto h_1^{\perp(1)}(x) E(z)$$

Beam SSA analyzed in terms of the Sivers effect by F.Yuan using $h_1^{\perp}$ from MIT bag model



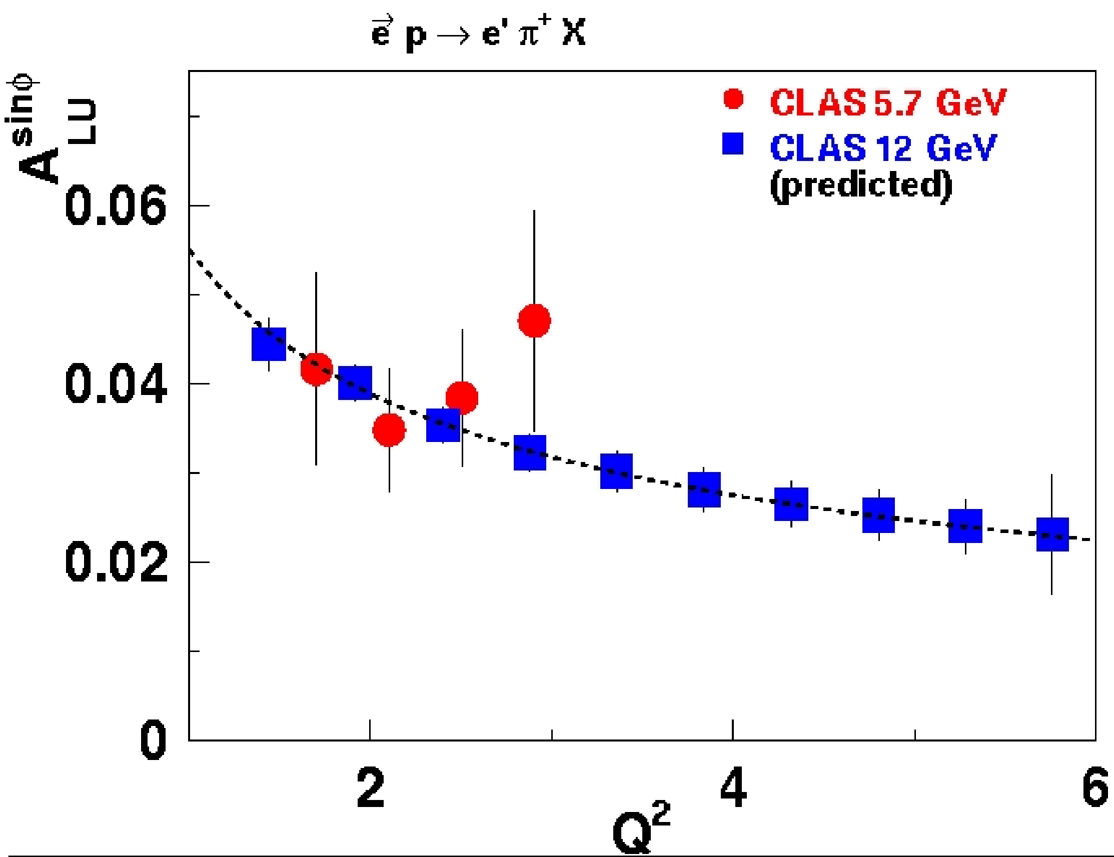
$$A_{LU}^{Collins} \propto e(x) H_1^{\perp(1)}(z)$$

Beam SSA analyzed in terms of the Collins effect by Schweitzer et al. using e(x) from χQSM

Knowledge of polarized fragmentation function required to extract distribution functions.

Measuring the Q^2 dependence of SSA

$\sigma^{\sin\phi}_{LU(UL)} \sim F_{LU(UL)} \sim 1/Q$ (Twist-3)



For fixed x, 1/Q behavior expected

Wide kinematic coverage and higher statistics will allow to check the higher twist nature of beam and longitudinal target SSAs

Flavor decomposition of T-odd $g^{\perp}$

In jet SIDIS with massless quarks contributions from $H_1^{\perp}$,E vanish

$$\sigma_{UU} \propto \left(1 - y + y^2/2\right) \sum_{q,\bar{q}} e_q^2 f_1^q(x) D_1^q(z)$$

$$\sigma_{LU}^{\sin\phi} \propto S_L \frac{M}{Q} y\sqrt{1-y} \sum_{q,\bar{q}} e_q^2 x g^{\perp q}(x) D_1^q(z) \longrightarrow$$

gauge link contribution

$$\sigma_{LU}^{\sin\phi} \propto S_L \frac{M}{Q} y\sqrt{1-y} \sum_{q,\bar{q}} e_q^2 x e^q(x) H_1^{\perp q}(z)$$

With SSA measurements for $\pi^+ + \pi^-$ and π^0 on neutron and proton ($\pi = \pi^+ + \pi^-$) assuming $H^{fav} = H^{u\to\pi+} \approx -H^{u\to\pi-} = -H^{unfav}$

$$xg^{\perp u}(x) = \frac{4}{15}\left[A^{\pi}_{LU,p}\left(4u+d\right) - A^{\pi}_{LU,n}\left(d+u/4\right)\right]$$

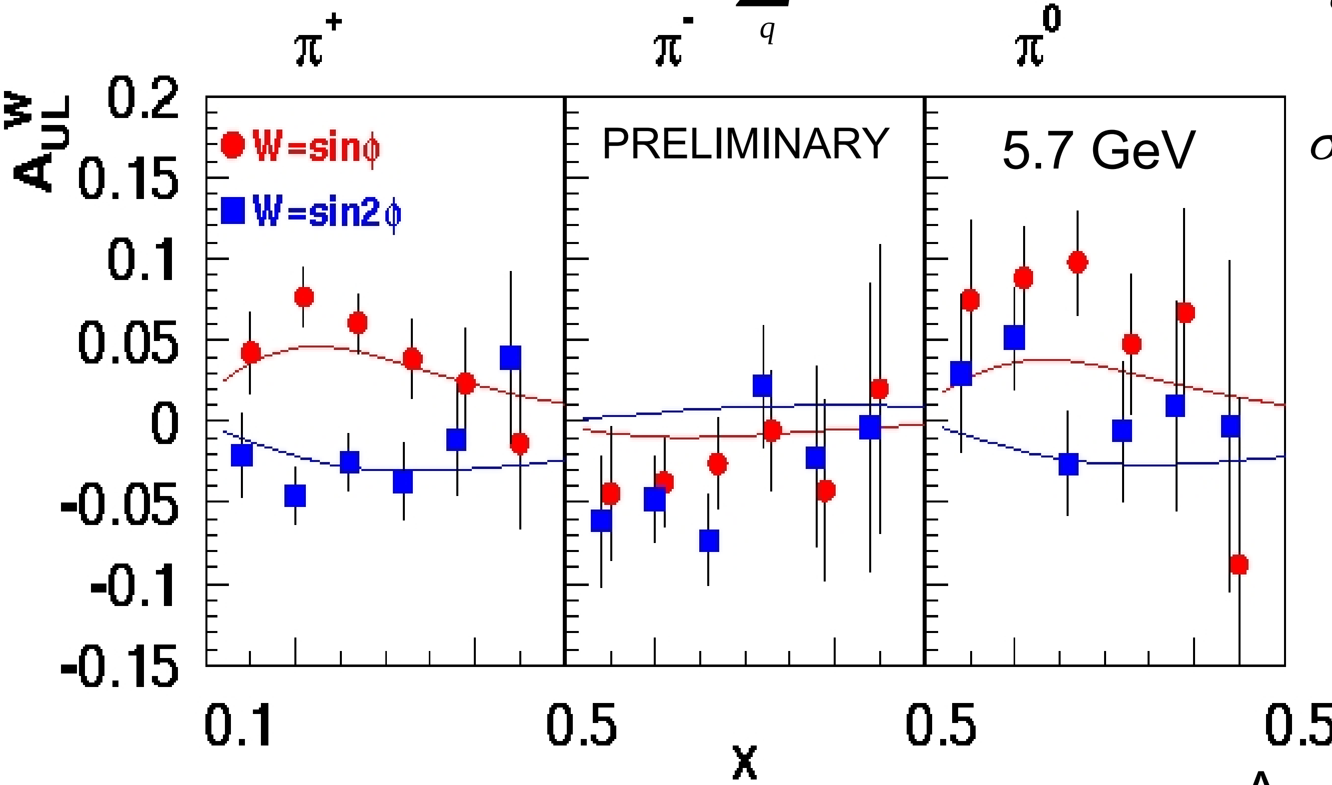
$$xg^{\perp d}(x) = \frac{4}{15}\left[A^{\pi}_{LU,n}\left(4d+u\right) - A^{\pi}_{LU,p}\left(u+d/4\right)\right]$$

SSA: x-dependence

$$A_{UL}^{\sin 2\phi} = P_T D_{UL} \frac{\sum_q h_{1L}^{q\perp}(x) H_1^{q\perp}(z)}{\sum_q f_1^q(x) D_1^q(z)}$$

$$\sigma_{UT}^{\sin\phi} \propto S_T \sum_{q,\bar{q}} e_q^2 f_{1T}^{\perp q}(x) D_1^q(z)$$

$$\sigma_{UL}^{\sin\phi} \propto S_L \frac{M}{Q} \sum_{q,\bar{q}} e_q^2 x h_L(x) H_1^{\perp q}(z)$$



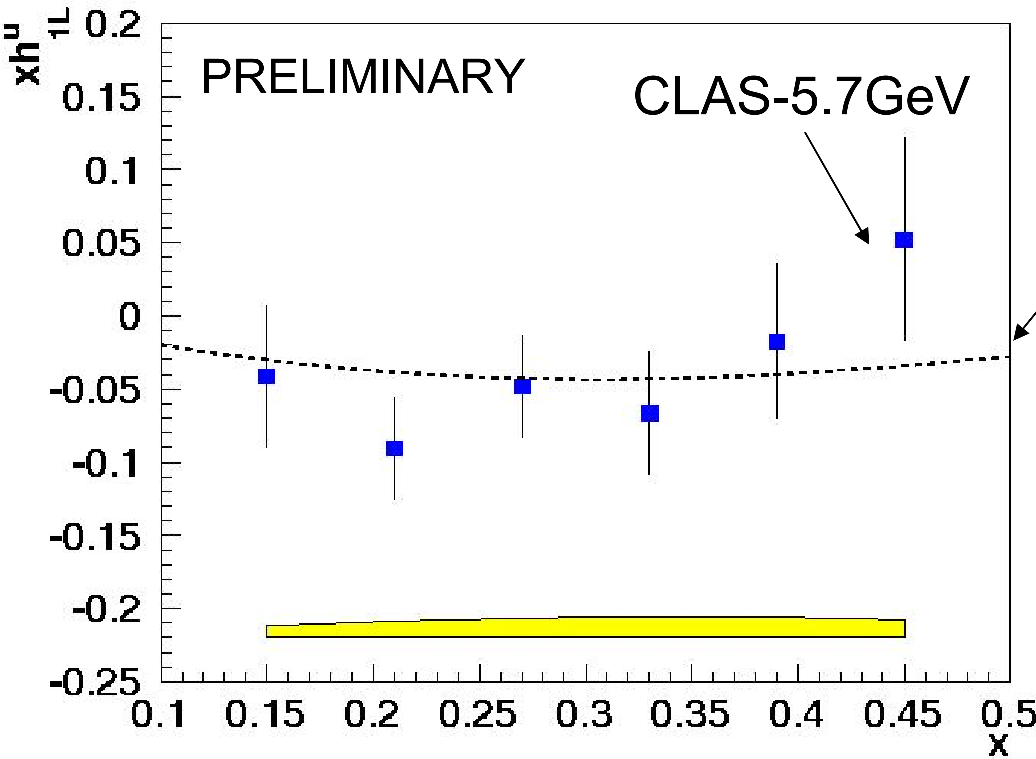
HT–SSA significant for π^+ and π^0 (non-Collins?)

$A_{UL}(\pi^0) \sim H_1^{favore} + H_1^{unfavored}$

- Study the Collins fragmentation mechanism with long. polarized target
- For π^- and π^0 SSA is sensitive to unfavored fragmentation

First glimpse of Twist-2 TMD $h_{1L}^{\perp}$

For Collins fragmentation use chirally invariant Manohar-Georgi model (Bacchetta et al)



Distribution functions from χQSM from Efremov et al

Systematic error only from unknown ratio of favored and unfavored Collins functions ($R = H_1^{d\rightarrow\pi+}/H_1^{u\rightarrow\pi+}$), band correspond to $-2.5<R<0$

- More data required with π- & π^0
- Exclusive 2 pion background may be important

π- and π^0 SSA will also give access to h_{1L}^{d} (If $R \approx -1$ deuteron data could be crucial)

Future: more π^0 data in SIDIS

advantages:

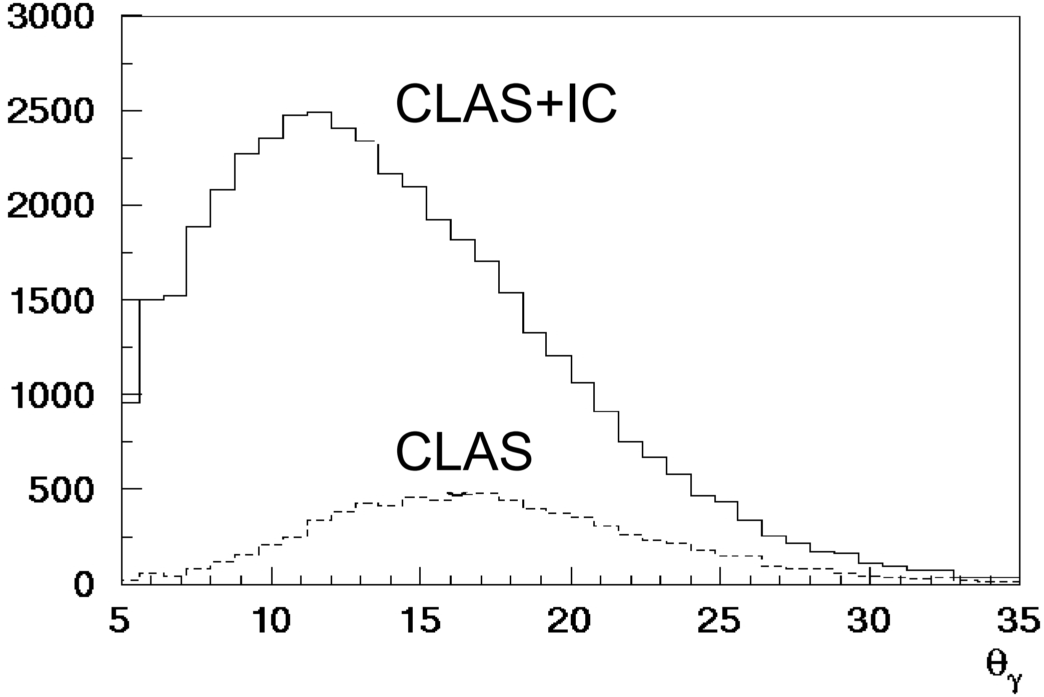
1) **SIDIS π^0 production is not contaminated by diffractive ρ**
2) **HT effects and exclusive π^0 suppressed**
3) **Simple PID by π^0-mass (no kaon contamination)**
4) **Provides complementary to $\pi^{+/-}$ information on PDFs**

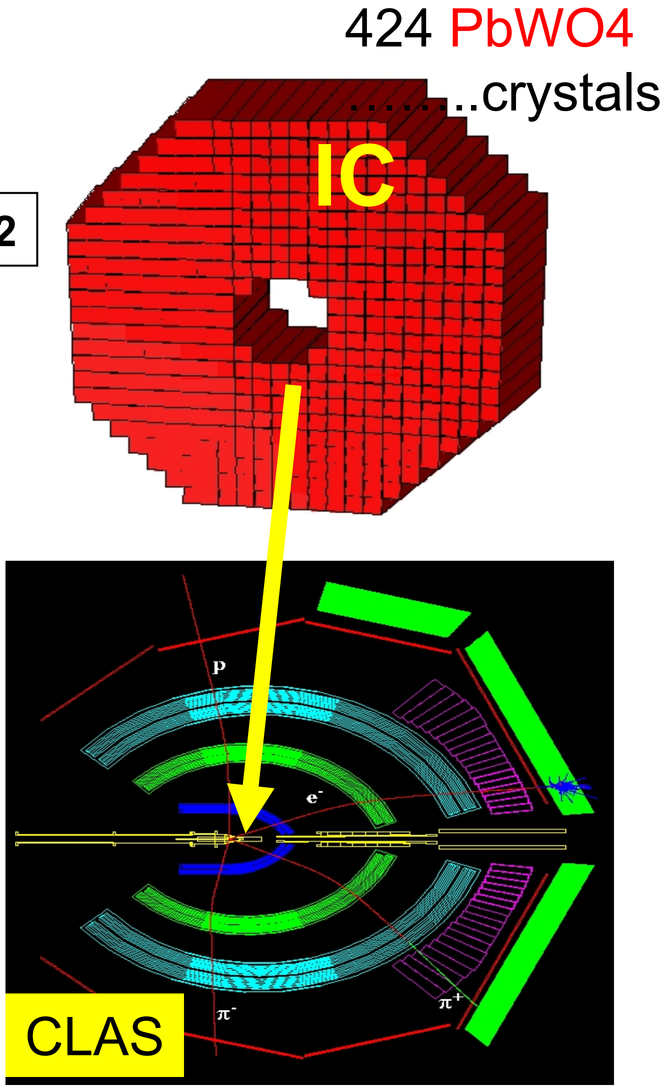
disadvantages:

reconstruction efficiency (requires detection of 2γ)

CLAS+Inner Calorimeter (IC)

IC $\sigma_E/E=0.0034/E+0.038/\sqrt{E}+0.022$



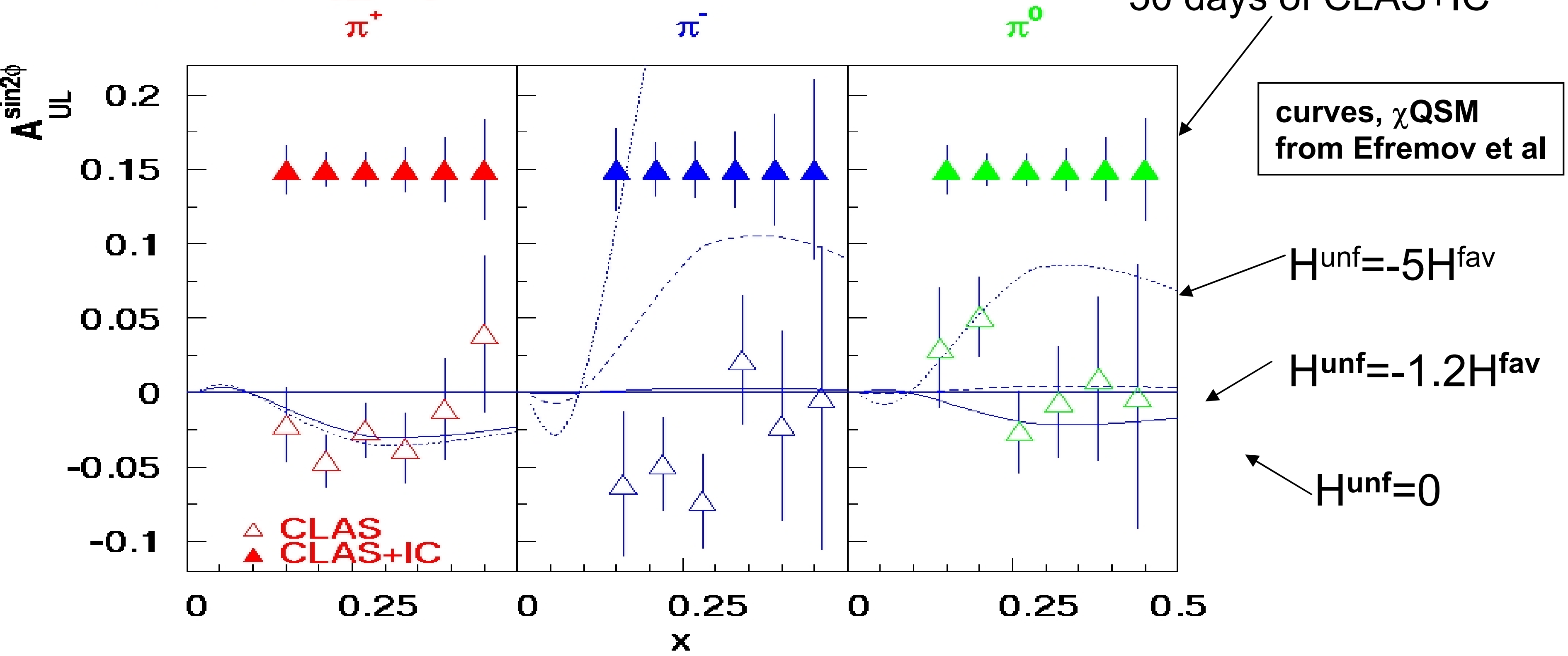


Reconstruction efficiency of high energy π^0 with IC increases ~ 4 times due to small angle coverage

IC at CLAS opens new avenue for studies of spin and azimuthal asymmetries of exclusive and semi-inclusive $\gamma, \pi^0, \eta, \rho^+$

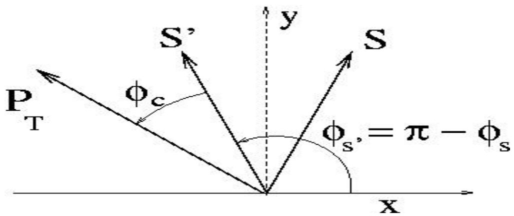
Longitudinally polarized target SSA using CLAS+IC

$\sigma_{UL}^{KM} \sim (1-y) h_{1L}^{\perp} H_1^{\perp}$



- Provide measurement of SSA for all 3 pions, extract the Mulders TMD and study Collins fragmentation with longitudinally polarized target
- Allows also measurements of 2-pion asymmetries

Transverse Target SSA at CLAS @5.7GeV

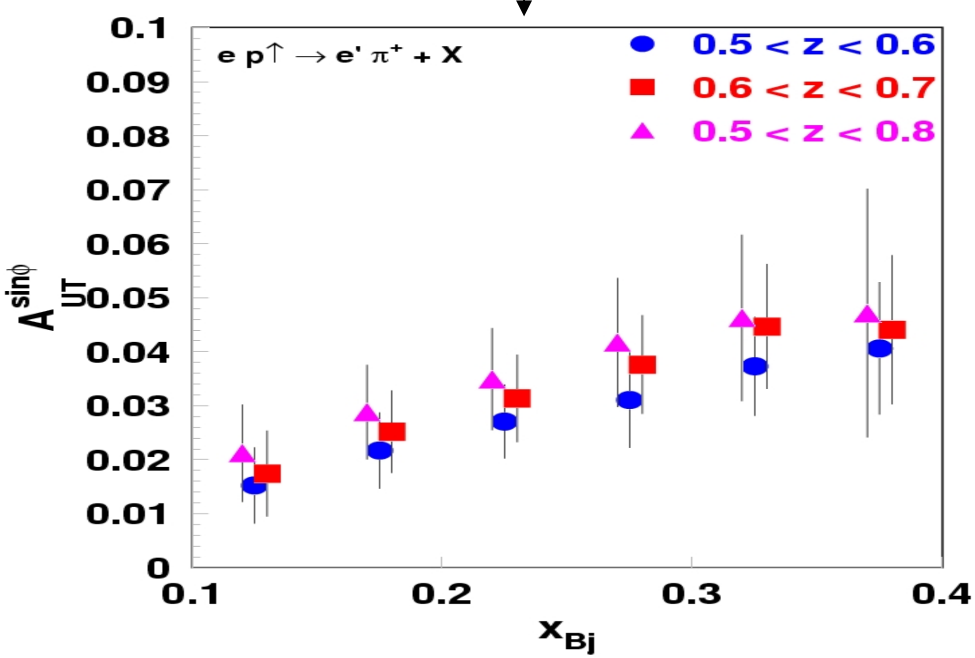


$$A_{UT}^{\text{Collins}} \sim (1-y)\, h_1 H_1^{\perp}$$

Collins effect at CLAS kinematically suppressed compared to the Sivers effect.

$$A_{UT}^{\text{Sivers}} \sim (2-2y+y^2) f_{1T}^{\perp} D_1$$

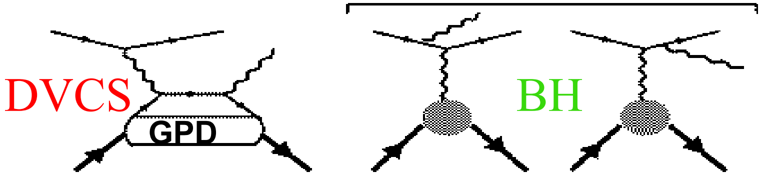
Expected precision of the A_{UT} with transversely polarized target



Simultaneous measurement of SIDIS, exclusive $\rho,\rho+,\omega$ and DVCS asymmetries with a transversely polarized target.

more details in X.Jiang's talk

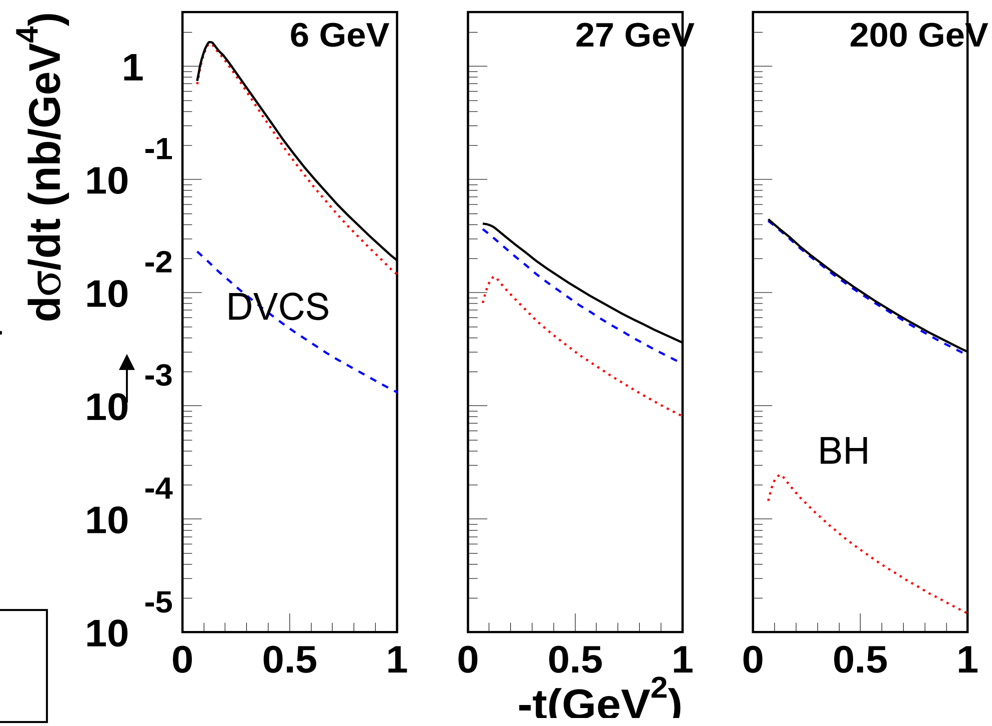
Deeply Virtual Compton Scattering ep->e'p'γ



$$\frac{d^4\sigma}{dQ^2 dx_B dt d\phi} \sim |T^{DVCS} + T^{BH}|^2$$

T^{BH}: given by elastic form factors

T^{DVCS}: determined by GPDs



Polarized beam, unpolarized target:

$$\Delta\sigma_{LU} \sim \sin\phi \, \mathrm{Im}\{F_1 H + \xi(F_1+F_2)\tilde{H} + kF_2 E\}$$

Kinematically suppressed

Unpolarized beam, longitudinal target:

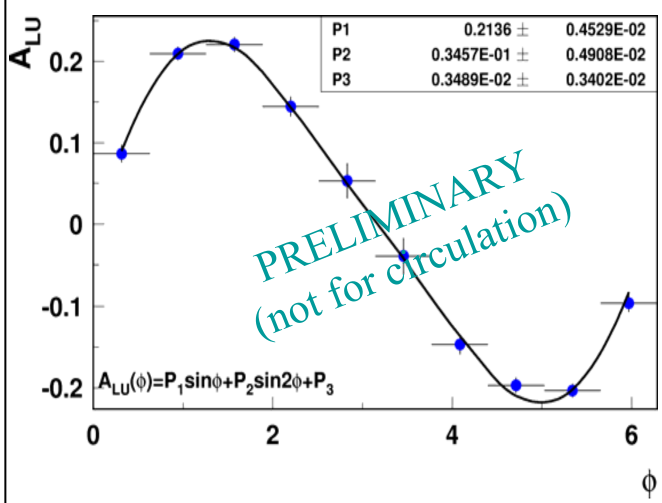
$$\Delta\sigma_{UL} \sim \sin\phi \, \mathrm{Im}\{F_1\tilde{H} + \xi(F_1+F_2)(H + .. \}$$

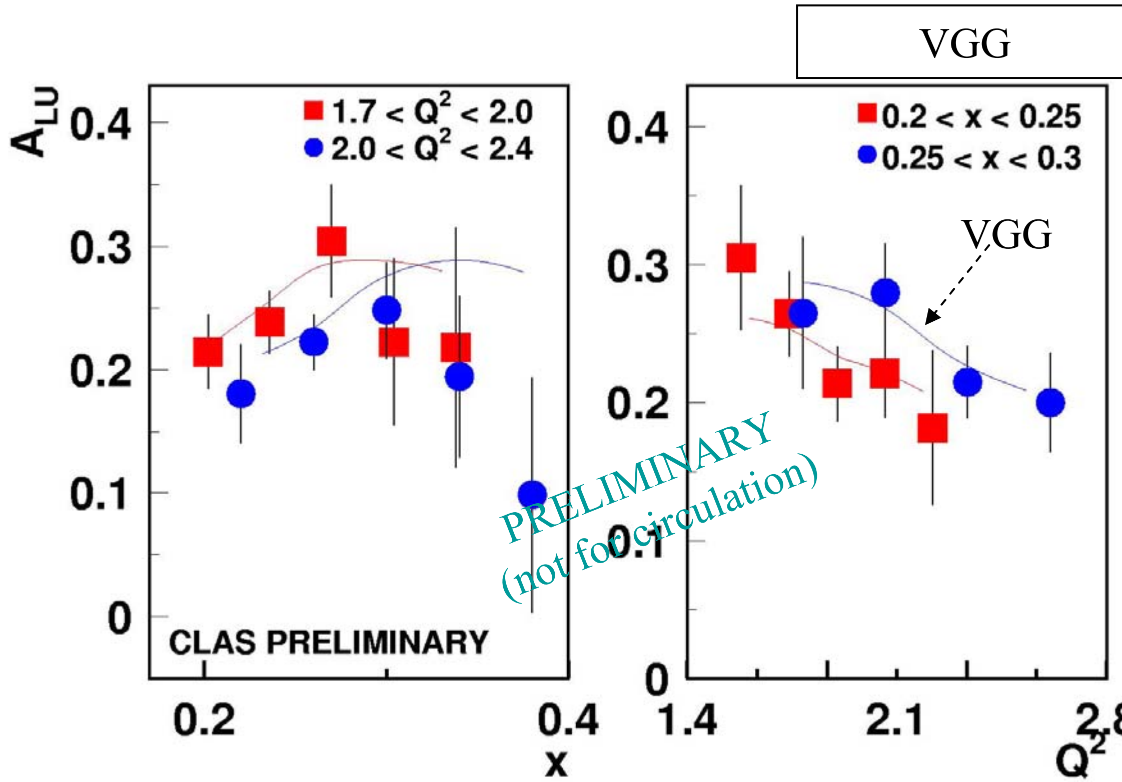
Kinematically suppressed

$\xi = x_B/(2-x_B)$, $k = t/4M2$

GPD combinations accessible as **azimuthal moments** of the total cross section.

CLAS/DVCS (ep → epX) at 5.75 GeV





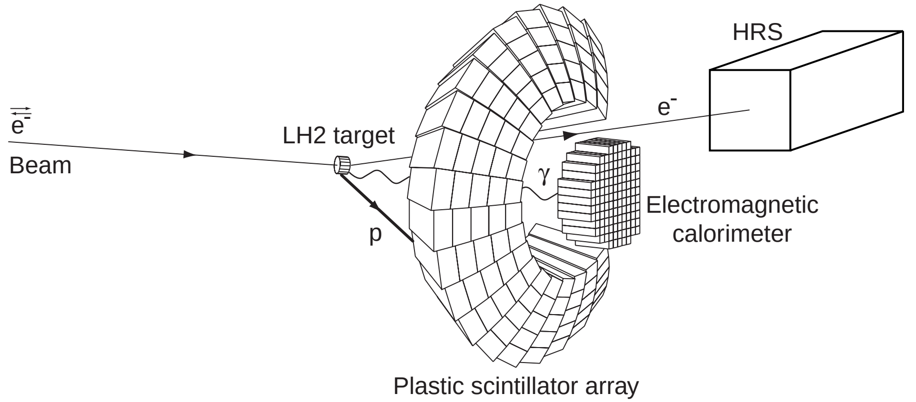
$0.15 < x_B < 0.4$
$1.50 < Q^2 < 4.5$ GeV^2
$-t < 0.5$ GeV^2

$$\Delta\sigma_{LU} \sim \sin\phi\,\mathrm{Im}\{F_1 H + \xi(F_1+F_2)\tilde{H} + kF_2 E\}$$

Kinematic dependences of DVCS beam SSA consistent with GPD based predictions (same pdfs)

JLab dedicated DVCS experiments in 2004 - 2005

JLab/Hall A



<u>Dedicated, high statistics, DVCS experiments</u>

⟶ Detection of 3 particles e, p and γ in final state

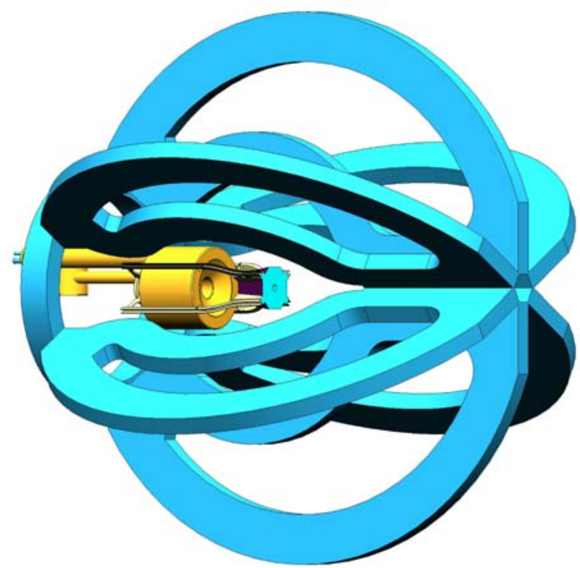
⟶ Firmly establish scaling laws (up to $Q^2 \sim 5$ GeV^2), if observed, or deviations thereof understood, first significant measurement of GPDs.

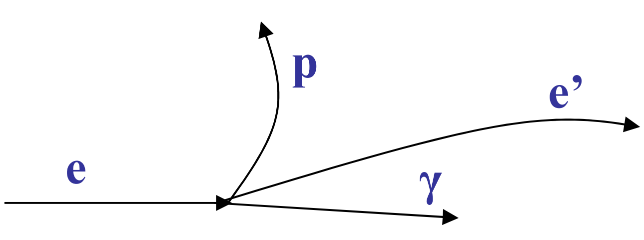
⟶ Large kinematical coverage in x_B and t leads to femto-tomography of the nucleon

⟶ Opens the way for an ambitious program with JLab@12GeV (CLAS12 and other)

JLab/CLAS

Calorimeter and superconducting magnet within CLAS torus

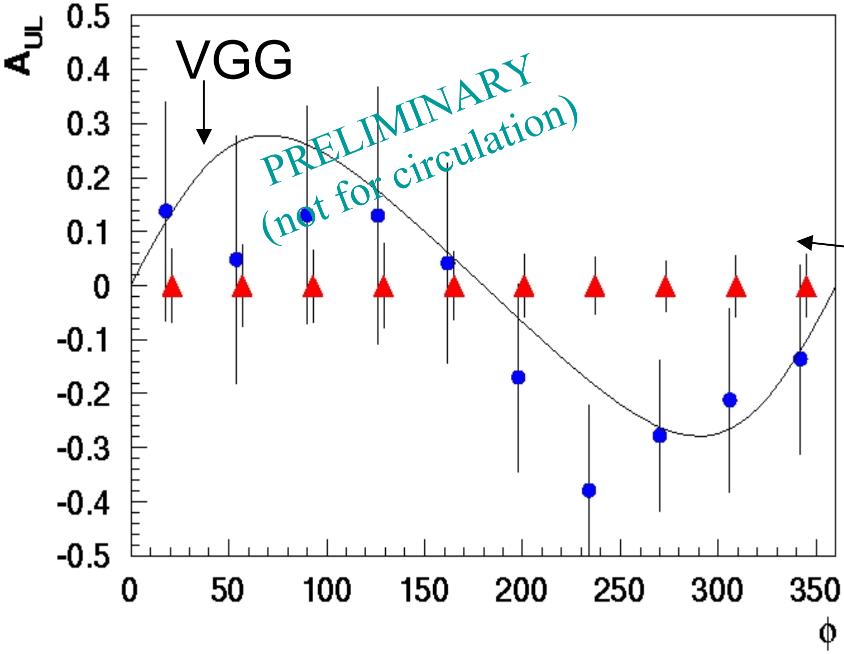




details in J-P.Chen's talk

DVCS with a polarized target in CLAS

5.7 GeV run with **NH_3** longitudinally polarized target, Q^2 up to 4.5 GeV^2



Exclusive $e\vec{p} \rightarrow ep\gamma$

- **Detect all 3 particles** in the final state (e,p,γ) to eliminate contribution from N
- * π^0 asymmetry measured

$$\Delta\sigma_{UL} \sim \sin\phi \,\mathrm{Im}\{F_1\tilde{H} + \xi(F_1+F_2)(H + .. \}$$

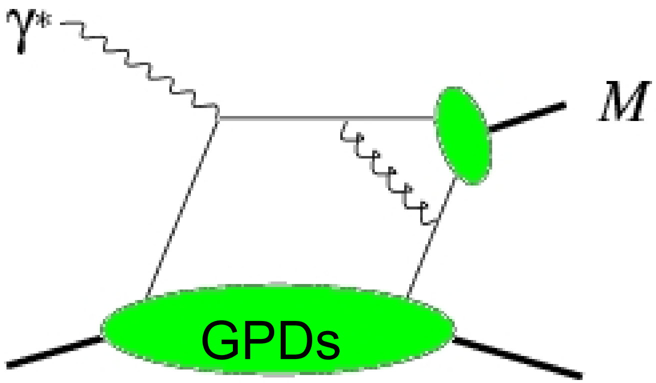
A

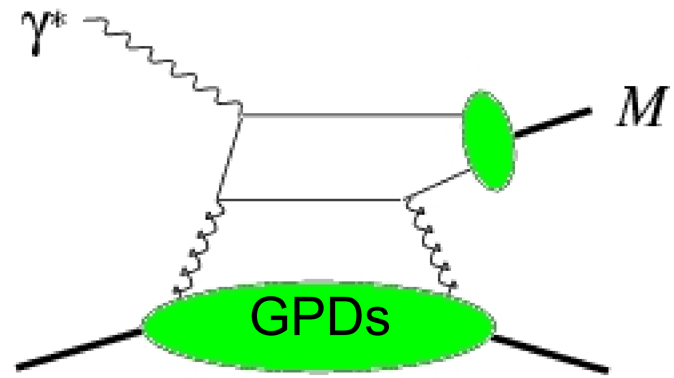
Projections for 50 days with IC

Kinematical dependences of DVCS target SSA consistent with GPD based predictions

Meson production in GPD framework

Only longitudinal photons



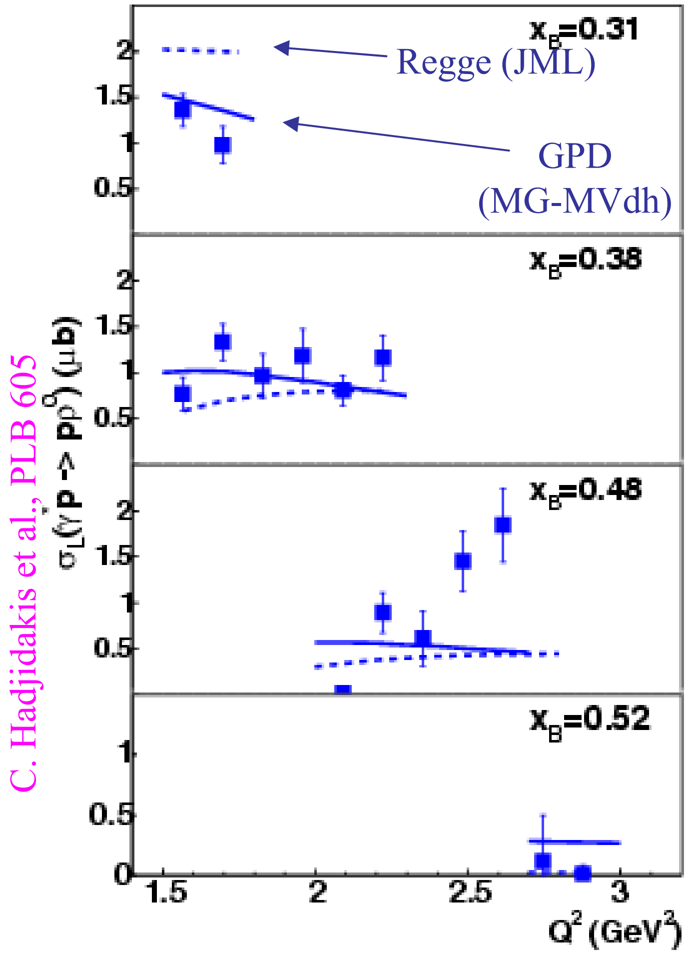


1. Different final state mesons filter out different combinations of unpolarized (H,E) and polarized $(\tilde{H},\tilde{E})$ GPDs.
2. Studies needed to define on how far is the asymptotic regime and guide theory in describing HT.

Meson	GPD flavor composition
π^+	$\Delta u - \Delta d$
π^0	$2\Delta u + \Delta d$
η	$2\Delta u - \Delta d$
ρ^0	$2u + d$
ρ^+	$u - d$
ω	$2u - d$

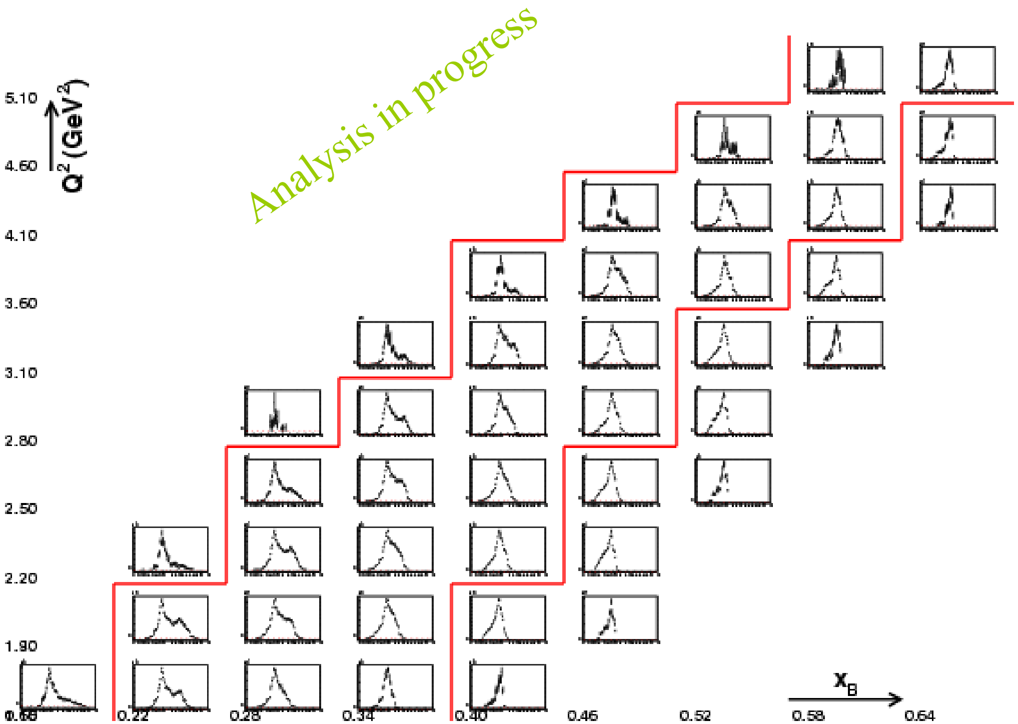
Exclusive ρ meson production: ep → epρ

CLAS (4.2 GeV)



CLAS (5.75 GeV)

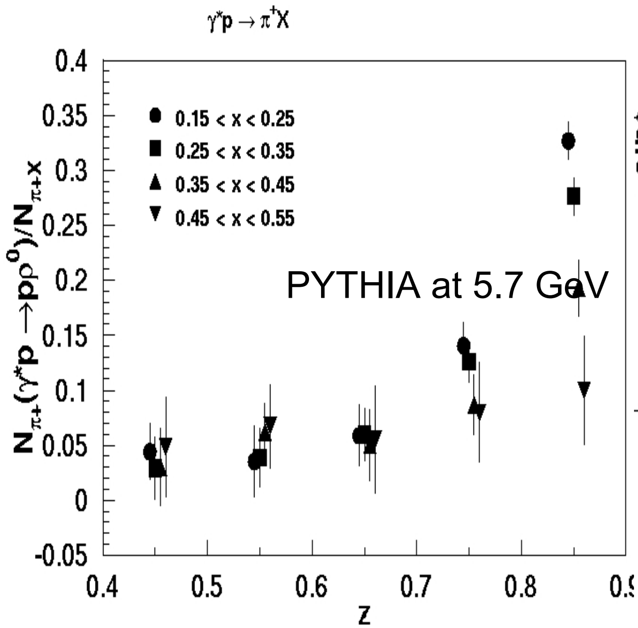
GPD formalism (beyond leading order) describes approximately data for x_B<0.4, Q^2 >1.5 GeV^2

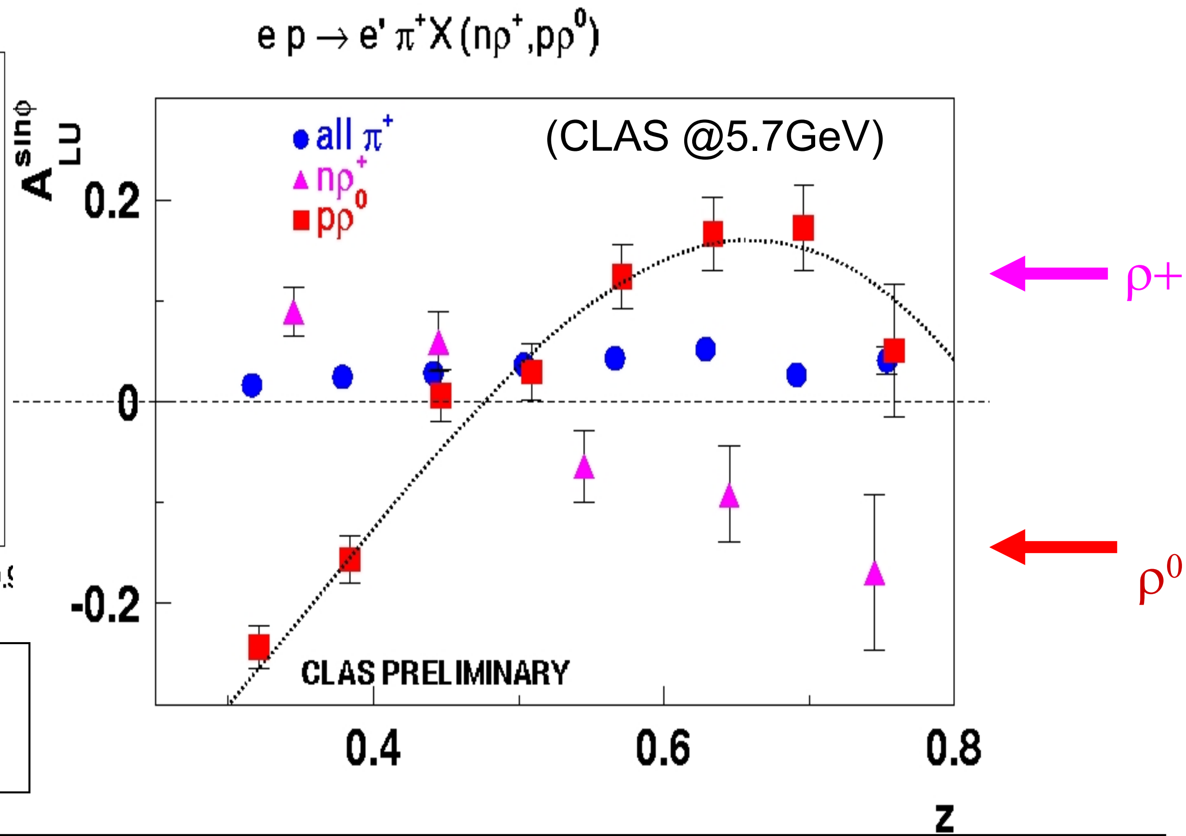


Two-pion invariant mass spectra

Decent description in pQCD framework already at moderate Q^2

pion SSA from $\rho(\pi^+\pi^-/\pi^+\pi^0)$





Larger fraction of π+ from ρ at low **x** and large **z**

π+ SSA at large z may also have a significant (~20%) contribution from ρ

Exclusive ρ (higher twist for SIDIS) crucial for πX and $\pi\pi$X studies

Summary

Spin and azimuthal asymmetries measured at 5.7 GeV with polarized beam and longitudinally polarized target at JLab.

• SIDIS multiplicities and double spin asymmetries of pions are consistent with factorization and partonic picture: may be used in future NLO QCD fits.

• sinϕ and sin2ϕ beam and target SSA measured, providing access to the twist-2 and twist-3 TMD distributions and testing the Collins fragmentation function

• Studies of hard exclusive photon and vector meson production underway, allowing access to GPDs and also providing important info for the interpretation of SIDIS SSAs.

• Ongoing and future measurements with CLAS at 6GeV, will greatly improve $\pi^{0/+/-}$, ρ, and DVCS data, allowing extraction of underlying TMDs and GPDs.