Transversity and Orbital Motion at CLAS

(Past, Present and Future)

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Jlab User's Meeting

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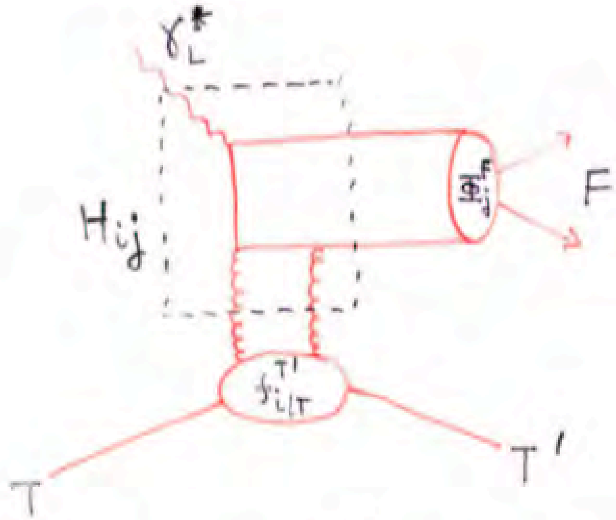
The Players

- Transversity: $h_1(x)$, momentum distribution of transversely polarized quarks in a transversely polarized nucleon
- Boer-Mulders Function: $h_1^{perp}(x,k_{perp})$, momentum distribution of transversely polarized quarks in an unpolarized nucleon
- Sivers Function: $f_{1T}^{perp}(x,k_{perp})$, momentum distribution of unpolarized quarks in a transversely polarized proton.

Outline

- Past
  - No transversely polarized target at CLAS
- Present
  - No transversely polarized target at CLAS
- Future
  - No transversely polarized target planned for CLAS (yet, but it would be nice to get one)
- What then?
  - Use longitudinal or unpolarized targets.

Factorization Theorem



$$\mathcal{M} \sim \sum_{ij} \int dz\, dx_1\, \underbrace{f_{i/T}^{T'}(x_1, x_1 - x_{Bj}, t)}_{\text{GPD}}\, \underbrace{H_{ij}\left(\frac{x_1}{x_{Bj}}, Q^2, z\right)}_{\text{pQCD}}\, \underbrace{\Phi_j^F(z)}_{\text{distribution amplitude for hadronic state F}}$$

$+\,\mathcal{O}\left(\frac{1}{Q}\right)$ corrections

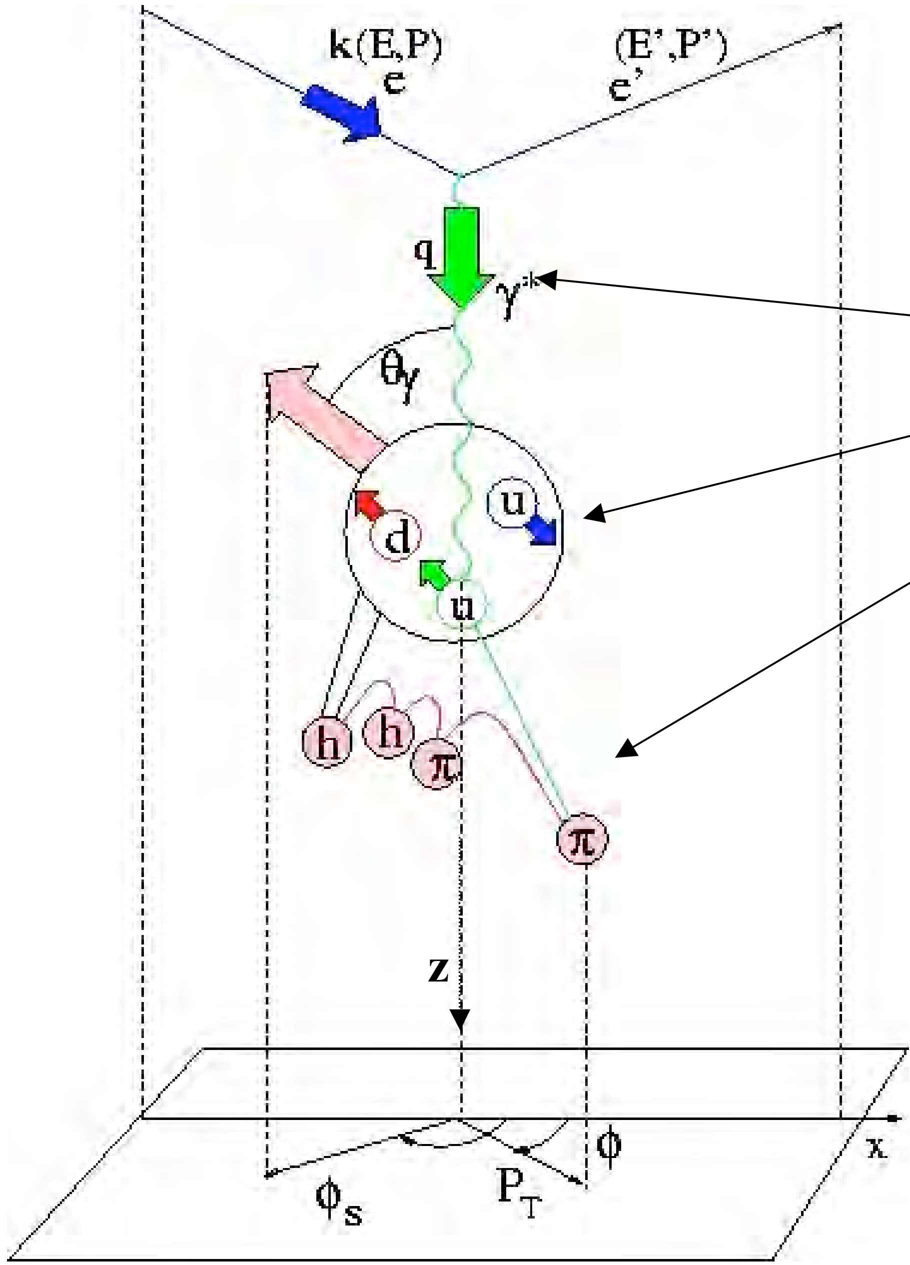
<u>Factorization Theorem</u> Collins, Frankfurt, Strikman PRD 56 (97) 2982.

no proven factorization Thrm for γ_T^* (transverse photons) but amplitudes are down by $1/Q$ w.r.t. γ_L^*

Higher Twist

- A problem (factorization is probably destroyed)
- An opportunity (not all interactions in nature occur at high momentum transfer)
- Necessary to fully understand the nucleon (learn to enjoy it)
- Remarkably hard to pin down experimentally (large Q^2 range necessary)

Polarized Semi-Inclusive DIS



Cross section a function of scale variables ***x,y,z***

$\nu = E\text{-}E'$

$y = \nu / E$

$x = Q^2 / 2M\nu$

$z = E_h / \nu$

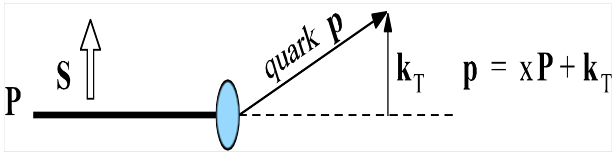
Hadron-Parton transition: by distribution function $f_1^u(x)$:
probability to find a **u**-quark with a momentum fraction ***x***

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

N(e,e'h)X Observables

- A_{LL} -> g_1
- A_{LT} -> g_2
- A_{UL} -> tangled mess
- A_{LU} -> ditto
- Asymmetries are functions of x, y, z, Q^2, p_T, ϕ, ϕ_S, θ, etc.
- These asymmetries are well-defined experimental quantities for all Q^2; however, they have their simplest interpretation at high Q^2

Polarized SIDIS and TMD PDFs



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 , $h_{1T}^{\perp}$

$$\sigma_{UU} \propto (1-y+y^2/2)\sum_{a,\bar{a}} e_a^2 x f_1^a(x) D_1^a(z)$$

$$\sigma_{UU}^{\cos 2\phi} \propto (1-y)\cos 2\phi \sum_{a,\bar{a}} e_a^2 x h_1^{\perp(1)}(x) H_1^{\perp(1)a}(z)$$

$$\sigma_{LL} \propto \lambda_e S_L y(2-y)\sum_{a,\bar{a}} e_a^2 x g_1^a(x) D_1^a(z)$$

$$\sigma_{UL}^{\sin 2\phi} \propto S_L 2(1-y)\sin 2\phi \sum_{a,\bar{a}} e_a^2 x h_{1L}^{\perp(1)}(x) H_1^{\perp(1)a}(z)$$

$$\sigma_{UT}^{\sin\phi} \propto S_T(1-y)\sin(\phi-\phi_{S'})\sum_{a,\bar{a}} e_a^2 x h_1^a(x) H_1^{\perp(1)a}(z)$$

$$\sigma_{UT}^{\sin\phi} \propto S_T(1-y+y^2/2)\sin(\phi-\phi_S)\sum_{a,\bar{a}} e_a^2 x f_{1T}^{\perp}(x) D_1^a$$

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

λ_e, S_L, S_T polarizations
$\sum_{a,\bar{a}} \rightarrow$ sum over quarks and anti-quarks.

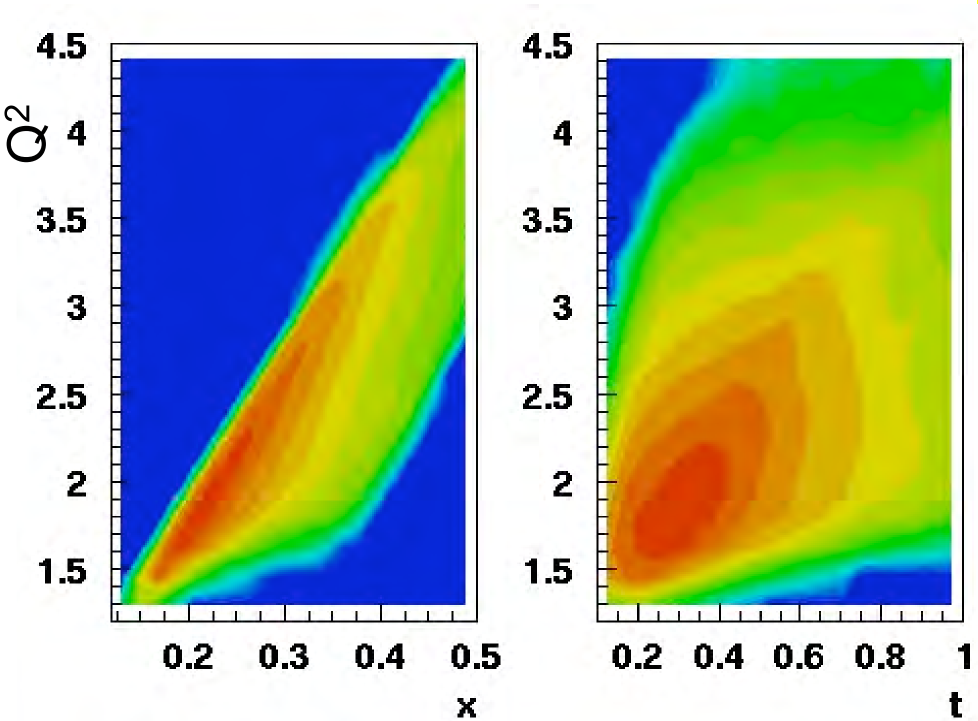
Gauge invariant definition of TMDs discussed by Collins and Belitsky,Ji & Yuan Nucl.Phys. B656 165, 2003

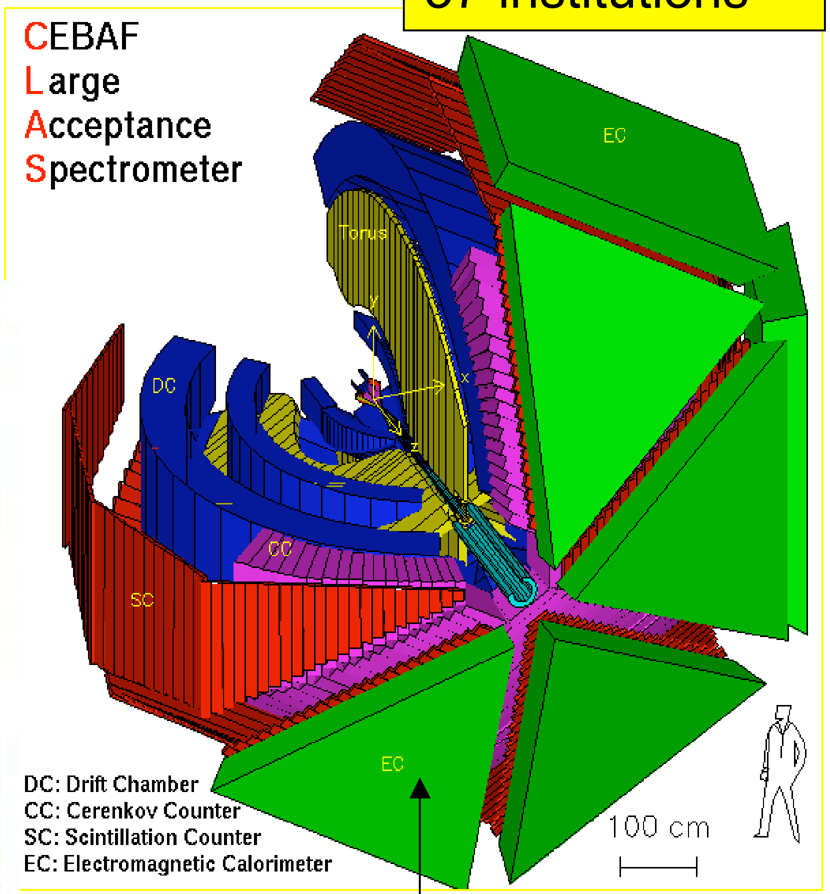
Two fundamental QCD mechanisms (**Collins** and **Sivers**) identified, to generate **SSA**:

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

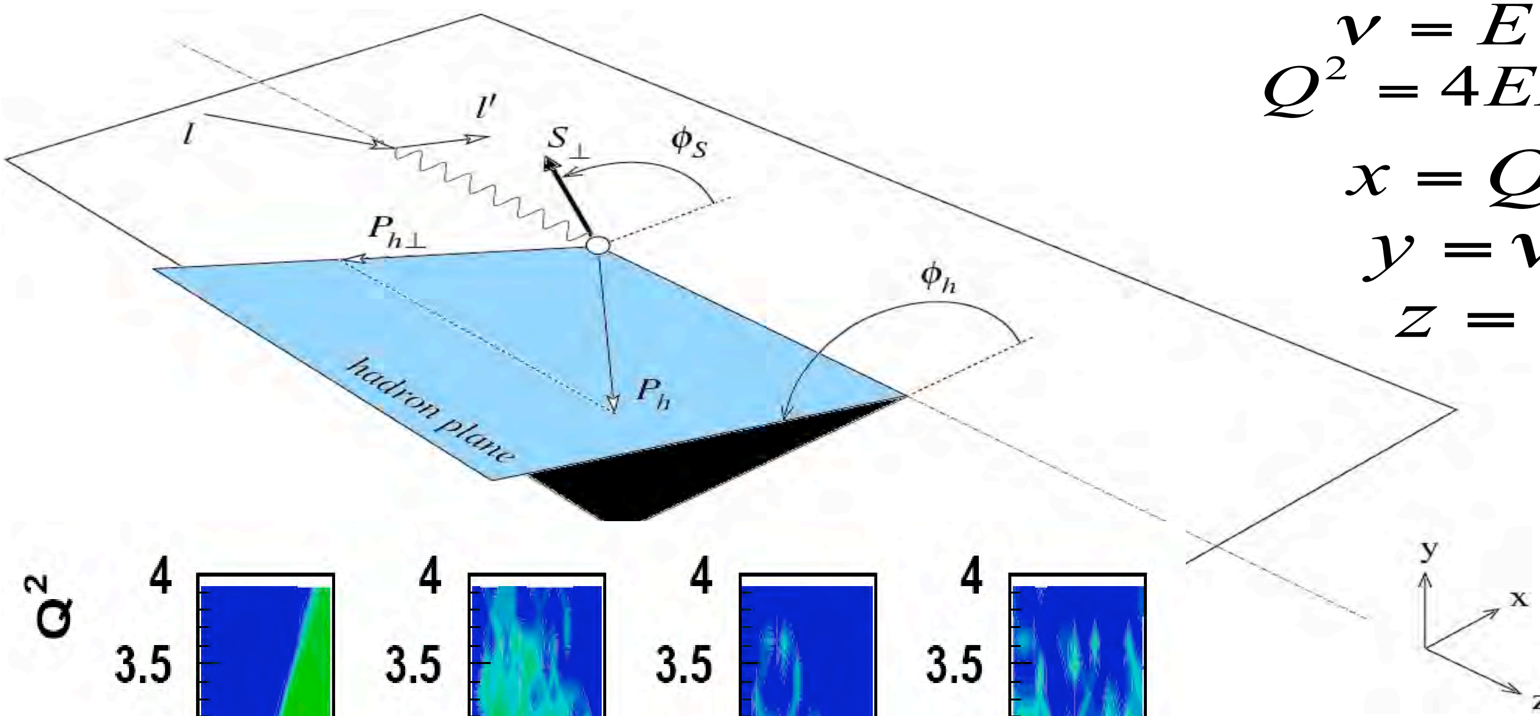
~ 200 physicists
37 institutions



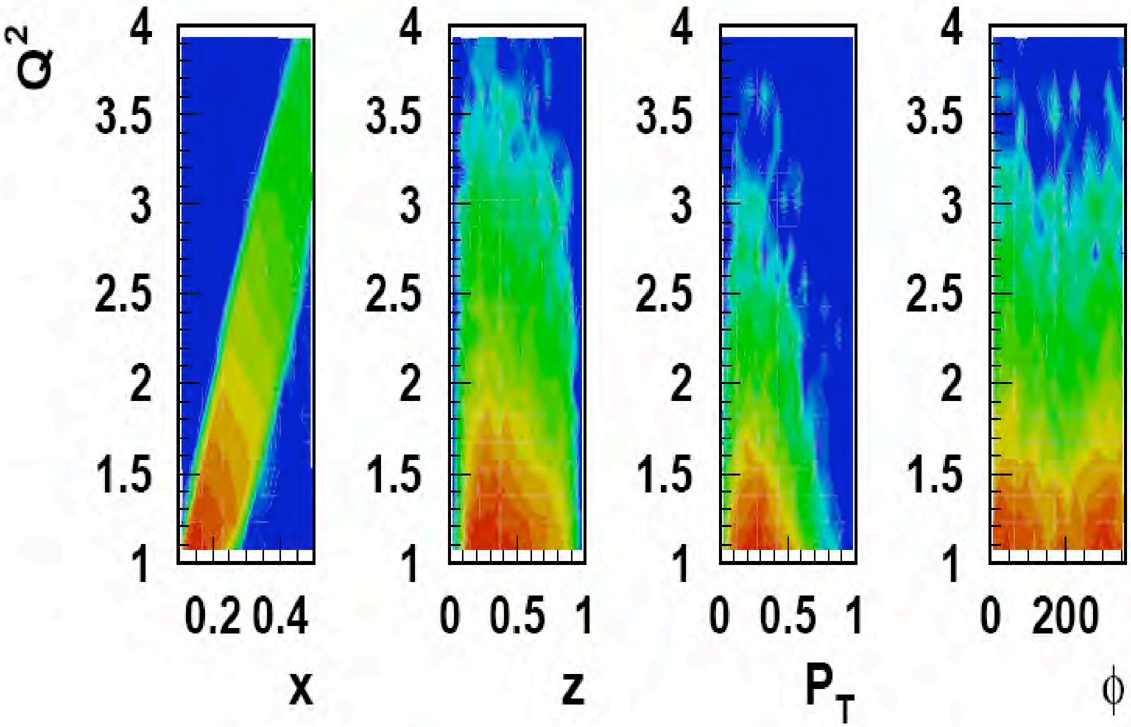


Forward CALO

SIDIS kinematic plane and coverage at 6 GeV

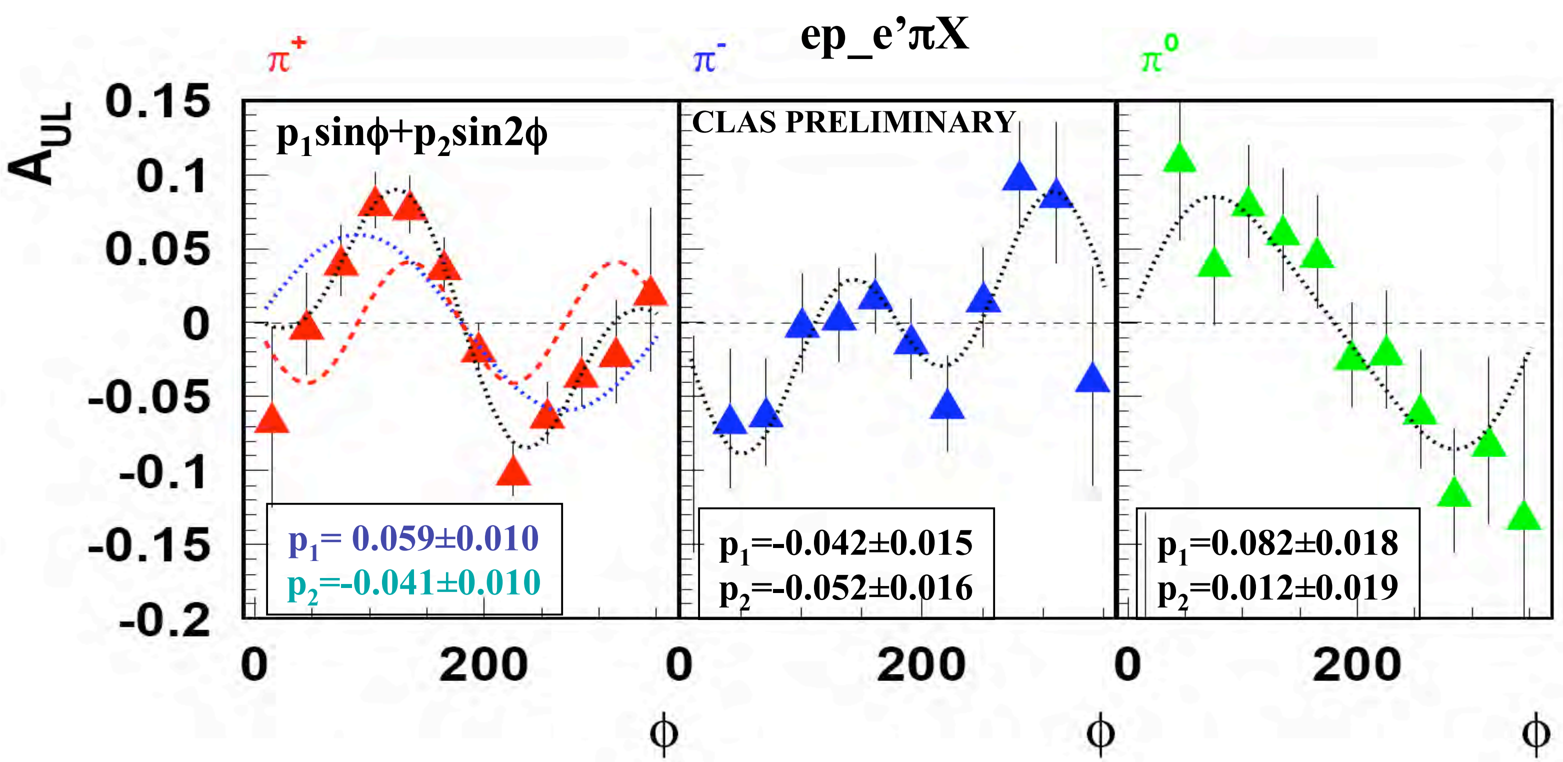


$$\nu = E - E'$$
$$Q^2 = 4EE' \sin(\theta / 2)$$
$$x = Q^2 / 2M\nu$$
$$y = \nu / E$$
$$z = E_h / \nu$$



SSA measurements at CLAS (eg1)

$$A_{UL}(\phi) = \frac{1}{P_T} \frac{N^+ - N^-}{N^+ + N^-}$$



W²>4 GeV²
Q²>1.1 GeV²
y<0.85

0.4<z<0.7
M_X>1.4 GeV

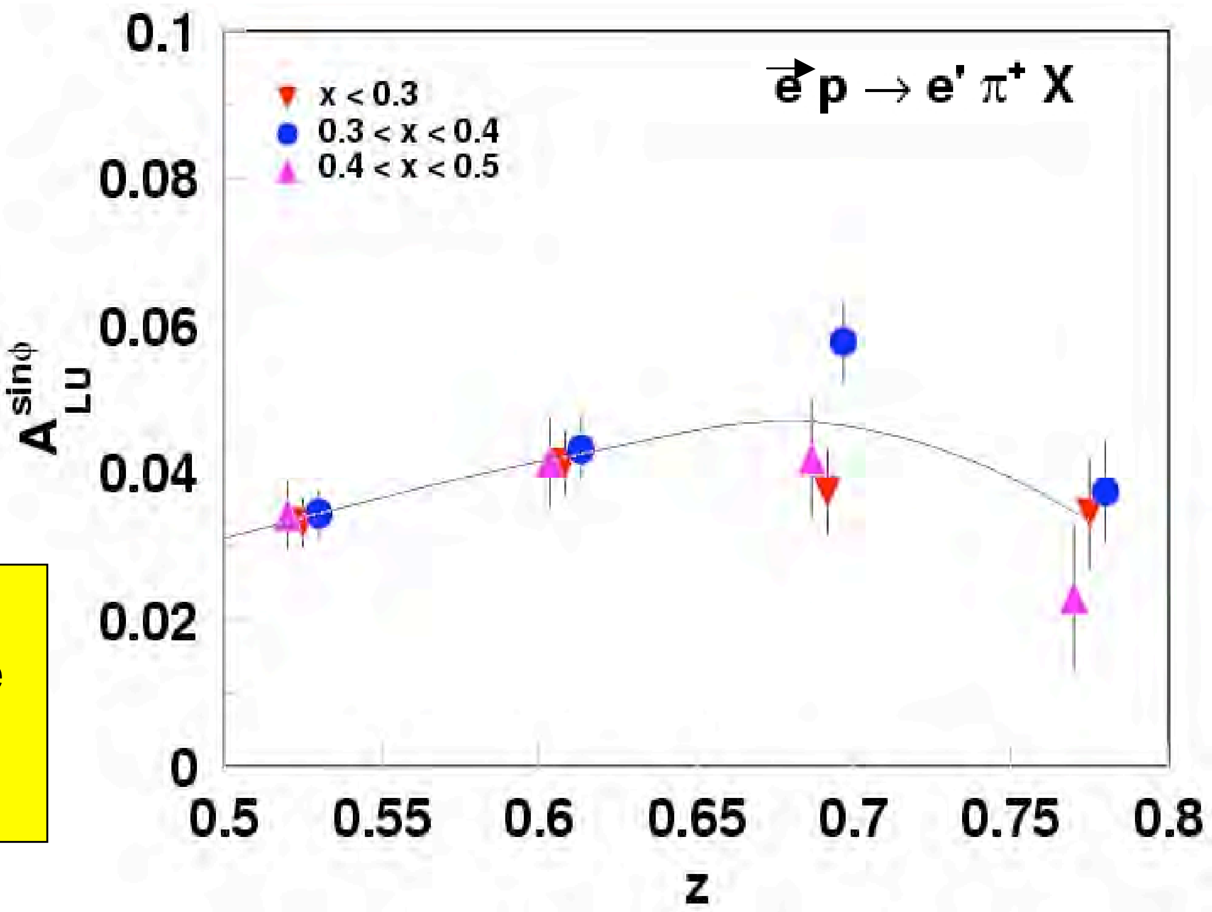
P_T<1 GeV
0.12<x<0.48

- Significant SSA measured for pions with longitudinally polarized target
- Complete azimuthal coverage crucial for separation of sinφ, sin2φ moments

Factorization studies in CFR at CLAS

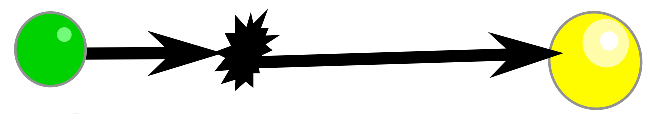
In terms of Collins fragmentation

$$A^{\sin\varphi}{}_{LU} \propto \lambda \frac{e(x)}{f(x)} \frac{H_1^{\perp}(z)}{D(z)}$$



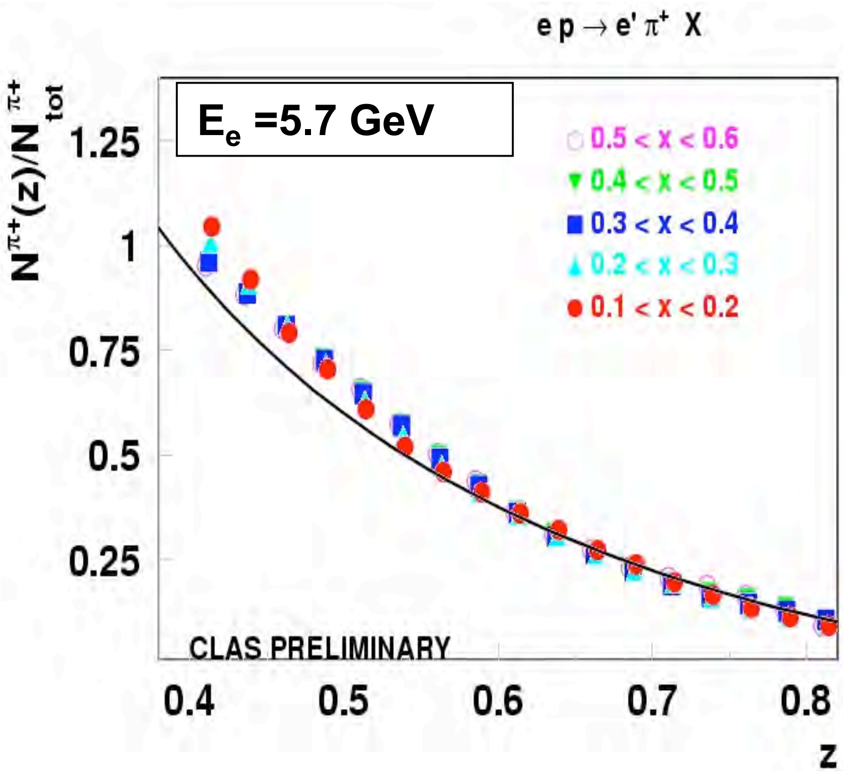
No significant variation observed in z dependence of A_{LU} for different **x** ranges

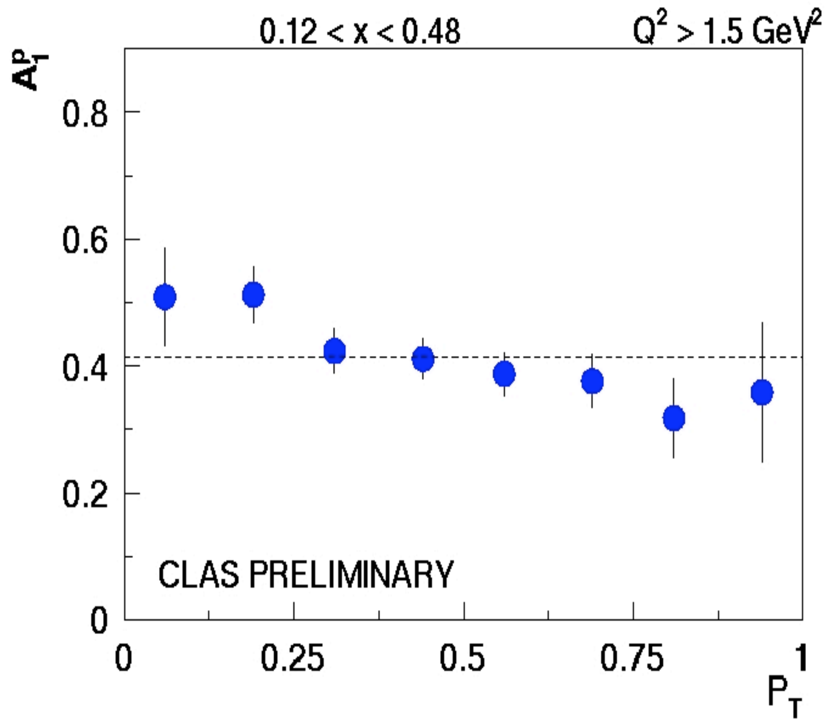
Collinear Fragmentation



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

$$A_{LL} = P_T D_{LL} \frac{\sum_q g_1^q(x) D_1^q(z)}{\sum f_1^q(x) D_1^q(z)}$$



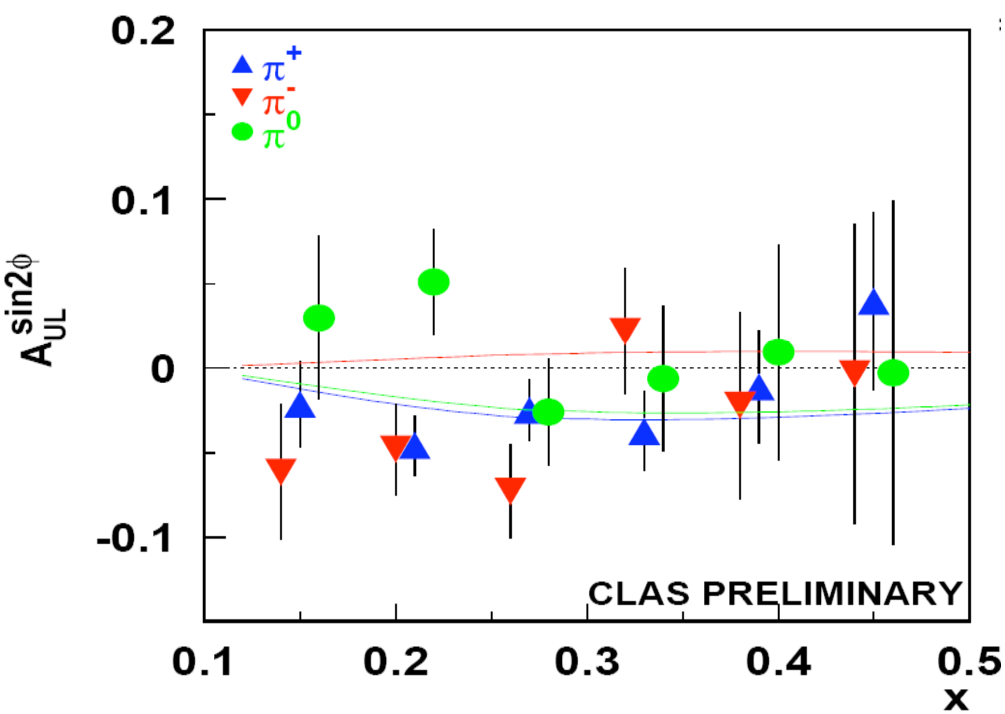


No significant variation observed in z distributions of π+ for different **x** ranges (0.4<z<0.7, M_X>1.5) and for A1p as a function of $\mathbf{P_T}$

SSA: kinematical dependence

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 $h_{1T}^{\perp}$

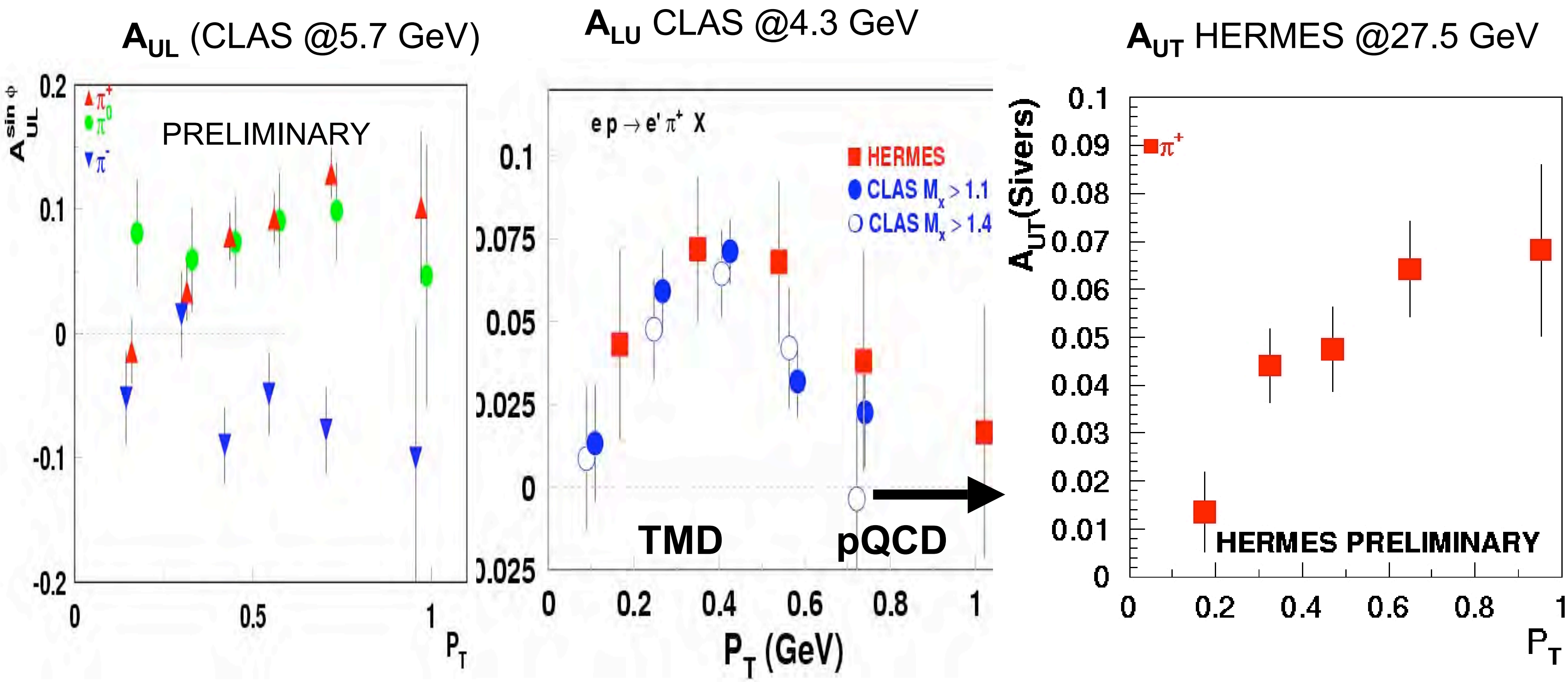
$$A_{UL}^{\sin 2\phi} = D_{UL} \frac{\sum_q h_{1L}^{q\perp}(x) H_1^{q\perp}(z)}{\sum_q f_1^q(x) D_1^q(z)}$$



- Indicate a negative sin2ϕ moment measured for π^+.
- Some indication of negative π^- SSA (more data required for π^- and π^0)
- More data required to correct for exclusive 2π contribution.

SSA: P_T-dependence of sinϕ moment

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



Beam and target SSA for π+ are consistent with increase with P_T
In the perturbative limit is expected to behave as $1/P_T$

SIDIS with neutral pions (E05-115)

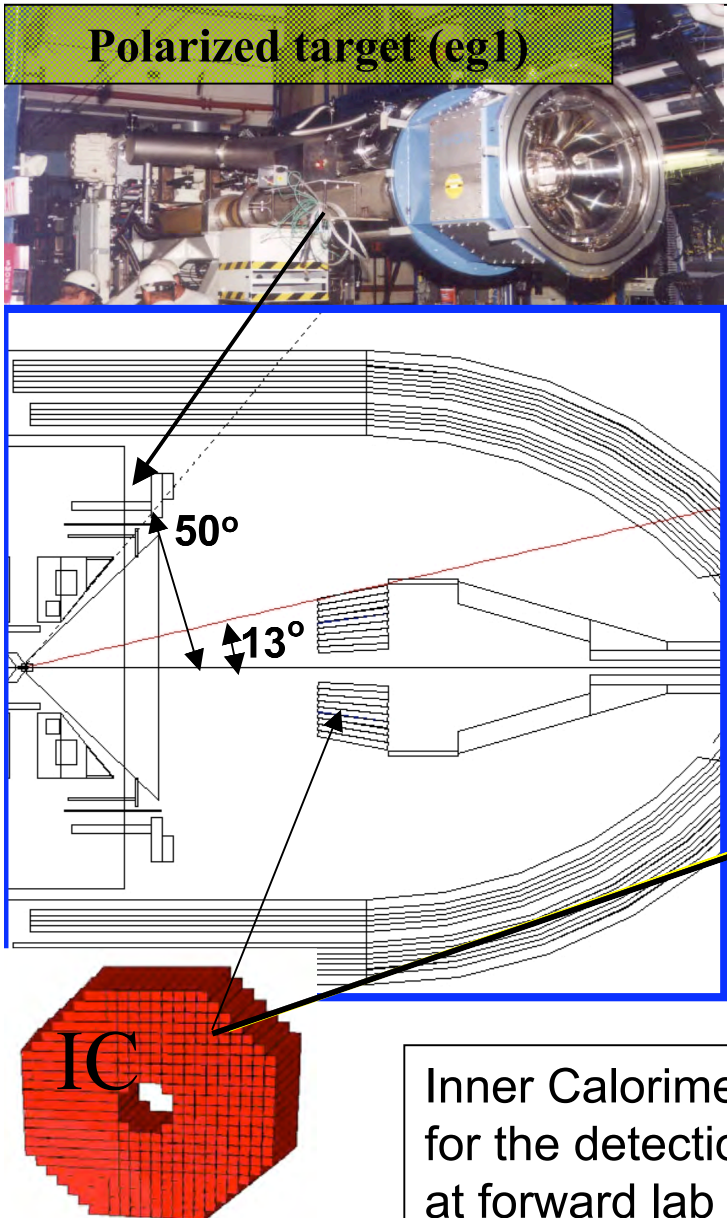
$A_{UL}(\pi^+) \sim H_1^{favored}$
$A_{UL}(\pi^0) \sim H_1^{favored} + H_1^{unfavored}$

π^0 SSA sensitive to the ratio of unfavored to favored polarized fragmentation functions

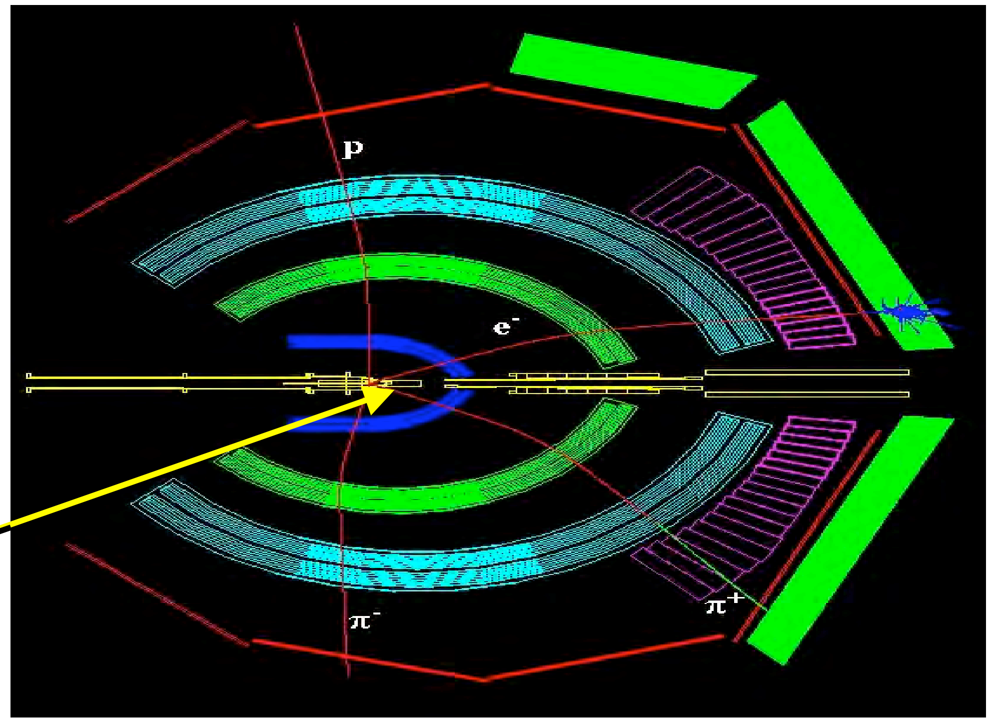
1) **SIDIS π^0 production is not contaminated by diffractive ρ**
2) **HT effects and exclusive π^0 suppressed**
3) **Simple PID by π^0-mass (no kaon contamination)**
4) **Provides information complementary to $\pi^{+/-}$ information on PDFs**

SIDIS π^0 : main focus of the experiment

Experimental Setup (CLAS EG1+IC)

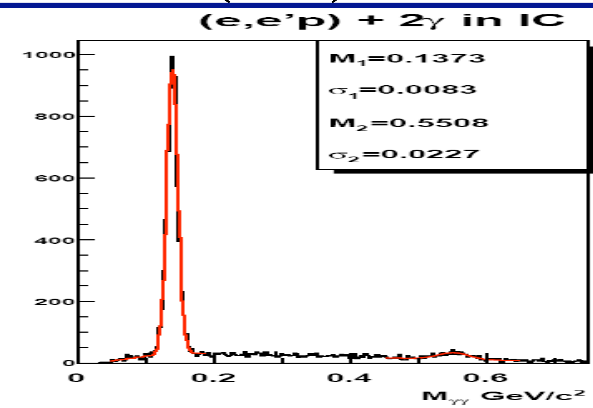


- solid NH_3 polarized target
- proton polarization >75%
- high lumi ~ $1.5\times10^{34}\ s^{-1}cm^{-2}$

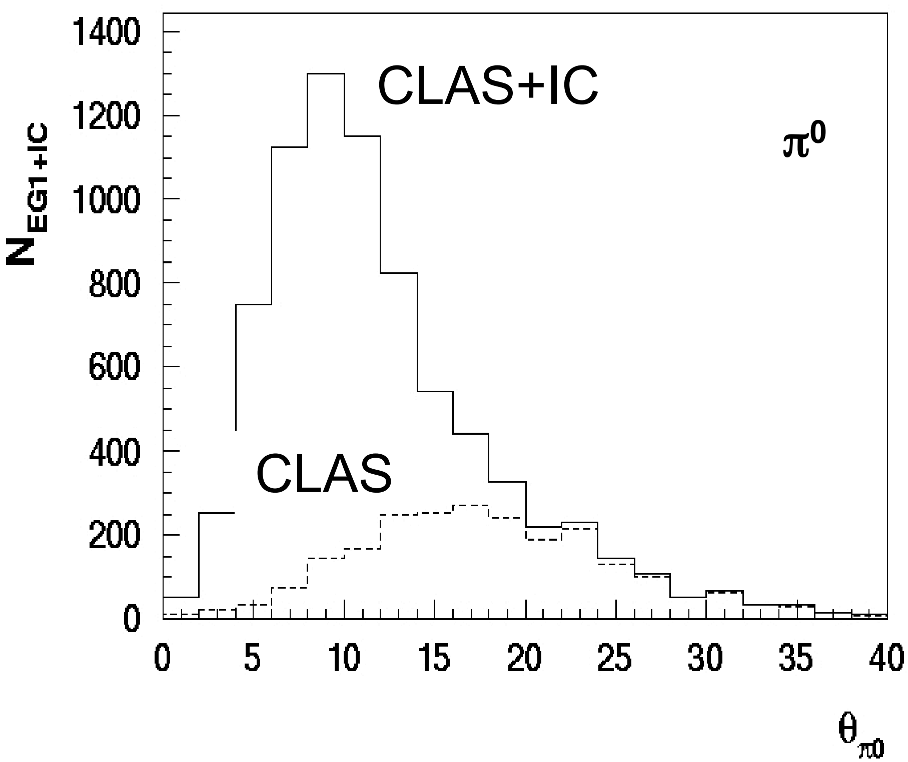


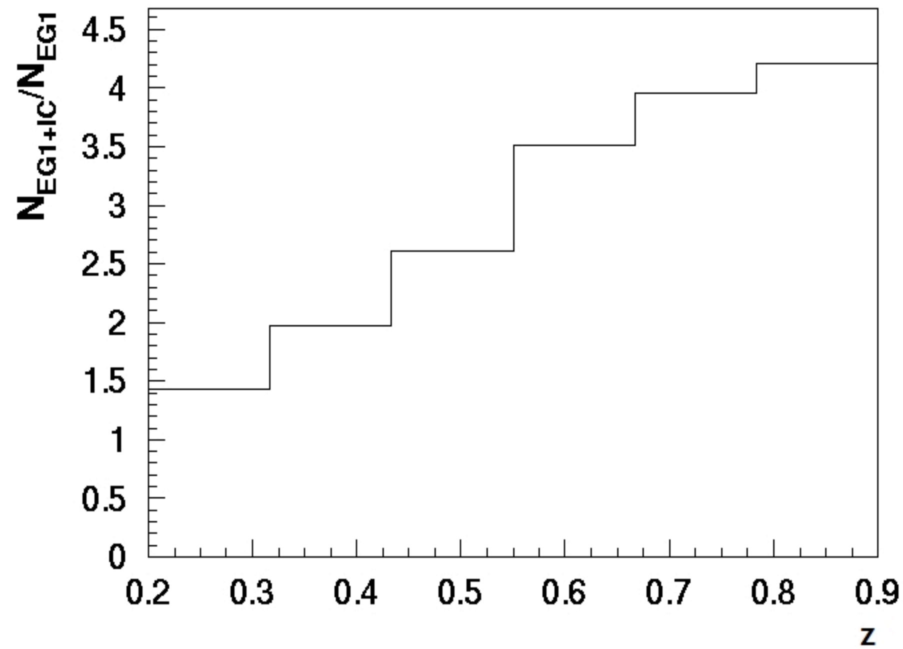
Inner Calorimeter (424 $PbWO_4$ crystals) for the detection of high energy photons at forward lab angles (e1-DVCS).

CLAS+Inner Calorimeter (IC)



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

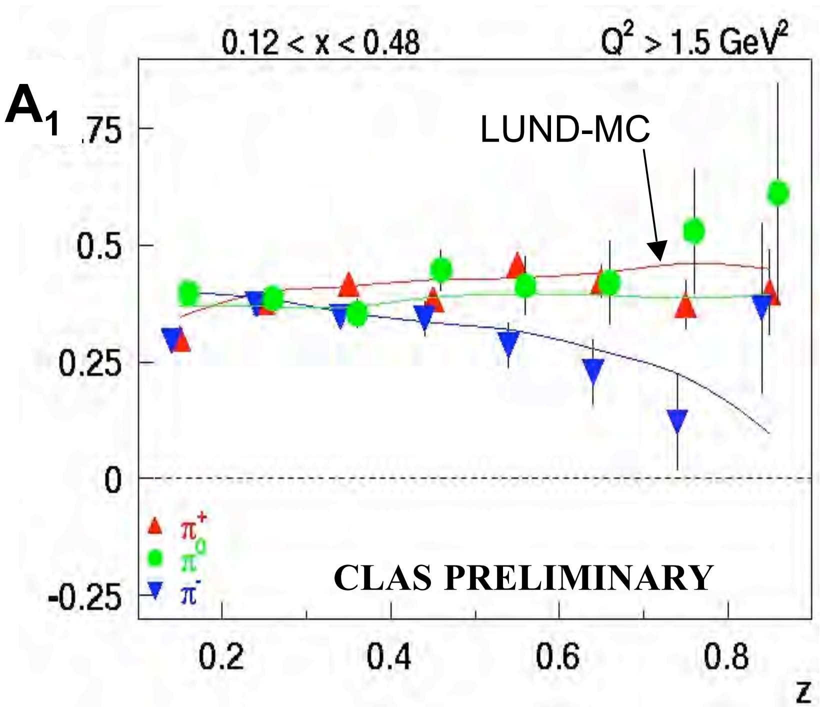


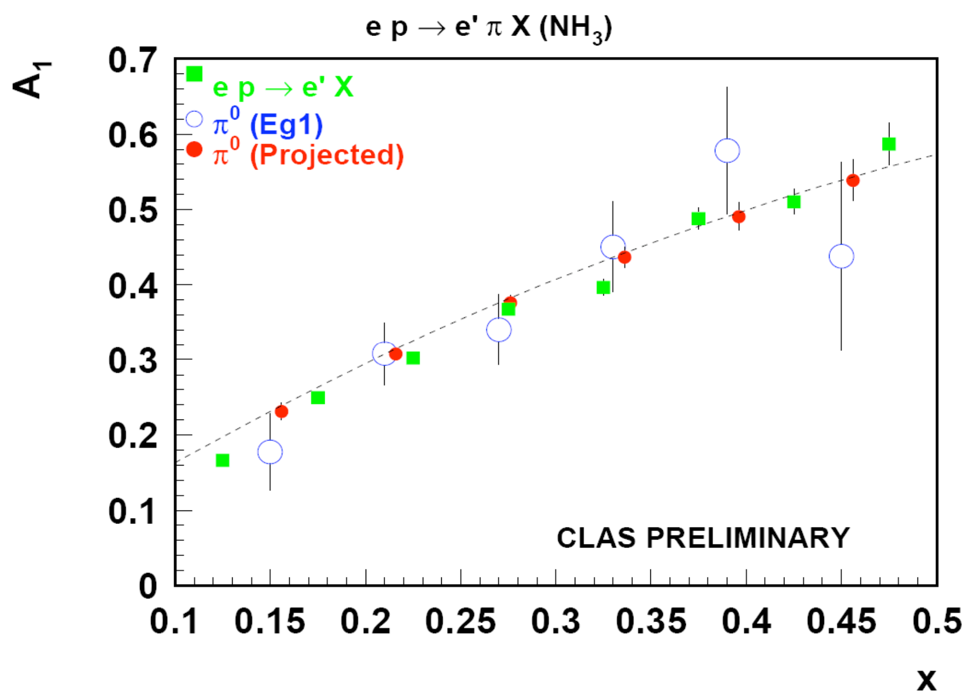


Reconstruction efficiency of high energy π^0 with IC increases ~ 3 times at large z due to small angle coverage (target in ~60cm from IC)

Factorization studies with π^0

$$A_1 = \frac{\sum_q g_1^q(x) D_1^q(z)}{\sum_q f_1^q(x) D_1^q(z)}$$

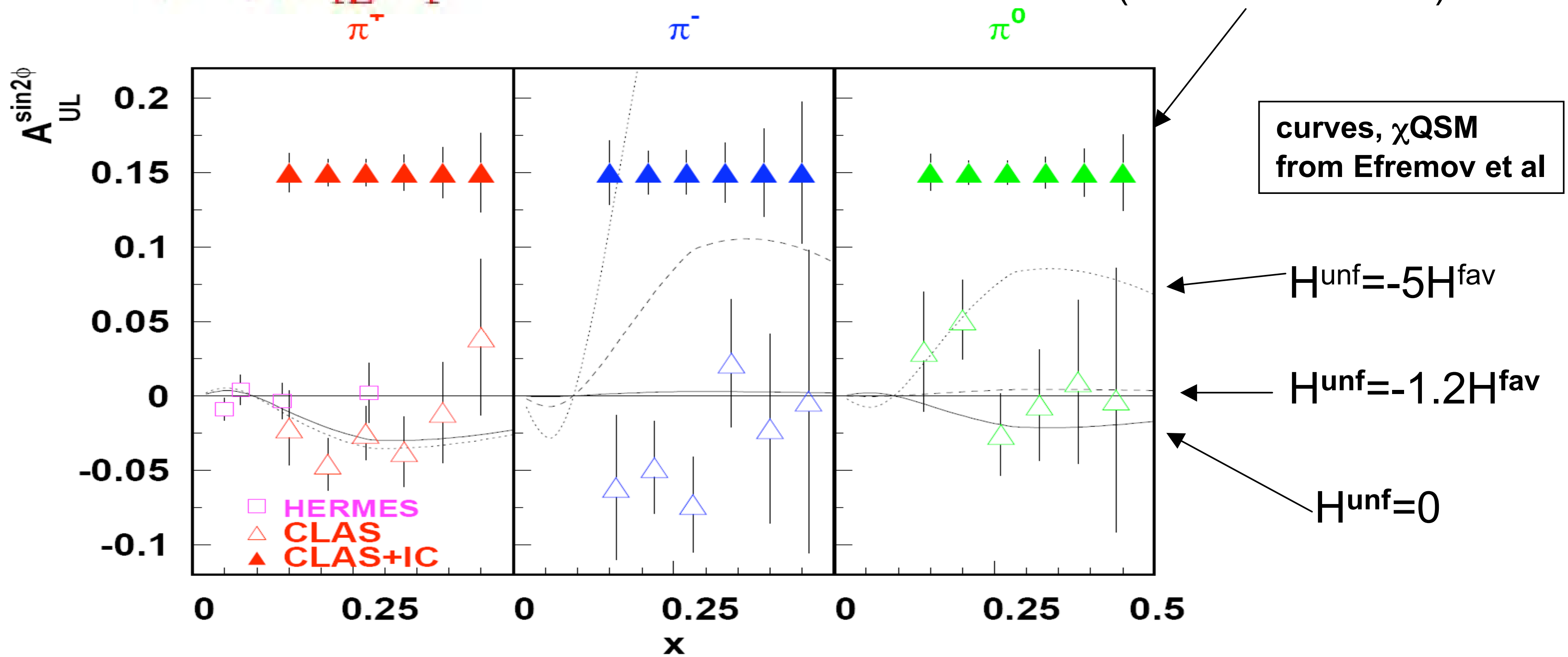




- Double spin asymmetries consistent with simple partonic picture
- $\mathbf{A_1^p}$ inclusive and π^0 can serve as an important check of HT effects and applicability of the simple partonic description.

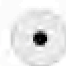
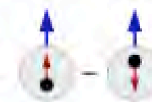
Longitudinally polarized target SSA using CLAS+IC

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



- 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

The h_1 Structure Function

$f_1 =$  $g_1 =$  $h_1 =$ 

Characteristics of h_1:

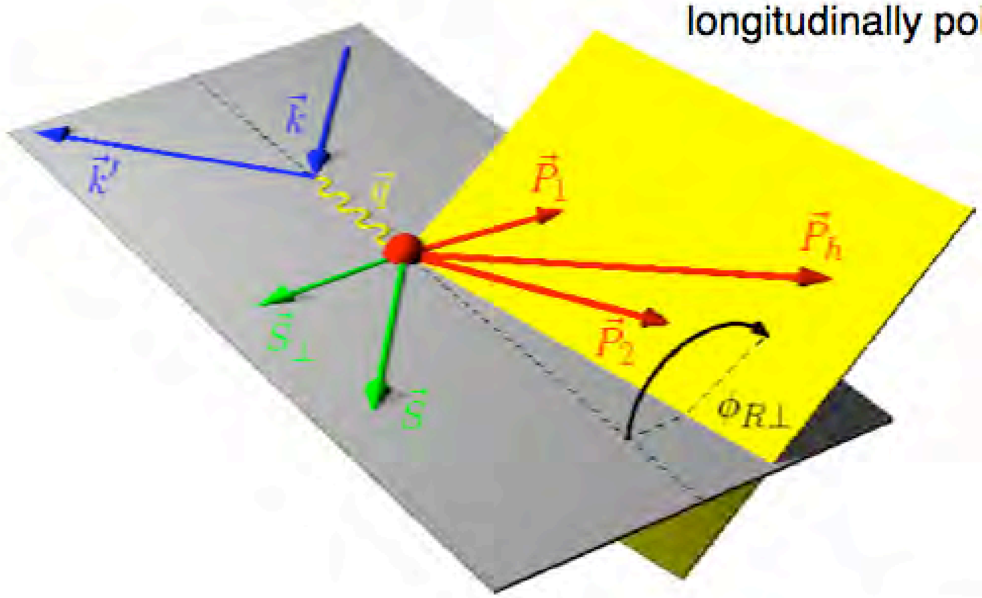
- leading twist -> on equal footing with f_1 and g_1
- chiral-odd -> can NOT be probed in inclusive DIS

Solution: couple h_1 to chiral-odd fragmentation function

Two options: 1 or 2 particle semi-inclusive DIS

2-π Single Spin Asymmetry

longitudinally polarized deuterium target



$\vec{P}_h \equiv \vec{P}_1 + \vec{P}_2$

$$A_{UL}(\phi_{R\perp}) = \frac{1}{|P_T|} \frac{N^{\rightarrow}(\phi_{R\perp})/L^{\rightarrow} - N^{\leftarrow}(\phi_{R\perp})/L^{\leftarrow}}{N^{\rightarrow}(\phi_{R\perp})/L^{\rightarrow} + N^{\leftarrow}(\phi_{R\perp})/L^{\leftarrow}}$$

Theoretical Asymmetries

A. Bacchetta, M Radici, PRD 69 (2004) 074026

$$A'_{UT} \sim B(y) \sin(\phi_{R\perp} + \phi_S) h_1 H_1^{\sphericalangle} + V(y) \sin(\phi_S) \frac{M}{Q} (\cdots)$$

$$A'_{UL} \sim V(y) \sin(\phi_{R\perp}) \frac{M}{Q} (h_L H_1^{\sphericalangle} + g_1 \tilde{G}^{\sphericalangle})$$

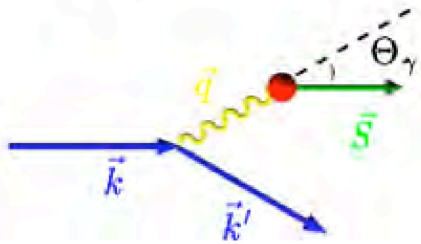
$T/L \Longrightarrow$ target spin defined w.r.t. virtual photon

Experimental Asymmetries

$$A_{UL} \simeq A'_{UL} - \sin\Theta_\gamma A'_{UT}$$

target spin defined w.r.t. beam

target spin w.r.t. virtual photon



$$\langle \sin\Theta_\gamma \rangle = \langle \tfrac{2Mx}{Q}\sqrt{1-y} \rangle \simeq 0.045$$

if $H_1^{\sphericalangle} \neq 0$:

$\Longrightarrow$ 2 hadron fragmentation can probe transversity!

$$A_{UL}(\phi) \sim \frac{N^{\rightarrow} - N^{\leftarrow}}{N^{\rightarrow} + N^{\leftarrow}}$$

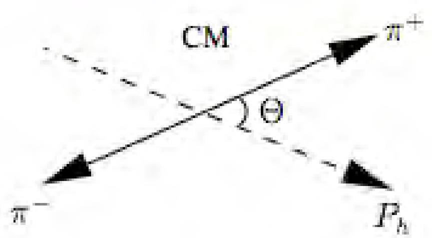
fit with $\Longleftarrow$

$$f(\phi_{R\perp}) = a_0 + a_1 \sin\phi + b_1 \cos\phi + \ldots$$

$a_1 \rightarrow A_{UL}^{\sin\phi}$

Interference Fragmentation Functions

$$H_1^{\sphericalangle}(z, \cos\Theta, M_{\pi\pi}^2) = H_1^{\sphericalangle,sp}(z, M_{\pi\pi}^2) + \cos\Theta H_1^{\sphericalangle,pp}(z, M_{\pi\pi}^2)$$



$\langle \cos\Theta \rangle \approx 0 \implies H_1^{\sphericalangle,pp}$ drops out!

Separations are possible from angular distribution.
These require a large acceptance (e.g. CLAS)

Quark Angular Momentum Sum Rule

GPDs H^u, H^d, E^u, E^d provide access to total quark contribution to proton angular momentum.

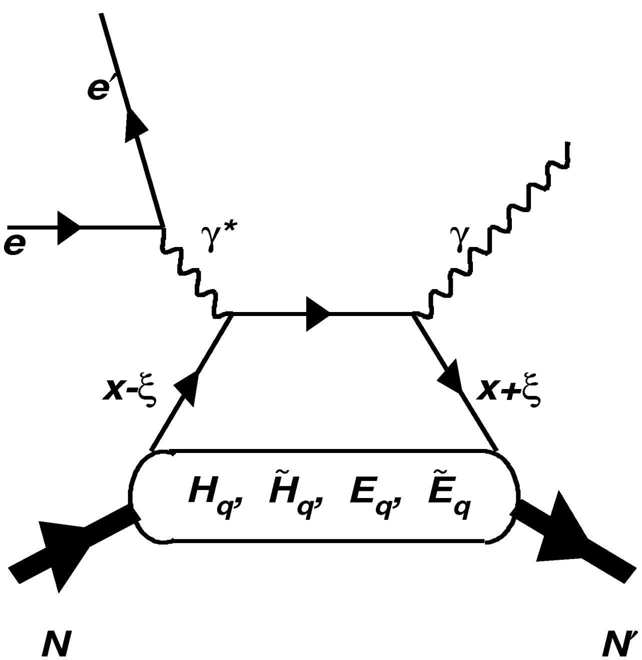
$$J^q = \frac{1}{2} - J^G = \frac{1}{2}\int_{-1}^{1} x\,dx \left[H^q(x,\xi,0) + E^q(x,\xi,0)\right]$$

X. Ji, Phy.Rev.Lett.78,610(1997)

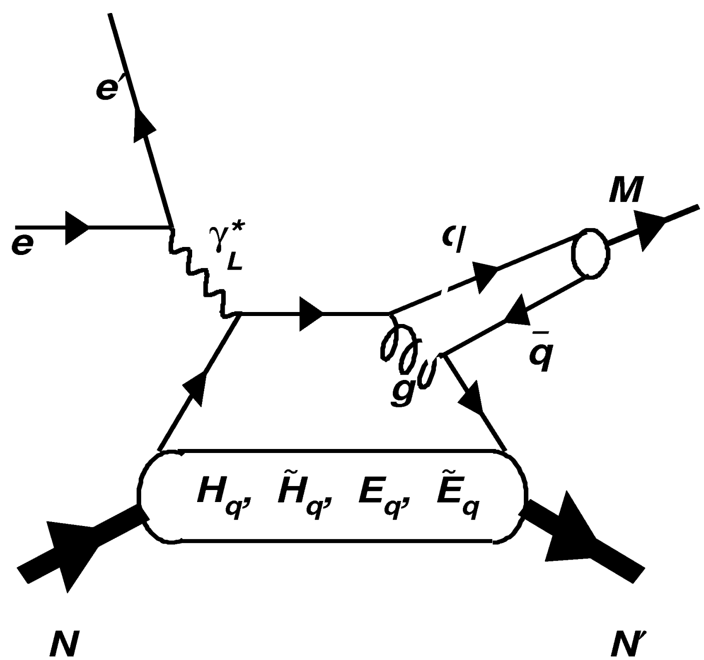
Large x contributions important.

Hard Exclusive Processes and GPDs

DVCS



DVMP



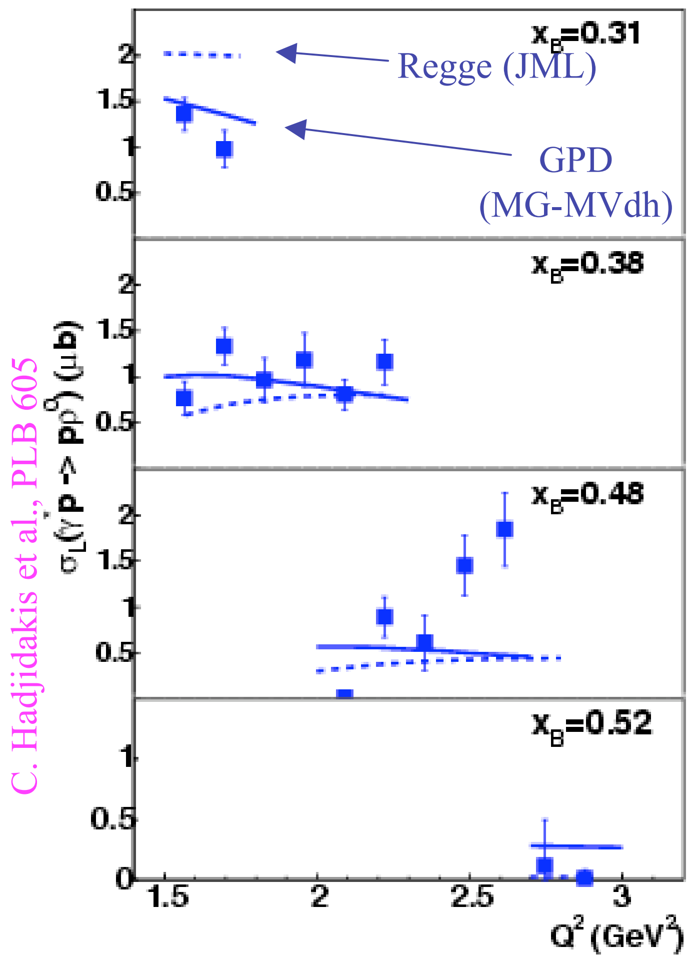
DVCS – for different polarizations of beam and target provide access to different combinations of GPDs H, $\tilde{H}$, E

DVMP for different mesons is sensitive to flavor contributions (ρ^0/ρ^+ select H, E, for u/d flavors, π, η, K select $\tilde{H}$, $\tilde{E}$)

Study the asymptotic regime and guide theory in describing HT.

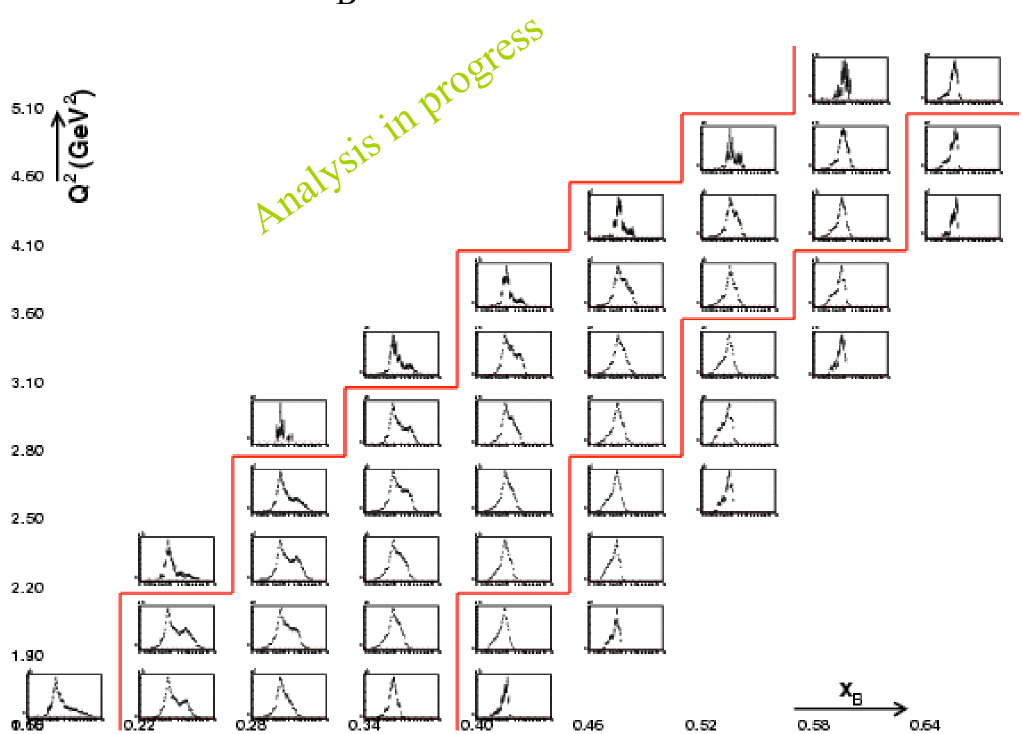
Exclusive ρ meson production: $ep \to ep\,\rho^0$

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

Upcoming 12 GeV CLAS Proposal

SIDIS (γ*p_πX) : Unpolarized target

e →

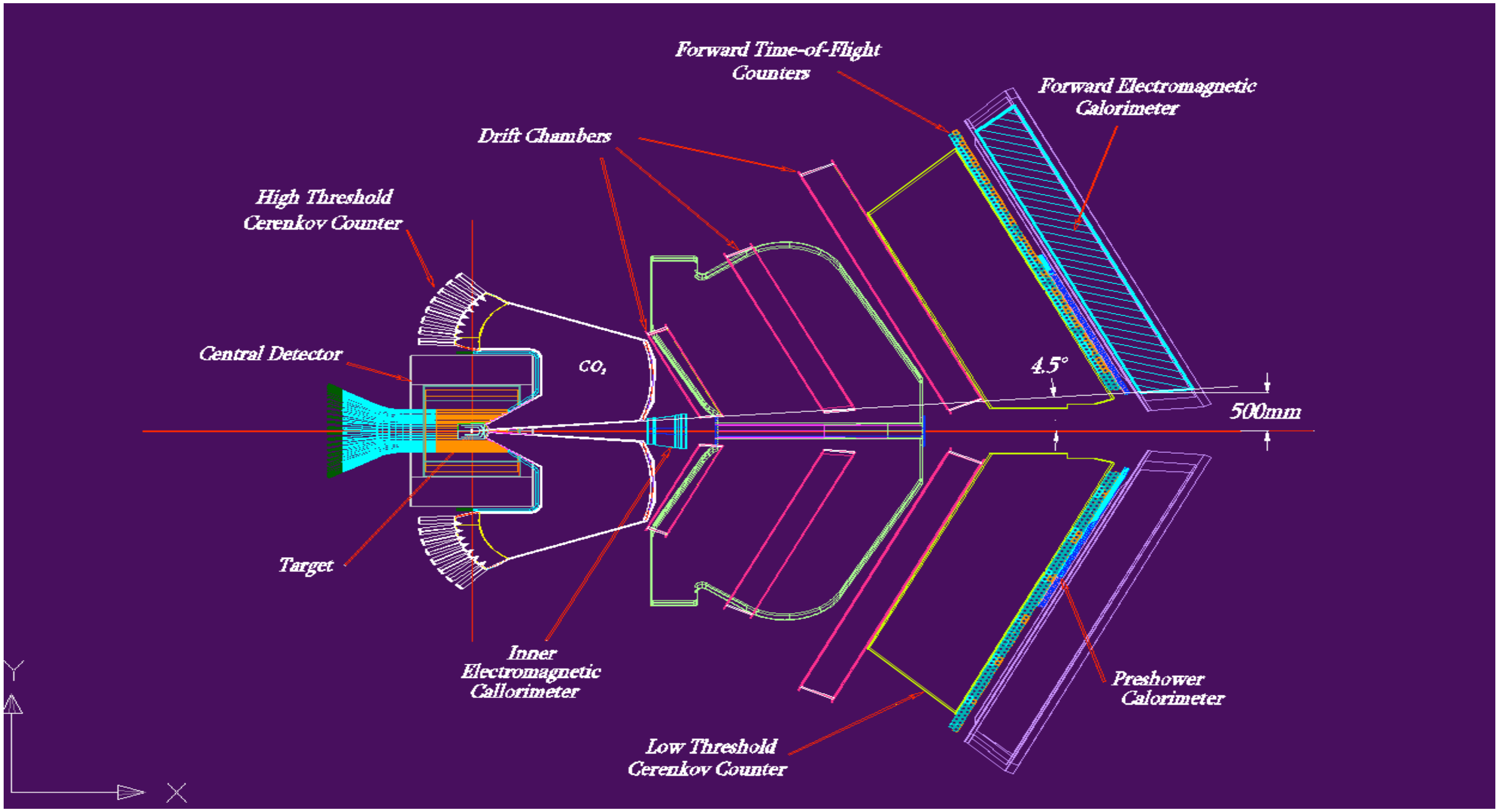
- **Azimuthal moments in pion production in SIDIS**
  - **cos2ϕ (Boer-Mulders function $h_{1}^{\perp}$) and relation with GPDs**
  - **cosϕ, cos2ϕ moments to study Cahn effect and Berger HT**
  - **sinϕ (g_) azimuthal moments of the x-section as a function of x,Q2,P_T,z to study transition from non-perturbative to perturbative description at large P_T**
- **Target fragmentation (Lambda, azimuthal moments)**

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 $h_{1T}^{\perp}$

Main focus

Study the transverse polarization of quarks in the unpolarized nucleon.

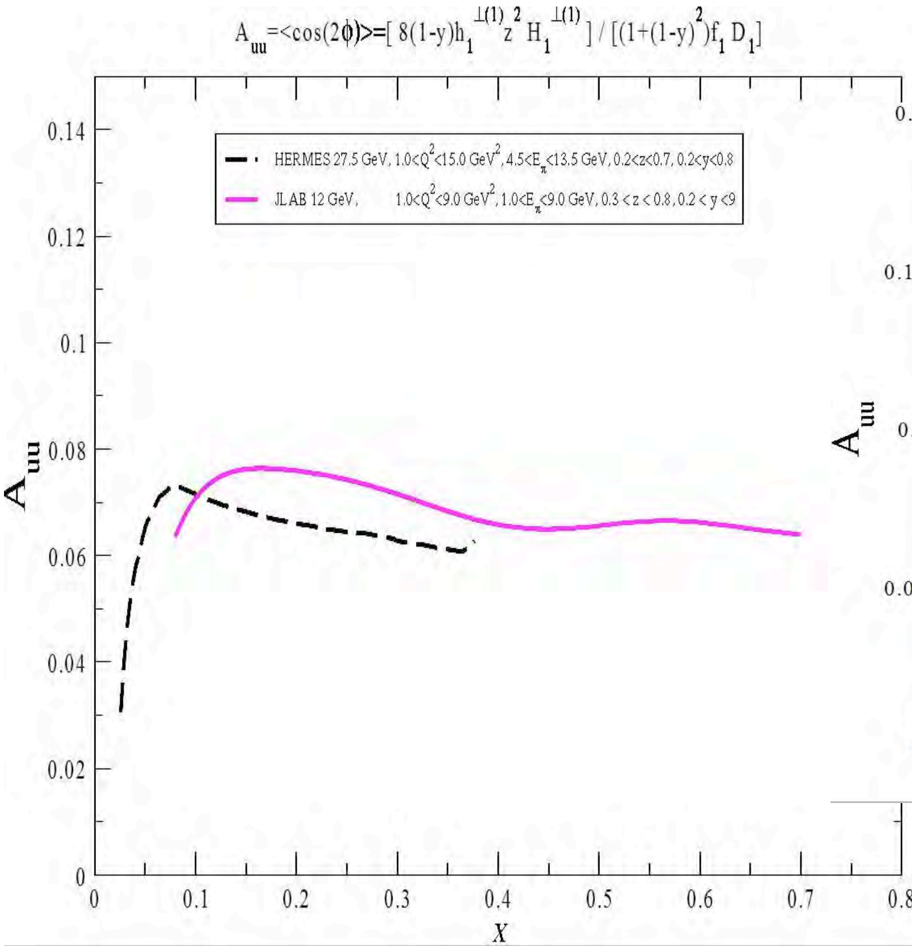
CLAS12

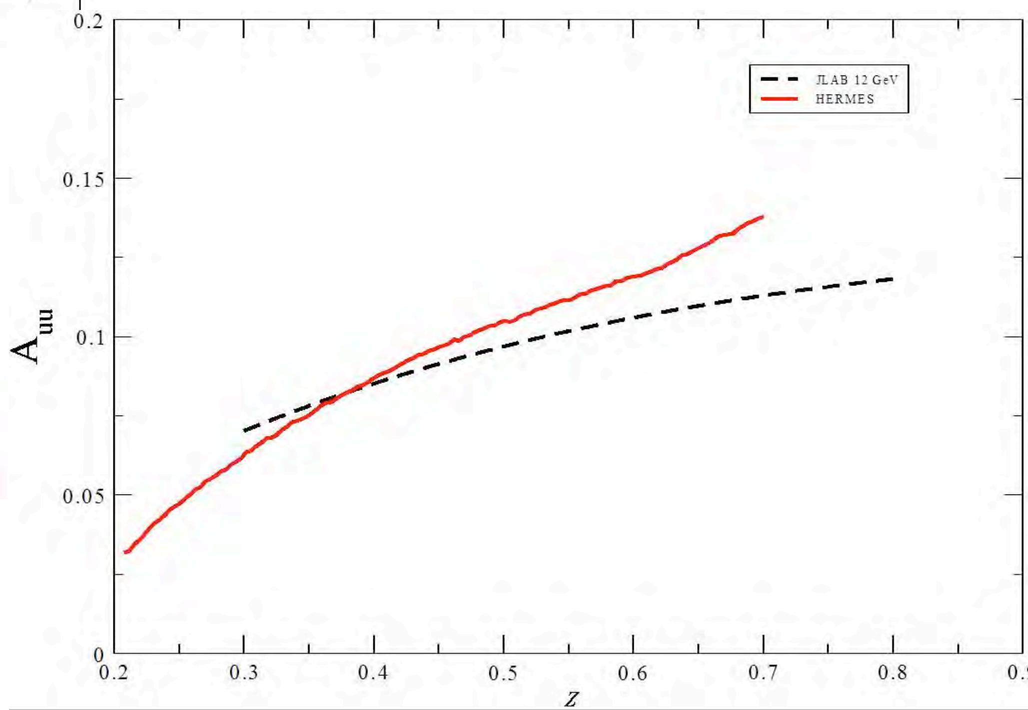


- High luminosity polarized (~80%) CW beam
- Wide geometric acceptance
- Wide physics acceptance

Provides new insight into
- quark orbital angular momentum contributions
- 3D structure of the nucleon's interior and correlations
- quark flavor polarization

cos2ϕ: predictions **L.Gamberg**

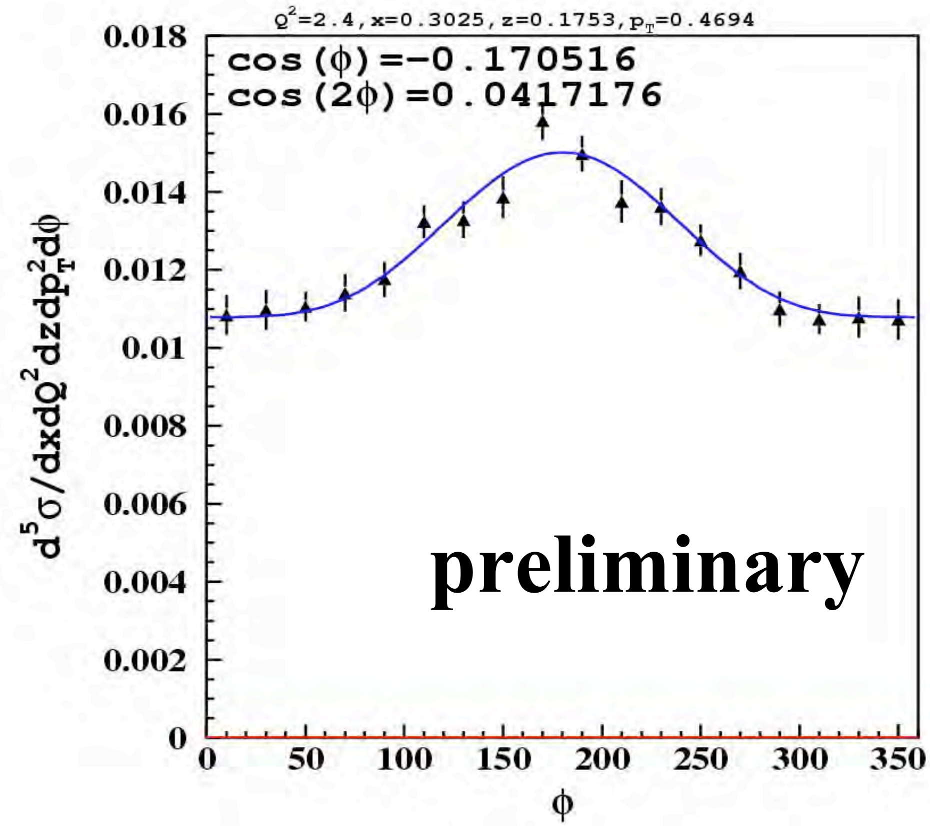


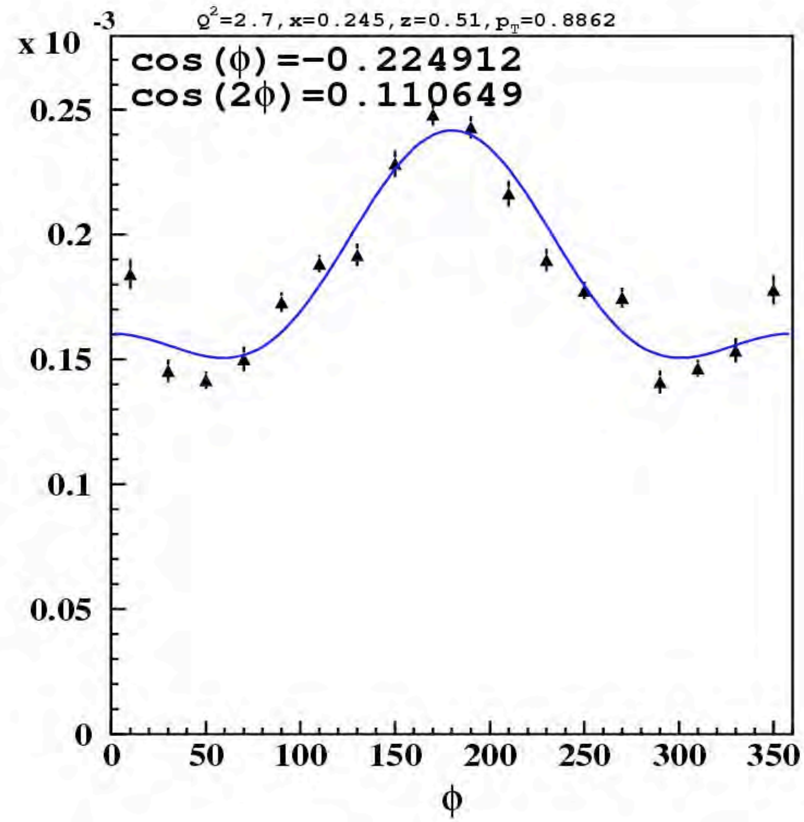


- **Significant Boer-Mulders asymmetry predicted for CLAS12**

M.Osipenko

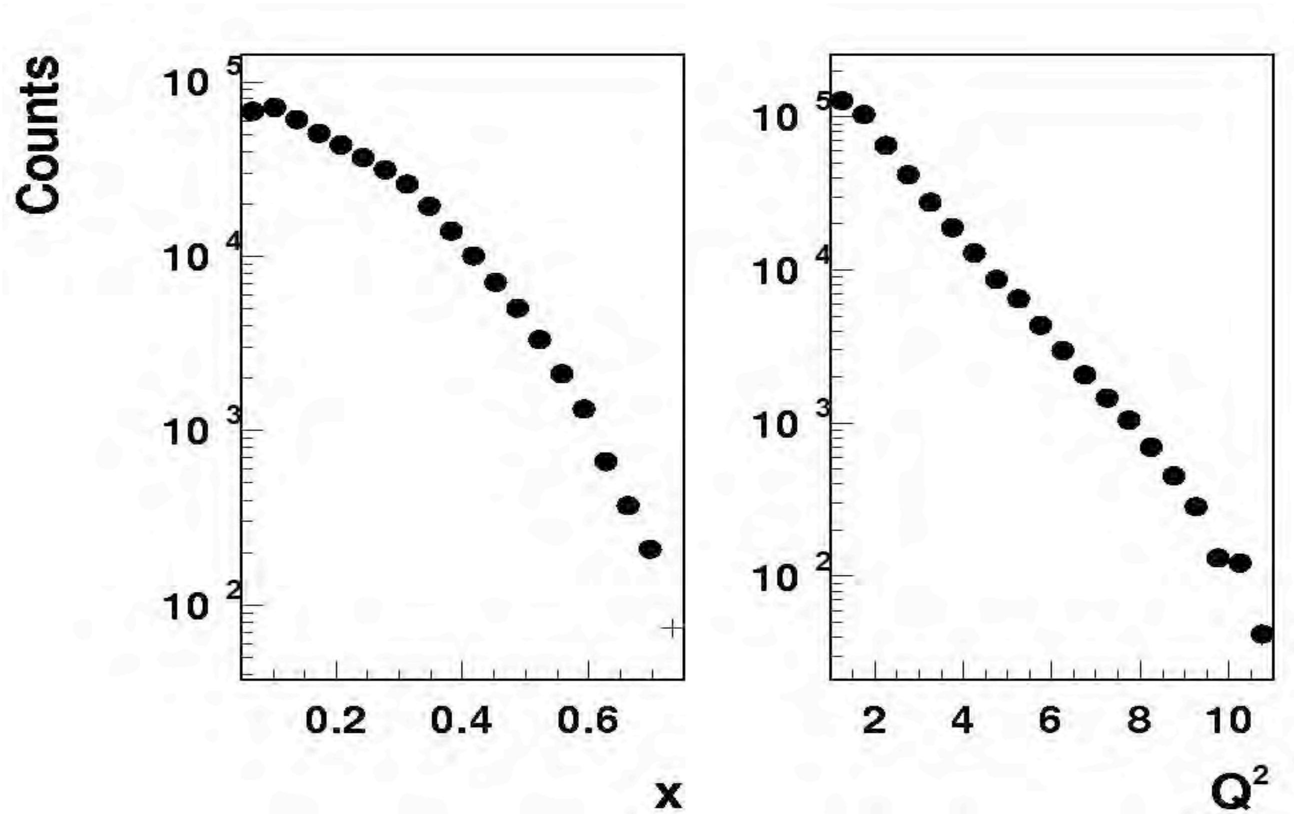
CLAS6 data





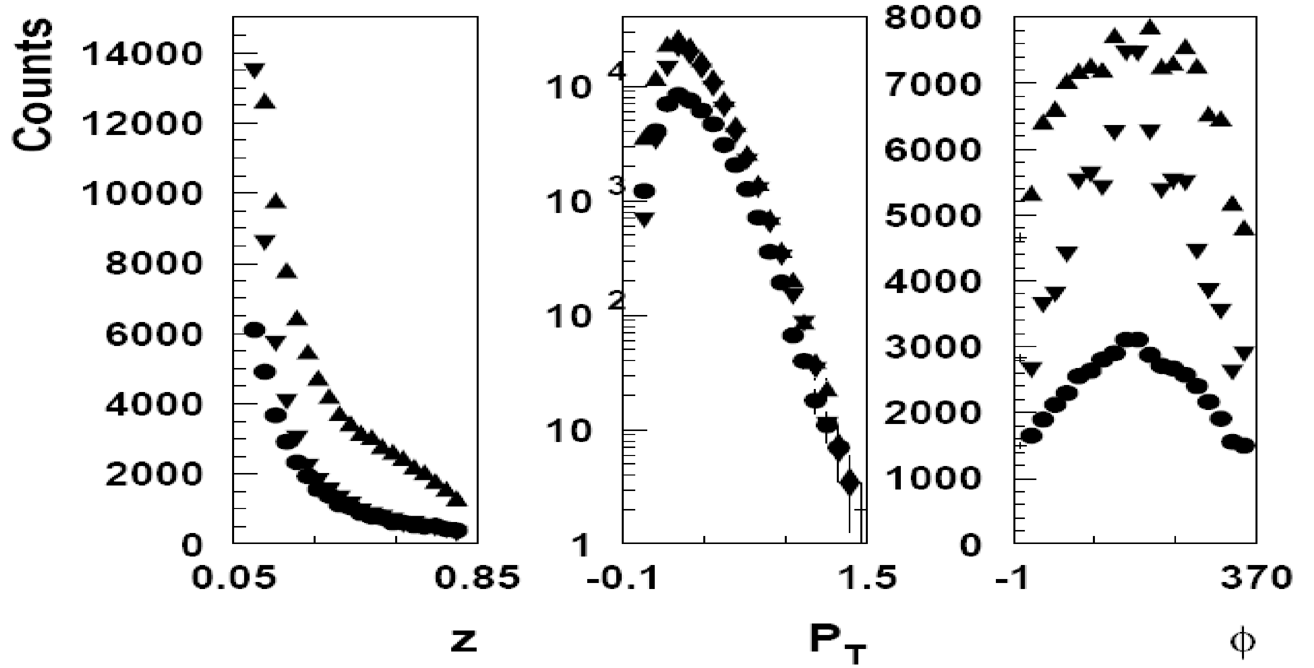
Significant cos2ϕ observed at large P_T

CLAS12: kinematic distributions



Large Q^2 accessible with CLAS12 are important for $\cos 2\phi$ studies

CLAS12: kinematic distributions



Kinematic distributions of π^+ (triangles up) π^- (triangles down) and π^0 for $\sim$ 10 min of CLAS12 running with hydrogen at luminosity of $10^{35} sec^{-1} cm^{-2}$.

CLAS12 allow wide kinematical coverage of SIDIS

P_T-dependence of beam SSA

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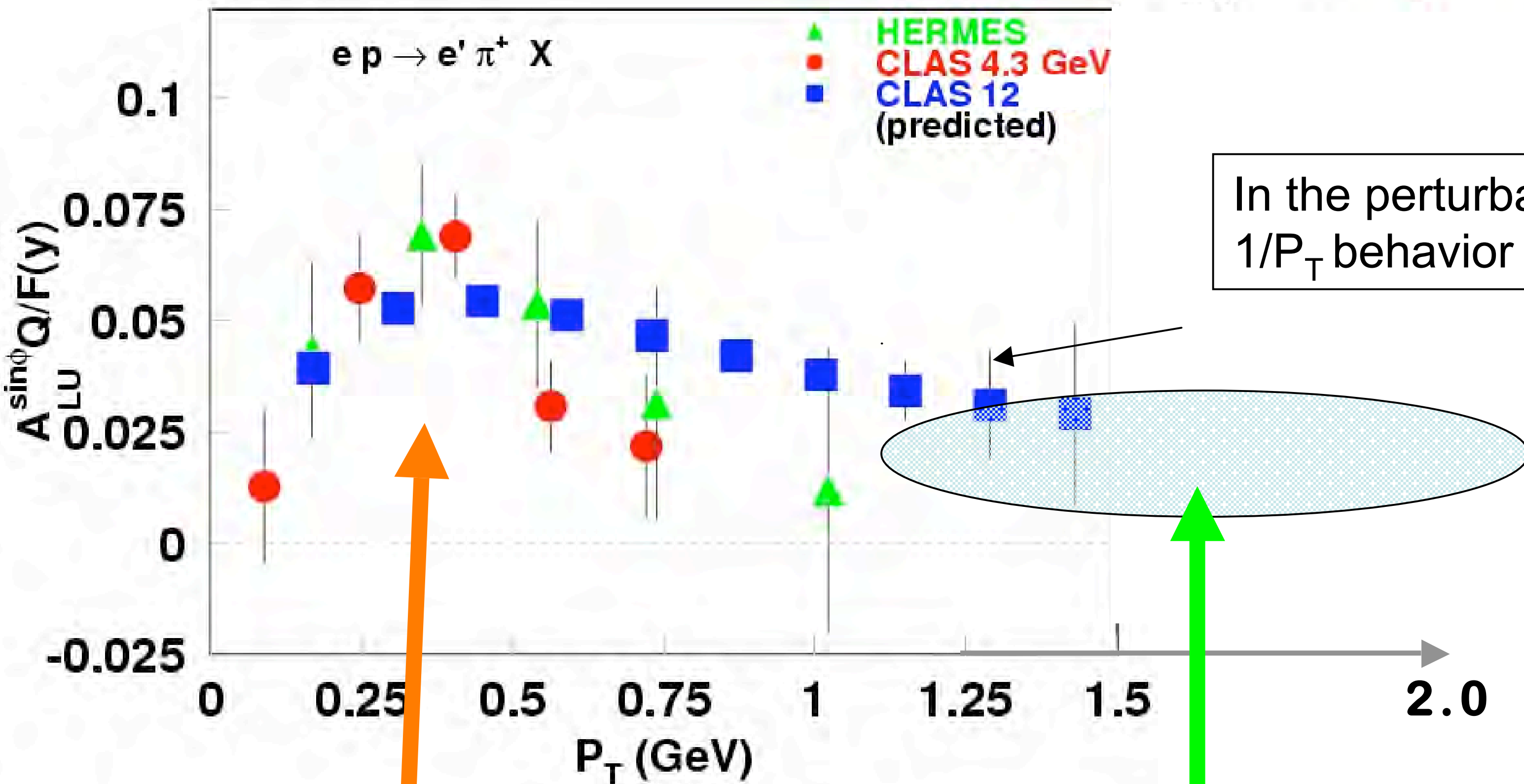
$\sigma^{\sin\phi}_{LU(UL)} \sim F_{LU(UL)} \sim 1/Q$ (Twist-3)

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



In the perturbative limit
$1/P_T$ behavior expected

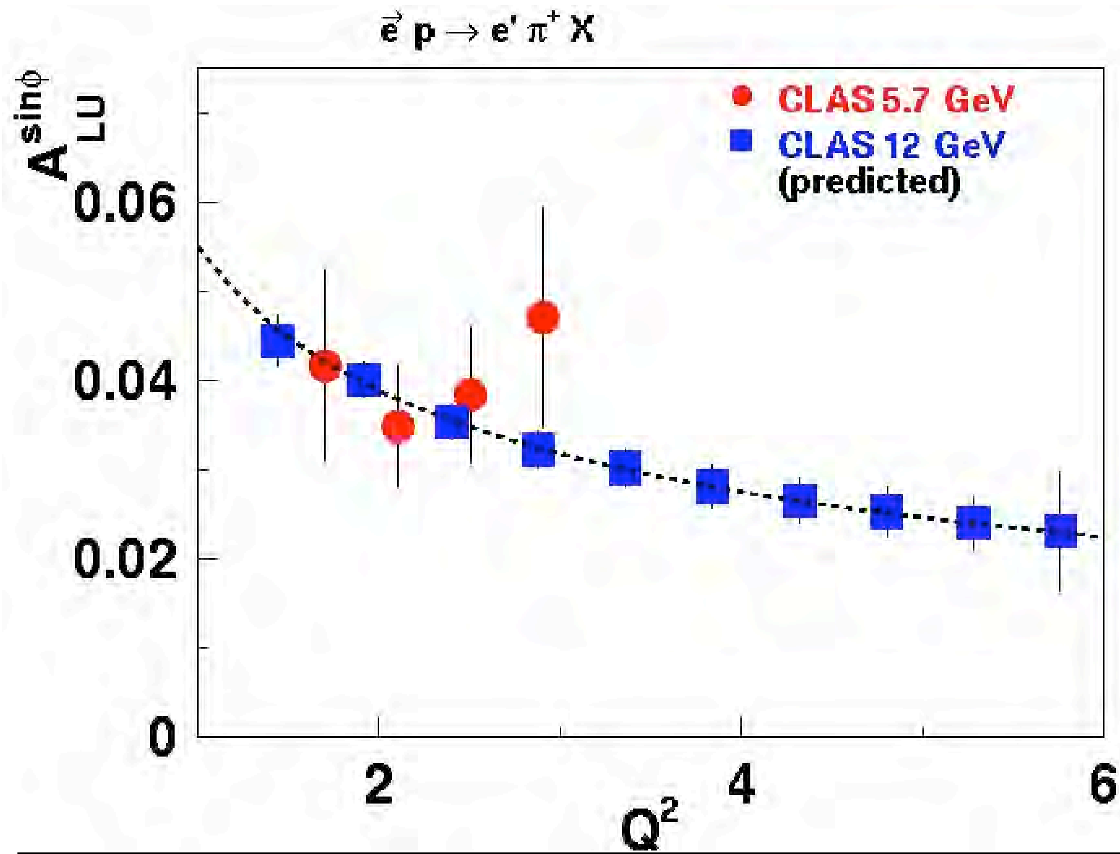
Non-perturbative TMD

Perturbative region

Asymmetries from k_T-odd (g_-,h_{1-}) and k_T-even (g_1) distribution functions are expected to have a very different behavior.

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

Conclusions

- Transversity is more easily studied with a transversely polarized target, but until we get one, we can learn quite a bit with longitudinally polarized targets
- The large acceptance of CLAS and CLAS++ allows a wide variety of single-spin asymmetry measurements that probe the spin and angular-momentum of the nucleon