Exclusive and Semi-Inclusive Processes in Hard Scattering Kinematics at JLab

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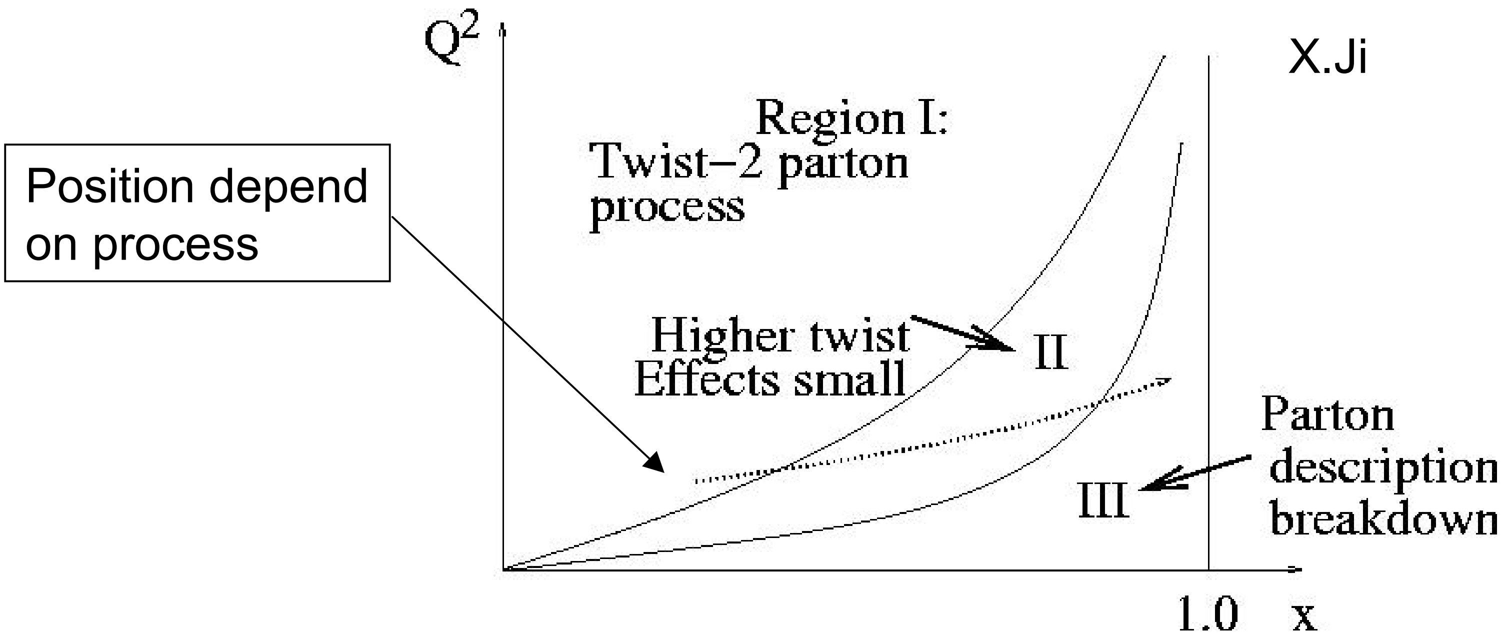
GPD Workshop Seattle 2003

- Hard scattering kinematics
- SSA in DVCS and HMP
    - MC studies
    - Different methods and cuts
- SIDIS and x,z factorization studies
    - Multiplicities
    - Spin Asymmetry (A_1)
    - Azimuthal Asymmetries
- Summary

Hard scattering at JLab



Utilizing high luminosity and large *x* coverage:

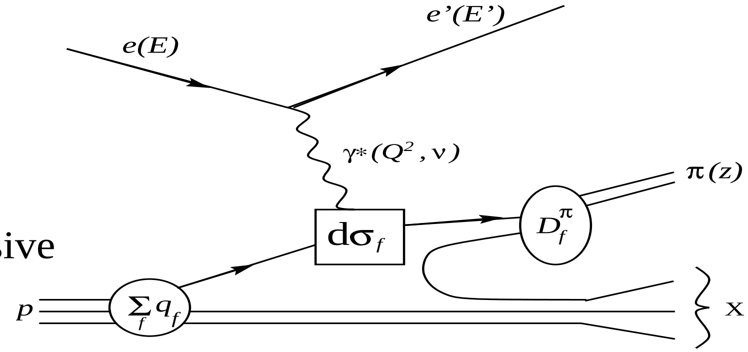
- study the transition between the nonperturbative and perturbative regimes of QCD
- test factorization
- measure higher twists
- orbital angular momentum of quarks

Single pion production

HARD

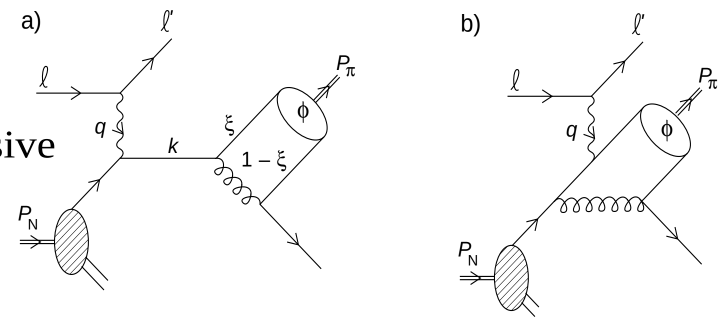
PDFs

0.5−0.7
semi−inclusive



0.7−0.9
semi−exclusive

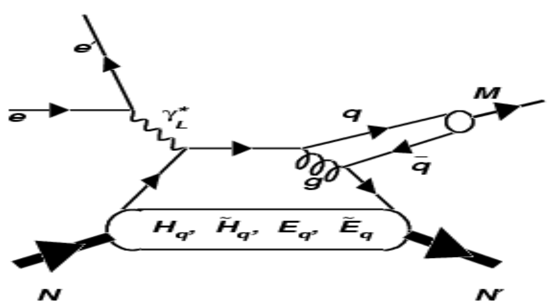
HT



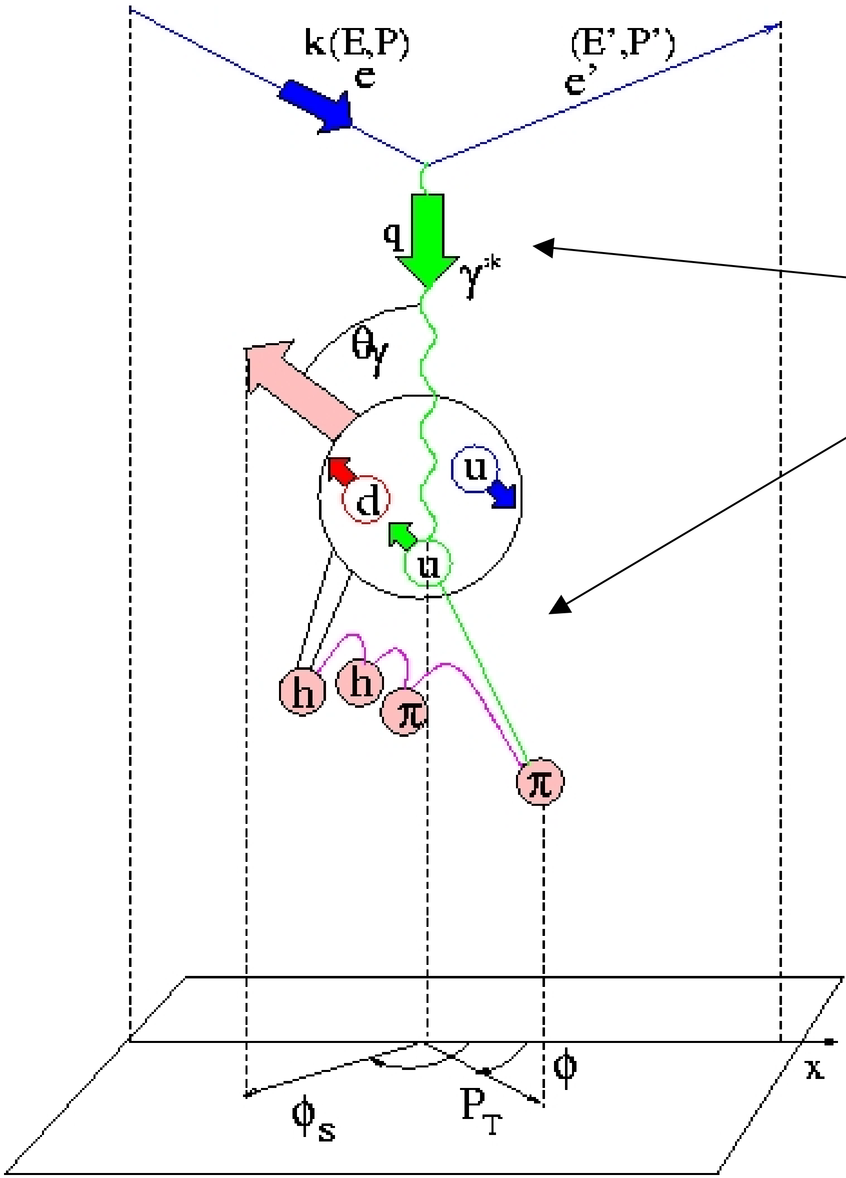
> 0.9
exclusive

$z=E_h/E_\gamma$

GPDs



Single Pion Production Kinematics



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

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

Spin Azimuthal Asymmetries can be extracted as **azimuthal moments** of the total cross section.

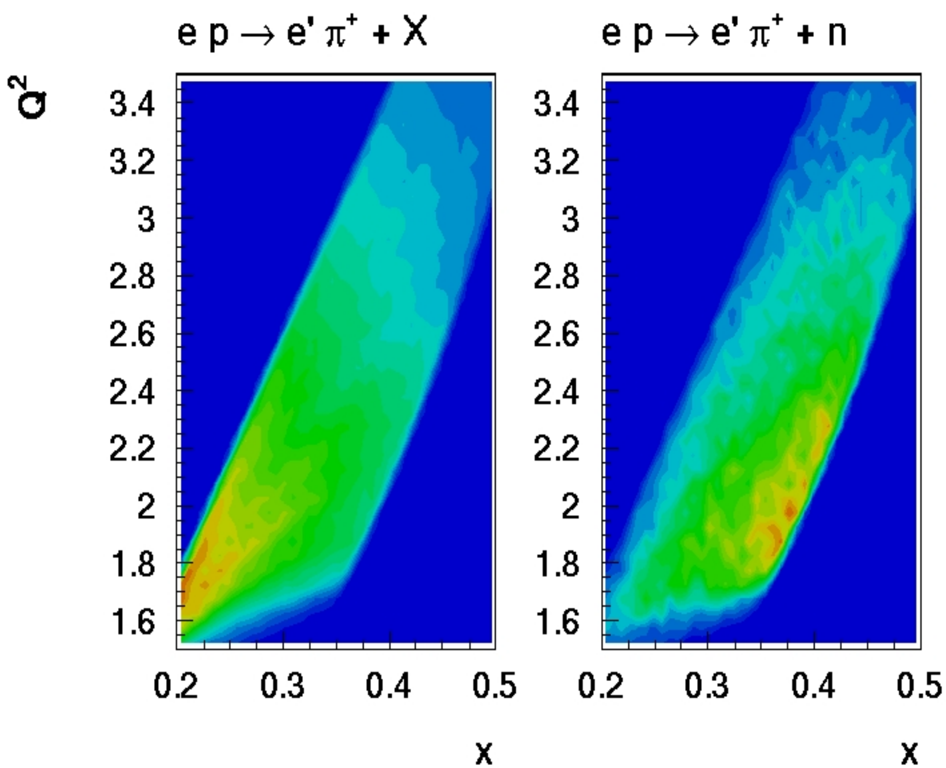
$$
A_{LU}^{\sin\phi} = \frac{<\sin\phi>}{<\sin^2\phi>} = \frac{1}{P^\pm}\frac{\sum_{i=1}^{N^\pm}\sin\phi_i}{\sum_{i=1}^{N^\pm}\sin^2\phi_i}
$$

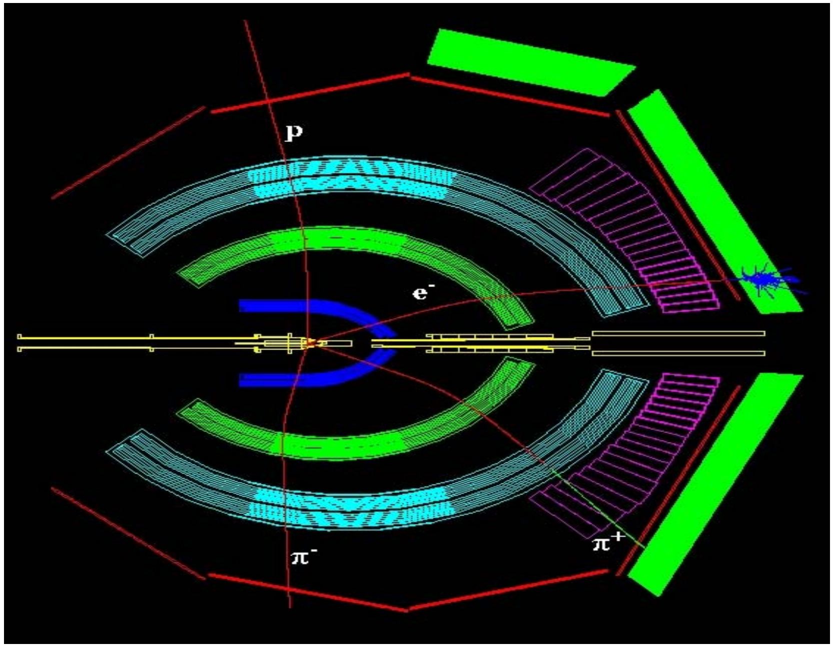
Hard scattering processes at JLab

- Study x,z dependence for different observables
- compare with measurements at higher energies (HERMES,SMC)
- compare with realistic MC (LUND-MC, DVCS-MC)
- compare with QCD based predictions (assuming factorization) for different observables, different final states

The CLAS Detector

Scattering of 5.7 GeV polarized electrons off polarized NH_3 and unpolarized hydrogen





- **~8M π^+ / 4M γ in DIS kinematics, SIDIS/DVCS $Q^2>1.5$ GeV^2, $W^2>4$, $y<0.85$, HMP $Q^2>2.5$ GeV^2, $W^2>5$, $y<0.85$**
- **beam polarization 73%**
- **target polarization 72% (f=0.2)**

Contributions to σ in ep->e'p'γ

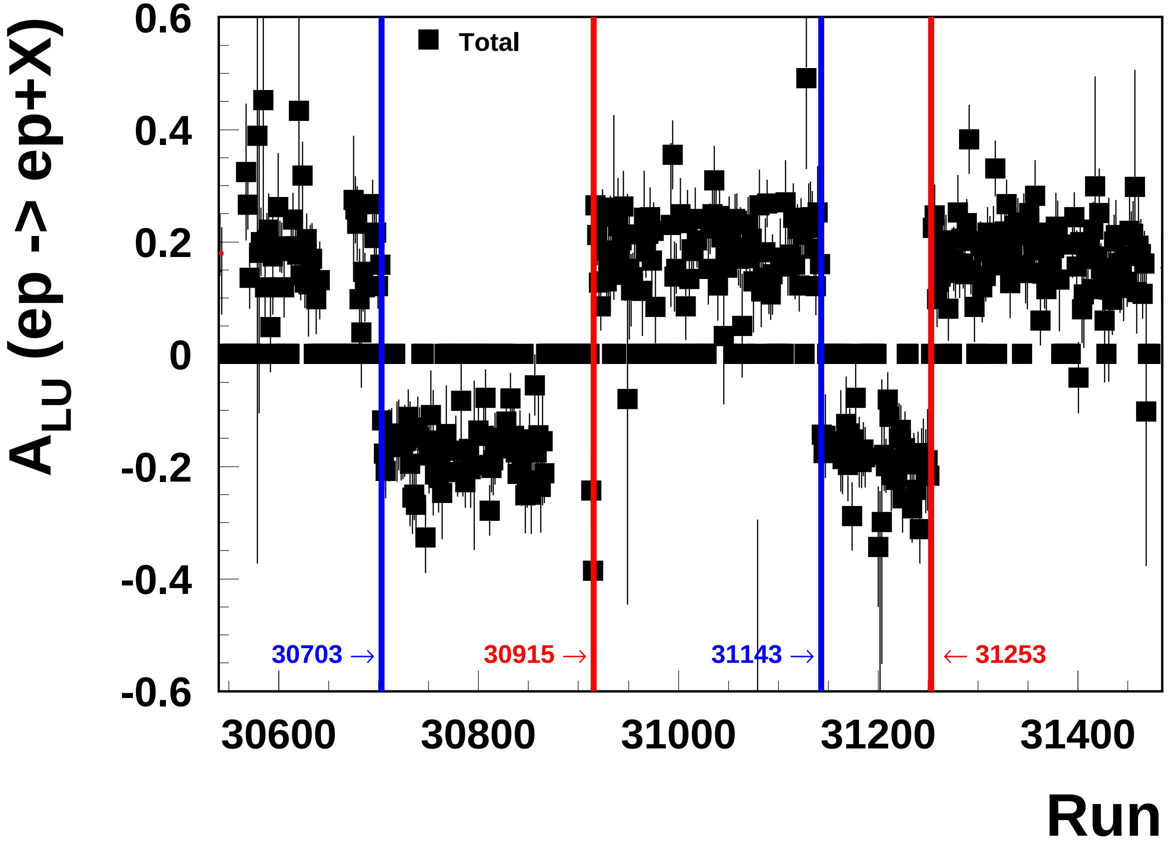
$$|\mathcal{T}_{\rm BH}|^2 = \frac{e^6}{x_{\rm B}^2 y^2 (1+\epsilon^2)^2 \Delta^2 \mathcal{P}_1(\phi)\mathcal{P}_2(\phi)} \left\{ c_0^{\rm BH} + \sum_{n=1}^{2} c_n^{\rm BH} \cos(n\phi) + s_1^{\rm BH} \sin(\phi) \right\}$$

$$\mathcal{I} = \frac{\pm e^6}{x_{\rm B} y^3 \Delta^2 \mathcal{P}_1(\phi)\mathcal{P}_2(\phi)} \left\{ c_0^{\mathcal{I}} + \sum_{n=1}^{3} \left[c_n^{\mathcal{I}} \cos(n\phi) + s_n^{\mathcal{I}} \sin(n\phi) \right] \right\},$$

Different contributions can be extracted as **azimuthal moments** of the total cross section.

Extraction more complicated due to ϕ–dependent amplitude

CLAS 5.7 GeV: beam ssa



Monitor beam spin flips with DVCS SSA

A_{LU} in ep->e'p'γ

Two methods used so far:
$A_{LU} = \langle\sin\phi\rangle / \langle\sin^2\phi\rangle$ and $(N^+ - N^-)/(N^+ + N^-)$
provide different approximations of $s_2^I(H,\tilde{H})$.

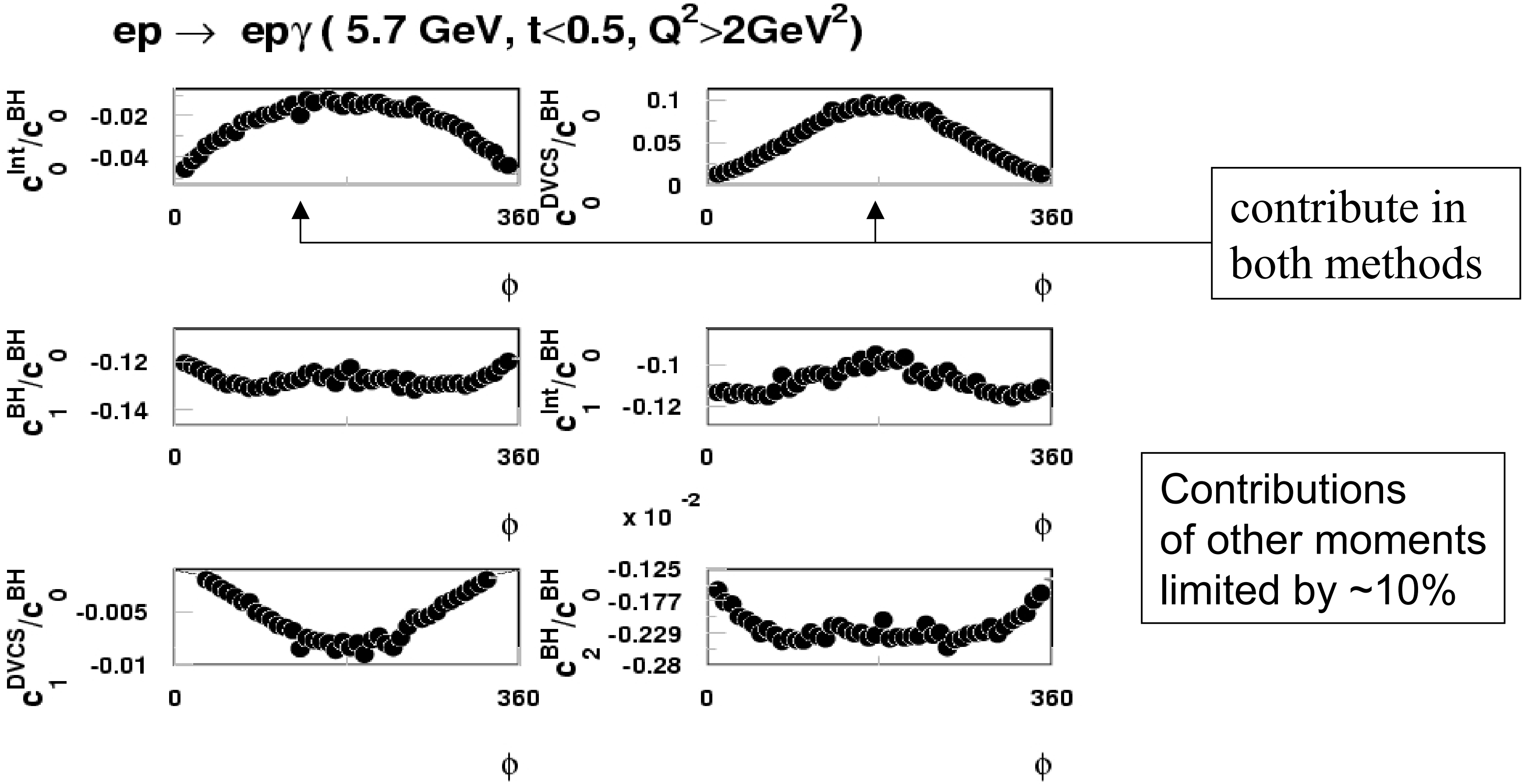
Requirements for precision (<15%) measurements of GPDs from DVCS SSA:

- Define relation between A_{LU} and s_2^I
  - effect of other non-0 moments
  - effect of finite bins
- Define background corrections
  - pion contamination
  - ADVCS
  - radiative background

~

Azimuthal moments in ep->e'p'γ

$A_{LU} = \langle \sin\phi \rangle / \langle \sin^2\phi \rangle$ and $(N^+ - N^-)/(N^+ + N^-)$ are related to s_2^I



MC:Contributions to σ in ep->e'p'π

$$\frac{d\sigma}{dt}(\gamma_L\ p \to \pi^0\ p) = \frac{d\sigma}{dt}(x, Q^2)\Big|_{t=\mathrm{t}_{\mathrm{min}}} \times e^{B(t - t_{min})},$$

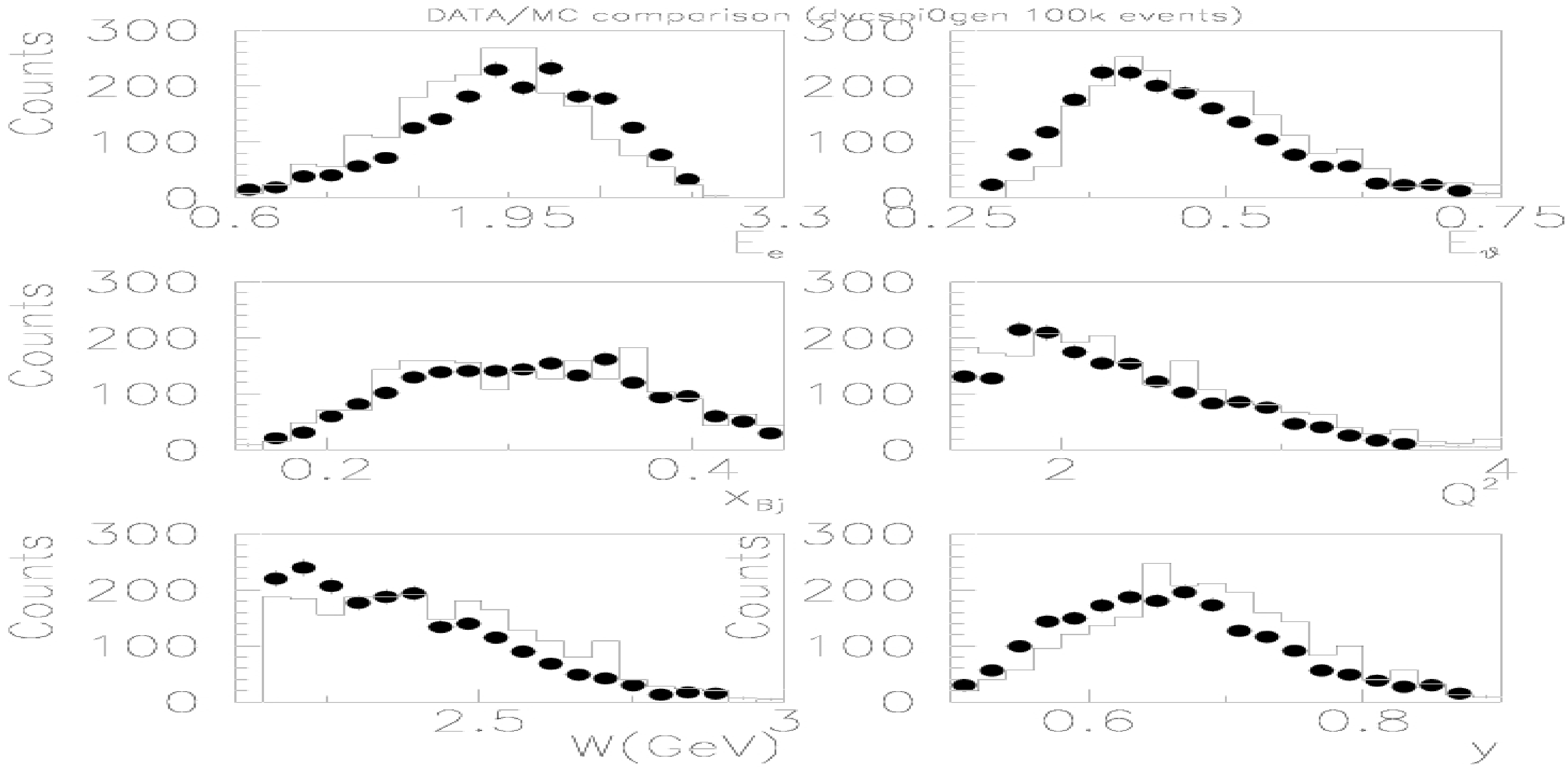
where:

$$\frac{d\,\sigma}{d\,t}(x, Q^2)\Big|_{t=\mathrm{t}_{\mathrm{min}}} = \frac{{\alpha_S}^2(Q^2)\cdot \mathrm{PF}(x, Q^2)\cdot \mathrm{UF}(x)}{Q^2(Q^2 + M^2)^2}.$$

$$\mathrm{PF}(x, Q^2) = \frac{Q^4\ (1 - x)^2}{(-Q^2 - 0.881721\,x + Q^2\,x)^2}.$$

UF(x) is defined by GPD $\tilde{H}$

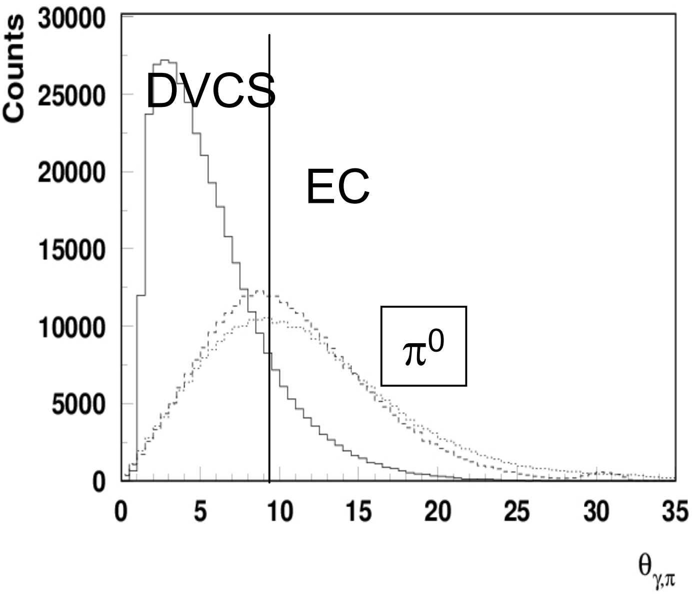
Mankievicz,Piller Vanderhaeghen… hep-ph/9909534

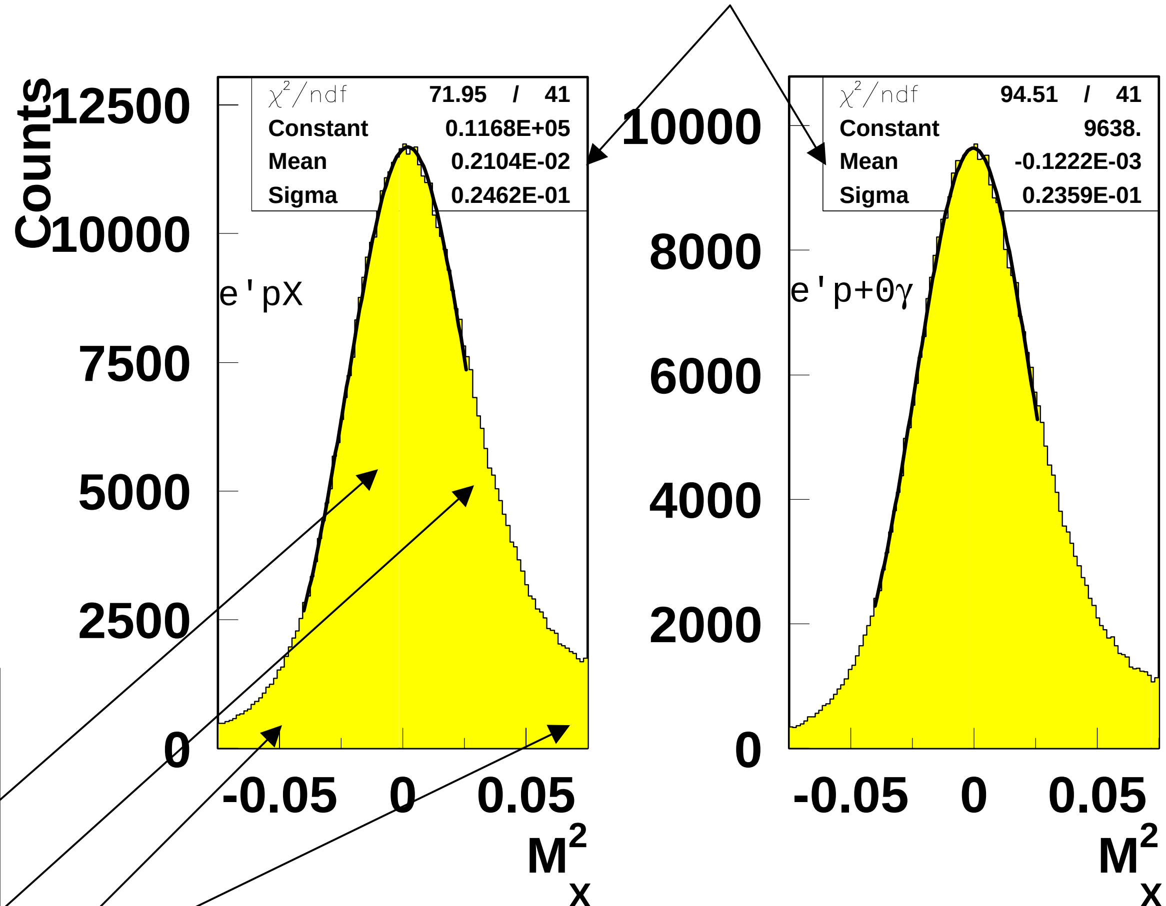


MC/data comparison for π^0 **(-t<0.5 GeV²)**

Angular and mass distribution of DVCS photons

0γ cuts 20% of events (M^2_x=0.018 for π^0)

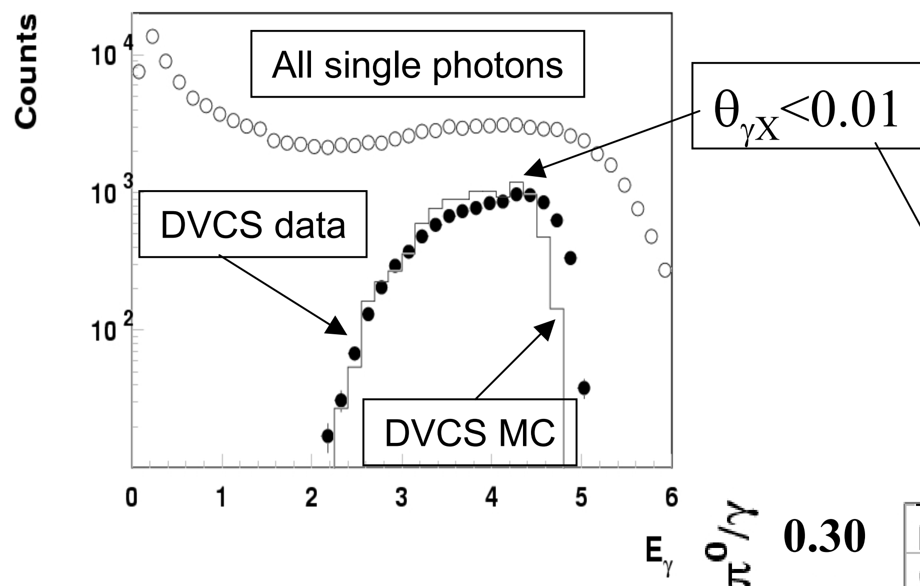


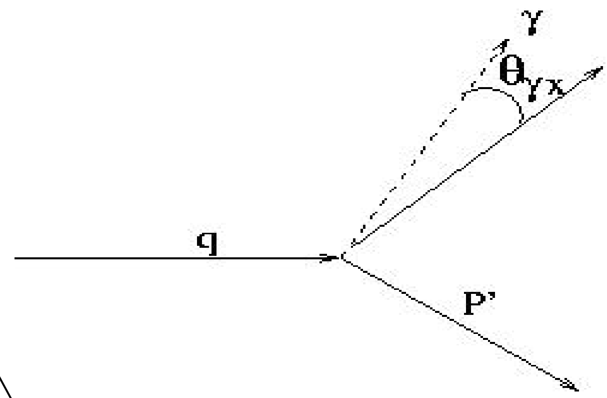


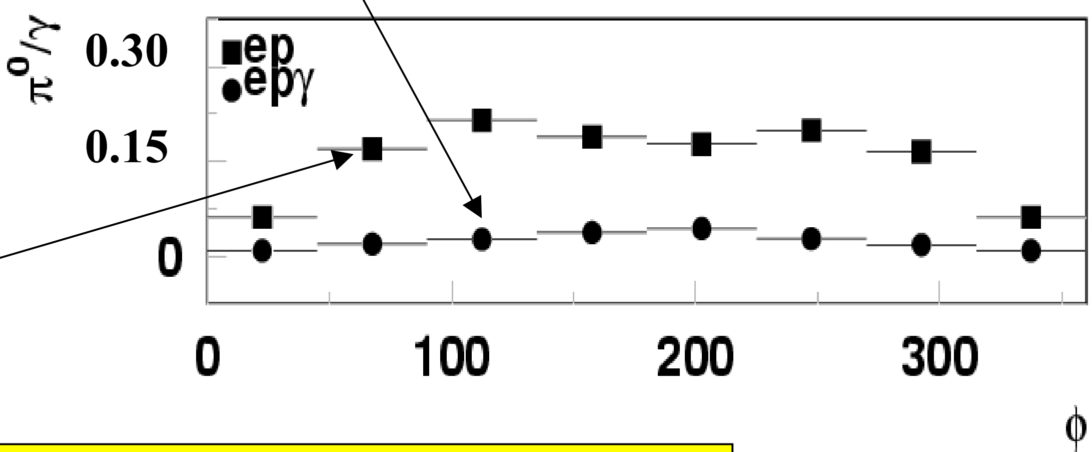
Contributions:

1) epγ
2) epγπ0 (ADVCS)
3) epπ0
4) Rad.back. From 1-3

DVCS MC: separating DVCS photons





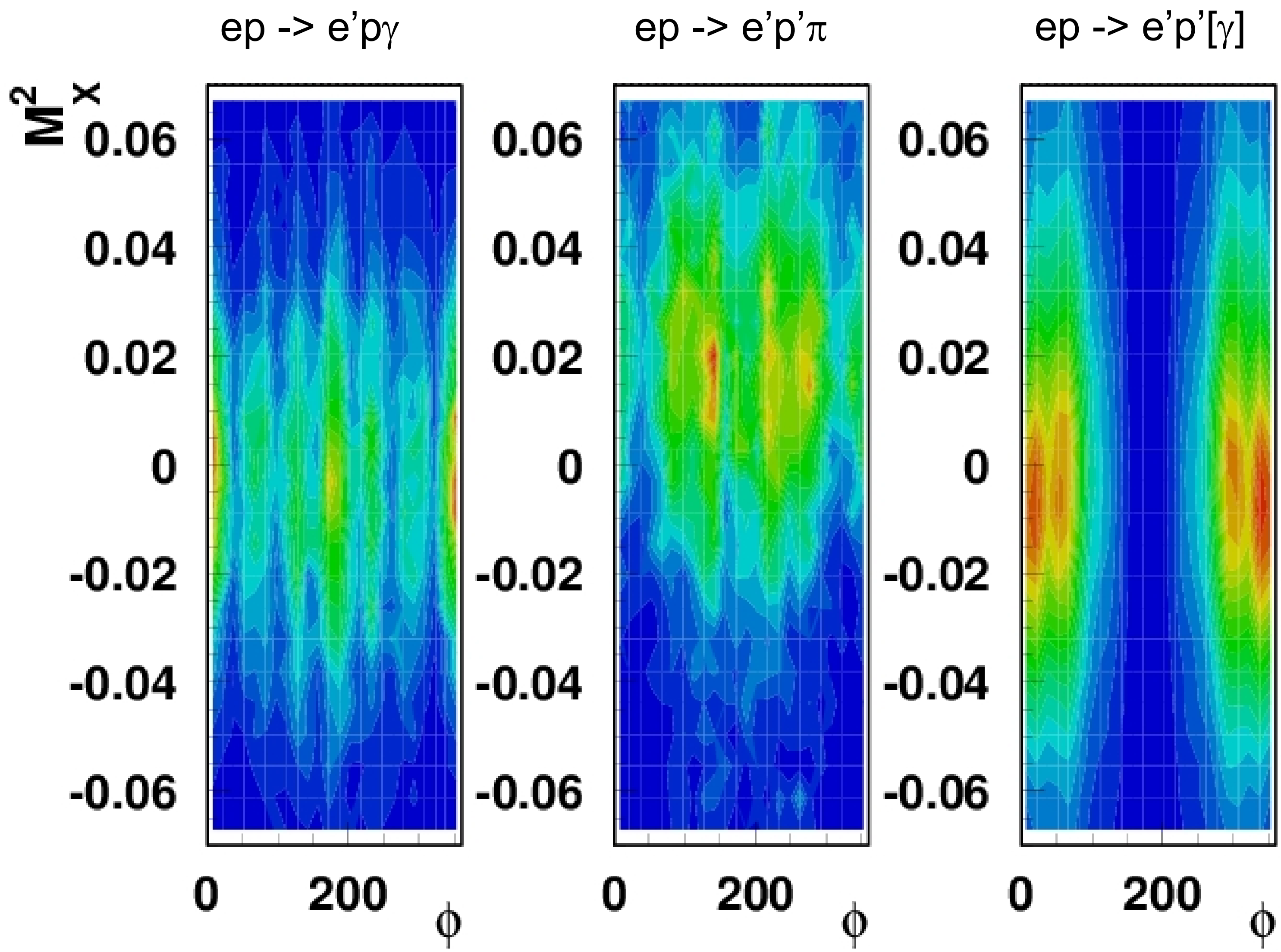


Samples:

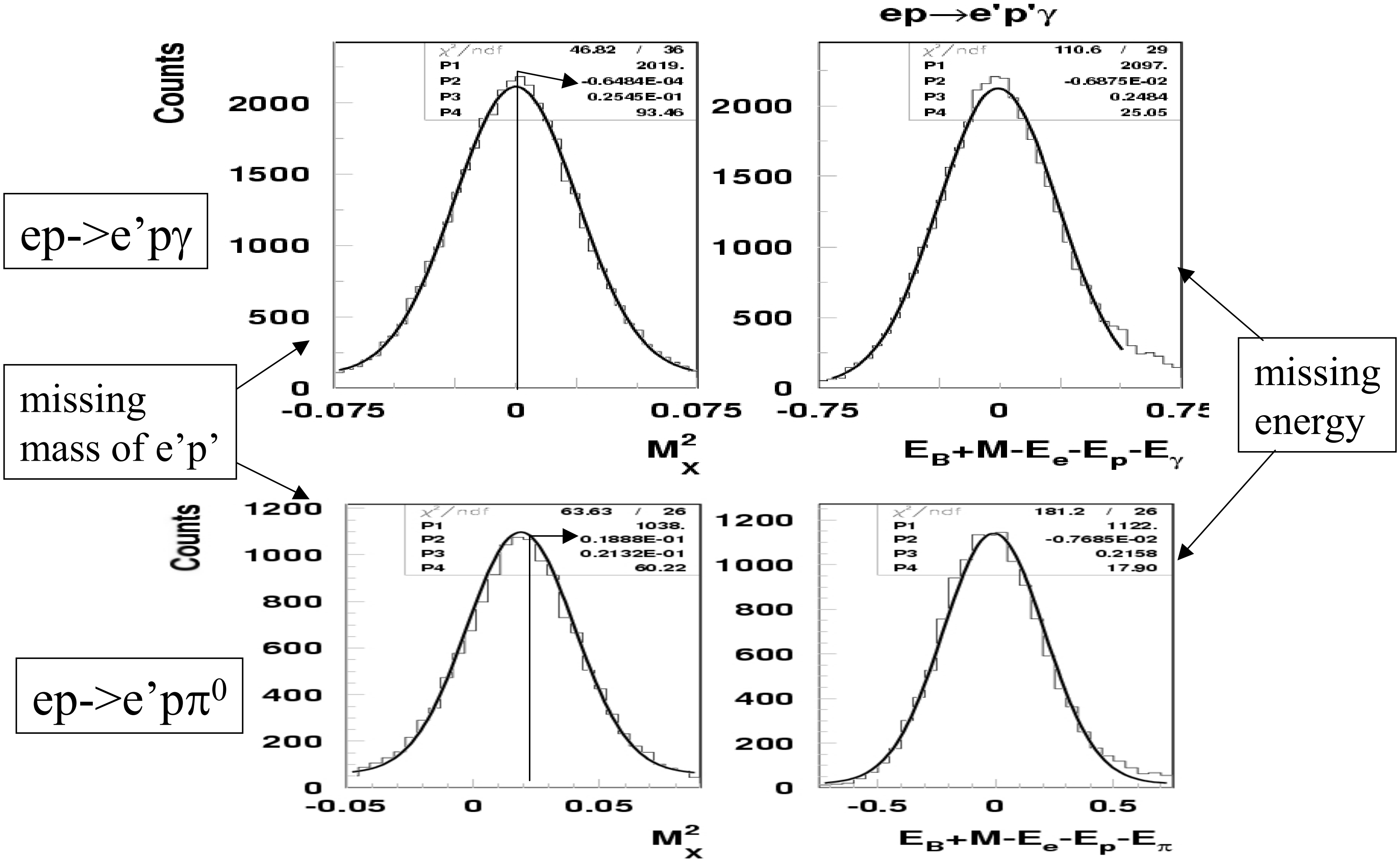
1)ep (0γ)
2)epγ
3)$ep\pi^0$

π^0 contribution small and under control

ϕ-dependence of M_X^2 for γ and π^0

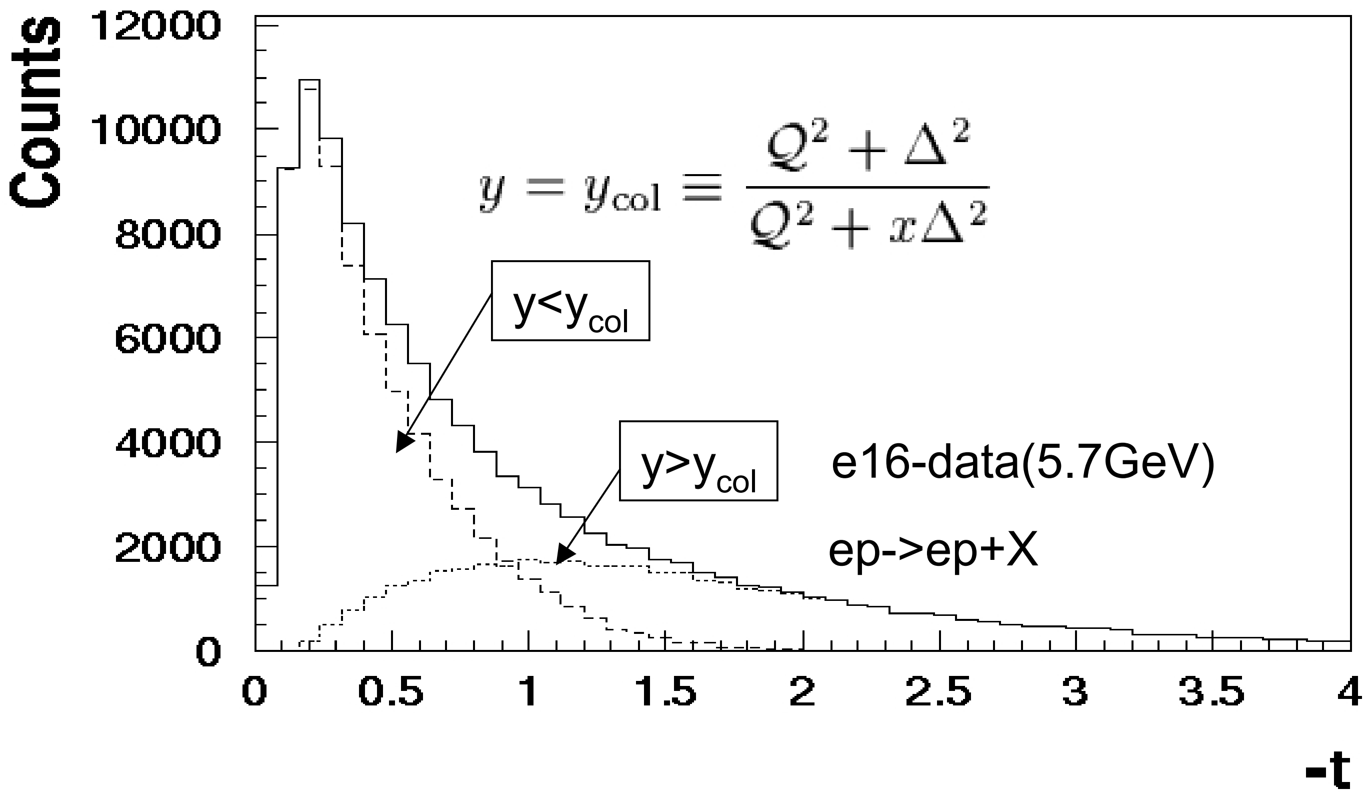


CLAS 5.7 GeV: Single photon and π^0



Collinearity cut (for ep[γ] sample)

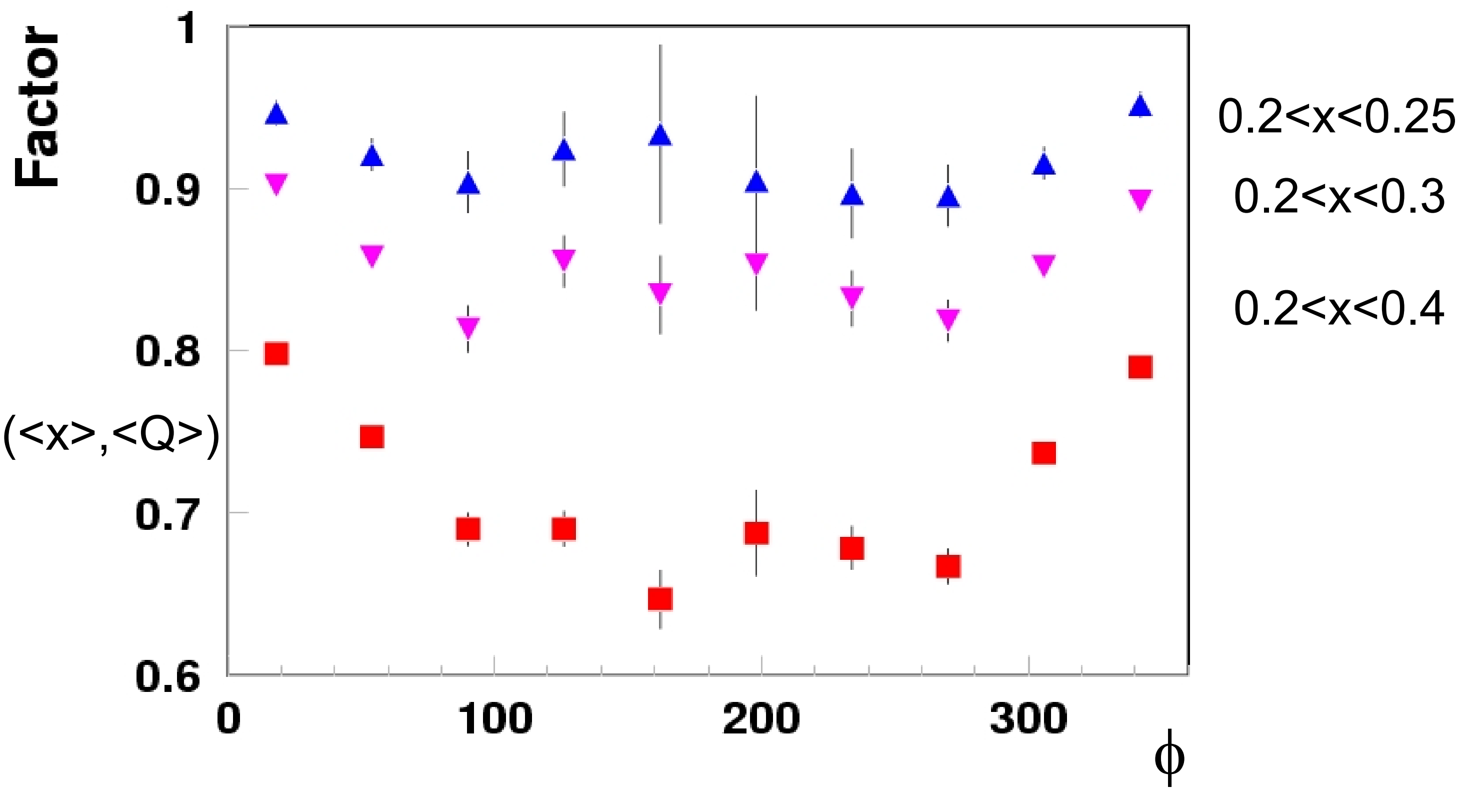
$$\mathcal{P}_1 = -\frac{1}{y(1+\epsilon^2)}\{J + 2K\cos(\phi)\}\ , \qquad \mathcal{P}_2 = 1 + \frac{\Delta^2}{\mathcal{Q}^2} + \frac{1}{y(1+\epsilon^2)}\{J + 2K\cos(\phi)\}$$



Correction factor as a function of bin size

<Int>/<BH>

Int(<x>,<Q>)/BH(<x>,<Q>)

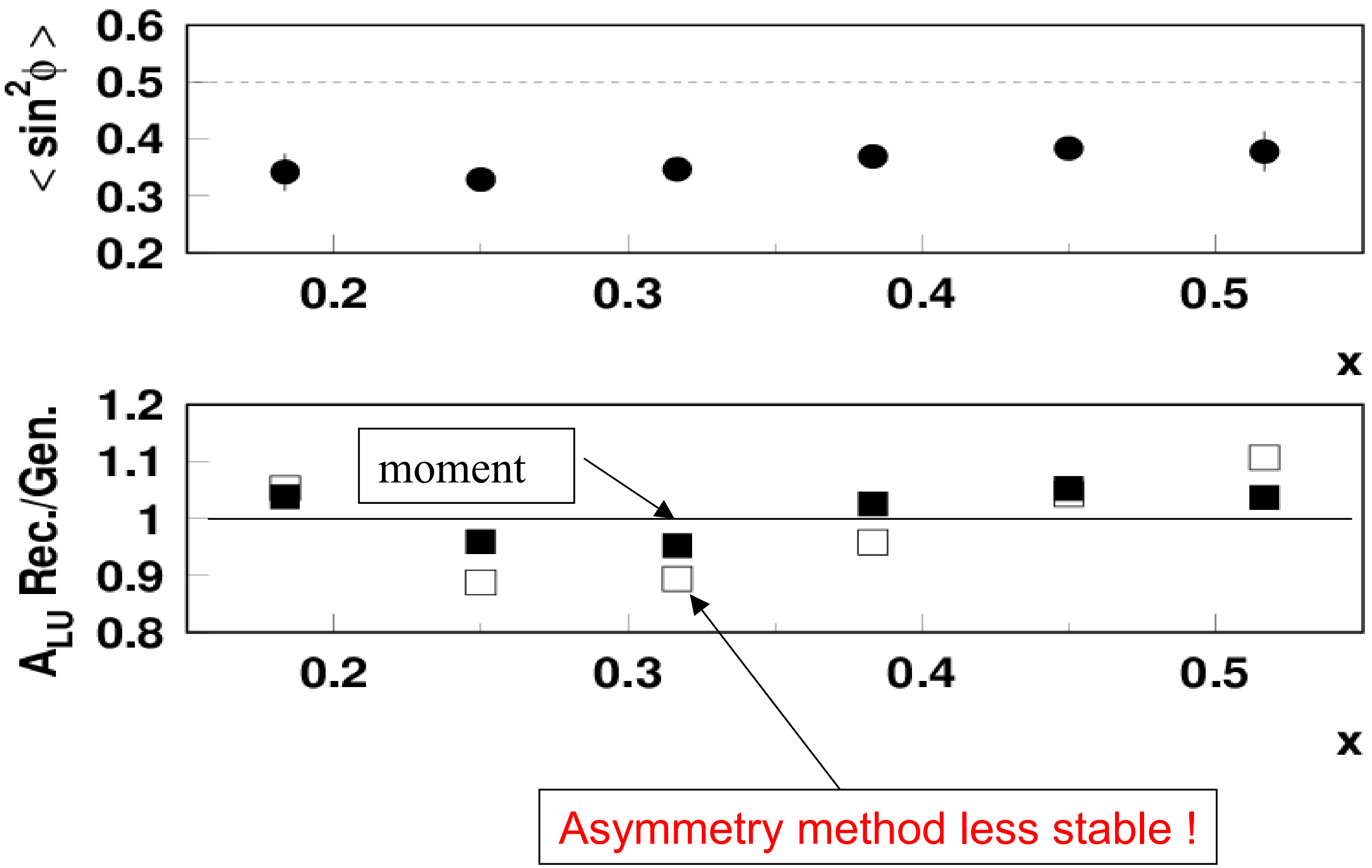


ϕ – dependence of $\mathcal{P}_1 = -\frac{1}{y(1+\epsilon^2)}\{J + 2\,K\cos(\phi)\}$

in BH and INTerference terms doesn't cancel for finite bins

Comparing A_{LU} extraction methods for DVCS

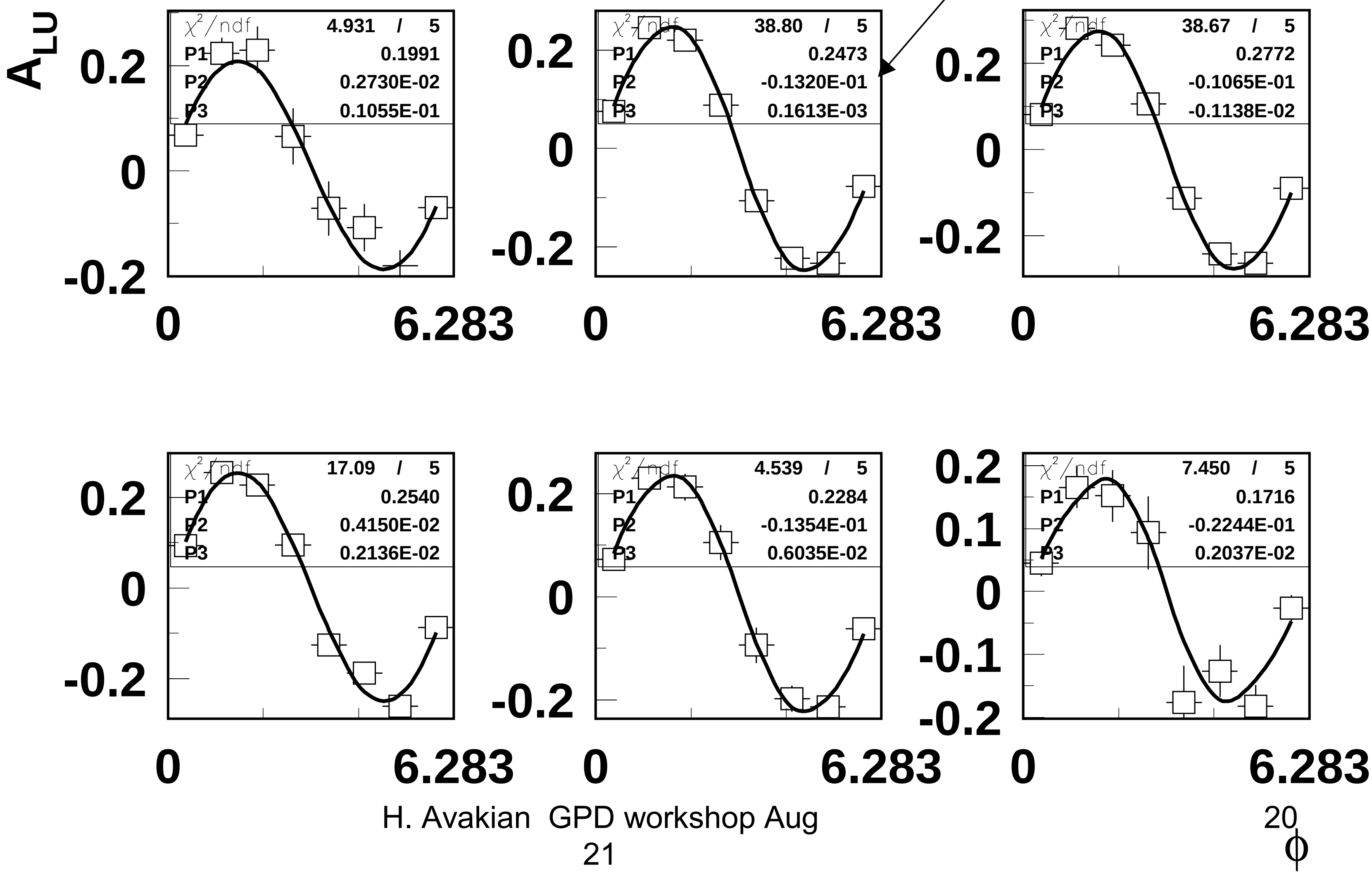
$A_{LU} = \langle \sin\phi \rangle / \langle \sin^2\phi \rangle$



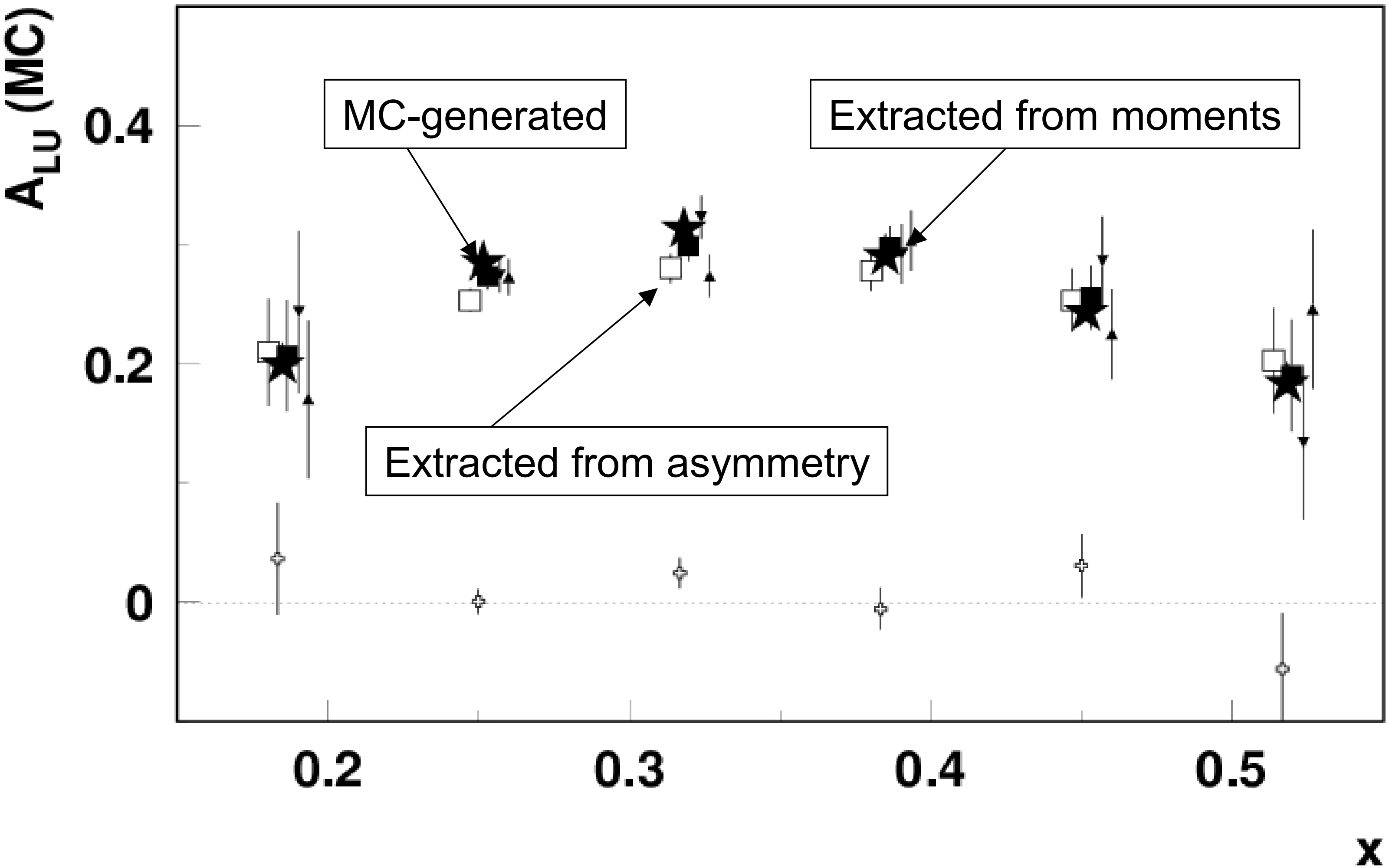
A_{LU} from MC (false sin2ϕ)

Fit with P1*sin(ϕ)+P2*sin(2*ϕ)+P3

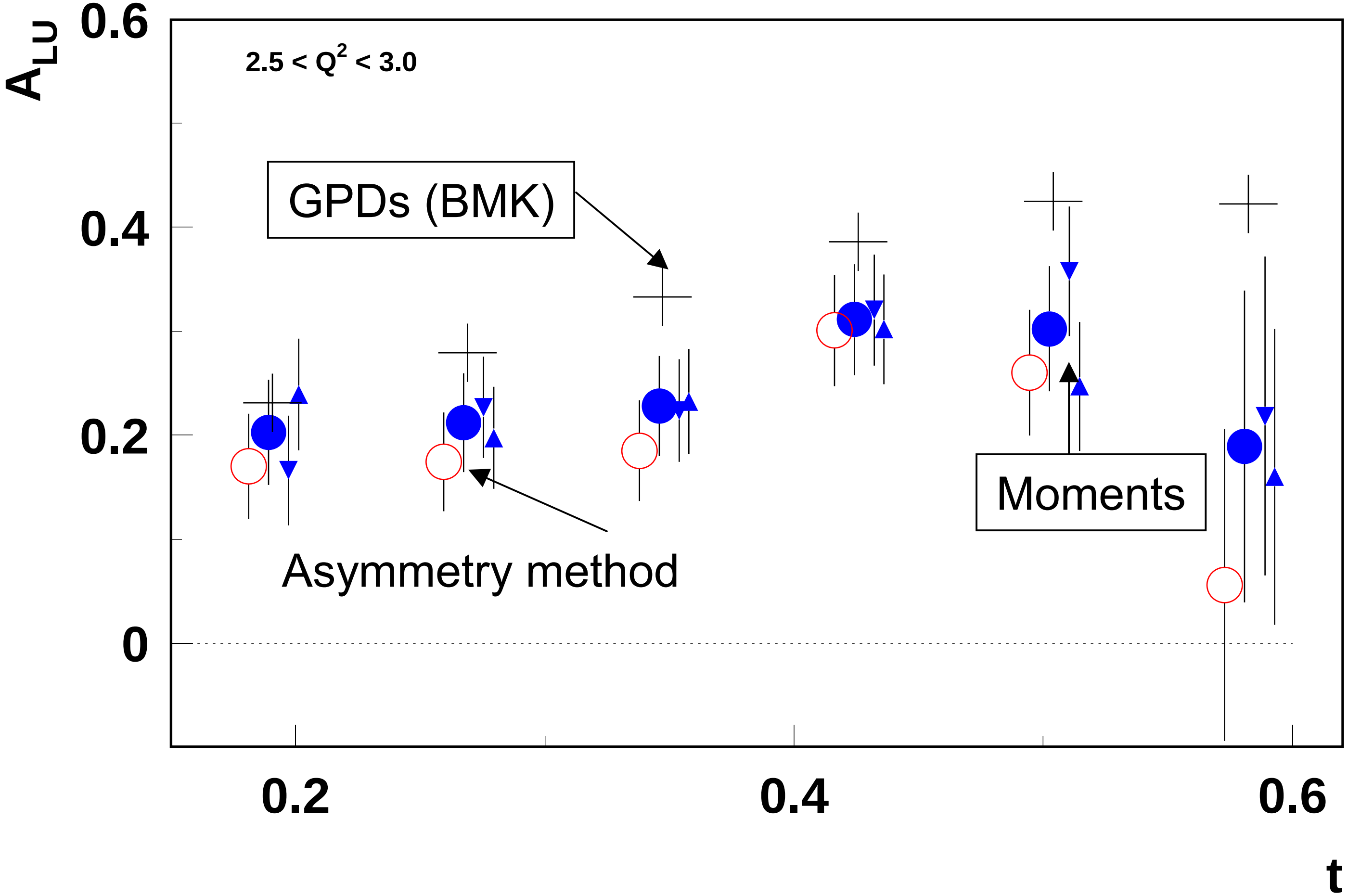
No sin2ϕ in generator !



DVCS A_{LU} extracted from MC (ep->e'p'[γ])



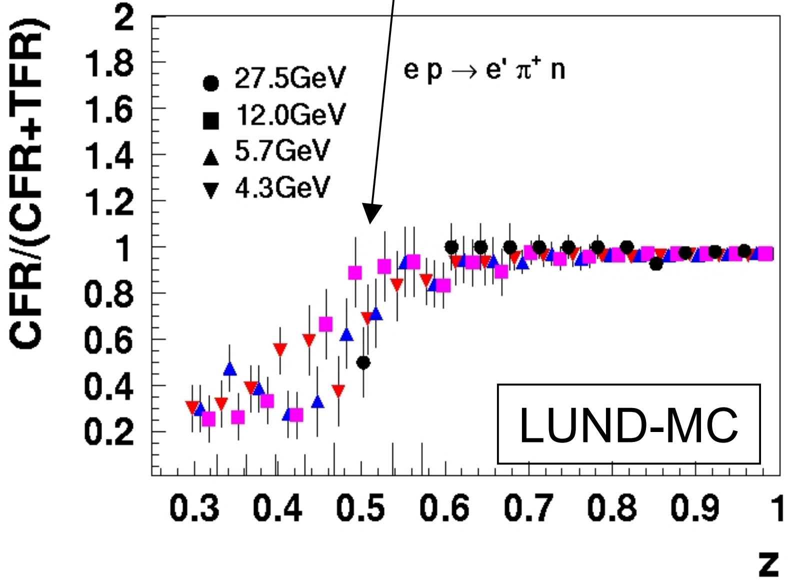
DVCS t-dependence (CLAS 5.7 GeV vs MC)

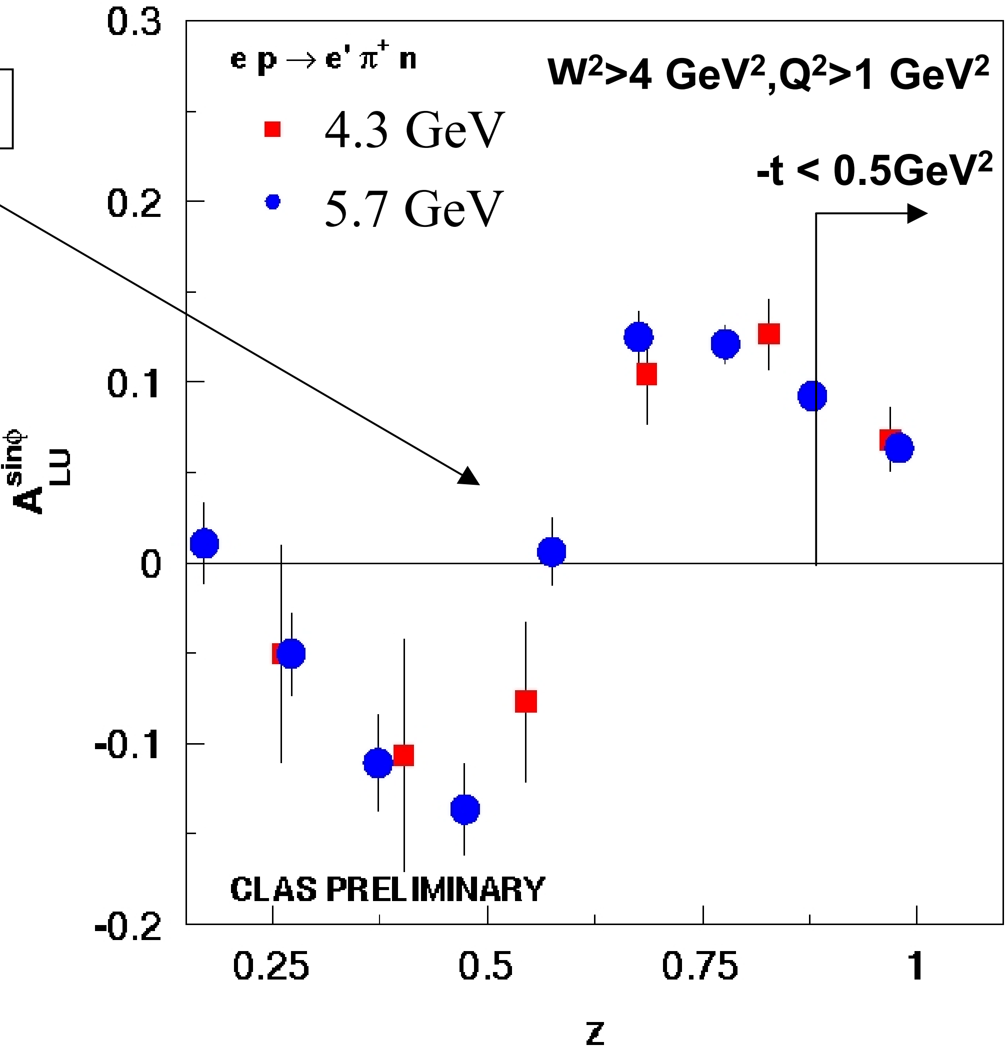


Exclusive pions: CLAS 4.3 vs. 5.7GeV

Sign flip at z ~ 0.5

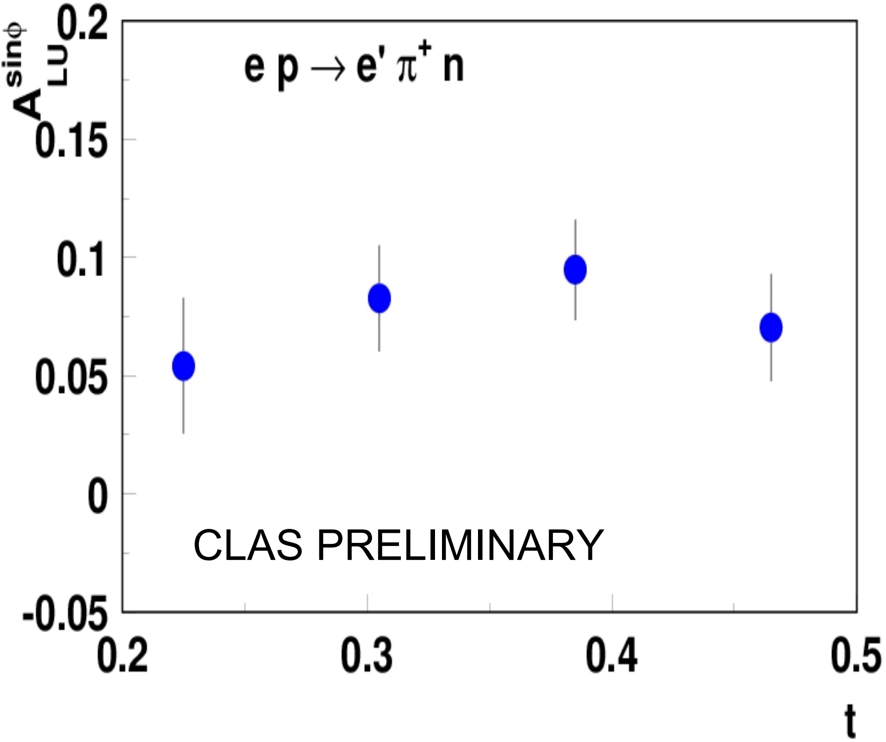
At z>0.5 struck quark in pion

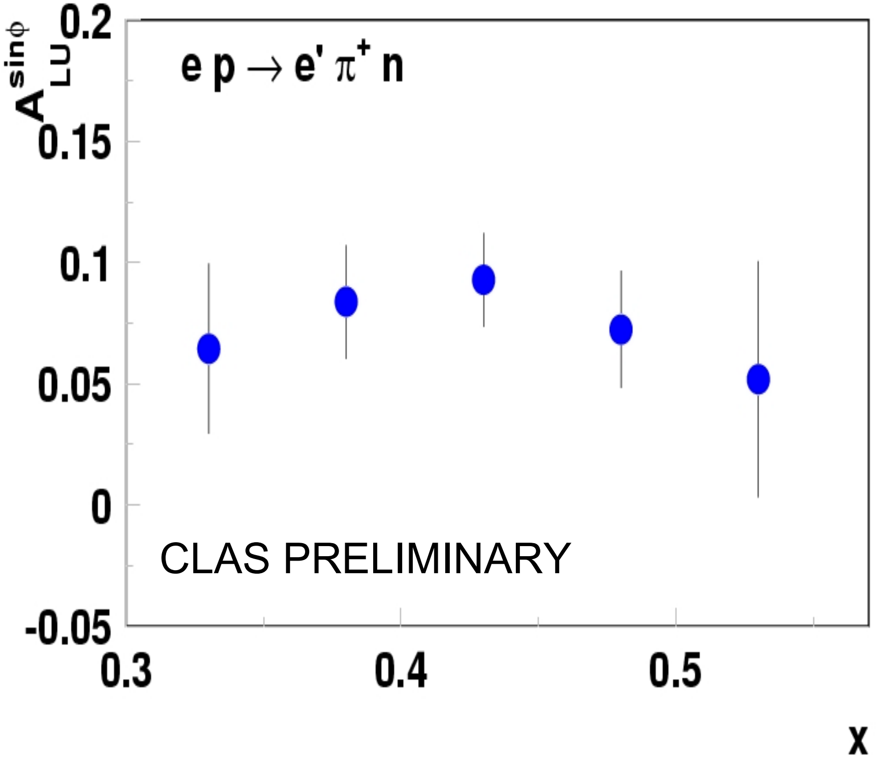




Beam SSA in HMP: x,t-dependence

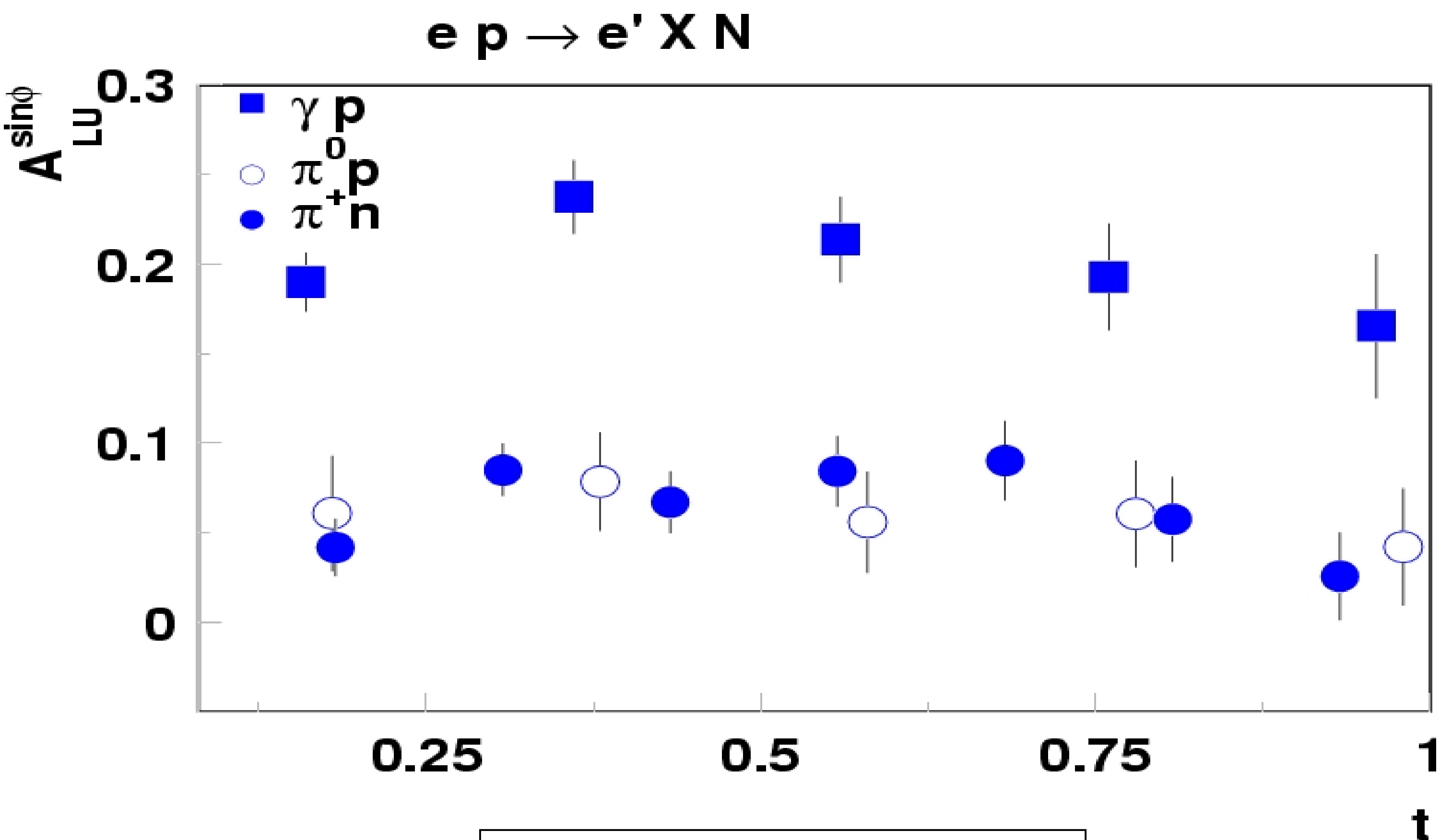
$t=(P_N-P_{N'})^2 <0.5$, $W^2>5$, $Q^2>2.5GeV^2$ ($<Q^2>=3.0GeV^2>$)





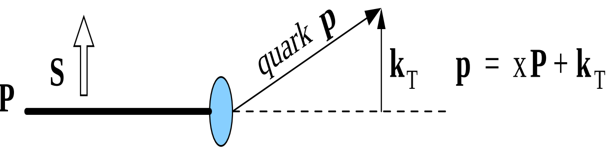
In SSA, certain cancelation expected for higher order and higher twist corrections.

SSA t-dependence (CLAS 5.7GeV)



SSA for π- and ρ underway

Contributions to σ in Polarized SIDIS



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

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

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

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

$$\sigma_{LT}^{\cos\phi} \propto \lambda_e S_T y(2-y)\cos(\phi-\phi_S)\sum_{a,\bar{a}} e_a^2 x g_{1T}(x) D_1^a(z)$$

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

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

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

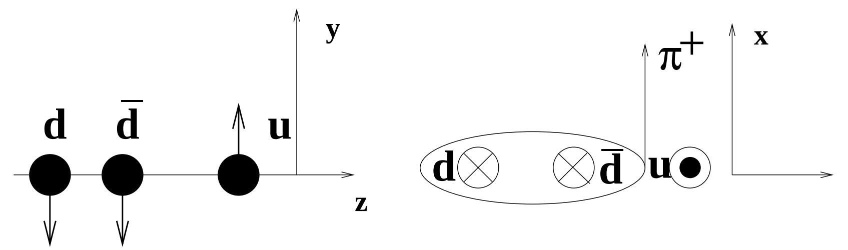
$$\sigma_{LU}^{\sin\phi} \propto \lambda_e \sin\phi\, y\sqrt{1-y}\frac{M}{Q}\sum_{a,\bar{a}} e_a^2 x^2 e^a(x) H_1^{\perp a}(z)$$

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

Semi-Classical Models

Collins effect:

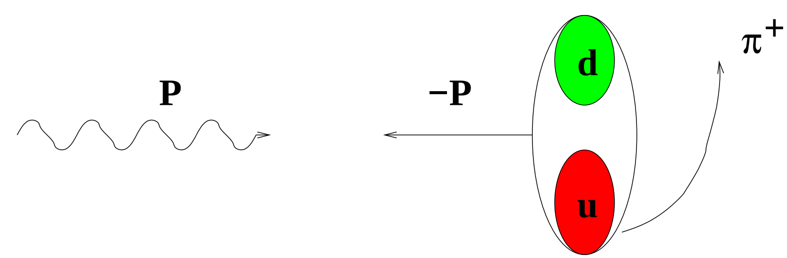
asymmetric fragmentation



Orbital momentum generated in string breaking and $q\bar{q}$ pair creation produces left-right asymmetry from transversely polarized quark fragmentation (Artru-hep-ph/9310323).

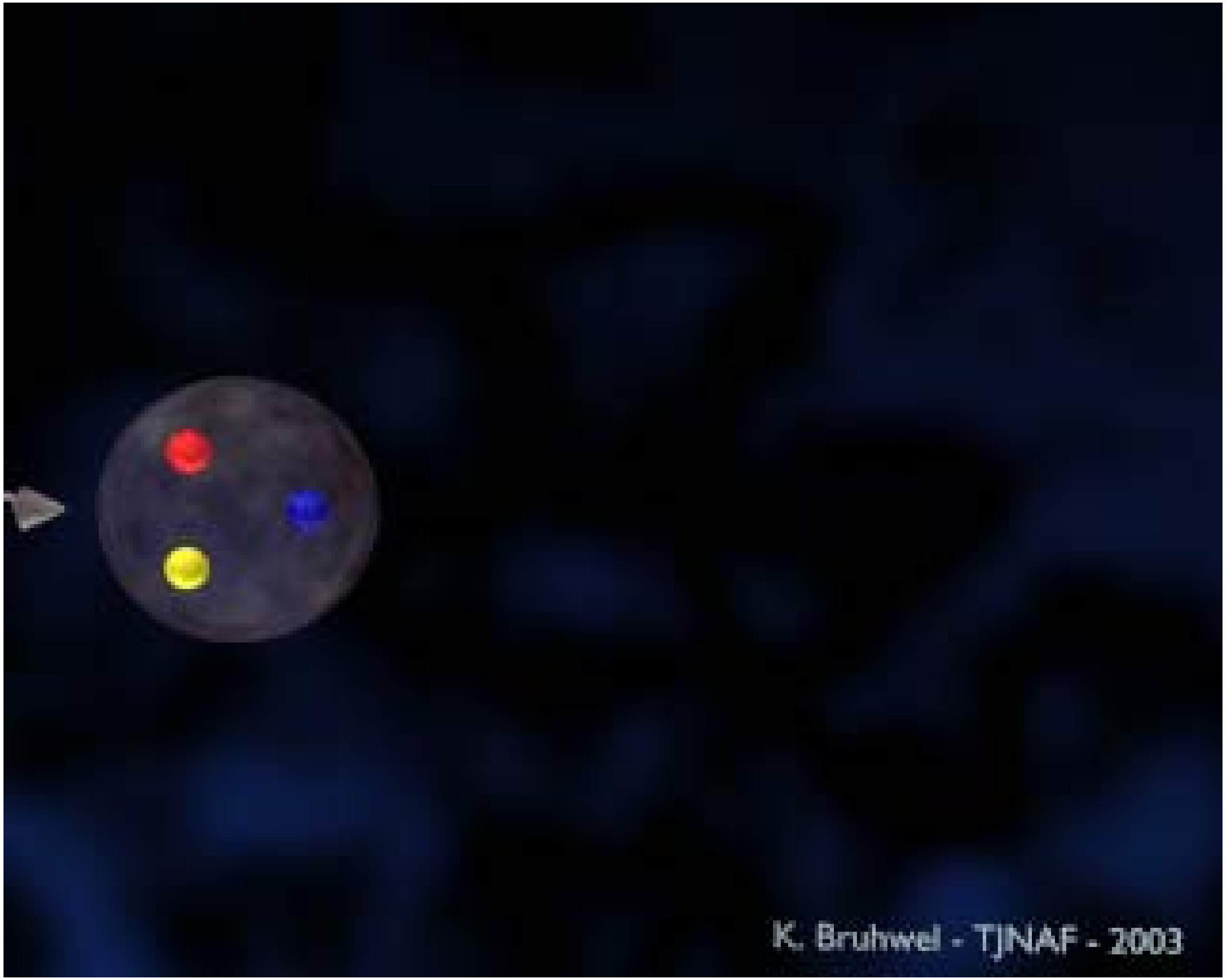
Sivers effect:

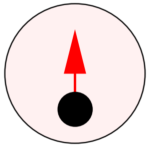
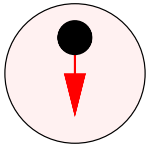
asymmetric distribution



In the transversely polarized proton **u** quarks are shifted down and **d** quark up giving rise to SSA (Burkardt-hep-ph/02091179).
The shift (~ 0.4 fm) is defined by spin-flip GPD **E** and anomalous magnetic moment of proton.

Collins Effect:



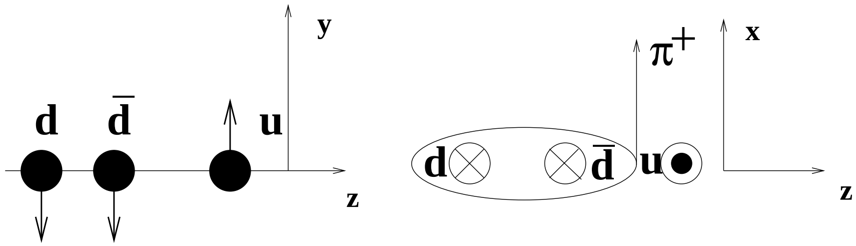
$H_1^{\perp}$ =  - 

Left-right asymmetry in the fragmentation of transversely polarized quarks

Semi-Classical Models

Collins effect:

asymmetric fragmentation



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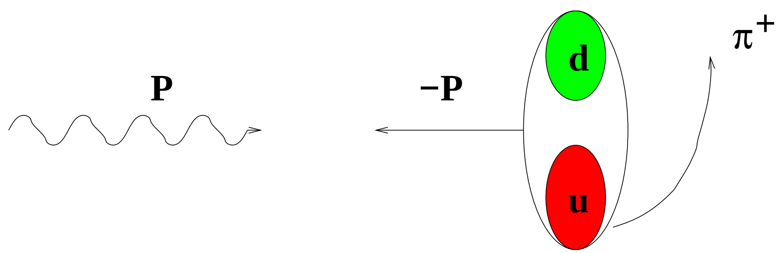

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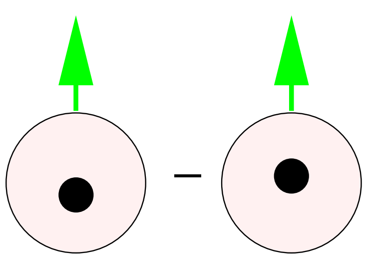
Sivers Effect:

$f_{1T}^{\perp} =$

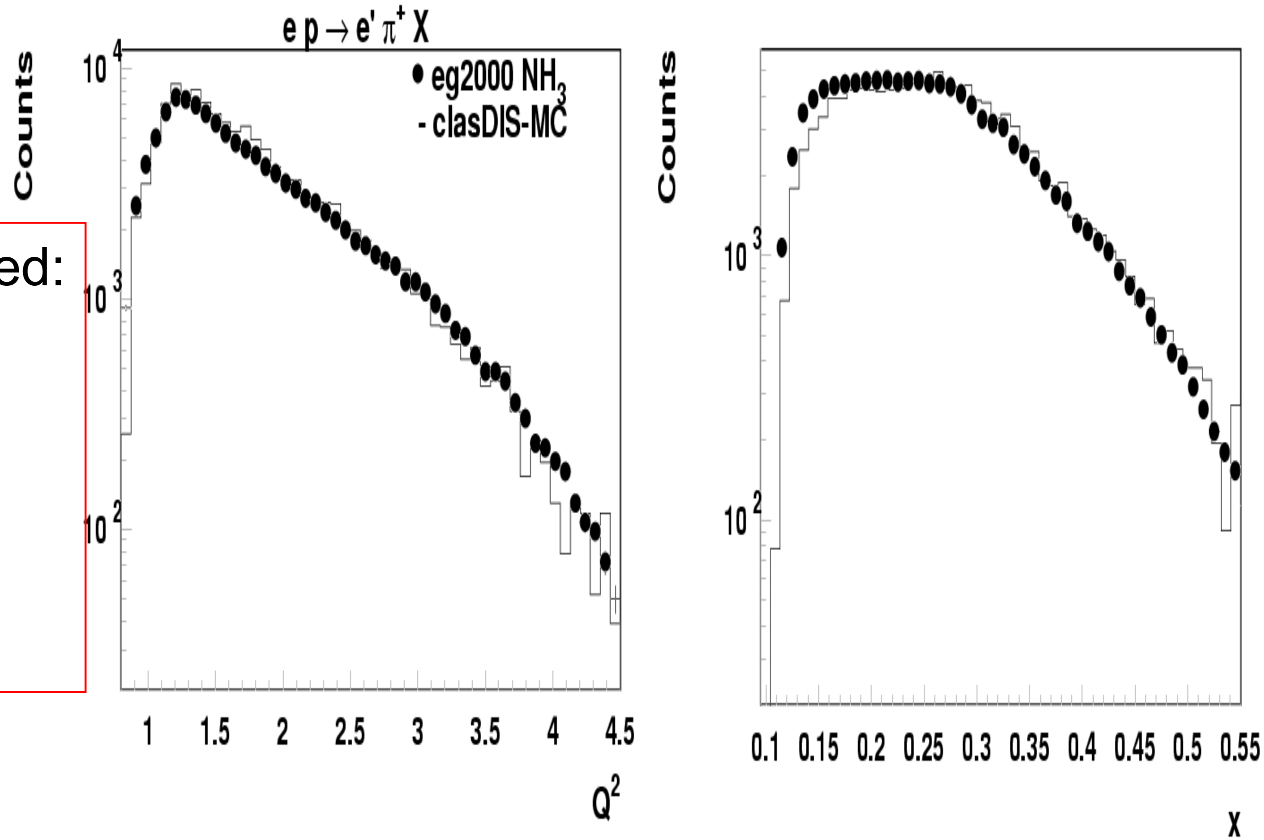


Left-right asymmetry in the distribution function

LUND-MC vs Polarized CLAS data

DIS kinematics defined:

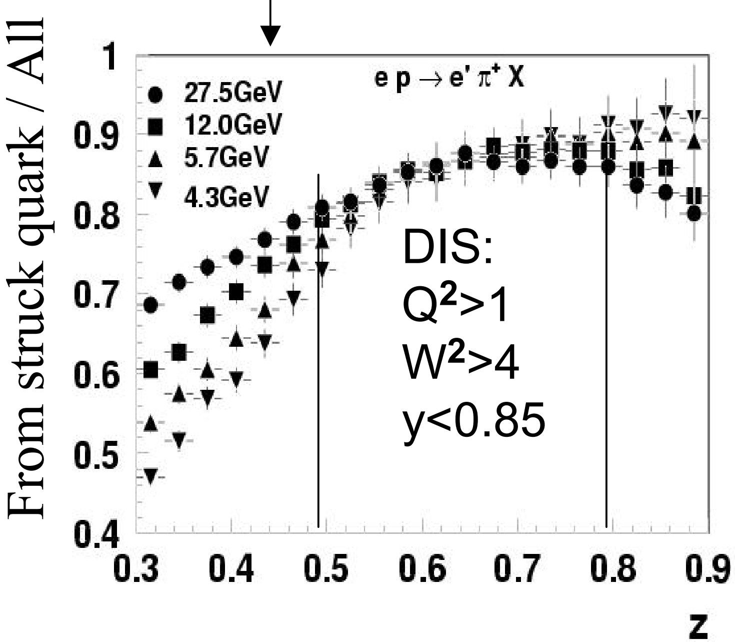
$Q^2>1$ GeV^2
$W^2>4$
$y<0.85$
$0.5<z<0.8$
M_X^2 **>1.1**

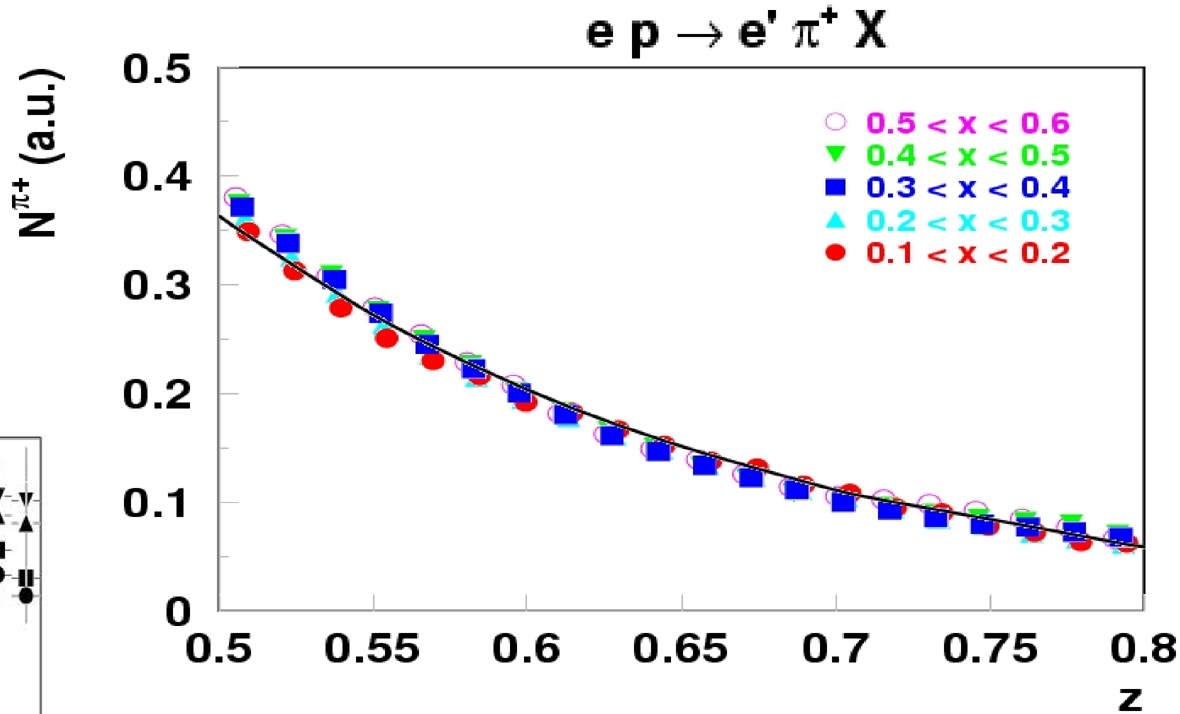


x and $\mathbf{Q^2}$ distributions from LUND-MC vs 5.7 CLAS NH_3 data.

Factorization studies in CFR at CLAS

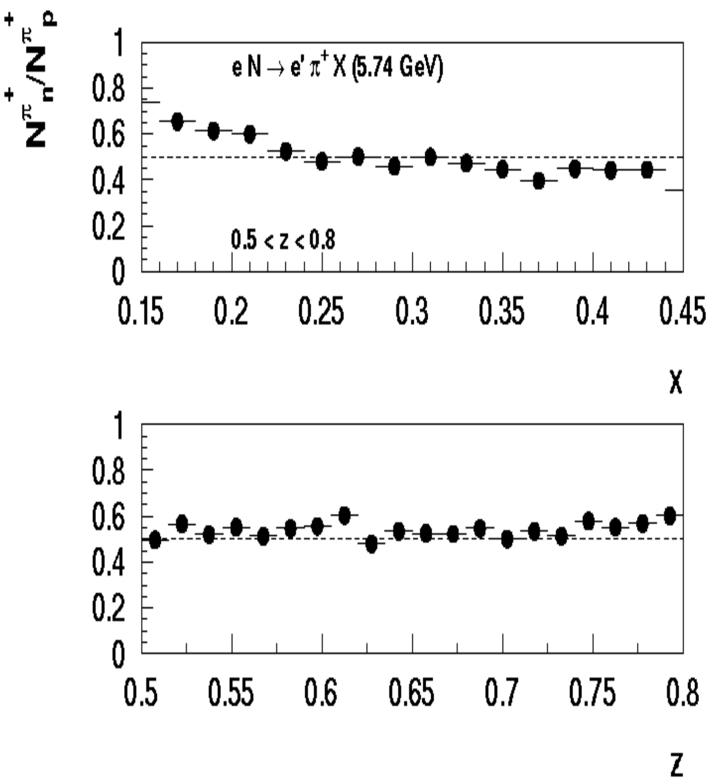
The fraction of π from struck quark in a range 0.5<z<0.8 is not changing significantly with beam energy.

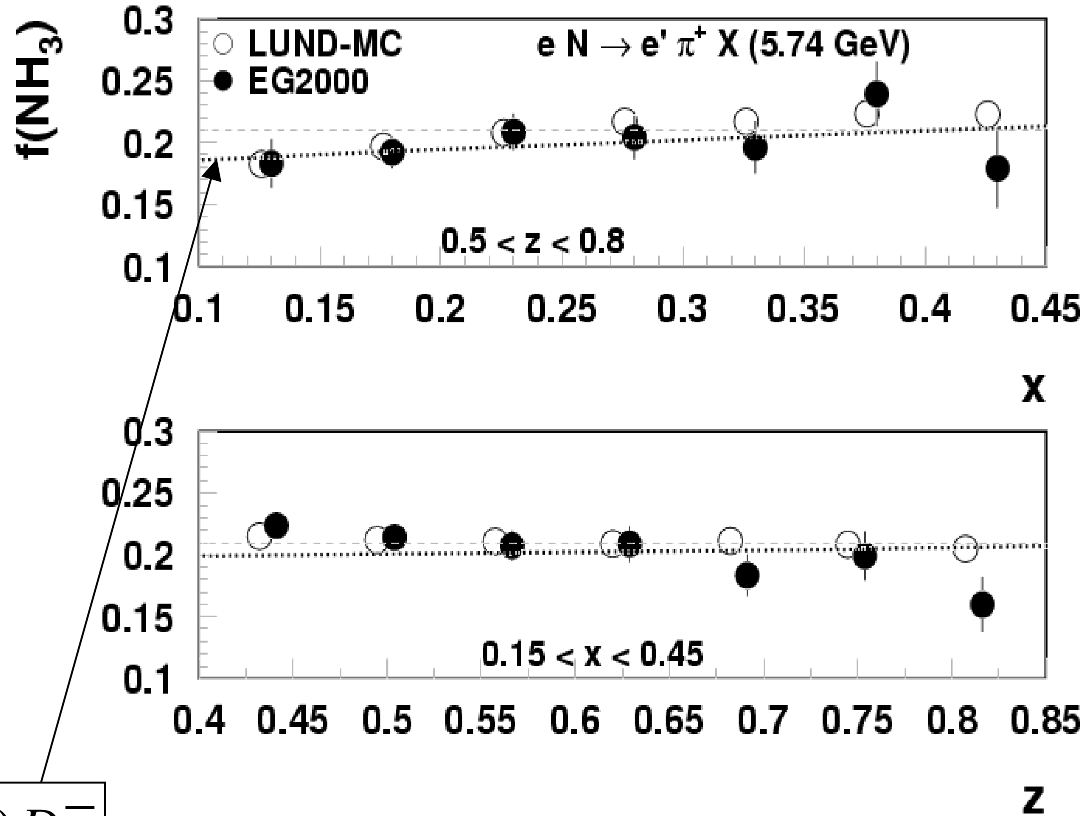




No significant variation observed in z distributions of π+ for different **x** ranges

LUND-MC: Dilution in NH_3





$$N_p^{\pi+} \propto (4u + \bar{d})D^+ + (4\bar{u} + d)D^-$$
$$N_n^{\pi+} \propto (4d + \bar{u})D^+ + (4\bar{d} + u)D^-$$

NH3 dilution factor (f=0.21) from data is consistent with LUND and simple quark counting (dotted line).

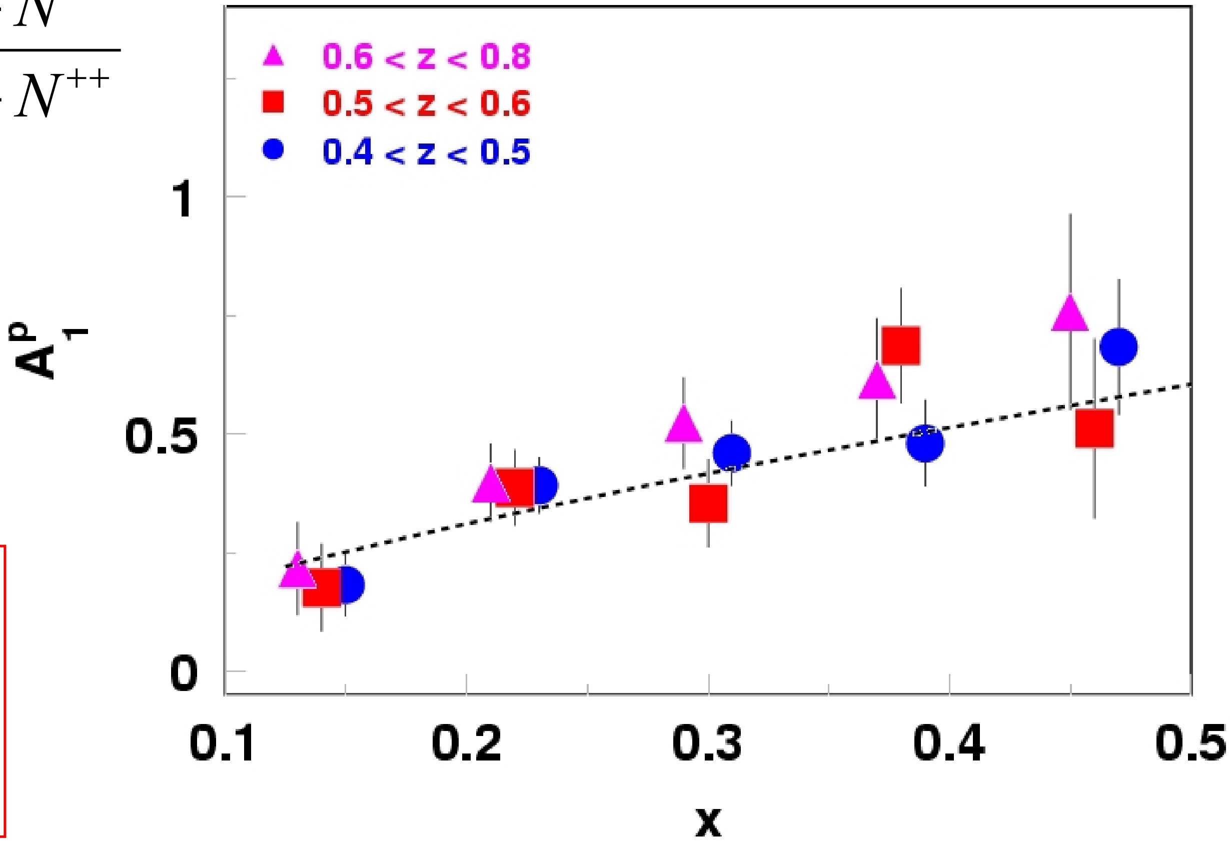
Polarized target: x,z factorization studies at 5.7GeV

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

A_1^p consistent with HERMES data, world inclusive fit **$x^{0.727}$**

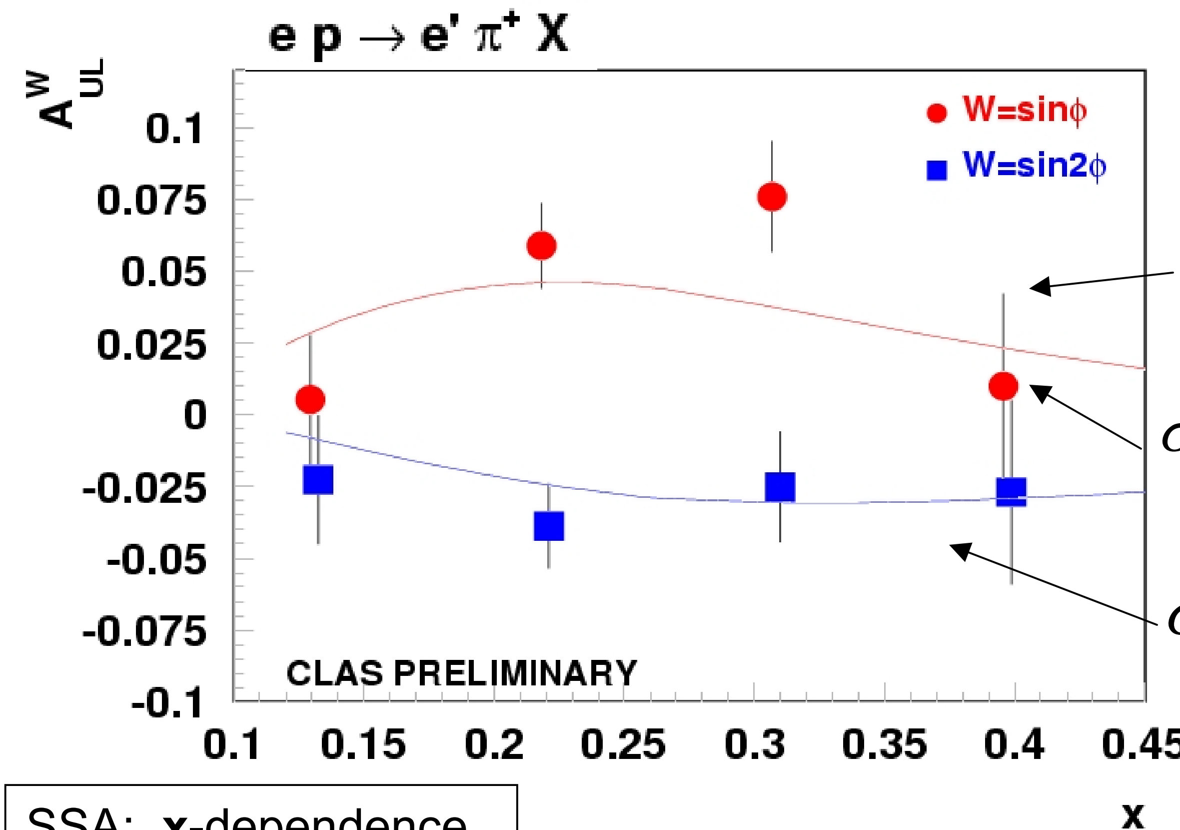
No significant variation observed in **x** dependence of **A_1^p** for different **z** ranges.

ep -> e' π^+ X (E_e =5.7 GeV, M_X > 1.1)



z-independent **A_1^p** consistent with factorization!

Longitudinally Pol Target: SSA for π^+



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

$$\sigma_{UT}^{\sin\phi} \propto S_T \sum_{q,\bar{q}} e_q^2 h_1(x) H_1^{\perp q}(z)$$

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

$$\sigma_{UL}^{\sin 2\phi} \propto S_L \sum_{q,\bar{q}} e_q^2 h_{1L}^{\perp(1)q}(x) H_1^{\perp q}$$

$H_1^{\perp}$ - Collins FF

SSA: **x**-dependence CLAS (5.7 GeV) is consistent with predictions for **Collins effect** from Efremov et al. hep-ph/0208124

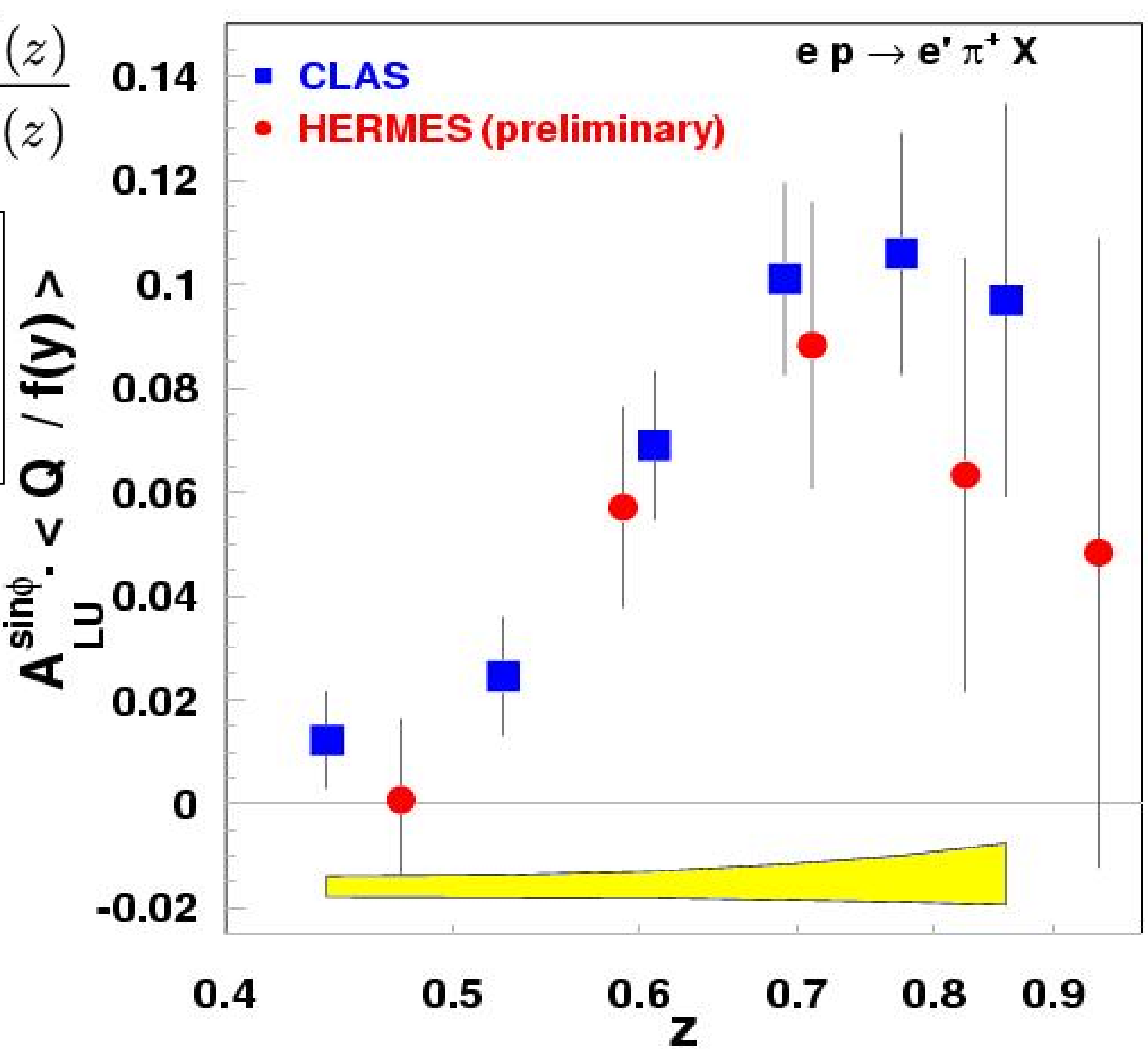
- First indication of a non-zero **sin2ϕ** moment (Kotzinian-Mulders asymmetry)
- $A_{UL}^{\sin 2\phi}$ is a clean source of Collins SSA

Beam SSA: sinϕ Moment

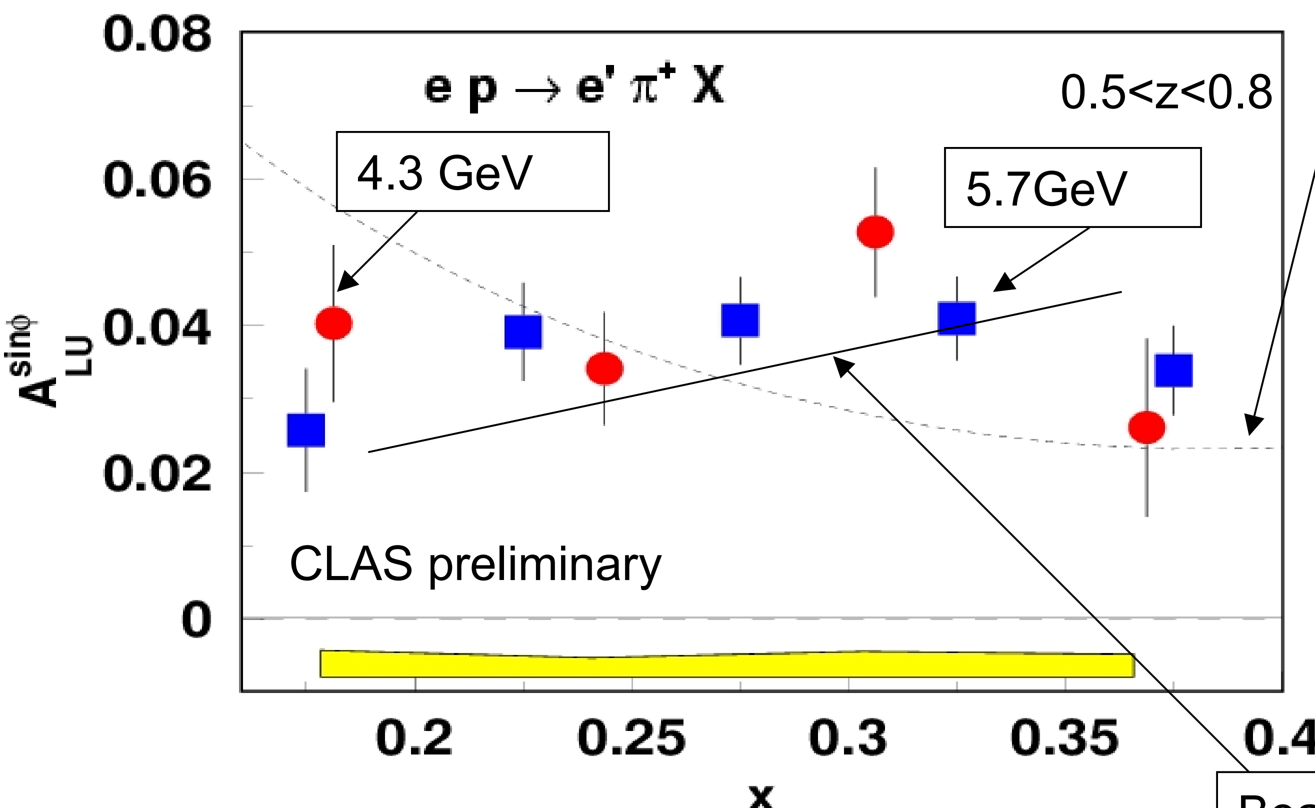
$$A_{LU} \propto \lambda_e \boxed{f(y)\frac{M}{Q}} \frac{H_1^{u,\pi^+}(z)}{D_1^{u,\pi^+}(z)}$$

Kinematic factor to be excluded in comparison (like D(y) depolarization function for g_1/f_1 case in A_1)

Beam SSA measurements for CLAS at 4.3GeV and HERMES (SPIN-2002) are consistent.



A_{LU} x-dependence: CLAS 4.3 vs. 5.7 GeV



Photon Sivers Effect
Afanasev & Carlson
(using BHS mechanizm)

Sivers contribution in case of beam SSA has the same source (FSI) as in case of target SSA, providing access to essential parameters with less ambiguities

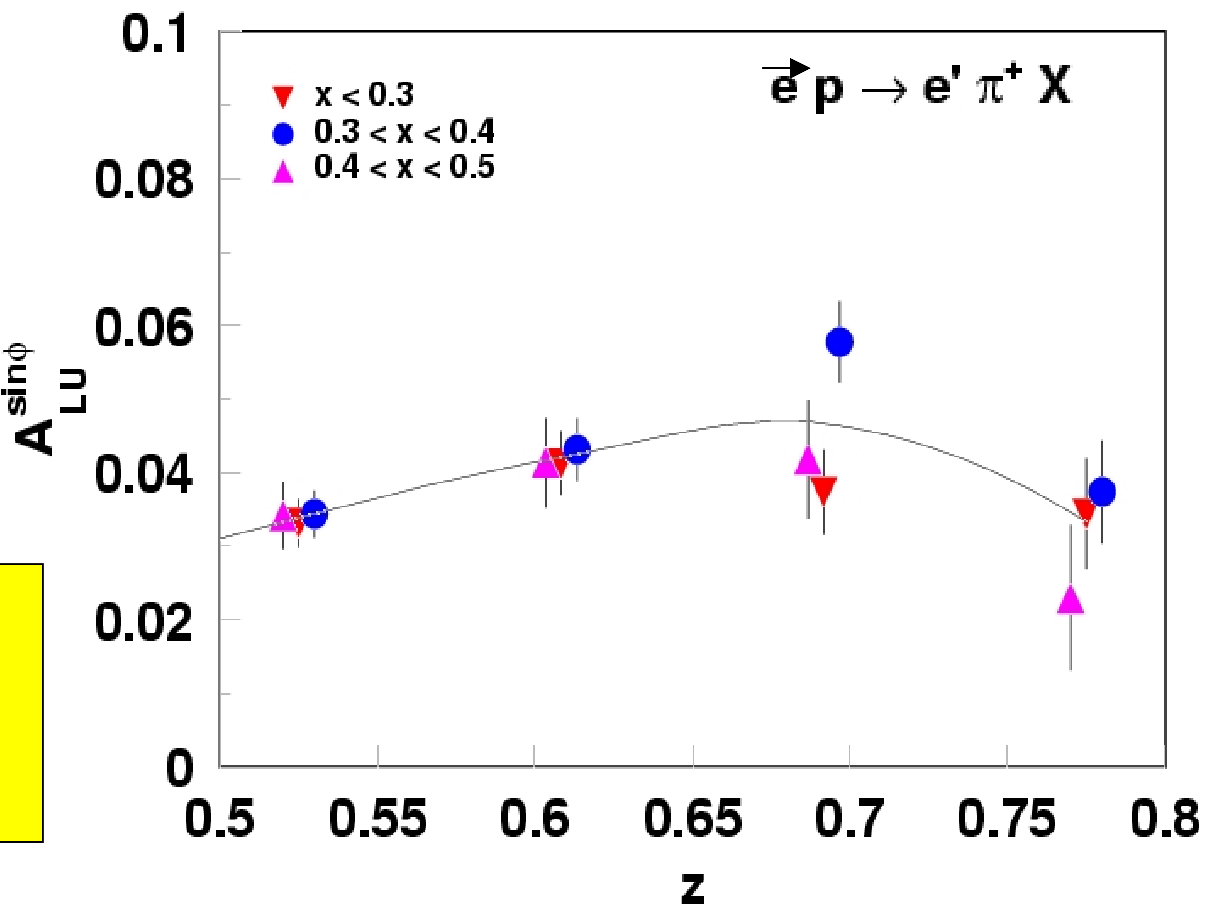
4.3 GeV and 5.7 GeV data consistent

Beam SSA analyzed also in terms of Collins effect by Efremov et al.

Factorization studies in CFR at CLAS

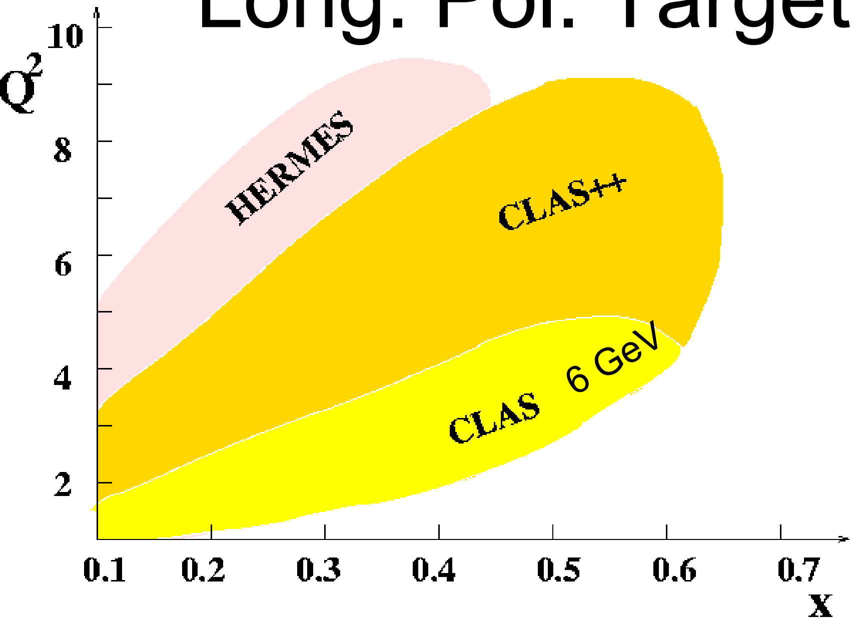
In terms of Collins fragmentation

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



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

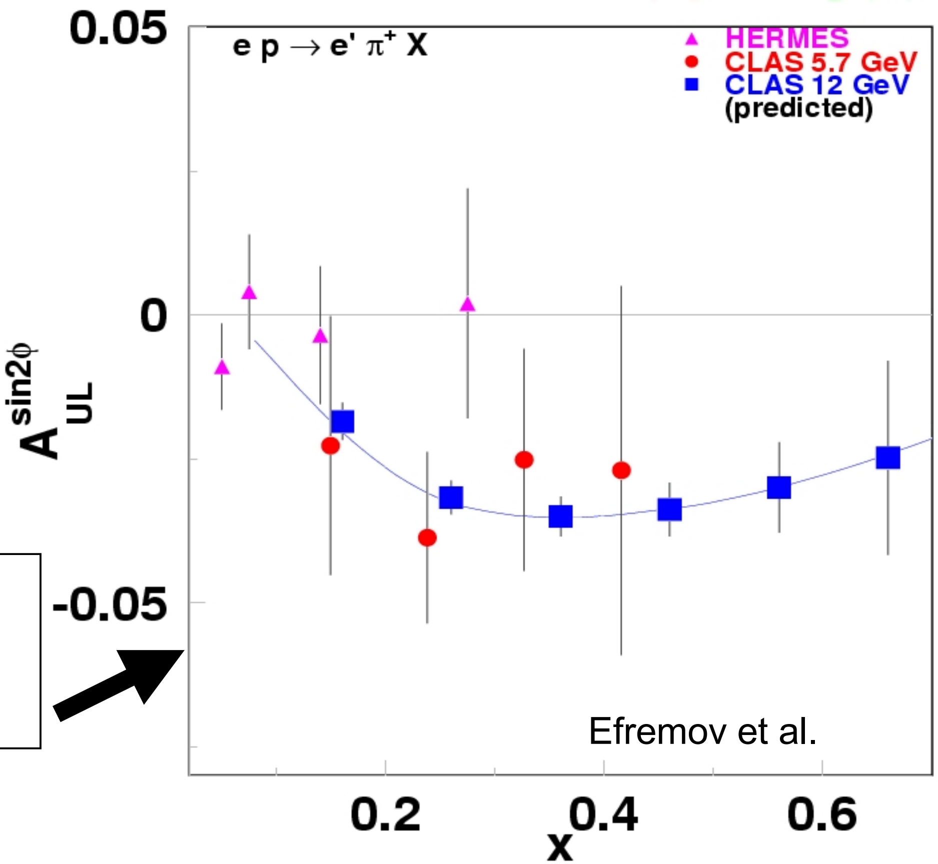
Long. Pol. Target SSA for π^+ at 12GeV



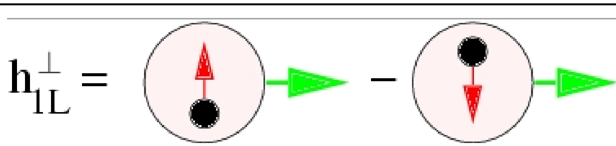
large x + high luminosity

$$A_{UL}^{\sin 2\phi} \propto \frac{h_{1L}^{\perp u}(x)}{u(x)} \frac{H_1^{\perp u}(z)}{D_1^u(z)}$$

The sin 2ϕ asymmetry for 2000 h of projected CLAS++ data.



Direct measurement of k_T dependent twist-2 distribution and fragmentation functions at CLAS++



Summary

- **Current CLAS data are consistent with a partonic picture, and can be described by a variety of theoretical models**
  - **DVCS SSA consistent with GPD based predictions**
  - **No x/z-dependence observed in single and double spin asymmetry measurements in SIDIS (consistent with factorization).**
  - **Spin and azimuthal asymmetries in agreement with HERMES and SMC.**
  - **Single-Spin asymmetries extracted for SIDIS π+ are in agreement with predictions from χQSM model .**
  - **Kinematic distributions in agreement with LUND-MC**

- **Global analysis of SSA for polarized beam and target needed to separate different contributions and extract underlying distribution functions (GPDs ,TMDs,...).**