The Transverse Spin Structure of the Nucleon

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JEFFERSON LAB

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Lessons Scheme

LECTURES 1 & 2

- Introduction
- Deep Inelastic Scattering and 1D parton distribution functions
- From 1D to 3D nucleon structure: Transverse Momentum Dependent (TMD) parton distribution functions
- TMD Measurements @ Jlab in Hall B

LECTURES 3 & 4

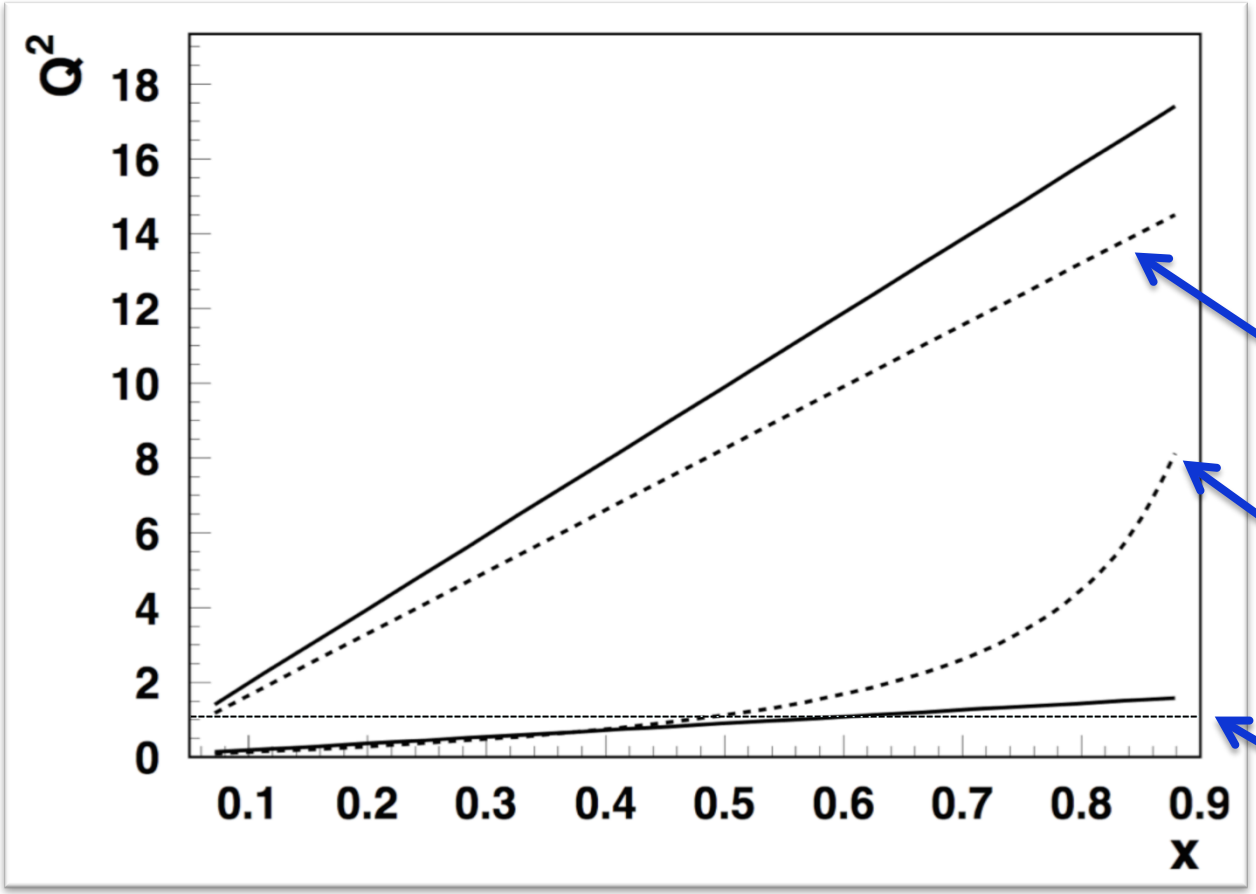
- Data analysis
- Monte Carlo simulations
- Asymmetries extraction
- TMDs extraction

LECTURE 5

- Where are we? What's next

Kinematical Coverage

$$x_B = \frac{Q^2}{2M\nu} \quad \nu = E - E' \quad y = \frac{\nu}{E} \quad W^2 = M^2 + 2M\nu - Q^2$$



$$0.1 < x_B < 0.9$$
$$1 < \nu < 11$$

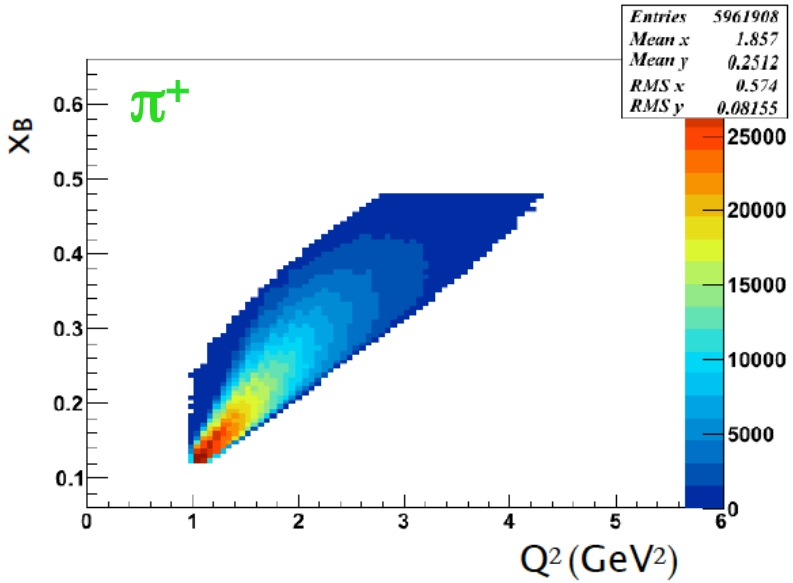
(E=12 GeV)

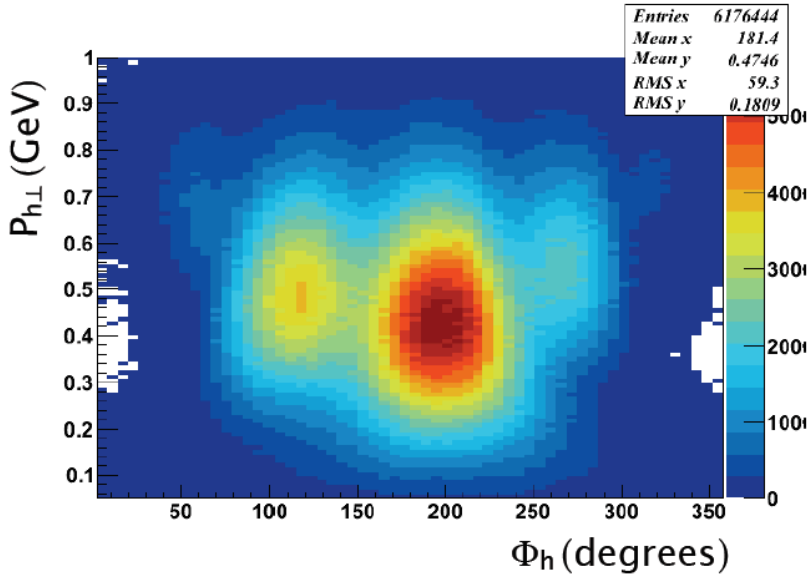
$y < 0.85$

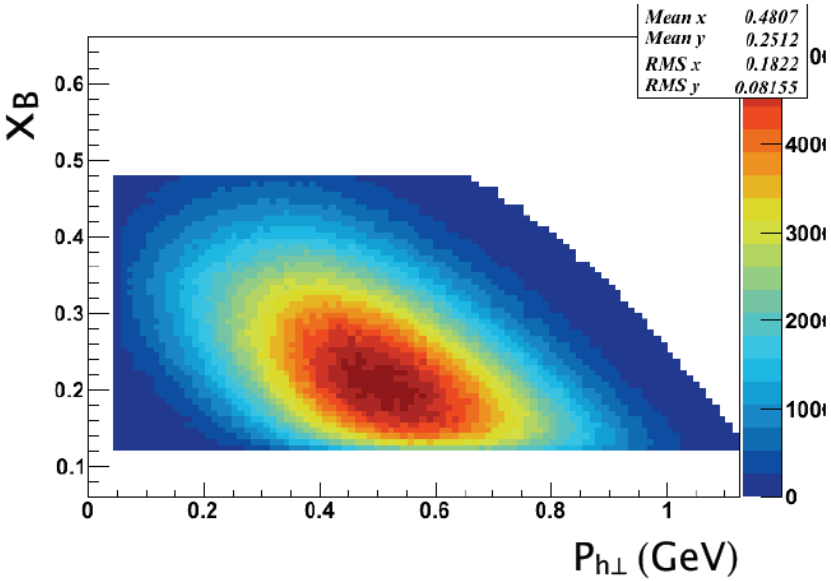
$W > 2$

$Q^2 > 1$

Kinematical Coverage

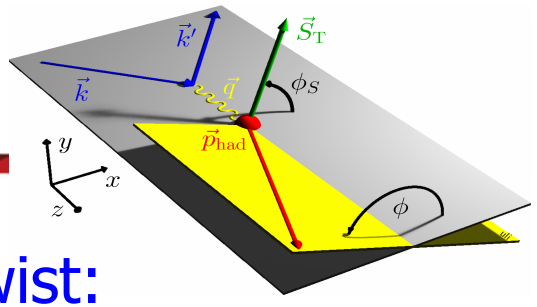






Data are binned in: Q^2 , ϕ_h , z , $P_{h\perp}$, x_B

Polarized SIDIS Cross Section



For a longitudinal polarized target at leading twist:

$$\frac{d\sigma}{dx\,dy\,dz\,d\phi_S\,d\phi_h\,dP_{h\perp}^2} = \frac{\alpha^2}{xQ^2}\frac{y}{2\,(1-\varepsilon)}$$

$$\times\Big\{F_{UU,T} + \varepsilon\cos(2\phi_h)\,F_{UU}^{\cos 2\phi_h} + S_L\,\varepsilon\sin(2\phi_h)\,F_{UL}^{\sin 2\phi_h}$$

$$+ S_L\lambda_e\sqrt{1-\varepsilon^2}\,F_{LL} + |\boldsymbol{S}_T|\Big[\sin(\phi_h-\phi_S)\,F_{UT,T}^{\sin(\phi_h-\phi_S)}$$

$$+\varepsilon\,\sin(\phi_h+\phi_S)\,F_{UT}^{\sin(\phi_h+\phi_S)} + \varepsilon\,\sin(3\phi_h-\phi_S)\,F_{UT}^{\sin(3\phi_h-\phi_S)}\Big]$$

$$+|\boldsymbol{S}_T|\,\lambda_e\Big[\sqrt{1-\varepsilon^2}\,\cos(\phi_h-\phi_S)\,F_{LT}^{\cos(\phi_h-\phi_S)}\Big]\Big\},$$

Asymmetries

$$\sigma = \sigma_{UU} + \lambda_l \sigma_{LU} + S_L \sigma_{UL} + \lambda_l S_L \sigma_{LL} + S_T \sigma_{UT} + \lambda_l S_T \sigma_{LT}$$

For a longitudinally polarized target $S_T = 0$

$$\sigma = \sigma_{UU} + \lambda_l \sigma_{LU} + S_L \sigma_{UL} + \lambda_l S_L \sigma_{LL} \qquad \lambda = \pm 1, S_L = \pm 1$$

The Target Spin asymmetry is defined as:

$$\mathbf{A_{UL}} = \frac{\mathbf{1}}{\mathbf{f}} \frac{(\mathbf{N}^{++} + \mathbf{N}^{-+}) - (\mathbf{N}^{+-} + \mathbf{N}^{--})}{|\mathbf{P_t^-}|(\mathbf{N}^{++} + \mathbf{N}^{-+}) + |\mathbf{P_t^+}|(\mathbf{N}^{+-} + \mathbf{N}^{--})}$$

Dilution factor

λS_L

$$N^{++} = \sigma^{++} = \sigma_{UU} + \sigma_{LU} + \sigma_{UL} + \sigma_{LL}$$

Target Polarization

$$\mathbf{A_{UL}} \propto \frac{\sigma_{\mathbf{UL}}}{\sigma_{\mathbf{UU}}}$$

Asymmetries

$$\frac{d\sigma}{dx\,dy\,dz\,d\phi_S\,d\phi_h\,dP_{h\perp}^2} = \frac{\alpha^2}{xQ^2}\frac{y}{2\,(1-\varepsilon)}$$

$$\times\left\{F_{UU,T} + \varepsilon\cos(2\phi_h)\,F_{UU}^{\cos 2\phi_h} + S_L\,\varepsilon\sin(2\phi_h)\,F_{UL}^{\sin 2\phi_h}\right.$$

$$\left. + S_L\lambda_e\sqrt{1-\varepsilon^2}\,F_{LL} + \ldots\ldots\right.$$

$\mathbf{h_{1L}^{\perp}H_1^{\perp}}$

$g_1 D_1$

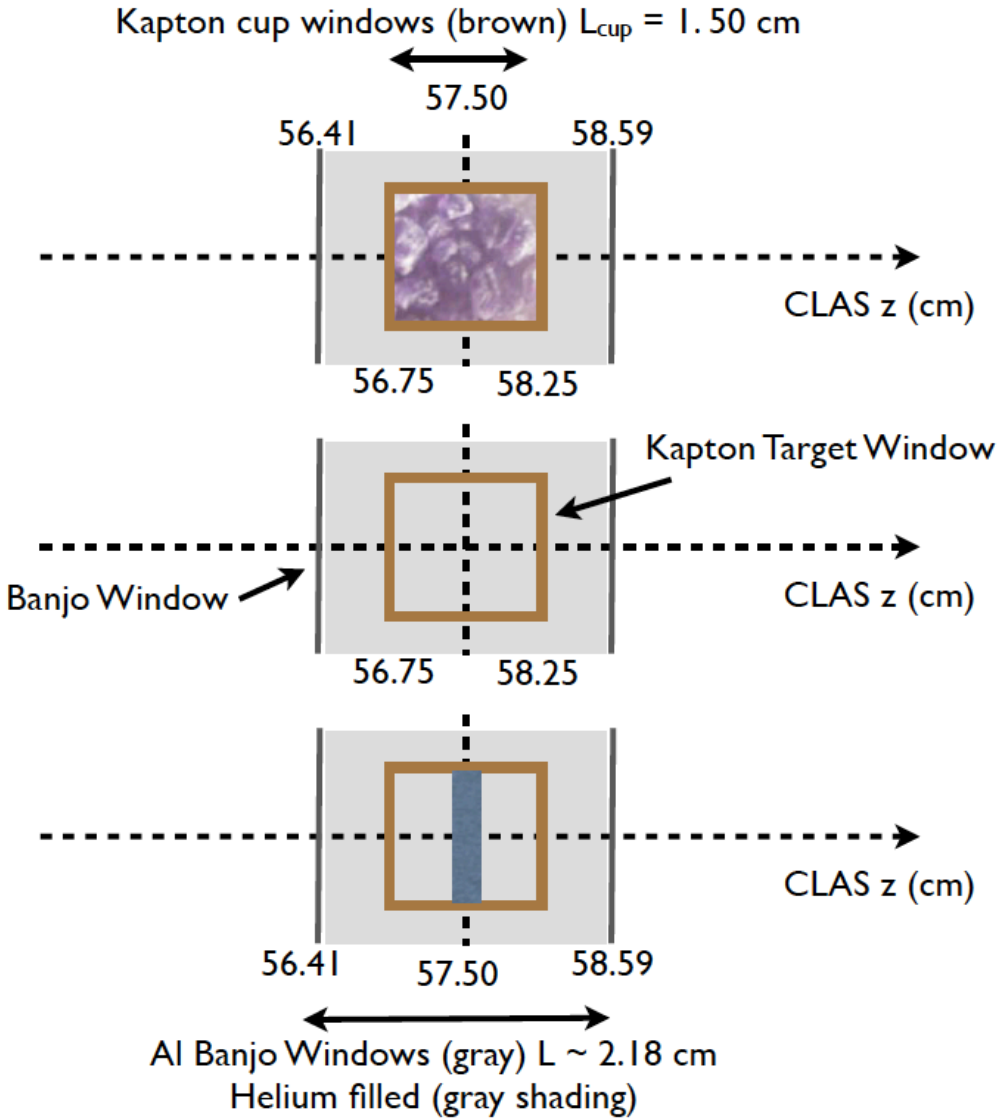
$$\mathbf{A_{UL}} = \frac{\sigma_{\mathbf{UL}}}{\sigma_{\mathbf{UU}}} = \frac{\mathbf{F_{UL}^{sin2\phi}}}{\mathbf{F_{UU,T}}}\frac{\mathbf{sin2\phi_h}}{(\mathbf{1}+\epsilon\mathbf{cos2\phi}\frac{\mathbf{F_{UU}^{cos2\phi}}}{\mathbf{F_{UU,T}}})} \propto \mathbf{A_{UL}^{sin2\phi}sin2\phi_h}$$

The moment, $\mathbf{A_{UL}^{sin2\phi}}$ contains the twist 2 TMD $\mathbf{h_{1L}^{\perp}}$ convoluted with the Collins FF $\mathbf{H_1^{\perp}}$

Polarized target

NH_3 solid state target

The target stick used during the experiment. The first two cups contained ammonia and the third had a carbon disk. The last one was left empty for background studies. The cross-hairs at the bottom were used to align the beam on the target.



Dilution factor

In the measurement of the asymmetry we have to account for the unpolarized contribution from the target.

The **dilution factor** is the ratio of counts from polarized target nucleons to unpolarized target nucleons.

$$f = \frac{n_{proton}}{n_{NH_3} + n_{He} + n_K + n_{Al}}$$

n = SIDIS event rate
n_i = proportional to the product of the areal density ρ and semi-inclusive DIS cross section

$$\mathbf{A_{UL}} = \frac{(\mathbf{N}^{++} - \mathbf{N}^{-+})}{(\mathbf{N}^{++} + \mathbf{N}^{-+})}$$

this from the polarized protons in NH3

this from NH_3+He+K+Al → the asymmetries are "diluted"

The value of *f* depends on the reaction kinematics (Q^2, x_B, z, P_{hT}, ϕ_h).

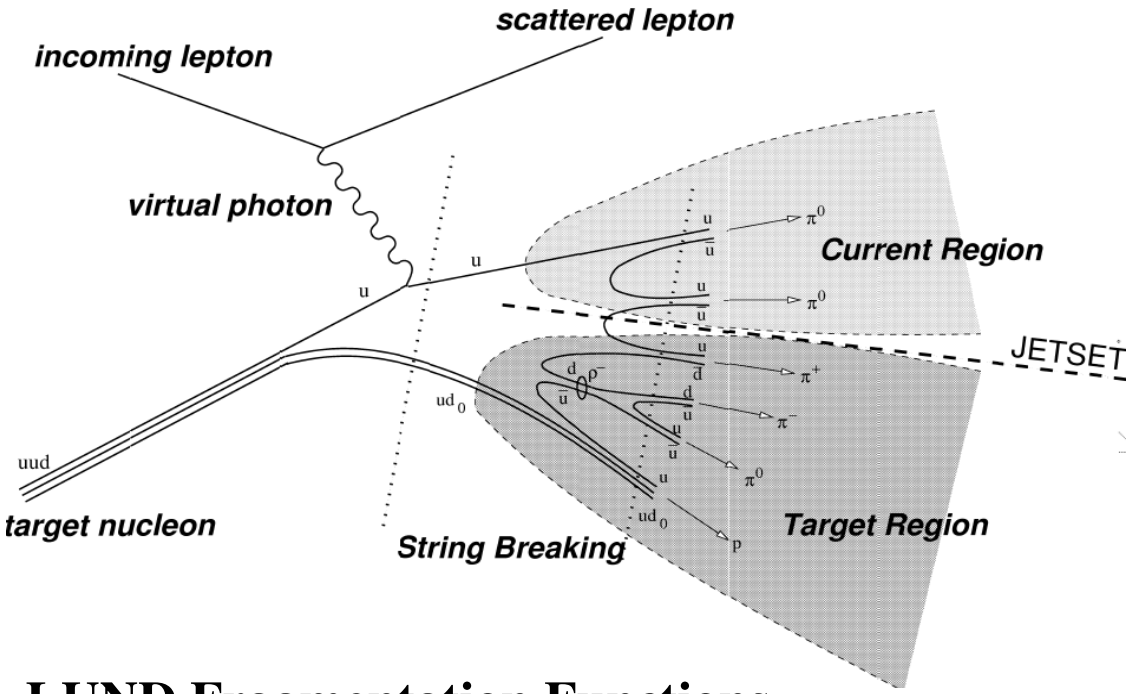
f ~ 0.2

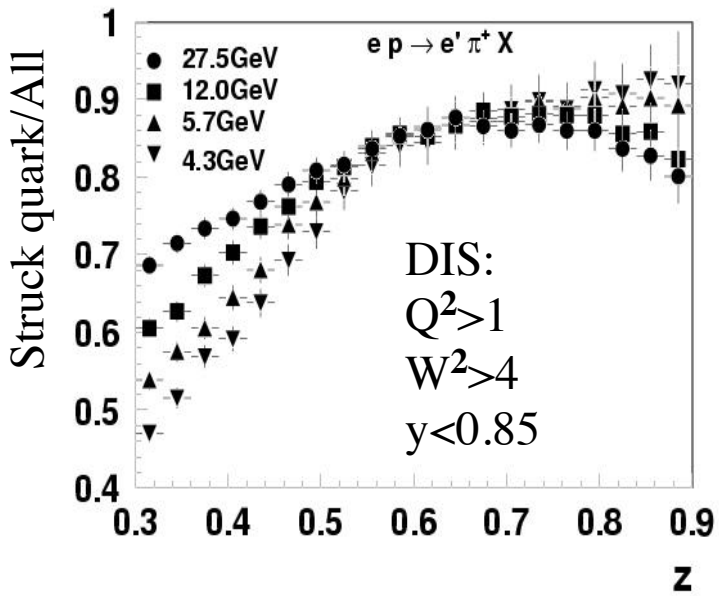
Monte Carlo Studies

- A LUND-MC based on single particle production is used at JLab energies for hard scattering process.
- The output of the generator is used as input for CLAS GEANT simulation package (GSIM).

- The main goal of MC studies is:
  - to identify the kinematical region where the contamination in the pion sample from target fragmentation is small
  - To calculate the detector acceptance
  - to provide tests for extraction of spin and azimuthal asymmetries
  - to estimate systematic uncertainties from extraction and fitting procedures

Monte Carlo Studies



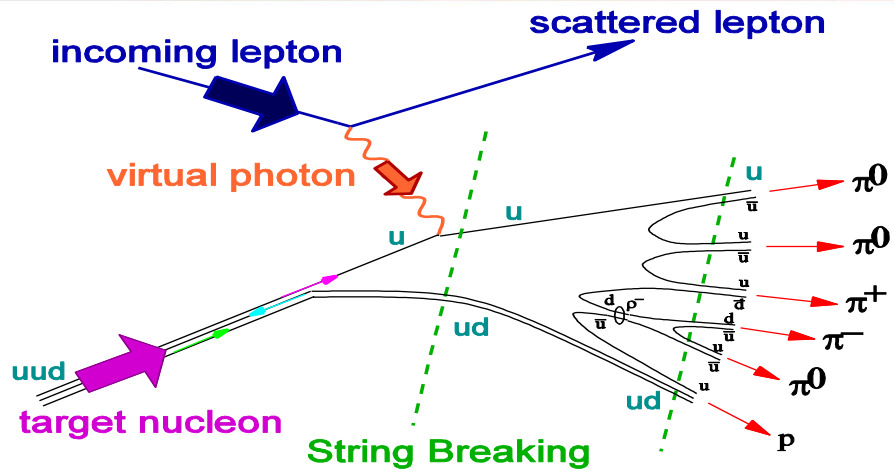


LUND Fragmentation Functions

- Before
- After Target remnant quark

The primary hadrons produced in string fragmentation come from the string as a whole, rather than from an individual parton

LUND Event



Particle number in the event
charge
status
Lund ID
Parent and first daughter line numbers

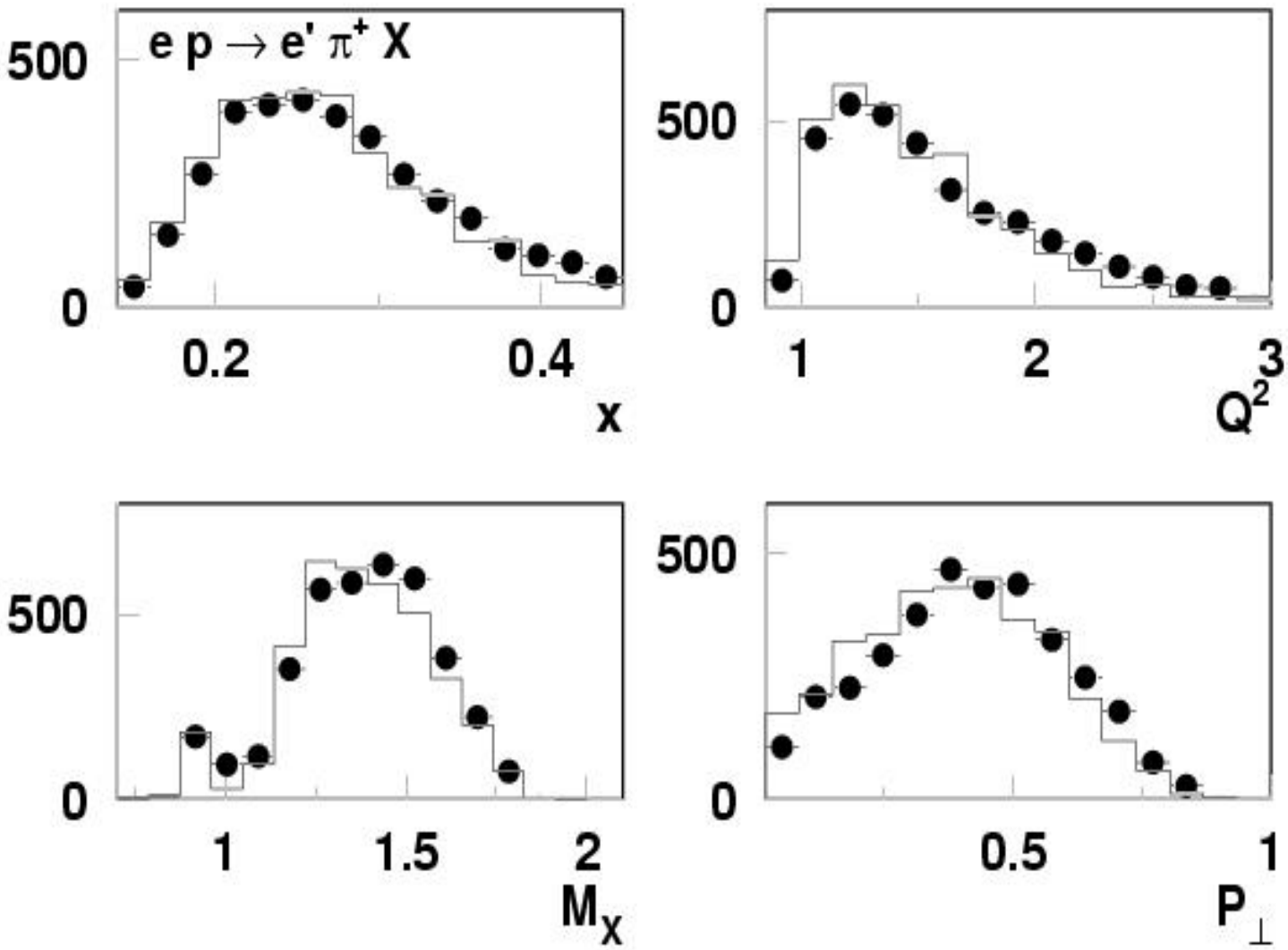
p_x p_y p_z Momentum in GeV, E m V_x V_y V_z, Vertex in cm

K^{*+}	10	1.	11	323	9	12	0.1932	0.1220	0.6115	1.0868	0.8689	0.0000	0.0000	0.0000
Λ	11	0.	11	3122	9	14	-0.5495	0.7719	2.4426	2.8476	1.1156	0.0000	0.0000	0.0000
K^+	12	1.	1	321	10	0	0.2099	0.2361	0.6789	0.8969	0.4936	0.0000	0.0000	0.0000
π^0	13	0.	11	111	10	16	-0.0166	-0.1141	-0.0674	0.1899	0.1350	0.0000	0.0000	0.0000
p	14	1.	1	2212	11	0	-0.4359	0.7296	2.2421	2.5748	0.9383	-0.3291	0.4622	1.4627
π^-	15	-1.	1	-211	11	0	-0.1136	0.0423	0.2005	0.2727	0.1396	-0.3291	0.4622	1.4627
γ	16	0.	1	22	13	0	0.0496	-0.0860	-0.0635	0.1179	0.0000	0.0000	0.0000	0.0000
	17	0.	1	22	13	0	-0.0662	-0.0281	-0.0039	0.0721	0.0000	0.0000	0.0000	0.0000

$ep \rightarrow e' \Lambda K^{*+} \rightarrow e' \pi^- p K^+ \pi^0 \rightarrow 2\gamma$

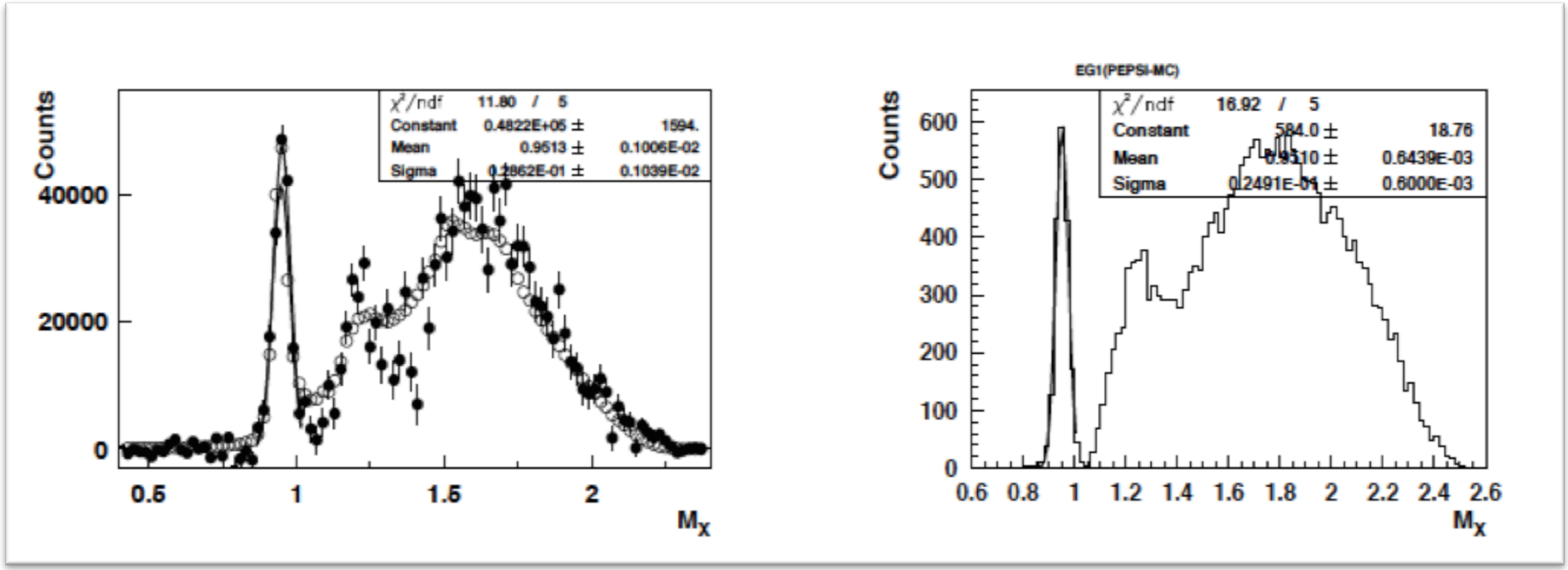
CLAS data compared to LUND Monte Carlo

$Q^2 > 1 GeV^2$,
$W^2 > 4\ GeV^2$,
$z > 0.5, y < 0.85$



CLAS data compared to LUND Monte Carlo

$ep \rightarrow e' \pi^+ X$ (E_{e-}=5.7 GeV)



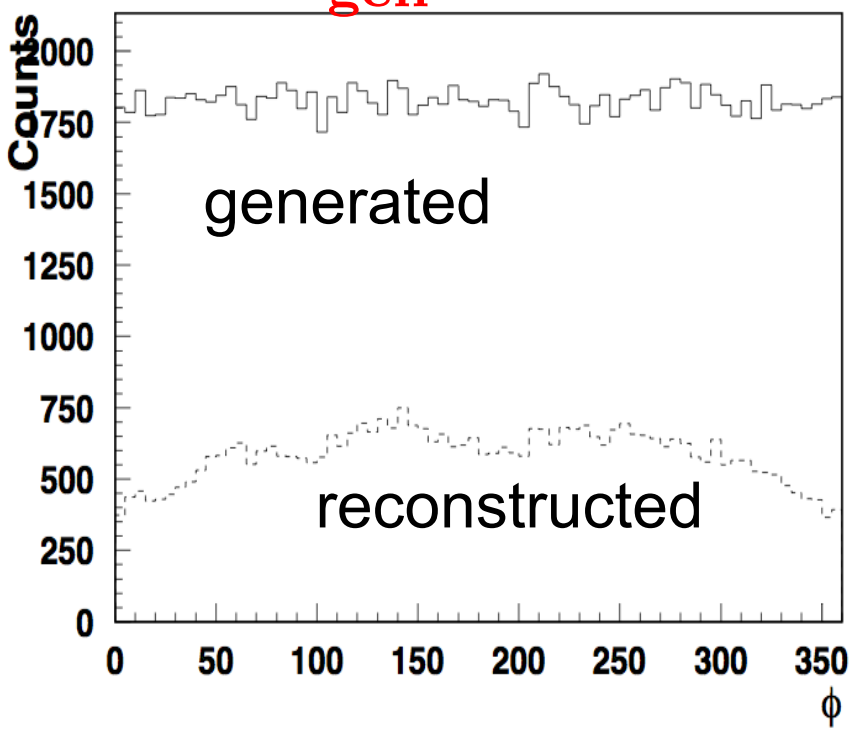
$$M^2_x = (p_e + p_p - p_{e'} - p_{\pi+})^2$$

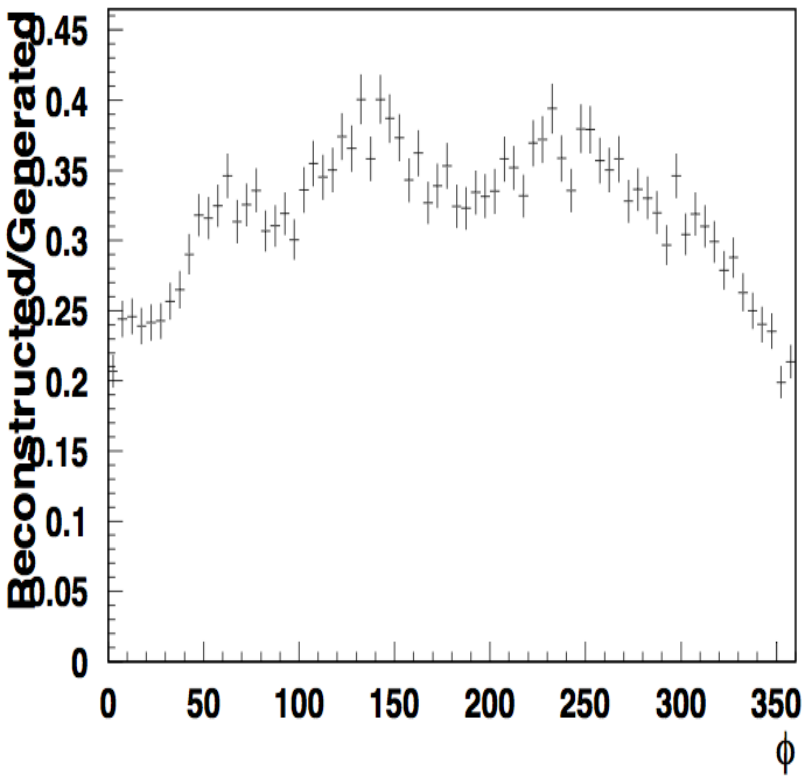
MC reasonably describes the resolution of the M_X

CLAS MC: Acceptance Studies

$$A = \frac{N_{rec}}{N_{gen}}$$

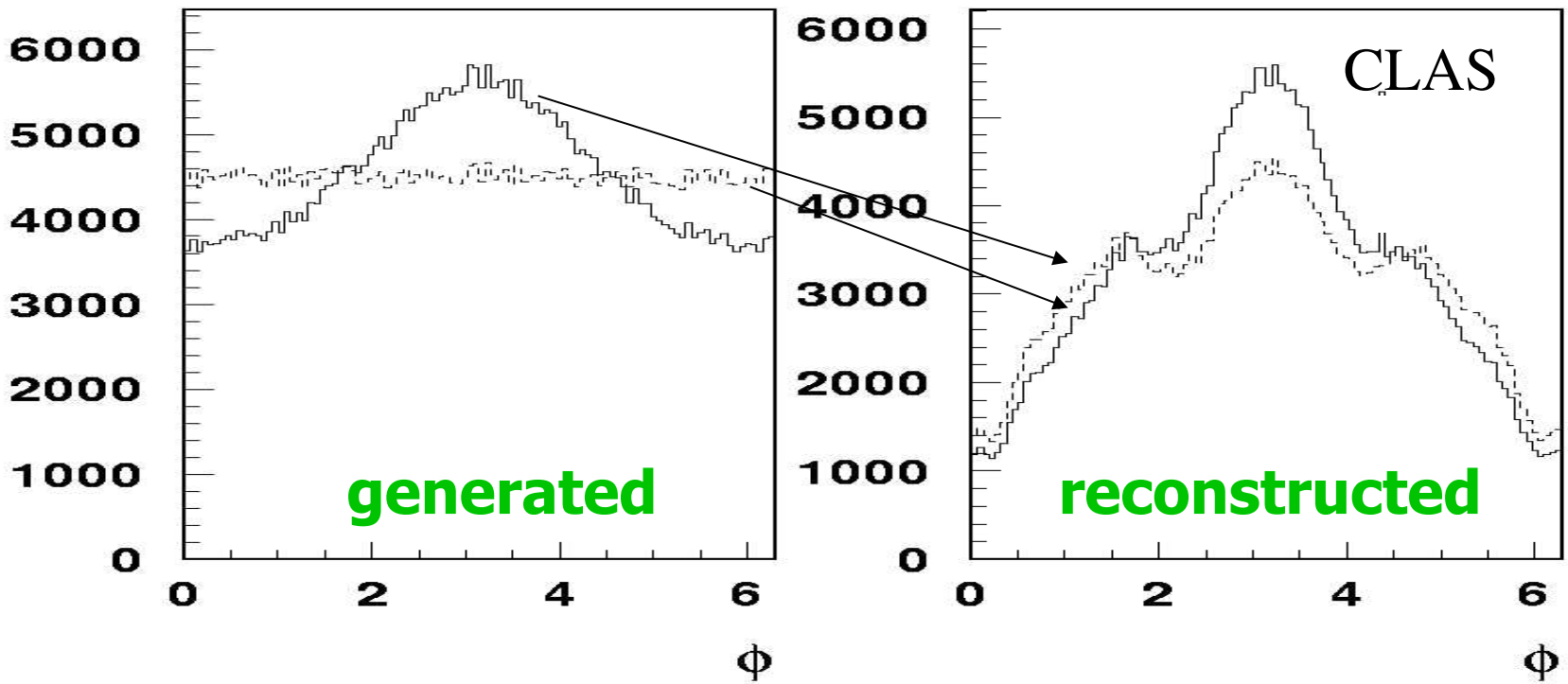
N_{gen} = generated events
N_{rec} = reconstructed events





- Only ~25% of epX events are reconstructed ($0.5<P_T<0.6$)
- Artificial azimuthal moments are introduced!!

Acceptance moments from MC



Two different initial generated distributions, give similar reconstructed ϕ-distributions

acceptance effects may dominate the reconstructed ϕ-distributions

3 Methods to analize the Azimuthal Moments

$$\frac{\sigma}{\sigma_0} = 1 + p_0 \cos\phi + P_B p_1 \sin\phi + P_B p_2 \sin 2\phi + \ldots$$

$$A_{LU}^{\sin\phi} = p_1 \qquad N^{\pm} \to \pm P_B$$

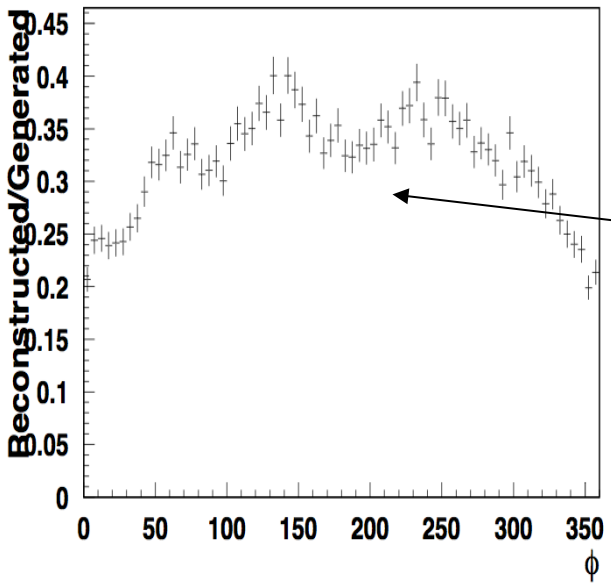
I $$A_{LU} = \frac{\pi}{2P_B} \frac{N(0<\phi<\pi) - N(\pi<\phi<2\pi)}{N(0<\phi<\pi) + N(\pi<\phi<2\pi)}.$$

II $$A_{LU}^{\sin\phi} = \frac{\sum_{i=1}^{N^{\pm}} \sin\phi_i}{P_B \sum_{i=1}^{N^{\pm}} \sin^2\phi_i}$$

III $$A(\phi)_{LU} = \frac{1}{P_B} \frac{N^+ - N^-}{N^+ + N^-}. \xrightarrow{\text{fit}} \frac{p_1 \sin\phi + p_2 \sin 2\phi}{1 + p_0 \cos\phi}$$

Different methods have different sensitivity to acceptance corrections

Acceptance moments from MC



$$\sigma(\phi) = \sigma_0(1 + \sum_{m=1}^{M} a_m \cos m\phi + \sum_{n=1}^{N} b_n \sin n\phi)$$

$$A(\phi) = A_0(1 + \sum_{l=1}^{\infty} A_l \cos l\phi + \sum_{k=1}^{\infty} B_k \sin k\phi)$$

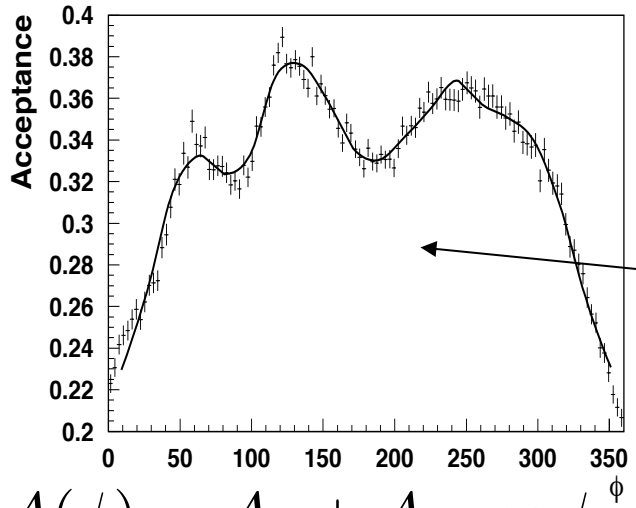
We measure the convolution of the acceptance with cross section

$$\sigma_M(\phi) = \sigma(\phi) * A(\phi)$$

$$\sigma_M(\phi) = \sigma_0 A_0(1 + \frac{1}{2}(\sum_{i=1}^{M} A_i a_i + \sum_{i=1}^{N} B_i b_i)$$
$$+ \cos\phi[a_1 + A_1 + \frac{1}{2}(\sum_{i=1}^{M-1} A_i a_{i+1} + \sum_{i=1}^{M-1} A_{i+1} a_i - \sum_{i=1}^{N-1} B_i b_{i+1} - \sum_{i=1}^{N} B_{i+1} b_i)]$$
$$+ \sin\phi[b_1 + B_1 + \frac{1}{2}(\sum_{i=1}^{M-1} B_i a_{i+1} - \sum_{i=1}^{M-1} B_{i+1} a_i + \sum_{i=1}^{N-1} A_i b_{i+1} - \sum_{i=1}^{N} A_{i+1} b_i)]$$

From measured moments we can calculate the cross section moments

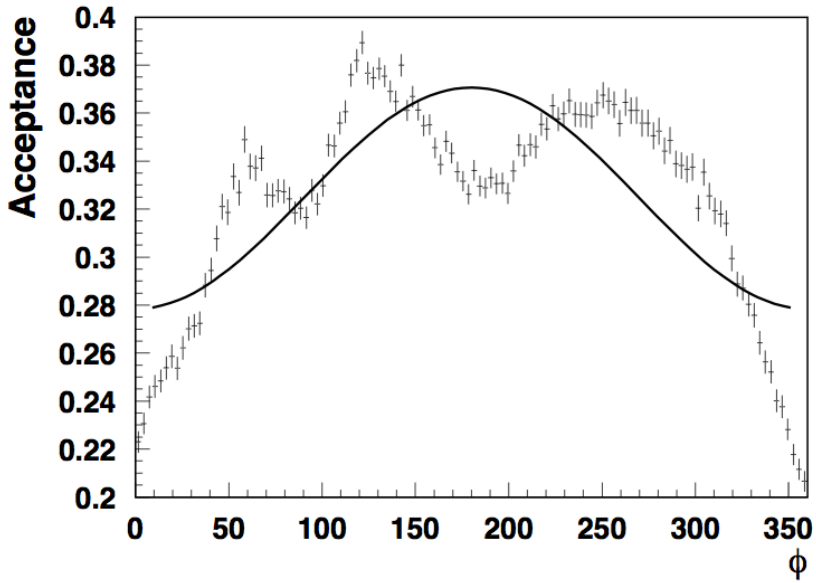
Acceptance moments from MC



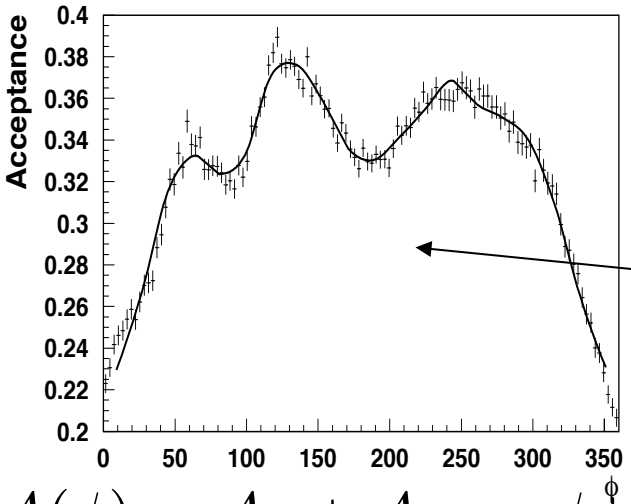
$$A(\phi) = A_0 + A_1 \cos\phi$$

$$A(\phi) = A_0(1 + \sum_{l=1}^{\infty} A_l \cos l\phi + \sum_{k=1}^{\infty} B_k \sin k\phi)$$

Extract acceptance moments A*l*,B*k* from MC



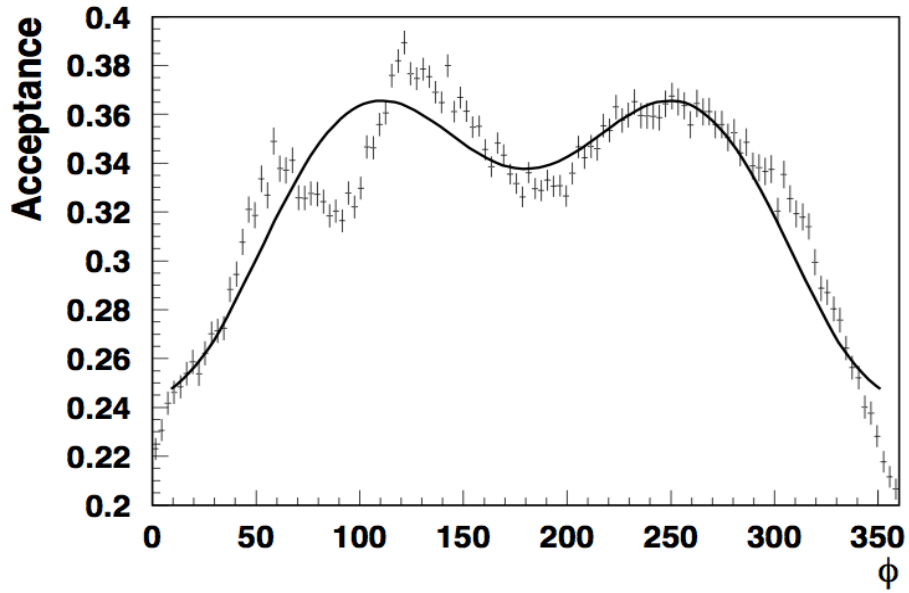
Acceptance moments from MC



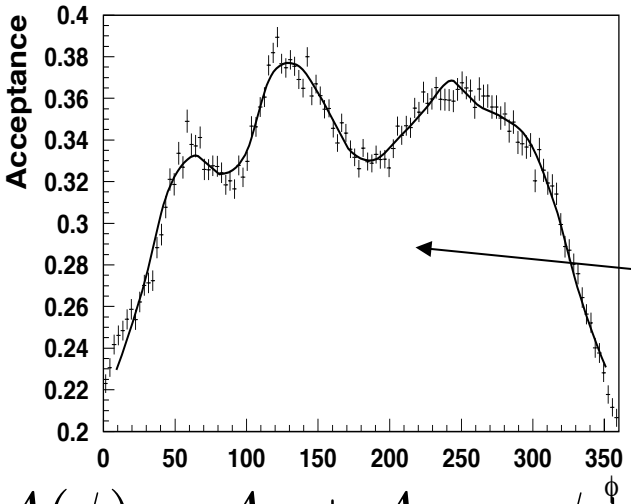
$$A(\phi) = A_0(1 + \sum_{l=1}^{\infty} A_l \cos l\phi + \sum_{k=1}^{\infty} B_k \sin k\phi)$$

Extract acceptance moments A*l*,B*k* from MC

$$A(\phi) = A_0 + A_1 \cos\phi + A_2 \cos 2\phi$$



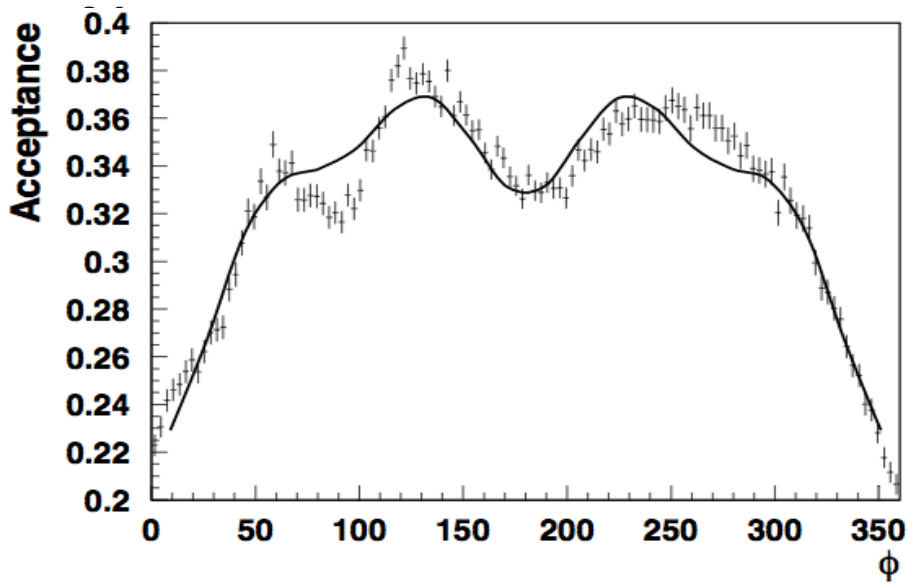
Acceptance moments from MC



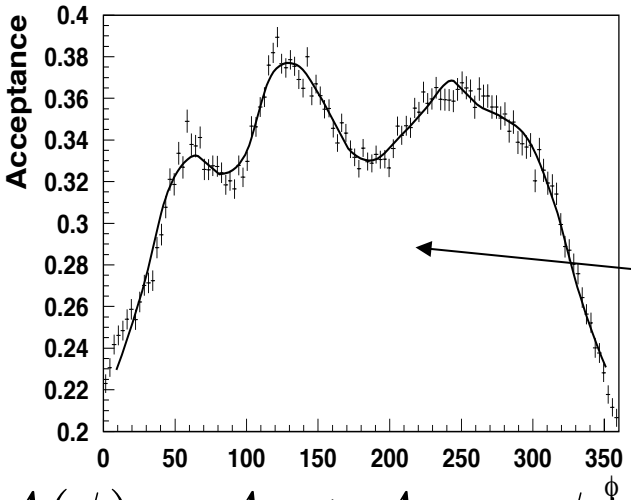
$$A(\phi) = A_0(1 + \sum_{l=1}^{\infty} A_l \cos l\phi + \sum_{k=1}^{\infty} B_k \sin k\phi)$$

Extract acceptance moments A*l*,B*k* from MC

$$A(\phi) = A_0 + A_1 \cos\phi + A_2 \cos 2\phi + A_3 \cos 3\phi + A_4 \cos 4\phi$$



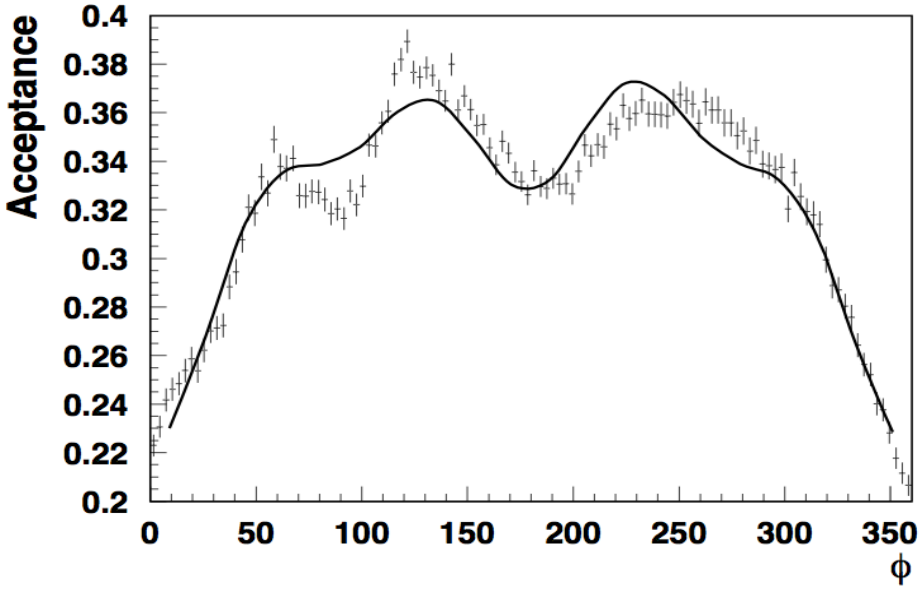
Acceptance moments from MC



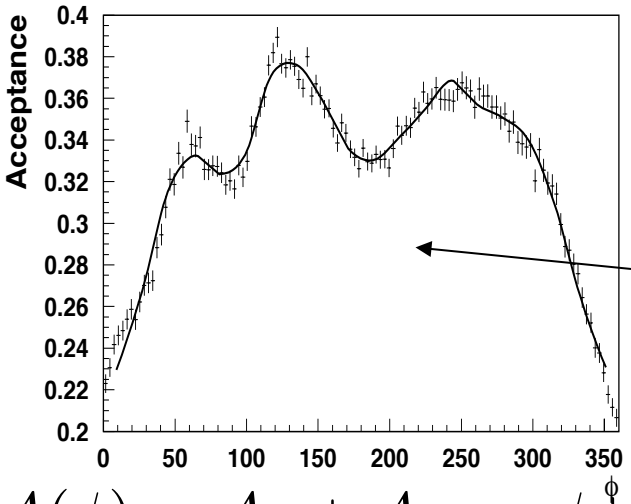
$$A(\phi) = A_0(1 + \sum_{l=1}^{\infty} A_l \cos l\phi + \sum_{k=1}^{\infty} B_k \sin k\phi)$$

Extract acceptance moments A*l*,B*k* from MC

$$A(\phi) = A_0 + A_1 \cos\phi + A_2 \cos 2\phi + A_3 \cos 3\phi + A_4 \cos 4\phi + B_3 \sin\phi$$



Acceptance moments from MC



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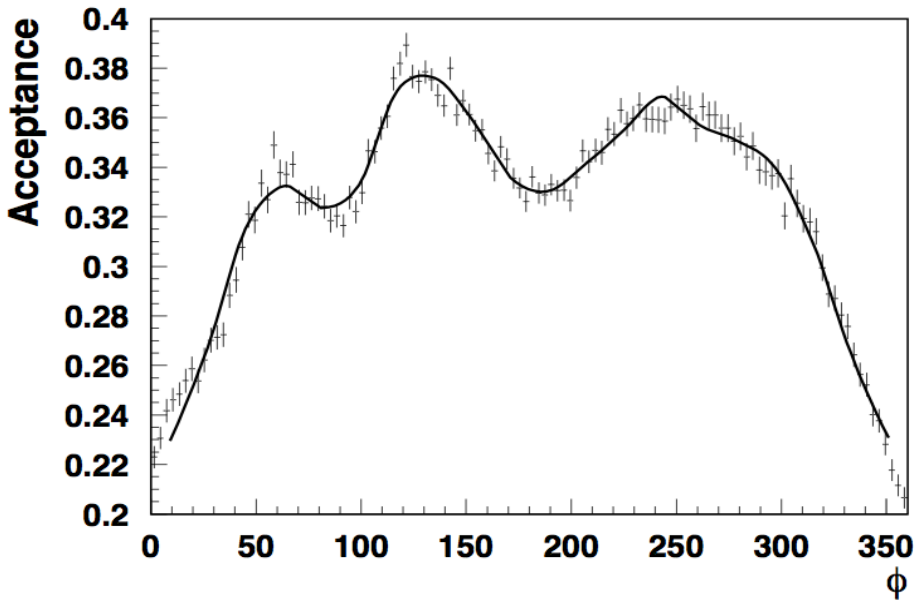
Extract acceptance moments A*l*,B*k* from MC

$$A(\phi) = A_0 + A_1 \cos\phi + A_2 \cos 2\phi + A_3 \cos 3\phi + A_4 \cos 4\phi + B_3 \sin\phi$$

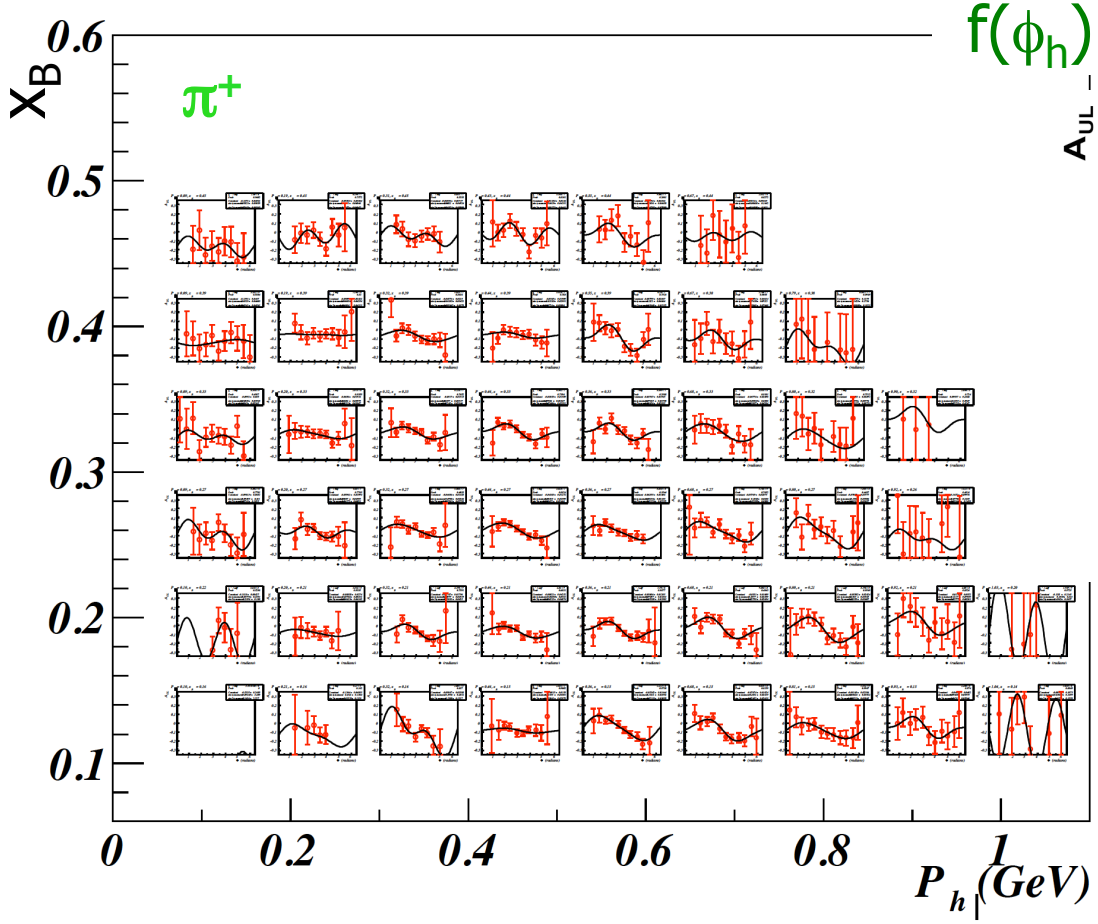


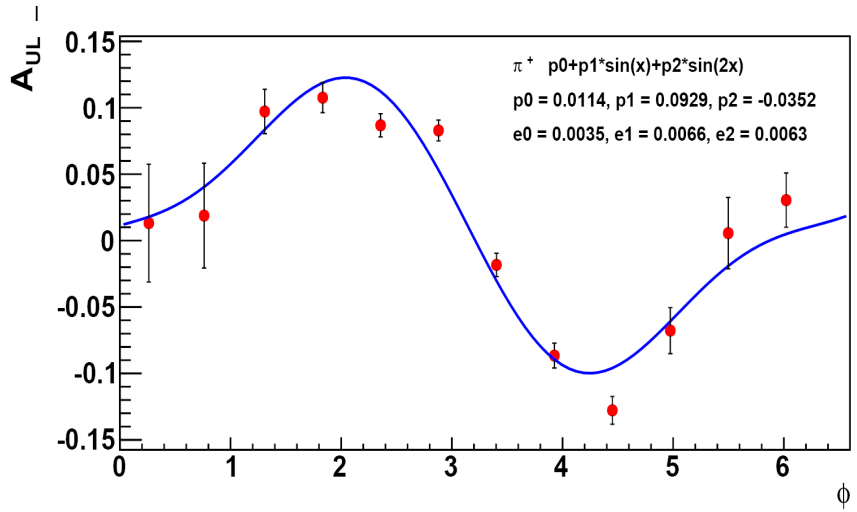
$+ \ldots\ldots$

Moments Extractions

$$A_{UL} = \frac{1}{f}\frac{N^{++} + N^{-+} - (N^{+-} + N^{--})}{|P_t^+|(N^{++} + N^{-+}) + |P_t^-|(N^{+-} + N^{--})} \propto A_{UL}^{\sin 2\phi} \sin 2\phi_h$$

$f(\phi_h) = p0 + p1\sin(\phi) + p2\sin2(\phi)$

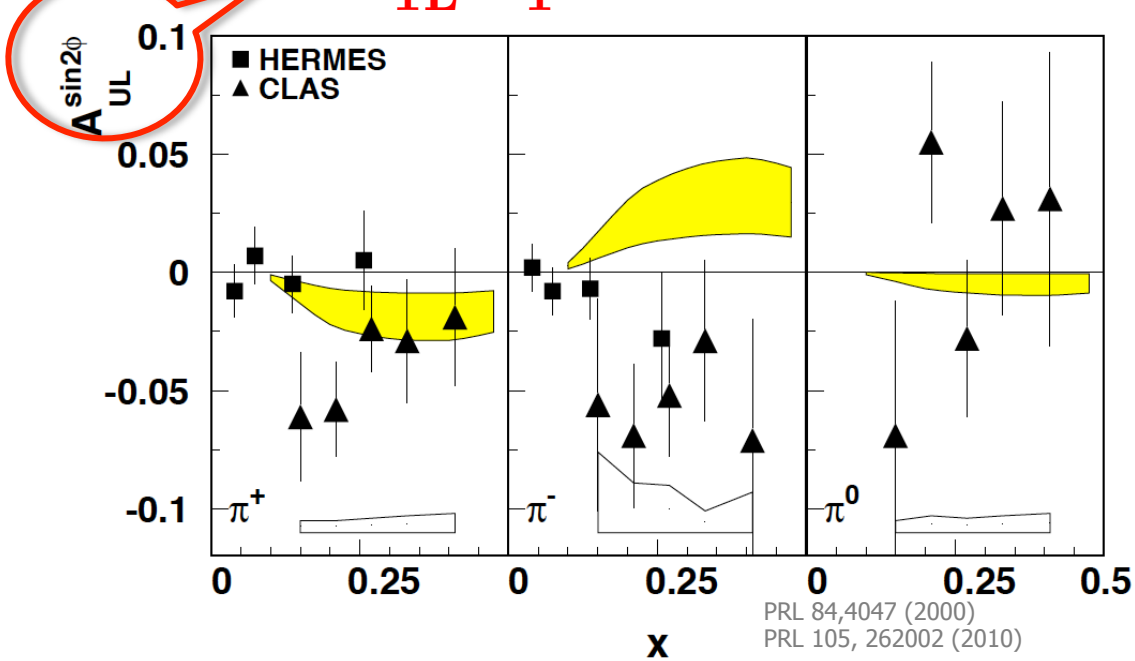




Bin in x_B, $P_{h\perp}$
integrated over Q^2 and z

Kotzinian-Mulders Asymmetry

$\propto h_{1L}^{\perp} H_1^{\perp}$



PRL 84,4047 (2000)
PRL 105, 262002 (2010)

- Significant sin2ϕ modulation for π^+ and π^-
- A relatively small sin2ϕ term for π^0

→ the Collins function for π^0 is suppressed

$D_u^{\pi+}(z) = D_d^{\pi-}(z) = D_{\bar{d}}^{\pi+}(z) = D_{\bar{u}}^{\pi-}(z) = D^+(z)$ *favored* $\pi^+ = u\bar{d}$

$D_d^{\pi+}(z) = D_u^{\pi-}(z) = D_{\bar{u}}^{\pi+}(z) = D_{\bar{d}}^{\pi-}(z) = D^-(z)$ *unfavored* $\pi^- = d\bar{u}$

→ Indication that favored and unfavored Collins functions are ~ equal and have opposite signs → they largely cancel for π^0