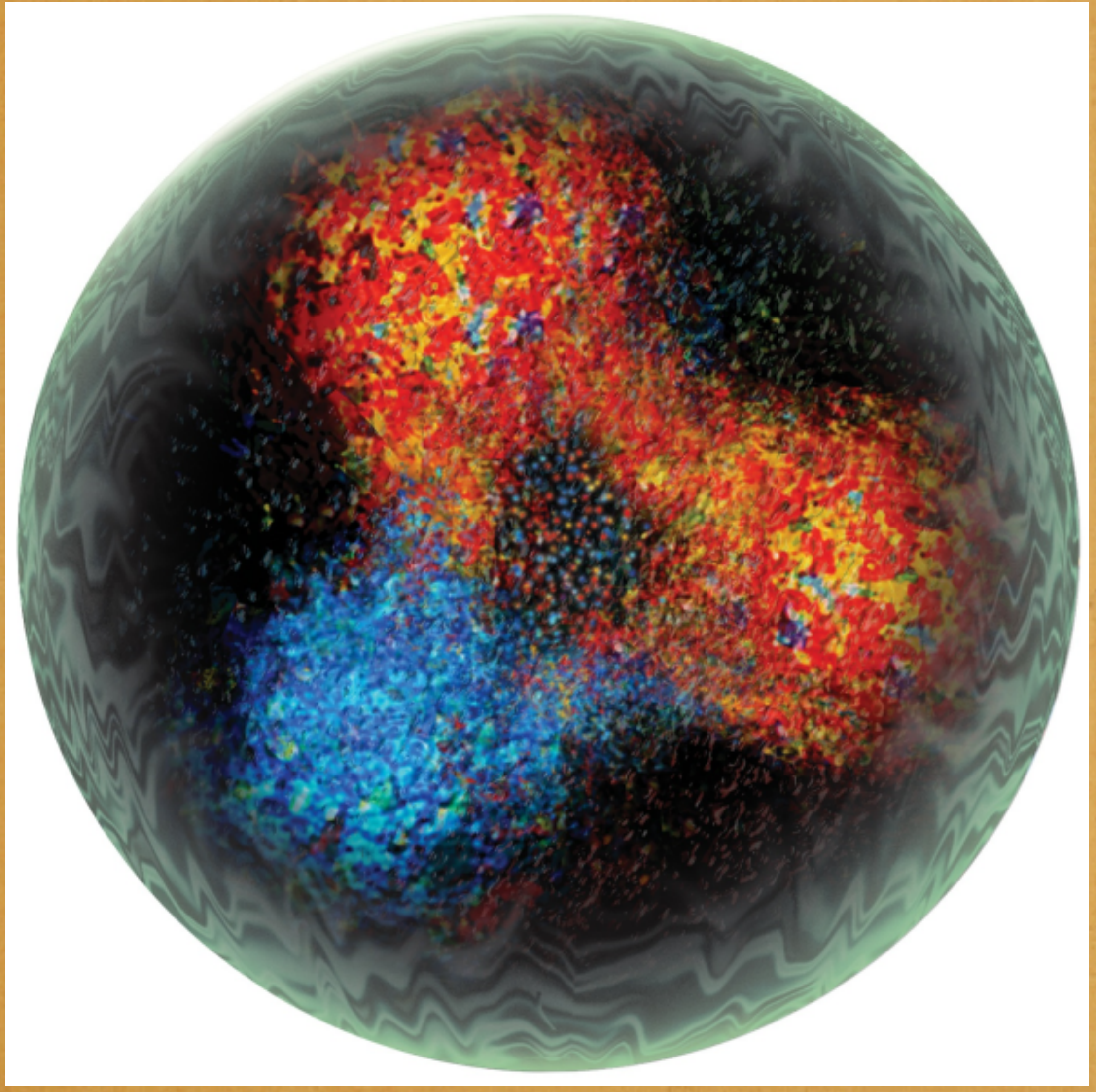
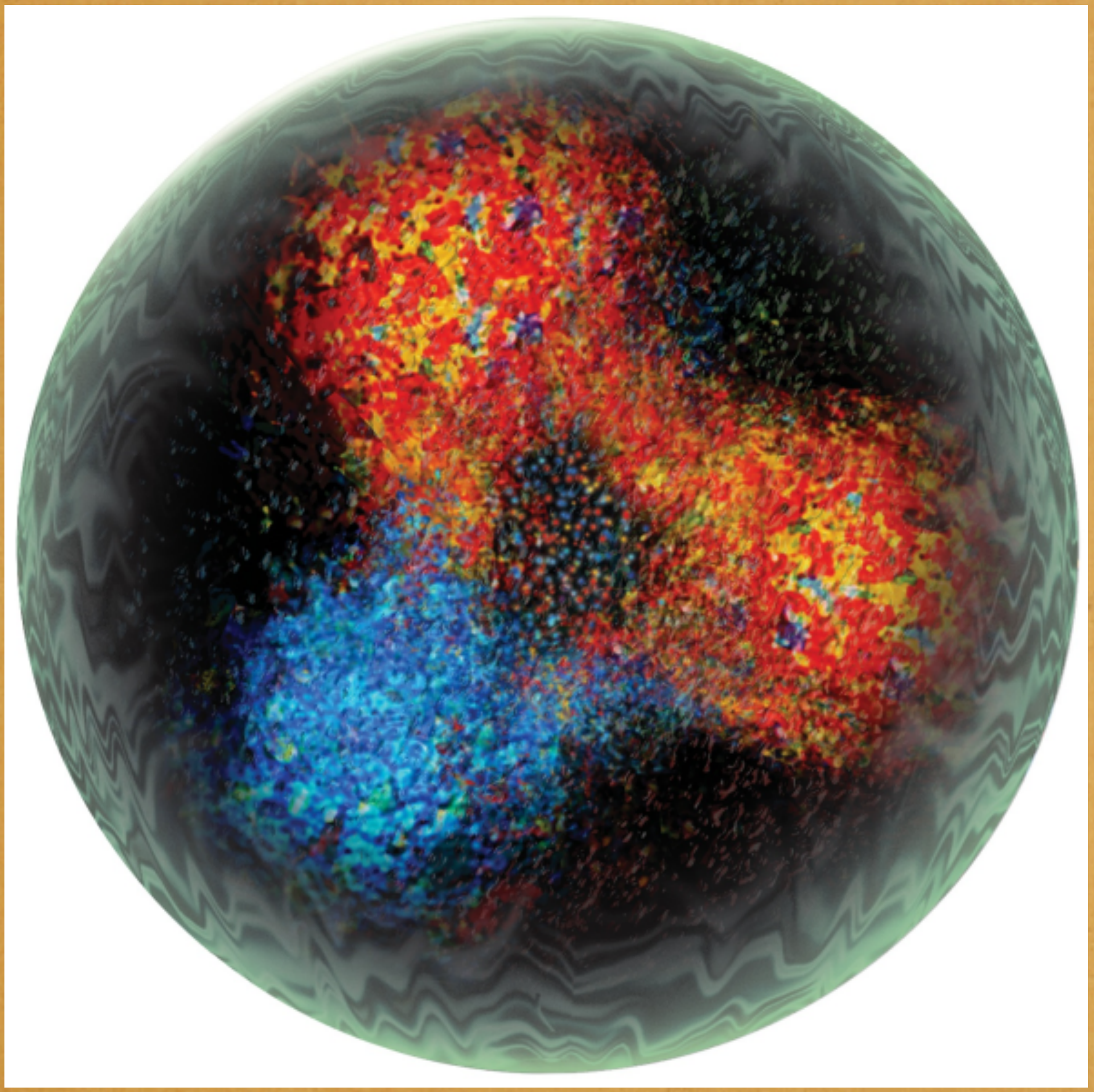
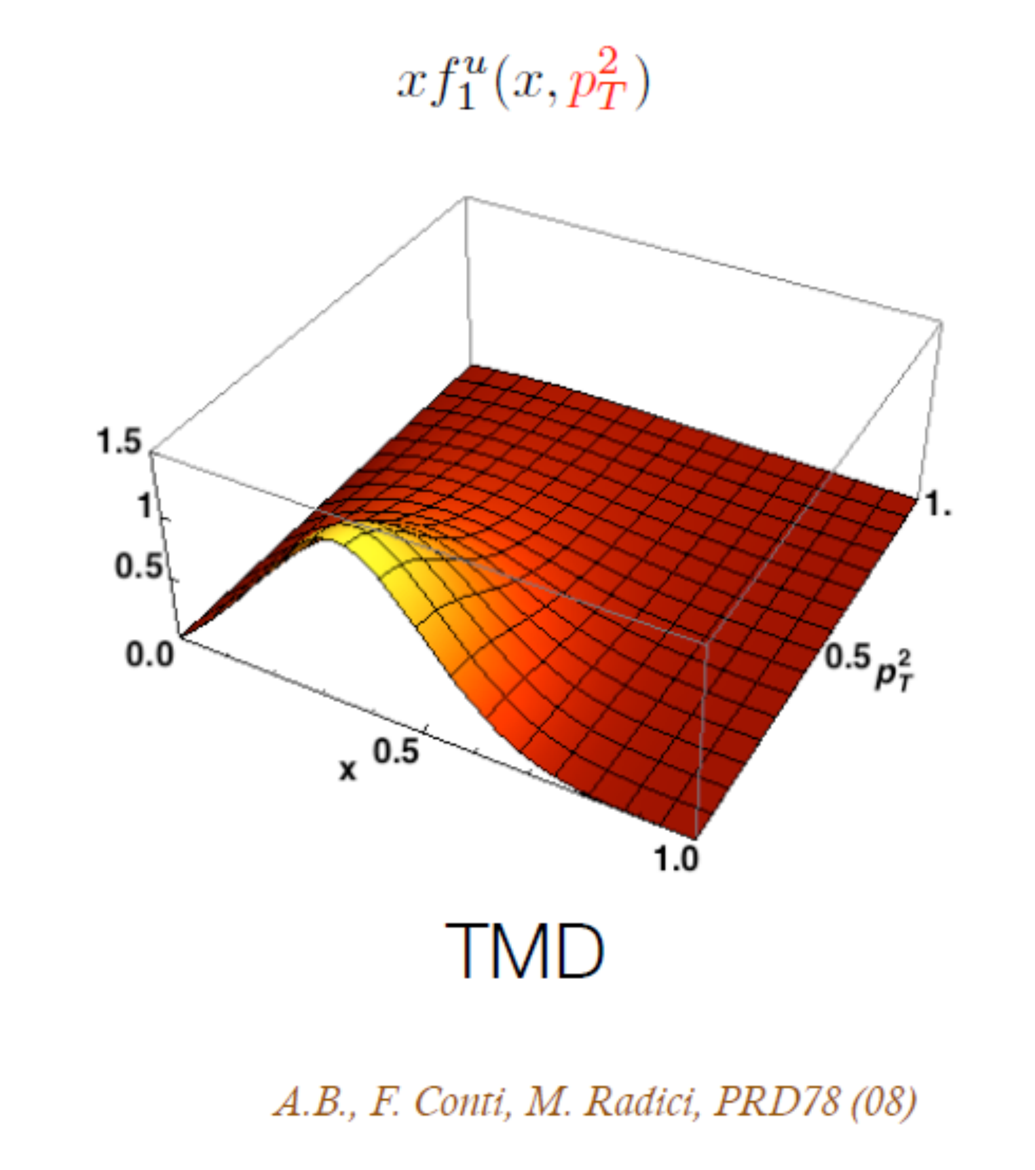
Measurements of Single and Double Spin Asymmetries in Semi-inclusive Deep Inelastic Scattering

Sucheta Jawalkar



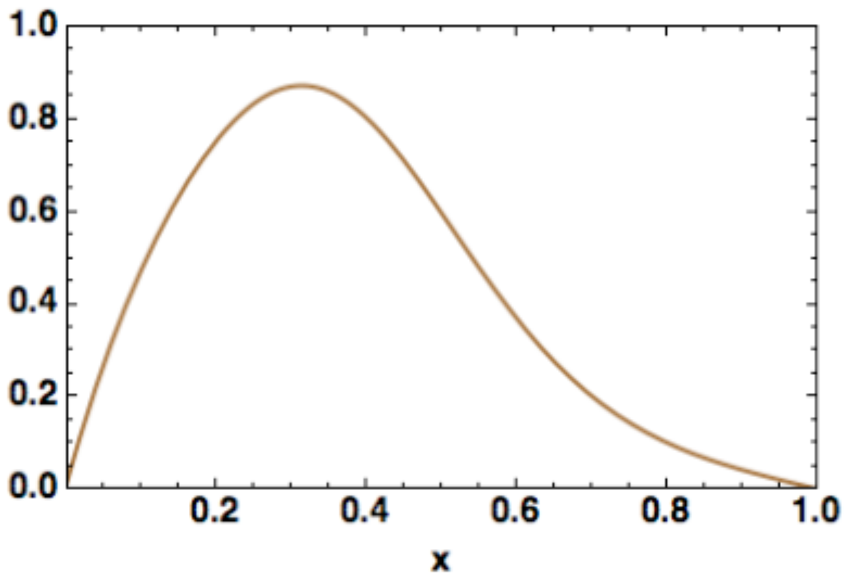
Goal is to study the internal structure of the nucleon in momentum space





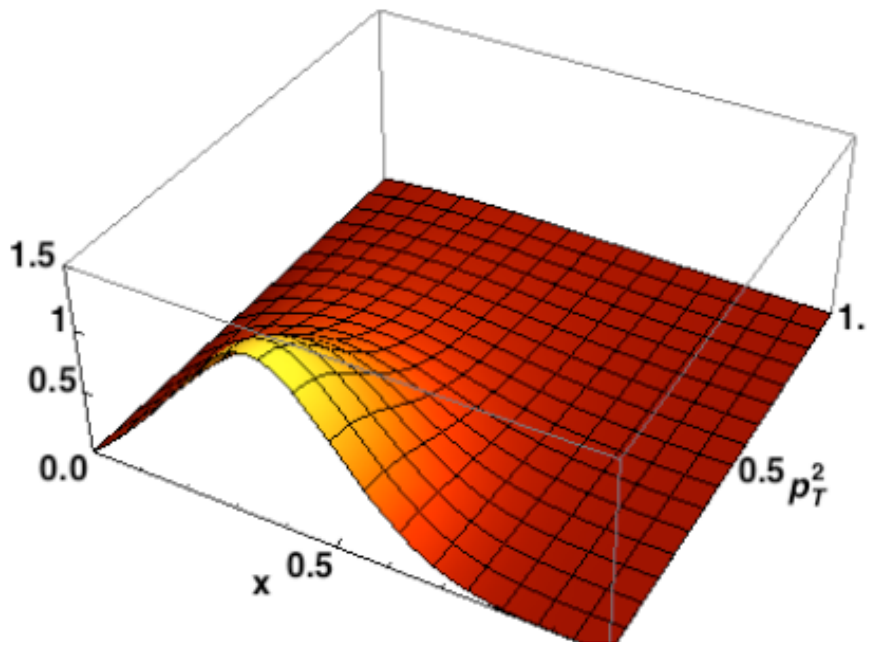
Transverse momentum distributions are probabilities in momentum space.

$x f_1^u(x)$



Standard Collinear PDF
Well known

$x f_1^u(x, p_T^2)$



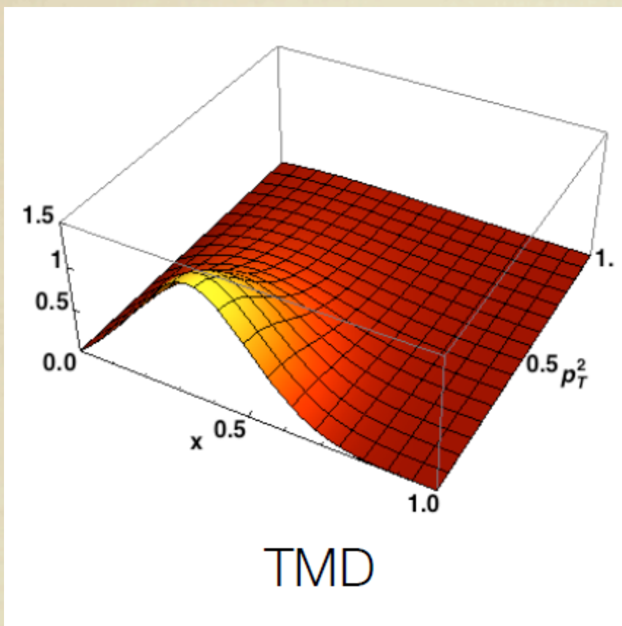
TMD
Not well known

A.B., F. Conti, M. Radici, PRD78 (08)

TMDs are accessed in Semi-inclusive Deep Inelastic Scattering.

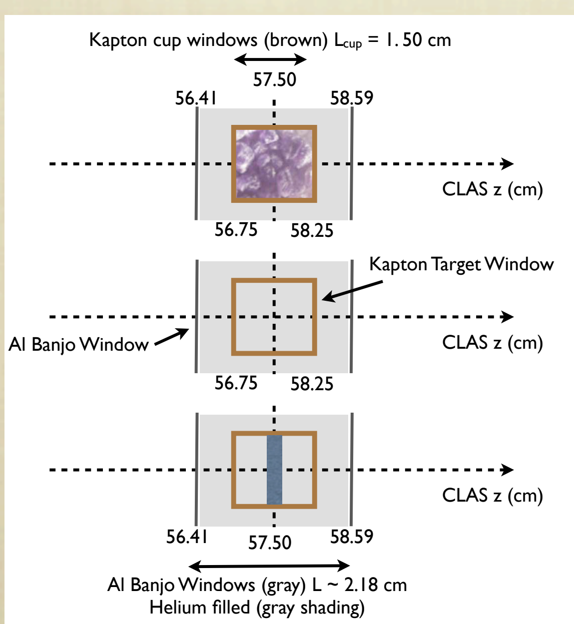
Searching for nucleon structure ...

1. Formalism

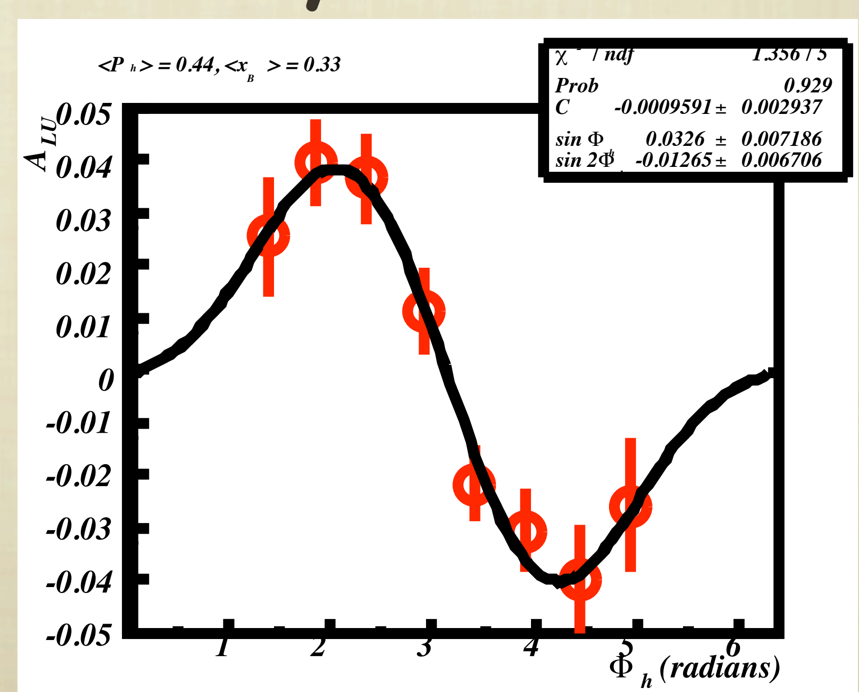


2. The eg1-dvcs Measurement

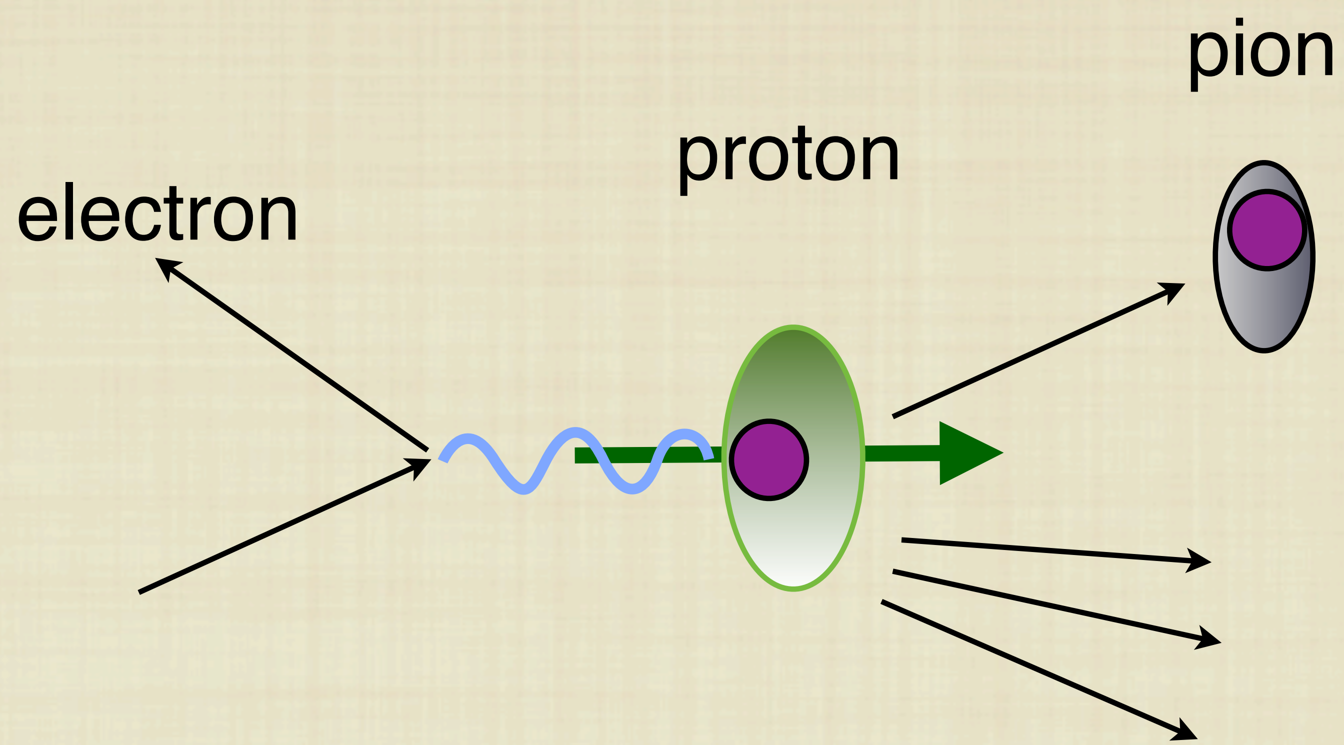
3. Data Analysis



4. Physics Results

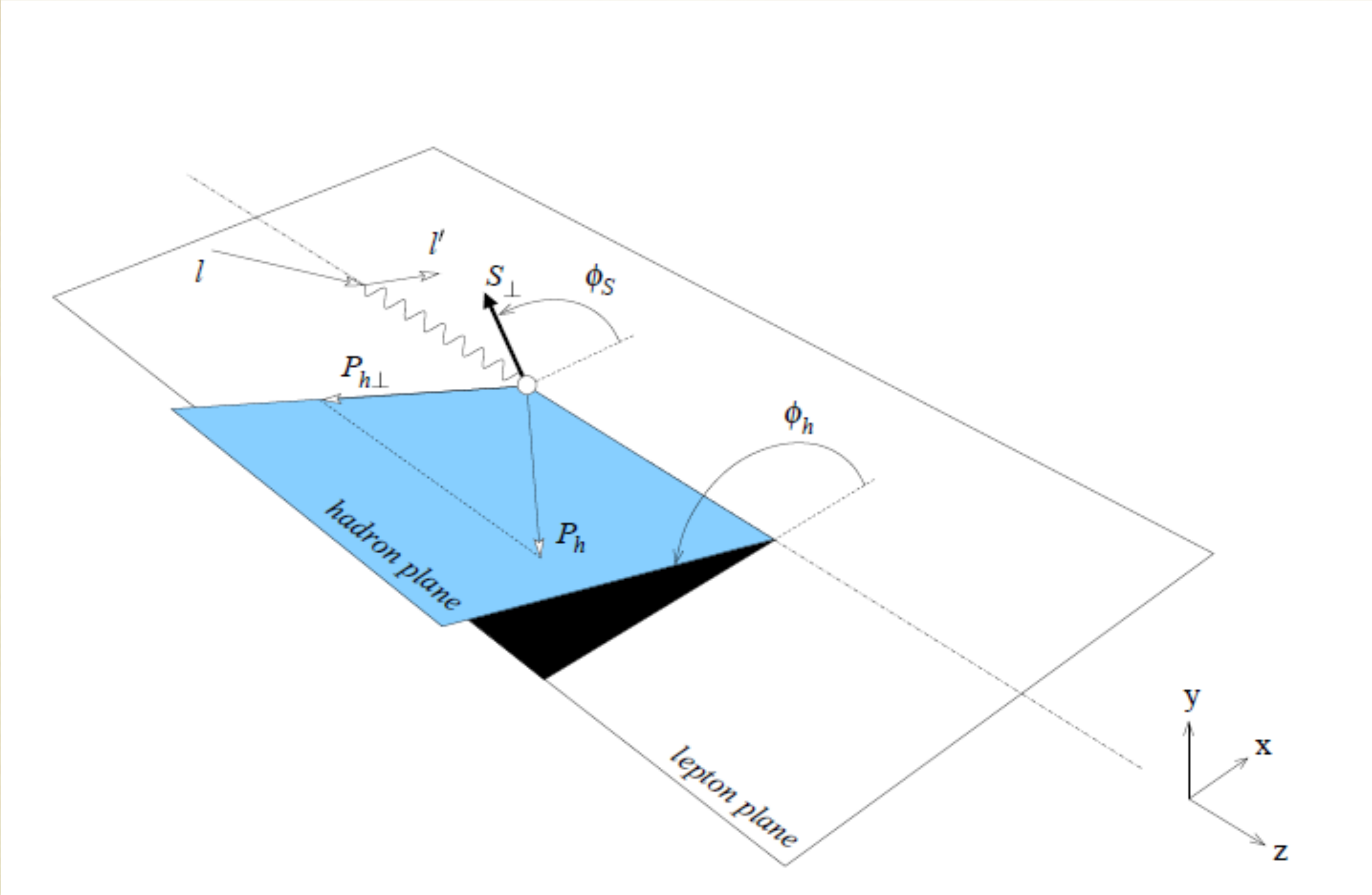


TMDs are accessed in Semi-inclusive Deep Inelastic Scattering.



Q^2 : Momentum transfer squared
x_B : Momentum fraction
$z = E_\pi/\nu$: Fractional energy of the struck pion
$P_{h\perp}$: Transverse momentum of the struck pion
Φ_h : Angle between hadron and lepton plane

The semi-inclusive DIS reaction is split between the hadron and lepton frame.



Q^2 : Momentum transfer squared

x_B : Momentum fraction

$z = E_\pi/\nu$: Fractional energy of the struck pion

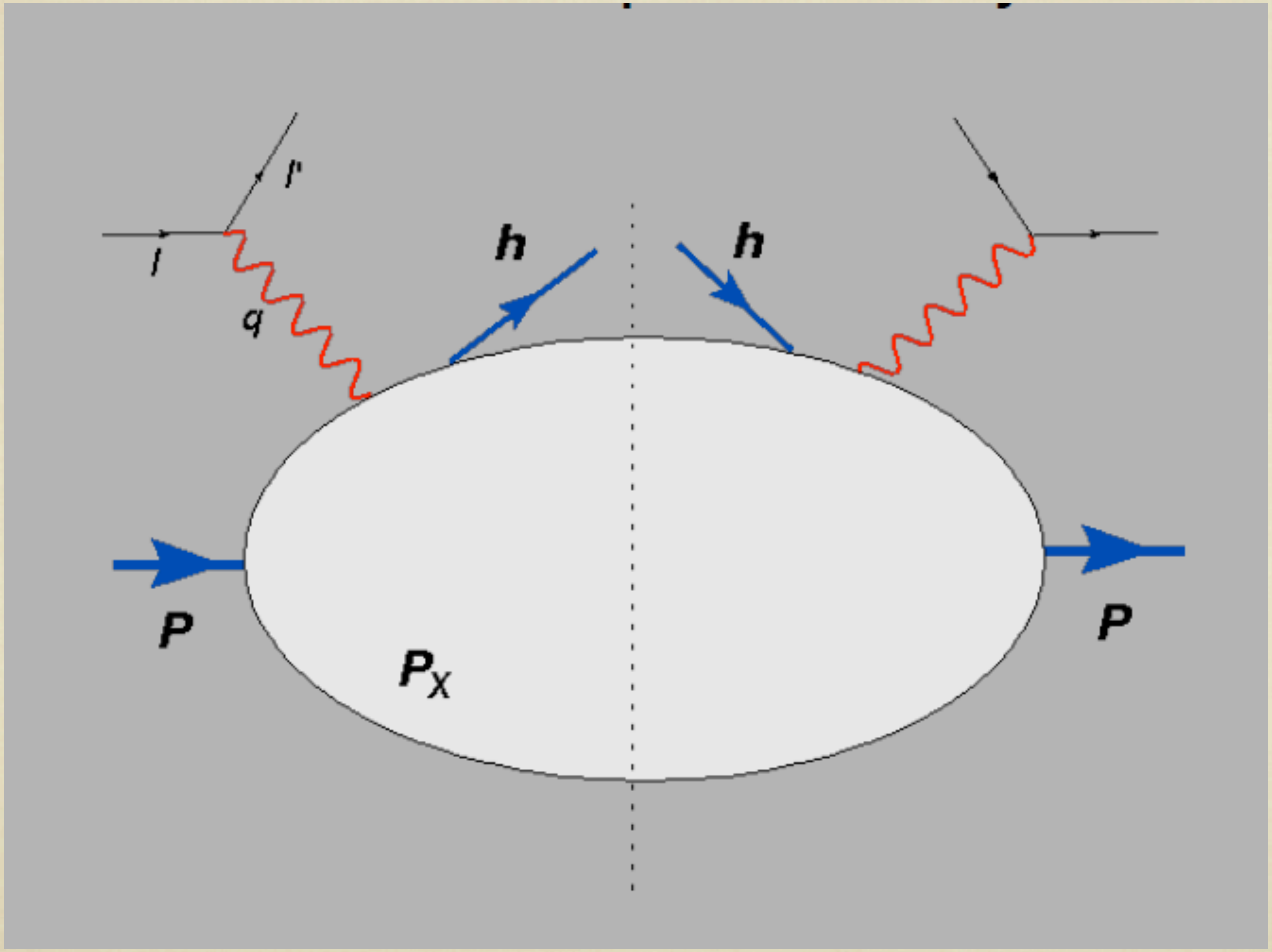
$P_{h\perp}$: Transverse momentum of the struck pion

Φ_h : Angle between hadron and lepton plane

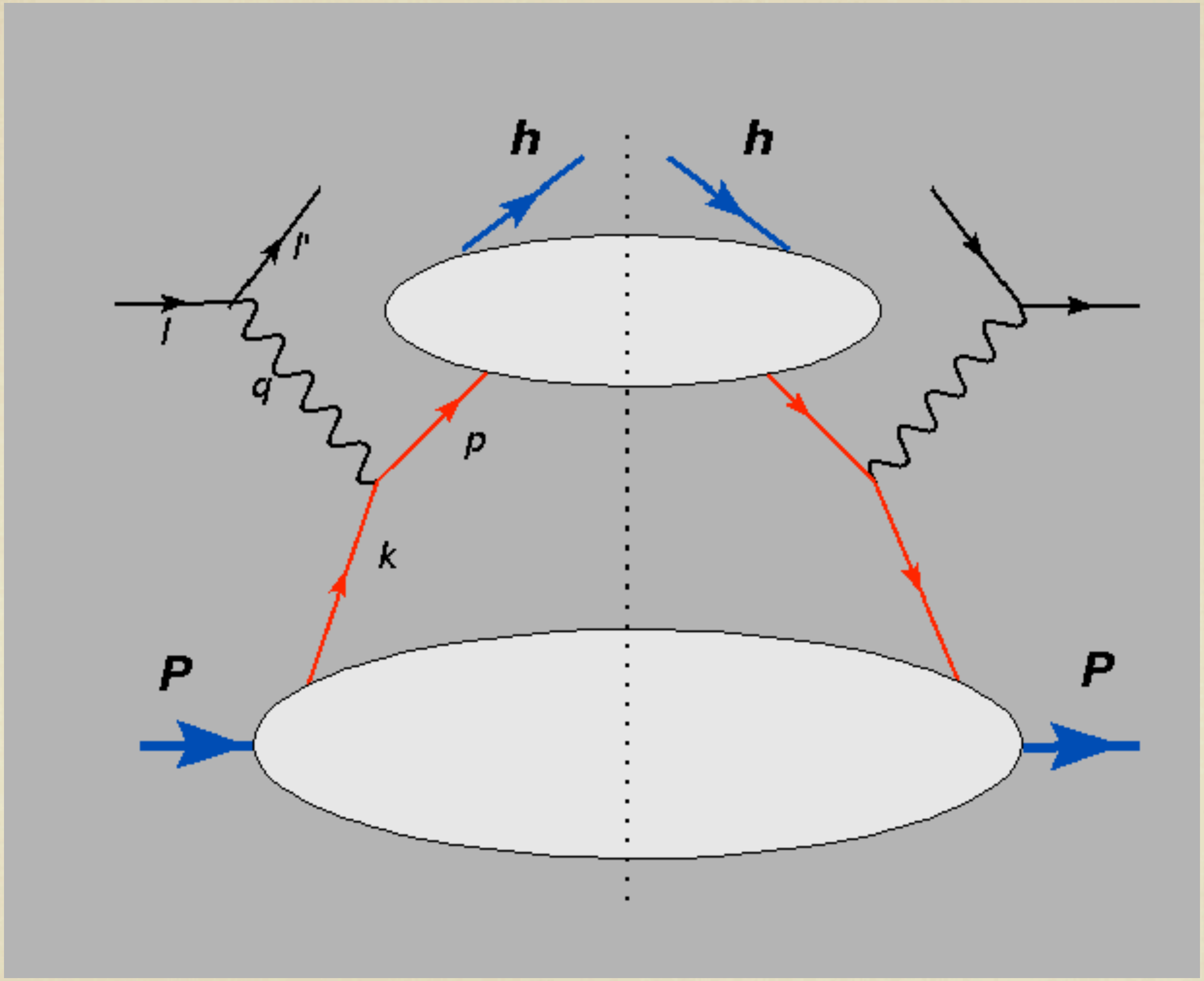
$y = \nu/E$

$\psi \Leftrightarrow \Phi_S$ in lepton frame

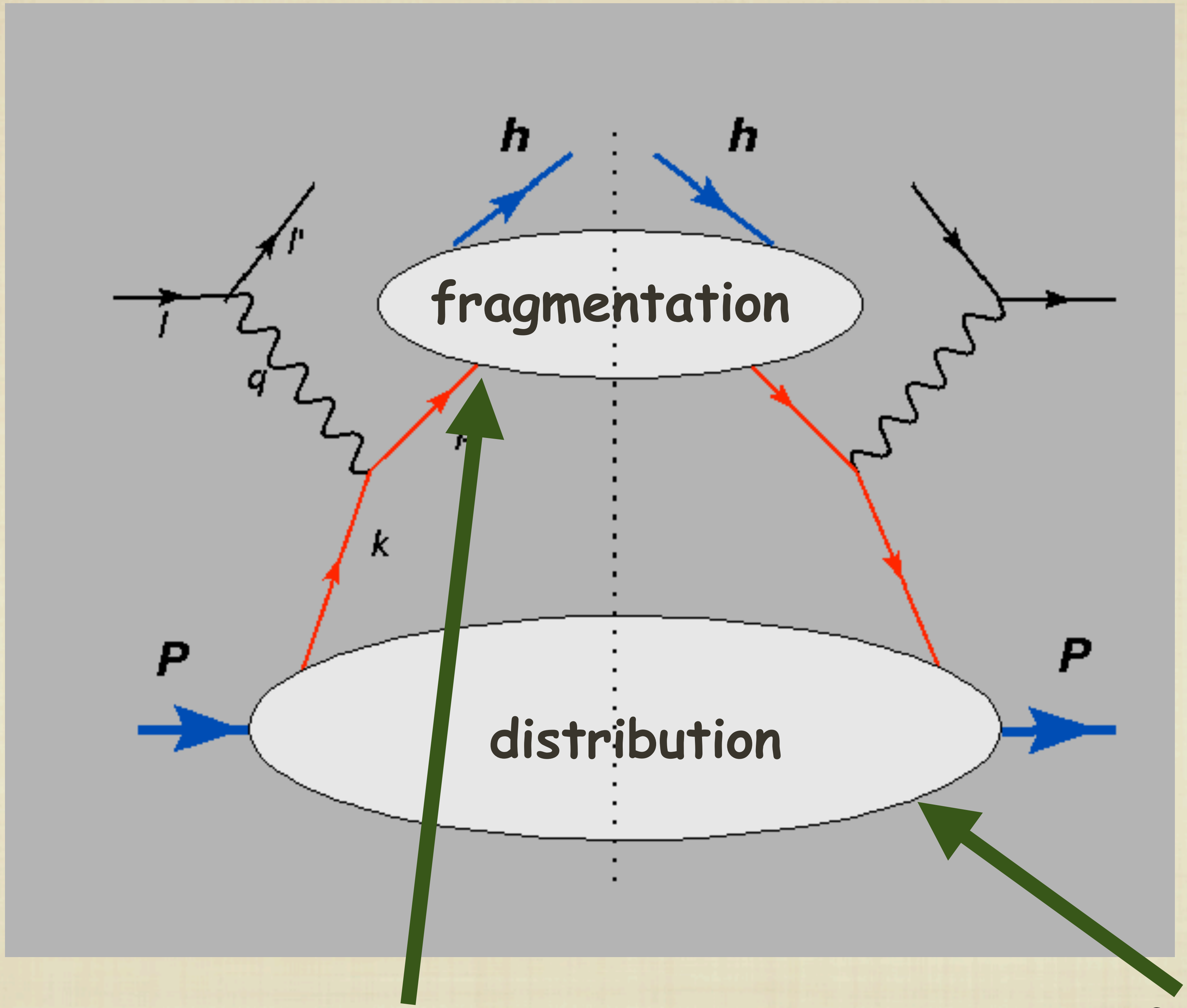
Experimentally we measure,



Theoretical assumption,



Theoretical assumption,

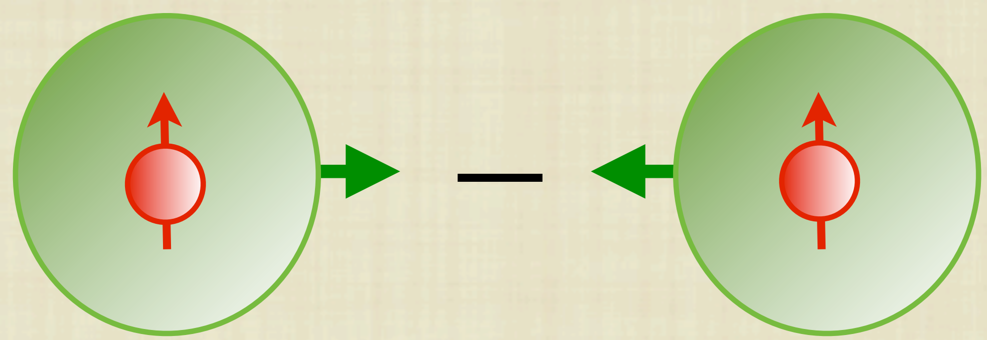


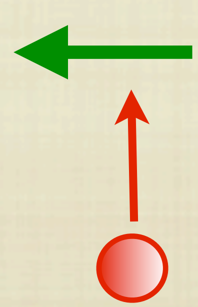
$$d\sigma_{SIDIS} = D_{q/h} \otimes \hat{\sigma}_{lq\to l'q'} \otimes f_{q/P}$$

Each helicity structure function is written as a convolution of a fragmentation and distribution function.

$$F_{UL}^{\sin 2\phi_h} = \mathscr{C}\left[-2\frac{(\hat{\mathbf{h}}\cdot\mathbf{k_T})(\hat{\mathbf{h}}\cdot\mathbf{p_T}) - \mathbf{k_T}\cdot\mathbf{p_T}}{MM_h} h_{1L}^{\perp}(x_B, p_T) H_1^{\perp}(z, k_T)\right]$$

$$h_{1L}^{\perp}(x_B, p_T) =$$





Nucleon with longitudinal spin

Parton with transverse spin

Parton transverse momentum

$$P_{h\perp} = p_T + z k_T$$

TMDs for different quark and nucleon polarizations

Quark Polarization

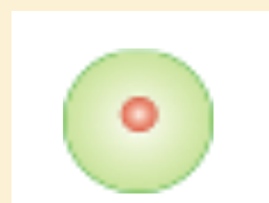
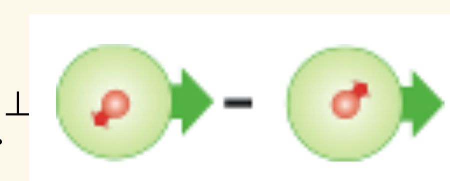
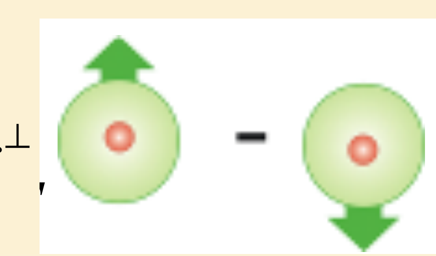
Nucleon Polarization

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 $h_{1T}^\perp$

Leading twist TMDs for different quark and nucleon polarizations

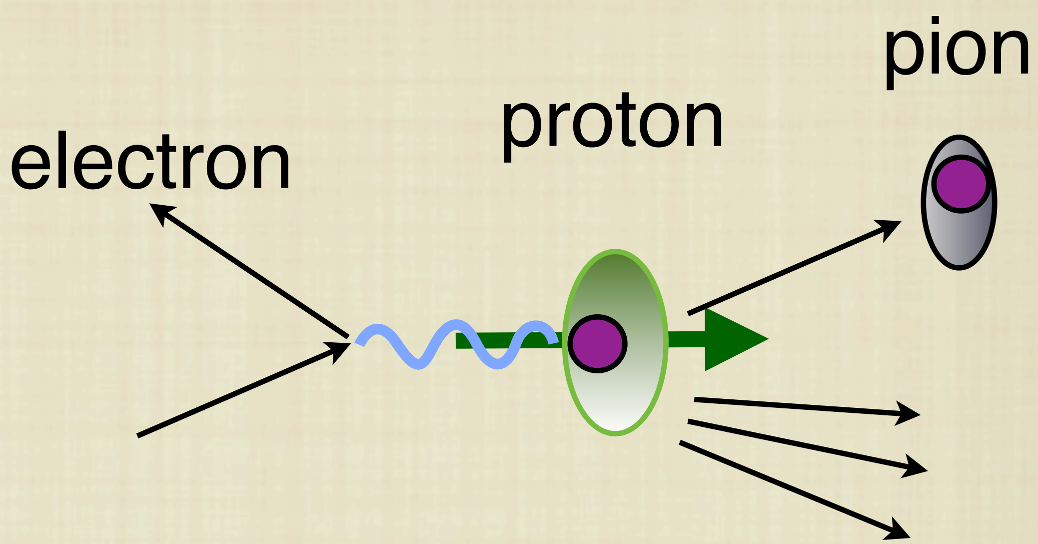
Quark Polarization

Nucleon Polarization

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  $h_{1T}^\perp$ 

The semi-inclusive DIS asymmetries are formed based on helicity of the incoming electron or target nucleon.

$$A_{UL} = \frac{d\sigma^{0\rightarrow} - d\sigma^{0\leftarrow}}{d\sigma^{0\rightarrow} + d\sigma^{0\leftarrow}}$$



$$A_{LU} = \frac{d\sigma^{\rightarrow 0} - d\sigma^{\leftarrow 0}}{d\sigma^{\rightarrow 0} + d\sigma^{\leftarrow 0}}$$

$$A_{LL} = \frac{d\sigma^{\rightarrow\rightarrow} - d\sigma^{\leftarrow\rightarrow} - d\sigma^{\rightarrow\leftarrow} + d\sigma^{\leftarrow\leftarrow}}{d\sigma^{\rightarrow\rightarrow} + d\sigma^{\leftarrow\rightarrow} + d\sigma^{\rightarrow\leftarrow} + d\sigma^{\leftarrow\leftarrow}}$$

2. The eg1-dvcs Measurement.

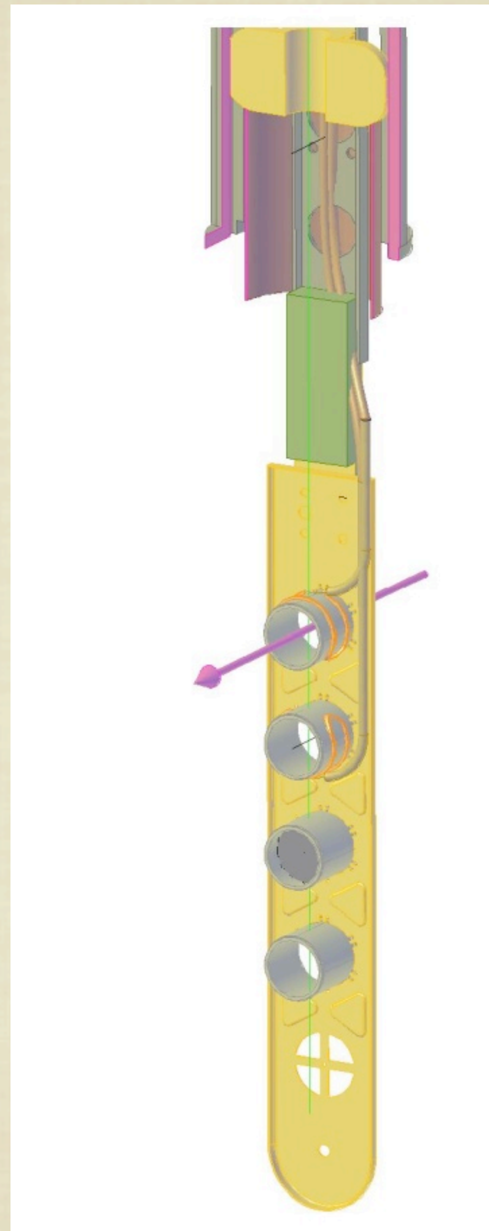
Solid, frozen ammonia is used as a target.

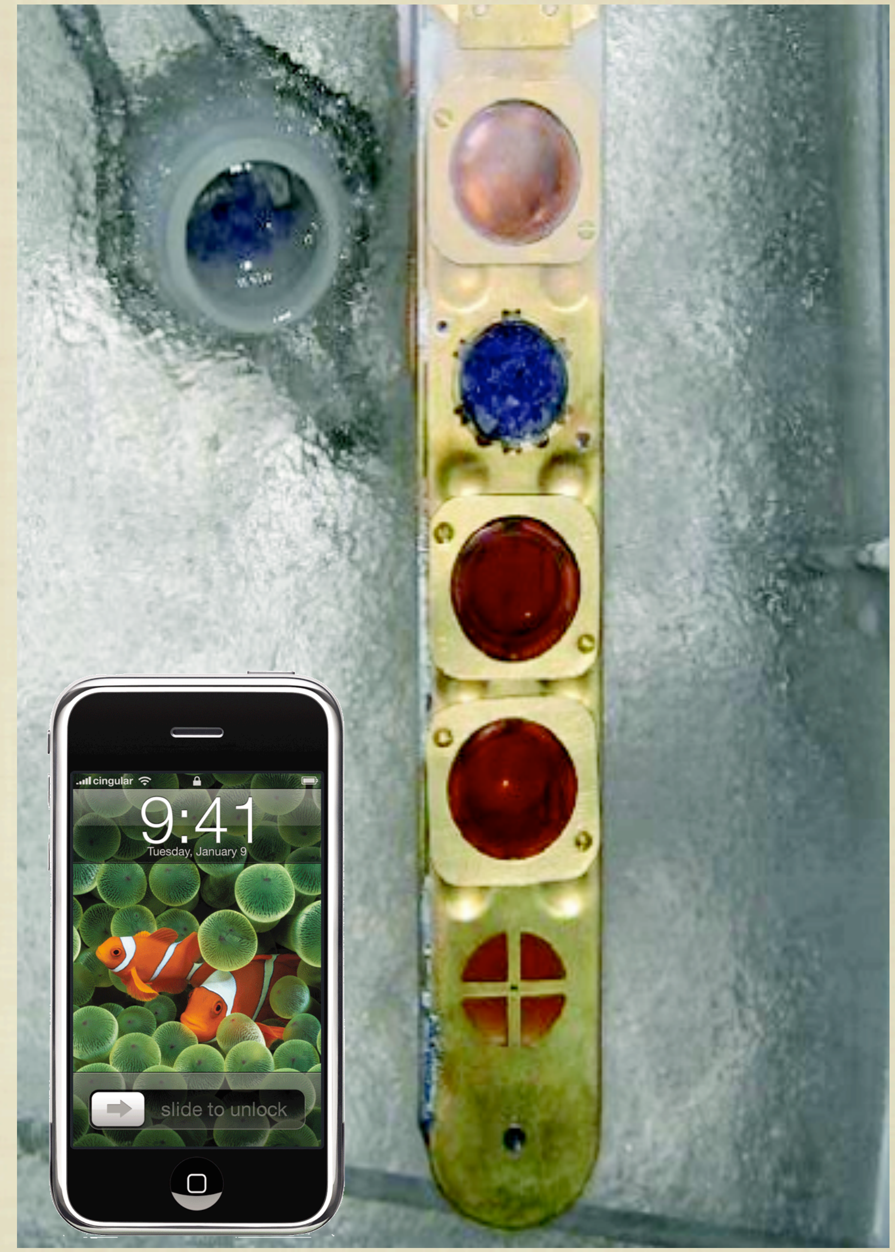
Polarized NH_3

Carbon disk

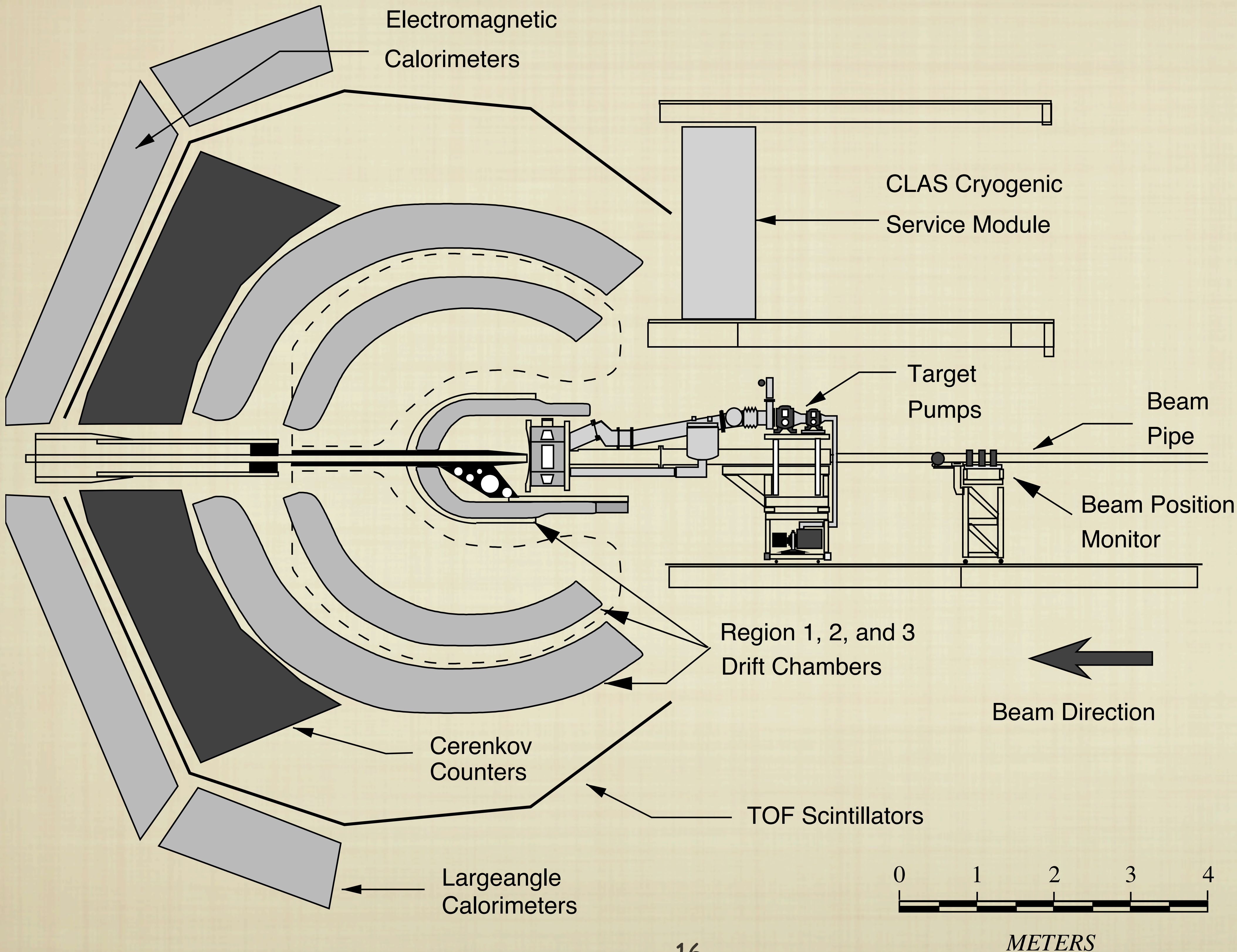
Empty Cup

Cross Hair

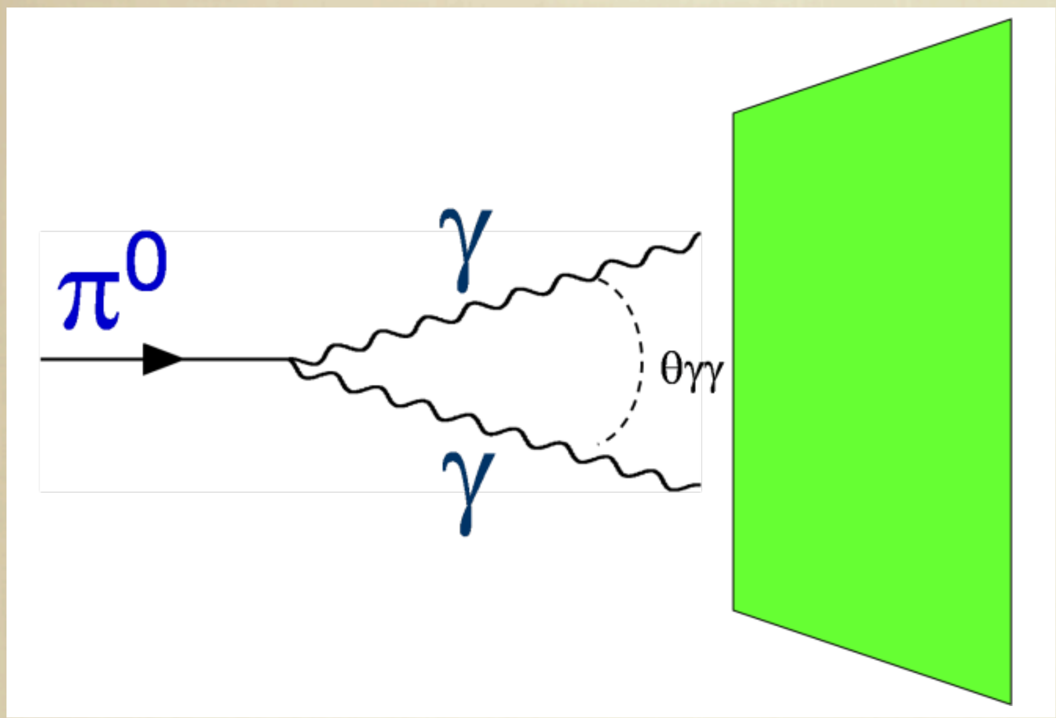


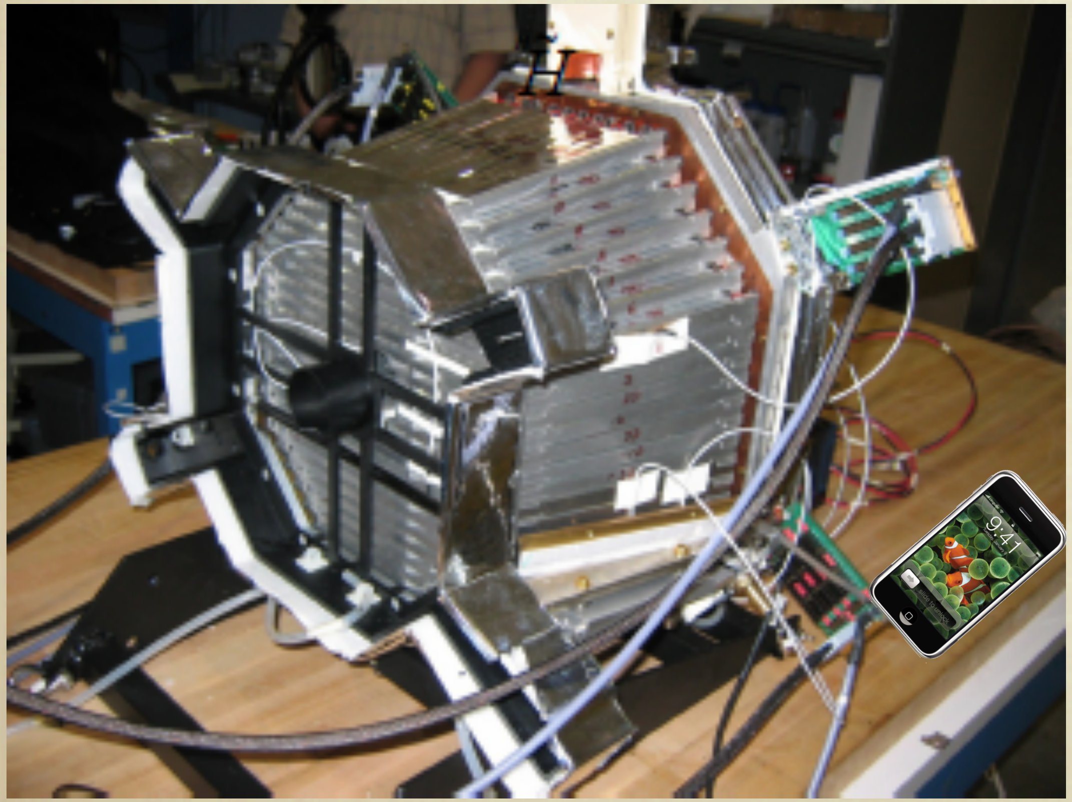


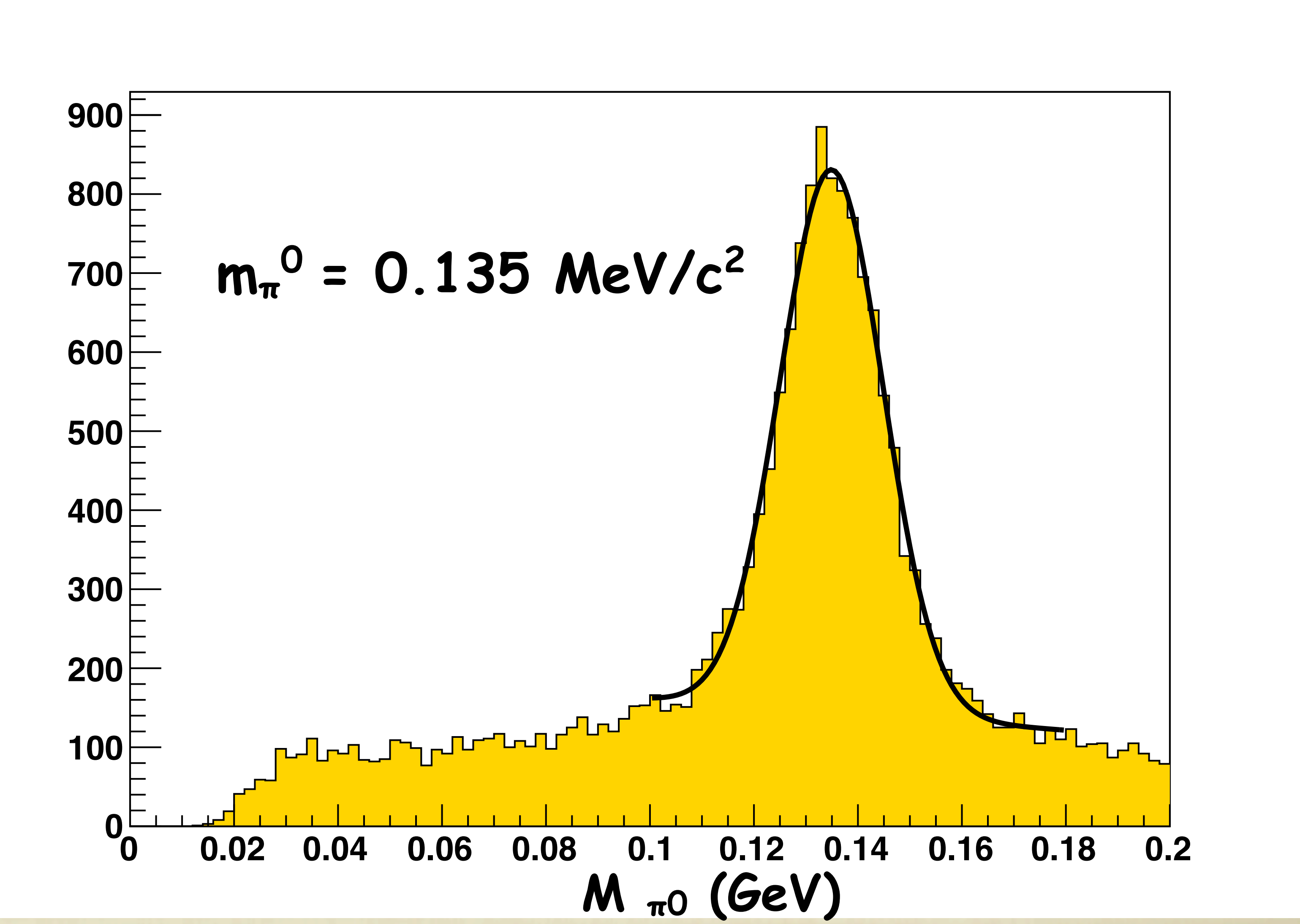
The target is wheeled into the CEBAF Large Acceptance Spectrometer (CLAS).



A small angle photon detector is used to detect photons are small angles.







3. Data Analysis

The measures asymmetries are scaled by,

$$A_{UL} = \frac{1}{f}\frac{1}{P_T}A_{UL}^{meas}$$

$$A_{LU} = \frac{1}{P_B}A_{LU}^{meas}$$

$$A_{LL} = \frac{1}{f}\frac{1}{P_B P_T}A_{LL}^{meas}$$

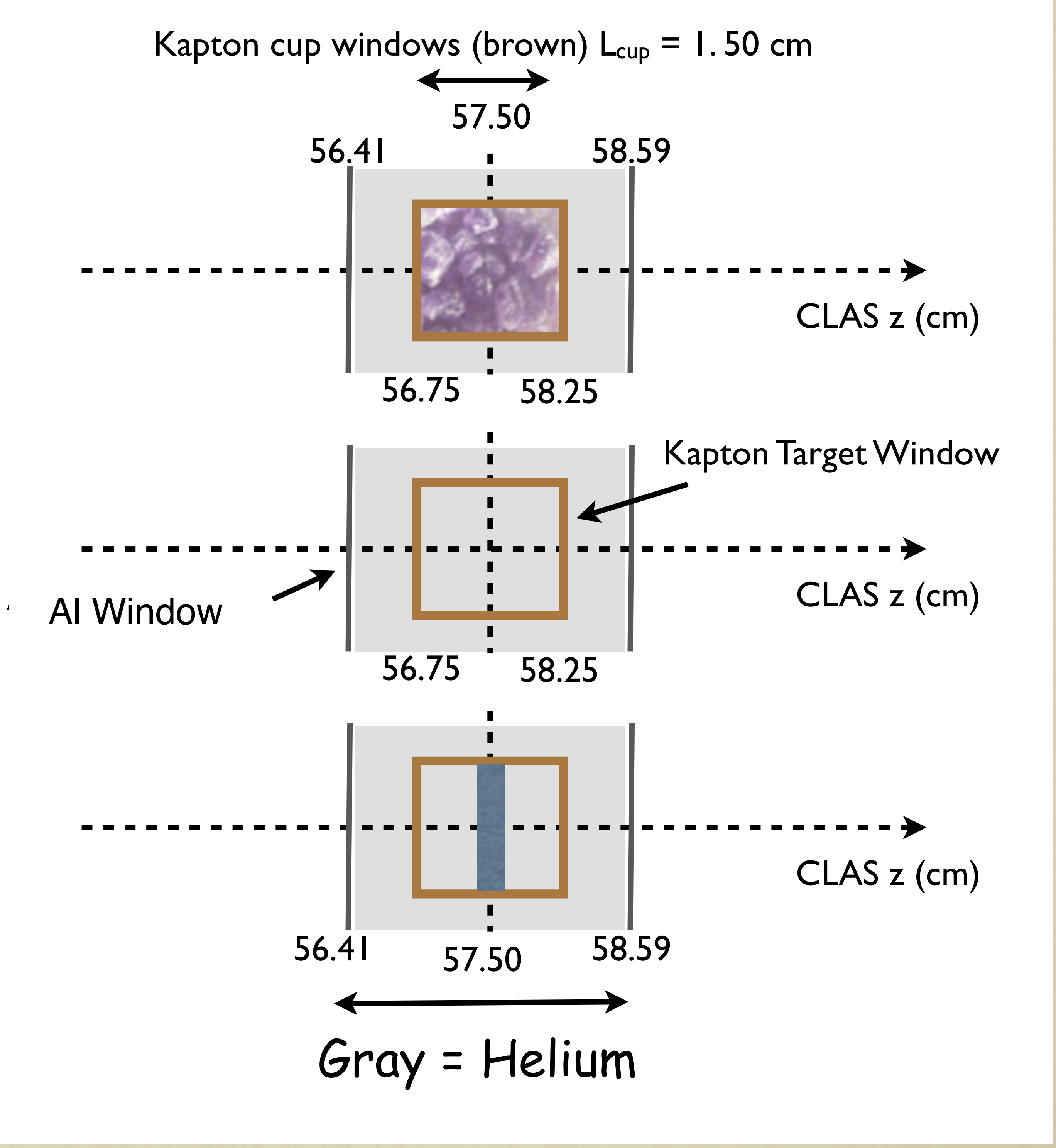
$$\frac{g_1}{F_1} = \frac{A_{LL}}{D'}$$

- Beam polarization (P_B)
- Target polarization (P_T)
- Dilution (f)
- Depolarization (D')

The dilution factor was predicted by a SIDIS model constrained by the ratio of ammonia to carbon data.

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

n = SIDIS event rate



The SIDIS model supports kinematic dependence of dilution in (x_B, Q^2, z, $P_{h\perp}$).

Start with the one nucleon cross-section using PDFs from GRV98

$$\sigma_p^{\pi^+} \propto (4u + d_s) + (4u_s + d) r_f$$

$$\sigma_n^{\pi^+} \propto (4d + u_s) + (4d_s + u) r_f$$

where r_f is the ratio of favored to unfavored fragmentation functions approximated by

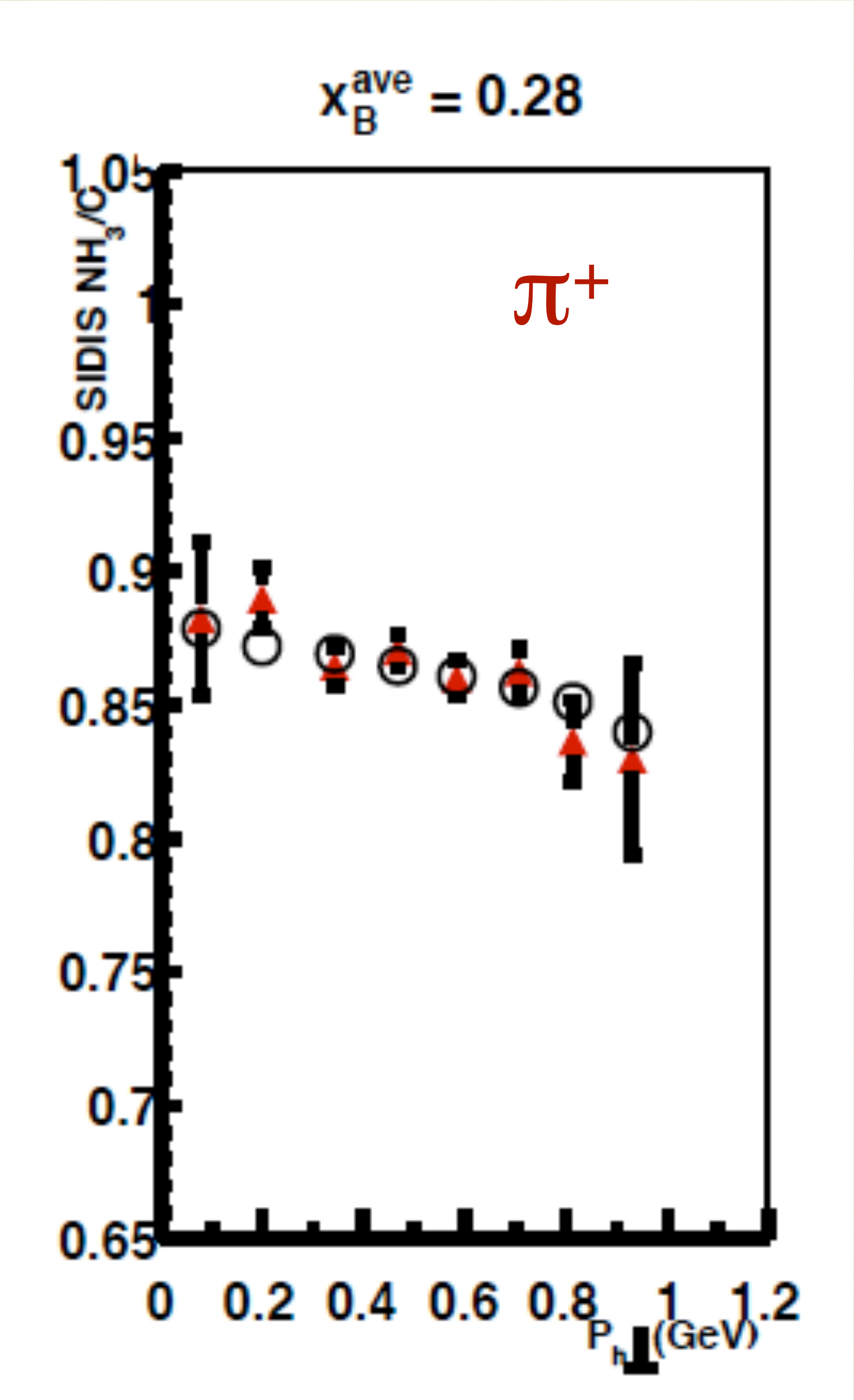
$$\frac{1}{(1+z)^2}$$

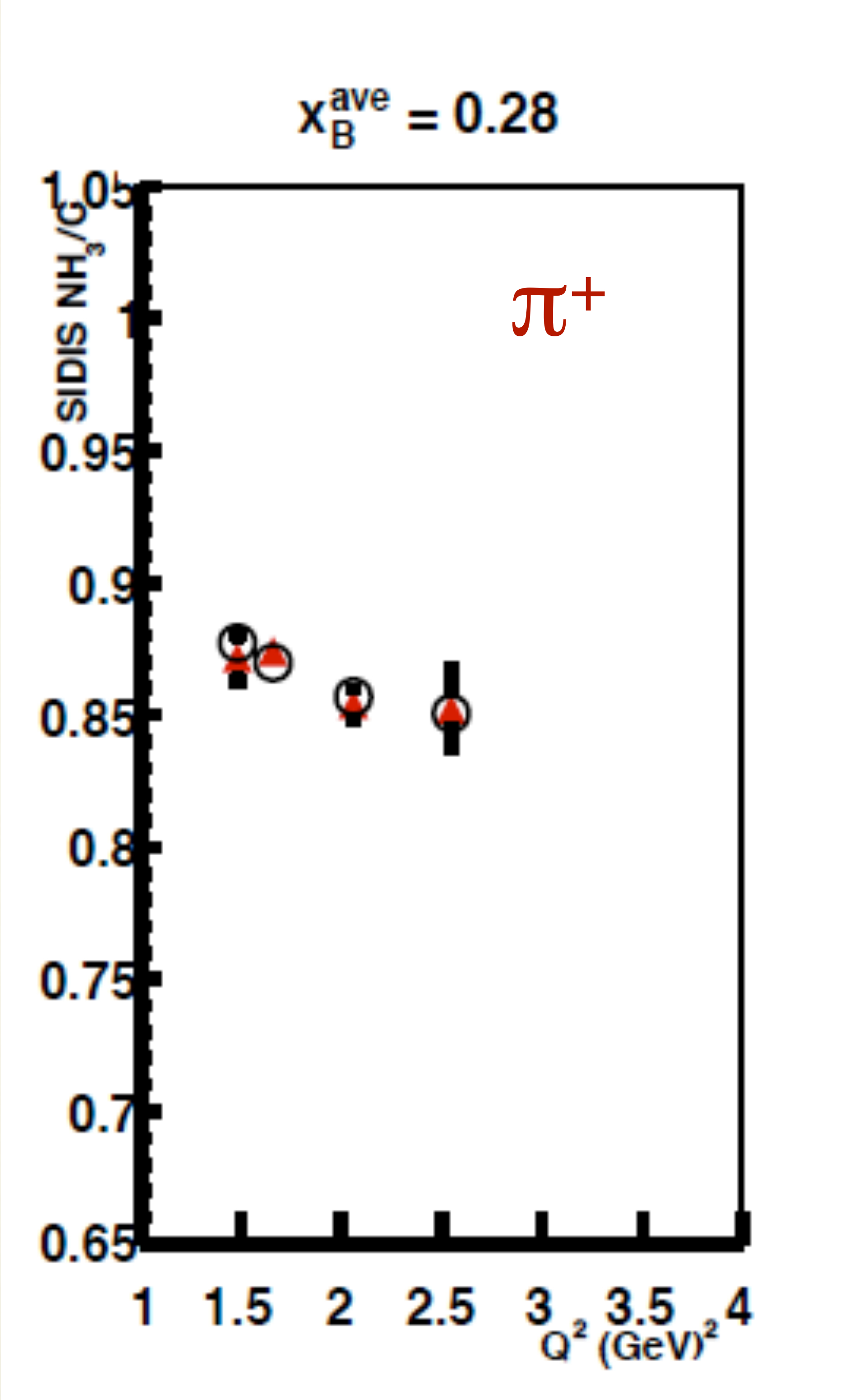
Add in nuclear attenuation, e.g. Aluminum

$$\sigma_{Al}^{\pi^+} = \frac{13\sigma_p^{\pi^+} + 14\sigma_n^{\pi^+}}{27} A_T^{Al}(Q^2, x_B, z, P_{h\perp})$$

Use.

The model is constrained by SIDIS data for NH_3/C data.





Physics Results.

1. Beam Spin Asymmetry (BSA)
2. Target Spin Asymmetry (TSA)
3. Double Spin Asymmetry (DSA)

eg1-dvcs measures moments of helicity structure functions.

$$A_{UL} = \frac{d\sigma^{0\rightarrow} - d\sigma^{0\leftarrow}}{d\sigma^{0\rightarrow} + d\sigma^{0\leftarrow}}$$

$$A_{UL} = A_{UL}^{\sin\phi_h} \sin\phi_h + A_{UL}^{\sin 2\phi_h} \sin 2\phi_h$$

$$A_{LU} = \frac{d\sigma^{\rightarrow 0} - d\sigma^{\leftarrow 0}}{d\sigma^{\rightarrow 0} + d\sigma^{\leftarrow 0}}$$

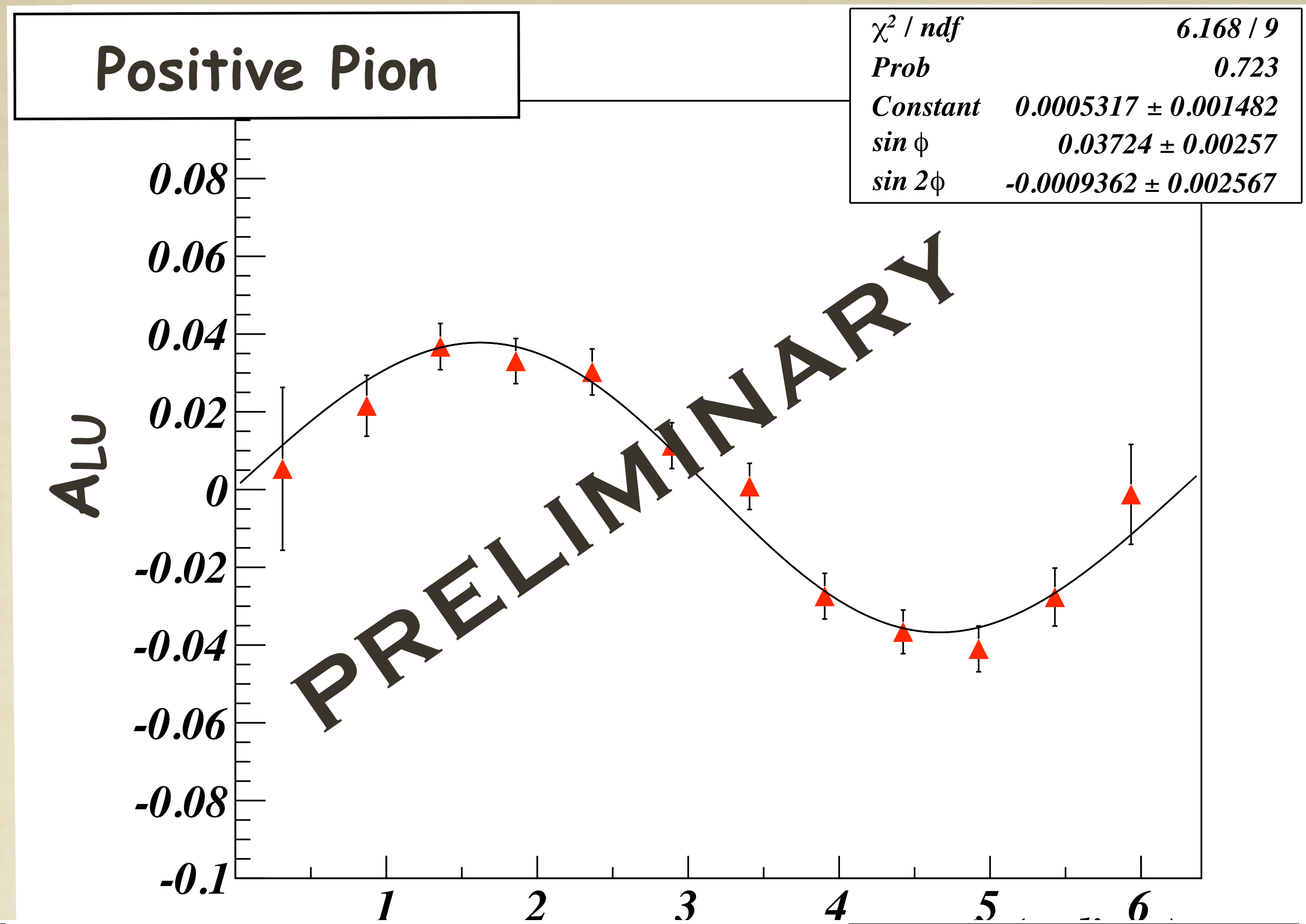
$$A_{LU} = A_{LU}^{\sin\phi_h} \sin\phi_h$$

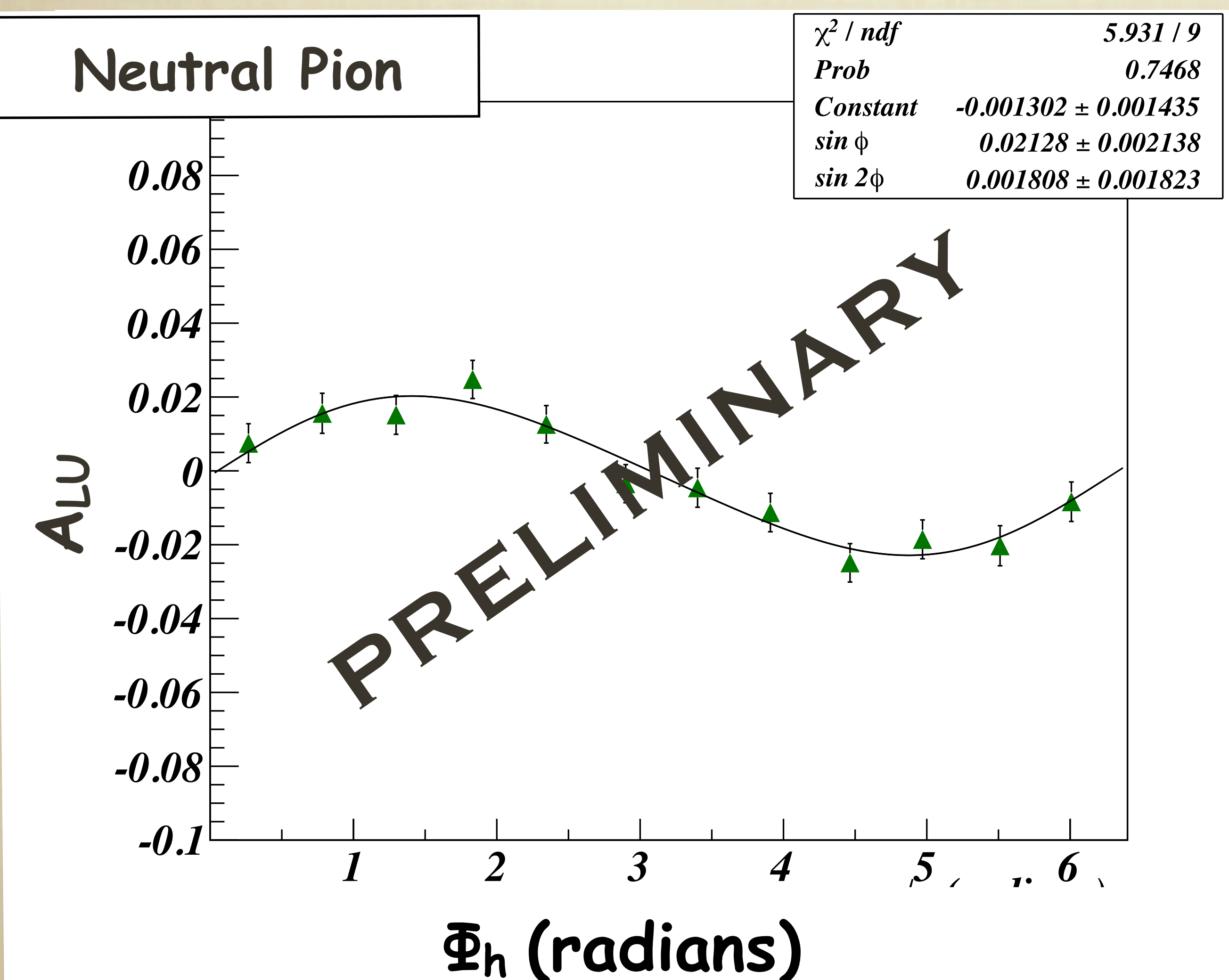
$$A_{LL} = \frac{d\sigma^{\rightarrow\rightarrow} - d\sigma^{\leftarrow\rightarrow} - d\sigma^{\rightarrow\leftarrow} + d\sigma^{\leftarrow\leftarrow}}{d\sigma^{\rightarrow\rightarrow} + d\sigma^{\leftarrow\rightarrow} + d\sigma^{\rightarrow\leftarrow} + d\sigma^{\leftarrow\leftarrow}}$$

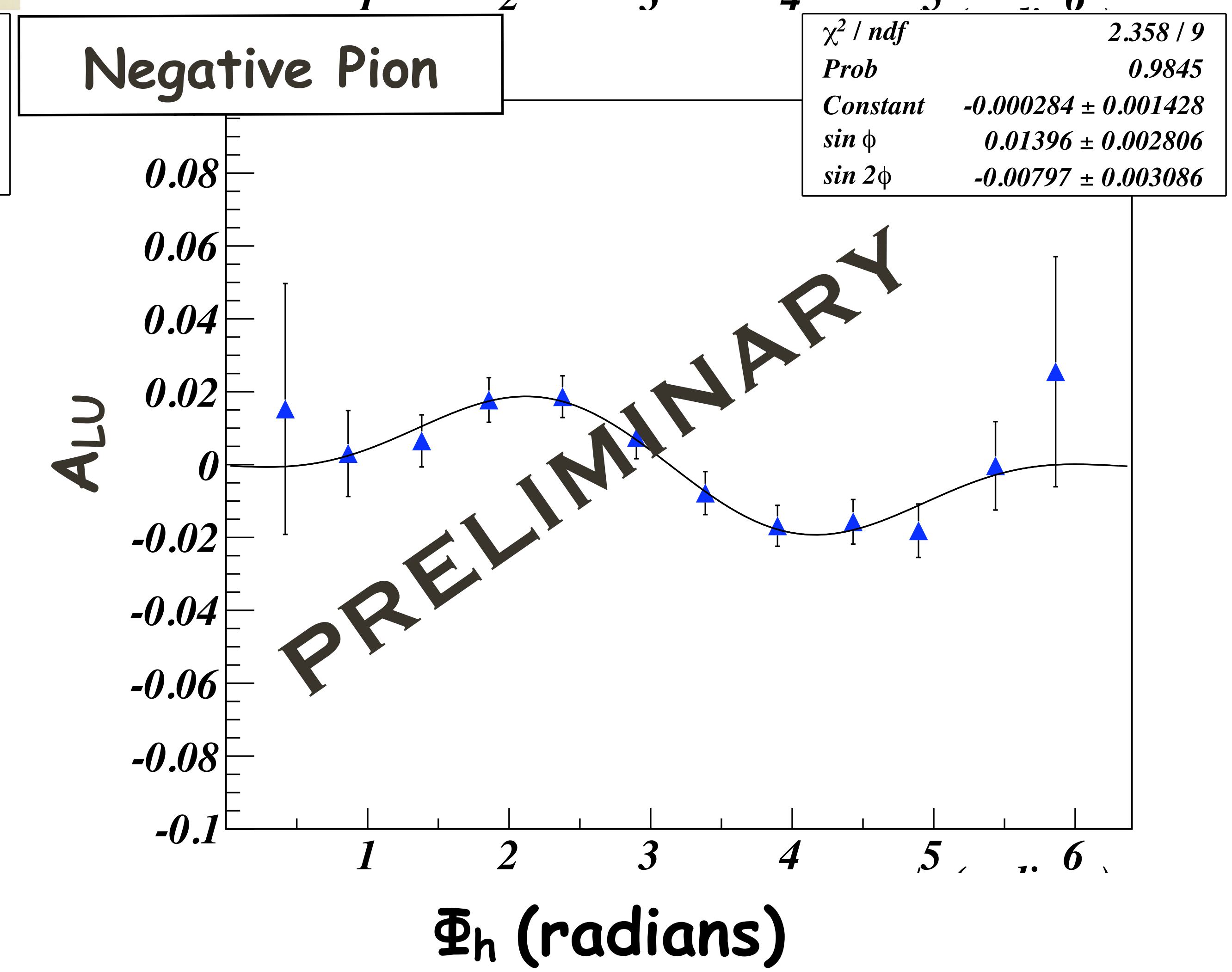
$$A_{LL} = A_{LL}^{C} + A_{LL}^{\cos\phi_h} \cos\phi_h$$

$$\frac{d^7\sigma}{dx_B\, dy\, d\psi\, dz\, d\phi_h\, dP_{h\perp}^2}$$

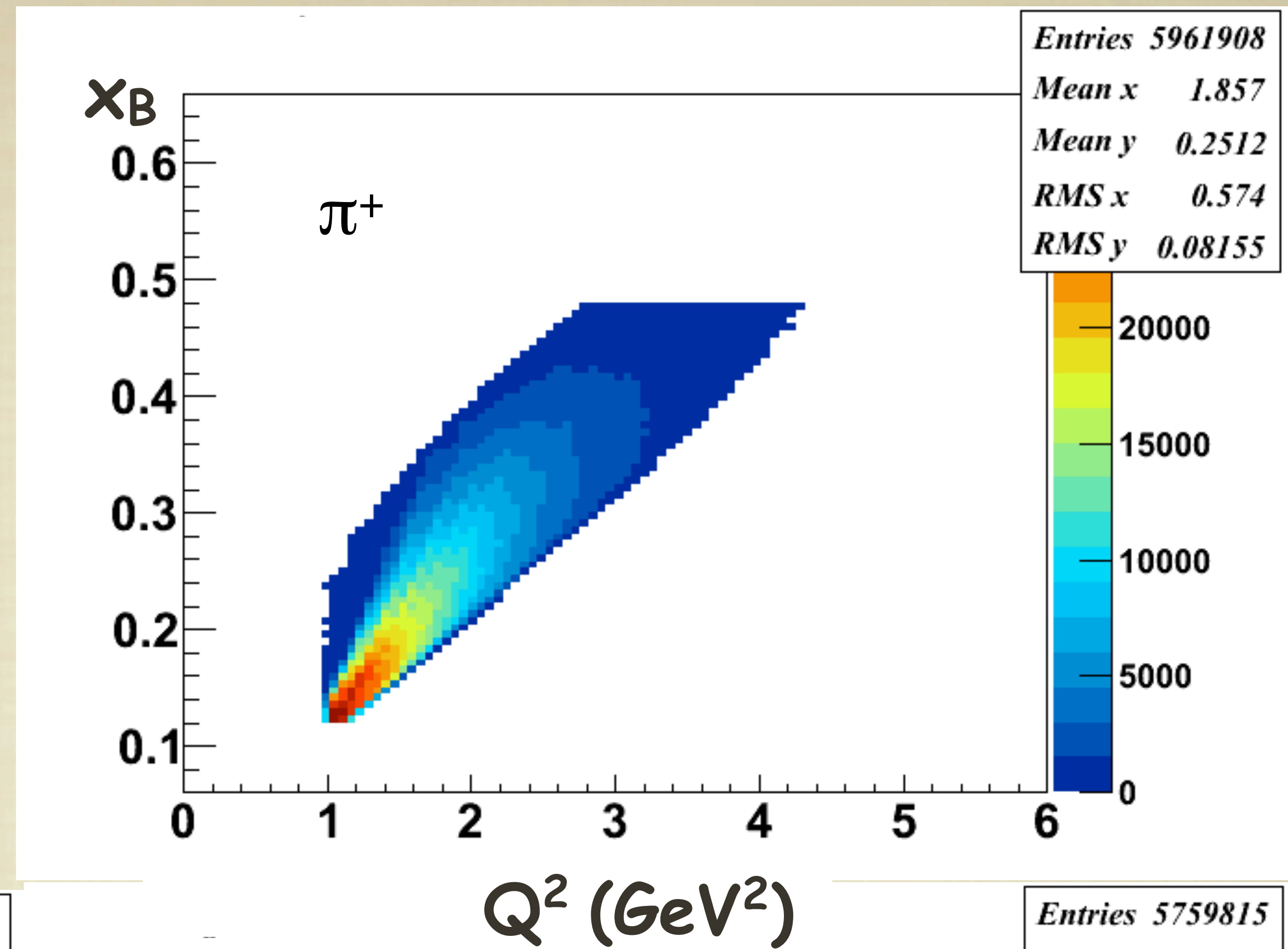
Asymmetries integrated over all except the azimuthal angle show clear sine moments.

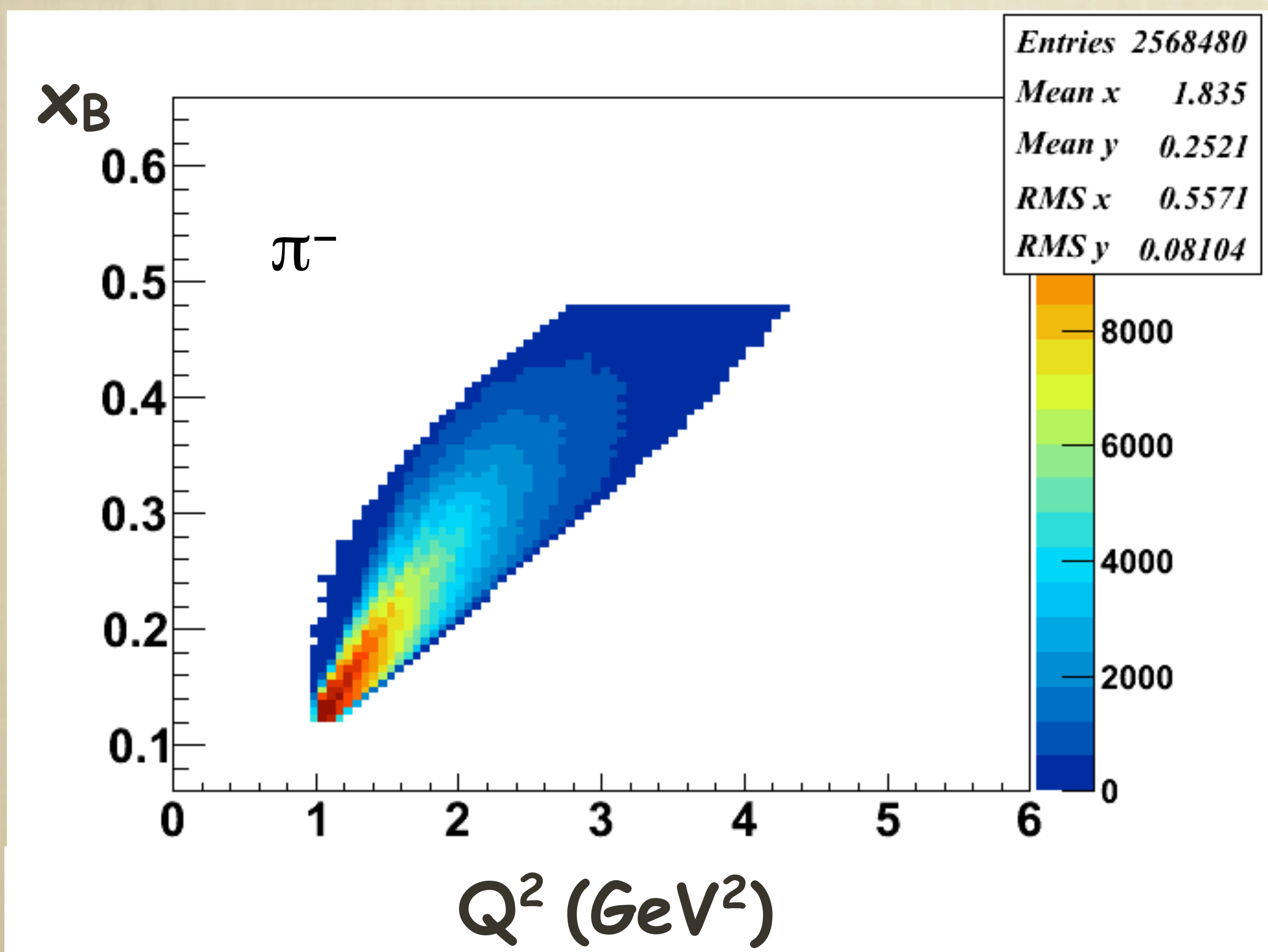


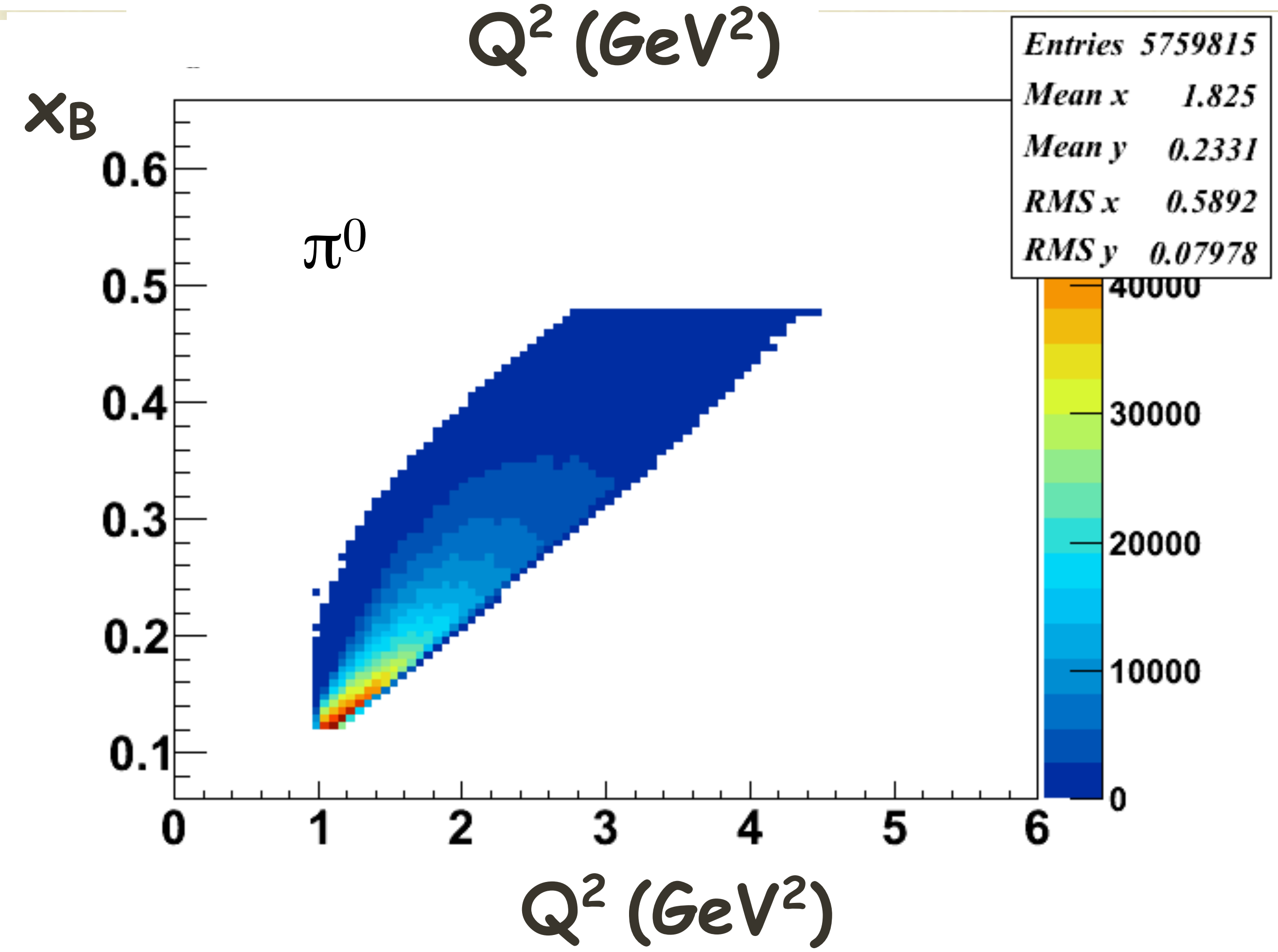




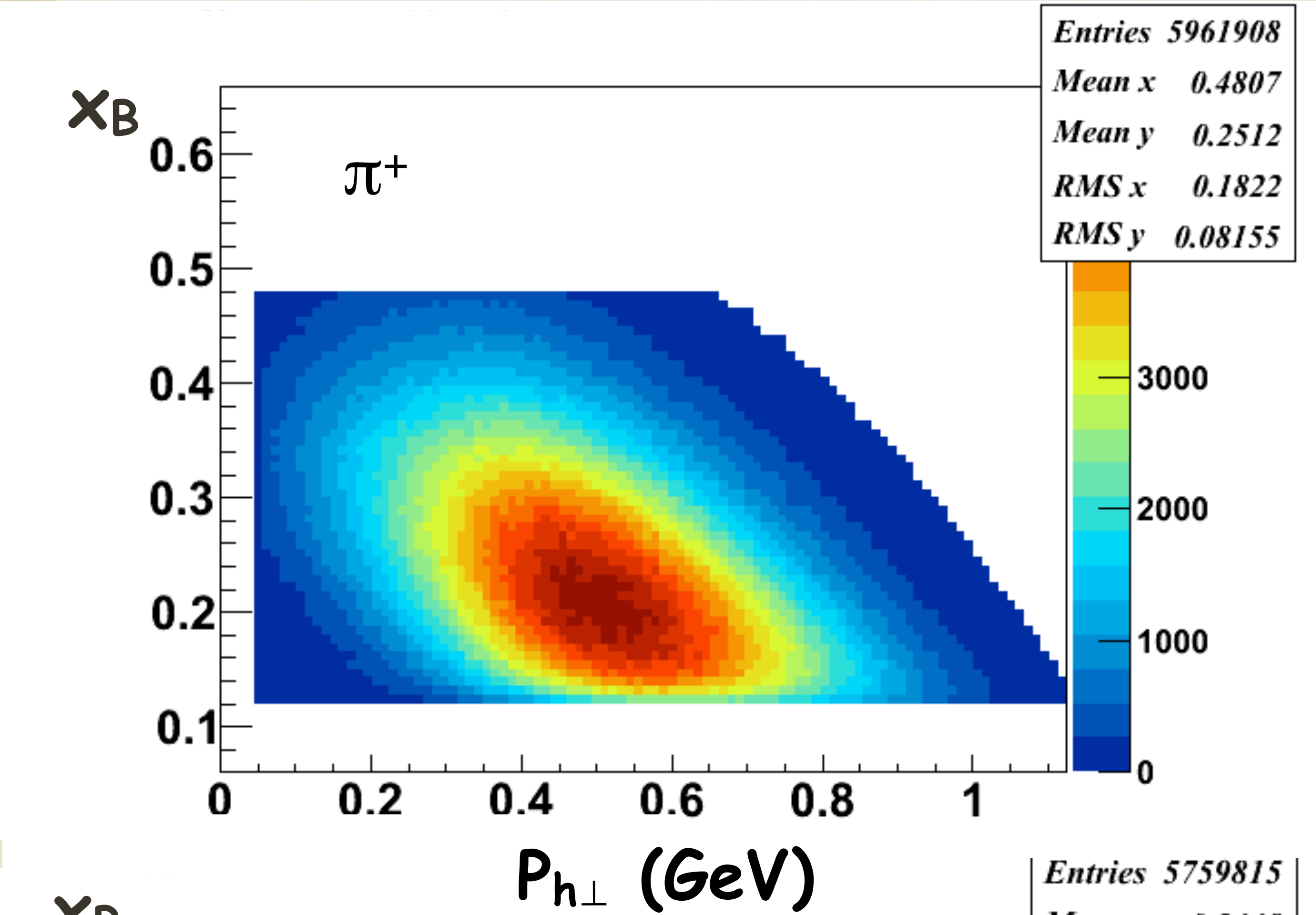
The kinematic coverage spanned by CLAS and the IC in terms of distribution variables.

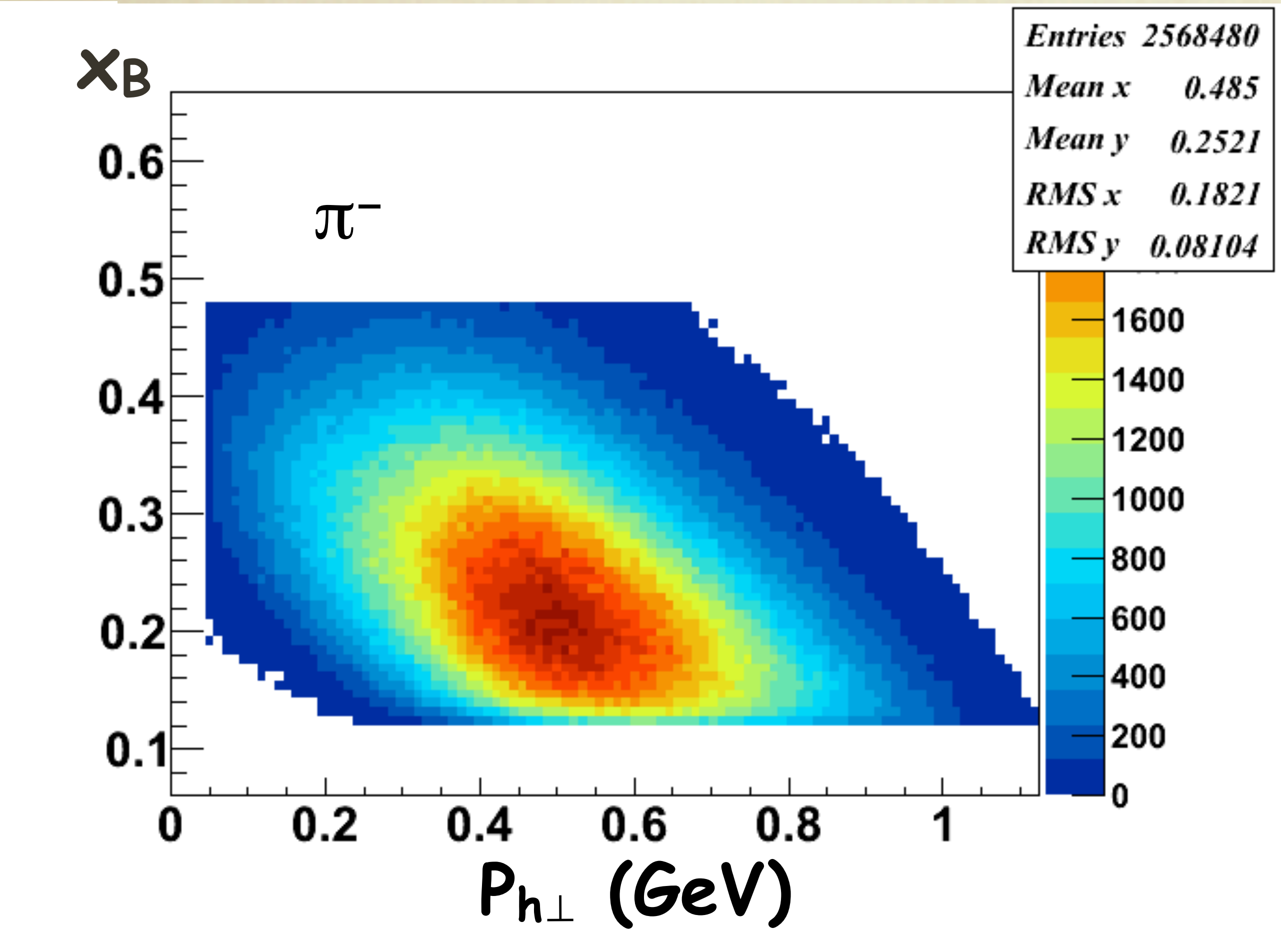


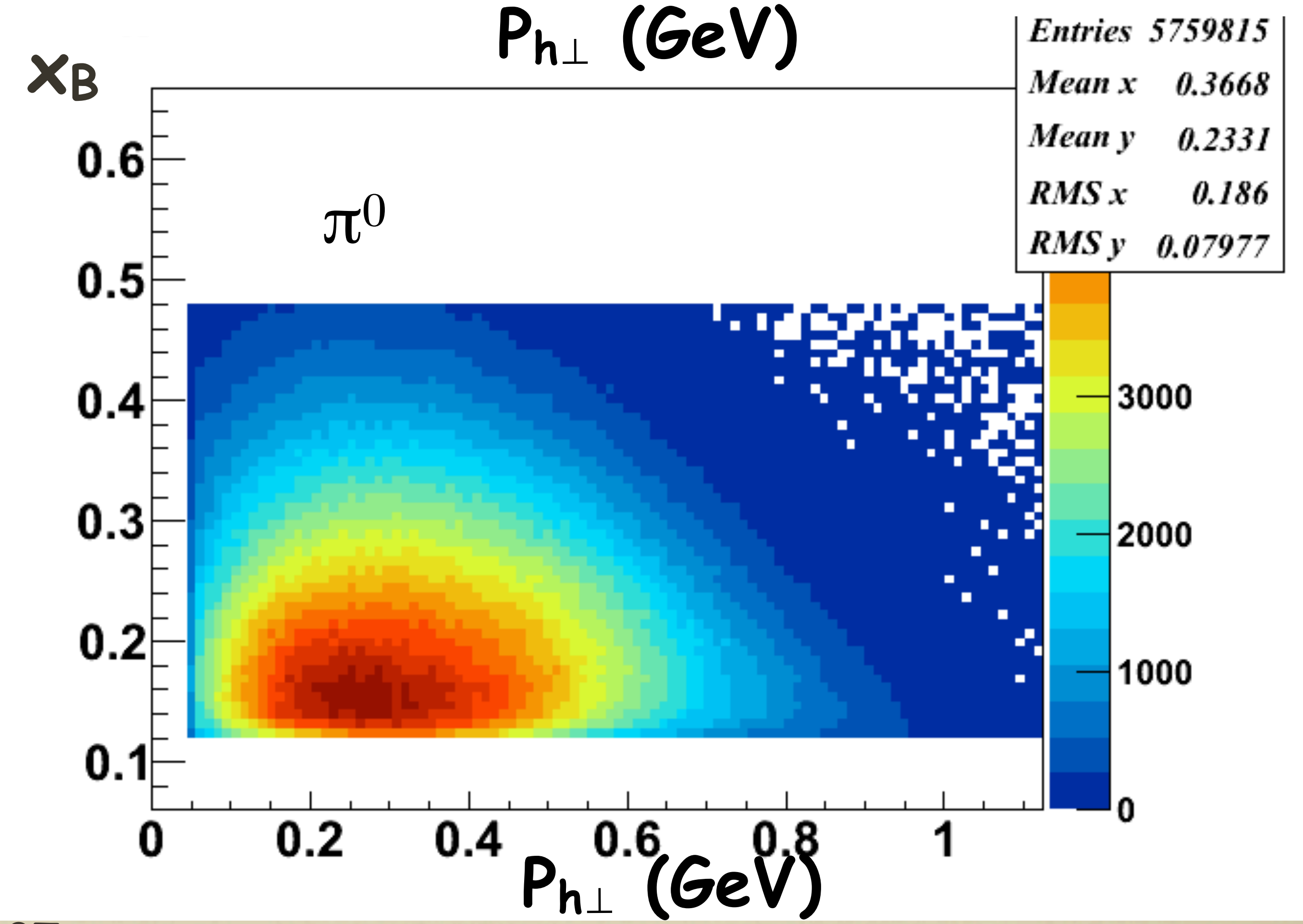


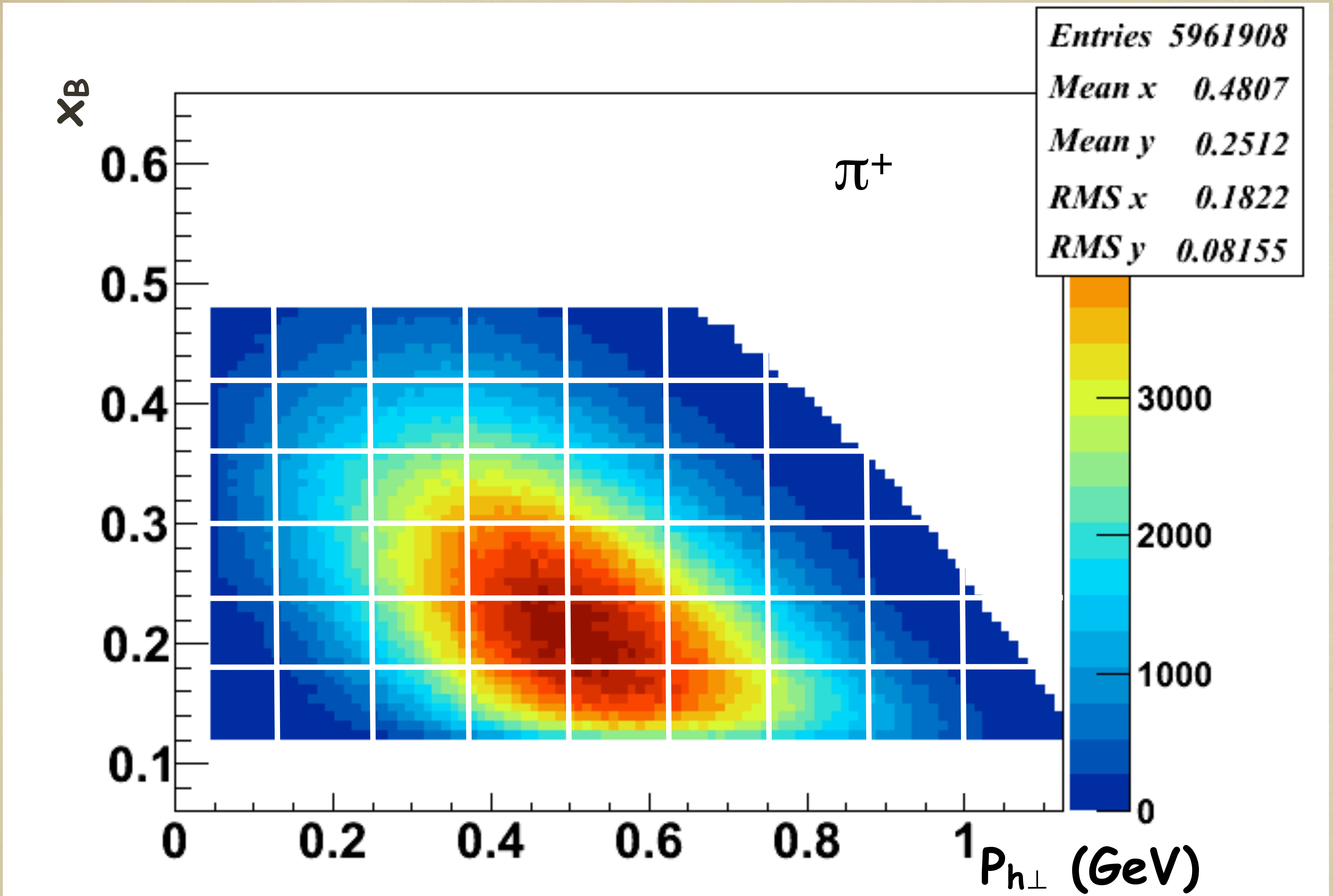


The kinematic coverage spanned by CLAS and the IC in terms of distribution and fragmentation variables.



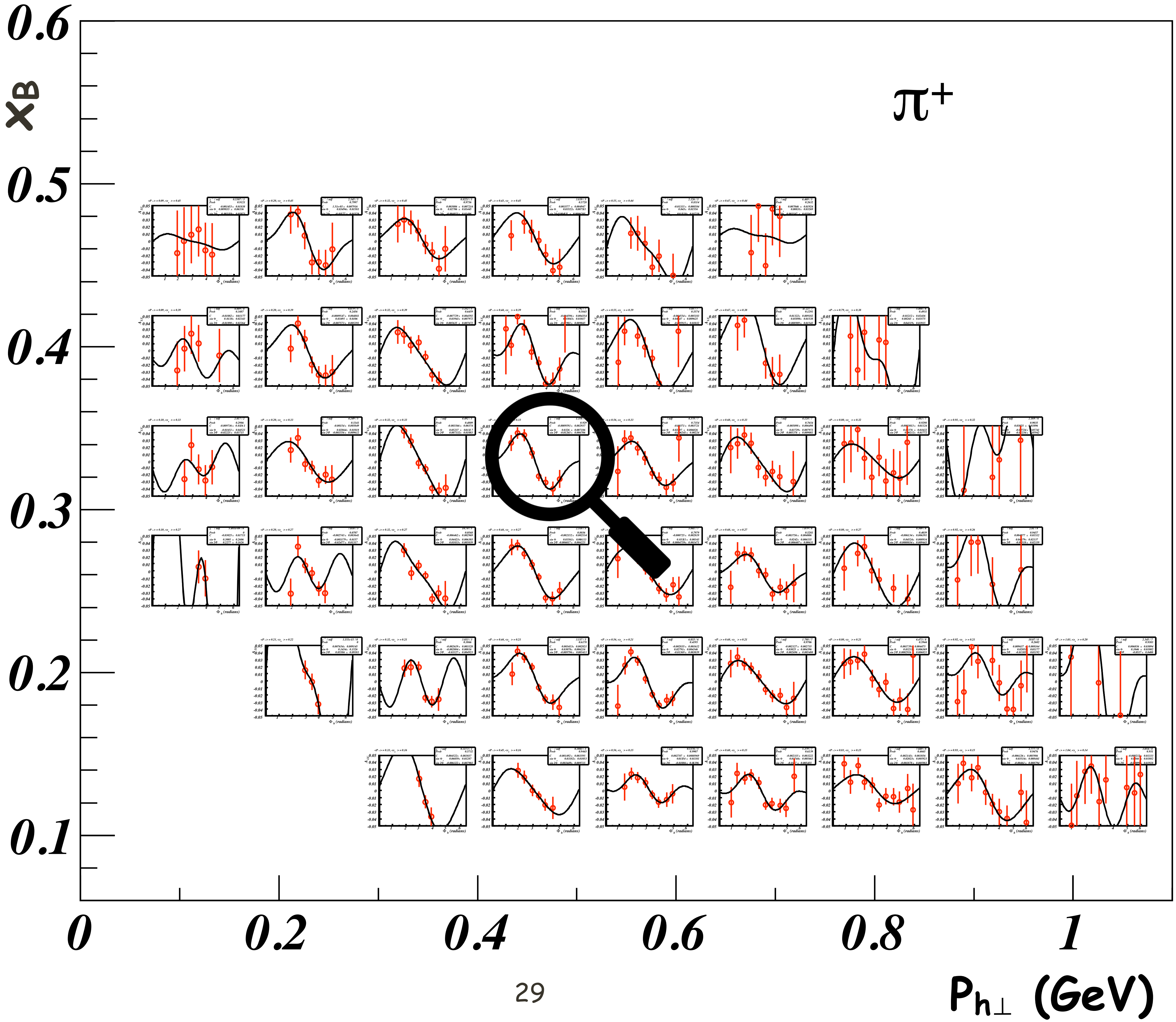






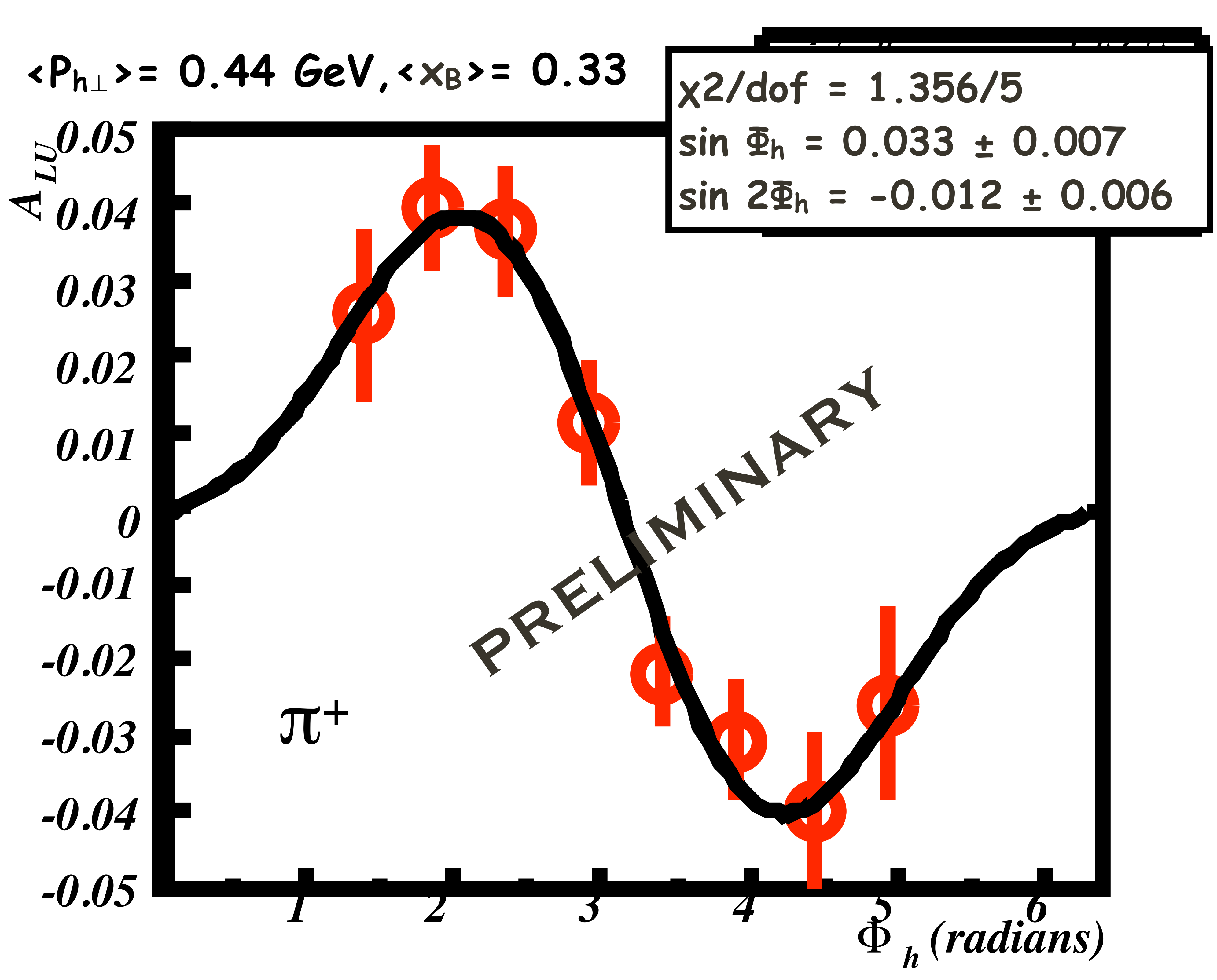
x_B
0.6
0.5
0.4
0.3
0.2
0.1
0
0.2
0.4
0.6
0.8
1
$P_{h\perp}$ (GeV)
π^+
Entries 5961908
Mean x 0.4807
Mean y 0.2512
RMS x 0.1822
RMS y 0.08155
3000
2000
1000
0

Beam Spin Asymmetry (A_{LU}) for π^+



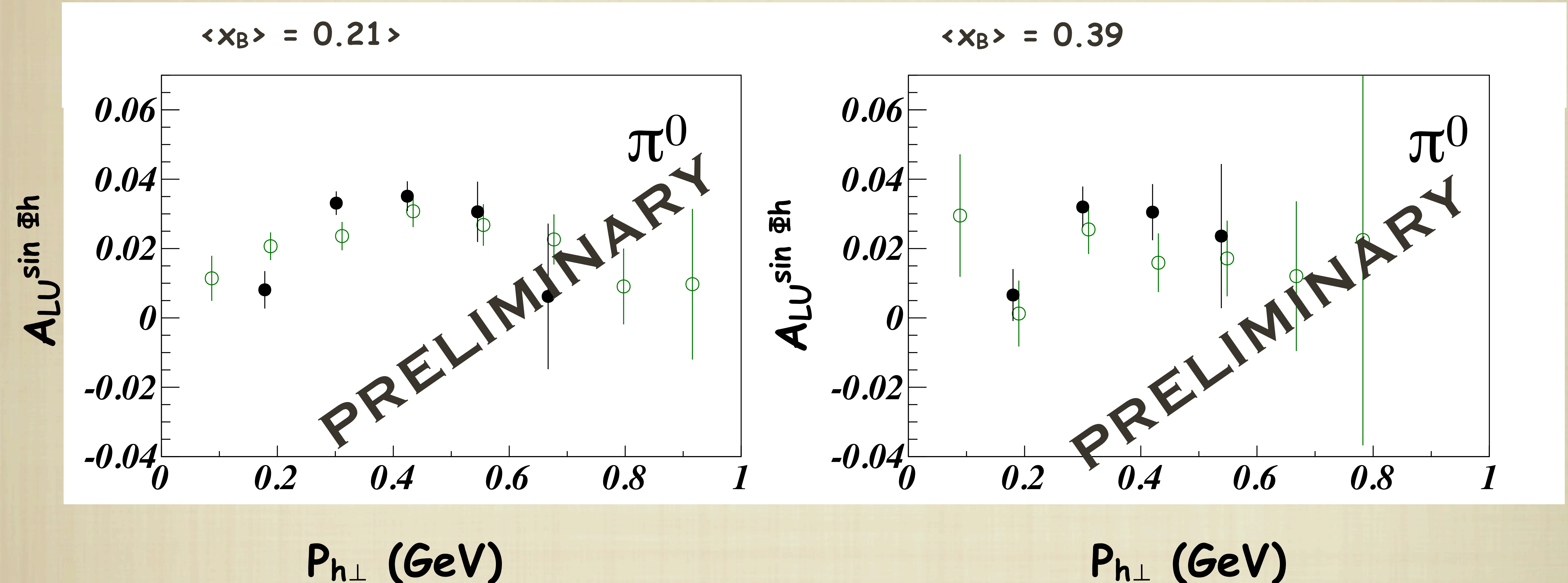
The function used to fit the BSA is,

$$A_{LU} = C + A_{LU}^{\sin \Phi h} \sin\Phi_h + A_{LU}^{\sin 2\Phi h} \sin 2\Phi_h.$$



Interpretation

The beam spin asymmetry is consistent with data on pure hydrogen.



Green Points from: **eg1-dvcs**

Black Points from: M. Aghasyan et al. **Phys.Lett. B704 (2011)**

A_{LU}

- **No noticeable nuclear effect in the beam spin asymmetry while comparing with pure hydrogen.**

Comparison to the model predictions by Anselmino et al. [hep-ph/0608048] are consistent with the data.

$$f_1^q(x_B,k_\perp) = f_1^q(x_B)\frac{1}{\pi\mu_0^2}\exp\left(-\frac{k_\perp^2}{\mu_0^2}\right)$$

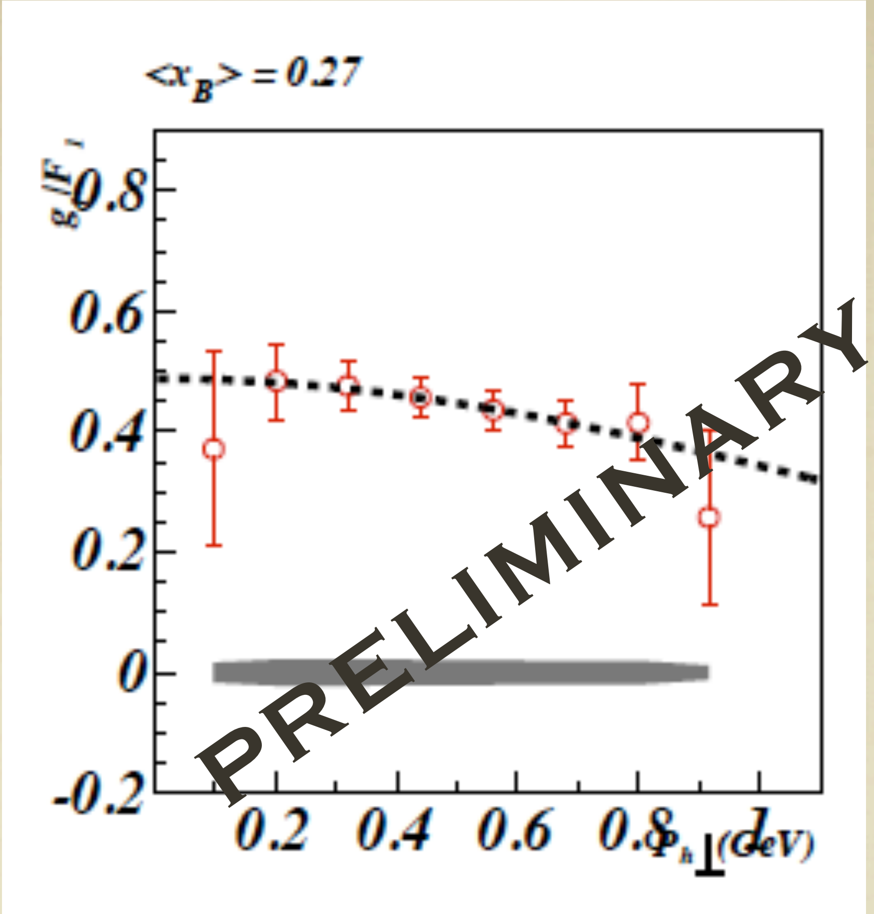
$$D_q^h(z,p_\perp) = D_q^h(z)\frac{1}{\pi\mu_D^2}\exp\left(-\frac{p_\perp^2}{\mu_D^2}\right)$$

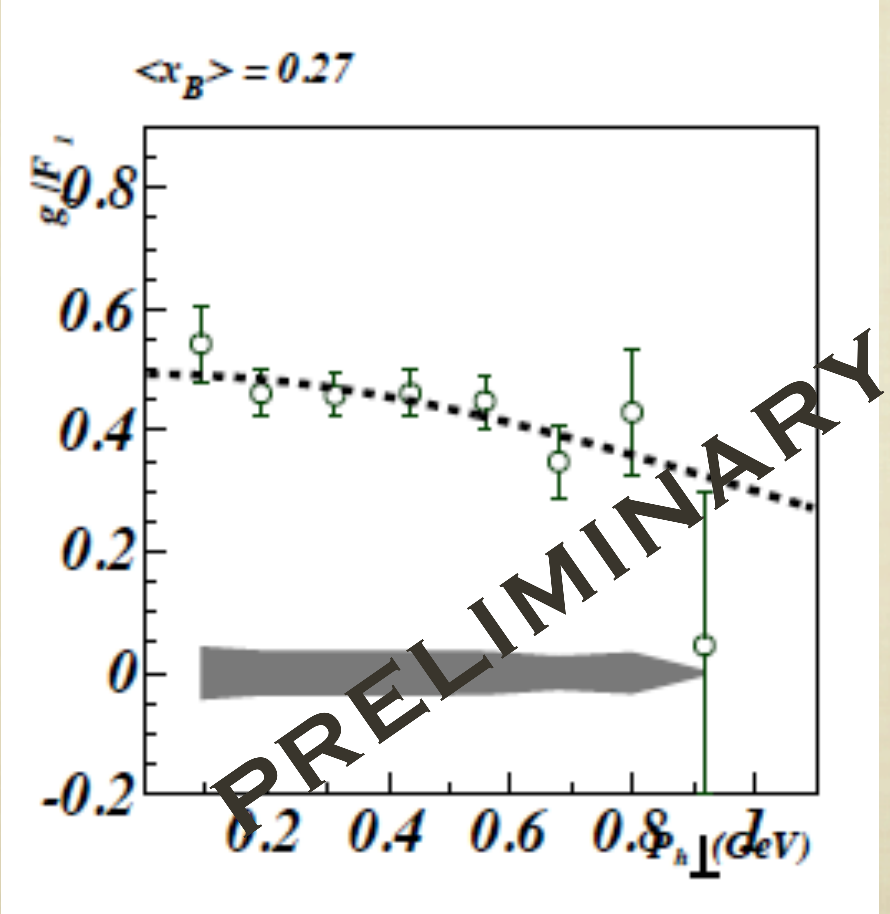
$$g_1^q(x_B,k_\perp) = g_1^q(x_B)\frac{1}{\pi\mu_2^2}\exp\left(-\frac{k_\perp^2}{\mu_2^2}\right)$$

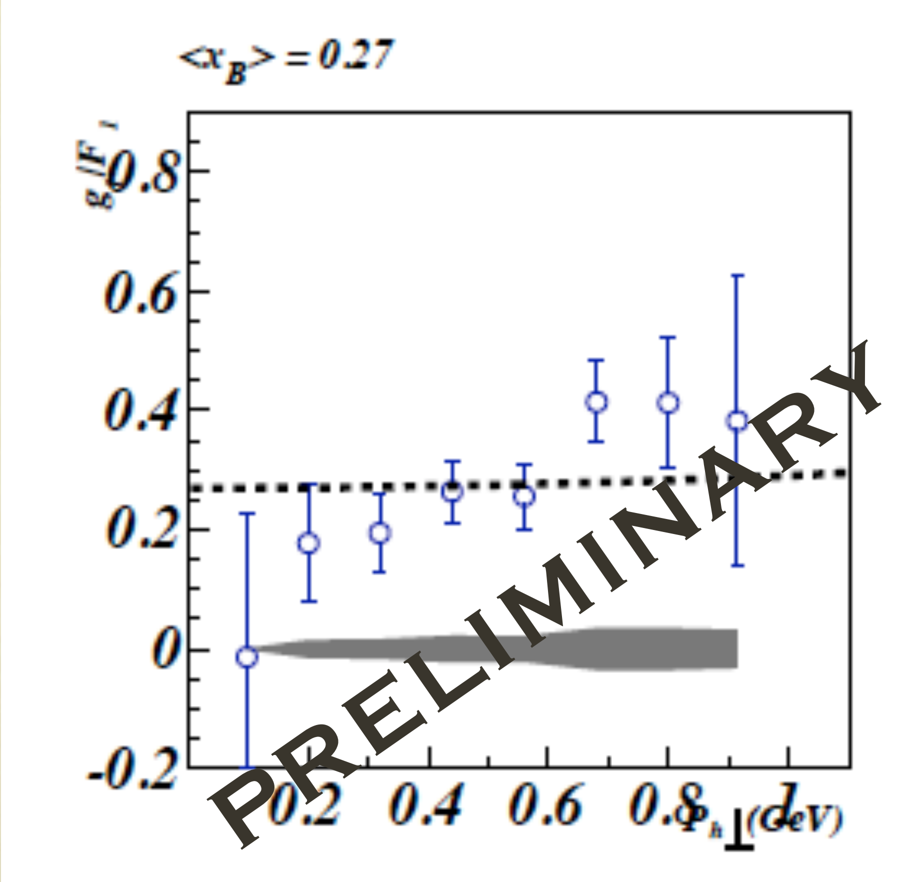
$$\frac{g_1}{F_1}(x_B,z,P_{h\perp}) = \frac{g_1}{F_1}(x_B,z)\left(\frac{\mu_D^2+z^2\mu_0^2}{\mu_D^2+z^2\mu_2^2}\right)\exp\left[z^2P_{h\perp}^2(\mu_2^2-\mu_0^2)\right]$$

- Simple picture assumes a Gaussian distribution for the TMD and FF
- Fit different widths for g_1 and F_1

g_1/F_1 shown in bins of $P_{h\perp}$ (GeV) and x_B for π^+, π^- and π^0.



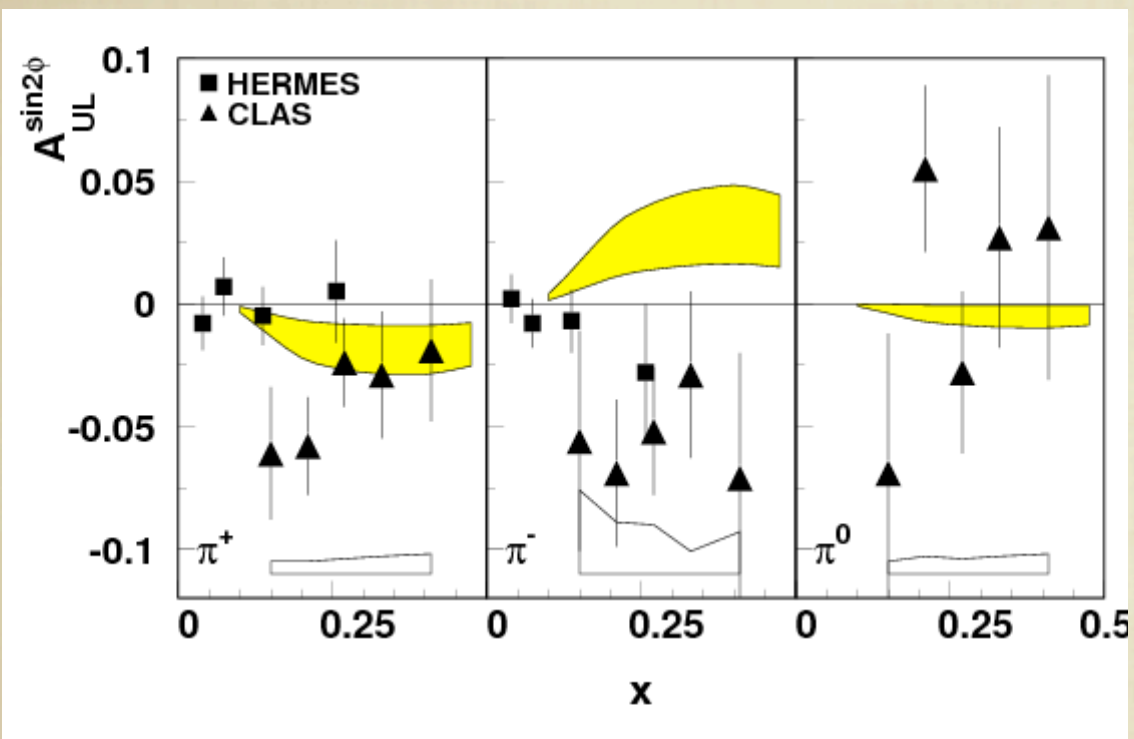


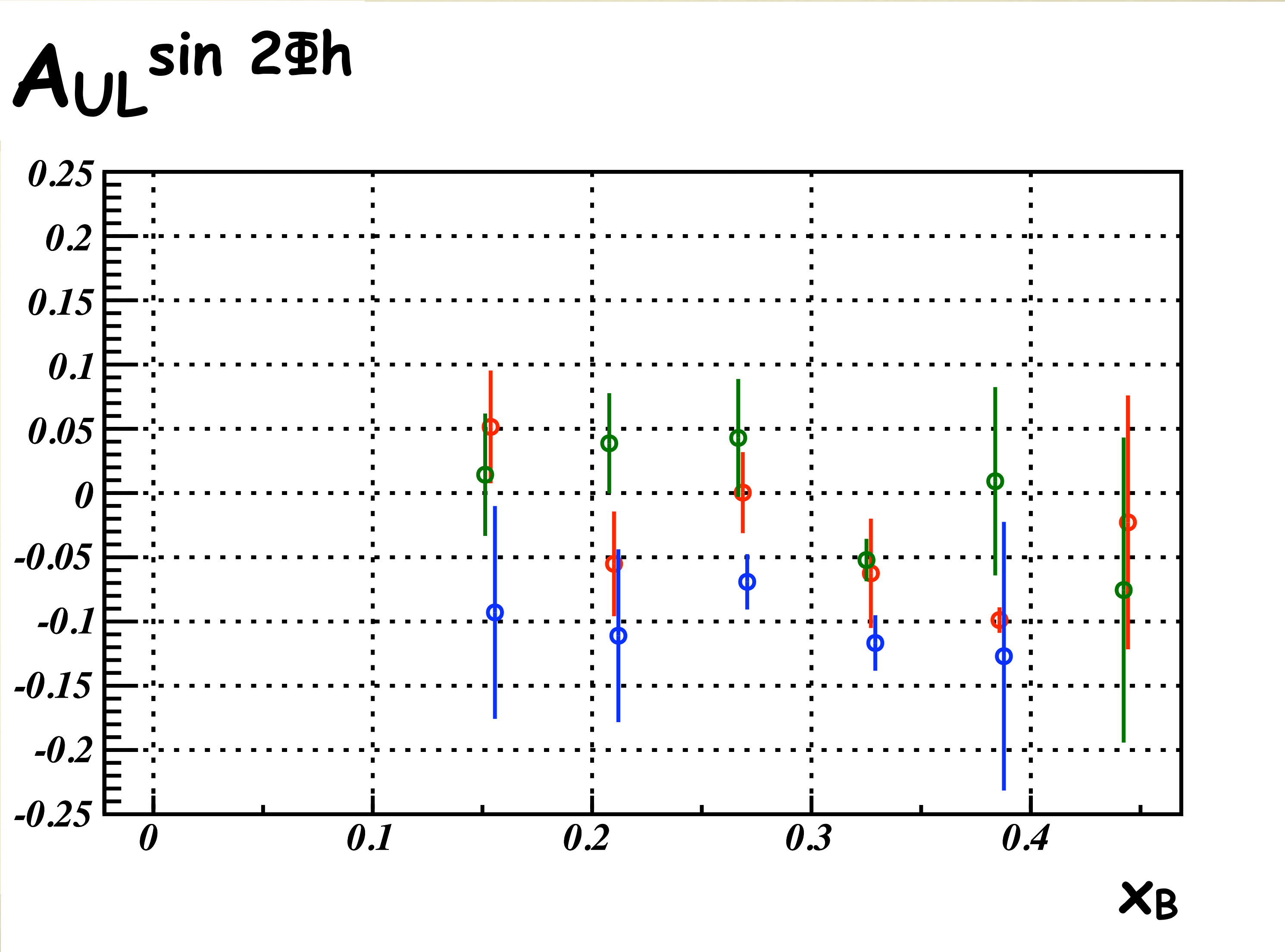


A_{LL}

- From the unintegrated data, g_1/F_1 consistent with Anselmino Model.

The TSA sin $2\Phi_h$ moment is confirmed below for $\langle P_{h\perp} \rangle$ = 0.43 GeV.





Effect first seen in H. Avakian et al. Phys.Rev.Lett. 105 (2010).

We measure semi-inclusive DIS asymmetries for a longitudinally polarized target, where we see

- No noticeable nuclear effect in the beam spin asymmetry while comparing with pure hydrogen. No significant difference in the neutron beam spin asymmetry

- From the unintegrated data, g1/F1 consistent with Anselmino Model.

- Confirmation of TSA sin $2\Phi_h$ moment. Higher twist term (sin Φ_h) dominates for TSA.

- Our data can be used in combination with other world data to get better determination of the TMDs, analogous to collinear PDFs





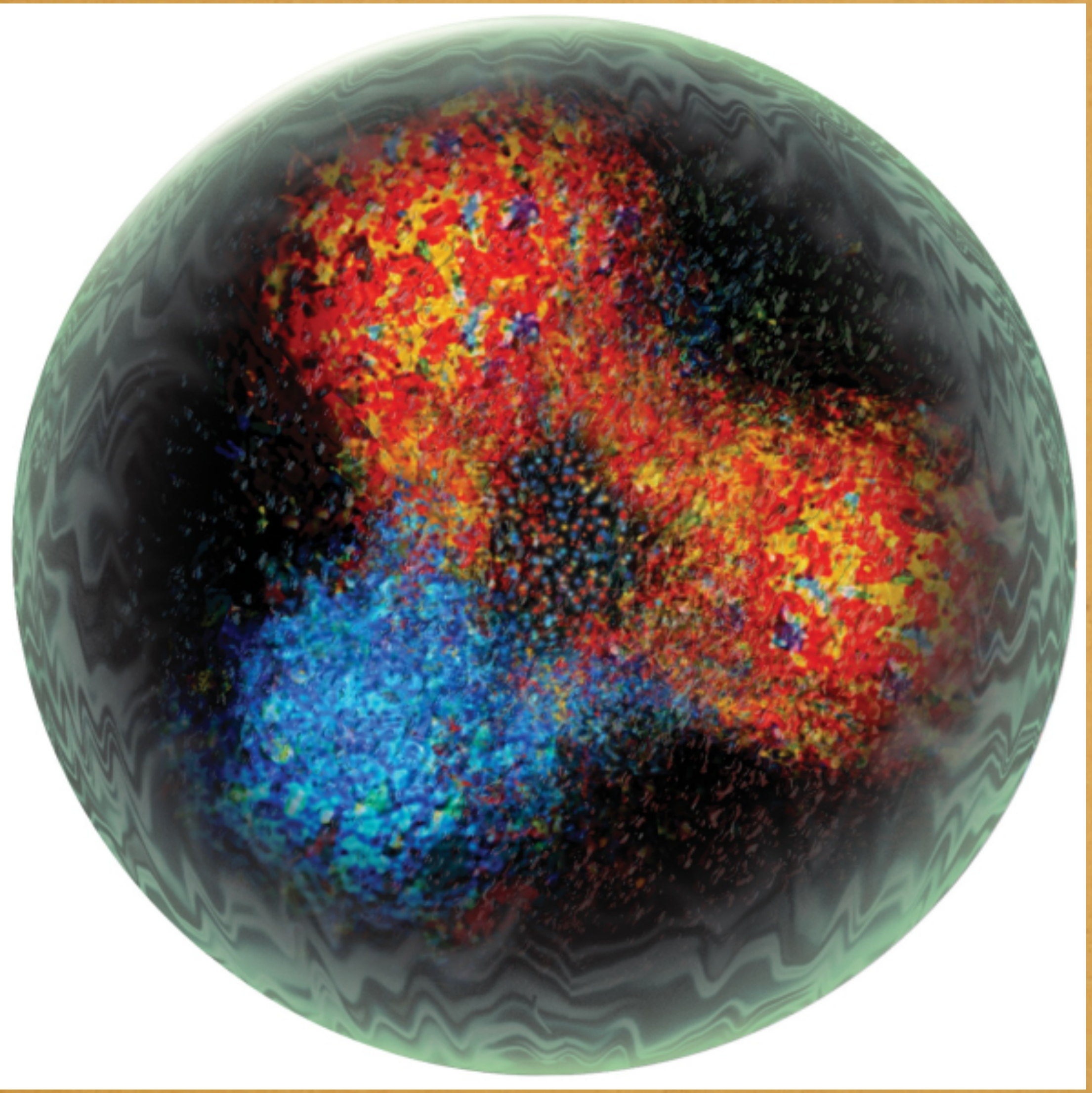


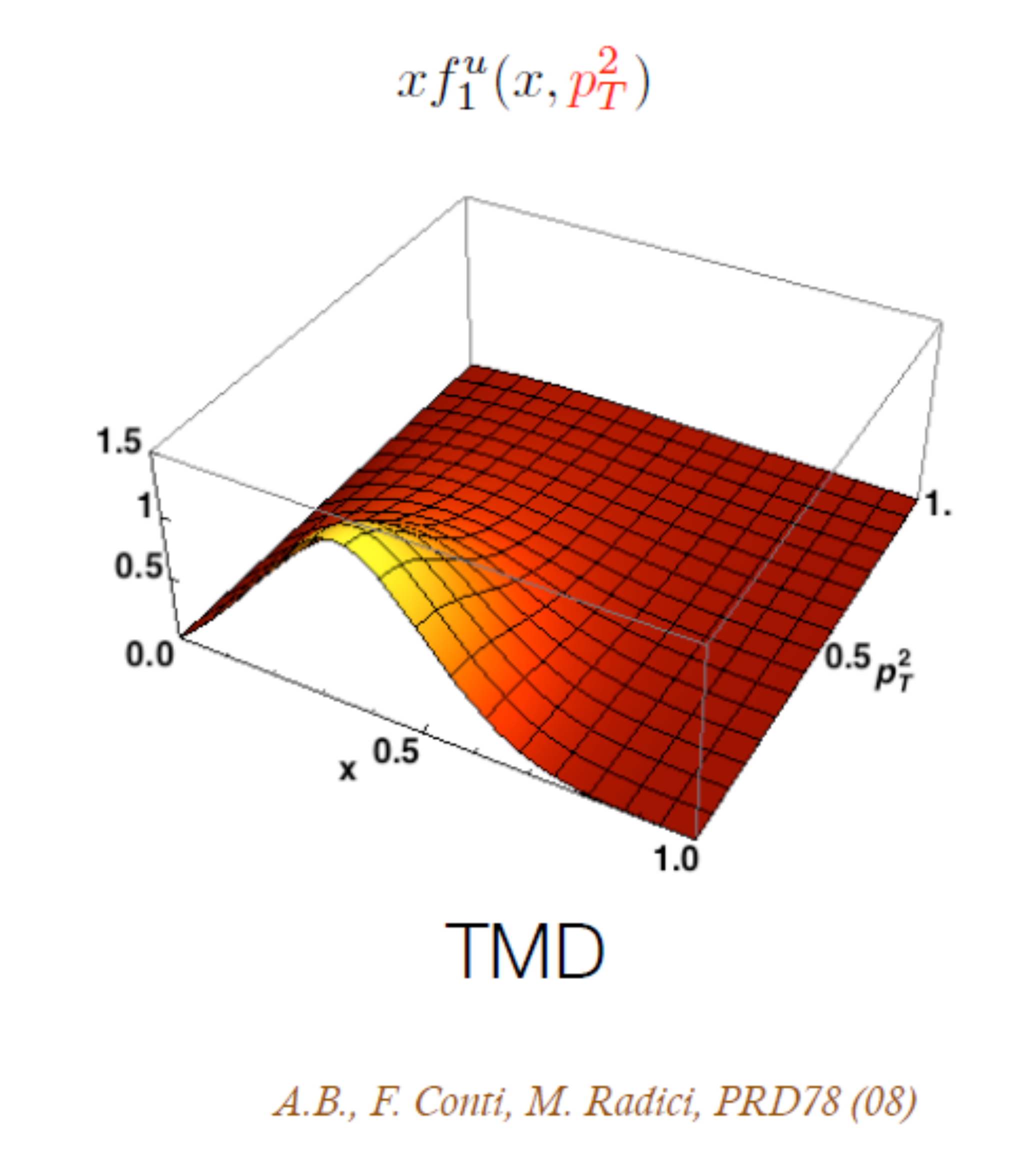




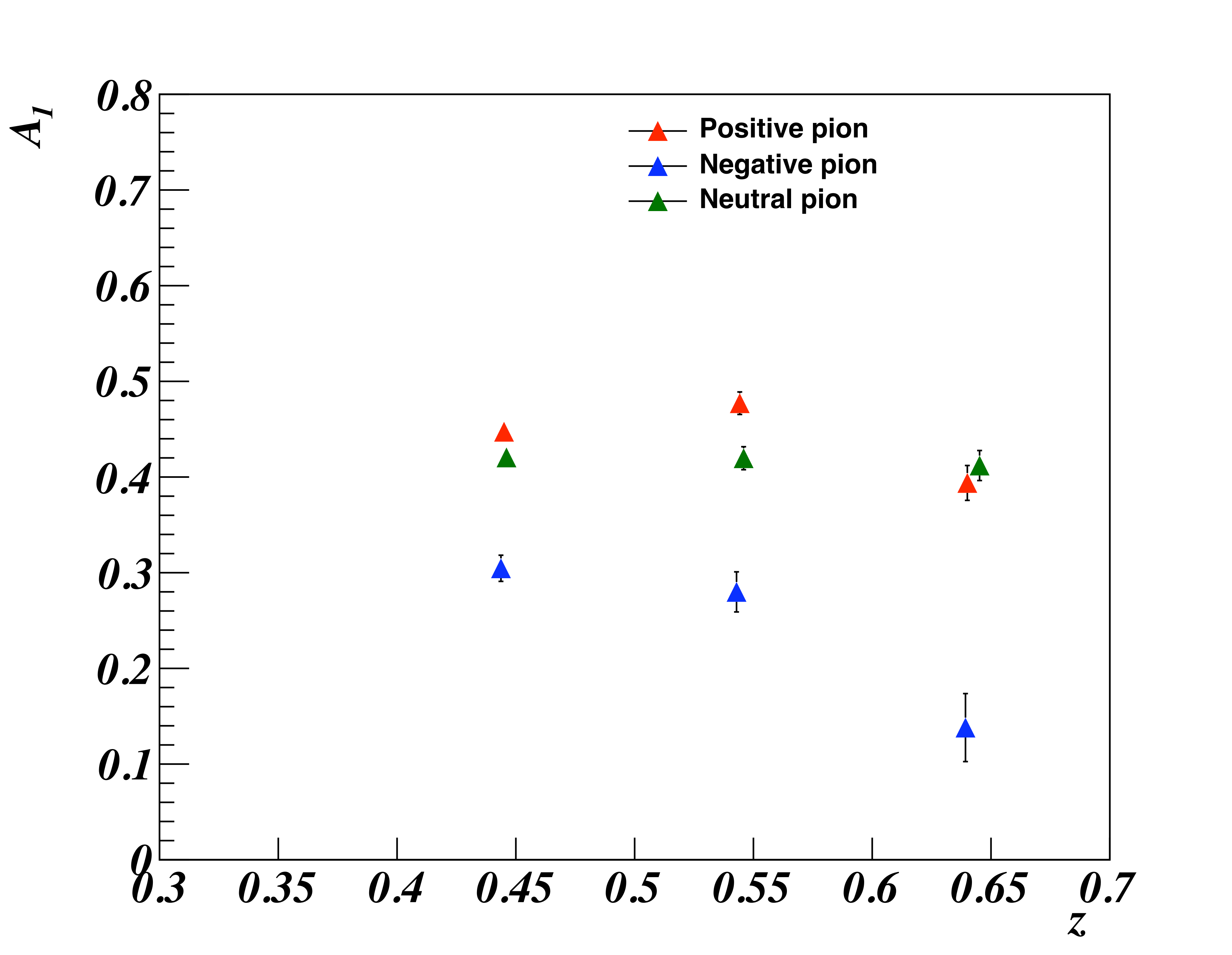



Goal is to study the internal structure of the nucleon in momentum space

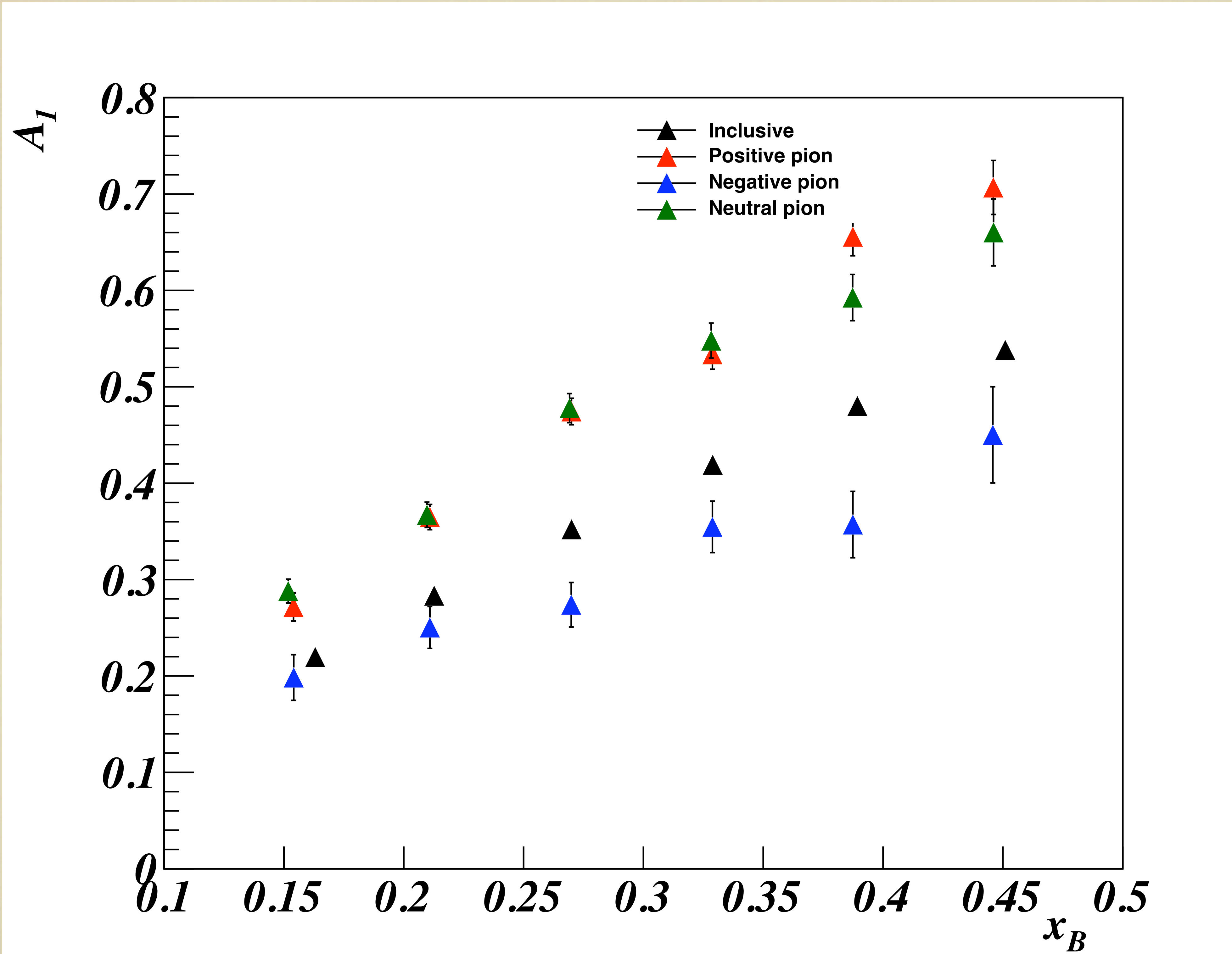




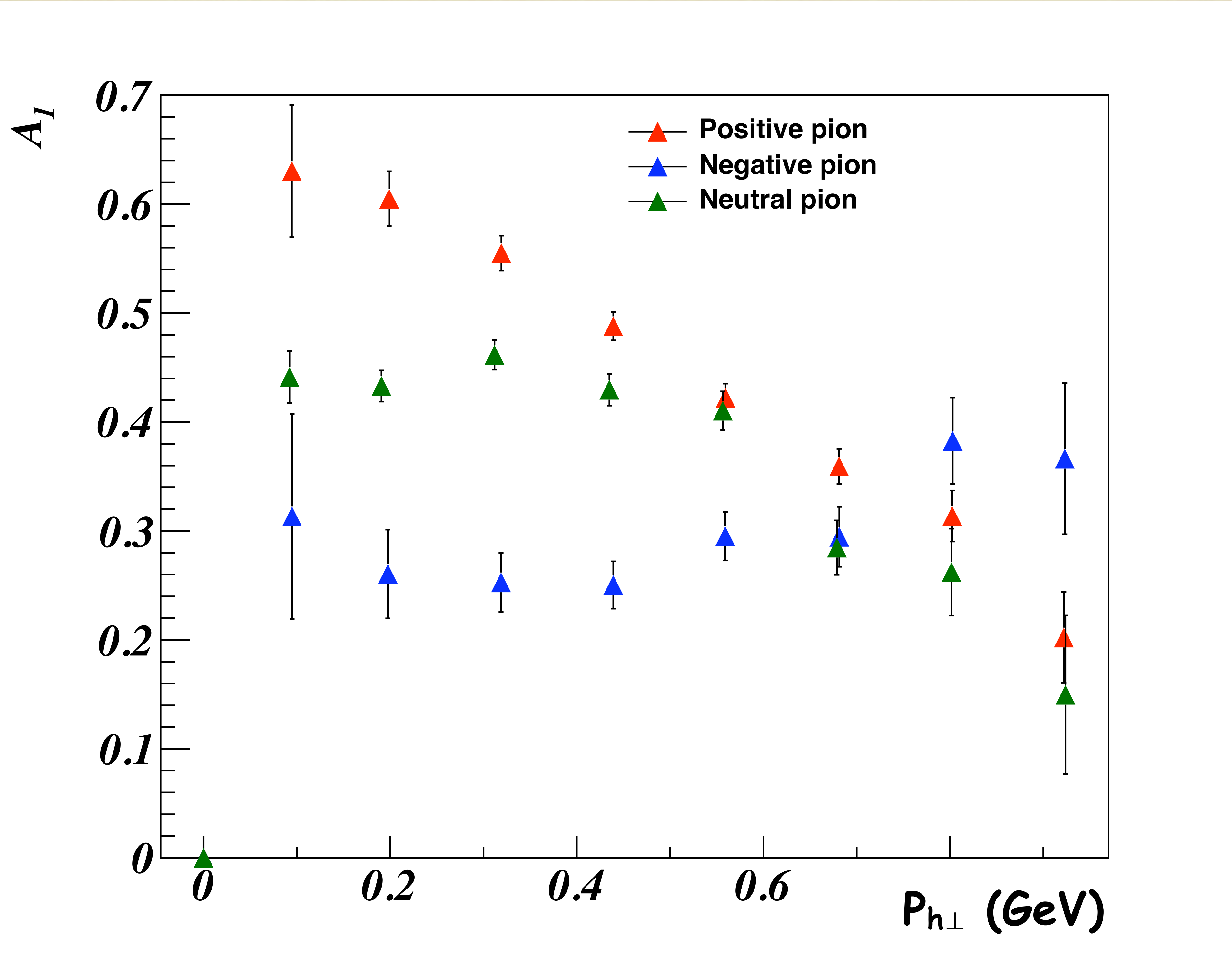
Data as a function of z



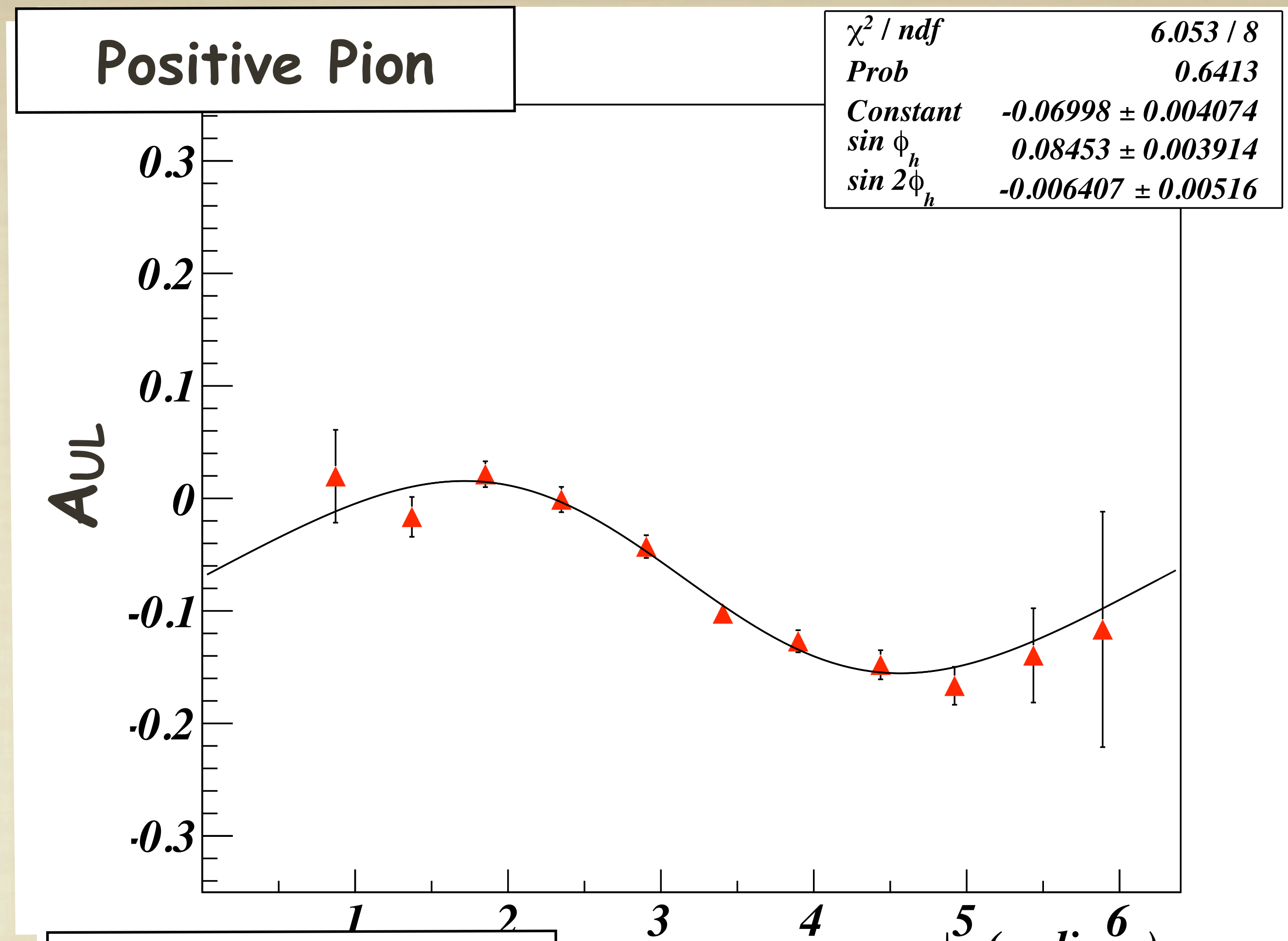
Data as a function of x_B.

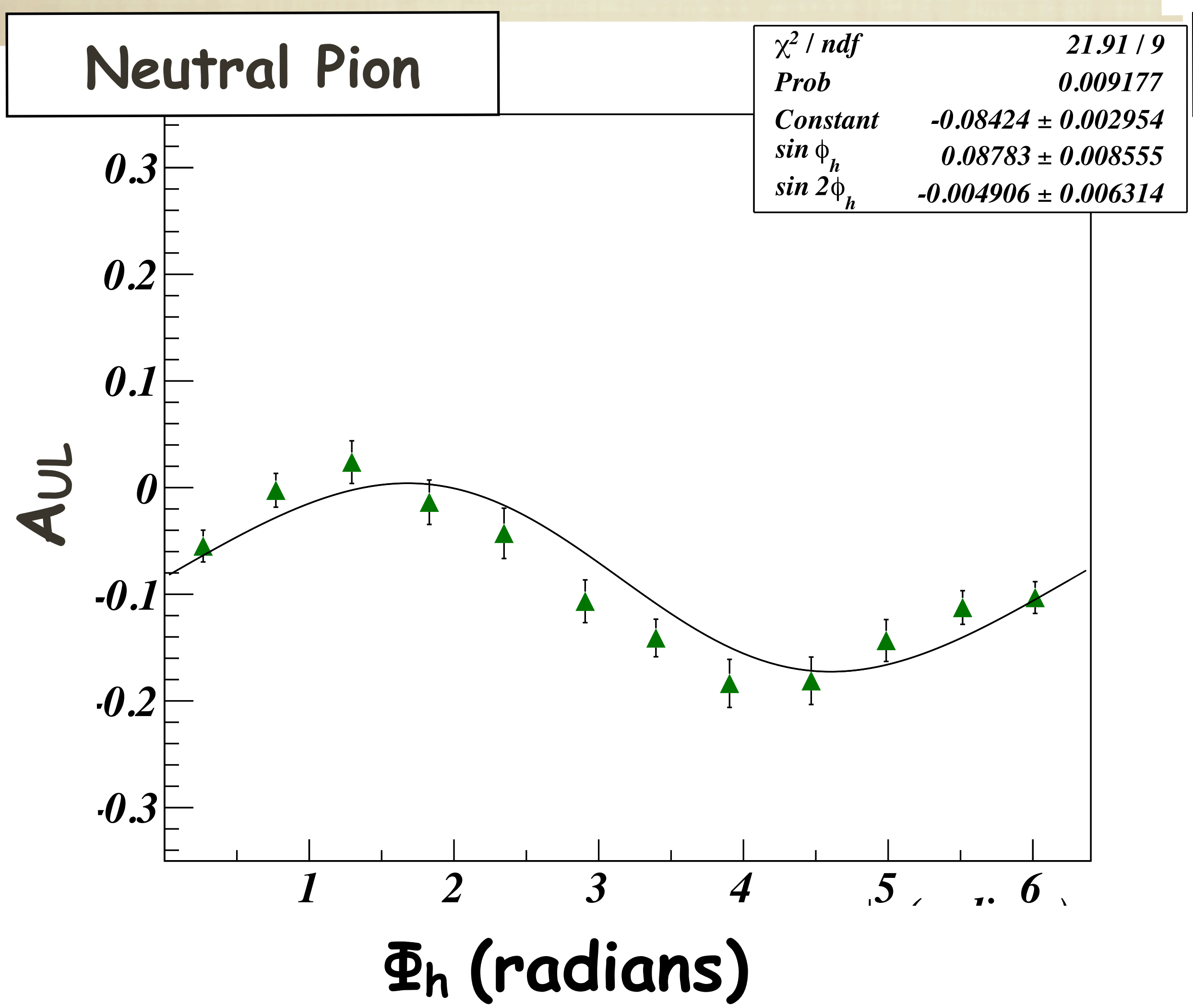


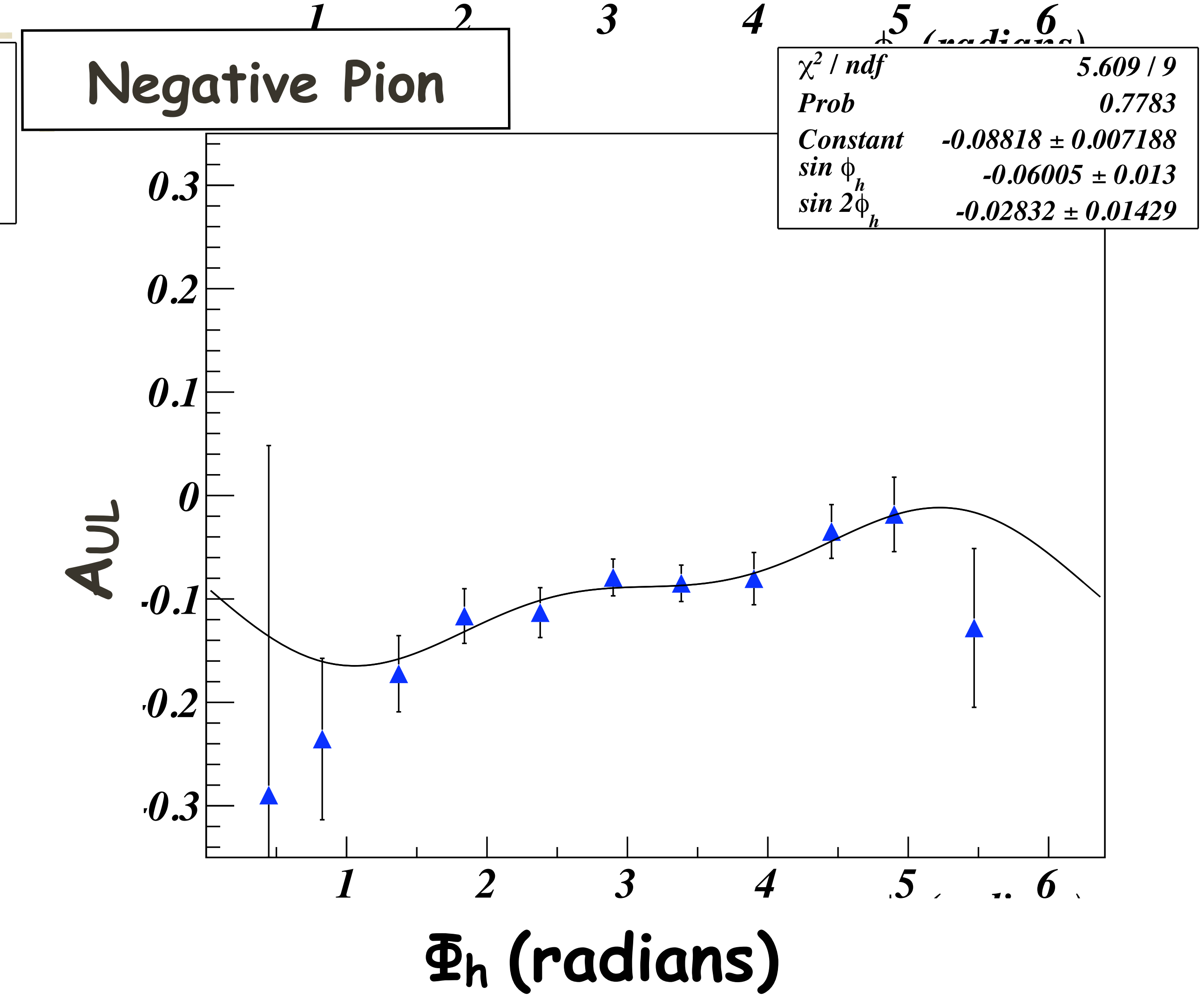
Data as a function of $P_{h\perp}$ (GeV).



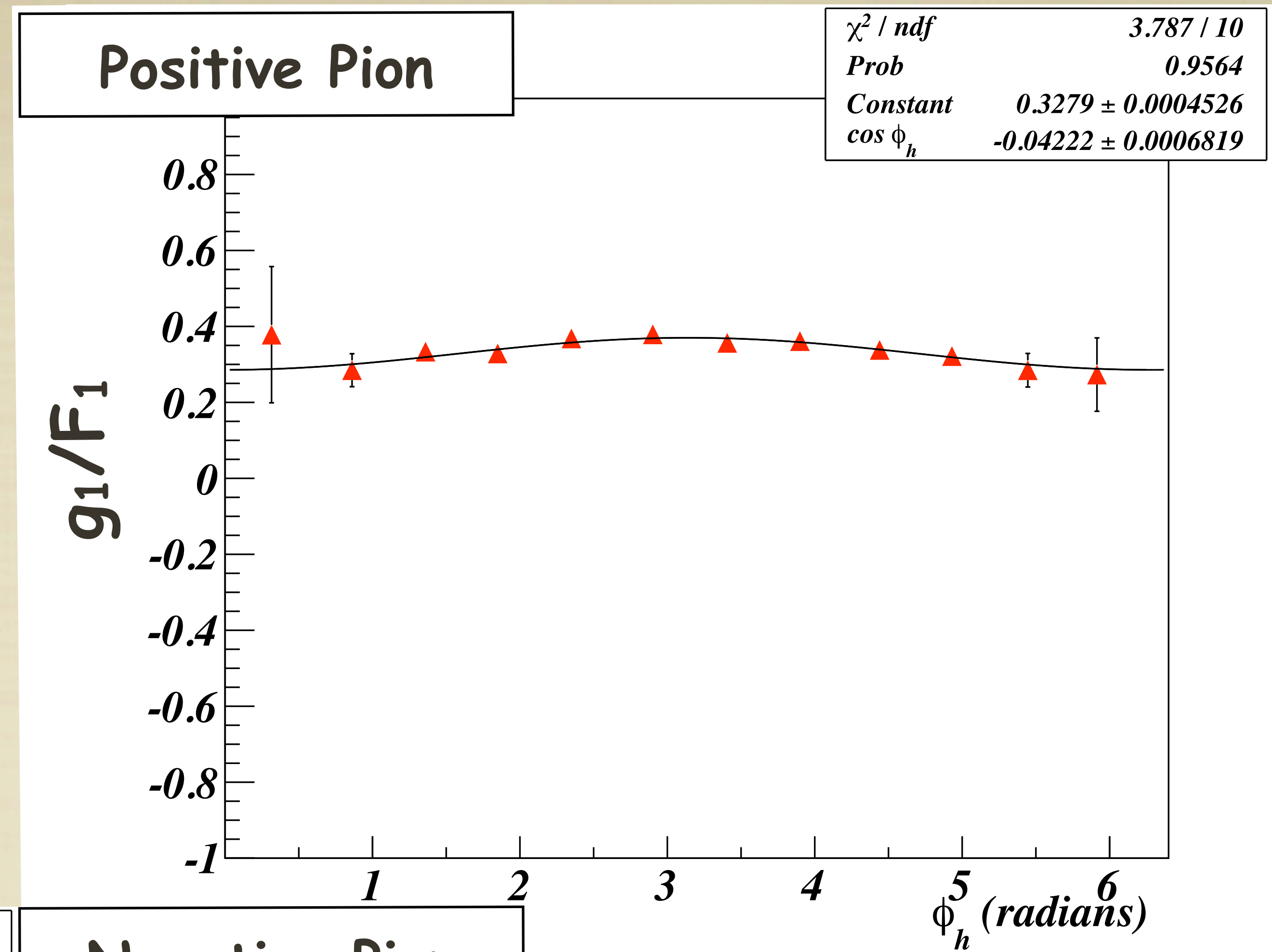
Asymmetries integrated over all except the azimuthal angle show clear sine moment.

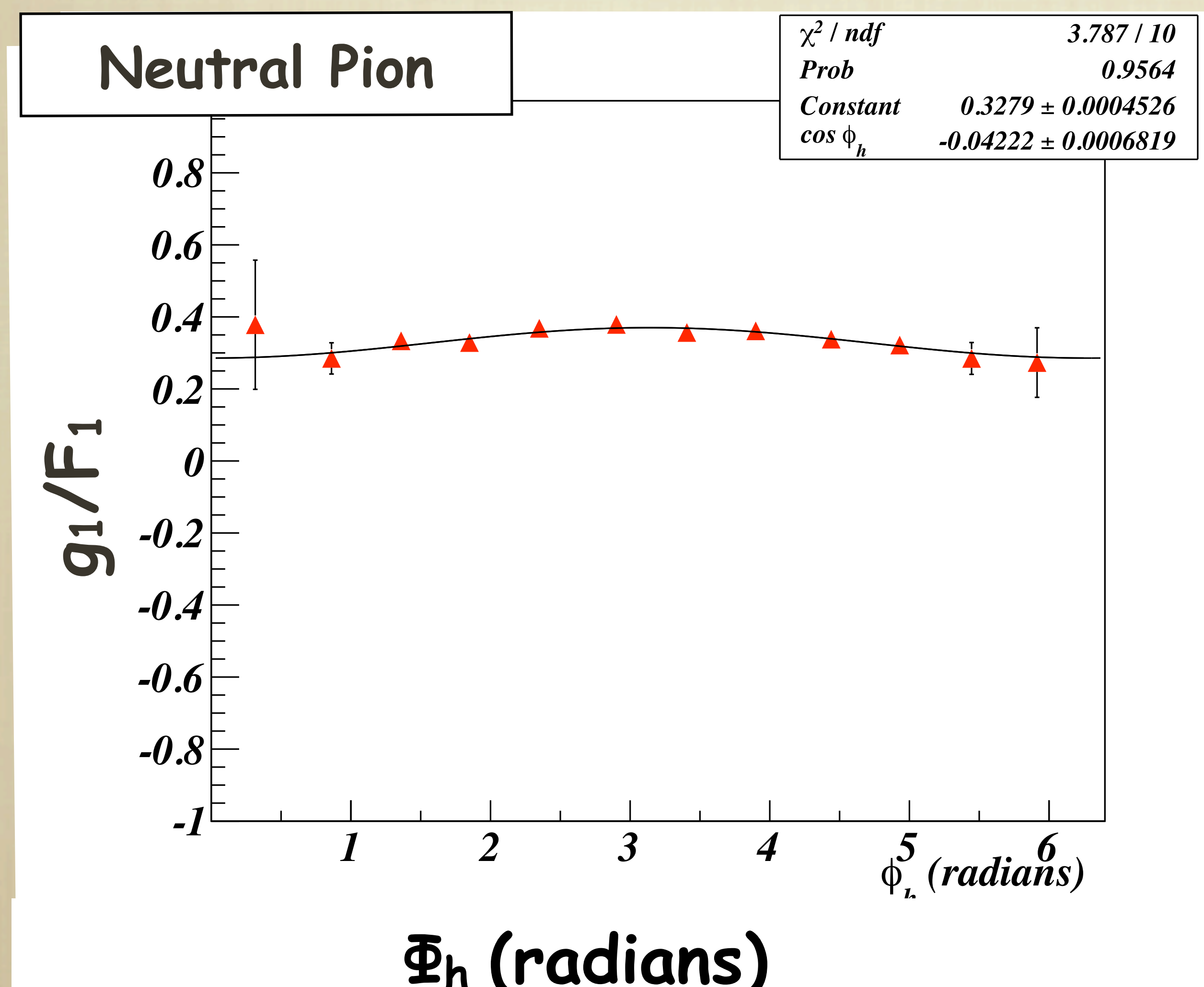


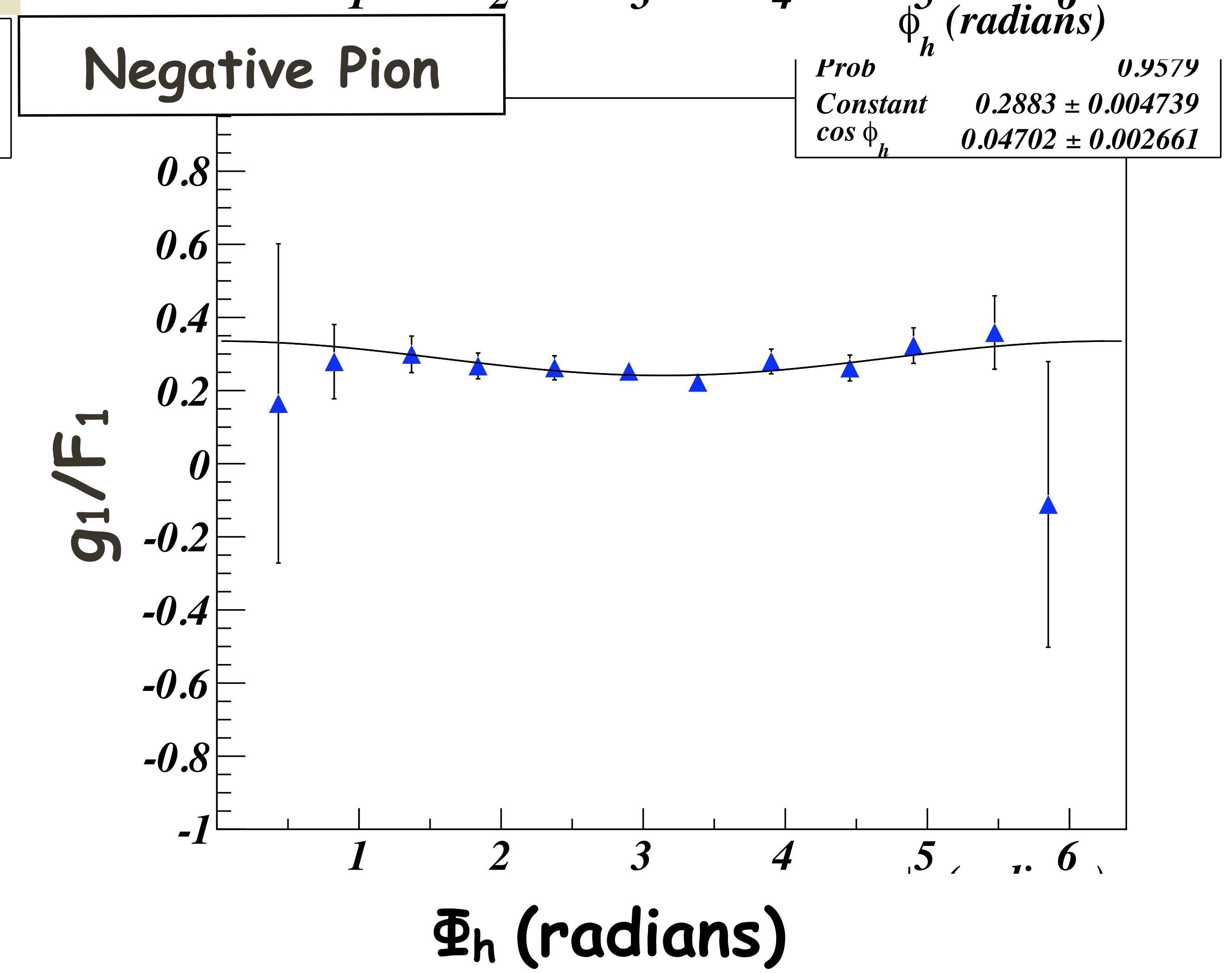




Asymmetries integrated over all except the azimuthal angle show clear cosine moment.







Attenuation interpretation

- Add in nuclear attenuation for He, C, N
- 4 fit parameters
- Use ratio of carbon and NH_3 to test model (More details in eg1-dvcsTN013)

$$A_T^{He}(Q^2,x_B,z,P_{h\perp}) = 1 + A_T^{He}(Q^2,x,z)\left\{\left[\frac{P_{h\perp}}{p_T^{zshift}}\right]^{p_{Tp}} - 1\right\}$$

$$A_T^{C}(Q^2,x_B,z,P_{h\perp}) = 1 + A_T^{C}(Q^2,x,z)\left\{\left[\frac{P_{h\perp}}{p_T^{zshift}}\right]^{p_{Tp}} - 1\right\}$$

$$A_T^{N}(Q^2,x_B,z,P_{h\perp}) = 1 + A_T^{N}(Q^2,x,z)\left\{\left[\frac{P_{h\perp}}{p_T^{zshift}}\right]^{p_{Tp}} - 1\right\}$$

$$A_T^{Al}(Q^2,x_B,z,P_{h\perp}) = 1 + A_T^{Al}(Q^2,x,z)\left\{\left[\frac{P_{h\perp}}{p_T^{zshift}}\right]^{p_{Tp}} - 1\right\}$$

Attenuation interpretation

- Add in nuclear attenuation for He, C, N
- 4 fit parameters
- Use ratio of carbon and NH_3 to test model (More details in eg1-dvcsTN013)

$$A_T^{He}(Q^2, x_B, z) = \frac{a}{\nu_F}\sqrt{4/12}$$
$$A_T^{C}(Q^2, x_B, z) = \frac{a}{\nu_F}\sqrt{12/12}$$
$$A_T^{N}(Q^2, x_B, z) = \frac{a}{\nu_F}\sqrt{14/12}$$
$$A_T^{Al}(Q^2, x_B, z) = \frac{a}{\nu_F}\sqrt{27/12}.$$

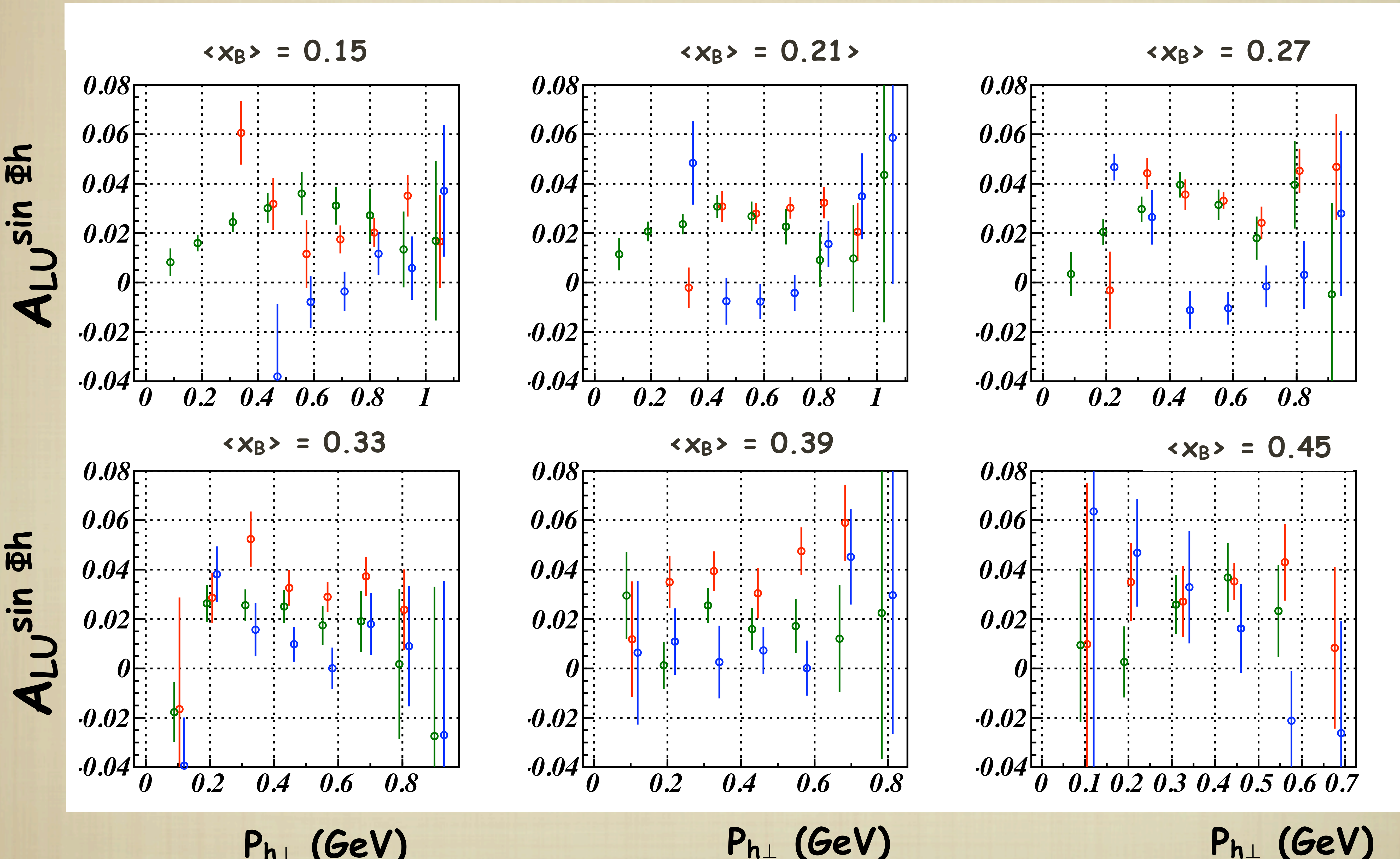
$$p_T^{zshift} = p_{Tz} + \tfrac{1}{2}(z - 0.4)$$

$$\nu_F = \left[\frac{\nu}{2.5}\right]^{\nu_p}(1 + (z - 0.55))$$

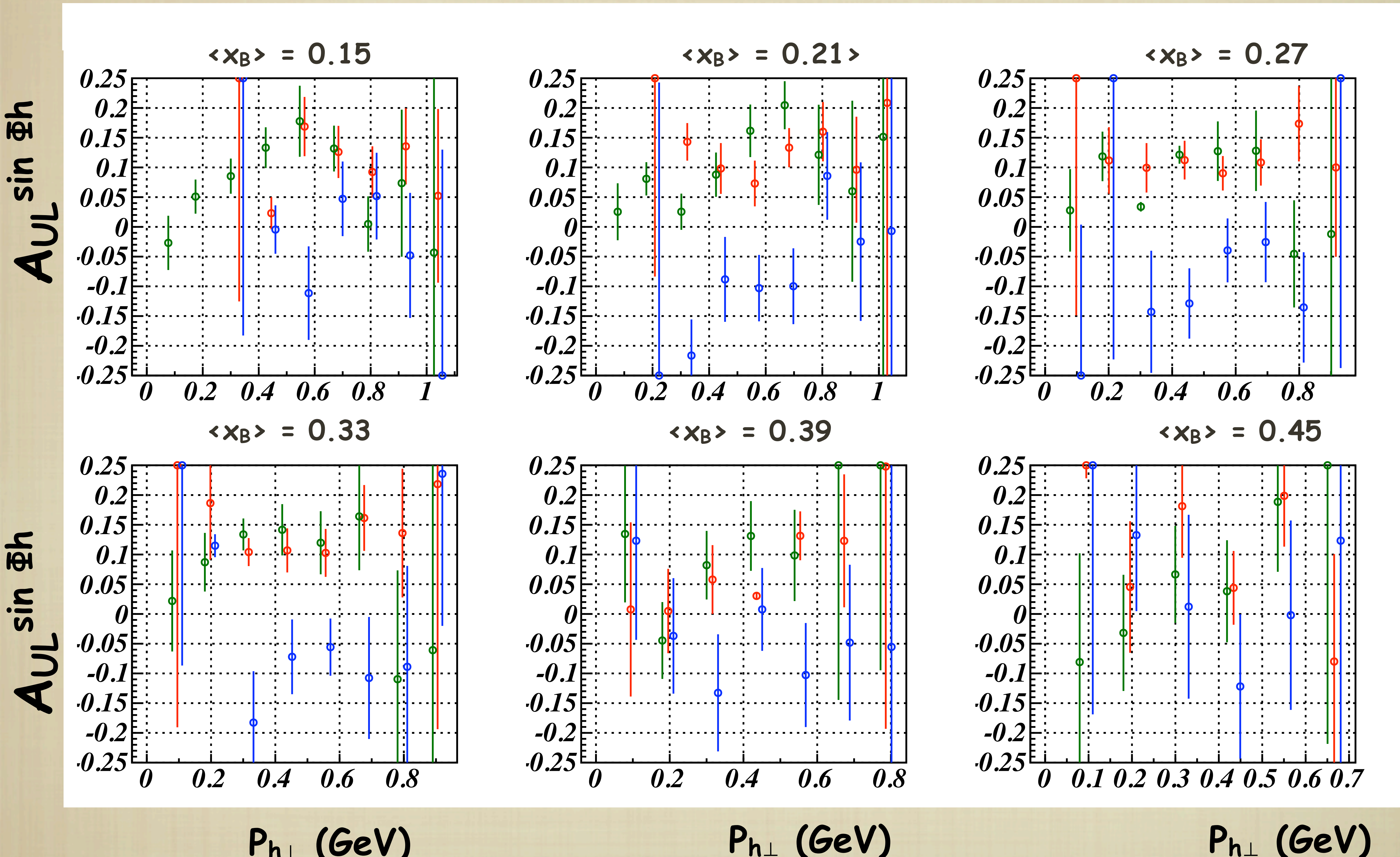
In summary,

Beam Energy (GeV)	P_B	$P_B P_{T(+)}$	$P_B P_{T(-)}$	$P_{T(+)}$	$P_{T(-)}$
5.887	86.8%	0.63	-0.61	72%	-69%
5.954	83.6%	0.65	-0.57	79%	-68%

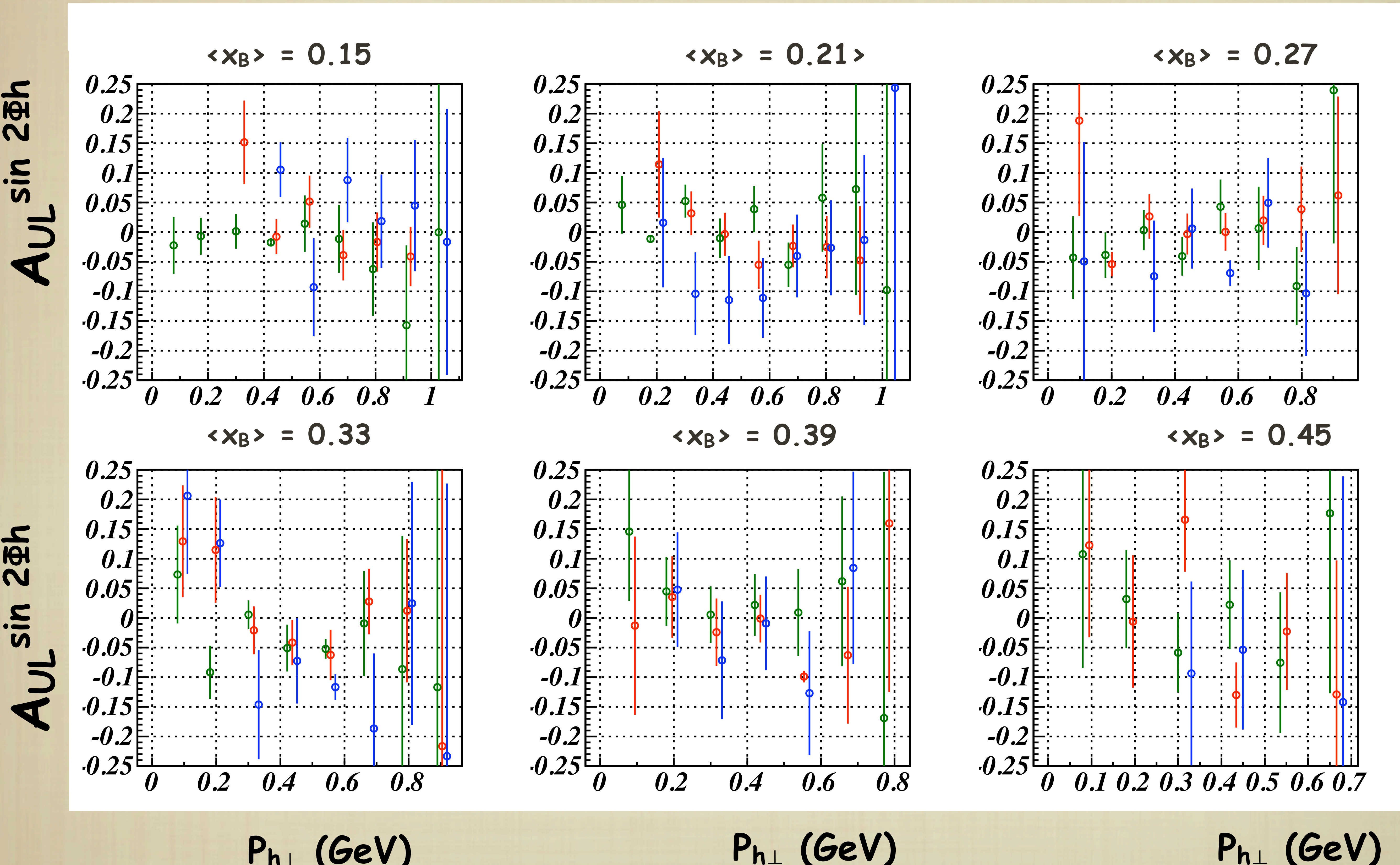
Moments of the BSA for π^+, π^-, and π^0.



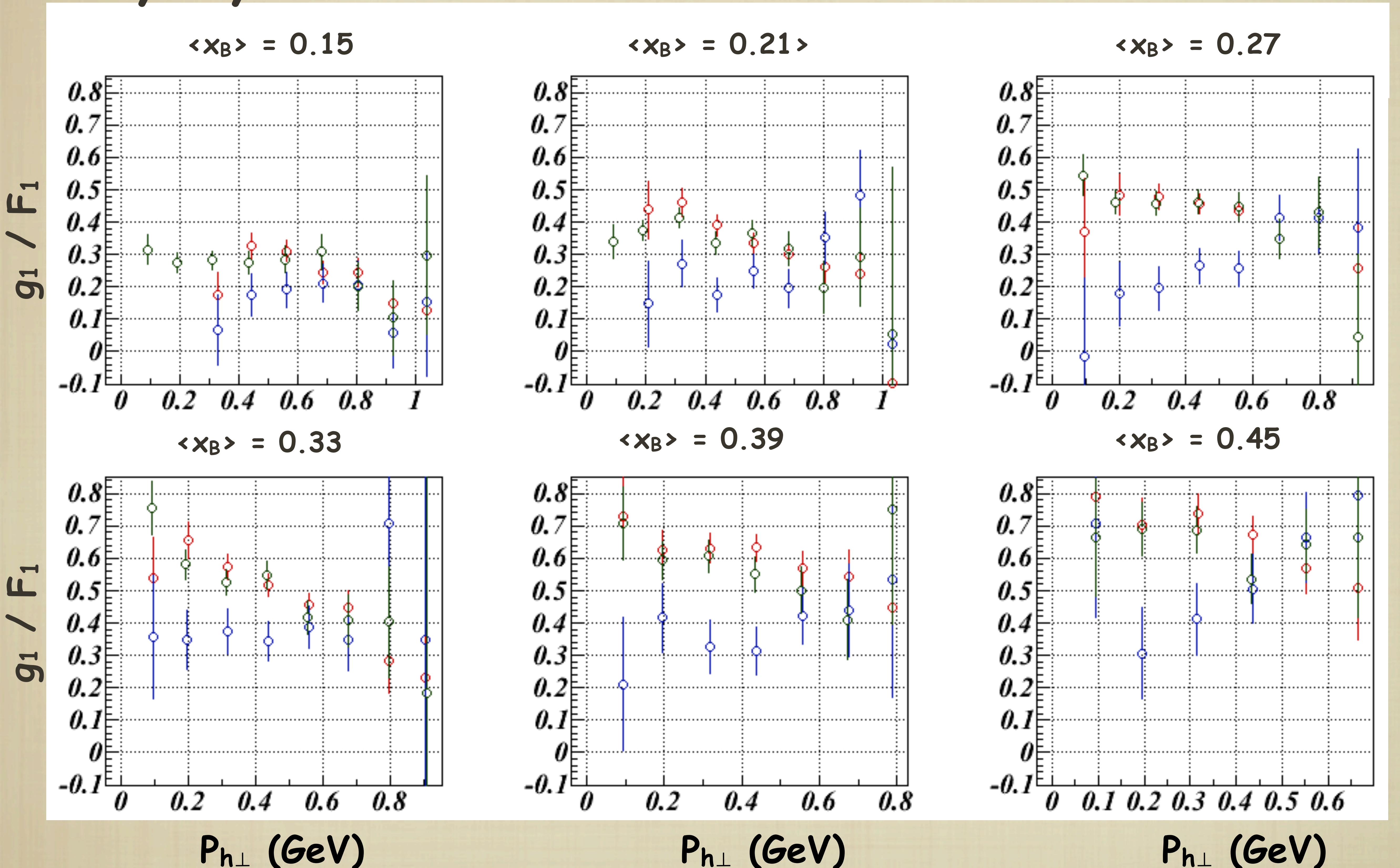
Moments of the TSA for π^+, π^-, and π^0.



Moments of the TSA for π^+, π^-, and π^0.



g_1/F_1 shown in bins of $P_{h\perp}$ (GeV) and x_B for π^+, π^-, and π^0.



For a polarized electron and proton the SIDIS cross-section is written as

$$\frac{d^7\sigma}{dx_B\ dy\ d\psi\ dz\ d\phi_h\ dP_{h\perp}^2} = d\sigma_{UU} + d\sigma_{UL} + d\sigma_{LU} + d\sigma_{LL} + [...]$$

$$d\sigma_{UU} = \frac{\alpha^2}{x_B y Q^2}\frac{y^2}{2(1-\varepsilon)}\left(1+\frac{\gamma}{2x}\right)\left[F_{UU} + \varepsilon\cos(2\phi_h)F_{UU}^{\cos 2\phi_h}\right]$$

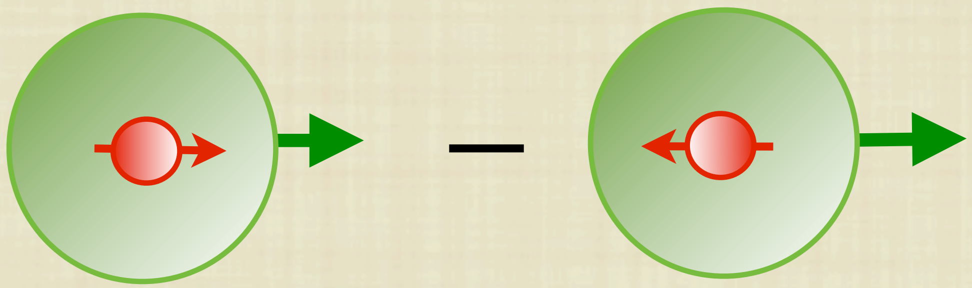
$$d\sigma_{UL} = \frac{\alpha^2}{x_B y Q^2}\frac{y^2}{2(1-\varepsilon)}\left(1+\frac{\gamma}{2x}\right)S_{\parallel}\left[\sqrt{2\varepsilon(1+\varepsilon)}\sin\phi_h F_{UL}^{\sin\phi_h} + \varepsilon\sin(2\phi_h)F_{UL}^{\sin 2\phi_h}\right]$$

$$d\sigma_{LU} = \frac{\alpha^2}{x_B y Q^2}\frac{y^2}{2(1-\varepsilon)}\left(1+\frac{\gamma}{2x}\right)\sqrt{2\varepsilon(1+\varepsilon)}\sin\phi_h F_{LU}^{\sin\phi_h}$$

$$d\sigma_{LL} = \frac{\alpha^2}{x_B y Q^2}\frac{y^2}{2(1-\varepsilon)}\left(1+\frac{\gamma}{2x}\right)S_{\parallel}\lambda_e\left[\sqrt{1+\varepsilon^2}F_{LL} + \sqrt{2\varepsilon(1+\varepsilon)}\cos\phi_h F_{LL}^{\cos\phi_h}\right]$$

We look for the unintegrated version of the standard parton distribution function.

$$g_1^p(x_B) = \sum_i e_i^2 (\Delta q_i + \Delta \bar{q}_i)$$



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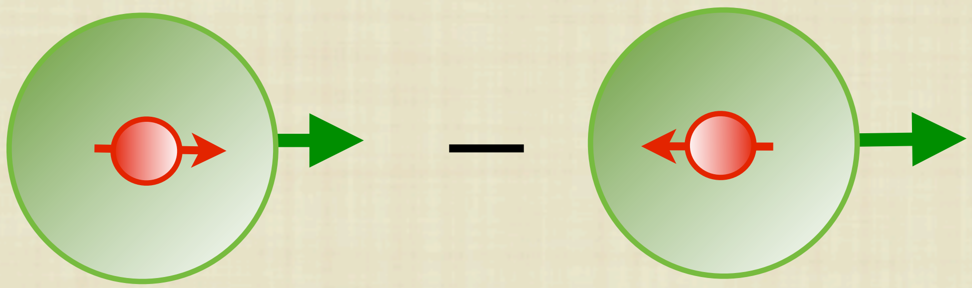

$$\Delta u = p_\uparrow [u_\uparrow(x_B)] - p_\uparrow [u_\downarrow(x_B)]$$

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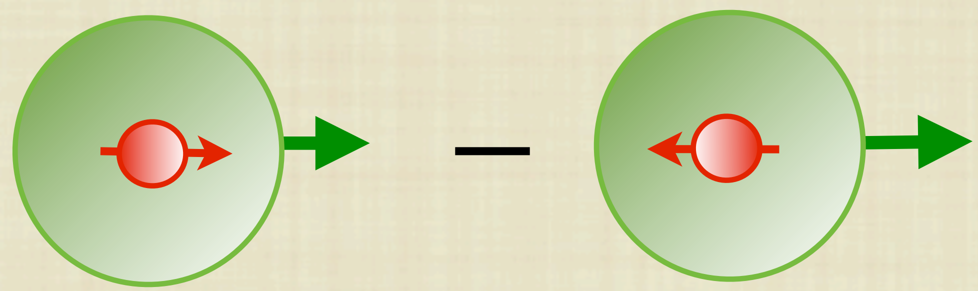

$$\Delta u = p_\uparrow[u_\uparrow(x_B)] - p_\uparrow[u_\downarrow(x_B)]$$

$$\Delta u = p_\uparrow[u_\uparrow(x_B, p_T)] - p_\uparrow[u_\downarrow(x_B, p_T)]$$