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Measurements of Transverse Momentum in Semi-Inclusive Deep-Inelastic Scattering at CLAS

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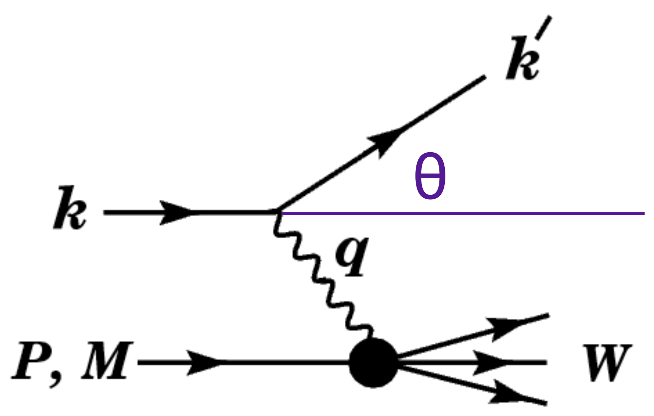
eN Scattering

Inclusive structure functions F_T, F_L g_1 and g_2 have been measured for many years

$$\frac{d\sigma}{dx\,dy\,d\psi} = \frac{2\alpha^2}{xyQ^2}\frac{y^2}{2(1-\varepsilon)}\Big\{F_T + \varepsilon F_L + S_\parallel \lambda_e \sqrt{1-\varepsilon^2}\,2x(g_1-\gamma^2 g_2) - |\boldsymbol{S}_\perp|\lambda_e\sqrt{2\varepsilon(1-\varepsilon)}\,\cos\phi_S\,2x\gamma(g_1+g_2)\Big\}$$



Lorentz invariants:
$q \cdot q = -Q^2$
$p \cdot q/M = \nu$
$(p+q)^2 = W^2$
$(k+p)^2 = s$
$-q \cdot q/(2p \cdot q) = x$
$p \cdot q/p \cdot k = y = (\nu/E)_{lab}$
$E_h/\nu = z$
$\gamma = \nu^2/Q^2$

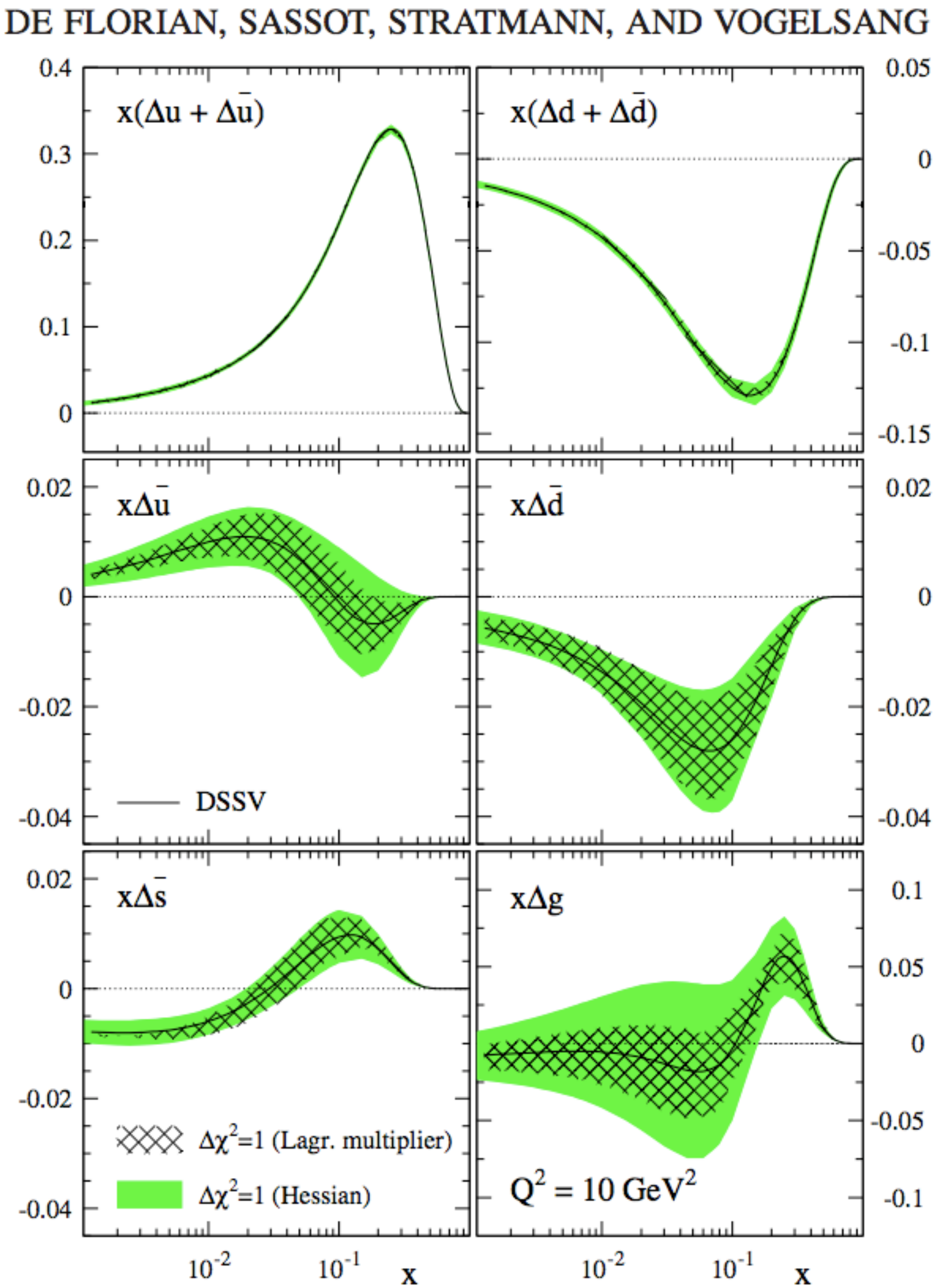
- Thus, F_T, F_L, g_1, $g_2(x,Q^2)$ can be extracted for all x, Q^2.
- Experiment tells us where these can be interpreted in terms of parton distribution functions (PDFs) in pQCD and where complications show up.
- PDFs are known only through model fitting of structure functions.

$F_L = (1+\gamma^2)F_2 - 2xF_1$ $\quad F_T = 2xF_1$

Parton Model:

$$F_1(x,Q^2) = \tfrac{1}{2}\Sigma_i e_i^2(q^\uparrow(x) + q^\downarrow(x) + \bar{q}^\uparrow(x) + \bar{q}^\downarrow(x))$$
$$F_2(x,Q^2) = 2xF_1(x,Q^2)$$
$$g_1(x,Q^2) = \tfrac{1}{2}\Sigma_i e_i^2(q^\uparrow(x) - q^\downarrow(x) + \bar{q}^\uparrow(x) - \bar{q}^\downarrow(x))$$

Proton Spin



PRD**80**(09)034030

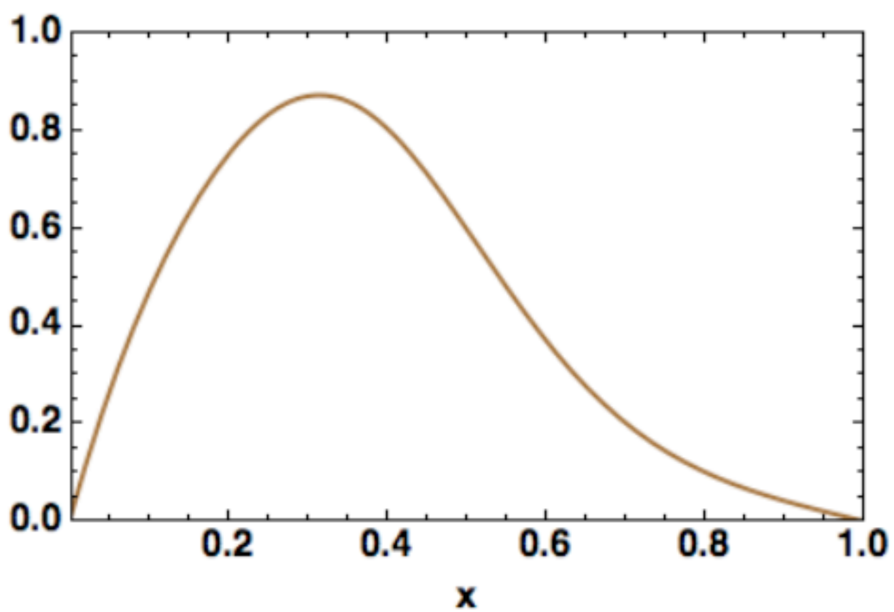
$$\frac{1}{2} = \frac{\Delta\Sigma}{2} + \Delta G + L_z$$

- Next-to-leading-order fits to all spin structure data in (semi-) inclusive deep-inelastic lepton scattering and pp scattering.
- At Q^2=4 GeV^2:
  - $\Delta G = -0.10$ (with large errors)
  - $\Delta\Sigma = 0.25$ (quark spin)
  - $\therefore$ $\mathbf{L_z \sim 0.48}$ (must be large!)
- Small ΔG is corroborated by photon-gluon fusion measurements
- Measurements sensitive to L_z are critical.
- Transverse momentum dependent parton distributions (TMDs) are key.

TMDs

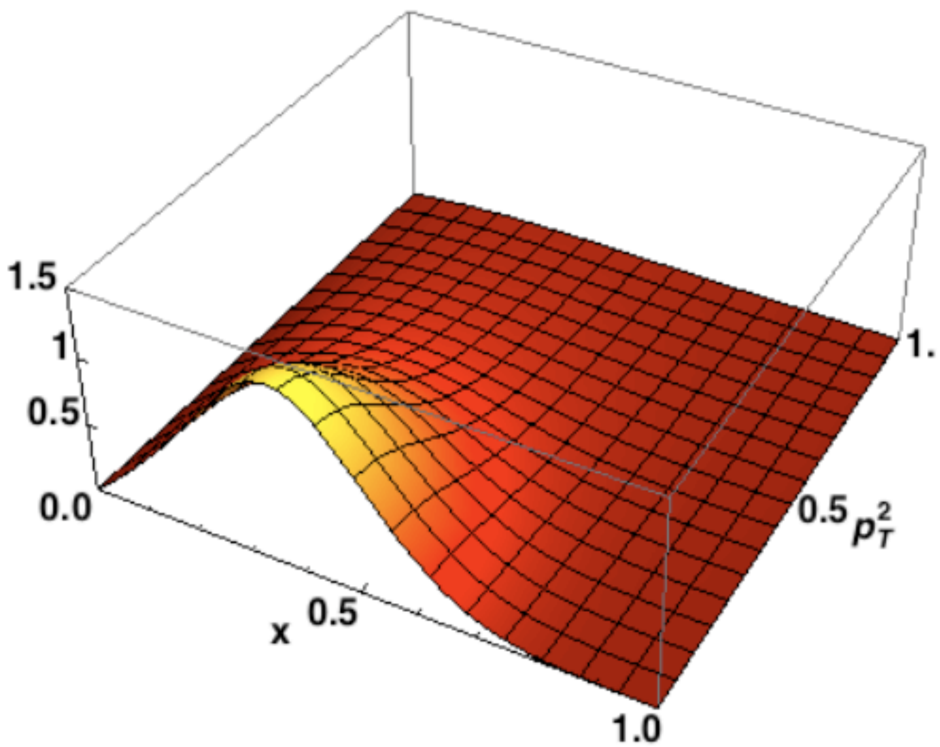
- Any confined quark must have transverse momentum
- Therefore, colinear PDFs cannot give the whole story
- Transverse momentum is related to L_z
- There has been much recent work trying to understand transverse momentum distributions (TMDs)

$x f_1^u(x)$



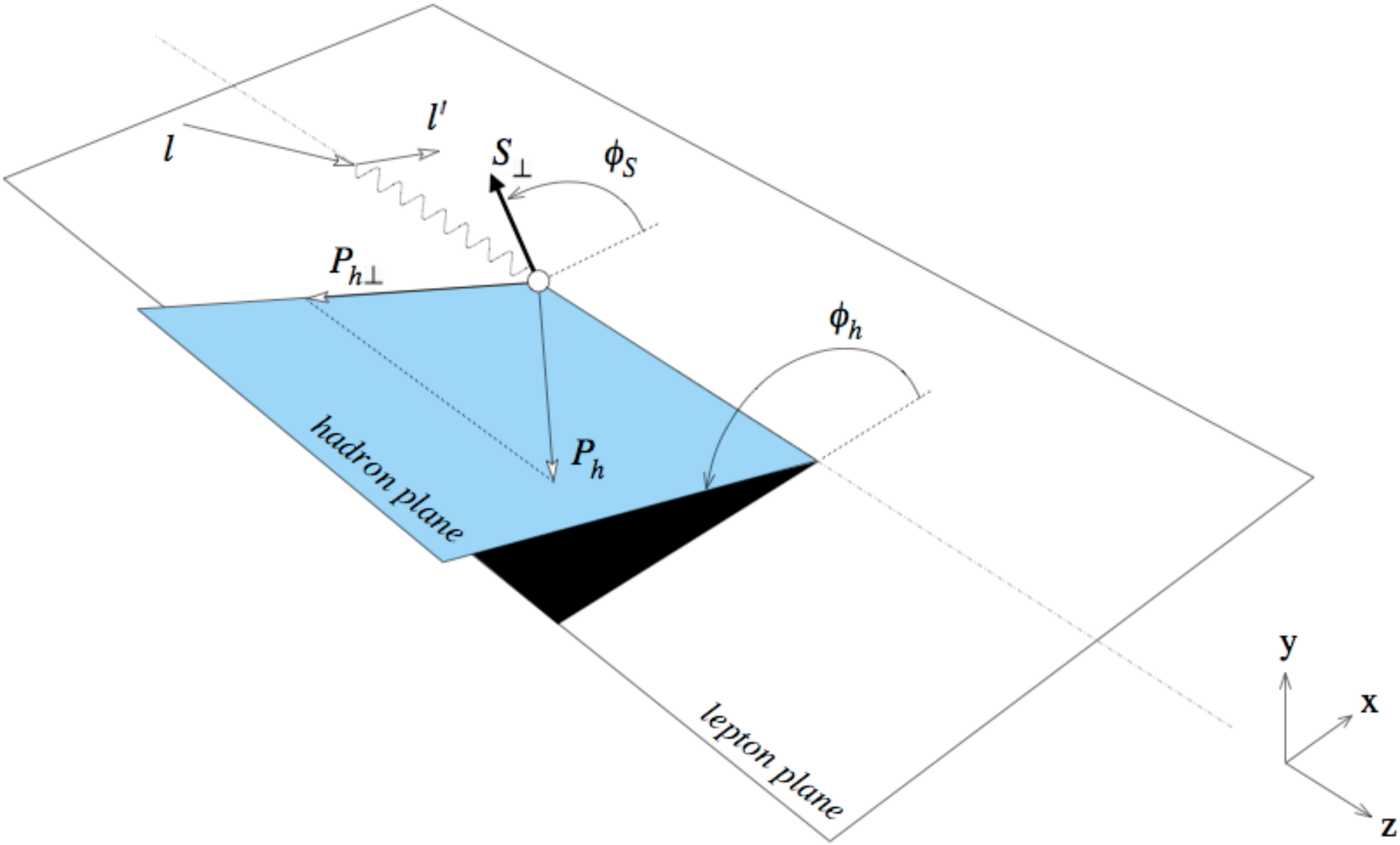
Standard collinear PDF

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



TMD

Semi-Inclusive DIS



SIDIS Cross Section

Bacchetta, et al., JHEP 2(2007)093

$$
\begin{aligned}
\frac{d\sigma}{dx\,dy\,d\psi\,dz\,d\phi_h\,dP_{h\perp}^2} &= \\
\frac{\alpha^2}{xyQ^2}\,\frac{y^2}{2\,(1-\varepsilon)}\left(1+\frac{\gamma^2}{2x}\right)\Bigg\{ & F_{UU,T} + \varepsilon\, F_{UU,L} + \sqrt{2\,\varepsilon(1+\varepsilon)}\,\cos\phi_h\, F_{UU}^{\cos\phi_h} \\
&+ \varepsilon\cos(2\phi_h)\, F_{UU}^{\cos 2\phi_h} + \lambda_e\,\sqrt{2\,\varepsilon(1-\varepsilon)}\,\sin\phi_h\, F_{LU}^{\sin\phi_h} \\
&+ S_\parallel \left[\sqrt{2\,\varepsilon(1+\varepsilon)}\,\sin\phi_h\, F_{UL}^{\sin\phi_h} + \varepsilon\sin(2\phi_h)\, F_{UL}^{\sin 2\phi_h}\right] \\
&+ S_\parallel \lambda_e \left[\sqrt{1-\varepsilon^2}\, F_{LL} + \sqrt{2\,\varepsilon(1-\varepsilon)}\,\cos\phi_h\, F_{LL}^{\cos\phi_h}\right] \\
&+ |\boldsymbol{S}_\perp| \Bigg[\sin(\phi_h-\phi_S)\left(F_{UT,T}^{\sin(\phi_h-\phi_S)} + \varepsilon\, F_{UT,L}^{\sin(\phi_h-\phi_S)}\right) \\
&\quad + \varepsilon\,\sin(\phi_h+\phi_S)\, F_{UT}^{\sin(\phi_h+\phi_S)} + \varepsilon\,\sin(3\phi_h-\phi_S)\, F_{UT}^{\sin(3\phi_h-\phi_S)} \\
&\quad + \sqrt{2\,\varepsilon(1+\varepsilon)}\,\sin\phi_S\, F_{UT}^{\sin\phi_S} + \sqrt{2\,\varepsilon(1+\varepsilon)}\,\sin(2\phi_h-\phi_S)\, F_{UT}^{\sin(2\phi_h-\phi_S)}\Bigg] \\
&+ |\boldsymbol{S}_\perp|\lambda_e \Bigg[\sqrt{1-\varepsilon^2}\,\cos(\phi_h-\phi_S)\, F_{LT}^{\cos(\phi_h-\phi_S)} + \sqrt{2\,\varepsilon(1-\varepsilon)}\,\cos\phi_S\, F_{LT}^{\cos\phi_S} \\
&\quad + \sqrt{2\,\varepsilon(1-\varepsilon)}\,\cos(2\phi_h-\phi_S)\, F_{LT}^{\cos(2\phi_h-\phi_S)}\Bigg]\Bigg\},
\end{aligned}
$$

Leading Twist

Sub-Leading Twist (extra factor of 1/Q)

0 (i.e. $R=\sigma_L/\sigma_T=0$)

A_{UL} = {UL terms} / {UU terms}

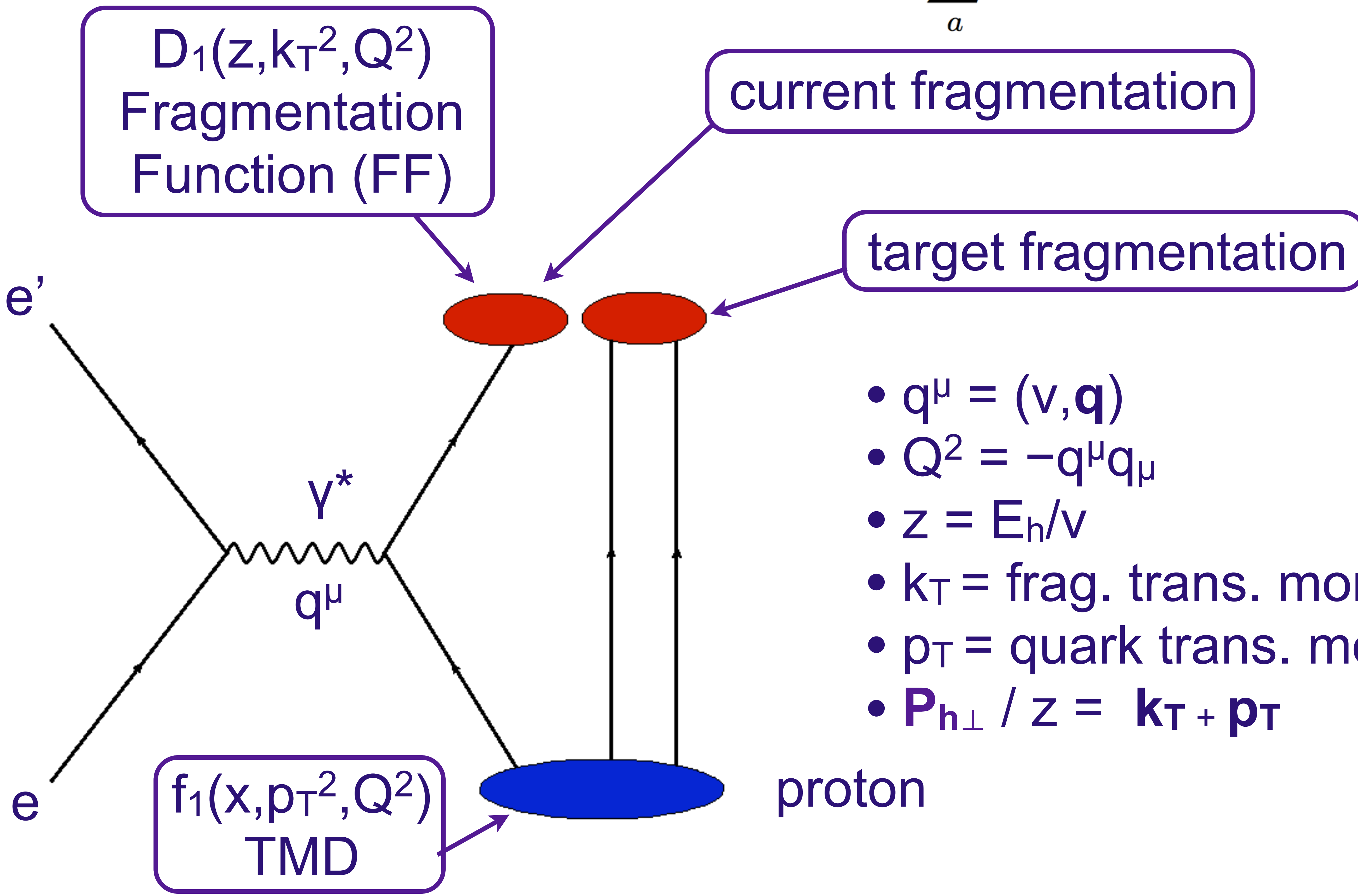
A_{LL} = {LL terms} / {UU terms}

etc.

Each F now depends also on transverse hadron momentum $P_{h\perp}$

TMDs and FFs

$$F_{UU,T} = x \sum_a e_a^2 \, f_1^a(x) \, D_1^a(z)$$



- $q^\mu = (\nu,\mathbf{q})$
- $Q^2 = -q^\mu q_\mu$
- $z = E_h/\nu$
- k_T = frag. trans. mom.
- p_T = quark trans. mom.
- $\mathbf{P_{h\perp}} / z = \mathbf{k_T} + \mathbf{p_T}$

TMDs at Leading Twist

$$\mathcal{C}\left[w\, f\, D\right] = x \sum_a e_a^2 \int d^2\boldsymbol{p}_T\, d^2\boldsymbol{k}_T\, \delta^{(2)}\left(\boldsymbol{p}_T - \boldsymbol{k}_T - \boldsymbol{P}_{h\perp}/z\right) w(\boldsymbol{p}_T, \boldsymbol{k}_T)\, f^a(x, p_T^2)\, D^a(z, k_T^2)$$

$$F_{UU,T} = \mathcal{C}\left[f_1 D_1\right]$$

$$F_{LL} = \mathcal{C}\left[g_{1L} D_1\right]$$

$$F_{UL}^{\sin 2\phi_h} = \mathcal{C}\left[-\frac{2\left(\hat{\boldsymbol{h}}\cdot\boldsymbol{k}_T\right)\left(\hat{\boldsymbol{h}}\cdot\boldsymbol{p}_T\right) - \boldsymbol{k}_T\cdot\boldsymbol{p}_T}{M M_h} h_{1L}^{\perp} H_1^{\perp}\right]$$

$$F_{UU}^{\cos 2\phi_h} = \mathcal{C}\left[-\frac{2\left(\hat{\boldsymbol{h}}\cdot\boldsymbol{k}_T\right)\left(\hat{\boldsymbol{h}}\cdot\boldsymbol{p}_T\right) - \boldsymbol{k}_T\cdot\boldsymbol{p}_T}{M M_h} h_1^{\perp} H_1^{\perp}\right]$$

Primary TMDs

Red: T-odd

Black: survive p_T integration

Yellow box: chiral-odd

quark pol.

nucleon pol.	U	L	T
U	f_1		$h_1^{\perp}$
L		g_{1L}	$h_{1L}^{\perp}$
T	$f_{1T}^{\perp}$	g_{1T}	h_1, $h_{1T}^{\perp}$

Twist-2 TMDs

Helicity → g_{1L}

Boer-Mulders → $h_1^{\perp}$

Sivers → $f_{1T}^{\perp}$

Worm Gear → g_{1T}, $h_{1L}^{\perp}$

Transversity → h_1

Pretzelocity → $h_{1T}^{\perp}$

TMDs with L Polarization

$$F_{UU,T} = \mathcal{C}\big[f_1 D_1\big] \qquad F_{UU,L} = 0 \qquad F_{UU}^{\cos 2\phi_h} = \mathcal{C}\left[-\frac{2\,(\hat{\boldsymbol{h}}\cdot\boldsymbol{k}_T)\,(\hat{\boldsymbol{h}}\cdot\boldsymbol{p}_T) - \boldsymbol{k}_T\cdot\boldsymbol{p}_T}{M M_h} h_1^{\perp} H_1^{\perp}\right]$$

$$F_{UU}^{\cos\phi_h} = \frac{2M}{Q}\,\mathcal{C}\left[-\frac{\hat{\boldsymbol{h}}\cdot\boldsymbol{k}_T}{M_h}\left(xh\,H_1^{\perp} + \frac{M_h}{M}\,f_1\frac{\tilde{D}^{\perp}}{z}\right) - \frac{\hat{\boldsymbol{h}}\cdot\boldsymbol{p}_T}{M}\left(xf^{\perp}D_1 + \frac{M_h}{M}\,h_1^{\perp}\frac{\tilde{H}}{z}\right)\right]$$

$$F_{LU}^{\sin\phi_h} = \frac{2M}{Q}\,\mathcal{C}\left[-\frac{\hat{\boldsymbol{h}}\cdot\boldsymbol{k}_T}{M_h}\left(xe\,H_1^{\perp} + \frac{M_h}{M}\,f_1\frac{\tilde{G}^{\perp}}{z}\right) + \frac{\hat{\boldsymbol{h}}\cdot\boldsymbol{p}_T}{M}\left(xg^{\perp}D_1 + \frac{M_h}{M}\,h_1^{\perp}\frac{\tilde{E}}{z}\right)\right]$$

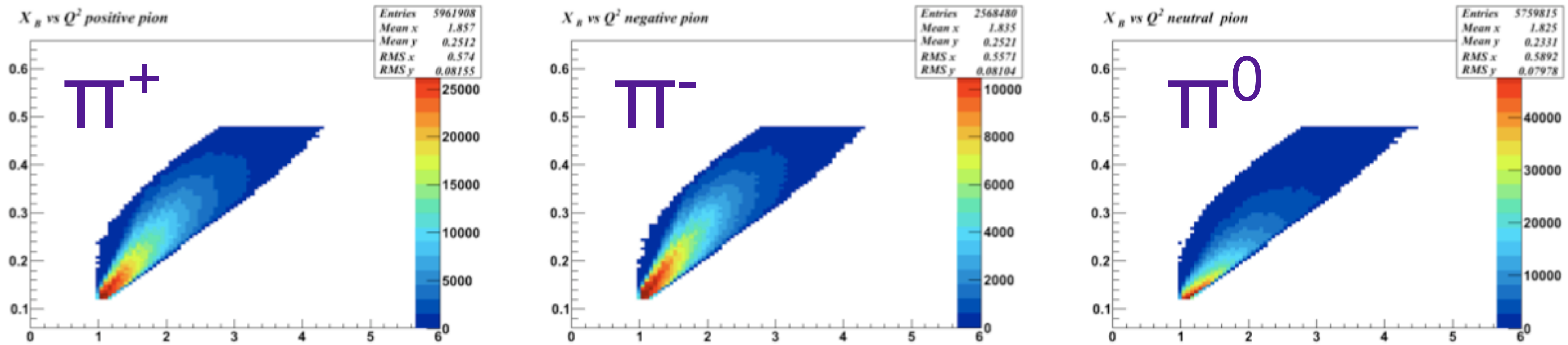
$$F_{UL}^{\sin 2\phi_h} = \mathcal{C}\left[-\frac{2\,(\hat{\boldsymbol{h}}\cdot\boldsymbol{k}_T)\,(\hat{\boldsymbol{h}}\cdot\boldsymbol{p}_T) - \boldsymbol{k}_T\cdot\boldsymbol{p}_T}{M M_h} h_{1L}^{\perp} H_1^{\perp}\right]$$

$$F_{UL}^{\sin\phi_h} = \frac{2M}{Q}\,\mathcal{C}\left[-\frac{\hat{\boldsymbol{h}}\cdot\boldsymbol{k}_T}{M_h}\left(xh_L\,H_1^{\perp} + \frac{M_h}{M}\,g_{1L}\frac{\tilde{G}^{\perp}}{z}\right) + \frac{\hat{\boldsymbol{h}}\cdot\boldsymbol{p}_T}{M}\left(xf_L^{\perp}D_1 - \frac{M_h}{M}\,h_{1L}^{\perp}\frac{\tilde{H}}{z}\right)\right]$$

$$F_{LL} = \mathcal{C}\big[g_{1L} D_1\big]$$

$$F_{LL}^{\cos\phi_h} = \frac{2M}{Q}\,\mathcal{C}\left[\frac{\hat{\boldsymbol{h}}\cdot\boldsymbol{k}_T}{M_h}\left(xe_L\,H_1^{\perp} - \frac{M_h}{M}\,g_{1L}\frac{\tilde{D}^{\perp}}{z}\right) - \frac{\hat{\boldsymbol{h}}\cdot\boldsymbol{p}_T}{M}\left(xg_L^{\perp}D_1 + \frac{M_h}{M}\,h_{1L}^{\perp}\frac{\tilde{E}}{z}\right)\right]$$

EG1-DVCS at JLab CLAS



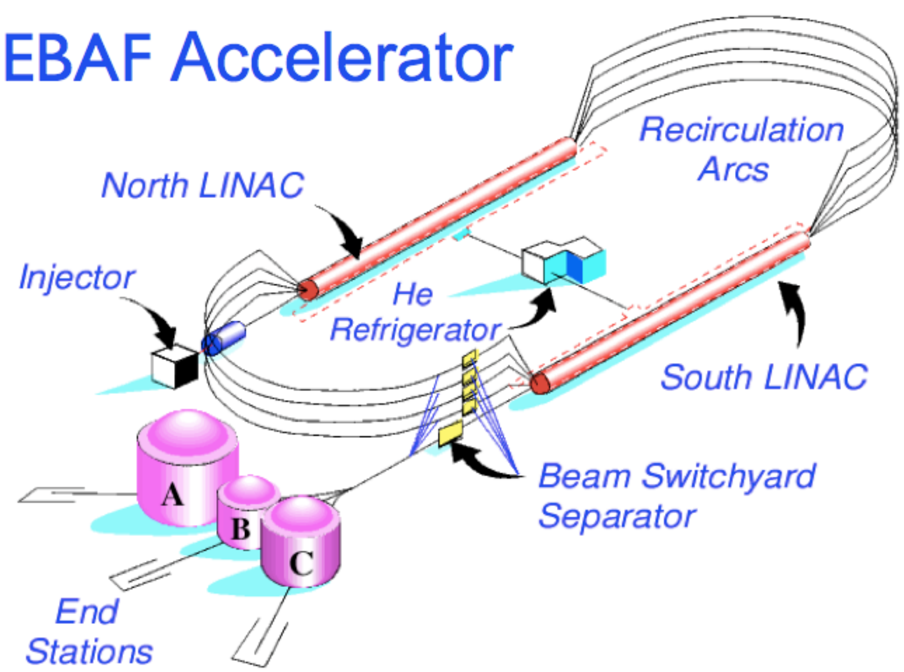
x (0.1 – 0.6)

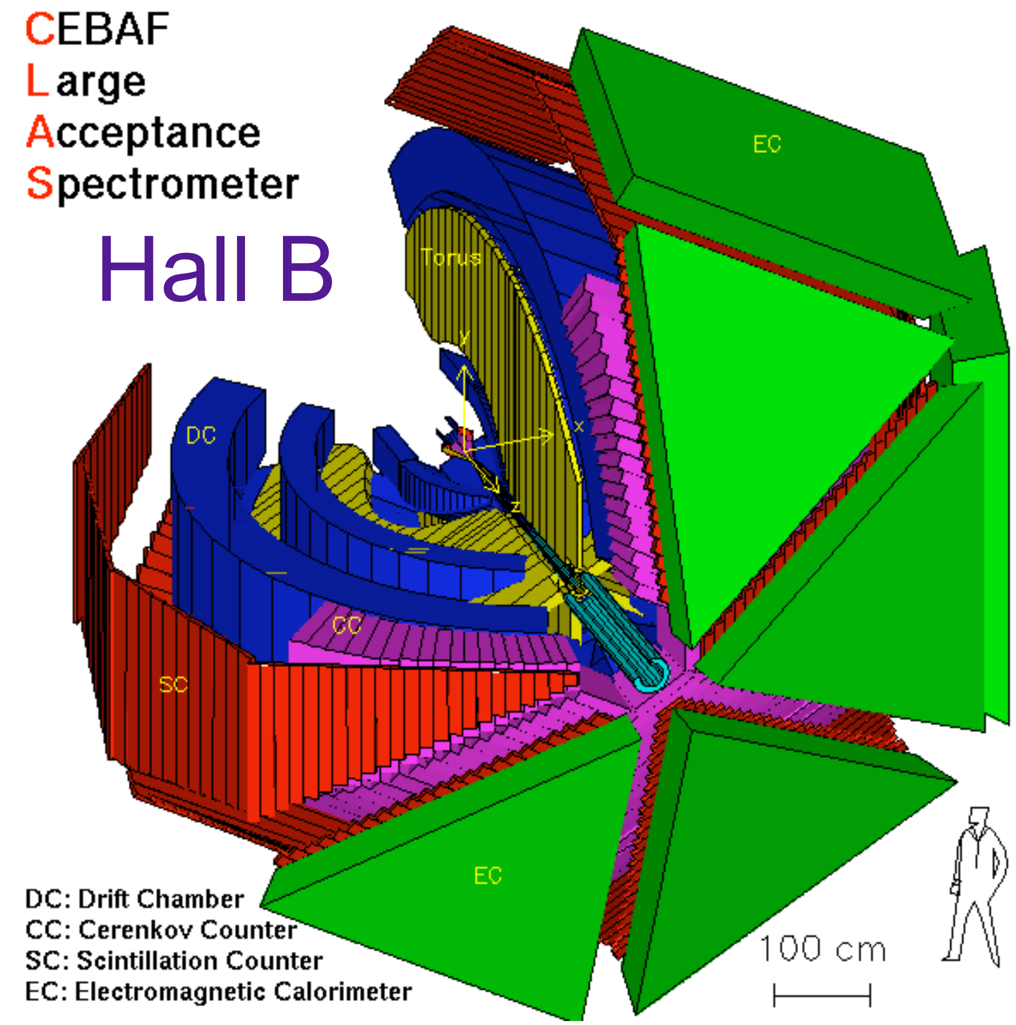
Q^2 (GeV^2) (0 – 6)

- Beam time: February to September 2009
- ~6 GeV Polarized electron beam (P_b~85%)
- Frozen $^{14}NH_3$ target (P_t~75%)
- CEBAF large acceptance spectrometer (CLAS) plus Inner Calorimeter
- ~19 billion electron triggers on NH3 target

$$A = \frac{N^+ - N^-}{N^+ + N^-}$$

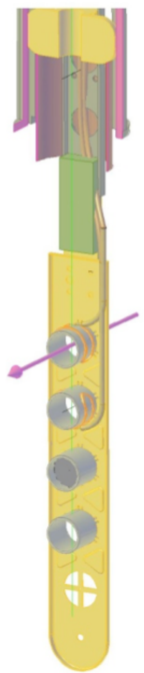
The CEBAF Accelerator

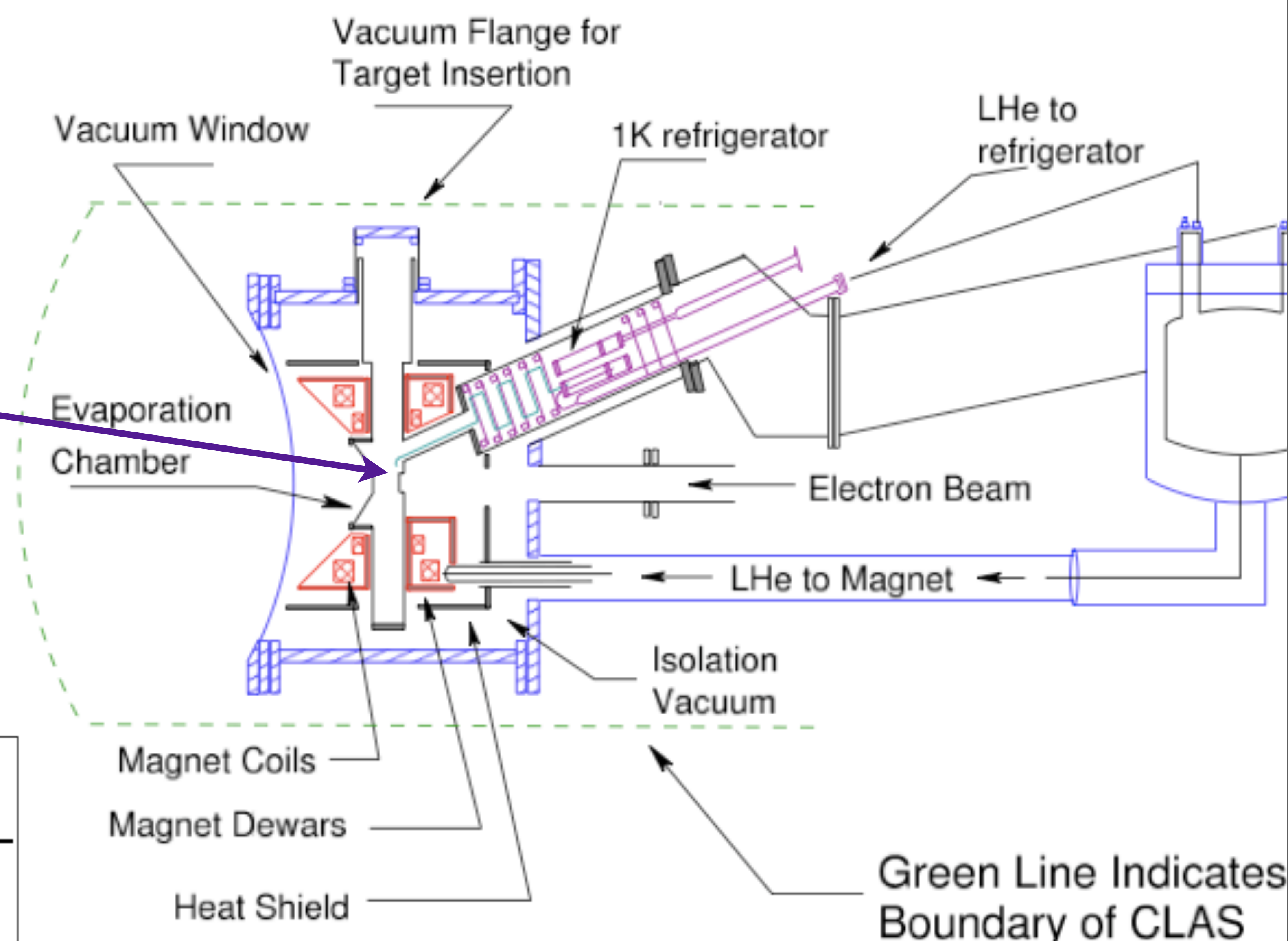


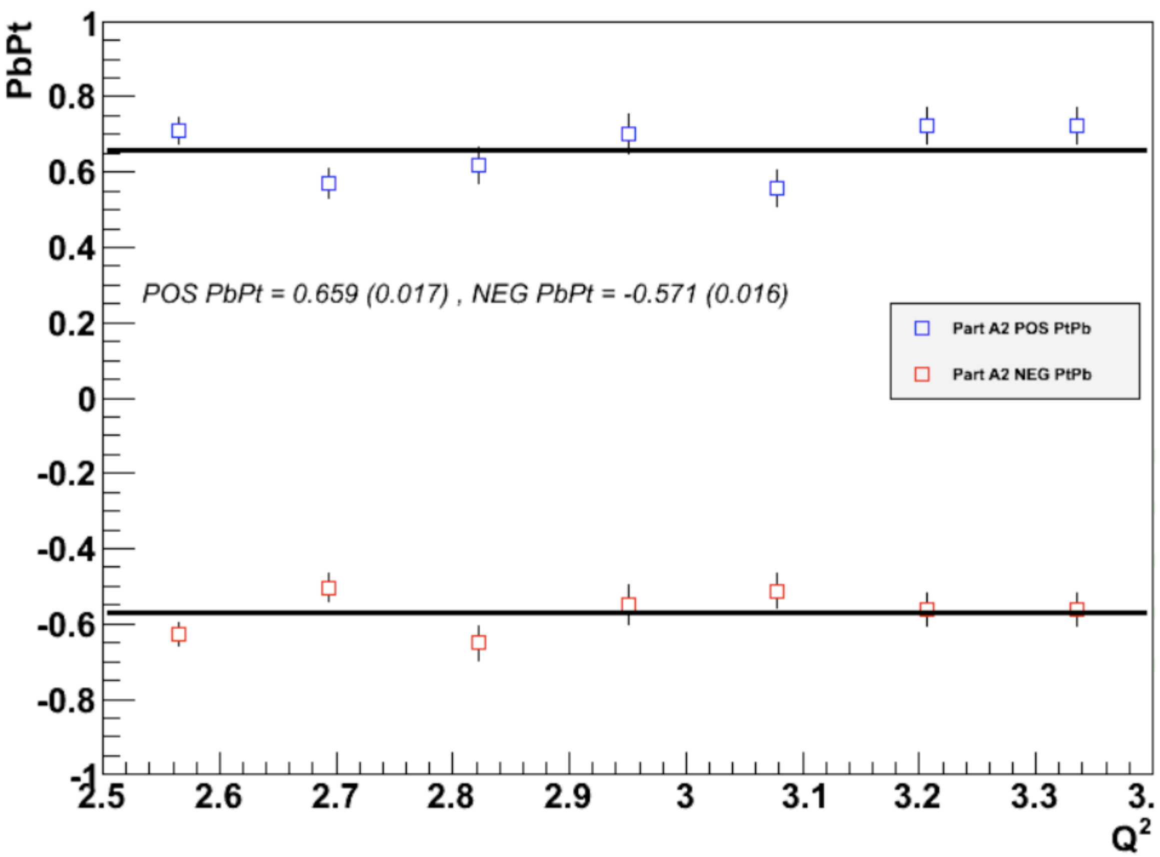


Polarized Target

- $^{14}NH_3$ solid
- $^{14}ND_3$ solid
- Carbon
- Dynamic Nuclear Polarization







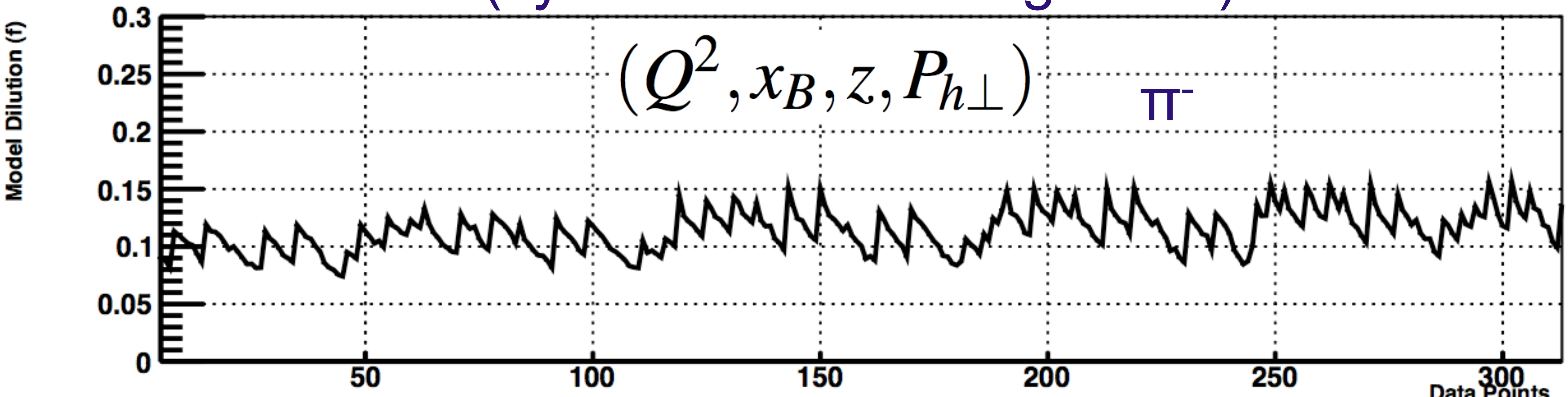
- p(e,e′p) elastic asymmetries yield P_bP_t
- $P_bP_t = A_{||}^{exp} / A_{||}^{theory}(G_E/G_M)$
- P_b separately from Møller

Dilution Factor

$$A = \frac{A^{raw}}{f} \qquad f = \frac{n_{proton}}{n_{NH_3} + n_{He} + n_K + n_{Al}}$$

$$\frac{n^{SIDIS}_{NH_3}}{n^{SIDIS}_{C}}$$ is fit to a parameterized model of SIDIS on nuclei, which is used to calculate *n* for all materials in the beamline. *f* ~ 3/17= 0.18

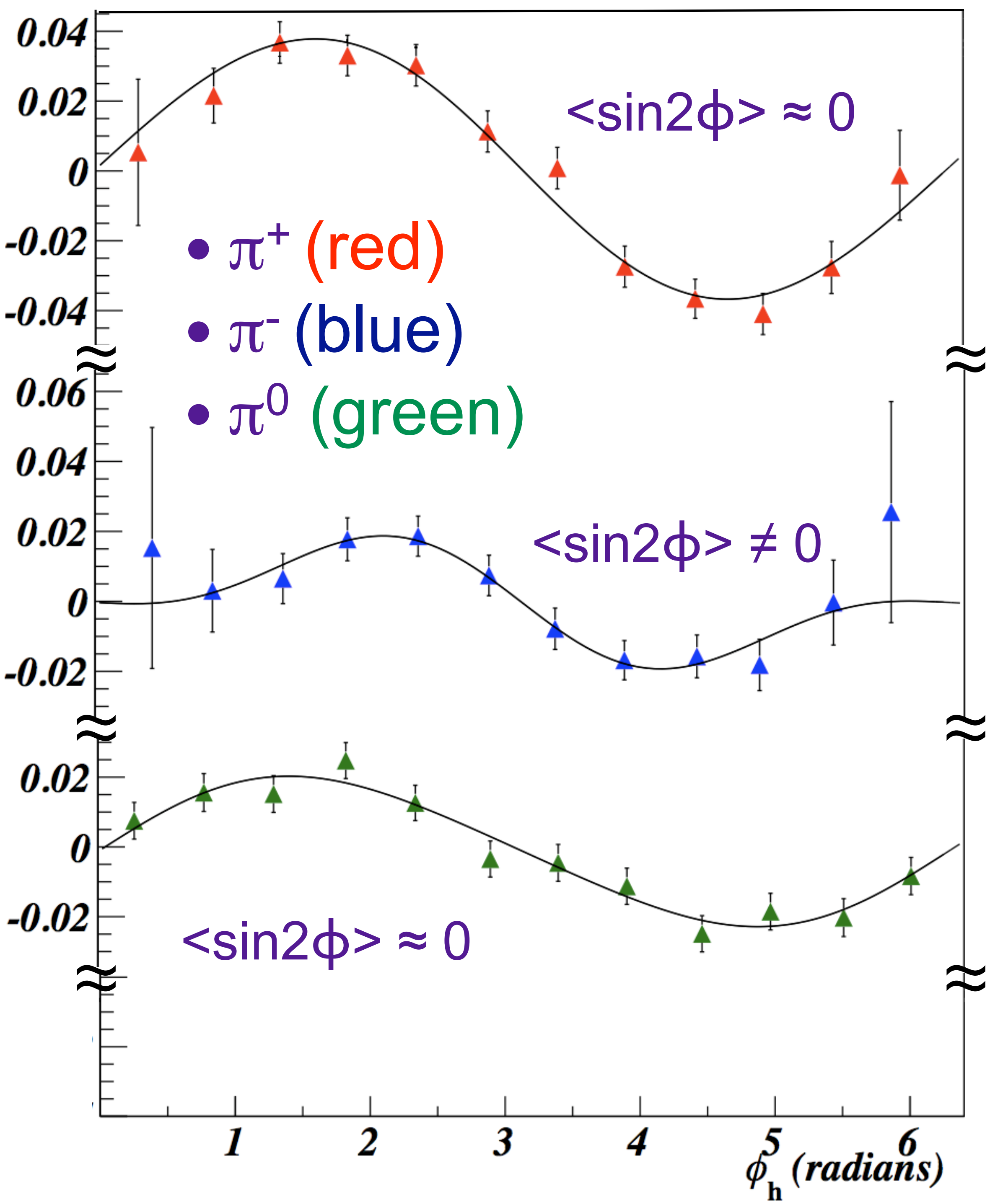
f (cyclic rotation through bins):

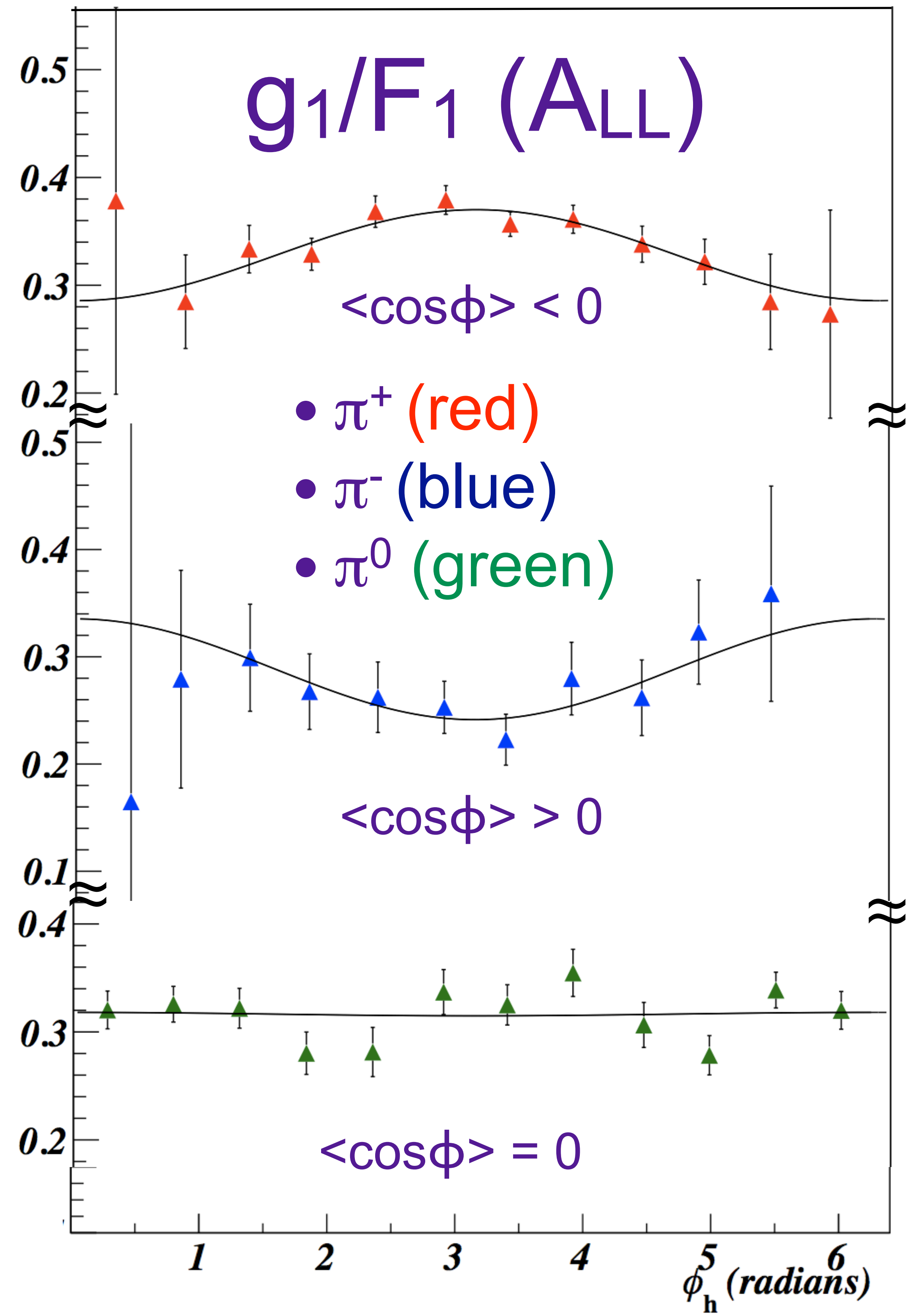


f is still under study, as are radiative corrections

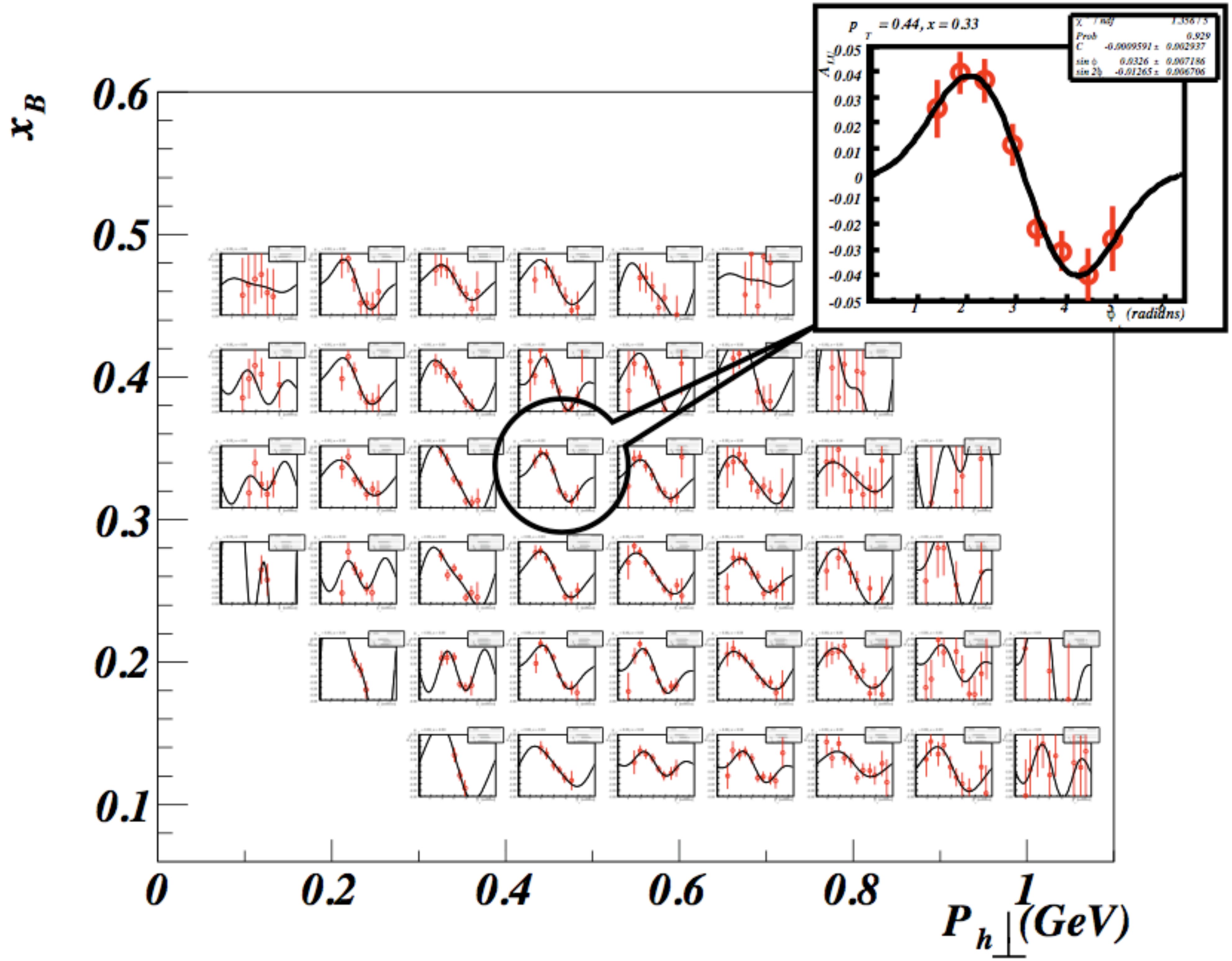
Integrated Asymmetries

$$A_{LU} = \frac{1}{|P_b|} \frac{n^{++} - n^{-+} - n^{--} + n^{+-}}{n^{++} + n^{-+} + n^{--} + n^{+-}}$$





Differential Asymmetries



π^+ A_{LU}
vs. ϕ

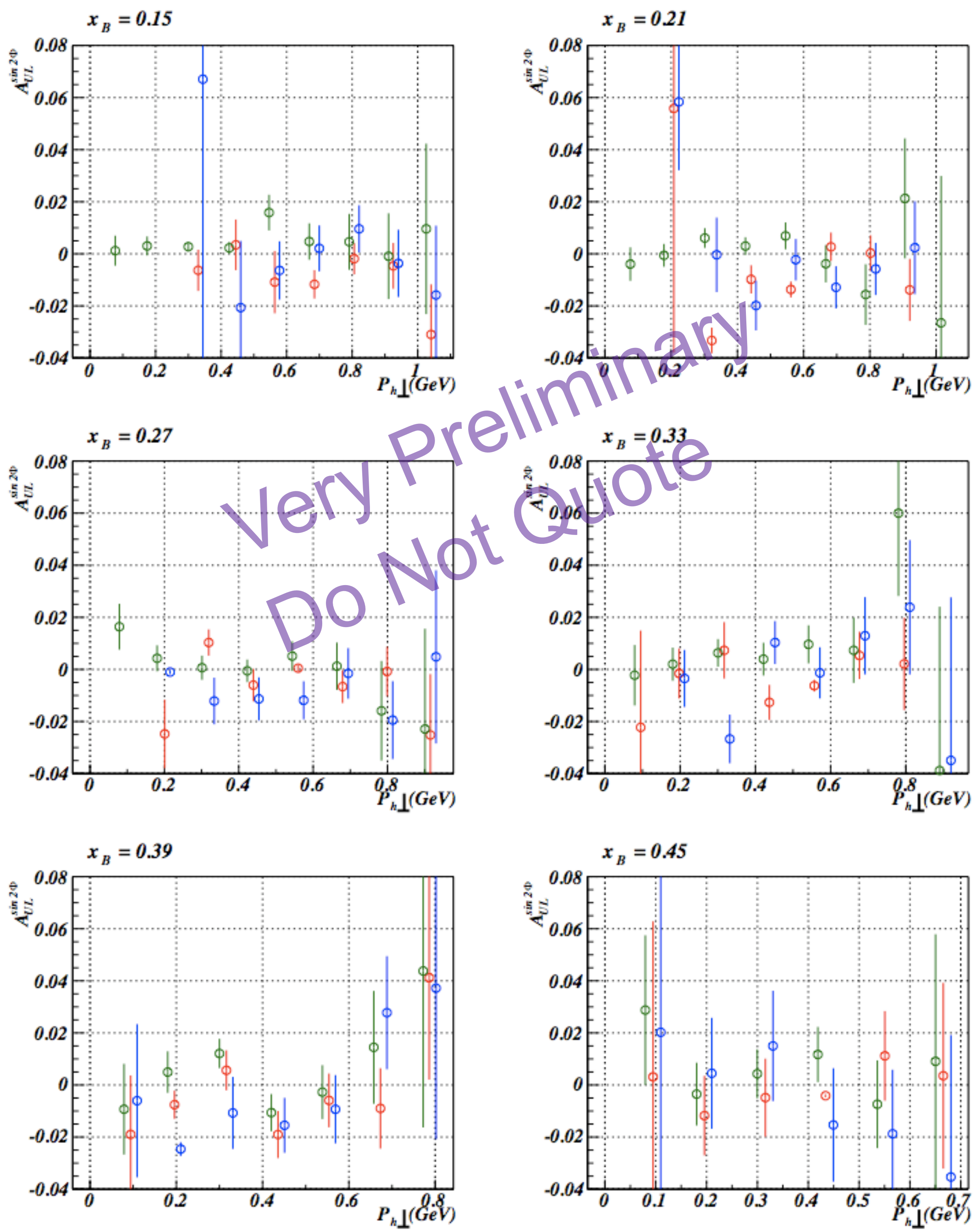
CLAS A_{LU}

$$A_{LU}^{\sin 2\phi_h} = \frac{F_{LU}^{\sin 2\phi_h}}{F_{UU,T}}$$

$$A_{LU} = \frac{1}{|P_b|}\frac{n^{++} - n^{-+} - n^{--} + n^{+-}}{n^{++} + n^{-+} + n^{--} + n^{+-}}$$

Higher Twist
Asymmetries are small

- π^+ (red)
- π^- (blue)
- π^0 (green)

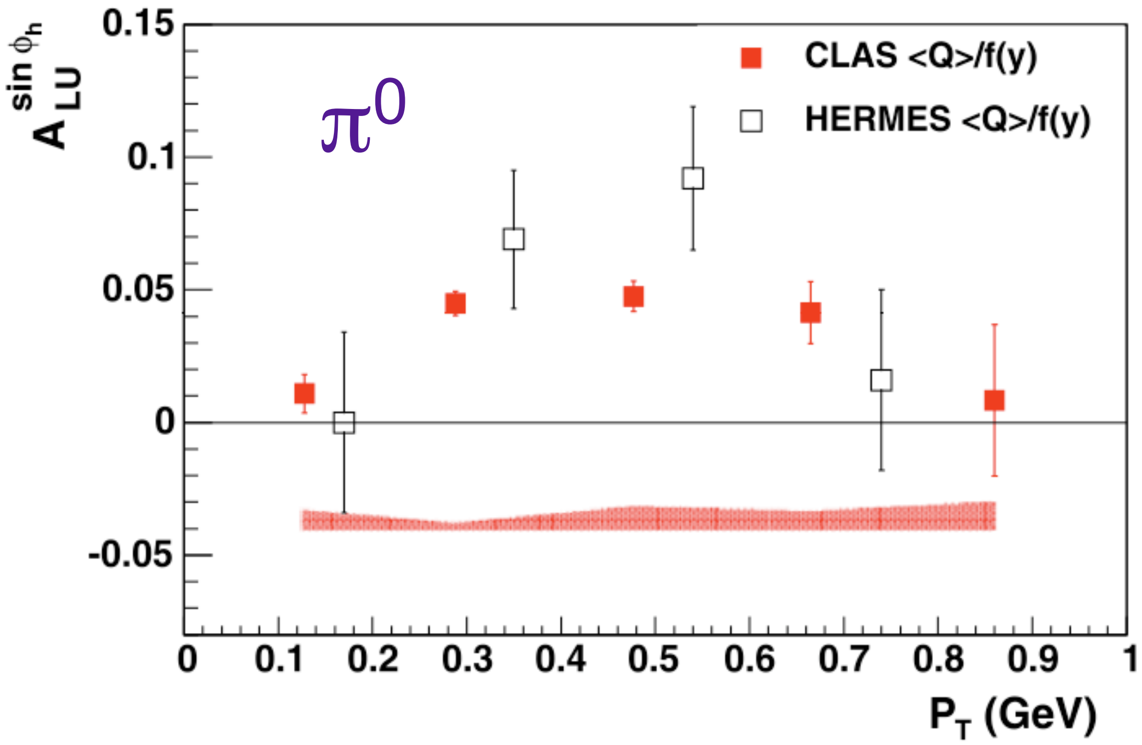


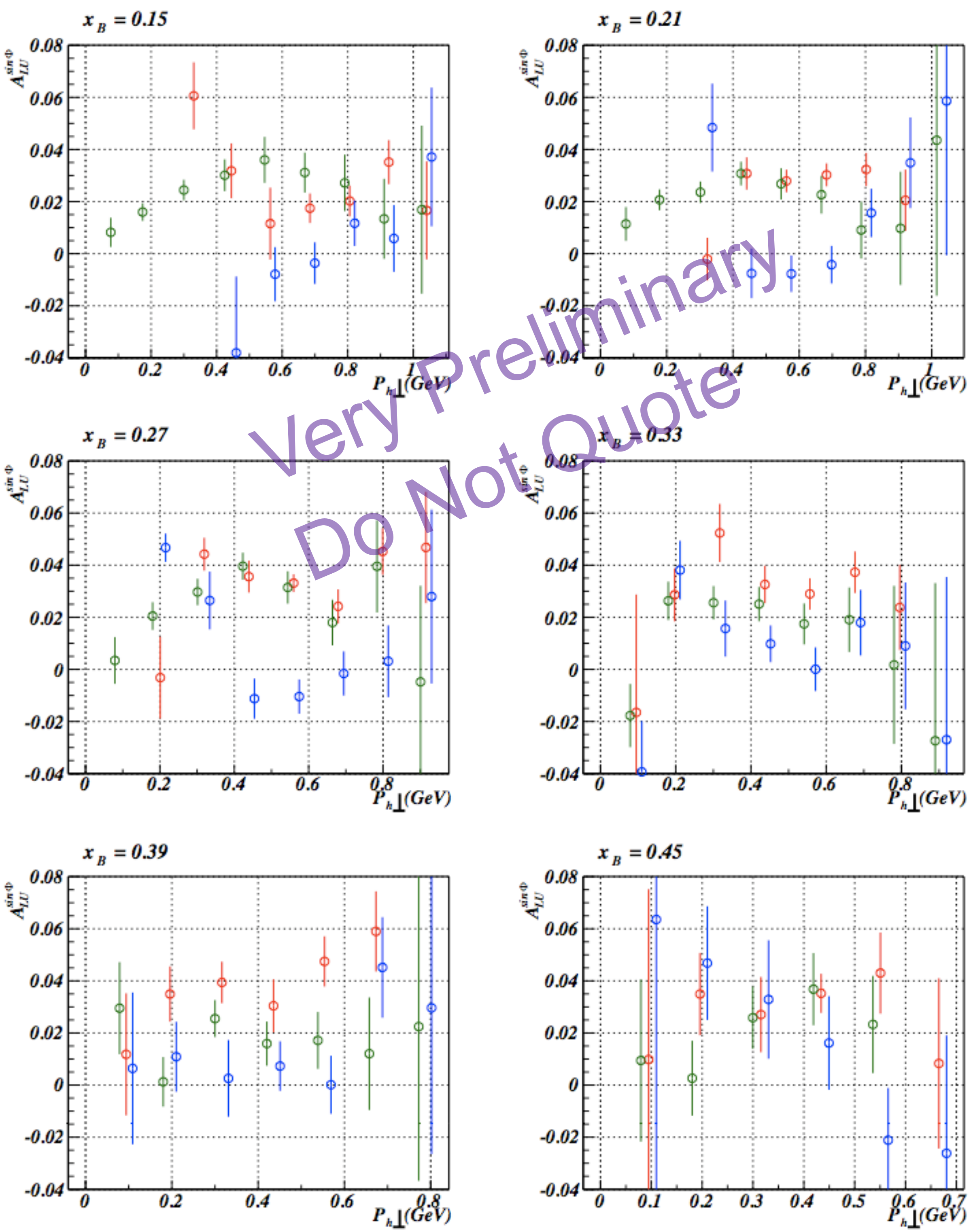
CLAS A_{LU}

$$F_{LU}^{\sin\phi_h} = \frac{2M}{Q}\,\mathcal{C}\left[-\frac{\hat{\boldsymbol{h}}\cdot\boldsymbol{k}_T}{M_h}\left(xe\,H_1^{\perp} + \frac{M_h}{M}\,f_1\frac{\tilde{G}^{\perp}}{z}\right) + \frac{\hat{\boldsymbol{h}}\cdot\boldsymbol{p}_T}{M}\left(xg^{\perp}D_1 + \frac{M_h}{M}\,h_1^{\perp}\frac{\tilde{E}}{z}\right)\right]$$

- π^+ (red)
- π^- (blue)
- π^0 (green)

Aghasyan, PLB704(11)397





CLAS A_{LL}

$$F_{LL} = \mathcal{C}\left[g_{1L} D_1\right]$$

$$A_{LL} = -\frac{1}{f}\frac{n^{++} - n^{-+} + n^{--} - n^{+-}}{|P_b P_t^-|(n^{++} + n^{-+}) + |P_b P_t^+|(n^{--} + n^{+-})}$$

$$\frac{g_1}{F_1} = \frac{[A_{LL} + A_\perp \tan(\theta/2)]}{D'}$$

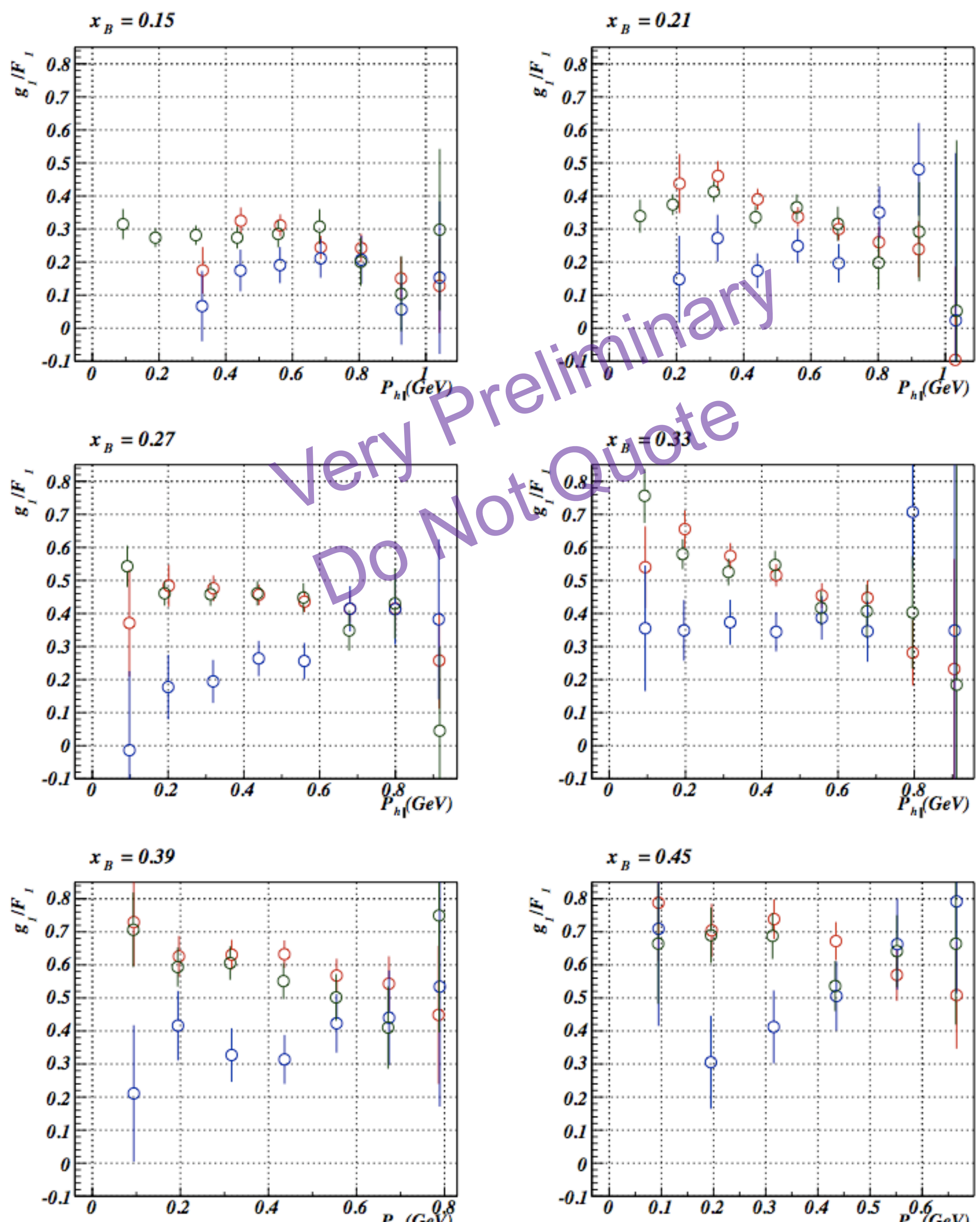
small

$$D'(y) = \frac{y(2-y)(1+\gamma^2)}{y^2 + 2\left(1 - y - \frac{1}{4}y^2\gamma^2\right)(1+R)}$$

$$\gamma^2 = 2Mx_B/Q^2$$

$$R = \frac{\sigma_L}{\sigma_T}$$

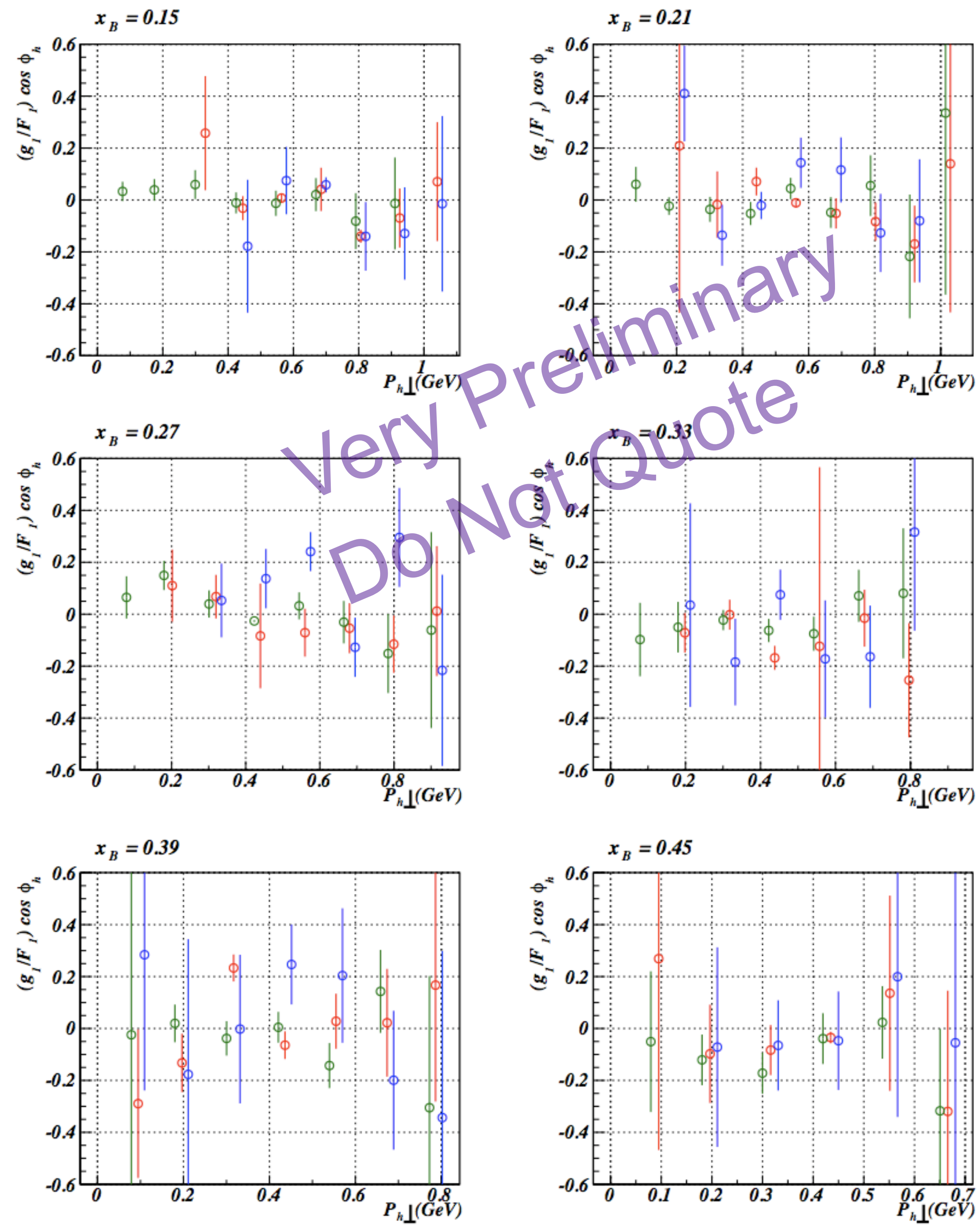
- π^+ (red)
- π^- (blue)
- π^0 (green)



CLAS A_{LL}

$$F_{LL}^{\cos\phi_h} = \frac{2M}{Q}\,\mathcal{C}\left[\frac{\hat{\boldsymbol{h}}\cdot\boldsymbol{k}_T}{M_h}\left(x e_L H_1^{\perp} - \frac{M_h}{M}\,g_{1L}\frac{\tilde{D}^{\perp}}{z}\right) - \frac{\hat{\boldsymbol{h}}\cdot\boldsymbol{p}_T}{M}\left(x g_L^{\perp} D_1 + \frac{M_h}{M}\,h_{1L}^{\perp}\frac{\tilde{E}}{z}\right)\right]$$

- π^+ (red)
- π^- (blue)
- π^0 (green)

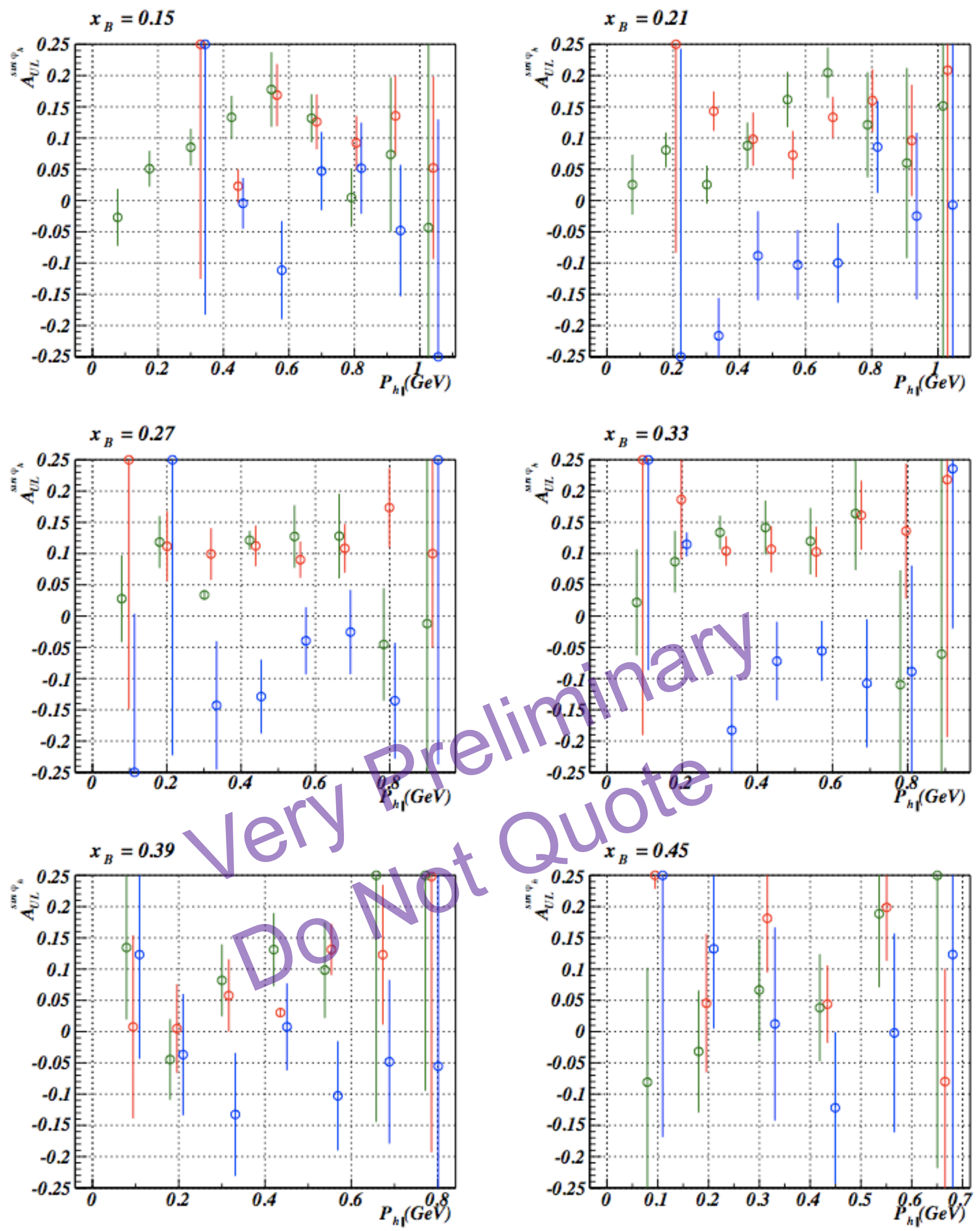


CLAS A_{UL}

$$F_{UL}^{\sin\phi_h} = \frac{2M}{Q}\,\mathcal{C}\left[-\frac{\hat{\boldsymbol{h}}\cdot\boldsymbol{k}_T}{M_h}\left(x h_L H_1^{\perp} + \frac{M_h}{M}\, g_{1L}\,\frac{\tilde{G}^{\perp}}{z}\right) + \frac{\hat{\boldsymbol{h}}\cdot\boldsymbol{p}_T}{M}\left(x f_L^{\perp} D_1 - \frac{M_h}{M}\, h_{1L}^{\perp}\,\frac{\tilde{H}}{z}\right)\right]$$

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

- π^+ (red)
- π^- (blue)
- π^0 (green)

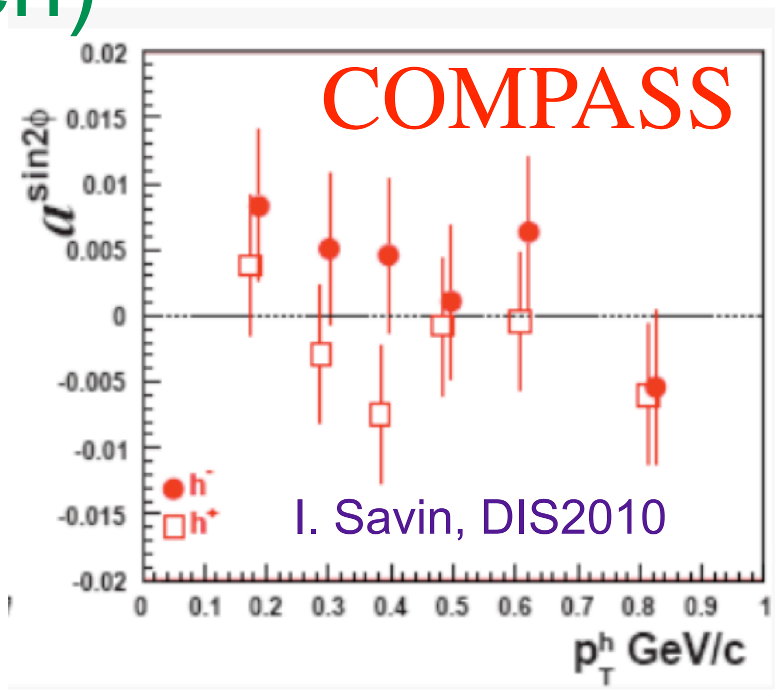


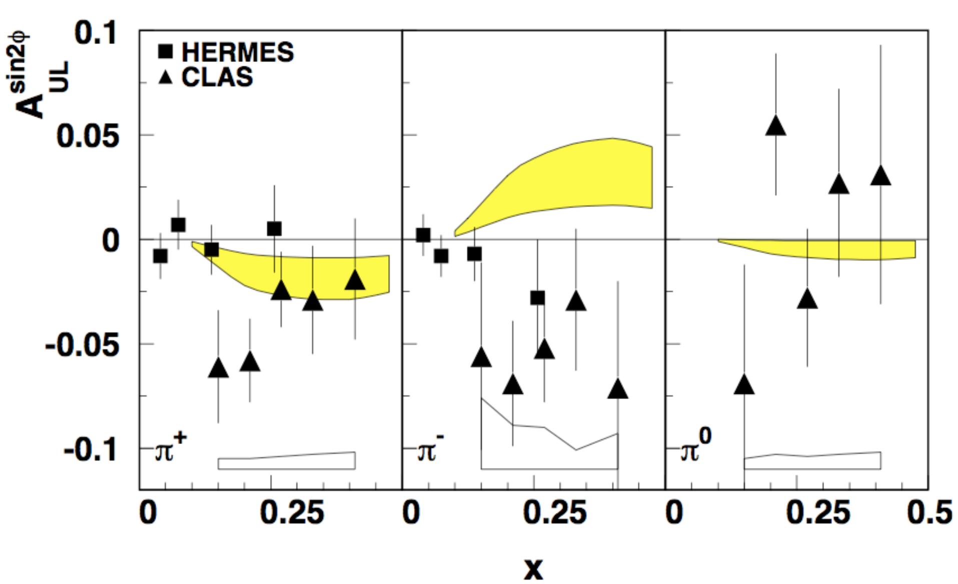
CLAS A_{UL}

- π^+ (red)
- π^- (blue)
- π^0 (green)

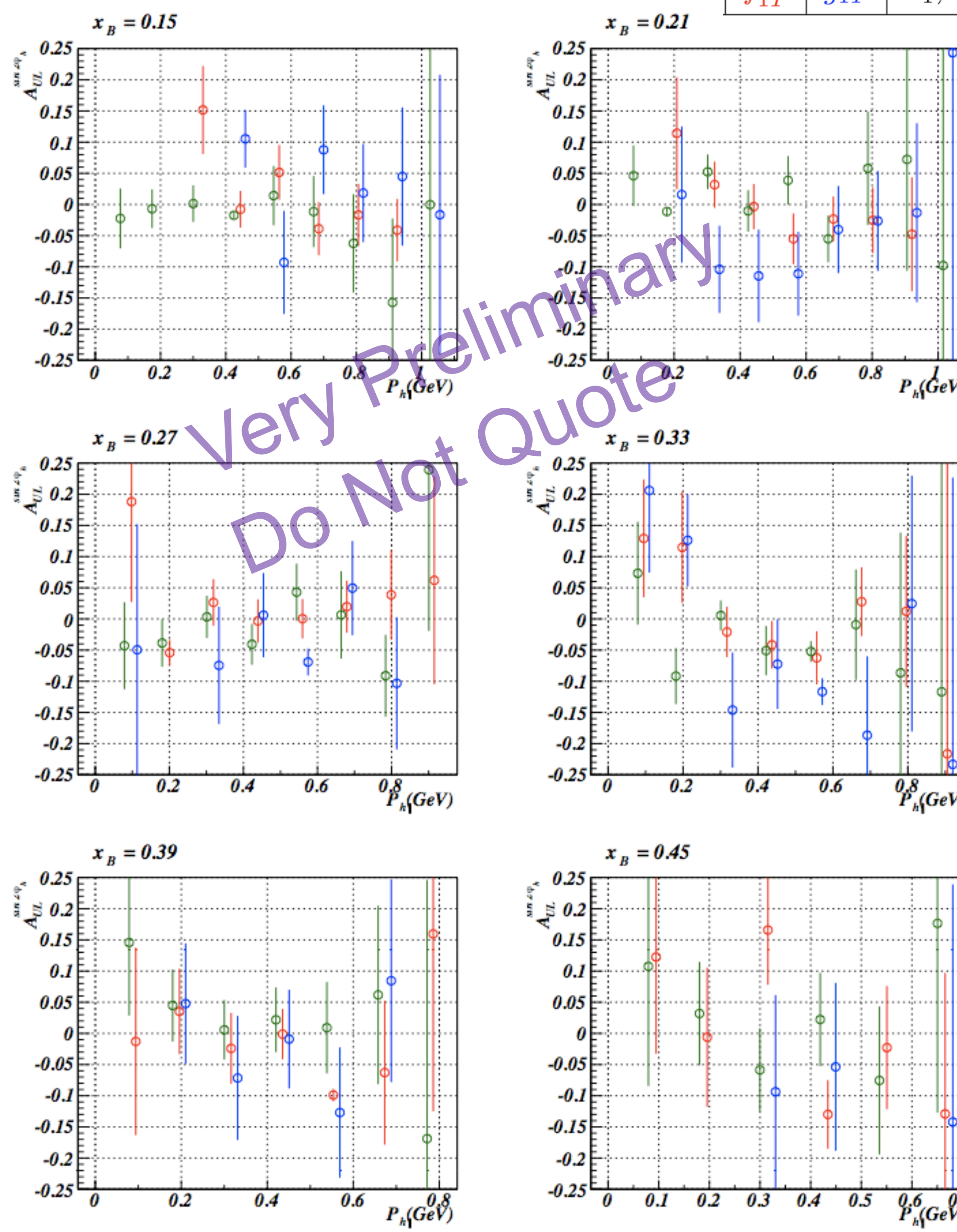
$$F_{UL}^{\sin 2\phi_h} = \mathcal{C}\left[-\frac{2\left(\hat{\boldsymbol{h}}\cdot\boldsymbol{k}_T\right)\left(\hat{\boldsymbol{h}}\cdot\boldsymbol{p}_T\right)-\boldsymbol{k}_T\cdot\boldsymbol{p}_T}{M M_h} h_{1L}^{\perp} H_1^{\perp}\right]$$

f_1		$h_1^{\perp}$
	g_{1L}	$h_{1L}^{\perp}$
$f_{1T}^{\perp}$	g_{1T}	$h_1,\ h_{1T}^{\perp}$





Avakian, PRL**105**(10)262002



Conclusions

- TMDs are needed to understand nucleon spin. Watch for them in the future.
- The EG1-DVCS experiment using CLAS at JLab has taken extensive π^+, π^-, and π^0 SIDIS data with a longitudinally polarized beam and target for Q^2~1-2 GeV^2.
- The resulting asymmetries A_{UL}, A_{LU} and A_{LL} have significant azimuthal moments. Analysis is ongoing.
- For the first time these azimuthal moments can be resolved in 2 dimensions (x, $P_{h\perp}$) simultaneously.
- CLAS12 is approved to improve on this at 12 GeV for higher Q^2.