Semi-Inclusive π^0 target and beam-target asymmetries from 6 GeV electron scattering with CLAS

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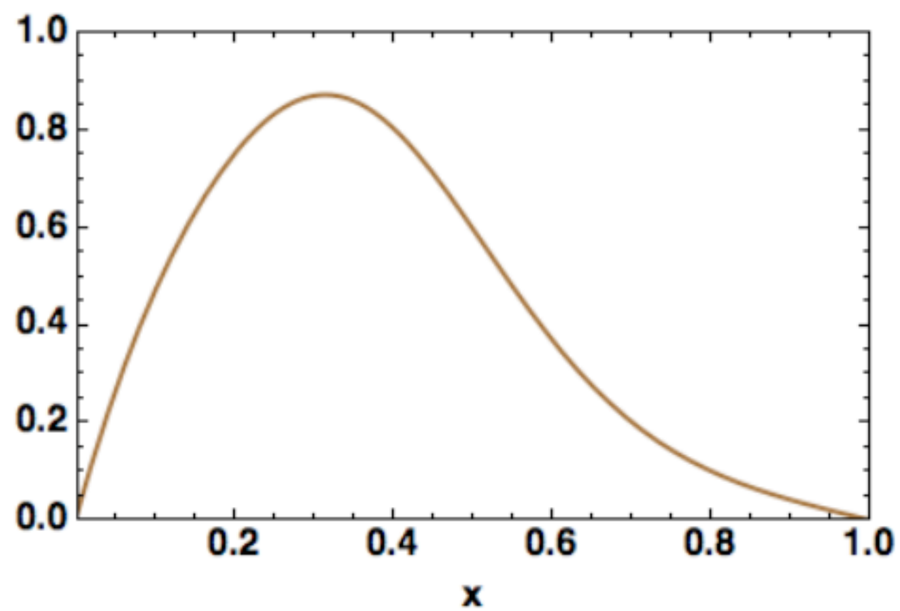
TMDs

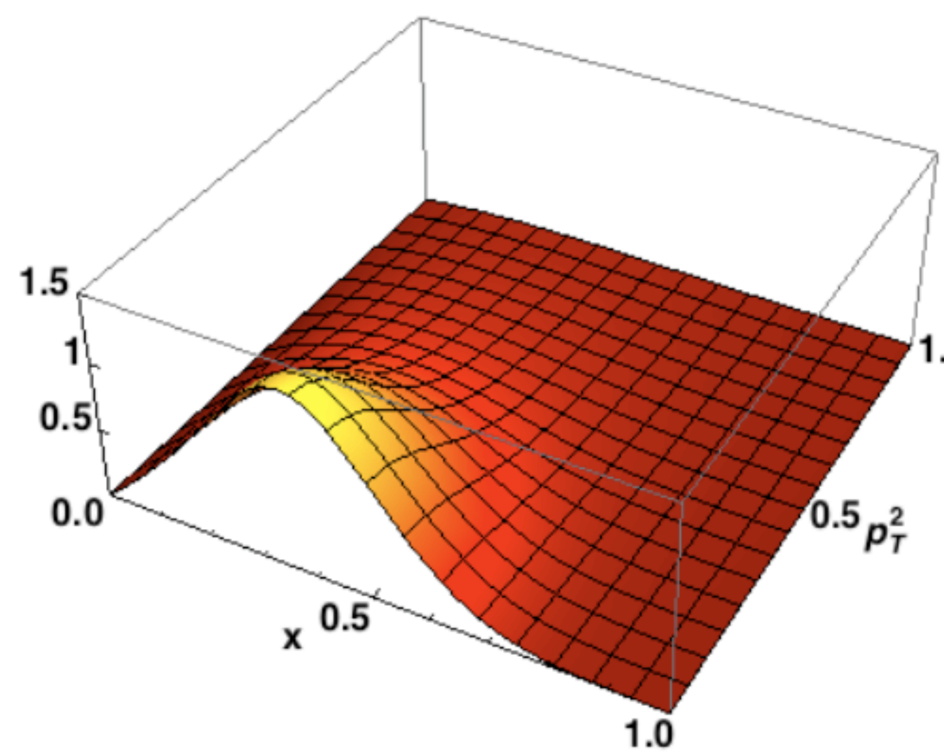
- Any confined quark must have transverse momentum
- Therefore, colinear PDFs cannot give the whole story
- Transverse momentum is related to L_z
- There has been much recent work trying to understand transverse momentum distributions (TMDs)

$x f_1^u(x)$



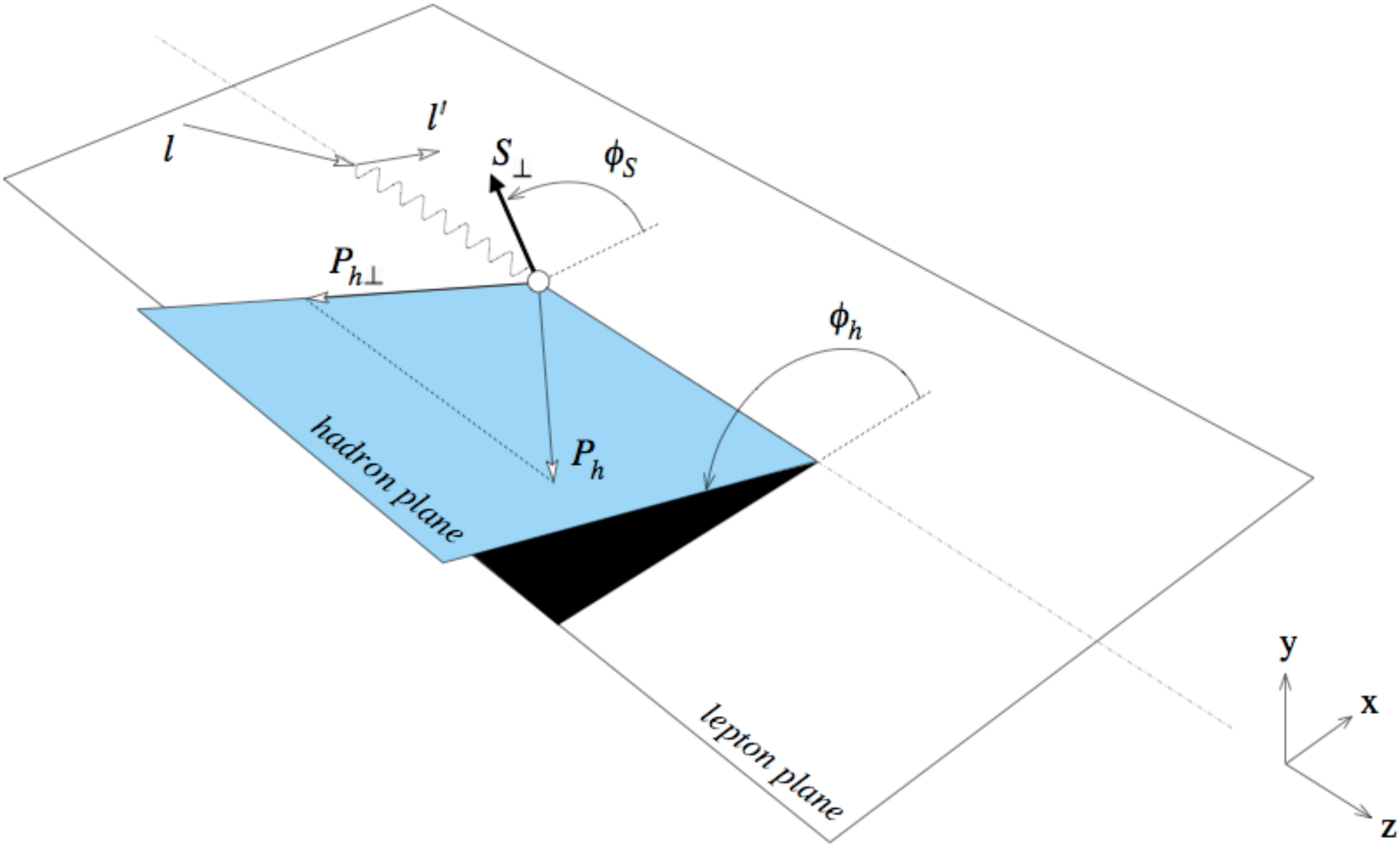
Standard collinear PDF

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



TMD

Semi-Inclusive DIS



SIDIS Cross Section

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

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

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.

TMD Structure Functions

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

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

Unpolarized fragmentation function; integrates to $D_1(z,Q^2)$

Unpolarized structure function; integrates to $F_1(x,Q^2)$

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

Polarized structure function; integrates to $g_1(x,Q^2)$

$$F_{UT}^{\sin(\phi_h+\phi_S)} = \mathcal{C}\left[-\frac{\hat{\boldsymbol{h}}\cdot\boldsymbol{k}_T}{M_h} h_1 H_1^{\perp}\right]$$

The Collins fragmentation function

$$F_{UT,T}^{\sin(\phi_h-\phi_S)} = \mathcal{C}\left[-\frac{\hat{\boldsymbol{h}}\cdot\boldsymbol{p}_T}{M} f_{1T}^{\perp} D_1\right]$$

The Sivers structure function

And there are more...

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

Boer-Mulders

Pretzelocity

Sivers

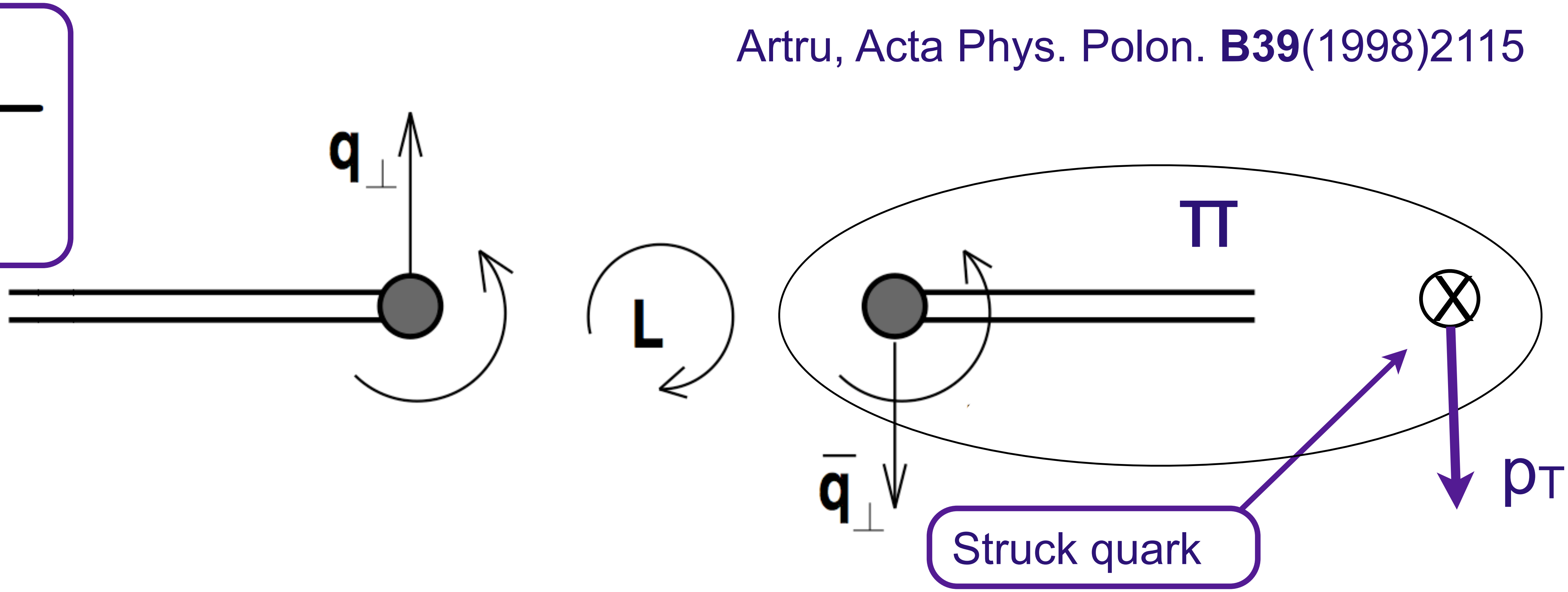
Worm Gear

Transversity

Collins Fragmentation

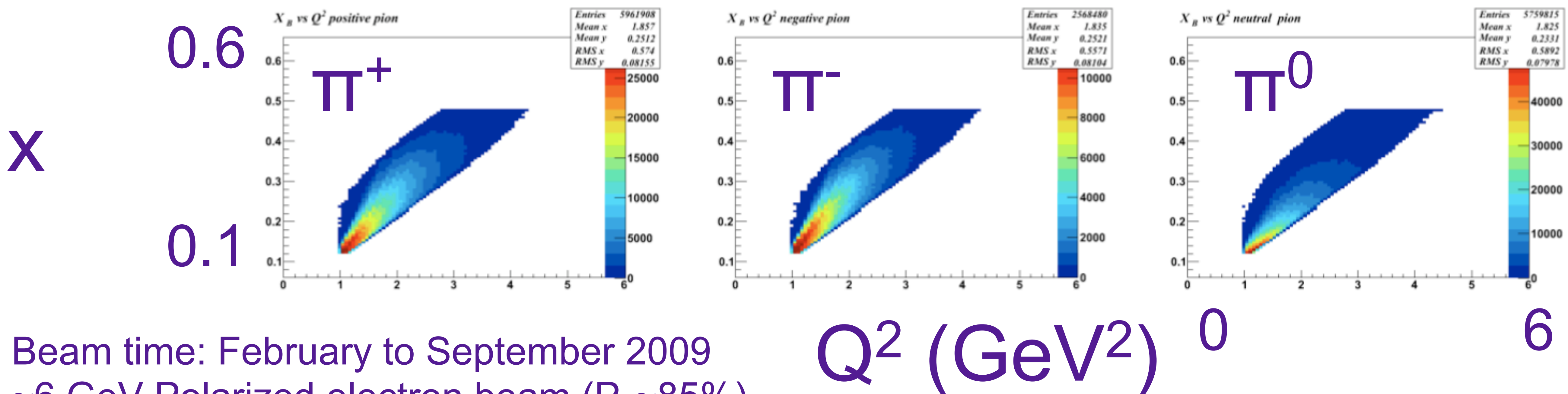
$$H_1^\perp$$

Artru, Acta Phys. Polon. **B39**(1998)2115

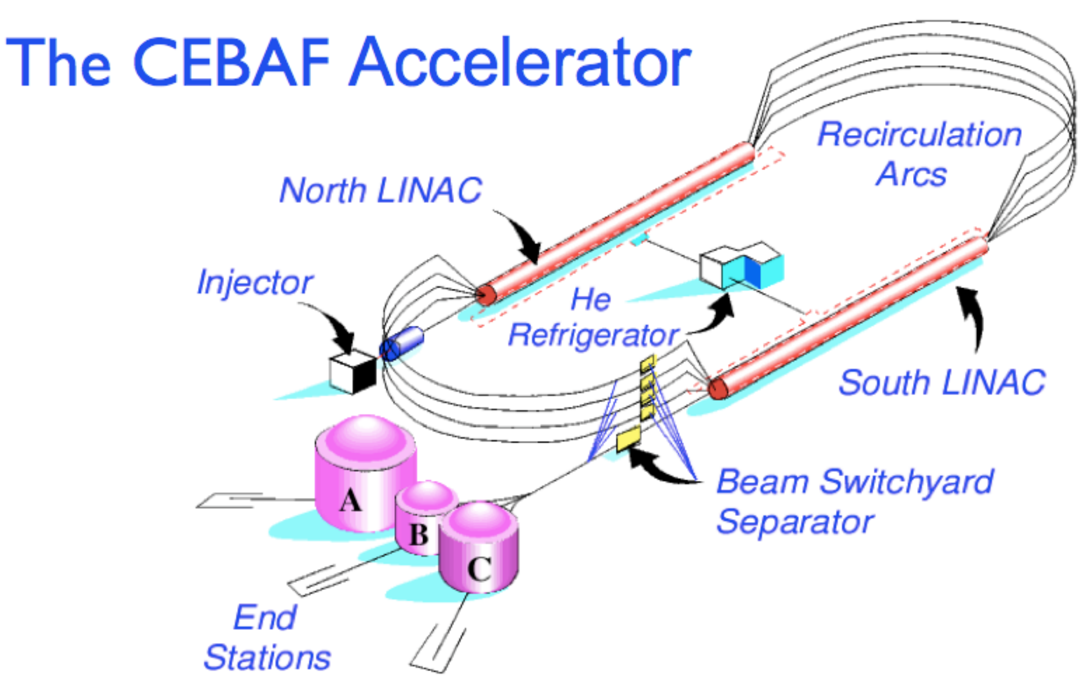


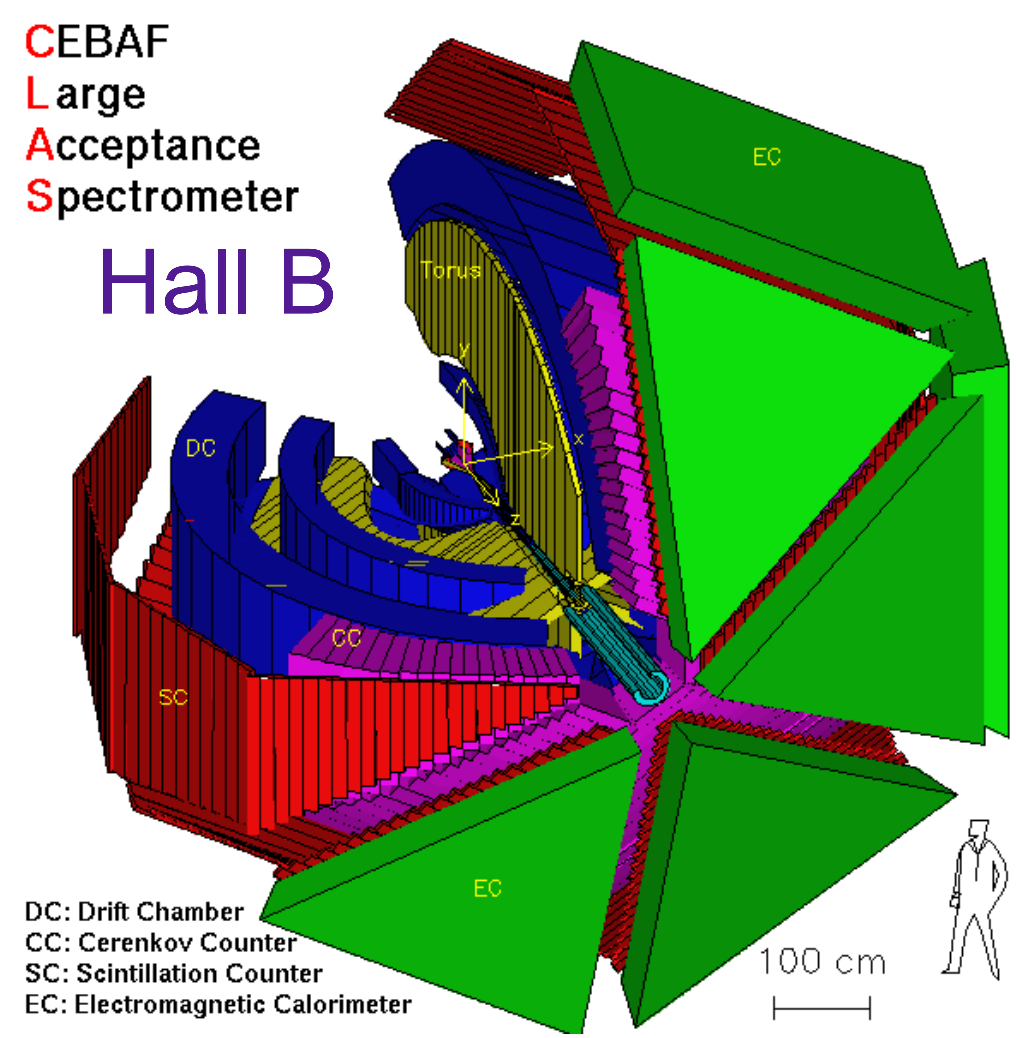
- Imagine that the $q\bar{q}$ pair is created in a $^3P_0$ spin state with vacuum quantum numbers $J^{PC}=0^{++}$
- Quark spins are opposite the orbital ang. mom. L=1
- Pion (with no spin) acquires transverse momentum
- This simple model breaks down if the fragmentation string does not conserve J (i.e. if there are torques)

EG1-DVCS at JLab

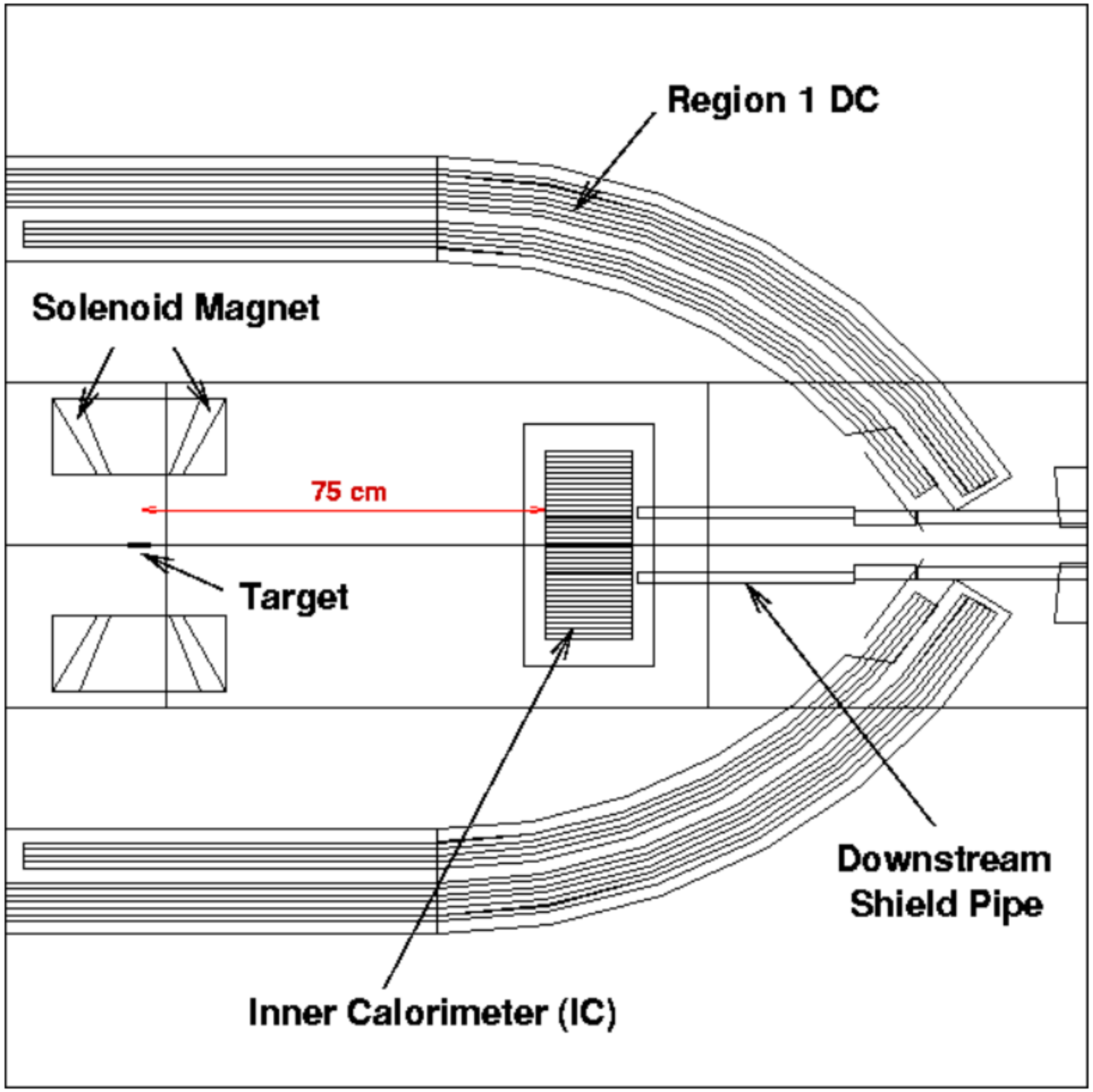


- Beam time: February to September 2009
- ~6 GeV Polarized electron beam (P_b~85%)
- Frozen $^{14}NH_3$ target (P_t~75%)
- CEBAF large acceptance spectrometer (CLAS) plus Inner Calorimeter
- ~19 billion electron triggers on NH_3 target





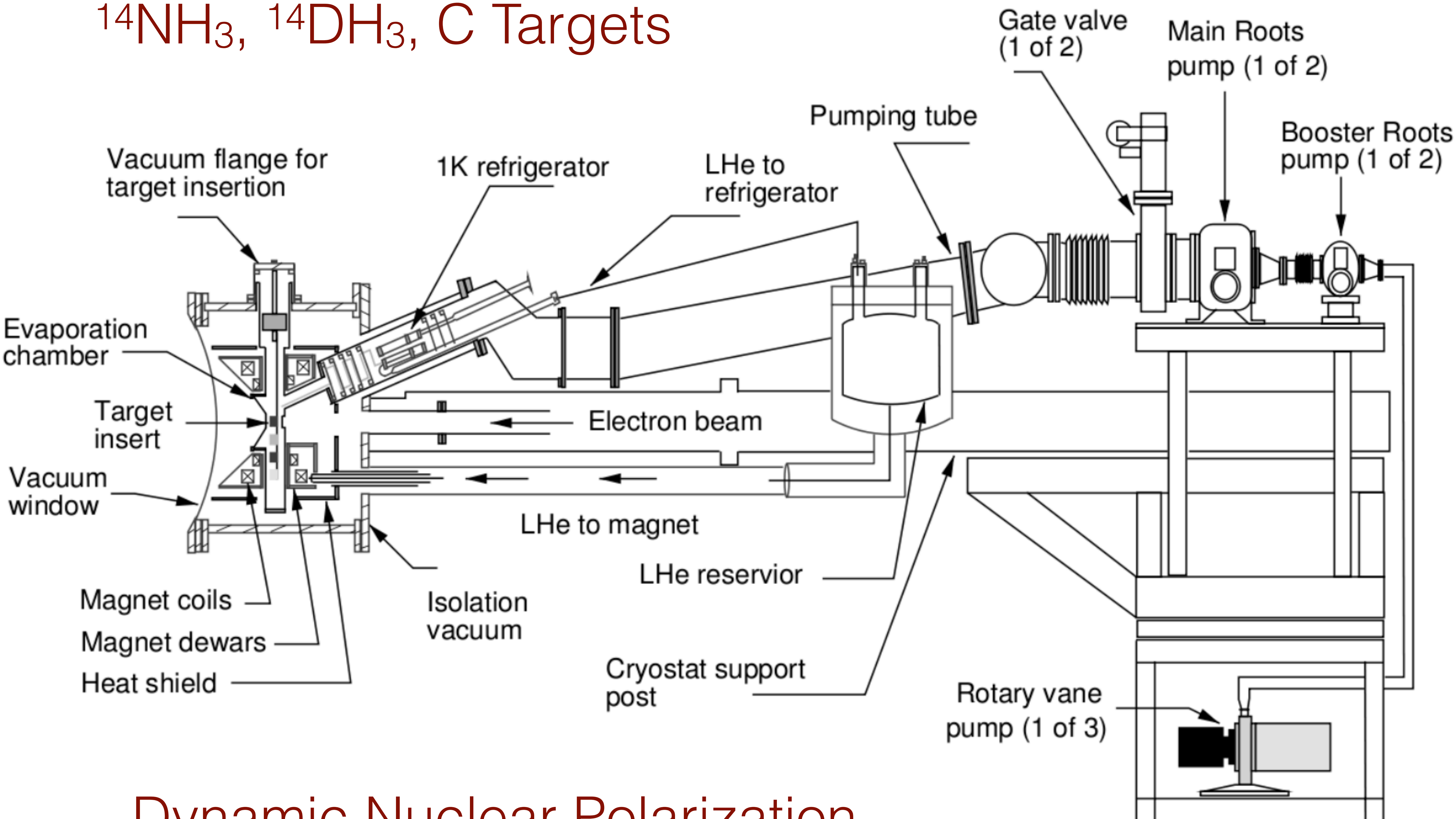
Inner Calorimeter



$\pi^0 \rightarrow \gamma\gamma$

Polarized Target

$^{14}NH_3$, $^{14}DH_3$, C Targets



Dynamic Nuclear Polarization

Asymmetries

$$A_{LU} = \frac{(d\sigma^{\uparrow\Uparrow} - d\sigma^{\downarrow\Uparrow}) + (d\sigma^{\uparrow\Downarrow} - d\sigma^{\downarrow\Downarrow})}{(d\sigma^{\uparrow\Uparrow} + d\sigma^{\downarrow\Uparrow}) + (d\sigma^{\uparrow\Downarrow} + d\sigma^{\downarrow\Downarrow})},$$

$$A_{UL} = \frac{d\sigma^{\uparrow\Uparrow} + d\sigma^{\downarrow\Uparrow} - d\sigma^{\uparrow\Downarrow} - d\sigma^{\downarrow\Downarrow}}{(d\sigma^{\uparrow\Uparrow} + d\sigma^{\downarrow\Uparrow}) + (d\sigma^{\uparrow\Downarrow} + d\sigma^{\downarrow\Downarrow})},$$

$$A_{LL} = \frac{-d\sigma^{\uparrow\Uparrow} + d\sigma^{\downarrow\Uparrow} + d\sigma^{\uparrow\Downarrow} - d\sigma^{\downarrow\Downarrow}}{(d\sigma^{\uparrow\Uparrow} + d\sigma^{\downarrow\Uparrow}) + (d\sigma^{\uparrow\Downarrow} + d\sigma^{\downarrow\Downarrow})},$$

ALU, AUL, ALL

$$A_{LU} = \frac{A_{LU}^{\sin\phi_h}\sin\phi_h}{1 + A_{UU}^{\cos\phi_h}\cos\phi_h + A_{UU}^{\cos 2\phi_h}\cos 2\phi_h}$$

$$A_{UL} = \frac{A_{UL}^{\sin\phi_h}\sin\phi_h + A_{UL}^{\sin 2\phi_h}\sin 2\phi_h}{1 + A_{UU}^{\cos\phi_h}\cos\phi_h + A_{UU}^{\cos 2\phi_h}\cos 2\phi_h}$$

$$A_{LL} = \frac{A_{LL}^{Const} + A_{LL}^{\cos\phi_h}\cos\phi_h}{1 + A_{UU}^{\cos\phi_h}\cos\phi_h + A_{UU}^{\cos 2\phi_h}\cos 2\phi_h};$$

π^0 Reconstruction

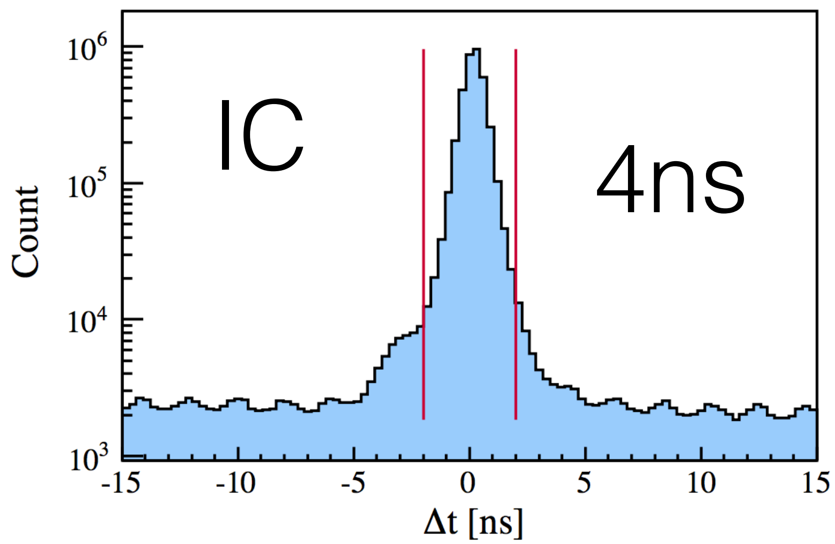


Figure 3.31: Δt distribution for IC photons after applying all other photon cuts. For a good IC photon candidate, Δt is required to be within ± 2 ns.

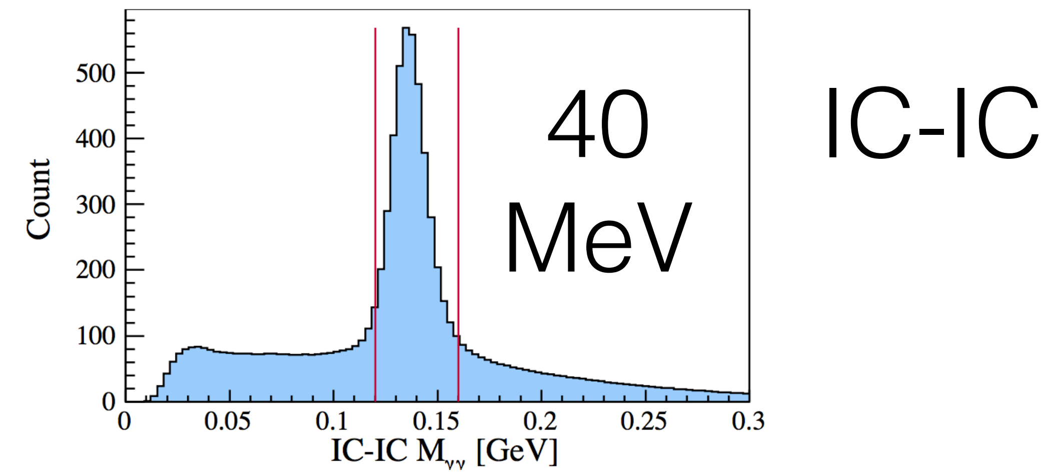


Figure 3.35: $M_{\gamma_{IC}-\gamma_{IC}}$. The invariant mass distribution of two photons, both in the IC. The vertical red lines represent the applied cuts, 0.12 GeV $\leq M_{\gamma_{IC}-\gamma_{IC}} \leq$ 0.16 GeV.

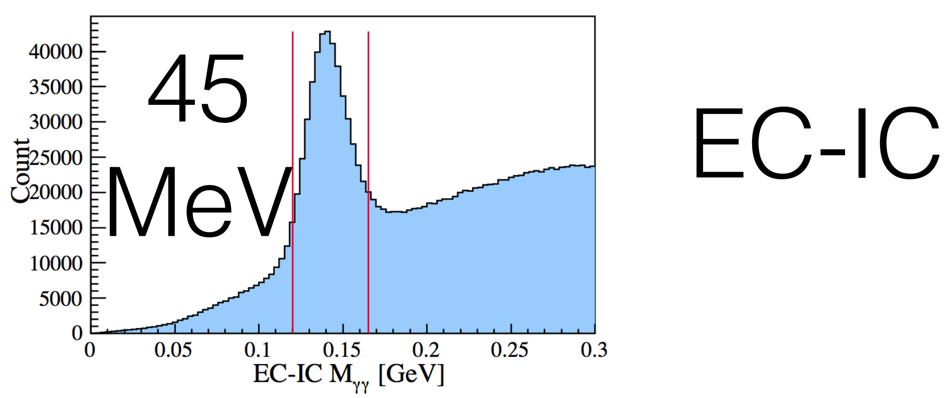


Figure 3.34: $M_{\gamma_{EC}-\gamma_{IC}}$. The invariant mass distribution of two photons, one in EC and one in IC. The vertical red lines represent the applied cuts, 0.12 GeV $\leq M_{\gamma_{EC}-\gamma_{IC}} \leq$ 0.165 GeV.

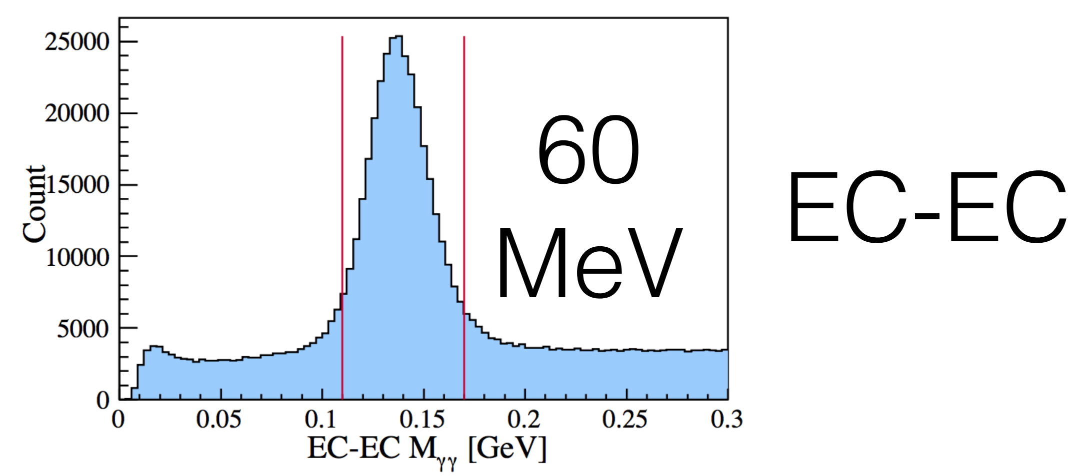
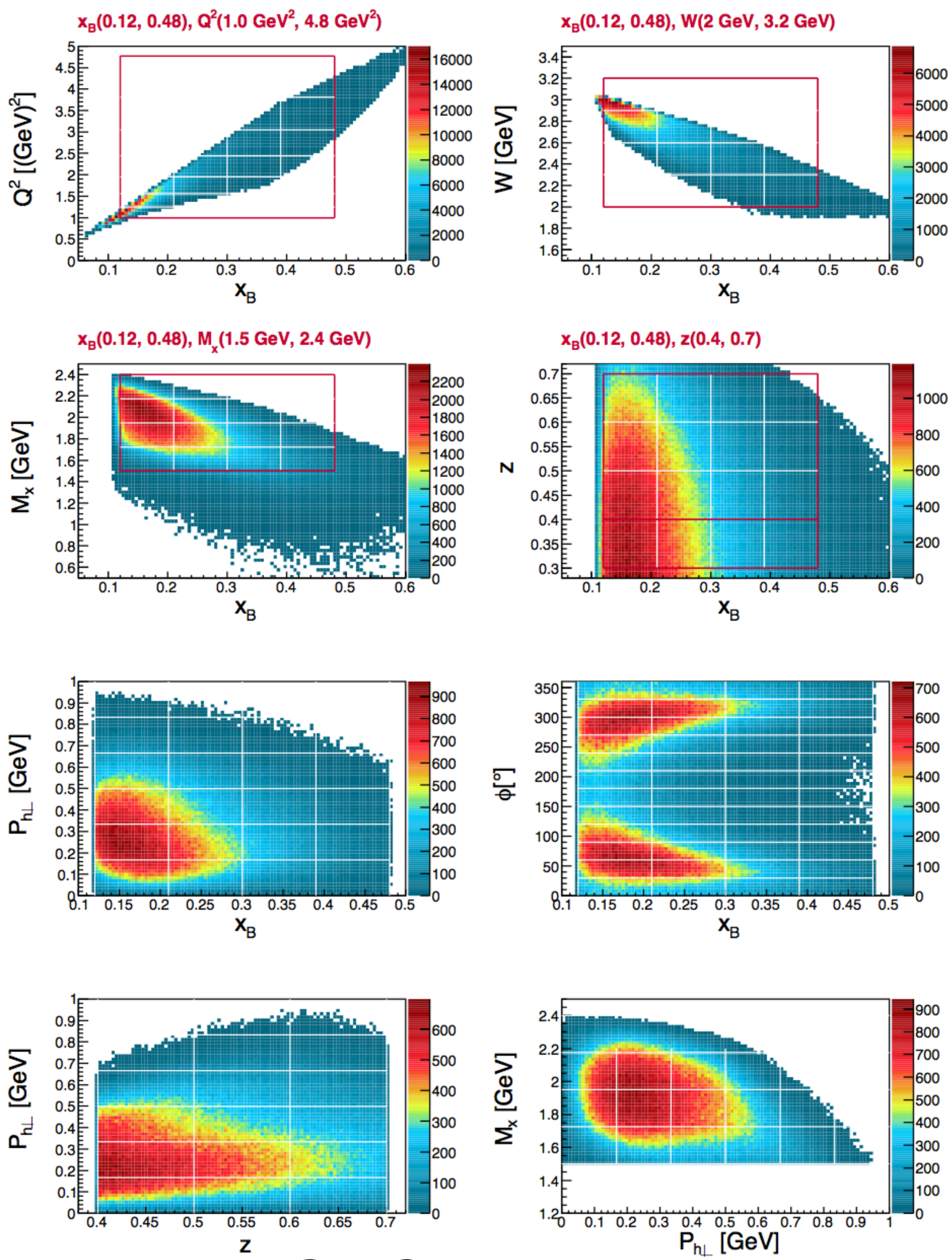
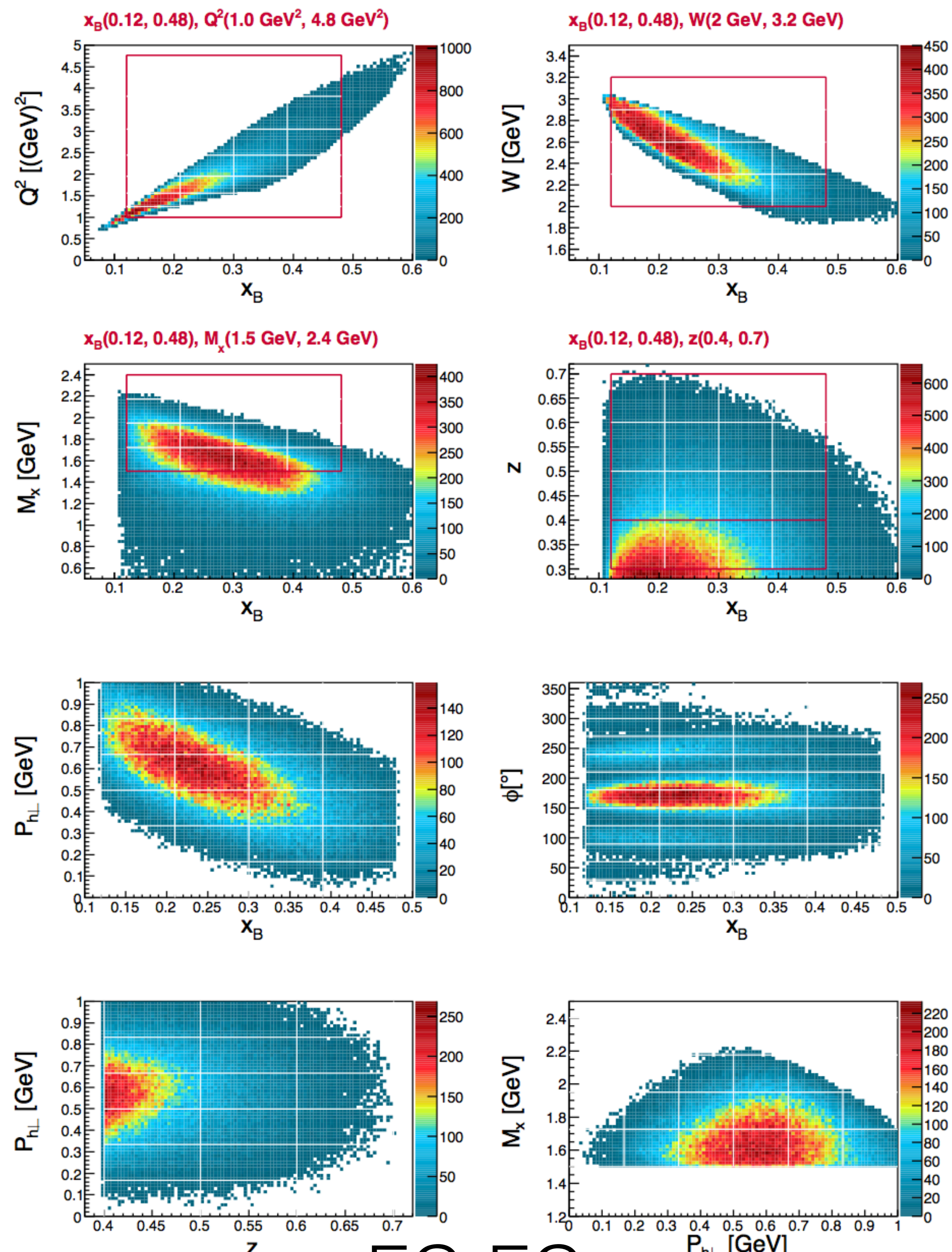


Figure 3.33: $M_{\gamma_{EC}-\gamma_{EC}}$. The invariant mass distribution of two photons, both in the EC. The vertical red lines represent the applied cuts, 0.11 GeV $\leq M_{\gamma_{EC}-\gamma_{EC}} \leq$ 0.17 GeV.

π^0: IC-IC & EC-EC



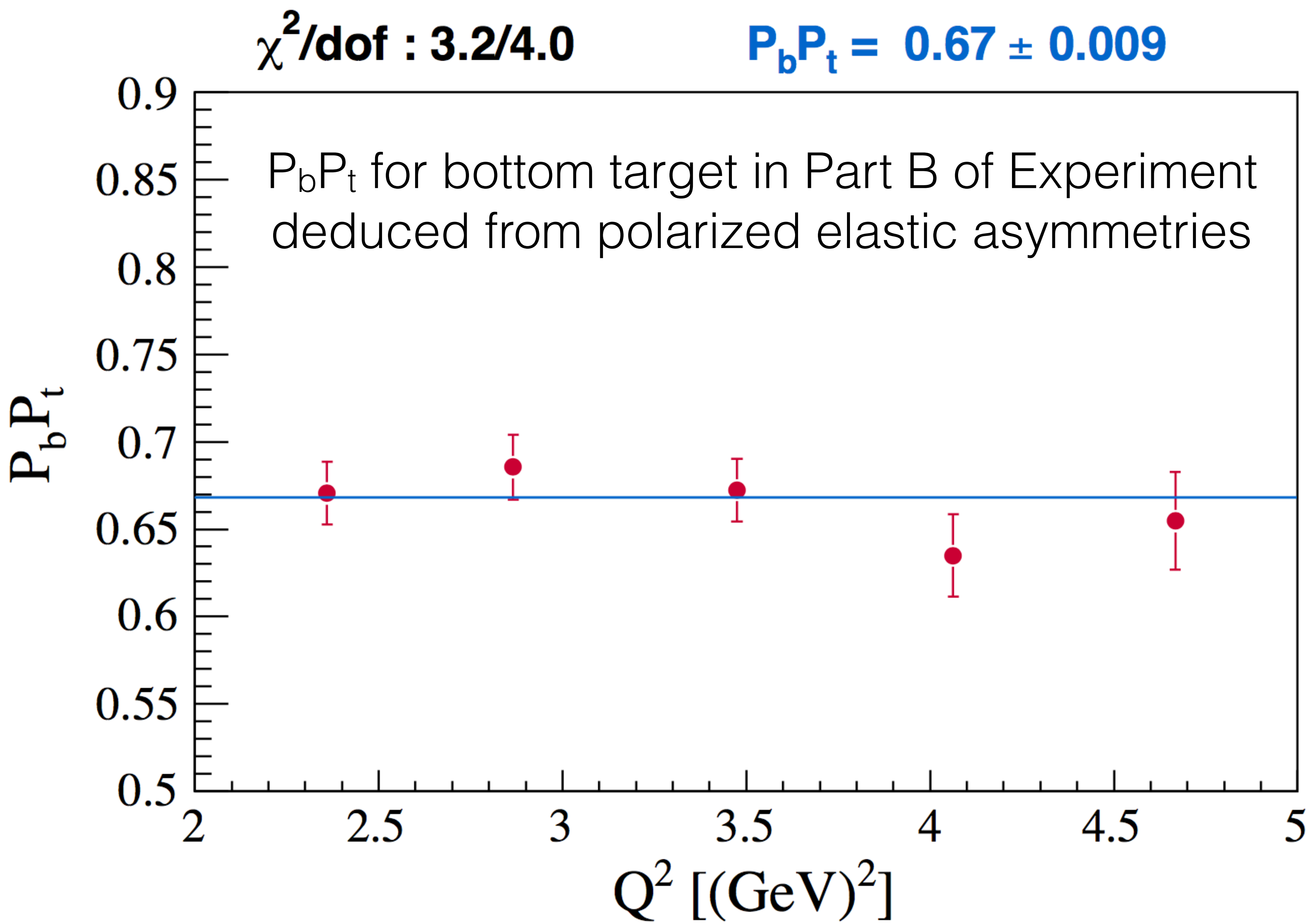
IC-IC



EC-EC

P_bP_t

P_b measured using Moller Scattering



Dilution Factor

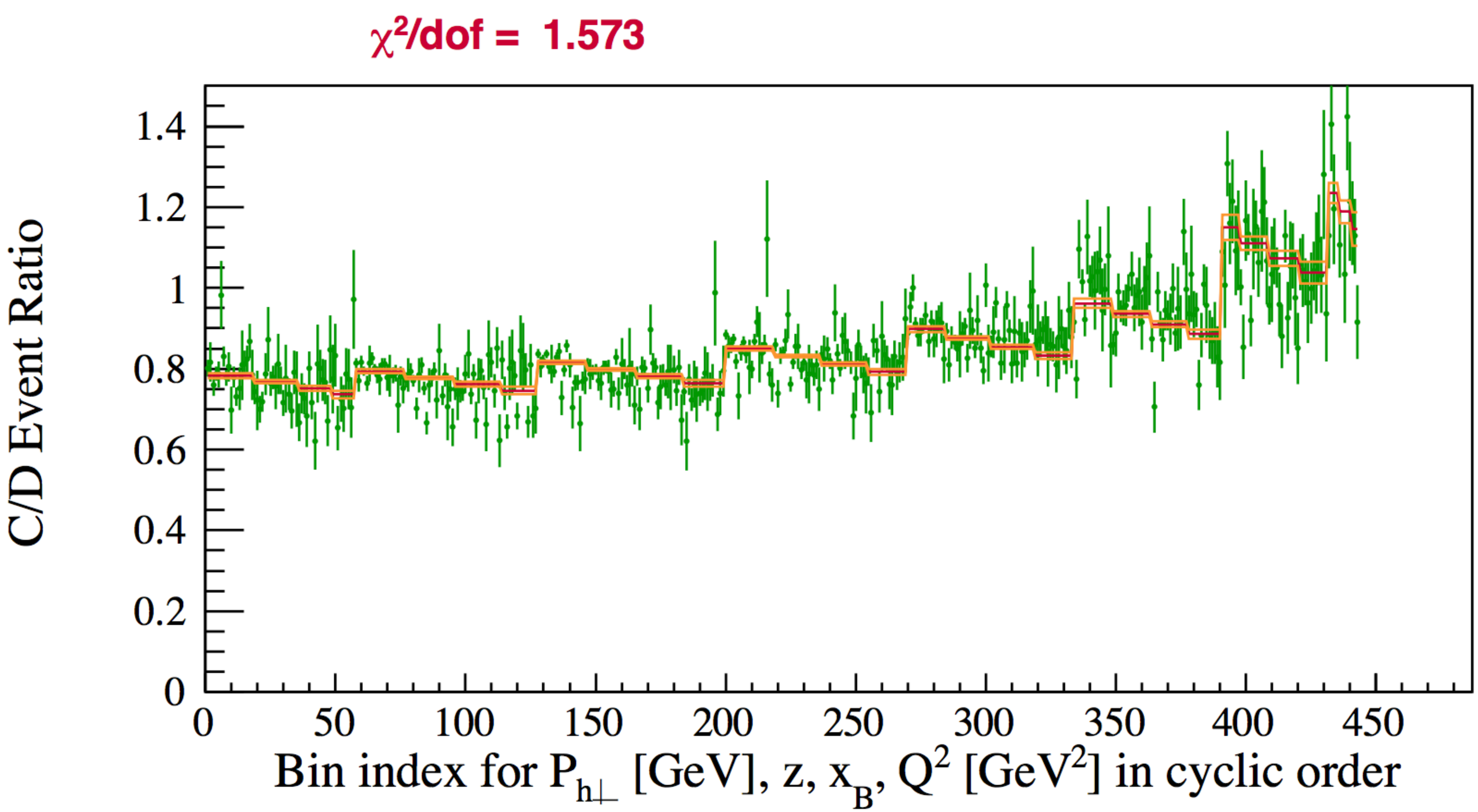


Figure 4.9: Fits of the ratio of neutral pion events on ^{12}C and ^{2}H from the EG2 experiment. Plotted along the x-axis are kinematic bins with $P_{h\perp}$ in the outer loop, then z, then x_B and Q^2 in the inner loop. The red line is the best fit; the two orange lines are the $\pm 1\sigma$ uncertainty of the fits. The ordering of the kinematic bin index in this figure is reverse of the following plots.

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Radiative Corrections

Complete lowest order radiative corrections to five-fold differential cross-section of hadron leptoproduction
I. Akushevich (Duke U.), A. Ilyichev (Minsk, High Energy Phys. Ctr.), M. Osipenko (INFN, Genoa & SINP, Moscow). Nov 2007. 15 pp.
Published in **Phys.Lett. B672 (2009) 35-44**
DOI: 10.1016/j.physletb.2008.12.058

Radiative effects in the processes of exclusive photon electroproduction from polarized protons
Igor Akushevich (Duke U. & Jefferson Lab), Alexander Ilyichev (Fermilab & Minsk, High Energy Phys. Ctr.). Jan 2012. 11 pp.
Published in **Phys.Rev. D85 (2012) 053008**
JLAB-PHY-11-1475
DOI: 10.1103/PhysRevD.85.053008

CLAS Collaboration (P.E. Bosted (William-Mary Coll.) *et al.*). Nov 15, 2016. 12 pp.
Published in **Phys.Rev. C95 (2017) no.3, 035207**
JLAB-PHY-16-2388
DOI: 10.1103/PhysRevC.95.035207

CLAS Collaboration (P.E. Bosted (William-Mary Coll.) *et al.*). Jul 25, 2016. 12 pp.
Published in **Phys.Rev. C95 (2017) no.3, 035206**
JLAB-PHY-16-2294
DOI: 10.1103/PhysRevC.95.035206

CLAS Collaboration (P.E. Bosted (William-Mary Coll.) *et al.*). Apr 15, 2016. 25 pp.
Published in **Phys.Rev. C94 (2016) no.5, 055201**
JLAB-PHY-16-2294
DOI: 10.1103/PhysRevC.94.055201

SIDIS radiative corrections are dominated by exclusive processes that radiate into the deep-inelastic region

A_{LU}

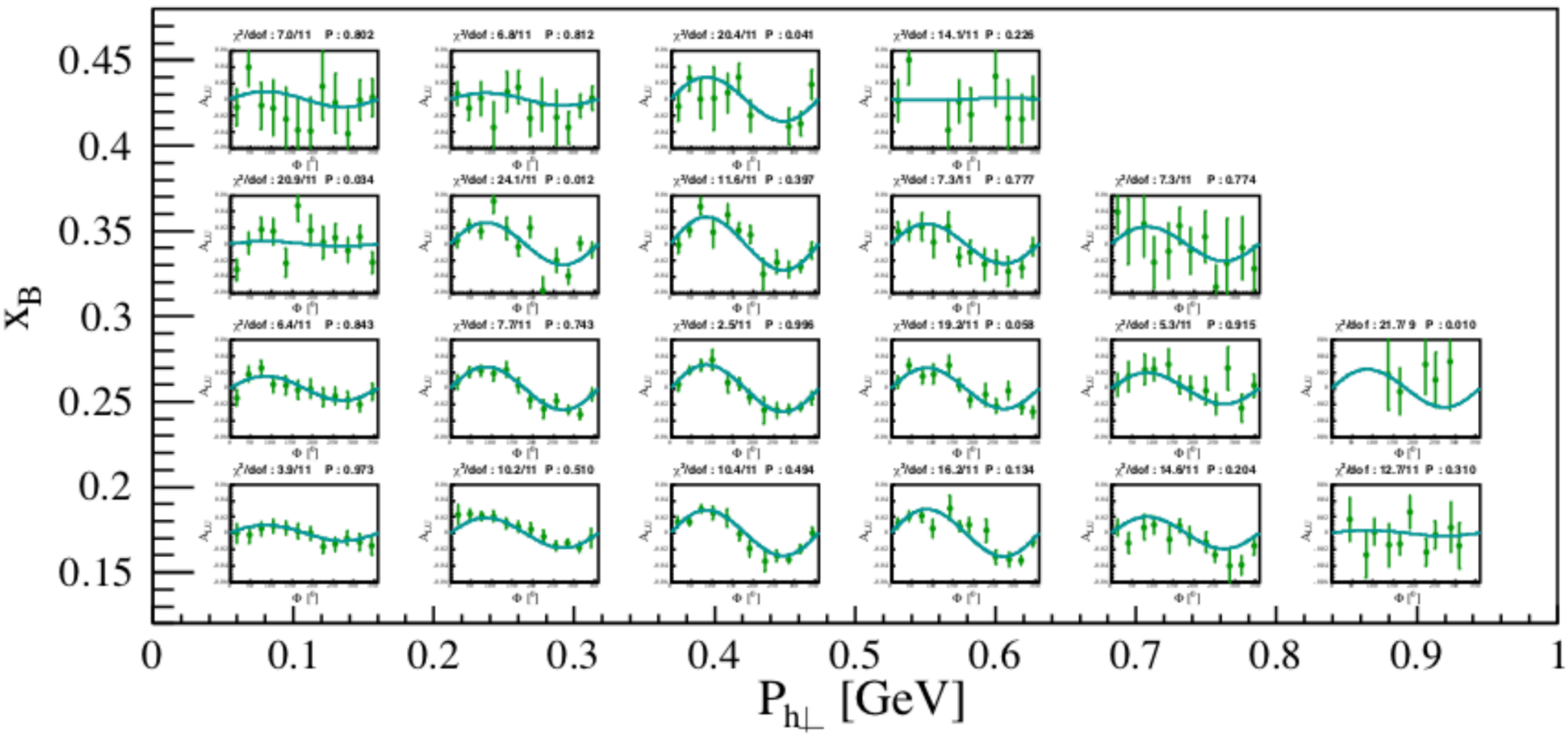


Figure 5.6: $A_{LU}(x_B, P_{h\perp}, \phi_h)$ on the proton for π^0

A_{UL}

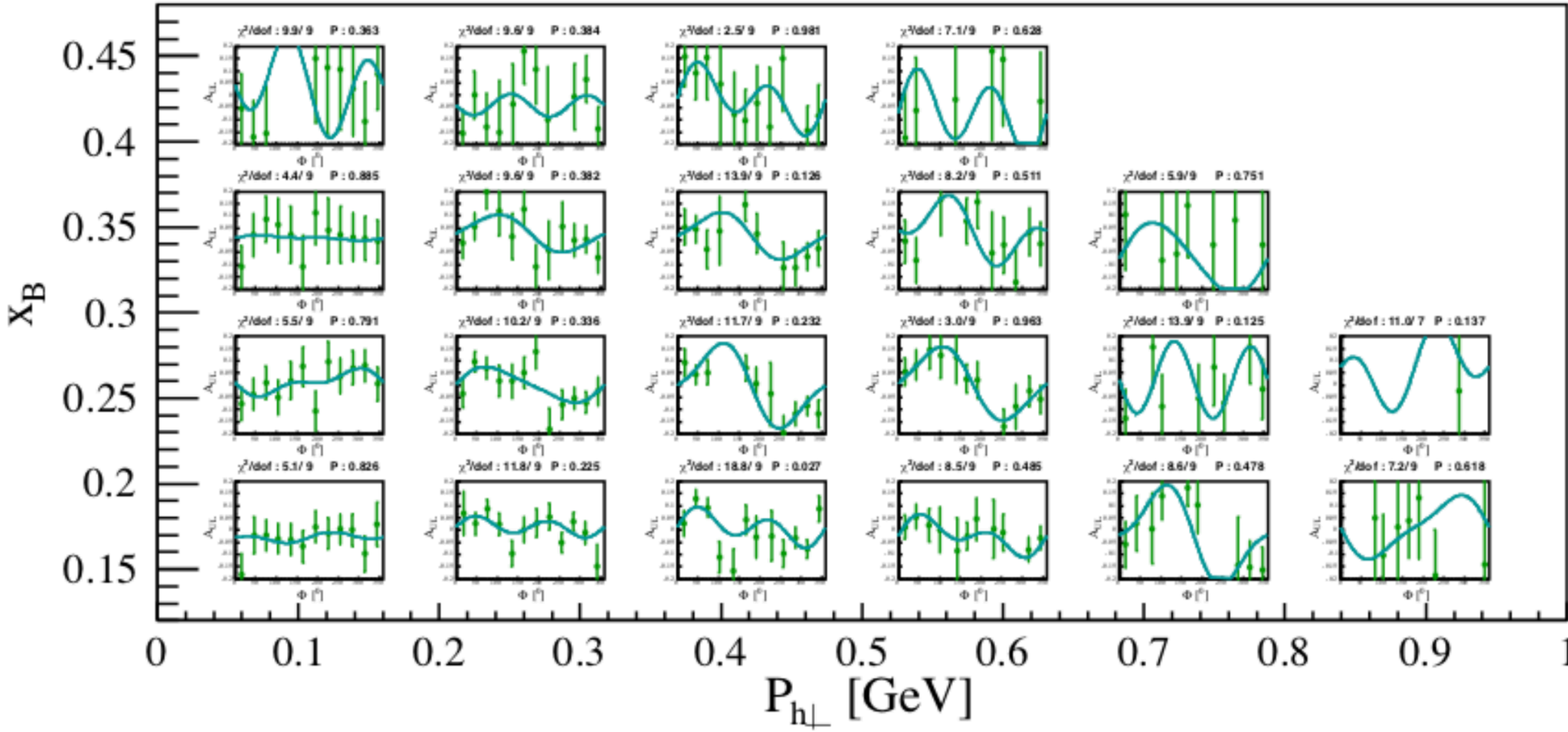


Figure 5.7: $A_{UL}(x_B, P_{h\perp}, \phi_h)$ on the proton for π^0

A_{LL}

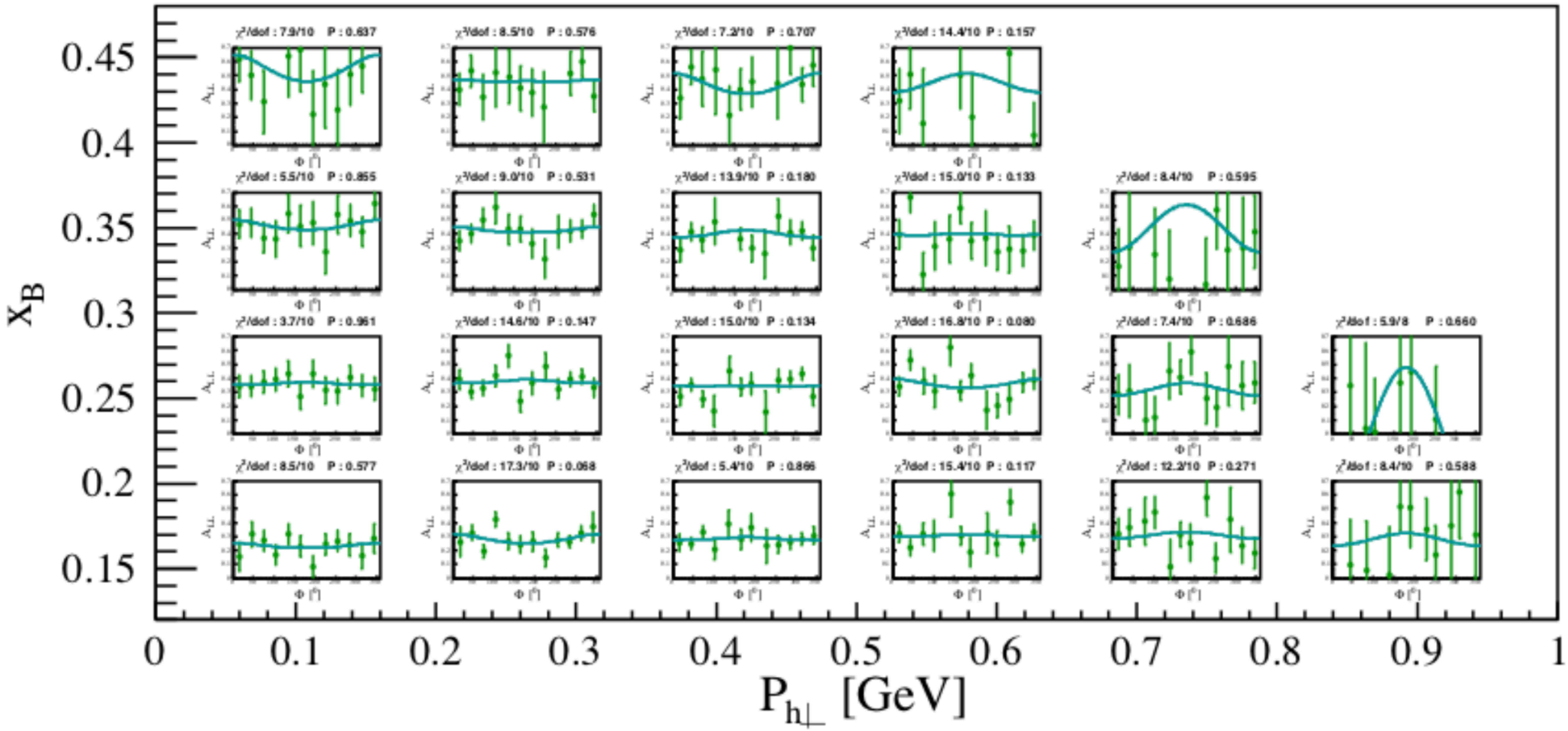


Figure 5.8: $A_{LL}(x_B, P_{h\perp}, \phi_h)$ on the proton for π^0

Monte Carlo Simulations

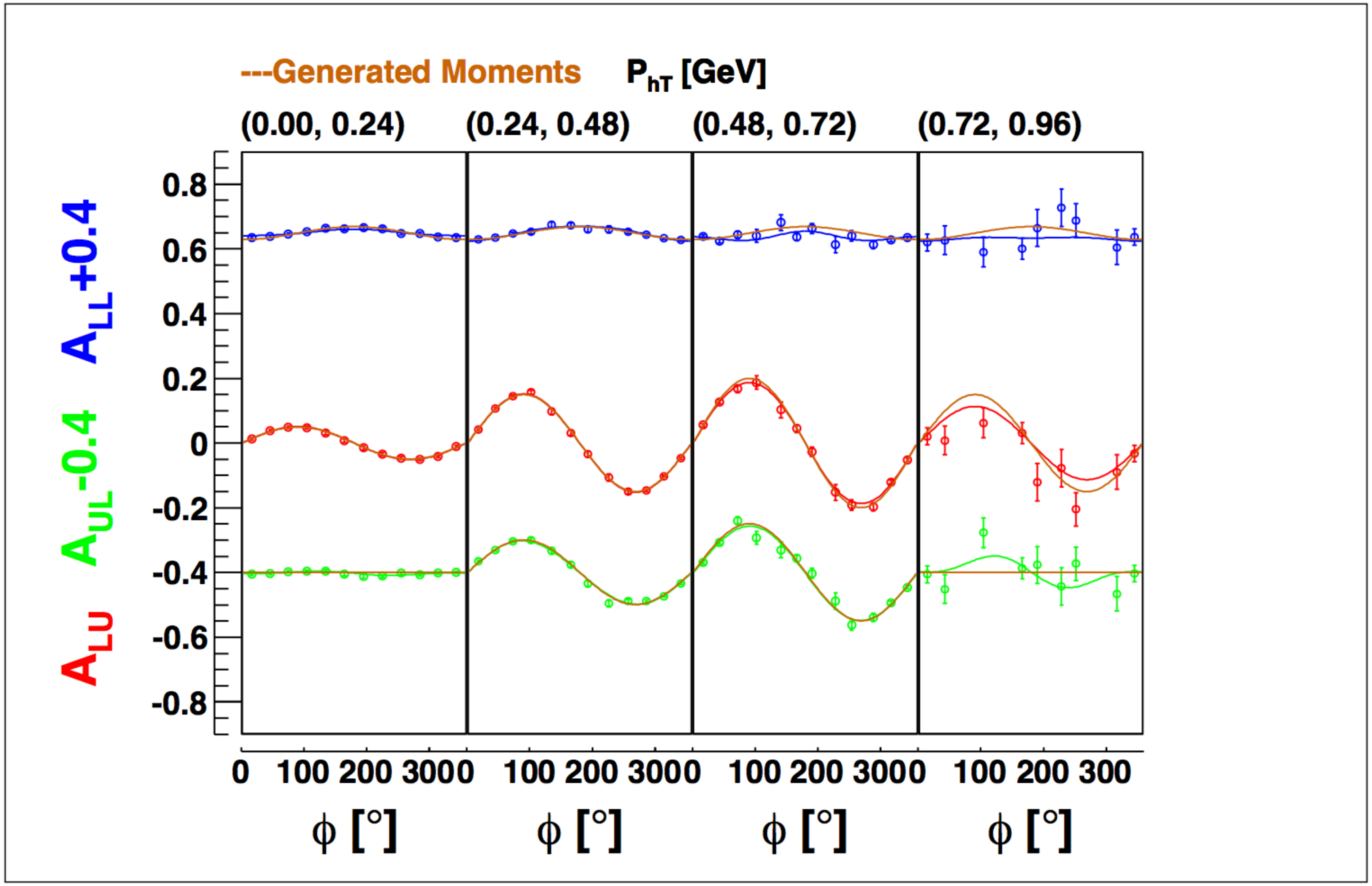


Figure 5.21: Comparison of generated and reconstructed asymmetries as a function of $P_{h\perp}$ for neutral pions.

g_1/f_1

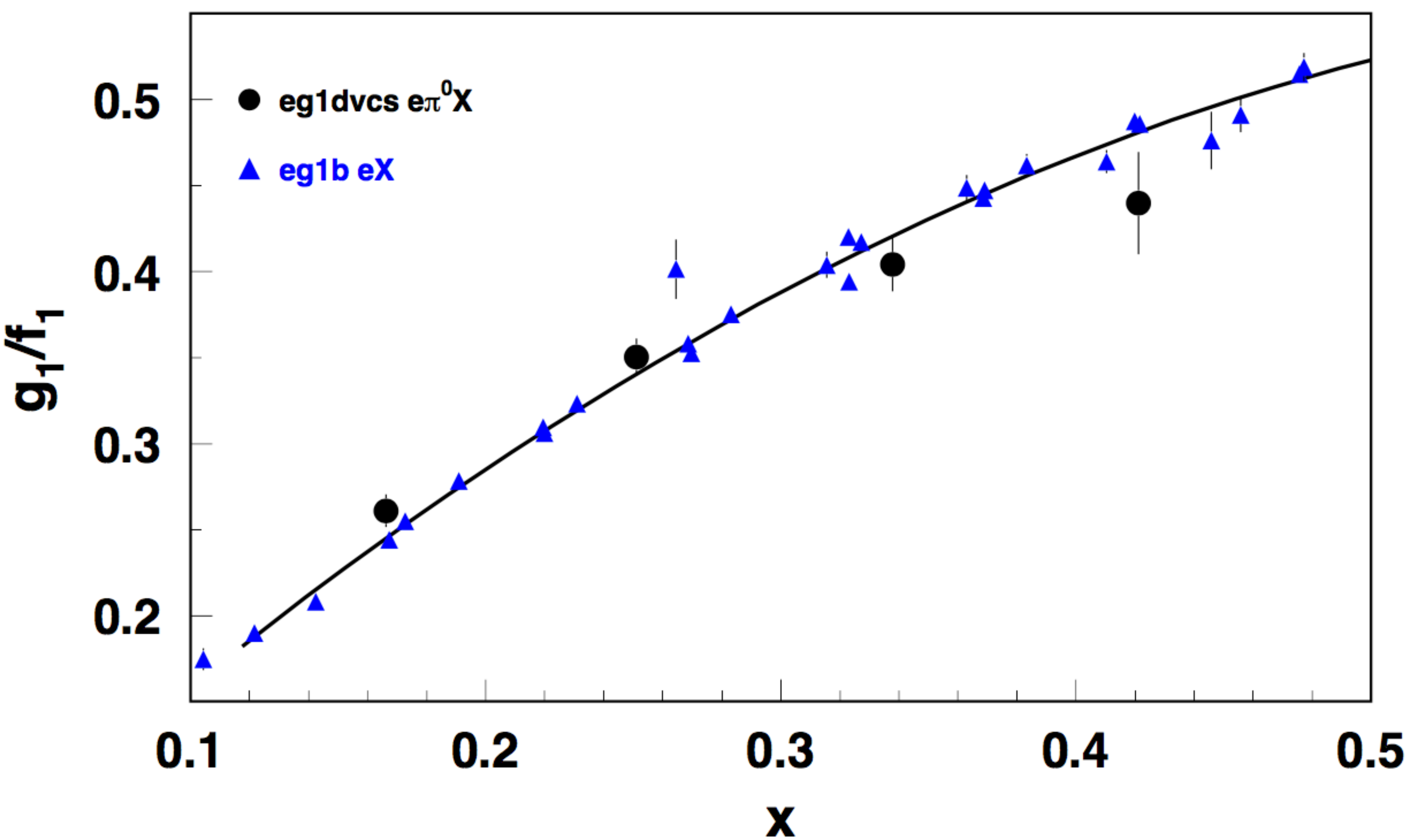


FIG. 1. g_1/f_1 versus x for π^0 compared with CLAS inclusive measurements [33]. The depolarization factor (Eq. 2 from Ref. [16]) has been calculated assuming $R = 0.1$ for the ratio of longitudinal to transverse photon cross sections.

g_1/f_1 vs. P_T

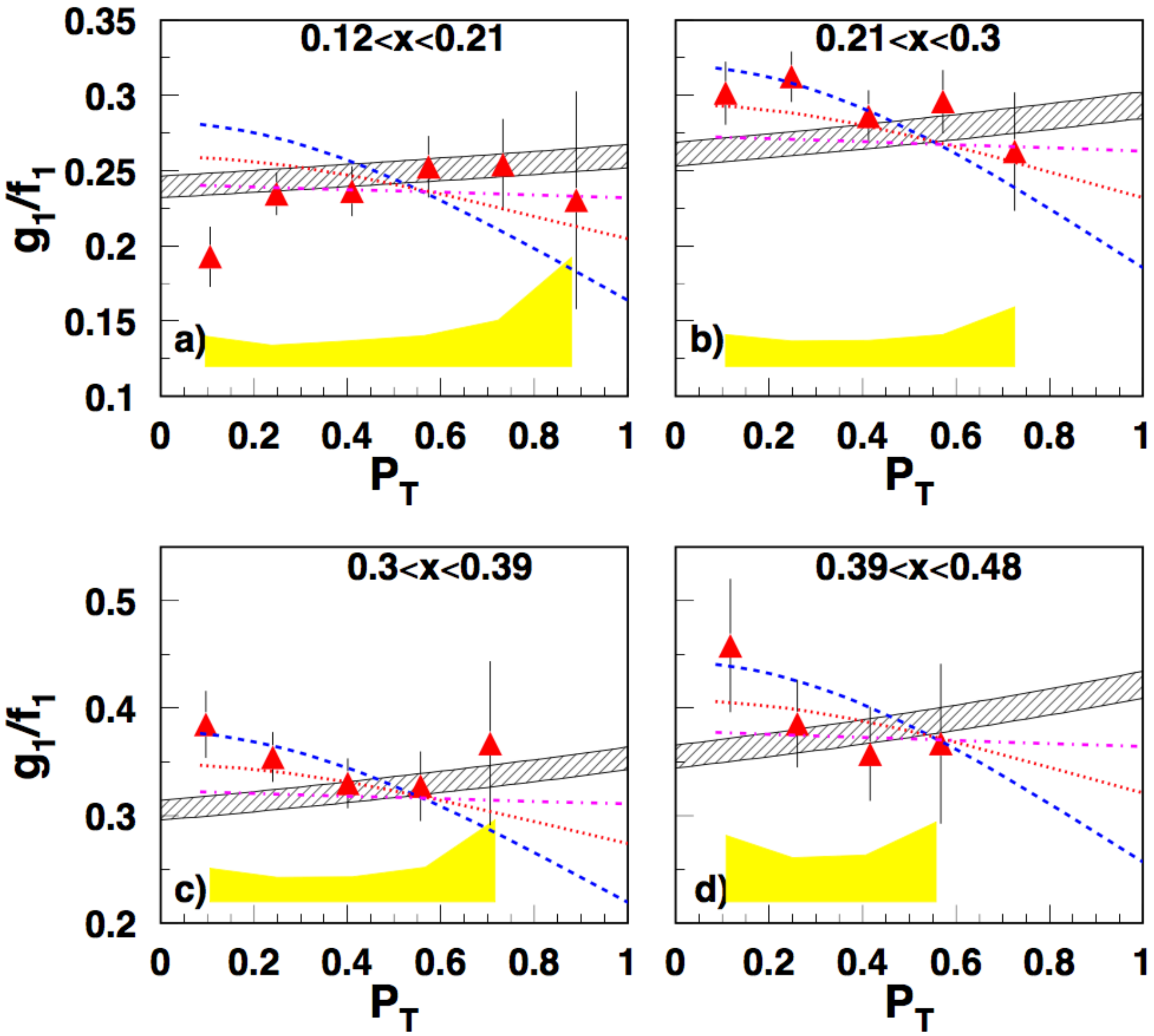


FIG. 2. The ratio g_1/f_1 versus P_T for π^0 DSAs, compared with calculations using the quantum statistical approach to parton distributions [41, 42] (gray bands). The dashed, dotted, and dash-dotted curves are calculations assuming assuming that the g_1 to f_1 transverse momentum width ratios are 0.40, 0.68, and 1.0, respectively, using a fixed width for f_1 (0.25 GeV^2) [44]. The yellow bands are experimental total systematic errors.

[41] C. Bourrely, J. Soffer, and F. Buccella, Mod. Phys. Lett. **A21**, 143 (2006), arXiv:hep-ph/0507328 [hep-ph].
[42] C. Bourrely and J. Soffer, Nucl. Phys. **A941**, 307 (2015), arXiv:1502.02517 [hep-ph].

[44] M. Anselmino, A. Efremov, A. Kotzinian, and B. Parsamyan, Phys. Rev. **D74**, 074015 (2006), arXiv:hep-ph/0608048 [hep-ph].

A_{UL} Sin(2Φ) Moments

Collins fragmentation function $H_1^{\perp}$ is large and has opposite sign for the favored and unfavored cases. This suggests a significant suppression of the Collins fragmentation function for π^0

[41] C. Bourrely, J. Soffer, and F. Buccella, Mod. Phys. Lett. **A21**, 143 (2006), arXiv:hep-ph/0507328 [hep-ph].
[42] C. Bourrely and J. Soffer, Nucl. Phys. **A941**, 307 (2015), arXiv:1502.02517 [hep-ph].

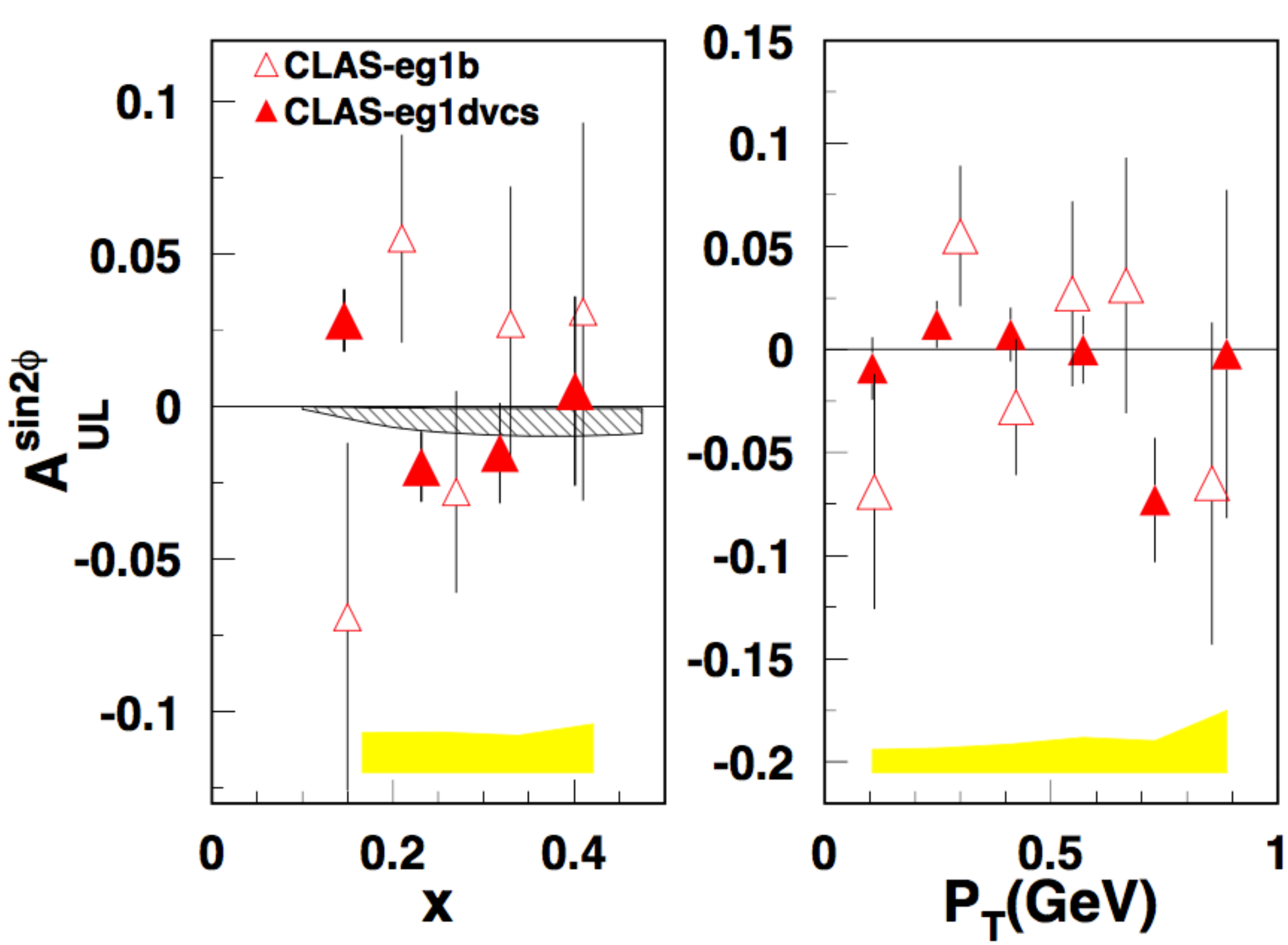
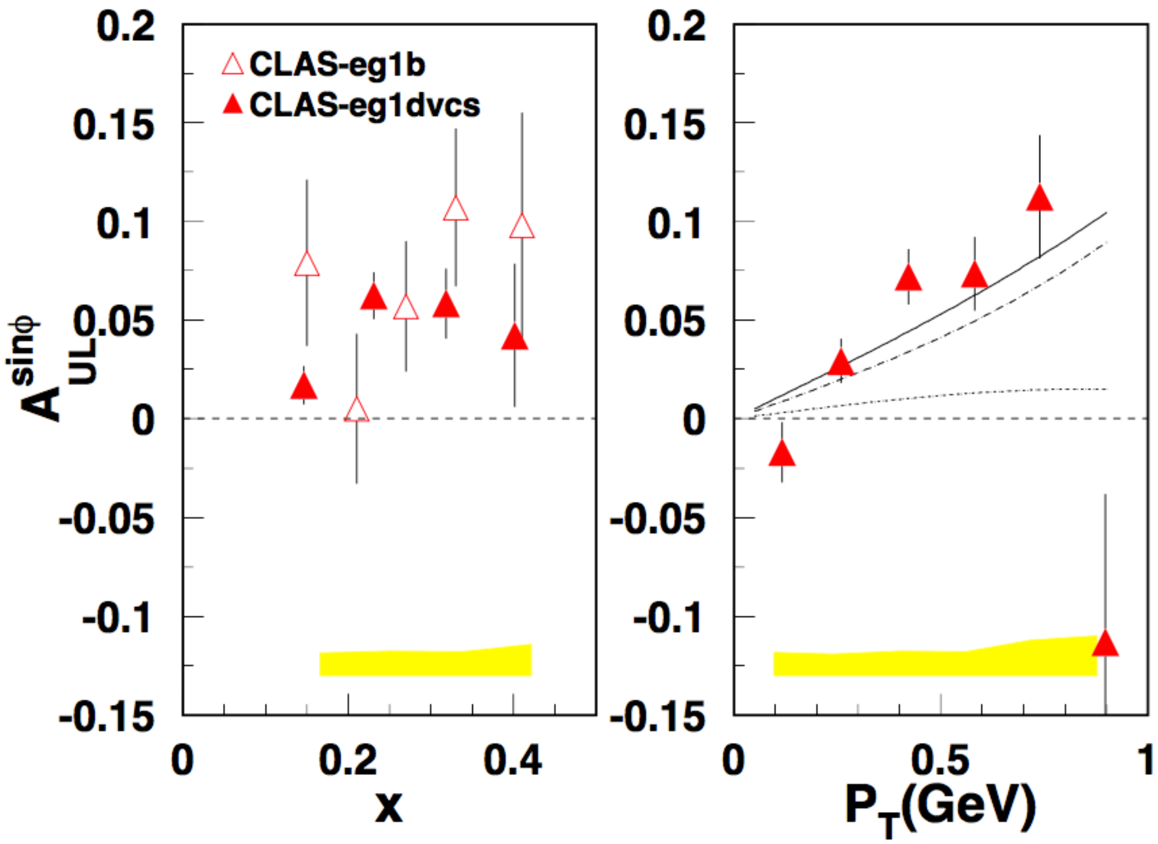


FIG. 3. $\sin 2\phi_h$ moments for A_{UL} plotted versus x (left) and P_T (right) compared to previous CLAS measurements [16] (which had limited π^0 kinematics) and theory predictions (gray band) [41, 42]. The yellow bands are experimental total systematic errors.

A_{UL} Sin(Φ) Moments



- Data suggest that a Sivers-type contribution coming from the convolution of $f_L^{\perp}$ and D1

FIG. 4. $\sin\phi_h$ moments for A_{UL} vs P_T. The open triangles are the old eg1b CLAS data [16] (which had limited π^0 acceptance), the and solid triangles are new measurements. The dashed and dotted lines are twist-3 calculations from Sivers (larger) and Collins (smaller) type terms [53, 54], respectively, and the solid line is the sum of the two. The yellow bands are experimental total systematic errors.

[53] W. Mao and Z. Lu, Phys. Rev. **D87**, 014012 (2013), arXiv:1210.4790 [hep-ph].

[54] Z. Lu and W. Mao, *Proceedings, 21st International Symposium on Spin Physics (SPIN 2014)*, Int. J. Mod. Phys. Conf. Ser. **40**, 1660045 (2016).

Conclusions

In summary, kinematic dependencies of single and double spin asymmetries for neutral pions have been measured in multidimensional bins over a wide kinematic range in x and P_T using CLAS with a polarized proton target. Measurements of the P_T-dependence of the double spin asymmetry, performed for the first time for different x-bins, indicate the possibility of different average transverse momenta for quarks aligned or anti-aligned with the nucleon spin. A non-zero $\sin\phi_h$ target single-spin asymmetry was measured for neutral pions with high precision, indicating that the target SSA may be generated through the Sivers mechanism. A small $\sin 2\phi_h$ moment of the target SSA is consistent with expectations of strong suppression of the Collins effect for neutral pions, due to cancellation of roughly equal favored and unfavored Collins functions.

Fine

End

EG1-DVCS Experiment

Ran February through September 2009

$^{14}NH_3$ and $^{14}ND_3$ Targets

80% and 30% polarizations, respectively

Expt. Part	Runs	Target	Vertex	Beam Energy	Torus Current
Part-A	58799 - 59155	NH_3	-58 cm	5.88 GeV	+2250 A
Part-B	59456 - 60184	NH_3	-68 cm	5.95 GeV	+2250 A
Part-C (a)	60304 - 60565	ND_3	-68 cm	5.75 GeV	+2250 A
Part-C (b)	60566 - 60648	ND_3	-68 cm	5.75 GeV	-2250 A