Azimuthal distributions in unpolarized SIDIS

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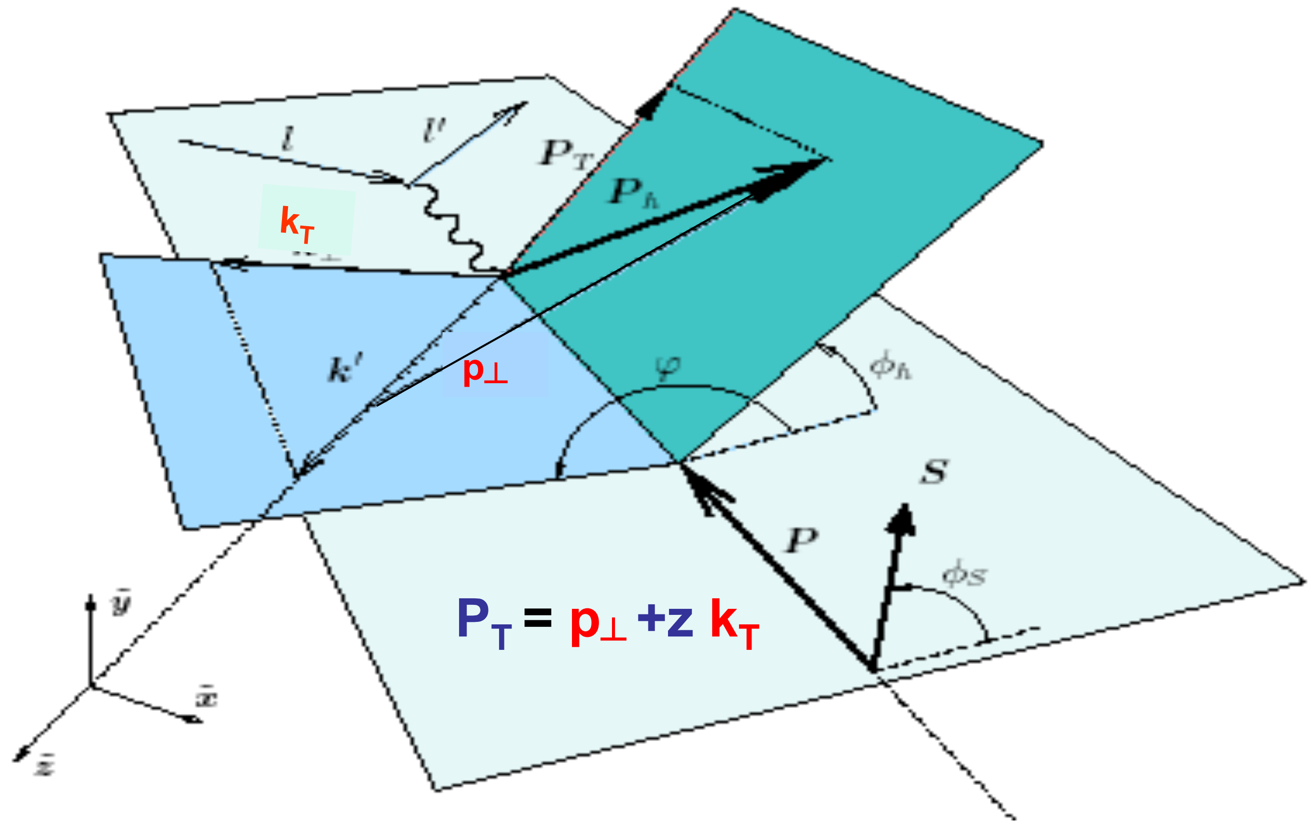
Outline

- Motivation
- The Experiment
- Analysis
  - event selection & binning
  - acceptance studies
  - radiative corrections
- Results
- Comparison with higher energies
- Summary

SIDIS kinematical plane

$$\nu = (qP)/M$$
$$Q^2 = (k-k')^2$$
$$y = (qP)/(kP)$$
$$x = Q^2/2(qP)$$
$$z = (qP_h)/(qP)$$



$$\sigma = \sigma_{UU} + \sigma_{UU}^{\cos\phi} cos\phi + \sigma_{UU}^{\cos 2\phi}\cos 2\phi + \lambda\sigma_{LU}^{\sin\phi}\sin\phi + ...$$

SIDIS ($\gamma^*p\to\pi X$) : k_T-dependences

$$\frac{d\sigma}{dx_B\,dy\,d\psi\,dz\,d\phi_h\,dP_{h\perp}^2} = \frac{\alpha^2}{x_B y Q^2}\frac{y^2}{2(1-\varepsilon)}\left(1+\frac{\gamma^2}{2x_B}\right)\Big\{F_{UU,T}+\varepsilon F_{UU,L}+\sqrt{2\,\varepsilon(1+\varepsilon)}\,\cos\phi_h\,F_{UU}^{\cos\phi_h}$$

$$+\,\varepsilon\cos(2\phi_h)\,F_{UU}^{\cos 2\phi_h}+\lambda_e\sqrt{2\,\varepsilon(1-\varepsilon)}\,\sin\phi_h\,F_{LU}^{\sin\phi_h}\Big\},$$

$f_1 \otimes D_1$

HT

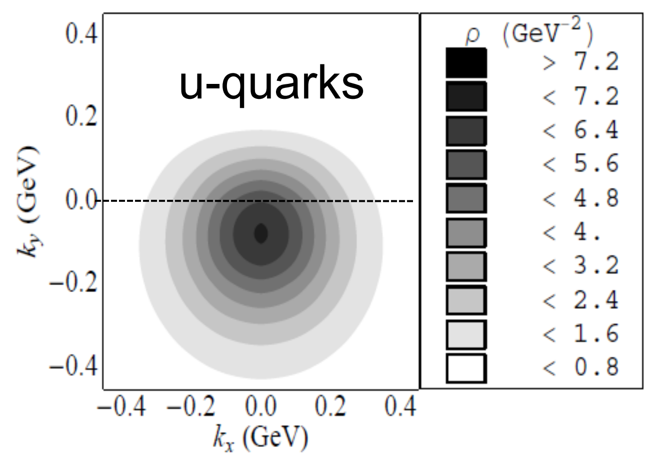
HT

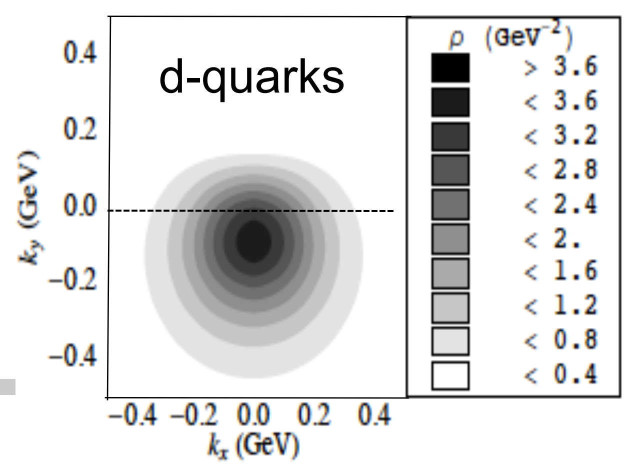
$h_1^\perp \otimes H_1^\perp$

HT

N/q	U	L	T
U	f_1		$h_1^\perp$
L		g_1	$h_{1L}^\perp$
T	$f_{1T}^\perp$	$g_{1T}^\perp$	$h_1\ h_{1T}^\perp$

Pasquini&Yuan(2010)





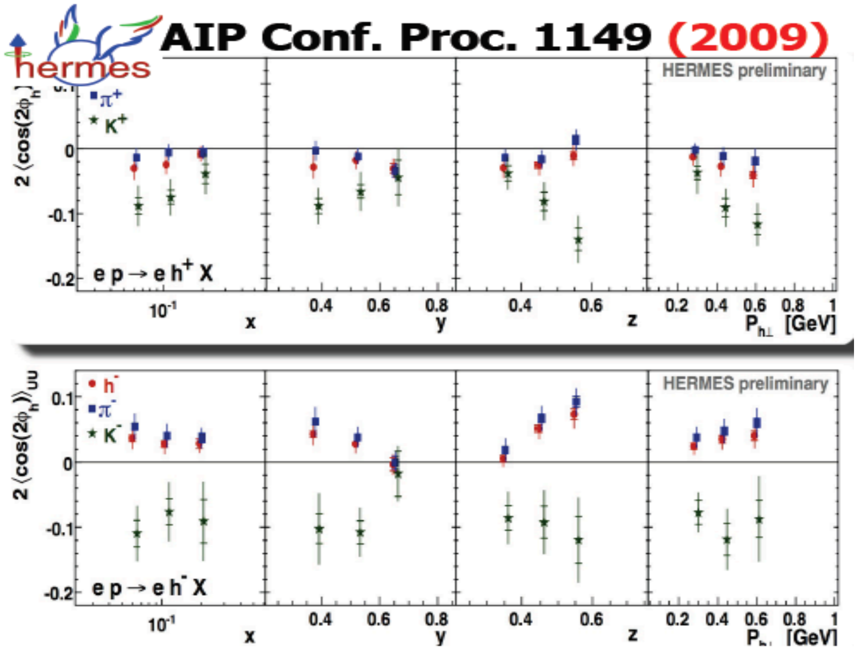
BM TMD (1998) describes correlation between the transverse momentum and transverse spin of quarks, requires FSI or ISI

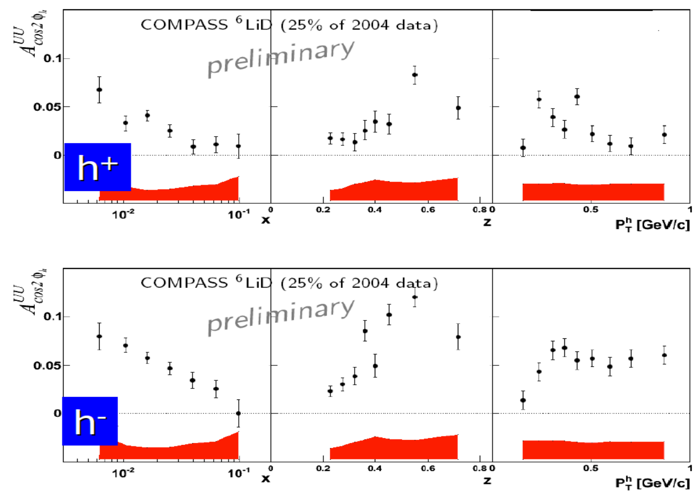
$$f_{q/p}(x,k_\perp^2)=\frac{1}{2}[f_1^q(x,k_\perp^2)-h_1^{\perp q}(x,k_\perp^2)\frac{(\hat{P}\times k_\perp)\cdot S_q}{M}]$$

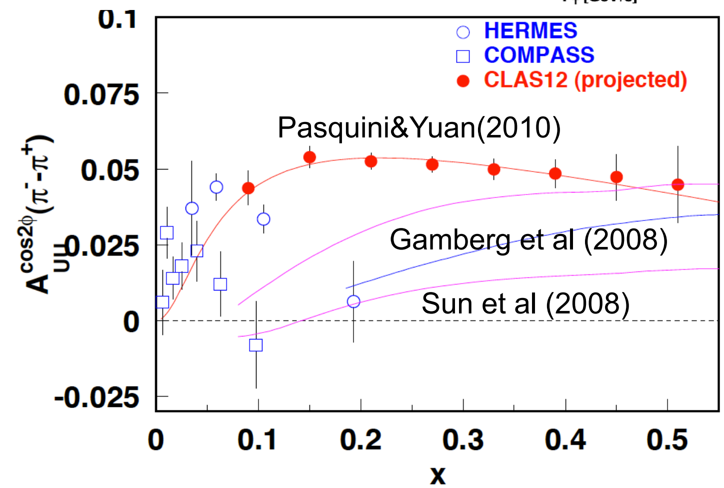
$$h_1^{\perp q}(SIDIS)=-h_1^{\perp q}(DY)$$

BM TMD under intensive studies worldwide, including SIDIS and DY experiments, model calculations, lattice simulations.

HT effects as background: Boer-Mulders distribution







Background contributions :
Higher twist azimuthal moments
 kinematical HT (Cahn)
 dynamical HT (Berger-Brodsky)
Radiative correction
Acceptance

"flavor blind"

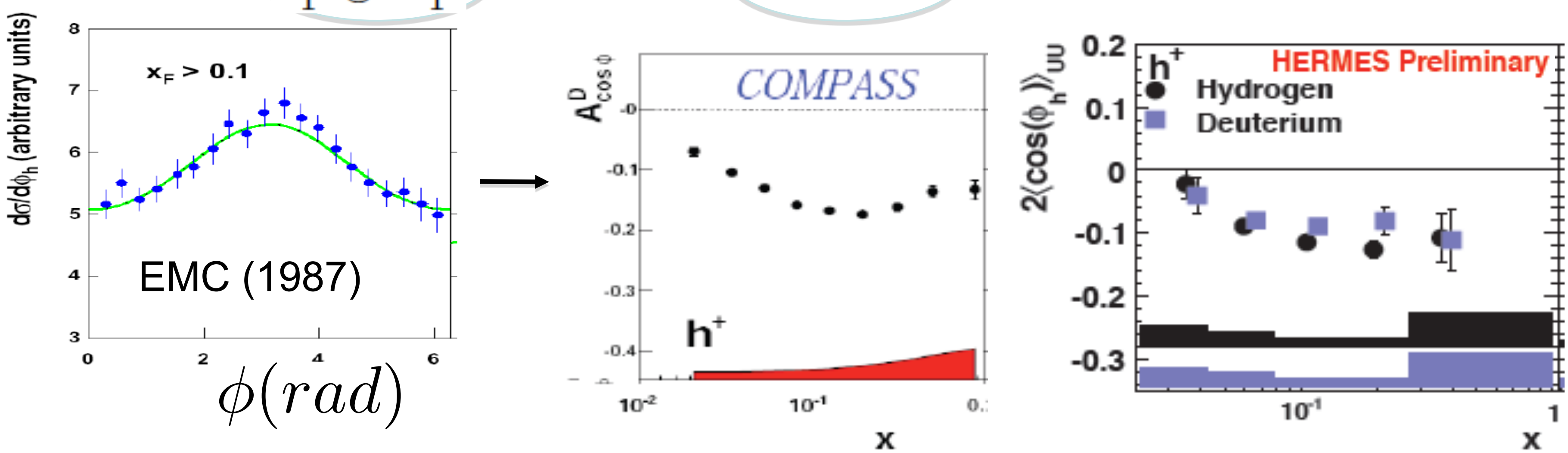
$$A_{UU}^{\cos 2\phi}(\pi^0) \approx A_{UU,Cahn}^{\cos 2\phi}$$

Wide range in Q^2 and P_T accessible with CLAS12 are important for cos2ϕ studies (all background contributions are HT)

Azimuthal distributions in SIDIS

$$\frac{d\sigma}{dx_B\, dy\, d\psi\, dz\, d\phi_h\, dP_{h\perp}^2} = \frac{\alpha^2}{x_B y Q^2} \frac{y^2}{2(1-\varepsilon)} \left(1+\frac{\gamma^2}{2x_B}\right) \Bigg\{ F_{UU,T} + \varepsilon F_{UU,L} + \sqrt{2\varepsilon(1+\varepsilon)}\, \cos\phi_h\, F_{UU}^{\cos\phi_h} + \varepsilon \cos(2\phi_h)\, F_{UU}^{\cos 2\phi_h} + \lambda_e \sqrt{2\varepsilon(1-\varepsilon)}\, \sin\phi_h\, F_{LU}^{\sin\phi_h} \Bigg\},$$

$f_1 \otimes D_1$ ($F_{UU,T}$), h.t. ($F_{UU,L}$), h.t. ($F_{UU}^{\cos\phi_h}$), $h_1^\perp \otimes H_1^\perp$ ($F_{UU}^{\cos 2\phi_h}$), h.t. ($F_{LU}^{\sin\phi_h}$)

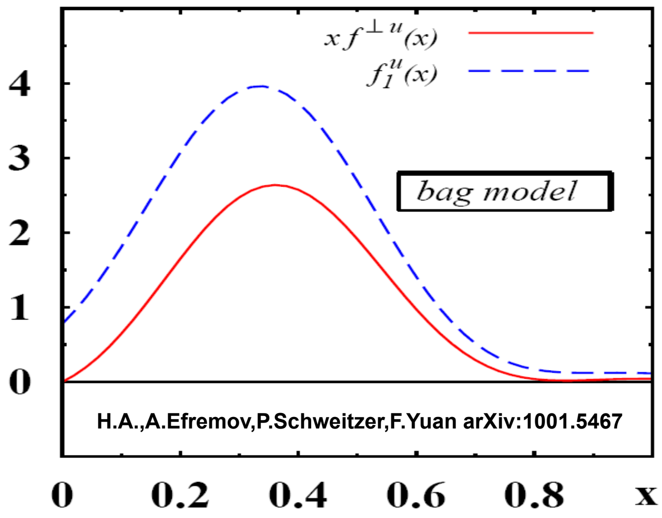


Large cosϕ modulations observed by EMC were reproduced in electroproduction of hadrons in SIDIS with unpolarized targets at COMPASS and HERMES

Model predictions for cosϕ

$$F_{UU,T} + \varepsilon F_{UU,L} + \sqrt{2\,\varepsilon(1+\varepsilon)}\ \cos\phi_h\, F_{UU}^{\cos\phi_h}$$

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



$$x f^{\perp q} = x\tilde{f}^{\perp q} + f_1^q$$

"interaction dependent"

$$F_{UU}^{\cos\phi} \propto f^{\perp q} D_1^q$$

Models agree on a large HT distributions

SIDIS cross-section

Expanding the contraction and integrating over ψ and the beam polarization, the cross-section for an unpolarized target can be written as

$$\frac{d^5\sigma}{dx\; dQ^2\; dz\; d\phi_h\; dP_{h\perp}^2} =$$

$$\underbrace{\frac{2\pi\alpha^2}{xyQ^2}\frac{y^2}{2(1-\epsilon)}\left(1+\frac{\gamma^2}{2x}\right)(F_{UU,T}+\epsilon F_{UU,L})}_{A_0}\left\{1+\underbrace{\frac{\sqrt{2\epsilon(1+\epsilon)}F_{UU}^{\cos\phi_h}}{(F_{UU,T}+\epsilon F_{UU,L})}}_{A_{UU}^{\cos\phi_h}}\cos\phi_h+\underbrace{\frac{\epsilon F_{UU}^{\cos 2\phi_h}}{(F_{UU,T}+\epsilon F_{UU,L})}}_{A_{UU}^{\cos 2\phi_h}}\cos 2\phi_h\right\}$$

According the the factorization theorem, structure functions can, in the Bjorken limit, be written as convolutions of TMDs and FFs $F = \sum \mathrm{TMD} \otimes \mathrm{FF}$

Bjorken Limit:

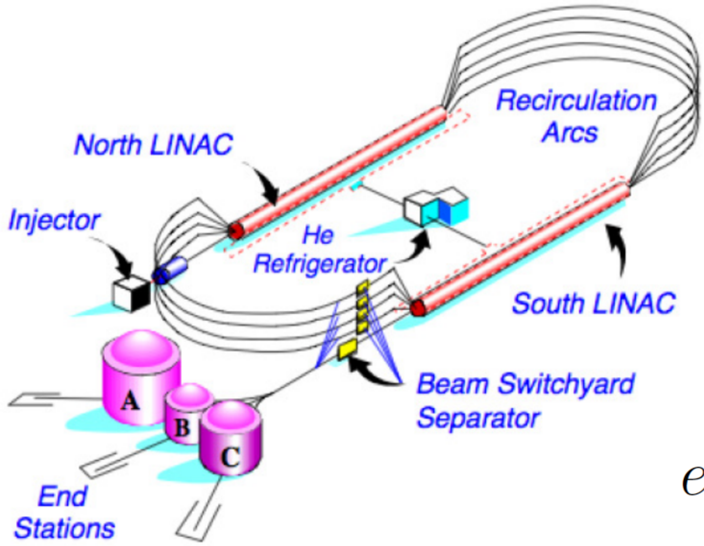
$Q^2 \to \infty$

$2P\cdot q \to \infty$

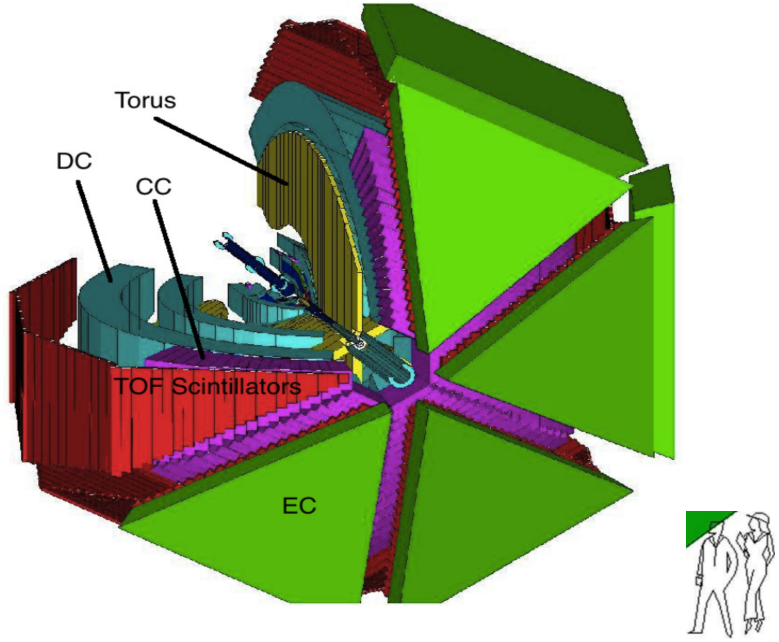
$P\cdot P_h \to \infty$

fixed $\begin{cases} x = Q^2/2P\cdot q \\ z = P\cdot P_h/P\cdot q \end{cases}$

CLAS: e1f data set



$$ep \to e\pi^{\pm}X$$



- Two 0.4 GeV linear accelerators.
- Nine recirculation arcs for five loops around the track.
- Continuous, polarized electron beam up to 6 GeV delivered simultaneously to 3 experimental halls.
- High luminosity of 0.5 x 10^{34} $(cm^2\ s)^{-1}$

- E1-f run: 5.498 GeV electron beam with ~75% polarization (averaged over for this analysis); unpolarized liquid hydrogen target; about 2 billion events; broad and comparable kinematic range for two channels:

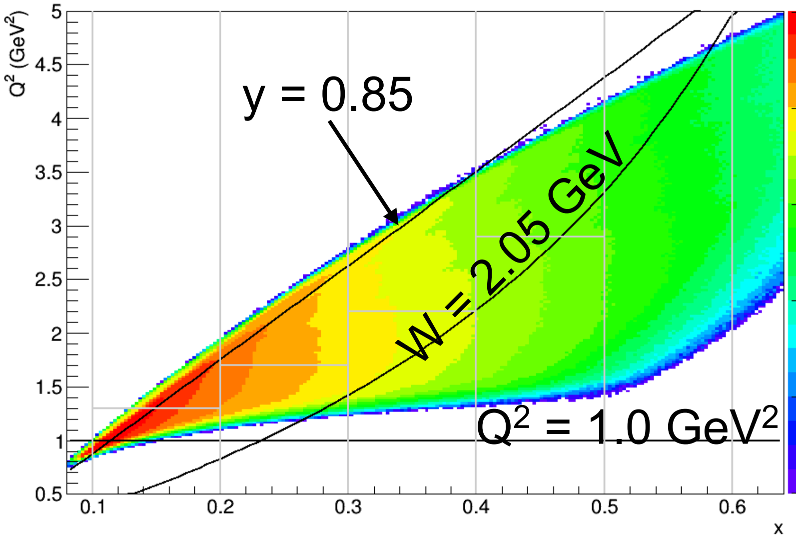
- Electromagnetic Calorimeter (EC) and Čerenkov Counter (CC) used in electron identification.

- Drift Chamber (DC) (3 regions) and time of flight Scintillators (SC) record position and timing information for each charged track.

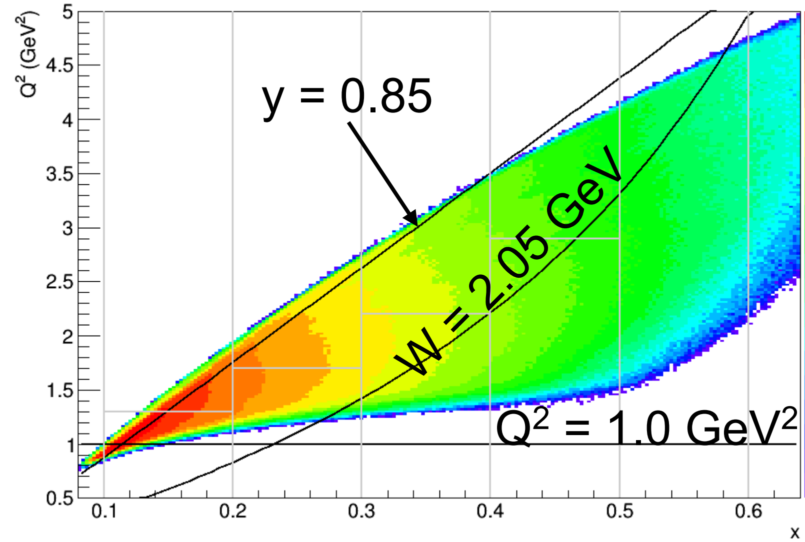
- Torus magnet creates toroidal magnetic field which causes charged tracks to curve while preserving the φ_{lab} angle.

SIDIS Cuts and Binning

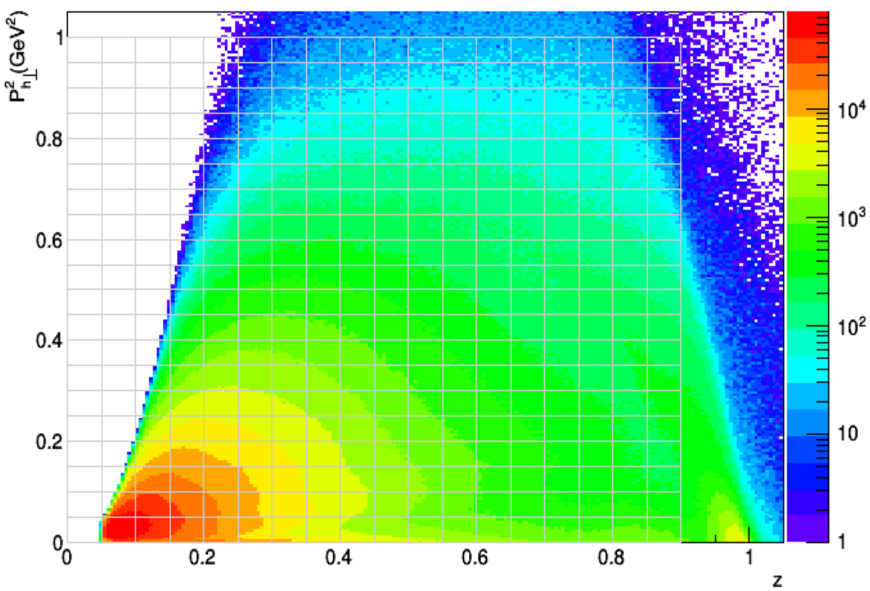
π+ channel

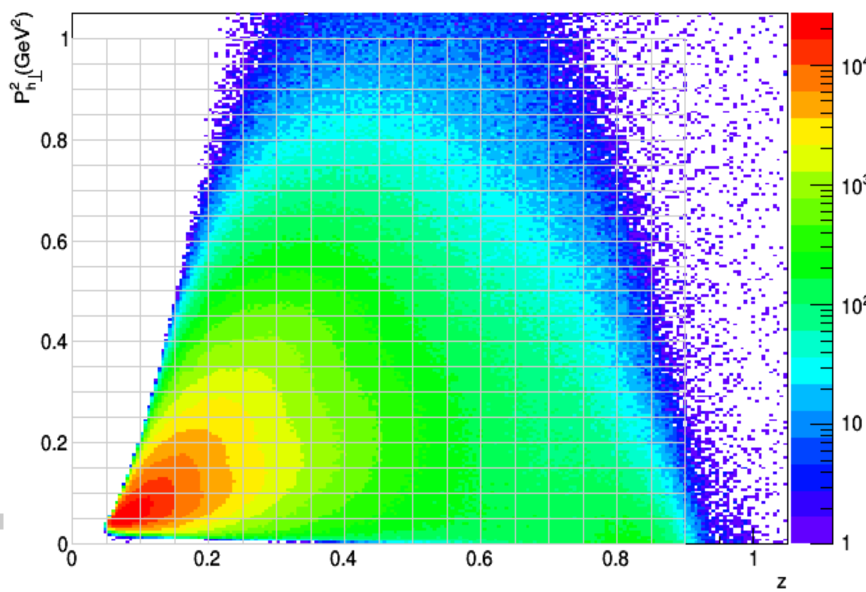


π- channel



The DIS region is defined as $Q^2 > 1.0$ GeV^2 and $W > 2.05$ GeV.





Simulation

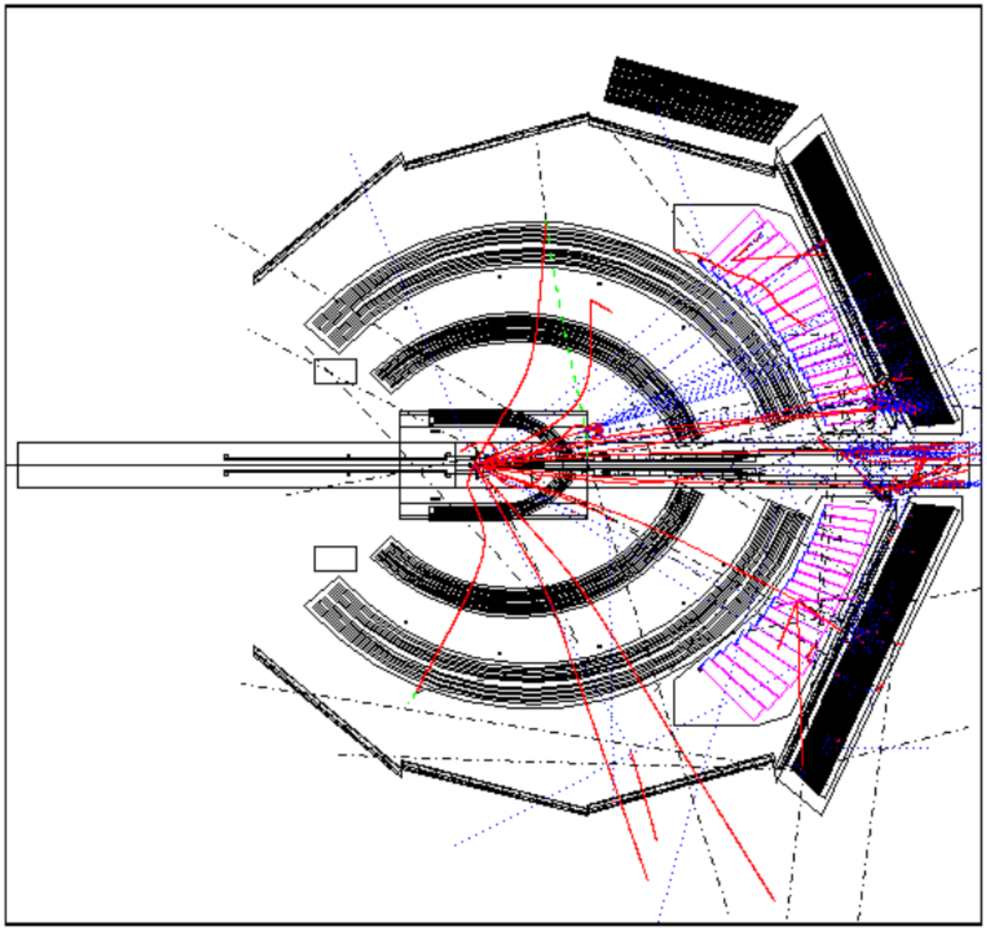
- 1B SIDIS events are generated with a PYTHIA based event generator.

- 3 different models were used to study model dependence.

- Generated events are put into a GEANT based Monte Carlo simulation of the CLAS detector (GSim).

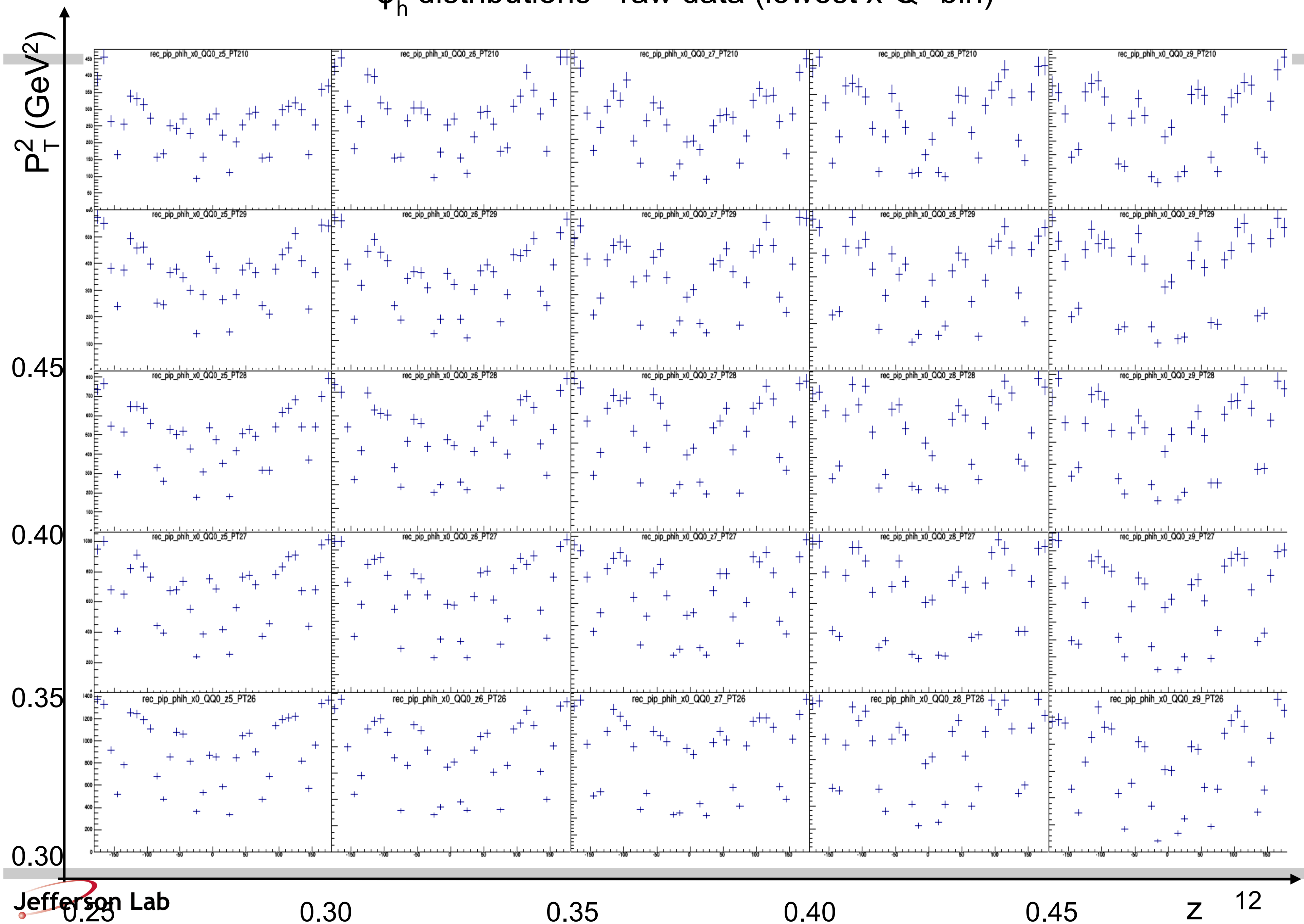
- Smearing and inefficiencies are introduced to the simulation to make it more realistic.

- The simulated data is then “cooked”, processed, and analyzed in the same way as the E1-f data set.

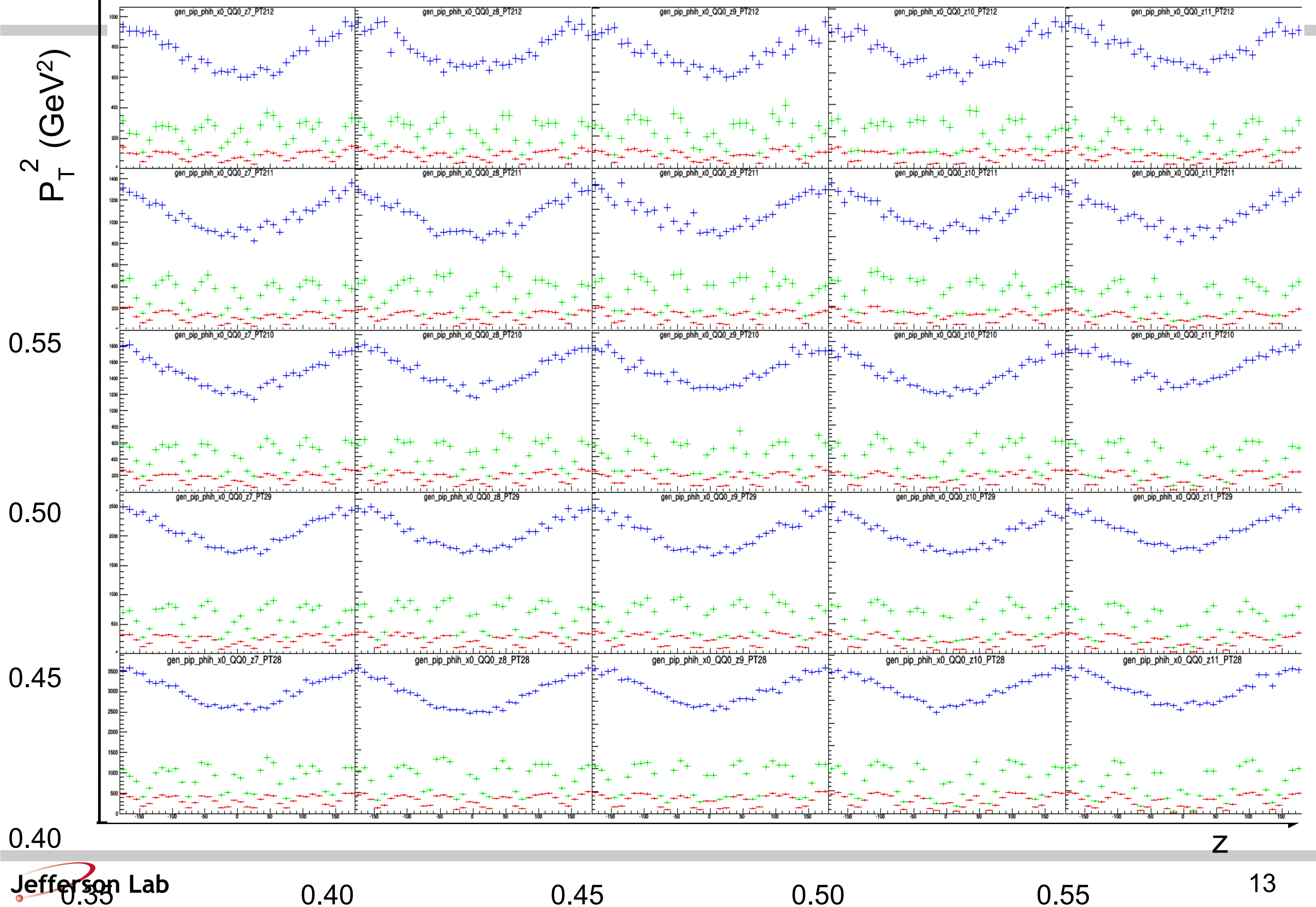


Above: Five generated events being reconstructed by GSim. Charged tracks are shown in red, neutral tracks in gray.

φ_h distributions - raw data (lowest x-Q^2 bin)



Monte Carlo φ generated, reconstructed, and acceptance for π+ (lowest x-Q^2 bin)



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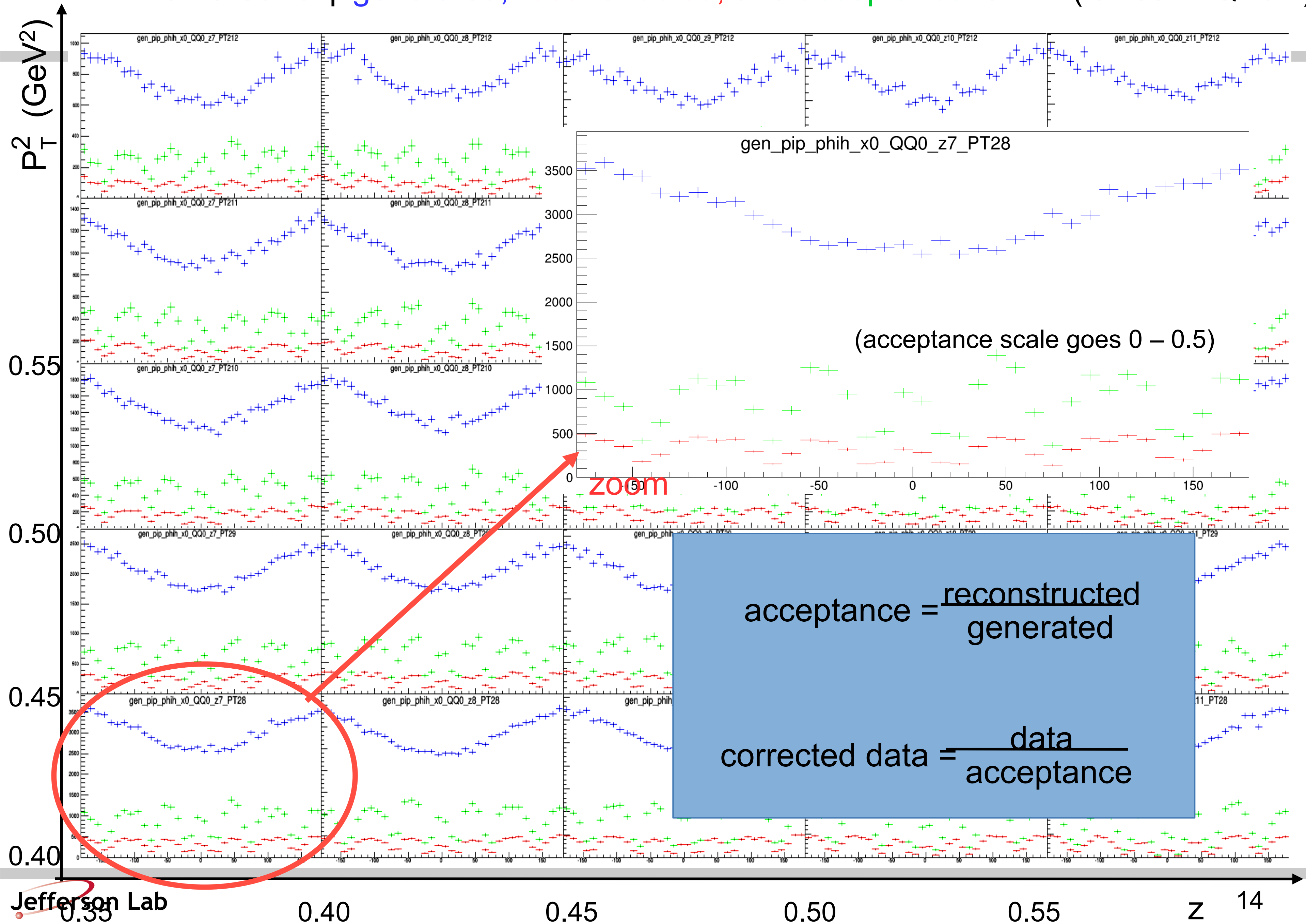


$$\text{acceptance} = \frac{\text{reconstructed}}{\text{generated}}$$

$$\text{corrected data} = \frac{\text{data}}{\text{acceptance}}$$

Radiative Corrections

- Radiative effects, such as the emission of a photon by the incoming or outgoing electron, can change all five SIDIS kinematic variables.

- Furthermore, exclusive events can enter into the SIDIS sample because of radiative effects ("exclusive tail").

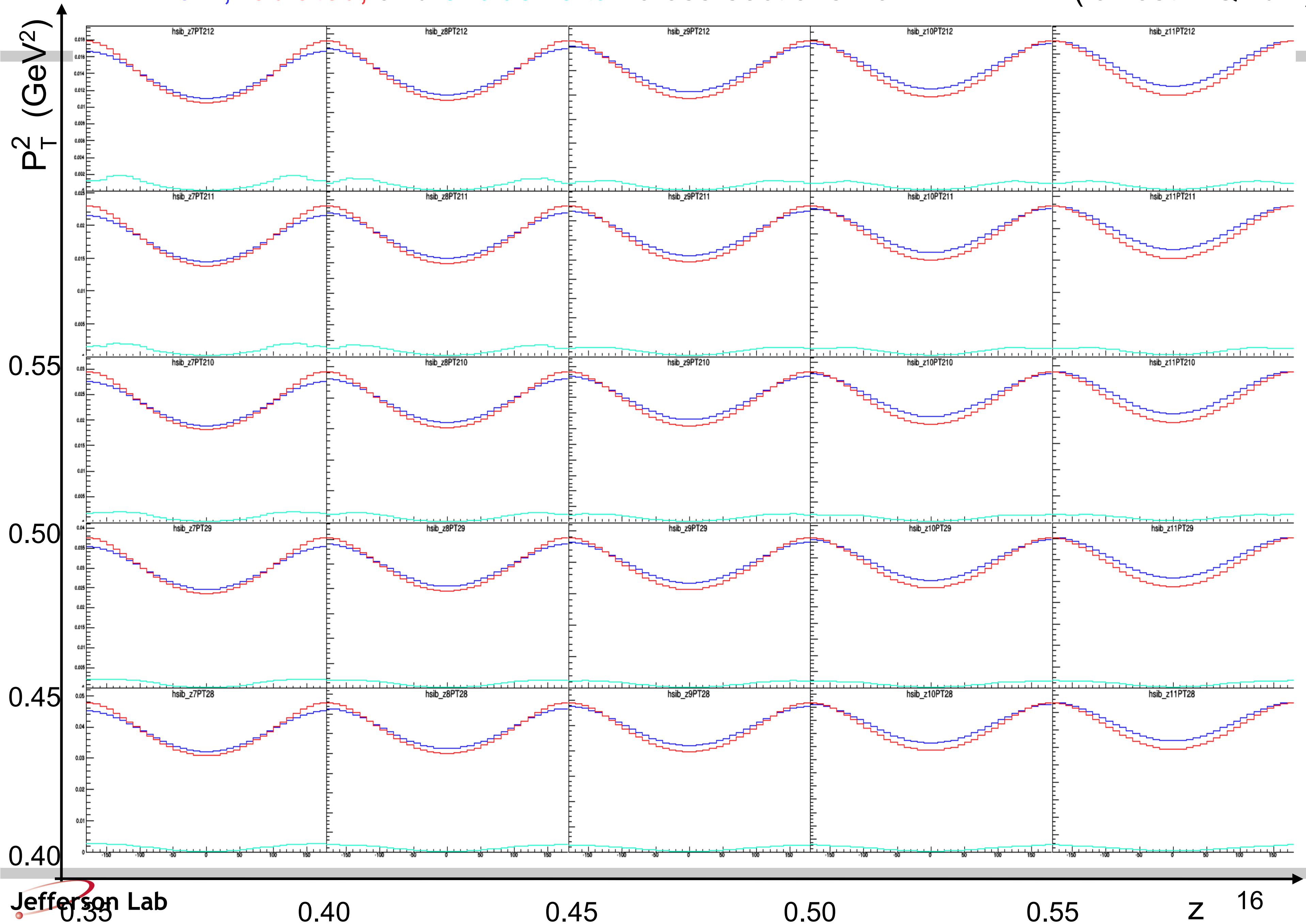
- HAPRAD 2.0 is used to do radiative corrections.

- For a given $\sigma_{Born}\left(x, Q^2, z, P_{h\perp}^2, \phi_h\right)$ (obtained from a model), HAPRAD calculates $\sigma_{rad+tail}\left(x, Q^2, z, P_{h\perp}^2, \phi_h\right)$. The correction factor is then:

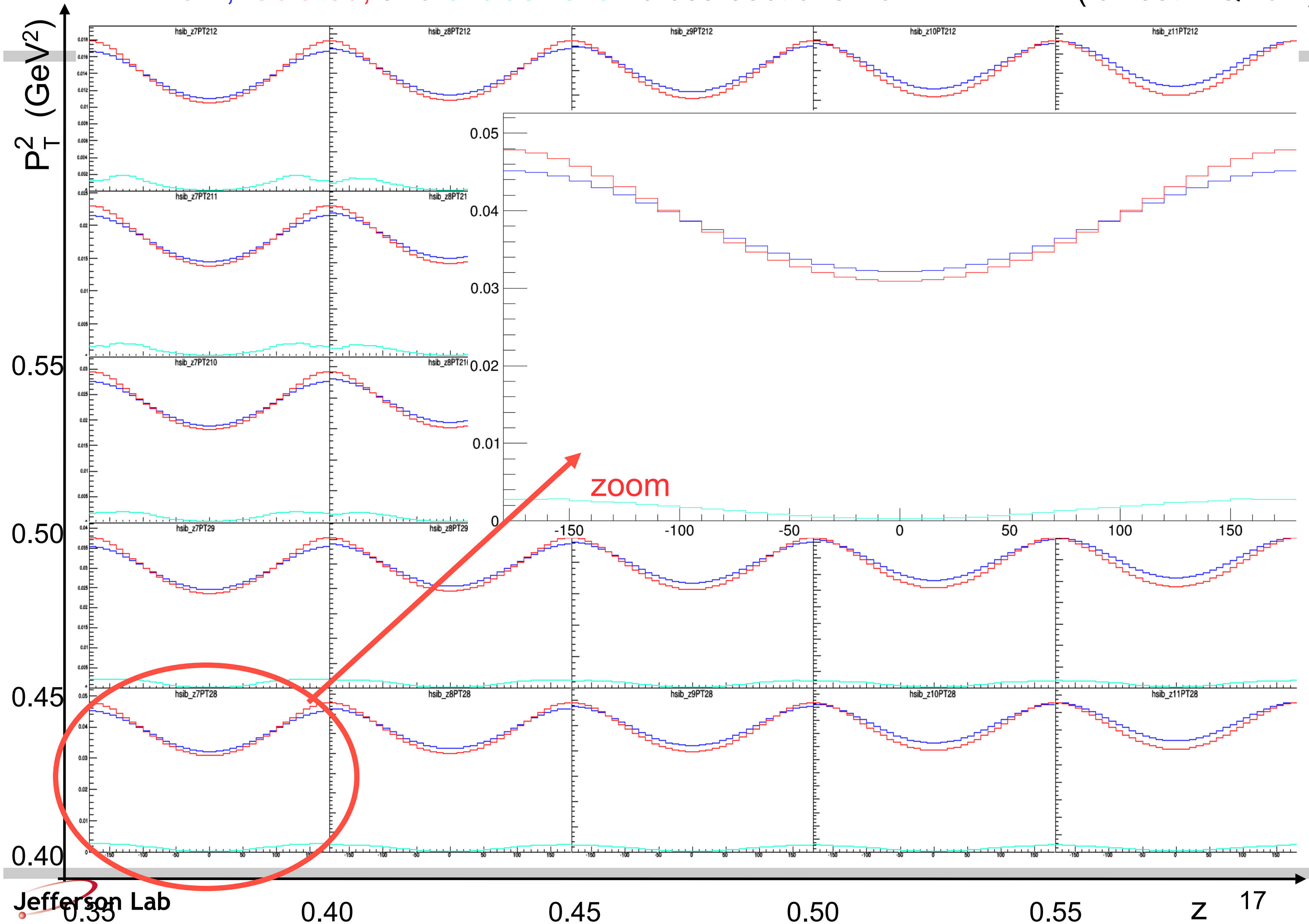
$$RC\ factor = \frac{\sigma_{rad+tail}\left(x, Q^2, z, P_{h\perp}^2, \phi_h\right)}{\sigma_{Born}\left(x, Q^2, z, P_{h\perp}^2, \phi_h\right)}$$

- 3 different models were used to study model dependence.

Born, radiated, and exclusive tail cross-sections from HAPRAD (lowest x-Q^2 bin)



Born, radiated, and exclusive tail cross-sections from HAPRAD (lowest x-Q^2 bin)



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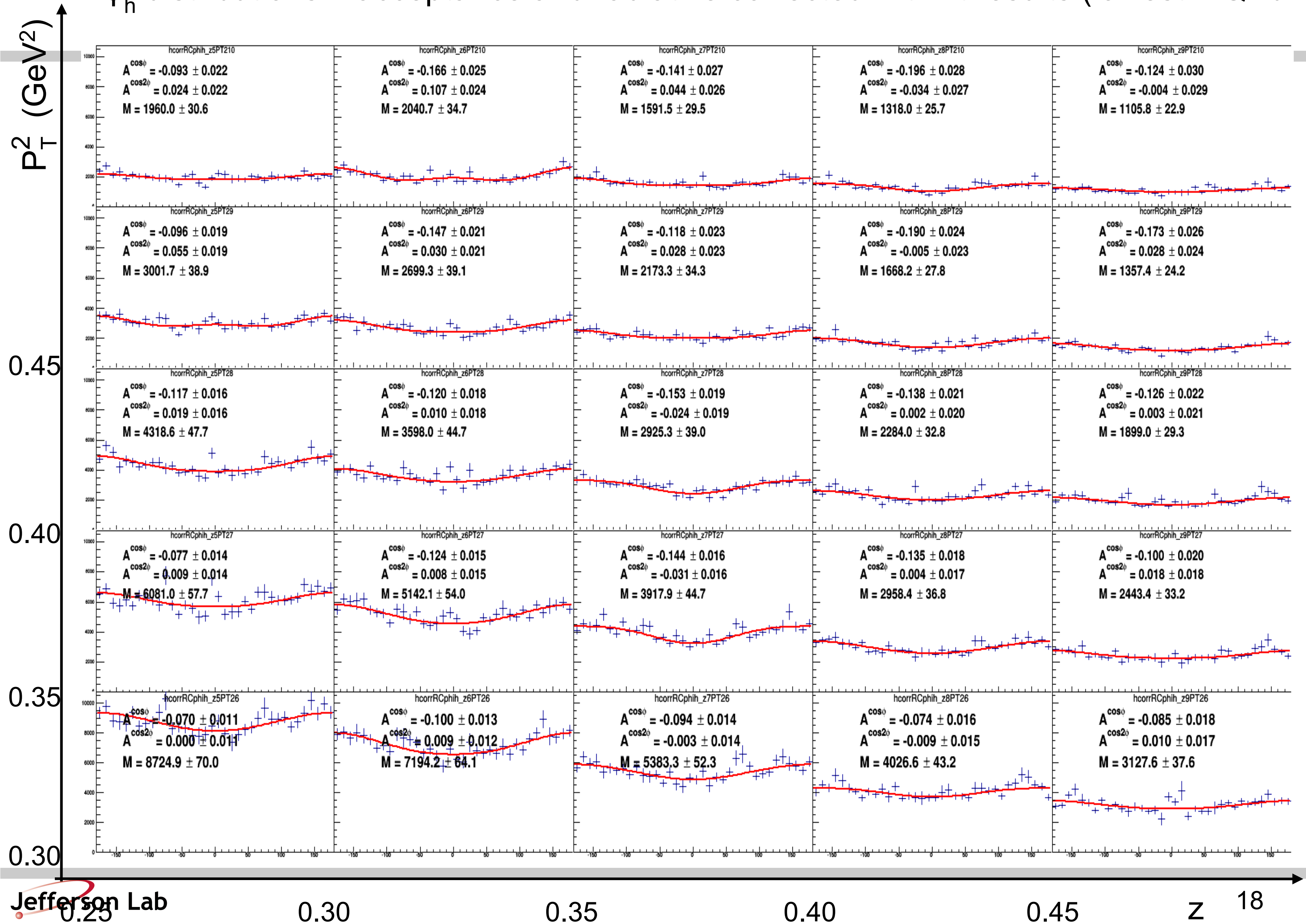
φ_h distributions – acceptance and radiative corrected with fit results (lowest x-Q^2 bin)



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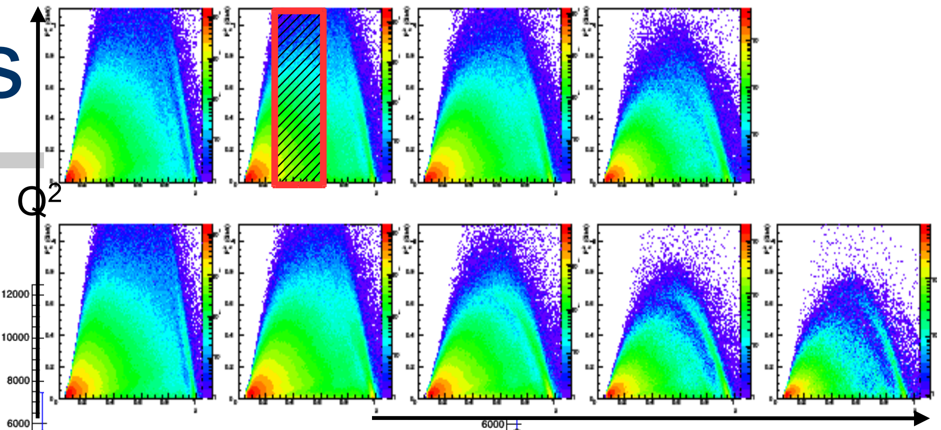
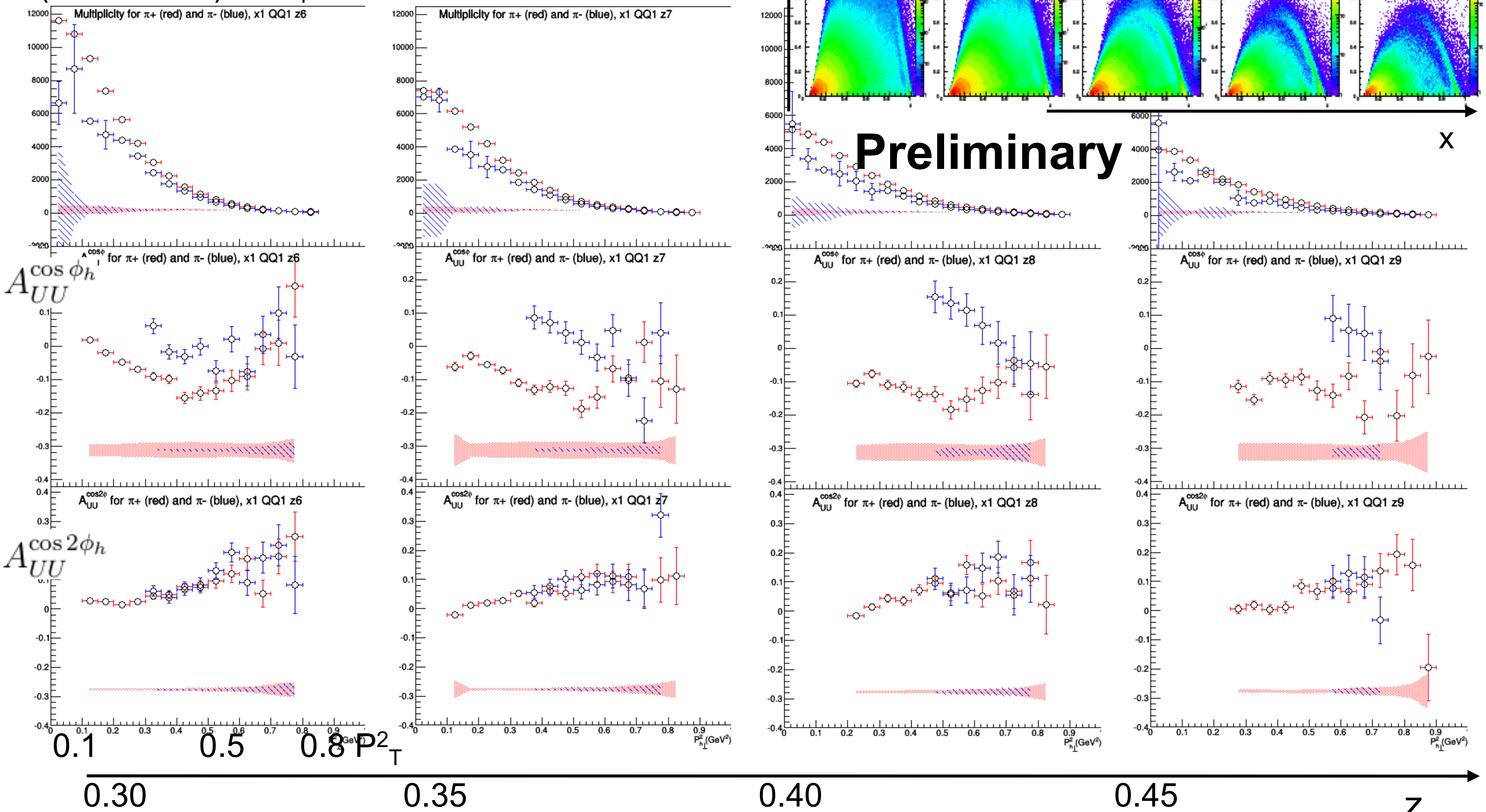
Representative Results



A_0 (top row), $A_{UU}^{\cos\phi_h}$ (middle row), and $A_{UU}^{\cos 2\phi_h}$ (bottom row) vs P_T^2 for π+ and π-

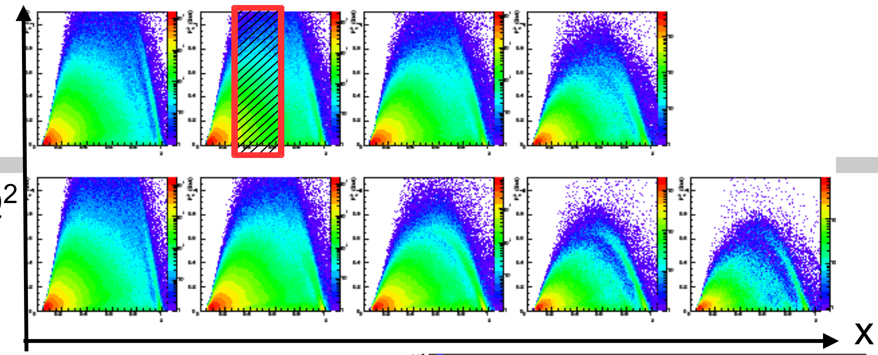


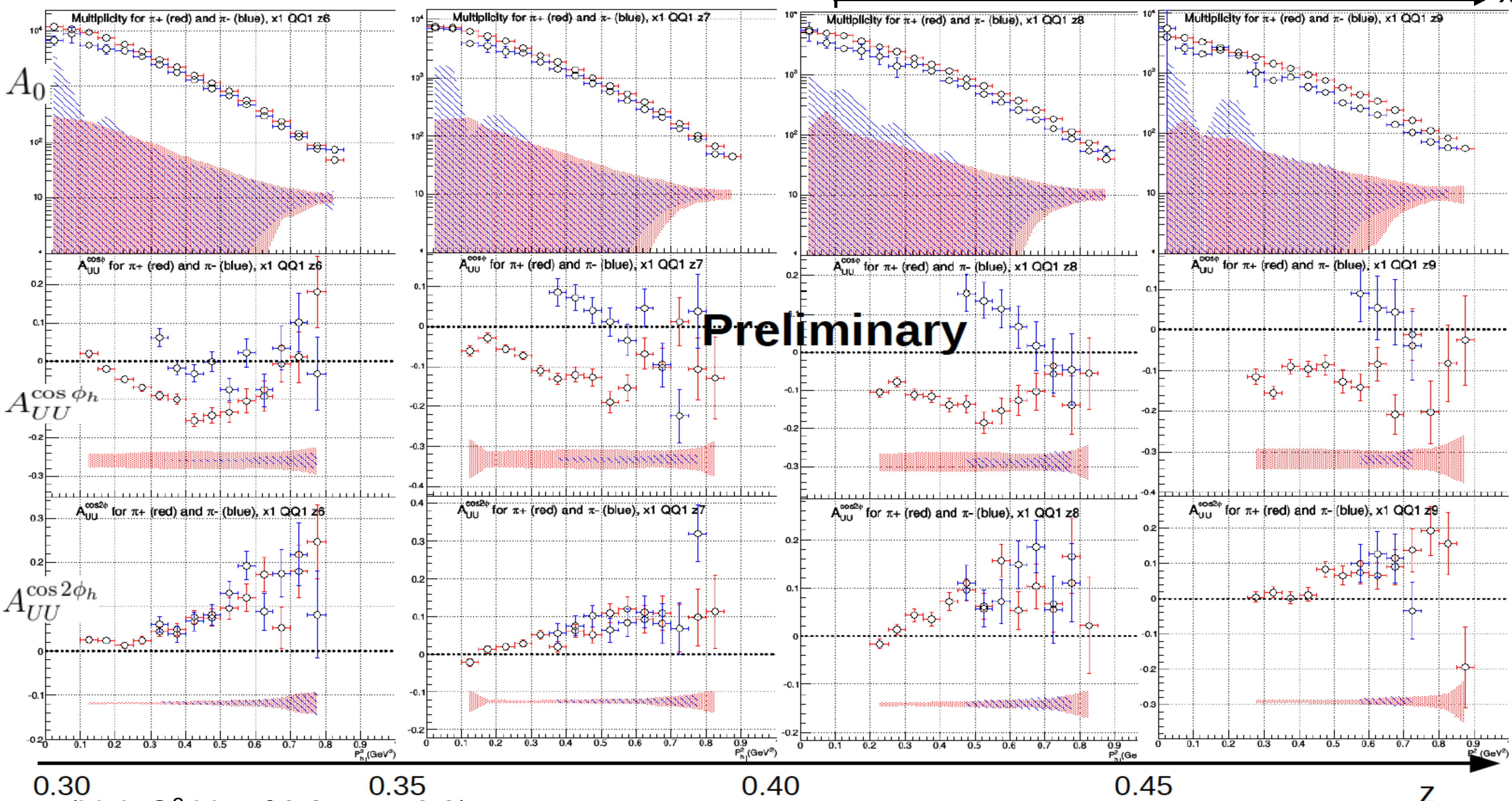
(high Q² bin of 0.2 < x < 0.3)

Jefferson Lab

Representative Results

A_0 (top row), $A_{UU}^{\cos\phi_h}$ (middle row), and $A_{UU}^{\cos 2\phi_h}$ (bottom row) vs P_T^2 for π+ and π-



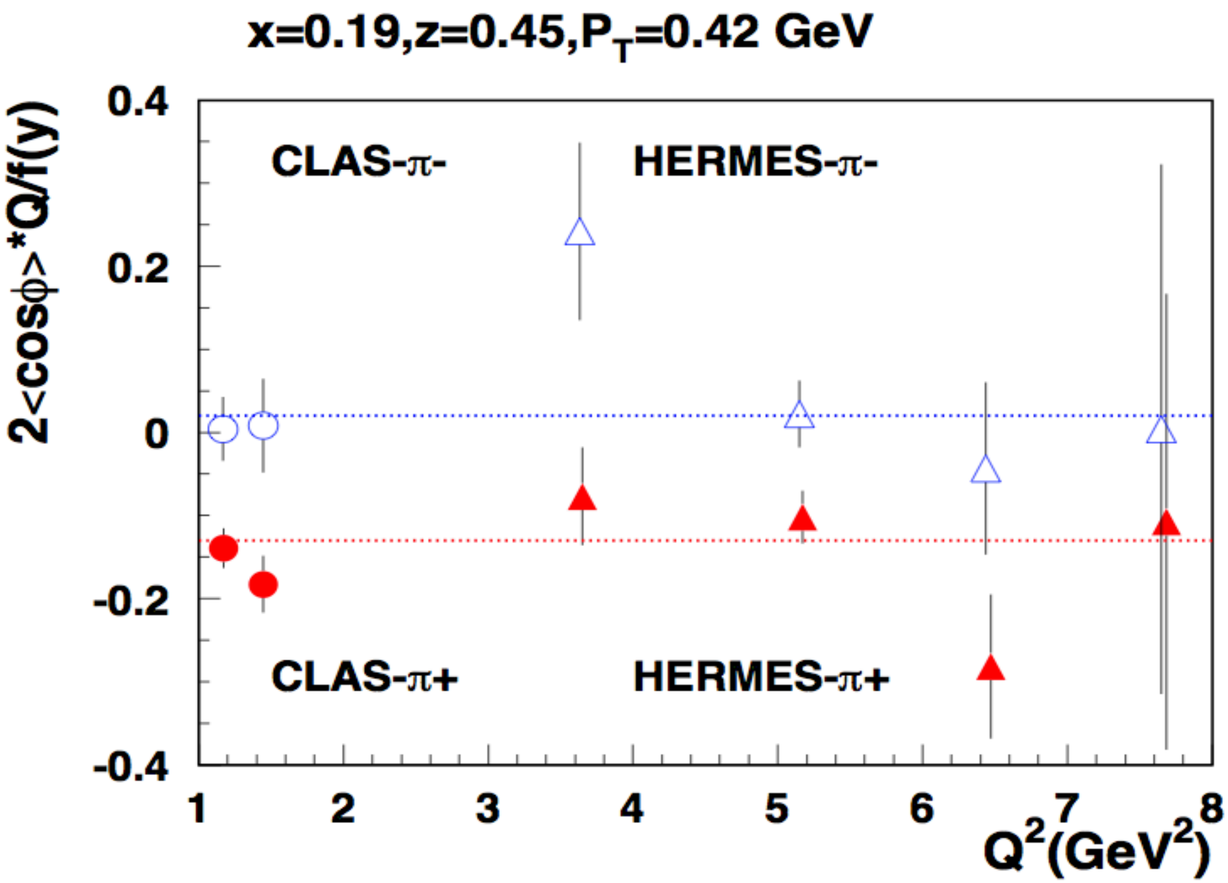


(high Q^2 bin of 0.2 < x < 0.3)

Comparing with HERMES

$$F_{UU,T} + \varepsilon F_{UU,L} + \sqrt{2\,\varepsilon(1+\varepsilon)}\,\cos\phi_h\,F_{UU}^{\cos\phi_h}$$

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



CLAS data consistent with HERMES (27.5 GeV)

Summary

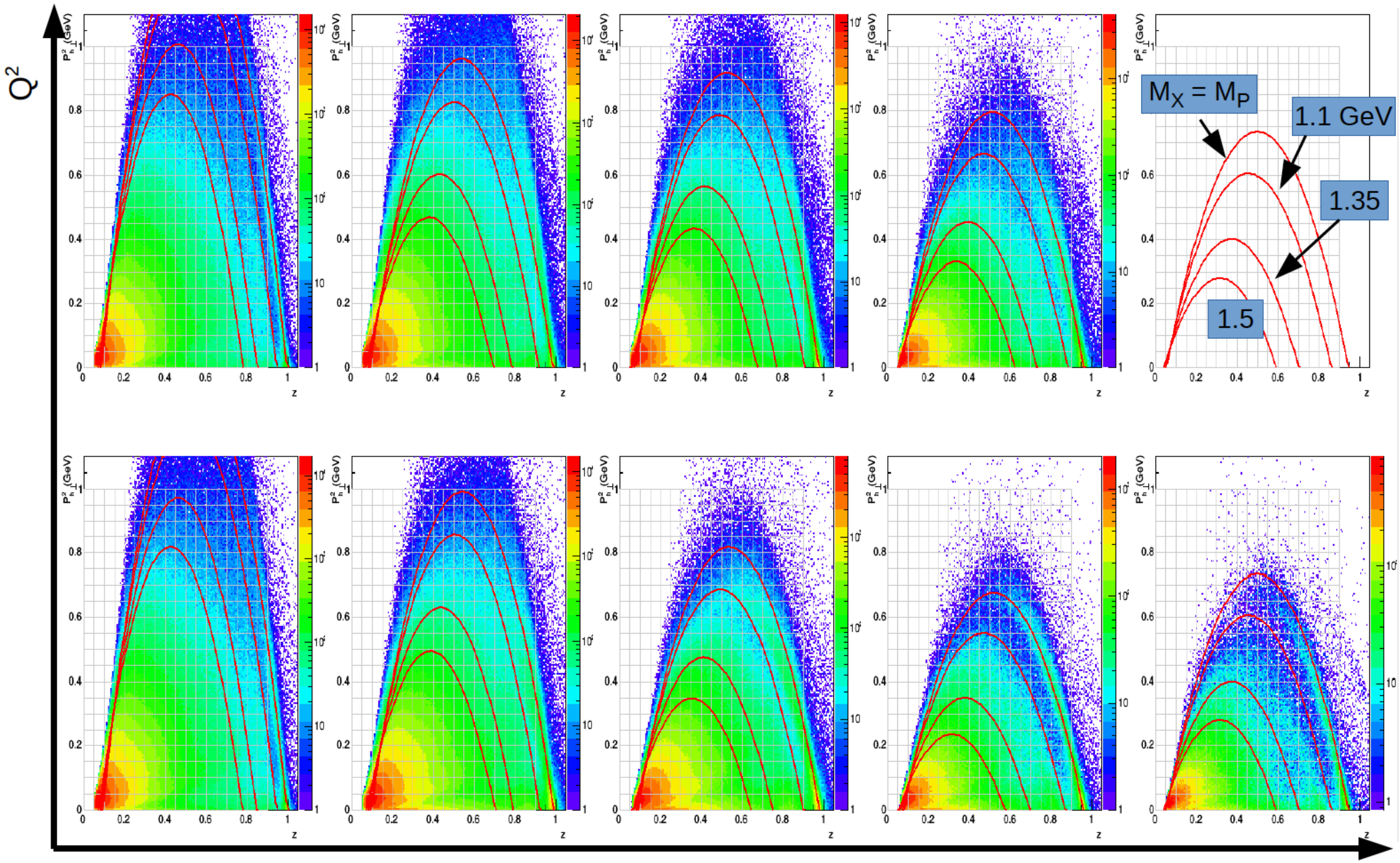
- The multiplicity, cosφ_h moment, and cos2φ_h moment of the unpolarized SIDIS cross-section have been measured for both charged pion channels in a fully differential way with good statistics and well controlled systematics over a wide kinematic range.

- The cosφ_h and cos2φ_h modulations are significant, depend on flavor, and their understanding is important for interpretation of spin-azimuthal asymmetries

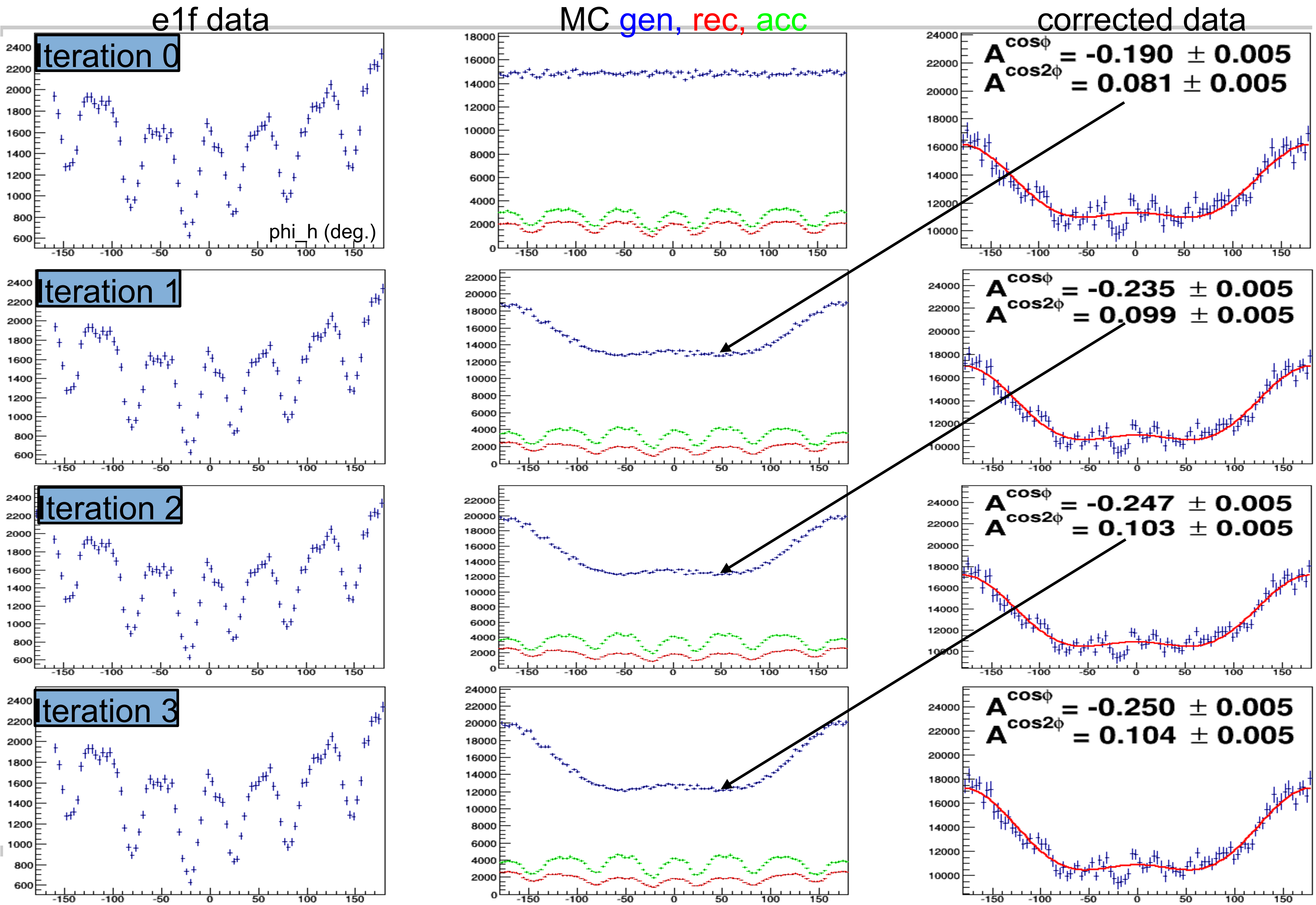
- Comparison of azimuthal moments with HERMES, supports the higher twist nature of the cos$\varphi_h$moment (Cahn effect).

Support slides….

π^+ $P^2_{h\perp}$ vs z for each x-Q^2 bin



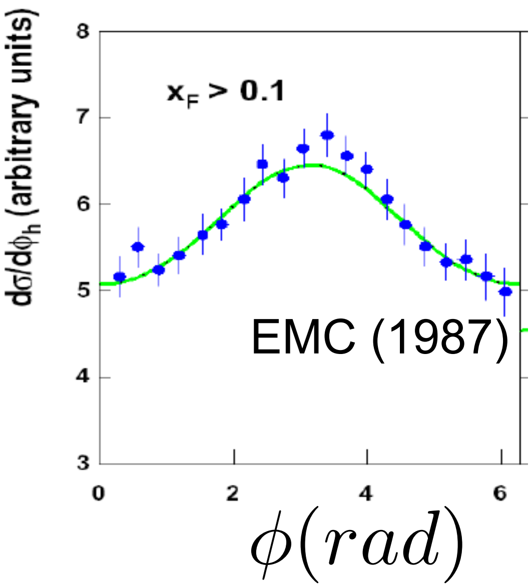
Effects of the shape of the generated ϕ distribution

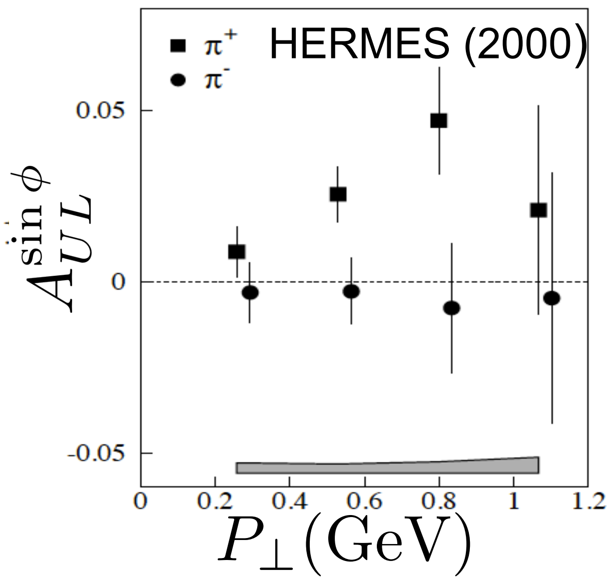


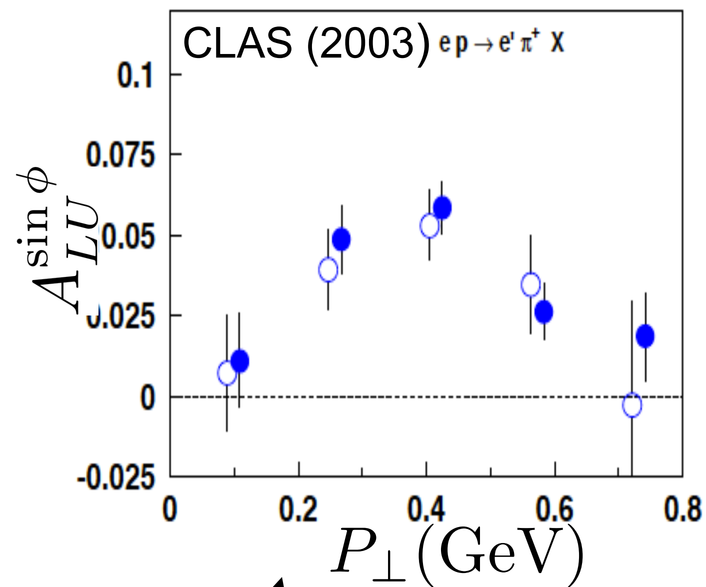
Measurements of SS azimuthal asymmetries in SIDIS

$$\sigma = \sigma_{UU}(1 + P_B A_{LU}^{\sin\phi} \sin\phi + P_T A_{UL}^{\sin\phi} \sin\phi + P_T A_{UT}^{\sin\phi-\phi_S} \sin(\phi-\phi_S) + ...)$$

Large cosϕ and sinϕ modulations have been observed in electroproduction of hadrons in SIDIS with polarized and unpolarized targets







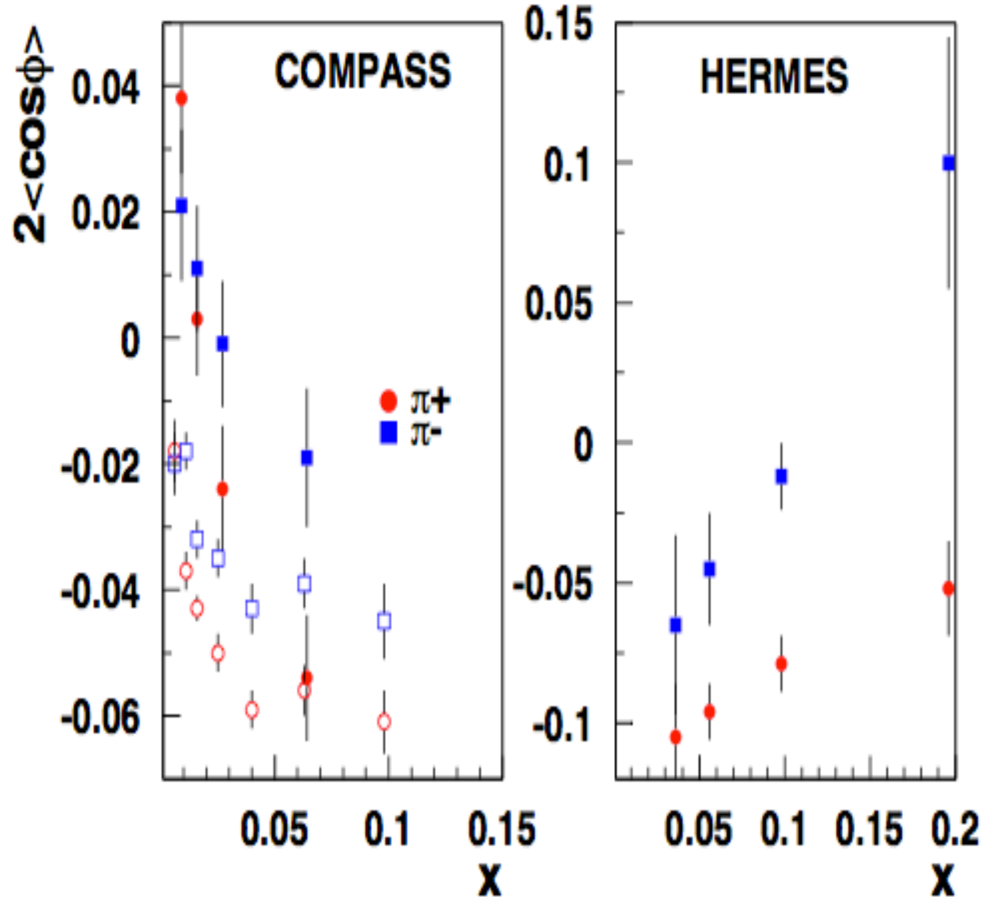
Related to spin-orbit correlations in fragmentation?

$A_{UU}^{\cos\phi}$: From measurements to interpretation

N/q	U	L	T
U	$f^{\perp}$	$g^{\perp}$	h, e
L	$f_L^{\perp}$	$g_L^{\perp}$	h_L, e_L
T	$f_T, f_T^{\perp}$	$g_T, g_T^{\perp}$	$h_T, e_T, h_T^{\perp}, e_T^{\perp}$

q/h	U	L	
U	D_1		
L		G_{1L}	
T	$H_1^{\perp}$	$H_{1L}^{\perp}$	H

$$A_{UU}^{\cos\phi} \propto f^{\perp} D_1 + h H_1^{\perp}$$



π^0 SSA less sensitive polarized fragmentation effects (Collins function suppressed)