Update on E1-f SIDIS Analysis for Azimuthal Modulations*

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Deep Processes Working Group
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* Based on PhD thesis work at UConn

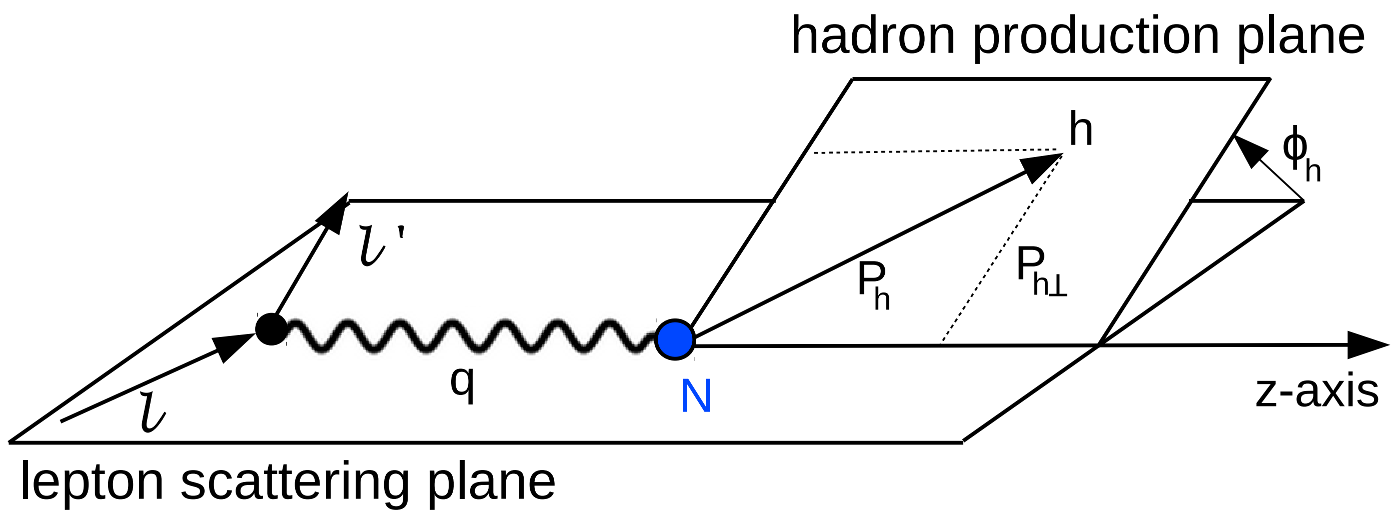
Outline

- Physics
  - SIDIS
  - TMDs & FFs
- Experiment
  - CLAS E1-f data set
- Analysis
  - event selection and binning for $ep \rightarrow e\pi^{\pm}X$
  - acceptance studies (Monte Carlo)
  - radiative corrections
  - systematic error studies
- Results
- Summary & conclusions

SIDIS kinematics

Goal: Study the transverse motion of quarks inside of the proton via semi-inclusive deep inelastic scattering (SIDIS):

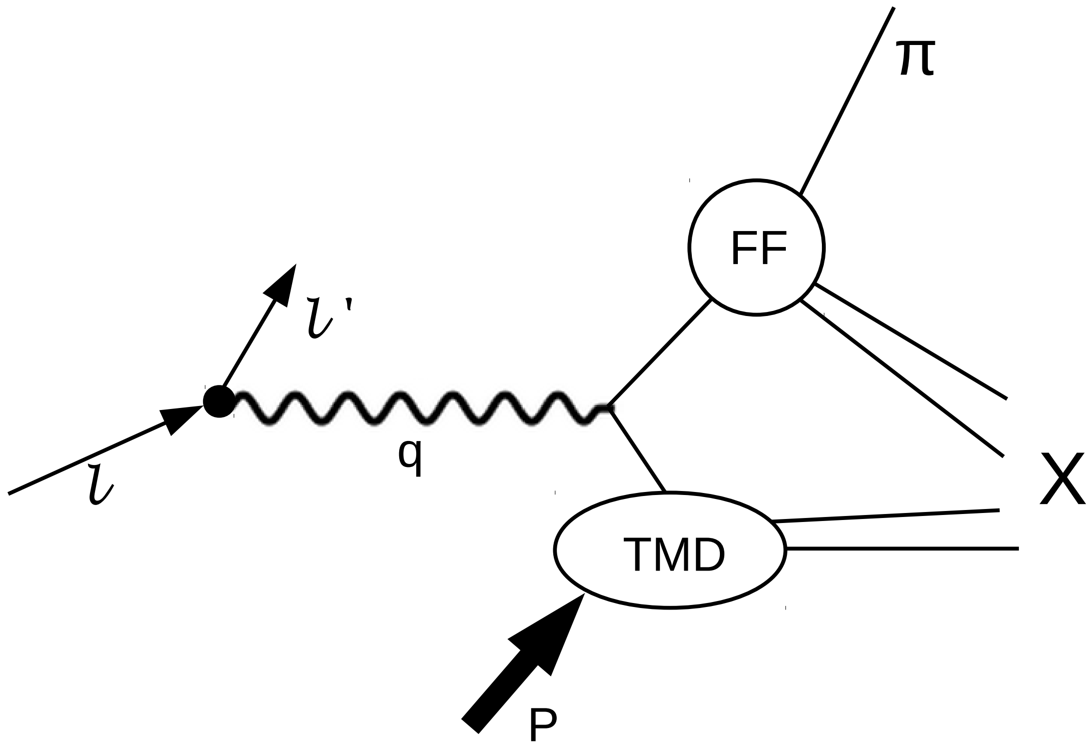
$$l\,(k) + N\,(P) \rightarrow l'\,(k') + h\,(P_h) + X\,(P_X)$$



$$Q^2 = -q^2 = -\left(k - k'\right)^2, \qquad x = \frac{Q^2}{2P\cdot q}, \qquad y = \frac{P\cdot q}{P\cdot k}, \qquad \gamma = \frac{2Mx}{Q}$$

$$W^2 = (P+q)^2, \qquad z = \frac{P\cdot P_h}{P\cdot q}, \qquad \varepsilon = \frac{1 - y - \frac{1}{4}\gamma^2 y^2}{1 - y + \frac{1}{2}y^2 + \frac{1}{4}\gamma^2 y^2}$$

SIDIS cross-section



- Motion of quarks inside of the proton is described by TMDs.

- The process of the struck quark forming into a hadron ("hadronization") is described by fragmentation functions (FFs).

Assuming single photon exchange, the leptoproduction cross-section can be written as:

$$\frac{d^6\sigma}{dx\ dQ^2\ d\psi\ dz\ d\phi_h\ dP_{h\perp}^2} = \frac{1}{2E_b M x}\frac{\alpha^2 y}{8zQ^4} 2MW^{\mu\nu}L_{\mu\nu}$$

$L_{\mu\nu}$ is the leptonic tensor.

$W^{\mu\nu}$ is the hadronic tensor.

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:

$$Q^2\to\infty$$

$$2P\cdot q\to\infty$$

$$P\cdot P_h\to\infty$$

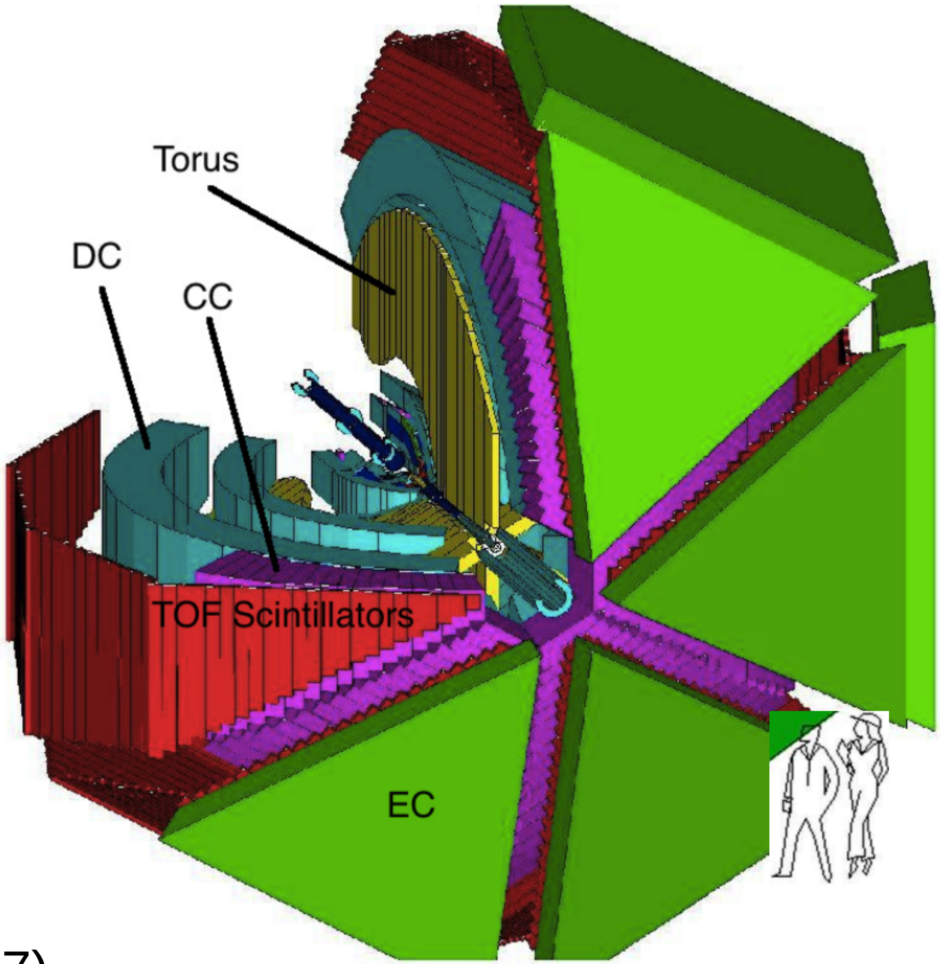
$$\text{fixed}\begin{cases} x=Q^2/2P\cdot q \\ z=P\cdot P_h/P\cdot q\end{cases}$$

CLAS E1-f Data Set

- 5.498 GeV electron beam with ~75% polarization (averaged over for this analysis)
- Unpolarized liquid hydrogen target
- About 2 billion events
- Torus at 60% to improve π- acceptance
- Broad and comparable kinematic coverage for both charged pion channels:

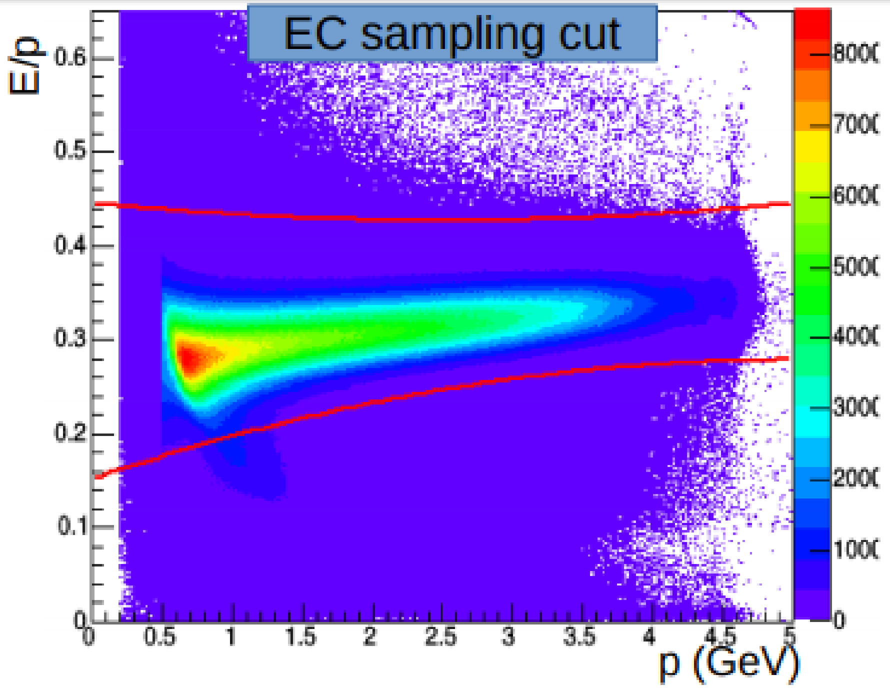
$$ep \rightarrow e\pi^{\pm}X$$

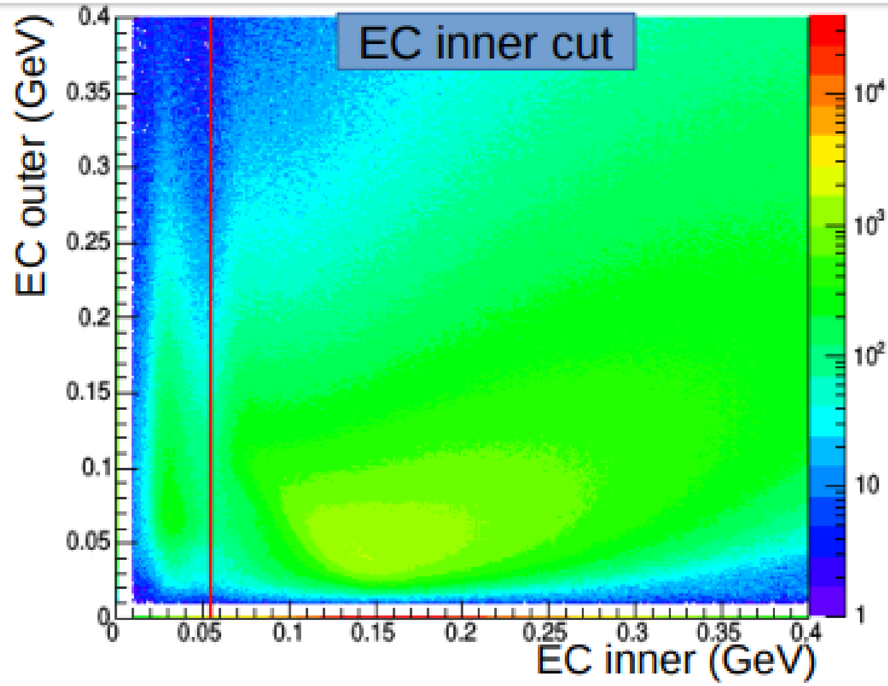
- Kinematic coverage ranges:
  - $x \approx 0.1 - 0.6$
  - $Q^2 \approx 1 - 5$ GeV^2
  - $P_{hT} \approx 0 - 1.5$ GeV
  - $z \approx 0.0 - 0.9$ (region of interest $0.4 < z < 0.7$)
  - $\varphi_h = -180^o - 180^o$

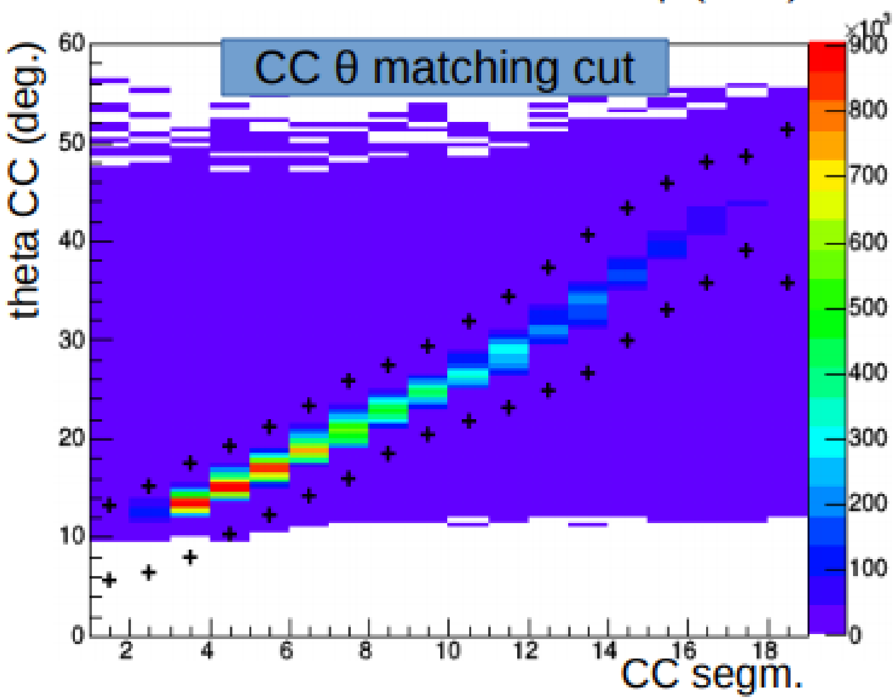


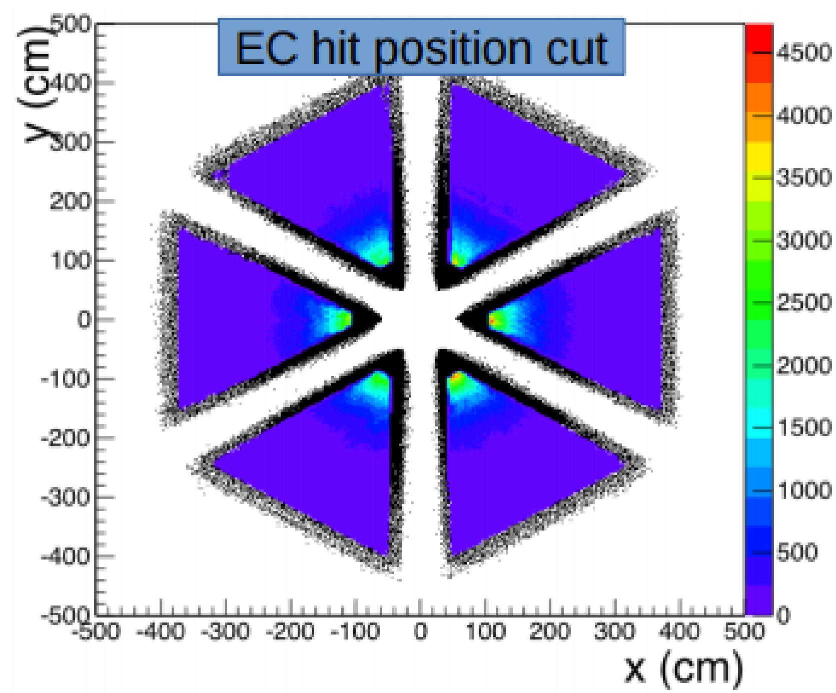
Electron ID

(sector 1)





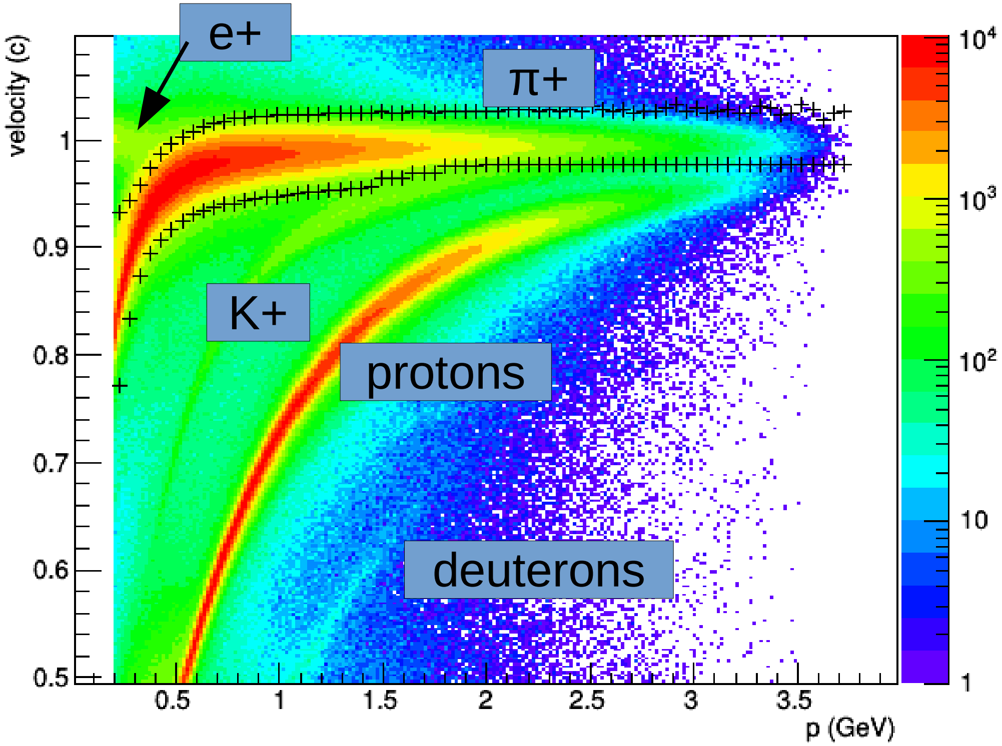




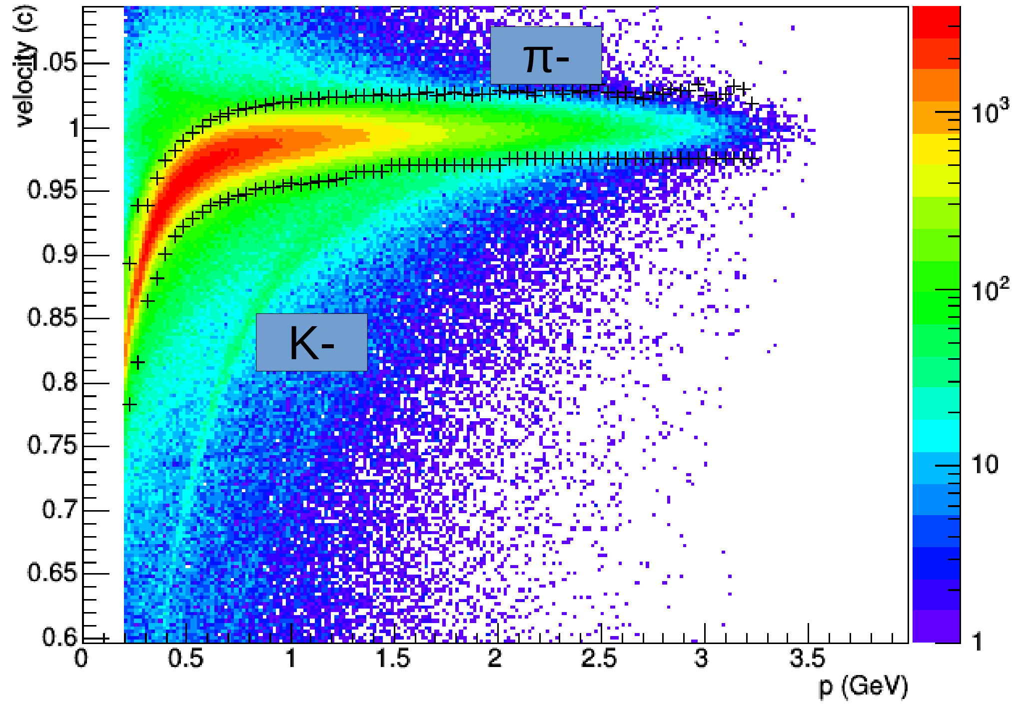
pion identification

(sector 1)

β vs momentum for positive tracks

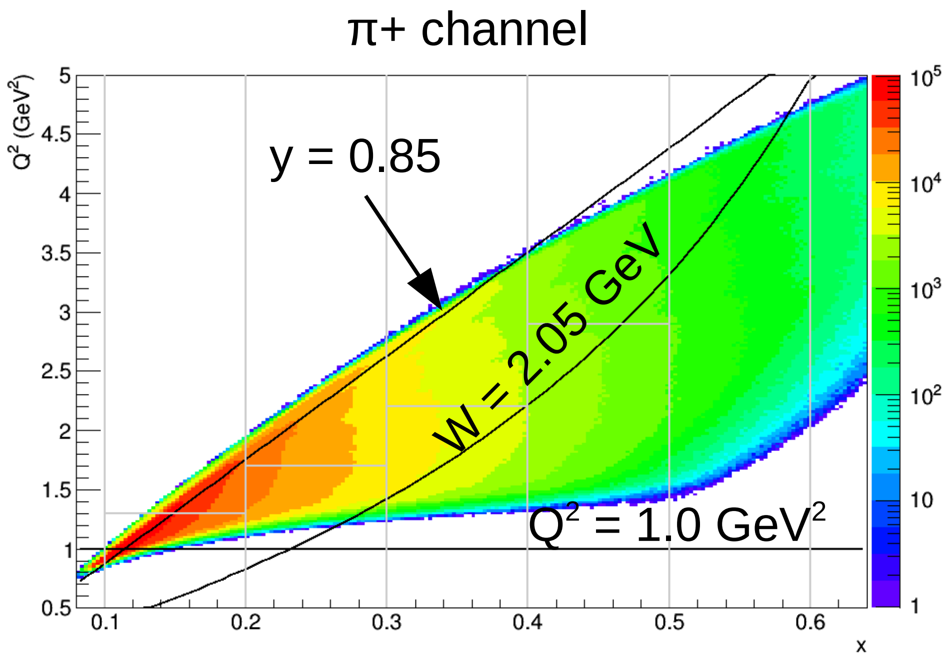


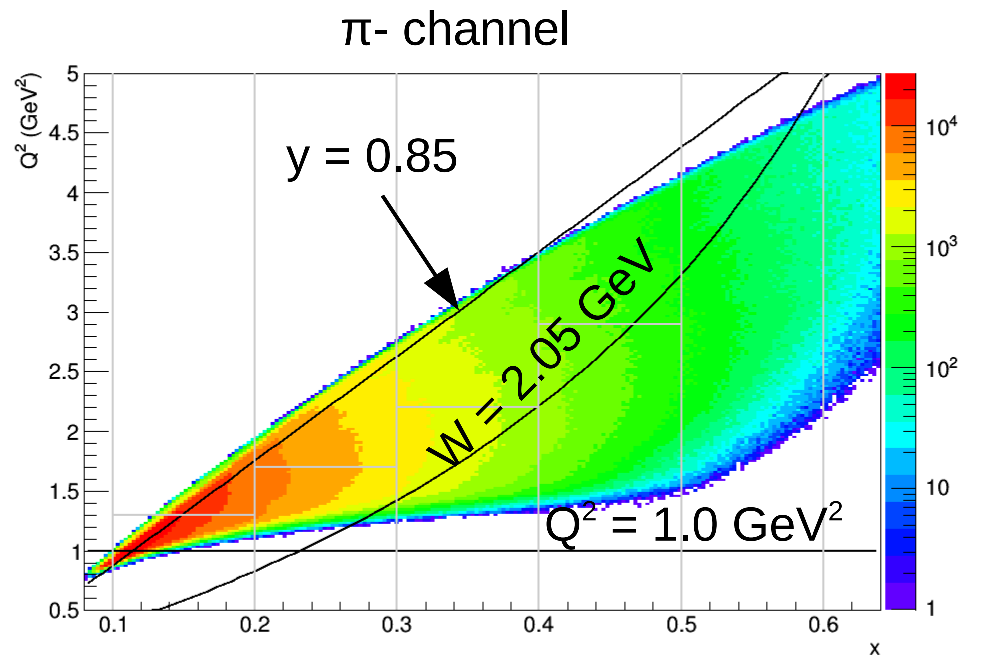
β vs momentum for negative tracks



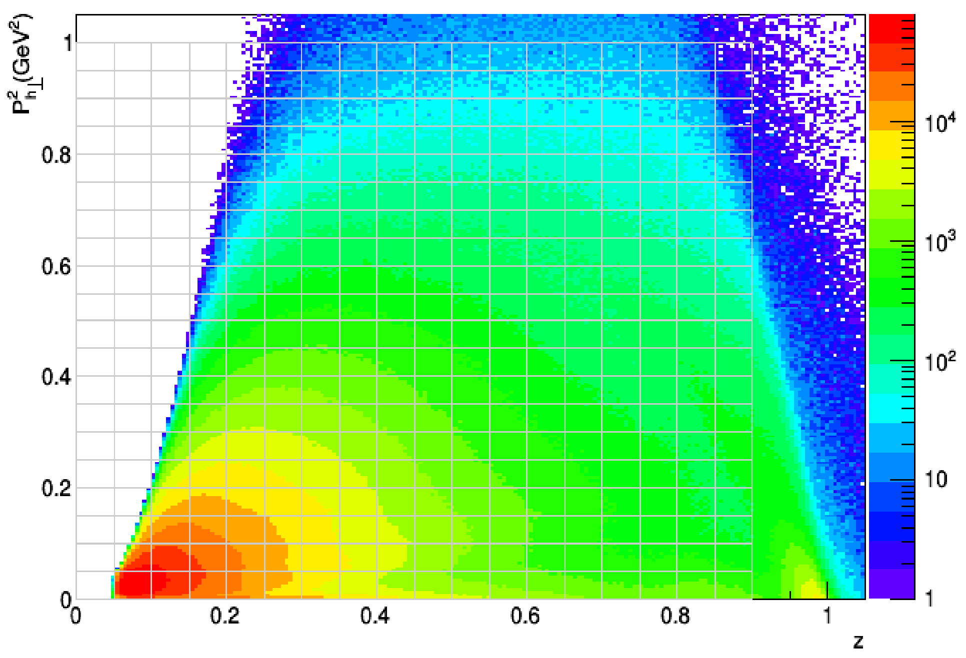
- 70 vertical slices fit with a gaussian
- 3σ cut at low momenta
- Cut tapers in at high momenta

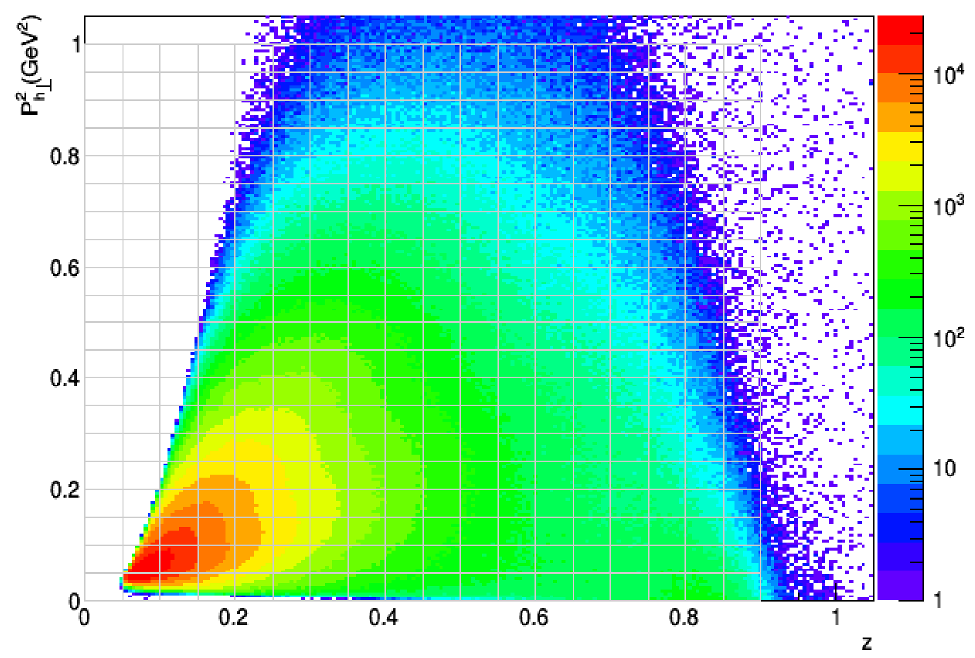
SIDIS Cuts and Binning



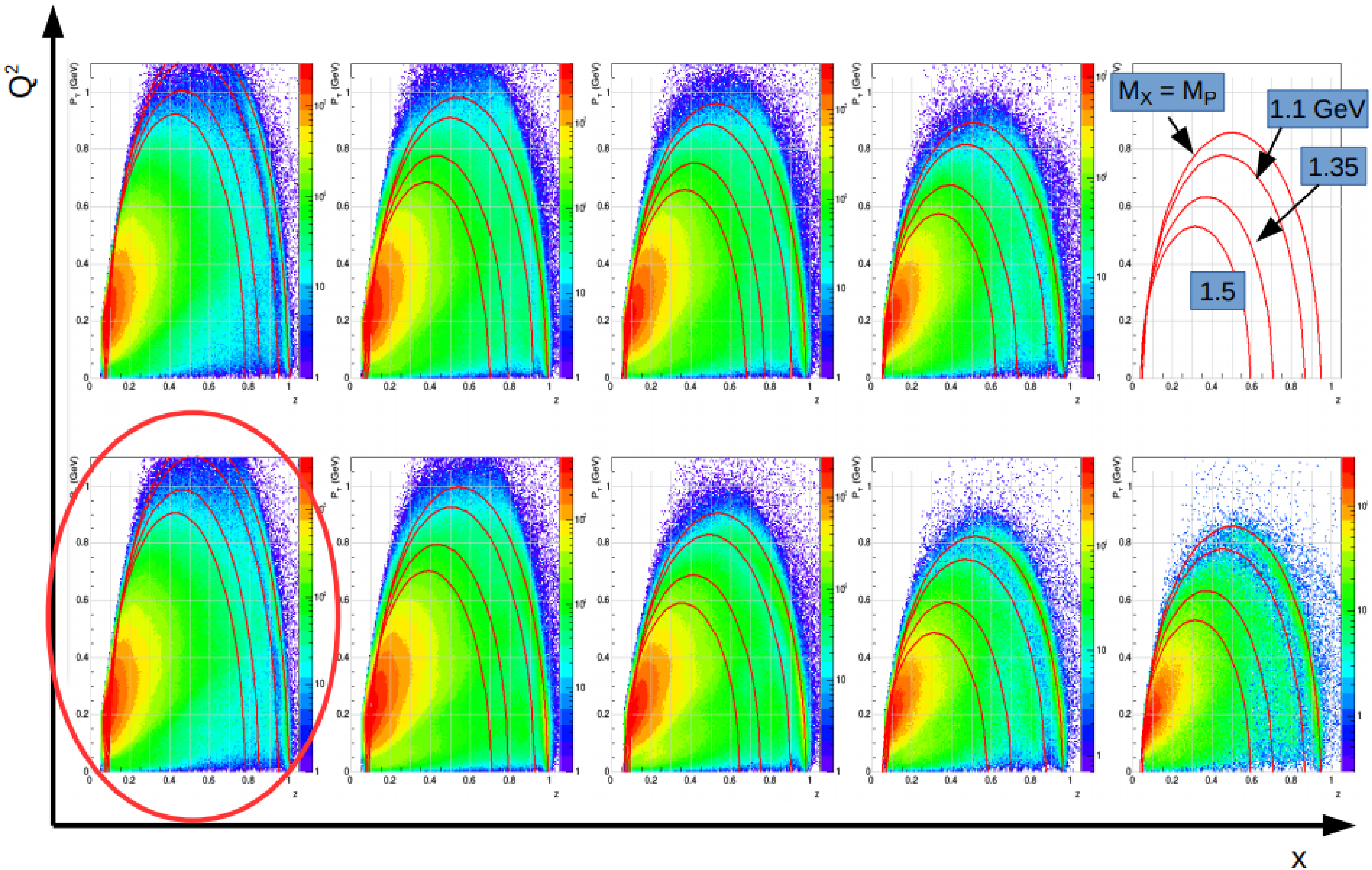


The DIS region is defined as $Q^2 > 1.0$ GeV^2 and $W > 2.05$ GeV.

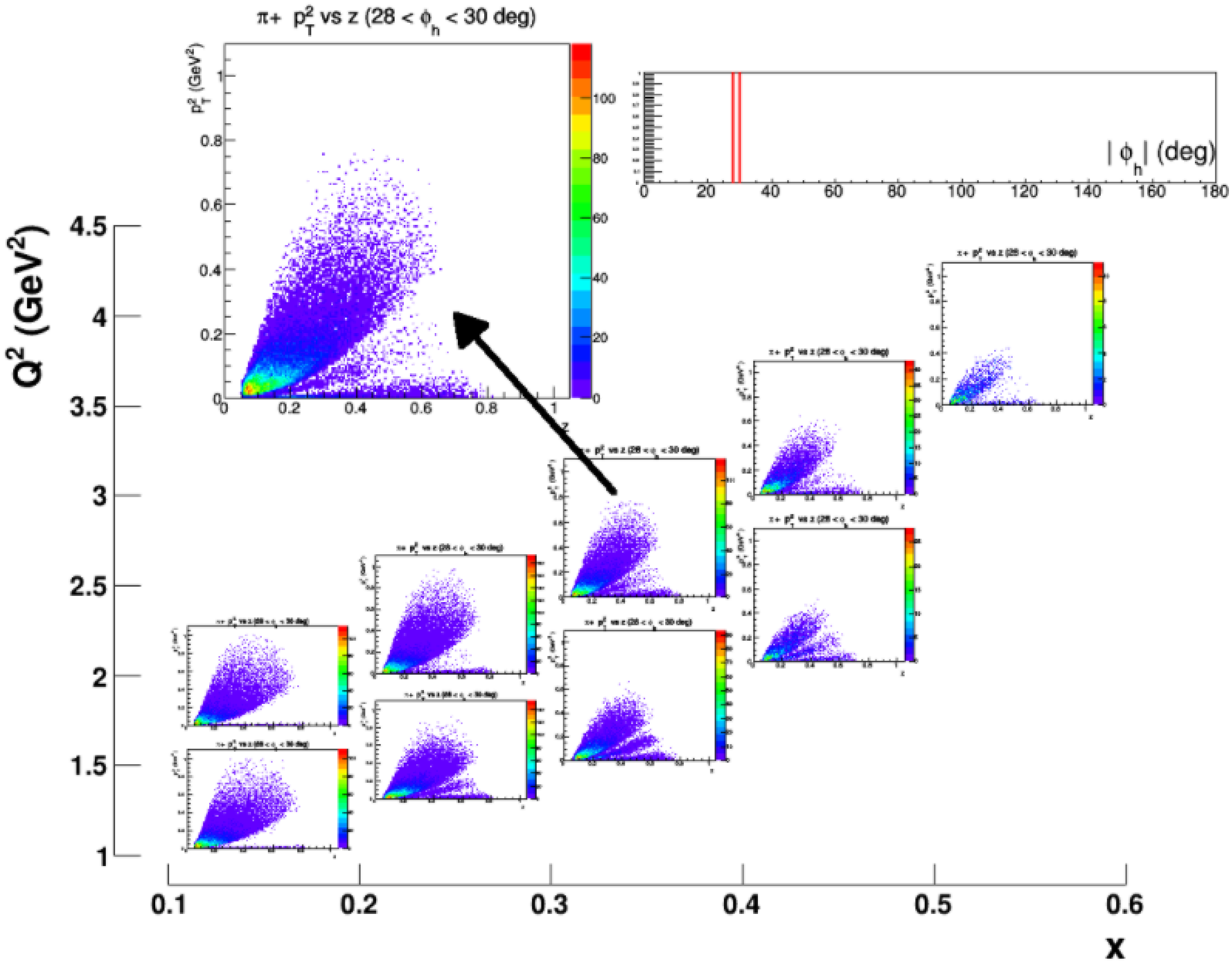




SIDIS Cuts and Binning



SIDIS Cuts and Binning



https://userweb.jlab.org/~nathanh/pip_5DaccPlot_scanPhih.gif
https://userweb.jlab.org/~nathanh/pim_5DaccPlot_scanPhih.gif

Simulation

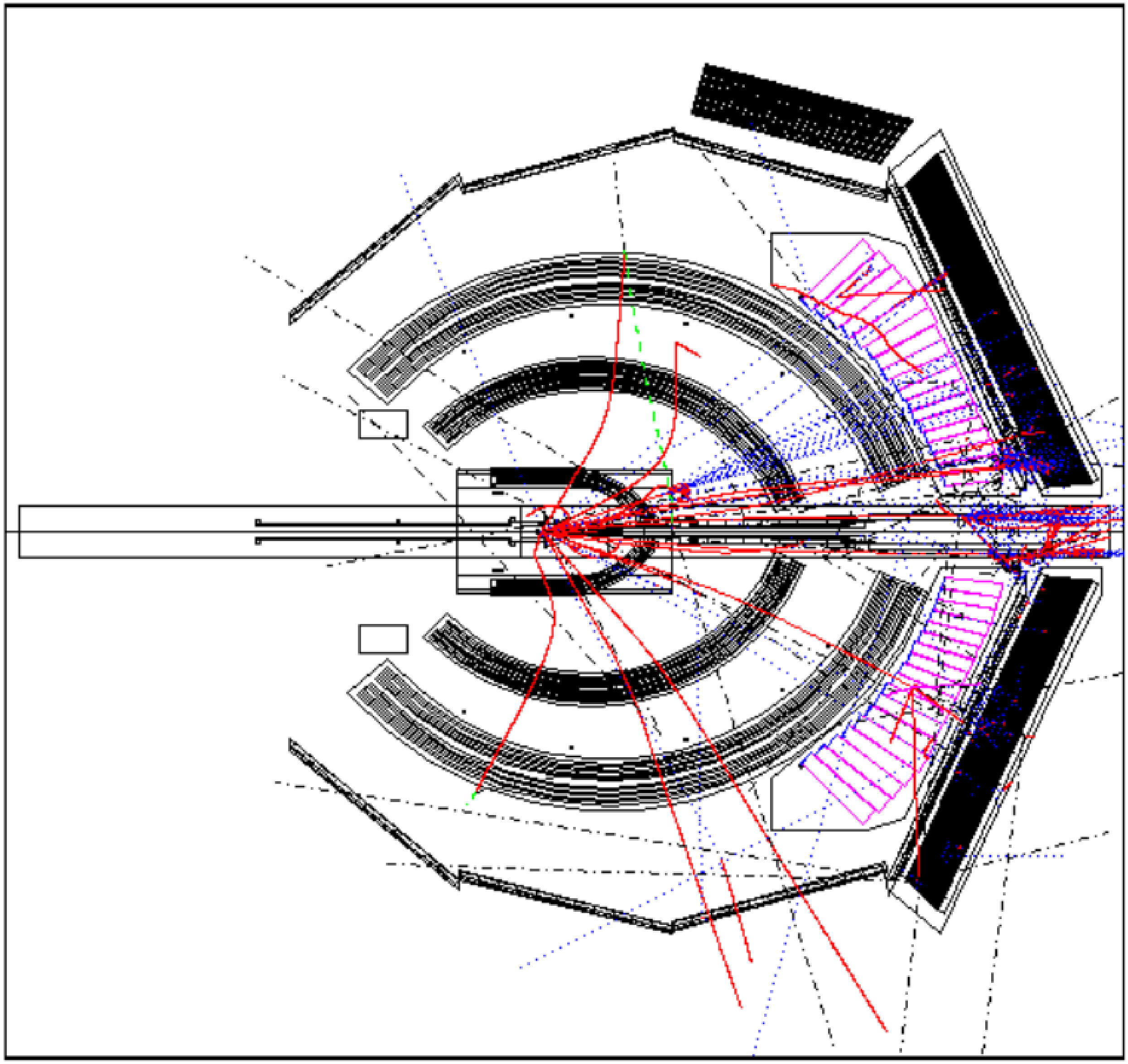
- 1B SIDIS events are generated with a PYTHIA based event generator.

- 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).

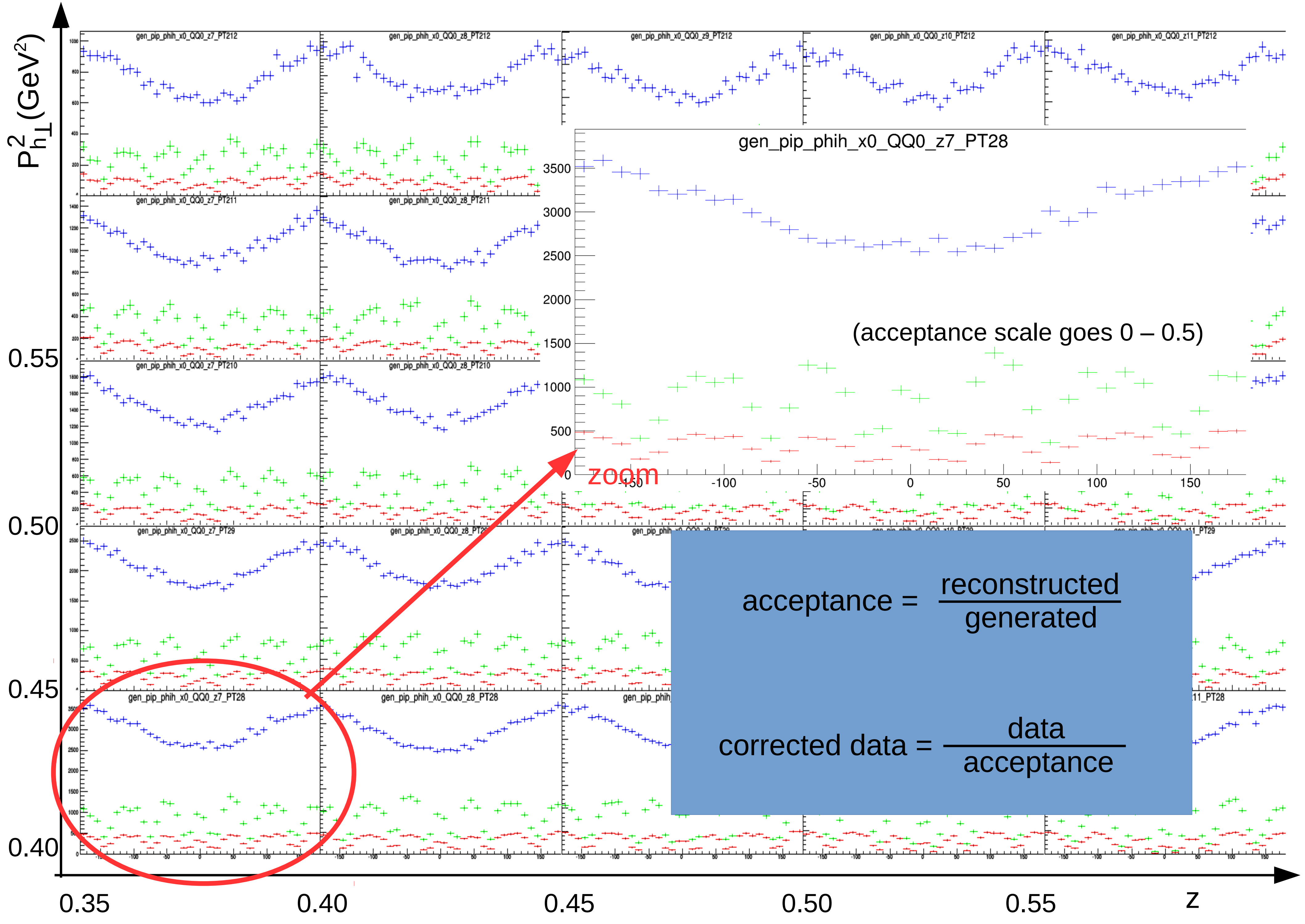
- Smearing and inefficiencies are introduced to the simulation to make it more realistic.

- 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.

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



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

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

Radiative Corrections

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

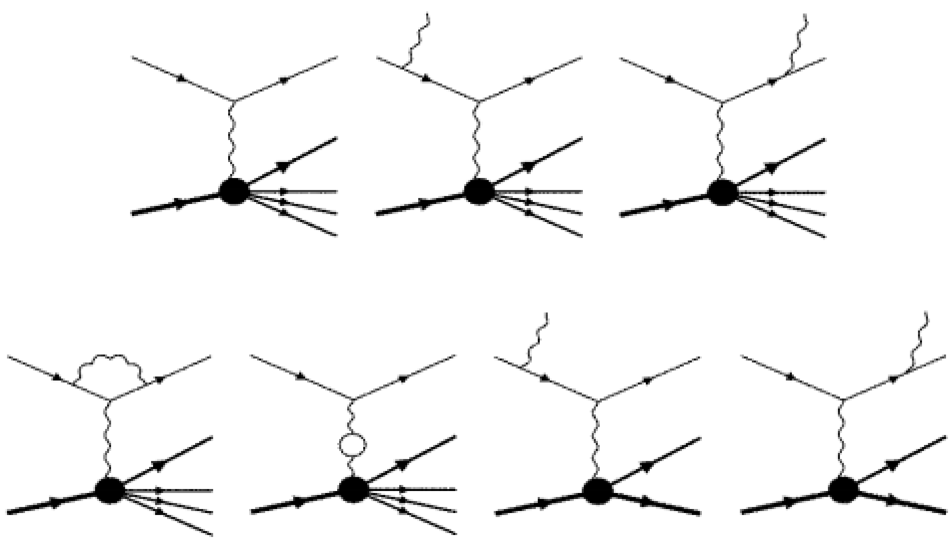
- Furthermore, exclusive events can enter into the SIDIS sample because of radiative effects ("exclusive tail").

- HAPRAD 2.0 is used to do radiative corrections.

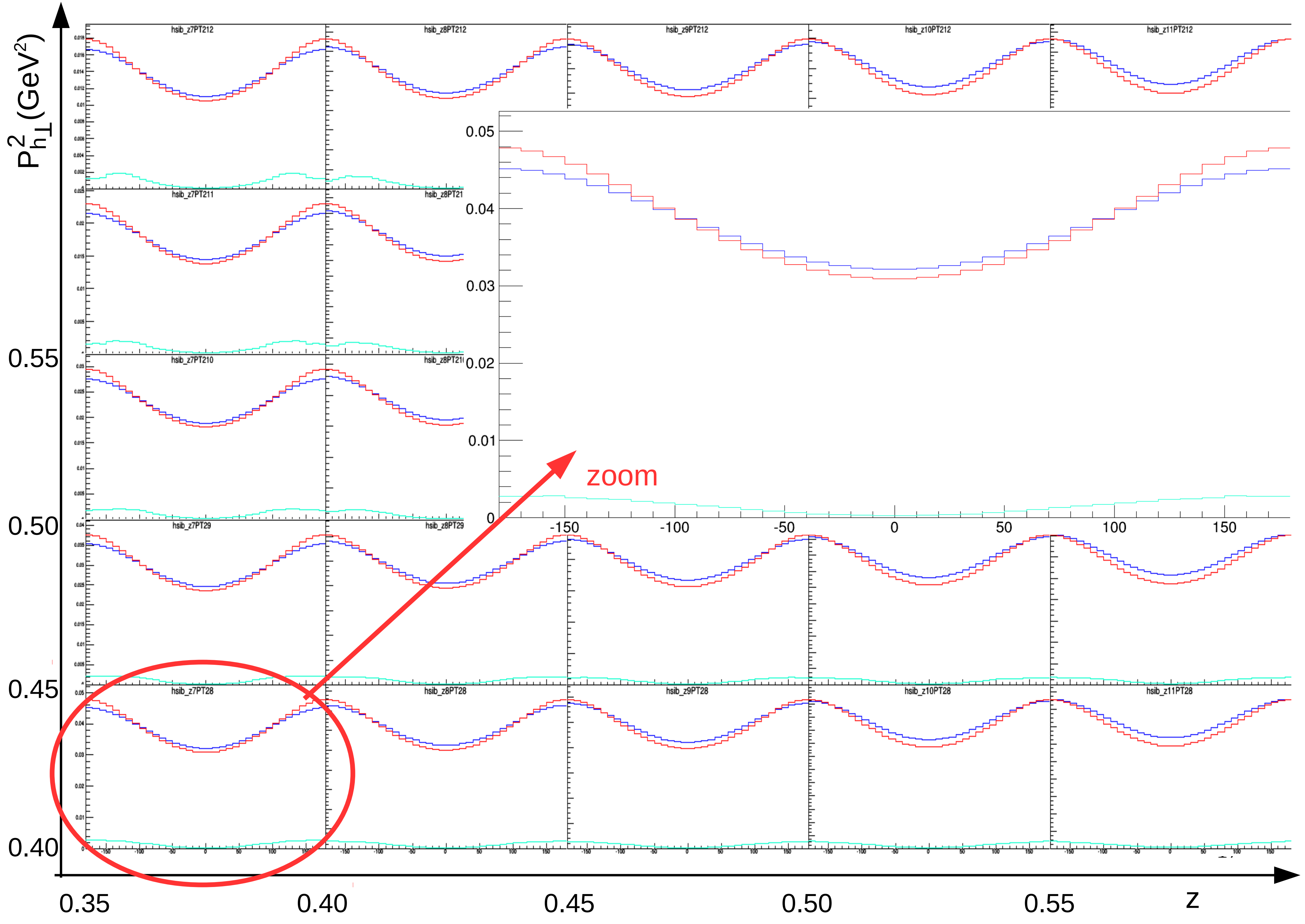
- For a given $\sigma_{Born}(x, Q^2, z, P_{h\perp}^2, \phi_h)$ (obtained from a model), HAPRAD calculates $\sigma_{rad+tail}\left(x, Q^2, z, P_{h\perp}^2, \phi_h\right)$. The correction factor is then:

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

- 3 different models were used to study model dependence.



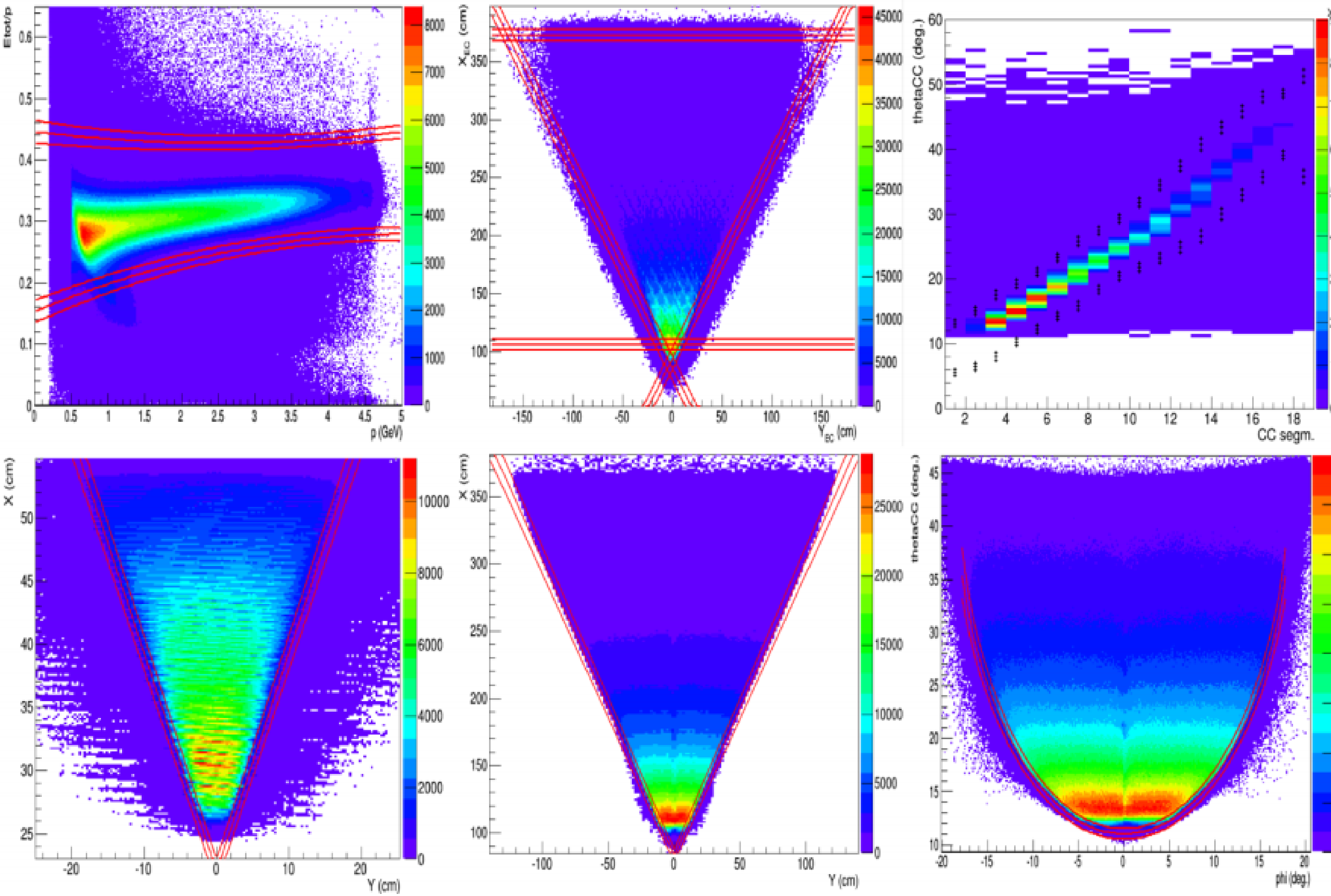
Born, radiated, and exclusive tail cross-sections from HAPRAD (lowest x-Q^2 bin)



Systematic Error Studies

Label	Source	# variations	Description
0	e- zvertex cut	2	+/- 0.2 cm
1	e- EC sampling cut	2	See figure
2	e- EC outer vs inner cut	2	+/- 0.005 GeV
3	e- EC geometric cut	2	See figure
4	e- CC θ matching cut	2	See figure
5	e- region 1 fiducial cut	2	See figure
6	e- region 3 fiducial cut	2	See figure
7	e- CC fiducial cut	2	See figure
8	Pion β cut	2	+/- 0.25σ
9	Pion region 1 fiducial cut	2	See figure
10	φ_h fiducial cut	2	+/- 10^o
11	Acc. model dependence	1	2^{nd} to last iteration is used
12	Rad. cor. model dependence	1	2^{nd} to last iteration is used
13	Sector dependence	6	1 result from each sector

Systematic Error Studies



Systematic Error Studies

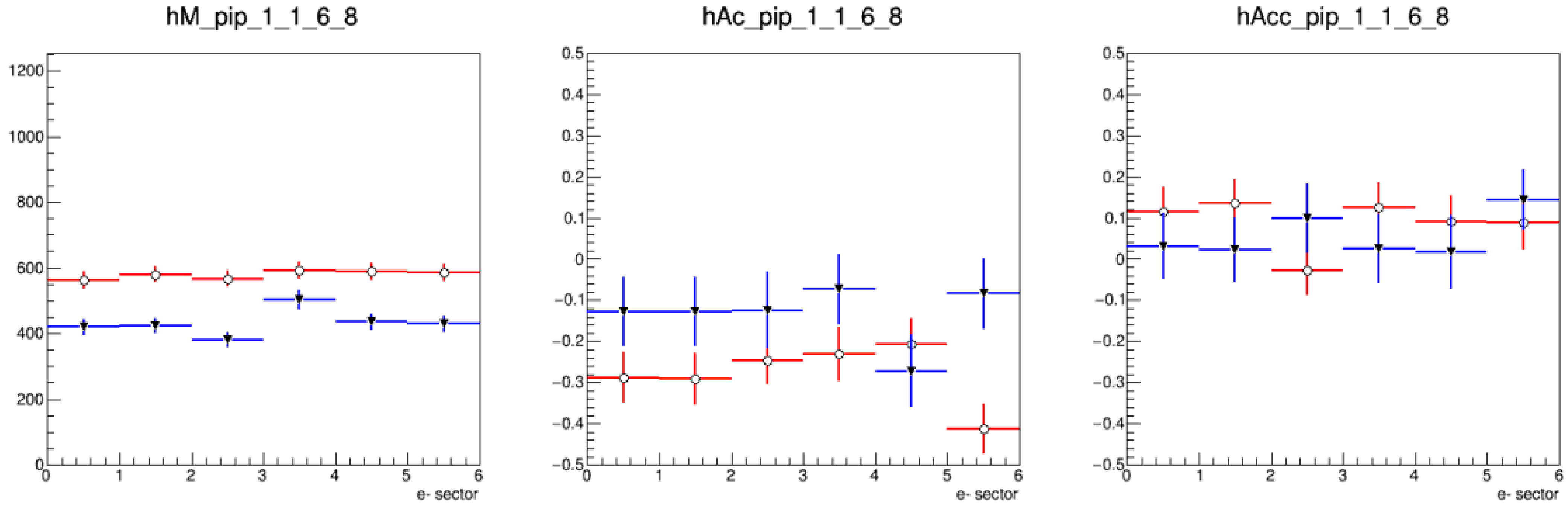


Figure 10.1: Measurements of A_0 (left), $A^{\cos\phi}$ (middle), and $A^{\cos 2\phi}$ (right) for a representitive bin as a function of the electron sector for $\pi+$ (red circles) and $\pi-$ (blue triangles). This kinematic bin is the high Q^2 bin of $0.2 < x < 0.3$, $0.3 < z < 0.35$, and $0.4 < P^2_{h\perp} < 0.45\ GeV^2$.

$$\sigma^2 = \sigma^2_{stat} + \sigma^2_{sys}$$

Systematic Error Studies

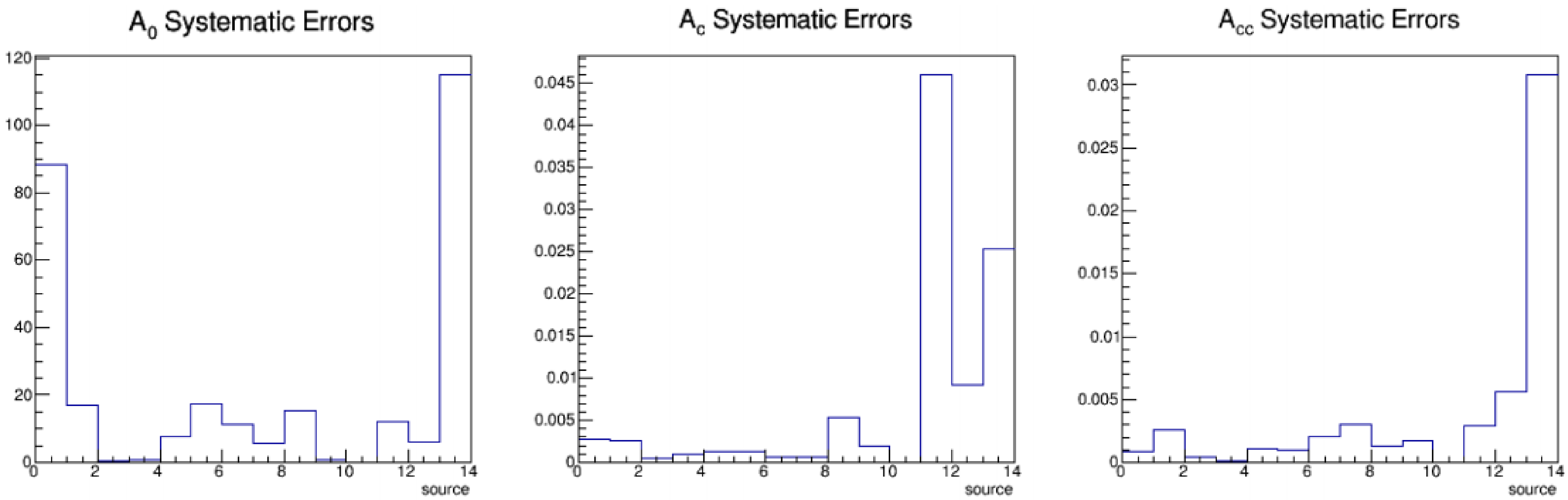
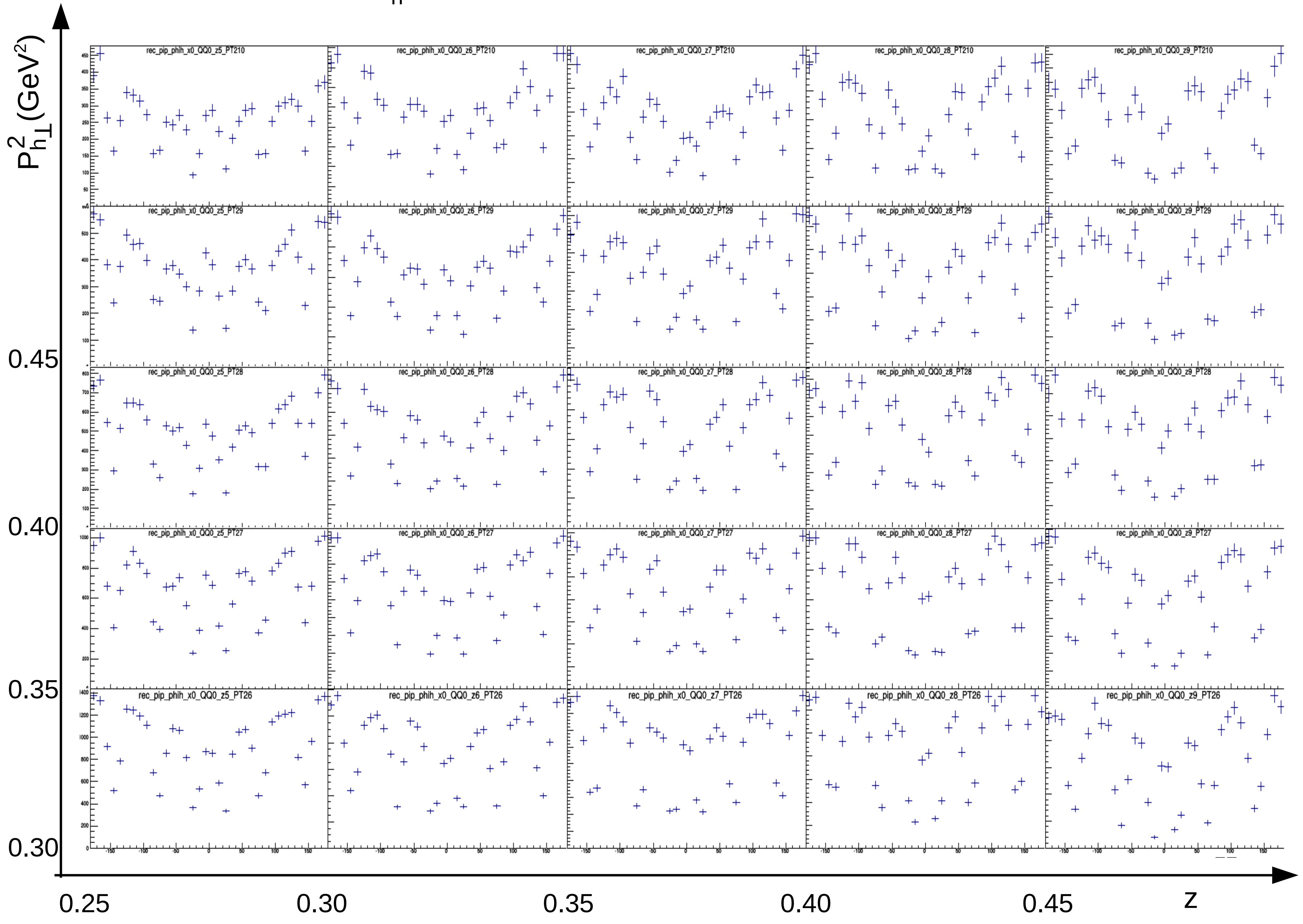
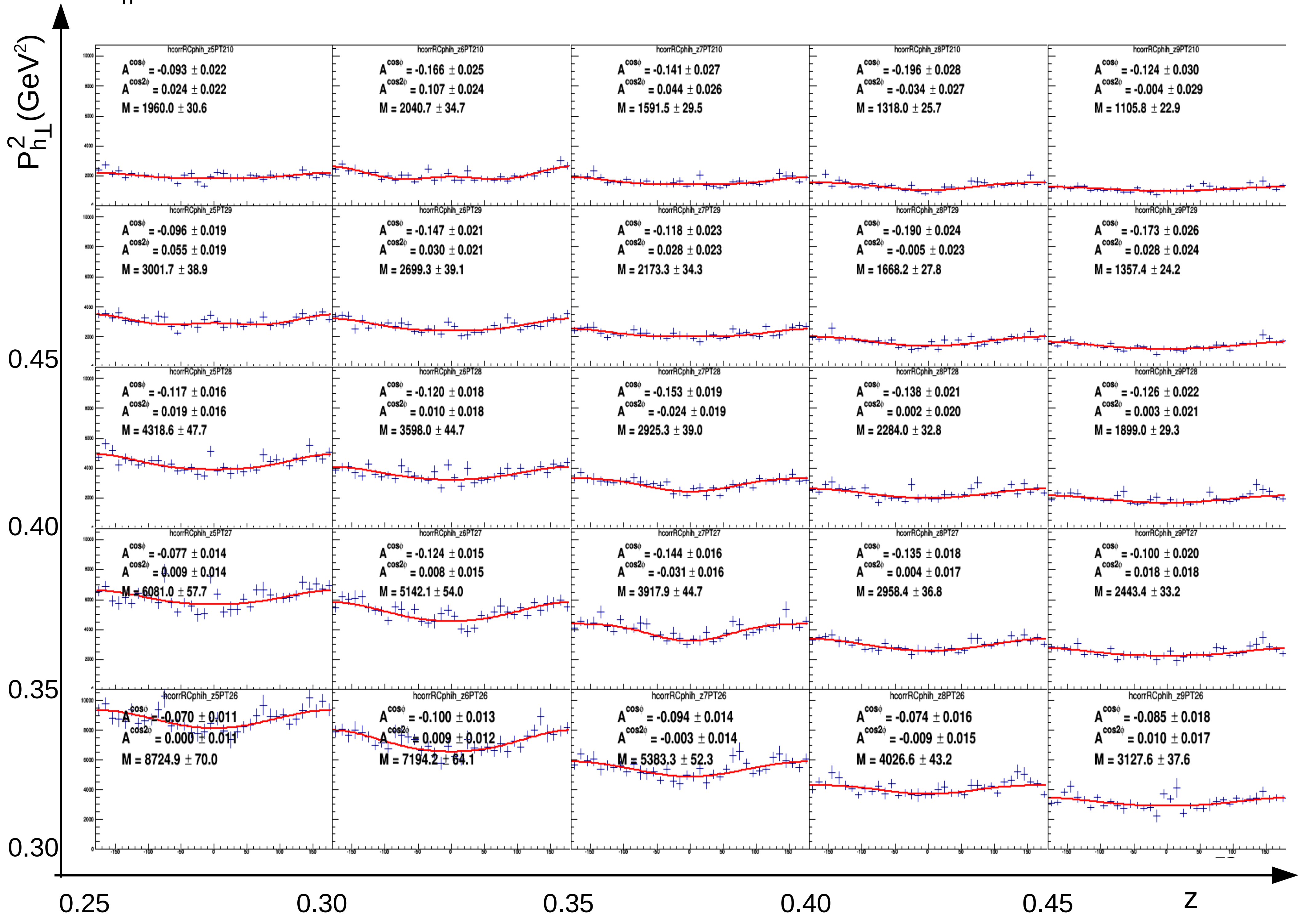


Figure 10.6: Systematic errors on A_0 (left), $A_{UU}^{\cos\phi_h}$ (middle), and $A_{UU}^{\cos 2\phi_h}$ (right) for each source for a representitive bin for the $\pi+$ channel. The first 13 sources are summarized in table 10.1, the 14th source is sector dependence. This kinematic bin is the high Q^2 bin of $0.2 < x < 0.3$, $0.35 < z < 0.4$, and $0.35 < P_{h\perp}^2 < 0.4$ GeV^2.

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

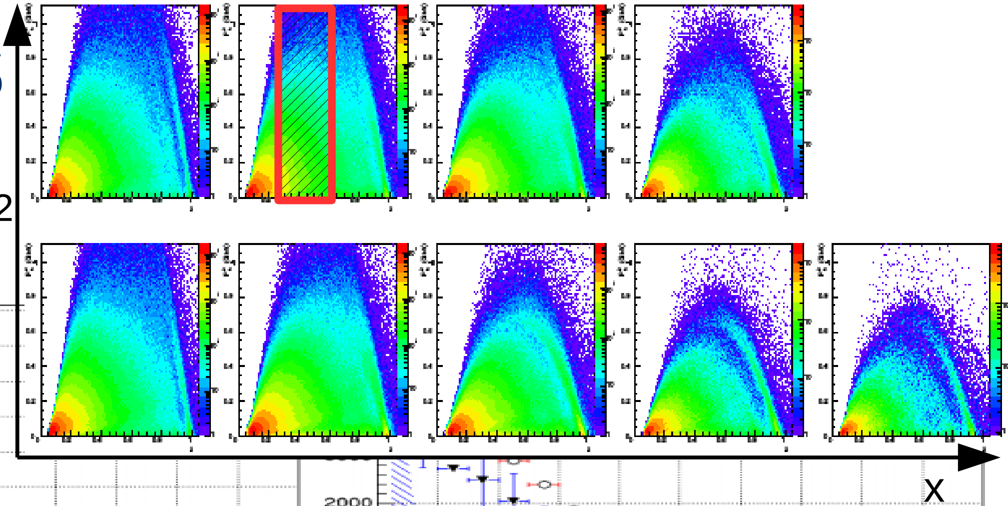


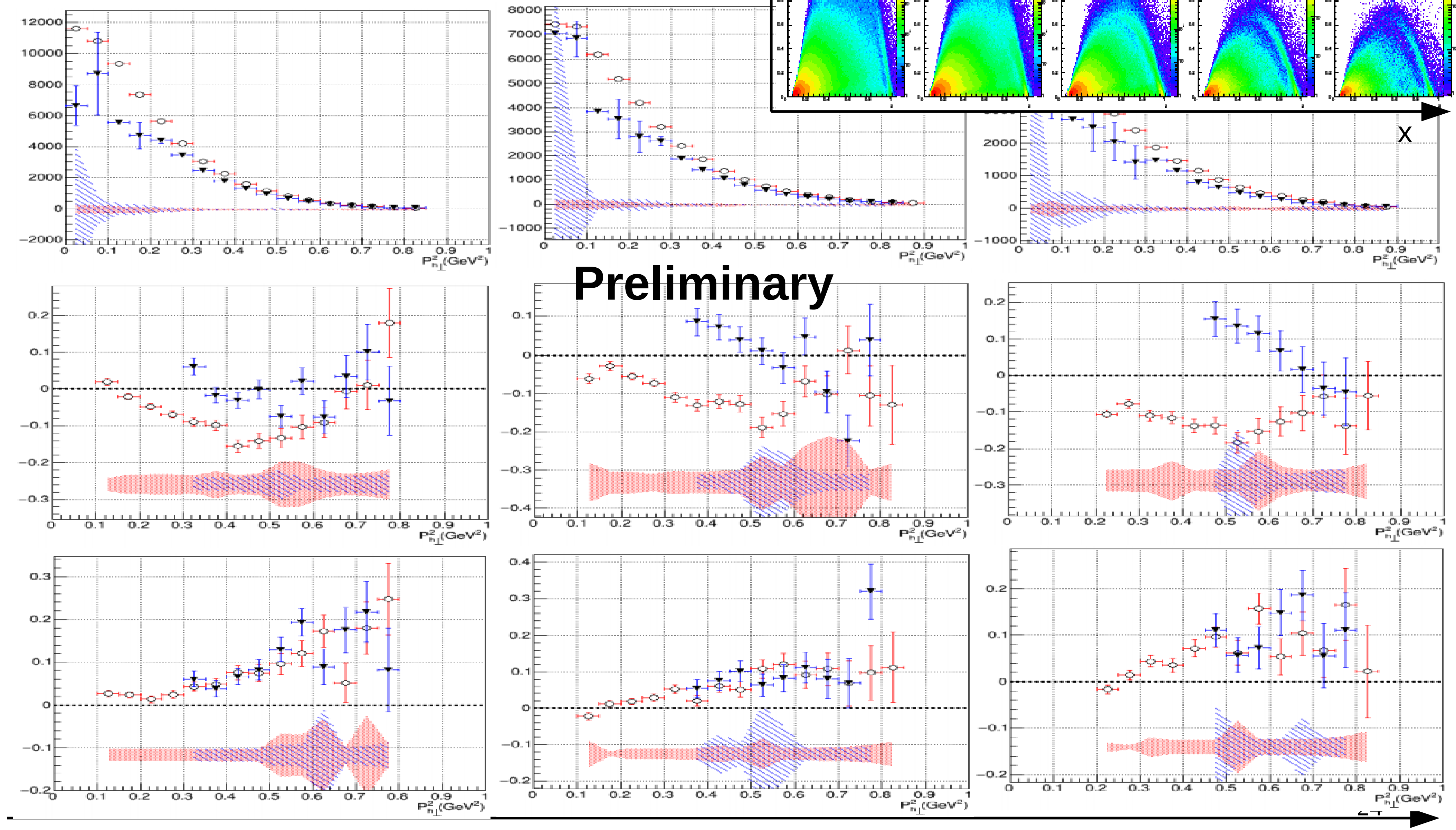
φ$_h$ distributions – acceptance and radiative corrected with fit results (lowest x-Q^2 bin)



Representative Results

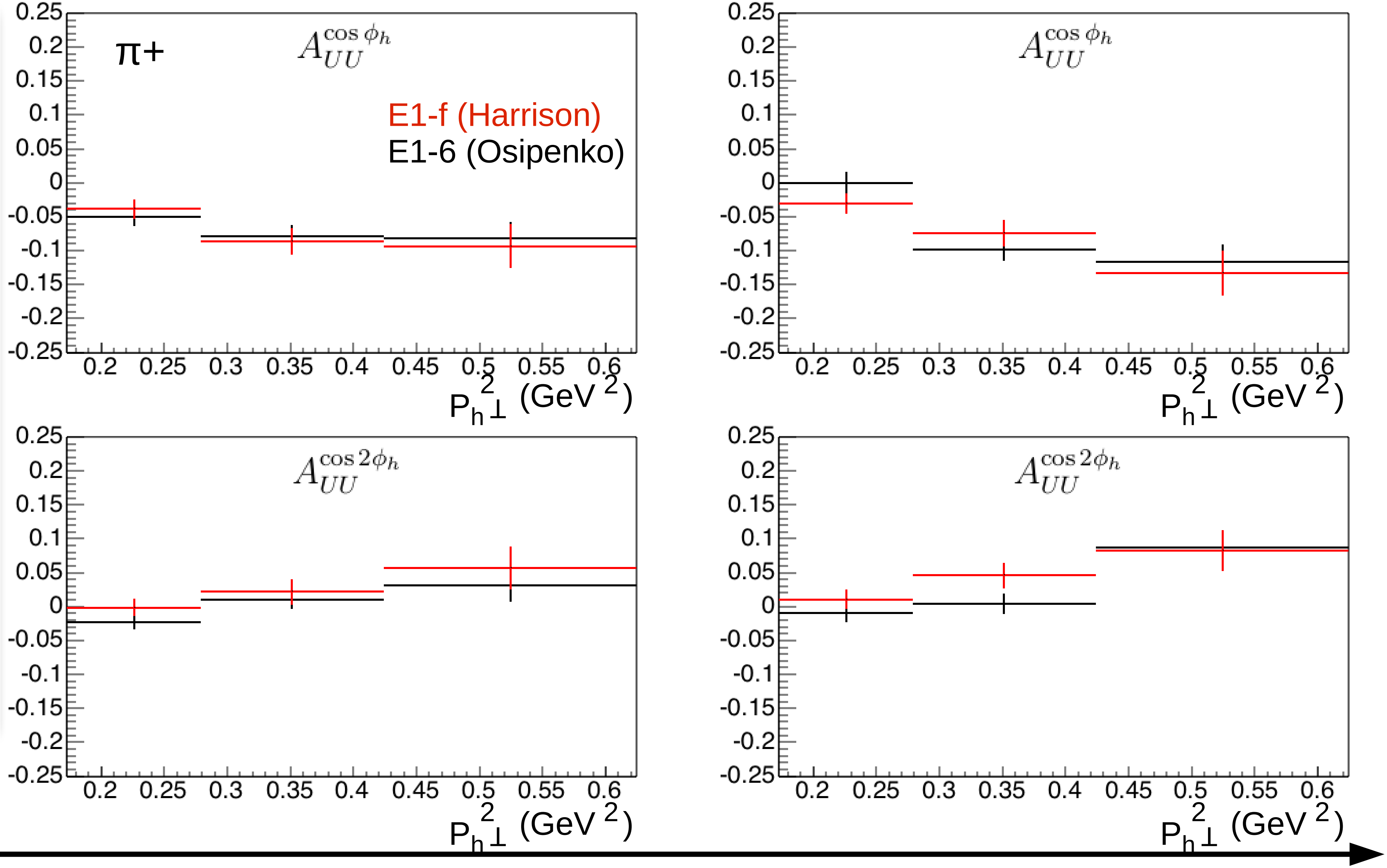
A_0 (top row), $A_{UU}^{\cos\phi_h}$ (middle row), and $A_{UU}^{\cos 2\phi_h}$ (bottom row) vs $P_{h\perp}^2$ for $\pi+$ and $\pi-$





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

Comparison with Other CLAS Data



0.29 0.32 0.35

(0.25 < x < 0.28, 1.9 < Q^2 < 2.2 GeV^2) z

Summary and Conclusions

- The constant term, $\cos\phi_h$ moment, and $\cos2\phi_h$ 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 $\cos\phi_h$ and $\cos2\phi_h$ modulations show a dependence on flavor which hints at a non-zero Boer-Mulders effect and could give insights into the quark orbital angular momentum contribution of the proton spin. Theoretical comparisons are in progress.

- Systematic errors have been studied and are comparable in size to statistical errors.

- Analysis note was recently approved by committee.

- A paper summarizing these results will be submitted soon to PRL.