Beam-spin asymmetry of Deeply Virtual Compton Scattering off the proton at 10.6 GeV with CLAS12 at Jefferson Lab

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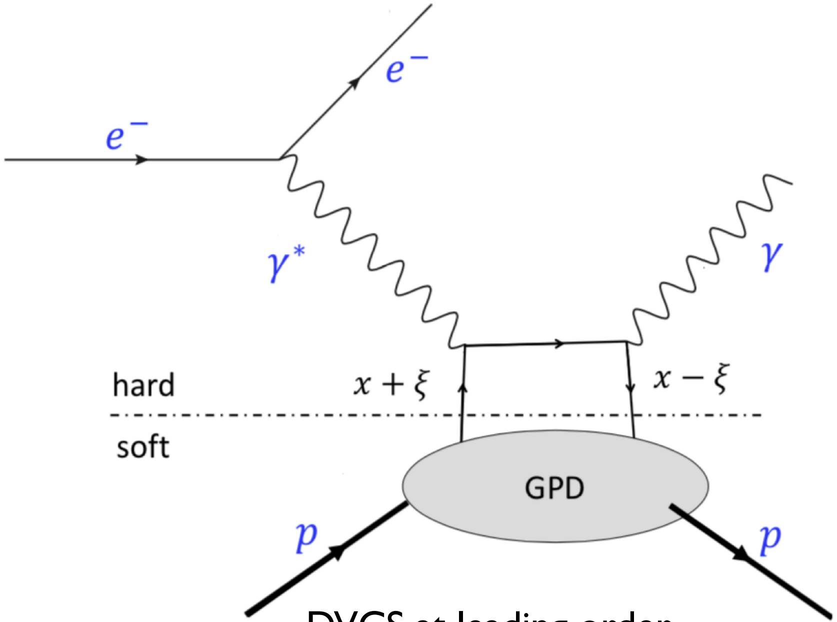
DVCS BSA to access GPDs

Deeply Virtual Compton Scattering

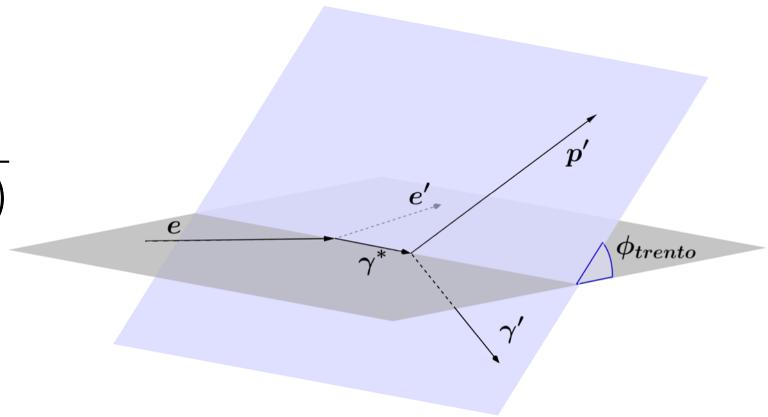
- Factorization:
  - hard scattering perturbative part
  - soft part parametrized by **Generalized Parton Distributions** inside Compton Form Factors



DVCS at leading order

DVCS Beam-spin asymmetry

- BSA: $$A_{LU} = \frac{d\sigma^{\uparrow} - d\sigma^{\downarrow}}{d\sigma^{\uparrow} + d\sigma^{\downarrow}}$$
- ϕ harmonic expansion of the amplitude
- First order BSA: $$A_{LU} \simeq \frac{A\sin(\phi_{trento})}{1 + B\cos(\phi_{trento})}$$
- Mainly sensitive to GPD H
  $A \propto \sim\Im m(\mathcal{H})$ and $B \propto \sim\Re e(\mathcal{H})$



DVCS Analysis Overview

Analysis steps:

- 0 - Pre-selection of events
- 1 - Kinematic binning
- 2 - Selection of exclusive DVCS events
- 3 - Background subtraction (π^0 electroproduction)
- 4 - Bin migration correction
- 5 - Estimation of uncertainties
- 6 - Results

Fall 2018 RG-A inbending 10.6 GeV data

but can be easily applied to the rest of data

0 - Pre-selection of events

0 - Pre-selection of events

Particles from event builder

- High energy **electron**
  $E_{electron} > 2\ GeV$
- High energy **photon**
  $E_{photon} > 2\ GeV$
- **Proton**

To deal with combinatorics:

- Remove events with more than 1 electron
- Selection of best proton and best photon candidates based their "distance" to an ideal DVCS event (using exclusivity variables)

Kinematic variables:

- Virtuality
  $Q^2 = -q^2 > 1\ GeV^2$
- Squared invariant mass of proton and photon
  $W^2 = (p+q)^2 > 4\ GeV^2$

1 - Kinematic binning

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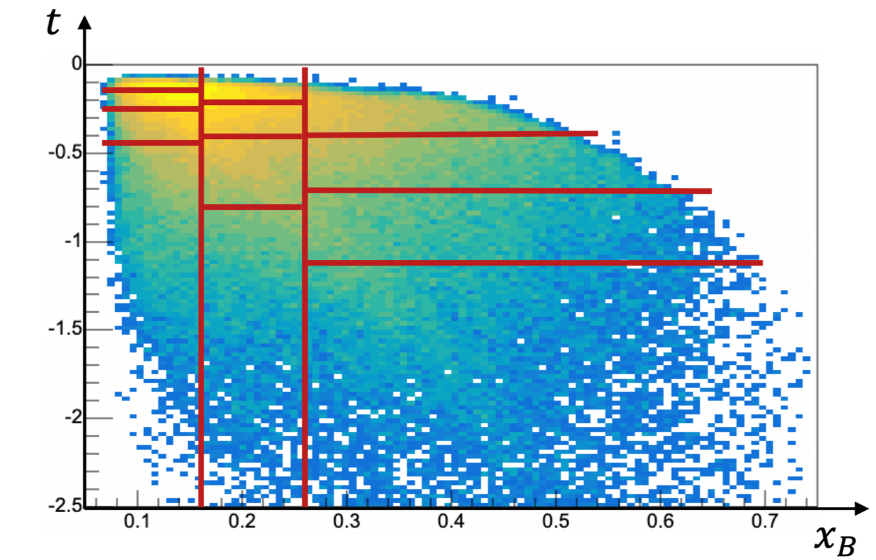
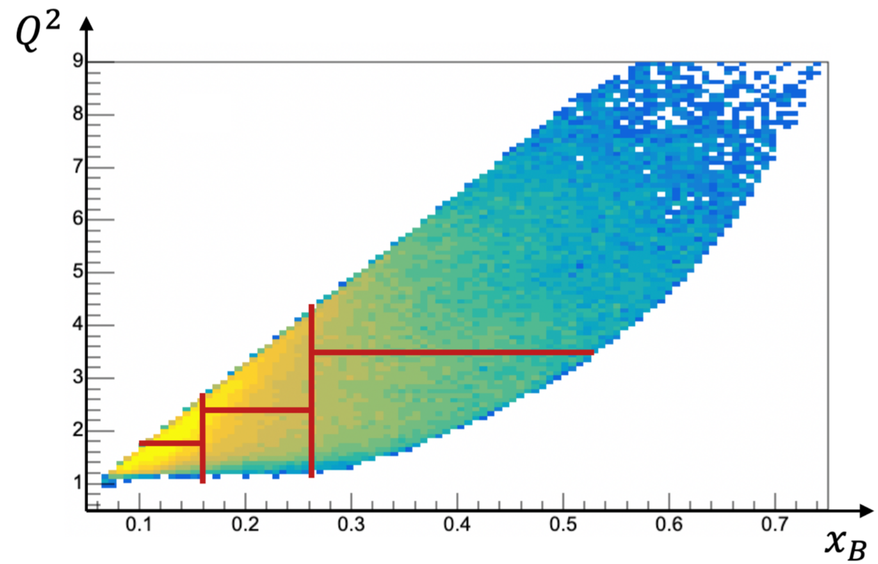
Choice of binning

- 4 t bins
- 3 x_B bins
- 2 Q^2 bins

} 24 bins

- 10 ϕ_{trento} bins





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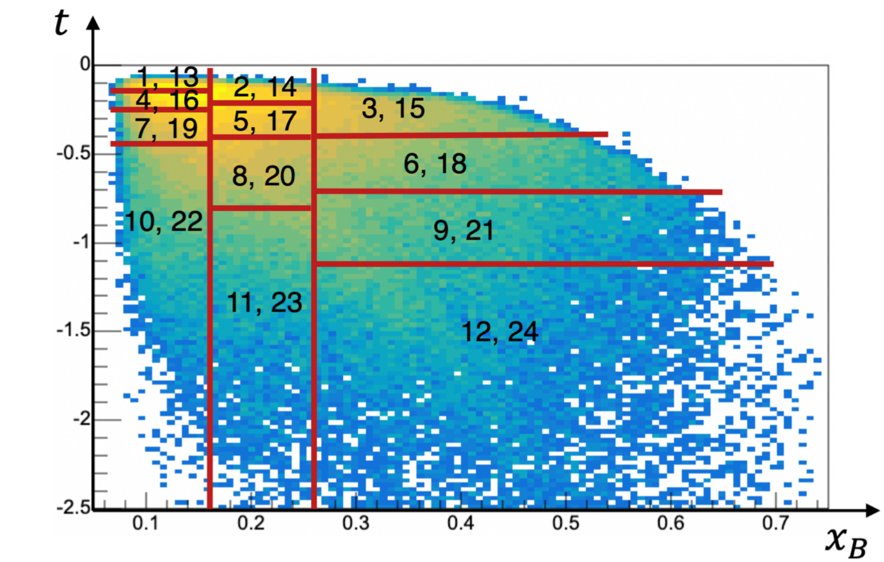
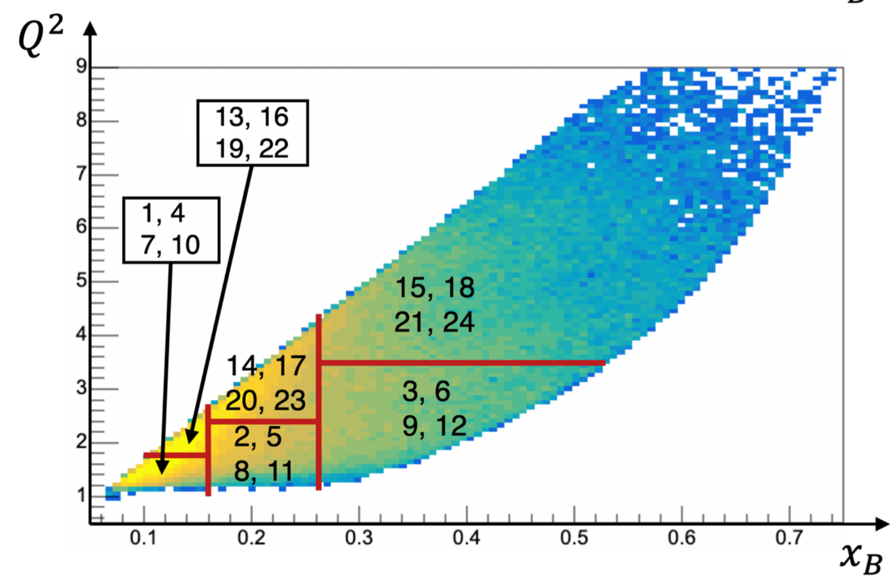
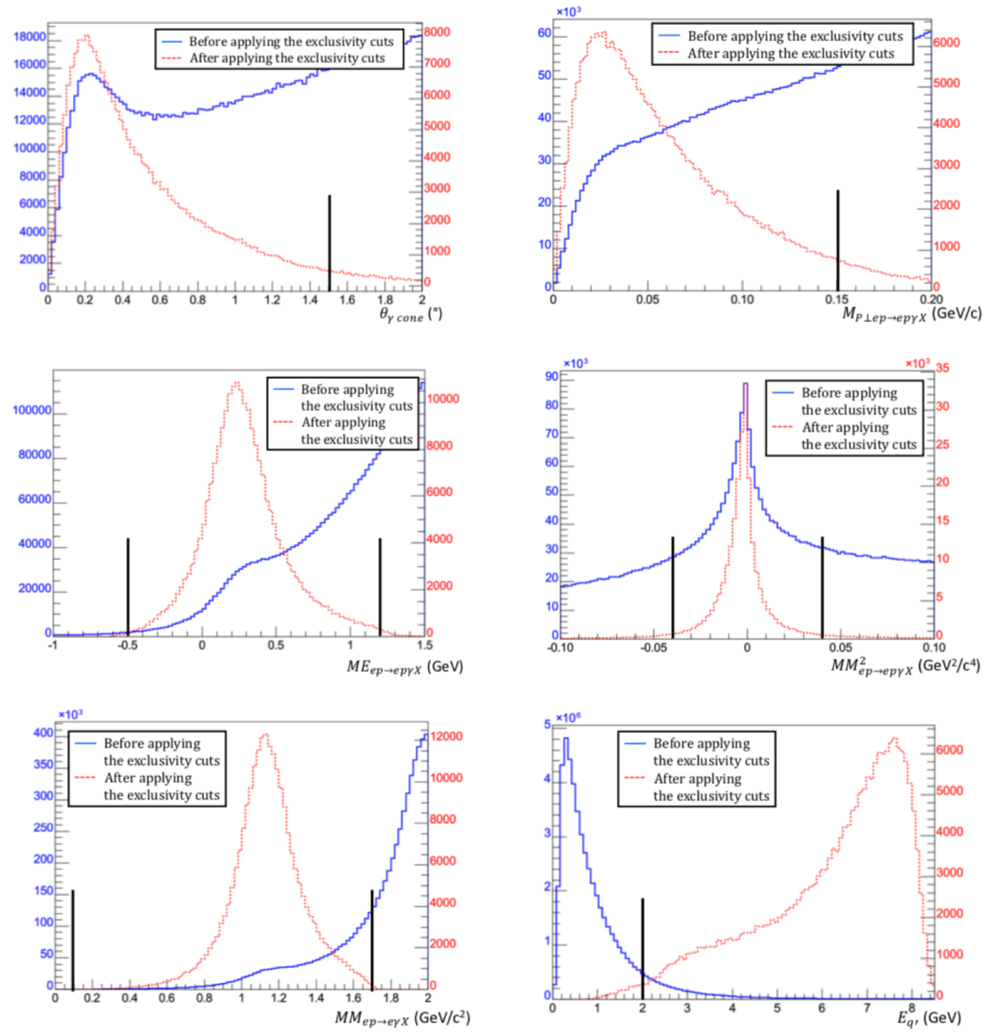




2 - Selection of exclusive DVCS events

2 - Selection of exclusive DVCS events

- **Photon cone angle** (angle between measured photon and exclusive missing photon)
- **Missing transverse momentum** $ep \to ep\gamma X$
- **Missing energy** $ep \to ep\gamma X$
- **Squared missing mass** $ep \to ep\gamma X$
- **Missing mass** $ep \to e\gamma X$
- **Photon energy**



2 - Selection of exclusive DVCS events

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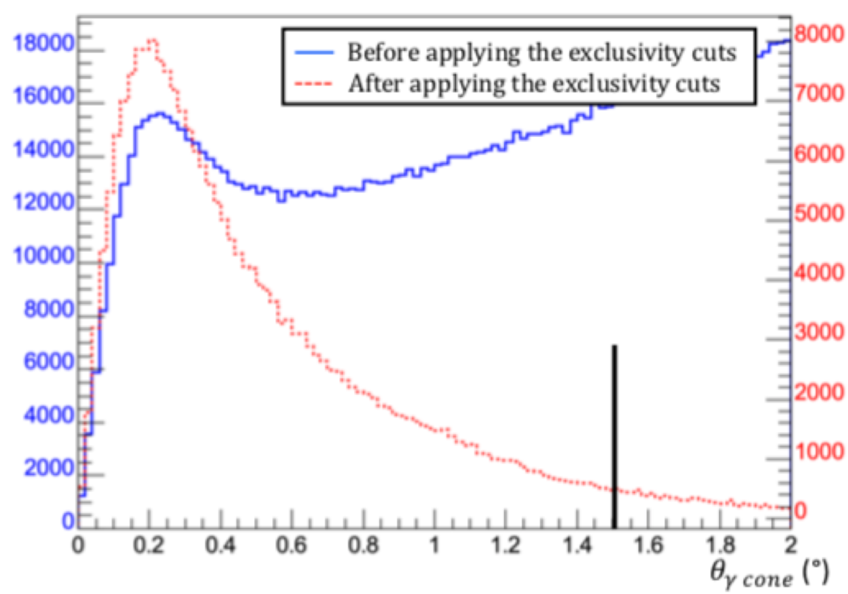
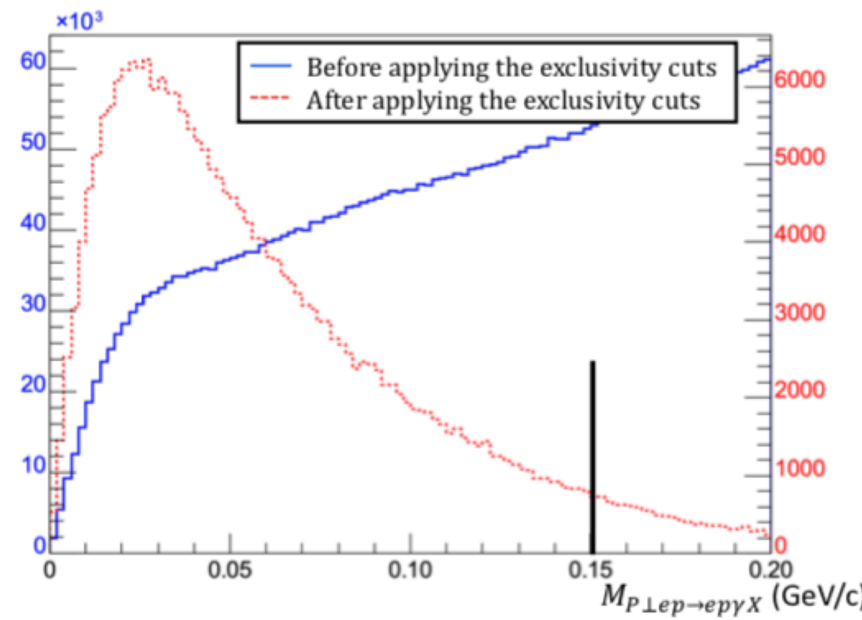
- **Photon cone angle**
  (angle between measured photon and exclusive missing photon)

$$\theta_{\gamma\, cone} < 1.5^\circ$$



- **Missing transverse momentum** $ep \to ep\gamma X$

$$M_{p_\perp\, ep\to ep\gamma X} < 0.15\ GeV/c$$



2 - Selection of exclusive DVCS events

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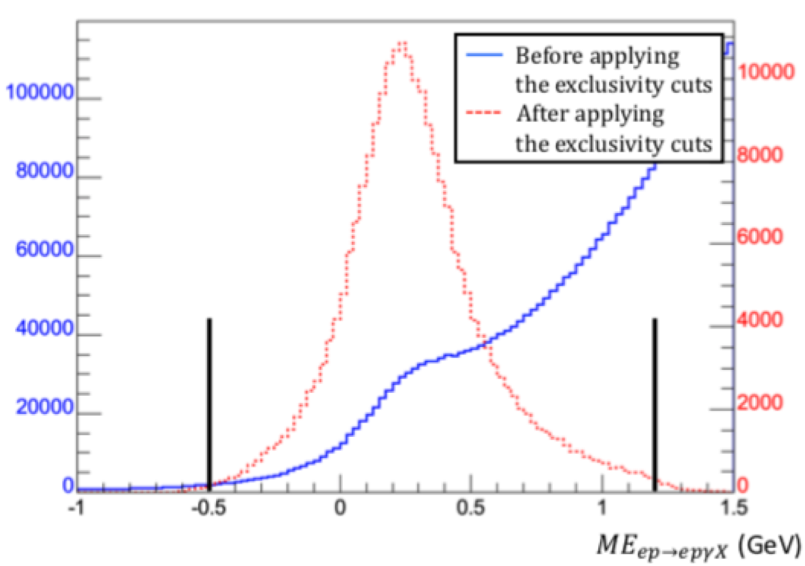
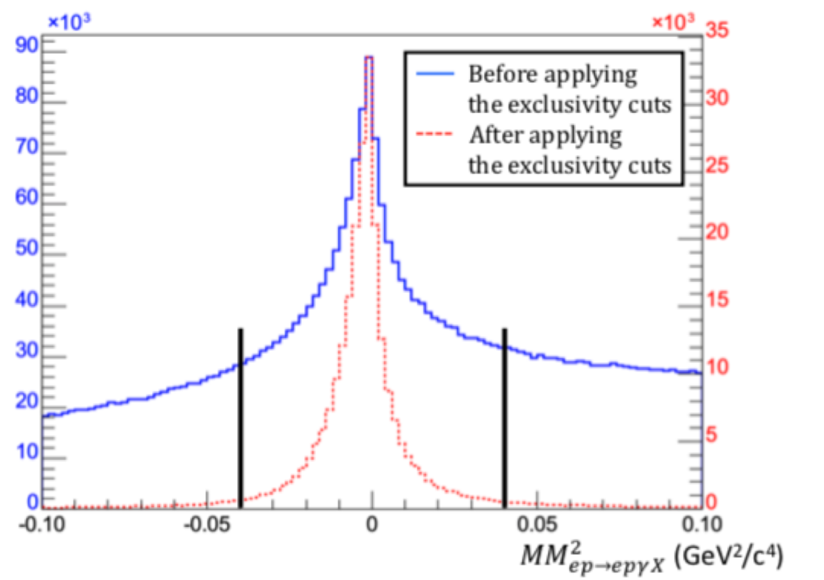
- **Missing energy** $ep \rightarrow ep\gamma X$

$$-0.5\ GeV \ < \ ME_{ep\rightarrow ep\gamma X} \ < \ 1.2\ GeV$$



- **Squared missing mass** $ep \rightarrow ep\gamma X$

$$-0.04\ GeV^2/c^4 \ < \ MM^2_{ep\rightarrow ep\gamma X} \ < \ 0.04\ GeV^2/c^4$$



2 - Selection of exclusive DVCS events

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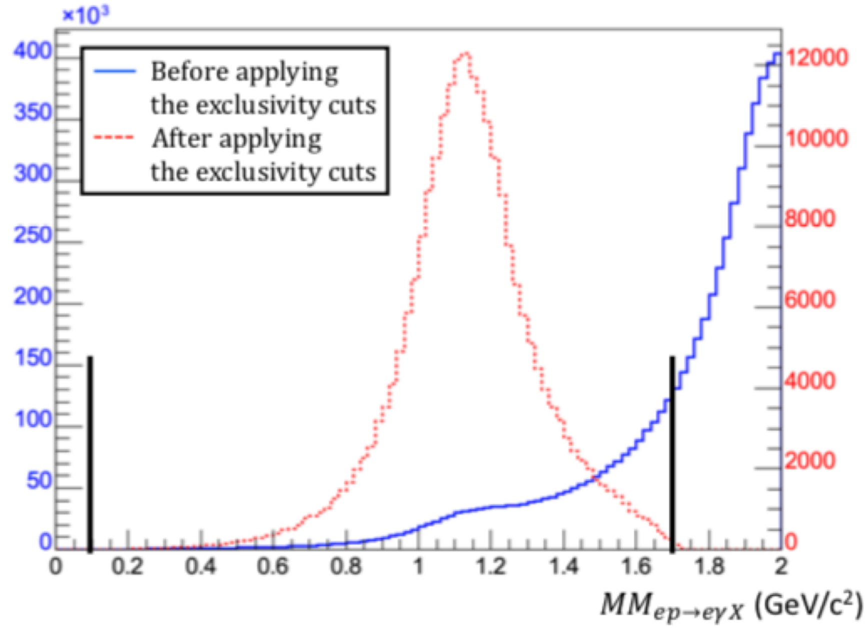
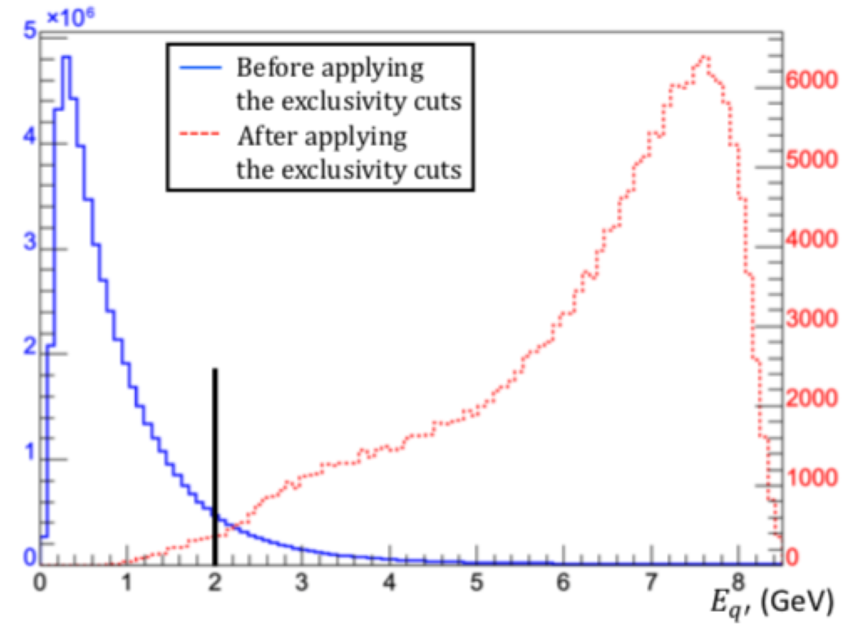
- **Missing mass** $ep \rightarrow e\gamma X$

$$0.1\ GeV/c^2 < MM_{ep\rightarrow e\gamma X} < 1.7\ GeV/c^2$$



- **Photon energy**

$$E'_q > 2\ GeV$$



2 - Selection of exclusive DVCS events

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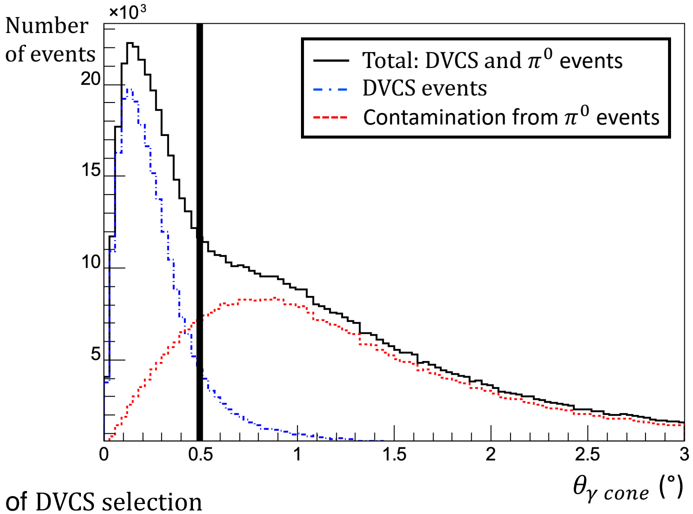
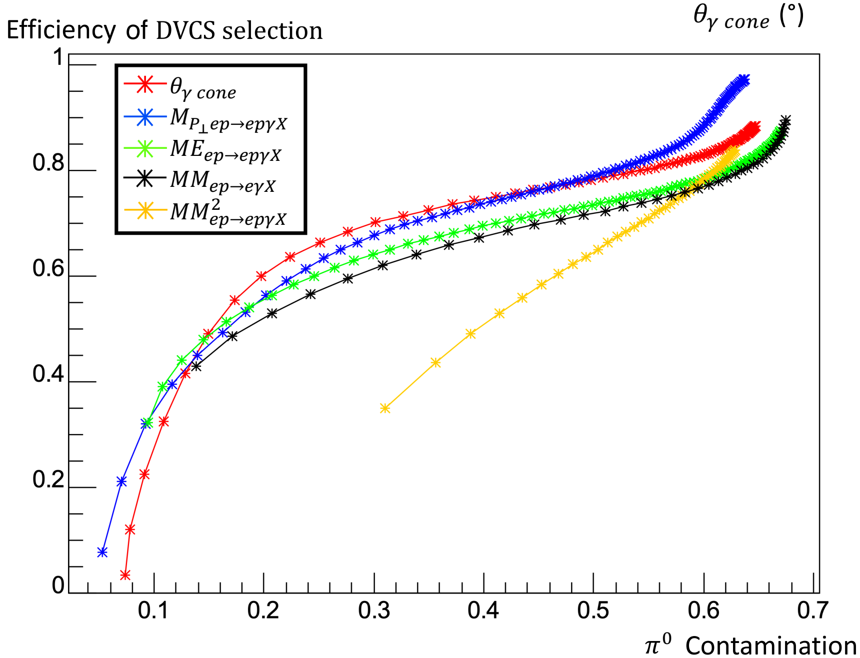
Optimization of the DVCS exclusivity selection based on the contamination

- **Identify the most discriminating variables in a DVCS + π^0 simulation**
- Optimize the position of the cut to minimize the statistical uncertainty DVCS + π^0
- Adapt the position of the cuts from simulation to “data” based on the resolution





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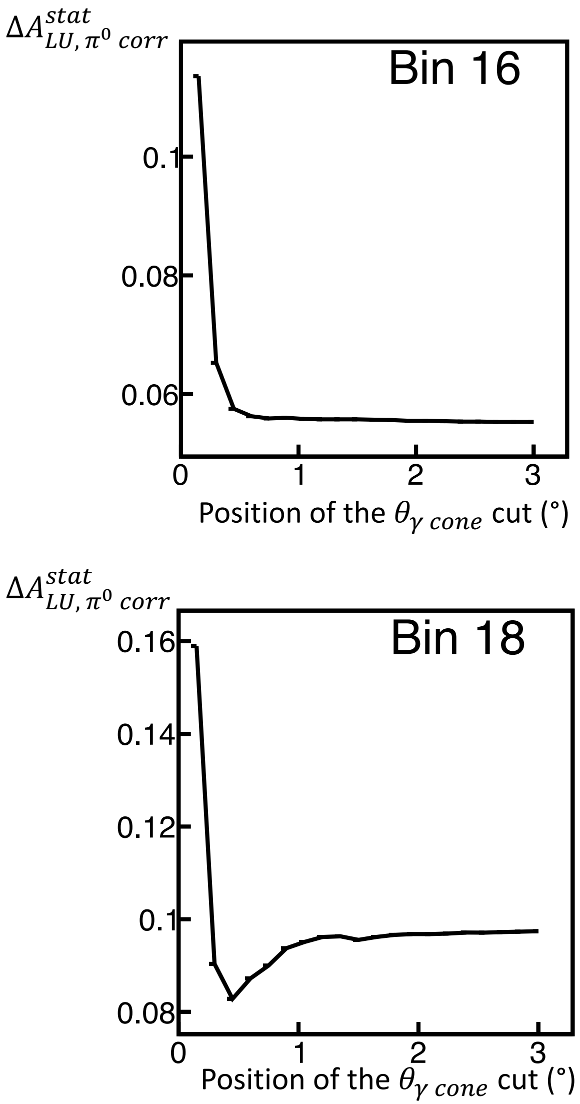

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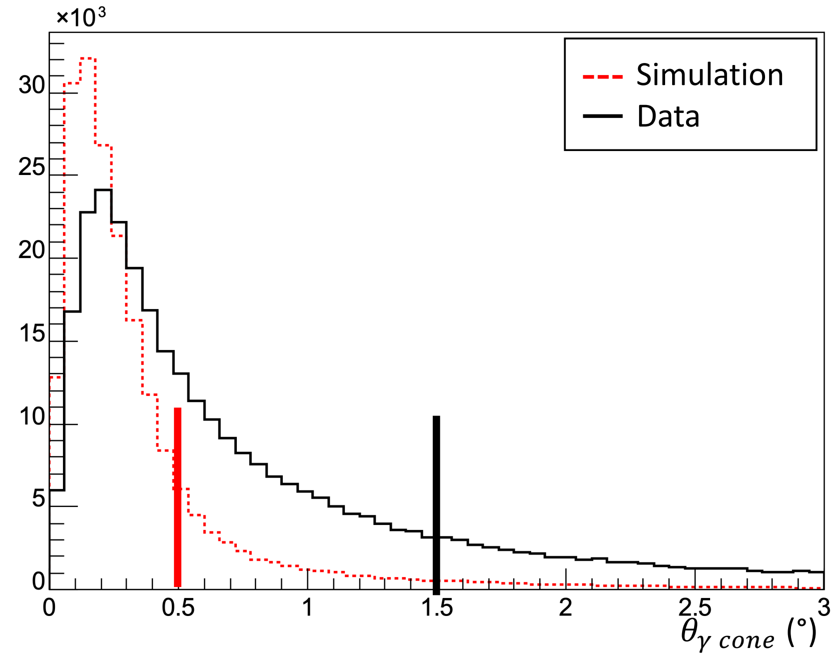


First look at beam-spin asymmetry

Raw asymmetry after DVCS selection (no background subtraction):

BSA for each bin:

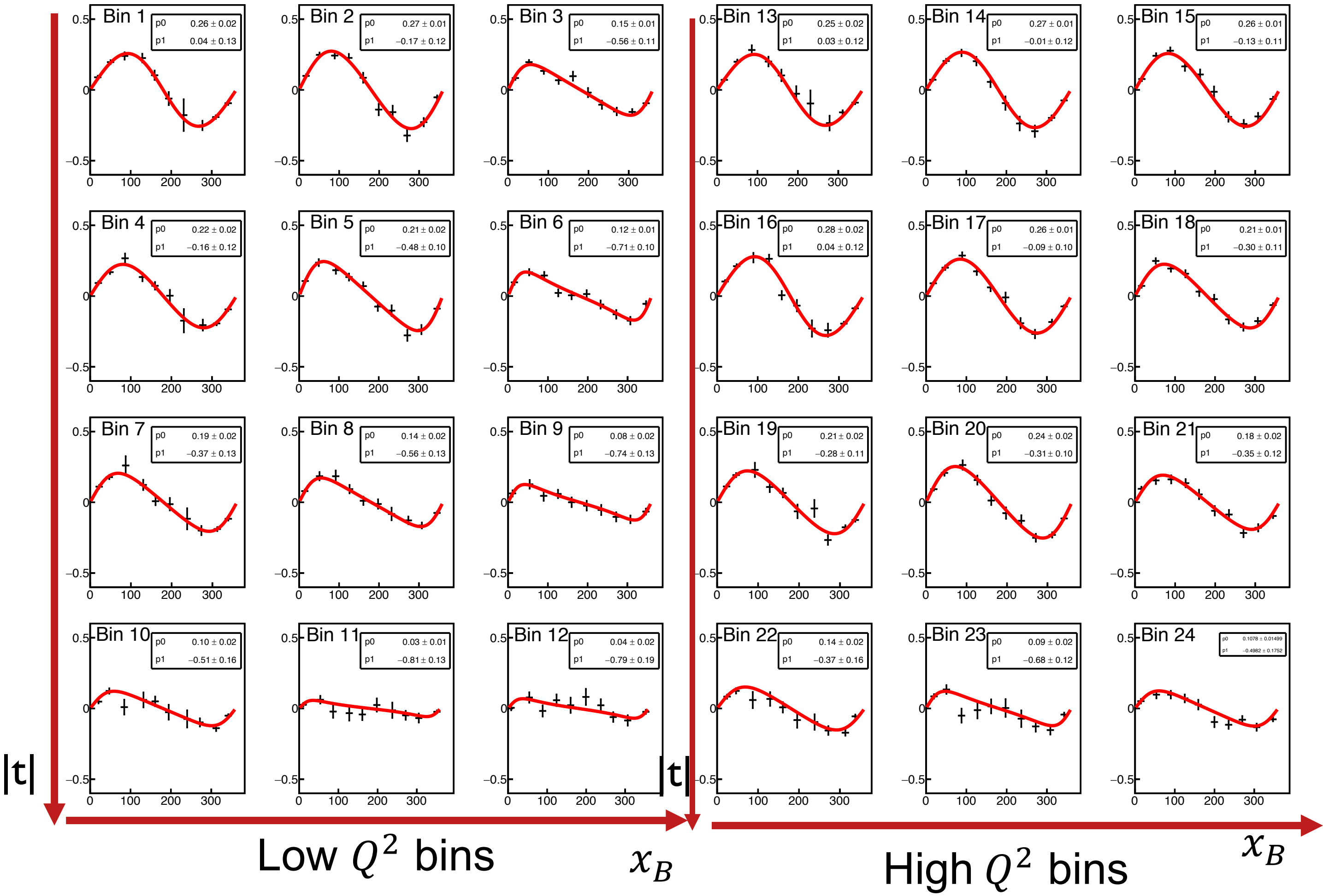
$$A_{LU} = \frac{1}{P}\frac{N^{+} - N^{-}}{N^{+} + N^{-}}$$

P Polarization
$N^{\pm}$ number of DVCS events with helicity $\pm$

Statistical uncertainties only

Fit function:

$$\frac{A \sin\varphi}{1 + B\cos\varphi}$$



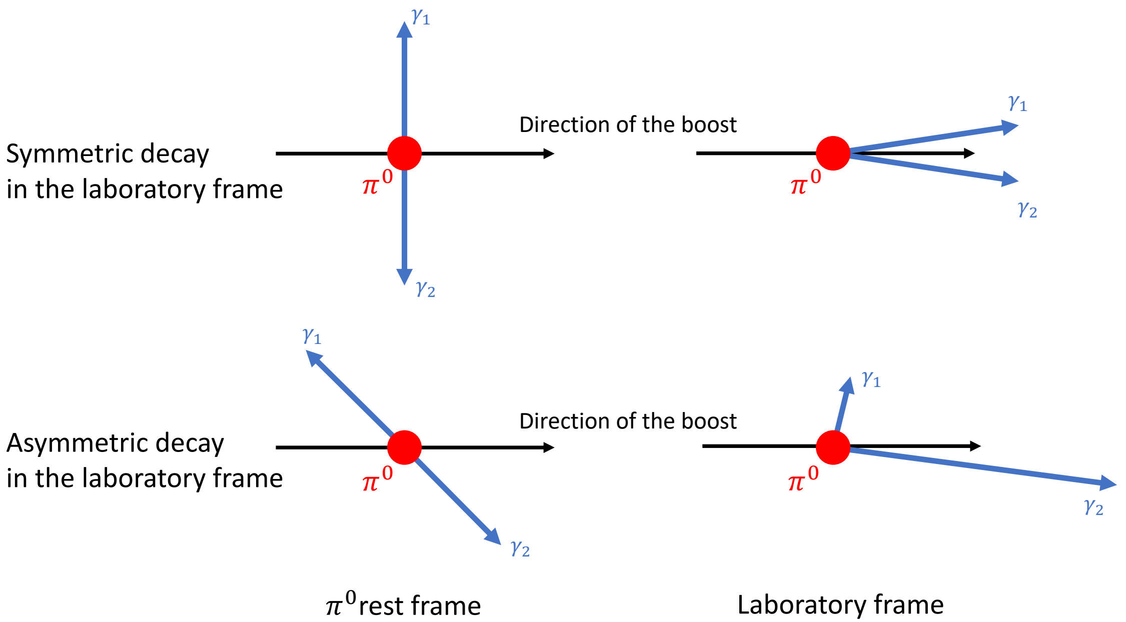
3 - Background subtraction (π^0)

3 - Background subtraction (π^0 electroproduction)

- π^0 electroproduction: $ep \rightarrow ep\pi^0$
- π^0decays very quickly into two photons (branching ratio ~ 99%):

$$ep \rightarrow ep\pi^0 \rightarrow ep\,\gamma\gamma$$

- Asymmetric π^0 decay:
  - mimics DVCS event
  - can pass DVCS exclusivity cuts



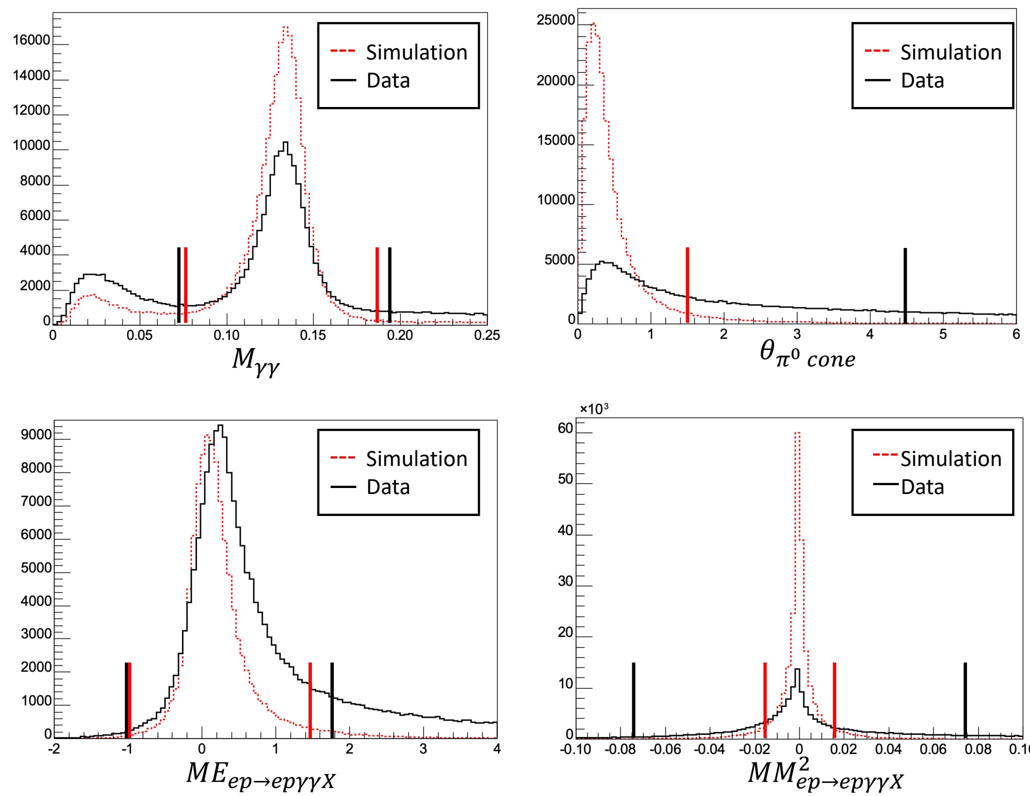
3 - Background subtraction (π^0)

3 - Background subtraction (π^0 electroproduction)

3.1 – Selection of π^0 electroproduction events

- **π^0 invariant mass**
  (mass of the two photons)
- **π^0 cone angle**
  (angle between measured π^0 (from the two photons and exclusive missing π^0)
- **Missing energy** $ep \to ep\gamma\gamma X$
- **Squared missing mass** $ep \to ep\gamma\gamma X$

Cuts based on the simulation and scaled in the data based on the resolution



After applying all other exclusivity cuts

3 - Background subtraction (π^0)

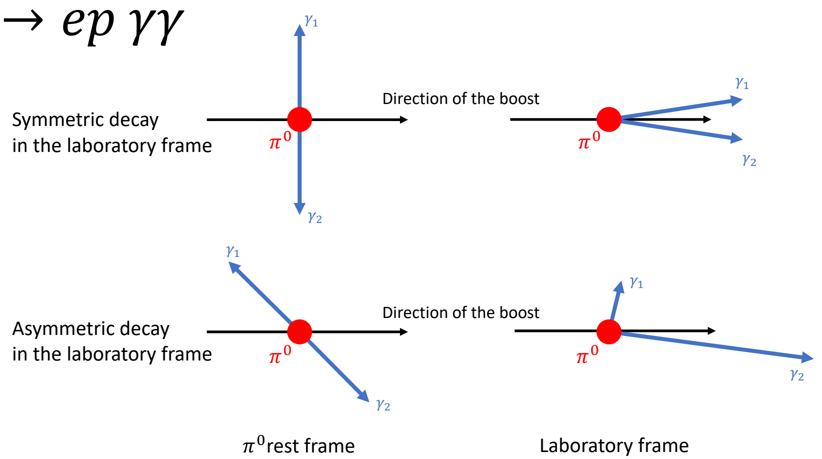
3 - Background subtraction (π^0 electroproduction)

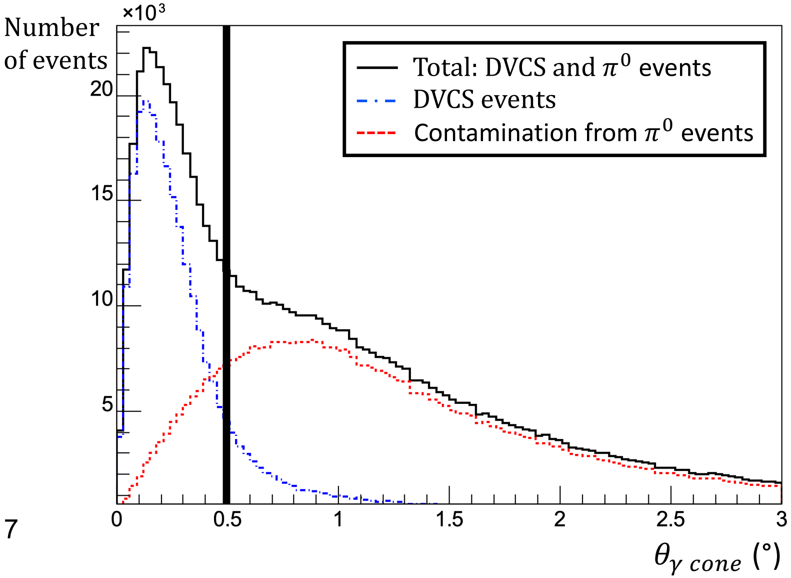
$$ep \rightarrow ep\pi^0 \rightarrow ep\,\gamma\gamma$$

- Asymmetric π^0 decay:
  - mimics DVCS event
  - can pass DVCS exclusivity cuts
  - **may not be identified as a π^0 event (if only one photon is reconstructed)**

→ Remaining π^0 background called **contamination**

→ **Not small**





3 - Background subtraction (π^0)

3 - Background subtraction (π^0 electroproduction)

$$ep \rightarrow ep\pi^0 \rightarrow ep\,\gamma\gamma$$

- Asymmetric π^0 decay:
  - can pass DVCS exclusivity cuts
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→ Remaining π^0 background called contamination
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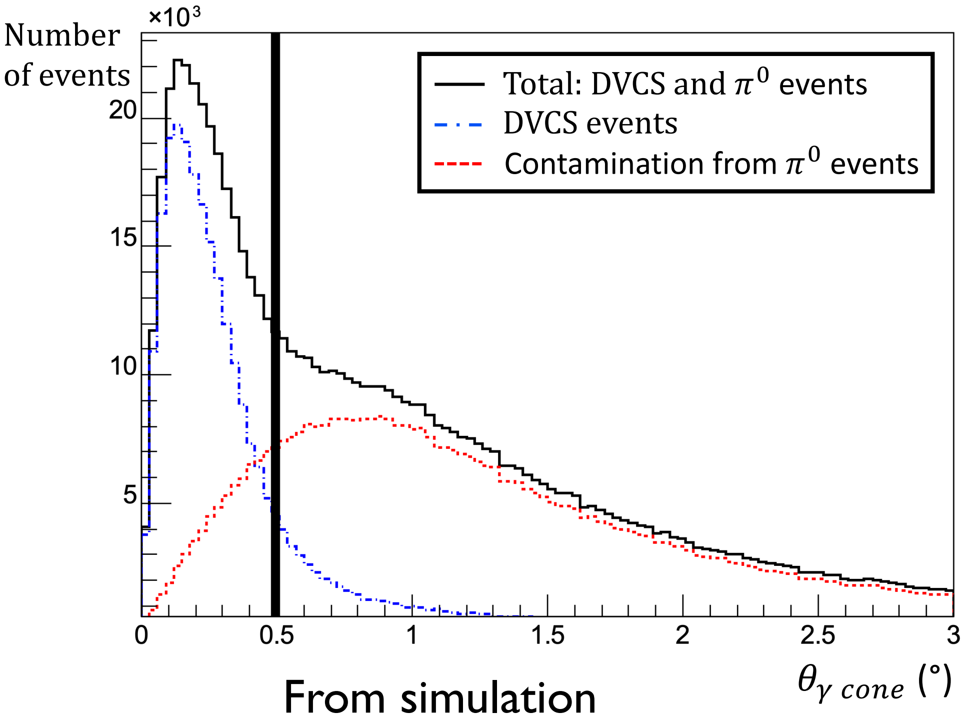


From simulation

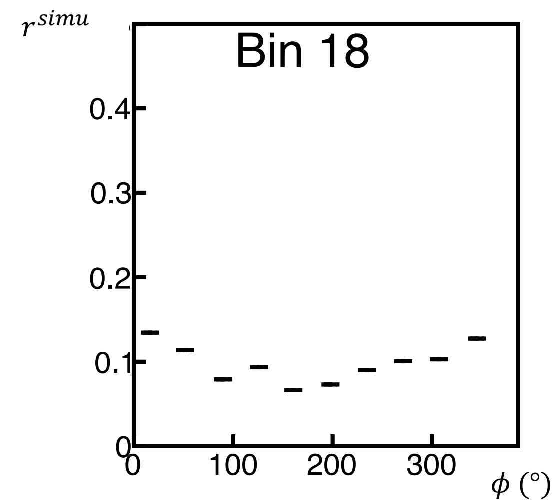
3 - Background subtraction (π^0)

3 - Background subtraction (π^0 electroproduction)

3.2 – Estimation of background

- π^0 contamination in a kinematic bin i: $$n_{\pi^0,\,cont}(i) = r(i)\; n_{\pi^0,\,id}(i)$$
- $r(i)$ is interpreted as the ratio between "size" of the phase space for π^0 decays detected as DVCS and for π^0 decays detected as π^0
- We assume that the simulation is good enough to have: $r(i) = r^{simu}(i)$
- In a π^0 simulation, we compute:

$$r^{simu}(i) = \frac{n^{simu}_{\pi^0,\,cont}(i)}{n^{simu}_{\pi^0,\,id}(i)}$$

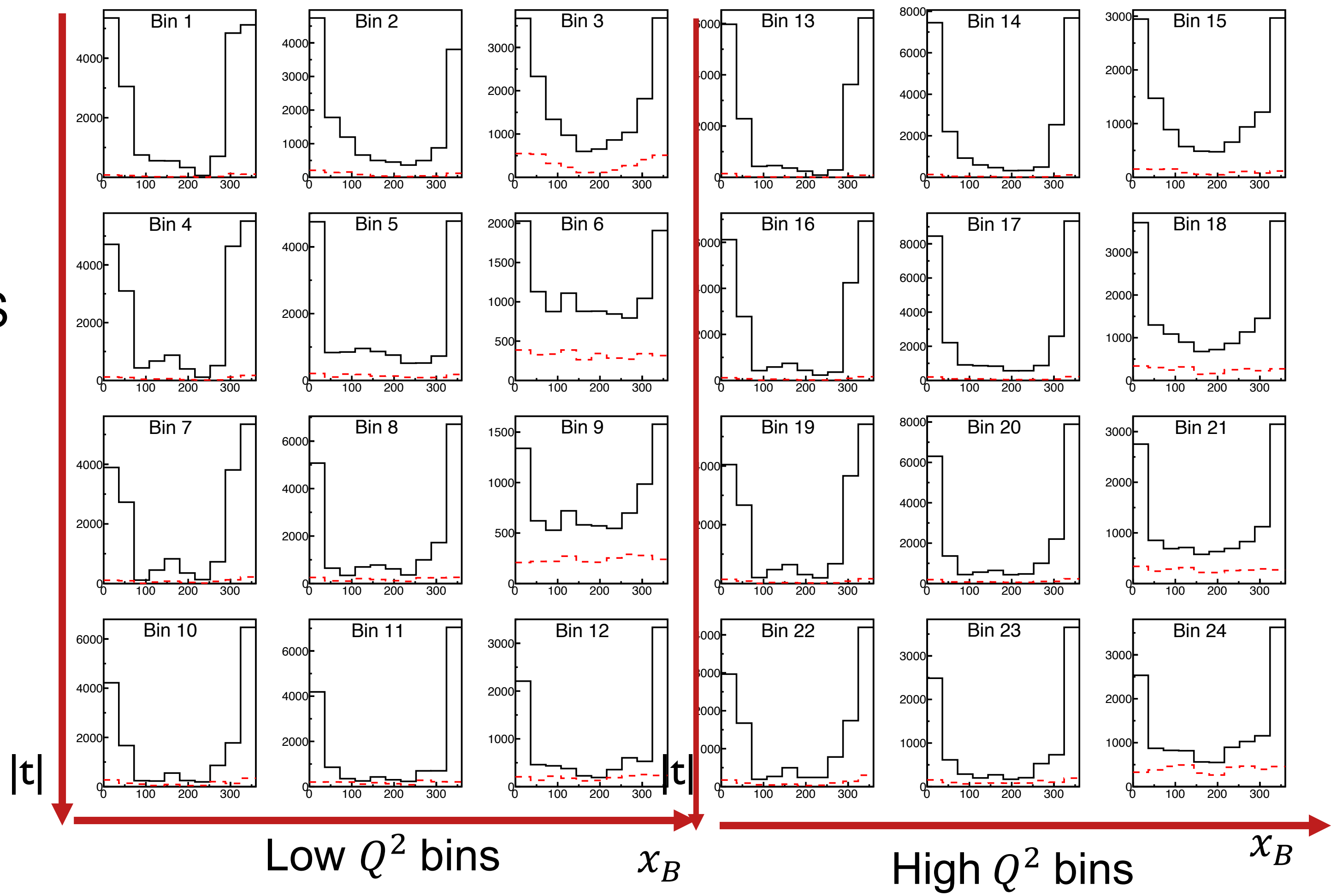


3 - Background subtraction (π^0)

3 - Background subtraction (π^0 electroproduction)

Black: total signal selected by DVCS exclusivity cuts

Red: estimated π^0 contamination



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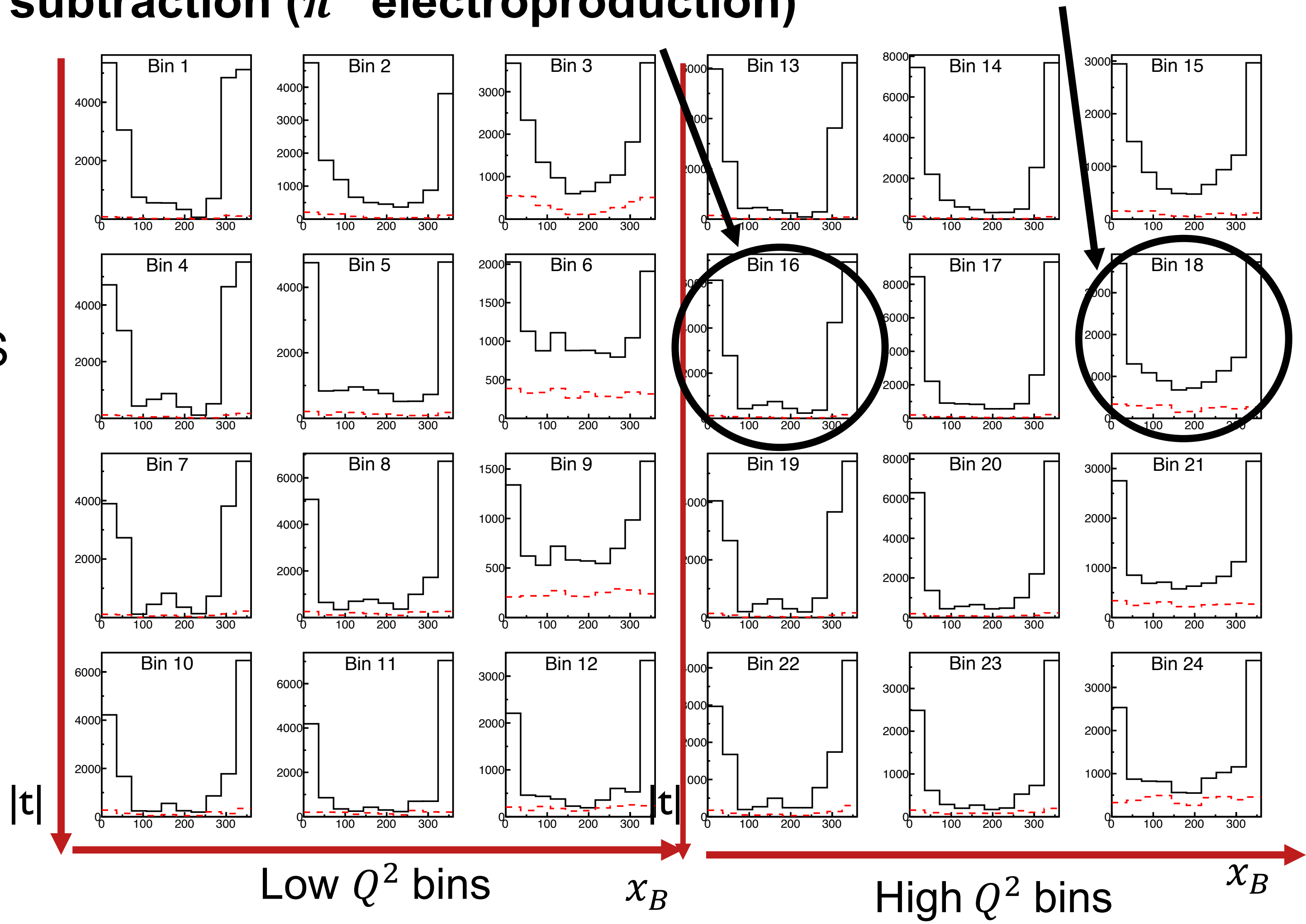

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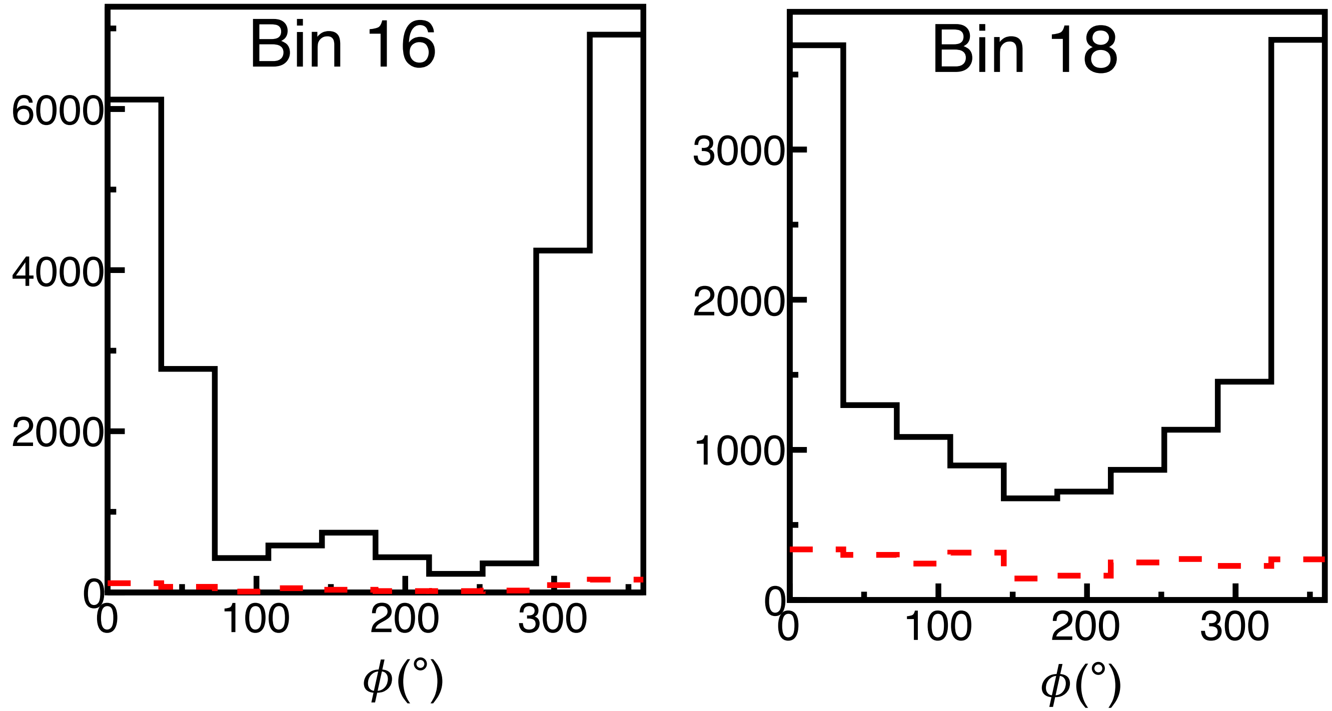


Low x_B

High x_B

3 - Background subtraction (π^0)

π^0 corrected asymmetry:

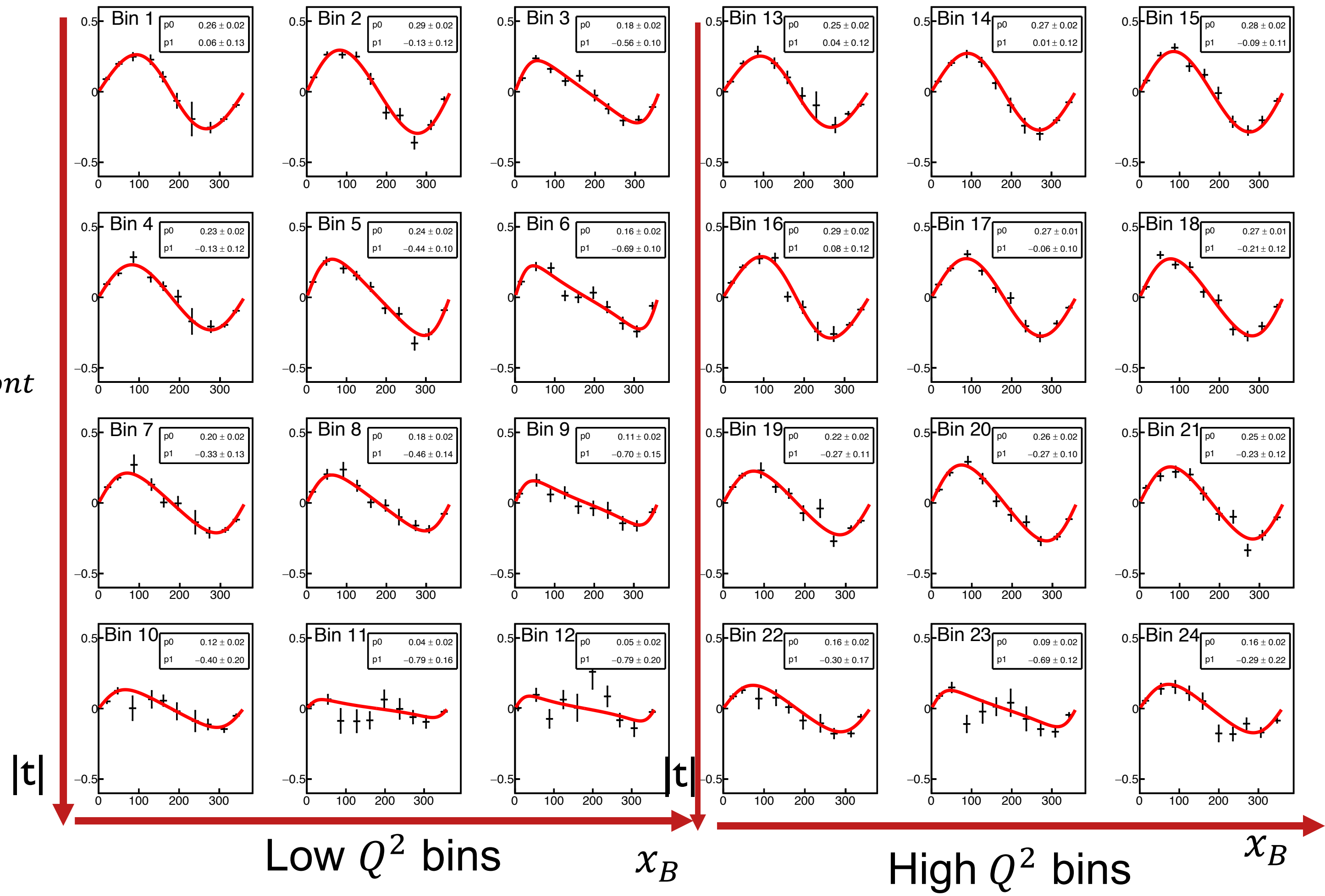
BSA for each bin:

$$A_{LU} = \frac{1}{P}\frac{N^+ - N^-}{N^+ + N^-}$$

P Polarization

$N^{\pm} = n^{\pm}_{DVCS,id} - n^{\pm}_{\pi^0,cont}$ corrected number of events with helicity $\pm$

Statistical uncertainties only



4 - Bin migration correction

4 - Bin migration correction

Correct for events that are generated in bin j but reconstructed in bin i

We note:

- $m_{j \to i}$ number of events generated in bin j but reconstructed in bin i
- $A_{corr}(j \to i)$ BSA of events from bin j but reconstructed in bin i
  $A_{corr}(i \to i)$= $A_{corr}(i)$ to simplify the notation
- $A_{\pi^0 corr}(i)$ BSA of all the events reconstructed in bin i (after π^0 correction)

We have:

$$A_{LU,\,\pi^0\,corr}(i) = m_{i \to i}\, A_{LU,\,corr}(i \to i) + \sum_{bin\ j \neq i} m_{j \to i}\, A_{LU,\,corr}(j \to i)$$

So:

$$A_{corr}(i) = \frac{A_{\pi^0\,corr}(i) - \sum_{bin\ j \neq i} m_{j \to i}\, A_{corr}(j \to i)}{m_{i \to i}}$$

4 - Bin migration correction

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Correct for events that are generated in bin j but reconstructed in bin i

$$A_{corr}(i) = \frac{A_{\pi^0\,corr}(i) - \sum_{bin\ j\neq i} m_{j\to i}\, A_{corr}(j\to i)}{m_{i\to i}}$$

We estimate $A_{corr}(i)$ with:

- $A_{corr}(j\to i)$ estimated by taking averaging $A_{\pi^0 corr}(i)$ and $A_{\pi^0 corr}(j)$ since this is, at the first order, the asymmetry of events coming from the edge of bin j

- $m_{j\to i}$ estimated from a simulation

4 - Bin migration correction

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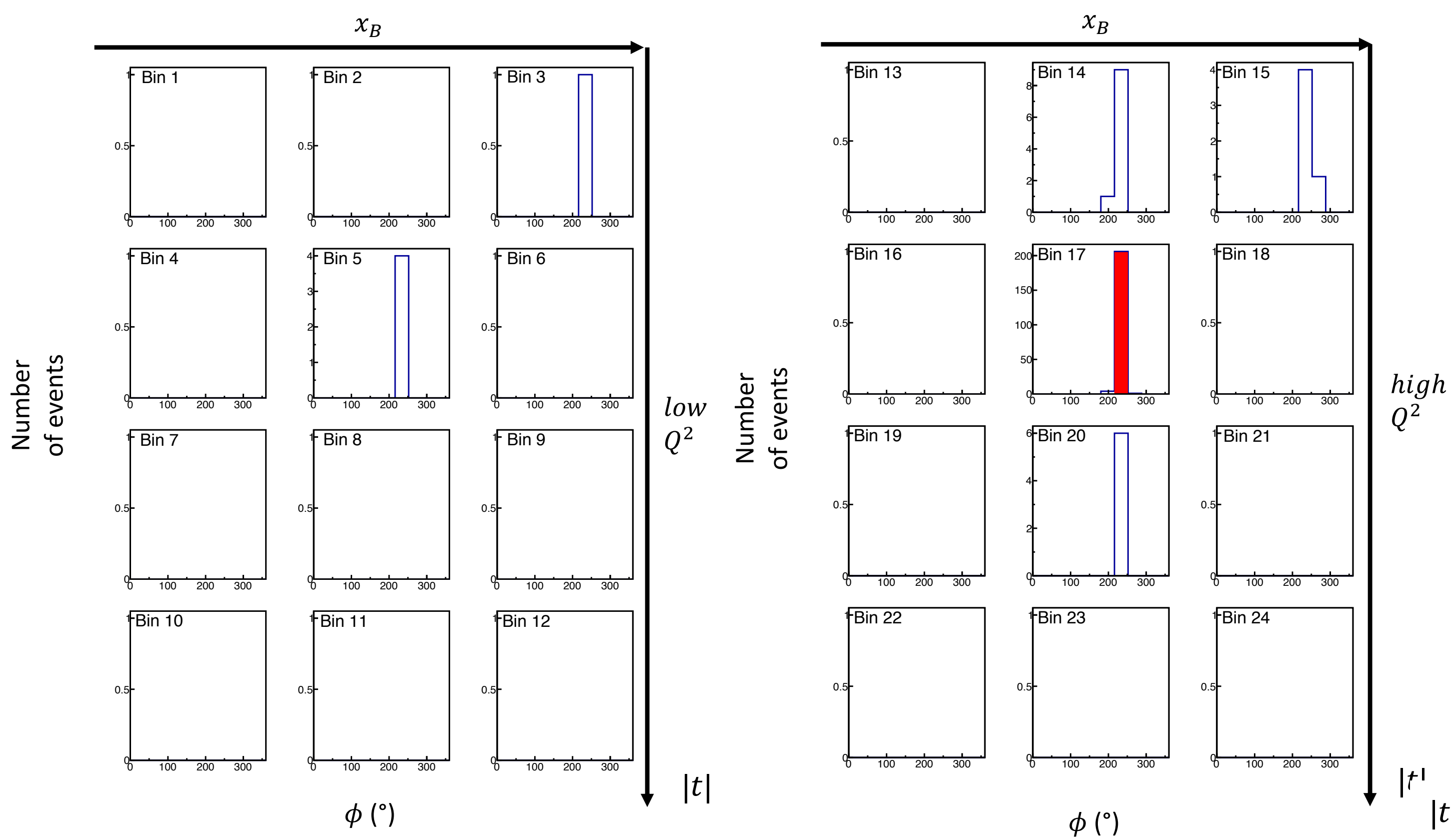
We estimate $A_{corr}(i)$ with:

- $m_{j \to i}$ estimated from a simulation



5 - Estimation of uncertainties

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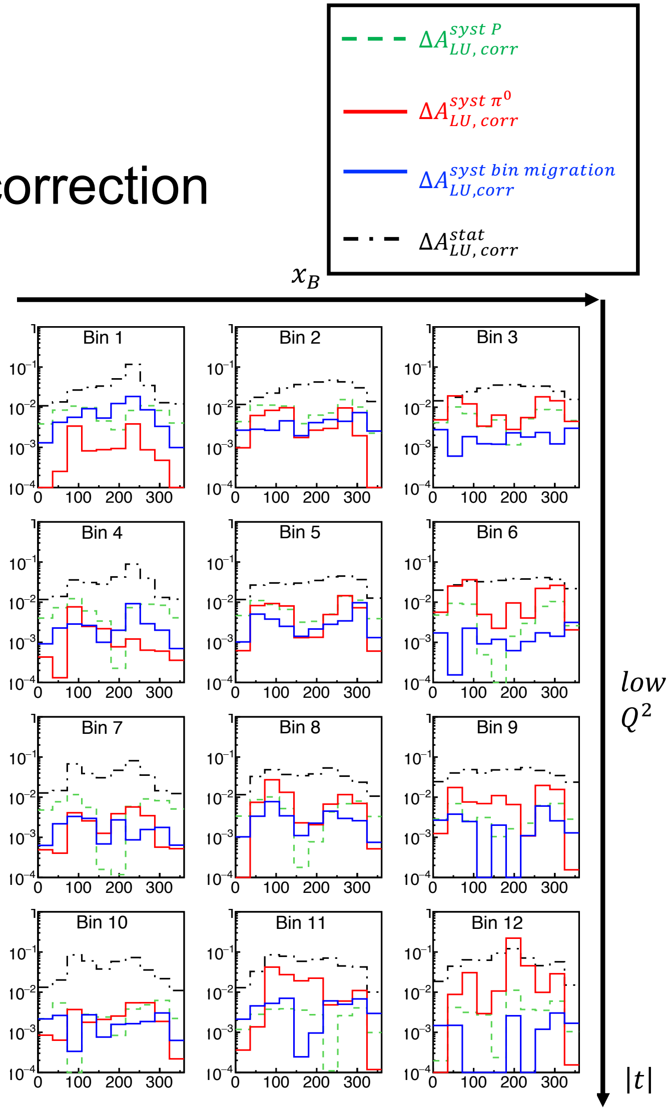
Statistical uncertainties propagated after the π^0 correction ~1 - 10%. (absolute uncertainty)

Systematic uncertainties associated with:

- π^0 subtraction: contamination fraction
  ~ 0.1 to 7%. (absolute uncertainty)

- Bin migration: estimation of the migration and asymmetries
  ~ 0.1 to 2%. (absolute uncertainty)

- Polarization: polarization measurement
  ~ 0.1 to 2%. (absolute uncertainty)



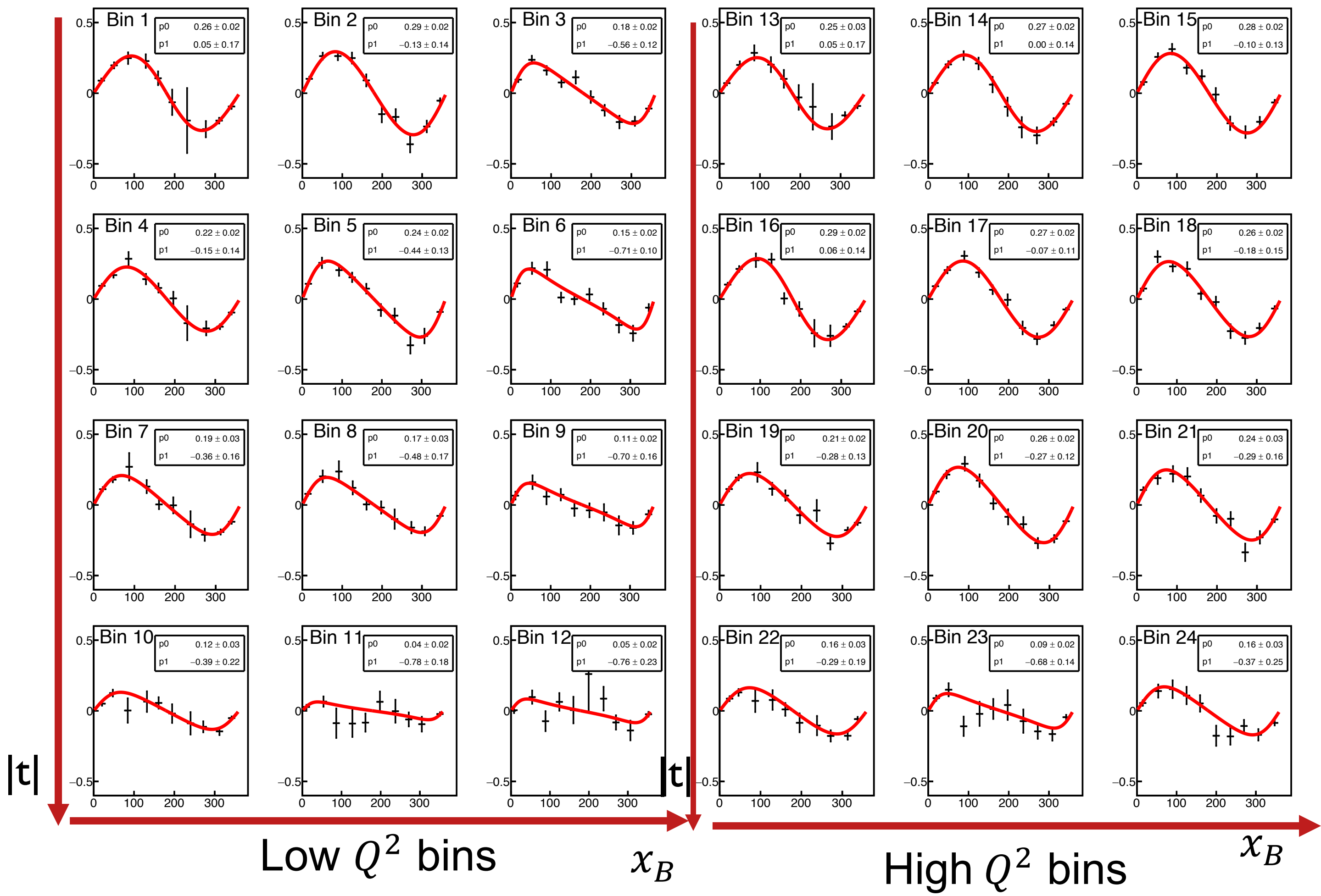
Results

Results

Statistical and systematic uncertainties added quadratically

Fit function:

$$\frac{A \sin\varphi}{1 + B\cos\varphi}$$

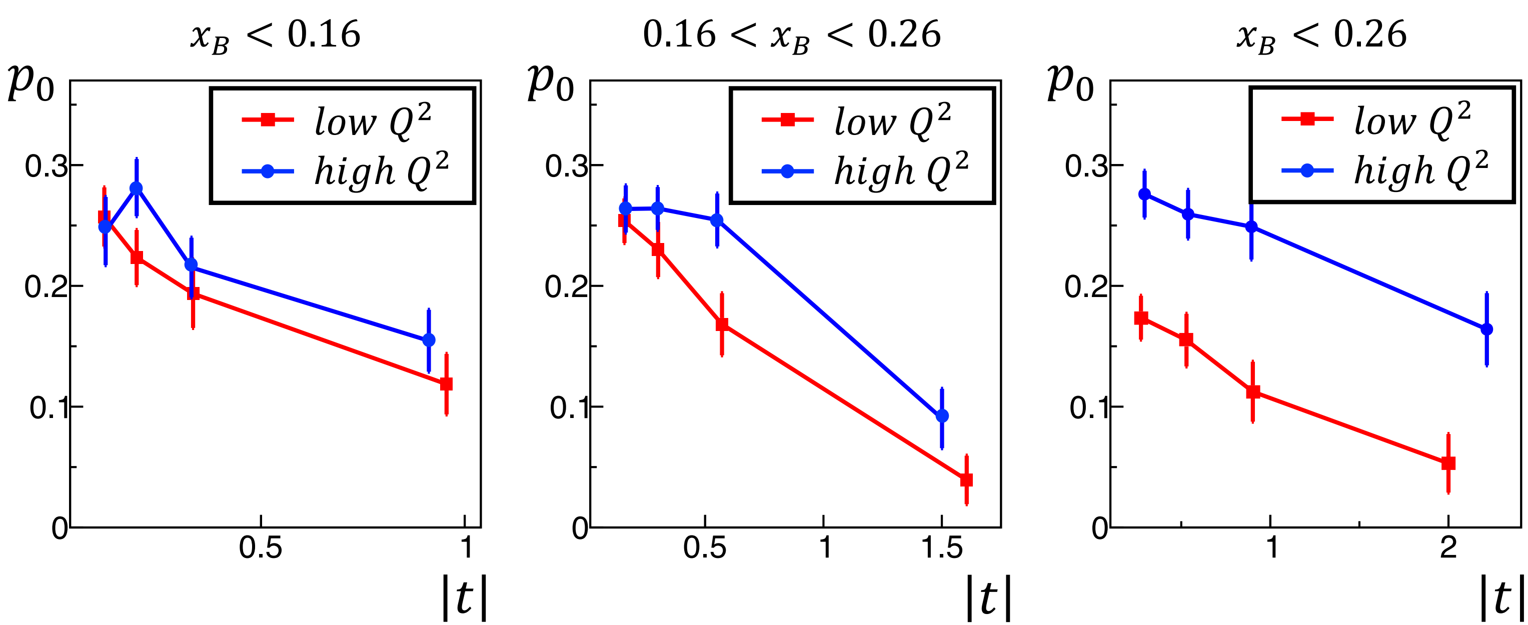


Results

Results

- Amplitude decreases with $|t|$
- Amplitude increases with Q^2

Careful with binning effects (difficult to provide 1-dimensional information)

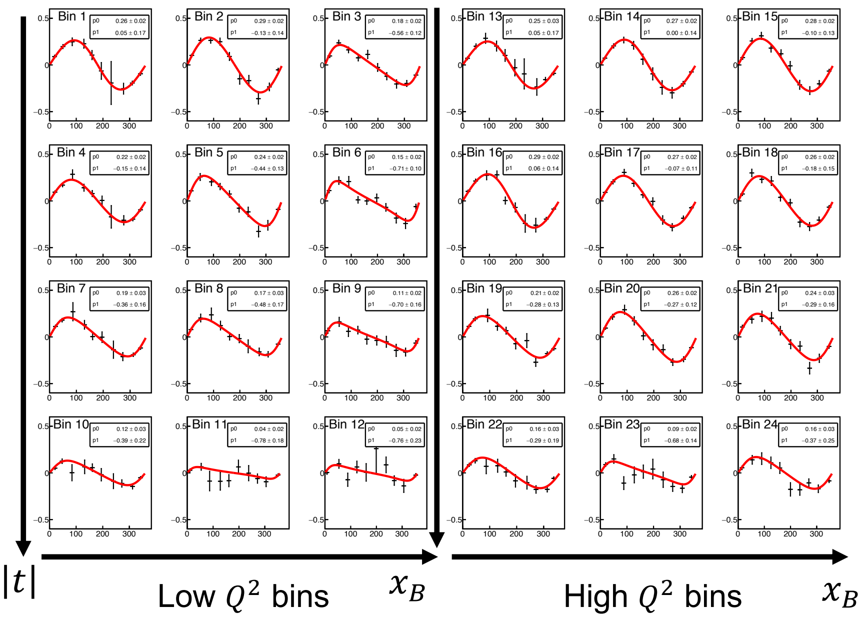


Summary and outlook

- Beam-spin asymmetry off the proton at 10.6 GeV

- Refinement of the π^0 correction still ongoing, mainly by Maxime Defurne (CEA Saclay):
  - Understanding of calorimeters and photon reconstruction
  - Comparison with other π^0 subtraction methods

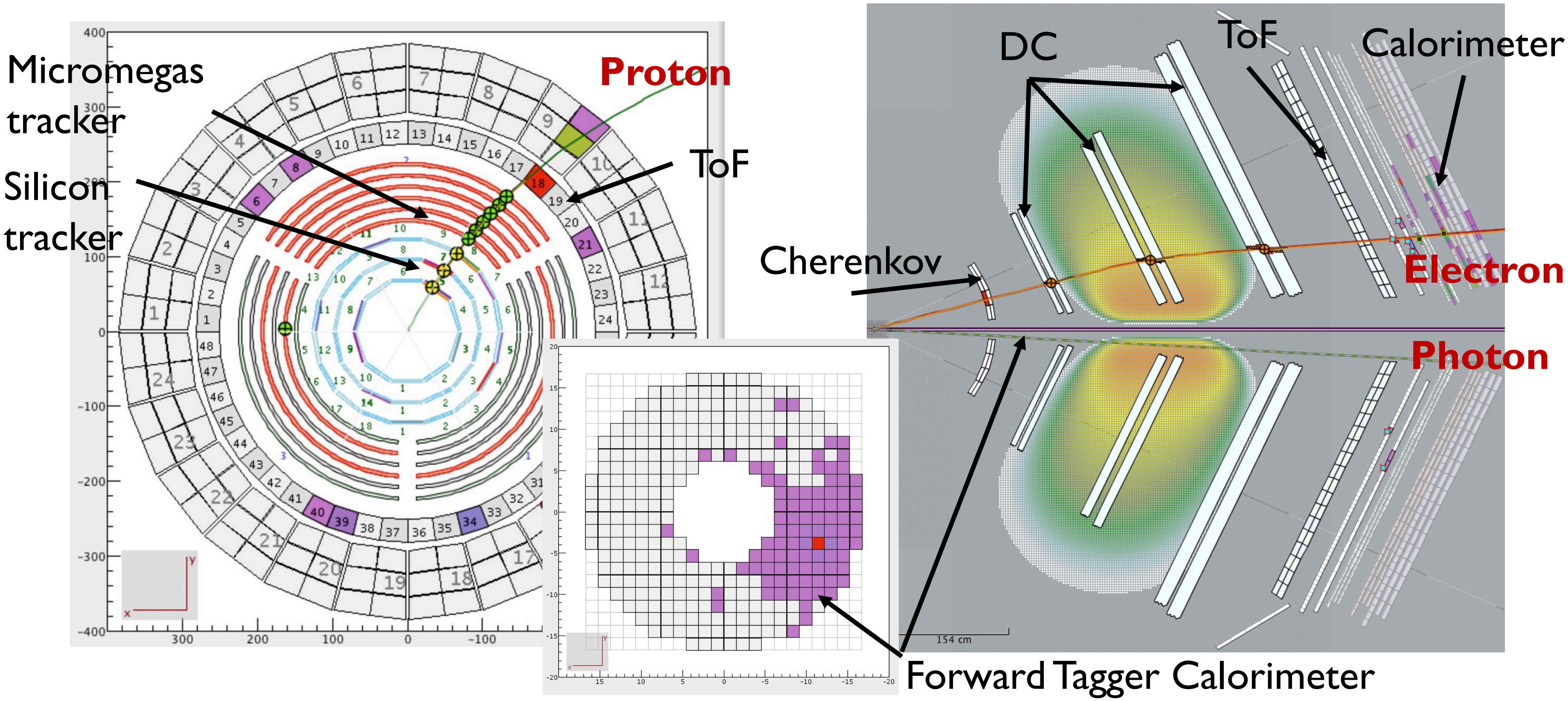
- Refinement of the estimation of uncertainties, in particular related to the π^0 correction



DVCS event in CLAS12

Typical DVCS event:

- Electron in the forward detector (torus, DC, ToF, Cherenkov, Calorimeter)
- Photon in the forward tagger (calorimeter)
- Proton in the central detector (solenoid, Silicon, Micromegas and ToF)



0 - Pre-selection of events

0 - Pre-selection of events

To deal with combinatorics:
Selection of best proton and best photon candidates based their “distance” to an ideal DVCS event (using exclusivity variables)

- Compute distance to an ideal DVCS events for each kinematic variable and for each event i

$$d^i = \frac{(x^i - x^i_{expected})^2}{(\eta^i)^2}$$

- Sum all the distances

$$d = \sum_{i=variables} d^i$$

- In each event, select the particles that have the smallest distance

Generator DVCS + π^0

Generator DVCS and π^0

- Generate DVCS and π^0 events following DVCS and π^0 cross-section
- This is a sampling problem: here we use Metropolis-Hastings algorithm
- We note x_i the points of the phase space

$$x_i = (Q^2, x_B, t, \phi)$$

- We note f the function that we want to sample: here we use

$$f = \sigma_{DVCS} + \sigma_{\pi^0}$$

we sample the sum of cross-sections

Generator DVCS + π^0

Generator DVCS and π^0 using Metropolis-Hastings algorithm

- Generate point $i + 1$ $\quad x_{i+1,\,proposed} = x_i + \mathcal{G}aus(x_i, \sigma)$
- Accept or reject the point

$$\alpha = \frac{f(x_{i+1,\,proposed})}{f(x_i)}$$

$$A = \mathcal{U}niform(0,1)$$

$$\begin{cases} \text{if } A < \alpha,\ x_{i+1} = x_{i+1,\,proposed} \\ \text{if } A > \alpha,\ x_{i+1} = x_i \end{cases}$$

- Choose DVCS or π^0

$$B = \mathcal{U}niform(0, f(x_{i+1}))$$

$$\begin{cases} \text{if } B < \sigma_{DVCS}, \text{ generated a DVCS event} \\ \text{if } B > \sigma_{DVCS}, \text{ generate a } \pi^0 \text{ event} \end{cases}$$

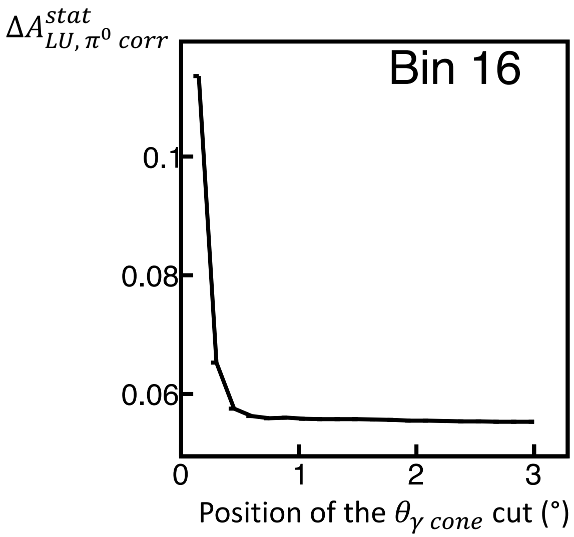
2 - Selection of exclusive DVCS events

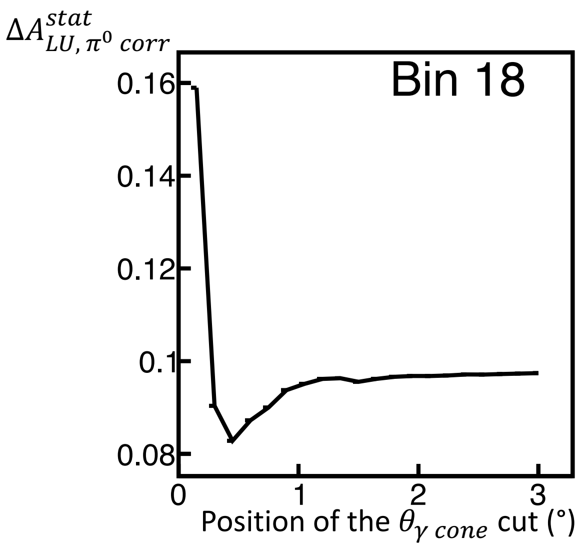
2 - Selection of exclusive DVCS events

Return on DVCS exclusivity:
optimization of the DVCS exclusivity selection
based on the contamination

- **Optimize the position of the cut to minimize the uncertainty DVCS + π^0**

- Here photon cone angle with wide exclusivity cuts





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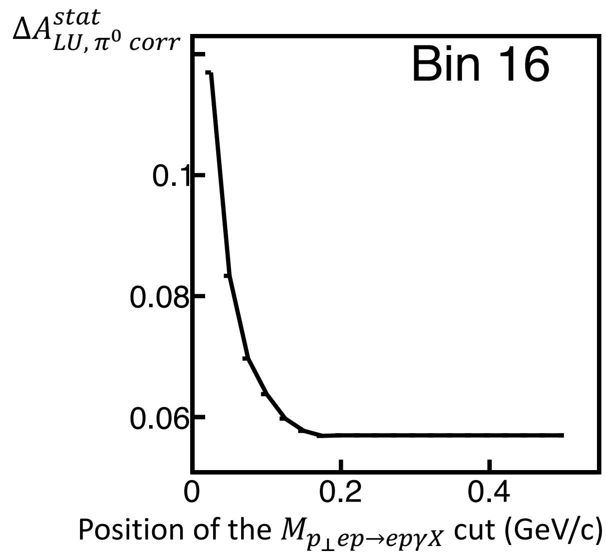
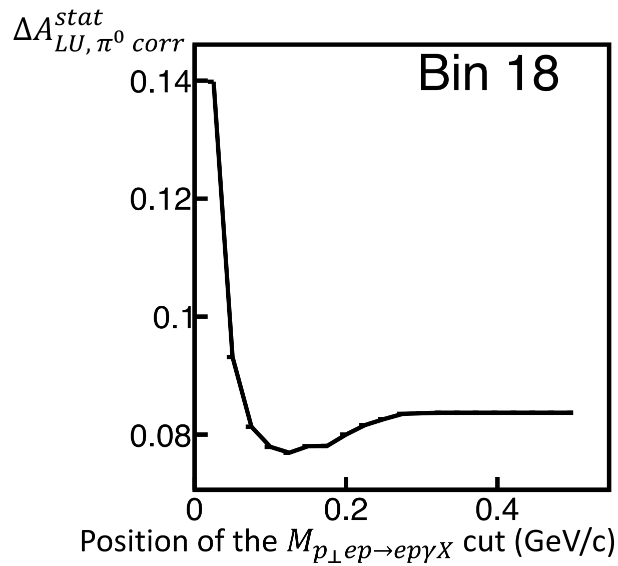
Return on DVCS exclusivity: optimization of the DVCS exclusivity selection based on the contamination

- **Optimize the position of the cut to minimize the uncertainty DVCS + π^0**

- Here missing transverse momentum with wide exclusivity cuts and the optimized photon cone angle cut





2 - Selection of exclusive DVCS events

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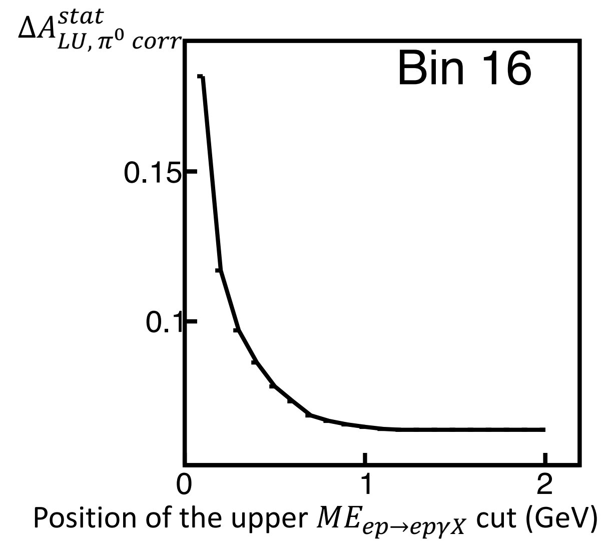
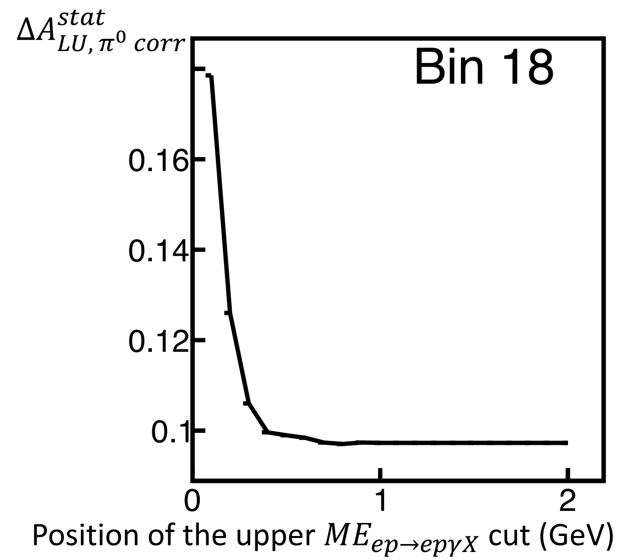
Return on DVCS exclusivity:
optimization of the DVCS
exclusivity selection
based on the contamination

- **Optimize the position of the cut to minimize the uncertainty DVCS + π^0**

- Here missing energy with wide exclusivity cuts and the optimized photon cone angle and missing transverse momentum cut





2 - Selection of exclusive DVCS events

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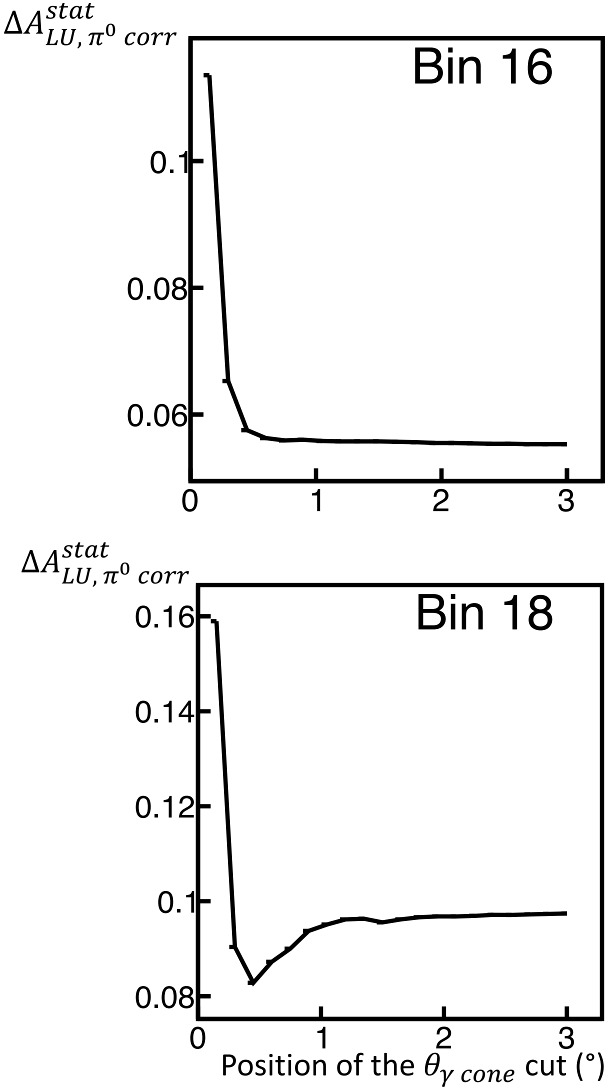
Return on DVCS exclusivity:
optimization of the DVCS exclusivity selection
based on the contamination

- **Optimize the position of the cut to minimize the uncertainty DVCS + π^0**

- Here missing energy with wide exclusivity cuts



5 - Estimation of uncertainties

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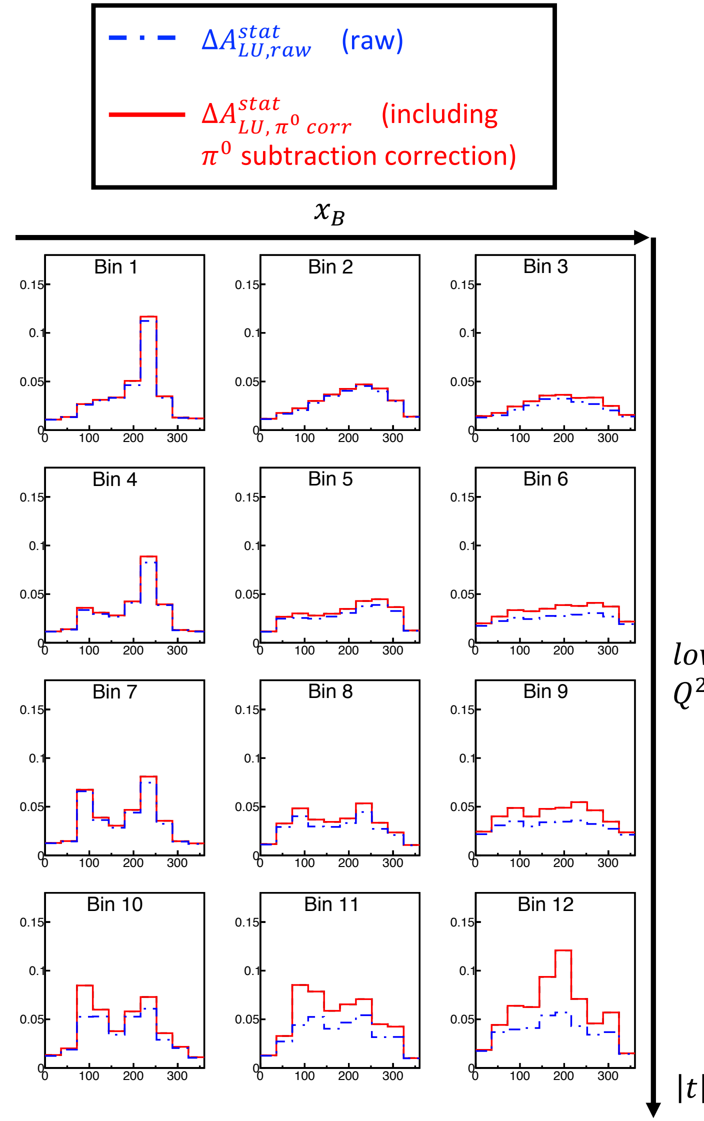
Statistical uncertainties propagated after the π^0 correction

$$\Delta A^{stat}_{LU,\,\pi^0\,corr}(i) = \frac{2}{P}\,\frac{\sqrt{\left[N^-_{\pi^0\,corr}(i)\,\Delta N^+_{\pi^0\,corr}(i)\right]^2 + \left[N^+_{\pi^0\,corr}(i)\,\Delta N^-_{\pi^0\,corr}(i)\right]^2}}{\left[N^+_{\pi^0\,corr}(i) + N^-_{\pi^0\,corr}(i)\right]^2}$$

$$\begin{aligned} N^{\pm}_{\pi^0\,corr}(i) &= \frac{1}{C^{\pm}}\left[n^{\pm}_{ep\gamma,\,id}(i) - n^{\pm}_{\pi^0,\,cont}(i)\right] \\ &= \frac{1}{C^{\pm}}\left[n^{\pm}_{ep\gamma,\,id}(i) - r(i)\,n^{\pm}_{\pi^0,\,id}(i)\right] \end{aligned}$$

$$\Delta N^{\pm}(i) = \frac{1}{C^{\pm}}\left[\sqrt{n^{\pm}_{ep\gamma,\,id}(i) + r(i)^2\,n^{\pm}_{\pi^0,\,id}(i) + \left[n^{\pm}_{\pi^0,\,id}(i)\,\Delta r(i)\right]^2}\right]$$



5 - Estimation of uncertainties

5 - Estimation of uncertainties

Systematic uncertainties associated with:

- π^0 subtraction: contamination fraction ~ 0.1 to 7%. (absolute uncertainty)

Contamination: $f(i) = \dfrac{n_{\pi^0,\,cont}(i)}{n_{ep\gamma,\,id}(i)}$

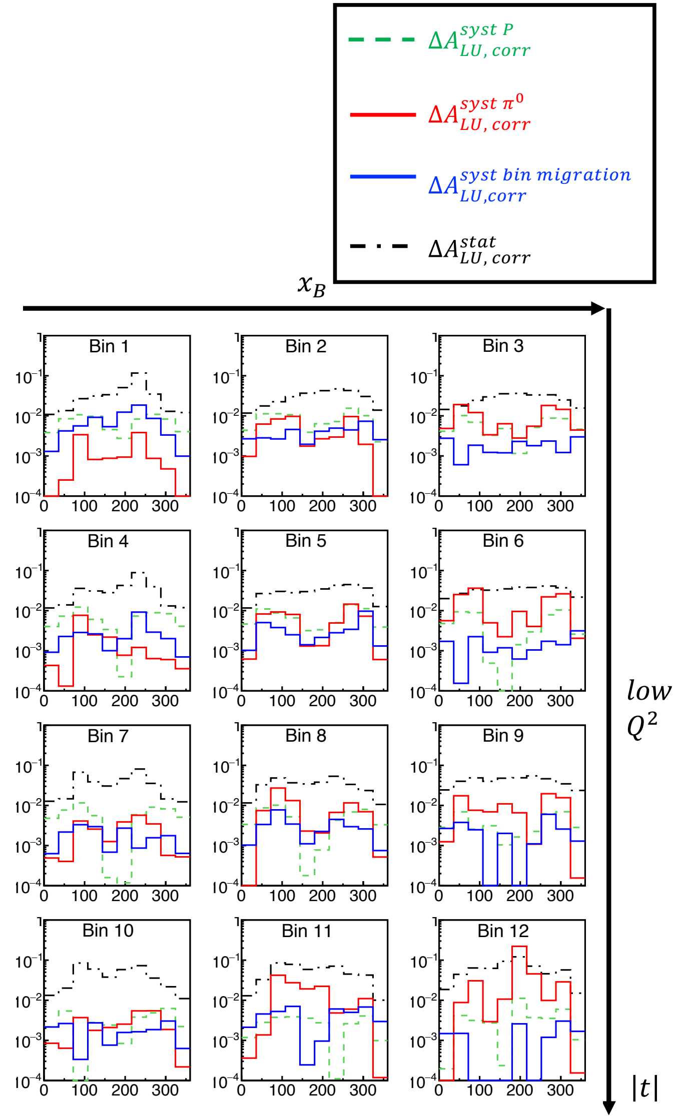
Asymmetry decomposition:

$$A_{LU,\,\pi^0\,corr}(i) = \frac{A_{LU,\,raw}(i) - f(i)\,A_{LU,\,\pi^0,\,cont}(i)}{1 - f(i)}$$

Systematic uncertainty:

$$\Delta A^{syst\ \pi^0}_{LU,\,\pi^0\,corr}(i) = \frac{A_{LU,\,raw}(i) - f(i)\,A_{LU,\,\pi^0\,cont}}{\left[1 - f(i)\right]^2}\Delta f(i)$$

Uncertainty on contamination $\Delta f(i) = 0.3\ f(i)$



5 - Estimation of uncertainties

5 - Estimation of uncertainties

Systematic uncertainties associated with:

- Bin migration: estimation of the migration and asymmetries
  ~ 0.1 to 2%. (absolute uncertainty)

Asymmetry decomposition:

$$A_{corr}(i) = \frac{A_{\pi^0\ corr}(i) - \sum_{bin\ j \neq i} m_{j \to i} A_{corr}(j \to i)}{m_{i \to i}}$$

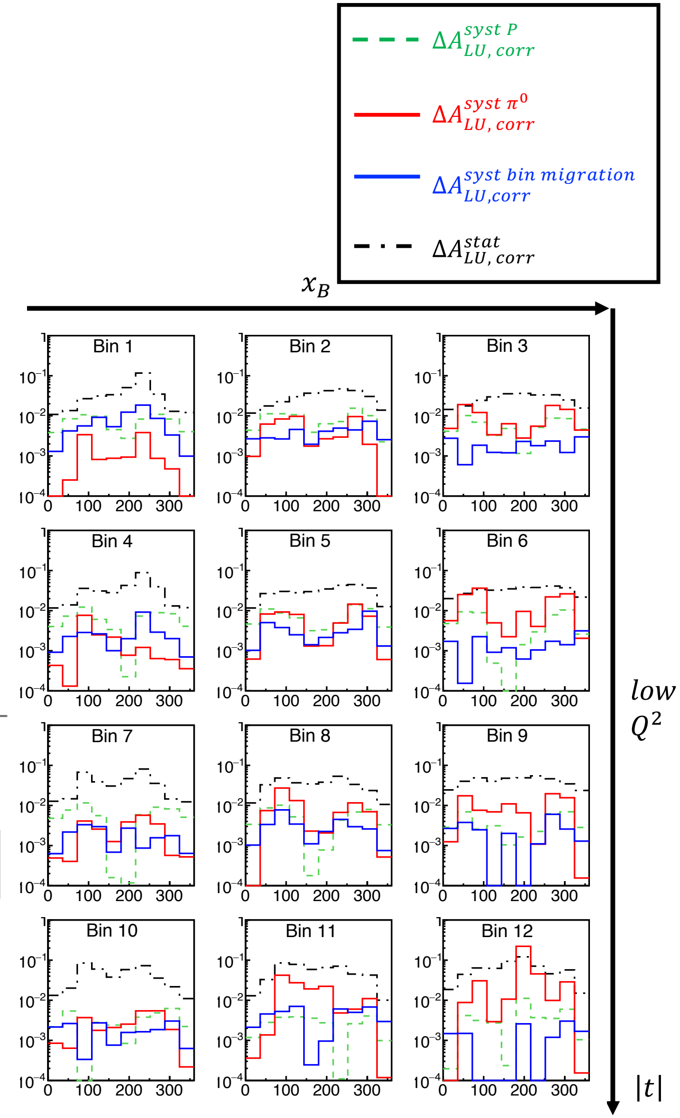
Systematic uncertainty:

$$\Delta A^{syst\ bin\ migration}_{LU\ corr.}(i) = \sqrt{\sum_{j \neq i} \left[\left(\frac{-m_{i \to i} A_{corr}(j \to i) + A_{\pi^0\ corr}(i) - \sum_{j \neq i} m_{j \to i} A_{corr}(j \to i)}{m^2_{i \to i}} \Delta m_{j \to i} \right)^2 + \left(\frac{-m_{j \to i}}{m_{i \to i}} \Delta A_{corr}(j \to i) \right)^2 \right]}$$

Uncertainty on contamination

$$\Delta m_{j \to i} = 0.1\ m_{j \to i}$$

$$\Delta A_{LU,\,corr}(j \to i) = \frac{|A_{LU,\,\pi^0\ corr}(i) - A_{LU,\,\pi^0\ corr}(j)|}{2}$$



5 - Estimation of uncertainties

5 - Estimation of uncertainties

Systematic uncertainties associated with:

- Polarization: polarization measurement ~ 0.1 to 2%. (absolute uncertainty)

$$\Delta A^{syst\ P}_{LU\ corr}(i) = \frac{A_{LU\ corr}}{P}\Delta P$$