Extraction of BSA of Deeply Virtual Exclusive ρ^0 Production with RGA

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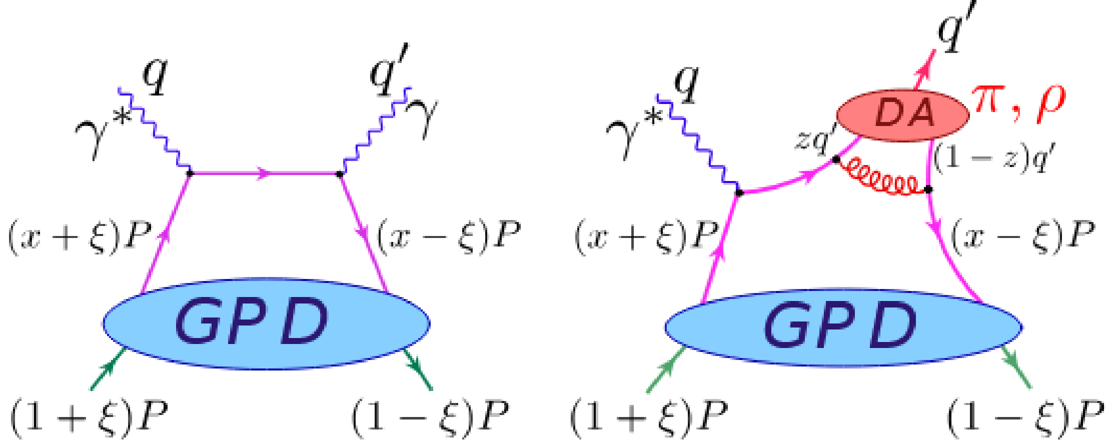
Motivation

- Generalized Parton Distributions (GPDs) give insight into the 3D structure of hadrons
- Deeply Virtual Compton Scattering (DVCS) and Deeply Virtual Meson Production (DVMP) as techniques to access GPDs
  - With DVMP, both pseudoscalar and vector meson production can access chiral even and chiral odd GPDs
- Vector meson production allow for study in the Bjorken regime (-t/Q2 << 1) where GPDs dominate
- Vector meson production access chiral even GPDs, H and E and chiral odd GPDs, H_T and $\bar{E}_T$

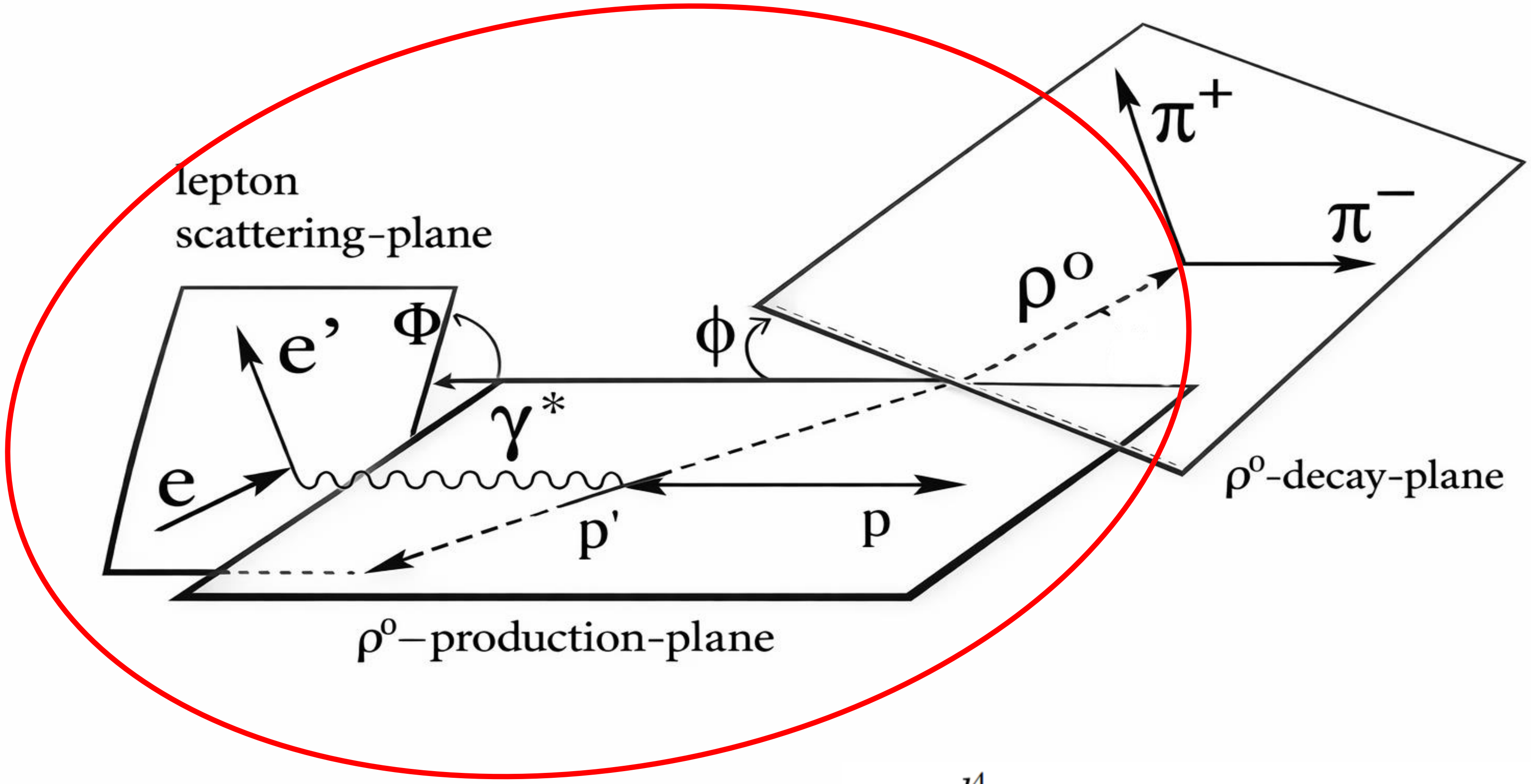


Valery Kubarovsky. “Deeply Virtual Exclusive Reactions with CLAS”. In: Nuclear1847 Physics B - Proceedings Supplements 219-220.0 (2011), pp. 118–125.

- 4 chiral-even GPDs: $H,\ E,\ \tilde{H},\ \tilde{E}$
- 4 chiral-odd GPDs: $H_T,\ E_T,\ \tilde{H}_T,\ \tilde{E}_T$

	Meson	GPD flavor composition
$\tilde{H},\ \tilde{E}$ / $H_T,\ \bar{E}_T$	π^+	$\Delta u - \Delta d$
	π^0	$2\Delta u + \Delta d$
	η	$2\Delta u - \Delta d$
$H,\ E$ / $H_T,\ \bar{E}_T$	ρ^0	$2u + d$
	ρ^+	$u - d$
	ω	$2u - d$

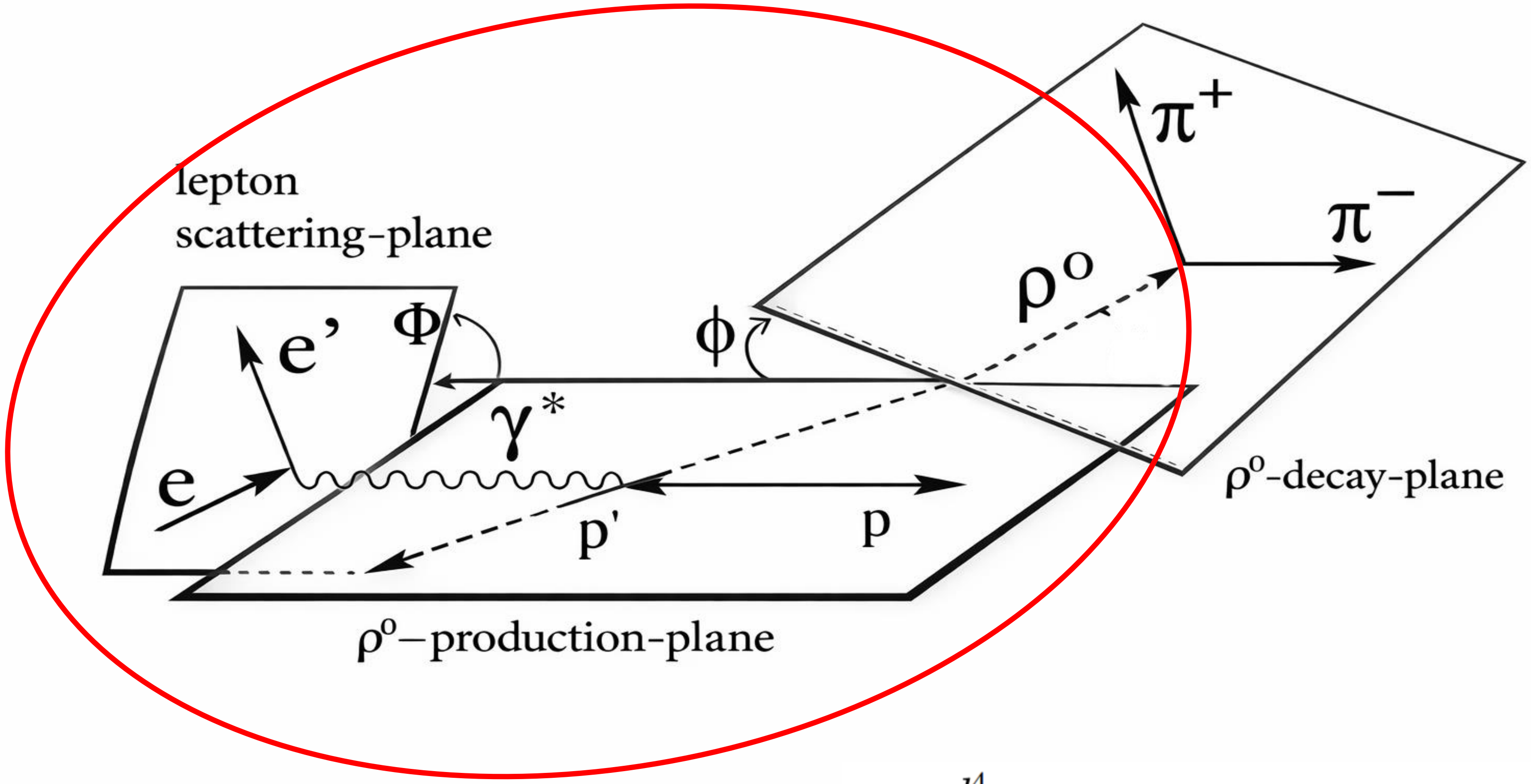
Meson Production Cross Section (γ*p->p'ρ0)



$$\frac{d^4\sigma}{dQ^2 dx_B dt d\Phi} = \sigma_T + \epsilon\sigma_L + \epsilon\sigma_{TT}^{cos2\Phi} cos2\Phi$$

$$+\sqrt{2\epsilon(1+\epsilon)}\sigma_{LT}^{cos\Phi} cos\Phi + P_b\sqrt{2\epsilon(1-\epsilon)}\sigma_{LT'}^{sin\Phi} sin\Phi$$

Meson Production Cross Section (γ*p->p'ρ0)



$$\frac{d^4\sigma}{dQ^2 dx_B dt d\Phi} = \sigma_T + \epsilon\sigma_L + \epsilon\sigma_{TT}^{cos2\Phi} cos2\Phi$$

$$+\sqrt{2\epsilon(1+\epsilon)}\sigma_{LT}^{cos\Phi} cos\Phi + P_b\sqrt{2\epsilon(1-\epsilon)}\sigma_{LT'}^{sin\Phi} sin\Phi$$

Beam Spin Asymmetry Extraction

- Beam Spin Asymmetry (BSA) come directly from the cross-section and allow for extraction of the ratio of the structure functions

$$\frac{d^4\sigma}{dQ^2 dx_B dt d\Phi} = \sigma_T + \epsilon\sigma_L + \epsilon\sigma_{TT}^{cos2\Phi} cos2\Phi + \sqrt{2\epsilon(1+\epsilon)}\sigma_{LT}^{cos\Phi} cos\Phi + P_b\sqrt{2\epsilon(1-\epsilon)}\sigma_{LT'}^{sin\Phi} sin\Phi$$

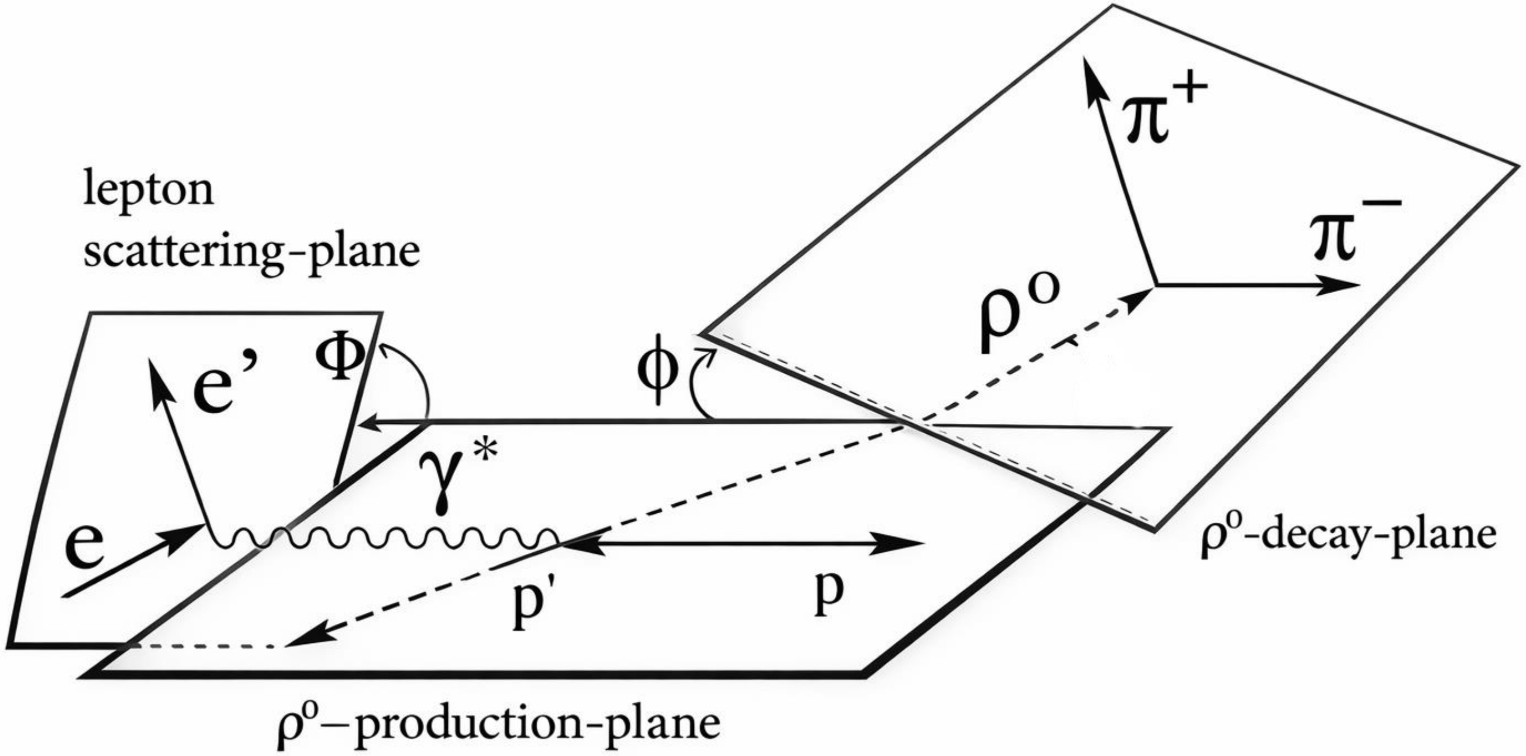
$$BSA = \frac{\sigma^+ - \sigma^-}{\sigma^+ + \sigma^-} \sim A_{LU}^{sin\Phi} sin\Phi$$

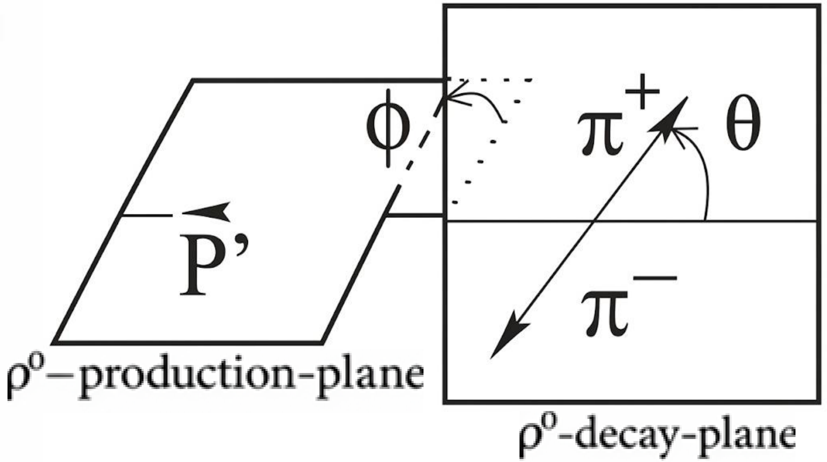
$$A_{LU}^{sin\Phi} = \sqrt{2\epsilon(1-\epsilon)}\frac{\sigma_{LT'}^{sin\Phi}}{\sigma_0}$$

- The structure functions can be described in terms of the two chiral even GPDs H and E and the two chiral odd GPDs, H_T and $\bar{E}_T$

$$\sigma_{LT'}^{sin\Phi} \sim [\bar{E}_T H + H_T E]$$

Differential Cross Section(**γ***p->p'ρ0->p'π+π-)





Differential Cross Section(γ*p->p'ρ0->p'π+π-)

23 Spin Density Matrix Elements

15 unpolarized terms

$$\mathcal{W}^U(\Phi,\phi,\cos\Theta) = \frac{3}{8\pi^2}\Bigg[\frac{1}{2}(1-r^{04}_{00}) + \frac{1}{2}(3r^{04}_{00}-1)\cos^2\Theta$$
$$- \sqrt{2}\mathrm{Re}\{r^{04}_{10}\}\sin 2\Theta\cos\phi - r^{04}_{1-1}\sin^2\Theta\cos 2\phi - \epsilon\cos 2\Phi\Big(r^1_{11}\sin^2\Theta$$
$$+ r^1_{00}\cos^2\Theta - \sqrt{2}\mathrm{Re}\{r^1_{10}\}\sin 2\Theta\cos\phi - r^1_{1-1}\sin^2\Theta\cos 2\phi\Big)$$
$$- \epsilon\sin 2\Phi\Big(\sqrt{2}\mathrm{Im}\{r^2_{10}\}\sin 2\Theta\sin\phi + \mathrm{Im}\{r^2_{1-1}\}\sin^2\Theta\sin 2\phi\Big)$$
$$+ \sqrt{2\epsilon(1+\epsilon)}\cos\Phi\Big(r^5_{11}\sin^2\Theta + r^5_{00}\cos^2\Theta - \sqrt{2}\mathrm{Re}\{r^5_{10}\}\sin 2\Theta\cos\phi$$
$$- r^5_{1-1}\sin^2\Theta\cos 2\phi\Big) + \sqrt{2\epsilon(1+\epsilon)}\sin\Phi\Big(\sqrt{2}\mathrm{Im}\{r^6_{10}\}\sin 2\Theta\sin\phi$$
$$+ \mathrm{Im}\{r^6_{1-1}\}\sin^2\Theta\sin 2\phi\Big)\Bigg],$$

$$W = W^U + P_b W^L$$

$$\mathcal{W}^L(\Phi,\phi,\cos\Theta) = \frac{3}{8\pi^2}\Bigg[\sqrt{1-\epsilon^2}\Big(\sqrt{2}\mathrm{Im}\{r^3_{10}\}\sin 2\Theta\sin\phi + \mathrm{Im}\{r^3_{1-1}\}\sin^2\Theta\sin 2\phi\Big)$$
$$+ \sqrt{2\epsilon(1-\epsilon)}\cos\Phi\Big(\sqrt{2}\mathrm{Im}\{r^7_{10}\}\sin 2\Theta\sin\phi + \mathrm{Im}\{r^7_{1-1}\}\sin^2\Theta\sin 2\phi\Big)$$
$$+ \sqrt{2\epsilon(1-\epsilon)}\sin\Phi\Big(r^8_{11}\sin^2\Theta + r^8_{00}\cos^2\Theta - \sqrt{2}\mathrm{Re}\{r^8_{10}\}\sin 2\Theta\cos\phi$$
$$- r^8_{1-1}\sin^2\Theta\cos 2\phi\Big)\Bigg].$$

8 polarized terms

Beam Spin Asymmetry ($A^{\sin\Phi}_{LU}$)

$$A_{LU}^{\sin\Phi} \sim (r_{00}^{8}) \sim IM[2M^{\rho^0 *}_{0+,++}M^{\rho^0}_{0+,0+} + M^{\rho^0 *}_{0-,++}M^{\rho^0}_{0-,0+}]$$
$$\sim [\bar{E}_T H + H_T E]$$

$$\begin{aligned}
\mathcal{W}^U(\Phi,\phi,\cos\Theta) &= \frac{3}{8\pi^2}\Bigg[\frac{1}{2}(1-r_{00}^{04}) + \frac{1}{2}(3r_{00}^{04}-1)\cos^2\Theta \\
&- \sqrt{2}\mathrm{Re}\{r_{10}^{04}\}\sin 2\Theta\cos\phi - r_{1-1}^{04}\sin^2\Theta\cos 2\phi - \epsilon\cos 2\Phi\Big(r_{11}^{1}\sin^2\Theta \\
&+ r_{00}^{1}\cos^2\Theta - \sqrt{2}\mathrm{Re}\{r_{10}^{1}\}\sin 2\Theta\cos\phi - r_{1-1}^{1}\sin^2\Theta\cos 2\phi\Big) \\
&- \epsilon\sin 2\Phi\Big(\sqrt{2}\mathrm{Im}\{r_{10}^{2}\}\sin 2\Theta\sin\phi + \mathrm{Im}\{r_{1-1}^{2}\}\sin^2\Theta\sin 2\phi\Big) \\
&+ \sqrt{2\epsilon(1+\epsilon)}\cos\Phi\Big(r_{11}^{5}\sin^2\Theta + r_{00}^{5}\cos^2\Theta - \sqrt{2}\mathrm{Re}\{r_{10}^{5}\}\sin 2\Theta\cos\phi \\
&- r_{1-1}^{5}\sin^2\Theta\cos 2\phi\Big) + \sqrt{2\epsilon(1+\epsilon)}\sin\Phi\Big(\sqrt{2}\mathrm{Im}\{r_{10}^{6}\}\sin 2\Theta\sin\phi \\
&+ \mathrm{Im}\{r_{1-1}^{6}\}\sin^2\Theta\sin 2\phi\Big)\Bigg],
\end{aligned}$$

$$\begin{aligned}
\mathcal{W}^L(\Phi,\phi,\cos\Theta) &= \frac{3}{8\pi^2}\Bigg[\sqrt{1-\epsilon^2}\Big(\sqrt{2}\mathrm{Im}\{r_{10}^{3}\}\sin 2\Theta\sin\phi + \mathrm{Im}\{r_{1-1}^{3}\}\sin^2\Theta\sin 2\phi\Big) \\
&+ \sqrt{2\epsilon(1-\epsilon)}\cos\Phi\Big(\sqrt{2}\mathrm{Im}\{r_{10}^{7}\}\sin 2\Theta\sin\phi + \mathrm{Im}\{r_{1-1}^{7}\}\sin^2\Theta\sin 2\phi\Big) \\
&+ \sqrt{2\epsilon(1-\epsilon)}\sin\Phi\Big(r_{11}^{8}\sin^2\Theta + r_{00}^{8}\cos^2\Theta - \sqrt{2}\mathrm{Re}\{r_{10}^{8}\}\sin 2\Theta\cos\phi \\
&- r_{1-1}^{8}\sin^2\Theta\cos 2\phi\Big)\Bigg].
\end{aligned}$$

R^8_{00} leading order term

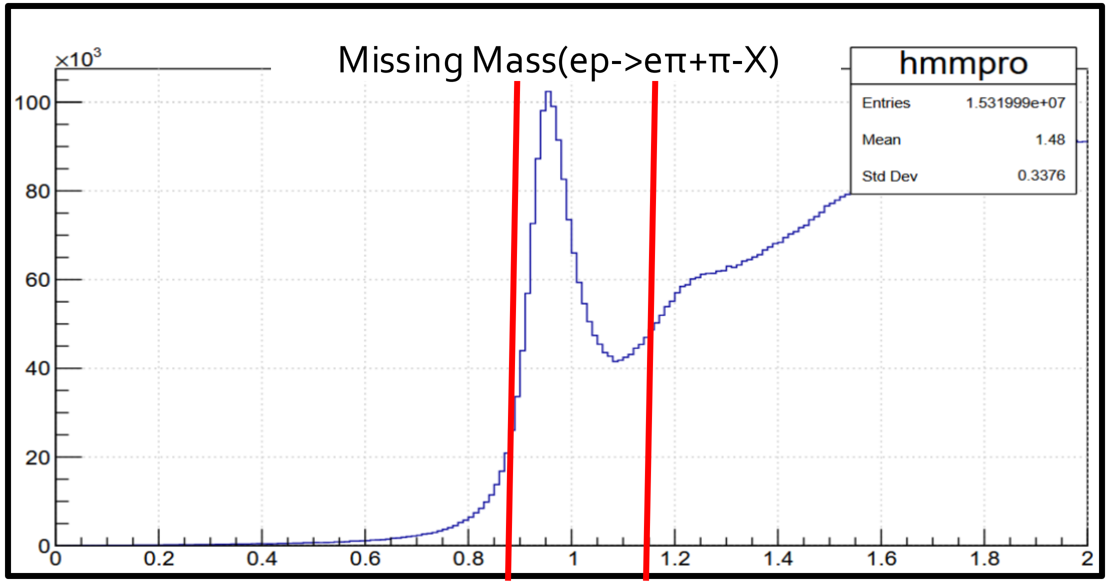
Event Selection

RGA's Fall 2018 data:

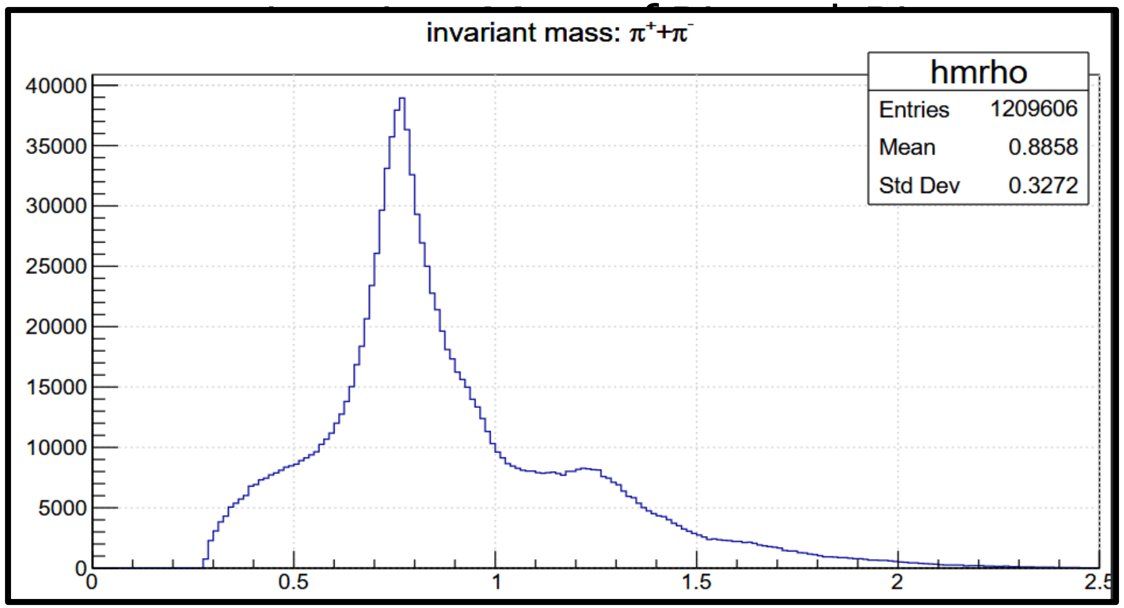
- 10.6 GeV longitudinally polarized electron beam
- 86% electron polarization
- Liquid hydrogen target

Channel:

- ep -> $e\rho^0 p$ -> $e\pi^+\pi^-$(p)
  - ρ^0 decays into $\pi^+\pi^-$
  - The electron, and pions are found using forward detector
  - The outgoing proton is identified by missing mass techniques
  - cuts: $Q^2 > 2$ GeV^2, $W > 2$ GeV, $-0.65 < \cos\theta < 0.65$

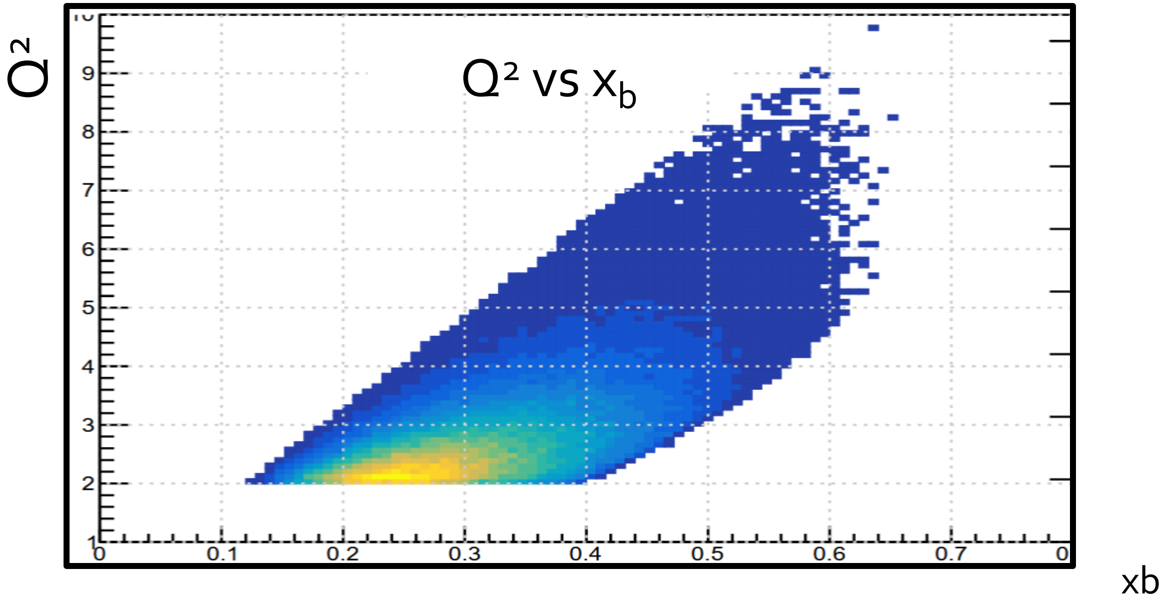


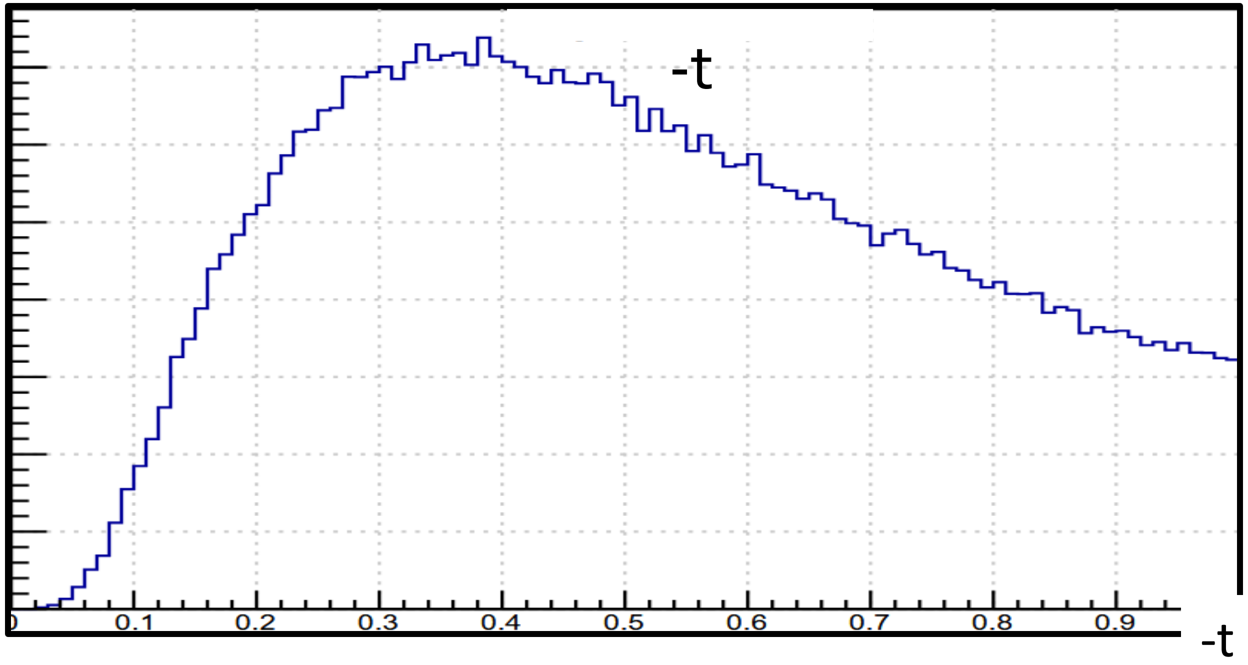
MM

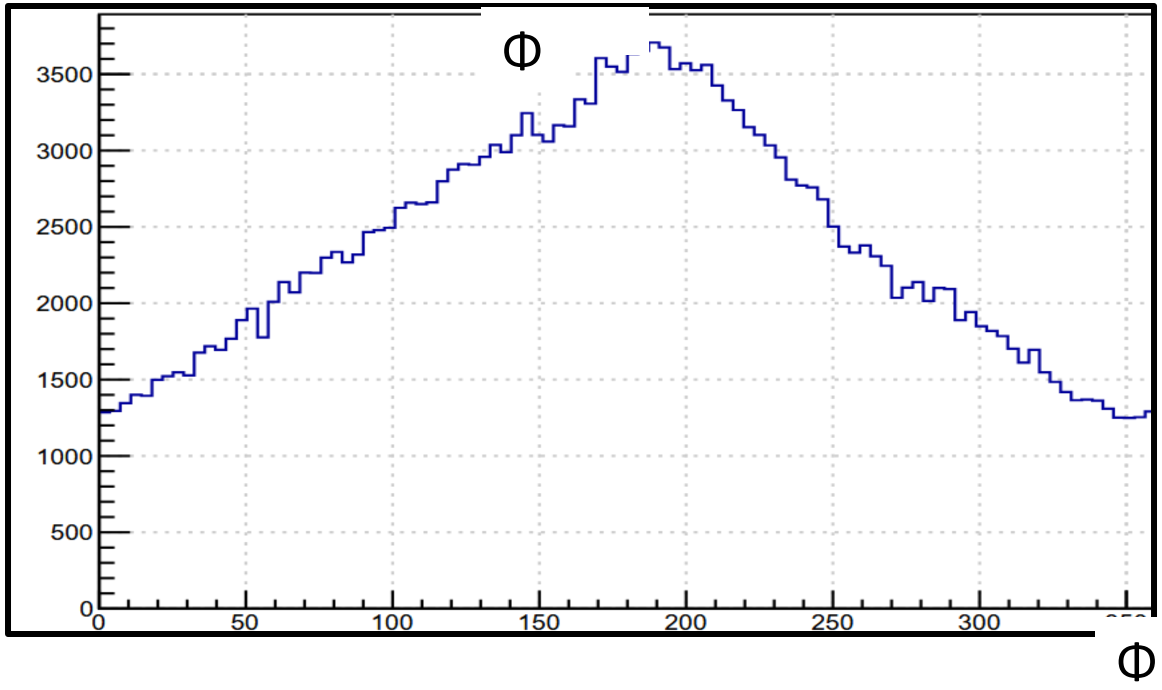


IM

Kinematics

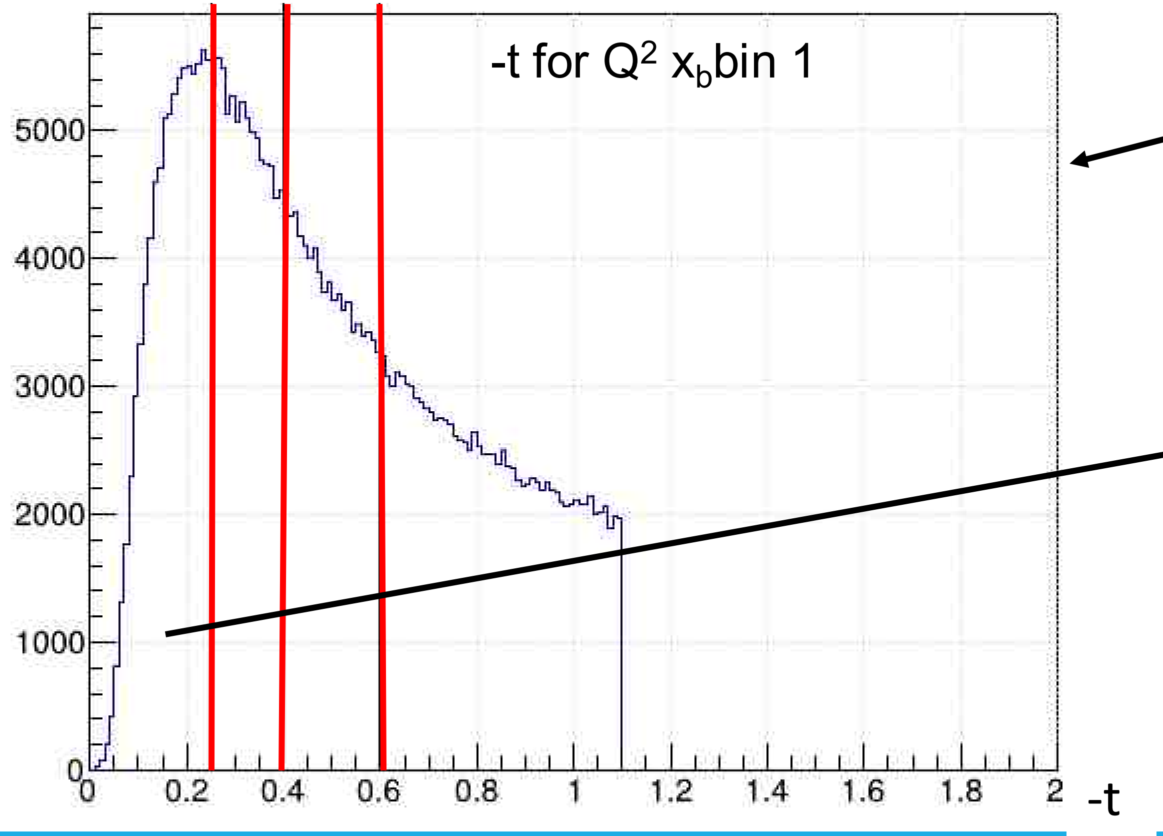

Q²
Q² vs x_b
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
1
2
3
4
5
6
7
8
9
xb

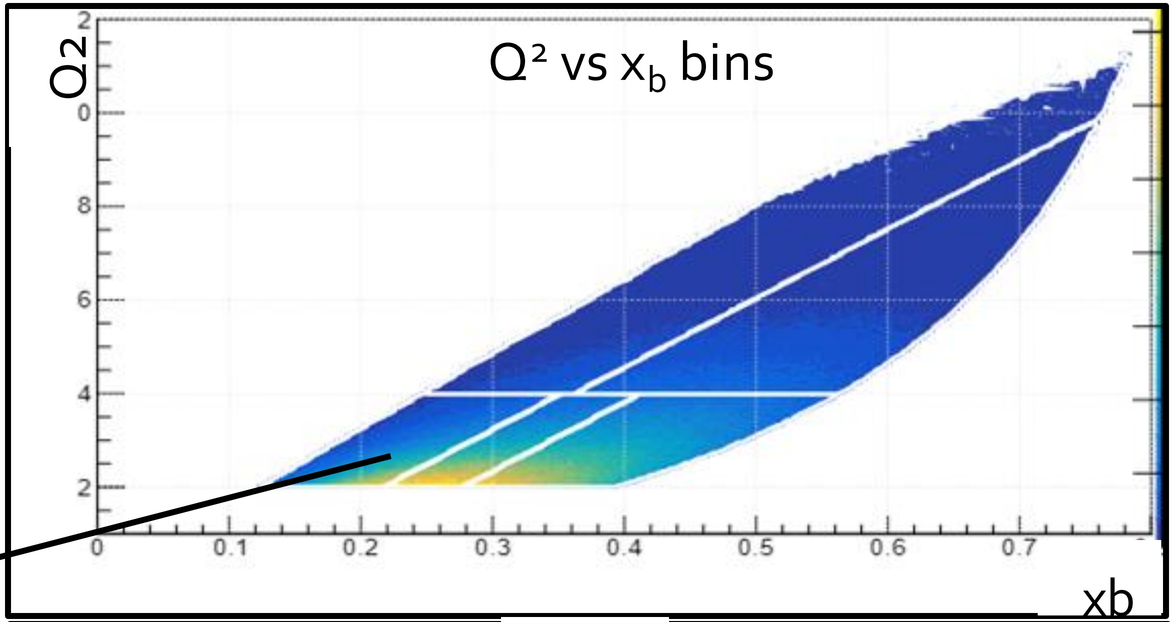

-t
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
-t

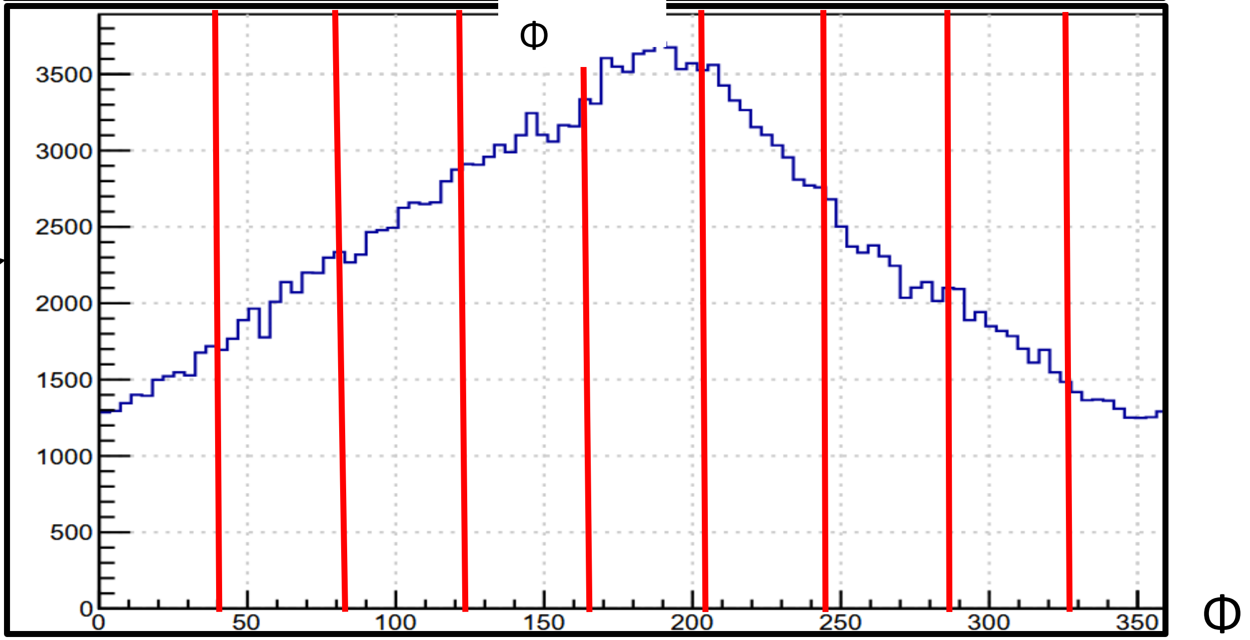

Φ
0
500
1000
1500
2000
2500
3000
3500
0
50
100
150
200
250
300
Φ

Kinematic Binning

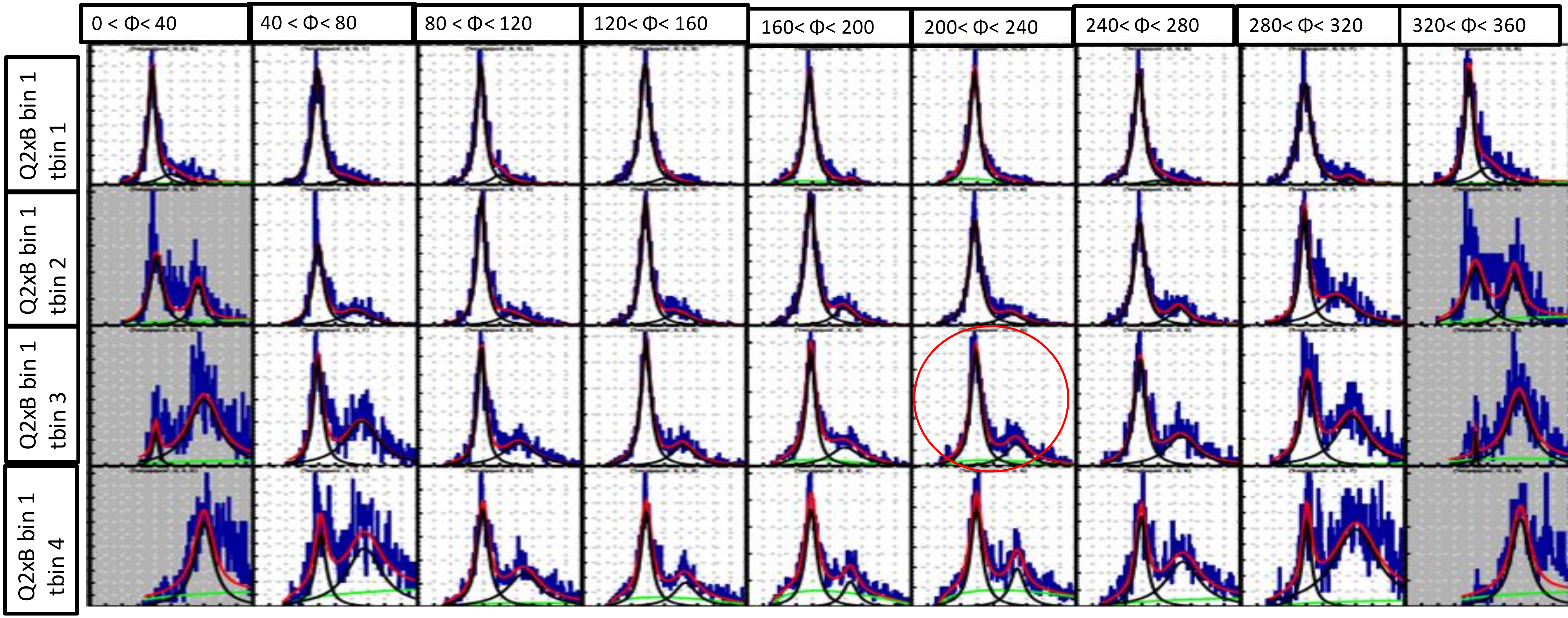
- 5 Kinematic bins are created in Q2 and xB
- Each of these 5 bins is further divided into –t plots
- In each –t bin, the events are further divided into 9 equidistance bins in Φ
- In Φ bins, each event is binned into positive or negative helicity



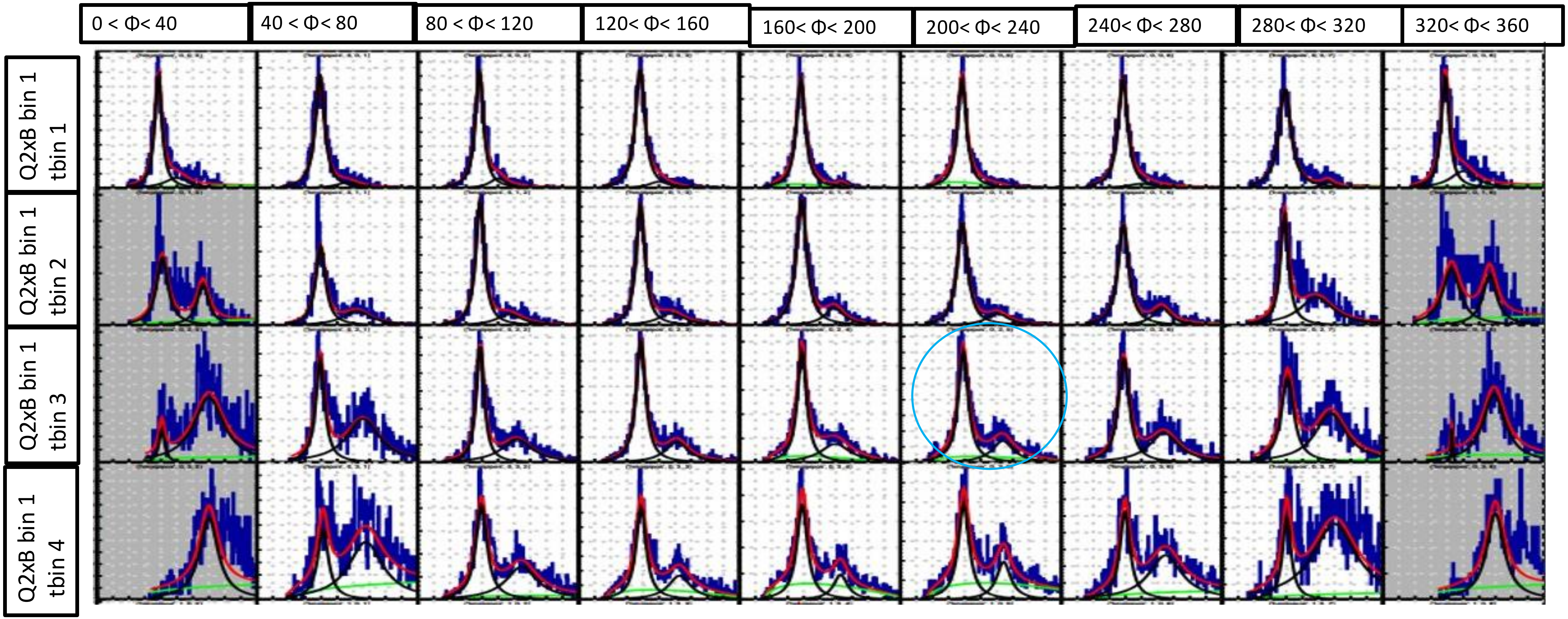




Invariant Mass with Positive Helicity (Q2xB bin 1)

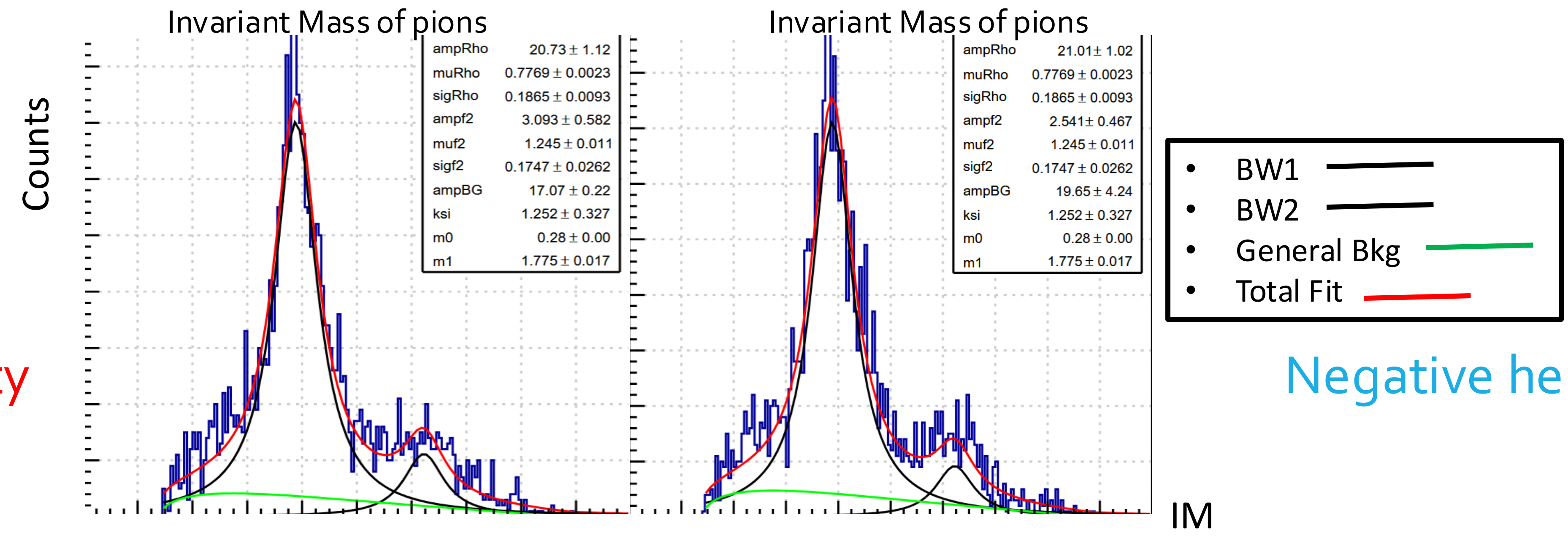


Invariant Mass with Negative Helicity (Q2xB bin 1)



Invariant Mass for Positive and Negative Helicities (Q2xB bin 1 tbin 3 Φ bin 6)

positive helicity



Negative helicity

- Invariant Mass is binned into positive helicity events and negative helicity events for each Φ bin
- Separate signal from the background with the fits
- Two Breit Wigners were assigned for two mesons

$$F_x^{bw} = \frac{1}{\pi}\frac{N_x \frac{1}{2}\Gamma}{x^2 + (\frac{1}{2}\Gamma)^2}$$

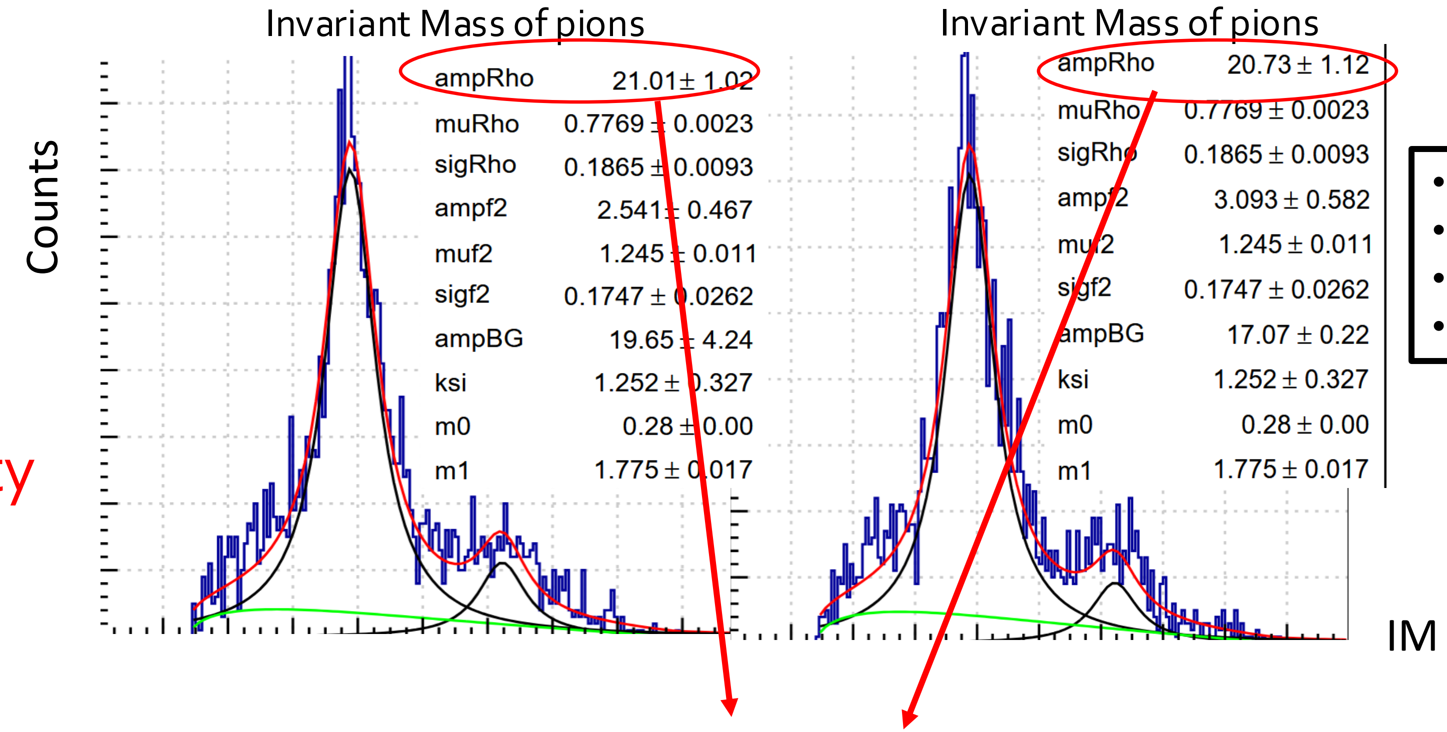
- An ARGUS inspired function was used as a general background

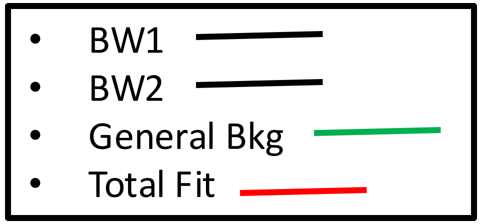
$$F_{bg}(x) = N_{bg}\xi^3 \frac{m_1 - x}{(m_1 - m_0)^2}\sqrt{1 - \frac{(m_1 - x)^2}{(m_1 - m_0)^2}}\exp\left\{-\frac{1}{2}\xi^2\left(1 - \frac{(m_1 - x)^2}{(m_1 - m_0)^2}\right)\right\}$$

Calculation of BSA

Pb is the average beam polarization, 0.8692

positive helicity



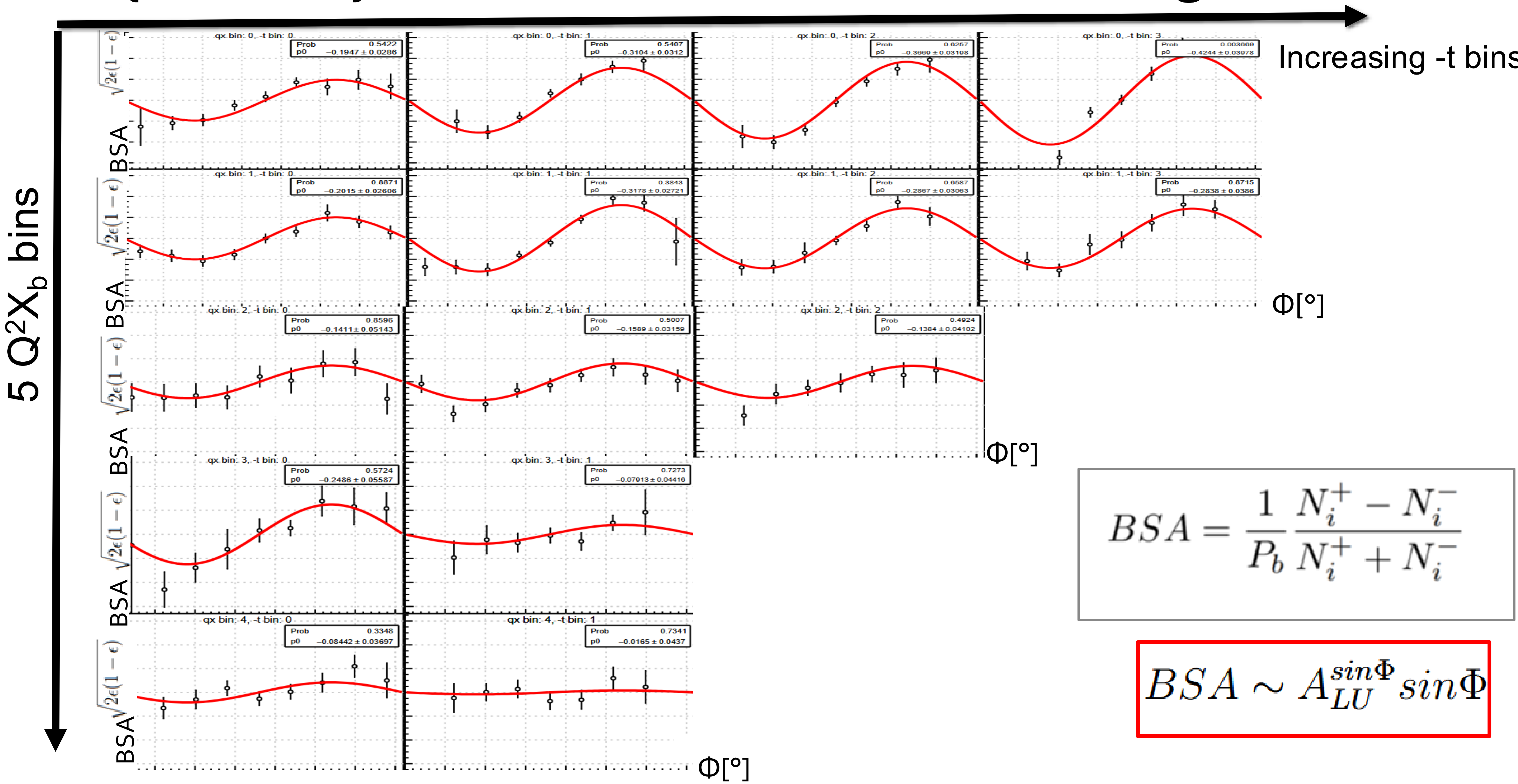


Negative helicity

$$BSA = \frac{1}{P_b}\frac{N_i^+ - N_i^-}{N_i^+ + N_i^-}$$

- The signal after background subtraction is taken from both invariant mass distributions
  - full 4 dimensional space {Q2,xb,-t,phi} in each helicity state
  - 270 Invariant Mass plots fitted; 135 BSA calculations in total

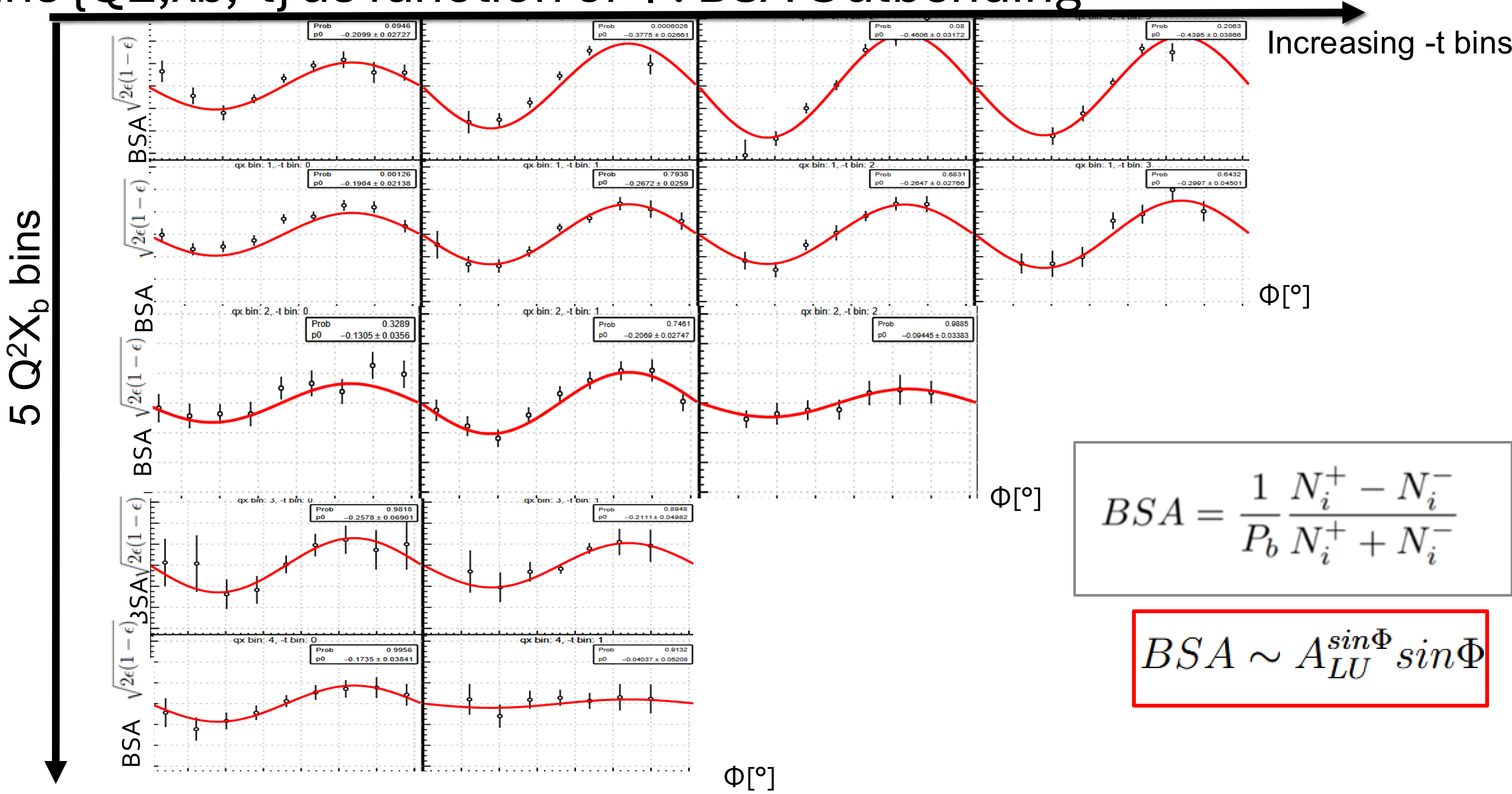
3D Bins {Q2,xb,-t} as function of Φ: BSA Inbending



$$BSA = \frac{1}{P_b}\frac{N_i^+ - N_i^-}{N_i^+ + N_i^-}$$

$$BSA \sim A_{LU}^{sin\Phi} sin\Phi$$

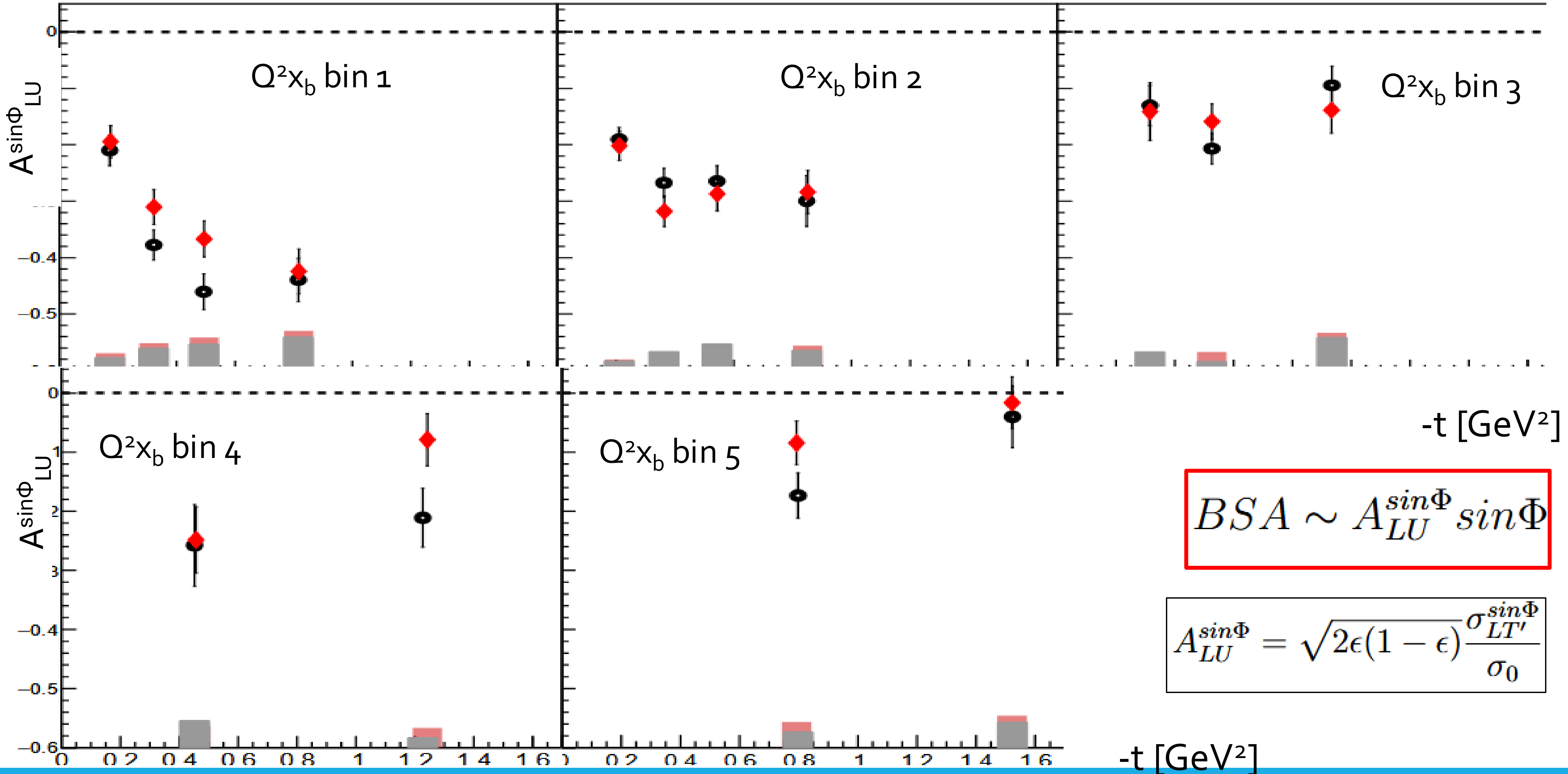
3D Bins {Q2,xb,-t} as function of Φ: BSA Outbending



$$BSA = \frac{1}{P_b}\frac{N_i^+ - N_i^-}{N_i^+ + N_i^-}$$

$$BSA \sim A_{LU}^{sin\Phi} sin\Phi$$

2D Bins {Q2,xb} as function of -t: $A^{\sin\Phi}_{LU}$ for both inbending and outbending



$$BSA \sim A_{LU}^{sin\Phi}\, sin\Phi$$

$$A_{LU}^{sin\Phi} = \sqrt{2\epsilon(1-\epsilon)}\frac{\sigma_{LT'}^{sin\Phi}}{\sigma_0}$$

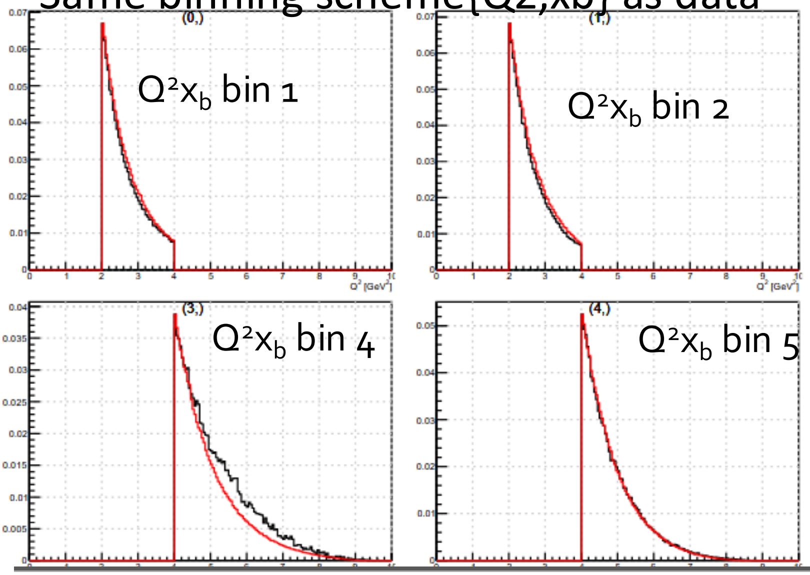
Systematic Studies

Systematic Studies: Monte Carlo Simulation

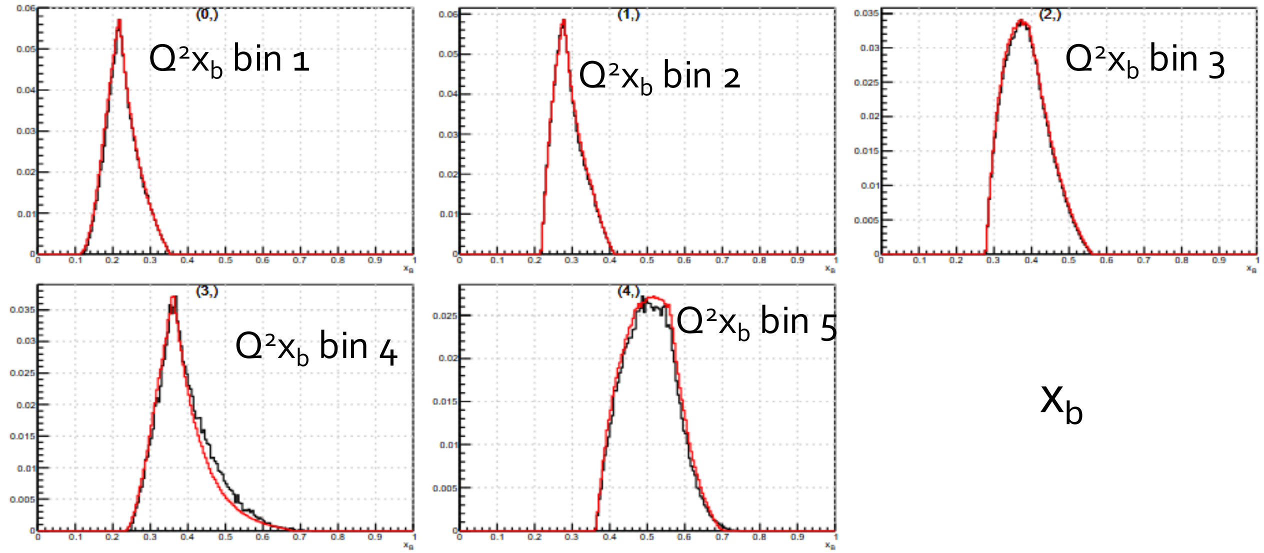
- Data
- MC,weighted

HepGen Injected with a realistic asymmetries for positive and negative helicity events

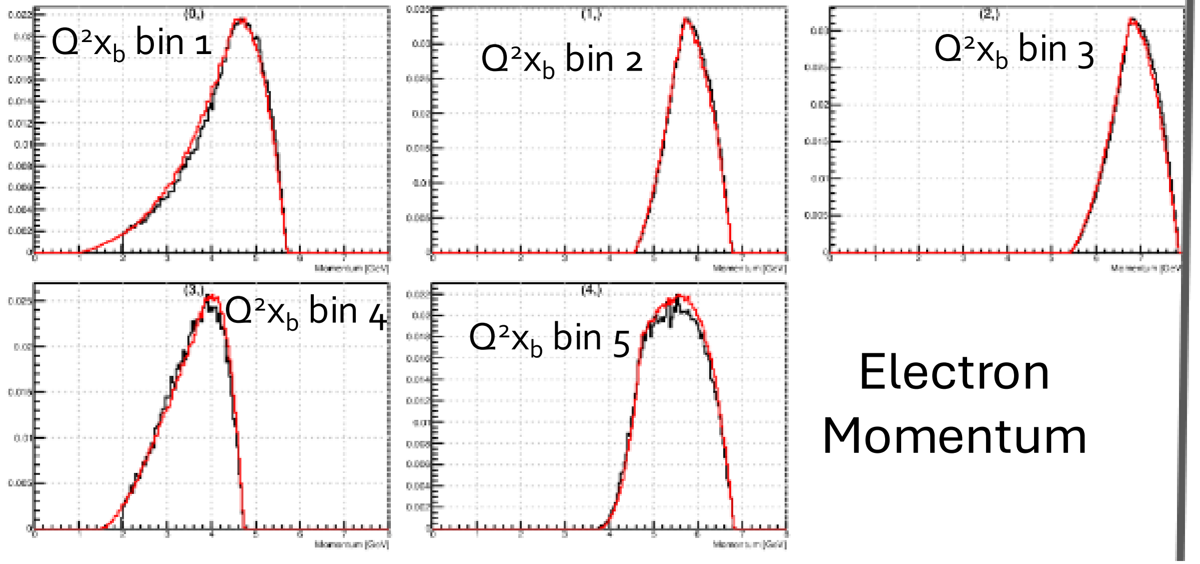
Same binning scheme{Q2,xb} as data



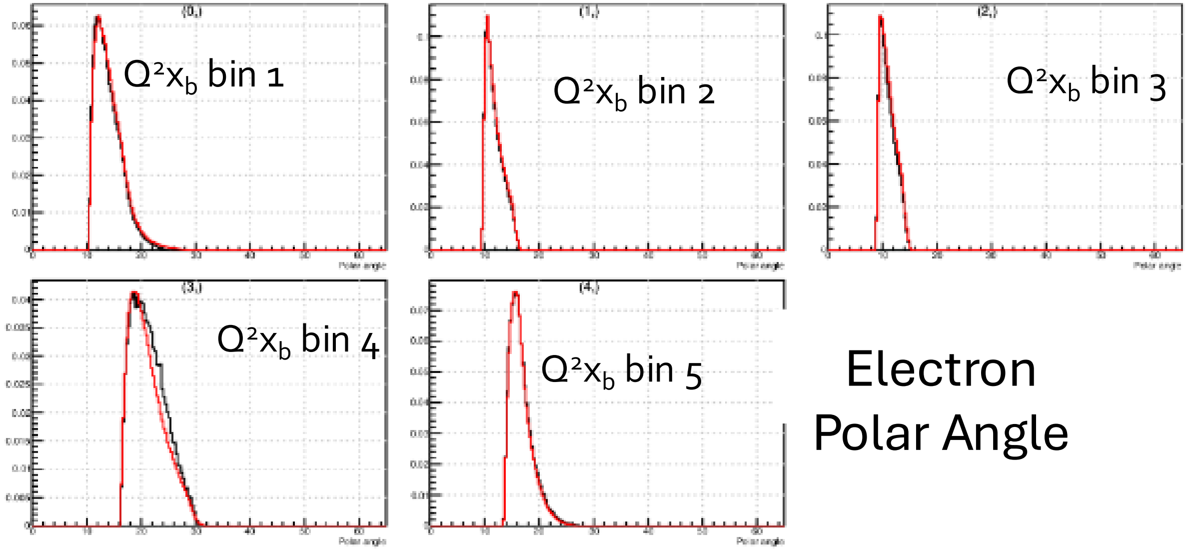
Q^2



x_b



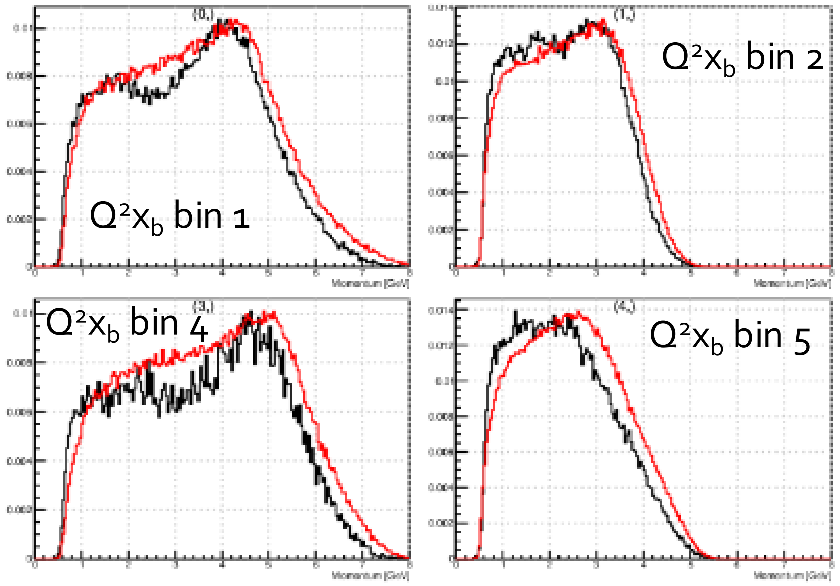
Electron Momentum



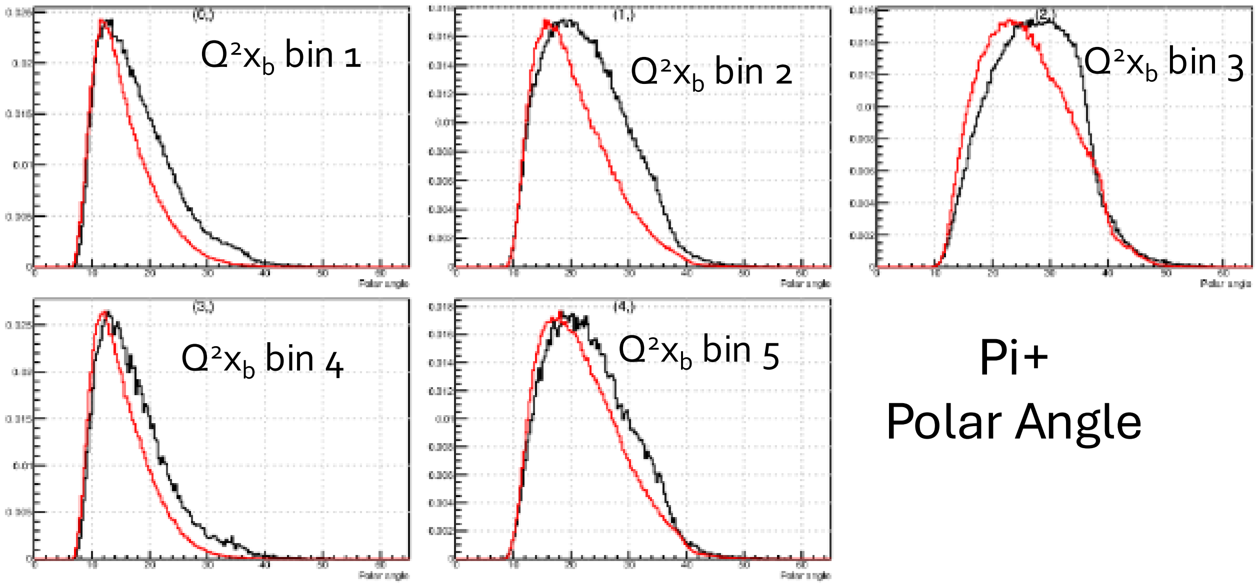
Electron Polar Angle

Systematic Studies: Monte Carlo Simulation

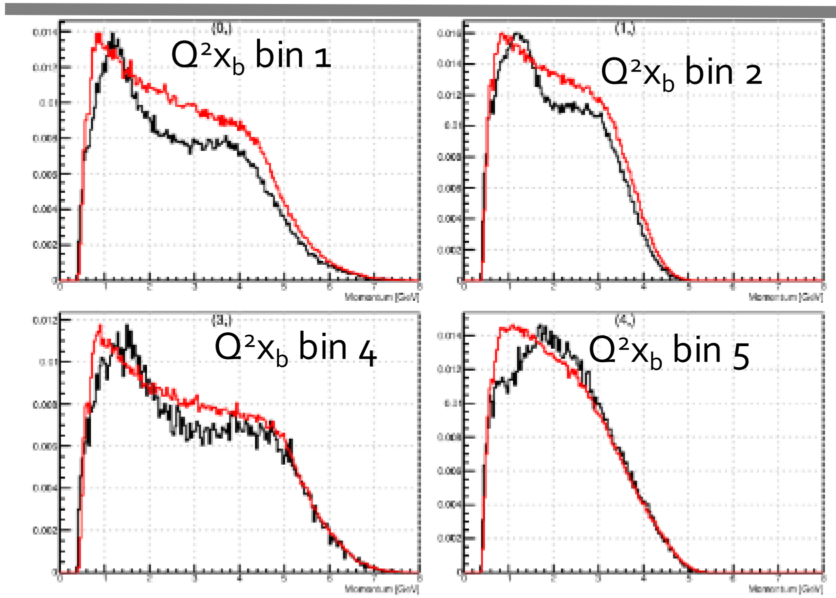
- Data
- MC,weighted



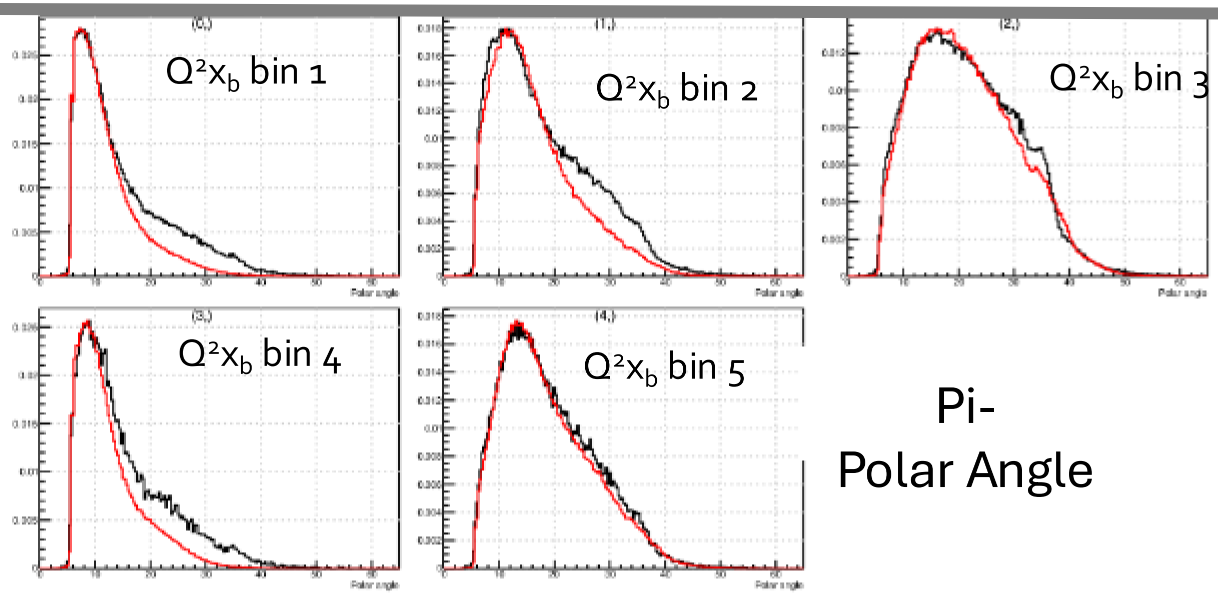
Pi+
Momentum



Pi+
Polar Angle

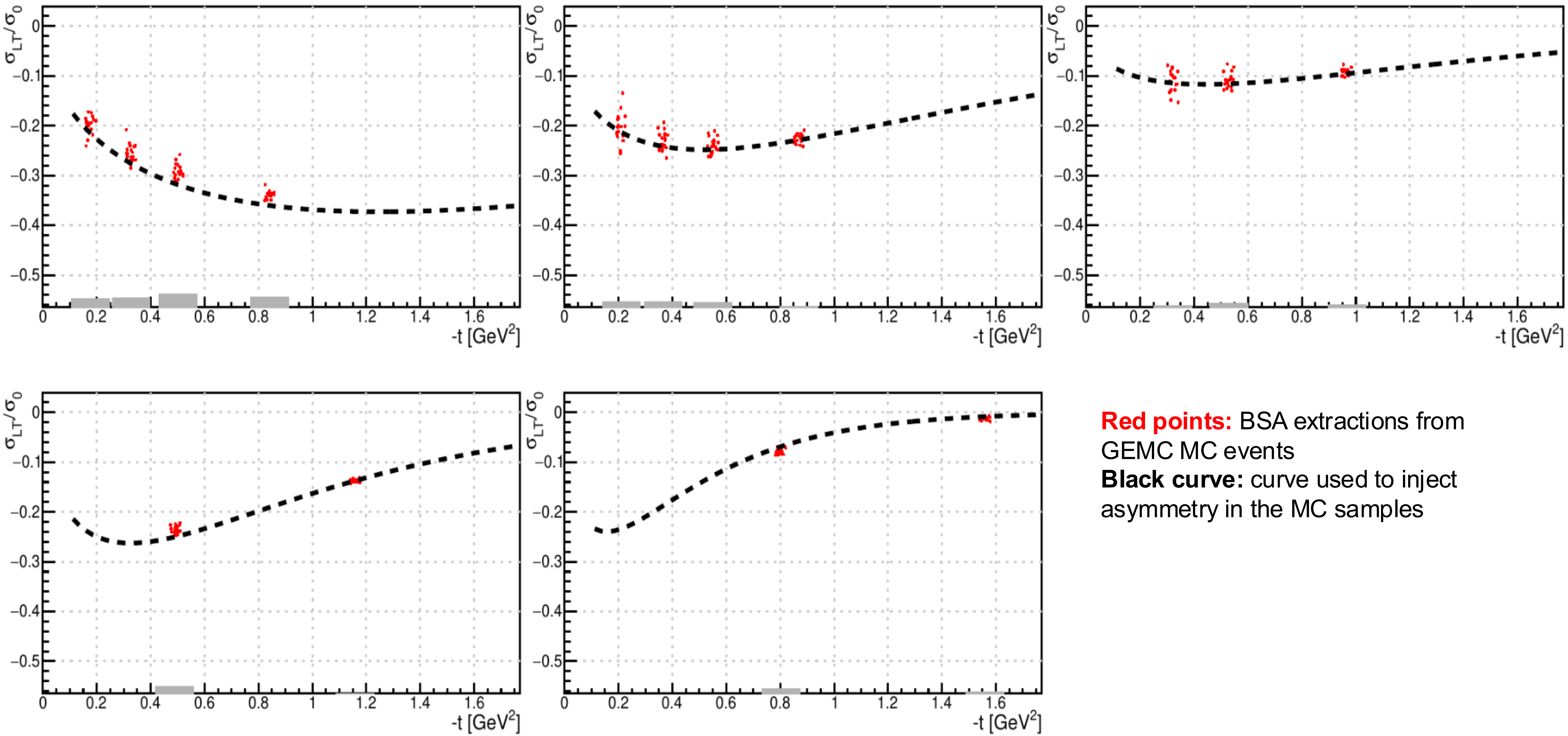


Pi-
Momentum



Pi-
Polar Angle

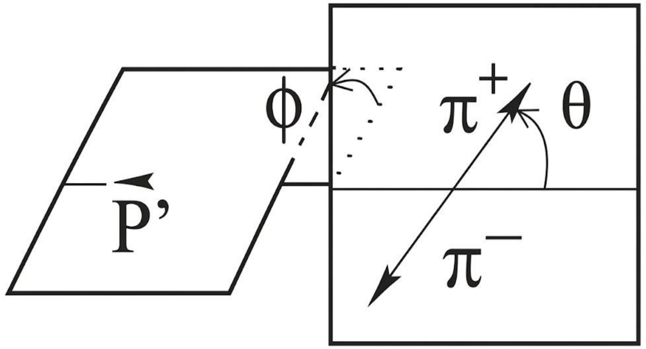
Effect of the CLAS12 acceptance

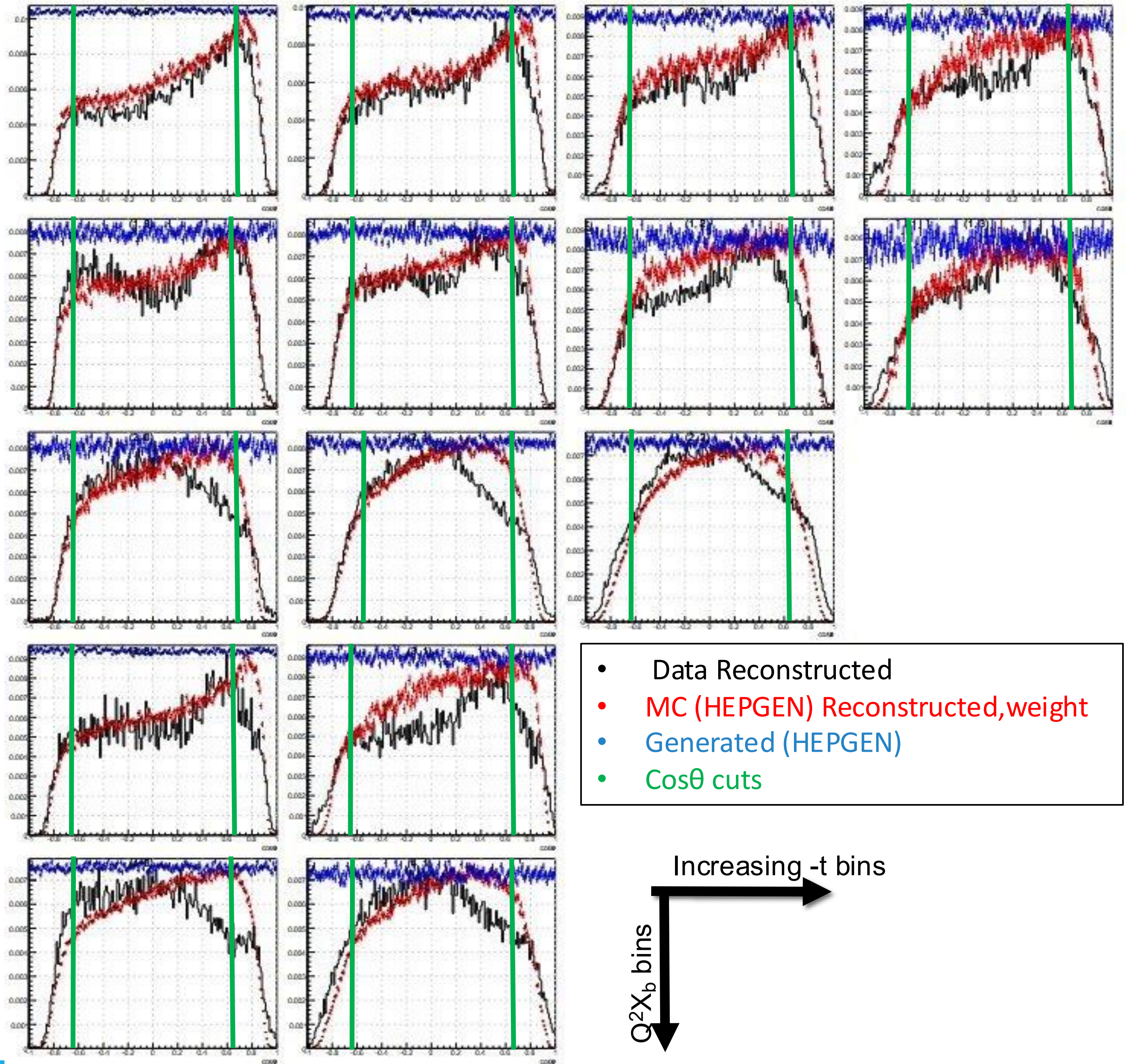


Red points: BSA extractions from GEMC MC events
Black curve: curve used to inject asymmetry in the MC samples

Acceptance of cosθ

- Low Acceptance was found near the edge of the cosθ distributions
- A cut was created -0.65 < cosθ< 0.65
    - Evaluated different systematic values at different limits to find the best cutting location





Outlook

- Analysis review recently completed
  - Preparation of the corresponding publication is currently in progress
  - looking into systematics associated with acceptance of second phi angle,ϕ, in decay plane

- The extraction of the Spin Density Matrix Elements
  - Extract using the Maximum Likelihood Method (MLM)
  - For MLM, we are looking into injection of background in MC

$$A_{LU}^{sin\Phi} \sim (r^{8}_{00}) \sim IM[2M^{\rho^0 *}_{0+,++}M^{\rho^0}_{0+,0+} + M^{\rho^0 *}_{0-,++}M^{\rho^0}_{0-,0+}]$$

Thank You!

References

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- K. SCHILLING and G. WOLF. “HOW TO ANALYSE VECTORMESON PRODUCTION IN INELASTIC LEPTON SCATTERING”.In: North-Holland Publishing Company (23 May 1973), pp. 381–413. url:http://nuclear.ucdavis.edu/~bhaag/NewPage/references/K._Schilling_and_G._Wolf,_Nucl._Phys._B61,_381_(1973).pdf.

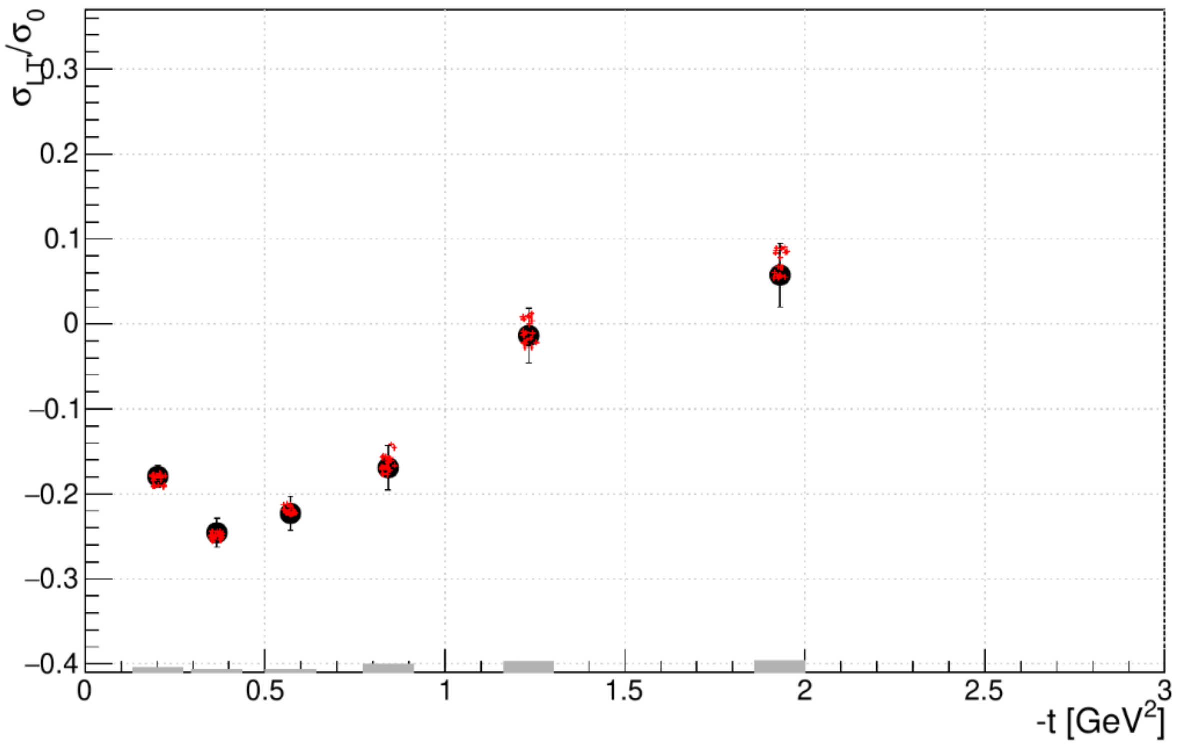
- COMPASS Collaboration. “Spin density matrix elements in exclusive ρ0 meson muoproduction”. In: Eur. Phys. J. C (2023). url: https://doi.org/10.1140/epjc/s10052-023-11359-4.

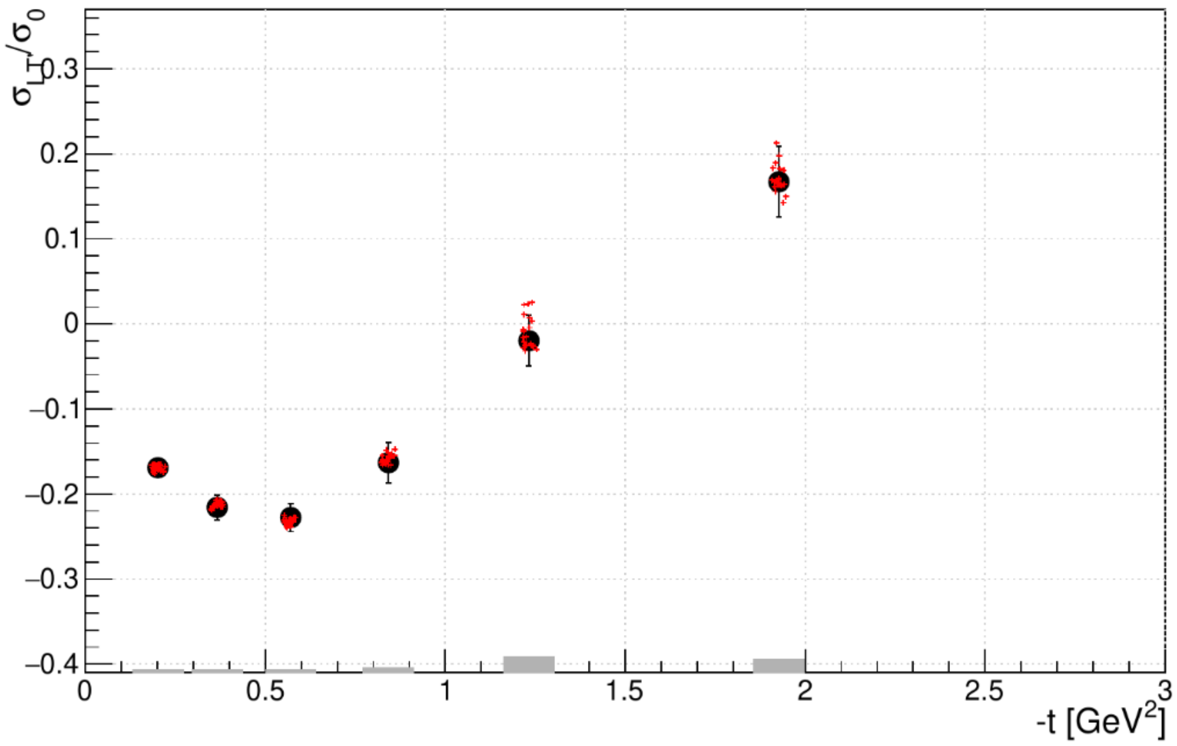
Backup

Systematic study of non-exclusive background separation

Red points represent BSAs extracted for different missing-mass cut configurations, corresponding to different levels of background contributions:

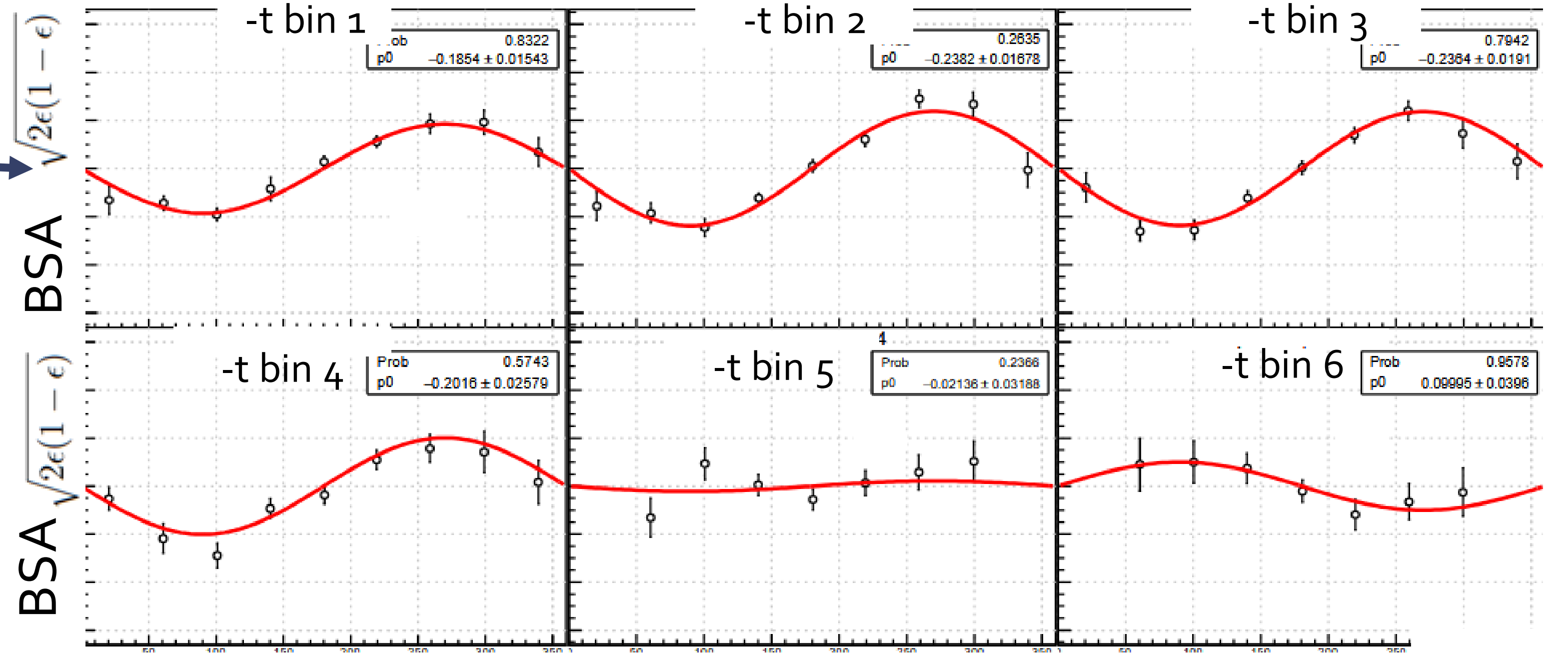
- 1 - 1.2 GeV with 0.1 step
- 21 variations



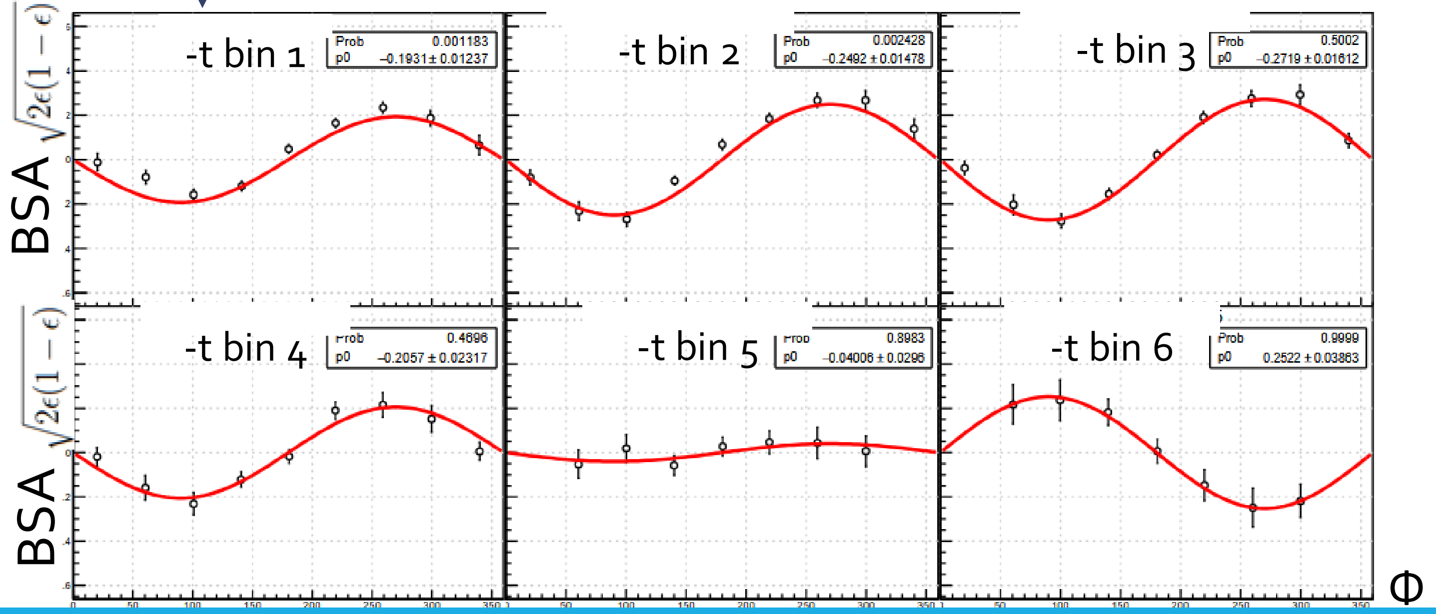


1D Bins in -t: BSA

Inbending



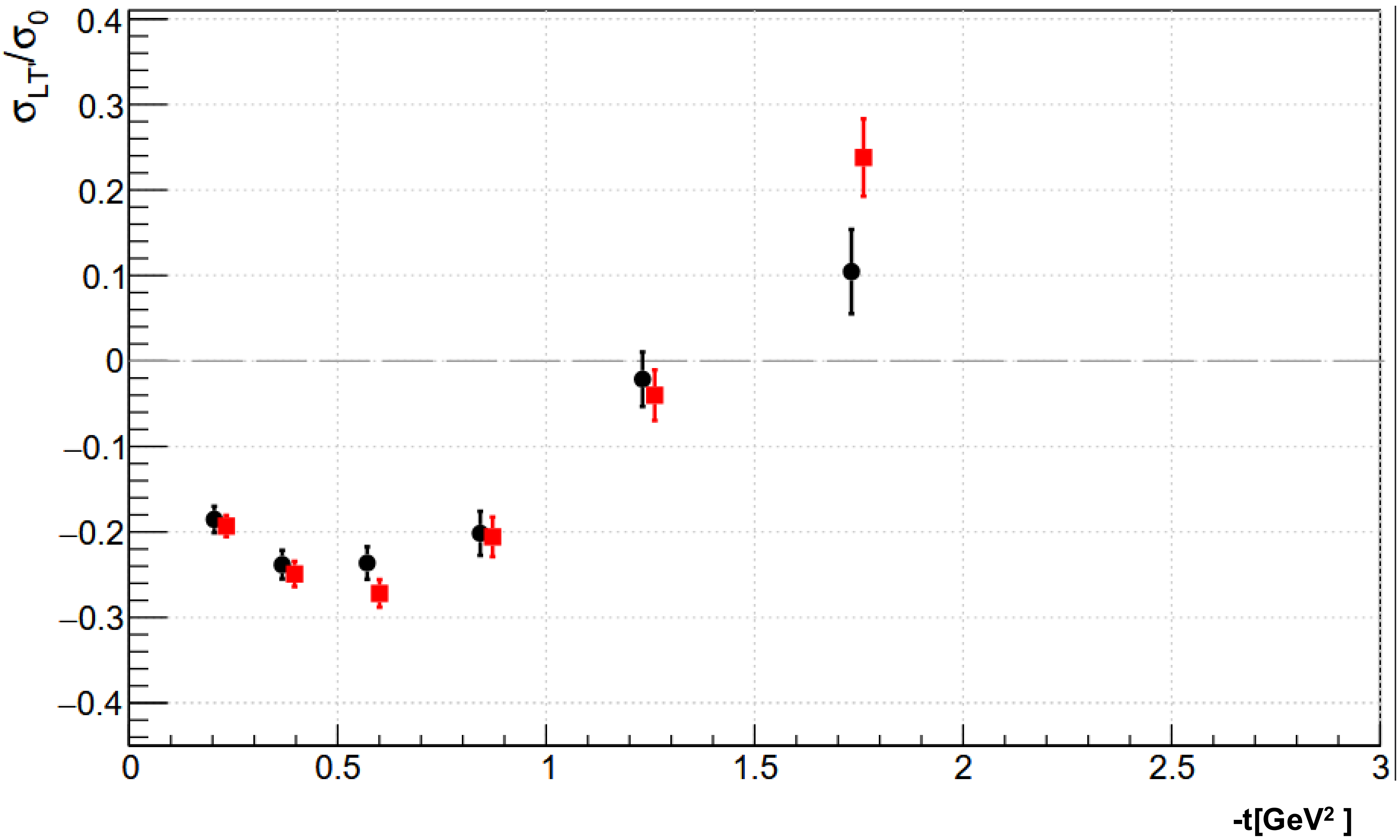
Outbending



$$BSA = \frac{1}{P_b}\frac{N_i^+ - N_i^-}{N_i^+ + N_i^-}$$

$$BSA = A_{LU} \sin\phi$$

1D Bins in -t: $\sigma_{LT`}/\sigma_0$ for both inbending and outbending

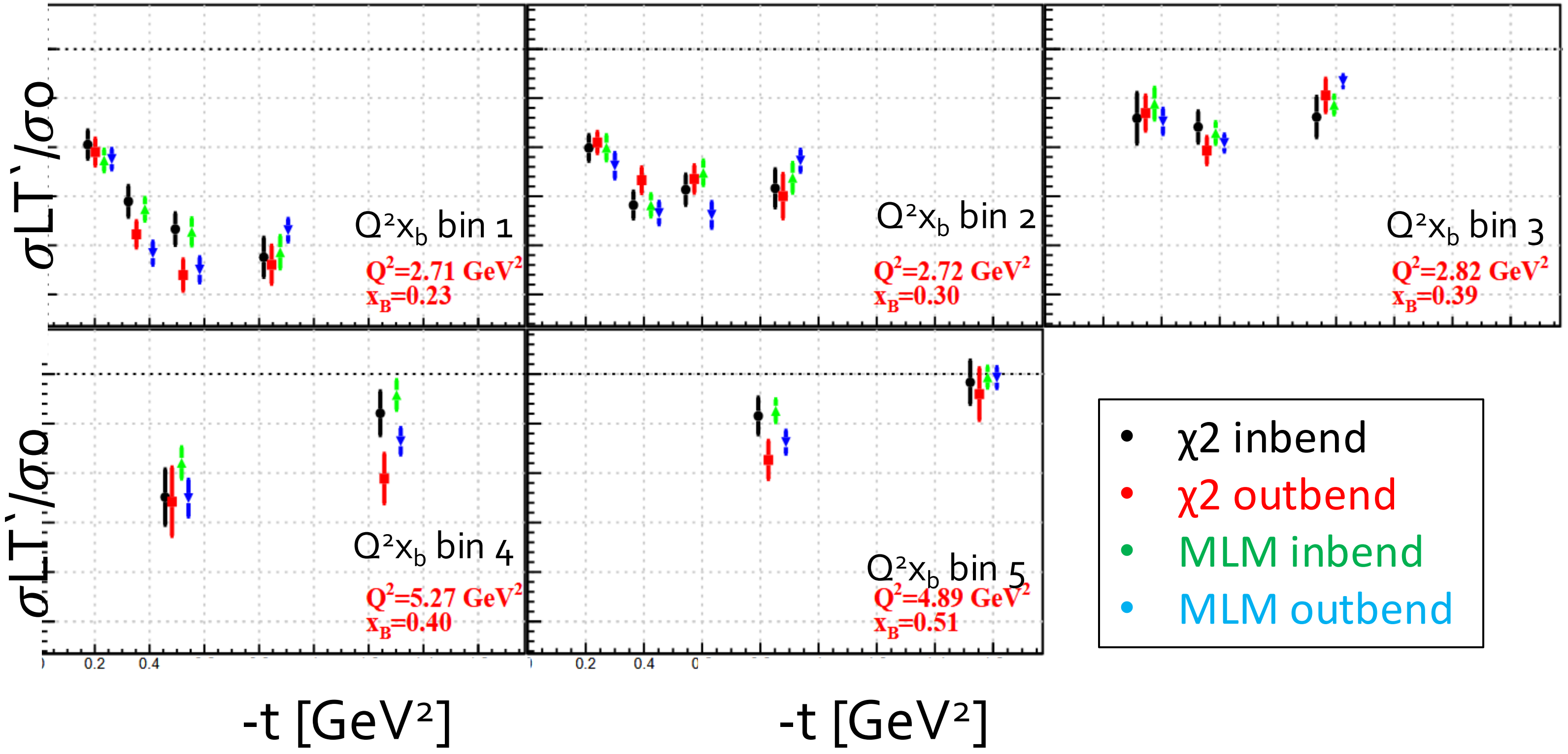


$$A_{LU}^{\sin\phi} = \sqrt{2\epsilon(1-\epsilon)}\frac{\sigma_{LT'}^{\sin\phi}}{\sigma_0}$$

$$BSA = A_{LU}\sin\phi$$

Monte Carlo Simulation-Maximum Likelihood Method

- As a cross check for the χ2 technique, we used the Maximum Likelihood Method (MLM) to find the σLT` /σ0 terms
- The Maximum Likelihood minimizes the negative log of the likelihood function without needing kinematic binning
- To remove the background, a side band method implemented
    - MLM fits are preformed in each side band
    - the side band results are removed proportionally in our signal region using the ratio of signal to background, Fs
    - Fs is found using the kinematic fit described by the chi2 method



Includes invariant mass cut: 0.6 < IM < 0.9 GeV