Exclusive ρ^0 Beam Spin Asymmetries from RGA

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CLAS12 Collaboration Meeting

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Deeply Virtual Meson Production and GPDs

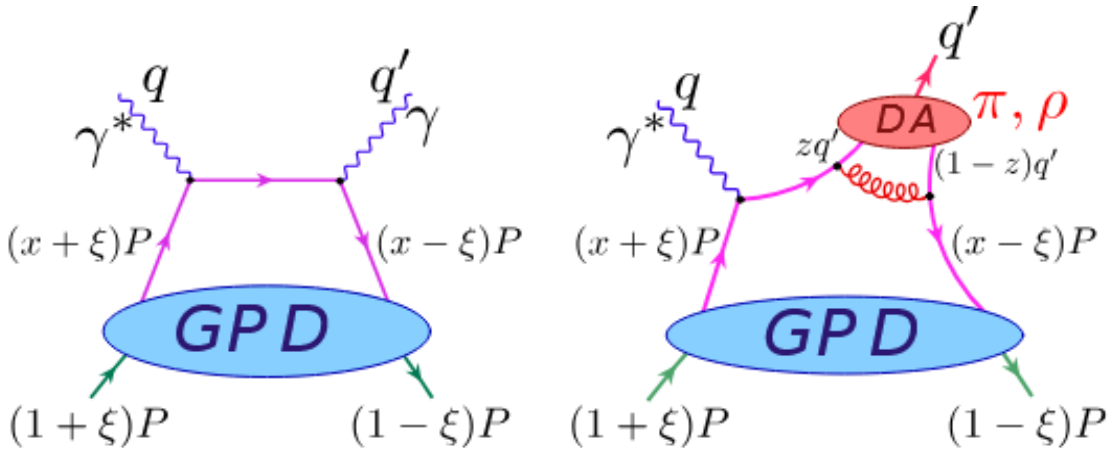
- Generalized Parton Distributions (GPDs) give insight into the 3D structure of hadrons
- Deeply Virtual Compton Scattering (DVCS) and Deeply Virtual Meson Production (DVMP) as techniques to access GPDs
- Vector Meson access H,E
- Pseudoscalar Mesons access $\tilde{H}, \tilde{E}$
- Chiral Odd GPDs: $\bar{E}_T, \tilde{E}_T, H_T, \tilde{H}_T$

$$\bar{E}_T = 2\tilde{H}_T + E_T$$

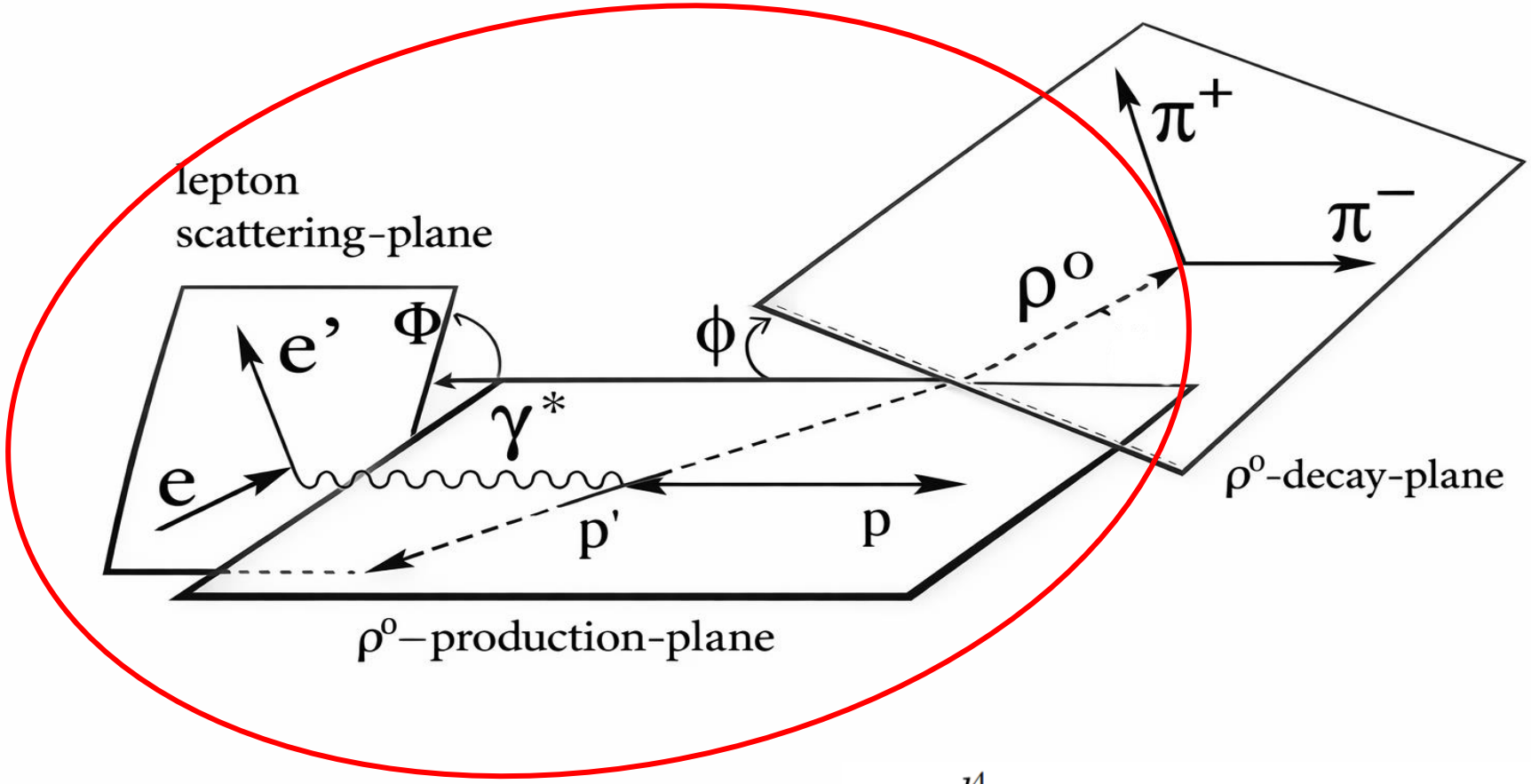
- Different Channels access different GPDs

ω, ρ⁰, ϕ, (J/ψ)

Chiral Even GPDs



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

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

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

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

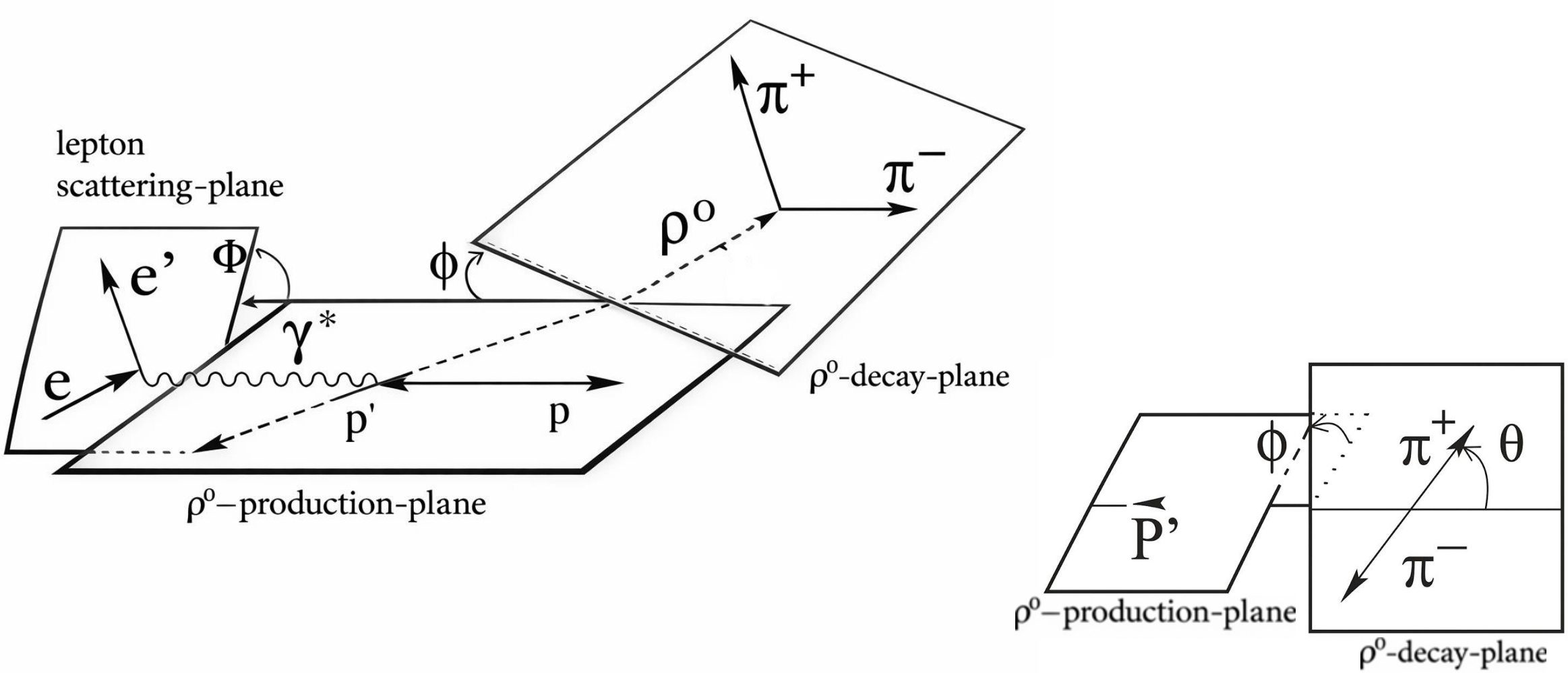
$$BSA = \frac{\sigma^+ - \sigma^-}{\sigma^+ + \sigma^-} = \frac{\sqrt{2\varepsilon(1-\varepsilon)}\,\frac{\sigma_{LT'}}{\sigma_0}\sin\phi}{1 + \sqrt{2\varepsilon(1+\varepsilon)}\,\frac{\sigma_{LT}}{\sigma_0}\cos\phi + \varepsilon\,\frac{\sigma_{TT}}{\sigma_0}\cos 2\phi}$$

- 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 $\bar{E}_T$

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

Ref:
S. V. Goloskokov and P. Kroll. “Transversity in exclusive vector-meson leptoproduction”. In: The European Physical Journal C 74.2 (Feb. 2014). doi: 10.1140/epjc/s10052-014-2725-6. url: https://doi.org/10.1140%2Fepjc%2Fs10052-014-2725-6

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

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

15 unpolarized terms

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

8 polarized terms

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

Beam Spin Asymmetry

$$\sigma_{LT'}^{sin\Phi} \sim (r_{00}^{8}) \sim IM[2M_{0+,++}^{\rho^0 *} M_{0+,0+}^{\rho^0} + M_{0-,++}^{\rho^0 *} M_{0-,0+}^{\rho^0}]$$
$$\sim [\bar{E}_T H + H_T E]$$

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

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

r^8_{00} leading order term

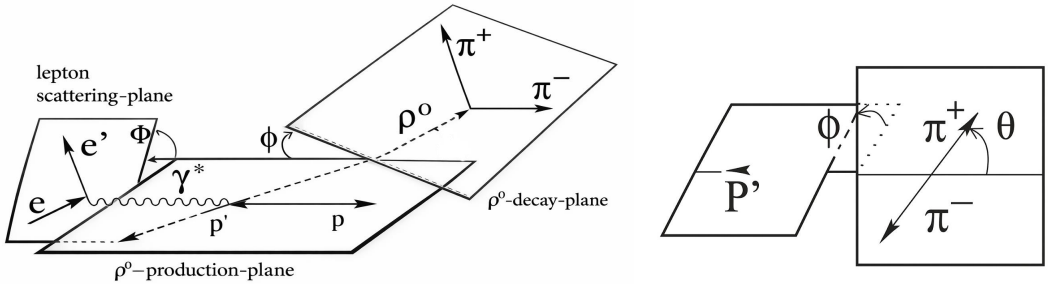
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Overview

- Data Set: RGA's Fall 2018 data -> polarized (~85%) 10.6 GeV electron beam on an unpolarized liquid hydrogen target
- Channel: $ep \rightarrow e\rho^0 p \rightarrow e\pi^+\pi^-(p)$
- Exclusive Cuts: $0.65 < \text{Missing Mass} < 1.1$ Gev, $Q^2 > 2$ GeV^2, $W > 2$ GeV, $-0.65 < \cos\theta < 0.65$
- Monte Carlos: Exclusive ρ^0- HepGen, Background SIDIS - CLASDIS

4D Cross Section (Q2,xb,-t, Φ)

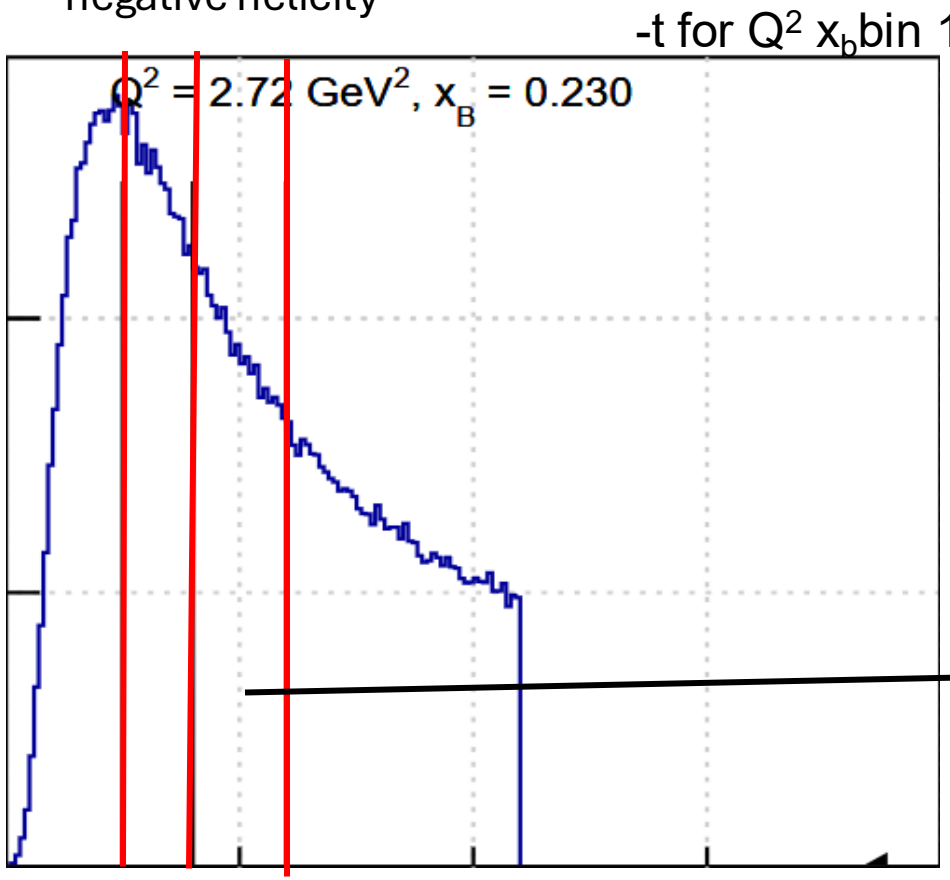
1. χ^2 fit on different helicity
2. Calculate BSA in 3D bins {Q2,xB,–t} as a function of Φ
3. Extract $A_{\sin\Phi}^{LU}$ as function of –t for 2D bins {Q2,xB}

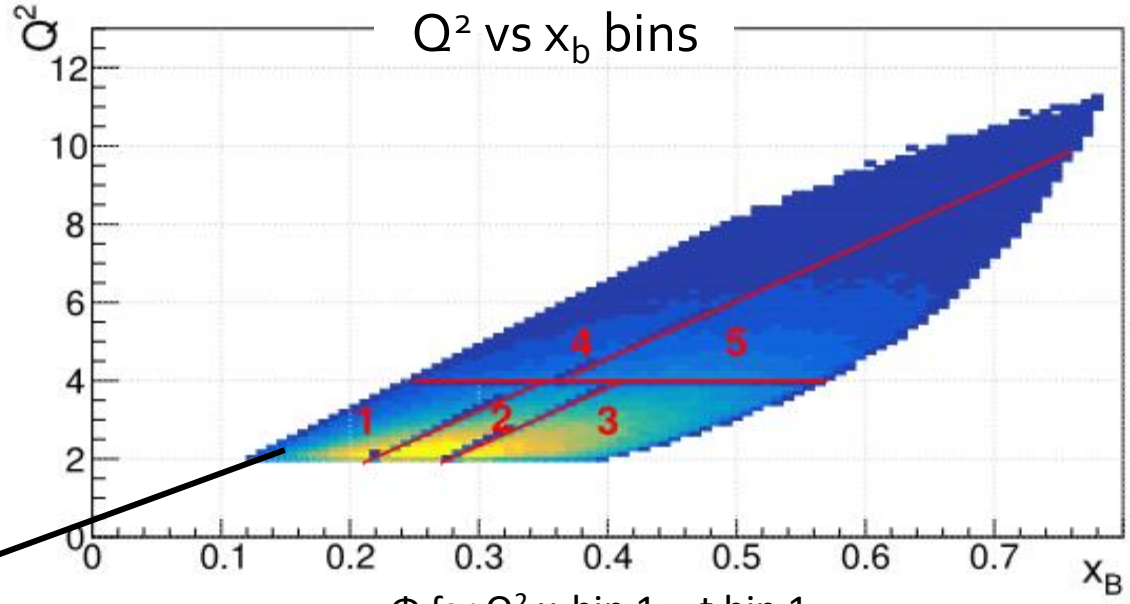


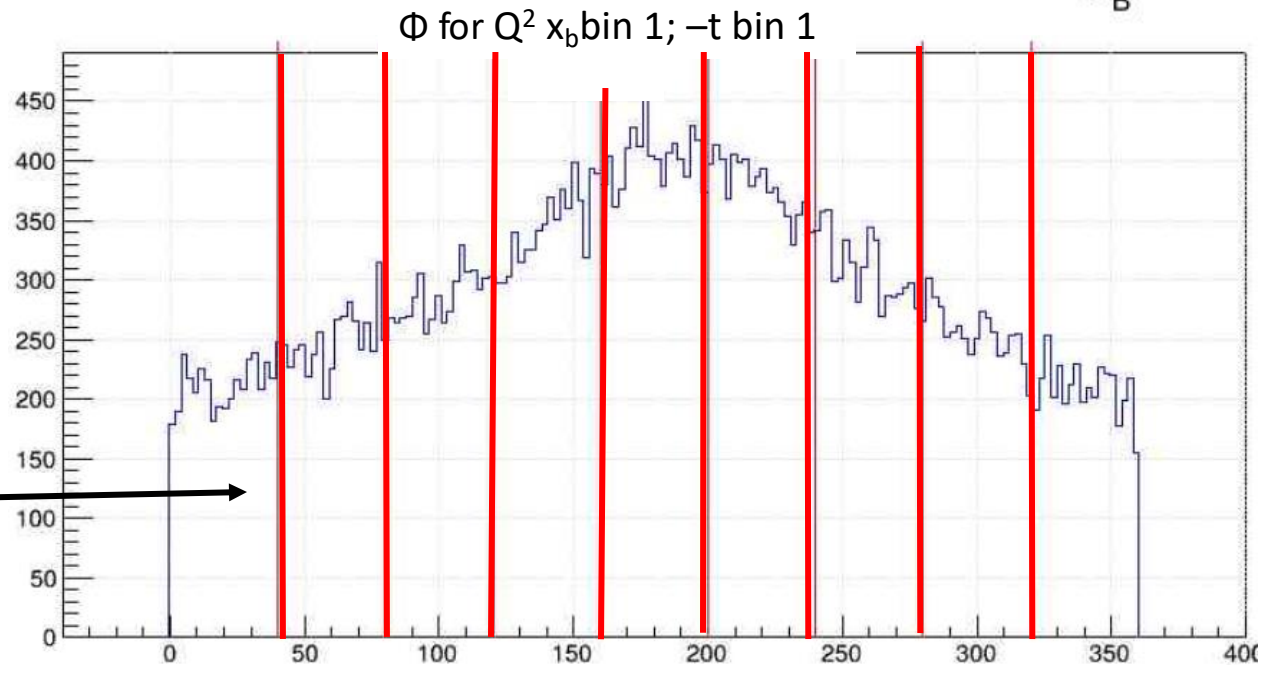
4D Cross Section (Q2,xb,-t, Φ)

Kinematic Binning

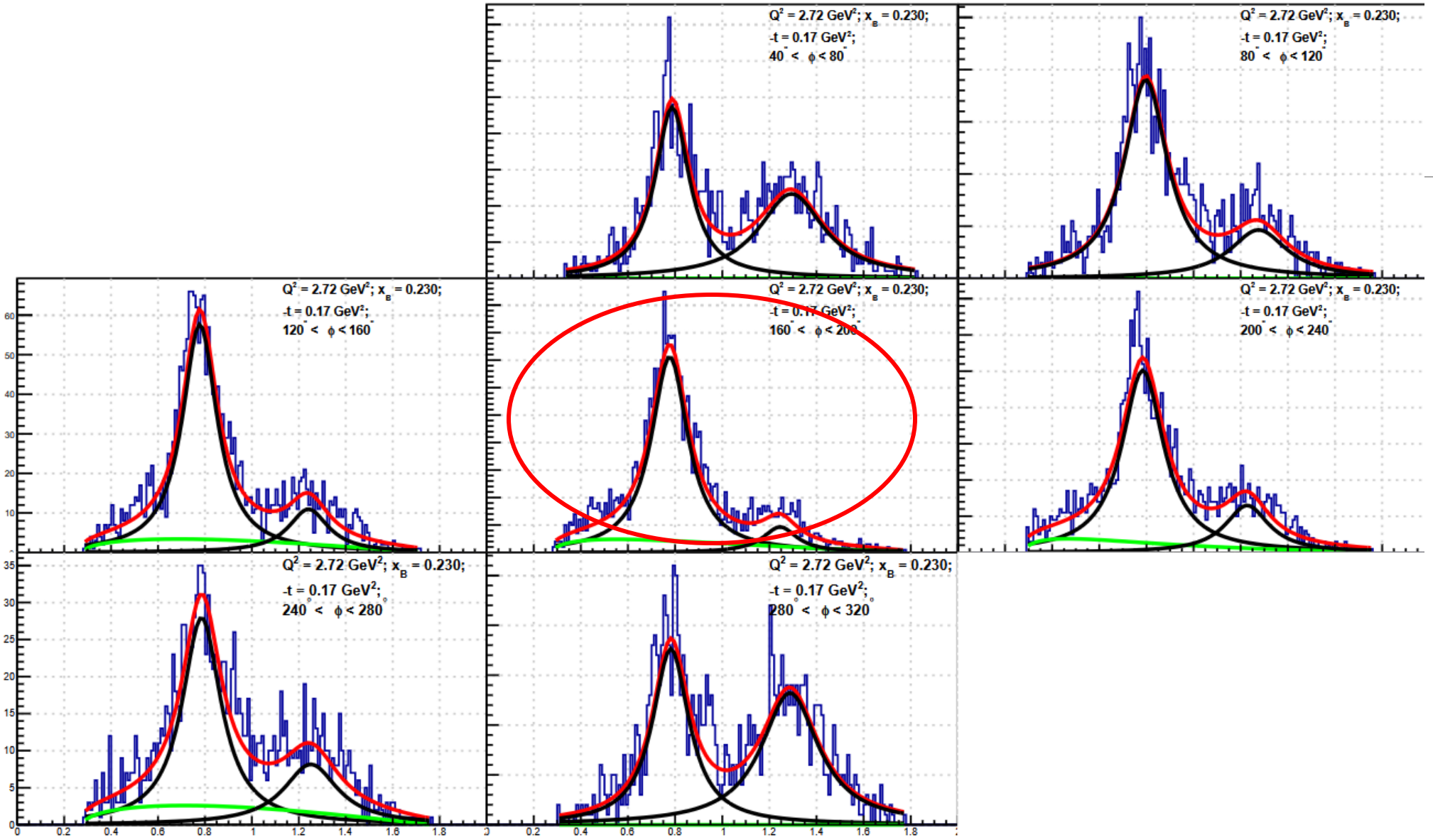
- 5 Kinematic bins are created in Q2 and xB
- Each of these 5 bins is further divided into –t plots
- In each –t bin, the events are further divided into 9 equidistance bins in Φ
- In Φ bins, each event is binned into positive or negative helicity



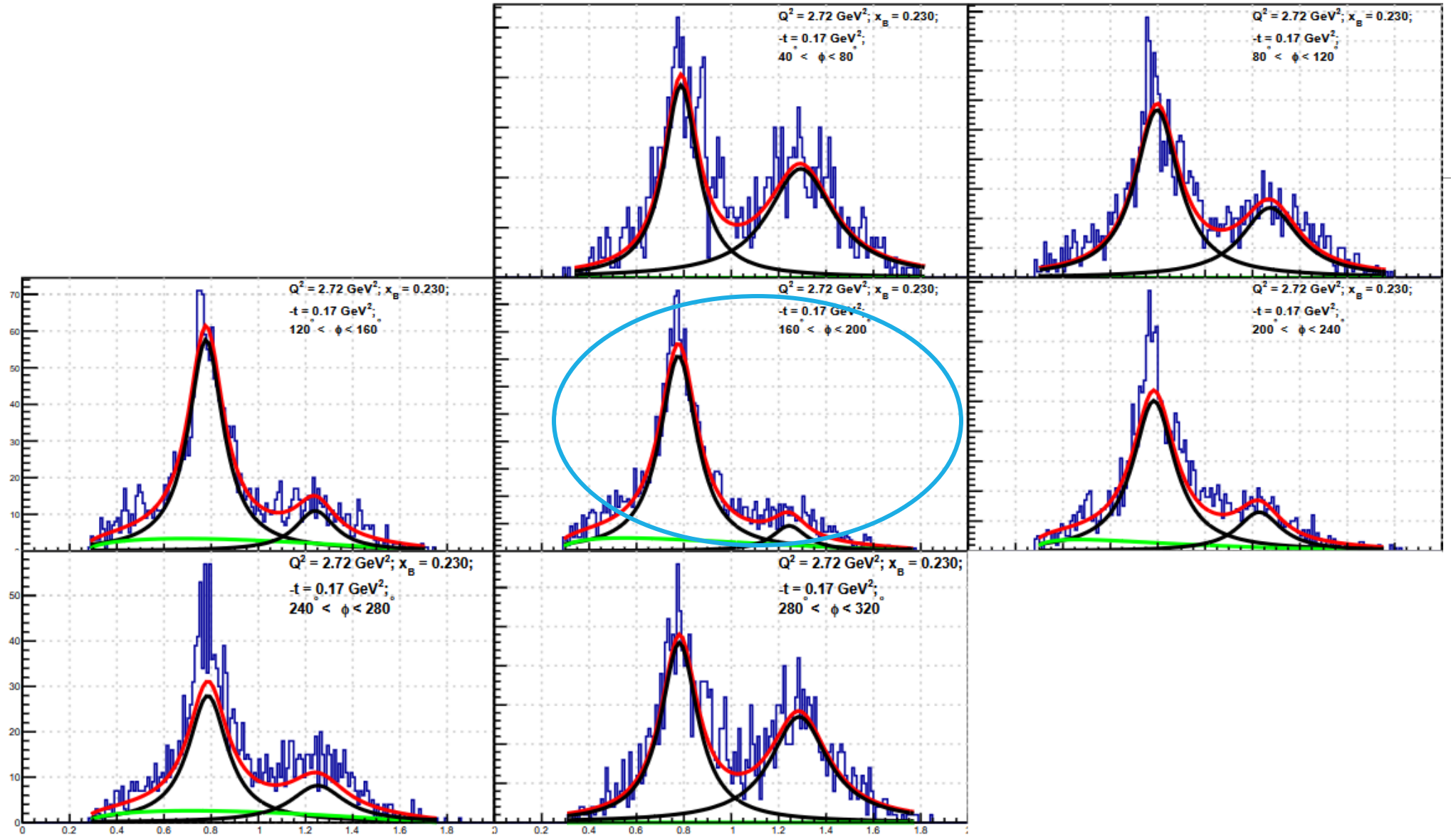




Invariant Mass with Positive Helicity (Q2xB bin 1; –t bin 3)



Invariant Mass with Negative Helicity (Q2xB bin 1; -t bin 3)



Calculation of BSA

Pb is the average beam polarization, 0.8692

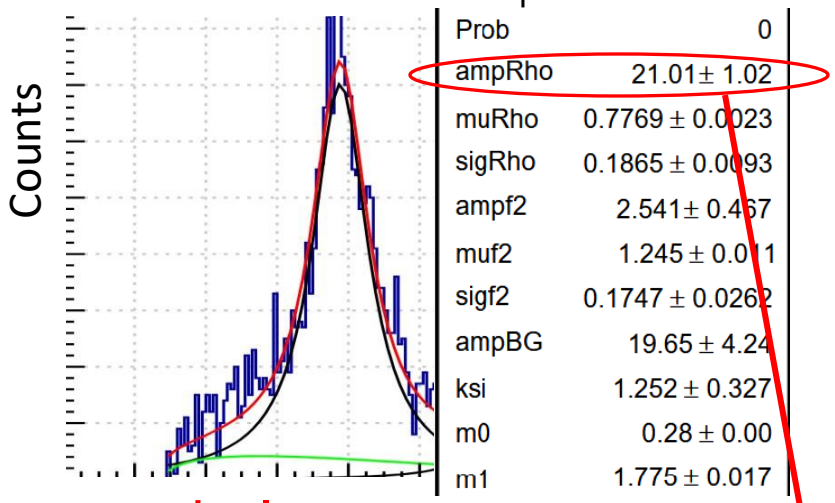
Breit Wigner:

$$F_x^{\mathrm{BW}}(M_{\pi\pi}) = \frac{N_x \Gamma_x}{(M_{\pi\pi} - M_x)^2 + \Gamma_x^2/4}$$

An ARGUS inspired function for general background:

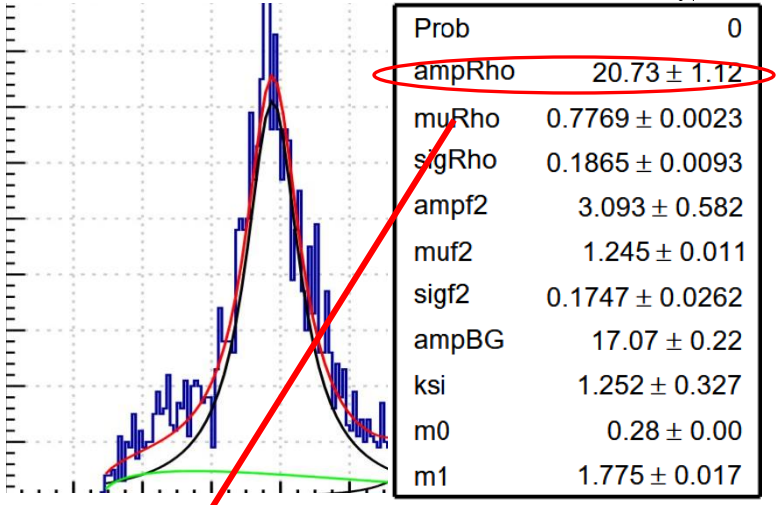
$$F^{\mathrm{BG}}(M_{\pi\pi}) = N_{\mathrm{bg}} \left(1 - \frac{M_{\pi\pi}^2}{M_{\mathrm{max}}^2}\right)^{1/2} \exp\left[-\alpha \left(1 - \frac{M_{\pi\pi}^2}{M_{\mathrm{max}}^2}\right)\right]$$

Invariant Mass of pions



positive helicity

Invariant Mass of pions



Negative helicity

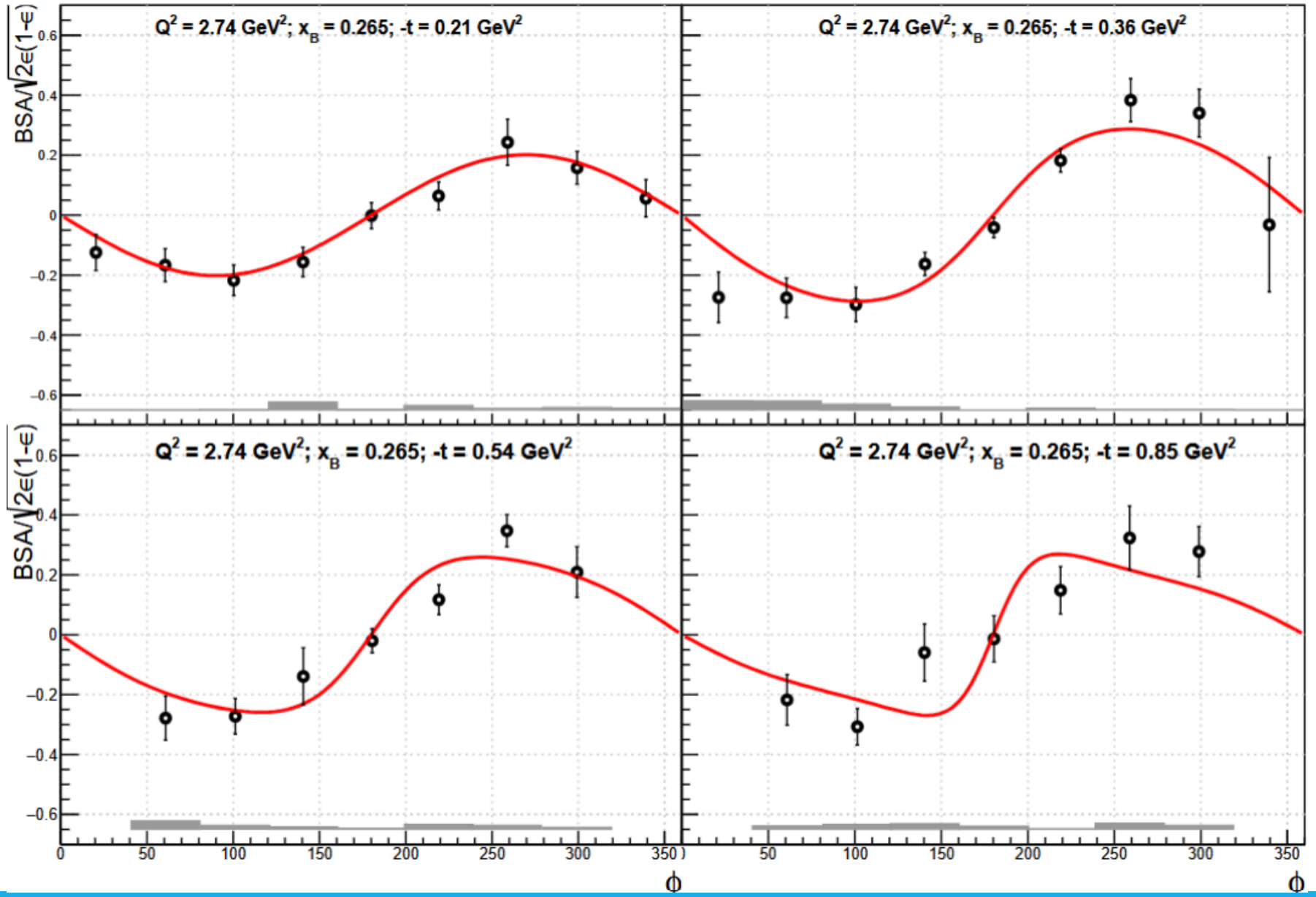
- BW1
- BW2
- Generl Bkg
- Total Fit

$$\mathrm{BSA}_i = \frac{1}{P_b} \frac{N^+_{\rho^0,i} - N^-_{\rho^0,i}}{N^+_{\rho^0,i} + N^-_{\rho^0,i}}$$

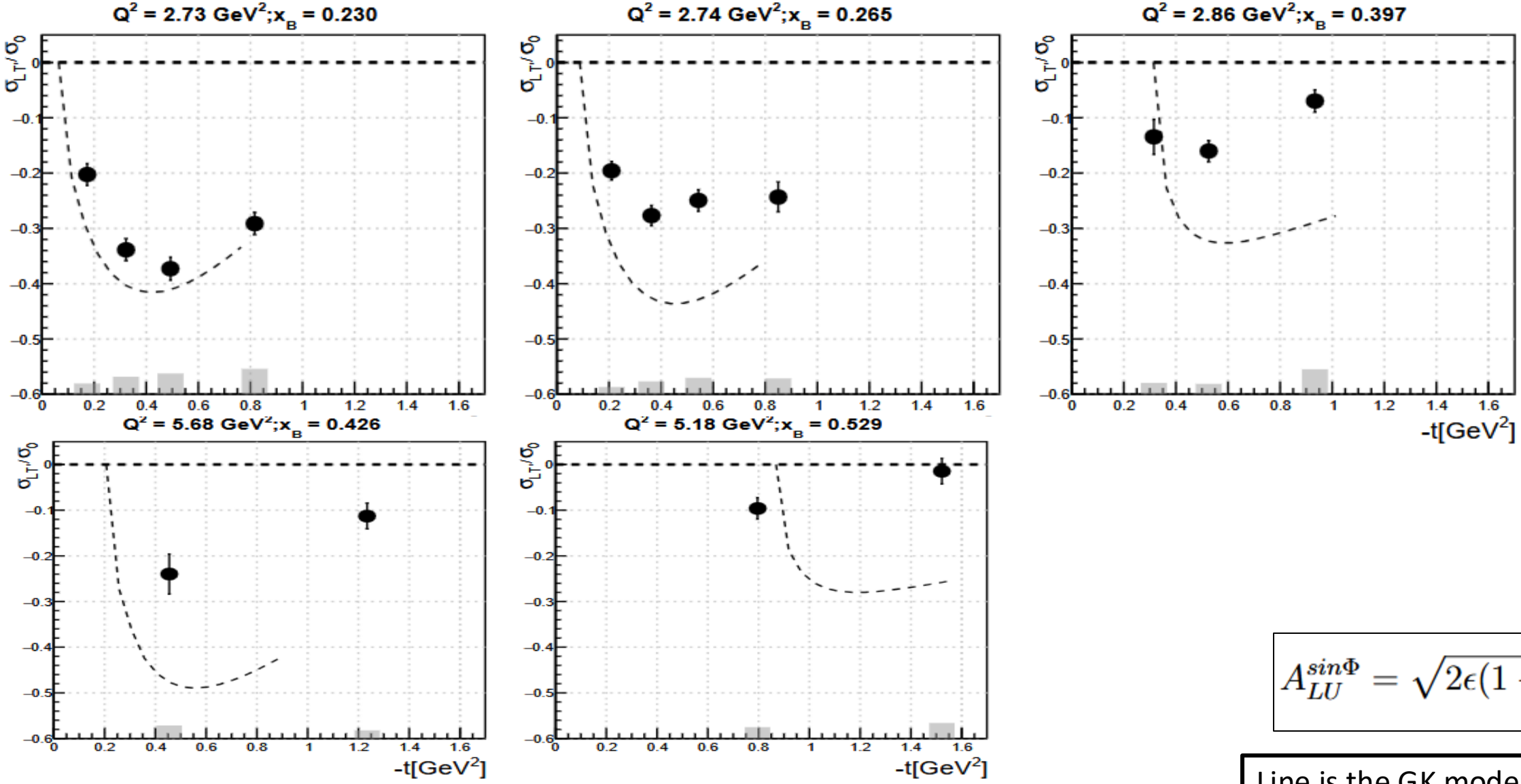
- The signal after background subtraction is taken from both invariant mass distributions
  - full 4 dimensional space {Q2,xb,-t,phi} in each helicity state
  - 270 Invariant Mass plots fitted; 135 BSA calculations in total

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

$$BSA_i = \frac{1}{P_b} \frac{N^+_{\rho^0,i} - N^-_{\rho^0,i}}{N^+_{\rho^0,i} + N^-_{\rho^0,i}}$$



2D Bins {Q2,xb} as function of -t: $\sigma_{LT'}/\sigma_0$ for combined inbending and outbending



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

Line is the GK model from ref 1

Conclusion and Outlook

- GK framework has interference between amplitudes involving the chiral-even GPD H and the chiral-odd GPDs H_T and $\bar{E}_T$
  - Data matches general behavior of model

- Results are part of a global effort for chiral-odd GPD determination

- The extraction of the Spin Density Matrix Elements

Thank You!

References

• S. V. Goloskokov and P. Kroll. “Transversity in exclusive vector-meson leptoproduction”. In: The European Physical Journal C 74.2 (Feb. 2014). doi: 10 . 1140 / epjc / s10052 - 014 - 2725 - 6. url: https : / /doi.org/10.1140%2Fepjc%2Fs10052-014-2725-6

•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

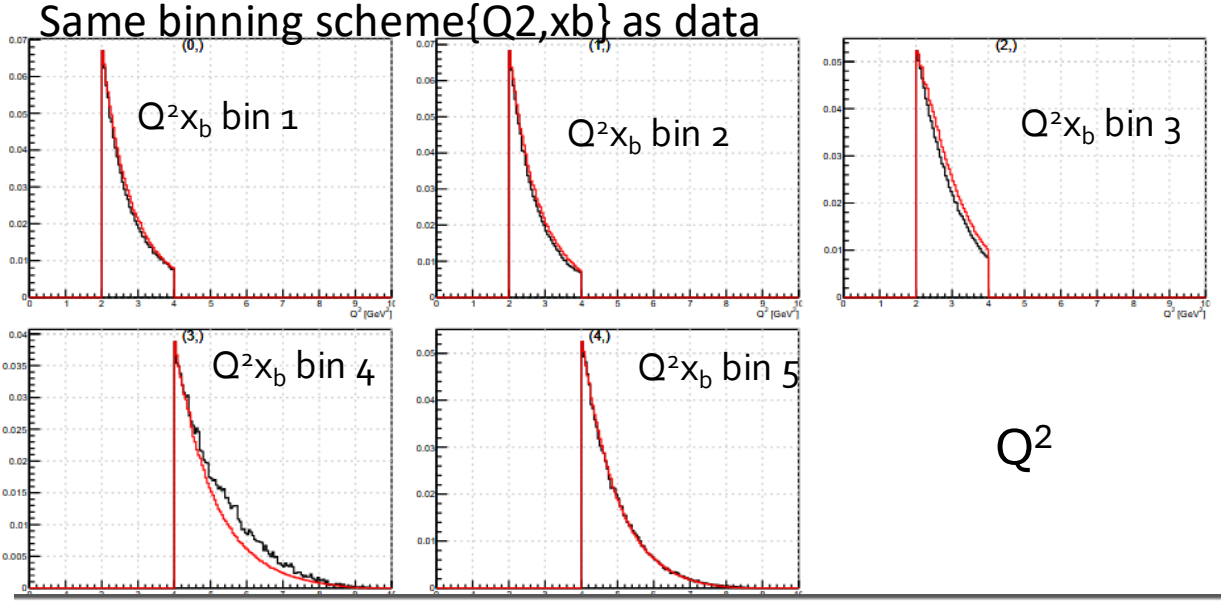
Monte Carlo

Systematic Studies: Monte Carlo Simulation

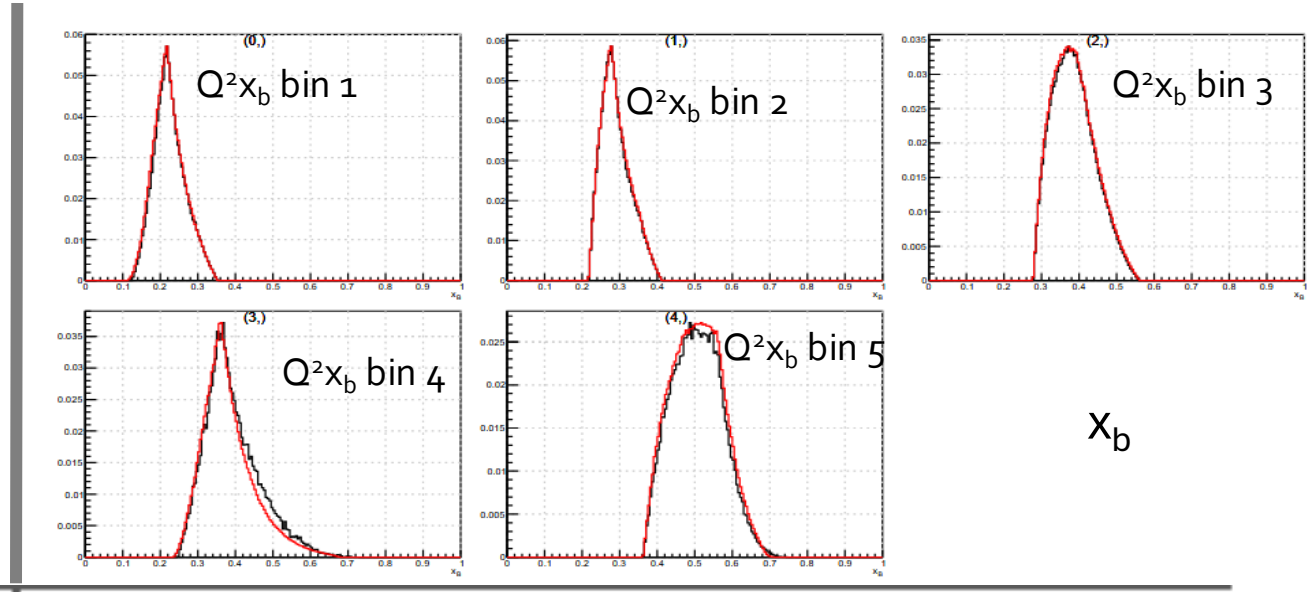
- Data
- MC,weighted

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

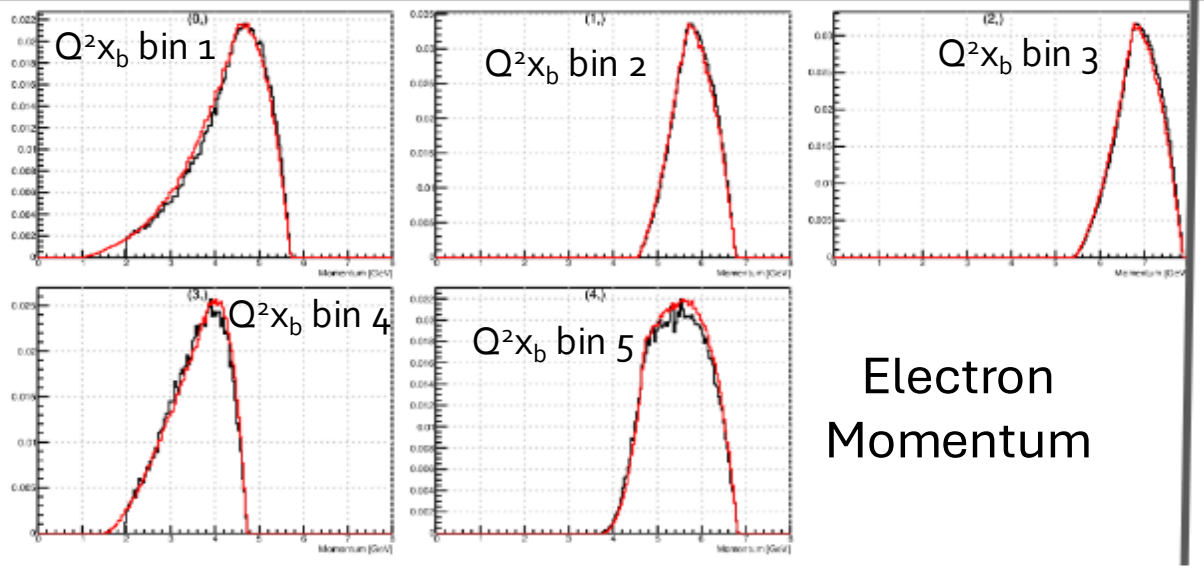
Same binning scheme{Q2,xb} as data



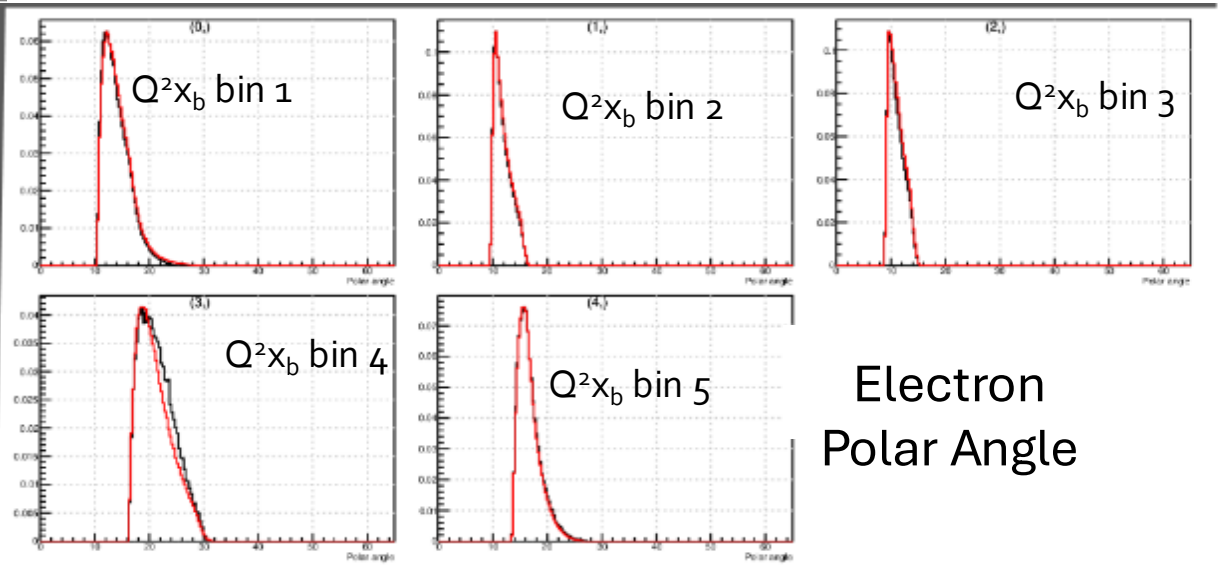
Q^2



x_b



Electron Momentum



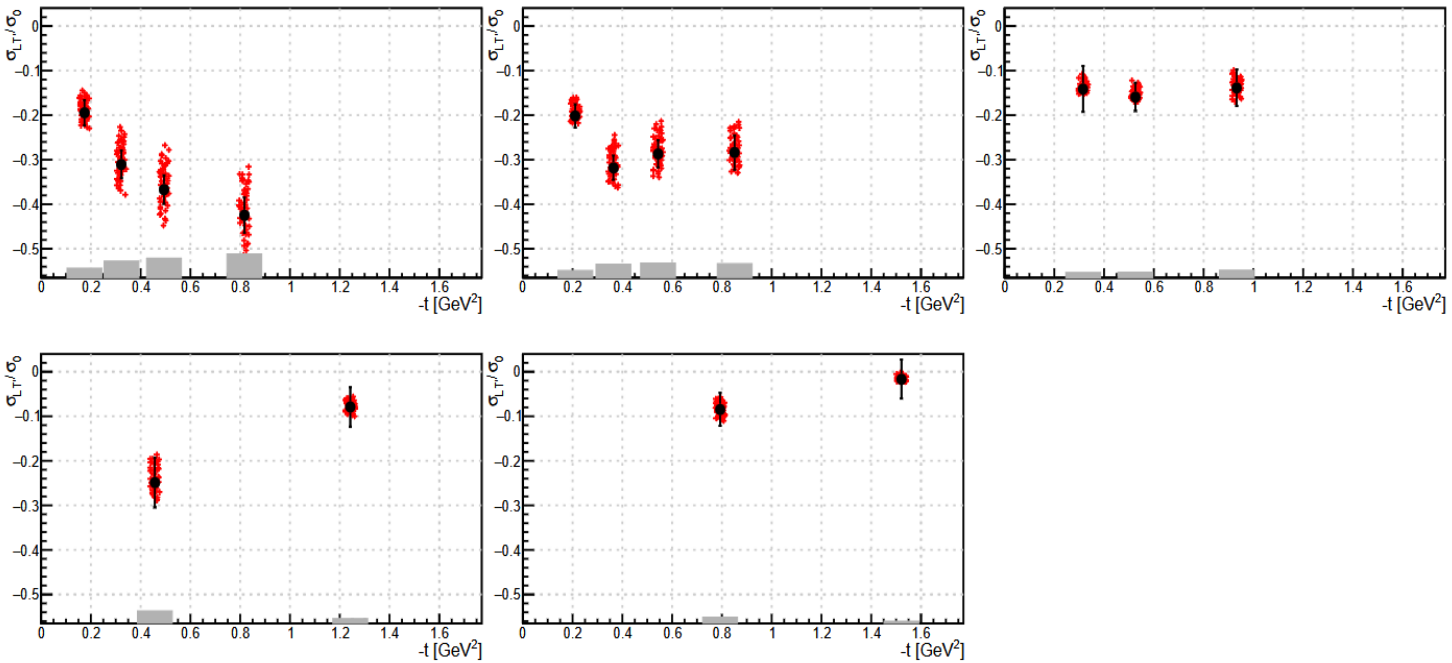
Electron Polar Angle

Systematic Studies

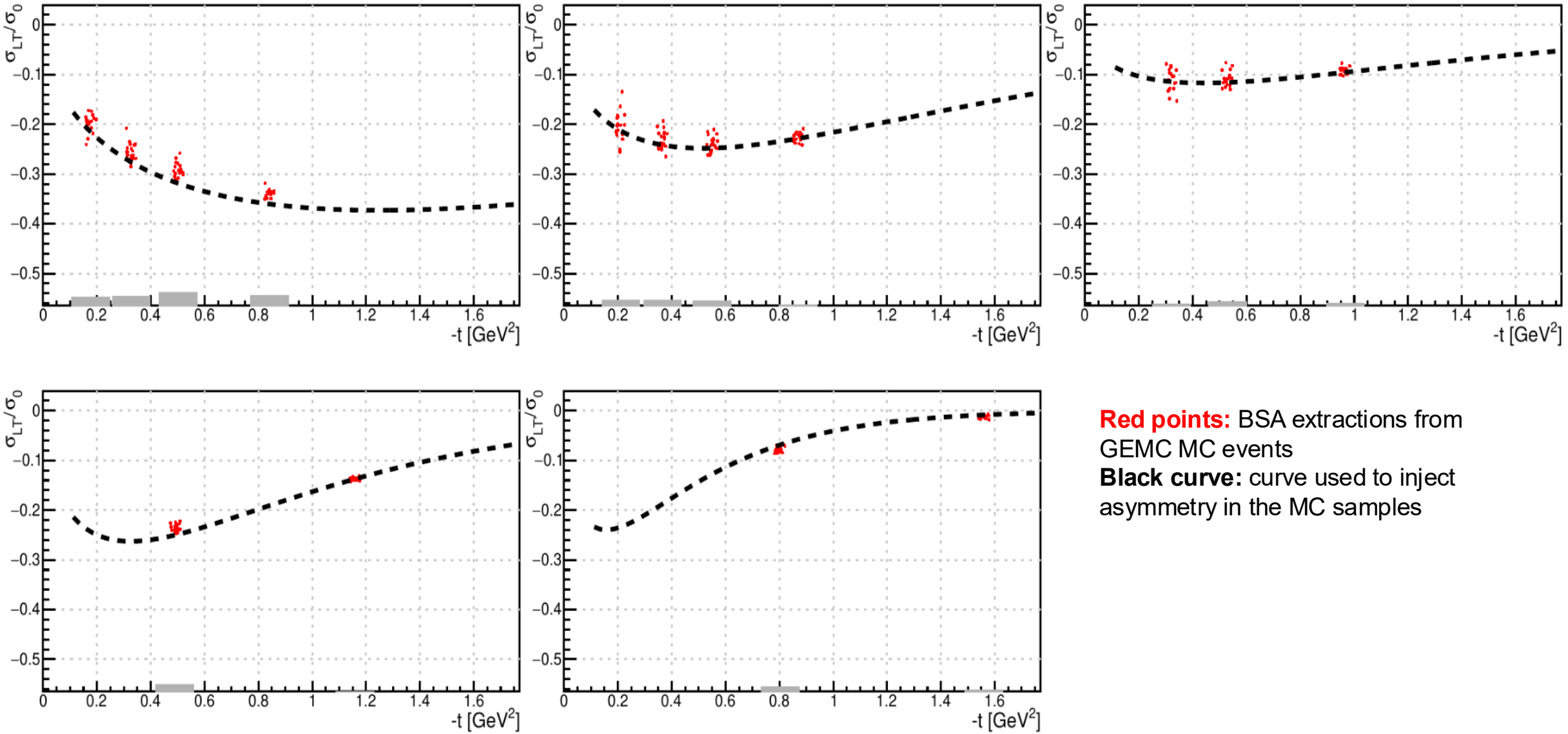
Systematic Studies for χ2

- Uncertainty of Beam Polarization
- Effect of Fiducial Cuts
- Effects on the signal event selection
  - Missing Mass Cut
- Effect of background subtraction
  - Extraction without background removal
- Effect on extraction of higher order terms
  - CosΦ and cos2Φ terms
- Effect on CLAS12 Acceptance
  - Total Acceptance
  - Acceptance of decay angle, cosθ

Inbending- systematic for extraction of higher order terms



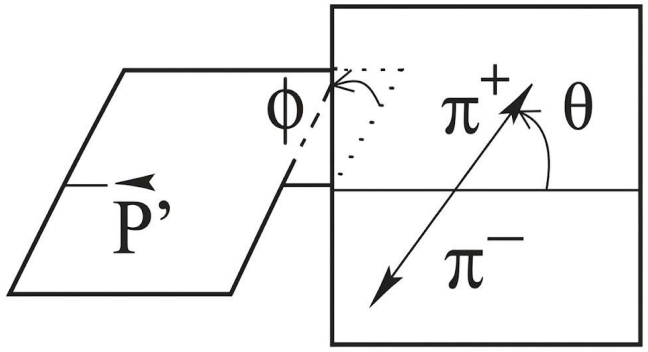
Effect of the CLAS12 acceptance

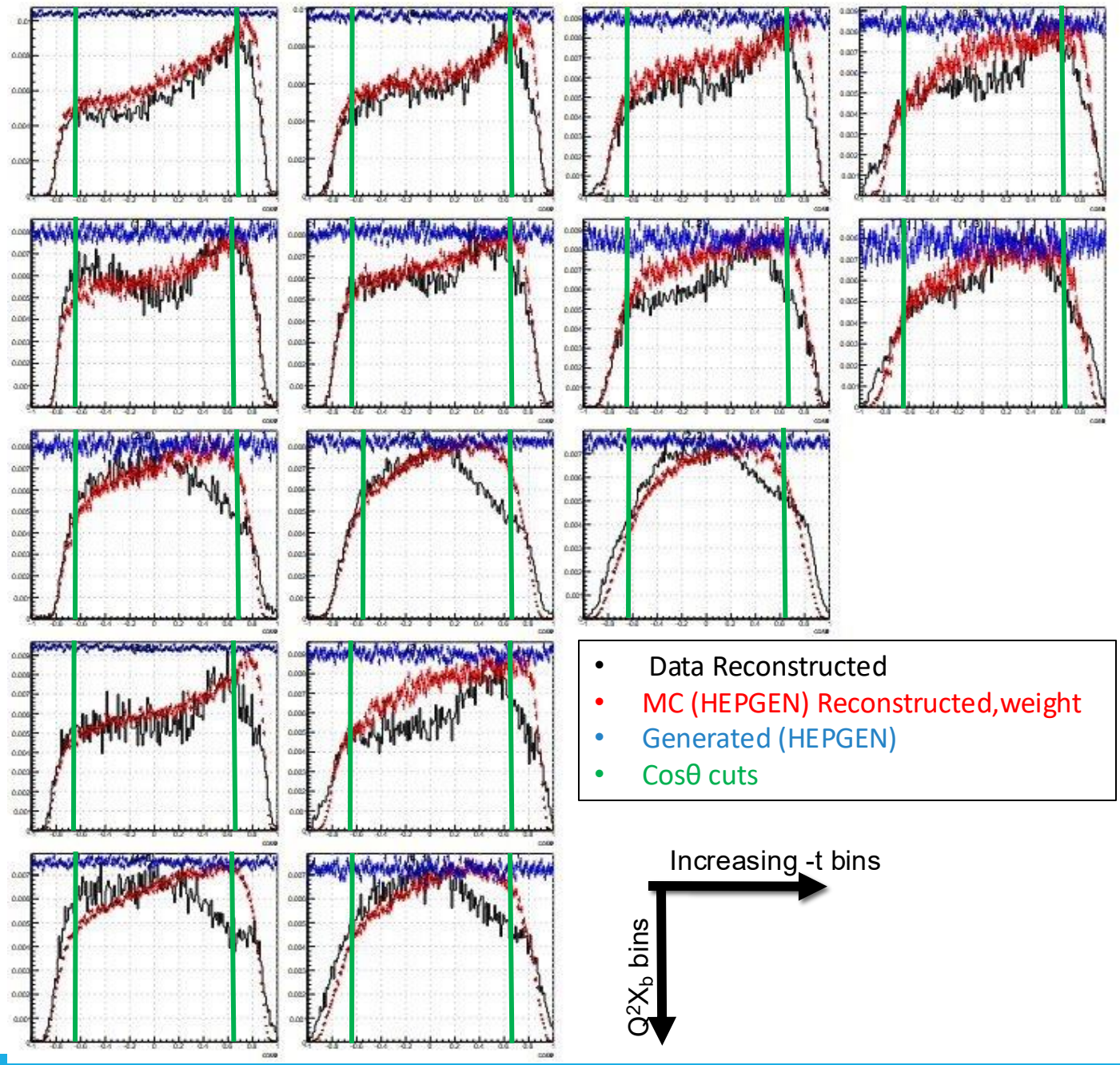


Red points: BSA extractions from GEMC MC events
Black curve: curve used to inject asymmetry in the MC samples

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





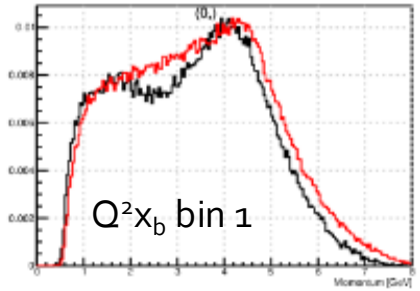
- Data Reconstructed
- MC (HEPGEN) Reconstructed,weight
- Generated (HEPGEN)
- Cosθ cuts

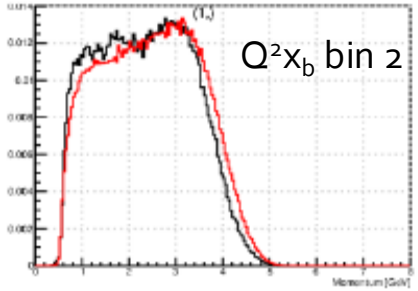
Increasing -t bins

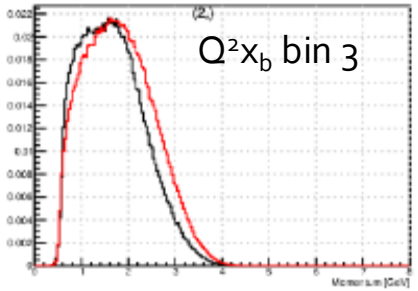
Q^2X_b bins

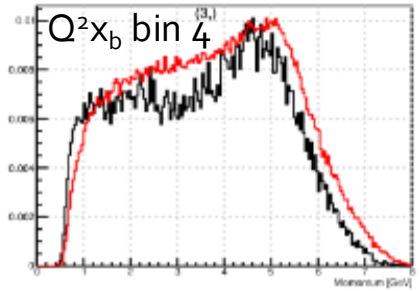
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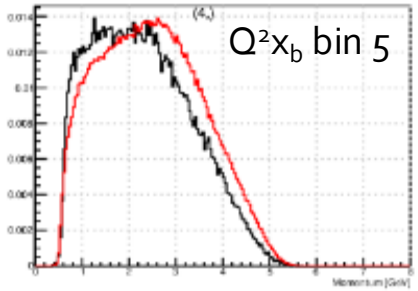
- Data
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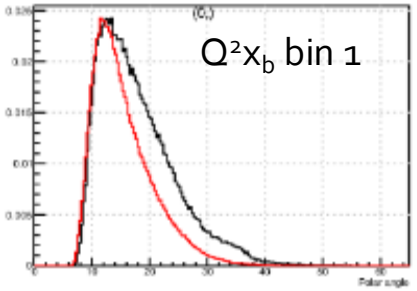


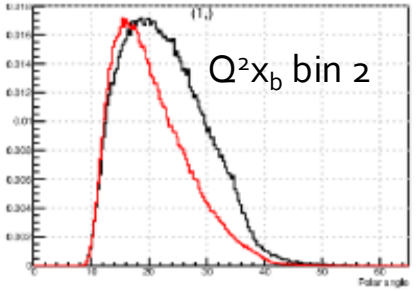


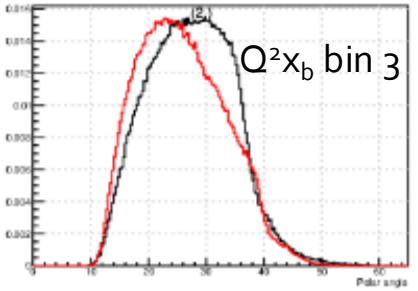


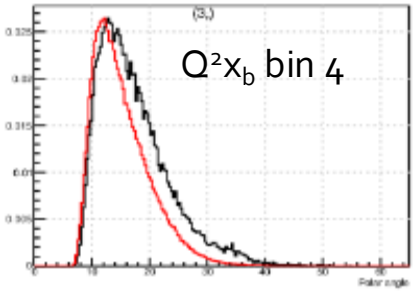


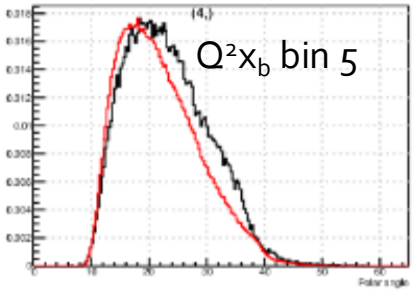
Pi+
Momentum



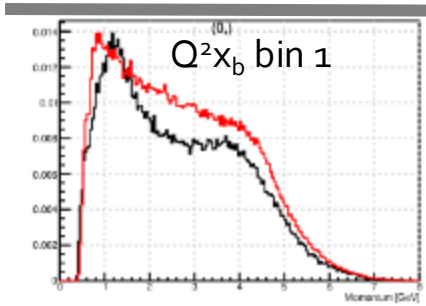


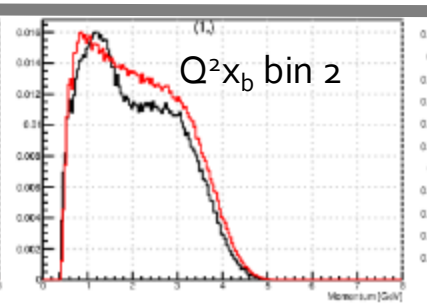


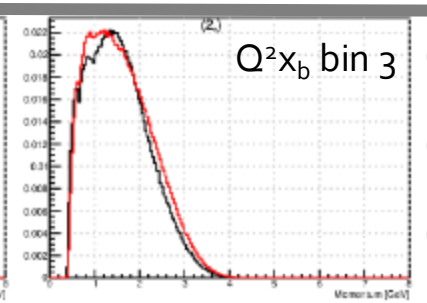


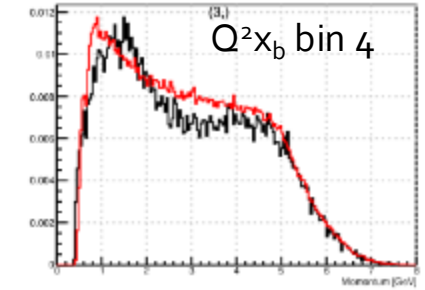


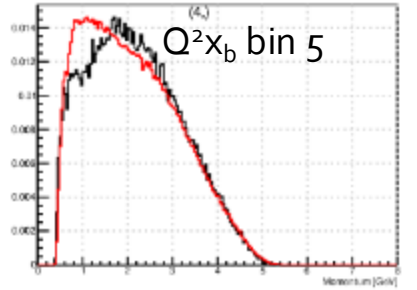
Pi+
Polar Angle



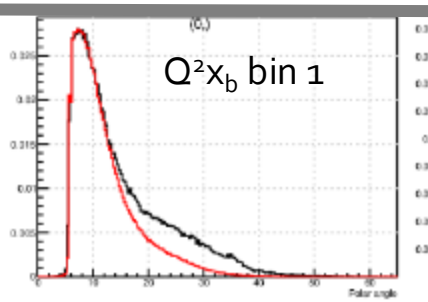


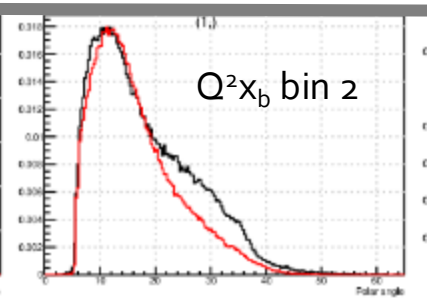


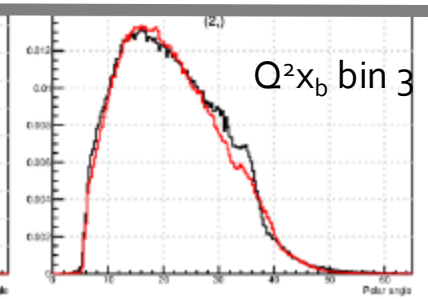


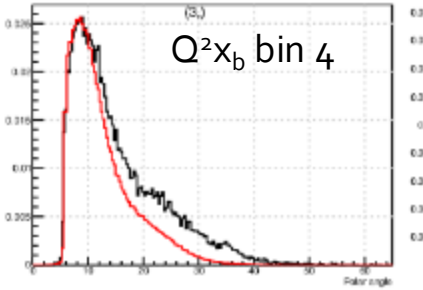


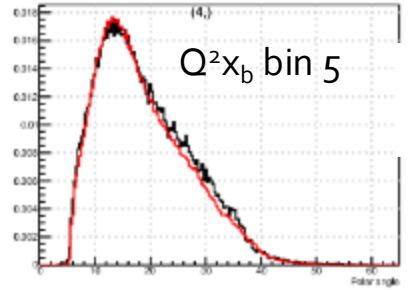
Pi-
Momentum











Pi-
Polar Angle

Spin Density Matrix Elements (SDMEs)

$$\rho^{\lambda_V \lambda'_V} = \frac{1}{2N} \sum_{\lambda_\gamma \lambda'_\gamma \lambda_N \lambda'_N} F^{\lambda_V \lambda'_N \lambda_\gamma \lambda_N} \varrho^{U+L}_{\lambda_\gamma \lambda'_\gamma} F^{*\,\lambda'_V \lambda'_N \lambda'_\gamma \lambda_N}$$

helicity of vector meson V

helicities of virtual photon γ and nucleon N

photon spin density matrix ($\mu \rightarrow \mu' + \gamma^*$); calculable on QED

- Helicity Amplitudes describe the transition of helicity states $\lambda\gamma\ \lambda_N \rightarrow \lambda_V\ \lambda_{N'}$
  - Depends on exclusive kinematics (Q^2,W, etc.)
- 23 vector meson SDMES are calculated
  - Vector meson SDMEs that come from different photon polarization states

$$r^{04}_{\lambda_V \lambda'_V} = (\rho^0_{\lambda_V \lambda'_V} + \epsilon R \rho^4_{\lambda_V \lambda'_V})(1+\epsilon R)^{-1}$$

$$R = \sigma_L / \sigma_T$$

$$r^{\alpha}_{\lambda_V \lambda'_V} = \begin{cases} \rho^{\alpha}_{\lambda_V \lambda'_V} (1+\epsilon R)^{-1}, & \alpha = 1,2,3, \\ \sqrt{R} \rho^{\alpha}_{\lambda_V \lambda'_V} (1+\epsilon R)^{-1}, & \alpha = 5,6,7,8. \end{cases}$$

K. Schilling and G. Wolf, Nucl. Phys. B **61**, 381(1973)

Reducing 6-D to 4-D

Integration over phi and theta:
- Integration is zero
- Integration is Constant

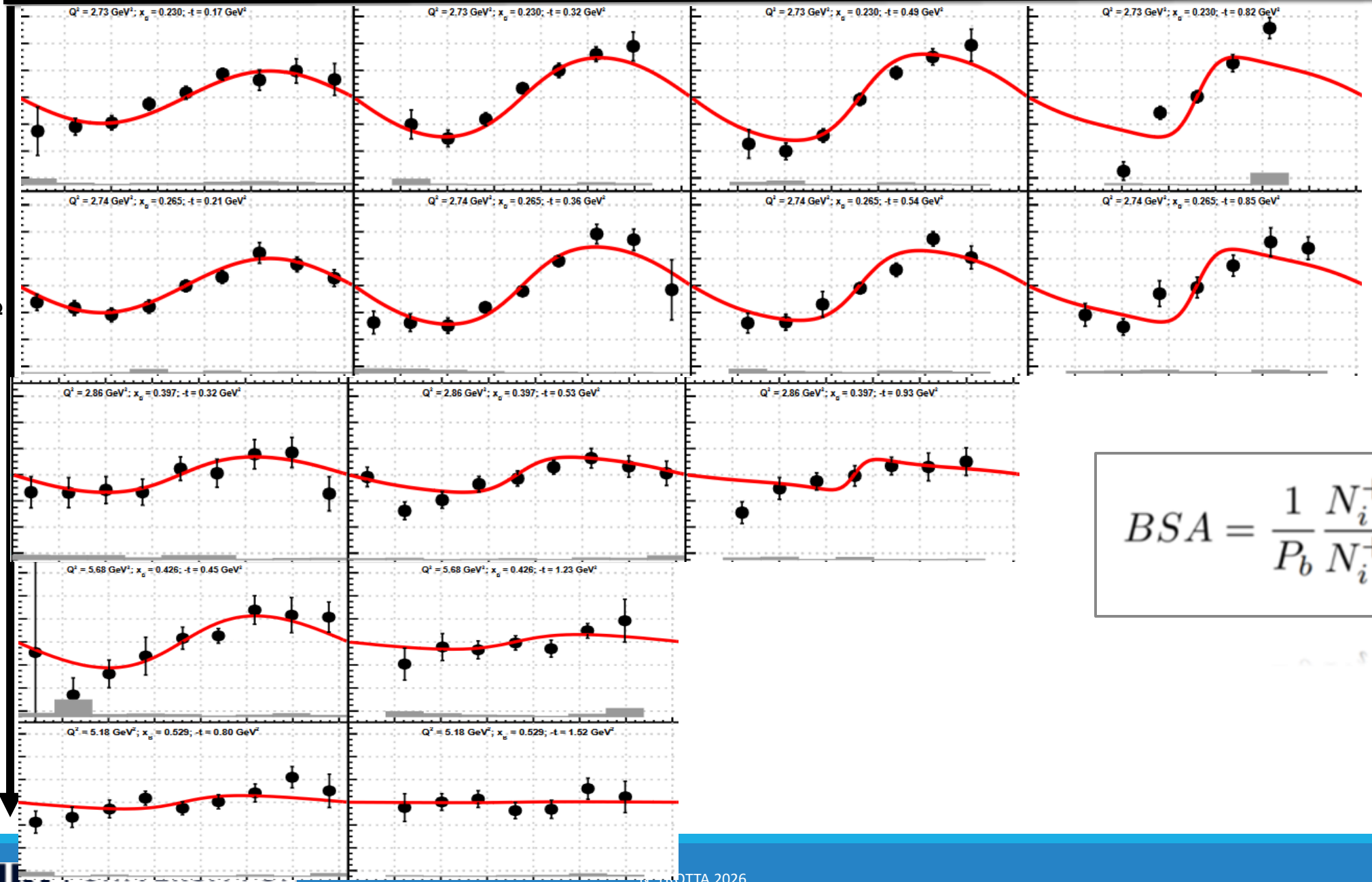
$$
\begin{aligned}
\mathcal{W}^U(\Phi,\phi,\cos\Theta) &= \frac{3}{8\pi^2}\Big[\frac{1}{2}(1-r^{04}_{00})+\frac{1}{2}(3r^{04}_{00}-1)\cos^2\Theta \\
&- \sqrt{2}\mathrm{Re}\{r^{04}_{10}\}\sin 2\Theta\cos\phi - r^{04}_{1-1}\sin^2\Theta\cos 2\phi - \epsilon\cos 2\Phi\Big(r^{1}_{11}\sin^2\Theta \\
&+ r^{1}_{00}\cos^2\Theta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

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

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

Increasing -t bins

5 Q^2X_b bins



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