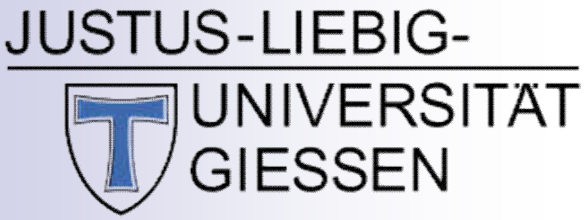
CLAS collaboration meeting, JLAB

March 03, 2021

# A Multidimensional Study of Hard Exclusive $\pi^+$ BSA in the GPD Regime



Stefan Diehl

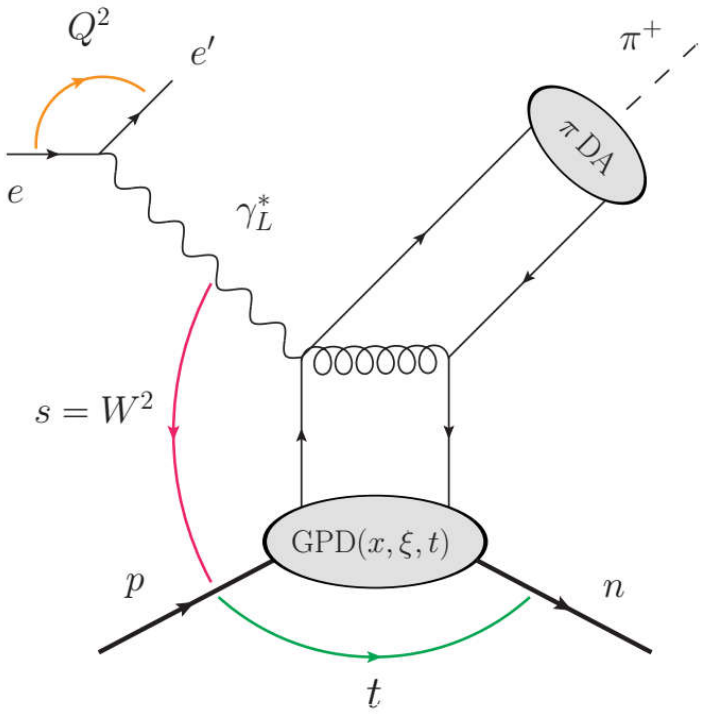
*Justus Liebig University Giessen*

*University of Connecticut*

# Motivation

$$ep \rightarrow en\pi^+$$

**t / Q² << 1:** GPD based description




**π⁺ in forward region**

**Goldstein, Hernandez, Liuti**
**Phys. Rev. D 84, 034007 (2011)**

**Goloskokov, Kroll**
**Eur. Phys. J. A. 47: 112 (2011)**

| nucleon pol. \ quark pol. | U | L | T |
|---|---|---|---|
| U | $H$ | | $\bar{E}_T$ |
| L | | $\widetilde{H}$ | $\widetilde{E}_T$ |
| T | $E$ | $\widetilde{E}$ | $H_T, \widetilde{H}_T$ |

**4 chiral even GPDs**

**4 chiral odd GPDs**

$$\delta_T^u = \int dx H_T^u(x,\xi,t=0)$$

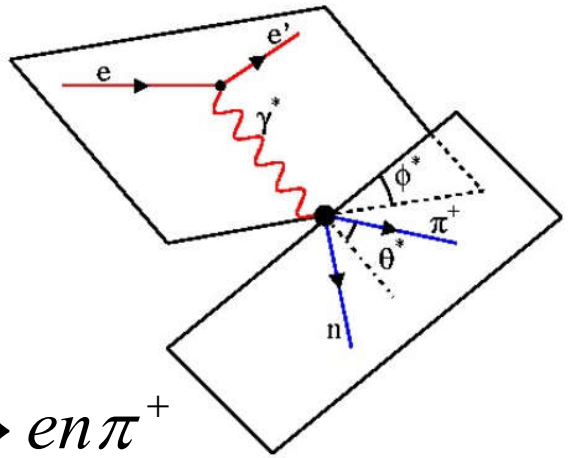
$$\delta_T^d = \int dx H_T^d(x,\xi,t=0)$$

**$H_T$ is related to the protons tensor charge**

# Hard Exclusive $\pi^+$ Electroproduction and BSA

**Cross section** (longitudinally pol. beam and unpol. target):

$$2\pi\frac{d^2\sigma}{dtd\phi} = \frac{d\sigma_T}{dt} + \epsilon\frac{d\sigma_L}{dt} + \epsilon\cdot cos(2\phi)\frac{d\sigma_{TT}}{dt} + \sqrt{2\epsilon(1+\epsilon)}\cdot cos(\phi)\frac{d\sigma_{LT}}{dt} + h\cdot\sqrt{2\epsilon(1-\epsilon)}\cdot sin(\phi)\frac{d\sigma_{LT'}}{dt}$$




$$ep \rightarrow en\pi^+$$

$$\sigma = \sigma_0(1 + A_{UU}^{\cos(2\phi)}\cos(2\phi) + A_{UU}^{\cos(\phi)}\cos(\phi) + hA_{LU}^{\sin(\phi)}\sin(\phi))$$

$$BSA(t,\phi,x_B,Q^2) = \frac{d\sigma^+ - d\sigma^-}{d\sigma^+ + d\sigma^-} = \frac{A_{LU}^{\sin\phi}\sin\phi}{1 + A_{UU}^{\cos\phi}\cos\phi + A_{UU}^{\cos 2\phi}\cos 2\phi}$$

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

# Theoretical Interpretation

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

$$\sigma_{LT'} \sim \xi\sqrt{1-\xi^2}\,\frac{\sqrt{-t'}}{2m}\,Im\left[\langle\overline{E}_{T-eff}\rangle^*\langle\widetilde{H}_{eff}\rangle + \langle H_{T-eff}\rangle^*\langle\widetilde{E}_{eff}\rangle\right]$$

→ $\sigma_{LT'}$ is a product of chiral-odd and chiral-even GPDs

$$\widetilde{E}_{eff} = \widetilde{E} + pole\ term$$

$$\sigma_L \sim \left\{\left(1-\xi^2\right)\left|\langle\tilde{H}\rangle\right|^2 - 2\xi^2\mathrm{Re}\left[\langle\tilde{H}\rangle^*\langle\tilde{E}\rangle\right] - \frac{t'}{4m^2}\xi^2\left|\langle\tilde{E}\rangle\right|^2\right\}$$

$$\sigma_T \sim \left[\left(1-\xi^2\right)\left|\langle H_T\rangle\right|^2 - \frac{t'}{8m^2}\left|\langle\bar{E}_T\rangle\right|^2\right]$$

$\overline{E}_T \sim F_u - F_d$

$$|\pi^0\rangle = \frac{1}{\sqrt{2}}\left[|u\bar{u}\rangle - |d\bar{d}\rangle\right] \quad |\pi^+\rangle = |u\bar{d}\rangle$$

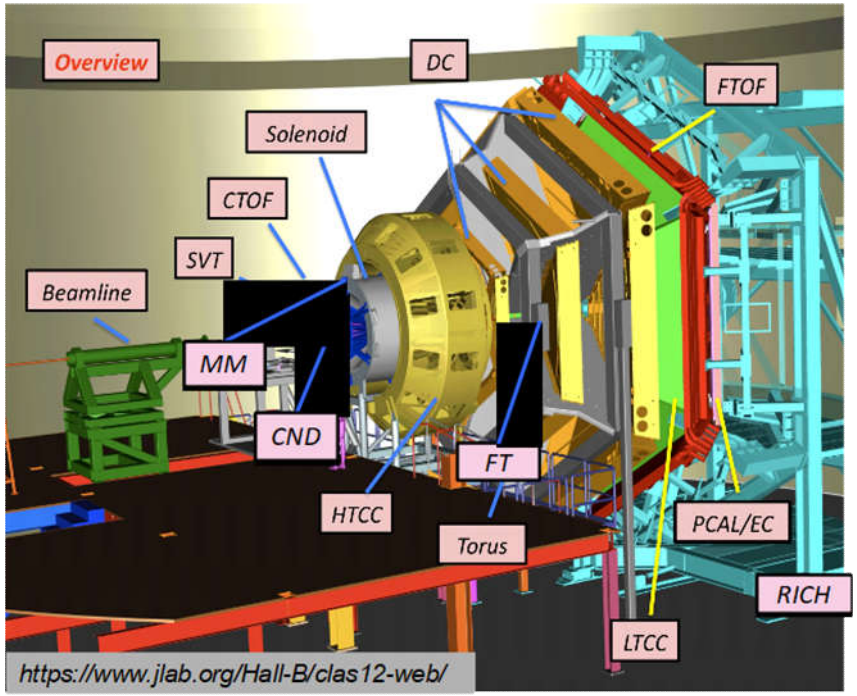
➔ Chiral odd GPDs are significantly amplified by the pion pole term in $\sigma_{LT'}$

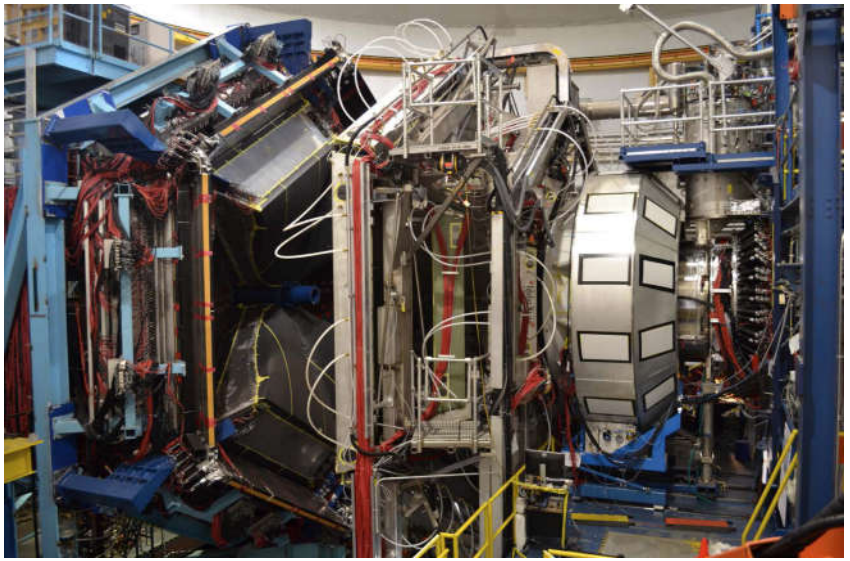
➔ Polarized $\pi^+$ observables show an increased sensitivity to chiral-odd GPDs

**exclusive $\pi^+$:** $\sigma_{LT'} \sim Im[< H_T >^*< \widetilde{E} >]$

**Goal:** Improve the extraction of $H_T$ [ $\pi^0$ → dominated by $\overline{E}_T$ ]

# CLAS12 Experimental Setup in Hall B



V. Burkert et al., Nucl.Instrum.Meth.A 959 (2020) 163419

➔ Data recorded with CLAS12 during fall of 2018

➔ 10.6 GeV electron beam ➔ 87 % average polarization ➔ liquid $H_2$ target

➔ Inbending and outbending torus field configuration

➔ Analysed data ~ 20 % of the approved RG-A beam time

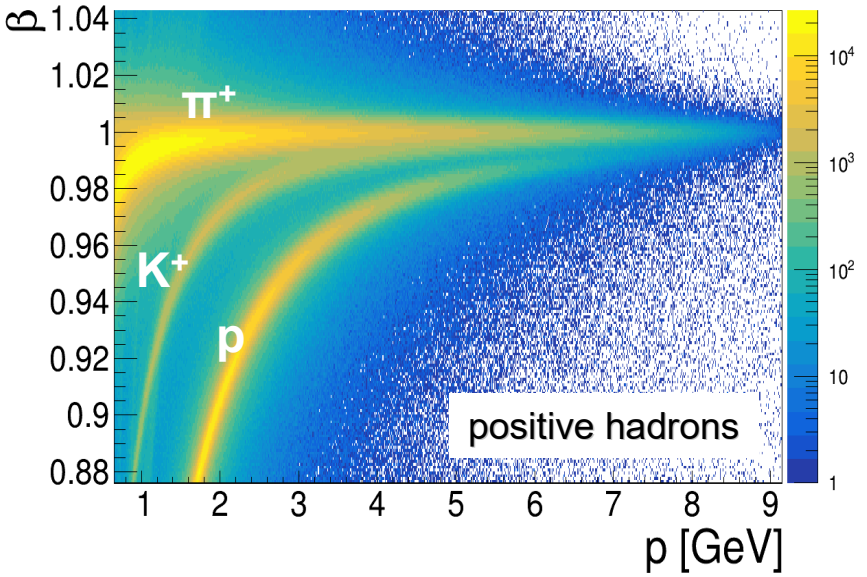
# Particle ID and Kinematic Cuts

**Electron ID**

→ eventbuilder PID
→ PCAL and DC fiducial cuts
→ PID refinements (see RG-A note)

**$\pi^+$ ID**

→ eventbuilder PID
→ DC fiducial cuts
→ $\Delta v_z$ cut and $|\chi^2_{pid}| < 2.64$ ($3\sigma$)

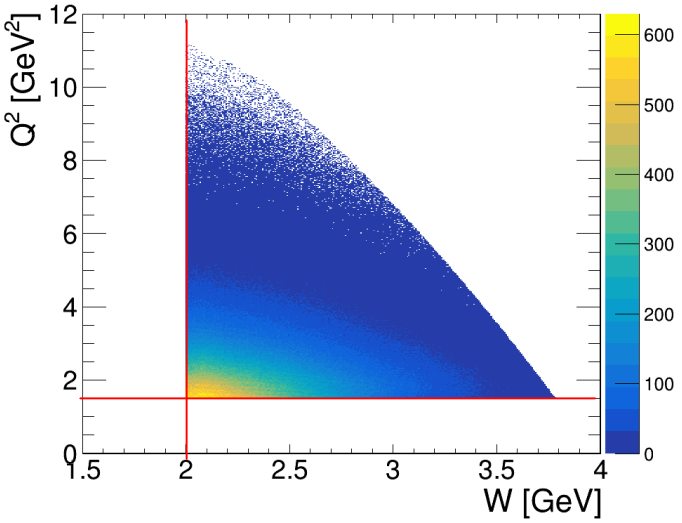



**Kinematic cuts:**

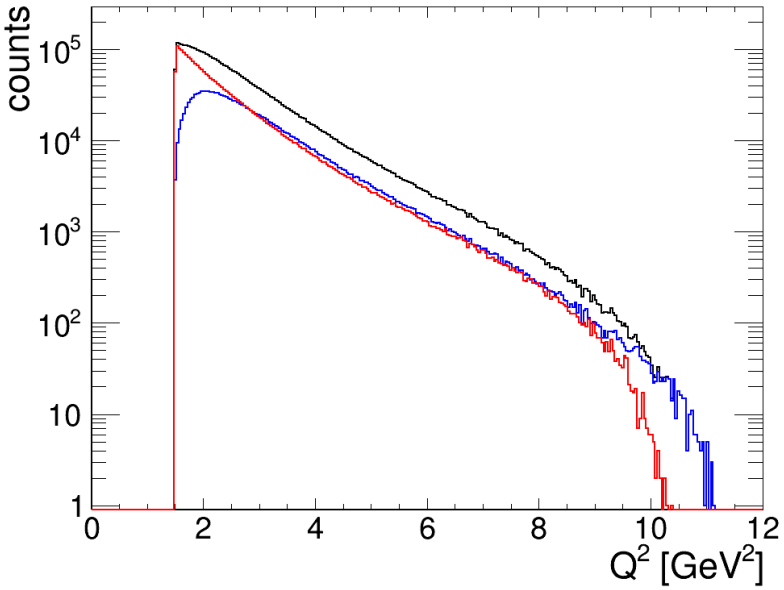
$Q^2 > 1.5$ GeV²  $W > 2$ GeV  $y < 0.75$

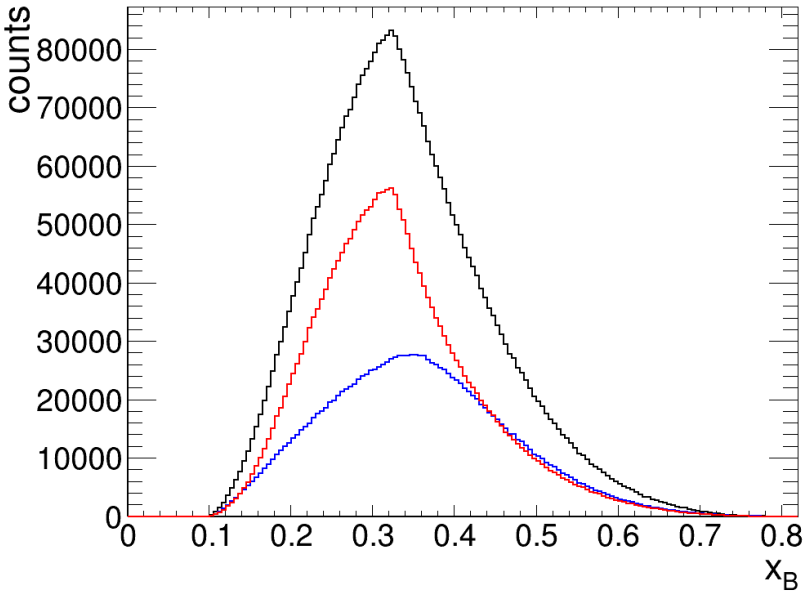
• event by event: $t > t_{min} + \sigma(t_{min})$

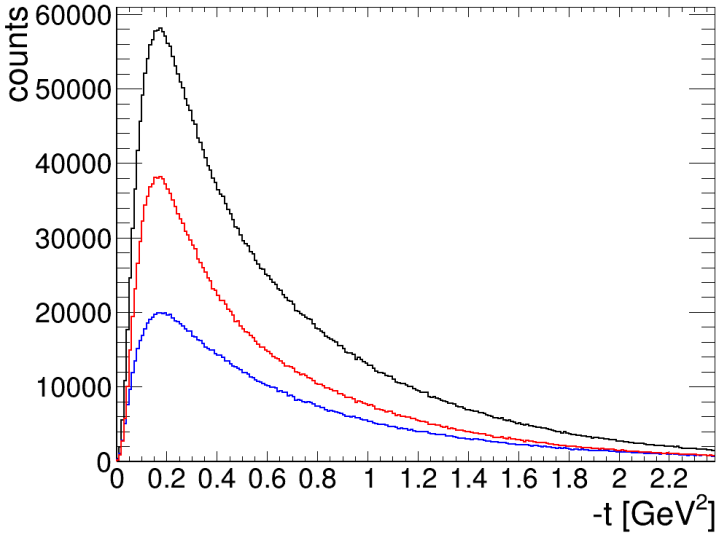
• Particles only detected in the FD



# Kinematic Coverage and Torus Field Settings




**inbending**

**outbending**

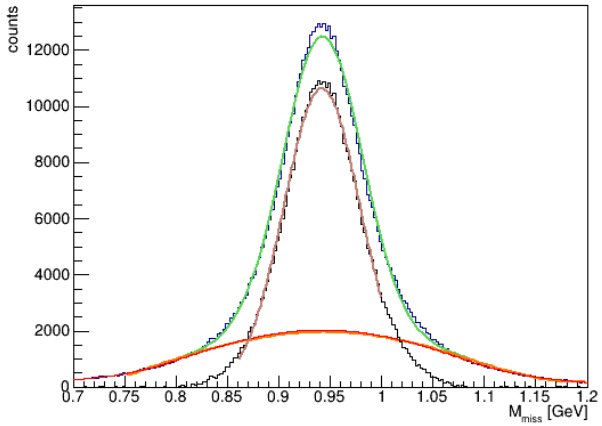
**combined**

# Exclusive Events: Missing Neutron Mass

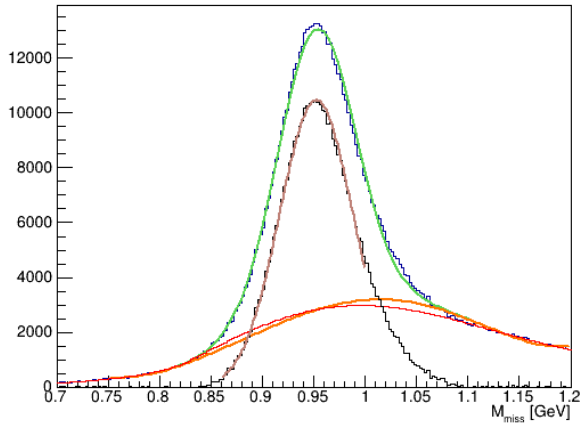
**Topology:** $e\pi^+X$

**plots are integrated over $Q^2 > 1.5$ GeV² and $x_B$**

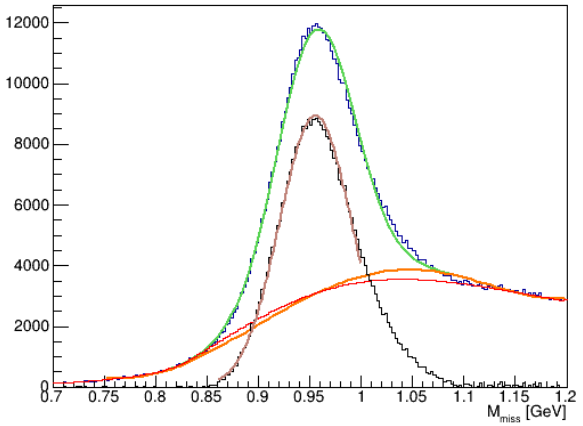
**0.05 GeV² < -t < 0.155 GeV²**



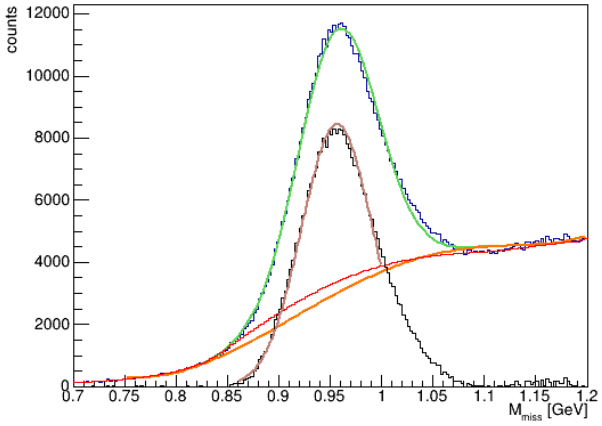

**0.155 GeV² < -t < 0.24 GeV²**



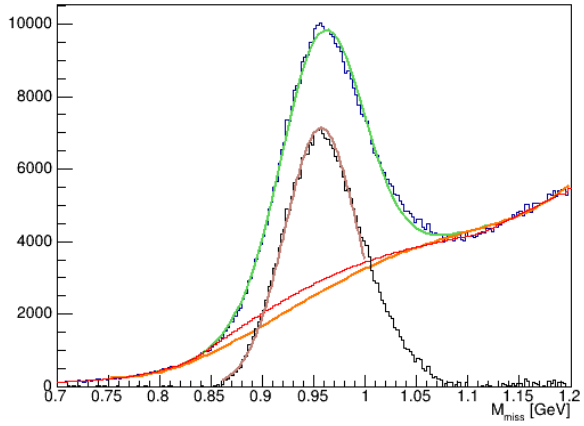

**0.24 GeV² < -t < 0.33 GeV²**



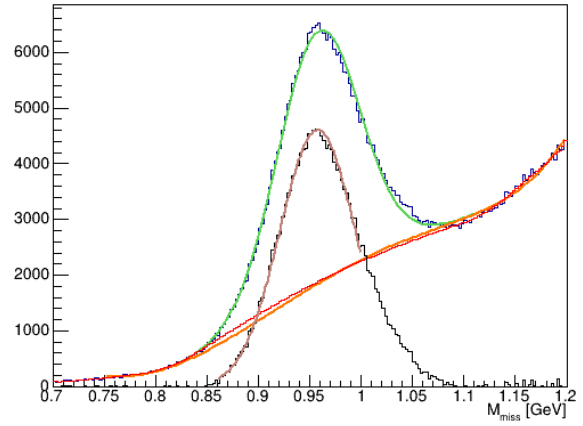

**0.33 GeV² < -t < 0.44 GeV²**




**0.4405 GeV² < -t < 0.56 GeV²**




**0.56 GeV² < -t < 0.68 GeV²**

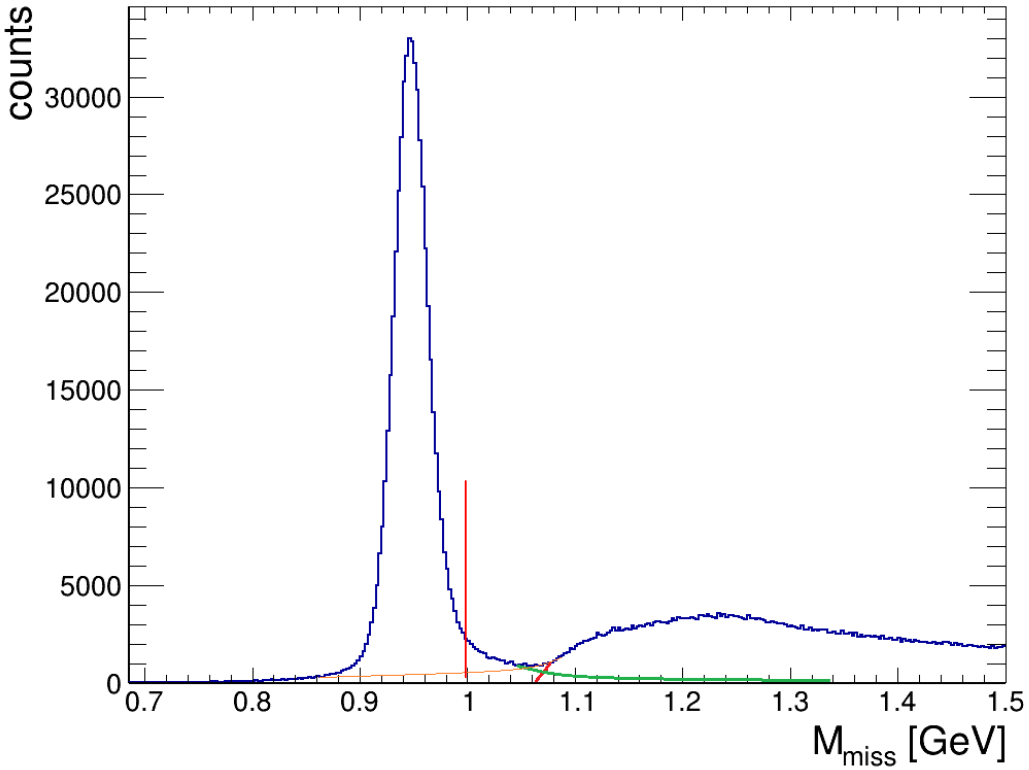



**root BG estimator** **fitted polyn. BG**

# Background Treatment

- Background is increasing with -t
- Background has to be subtracted

**SIDIS MC (clasdis):**




➔ Background does not originate from the SIDIS region

➔ A sideband subtraction may lead to a wrong result

➔ A **bin by bin background subtraction** has to be performed!

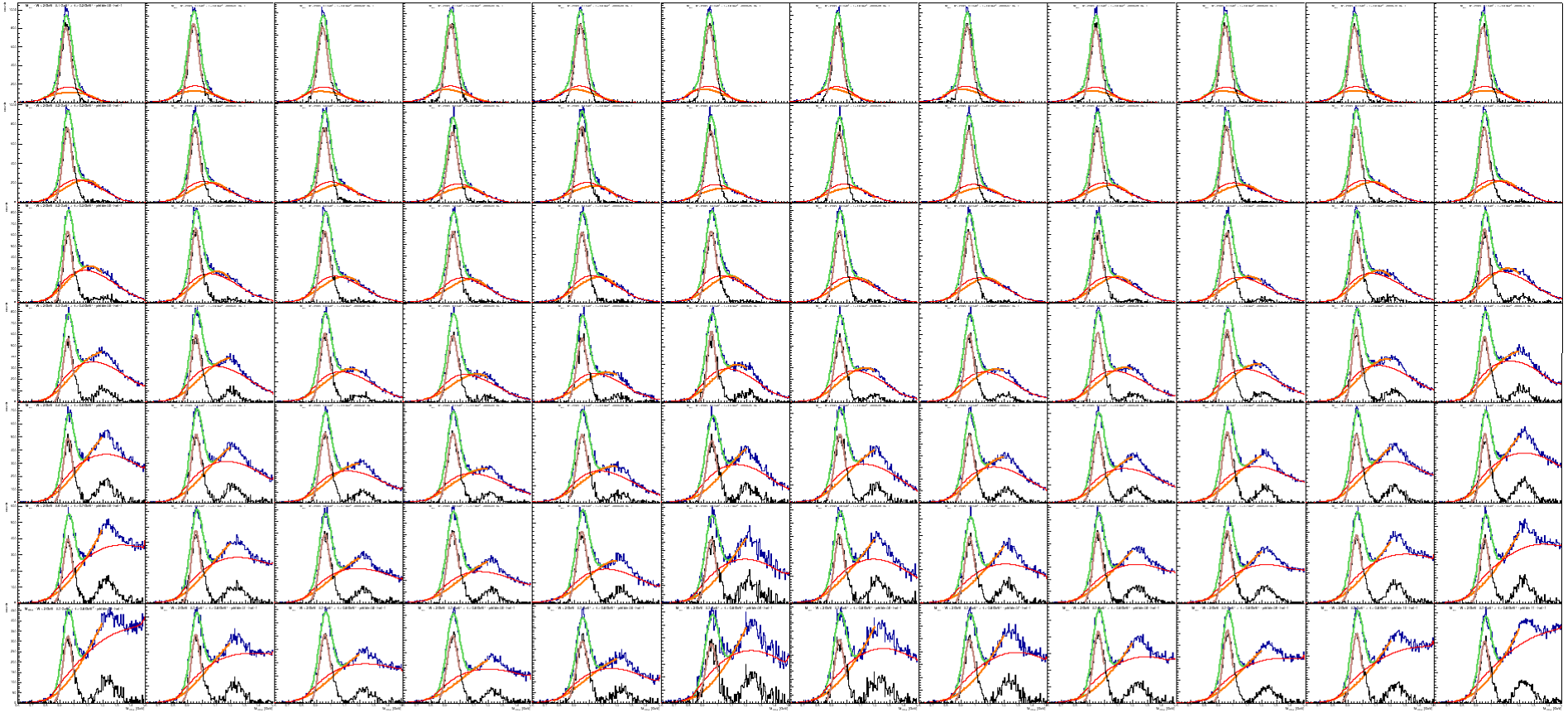
→ Plot the missing neutron peak in each φ and -t bin for each helicity state

# Bin by Bin Background Subtraction

-t from 0.05 GeV² to 0.8 GeV²

integrated over $Q^2 > 1.5$ GeV² and $x_B$

0° - 30° | 30° - 60° | 60° - 90° | 90° - 120° | 120° - 150° | 150° - 180° | 180° - 210° | 210° - 240° | 240° - 270° | 270° - 300° | 300° - 330° | 330° - 360°

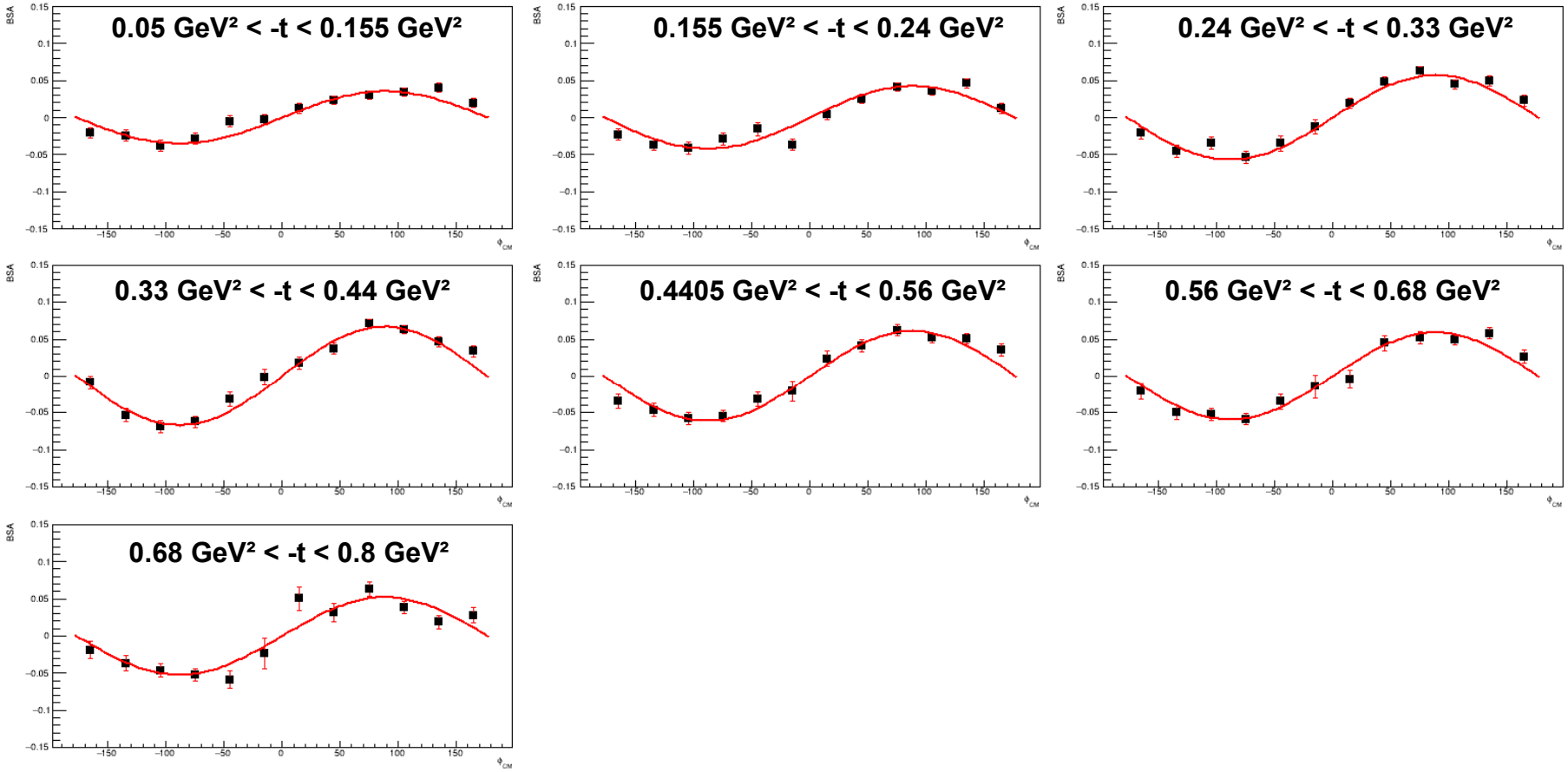


root BG estimator

fitted polynomial BG

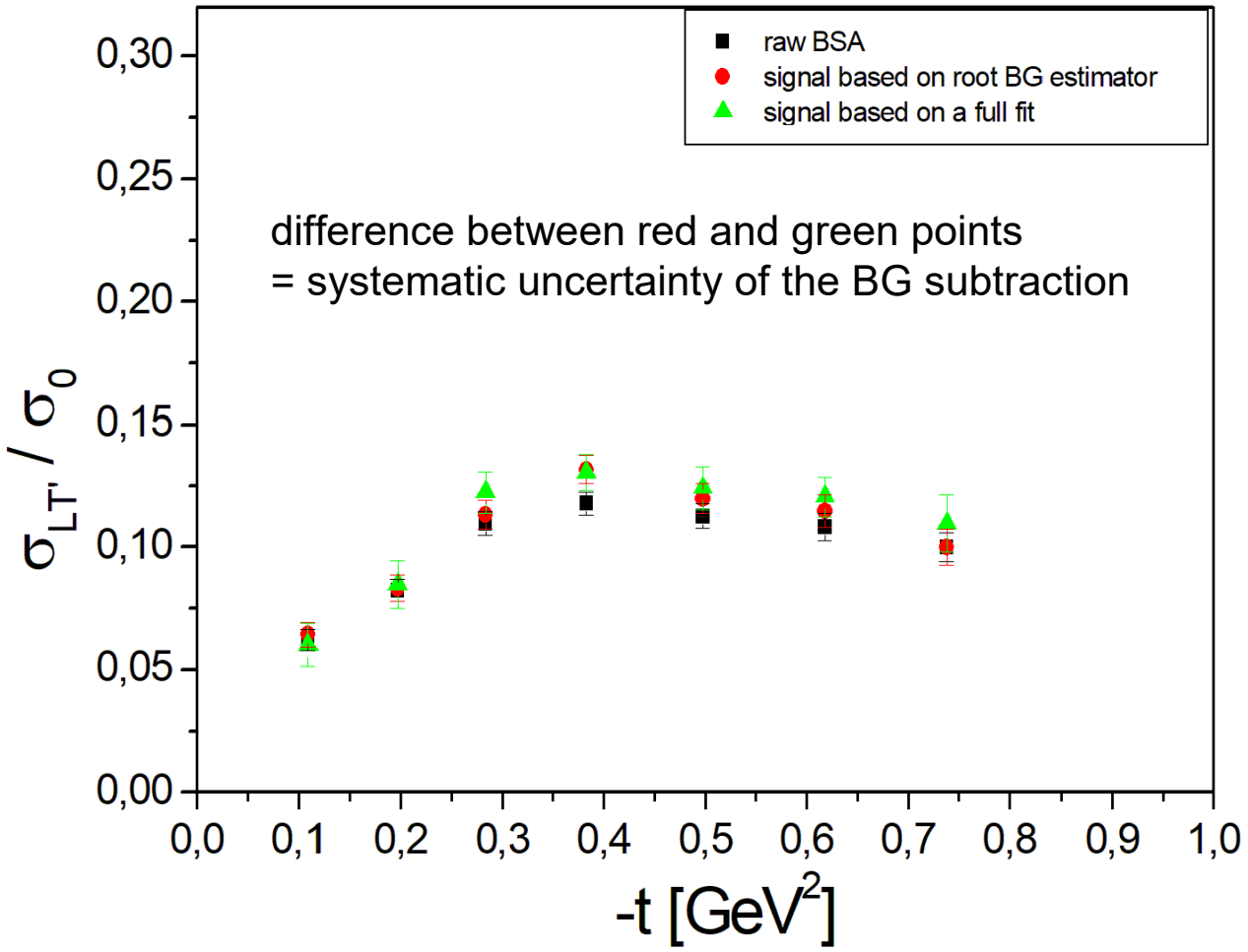
# Resulting Signal BSA

**integrated over $Q^2 > 1.5$ GeV² and $x_B$**

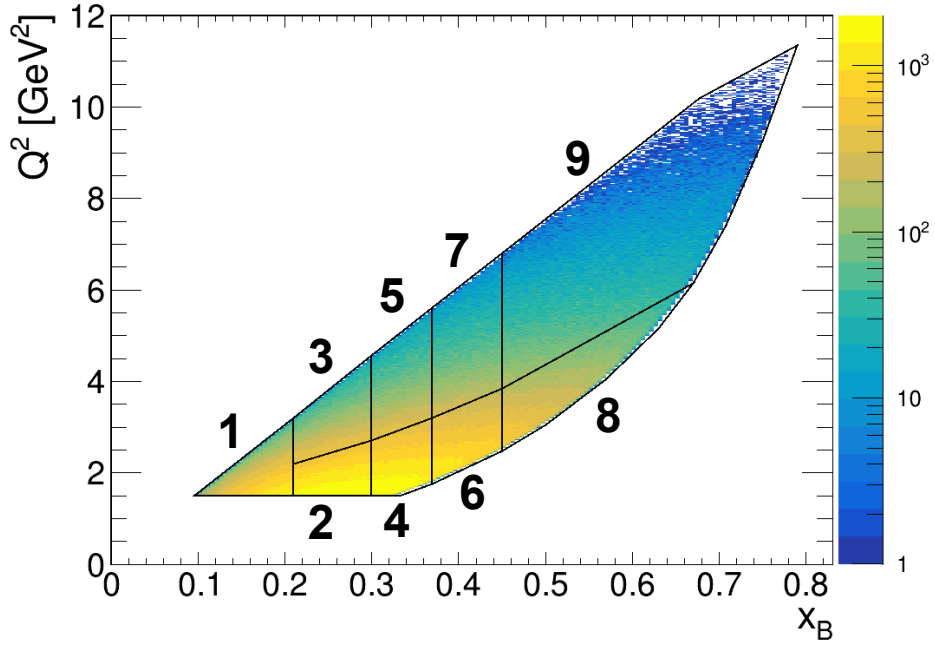


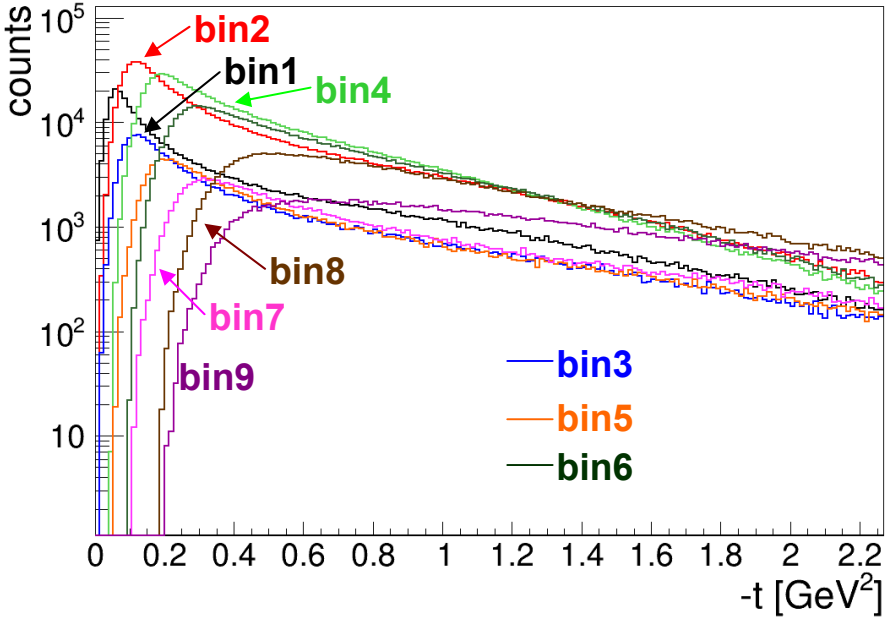
# Effect of the Background Subtraction on the Final Result

**integrated over $Q^2 > 1.5\ GeV^2$ and $x_B$**



# A Multidimensional Binning




**9 bins in $Q^2$ - $x_B$**

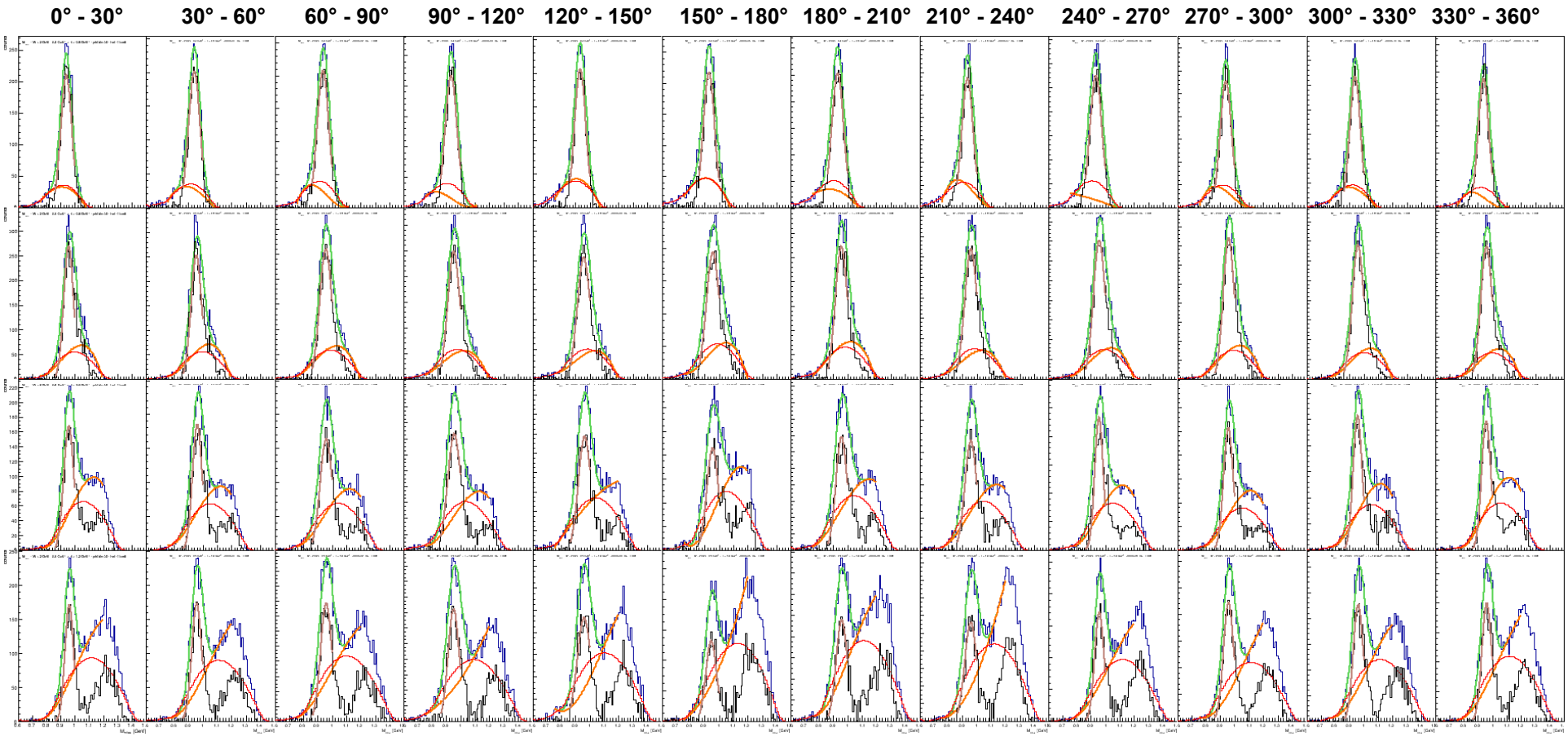
**4 – 6 bins in -t < 1.0 GeV² (1.2 GeV²)**

# Bin by Bin Background Subtraction

- A bin by bin fit of the signal shape has been performed for each $Q^2$, $x_B$, -t and Φ bin in each helicity state

**-t**

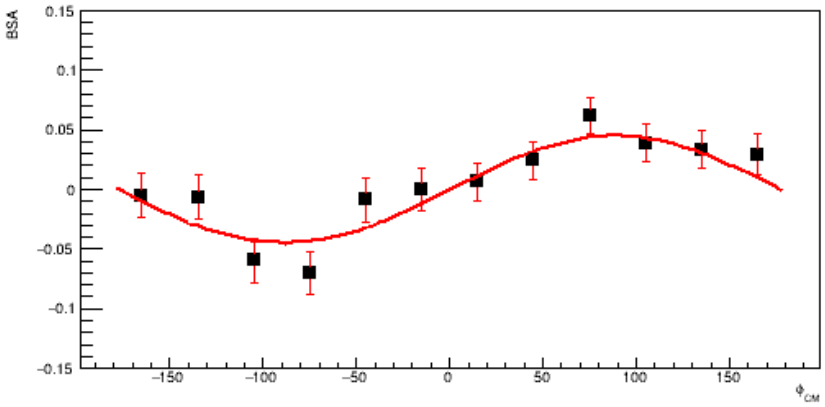
**Example: bin 8 (high $Q^2$, high $x_B$)**



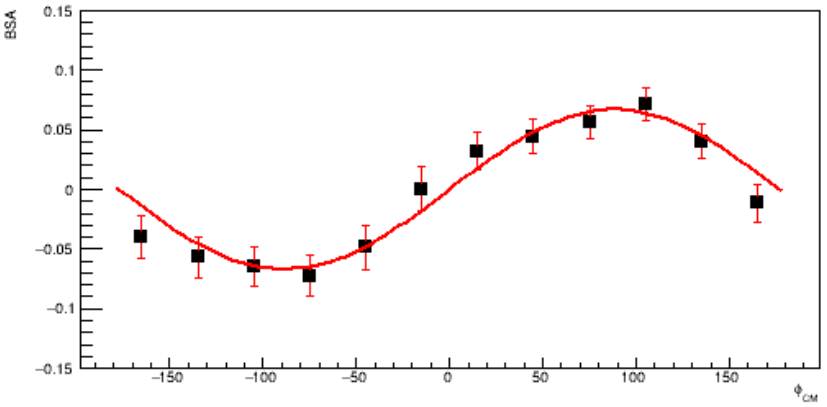
# Resulting Signal BSA

## Example: bin 8 (high $Q^2$, high $x_B$)

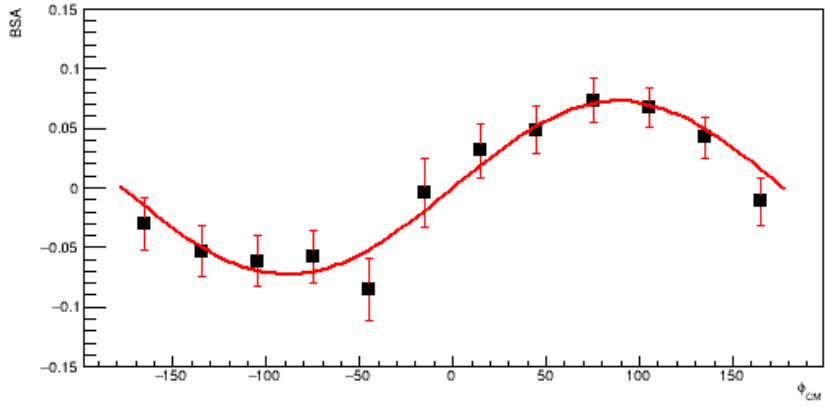
0.2 GeV² < -t < 0.52 GeV²



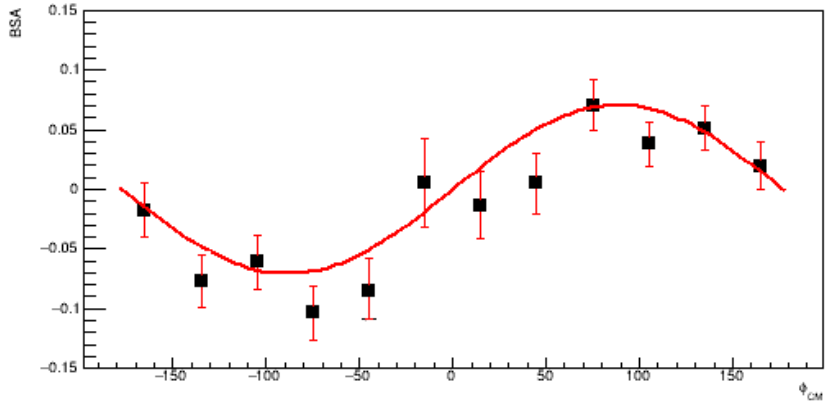

0.52 GeV² < -t < 0.75 GeV²

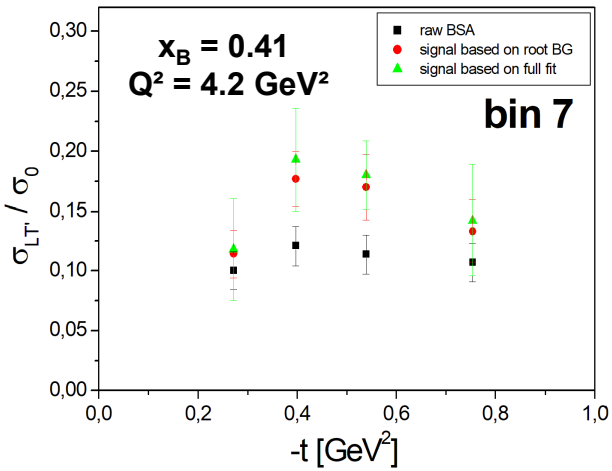


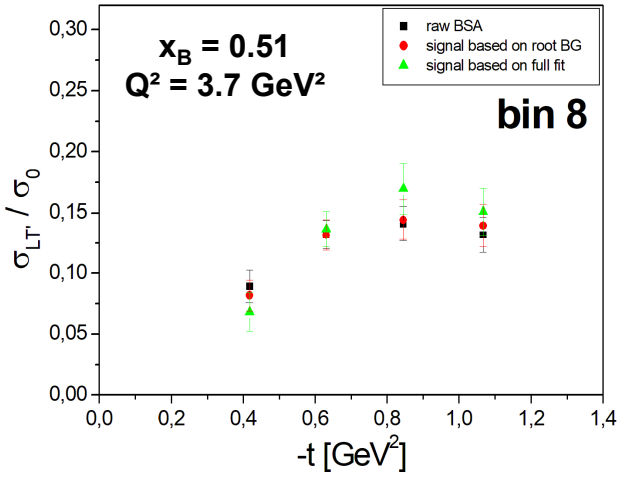

0.75 GeV² < -t < 0.95 GeV²

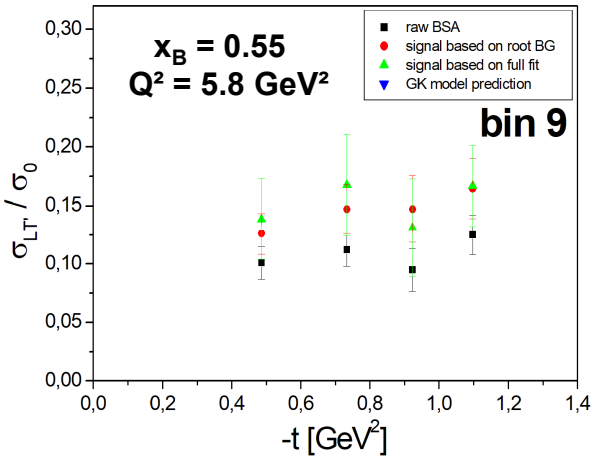


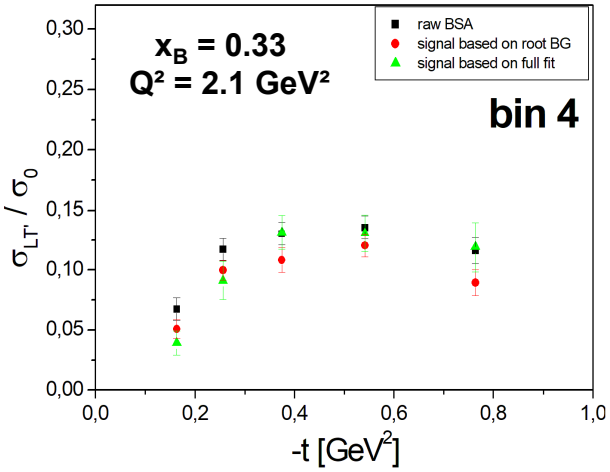

0.95 GeV² < -t < 1.2 GeV²

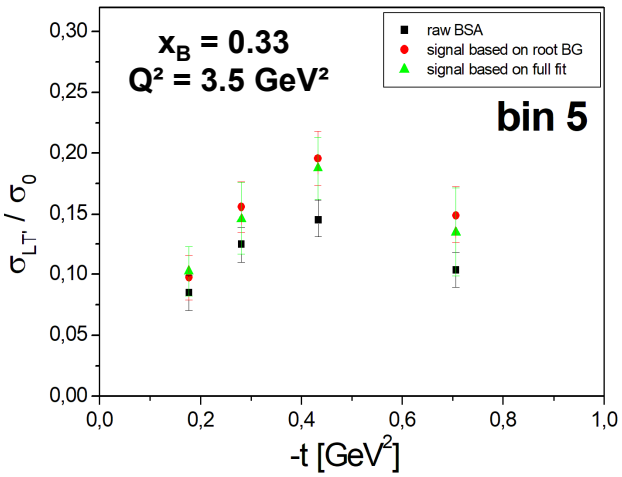


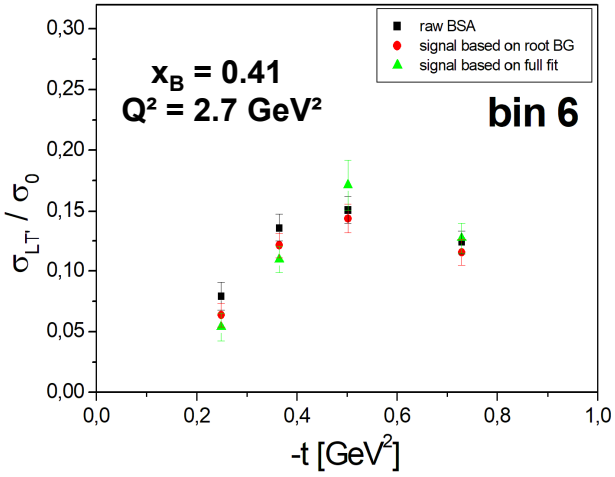

$x_B$ = 0.41
$Q^2$ = 4.2 GeV²
bin 7
raw BSA
signal based on root BG
signal based on full fit
$\sigma_{LT'} / \sigma_0$
-t [GeV²]

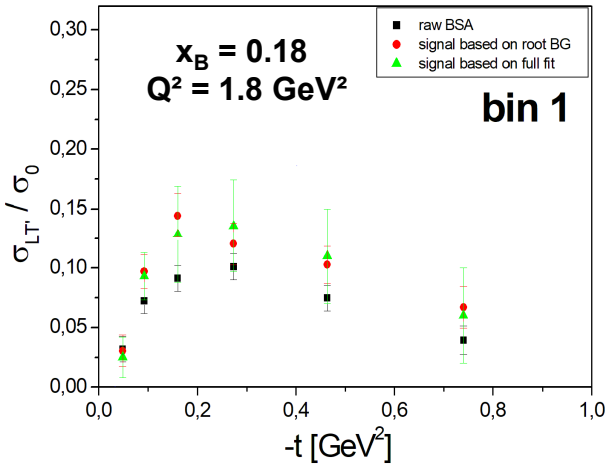

$x_B$ = 0.51
$Q^2$ = 3.7 GeV²
bin 8
raw BSA
signal based on root BG
signal based on full fit
$\sigma_{LT'} / \sigma_0$
-t [GeV²]

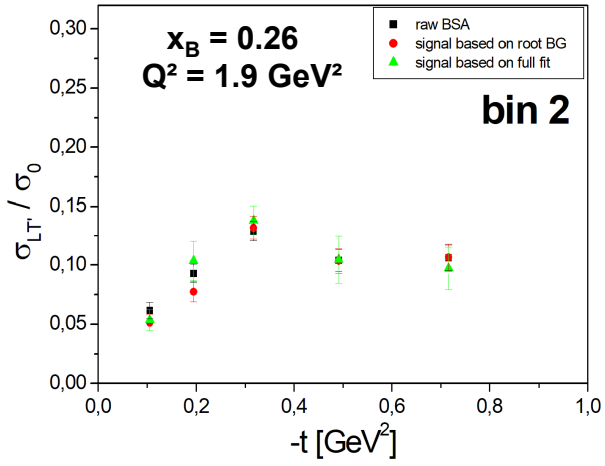

$x_B$ = 0.55
$Q^2$ = 5.8 GeV²
bin 9
raw BSA
signal based on root BG
signal based on full fit
GK model prediction
$\sigma_{LT'} / \sigma_0$
-t [GeV²]

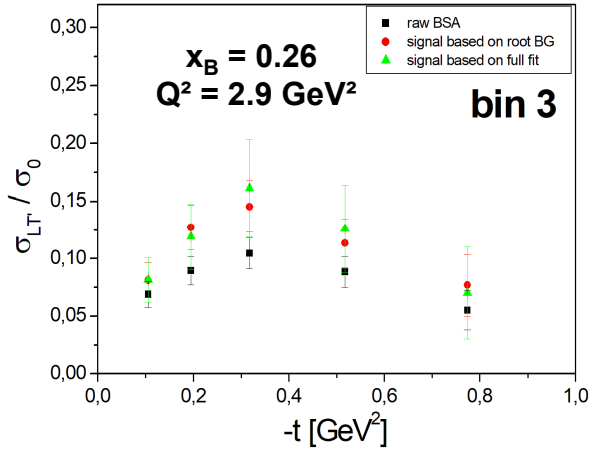

$x_B$ = 0.33
$Q^2$ = 2.1 GeV²
bin 4
raw BSA
signal based on root BG
signal based on full fit
$\sigma_{LT'} / \sigma_0$
-t [GeV²]


$x_B$ = 0.33
$Q^2$ = 3.5 GeV²
bin 5
raw BSA
signal based on root BG
signal based on full fit
$\sigma_{LT'} / \sigma_0$
-t [GeV²]


$x_B$ = 0.41
$Q^2$ = 2.7 GeV²
bin 6
raw BSA
signal based on root BG
signal based on full fit
$\sigma_{LT'} / \sigma_0$
-t [GeV²]


$x_B$ = 0.18
$Q^2$ = 1.8 GeV²
bin 1
raw BSA
signal based on root BG
signal based on full fit
$\sigma_{LT'} / \sigma_0$
-t [GeV²]


$x_B$ = 0.26
$Q^2$ = 1.9 GeV²
bin 2
raw BSA
signal based on root BG
signal based on full fit
$\sigma_{LT'} / \sigma_0$
-t [GeV²]


$x_B$ = 0.26
$Q^2$ = 2.9 GeV²
bin 3
raw BSA
signal based on root BG
signal based on full fit
$\sigma_{LT'} / \sigma_0$
-t [GeV²]

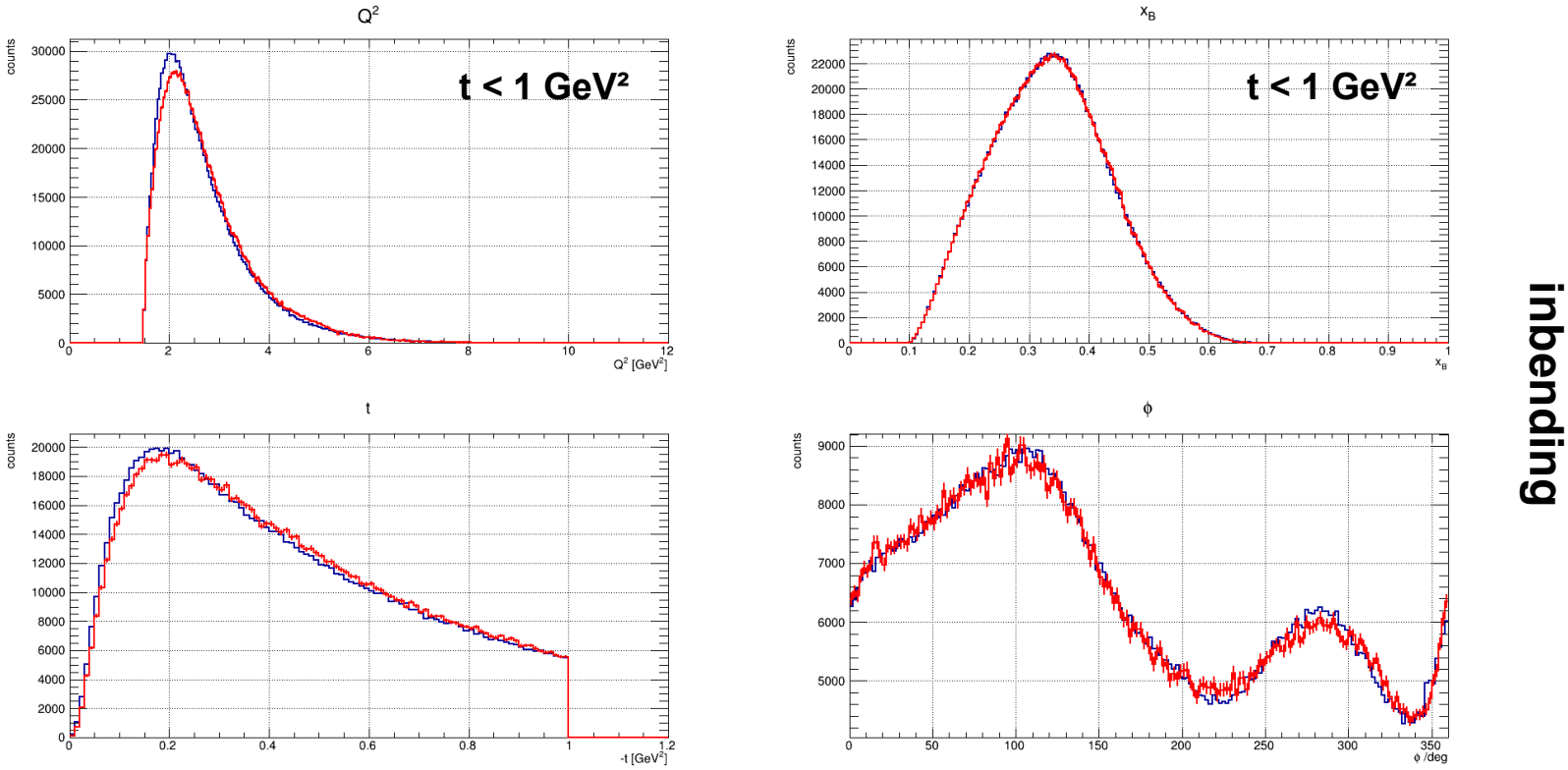
# Monte Carlo Studies

➔ A dedicated eventgenerator (aaorad / aanorad) is available

→ Generates exclusive $\pi^+$ events

→ Contains latest GPD parametrisations

→ A weight based on $Q^2$, $x_B$, t and φ is applied to improve the data - MC agreement

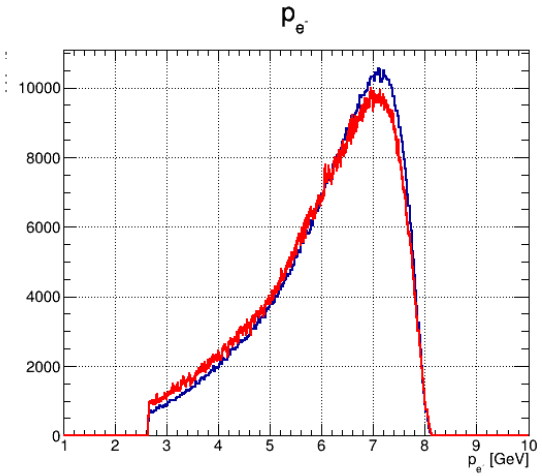


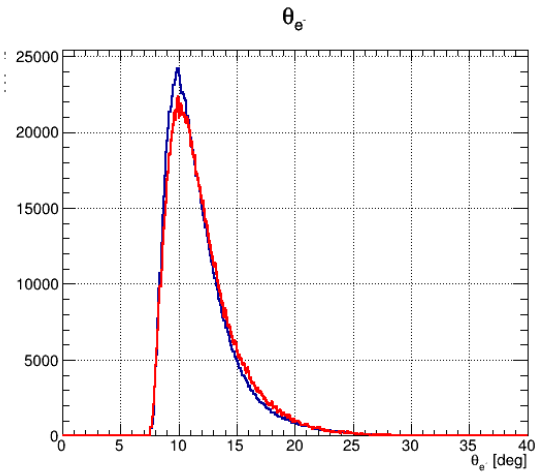
# Monte Carlo Studies

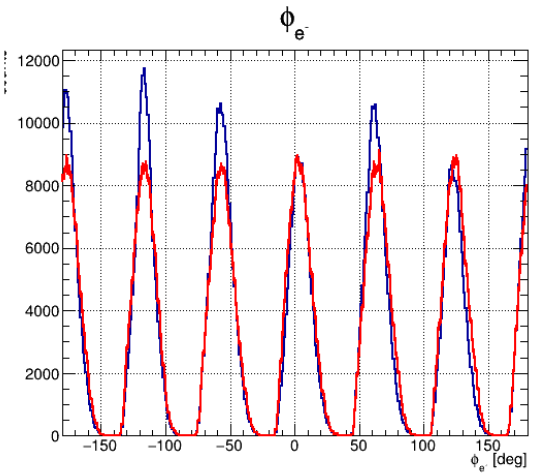
data MC

t < 1 GeV², inbending torus field

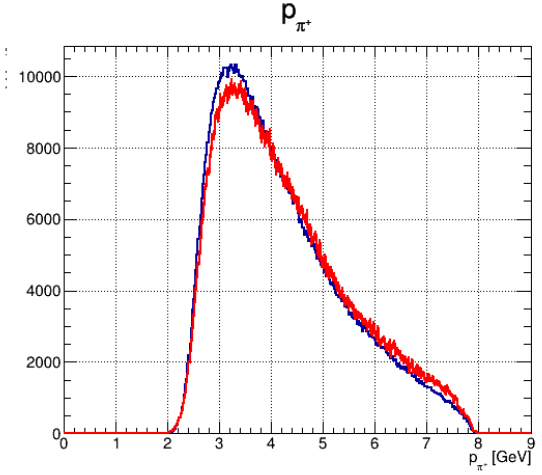
$e^-$

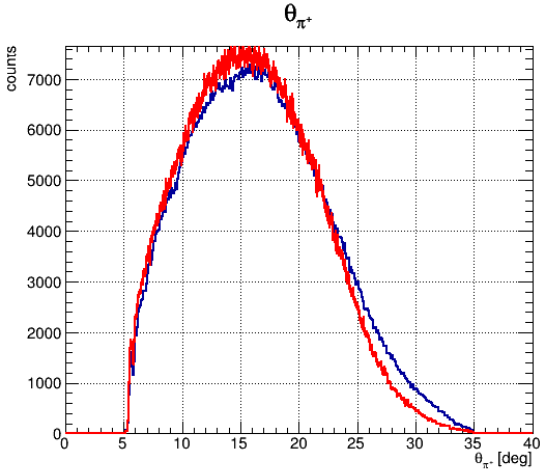


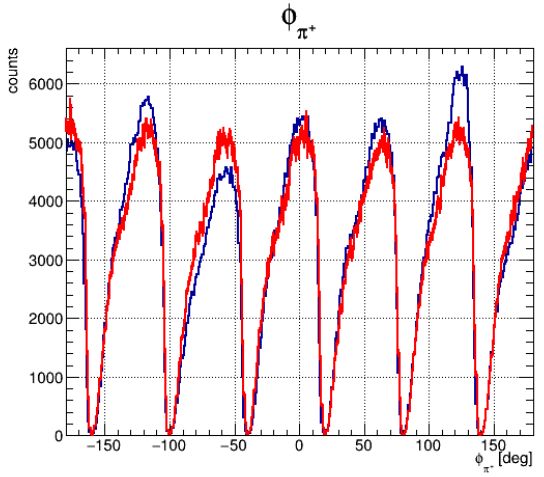




$\pi^+$



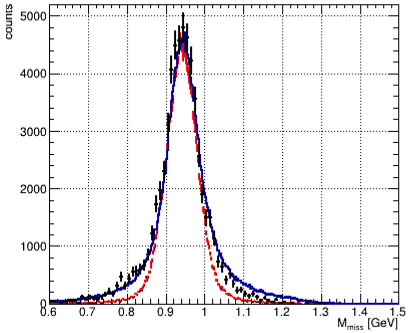



# Data MC Comparison

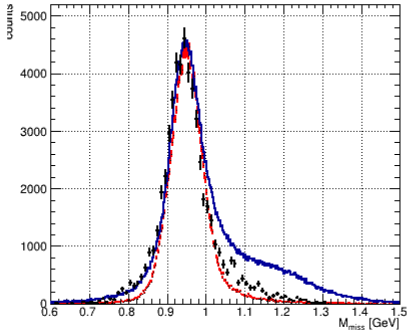
➔ **A realistic resolution has been introduced to the reconstructed events**

**Missing neutron peak for different -t bins:**

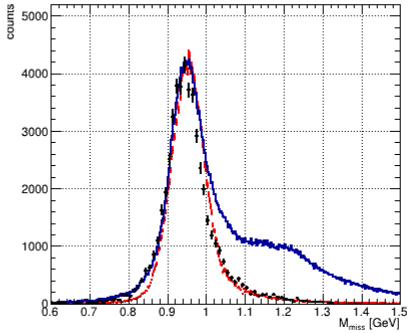
**0.05 GeV² < -t < 0.155 GeV²**



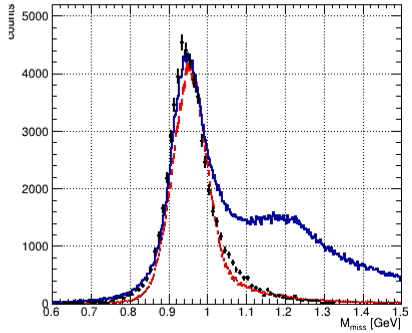

**0.155 GeV² < -t < 0.24 GeV²**



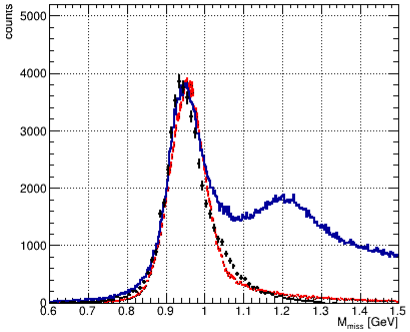

**0.24 GeV² < -t < 0.33 GeV²**



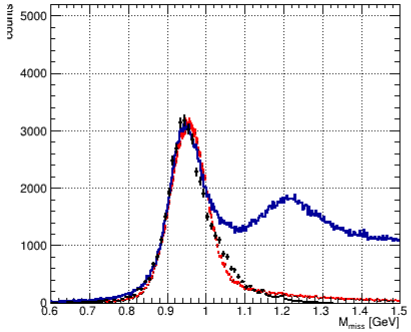

**0.33 GeV² < -t < 0.44 GeV²**



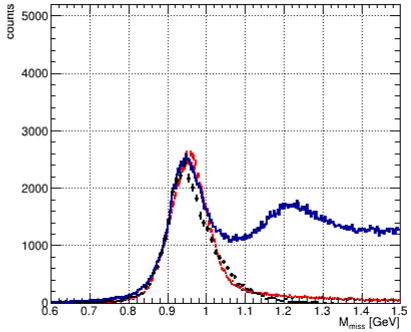

**0.44 GeV² < -t < 0.56 GeV²**




**0.56 GeV² < -t < 0.68 GeV²**




**0.68 GeV² < -t < 0.8 GeV²**




data eπ+X
data enπ+
MC excl. aaonorad (realistic resolution)

➔ ~ 43 M generated events are needed to match the data

➔ ~ 400 - 500 M events are currently in production

# Sources of Systematic Uncertainties

→ **Uncertainty of the beam polarization**
  → 3 % scale uncertainty

→ **Effect of the choice of fiducial cuts**

→ **Effect of the extraction method and higher order moments**

→ **Background subtraction and exclusivity cuts**
  → Difference between the two background subtraction methods

  Further background:
  a) random coincidences
  b) wrong PID
  c) charge sysmmetric background (well reduced by y < 0.75 cut)

  → Should be all taken care by the bin by bin background subtraction

→ **Radiative effects**
  → Radiative effects cause migration from the exclusive region to the SIDIS region

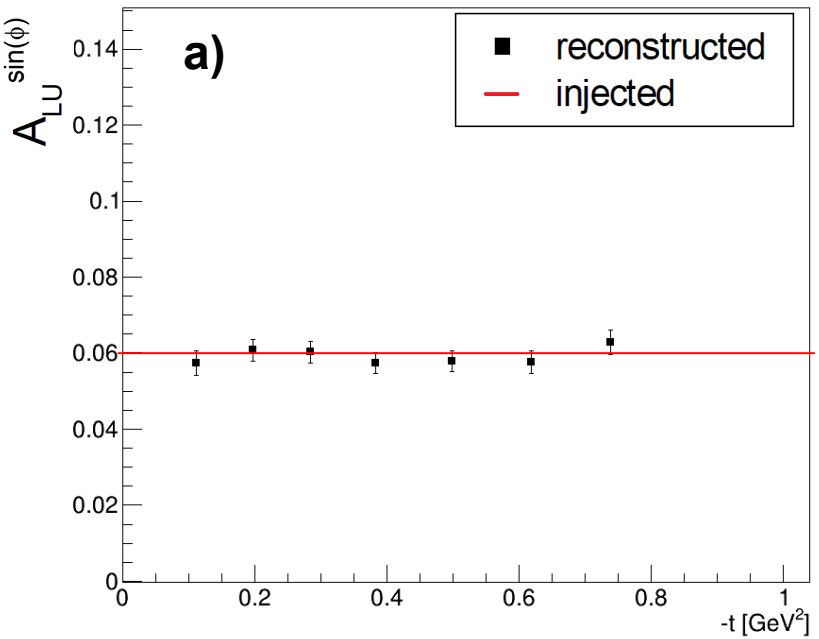
  → Small effect on selected events due to a tight cut on the missing mass

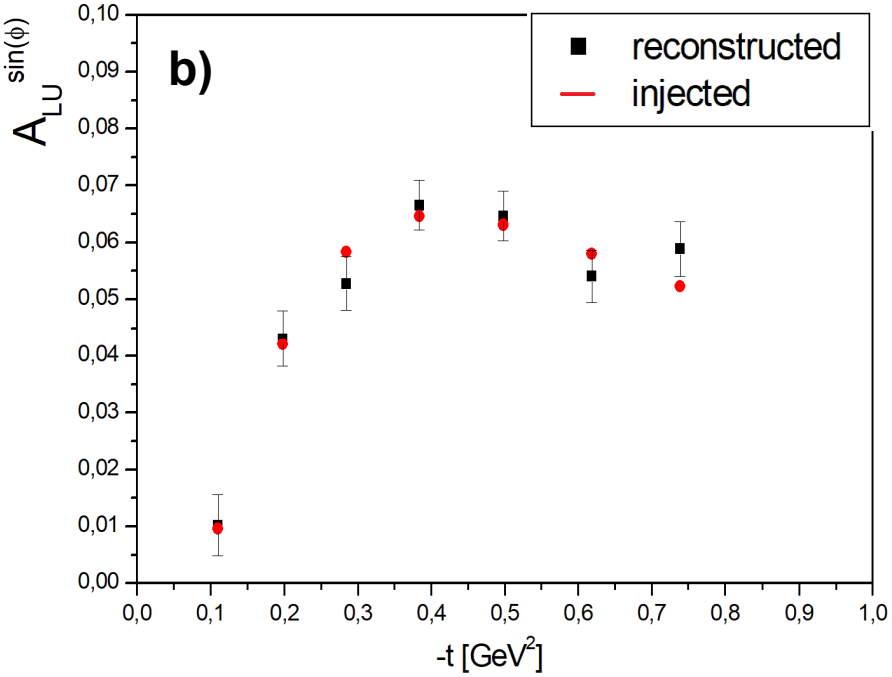
  → SIDIS: 3 % have been assumed → For exclusive << 3 %

# Systematic Uncertainties: Acceptance Effects

→ Implemented asymmetry: a) $A_{LU}^{\sin\Phi} = 0.06$ $(\sigma_{LT'}/\sigma_0 \sim 0.1)$

b) $A_{LU}^{\sin\Phi}(t)$ with typical t dependence




→ Study has been done for each multidimensional bin

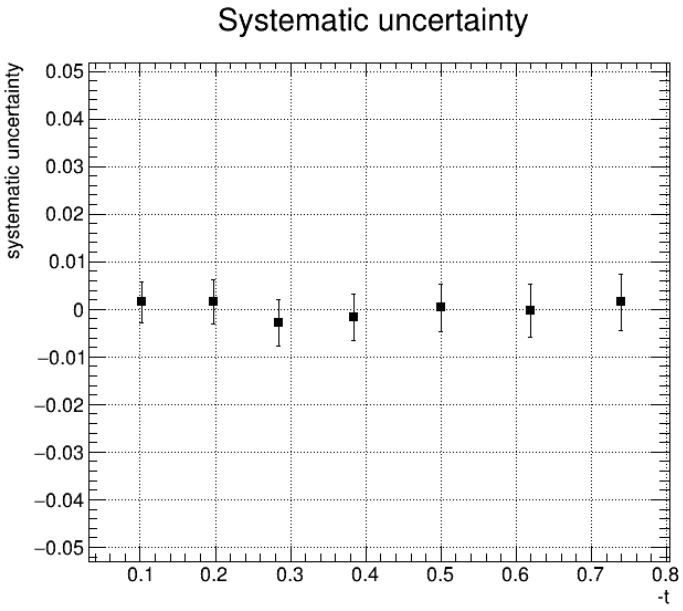
→ **Difference between the reconstructed and implemented value is used as a systematic uncertainty**

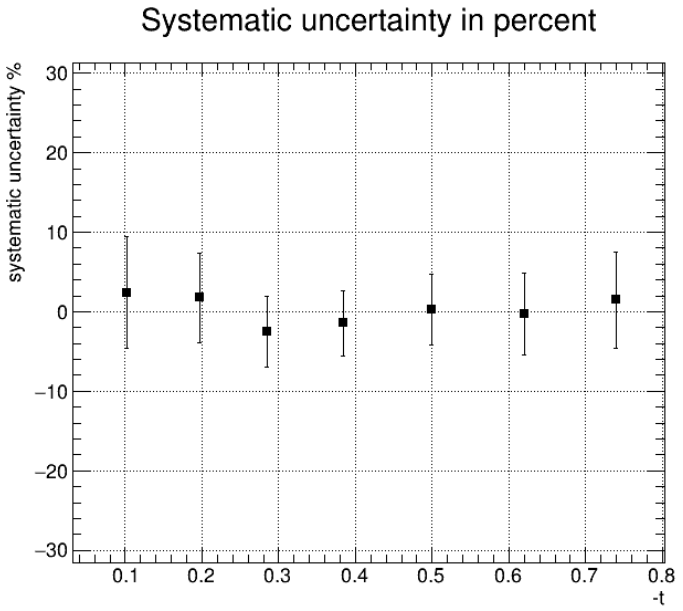
# Systematic Uncertainties: Bin Migration

$$\Delta A_i = (1 - \sum_{n=1}^{3} f_{i+n} - \sum_{n=1}^{3} f_{i-n}) A_i + \sum_{n=1}^{3} f_{i-n} A_{i-n} + \sum_{n=1}^{3} f_{i+n} A_{i-n} - A_i$$

$A_i$ is the asymmetry in bin $i$ and $f_{i+n}$ the contamination

$Q^2$ - $x_B$ integrated




→ Study has been done for each multidimensional bin

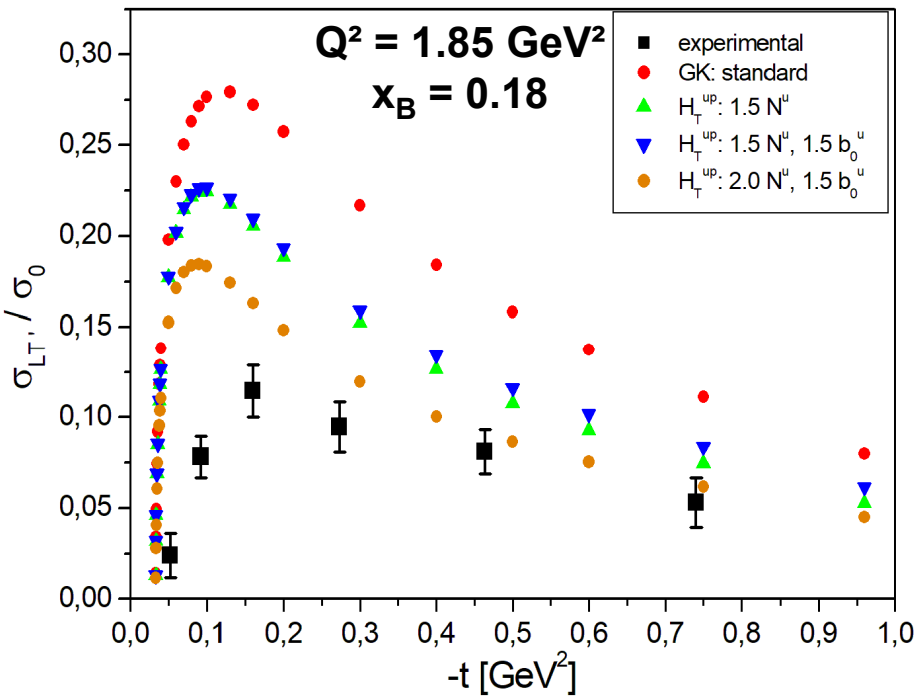
# Comparison to Theory Predictions (GK Model)

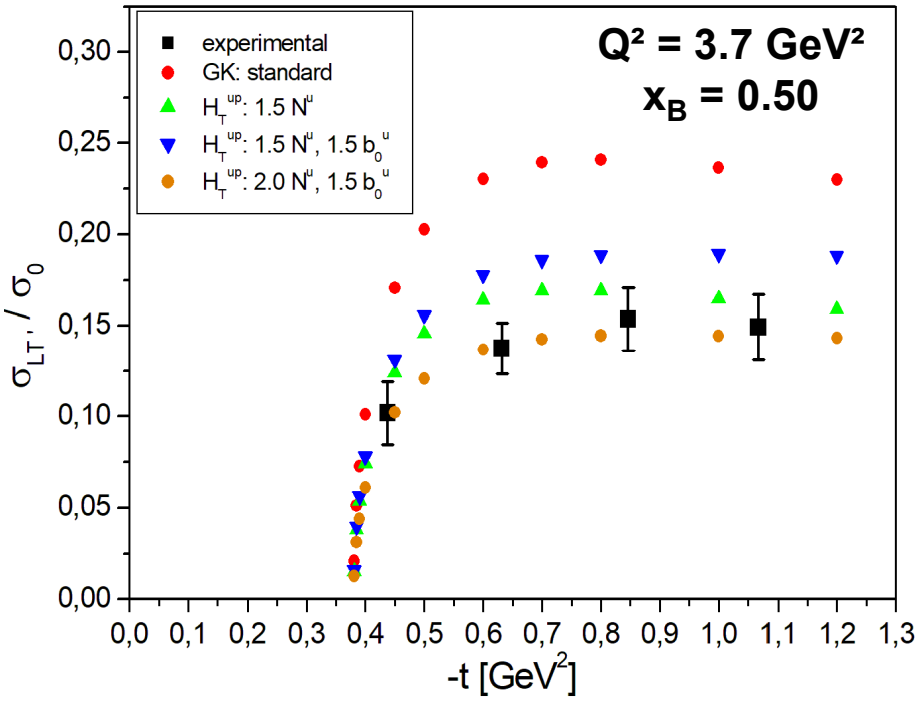
$$\sigma_{LT'} \sim Im\left[< \overline{E}_T >^* < \widetilde{H} > + < H_T >^* < \widetilde{E} >\right]$$

**For π⁺:** $\sigma_{LT'} \sim Im[< H_T >^* < \widetilde{E} >]$

$$H_T^u = N^u \cdot e^{b_0^u \cdot t} \cdot \sum_{i=1}^{6} c_i^u \cdot VE(x, i, \delta^u + \alpha^u \cdot t)$$

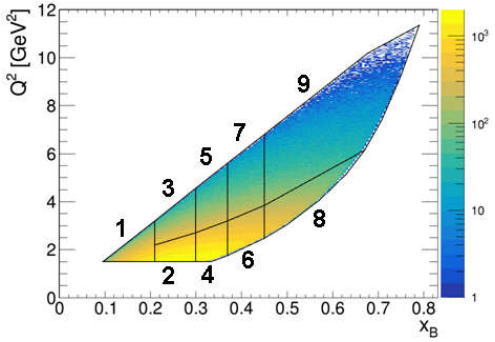
$$H_T^d = N^d \cdot e^{b_0^d \cdot t} \cdot \sum_{i=1}^{6} c_i^d \cdot VE(x, i, \delta^d + \alpha^d \cdot t)$$



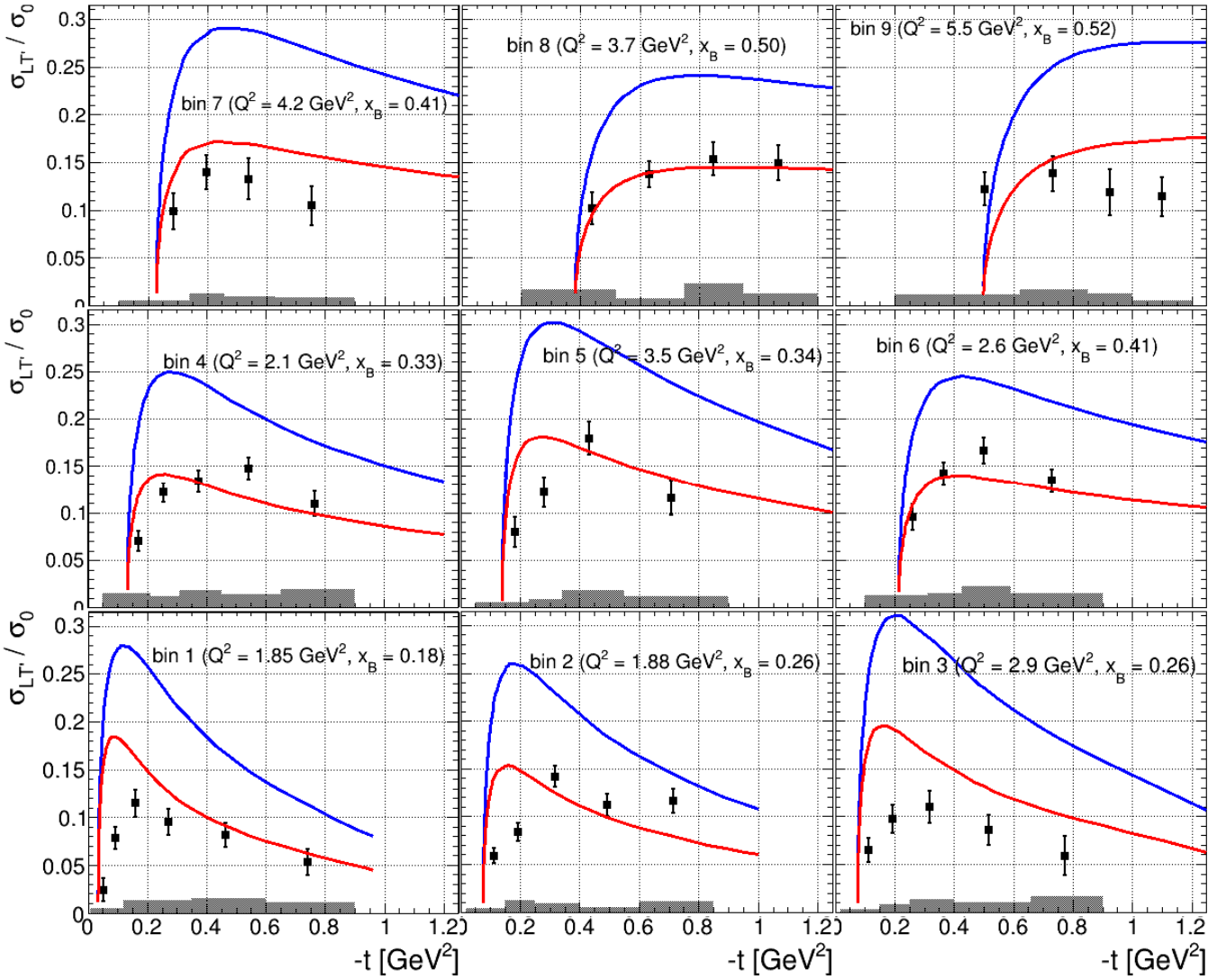
# Final Plots

preliminary




**GK model (original $H_T$)**

**GK model (optimized $H_T$)**



# Conclusion and Outlook

- Hard exclusive $\pi^+$ BSA in the GPD regime ($-t < 1$ GeV$^2$) can be well extracted from CLAS12 RG-A data using only the FD.
- The background shape is understood and based on a bin by bin fit, the background subtraction is well under controll.
- A dedicated eventgenerator (aaorad/aaonorad) is available.
- MC: ~ 500 Million MC are currently in production (~50M already produced).
- All methods for systematic studies are ready.
- Theory calculations based on the GK modell are available.
- Momentum correction will be finalized.
- Analysis note is in preparation.