Beam-Spin Asymmetry of Exclusive Pion Production in the KaonLT Experiment

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Introduction

- Measurement of beam single-spin asymmetry for two channels of exclusive π^+ production:

$$p(e,e'\pi^+)n/\Delta^0$$

- Polarized cross-section in Rosenbluth equation:

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

$$+h\sqrt{2\epsilon(1-\epsilon)}\frac{d\boldsymbol{\sigma_{LT'}}}{dt}\sin\phi$$

- BSA provides much cleaner access to $\sigma_{LT'}$:

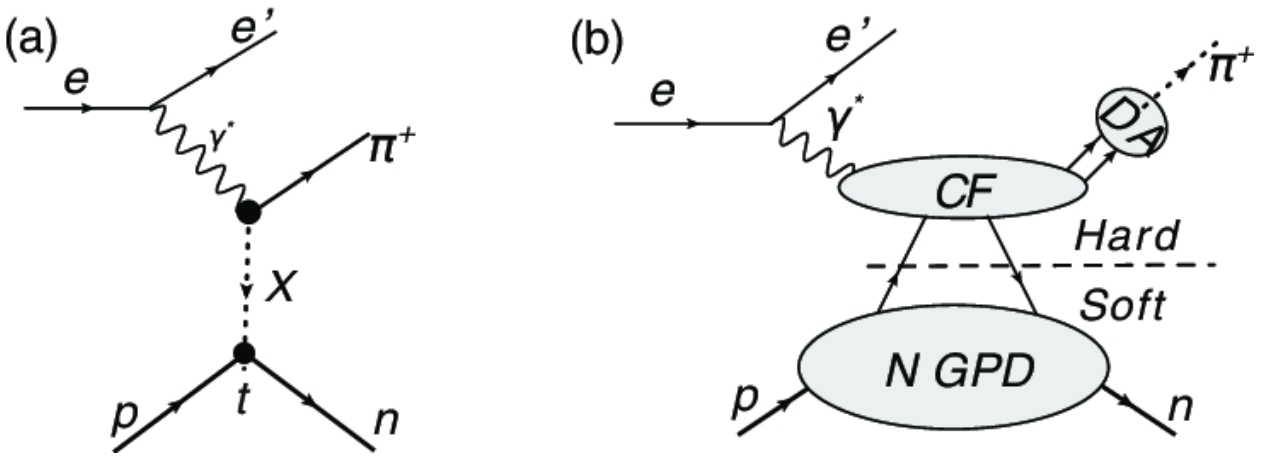
$$BSA = \frac{1}{P}\left(\frac{\sigma^+ - \sigma^-}{\sigma^+ + \sigma^-}\right) = \frac{1}{P}\left(\frac{Y^+ - Y^-}{Y^+ + Y^-}\right) \propto \frac{\boldsymbol{\sigma_{LT'}}}{\sigma_0}$$

Theoretical Motivation

The BSA should be equal to:

$$BSA = \frac{\sqrt{2\epsilon(1-\epsilon)}\frac{\sigma_{LT'}}{\sigma_0}\sin\phi}{1+\sqrt{2\epsilon(1+\epsilon)}\frac{\sigma_{LT}}{\sigma_0}cos\phi+\epsilon\frac{\sigma_{TT}}{\sigma_0}cos2\phi}$$

Regge (a) and GPD (b) approaches both predict $\sigma_{LT'}/\sigma_0$:



This work: Extract $\sigma_{LT'}/\sigma_0$, compare results to Regge-based **Vrancx-Ryckebush** (VR) model and GPD-based **Goloskokov-Kroll** (GK) model.

S. Basnet et al, Phys. Rev. C **100** 065204 (2019)
T. Vrancx, J. Ryckebusch & J. Nys, Phys. Rev C, **89** 065202 (2014).
S.V. Goloskokov, P. Kroll, Eur. Phys. J. C **65** 137 (2010).

GPD picture

GK model provides the expression for $\sigma_{LT'}$ in terms of the twist-2 longitudinal $(\widetilde{E}, \widetilde{H})$ and twist-3 transverse (E_T, H_T) GPDs:

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

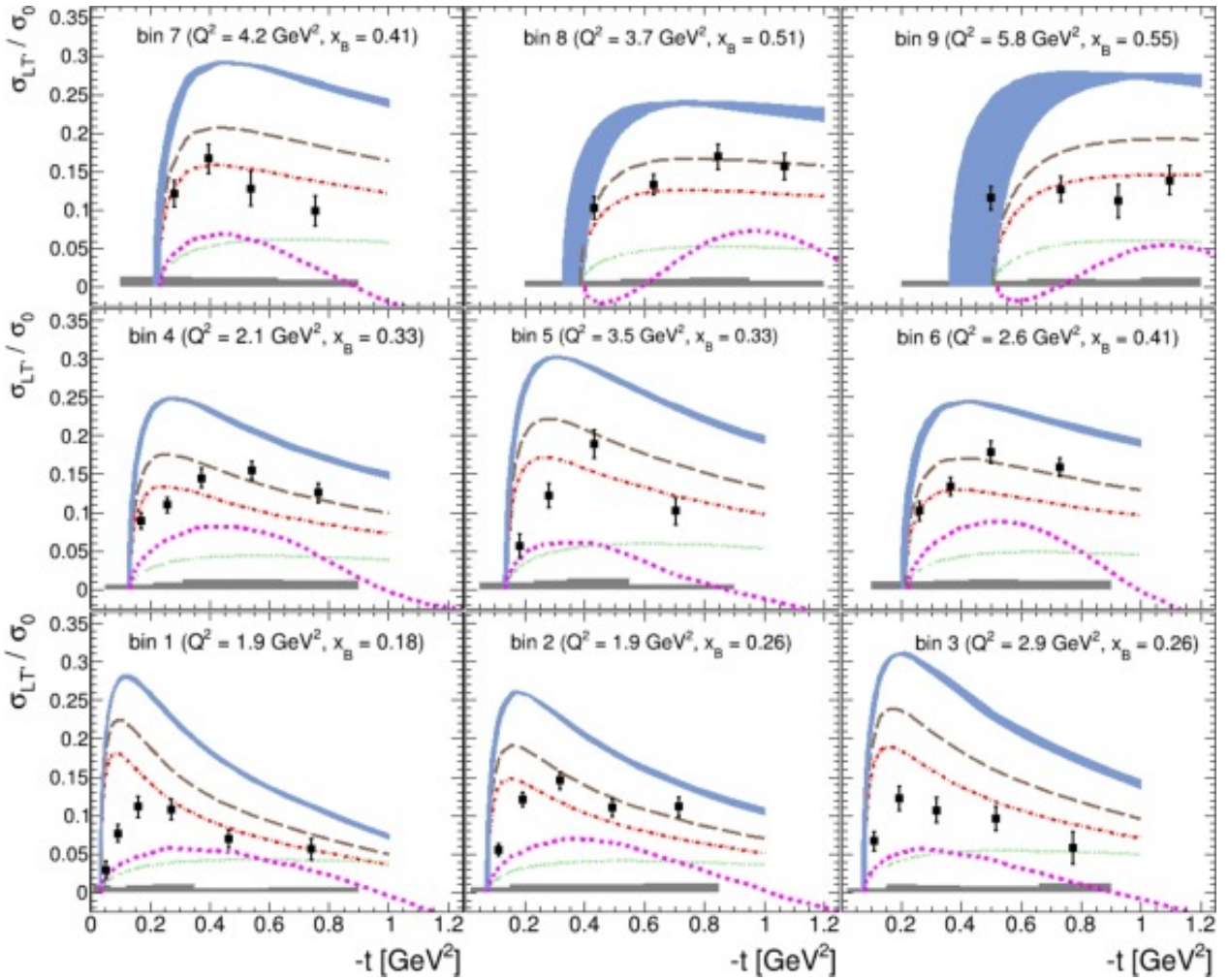
where $\overline{E}_T = 2\widetilde{H}_T + E_T$ and the "eff" in the subscript indicates the inclusion of the pion pole term.

- We expect the GPD picture to apply for $-t/Q^2 \ll 1$ and $Q^2 \gg 1$ for fixed x_B
- GK predictions generated using PARTONS, which allows for modifications to GPDs

S.V. Goloskokov, P. Kroll, Eur. Phys. J. C **65** 137 (2010).
B. Berthou et al, Eur. Phys. J. C **78** 478 (2018).
https://partons.cea.fr/

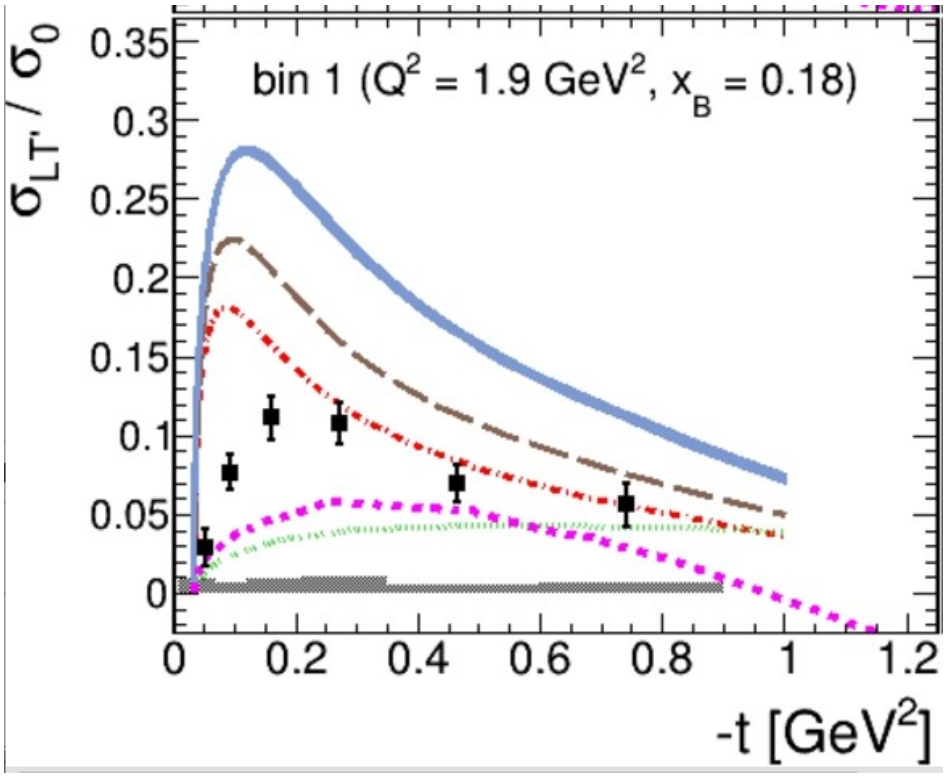
Recent Results from CLAS12

Similar study from Hall B extracts $\sigma_{LT'}/\sigma_0$ from BSA in $p(e,e'\pi^+)n$ and compares with **GK** and **JML** (Regge) models.



S. Diehl et al, Phys Lett B 839 (2023) 137761

Recent Results from CLAS12



Similar study from Hall B extracts $\sigma_{LT'}/\sigma_0$ from BSA in $p(e, e'\pi^+)n$ and compares with **GK** and **JML** (Regge) models.

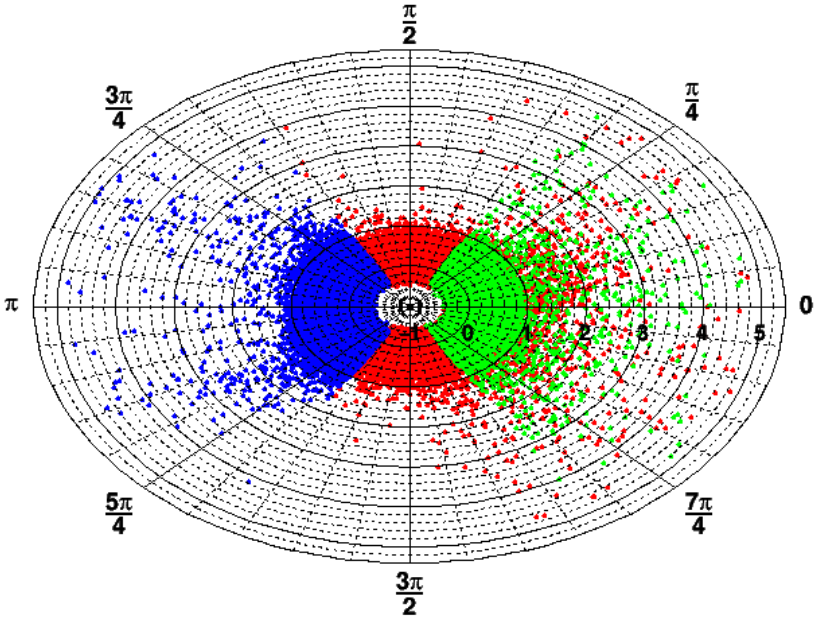
The GPD H_T in the GK model is then scaled by factors of **1.5** and **2**.

"... at low Q^2, the JML model shows a slightly better agreement than the GK model, while the situation changes for high Q^2 where the GPD-based model provides a better reproduction of the data."

S. Diehl et al, Phys Lett B 839 (2023) 137761

BSA in KaonLT

- HMS detecting electrons
- SHMS detecting positive hadrons
- NGC not installed in SHMS
- Full ϕ coverage given by taking data at three SHMS angles per setting (**left**, **center**, **right**)
- High ϵ data (Autumn 2018)
- Beam energy 10.6 GeV
- Beam polarization $89^{+1}_{-3}\%$

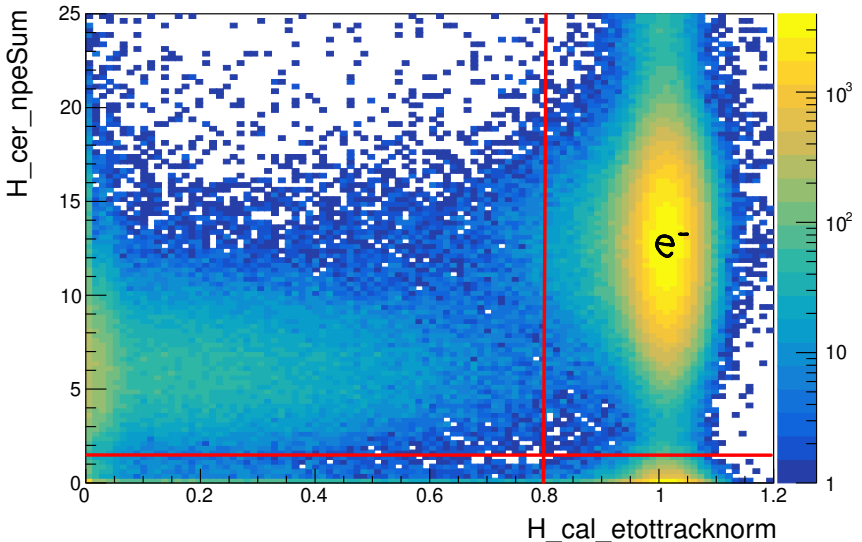


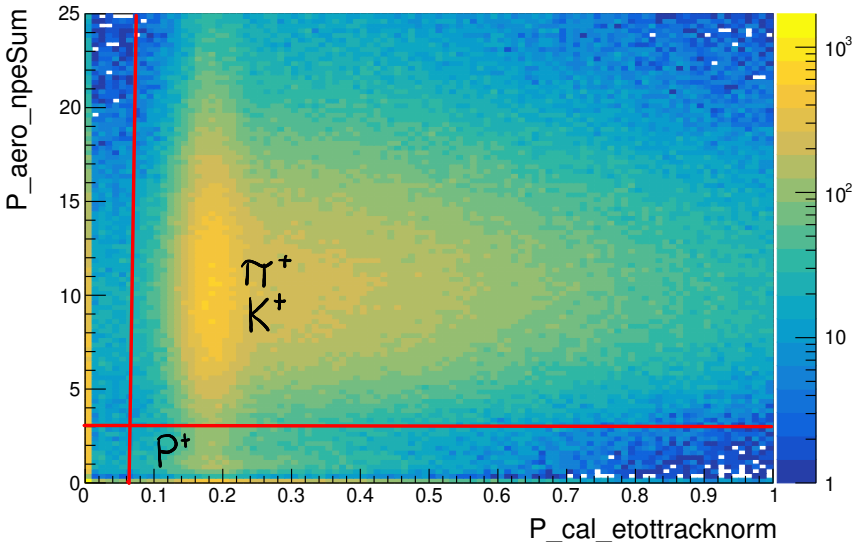
Q^2 (GeV)	W (GeV)	x_B	ϵ
2.115	2.95	0.21	0.79
3	3.14	0.25	0.67
3	2.32	0.40	0.88
4.4	2.74	0.40	0.71
5.5	3.02	0.40	0.53

$p(e, e'\pi^+)n$

Particle Identification

$p(e, e'\pi^+)n$





e^- in HMS

H_cal_etottracknorm > 0.8

H_cer_npeSum > 1.5

π^+ in SHMS

P_cal_etottracknorm > 0.05

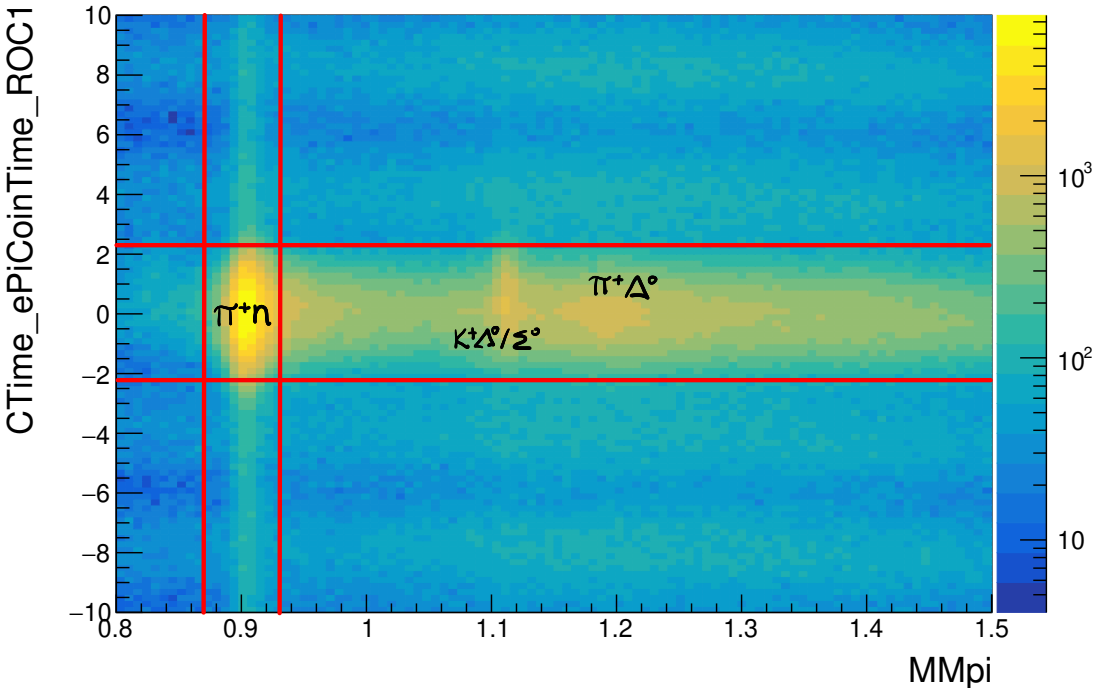
P_aero_npeSum > 3

Plots: Q^2=2.115, W=2.95, SHMS center.

Cuts applied: -2.25 < CTime_ePiCoinTime_ROC1 < 2.25, 0.8 < MMpi < 1.2.

Event Selection

$p(e,e'\pi^+)n$



Coincidence

$-2.25 <$ CTime_ePiCoinTime_ROC1 < 2.25

Missing mass

$0.884 <$ MMpi < 0.924

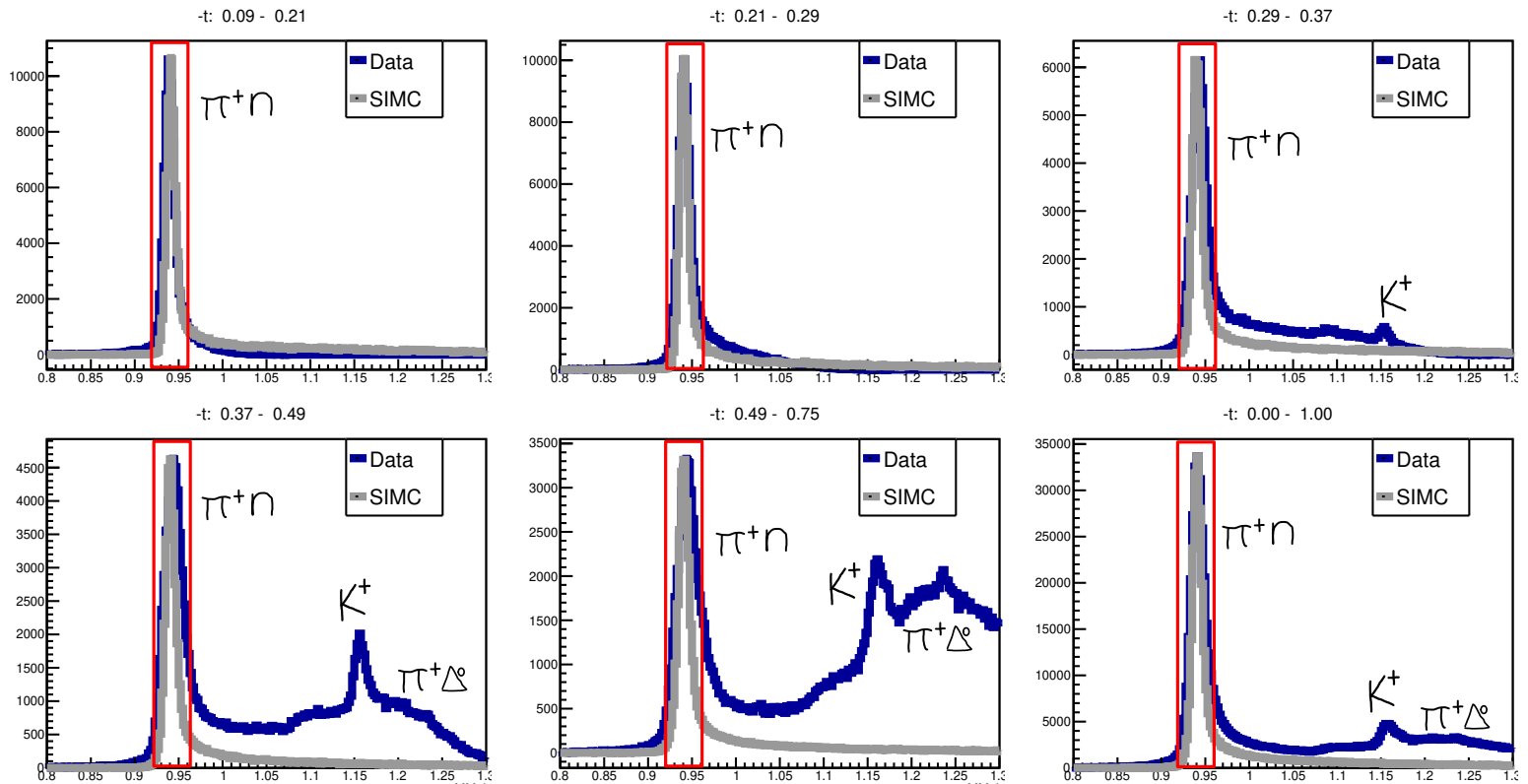
- Missing mass cut changes for each setting: ± 0.02 GeV of peak position, will change after offsets applied
- Cut dependence on coincidence time and missing mass contribute to systematic error

Plot: Q^2=2.115, W=2.95, SHMS center.
Cuts applied: P_cal_etottracknorm > 0.05, P_aero_npeSum > 3, H_cal_etottracknorm > 0.8, H_cer_npeSum > 1.5

Missing Mass

$p(e, e'\pi^+)n$

- Peak resolution wider than SIMC, effect dependent on $-t$
- Same for both helicities → small effect on BSA, consider cut dependence in systematic errors
- Likely related to δ_{fp} - study ongoing

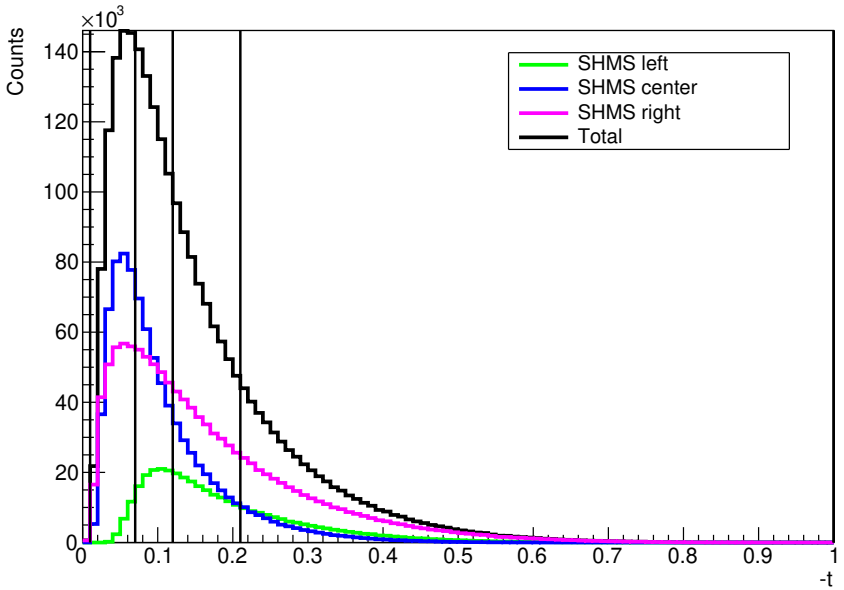


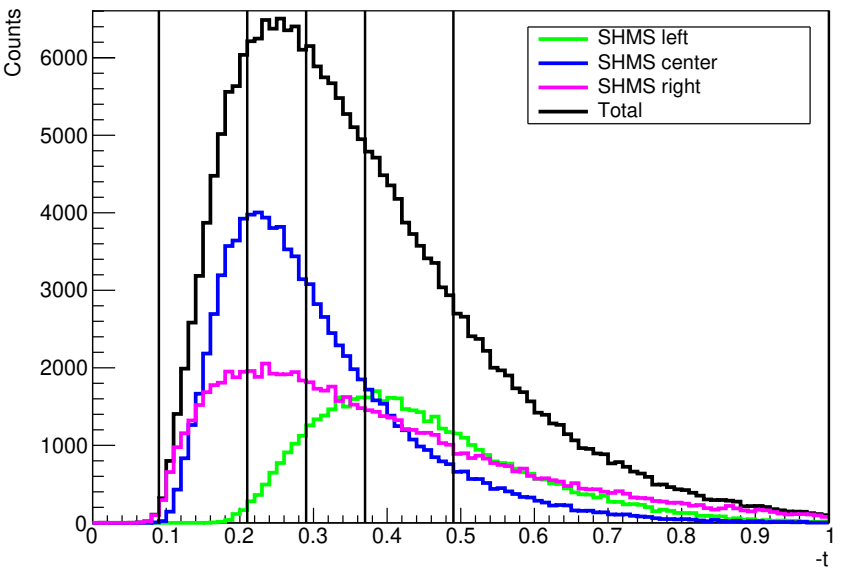
MMpi

-t Binning

$p(e,e'\pi^+)n$

- Sum all events at one (Q^2,W) and separate into $-t$ bins with similar numbers of events
- Some settings have significantly more statistics than others: final results will have different numbers of bins per setting



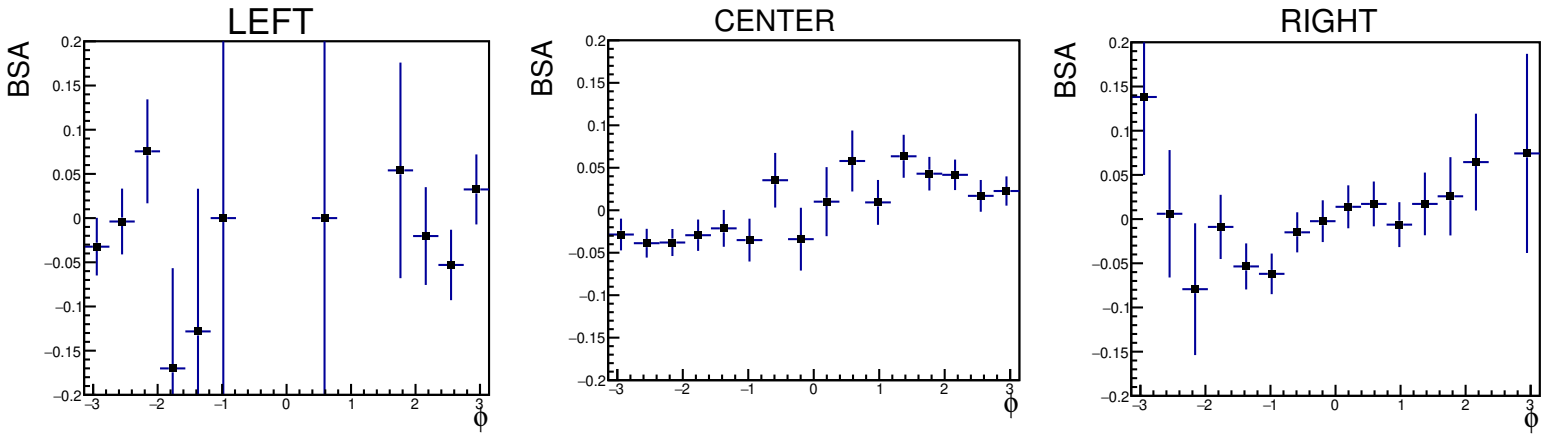


Plots: Q^2=2.115, W=2.95 (left), Q^2=4.4, W=2.74 (right).

Combining SHMS Settings

$p(e,e'\pi^+)n$

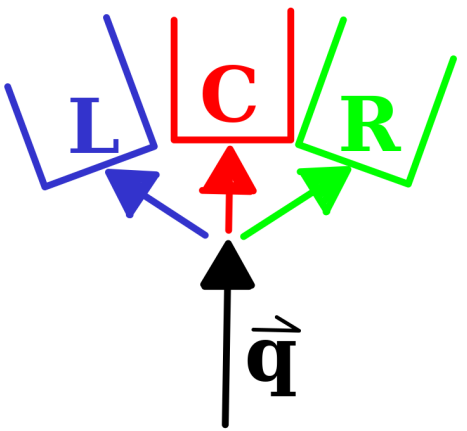
$$BSA = \frac{1}{P}\left(\frac{Y^+ - Y^-}{Y^+ + Y^-}\right), \qquad \delta_{BSA} = \frac{1}{P}\sqrt{\frac{2((Y^+)^2 + (Y^-)^2)}{(Y^+ + Y^-)^3}}$$



Asymmetry is calculated separately for three SHMS angles, then a weighted average is taken where the weight $W = \delta^{-2}$:

$$\overline{BSA} = \frac{BSA_L * W_L + BSA_C * W_C + BSA_R * W_R}{W_L + W_C + W_R}$$

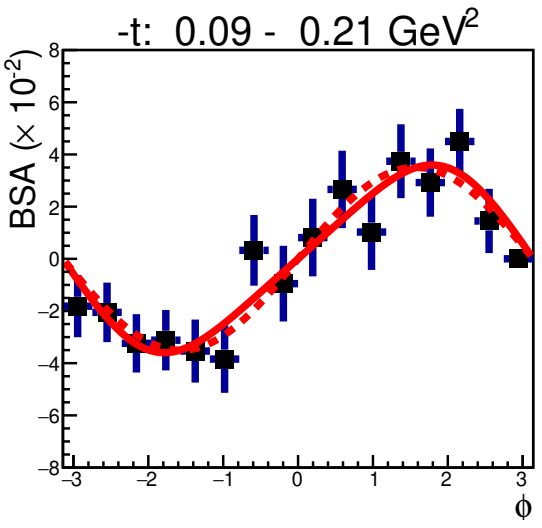
$$\delta_{\overline{BSA}} = \sqrt{\frac{1}{W_L + W_C + W_R}}$$

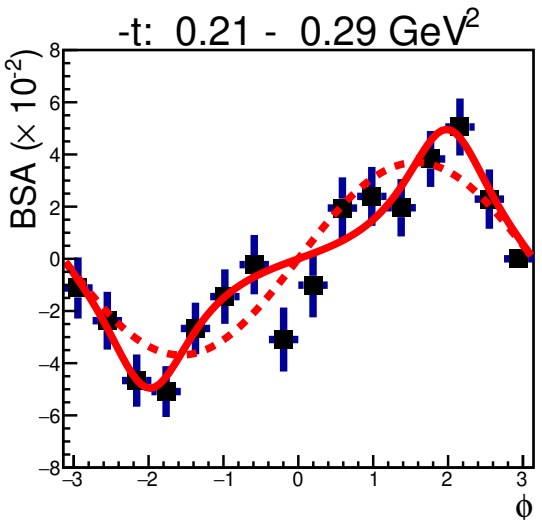


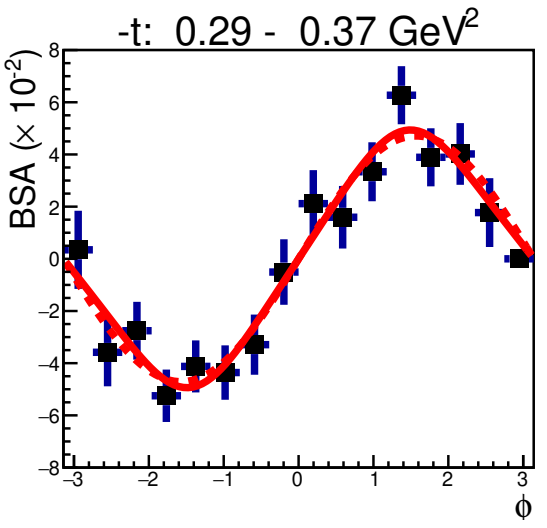
Plots: Q^2=3, W=2.32, $0.09 < -t < 0.21$ (bin 1).

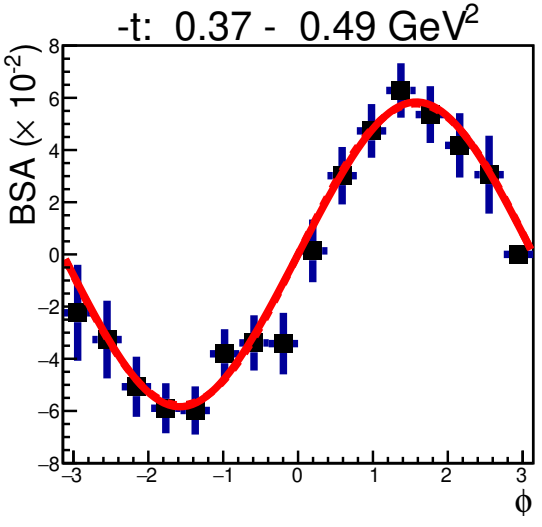
Asymmetry

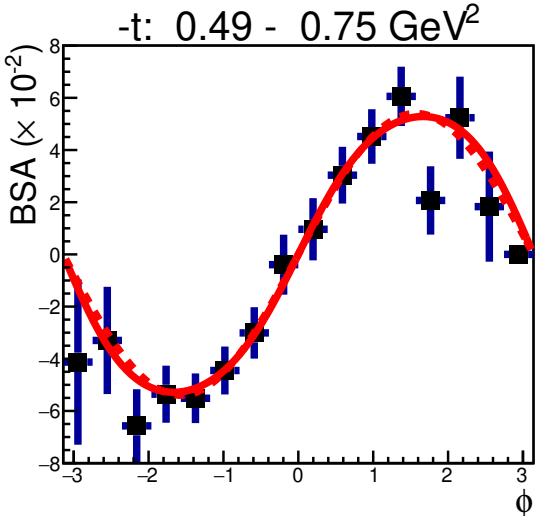
$p(e,e'\pi^+)n$











$A\sin\phi$

$$\frac{A\sin\phi}{1+B\cos\phi+C\cos 2\phi}$$

$$A \propto \frac{\sigma_{LT'}}{\sigma_0}$$

Plot: Q^2=3, W=2.32. Errors are purely statistical.

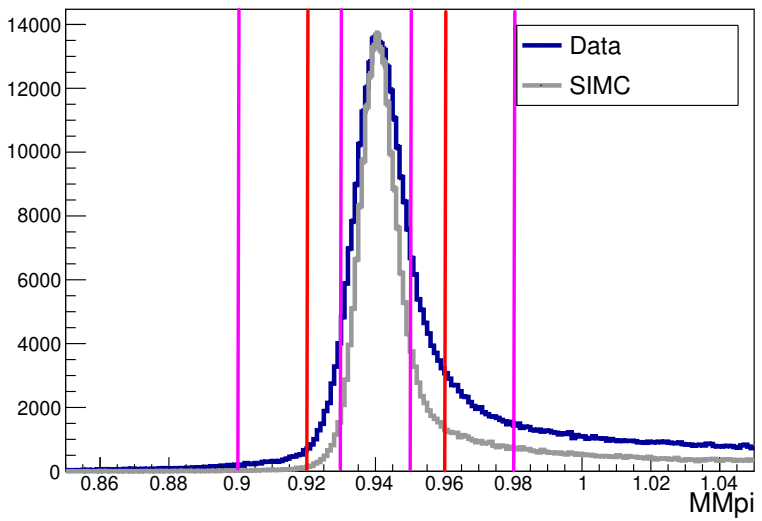
Systematics: Cut Dependence

$p(e, e'\pi^+)n$

- Varying values for PID cuts to determine effect on asymmetry
- Use tight, wide cuts to generate BSA estimates A', A'', then the error is calculated as:

$$\delta = \frac{|A - A'| + |A - A''|}{2}$$

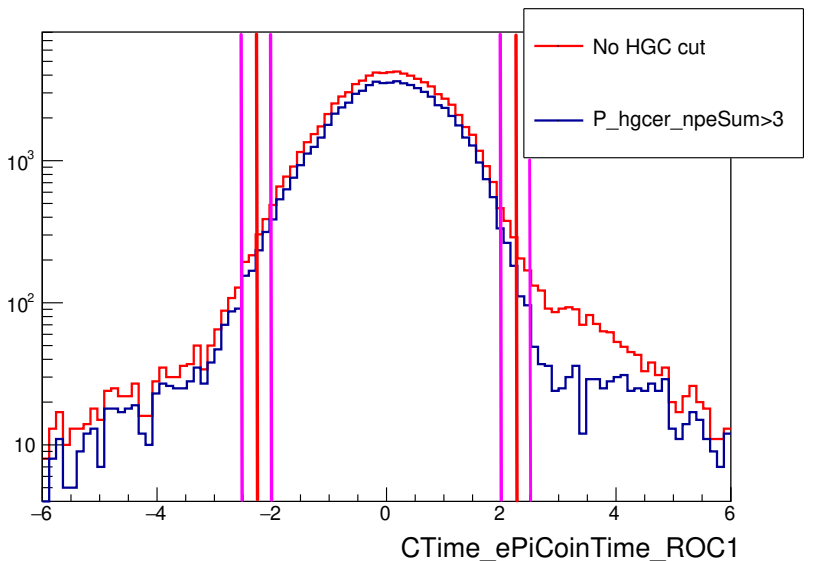
Missing Mass



$$MMpi = \sqrt{(E_e + m_p - E_{e'} - E\pi+)^2 - (p_e - p_{e'} - p_{\pi+})^2}$$

Nominal: ± 0.02 GeV
Tight: ± 0.01 GeV
Wide: ± 0.04 GeV

Coincidence Time



$$t_{COIN} = t_{SHMS} - t_{HMS}$$

Nominal: ± 2.25 ns
Tight: ± 2.00 ns
Wide: ± 2.50 ns

Systematics: Beam Polarization

$p(e,e'\pi^+)n$

- No measurements of P were made in Hall C
  → calculate spin precession to infer polarization in Hall C
- Source polarization (Mott polarimeter at injector):
  90.13% +/- 0.51% (stat) +/- 0.90% (sys) (1.04% tot)

$$dP/P_{source} = 1.15\%$$

- Beam energy: assumed valid to 5×10^{-4}

$$dP/P_{ebeam} = +0.51\%/-3.1\%$$

- Linac energy imbalance: nominal -5 ± 1.2 MeV

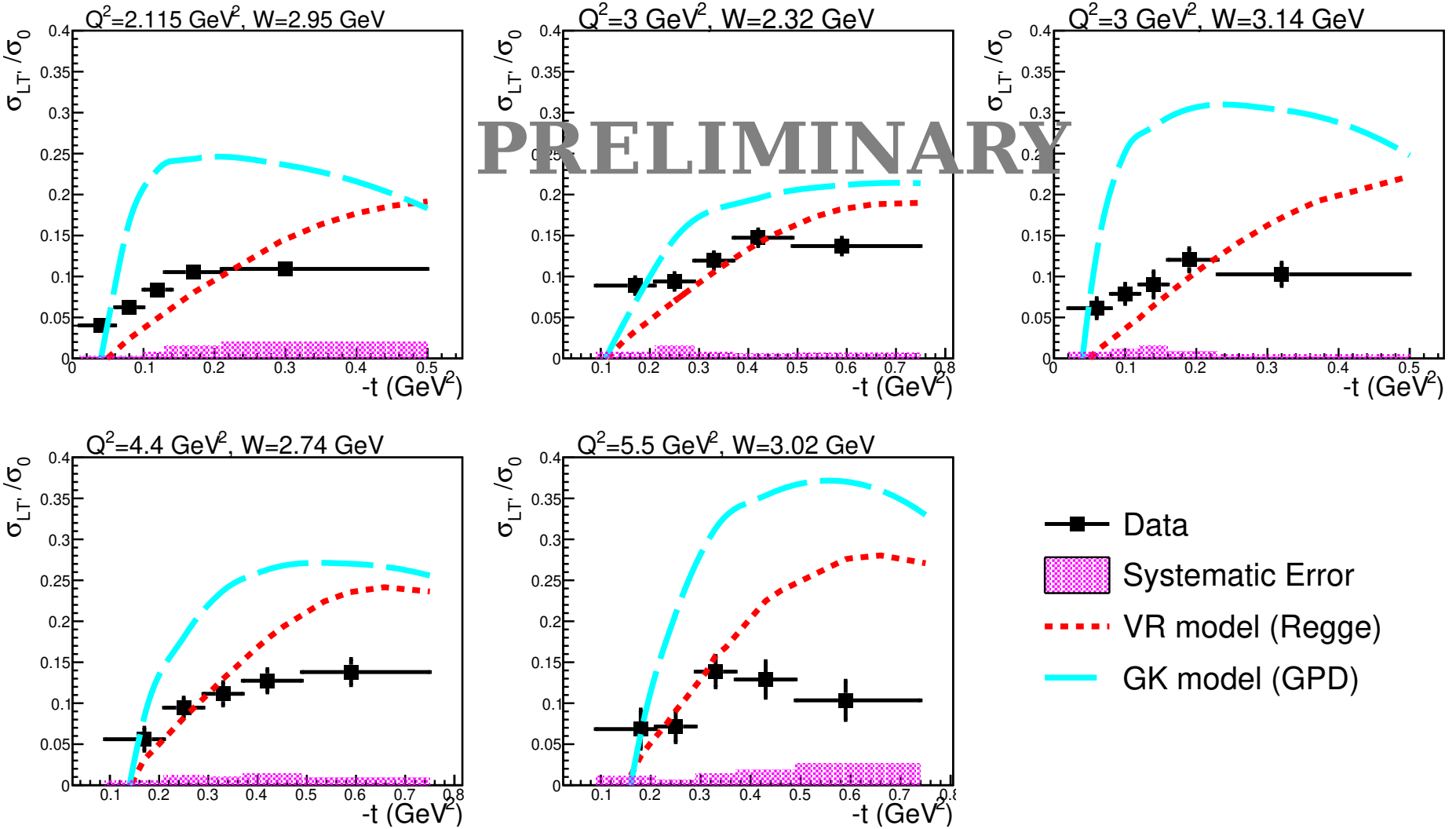
$$dP/P_{imbalance} = +0.39\%/-0.56\%$$

- Total uncertainty:

$$dP/P = +1.32\% \ / \ -3.35\%$$

Results

$p(e, e'\pi^+)n$



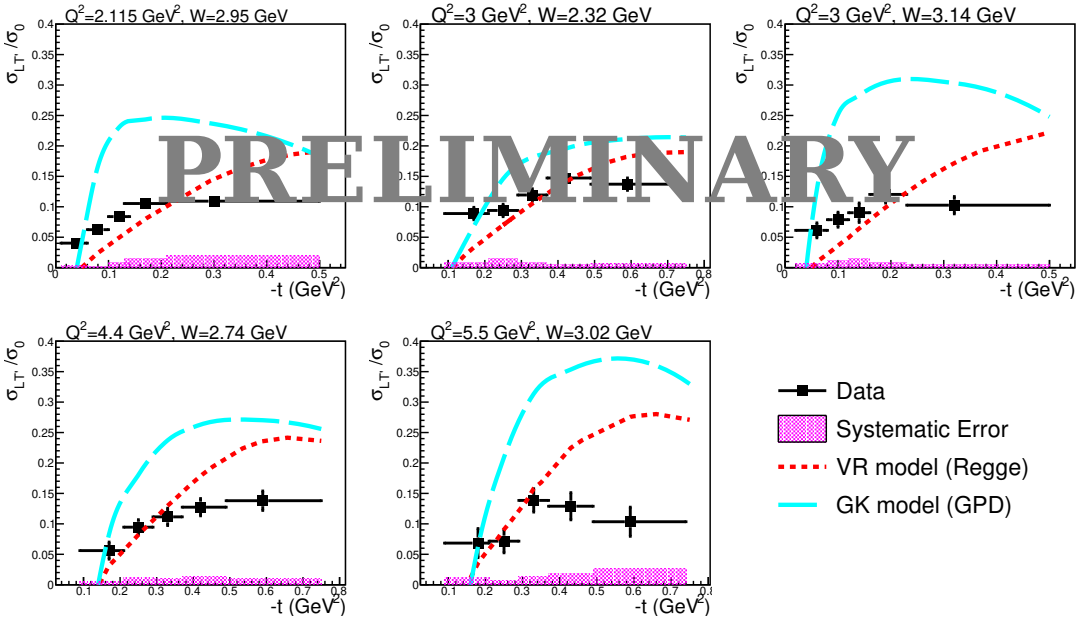
T. Vrancx, J. Ryckebusch & J. Nys, Phys. Rev C, **89** 065202 (2014).

B. Berthou et al, Eur. Phys. J. C **78** 478 (2018).

S.V. Goloskokov, P. Kroll, Eur. Phys. J. C **65** 137 (2010).

Comparison with Theory

$p(e, e'\pi^+)n$



VR model (Regge)

- Good agreement at low $-t$
- Poor agreement for higher $-t$

GK model (GPD)

- Good reproduction of $-t$ dependence (overall shape)
- Overestimates magnitude of $\sigma_{LT'}/\sigma_0$
- Increasing value of H_T in PARTONS will decrease magnitude of $\sigma_{LT'}/\sigma_0 \longrightarrow$ improve agreement with data

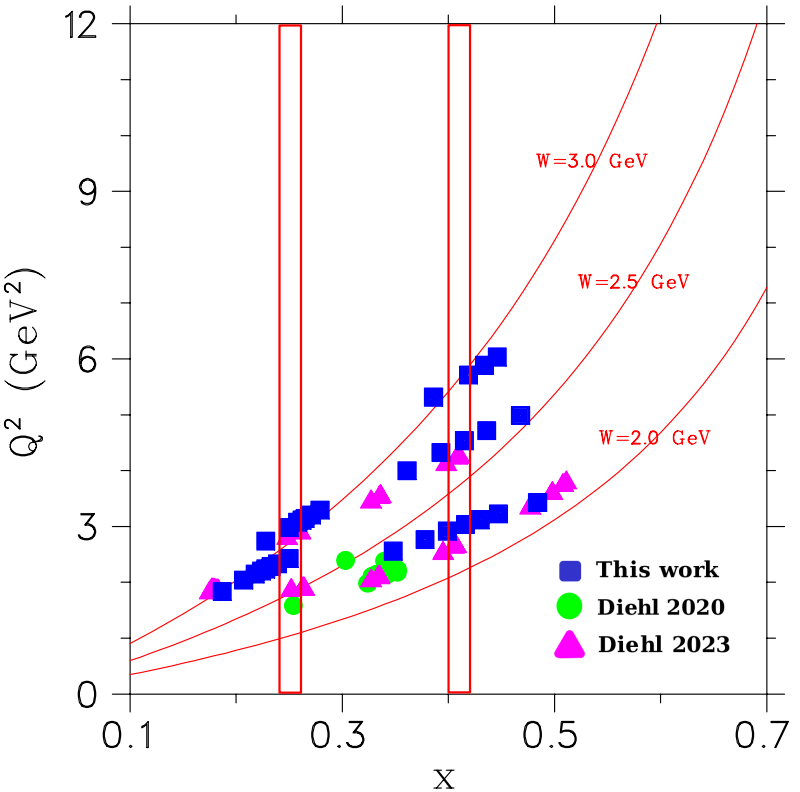
T. Vrancx, J. Ryckebusch & J. Nys, Phys. Rev C, **89** 065202 (2014).
B. Berthou et al, Eur. Phys. J. C **78** 478 (2018).
S.V. Goloskokov, P. Kroll, Eur. Phys. J. C **65** 137 (2010).

Q^2 Scan

$p(e,e'\pi^+)n$

- Combine results with recent papers from CLAS:
  Diehl et al 2023, Diehl et al 2020
- 2023 paper also uses data with E_{beam} =10.6 GeV from CLAS12, 2020 paper uses data with E_{beam} =5.5 GeV from CLAS6
- Plot dependence of $\sigma_{LT'}/\sigma_0$ on Q^2 at fixed $(x_B, -t)$

→ Allows GPD factorization to be explored



Plot by Garth Huber.

S. Diehl et al, Phys. Lett. B **839** (2023) 137761
S. Diehl et al, Phys. Rev. Lett. **125** (2020) 182001

Summary

$p(e, e'\pi^+)n$

- BSA calculated for five (Q^2, W) settings
- Plotted $\sigma_{LT'}/\sigma_0$ as a function of $-t$ at fixed (Q^2, W)
- Will plot $\sigma_{LT'}/\sigma_0$ as a function of Q^2 at fixed $(x_B, -t)$
- Results compared to VR model (Regge) and GK model (GPD)
- Offsets just finalized: data to be re-analyzed with corrected kinematics

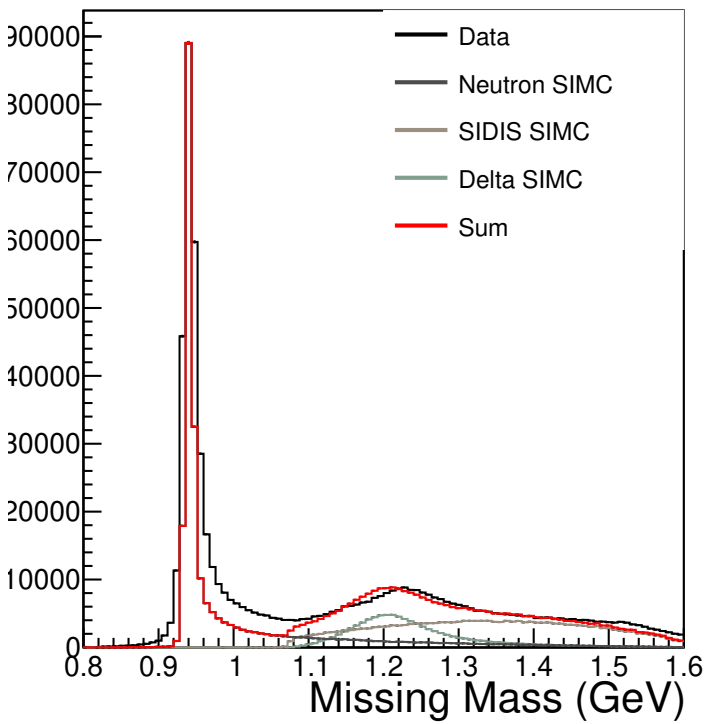
> Paper in progress, to be submitted to PRL this winter.

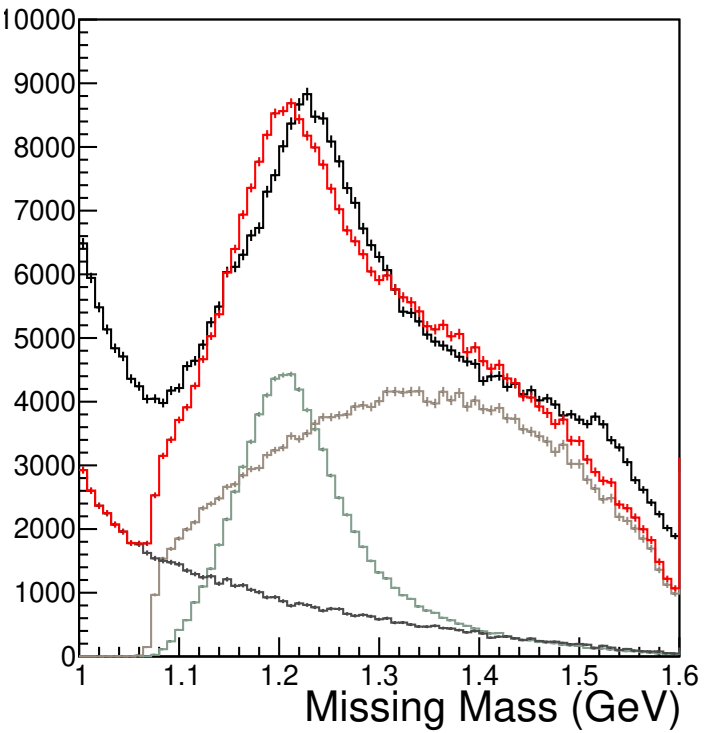
$$p(e, e'\pi^+)\Delta^0$$

Event Selection

$p(e,e'\pi^+)\Delta^0$

- Particle identification similar, added cut on heavy gas Cerenkov
- Missing mass much more complicated: shape study required



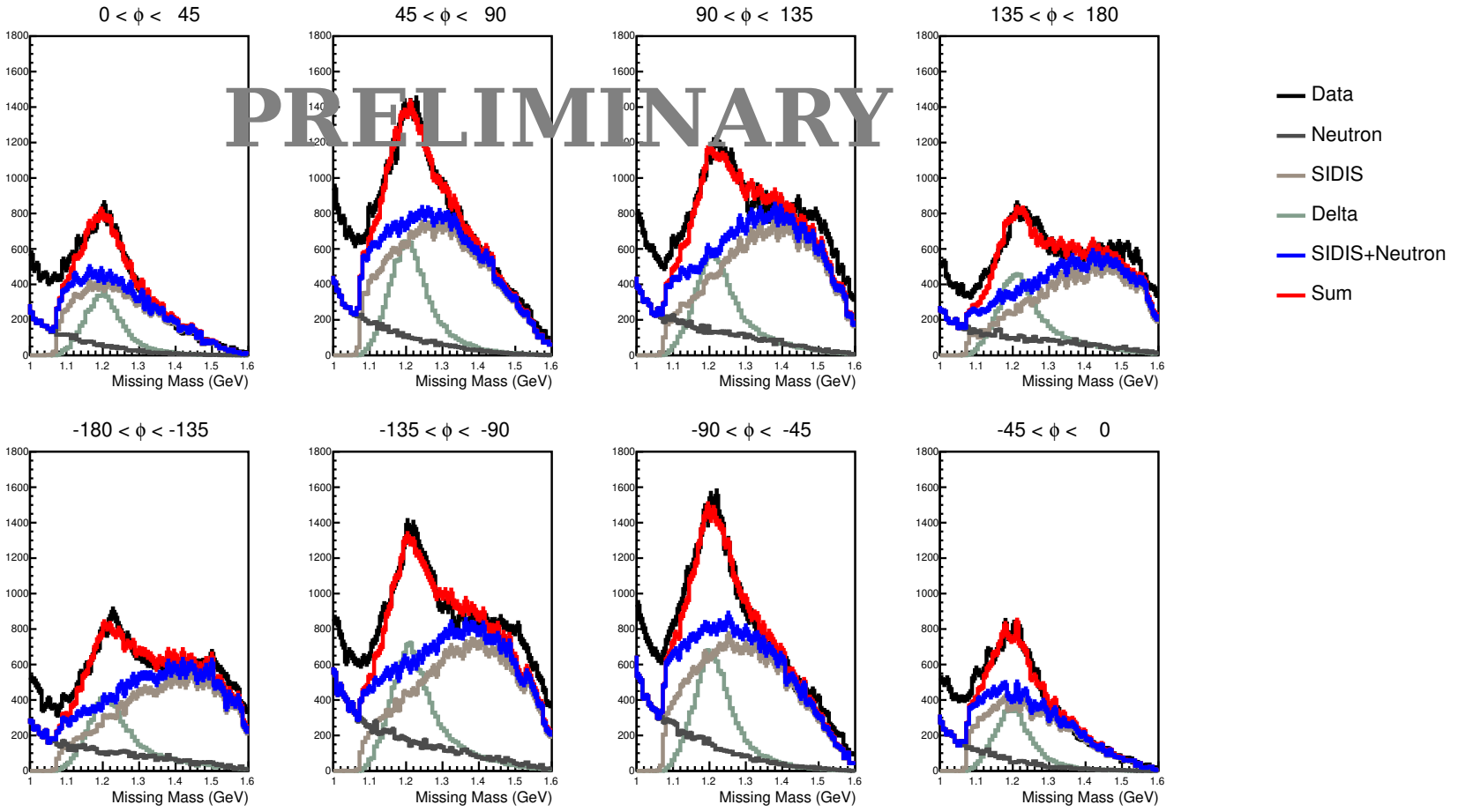


Plot by Ali Usman. Plot: Q^2=2.115, W=2.95, SHMS center

Thanks to Peter for SIMC SIDIS model!

Shape Study

$p(e, e'\pi^+)\Delta^0$



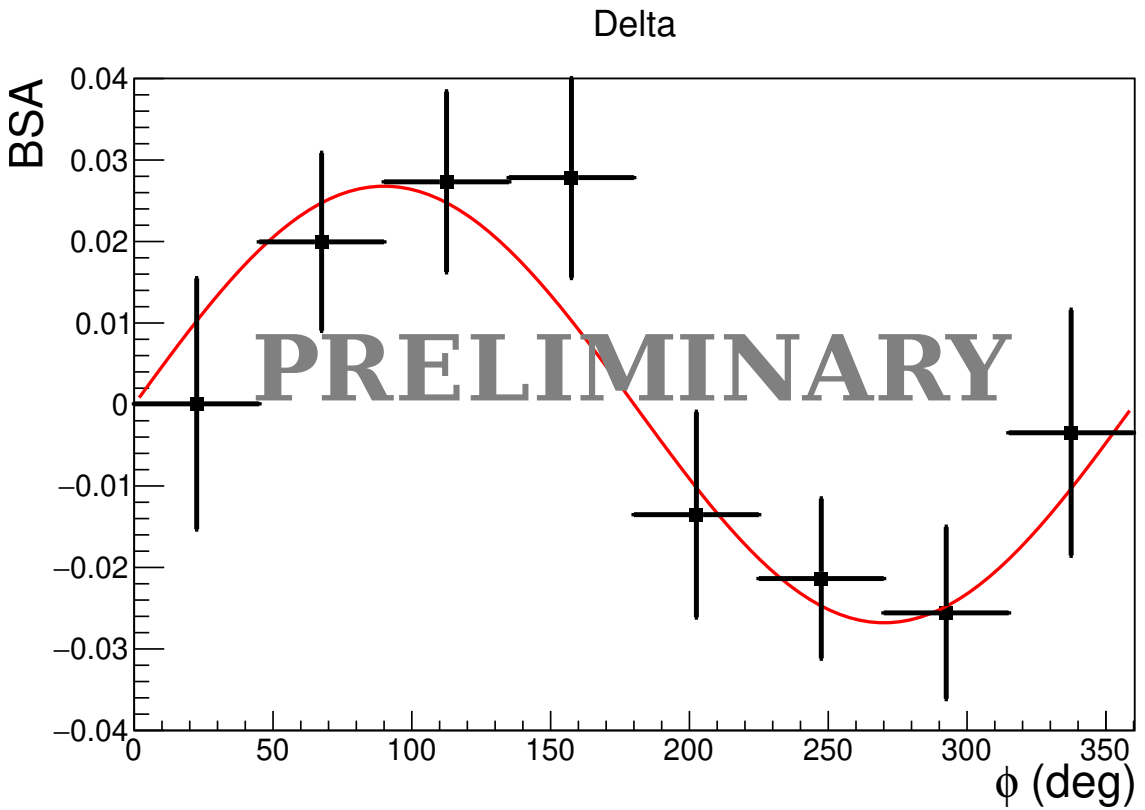
- Fit missing mass with sum of delta, neutron, and SIDIS SIMC
- Yield is integral of delta SIMC.

Initial work by Portia Switzer, plots by Ali Usman. Plots: Q^2=2.115, W=2.95, SHMS center

Asymmetry

$p(e,e'\pi^+)\Delta^0$

$$BSA = \frac{1}{P}\left(\frac{Y^+ - Y^-}{Y^+ + Y^-}\right), \qquad \delta_{BSA} = \frac{1}{P}\sqrt{\frac{2((Y^+)^2 + (Y^-)^2)}{(Y^+ + Y^-)^3}}$$

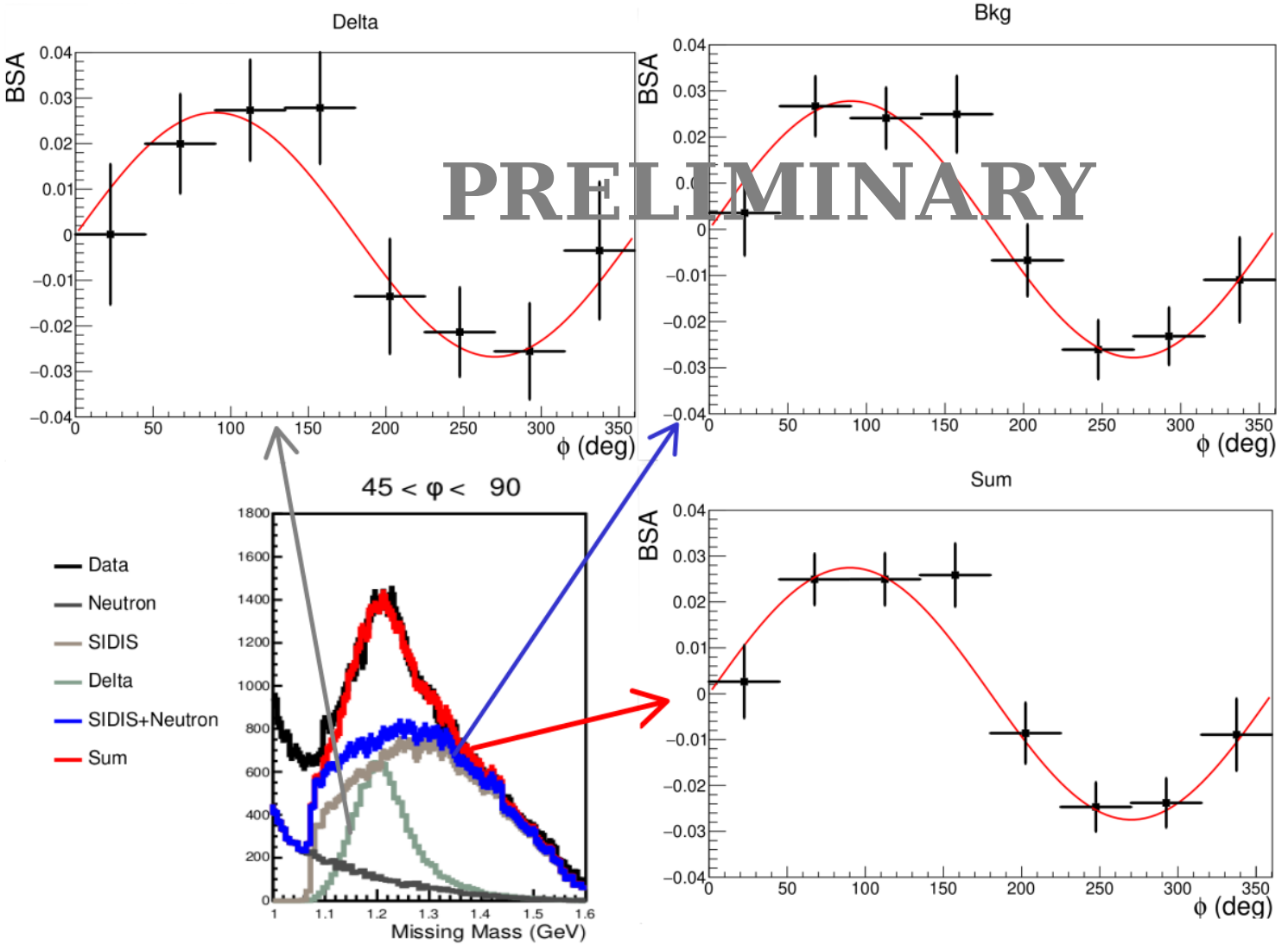


Center only → after adding left and right SHMS settings, statistics should improve by 2-3x.

Plot by Ali Usman. Plots: Q^2=2.115, W=2.95, SHMS center. Errors are purely statistical.

Background Asymmetry

$p(e, e'\pi^+)\Delta^0$



Plots by Ali Usman. Plots: Q^2=2.115, W=2.95, SHMS center. Errors are purely statistical.

Summary

$p(e, e'\pi^+)\Delta^0$

- Yields calculated from SIMC shape study on missing mass spectrum
- BSA can be calculated for a single $-t$ bin at each (Q^2, W) point (statistics not high enough for multiple bins)
- BSA similar for Δ^0 exclusive and for background
- Systematic errors still need to be determined
- Will compare $\sigma_{LT'}/\sigma_0$ for Δ^0 vs n

Conclusions

- BSA provides access to polarized cross-section $\sigma_{LT'}/\sigma_0$
- Extraction of BSA for $p(e,e'\pi^+)n$ over a range of kinematics to be published shortly
- BSA in $p(e,e'\pi^+)\Delta^0$ also being analyzed
- Similar analyses possible: exclusive K^+ or u-channel exclusive meson BSA, **PionLT data**

Author List

A.C. Postuma, G.M. Huber,* D. Gaskell, N. Heinrich, T. Horn,* M. Junaid, S.J.D. Kay, V. Kumar, P. Markowitz,* J. Roche, R. Trotta, A. Usman, S. Ali, R. Ambrose, D. Androic, W. Armstrong, A. Bandari, V. Berdnikov, H. Bhatt, D. Bhetuwal, D. Biswas, M. Boer, P. Bosted, E. Brash, A. Camsonne, J.P. Chen, J. Chen, M. Chen, M.E. Christy, S. Covrig, W. Deconinck, M. Diefenthaler, B. Duran, D. Dutta, M. Elaasar, R. Ent, H. Fenker, E. Fuchey, D. Hamilton, J.O. Hansen, F. Hauenstein, S. Jia, M.K. Jones, S. Joosten, M.L. Kabir, A. Karki, C. Keppel, E. Kinney, N. Lashley-Colthirst, W.B. Li, D. Mack, S. Malace, M. McCaughan, Z.E. Meziani, R. Michaels, R. Montgomery, M. Muhoza, C. Munoz Camacho, G. Niculescu, I. Niculescu, Z. Papandreou, S. Park, E. Pooser, M. Rehfuss, B. Sawatzky, G.R. Smith, H. Szumila-Vance, A. Teymurazyan, H. Voskanyan, B. Wojtsekhowski, S.A. Wood, C. Yero, J. Zhang, and X. Zheng

Working group, spokesperson*

THANK YOU!

Further Acknowledgements

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- Ali Usman for continuing $p(e, e'\pi^+)\Delta^0$ analysis

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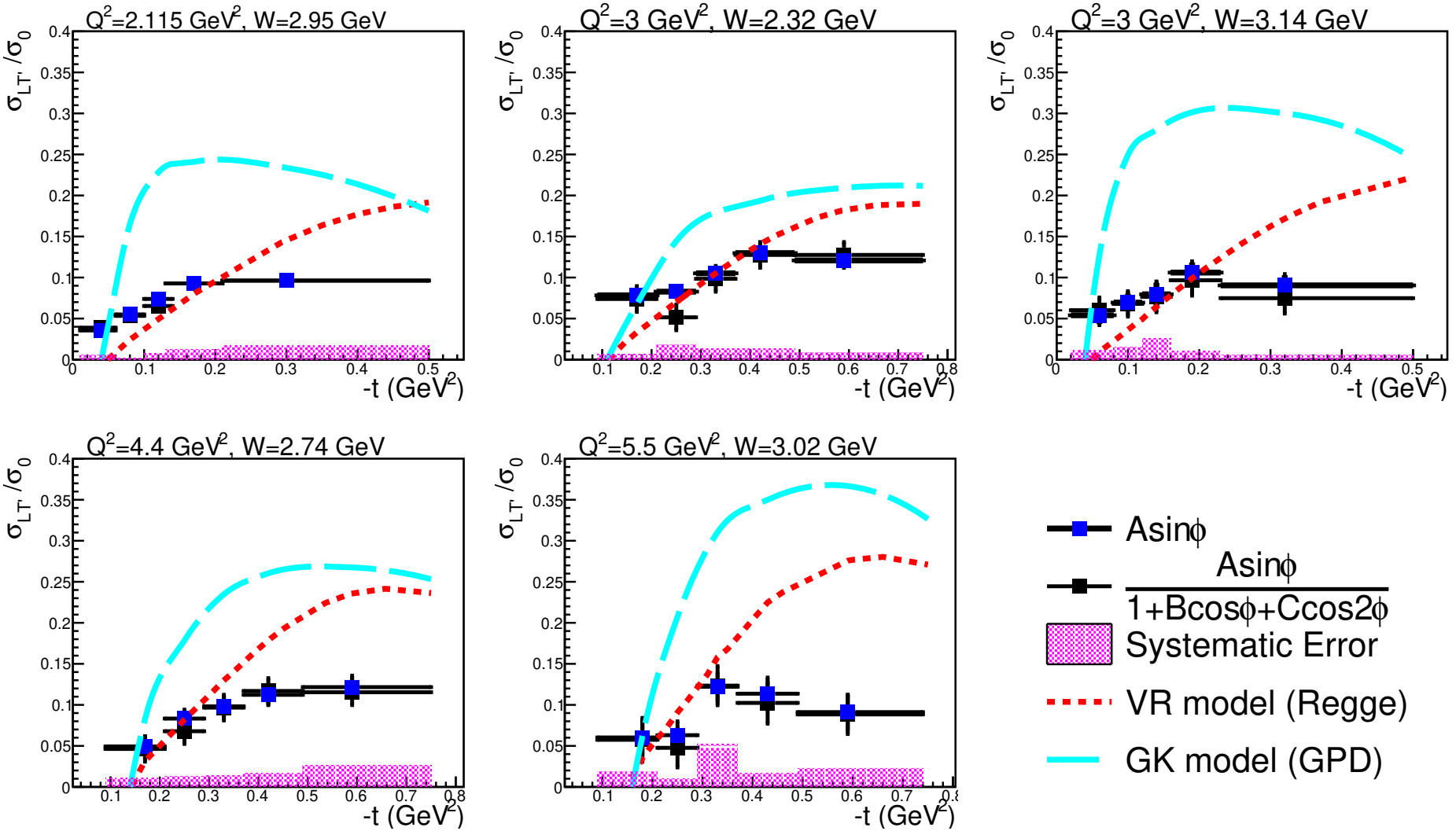
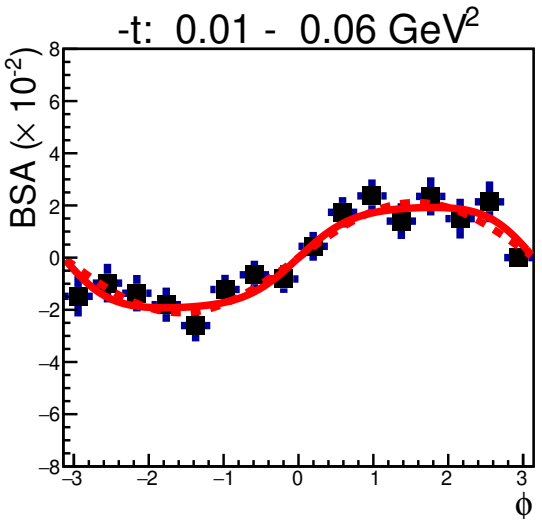
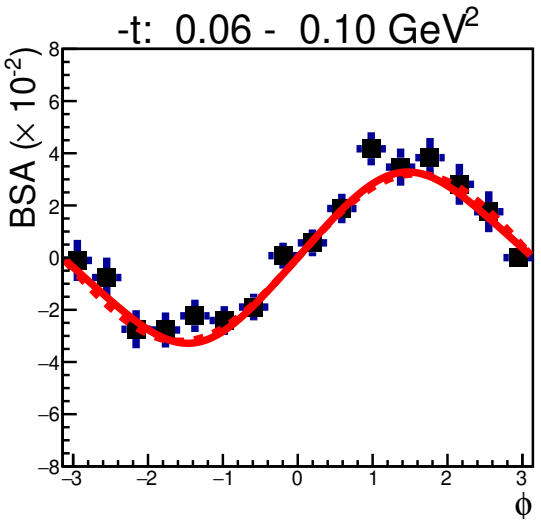
BACKUP

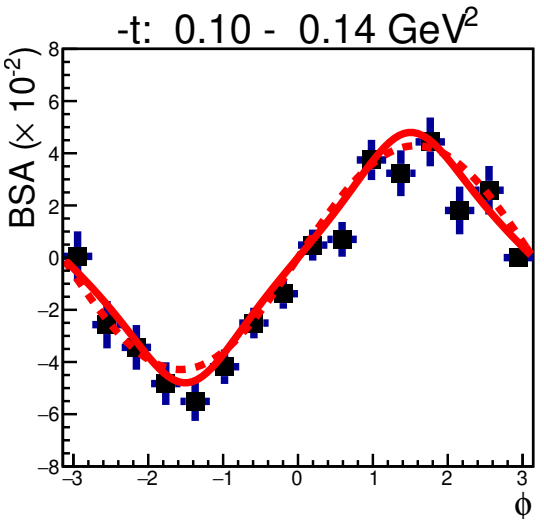
Both Fits

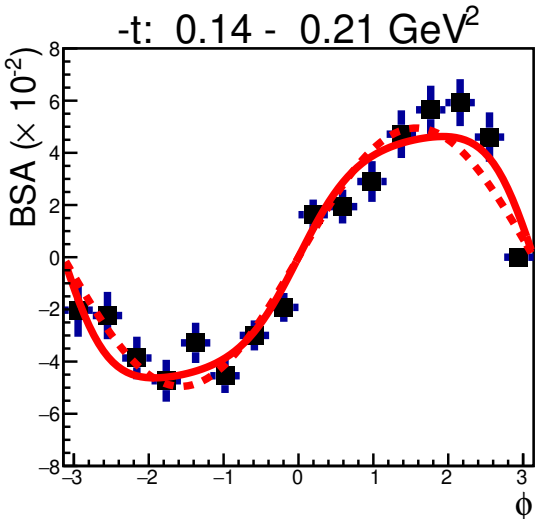

Q^2=2.115 GeV^2, W=2.95 GeV
Q^2=3 GeV^2, W=2.32 GeV
Q^2=3 GeV^2, W=3.14 GeV
Q^2=4.4 GeV^2, W=2.74 GeV
Q^2=5.5 GeV^2, W=3.02 GeV
$\sigma_{LT'}/\sigma_0$
-t (GeV^2)
Asinϕ
Asinϕ / (1+Bcosϕ+Ccos2ϕ)
Systematic Error
VR model (Regge)
GK model (GPD)

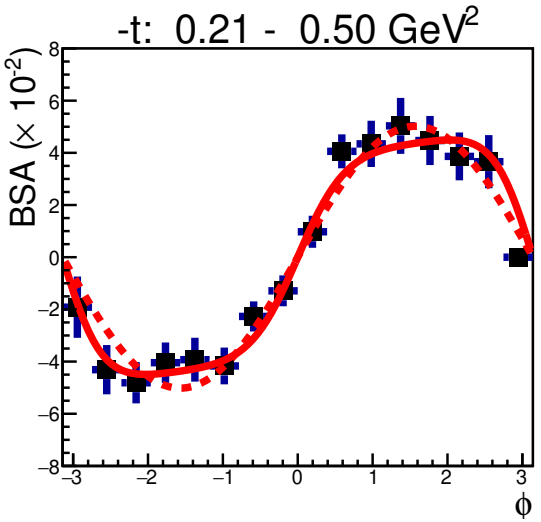
Asymmetry Q^2=2.115, W=2.95









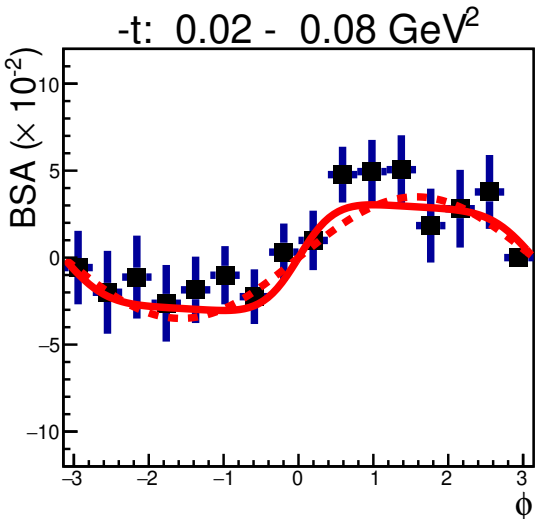


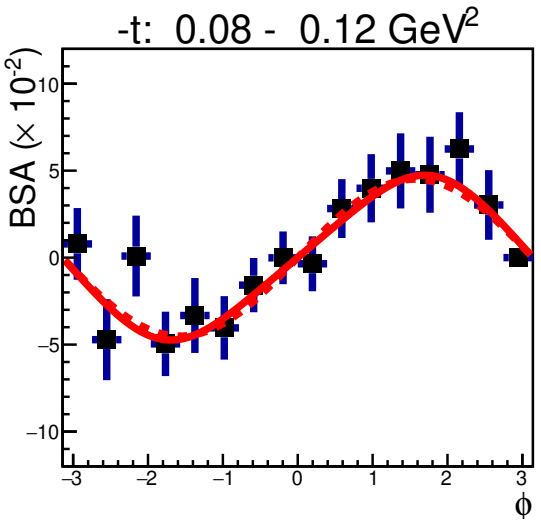
$A\sin\phi$

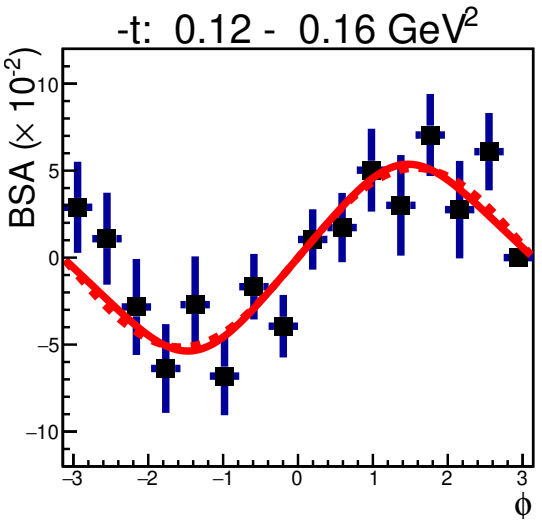
$$\frac{A\sin\phi}{1+B\cos\phi+C\cos 2\phi}$$

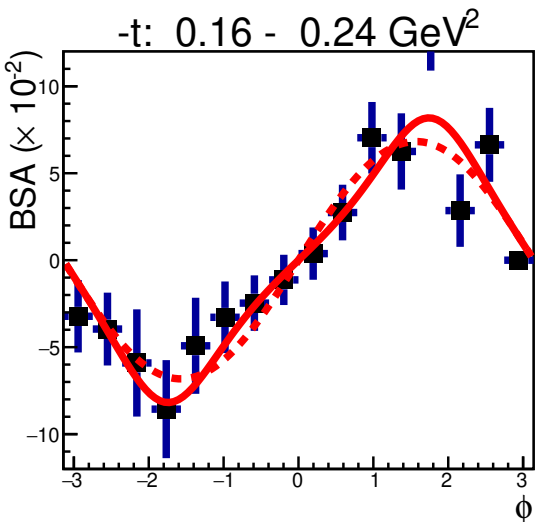
$$A \propto \frac{\sigma_{LT'}}{\sigma_0}$$

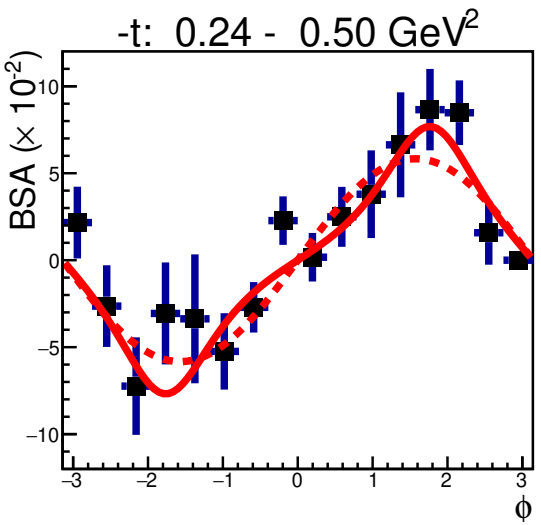
Asymmetry Q^2=3, W=3.14









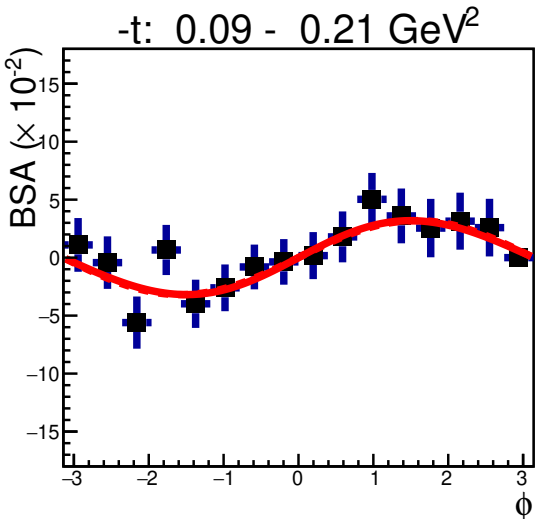


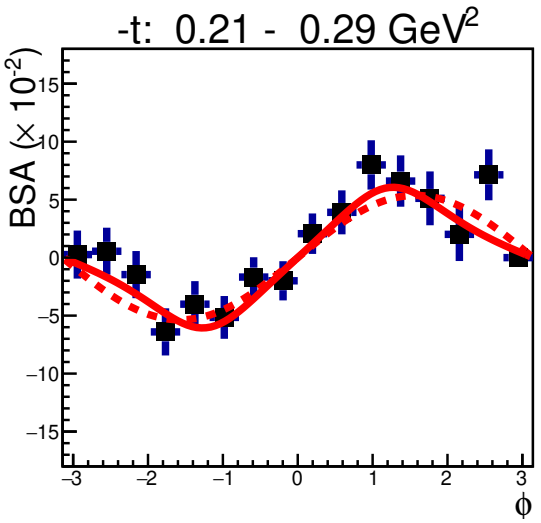
$A\sin\phi$

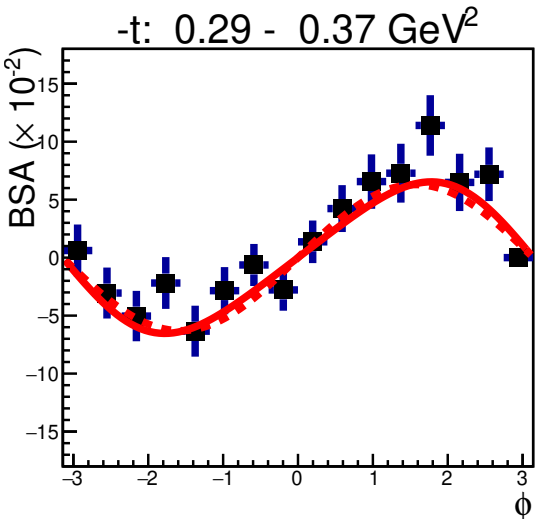
$$\frac{A\sin\phi}{1+B\cos\phi+C\cos 2\phi}$$

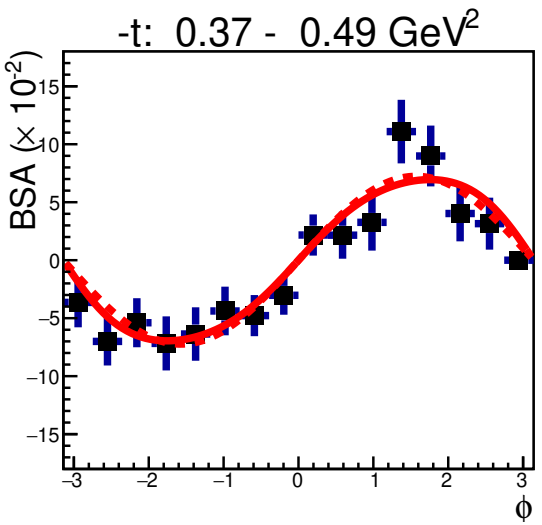
$$A \propto \frac{\sigma_{LT'}}{\sigma_0}$$

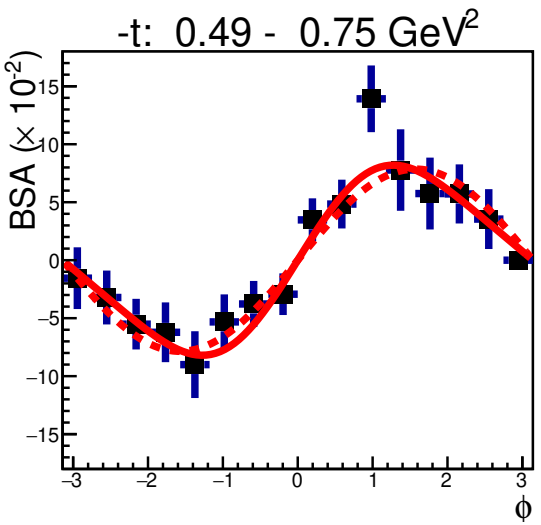
Asymmetry Q^2=4.4, W=2.74









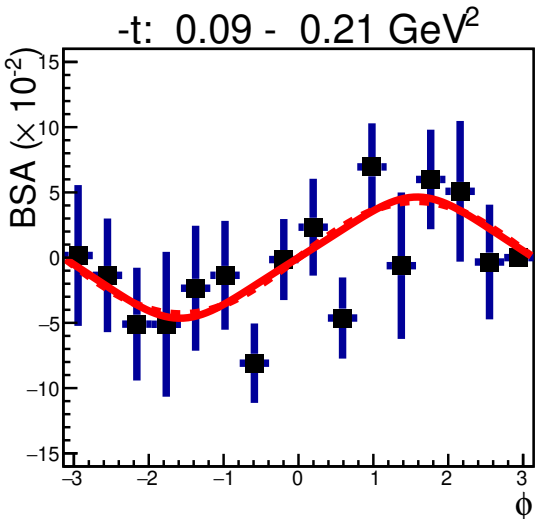


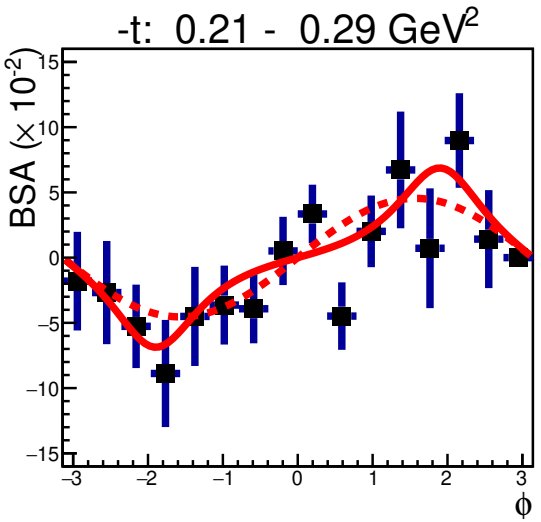
$A\sin\phi$

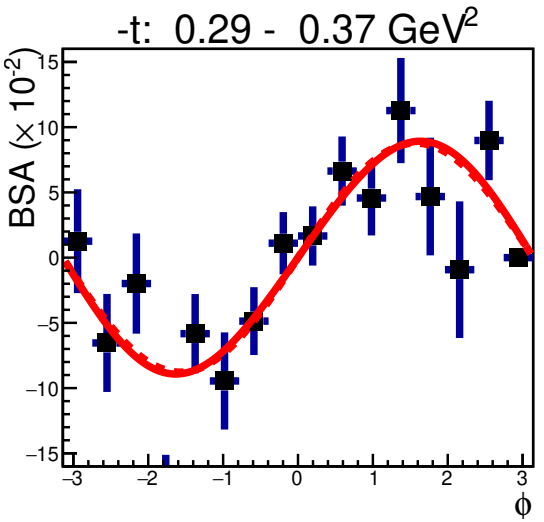
$$\frac{A\sin\phi}{1+B\cos\phi+C\cos 2\phi}$$

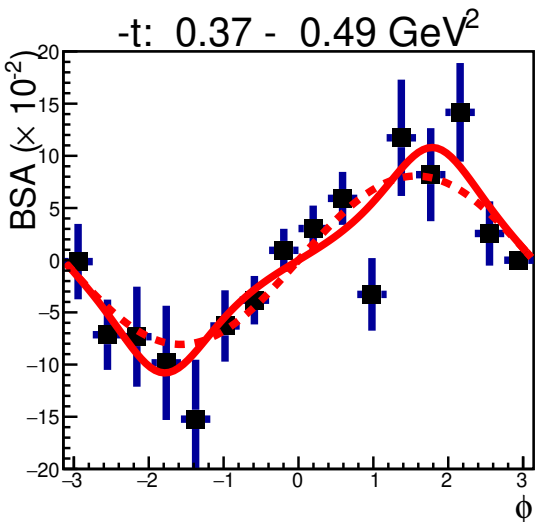
$$A \propto \frac{\sigma_{LT'}}{\sigma_0}$$

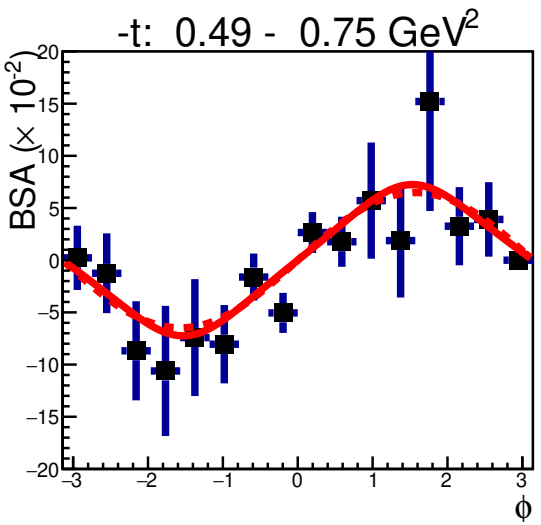
Asymmetry Q^2=5.5, W=3.02











$A\sin\phi$

$$\frac{A\sin\phi}{1+B\cos\phi+C\cos 2\phi}$$

$$A \propto \frac{\sigma_{LT'}}{\sigma_0}$$