Beam-Spin Asymmetry of Exclusive Pion Production

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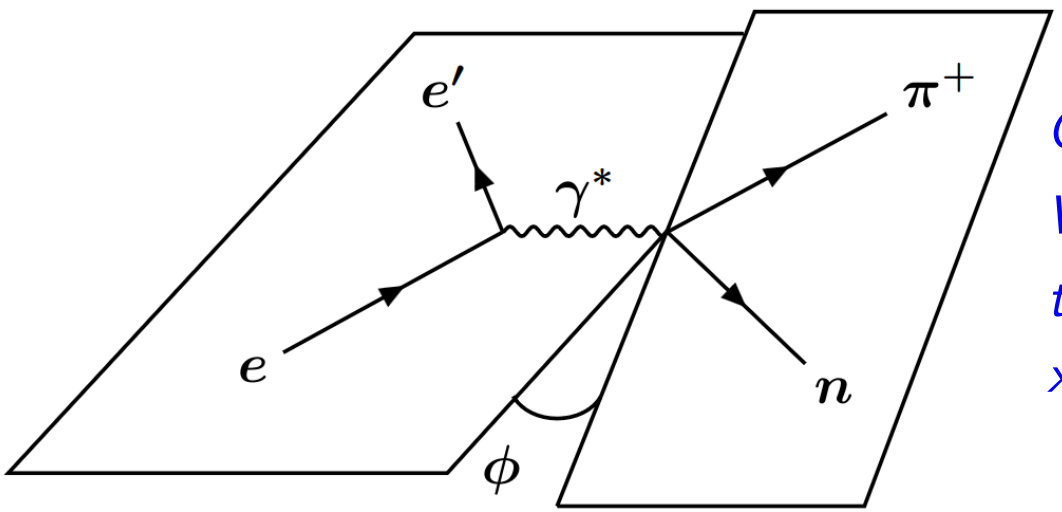
Introduction

- Measurement of beam spin asymmetry A_{LU} for two channels of exclusive π^+ production: $p(e, e'\pi^+)n/\Delta^0$
- Publication in preparation for $p(e, e'\pi^+)n$
- New preliminary results for $p(e, e'\pi^+)\Delta^0$
- Data from KaonLT experiment (E12-09-11)



$$Q^2 = -(p_e - p_{e'})^2$$
$$W = \sqrt{m_p^2 + 2m_p(E_e - E_{e'}) - Q^2}$$
$$t = (p_p - p_n)^2$$
$$x_B = Q^2/2m_p(E_e - E_{e'})$$

T. Horn, G.M. Huber, P. Markowitz et al (2008). Jefferson Lab 12 GeV Experiment E12-09-11.

Beam Spin Asymmetry

- Define the beam spin asymmetry A_{LU} as:

$$A_{LU} = \frac{1}{P}\left(\frac{\sigma^+ - \sigma^-}{\sigma^+ + \sigma^-}\right) = \frac{1}{P}\left(\frac{N^+ - N^-}{N^+ + N^-}\right)$$

- Polarized cross-section in Rosenbluth equation:

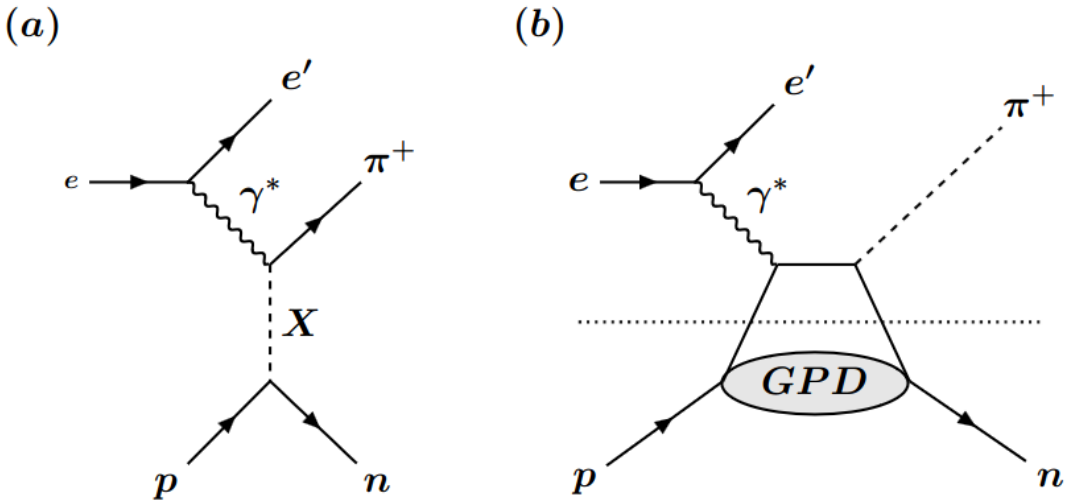
$$2\pi\frac{d^2\sigma}{dtd\phi} = \frac{d\sigma_T}{dt} + \epsilon\frac{d\sigma_L}{dt} + \sqrt{2\epsilon(1+\epsilon)}\frac{d\sigma_{LT}}{dt}\cos\phi + \epsilon\frac{d\sigma_{TT}}{dt}\cos 2\phi$$
$$+ h\sqrt{2\epsilon(1-\epsilon)}\frac{d\boldsymbol{\sigma_{LT'}}}{dt}\sin\phi$$

- Beam spin asymmetry provides much cleaner access to $\sigma_{LT'}$:

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

T. Arens, O. Nachtmann, M. Diehl, and P.V. Landshoff. Z. Phys C. 74, 651-669 (1997). arXiv:hep-ph/9605376

Regge and GPD Comparison



Regge process:
X represents the exchange of several particles along a **Regge trajectory**

Factorization:
reaction split into a **hard** scattering part and a **soft** part described by a **GPD**

This work: Extract $\sigma_{LT'}/\sigma_0$ over a range of kinematics and compare results to Regge and GPD predictions.

Models

- Vrancx-Ryckebusch (**VR**): exchange of $\pi(140)$, $\rho(770)$, and $a_1(1260)$ **Regge** trajectories
- Goloskokov-Kroll (**GK**): uses twist-2 longitudinal ($\widetilde{E}, \widetilde{H}$) and twist-3 transverse (E_T, H_T) **GPD**s, with pion pole contributions.
  GK1: default GK model
  GK2: modification $H_T \to H_T * 2$, as seen in [Diehl et al 2023]
- Yu-Choi-Kong (**YCK**): **Regge**-based, incorporates the exchange of tensor meson $a_2(1320)$ and axial mesons a_1 and $b_1(1235)$. *YCK are co-authors on this paper.*
  YCK1: nucleon EMFFs mediated by GPDs
  YCK2: nucleon EMFFs use dipole form

T. Vrancx, J. Ryckebusch & J. Nys, Phys. Rev C, **89** 065202 (2014). arXiv:1310.7715
S.V. Goloskokov, P. Kroll, Eur. Phys. J. C **65** 137 (2010). arXiv:1106.4897
T. K. Choi, K.-J. Kong & B.-G. Yu, J. Korean Phys. Soc. **67**, 1089-1094 (2015). arXiv:1508.00969

Beam Polarization

$$A_{LU} = \frac{1}{P}\left(\frac{N^+ - N^-}{N^+ + N^-}\right) \qquad \delta_{\text{stat}} = \frac{2}{P}\sqrt{\frac{N^+ N^-}{(N^+ + N^-)^3}}$$

- No dedicated polarization measurements in Hall C
- Mott polarimeter at injector gives source polarization: **90±1%**
- Spin precession calculation shows Hall C receives **99%** of the source polarization
- Final value $\mathbf{P=89^{+1}_{-3}\%}$
  Uncertainty from the beam energy uncertainty (3.6 MeV) and the range of possible linac energy imbalance

Thanks to Steve Wood and Dave Gaskell for polarization values and uncertainty.

BSA in KaonLT

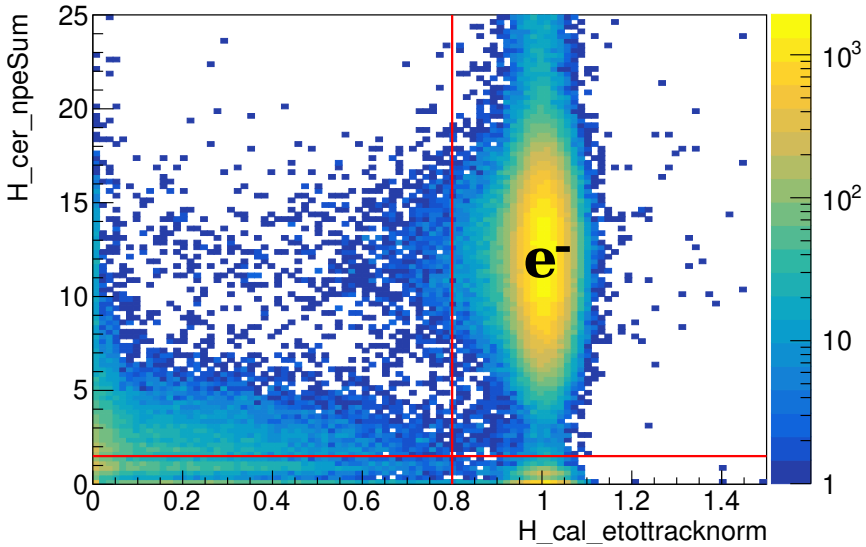
- **HMS** detecting **electrons**
- **SHMS** detecting **positive hadrons**
- Data taken Autumn 2018
- Beam energy 10.585 GeV
- Beam helicity flipped at 30 Hz
- Target 10 cm unpolarized LH_2

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

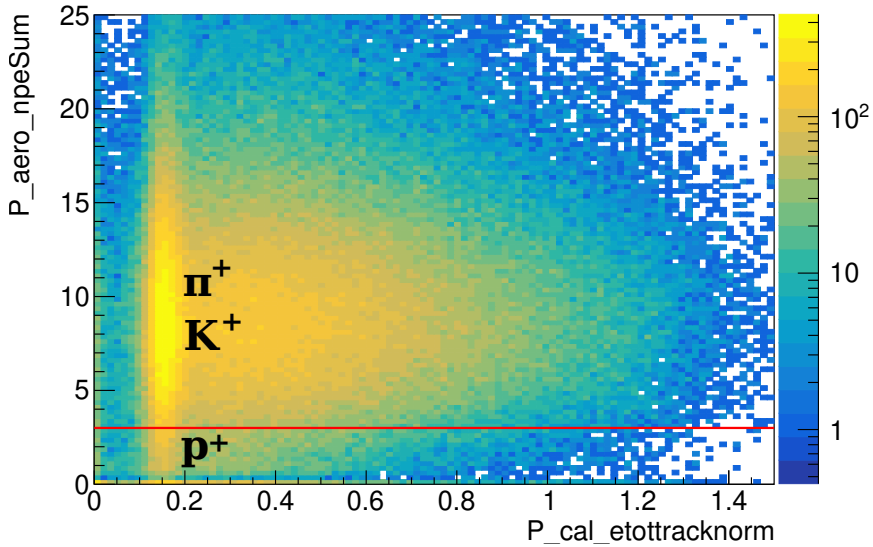
$p(e, e'\pi^+)n$



e^- in HMS

H_cal_etottracknorm > 0.8

H_cer_npeSum > 1.5



π^+ in SHMS

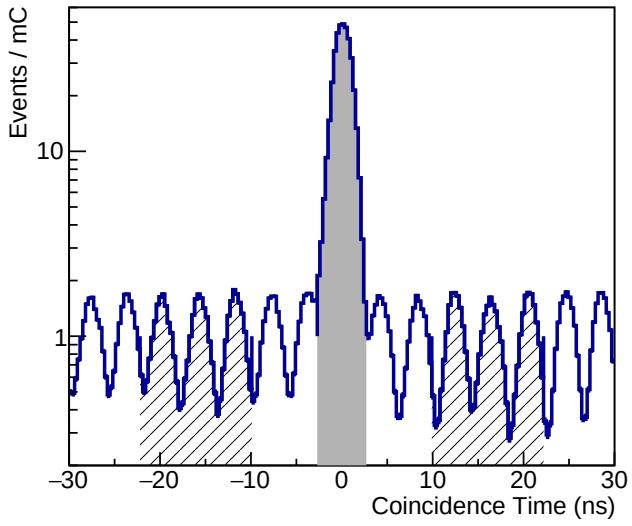
P_aero_npeSum > 3

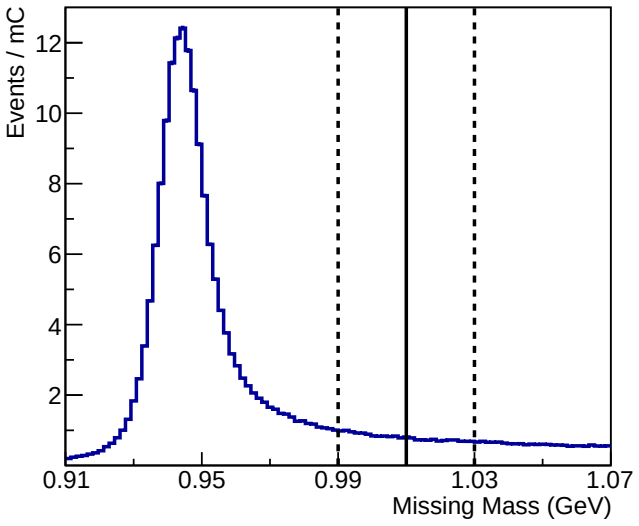
- Electrons identified with cut on gas Čerenkov (C_4F_{10} at 0.48 atm, $n = 1.0008$) in combination with lead-glass calorimeter
- Pions identified with cut on an aerogel Čerenkov ($n = 1.015$ or $n = 1.011$)

Plots: Q^2=3.0, x_B=0.25, SHMS center.

Event Selection

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





Coincidence time:

$t_{SHMS} - t_{HMS}$

showing selected prompt and random windows

Missing mass

$m_x^2 = (p_e - p_{e'} - p_\pi)^2$

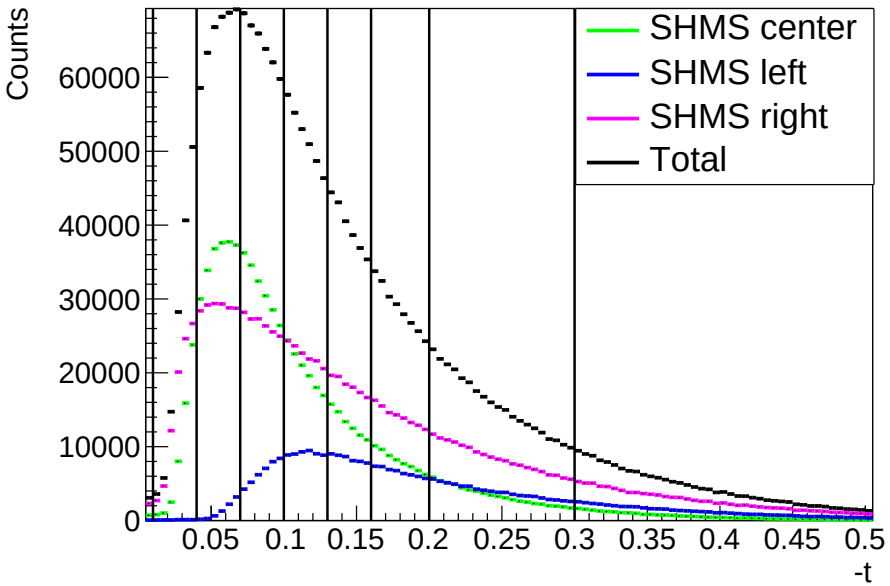
showing cut used in analysis

Plots: Q^2=3.0, x_B=0.25, SHMS center.

-t Binning

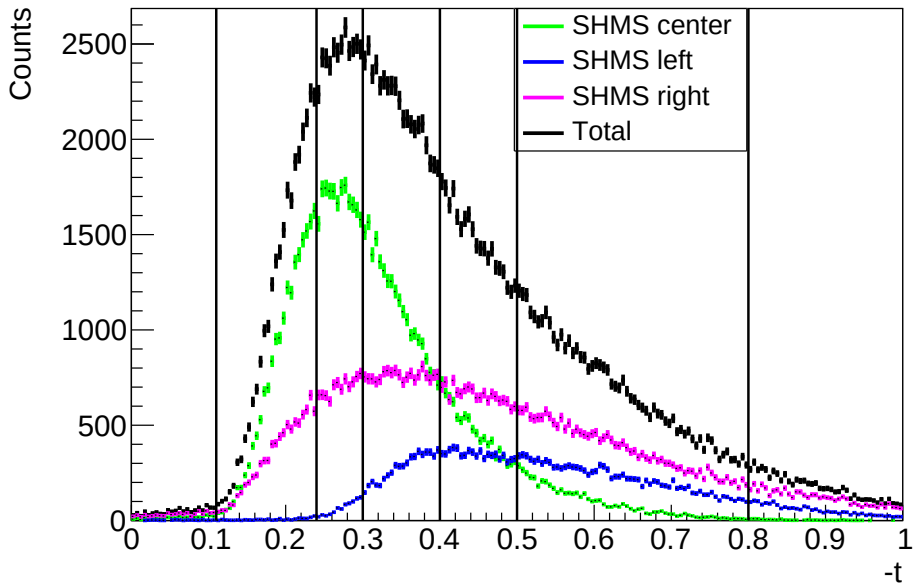
$p(e,e'\pi^+)n$

- Sum all events at one (Q^2,W) and separate into $-t$ bins with similar numbers of events



Q^2=2.1 GeV^2, x_B=0.25

$\mathcal{O}(10^6)$ events, 8 t-bins



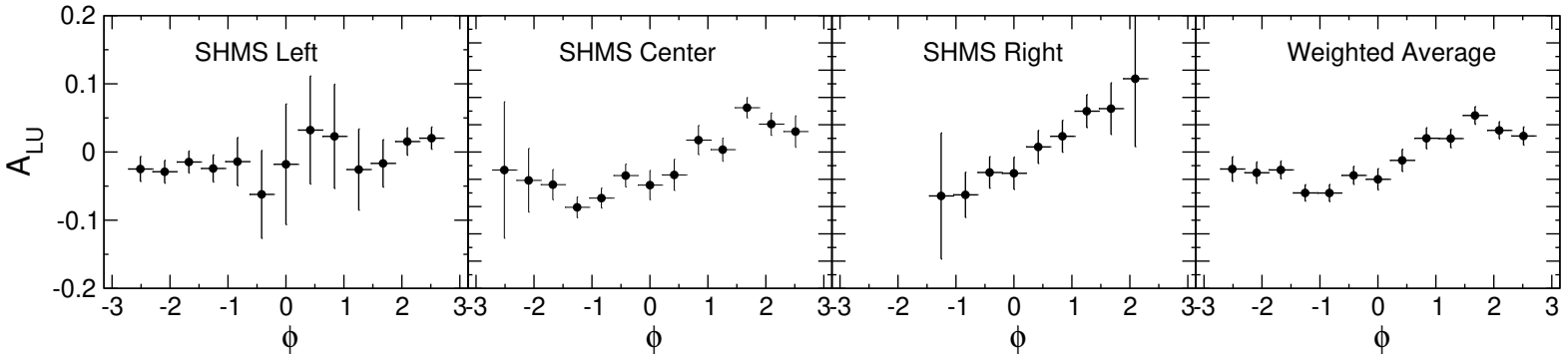
Q^2=5.5 GeV^2, x_B=0.40

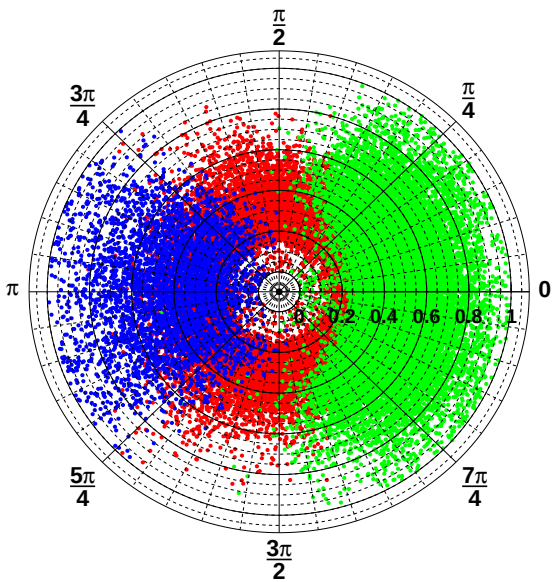
$\mathcal{O}(10^5)$ events, 5 t-bins

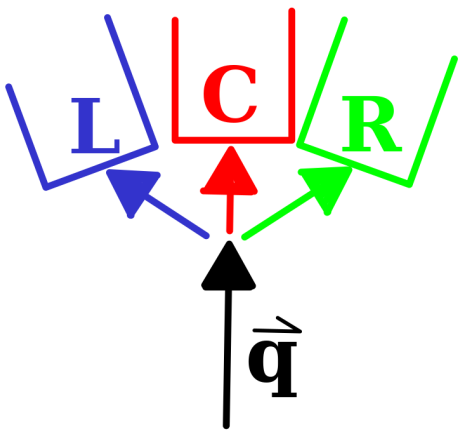
Combining SHMS Settings

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

Asymmetry is calculated separately for three SHMS angles (**left**, **center**, **right**), then a weighted average is taken for full ϕ coverage.



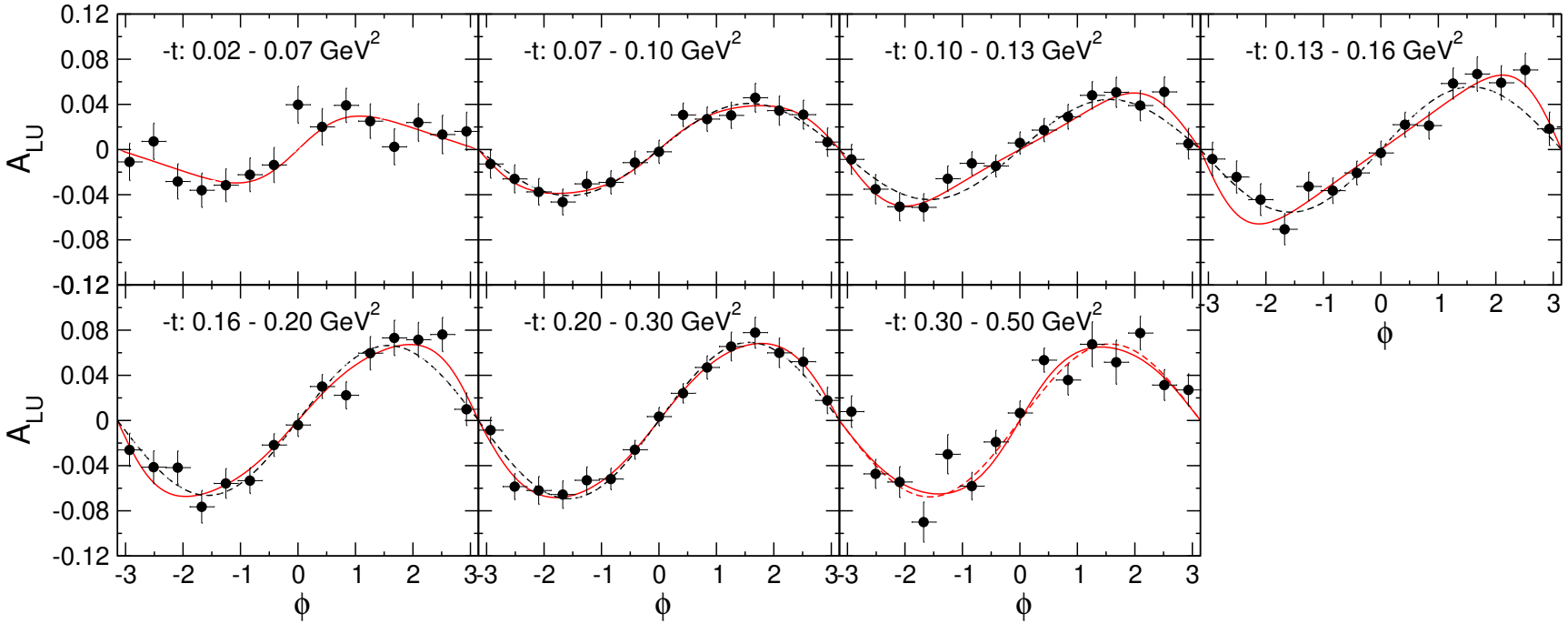




Plots: Q^2=3.0, x_B=0.40, 0.35< $-t$ <0.40 (A_{LU} vs ϕ) and Q^2=5.5, W=3.02 ($-t$ vs ϕ polar plot).

Asymmetry

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



- A_{LU} as a function of ϕ for each bin in $-t$
- Solid line shows the full fit and the dashed line an approximated fit
- Error bars are statistical only

Plots: $Q^2 = 3\ \text{GeV}^2$, x_B =0.25.

The Question of Fitting

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

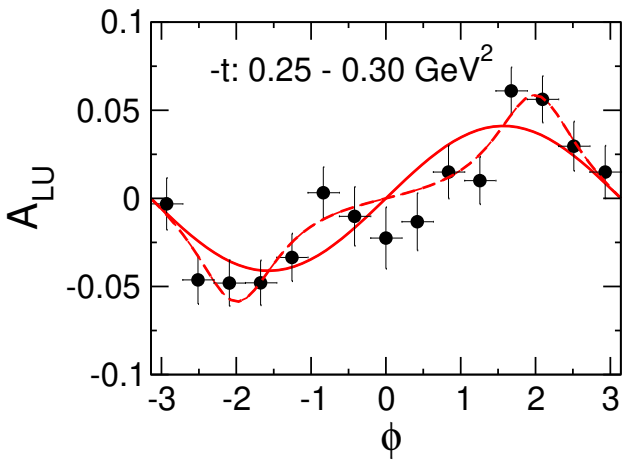
- Recall functional form of asymmetry:

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

- Previous work [Diehl et al 2023] has assumed $\frac{\sigma_{LT}}{\sigma_0} \ll 1$, $\frac{\sigma_{TT}}{\sigma_0} \ll 1$ such that

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

- This appears to be a low $-t$ approximation, which is not sufficient to describe our data in all bins

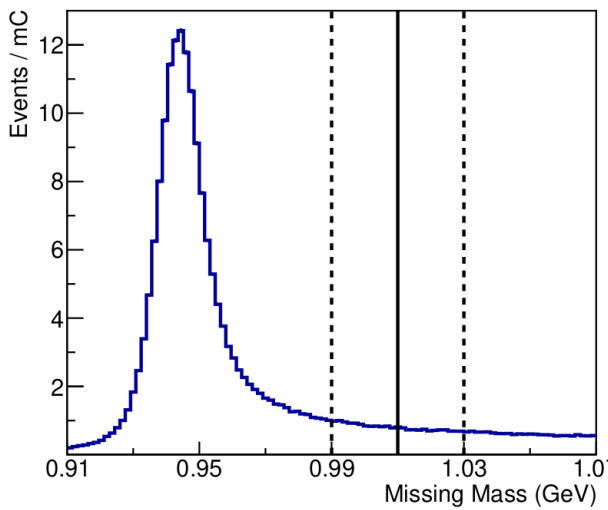


- Extract A_{LU} using full functional form
- Use difference in A_{LU} from approximate fit as a systematic error

Plot: $Q^2 = 3$ GeV^2, $x_B = 0.40$.

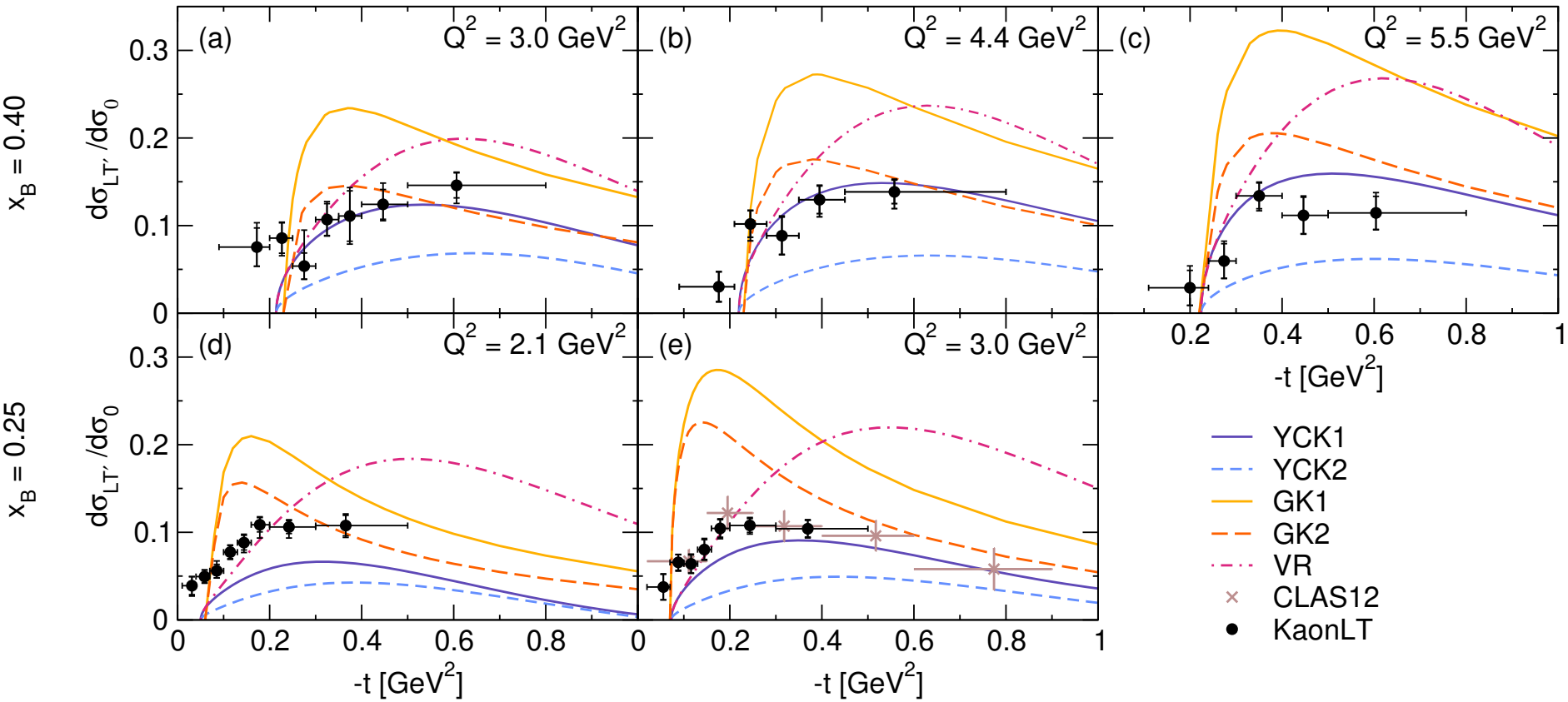
Systematics

1. **Fitting error**
   - Difference between A_{LU} extracted using full or approximate fit
   - Unidirectional, leads to asymmetric total error
   - Dominates point-to-point uncertainty: up to **70%** of A_{LU}
2. **Cut dependence**
   - RMS of differences in A_{LU} calculated using different values for coincidence time and missing mass cuts
   - Contributes uncertainty of **1-7%**
3. **Beam polarization**
   - Uncertainty propagated using general formula
   - Contributes ~ 3% error



Results

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



T. K. Choi, K.-J. Kong & B.-G. Yu, J. Korean Phys. Soc. **67**, 1089-1094 (2015).

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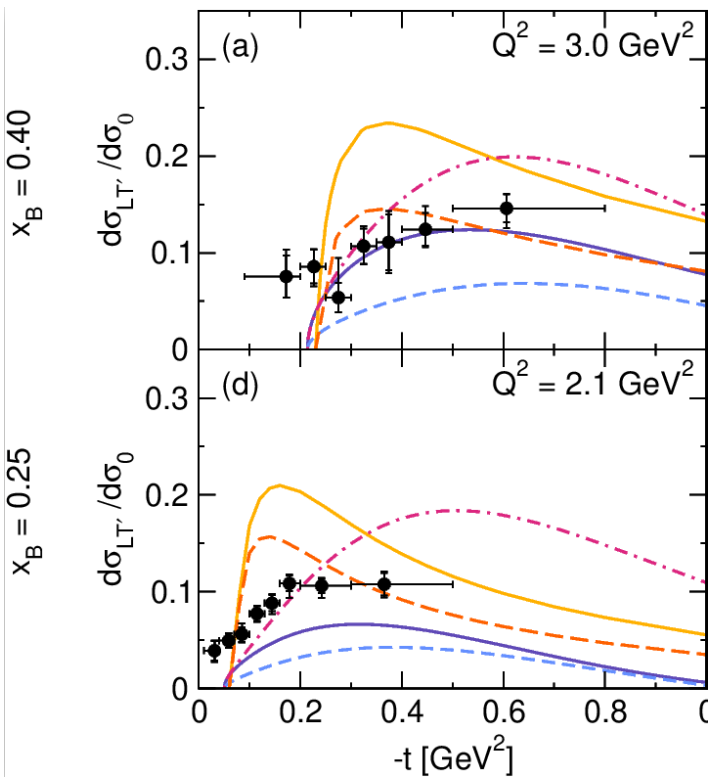
S.V. Goloskokov, P. Kroll, Eur. Phys. J. C **65** 137 (2010).

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

Comparison with Theory

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



VR (Regge): Good agreement at low $-t$, poor agreement for higher $-t$

GK1 (GPD): Decent reproduction of $-t$ dependence for $x_B = 0.4$ but overestimates magnitude

GK2 (GPD): Modification $H_T \rightarrow H_T * 2$ improves agreement

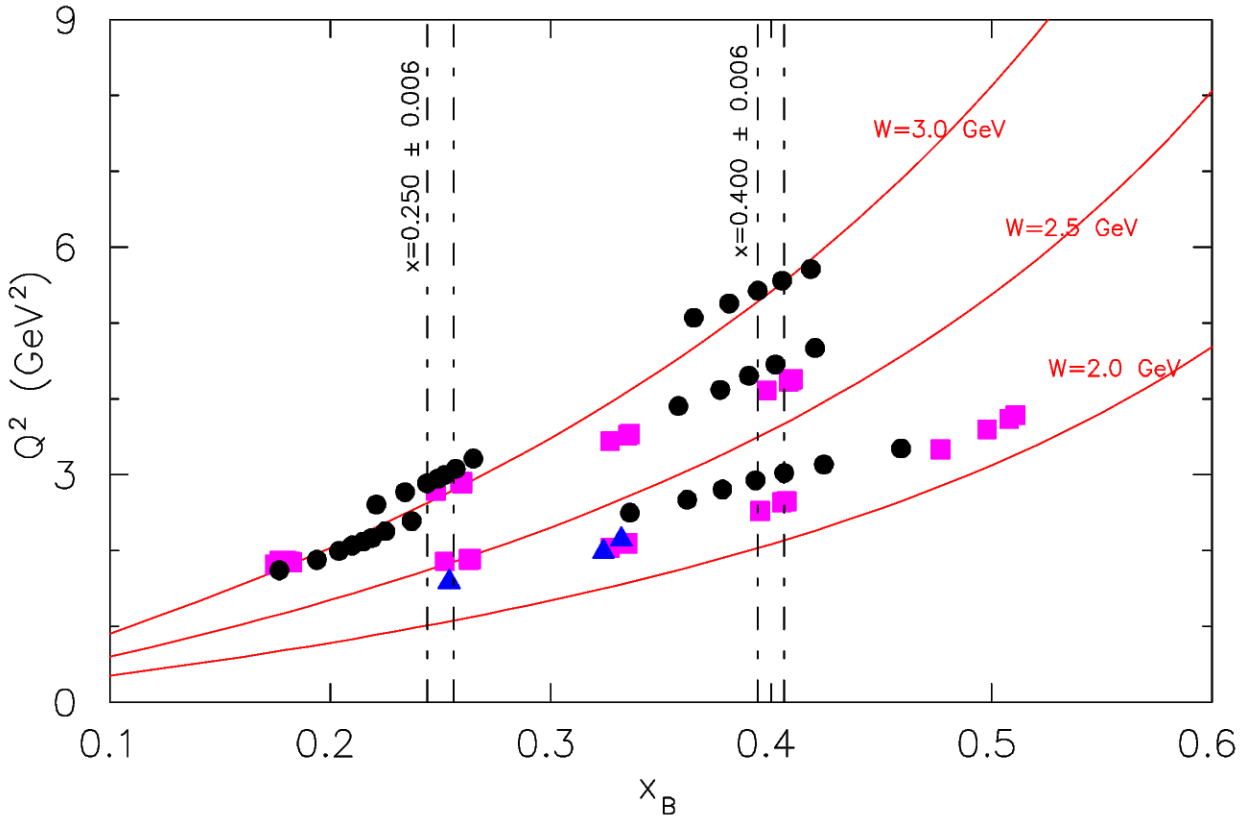
YCK1 (Regge + GPD): Best overall agreement

YCK2 (Regge): Underestimates magnitude

T. K. Choi, K.-J. Kong & B.-G. Yu, J. Korean Phys. Soc. **67**, 1089-1094 (2015).
T. Vrancx, J. Ryckebusch & J. Nys, Phys. Rev C, **89** 065202 (2014).
S.V. Goloskokov, P. Kroll, Eur. Phys. J. C **65** 137 (2010).
B. Berthou et al, Eur. Phys. J. C **78** 478 (2018).

Q^2 Scan

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



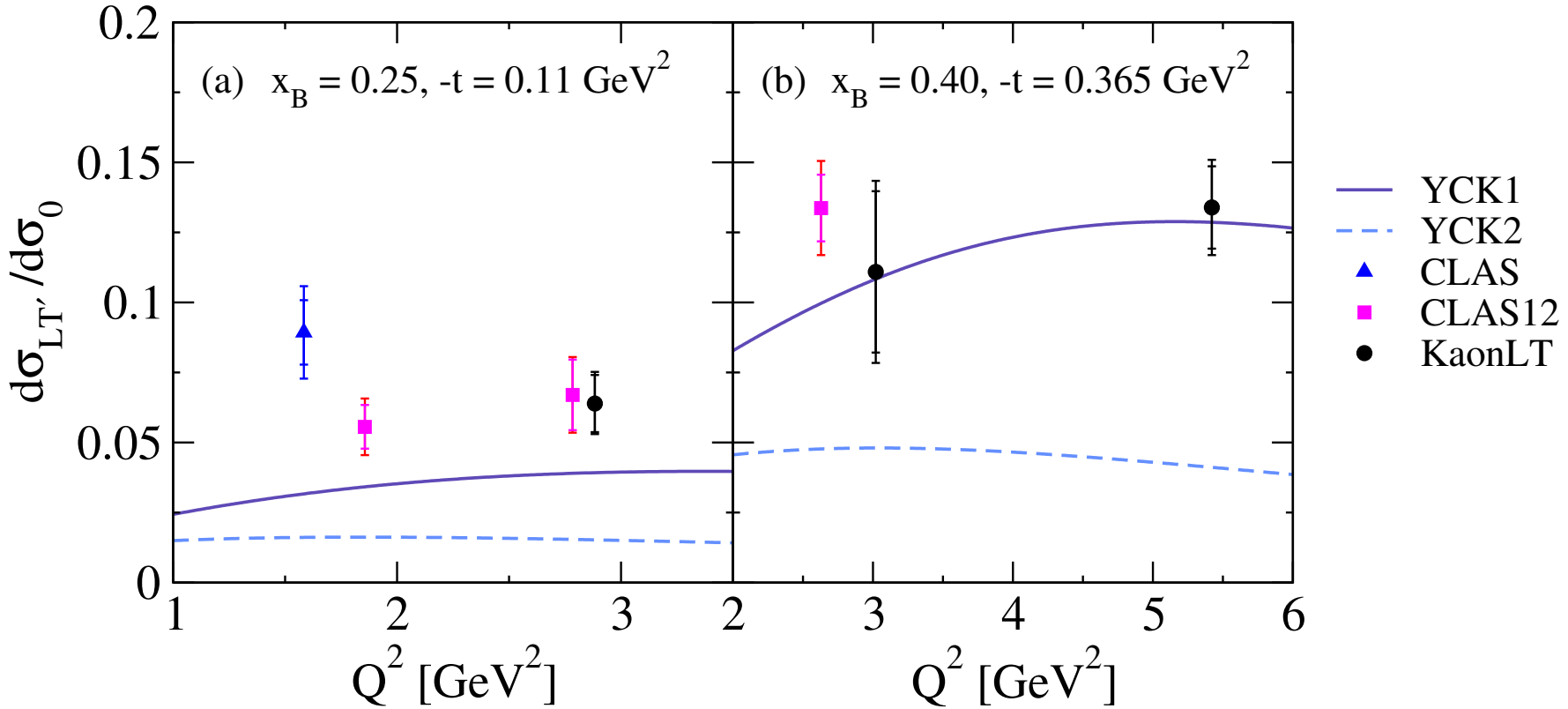
- Kinematics for measurements of $\sigma_{LT'}/\sigma_0$ from **KaonLT** [This work], **CLAS**, and **CLAS12**
- Combine data sets to determine Q^2 dependence at fixed $(x_B, -t)$

S. Diehl et al., Phys. Lett. B **839**, 137761 (2023). arXiv:2210.14557

S. Diehl et al., Phys. Rev. Lett. **125**, 182001 (2020). arXiv:2007.15677

Q^2 Dependence

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



- $\sigma_{LT'}/\sigma_0$ from **KaonLT** [This work], **CLAS**, and **CLAS12** as a function of Q^2
- Flat or weak Q^2 dependence

S. Diehl et al., Phys. Lett. B **839**, 137761 (2023). arXiv:2210.14557

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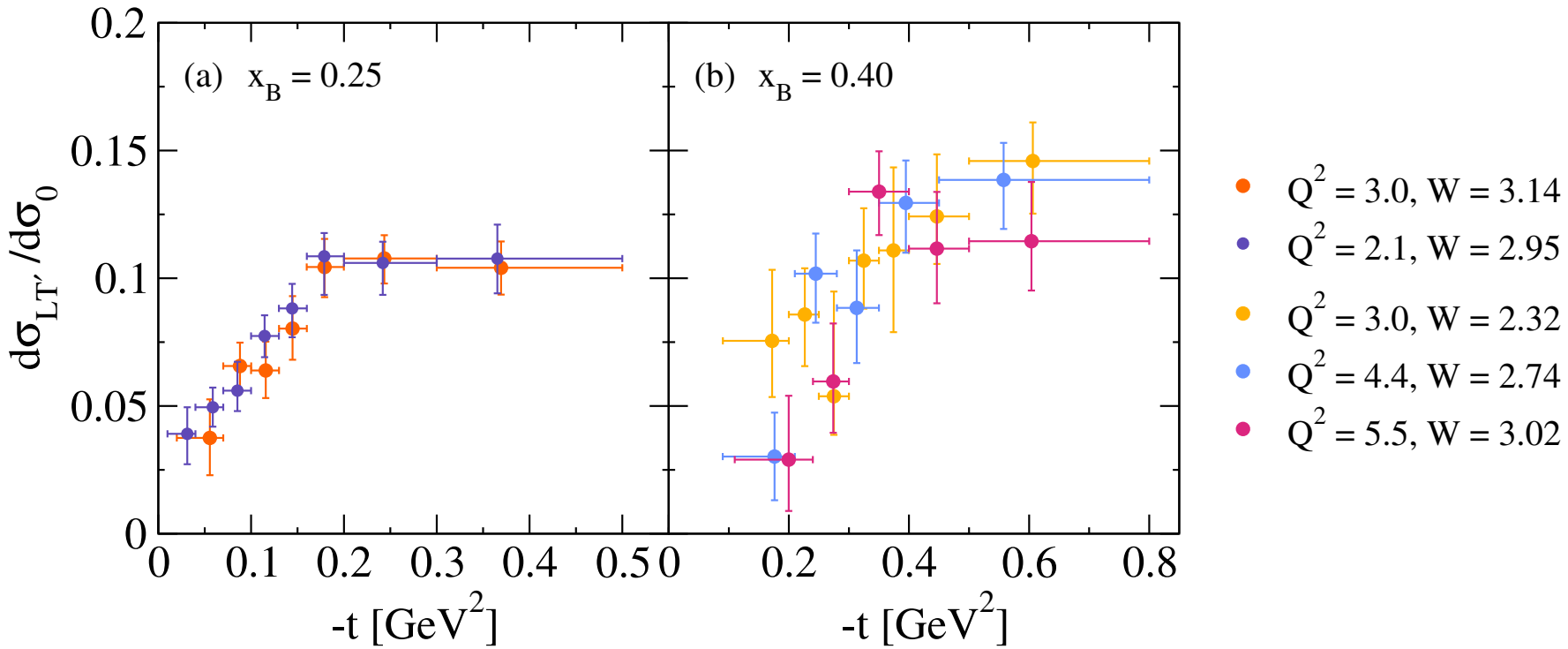
What If...

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



- No Q^2 dependence → overlay curves at same x_B
- Seems to show same $-t$ dependence within uncertainties

Summary

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

- $\sigma_{LT'}/\sigma_0$ extracted from KaonLT data over a wide range of kinematics
- Magnitude and $-t$ dependence closest to **YCK1**
- Combined Regge/GPD description likely most accurate
- Flat Q^2 dependence predicted by **YCK2**

For submission to Physical Review Letters **this week**
⟶ Comments from co-authors requested by **tomorrow** to
acp548@uregina.ca

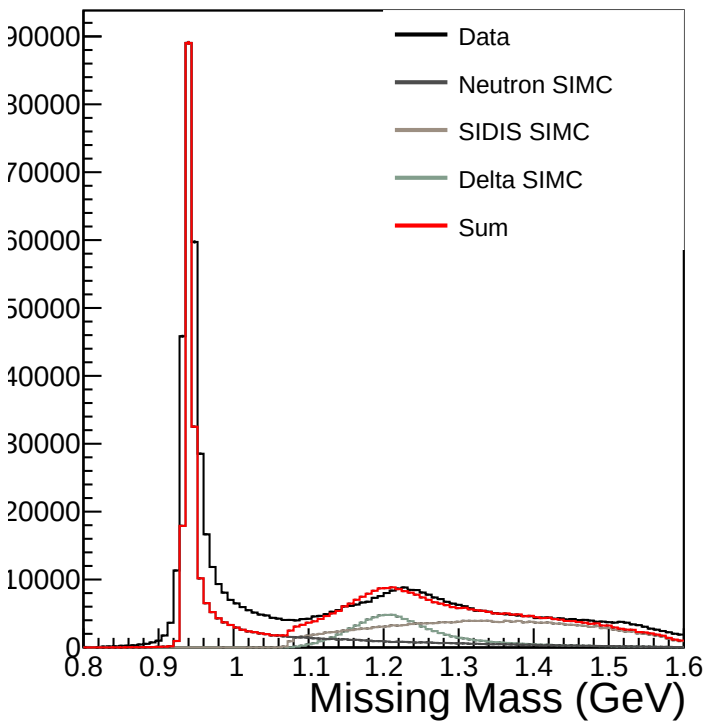
*Manuscript can be found **HERE***

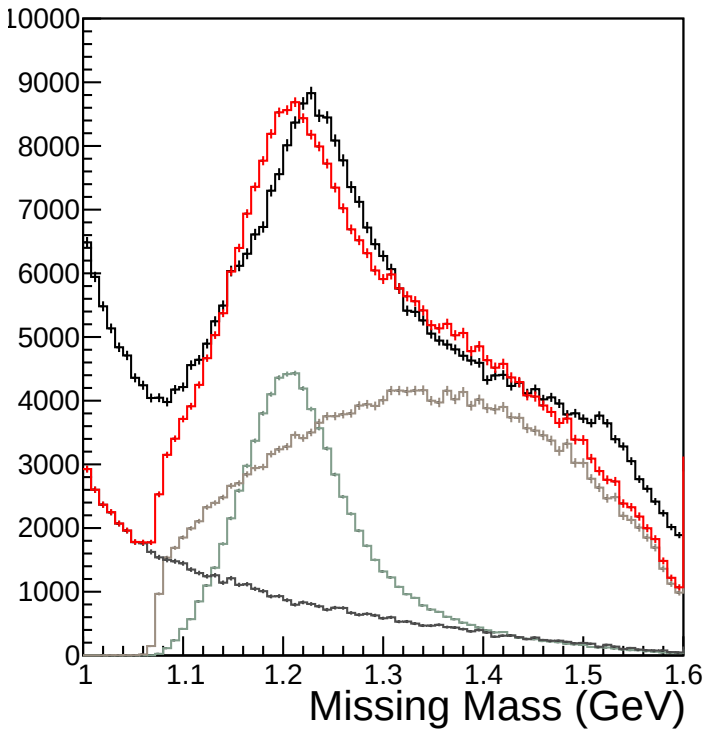
$p(e, e'\pi^+)\Delta^0$

Event Selection

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

- Missing mass much more complicated than $p(e,e'\pi^+)n$ due to overlapping channels

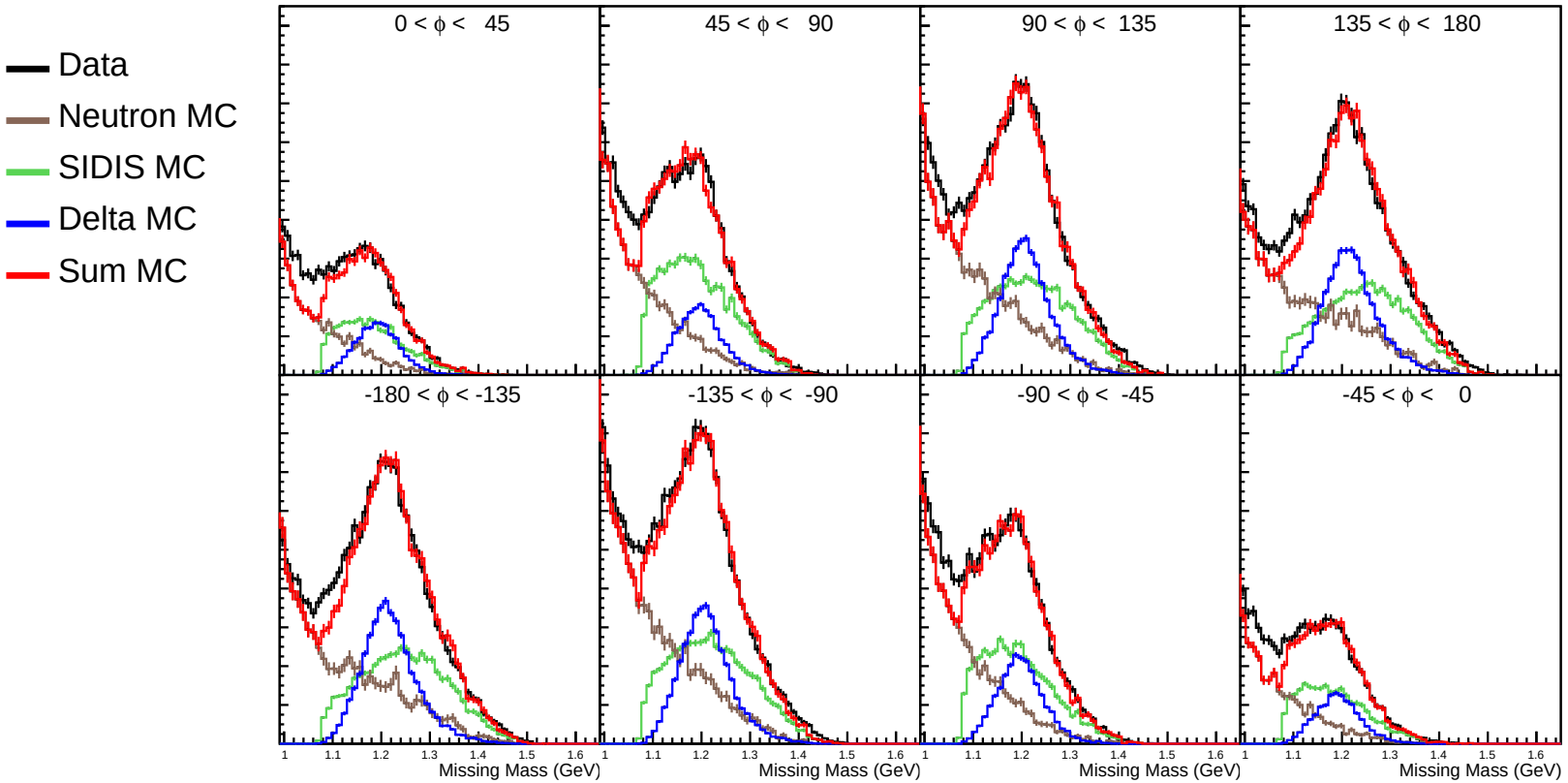




Plot by Ali Usman. Kinematics Q^2=2.115, W=2.95, SHMS center.

Shape Study

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



- Fit missing mass with sum of **delta**, **neutron**, and **SIDIS** MC
- Yield is integral of **delta** MC

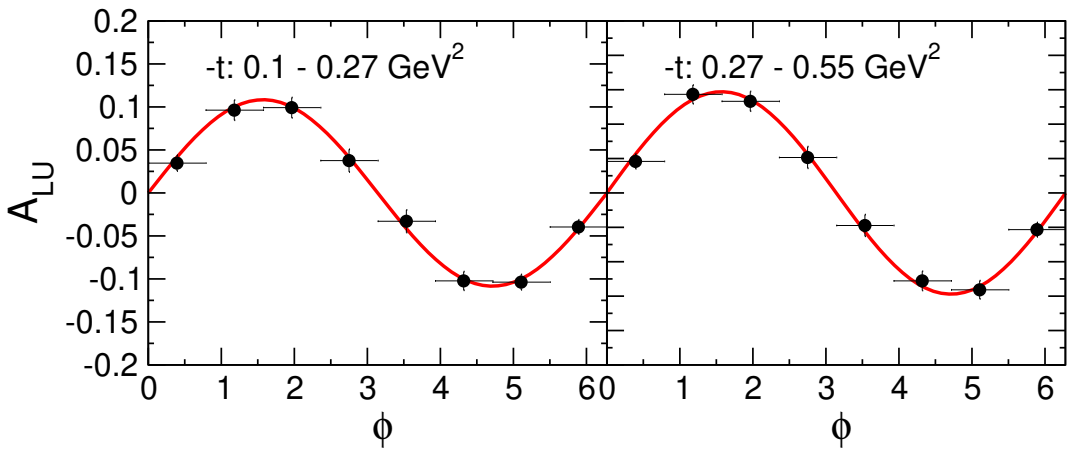
Plots by Ali Usman, based on initial work by Portia Switzer. Kinematics Q^2=2.115,x_B=0.25, SHMS center, $0.10 < -t < 0.27$.

Asymmetry

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

- Due to lower statistics, we have 1-2 bins in $-t$ and 9 in ϕ for $p(e,e'\pi^+)\Delta^0$
- Errors are purely statistical

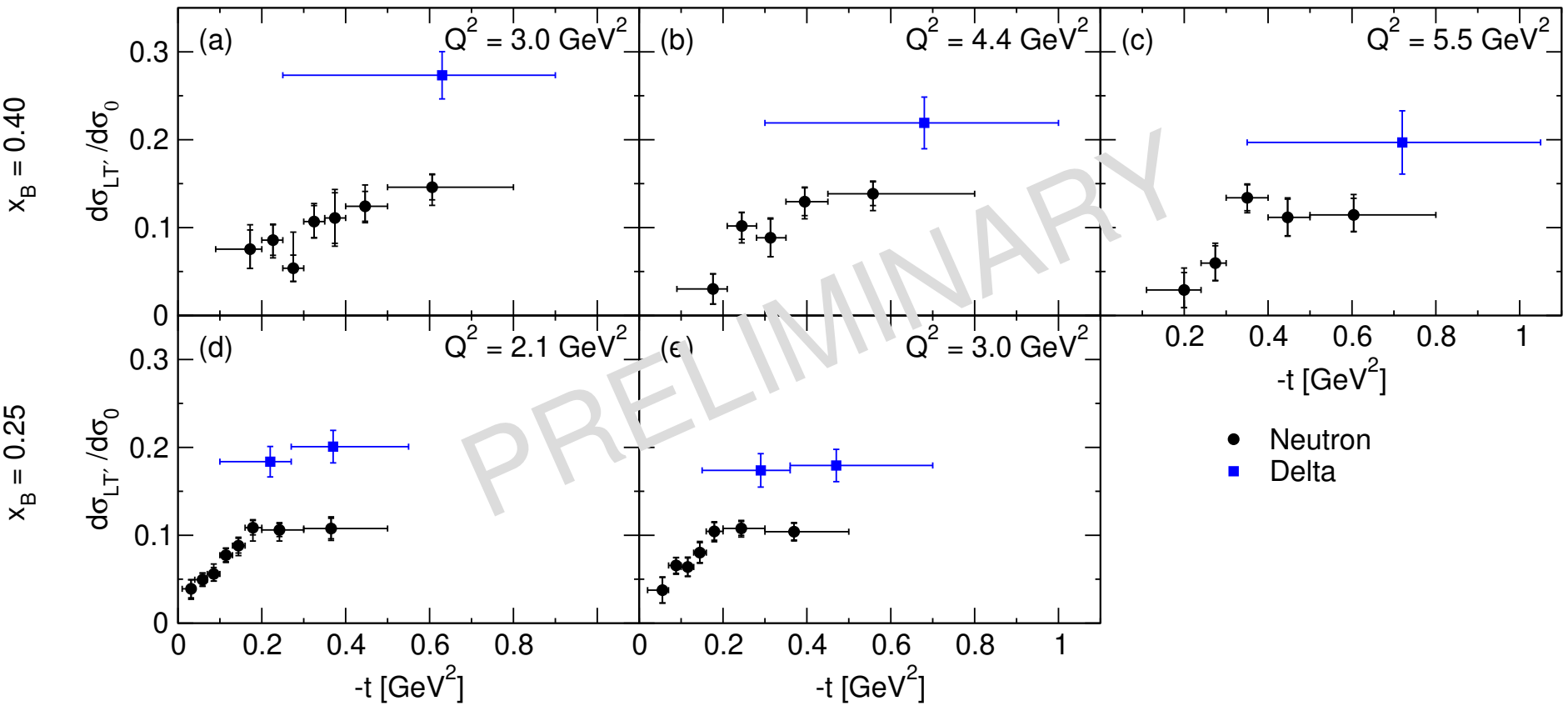
$$A_{LU} = \frac{1}{P}\left(\frac{N^+ - N^-}{N^+ + N^-}\right), \qquad \delta_{\text{stat}} = \frac{2}{P}\sqrt{\frac{N^+N^-}{(N^+ + N^-)^3}}$$



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

Results

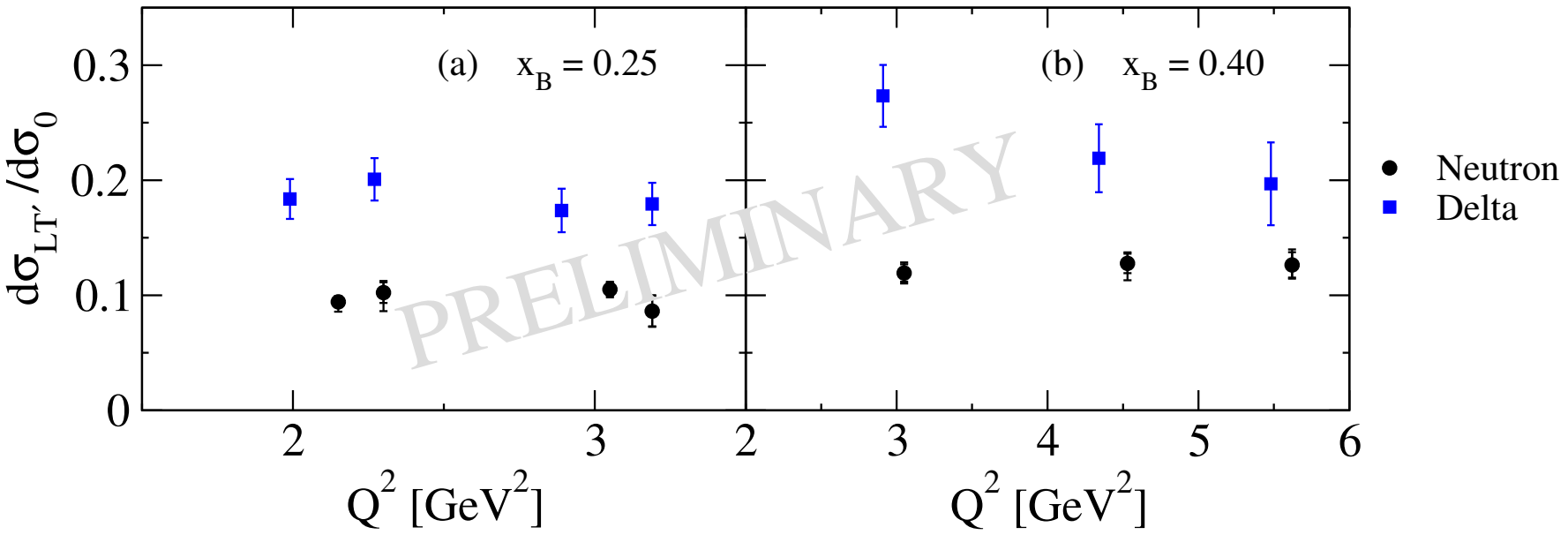
$p(e, e'\pi^+)\Delta^0$



- Extracted values of $\sigma_{LT'}/\sigma_0$ in exclusive π^+ production
- Errors on Δ^0 are only statistical

Q^2 Dependence

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



- Q^2 dependence of $\sigma_{LT'}/\sigma_0$ in exclusive π^+ production
- Neutron channel re-analyzed using bins optimized for Δ^0
- No systematic errors → trend in (b) Δ^0 likely not significant

Summary

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

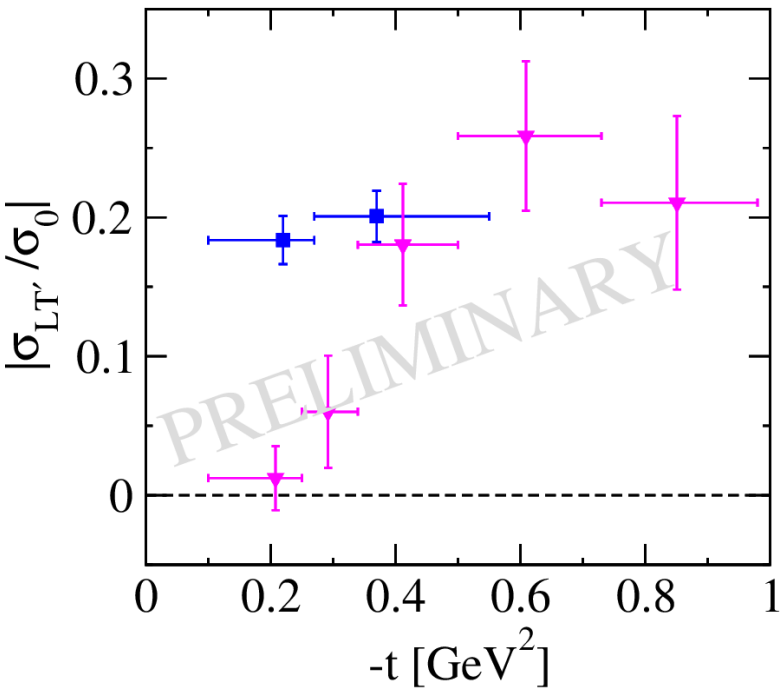
- This data is the first ever measurement of A_{LU} in $p(e,e'\pi^+)\Delta^0$
- No known theoretical predictions to use for comparison
- Systematic errors must be calculated

Compare with previous results in $e + p \rightarrow e' + \pi^- + \Delta^{++}$ from CLAS12

$\pi^+\Delta^0$ **KaonLT**: Q^2=2.1, x_B=0.25

$\pi^-\Delta^{++}$ **CLAS12**: Q^2=1.95, x_B=0.19

→ Note $\sigma_{LT'}/\sigma_0$ has **opposite sign** between these channels



S. Diehl et a. Phys. Rev. Lett. **131**, 021901 (2023). arXiv:2303.11762

Conclusions

- Submitting $p(e, e'\pi^+)n$ results to PRL (A. Postuma)
- Writing a manuscript for PRL on $p(e, e'\pi^+)\Delta^0$ (A. Usman)
- Next study: u-channel BSA (A. Postuma)
- Possible projects: BSA for K^+ production in KaonLT, numerous channels in **PionLT** data (unclaimed)
  suitable for undergraduate summer student projects

Thank You!

- KaonLT working group and shift takers

We thank the staff of the Accelerator and the Physics Divisions at Jefferson Lab for the excellent efforts during the experimental data taking. This work is supported by the Natural Sciences and Engineering Research Council of Canada (NSERC) SAPIN-2021-00026 and a Canadian Institute of Nuclear Physics Graduate Fellowship. Additional support from the University of Regina is gratefully acknowledged. This material is based upon work supported by the U.S. Department of Energy, Office of Science, Office of Nuclear Physics under contract DE-AC05-06OR23177. Support is also acknowledged from NSF grants PHY 2309976, 2012430 and 1714133 at the Catholic University of America, NSF grant PHY 2209199 at Ohio University, and by the National Research Foundation of Korea Grant No. NRF-2022R1A2B5B01002307.