Probing hard/soft factorization via beam-spin asymmetry in exclusive pion electroproduction from the proton

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KaonLT Overview

- Hall C E12-09-011
- **Main goal:** Rosenbluth separation of $p(e, e'K^+)\Lambda$ for extraction of kaon form factor $F_K(Q^2)$
- Also collected high quality e–π and e–p coincidence data
- **First results:** Beam-Spin Asymmetry of $p(e, e'\pi^+)n$

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Letter

Probing hard/soft factorization via beam-spin asymmetry in exclusive pion electroproduction from the proton

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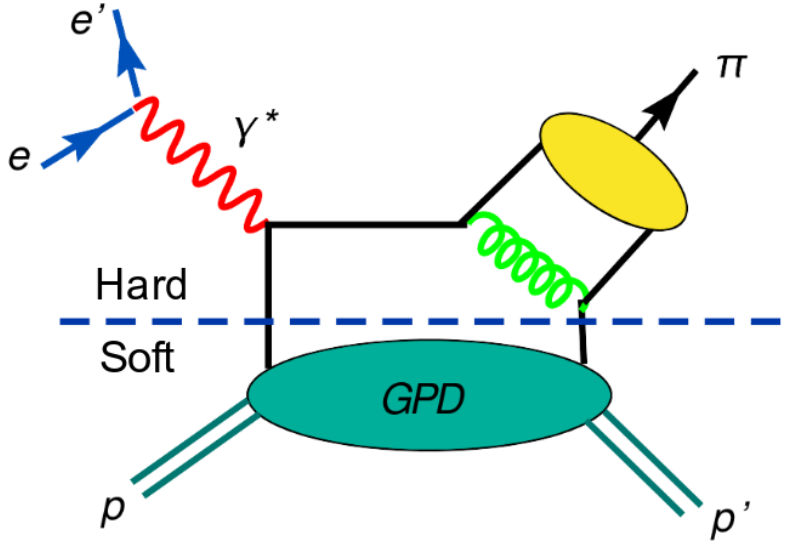
GPDs and Factorization

Hard/Soft Factorization:
hard scattering &
non-perturbative (soft)
subprocess
$\longrightarrow$ Expected to apply in the limit of large Q^2 at fixed x_B and t



- Factorization allows for the extraction of Generalized Parton Distributions (GPDs)
- GPDs unify parton distributions and hadronic form factors by correlating parton transverse position and longitudinal momentum
- **Minimum Q^2 for which factorization applies to Deep Exclusive Meson Production (DEMP) is still unknown...**

Beam-Spin Asymmetry

- Polarized cross-section in Rosenbluth equation:

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

- Define the Beam-Spin Asymmetry (BSA) as

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

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

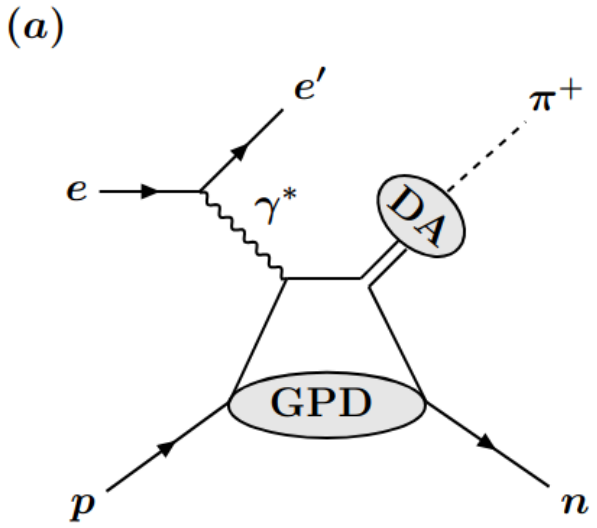
$$A_{LU} = \frac{\sqrt{2\epsilon(1-\epsilon)}\frac{\sigma_{LT'}}{\sigma_0}\sin\phi}{1 + \sqrt{2\epsilon(1+\epsilon)}\frac{\sigma_{LT}}{\sigma_0}cos\phi + \epsilon\frac{\sigma_{TT}}{\sigma_0}cos2\phi} \propto \frac{\boldsymbol{\sigma_{LT'}}}{\boldsymbol{\sigma_0}}$$

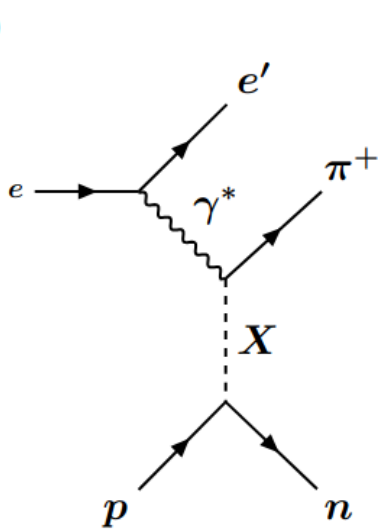
- High quality polarized beam from CEBAF ideal for BSA measurements!

M. Diehl and S. Sapeta, Eur. Phys. J. C 41, 515–533 (2005). arXiv:hep-ph/0503023

BSA as a Probe of Factorization

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





GPD process:
reaction factorized into **hard** scattering and a **soft** part described by a **GPD**

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

Motivation: Clear dominance of GPD models would be a stong indication of **factorization** at these kinematics.

GPD Parametrization of $\sigma_{LT'}/\sigma_0$

- **DVCS** probes **chiral-even** GPDs H, $\widetilde{H}$, E, and $\widetilde{E}$
- **DEMP** can also probe **chiral-odd** GPDs H_T, $\widetilde{H}_T$, E_T, and $\widetilde{E}_T$
- Polarized π^+ observables are particularly sensitive to H_T due to amplification by the pion pole
- The Goloskokov-Kroll (GK) GPD model parametrizes $\sigma_{LT'}/\sigma_0$ as:

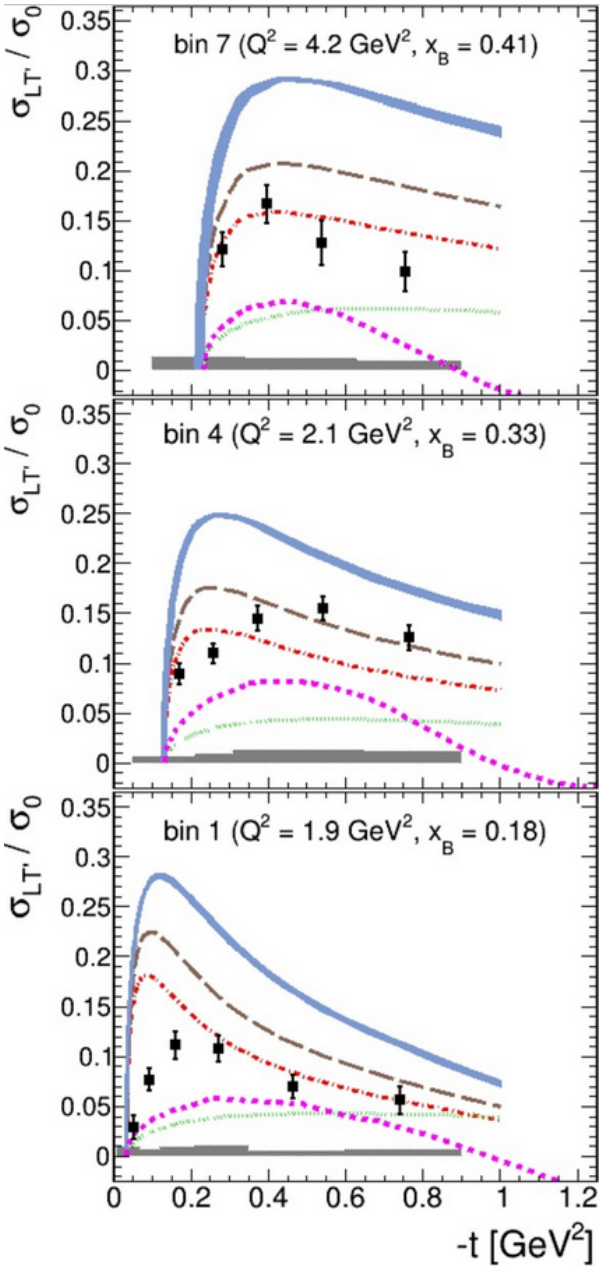
$$\frac{\sigma_{LT'}}{\sigma_0} \sim \frac{Im[\langle H_{T,eff}\rangle^* \langle \widetilde{E}_{eff}\rangle]}{|\langle H_{T,eff}\rangle|^2 + \epsilon\sigma_L}$$

- H_T very poorly constrained and related to the still unknown **tensor charge** of the nucleon

$$\delta_T^{u,d} = \int_{\xi-1}^{\xi} H_T^{u,d}(x,\xi,t=0)dx$$

S. Diehl et al, Phys. Lett. B **839** 137761 (2023). arXiv:2210.14557
G. R. Goldstein, J. O. G. Hernandez and S. Liuti, Phys. Rev. D **91** 114013 (2015). arXiv:1311.0483
S. V. Goloskokov and P. Kroll, Eur. Phys. J. A **47** 112 (2011). arXiv:1106.4897

Recent Results from CLAS12



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

Modifications to GK model explored:

- **Default**
- **No pion pole**
- **$H_T \rightarrow H_T$*1.5**
- **$H_T \rightarrow H_T$*2.0**

"It was found that the Regge model provides a better description at low Q^2, while the GPD model is more appropriate at high Q^2."

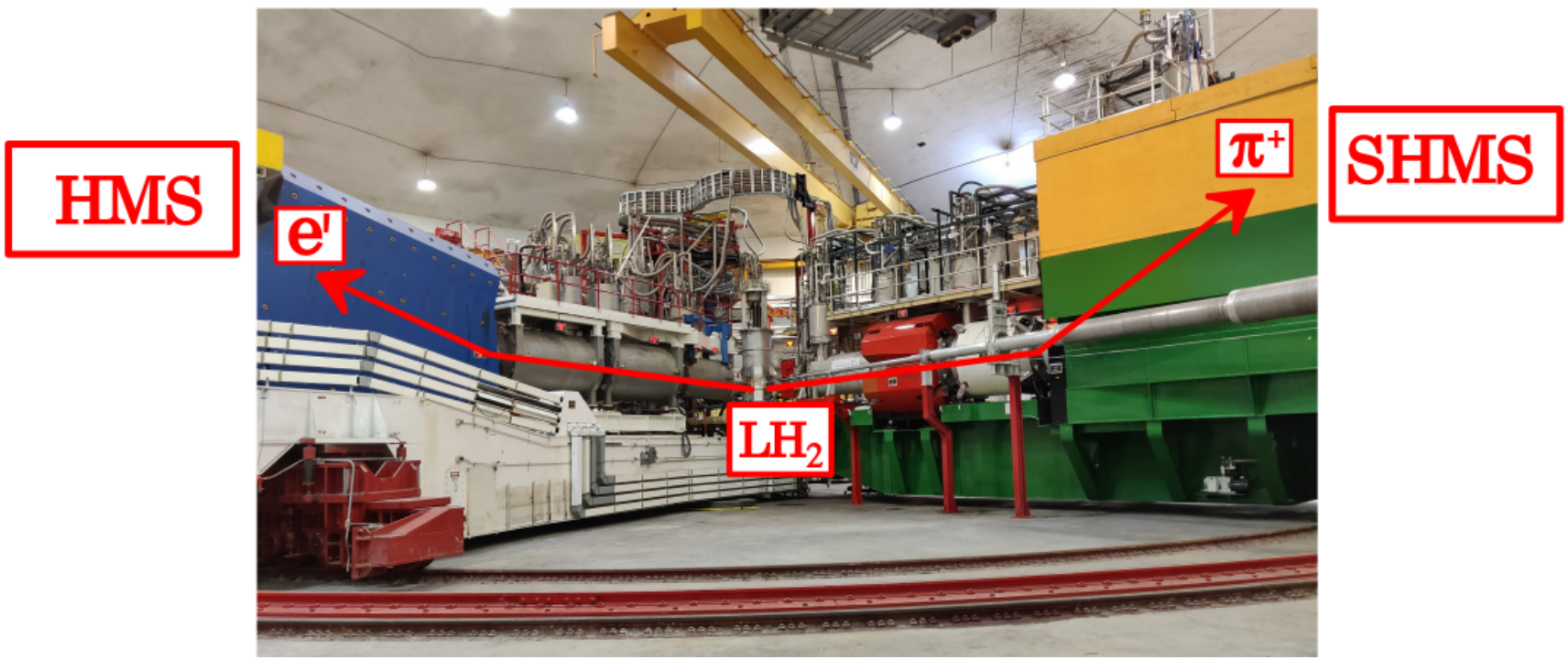
"The results and their comparison to theoretical models based on [GPDs] demonstrate the sensitivity to chiral-odd GPDs and the directly related tensor charge of the nucleon."

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

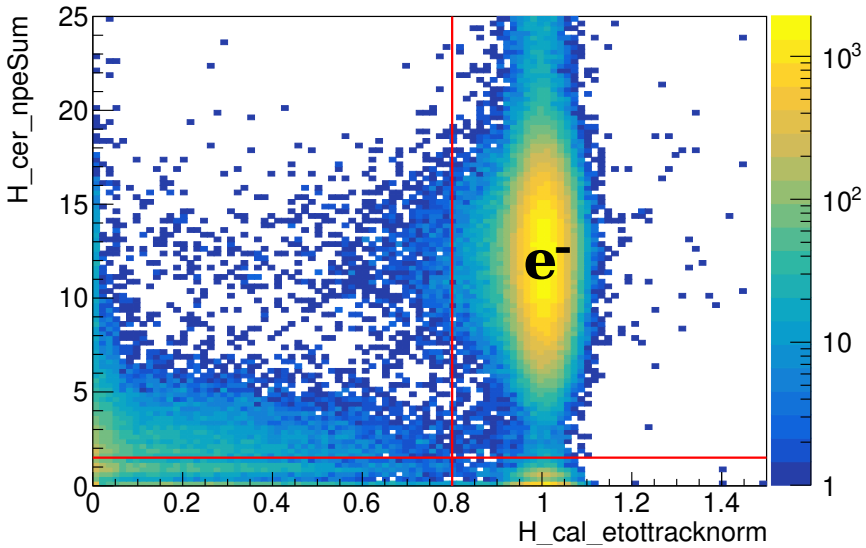
BSA in KaonLT

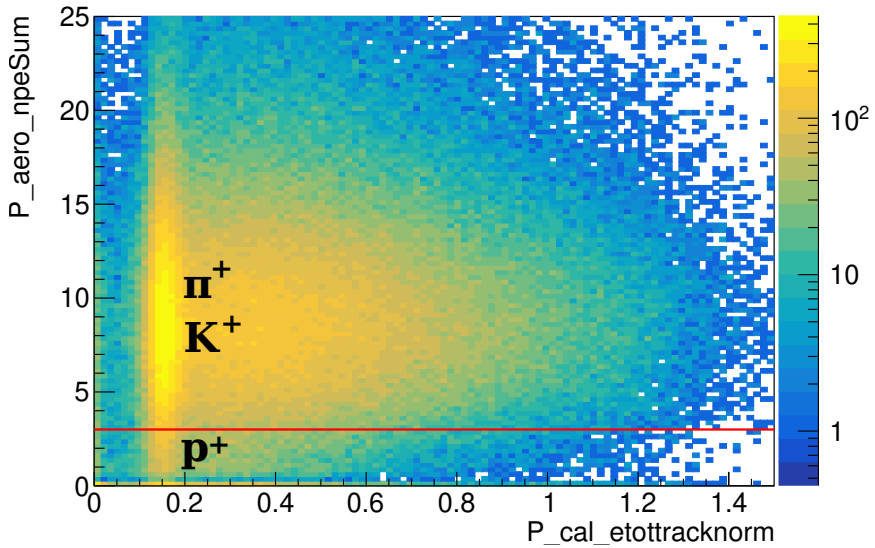
- Standard Hall C equipment
- HMS+SHMS coincidence
- Data taken Autumn 2018
- Beam energy 10.6 GeV
- Beam polarization P=89^{+1}_{-3}%

Q^2 (GeV^2)	W (GeV)	x_B	ϵ
2.1	2.95	0.21	0.79
3.0	3.14	0.25	0.67
3.0	2.32	0.40	0.88
4.4	2.74	0.40	0.71
5.5	3.02	0.40	0.53



Particle Identification





e^- in HMS

Calorimeter $p/E > 0.8$

Gas Čerenkov NPE > 1.5

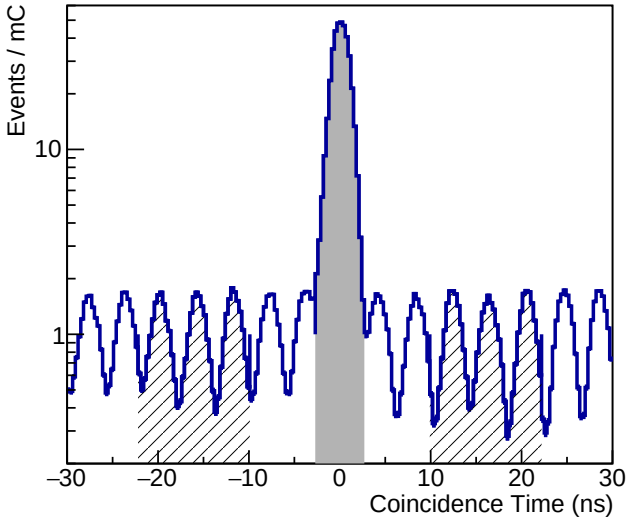
π^+ in SHMS

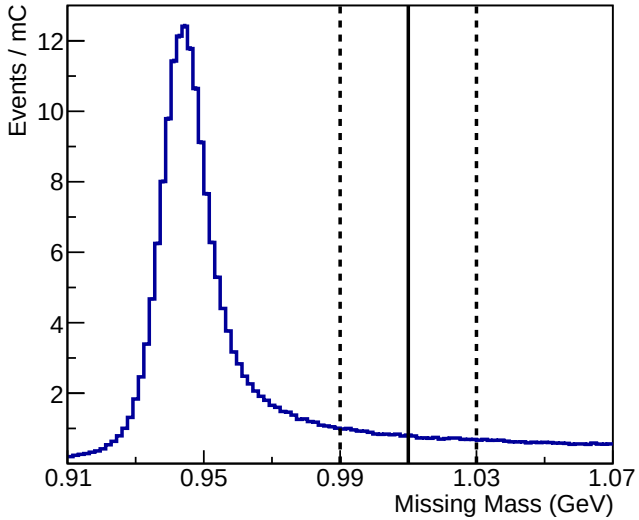
Aerogel Čerenkov NPE > 3

K^+ eliminated by missing mass

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

Event Selection





Coincidence time

$t_{SHMS} - t_{HMS}$

showing selected prompt and random windows

Missing mass

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

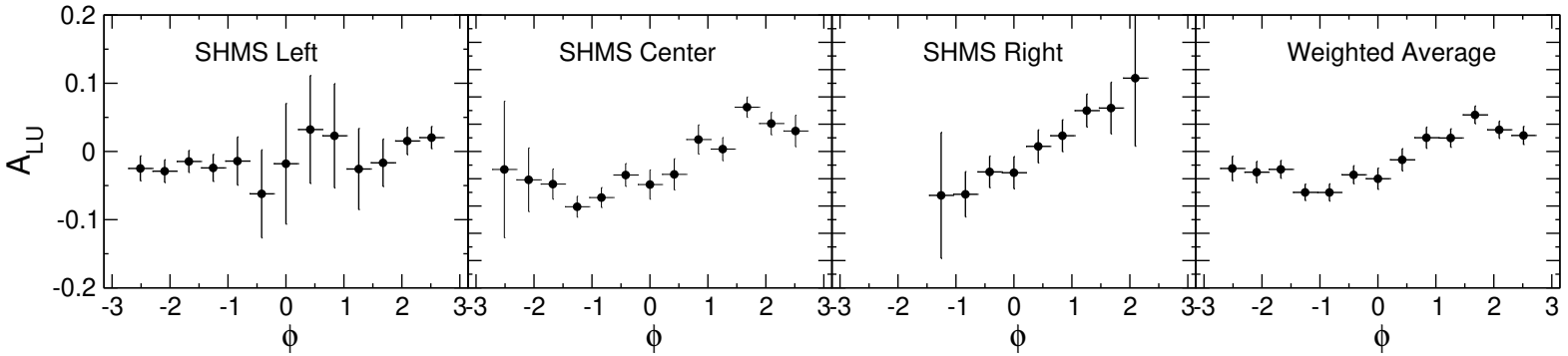
showing cut used in analysis

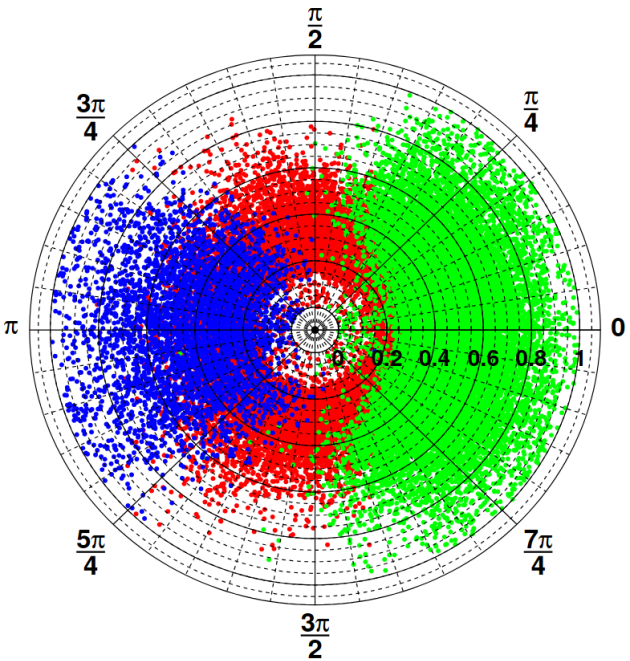
(dashed lines show alternate cuts used for evaluation of systematic uncertainty)

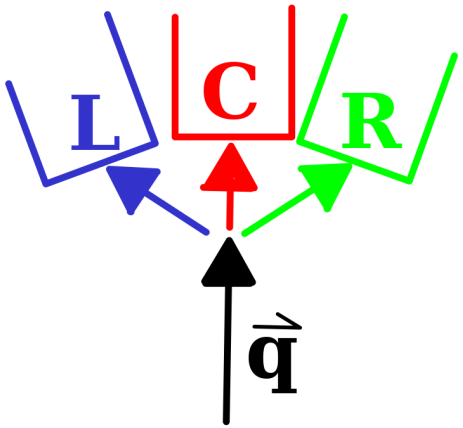
Plots: Q^2=3.0, x_B=0.25, SHMS center.

Combining SHMS Settings

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



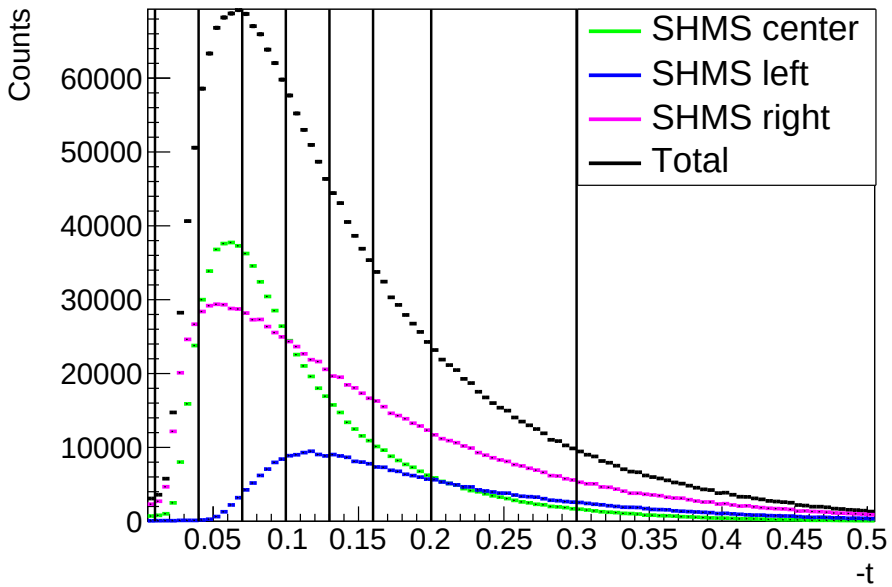




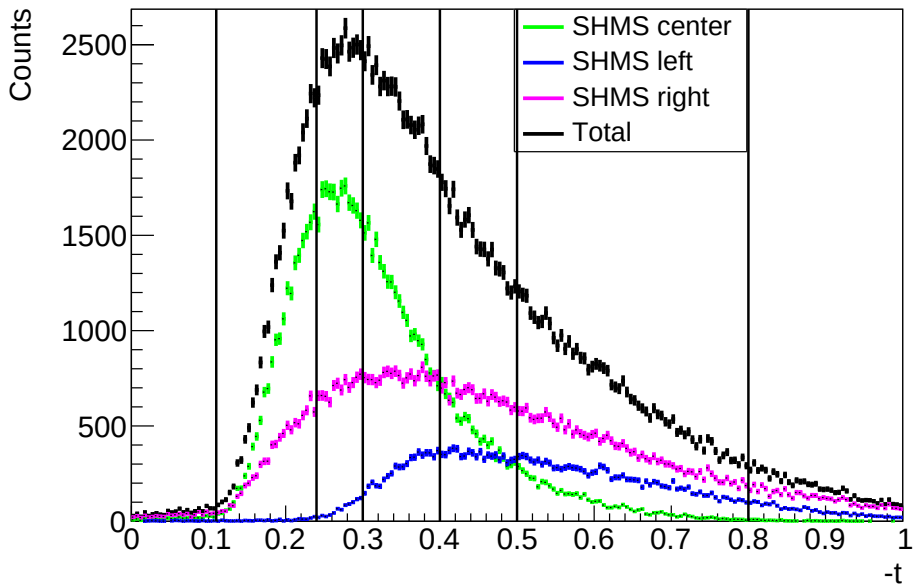
Plots: Q^2=3.0, x_B=0.40, 0.35< $-t$ <0.40 (A_{LU} vs ϕ) and Q^2=5.5, W=3.02 ($-t$ vs ϕ polar plot).

-t Binning

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

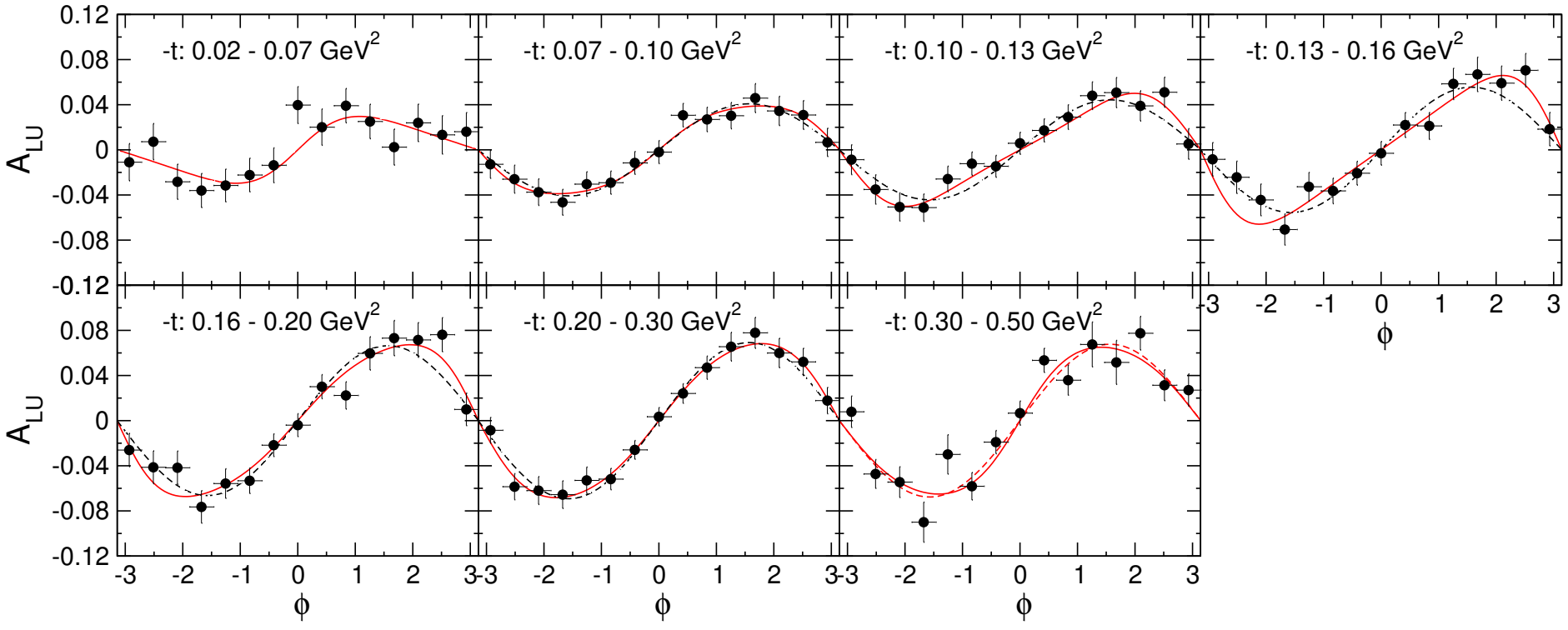


Q^2=2.1 GeV^2, x_B=0.25
$\mathcal{O}(10^6)$ events, 8 t-bins



Q^2=5.5 GeV^2, x_B=0.40
$\mathcal{O}(10^5)$ events, 5 t-bins

Asymmetry (Q^2=3 GeV^2, x_B=0.25)



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

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

The Question of Fitting

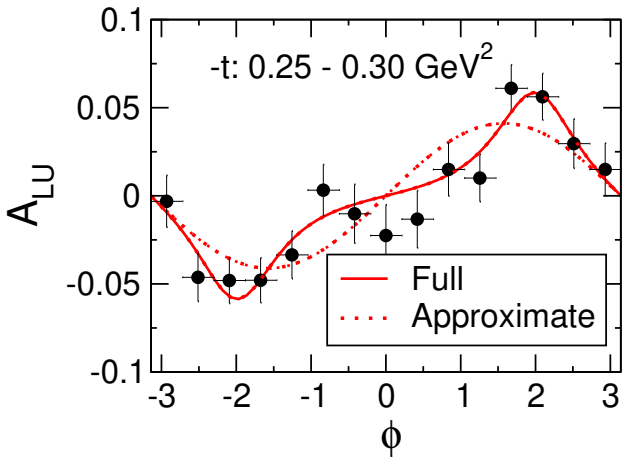
- Recall functional form of asymmetry:

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

- Previous work [Diehl et al 2023] 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, since all interference terms vanish as $(-t) \to (-t)_{min}$ where ϕ is undefined
- Approximation does not fully describe KaonLT data in all bins

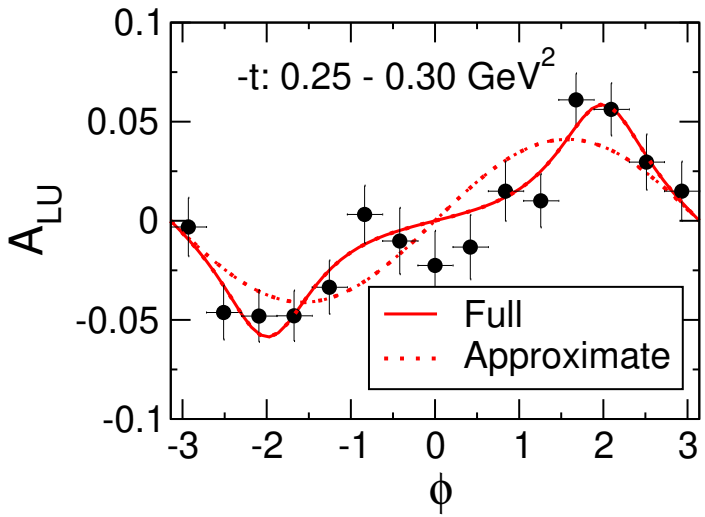


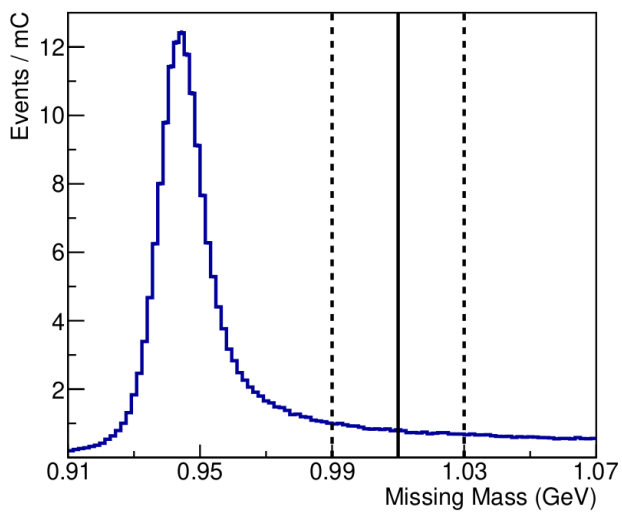
- Extract $\sigma_{LT'}/\sigma_0$ using full functional form
- Use difference in $\sigma_{LT'}/\sigma_0$ from approximate fit as a systematic error

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

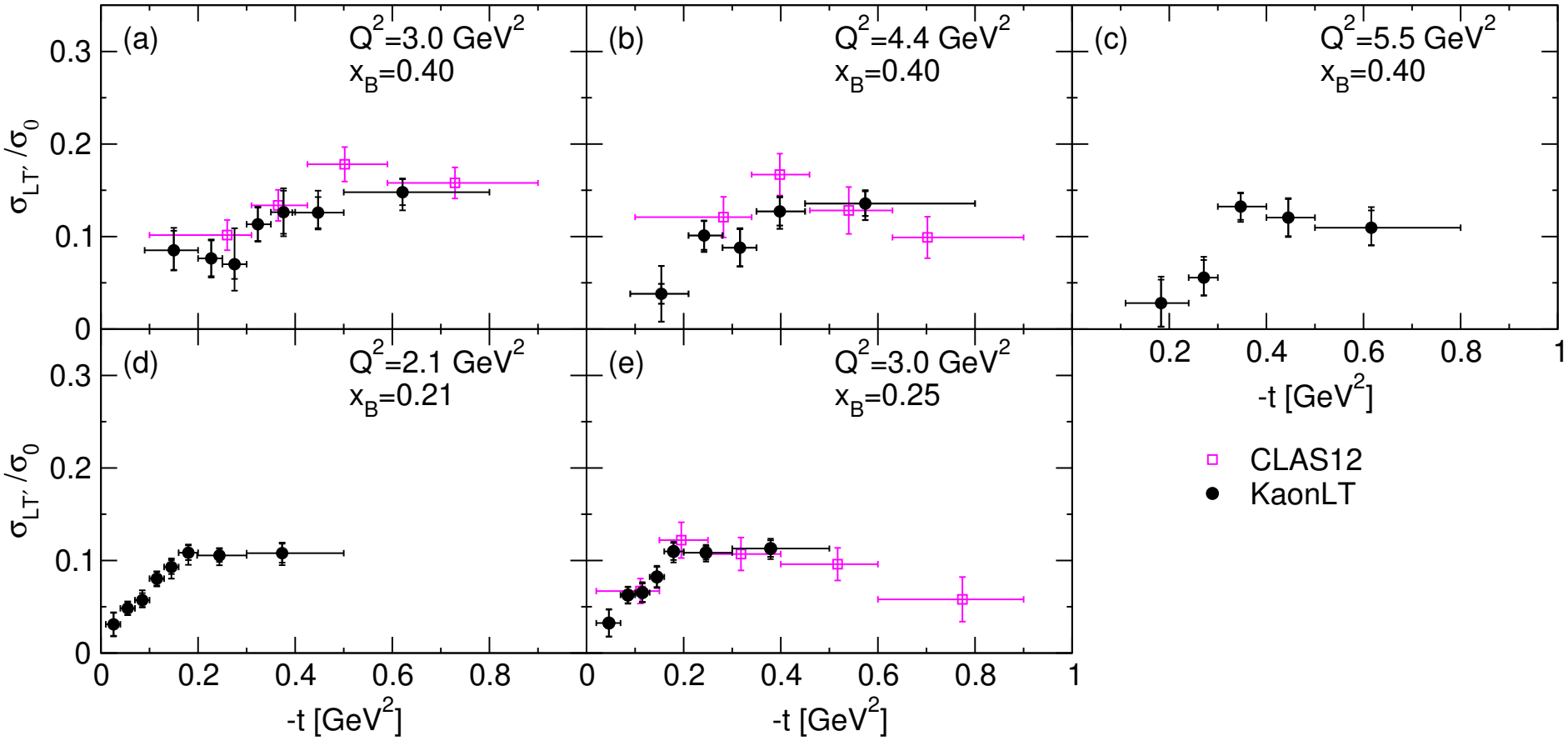
Systematic Uncertainties

1. **Fitting Error**
   - Difference between $\sigma_{LT'}/\sigma_0$ extracted using full or approximate fit
   - Unidirectional, leads to asymmetric total error
   - Dominates point-to-point uncertainty: up to **70%** of $\sigma_{LT'}/\sigma_0$
2. **Cut Dependence**
   - RMS of differences in $\sigma_{LT'}/\sigma_0$ calculated using different values for coincidence time and missing mass cuts
   - Contributes uncertainty of **1-7%**
3. **Beam Polarization**
   - $P = 89^{+1}_{-3}\% \rightarrow$ Propagate to $\sigma_{LT'}/\sigma_0$





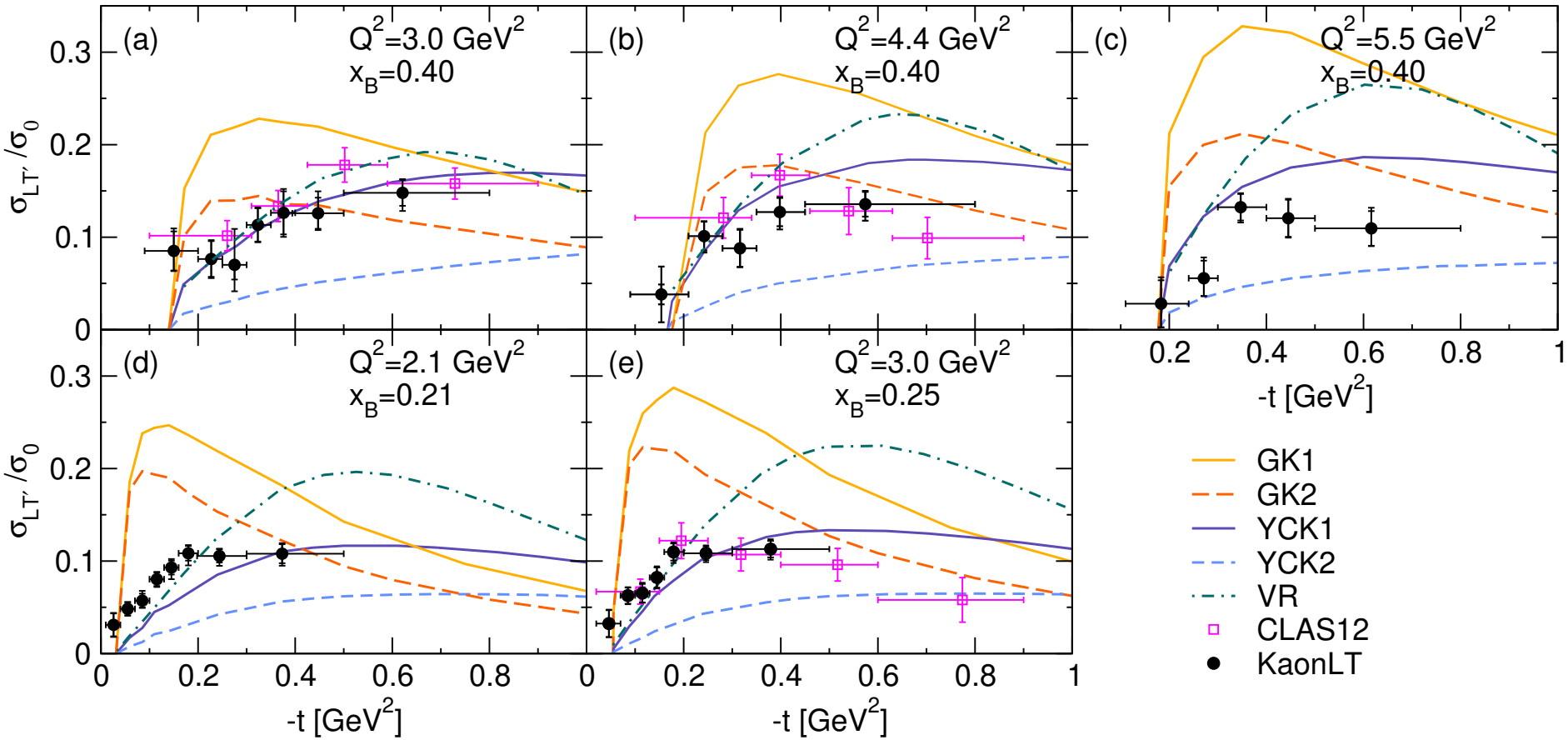
Results



- Good agreement between **KaonLT** [this work] and **CLAS12** where kinematics overlap
- Comparable uncertainties on both measurements

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

Results



S. Diehl et al., Phys. Lett. B **839**, 137761 (2023). arXiv:2210.14557
S.V. Goloskokov, P. Kroll, Eur. Phys. J. C **65** 137 (2010). arXiv:0906.0460
T. Vrancx, J. Ryckebusch & J. Nys, Phys. Rev C, **89** 065202 (2014). arXiv:1310.7715
T. K. Choi, K.-J. Kong & B.-G. Yu, J. Korean Phys. Soc. **67**, 1089-1094 (2015). arXiv:1508.00969
B. Berthou et al, Eur. Phys. J. C **78** 478 (2018). arXiv:1512.06714

Theoretical Models

- **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 $H_T \rightarrow H_T * 2$, as seen in [Diehl et al 2023]
- **Vrancx-Ryckebusch (VR)**: exchange of $\pi(140)$, $\rho(770)$, and $a_1(1260)$ **Regge** trajectories
- **Yu-Choi-Kong (YCK)**: **Regge**-based, incorporates the exchange of tensor meson $a_2(1320)$ and axial mesons a_1 and $b_1(1235)$
  YCK1: nucleon electromagnetic form factors mediated by GPDs
  YCK2: nucleon EMFFs use dipole form
  New! YCK are co-authors on this paper

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:0906.0460
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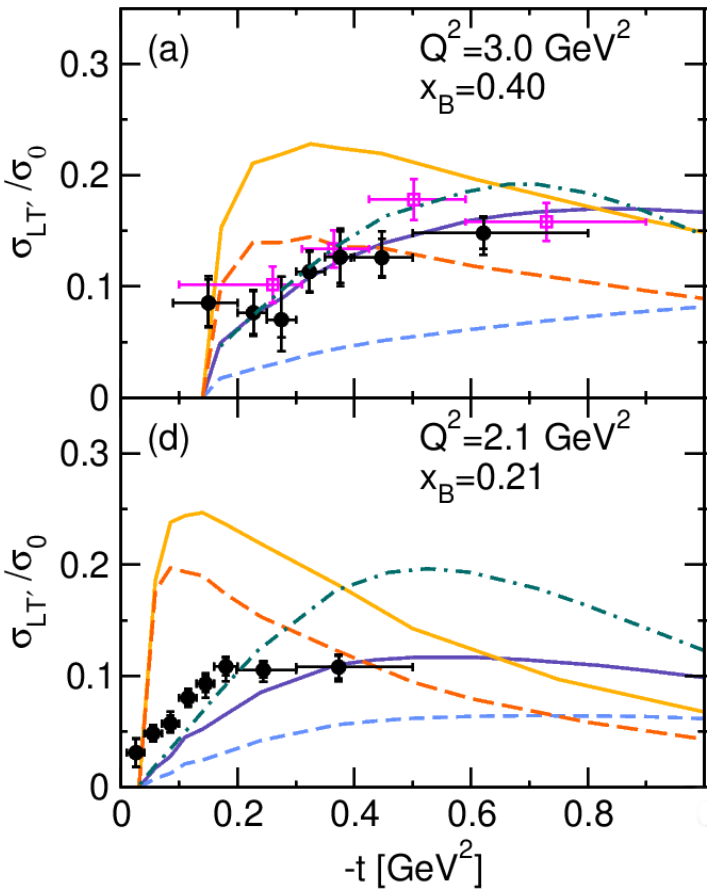
Comparison with Theory



GK1 (GPD): Overestimates magnitude

GK2 (GPD, H_T*2): Comparable magnitude, overall shape still different

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

YCK1 (Regge + GPD EMFF): Decent reproduction of magnitude and shape

YCK2 (Regge + dipole EMFF): Underestimates magnitude

Best overall agreement is **YCK1**: Regge model with GPD parametrization of nucleon electromagnetic form factors (EMFFs)

S. Diehl et al., Phys. Lett. B **839**, 137761 (2023). arXiv:2210.14557
S.V. Goloskokov, P. Kroll, Eur. Phys. J. C **65** 137 (2010). arXiv:0906.0460
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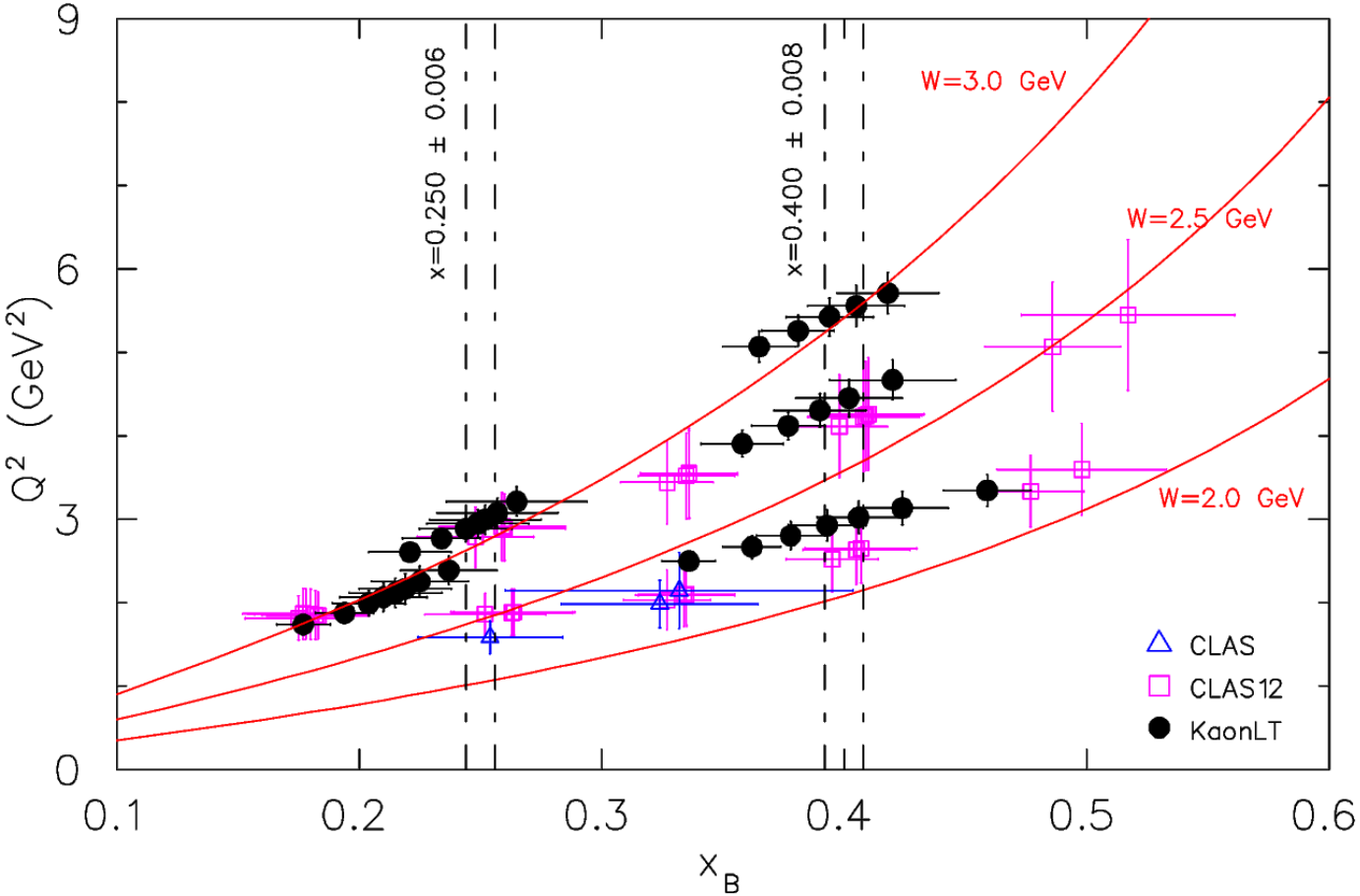
B. Berthou et al, Eur. Phys. J. C **78** 478 (2018). arXiv:1512.06714

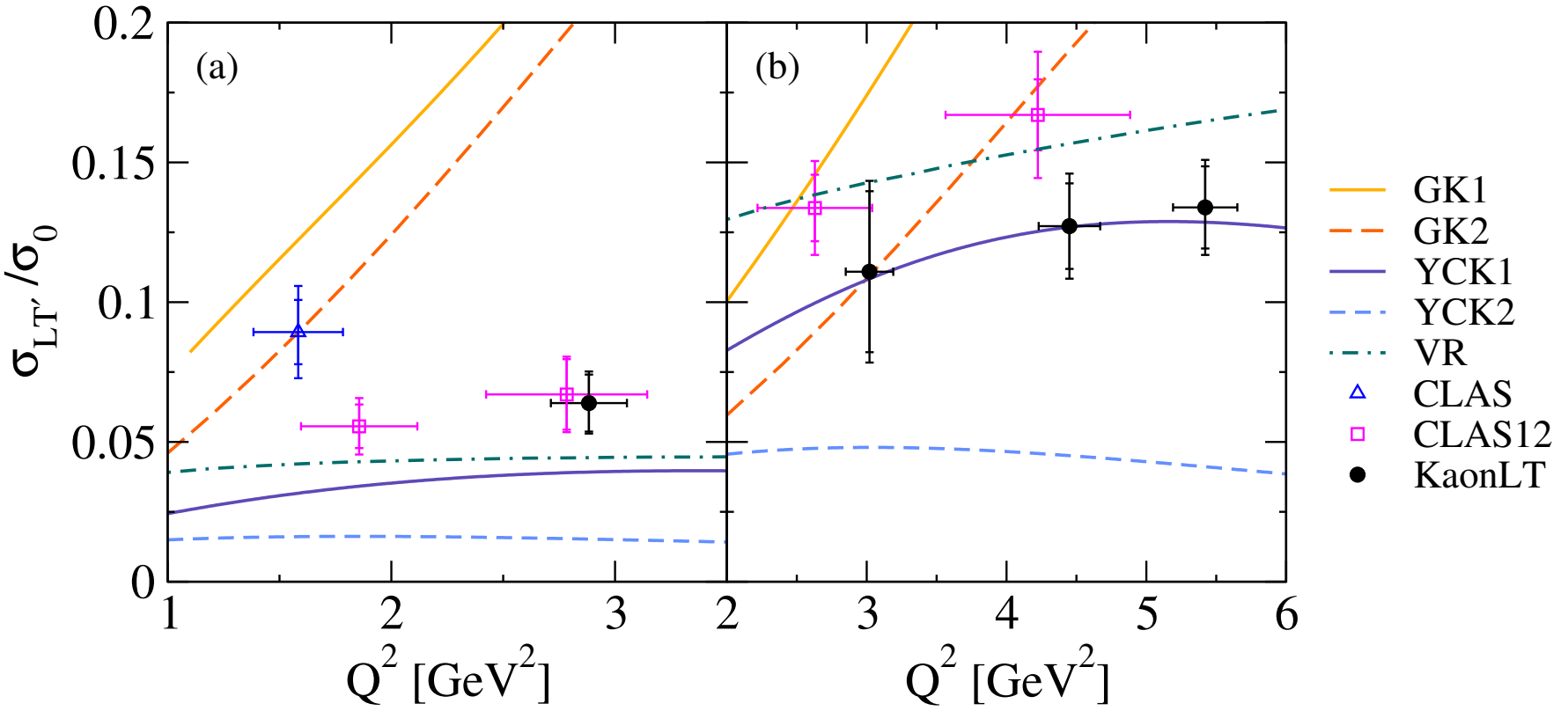
Q^2 Scan as a Second Probe of Factorization



- 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 at Fixed x_B and t (New!)



- $\sigma_{LT'}/\sigma_0$ from **KaonLT** [This work], **CLAS**, and **CLAS12** vs Q^2
- Flat or weak Q^2 dependence → closer to **Regge** models

S. Diehl et al., Phys. Lett. B **839**, 137761 (2023). arXiv:1310.7715
S. Diehl et al., Phys. Rev. Lett. **125**, 182001 (2020). arXiv:2007.15677
S.V. Goloskokov, P. Kroll, Eur. Phys. J. C **65** 137 (2010). arXiv:0906.0460
T. Vrancx, J. Ryckebusch & J. Nys, Phys. Rev C, **89** 065202 (2014).
T. K. Choi, K.-J. Kong & B.-G. Yu, J. Korean Phys. Soc. **67** 1089-1094 (2015). arXiv:1508.00969

Physics Interpretation

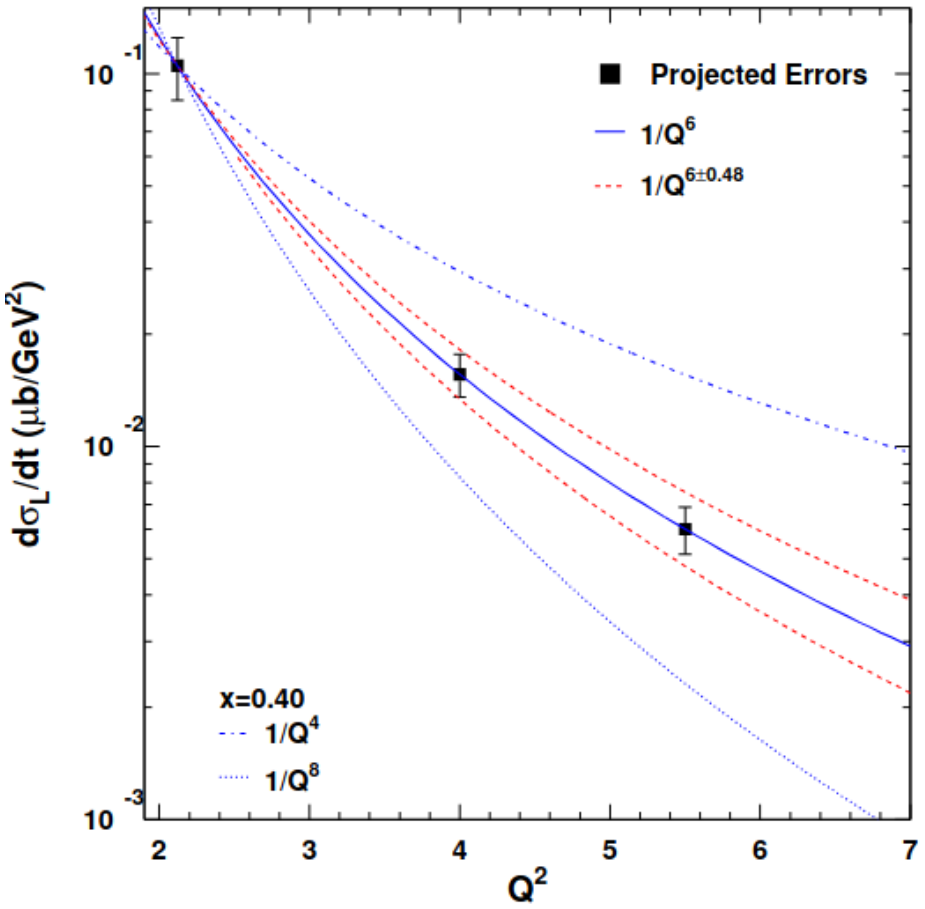
- Regge models outperform GPD models on both t-dependence and Q^2-dependence of $\sigma_{LT'}/\sigma_0$
  - $\longrightarrow$ No indications of factorization
  - $\longrightarrow$ Not sufficient to disprove factorization
- Different conclusion from CLAS12, in part due to new YCK model
  - $\longrightarrow$ Further study needed
- Conclusions are **model-dependent** and $\sigma_{LT'}/\sigma_0$ is a twist-3 quantity
  - $\longrightarrow$ Encourage development of future models
  - $\longrightarrow$ Prioritize a **model-independent** test of factorization

Model-Independent Test of Factorization

- Factorization predicts that at fixed x_B, the longitudinal cross-section scales as

$$\frac{d\sigma_L}{dt} \propto \frac{1}{Q^6}$$

- The PionLT experiment will test for scaling in $p(e, e'\pi^+)n$ for $Q^2 \leq 8.5$ GeV^2
- Data taken for Q^2 scans at $x_B = 0.31, 0.39, 0.55$
- L/T separations in progress by Muhammad Junaid & Nathan Heinrich (UR)



Projected errors in scaling study from PionLT proposal

Upcoming KaonLT Results

- $p(e,e'K^+)\Lambda$ L/T Separation – Richard Trotta (CUA/UVA) & Chi Kin Tam (CUA)
- $p(e,e'\pi^+)\Delta^0$ BSA – Ali Usman (UR)
- $p(e,e'K^+)\Lambda$ BSA – Ivan Zhenchuk (UR)
- u-channel $p(e,e'p')\omega$ L/T Separation – Alicia Postuma (UR)
- Low-Q^2 $p(e,e'K^+)\Lambda$ L/T Separation – Nacer Hamdi (UR)
- Low-Q^2 $p(e,e'\pi^+)n$ L/T separation – Vijay Kumar (UR)
- $K^+\Sigma^0/K^+\Lambda^0$ and $K^+\Sigma^*/K^+\Lambda^0$ ratios – Gabriel Niculescu (JMU) & Ioana Niculescu (JMU)

This paper is the first of many from KaonLT!

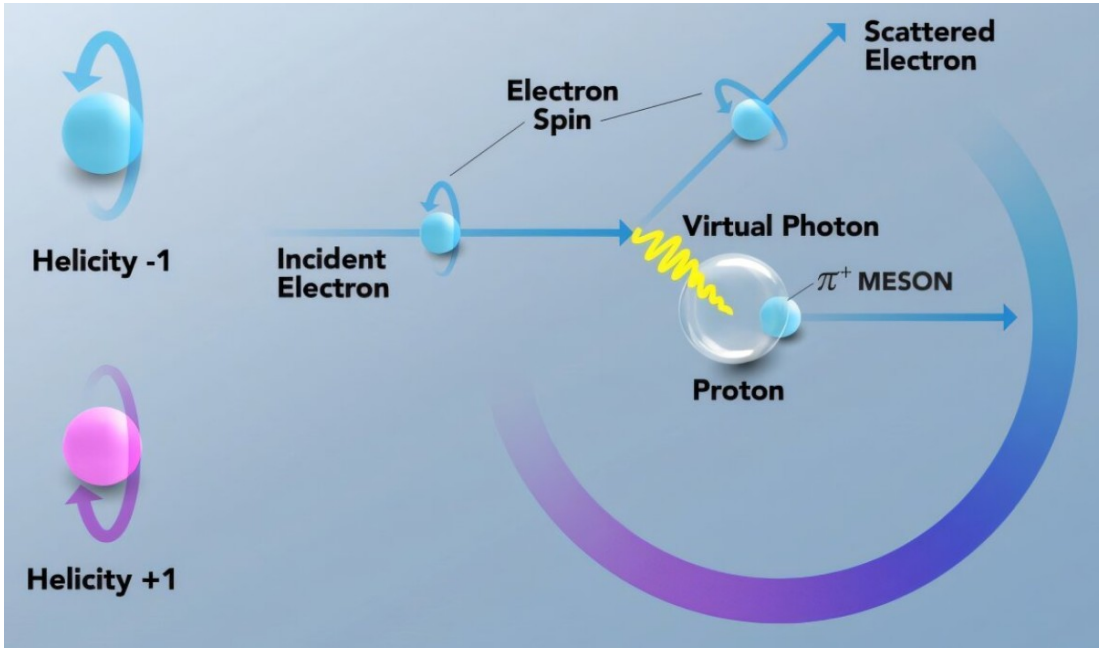
Summary

- Measured A_{LU} in $p(e, e'\pi^+)n$
- Extracted $\sigma_{LT'}/\sigma_0$ over a wide range of kinematics
- Magnitude and $-t$ **dependence** closest to Regge model YCK1
- Flat Q^2 **dependence** also better predicted by Regge models
- No indication of factorization (yet)
- Model-independent test of factorization in $p(e, e'\pi^+)n$ to be provided by PionLT
- Stay tuned for future results from KaonLT!

A.C. Postuma et al (KaonLT Collaboration), *Probing hard/soft factorization via beam-spin asymmetry in exclusive pion electroproduction from the proton,* Phys. Lett. B **872** 140094 (2026).

Beam-Spin Asymmetry Study Puts Proton Models to the Test

by Matt Cahill & Jefferson Lab Communications, 02/26/2026



This illustration visualizes meson production and beam-spin asymmetry. (Jefferson Lab illustration)

PRESS RELEASE

"Getting an up-close view of life at the cellular level can be as simple as placing onion skin under a microscope and adjusting the knobs. Peering deeper, into the heart of the atoms within, isn't as easy. It requires peeling through layers of particle accelerator data to shed light on protons, neutrons and the subatomic processes at play."

Jefferson Lab

PHYS.ORG

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