FROM SPIN TO STRUCTURE

Beam Spin Asymmetry in Exclusive Pion Electroproduction

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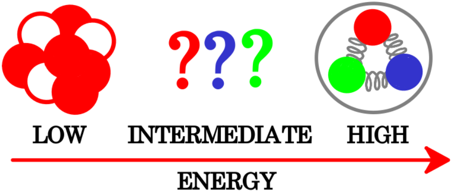
University of Regina
Jefferson Lab KaonLT/PionLT Collaboration

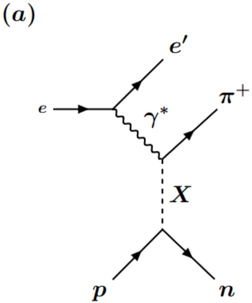
WNPPC 2025

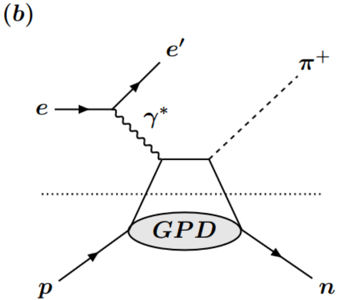
Motivation

- Many unknowns in theory of **strong force**
- Meson electroproduction in Jefferson Lab Hall C probes **hadron structure**
- Use observables to study **non-perturbative QCD** in the **transition regime**



Theoretical Approaches





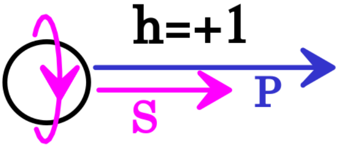
Regge: considers **baryon** and **meson** degrees of freedom

Generalized Parton Distribution (GPD): considers **quark** and **gluon** degrees of freedom

> Compare observables to Regge and GPD models
> = test **relevant degrees of freedom** at given kinematics

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

- Difference in cross-sections based on **helicity** (±1) of the incident electron

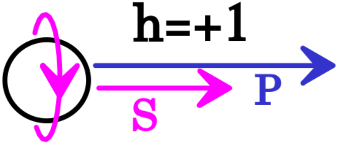


A. Bacchetta et al. Phys. Rev. D 70, 117504 (2004). M. Diehl and S. Sapeta. Eur. Phys. J. C 41, 515-533 (2005).

Beam Spin Asymmetry

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

- Difference in cross-sections based on **helicity** (±1) of the incident electron
- Caused by interference between transversely and longitudinally polarized virtual photons γ^*



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Beam Spin Asymmetry

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- Difference in cross-sections based on **helicity** (± 1) of the incident electron
- Caused by interference between transversely and longitudinally polarized virtual photons
- Acceptances cancel in a ratio

My research: asymmetry analysis of the reaction:

$$e^- + p \longrightarrow e^{-\prime} + \pi^+ + n$$

Extraction of $\sigma_{LT'}/\sigma_0$ over a range of kinematics

M. Diehl and S. Sapeta. Eur. Phys. J. C 41, 515-533 (2005).

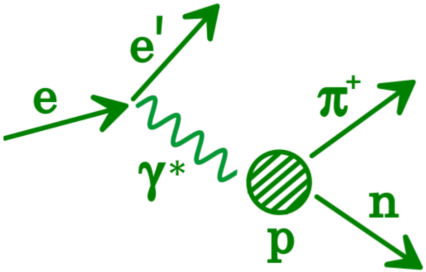
Some Definitions

$\mathbf{Q^2}$: 4-momentum of γ^*

$\mathbf{x_B}$: momentum fraction of struck parton

-t: 4-momentum transfer from γ^* to meson

ϵ: longitudinal to transverse γ^* flux ratio



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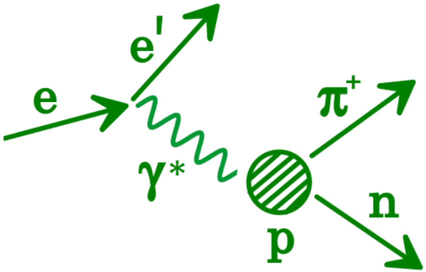

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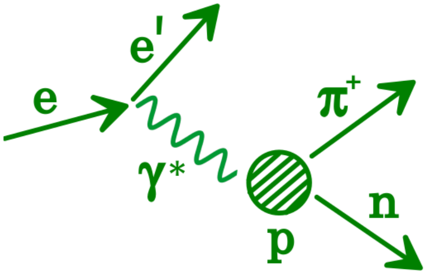

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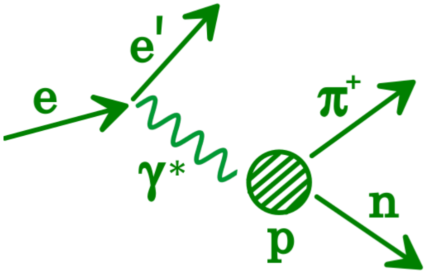

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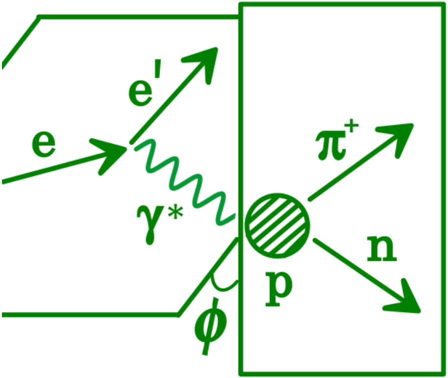

Welcome to Hall C!

- Hall C: electron beam → fixed target → spectrometers

- Spectrometers are magnetic and moveable → choose charge, momentum, and angles to detect
- Coincidence experiment: need simultaneous detection in **High Momentum Spectrometer** and **Super HMS**

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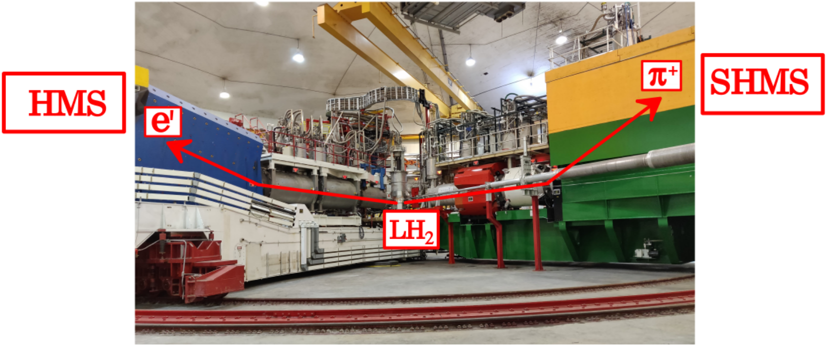
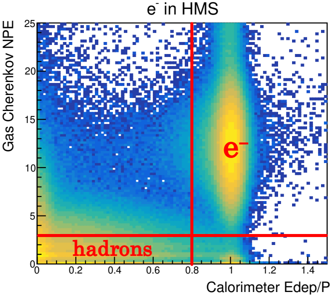


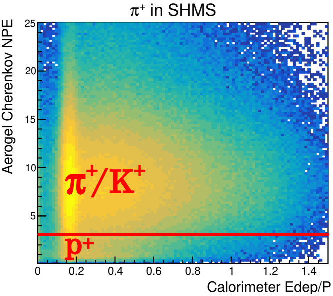
- Spectrometers are magnetic and moveable $\rightarrow$ choose charge, momentum, and angles to detect
- Coincidence experiment: need simultaneous detection in **High Momentum Spectrometer** and **Super HMS**

Particle Identification (PID)

- Spectrometer detector stack contains **drift chambers** for **tracking**, **hodoscopes** for **triggering**, **threshold Cherenkovs** and **calorimeter** for **PID**
- Fixed charge, momentum: PID via **mass separation**

→ Choose index of refraction to distinguish between particles





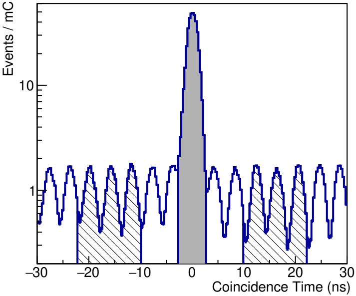
Event Selection

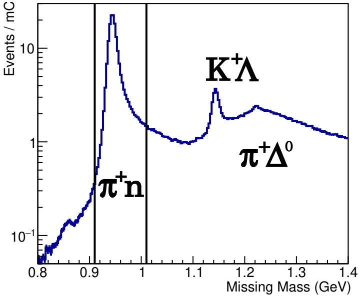
$$e^- + p \rightarrow e^{-\prime} + \pi^+ + n$$

- Select coincidences via $t_{COIN} = t_{HMS} - t_{SHMS} \approx 0$
- Neutron not detected $\rightarrow$ use missing mass $m_X \approx m_N$

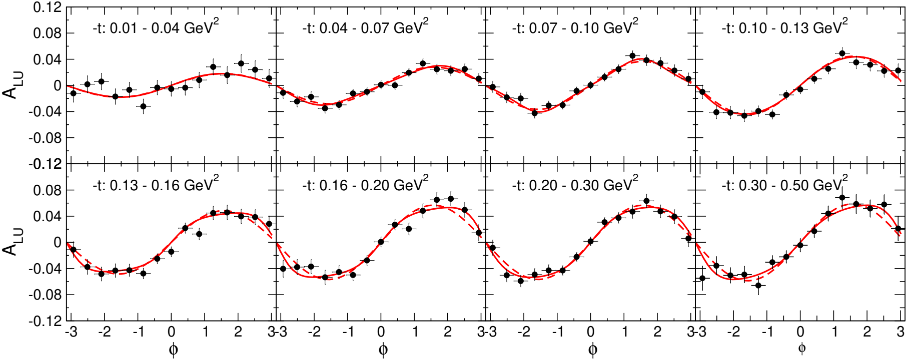
$$m_X^2 = (\boldsymbol{p}_e + m_p - \boldsymbol{p}_{e\prime} - \boldsymbol{p}_\pi)^2$$

- Subtract random time sample, empty target background





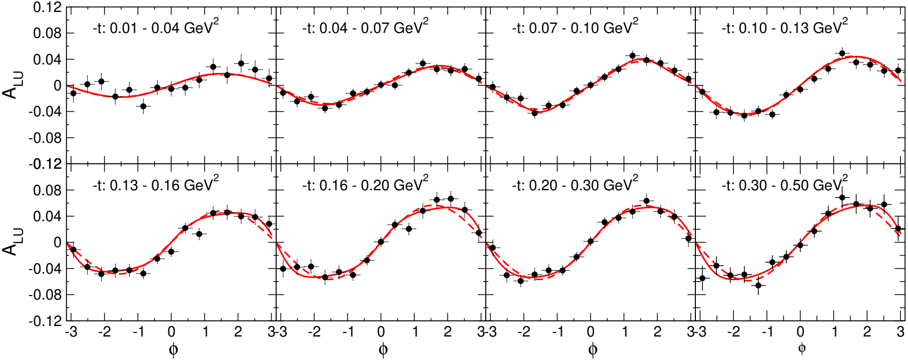
Asymmetry Q^2=2.1 GeV^2, x_B=0.21



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

$$\delta_{\rm stat} = \frac{2}{P}\sqrt{\frac{Y^+ Y^-}{(Y^+ + Y^-)^3}}$$

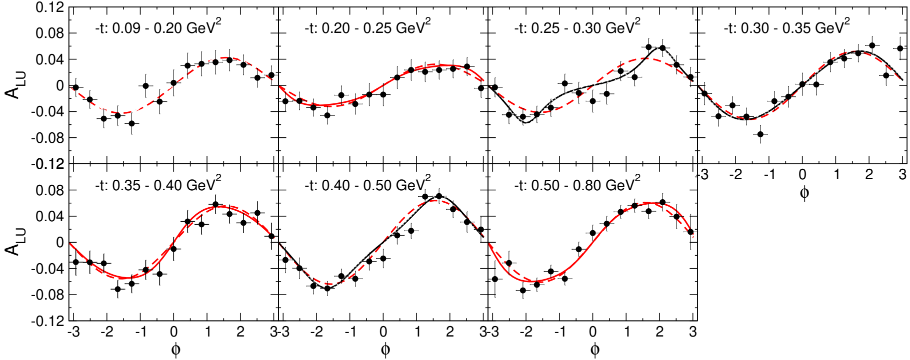
Asymmetry Q^2=2.1 GeV^2, x_B =0.21



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

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

Asymmetry $Q^2 = 3.0$ GeV^2, $x_B = 0.40$



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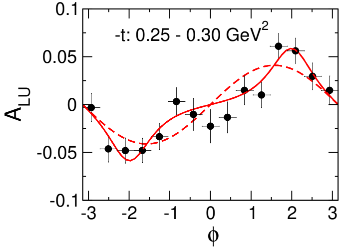
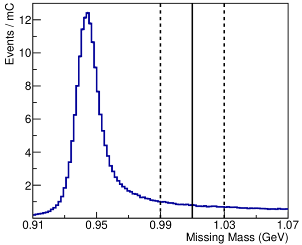
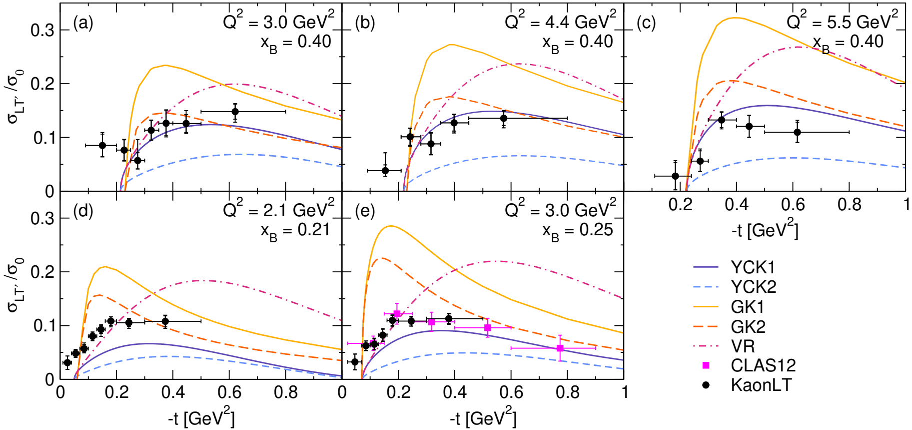
Systematic Errors

1. Fitting Error
   - Difference in $\sigma_{LT'}/\sigma_0$ extracted using full (solid line) or approximated (dashed) fit
   - Has a direction $\rightarrow$ total systematic error asymmetric
2. Cut Dependence
   - $\sigma_{LT'}/\sigma_0$ varies with exact values of missing mass and coincidence time cuts
3. Beam Polarization
   - $P = 89^{+1}_{-3}\%$ $\rightarrow$ Propagate to $\sigma_{LT'}/\sigma_0$





Results



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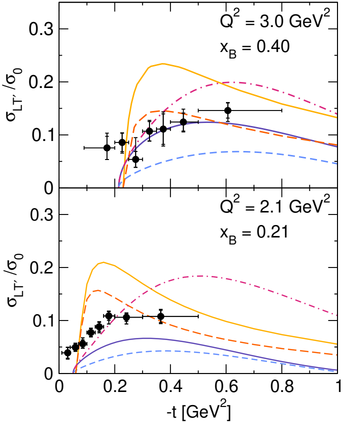
Comparison with Theory



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

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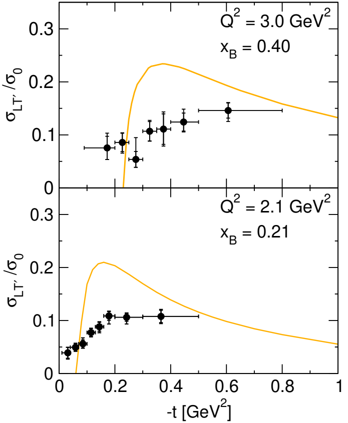

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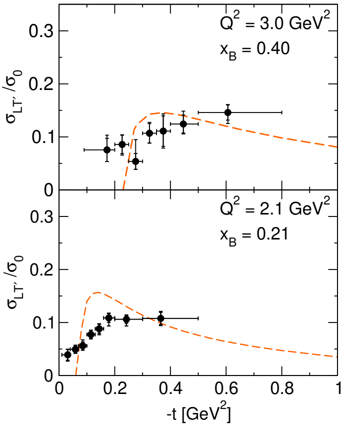

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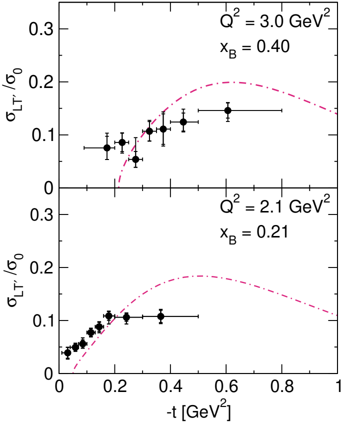

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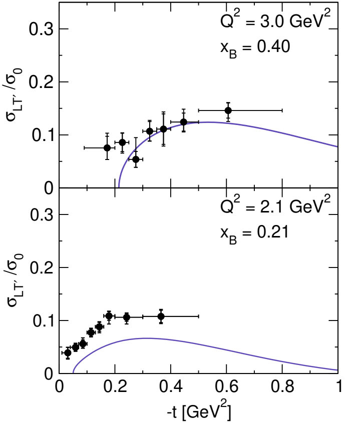

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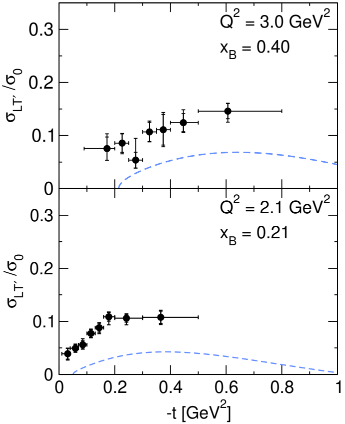

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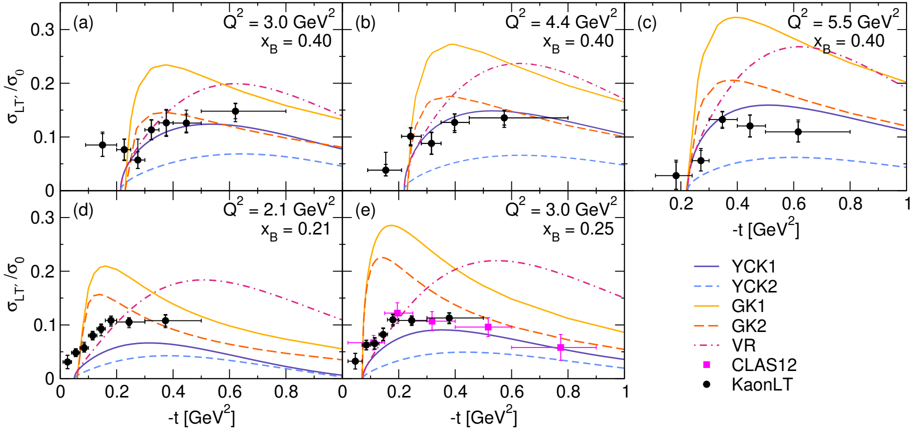
Comparison with Theory (2)



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

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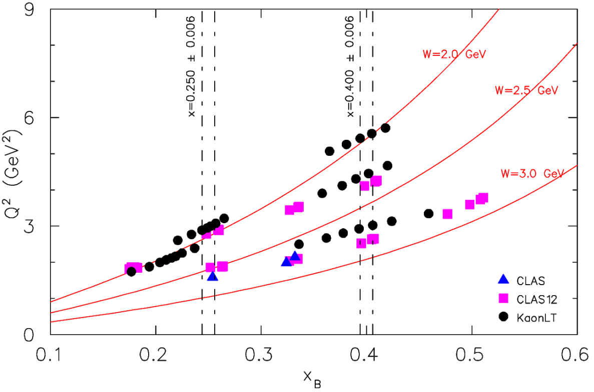
Q^2 Scan

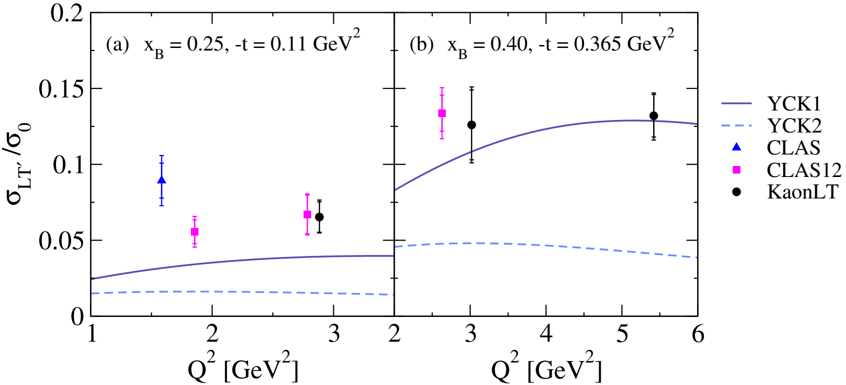
- Measurements of $\sigma_{LT'}/\sigma_0$ from **KaonLT**, **CLAS**, and **CLAS12**
- **KaonLT** data extends kinematic range with finer t-binning
- Combine to determine $\boldsymbol{Q^2}$ **dependence** at fixed $(x_B, -t)$



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

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

Q^2 Dependence (New!)



- $\sigma_{LT'}/\sigma_0$ from **KaonLT**, **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).
S. Diehl et al., Phys. Rev. Lett. **125**, 182001 (2020).
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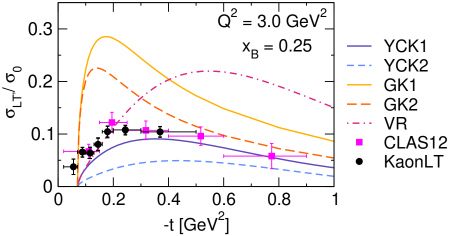
Physics Interpretation

CLAS12 conclusions: best fit is
GK2 (GPD H_T*2)
$\rightarrow$ GPD picture applicable

KaonLT conclusions: best fit is
YCK1 (Regge + GPD EMFF)



- Our measured $\sigma_{LT'}/\sigma_0$ is not explained by only quark and gluon degrees of freedom
- Hadronic degrees of freedom may be more relevant
- **YCK1** uses GPDs in EMFF parametrization $\rightarrow$ hybrid approach?

★ Need model-independent tests of GPD picture *(see next talk)*

S.V. Goloskokov, P. Kroll, Eur. Phys. J. C **65** 137 (2010). B. Berthou et al, Eur. Phys. J. C **78** 478 (2018).
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Summary and Conclusions

- Measured $\boldsymbol{A_{LU}}$ in $\boldsymbol{e} + \boldsymbol{p} \rightarrow \boldsymbol{e'} + \pi^+ + \boldsymbol{n}$ and extracted $\boldsymbol{\sigma_{LT'}/\sigma_0}$ from KaonLT data over range of kinematics
- No exact agreement with predictions, closest is **YCK1 (Regge + GPD EMFF)**
- Flat or weak Q^2 dependence of $\boldsymbol{\sigma_{LT'}/\sigma_0}$
- *Manuscript being prepared for Physics Letters B*

> Precision data of hadronic reaction observables critical for proton structure and the strong force!

Acknowledgements

KaonLT/PionLT Collaboration:
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Vijay Kumar, Pete Markowitz*,
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Richard Trotta, Ali Usman

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NSF PHY 2209199

NSERC
CRSNG

Canadian Institute of Nuclear Physics
Institut canadien de physique nucléaire

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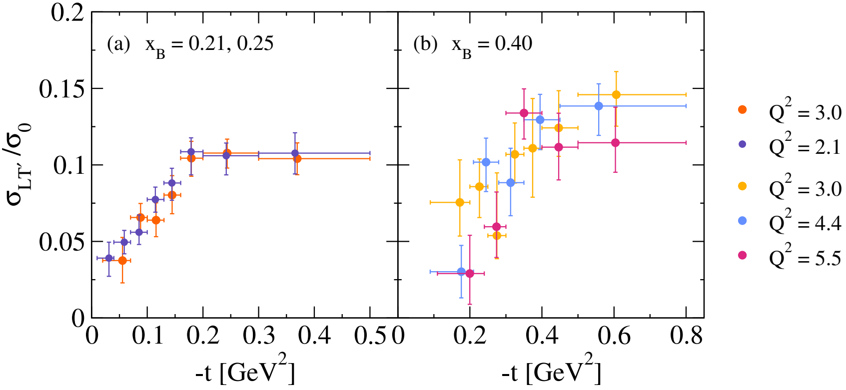
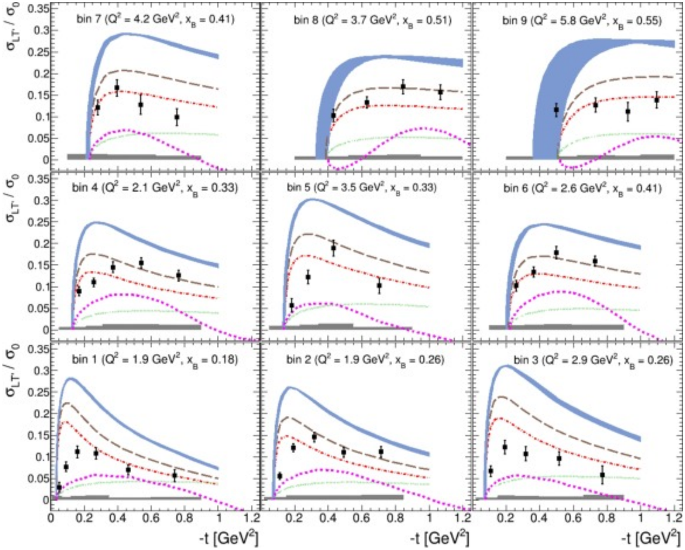
EXTRA SLIDES

What If...



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

CLAS12 Results



GK (default)

GK (H_T*1.5)

GK (H_T*2)

JML (Regge)

GK (no pion pole)

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

Quick Derivation

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

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

- Polarized cross-section in Rosenbluth equation appears when separating events by helicity:

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

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

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

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

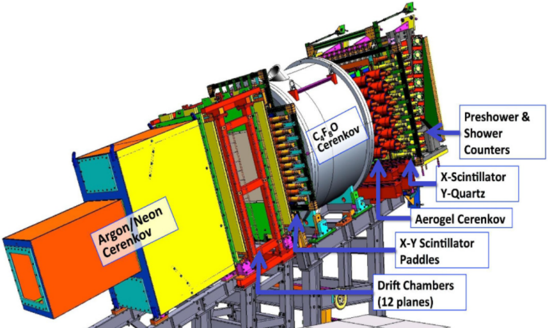
M. Diehl and S. Sapeta. Eur. Phys. J. C 41, 525-533 (2005).

SHMS Focal Plane Detectors

Photo by N. Heinrich.

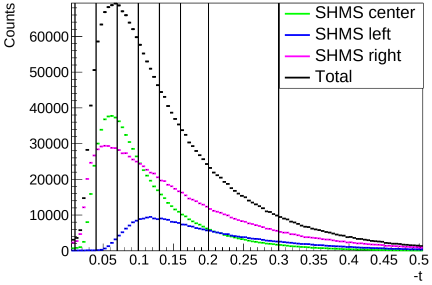
Detector	Purpose
Ar/Ne Cherenkov	Not installed
Drift chambers	Tracking
Hodoscopes	Triggering, tracking
C_4F_8O Cherenkov	Particle identification
Aerogel Cherenkov	Particle identification
Shower counters	Calorimetry

S. Ali et al, to be published (2022).



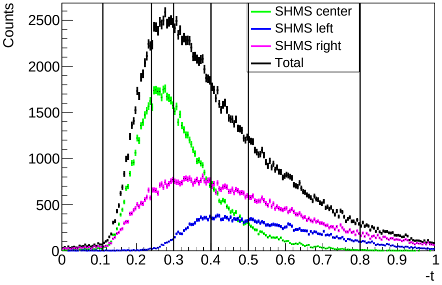
-t Binning

- Sum all events at one (Q^2,x_B) 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

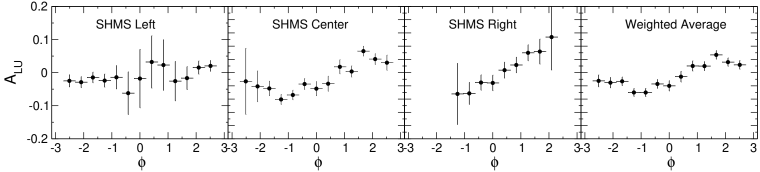


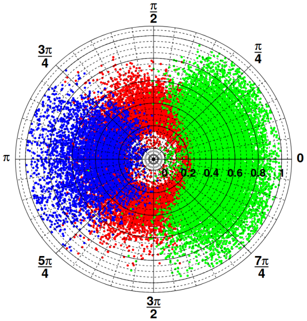
Q^2=5.5 GeV^2, x_B=0.40

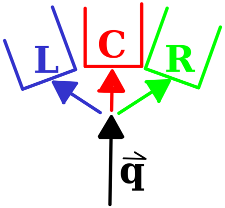
$\mathcal{O}(10^5)$ events, 5 t-bins

Combining SHMS Settings

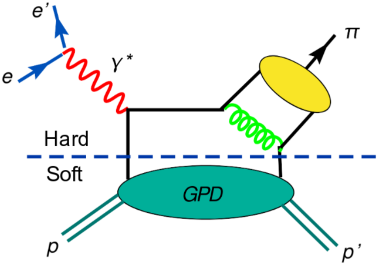
Asymmetry is calculated separately for three SHMS angles (**left**, **center**, **right**), then a weighted average is taken for full ϕ coverage.







GPDs and Hard/Soft Factorization

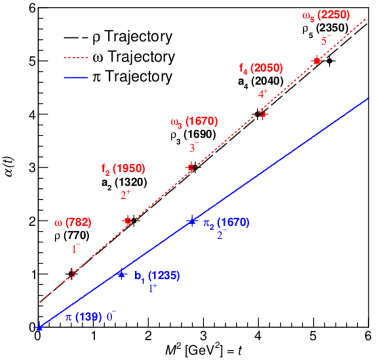


GPD models rely explicitly on **hard/soft factorization**: process can be written as convolution of hard (perturbative) scattering and soft (non-perturbative) object

- GPDs encode **3D nucleon structure** information: extraction is of high interest
- QCD predicts factorization at **"sufficiently high"** Q^2
- Experimental data needed to identify onset of factorization

R. Devenish and A. Cooper-Sarkar, *Deep Inelastic Scattering* (Oxford University Press, 2004). Figure by N. Heinrich.

Regge Models



Regge trajectories

Linear relationship observed between mass M^2 and spin α for baryons of the same quark content

- Feynman propagator replaced with Regge propagator
- Exchange of a series of particles along a Regge trajectory
- My reaction: mesons exchanged, typically π and ρ propagators
- Cutoff is a free parameter in many models

W. Li, *Exclusive Backward-Angle Omega Meson Electroproduction*, Ph.D. thesis, University of Regina (2017).

T. Regge. Introduction to complex orbital momenta. Nuovo Cim, 14:951– 976, 1959

Model Details

- 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 CLAS12 BSA paper
- Yu-Choi-Kong (**YCK**): **Regge** trajectories, including tensor meson $a_2(1320)$ and axial mesons a_1 and $b_1(1235)$, with pion pole contributions.
  YCK are co-authors on this paper.
  YCK1: nucleon EMFFs mediated by GPDs
  YCK2: nucleon EMFFs use dipole parametrization

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

Beam Polarization

- CEBAF produces polarized beam up to 12 GeV
- Polarization flipped at 30 Hz in a pseudo-random sequence
- Mott polarimeter at injector gives source polarization: $90 \pm 1\%$
- Spin precession calculation shows Hall C receives 99% of the source polarization
- Final value $P = 89^{+1}_{-3}\%$: Uncertainty from the beam energy uncertainty (3.6 MeV) and the range of possible linac energy imbalance

Thanks to Steve Wood for polarization calculations and Dave Gaskell for uncertainty estimate