

GPD Factorization in Pion Electroproduction: PionLT

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June 23 2026

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Motivation

The PionLT experiment took data at JLab Hall C from 2019 - 2022
 Want to better understand Hadron structure (Thus the Strong Force)

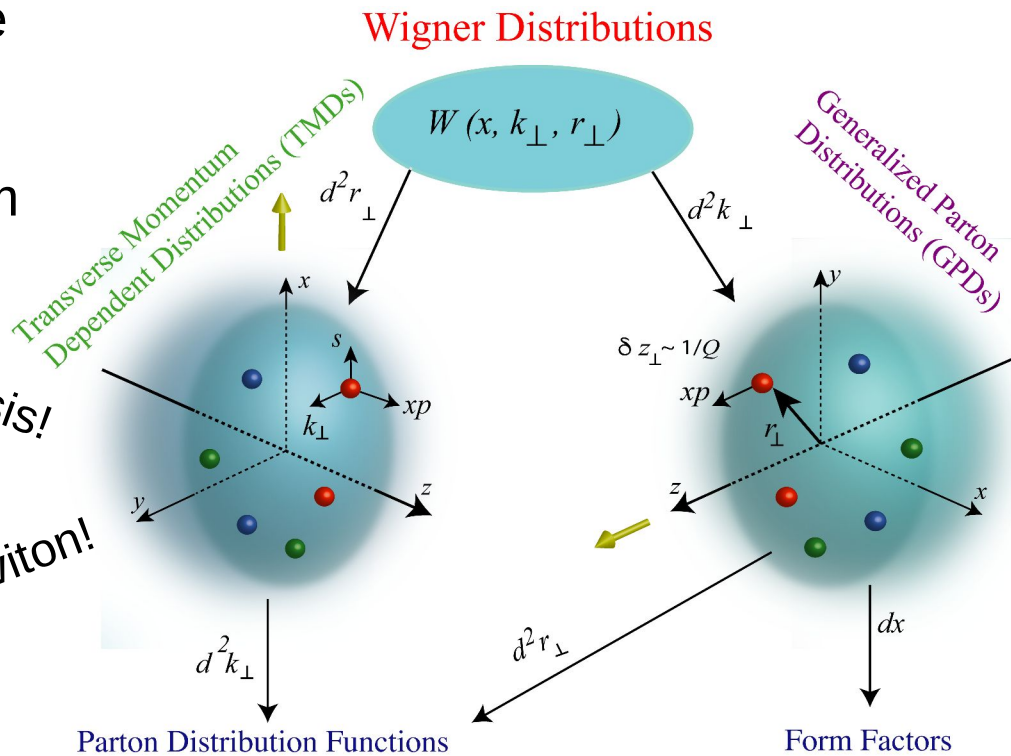
Generalized Parton Distributions (GPDs) are the next step in proton structure.

GPDs encode quark position and momentum

Useful for:

- Quark orbital angular momentum
- Pressure/sheer distribution in proton
- Mass radius of proton

Solve Spin Crisis!
 Otherwise need Graviton!



GPDs and Experiment

GPDs are universal quantities and reflect nucleon structure independent of reaction

- There are 2 main methods to extract the chirality conserving GPDs:

- **Deeply Virtual Compton Scattering (DVCS)**

- Sensitive to all 4

$H^{q,g}(x, \xi, t)$
spin avg
no hel. flip

$E^{q,g}(x, \xi, t)$
spin avg
helicity flip

- **Deep Exclusive Meson Production (DEMP)**

- Pseudoscalar mesons access $\tilde{H} \tilde{E}$

- Vector mesons access $H E$

$\tilde{H}^{q,g}(x, \xi, t)$
spin diff
no hel. flip

$\tilde{E}^{q,g}(x, \xi, t)$
spin diff
helicity flip

The combination of the 2 methods is needed to disentangle the different GPDs

Accessing GPDs with meson production

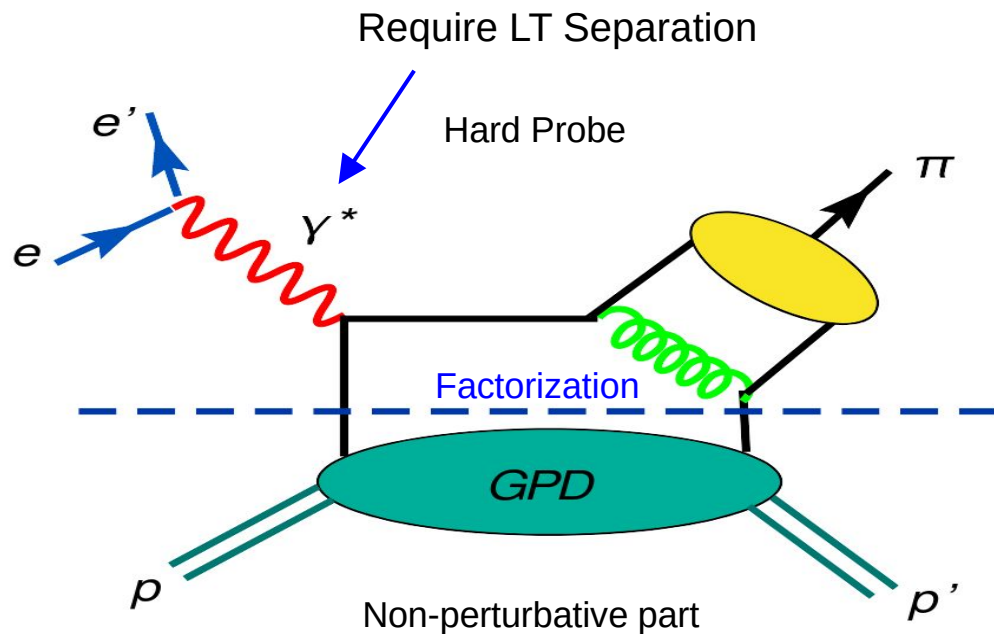
Using a recently proven factorization theorem to separate the process amplitude into two parts:

- A hard scattering process
 - perturbative QCD can be used.
- A non-perturbative part, parameterized by the GPDs

This is shown by the “Handbag Diagram”

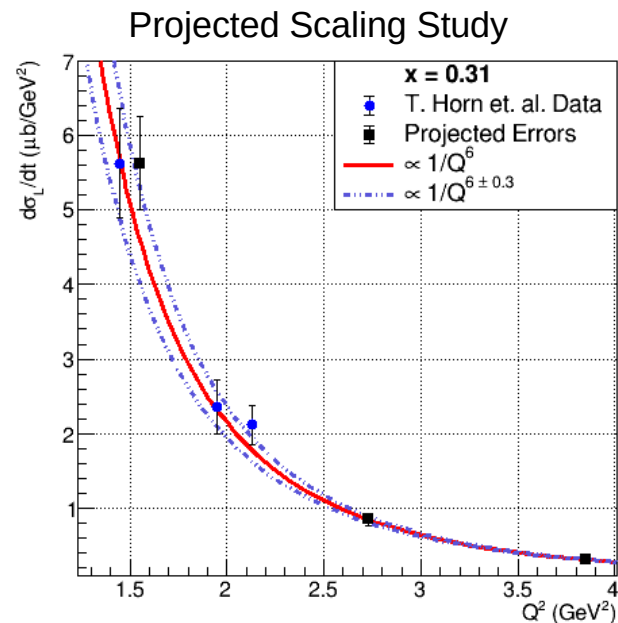
This applies to longitudinally polarized γ^* at sufficiently high Q^2

- First shown by Collins, Frankfurt & Strikman [PRD 56(1997)2982].



Tests for Factorization

- Factorization regime will have characteristic $1/Q^6$ scaling of σ_L with fixed x_B
- It should also have $\sigma_L \gg \sigma_T$
- Model independent test by extracting σ_L to see where this dependence begins
- This experiment does this for pion final state at 3 values of x_B :
 $x_B = 0.31, 0.39, 0.55$
- If in regime then this data can be used to extract GPDs, otherwise all results in this Q^2 thrown into question
- Previous studies inconclusive (T. Horn et. al. 2008), both predictions need to be met to be conclusive



x_B - Bjorken scaling variable, and represents longitudinal momentum fraction

JLab/Hall C

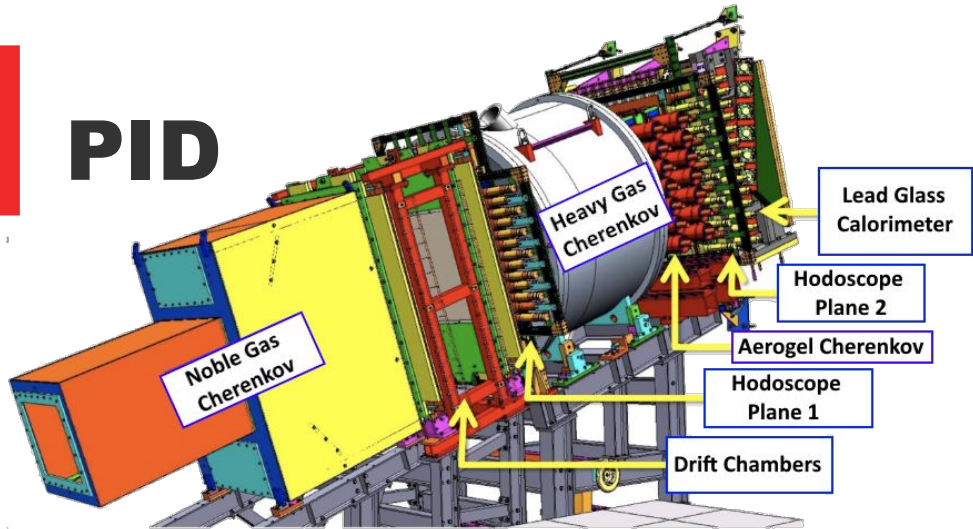
Experiment Conducted at JLab Hall C

Pushed the Lab's capabilities

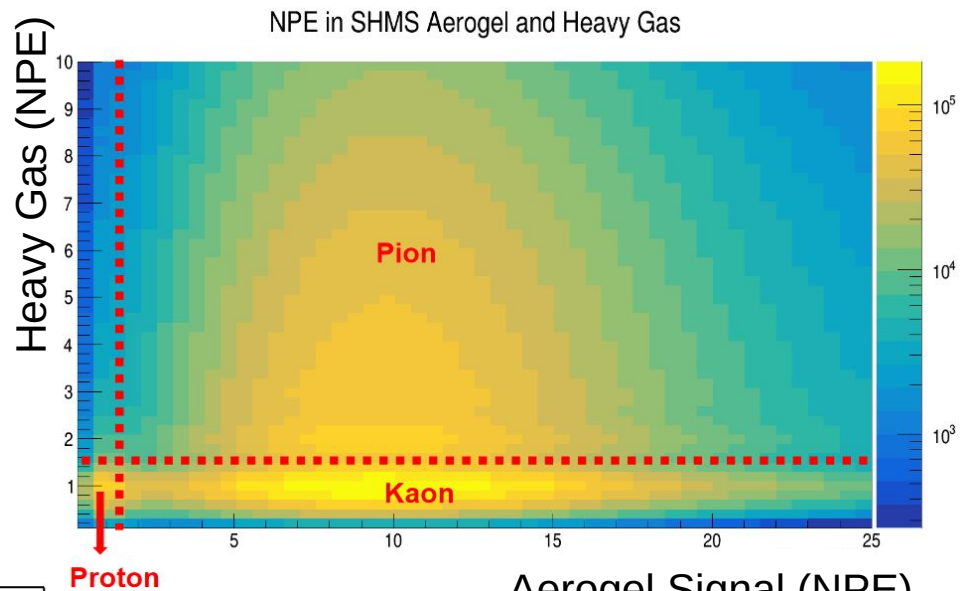
- SHMS rotated to 5.5 degrees from beamline
- Used high energy beam (up to 10.6GeV)
- Used high current polarized electrons (70uA)



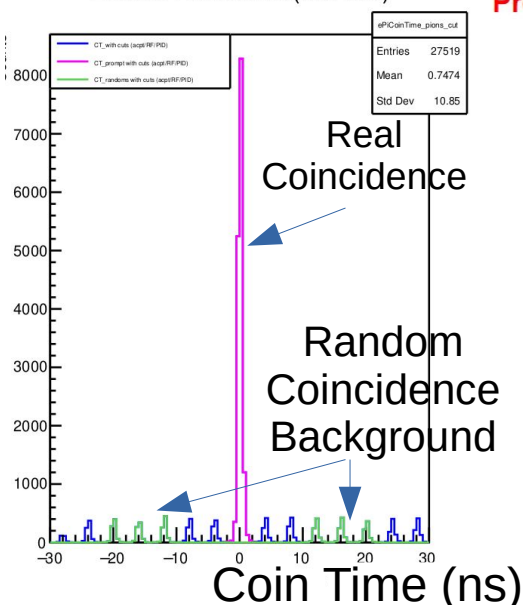
PID



SHMS Detector Stack

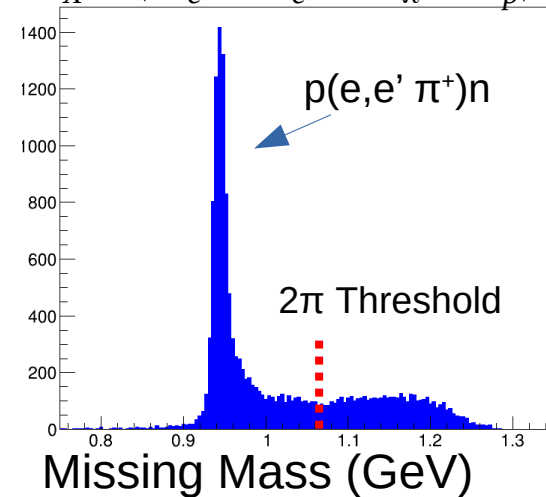


Electron-Pion CTime (with cuts)



Aerogel Signal (NPE)

$$m_X^2 = (E_e - E_{e'} - E_\pi + E_p)^2 - P_X^2$$



Use Cherenkovs, Calorimeters, and the HMS/SHMS coincidence time to select $p(e, e' \pi) X$

Then Missing Mass to select desired $p(e, e' \pi) n$ final state

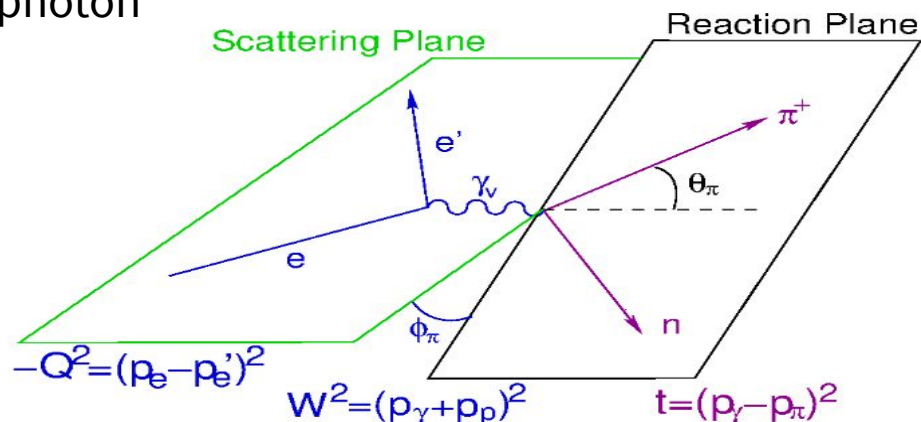
LT Separation

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

- To extract components of cross section based on virtual photon polarization, fit the above equation.
- To do this need to have full ϕ coverage and 2 values of ε while keeping Q^2 , W , and t fixed.
- To get 2 values of ε we need data from 2 different beam energies.

This means different background and physics rates

For GPD factorization we want σ_L corresponds to longitudinally polarized γ



Virtual-photon polarization:

$$\varepsilon = \left(1 + 2 \frac{(E_e - E_{e'})^2 + Q^2}{Q^2} \tan^2 \frac{\theta_{e'}}{2} \right)^{-1}$$

LT Sep – In detail

Each iteration is actually a multi-step process

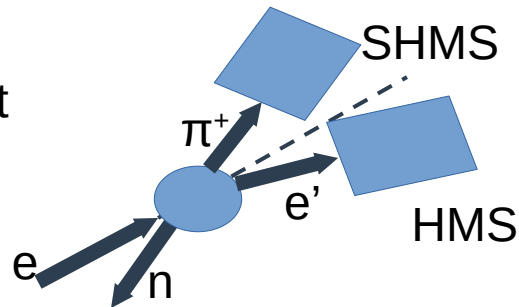
1. Choose functional form of $\sigma_T, \sigma_L, \sigma_{LT}, \sigma_{TT}$
 Arbitrary functions to fit Q^2, W variance across bin

2. Combine SHMS left, right, and centre
 Done because we need to have to get full coverage in ϕ at fixed $-t$

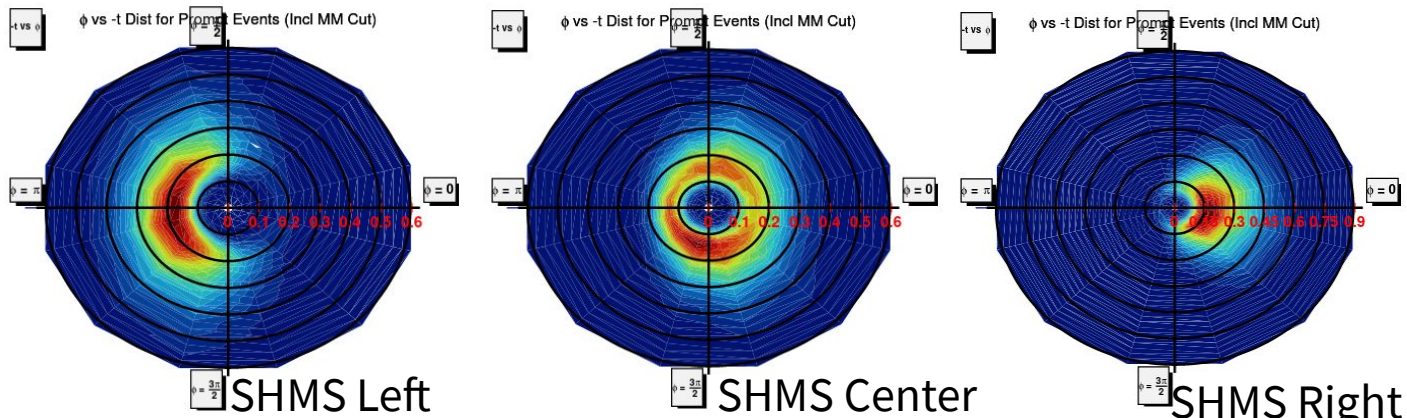
Fit parameters

$$\sigma_L = (A + B * \log(Q^2)) e^{-|t|(C + D * \log(Q^2))}$$

Example From F π -2 Experiment



Rotate SHMS to get ϕ coverage

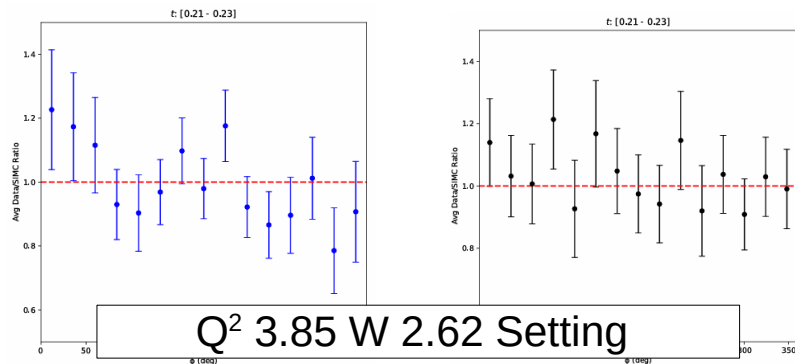


Example $-t$ vrs ϕ polar plots from setting: $Q^2=3.85, W=3.07, \text{high } \epsilon$

LT Sep – In detail

3. Bin in $-t$ and ϕ , calculate average W , Q^2 , θ , and ϵ
final value reported at average value in bin

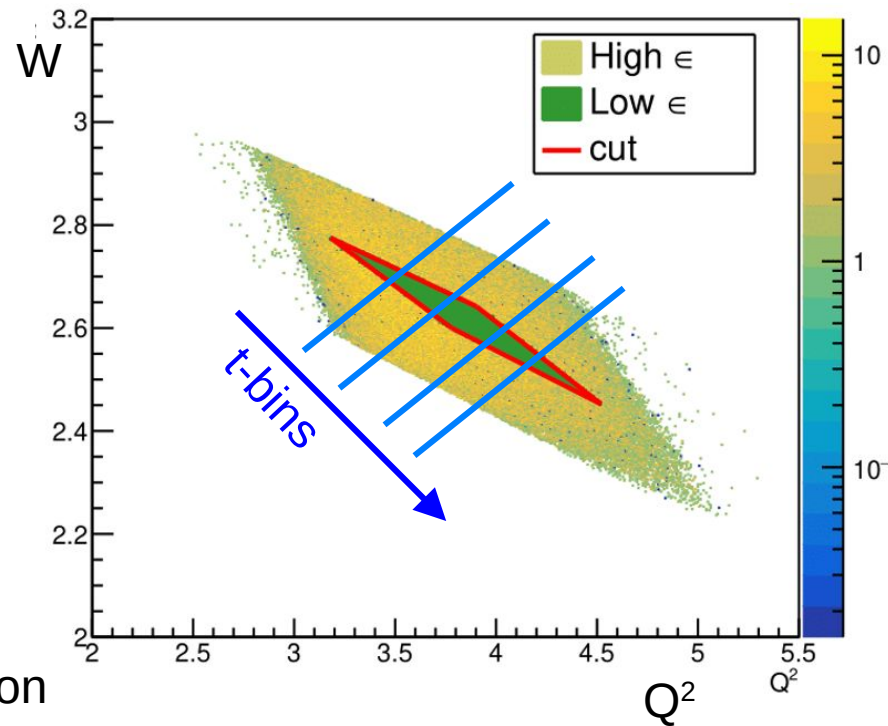
4. Calculate MC to Data ratio in all bins



5. Use Monte Carlo to calculate unseparated cross section using equation:

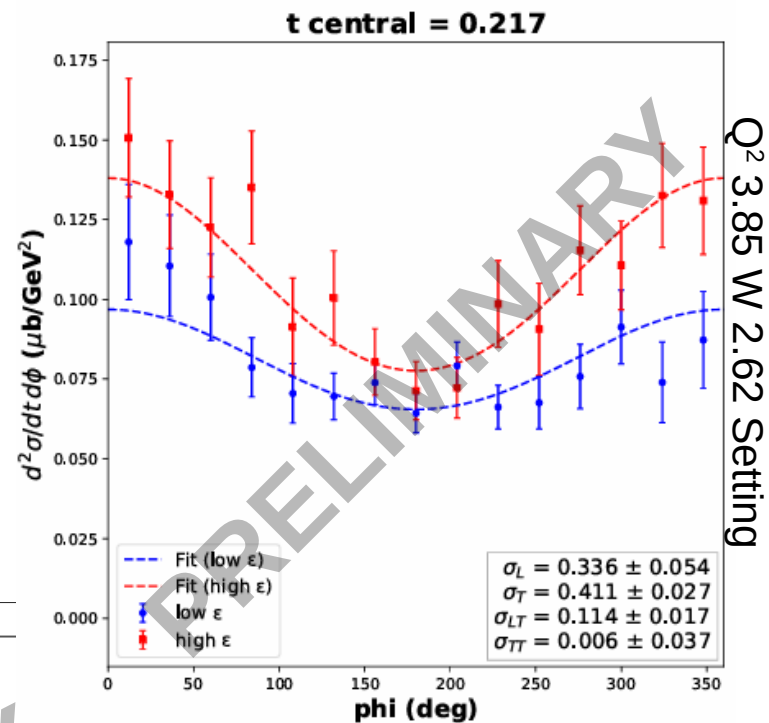
$$\sigma_{\text{exp}}(\bar{W}, \bar{Q}^2, t, \phi; \bar{\theta}, \bar{\epsilon}) = \frac{\langle Y_{\text{exp}} \rangle}{\langle Y_{\text{sim}} \rangle} \sigma_{\text{MC}}(\bar{W}, \bar{Q}^2, t, \phi; \bar{\theta}, \bar{\epsilon})$$

“Diamond plot” from Q^2 3.85 W 2.62 Setting

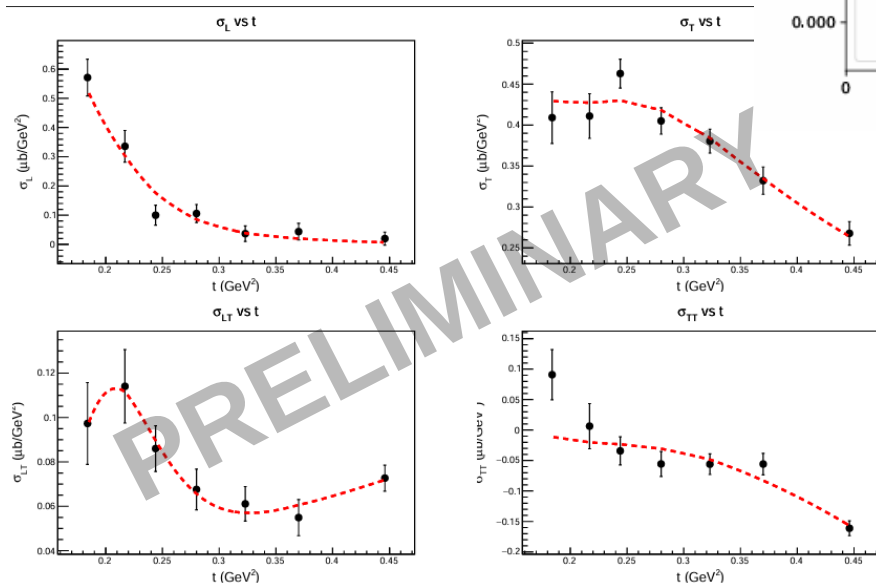


LT Sep – In detail

6. Fit Rosenbluth equation extract values of σ_T , σ_L , σ_{LT} , σ_{TT}



7. Fit the functional forms to your new values of σ_T , σ_L , σ_{LT} , σ_{TT}



Done when variation in σ_{exp} between iterations is less than 1%,
And data to MC ratios ~ 1

LT Separation Overview

Bin data and calculate MC to data ratio

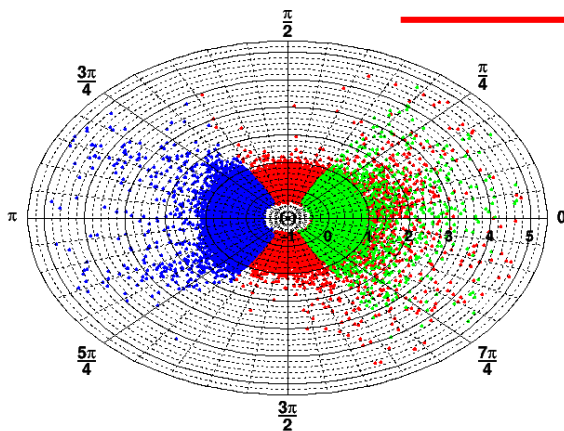
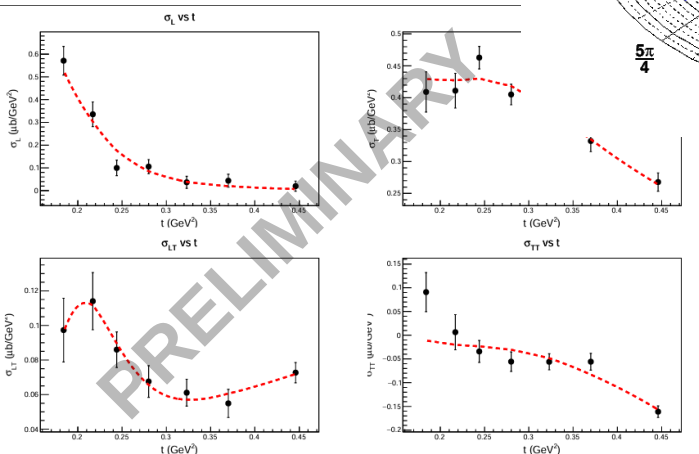
Calculate Unseparated Cross Sections

$$\sigma_{\text{exp}}(\bar{W}, \bar{Q}^2, t, \phi; \bar{\theta}, \bar{\epsilon}) = \frac{\langle Y_{\text{exp}} \rangle}{\langle Y_{\text{sim}} \rangle} \sigma_{\text{MC}}(\bar{W}, \bar{Q}^2, t, \phi; \bar{\theta}, \bar{\epsilon})$$

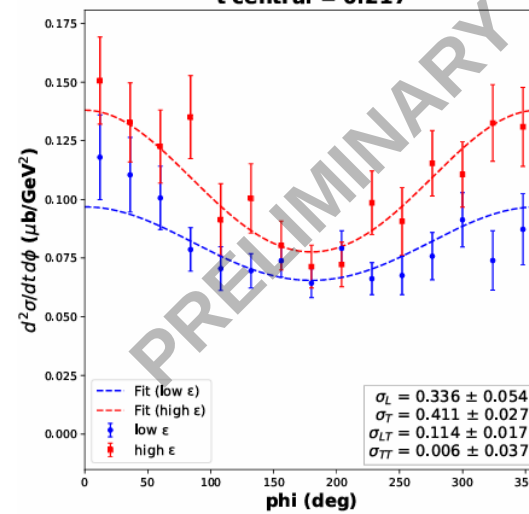
Fit Rosenbluth Equation

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

t central = 0.217



Repeat until self consistent



Summary

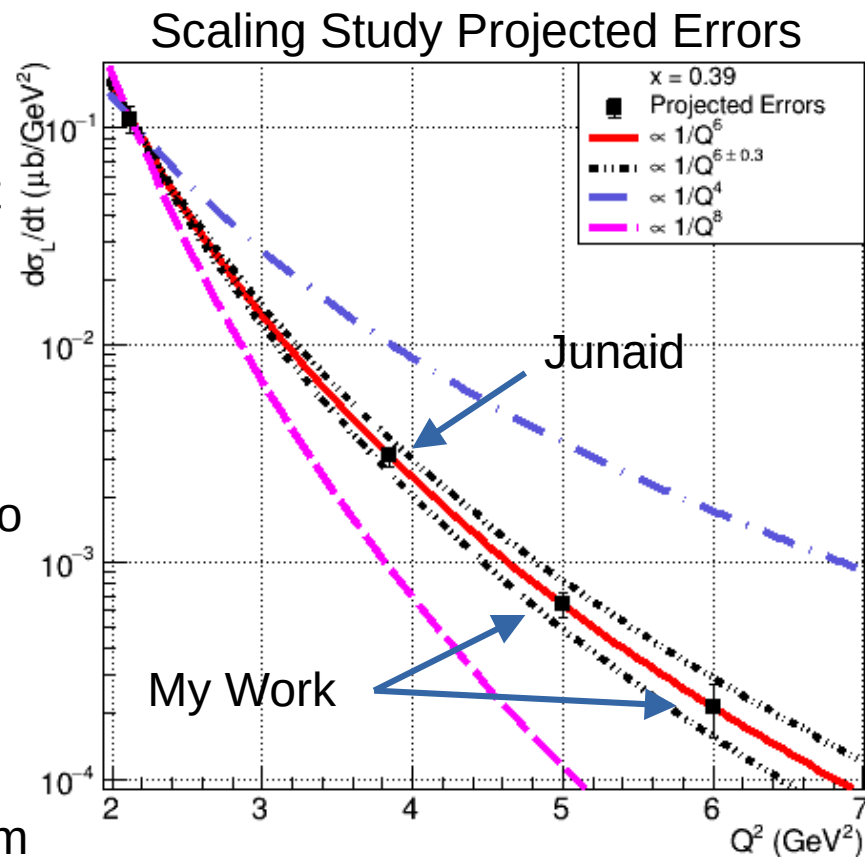
PionLT has begun to LT separate Cross Sections.

PionLT has data to test for hard soft factorization at 3 values of Broken x

The extraction 3 of 4 points for the $x = 0.39$ scan have begun.

This work will tell whether Jefferson lab can begin to extract Generalized Parton Distributions (GPDs) with current Data

I will graduate in Winter 2027, Expect first publication shortly after with first scan. Other 2 scans published later along with 7 more papers from PionLT data set.



Thank You

PionLT Working Group:

G. Huber, M. Junaid, A. Postuma, T. Horn, P. Markowitz, S. Kay,
V. Kumar, R. Trotta, J. Roche, D. Gaskell, P. Bosted, K. Aniol, A.
Hamdi, I. Niculescu, C. K. Tam, S. Jain, N. Sadoun, G. Niculescu,
D. Gaskell, K. Ramage, B. McKinnon, R. Montgomery, D.
Yadlowski



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Questions?

NSERC grant:
SAPIN-2026-00043



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Thomas Jefferson National Accelerator Facility

Solving the Spin Crisis

GPDs are related to the orbital angular momentum of the quarks and gluons:

Christine A. Aidala, Steven D. Bass, Delia Hasch, and Gerhard K. Mallot. The spin structure of the nucleon. Rev. Mod. Phys. 85, 655 – Published 12 April, 2013 <https://doi.org/10.1103/RevModPhys.85.655>

$$\frac{1}{2} = \frac{1}{2} \sum_q \Delta q + \Delta g + L_q + L_g$$

In the forward limit the GPDs H and \tilde{H} are related to the parton distributions studied in deep inelastic scattering

$$\begin{aligned} H(x, \xi, t)|_{\xi=t=0} &= q(x) \\ \tilde{H}(x, \xi, t)|_{\xi=t=0} &= \Delta q(x) \end{aligned} \quad (30)$$

GPDs contain vital information about quark total angular momentum in the nucleon. Ji's sum-rule (Ji, 1997b) relates J_q to the forward limit of the second moment in x of the spin-independent quark GPDs

$$J_q = \frac{1}{2} \int_{-1}^{+1} dx x \left[H^q(x, \xi, t=0) + E^q(x, \xi, t=0) \right]. \quad (32)$$

The gluon “total angular momentum” could then be obtained through the equation

$$\sum_q J_q + J_g = \frac{1}{2}. \quad (33)$$

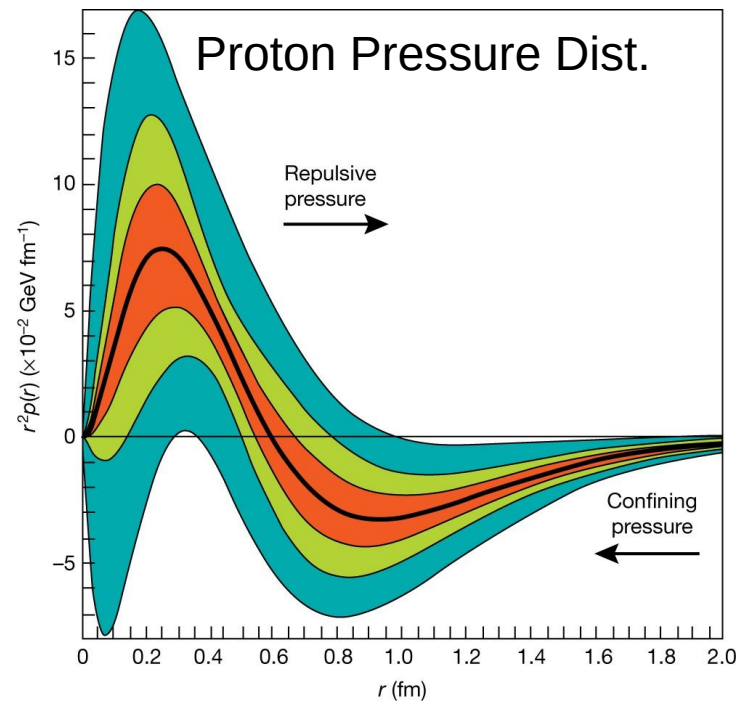
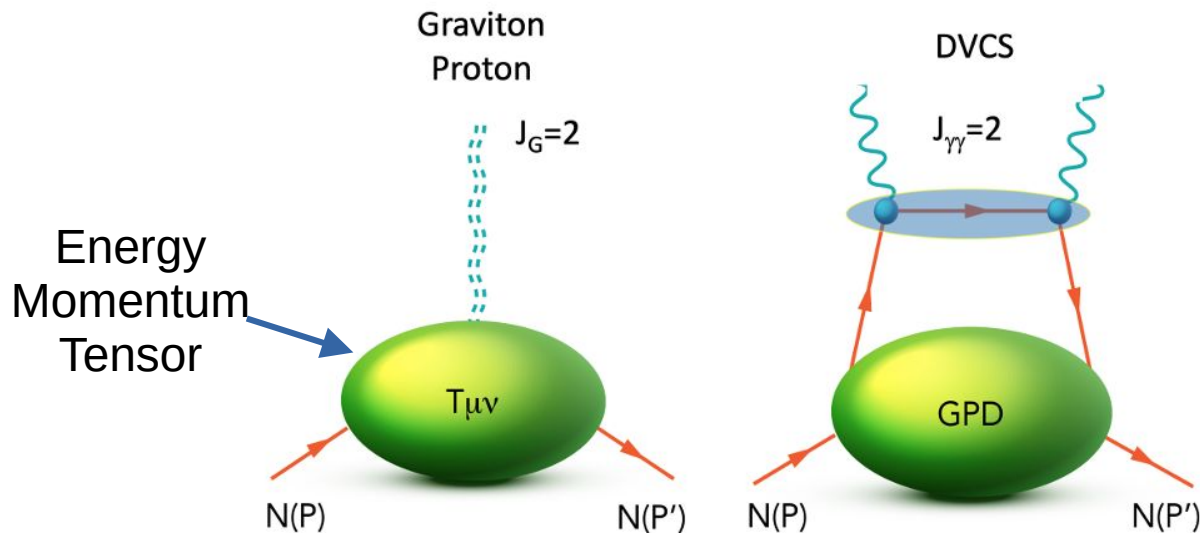
Pressure/Mass distribution

Recent papers show equivalence between hypothetical graviton-proton scattering and DVCS interaction:

Burkert, V.D., Elouadrhiri, L. & Girod, F.X. The pressure distribution inside the proton. Nature 557, 396–399 (2018). <https://doi.org/10.1038/s41586-018-0060-z>

V.D. Burkert, L. Elouadrhiri, F.X. Girod. The mechanical radius of the proton arXiv:2310.11568

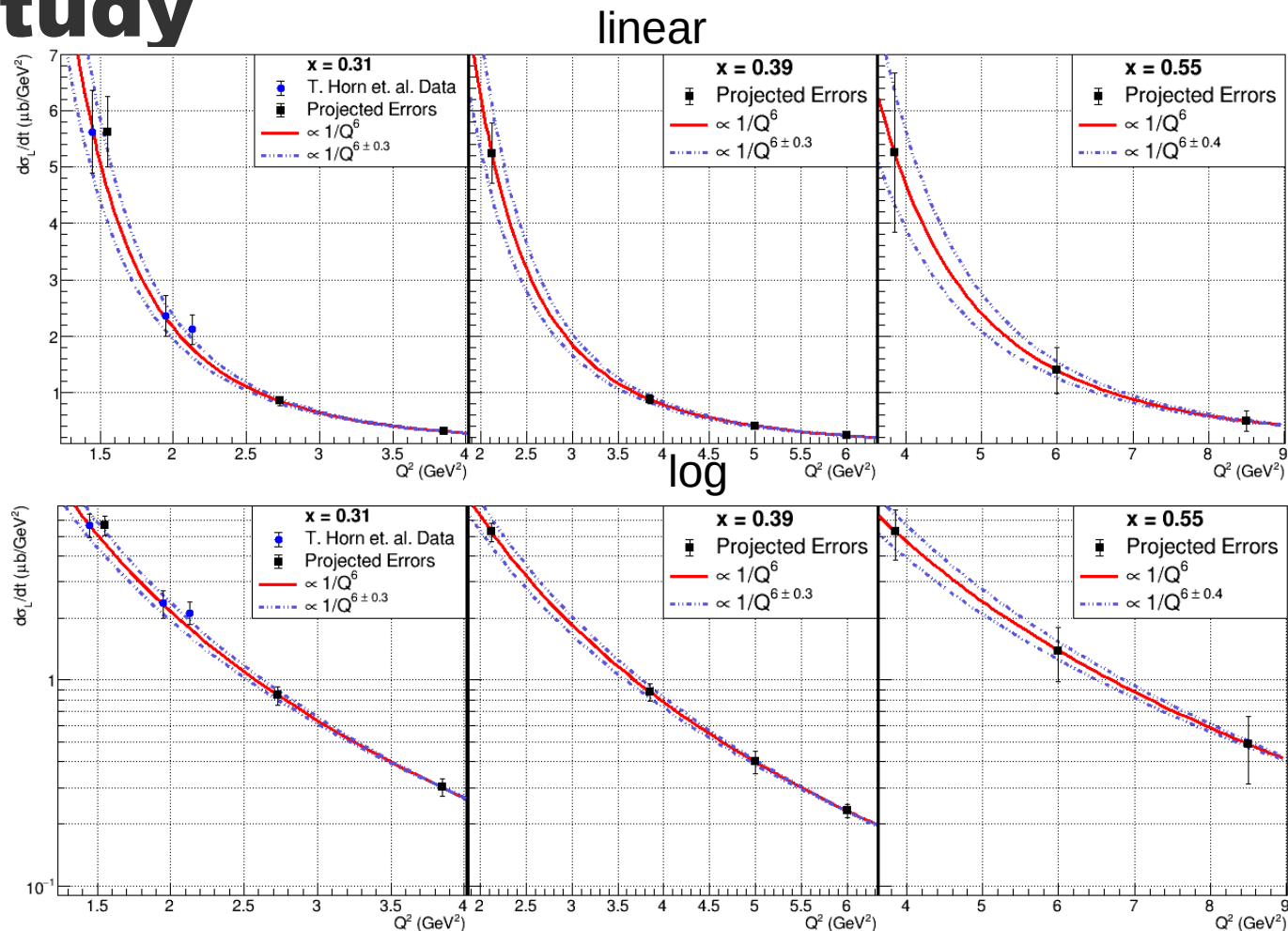
Allows extraction of Pressure, shear, and mass distribution from GPDs



Scaling study

Factorization regime will have characteristic $1/Q^6$ scaling of σ_L with fixed x_B

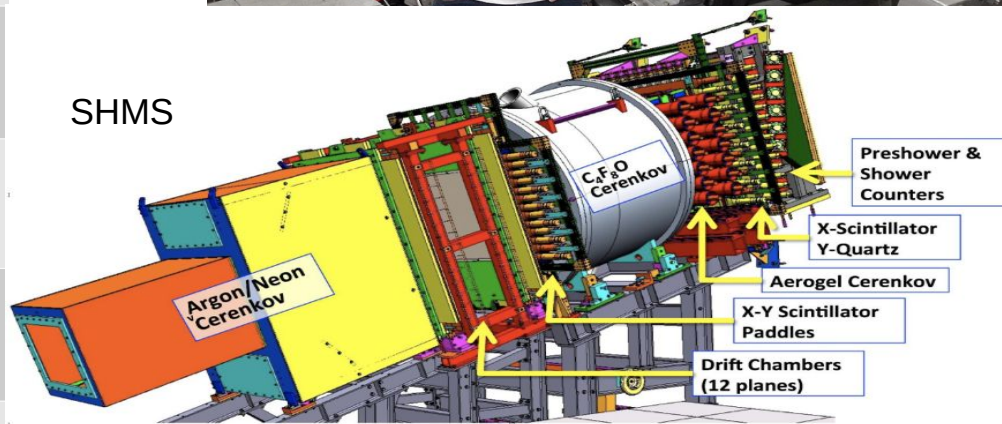
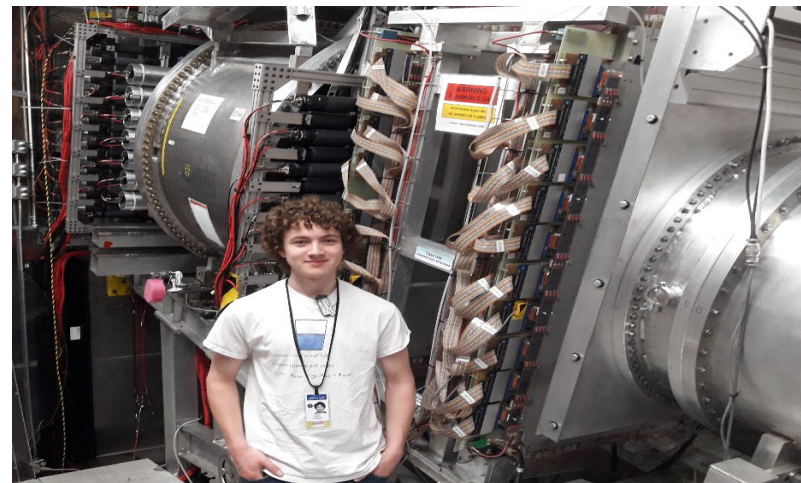
It should also have $\sigma_L \gg \sigma_T$



Detector Stack

Both the Spectrometers have a detector stack in their focal plane. Which give high momentum resolution and particle Identification

Detector	Purpose	Notes
Aerogel Cerenkov	Particle ID, K^+ / p discrimination	$n = 1.011, 1.015, 1.03, 1.05$
Heavy Gas Cerenkov (HGC)	Particle ID, Trigger, π^\pm/K^\pm discrimination	C_4F_{10} –Vary pressure to set n at K^\pm threshold
Noble Gas Cerenkov	Particle ID, Trigger. e^+/π^+ at high momentum	Only in SHMS
Hodoscopes	Trigger, Time reference, Measure β	
Drift Chambers	Momentum measurement, Tracking	5mm max. Drift, 300 micron resolution
Preshower and Shower Counters (Calorimeters)	Particle ID, Trigger, e^\pm Tagging	



Elastic Cross-section

Elastic Cross section is used to check systematic uncertainties

Studies this is used for:

- Spectrometer Offsets
- Target Boiling
- Detector rate dependence
- Tracking efficiency

Roughly 1 month from finishing study

$p(e, e'p)$ Reaction

W Distribution

