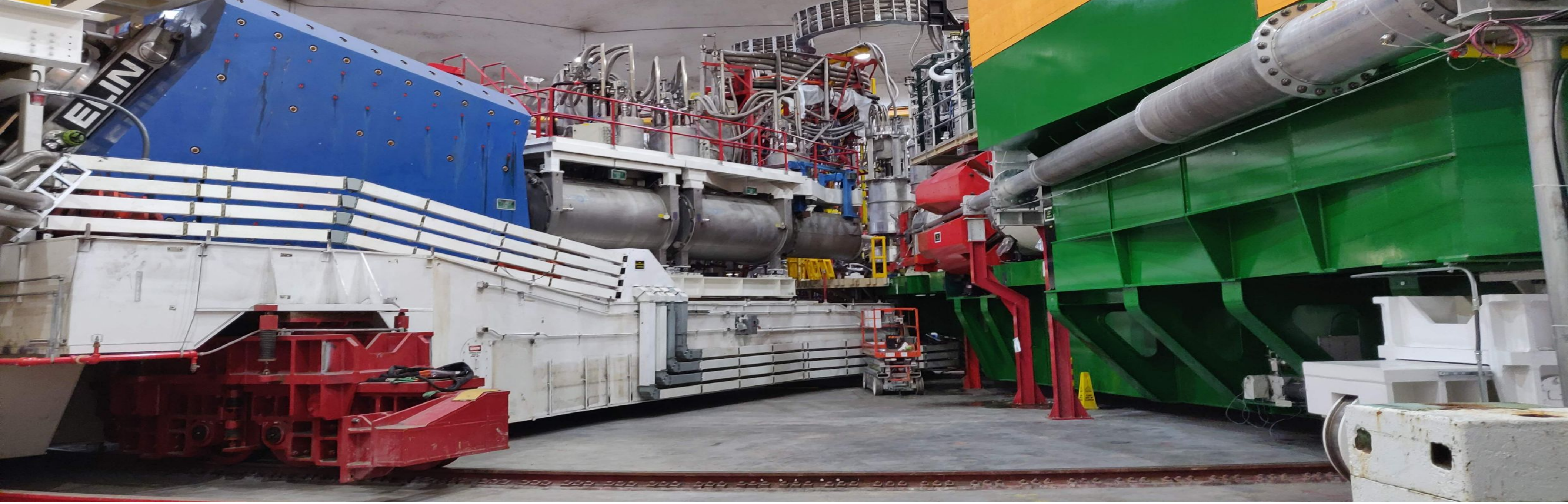


Update of PionLT DEMP Factorizability Studies

Nathan Heinrich
WNPPC 2025

Jefferson Lab
Thomas Jefferson National Accelerator Facility

University of Regina

Motivation

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

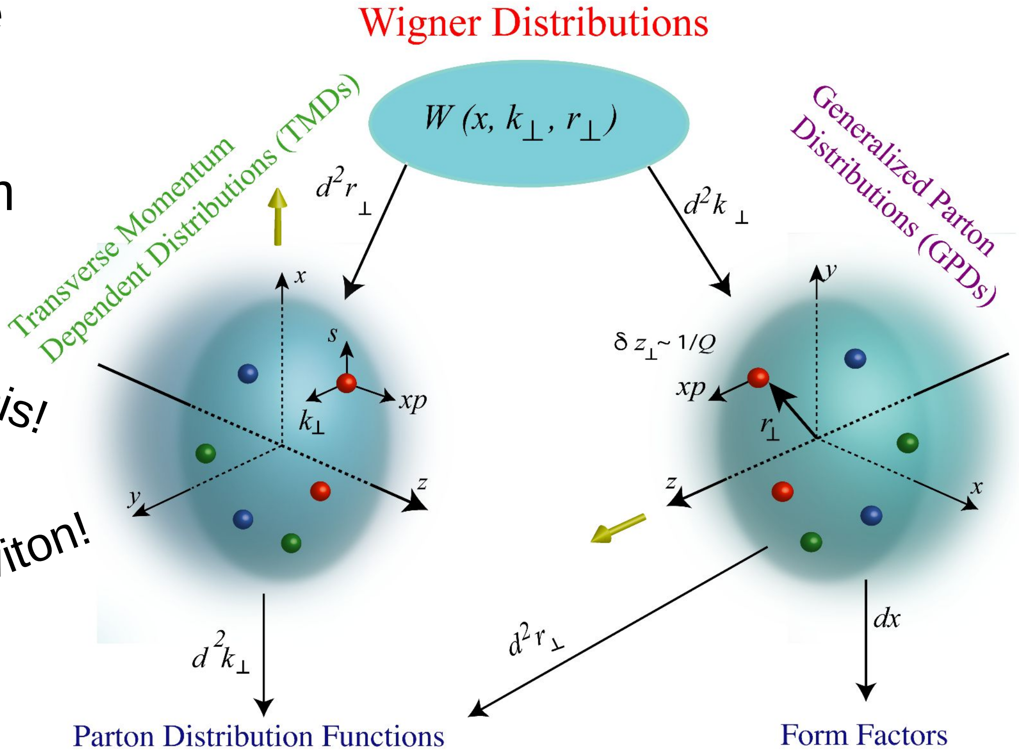
Generalized Parton Distributions (GPDs) are the next step in proton structure.

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:
  - **D**eeply **V**irtual **C**ompton **S**cattering (**DVCS**)
    - Sensitive to all 4
  - **D**eep **E**xclusive **M**eson **P**roduction (**DEMP**)
    - Pseudoscalar mesons access $\widetilde{H}$ $\widetilde{E}$
    - Vector mesons access H E

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

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

Accessing GPDs with meson production

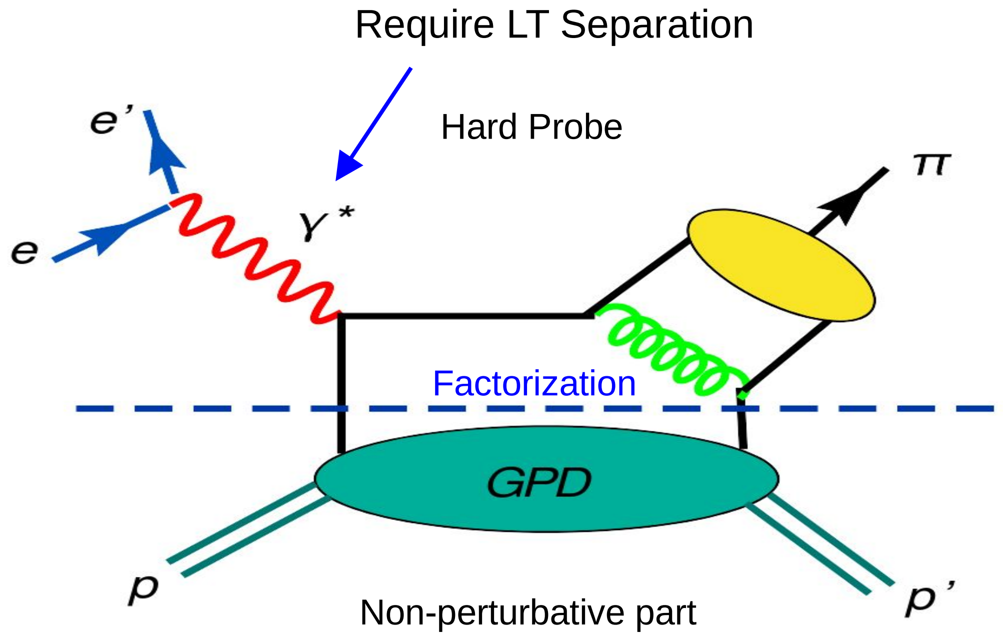
Using a recently proven factorization theorem to separate the process amplitude into two parts:

- 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].

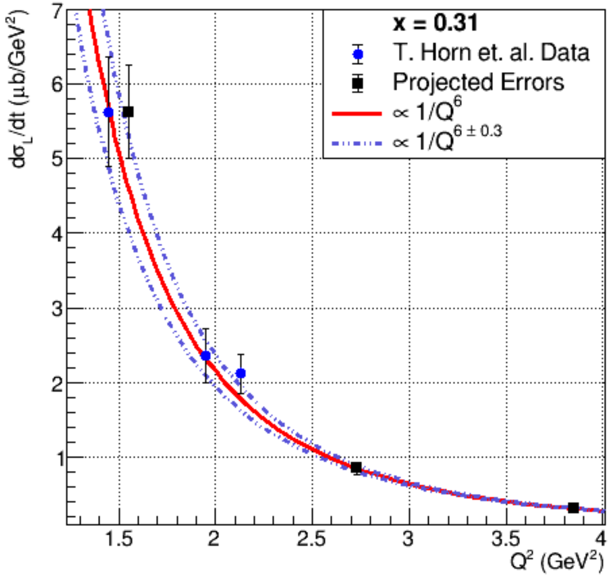


Factorizability

- Factorization regime will have characteristic $1/Q^6$ scaling of σ_L with fixed x_B
  - It should also have $\sigma_L >> \sigma_T$
- 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

Projected Scaling Study



X_B - Bjorken scaling variable, and represents longitudinal momentum fraction

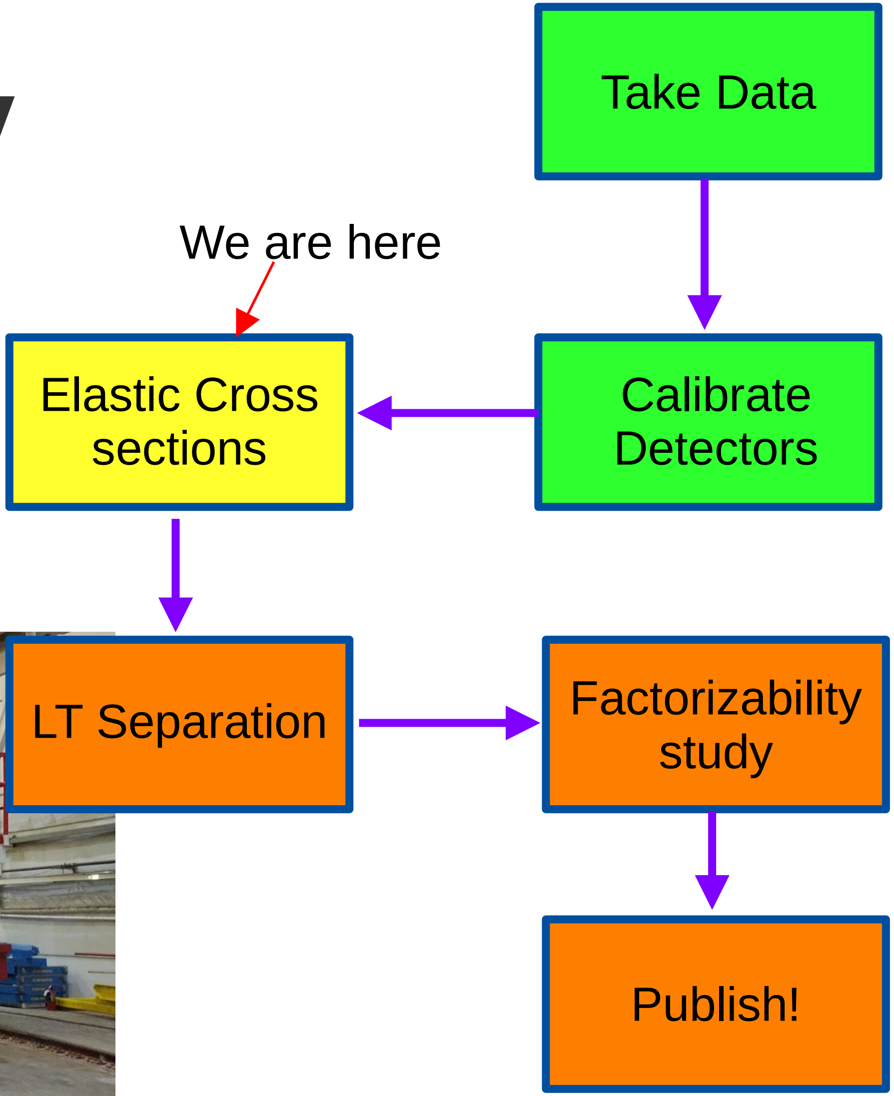
Analysis Overview

Took Data at Jefferson Lab Hall C in 2022

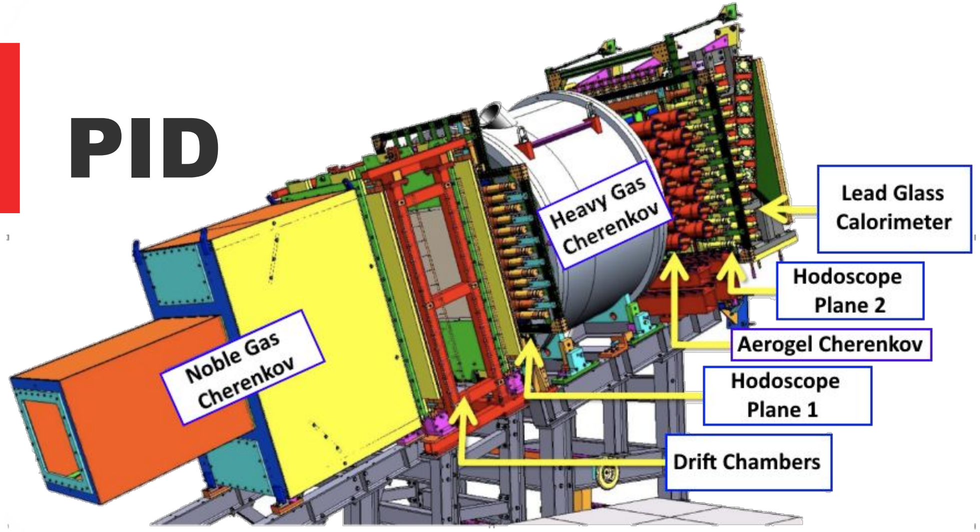
Finished Detector Calibrations

Working on Elastic Cross Sections,
-> Set our systematics

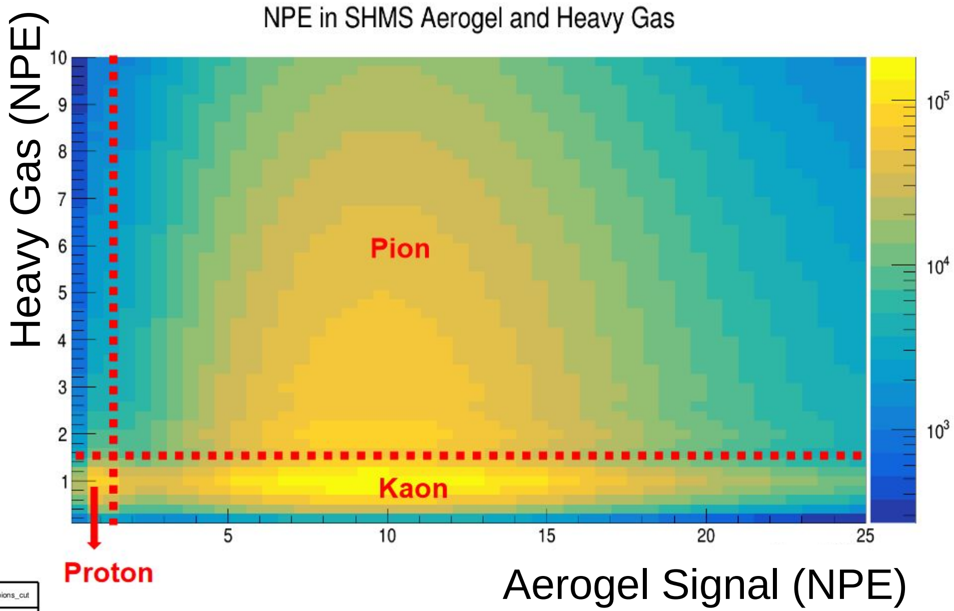
Move on to LT separations next

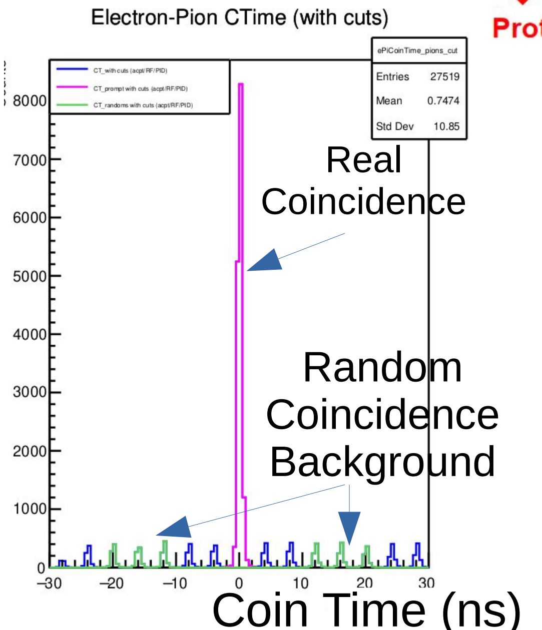


PID



SHMS Detector Stack

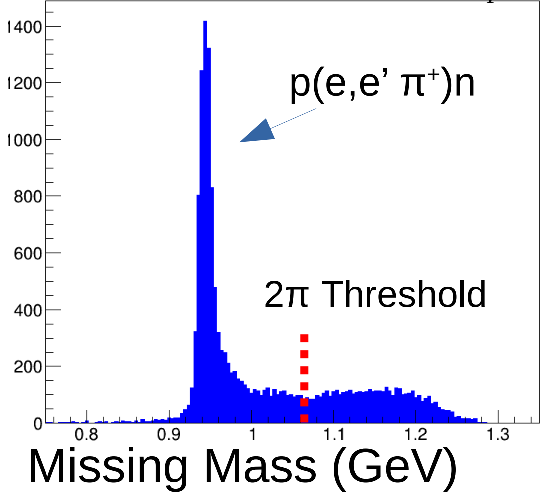




Use Cherenkovs, Calorimeters, and timing to select p(e,e'π)X

Then Missing Mass to select desired p(e,e'π)n final state

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



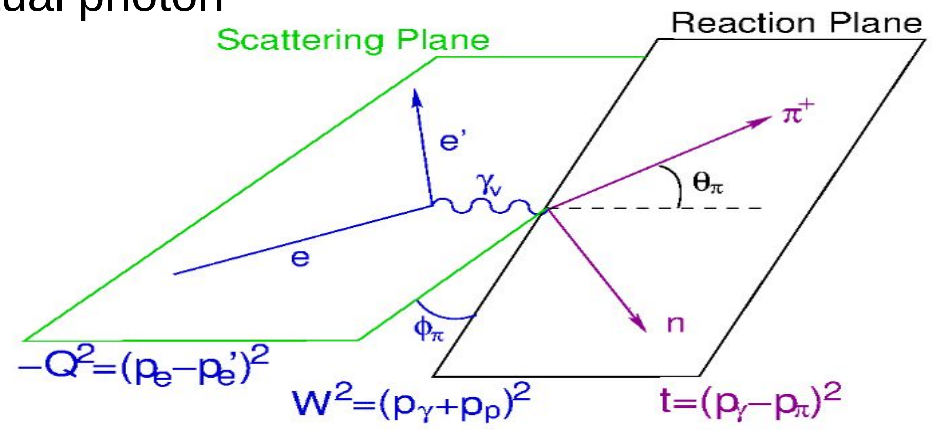
LT Separation - Simple

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

- 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

Fit parameters

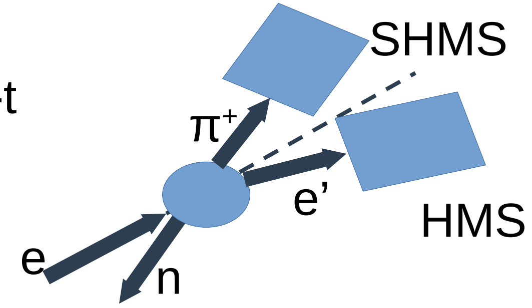
$$\sigma_L = \left(A + B * \log(Q^2)\right) e^{|t|(C + D * \log(Q^2))}$$

Example From Fπ-2 Experiment

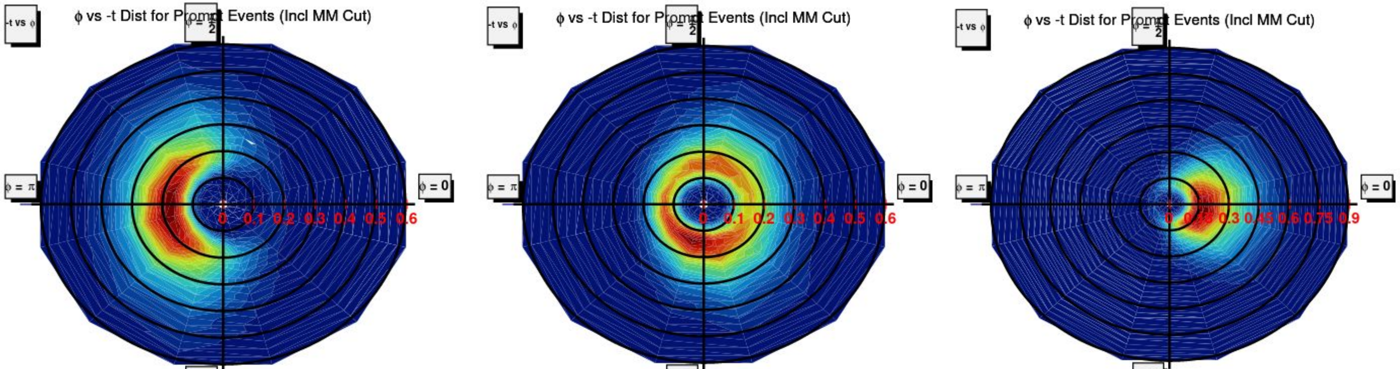
Each iteration is actually a multi-step process

1. Choose functional form of σ_T, σ_L, σ_{LT}, σ_{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



Rotate SHMS to get ϕ coverage



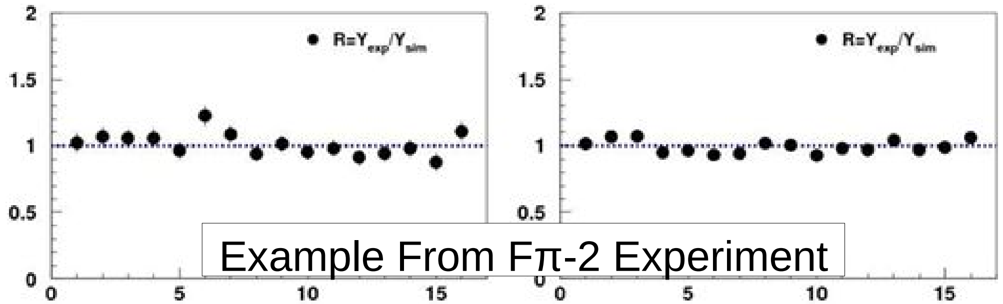
SHMS Left SHMS Center SHMS Right

Example -t vrs ϕ polar plots from setting: Q^2=3.85, W=3.07, high ε

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

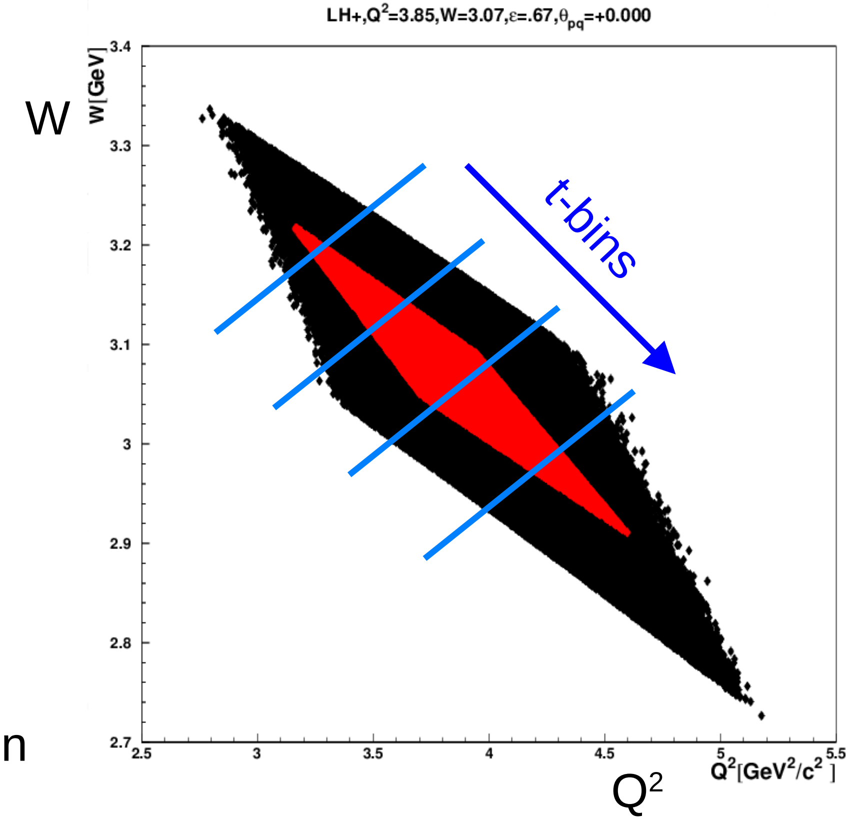
4. Calculate MC to Data ratio in all bins



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

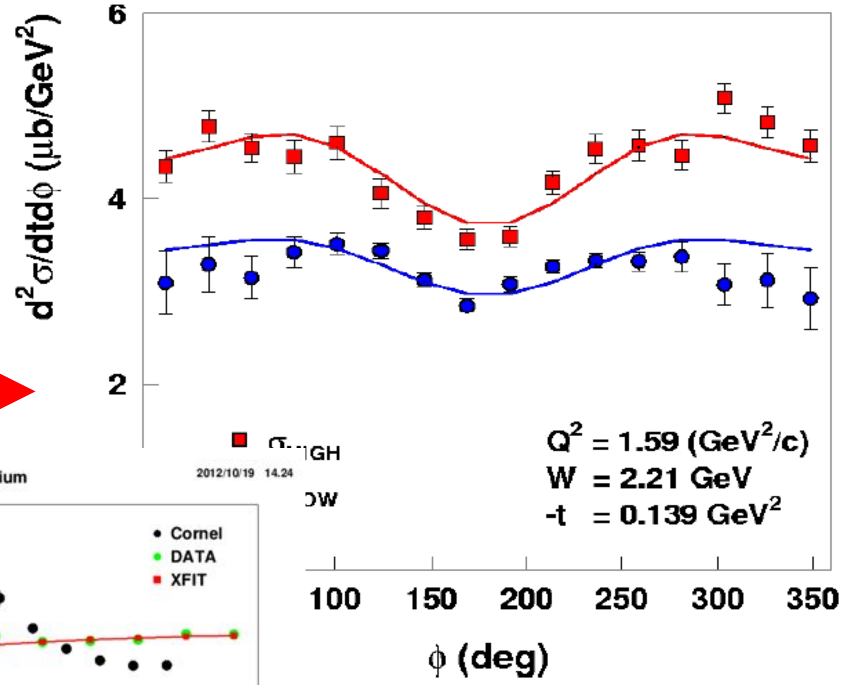
$$\sigma_{exp}(\bar{W},\bar{Q}^2,t,\phi;\bar{\theta},\bar{\epsilon})=\frac{\langle Y_{exp}\rangle}{\langle Y_{sim}\rangle}\sigma_{MC}(\bar{W},\bar{Q}^2,t,\phi;\bar{\theta},\bar{\epsilon})$$

Simulated Example "diamond plot"



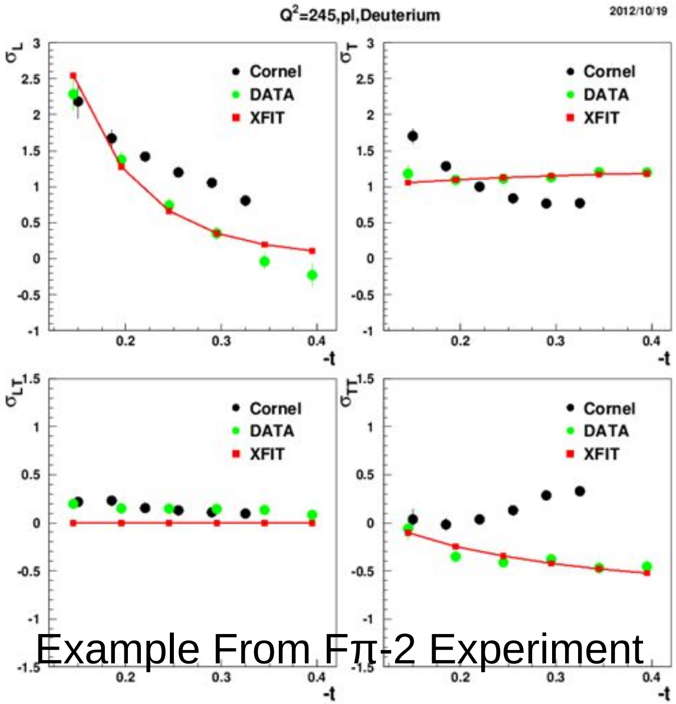
LT Sep – In detail

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



T. Horn, et al, PRL 97(2006) 192001

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

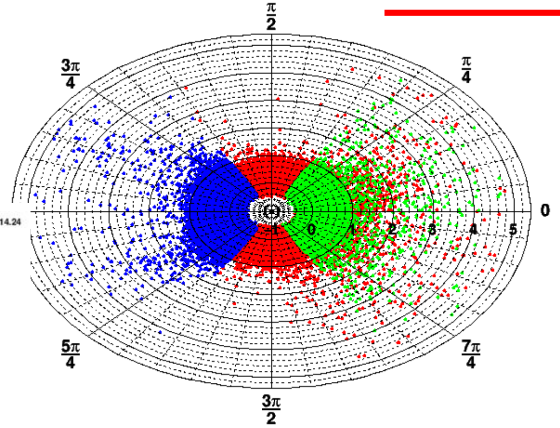


Example From Fπ-2 Experiment

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

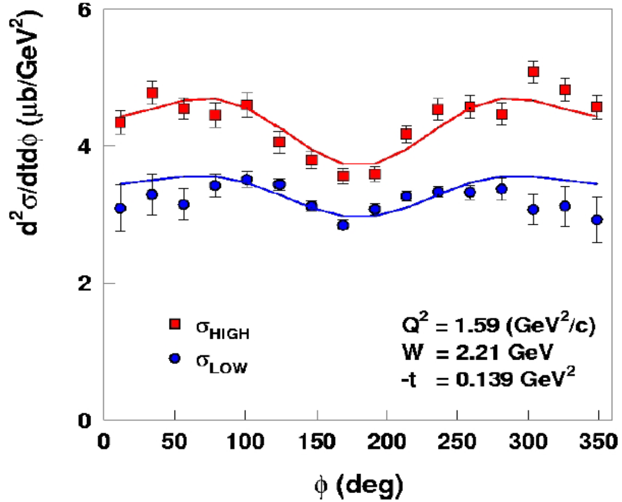


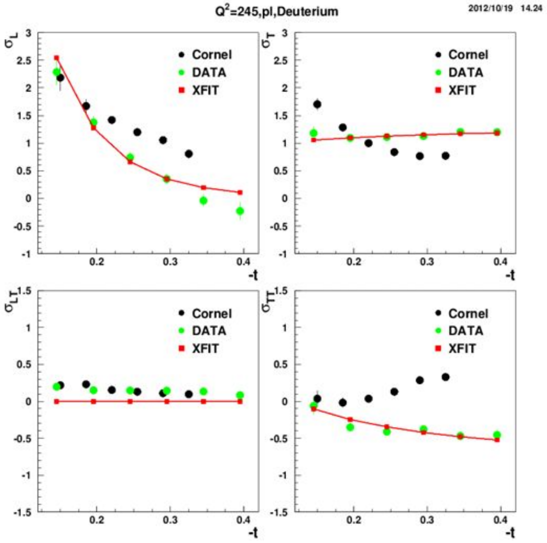
Calculate Unseparated Cross Sections

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

Fit Rosenbluth Equation

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





Repeat until self consistent

Fit arbitrary functions for σ_T, σ_L, σ_{LT}, σ_{TT}

Summary

The PionLT experiment is nearly ready to begin LT separation of cross-sections

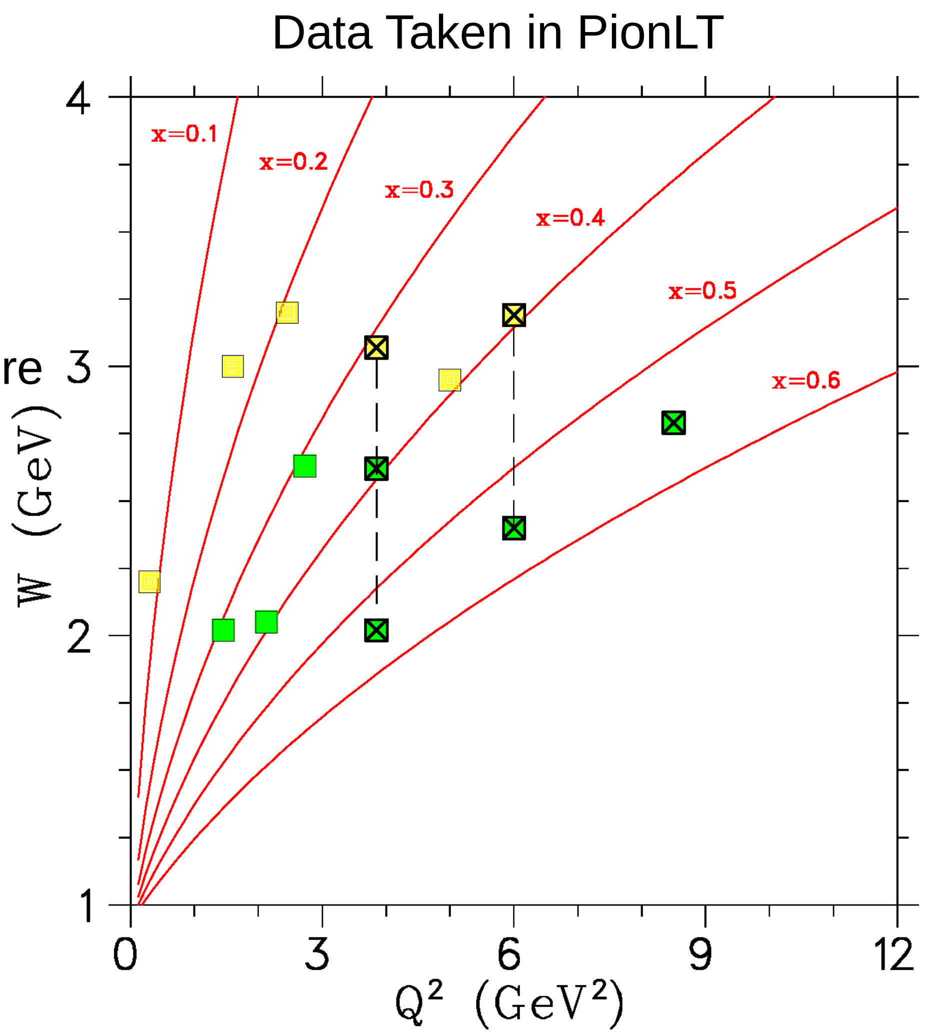
GPDs are the exciting new frontier of proton structure

LT Separations are crucial:

- Model independent check of factorization
  - Predict both $1/Q^6$ scaling of σ_L with fixed x_B and $\sigma_L >> \sigma_T$

- Allows access to GPD information

Expect multiple publications starting in December



Thank You

Questions?

NSERC grant:
SAPIN-2021-00026

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 $\widetilde{H}$ are related to the parton distributions studied in deep inelastic scattering

$$H(x,\xi,t)|_{\xi=t=0} = q(x)$$
$$\widetilde{H}(x,\xi,t)|_{\xi=t=0} = \Delta q(x) \qquad (30)$$

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

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

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

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

Pressure/Mass distribution

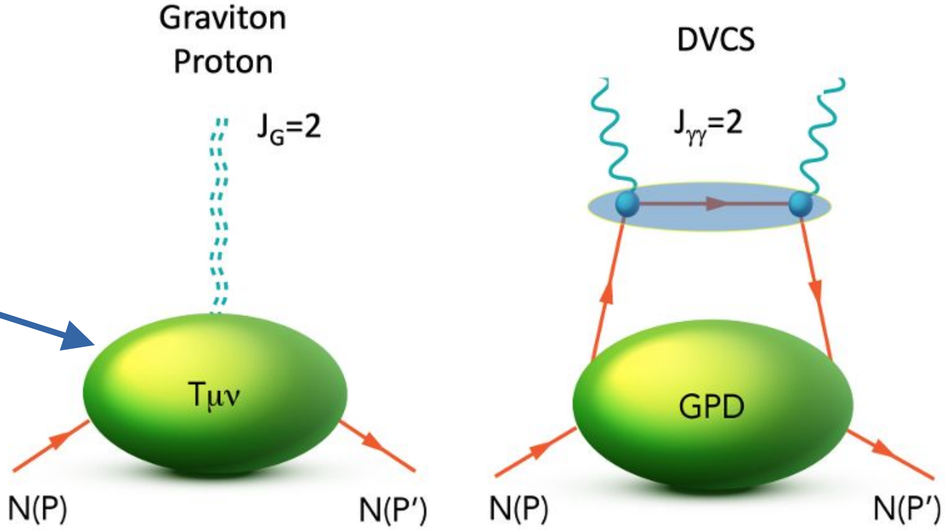
Recent papers show equivelence between hypothetical graviton-proton scattering and DVCS interaction:

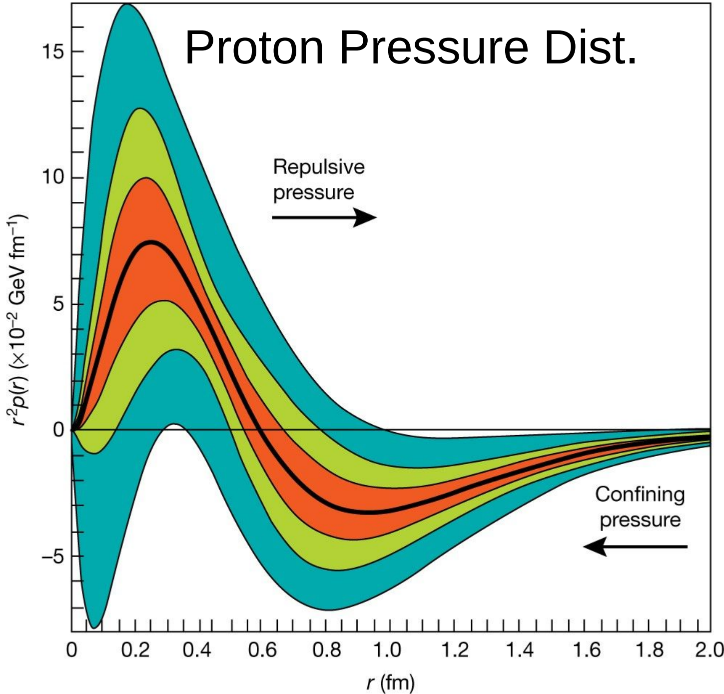
Burkert, V.D., Elouadrhiri, L. & Girod, F.X. The pressure distribution inside the proton. Nature 557, 396–399 (2018). https://doi.org/10.1038/s41586-018-0060-z

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

Energy Momentum Tensor

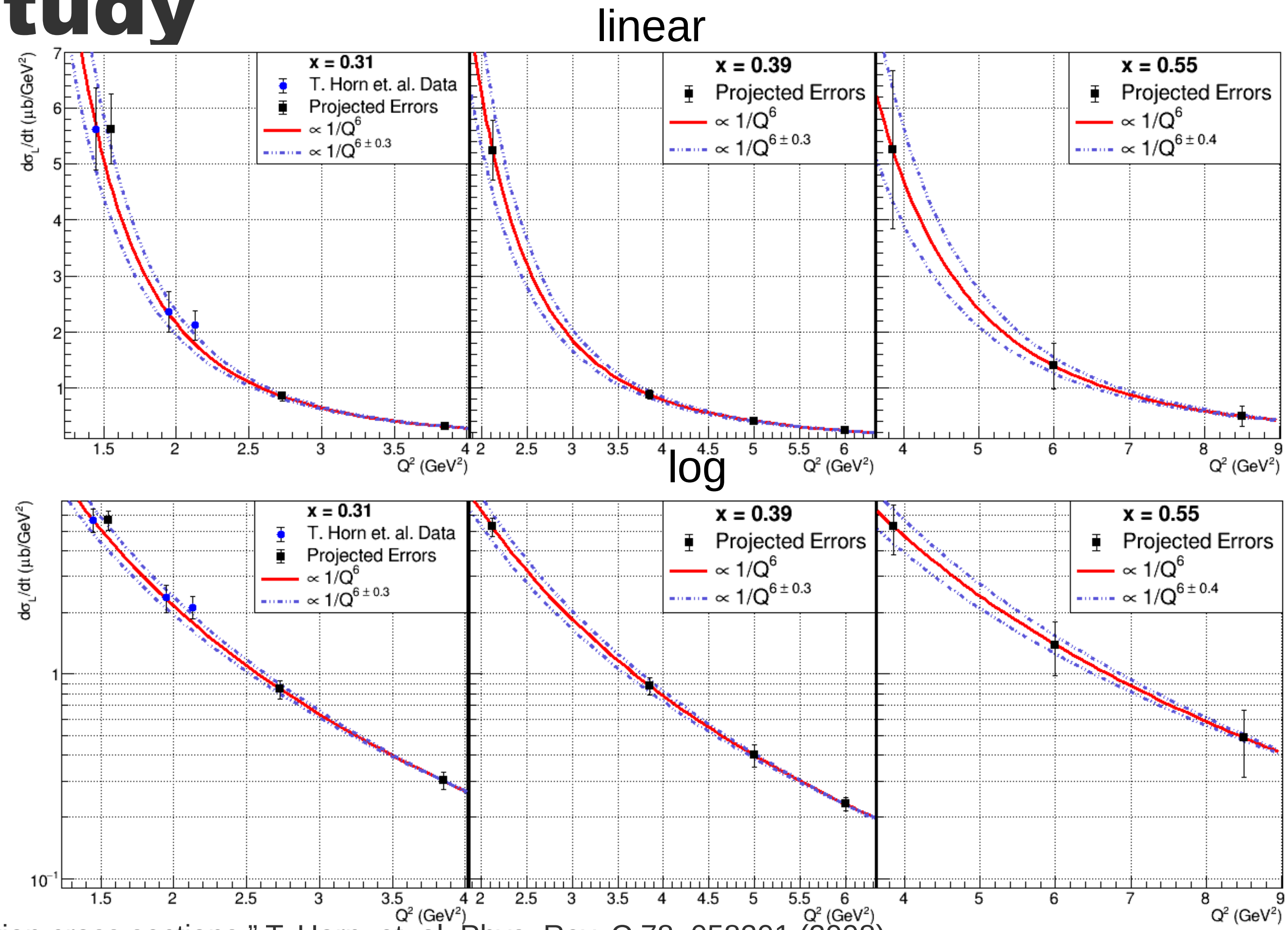




Scaling study

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

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

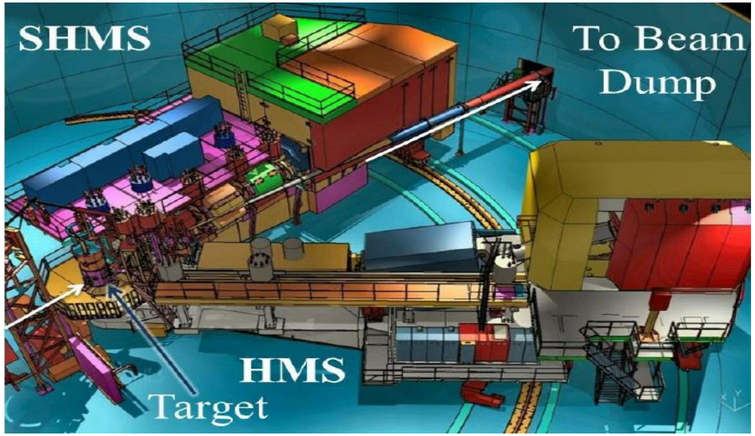


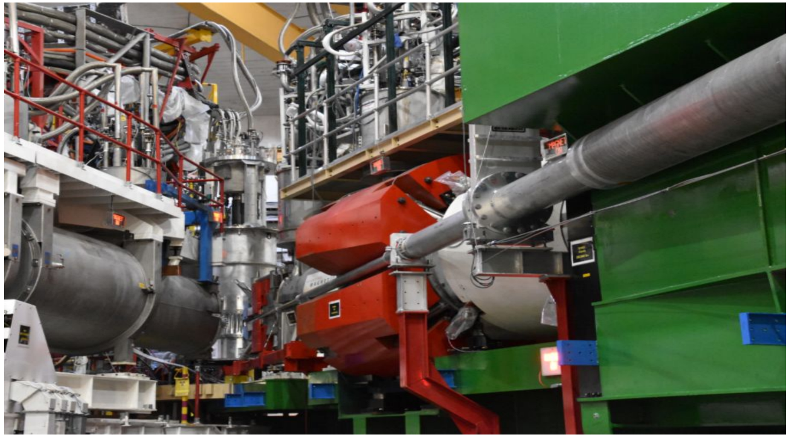
“Scaling study of the pion electroproduction cross sections,” T. Horn, et. al. Phys. Rev. C 78, 058201 (2008)

Hall C

The Hall Contains two highly sophisticated magnetic spectrometers

- Target can have Liquid H_2, Liquid D_2, or solid targets
  - Takes high power beam (~800kW)
- High Momentum Spectrometer (HMS) and Super High Momentum Spectrometer (SHMS):
  - Both arms have 3 Quadrupole and 1 Dipole super conducting magnet, the SHMS has an additional dipole before the first Quadrupole
  - Dipole allows studies at specific momenta
  - Both contain similar detector packages that support high rate (<1MHz)



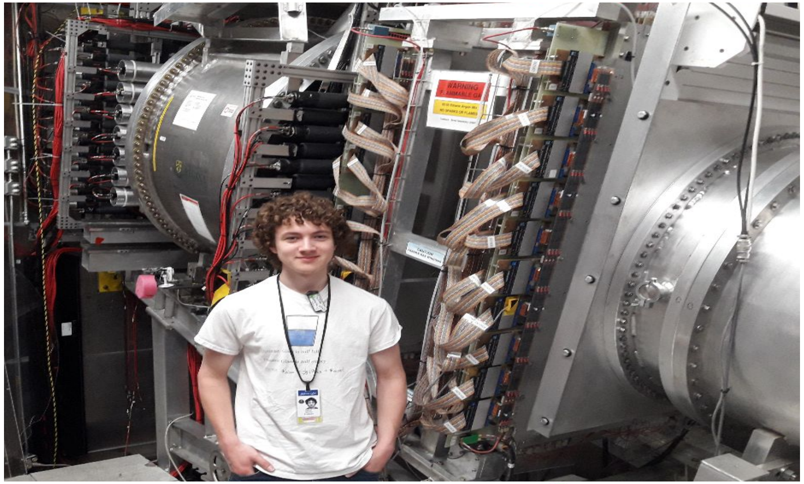


Spectrometer	Angle Range (Degrees)	Momentum Range (GeV/c)
HMS	10.5 - 90	0.5 - 7
SHMS	5.5 - 40	0.5 - 11

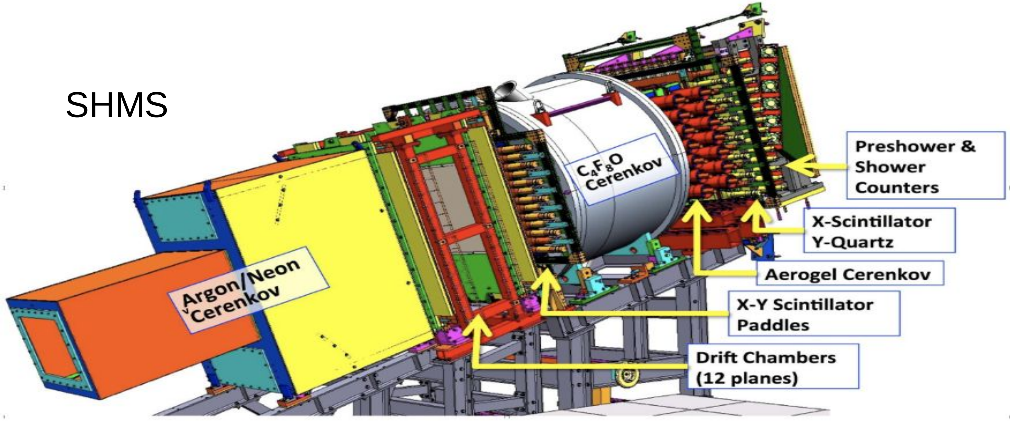
Detector Stack

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, $\pi^\pm/K^\pm$ 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	



SHMS



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