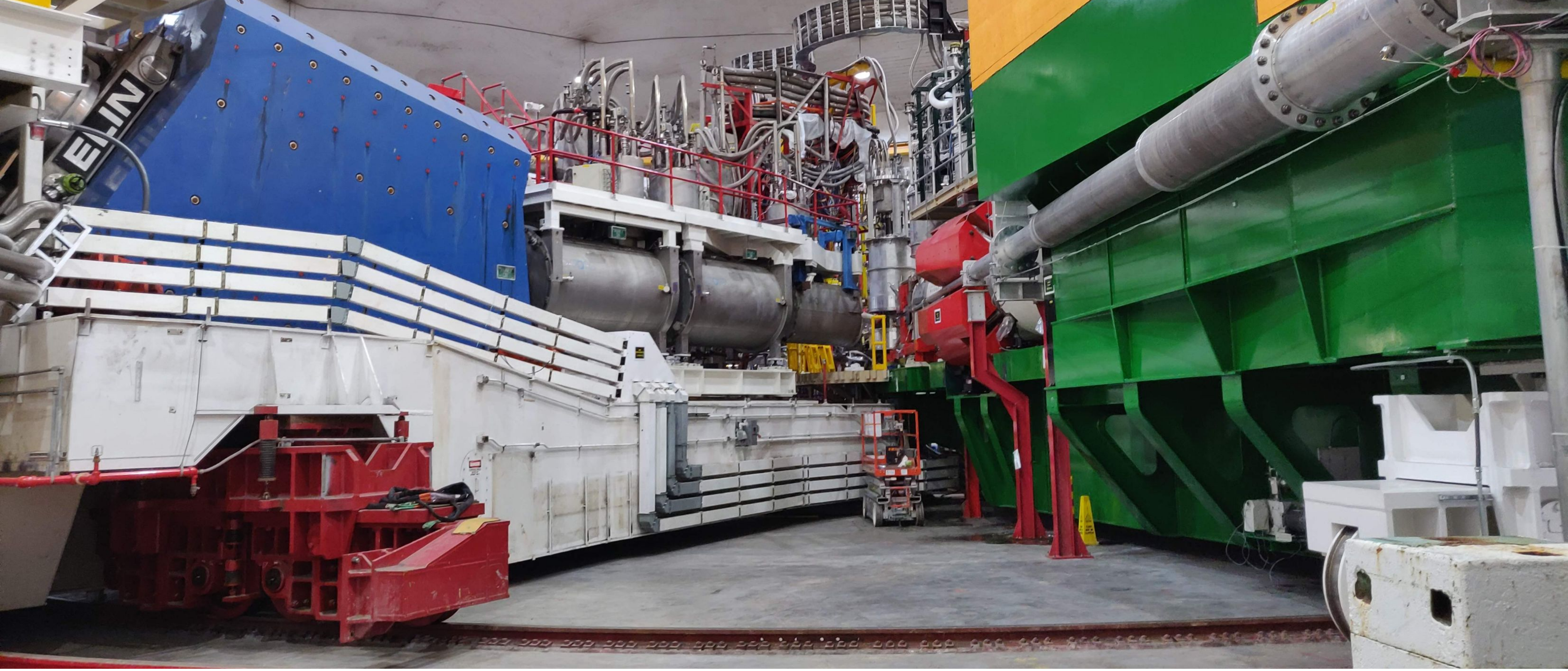


Update On GPD Factorization Validity Studies For Meson Production

Nathan Heinrich

Jefferson Lab
Thomas Jefferson National Accelerator Facility

University of Regina

Introduction

This talk will cover Generalized Parton Distribution (GPD) factorization validity studies from the recent PionLT experiment. This work is relevant to GPD studies done with Q^2 between 1.5 to 8.5 GeV^2.

PionLT (E12-19-006) is an experiment that recently finished collecting data at Jefferson Lab, Hall C.

This talk will answer the following questions:
- What are GPDs and why do we care?
- How does one access GPDs?
- What is a Longitudinal-Transverse (LT) separation?
- What experimental steps are needed to do a factorization study?

What are GPDs?

We’d like to be able to fully describe hadronic structure.

Wigner Distributions are 6 dimensional objects that describe both the position and momentum of a quantum system. These can be applied to the quark gluon D.o.F in QCD to describe hadrons.

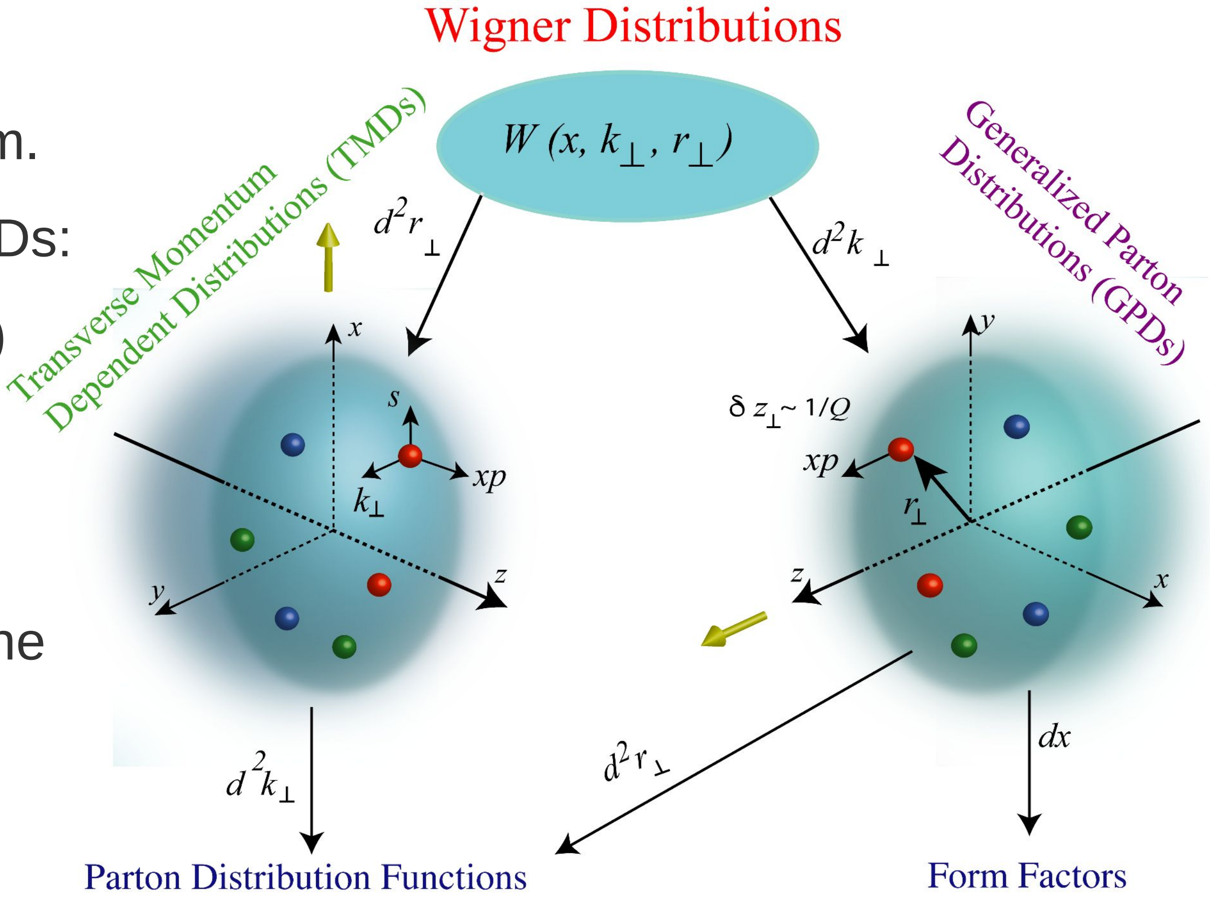
GPDs are these Wigner distributions integrated over transverse momentum.

For each quark flavor there are 8 GPDs:

- 4 conserve chirality (chiraly even) and 4 do not (chiraly odd).

Most experiments have focused on accessing the chiral even GPDs.

While there have been advances in the measuring the chiraly odd GPDs,
this talk will focus on the even GPDs.



GPDs and Experiment

GPDs are universal quantities and reflect nucleon structure independent of probing reaction

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

  - **D**eeply **V**irtual **C**ompton **S**cattering
    - Sensitive to all 4

  - **D**eep **E**xclusive **M**eson **P**roduction
    - Pseudoscalar mesons access $\tilde{H}$ $\tilde{E}$
    - 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 Average No Hel. Flip	$E^{q,g}(x,\xi,t)$ Spin Average 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

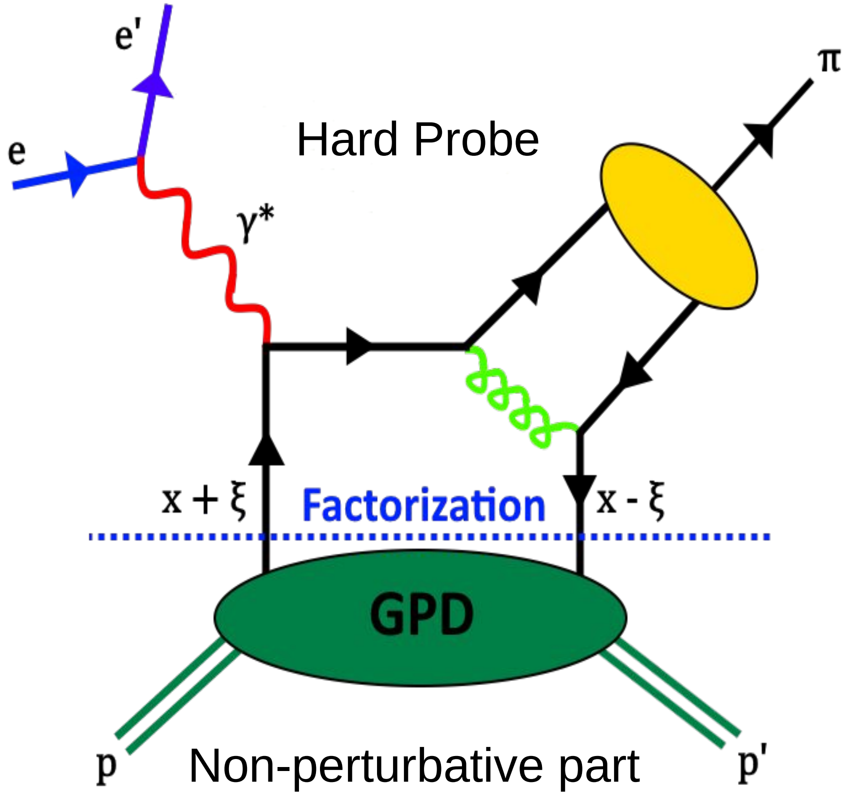
Using a recently proven factorization theorem to separate the process amplitude into two parts:

- 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

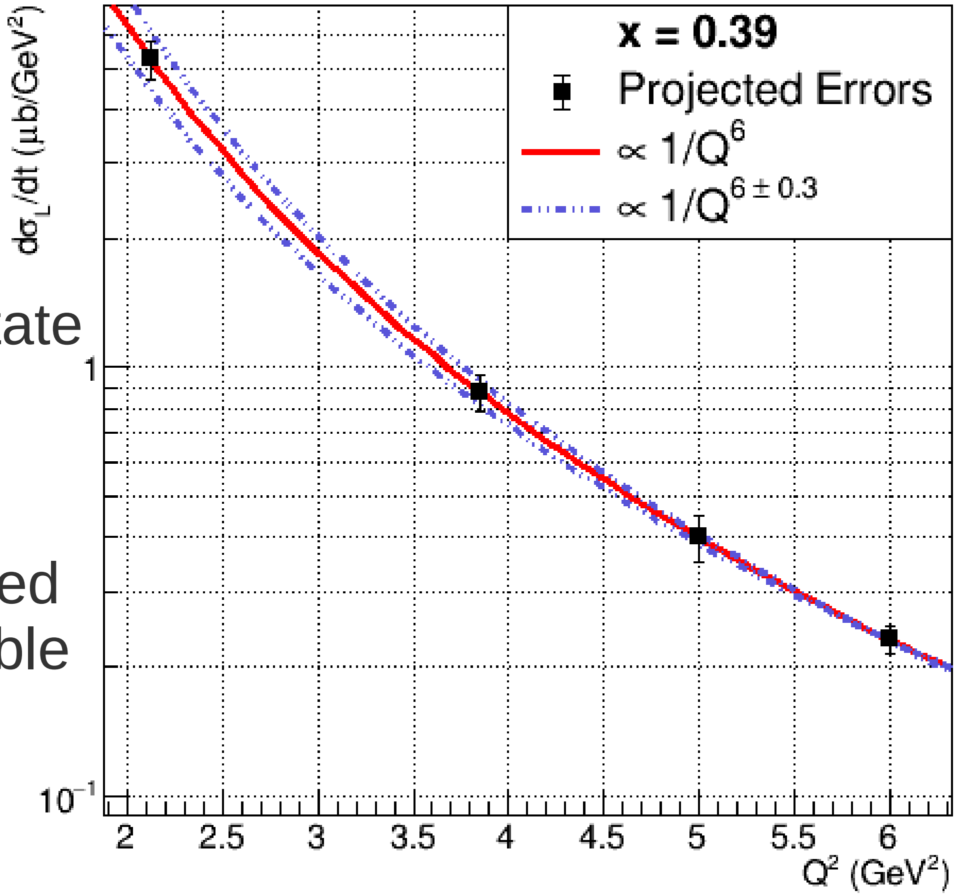
- First shown by Collins, Frankfurt & Strikman [PRD 56(1997)2982].



Factorization Validity

- Factorization regime will have characteristic $1/Q^6$ scaling of σ_L with fixed x_B
  - It should also have $\sigma_L >> \sigma_T$
- Can test for this 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 it is shown that this regime is not reached then even chirality GPDs are not accessible at these Q^2.

Projected Scaling Study



X_B - Bjorken scaling variable, and represents longitudinal momentum fraction

Factorization and Charged Pions

Data showing that the pions factorize give a conservative upper bound on the factorization regime for the meson production channel.

This data will be even more useful when combined with factorization studies using other mesons.

Multiple mesons showing factorization at the same Q^2 would remove any doubt that the dependence was accidental.

LT separated data is key to understanding GPDs.

For full treatment see:
“On the analysis of lepton scattering on longitudinally of transversely polarized protons”
M. Diehl, S. Sapeta Eur. Phys. J. C 41, 515-533 (2005)

Upcoming DEMP Experiments

Other experiments similar to PionLT (E12-19-006)

Experiment Name	Meson	Q^2 Range (GeV)	Comments
Exclusive ϕ Meson Electroproduction with CLAS 12	ϕ	2.5 – 8.5	Finished Taking data in JLab Hall B (E12-12-007) Gluon GPD and Q^2 scaling study
Exclusive π^0, η production with CLAS 12	π^0, η	1 - 4	Probes GPD's using π^0/η ratio (E12-06-108) Data taking ongoing in Jefferson Lab Hall B
Studies of the L-T Separated Kaon Electroproduction (KaonLT)	K^+	1 - 6	Sister experiment to this one Finished taking data in 2019 using JLab Hall C (E12-09-011)
Exclusive DVCS and Neutral Pion Cross-Section Measurements in Hall C	π^o	3 - 10	LT separation of π^o using Jlab Hall C, Also measuring DVCS for GPD information (E12-13-010)
Deep Exclusive π^- Production From Transversely Polarized ^{3}He	π^-	4 - 10	Uses beam spin asymmetry measurements to extract GPD information Experiment will be run as a part of SoLID (E12-10-006B)

Previous Factorization Results

An exploratory study has been done before:

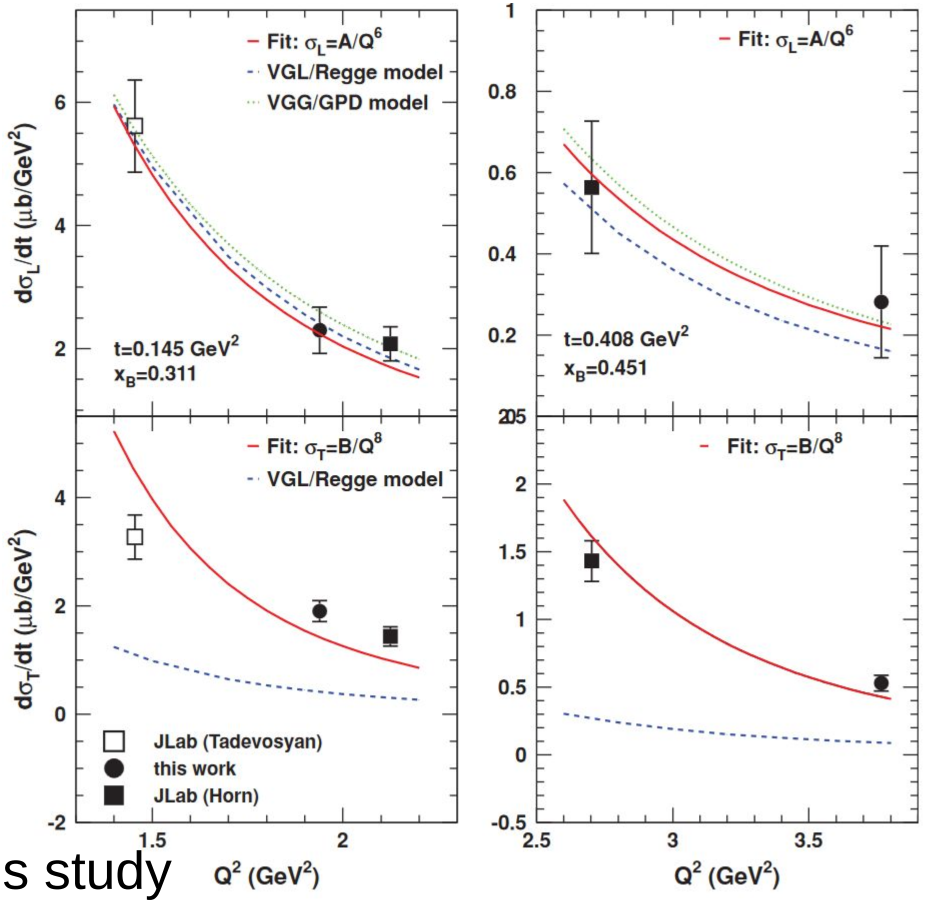
“Scaling study of the pion electroproduction cross sections,” T. Horn, et. al. Phys. Rev. C 78, 058201 (2008)

Did scaling studies with LT separated data at 2 values of x_B and -t

They found that σ_L followed Q^{-6} within errors.

Study was deemed inconclusive due to lack of statistics and large error bars

x_B	$-t$	$\sigma_L \sim Q^{-n}$ n	$\sigma_L \sim Q^{-6}$ $\chi^2/\nu\ (P)$	$\sigma_T \sim Q^{-m}$ m	$\sigma_T \sim Q^{-8}$ $\chi^2/\nu\ (P)$
0.31	0.15	5.08 ± 0.95	0.45 (0.64)	4.20 ± 0.78	$10.7(<10^{-3})$
0.45	0.41	4.17 ± 2.95	0.24 (0.62)	6.01 ± 0.90	4.5 (0.034)

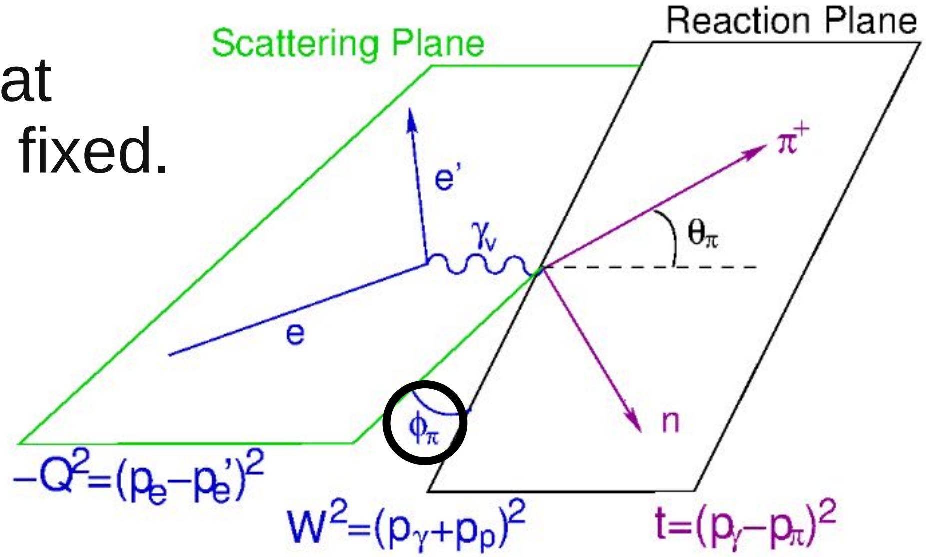


PionLT took data to do a dedicated version of this study

LT Separations

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

- To extract components of cross section based on virtual photon polarization, fit the above equation.
- To do this need to have full φ coverage at 2 values of ε while keeping Q^2, W, and t fixed.
- For GPD factorization we want σ_L
  - Corresponds to longitudinally polarized γ
- To get 2 values of ε we need data from 2 different beam energies.
  - This means different background and physics rates



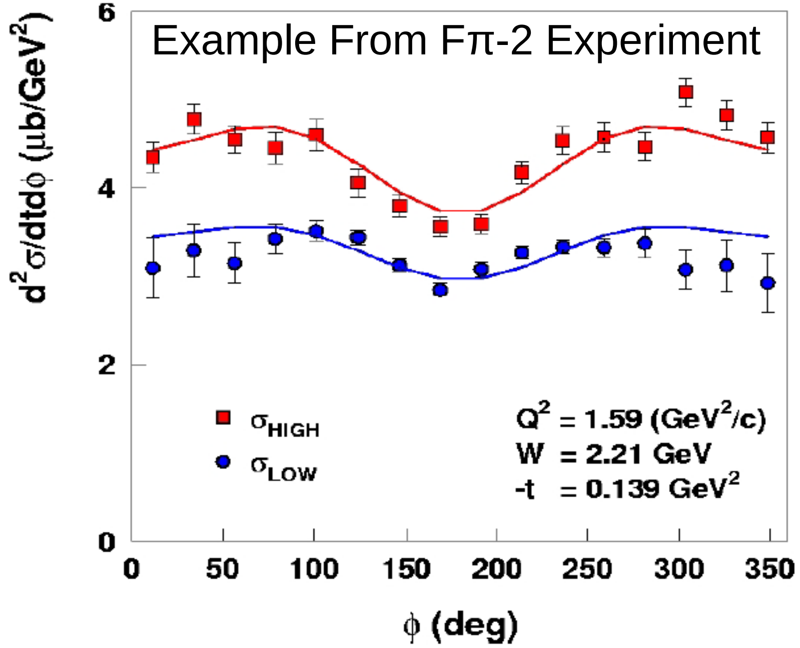
Virtual-photon polarization:

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

Error Amplification

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

Fitting gives something like this:



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

Control over the systematics is important as all uncorrelated errors are amplified:

$$\frac{\Delta\sigma_L}{\sigma_L} = \frac{1}{(\epsilon_1-\epsilon_2)}\frac{1}{\sigma_L}\sqrt{\Delta\sigma_1^2+\Delta\sigma_2^2}, \qquad \begin{array}{l}\sigma_1 = \sigma_T + \epsilon_1\sigma_L\\ \sigma_2 = \sigma_T + \epsilon_2\sigma_L\end{array}$$

Thus the errors are amplified by the Δε points (typically Δε ~ 0.3).

This means we must keep excellent control of our systematic errors.

Virtual-photon polarization:

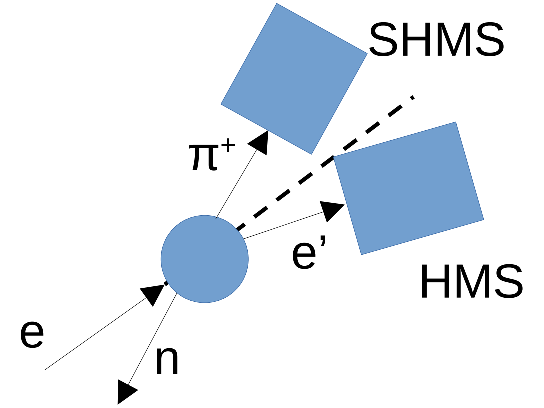
$$\varepsilon = \left(1 + 2\frac{(E_e - E_{e'})^2 + Q^2}{Q^2}\tan^2\frac{\theta_{e'}}{2}\right)^{-1}$$

Importance of ϕ Coverage

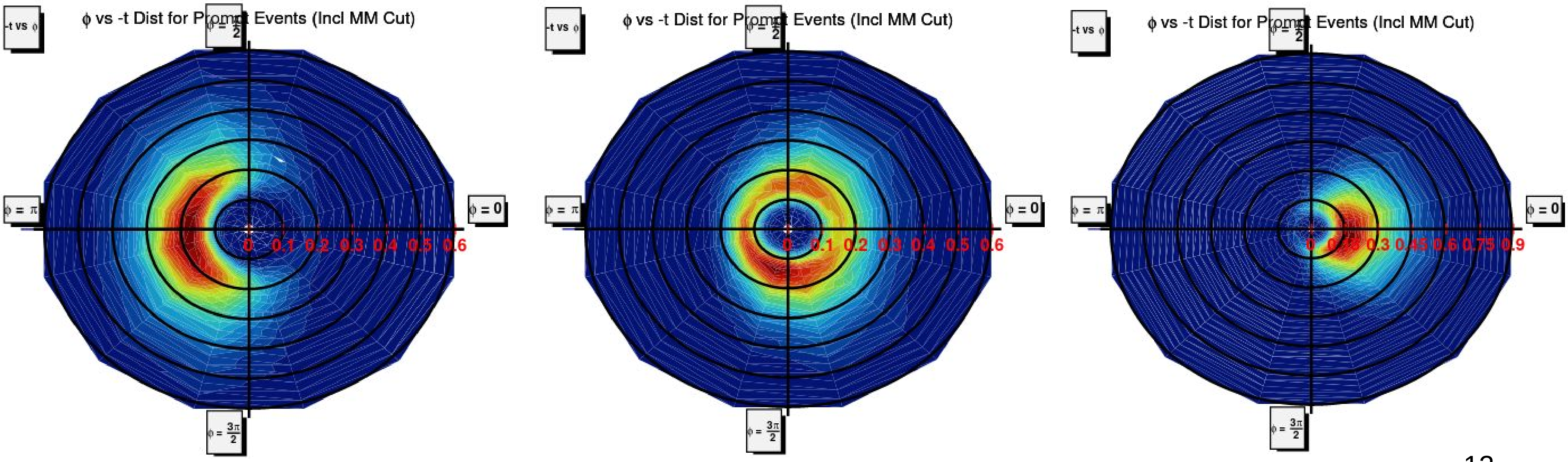
In order to obtain full ϕ coverage at fixed t we need to take data at three angles in the pion spectrometer.

This is done to determine the variation of $\boldsymbol{\sigma_L, \sigma_T, \sigma_{LT}}$, **and** $\boldsymbol{\sigma_{TT}}$.

To control systematics an excellent understanding of the spectrometers is required



Rotate SHMS to get ϕ coverage



SHMS Left

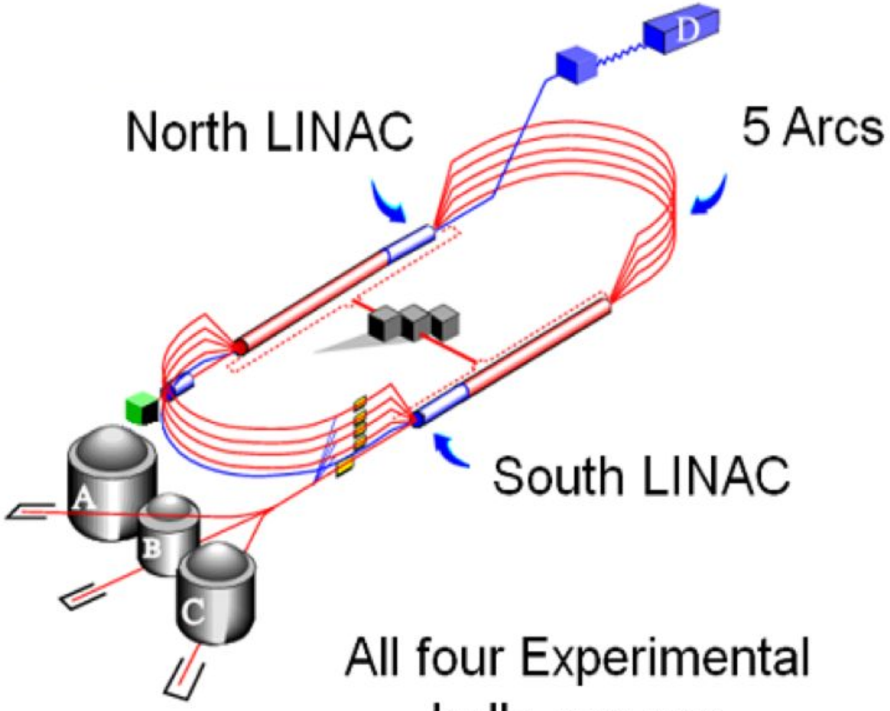
SHMS Center

SHMS Right

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

Jefferson Lab

- Located in Newport News, Virginia
- 2 Superconducting LINACs configured in "Racetrack"
- Produces continuous e^- beam at 1497MHz
- Capable of 12GeV polarized e^- at up to 200µA
- 4 halls all running unique experiments
- The 5 Arcs allow for 5 choices of beam energy at one LINAC gradient
  - Very important feature for LT Separation! $(\Delta \epsilon \propto \Delta E_{Beam})$



North LINAC

5 Arcs

South LINAC

All four Experimental halls can run simultaneously

Example beam energies for 1962 MeV gradient

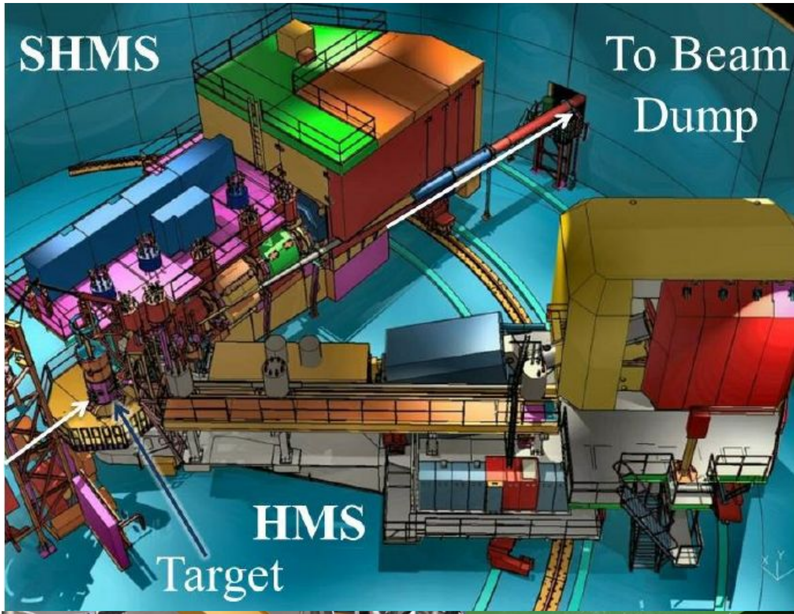
Pass	Beam Energy (GeV)
1	2.069
2	4.029
3	5.986
4	7.937
5	9.876

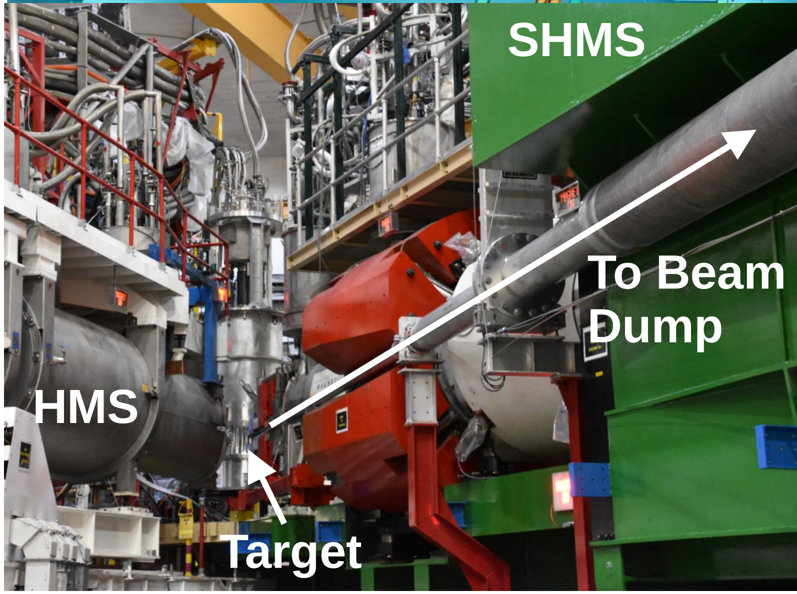
Hall C

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

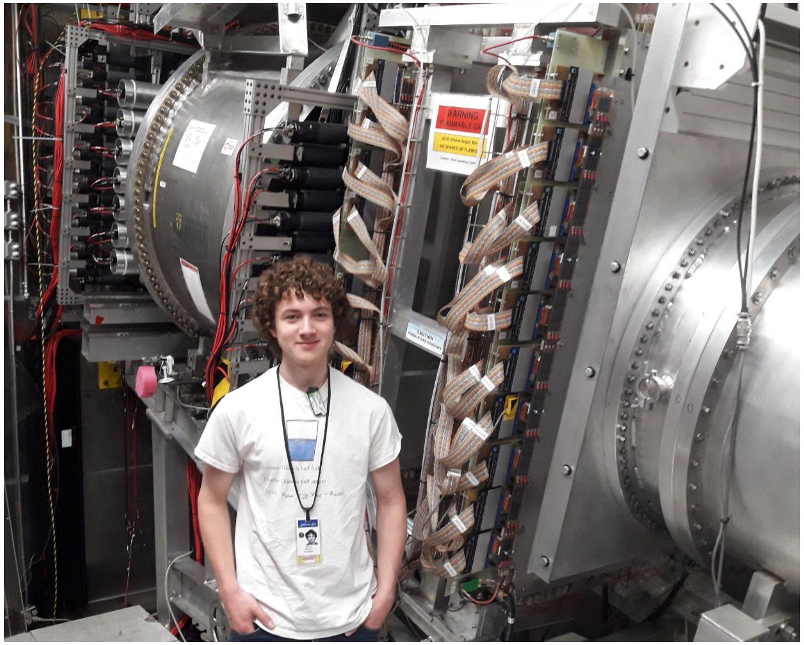




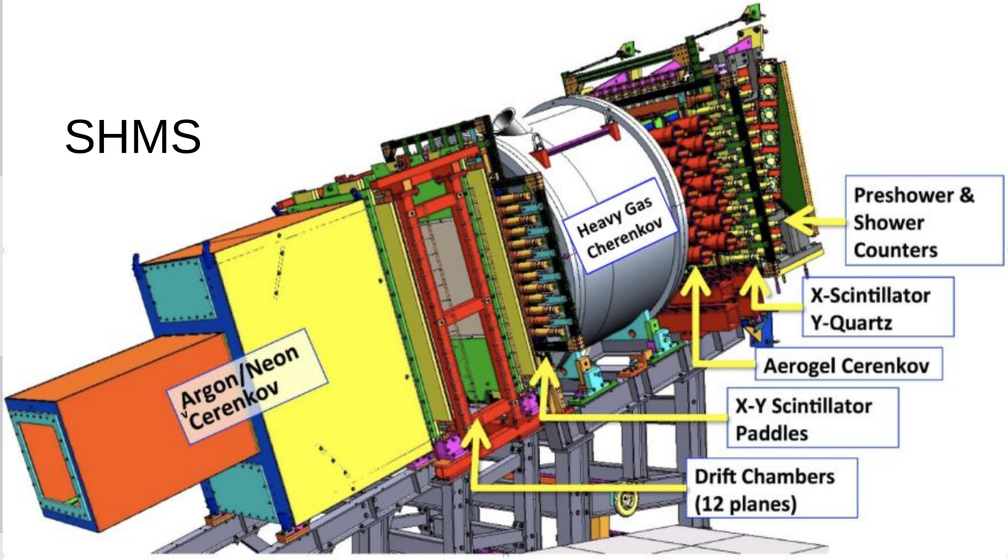
Detector Stack

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	

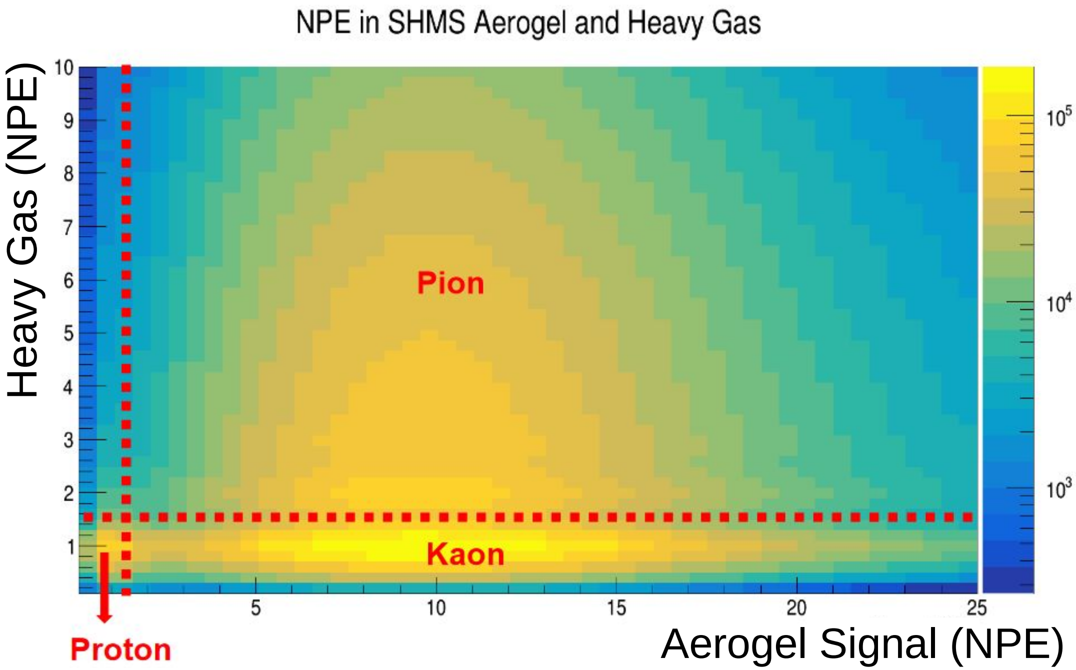


SHMS



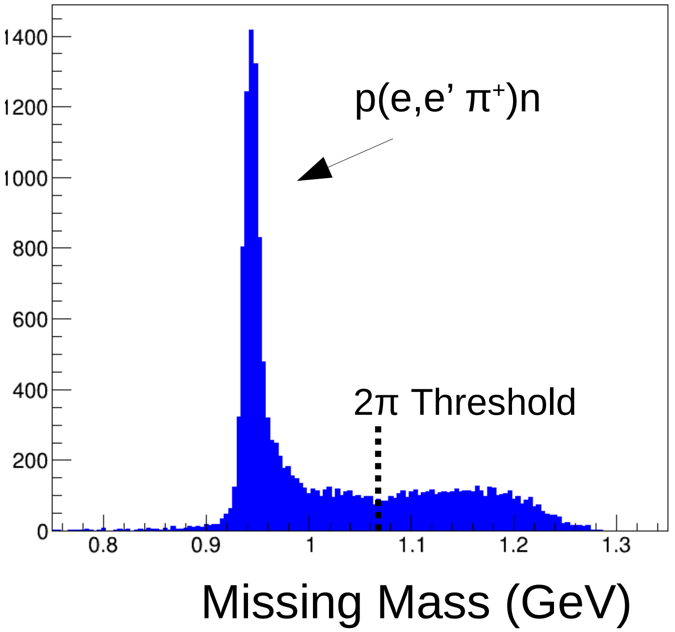
Event Selection

- Need to measure p(e, e’ π^+)n events with the required Q^2, and W.
- Set spectrometers with correct angle and magnetic field to select momentum of e’ and π^+.
- Then in analysis use particle ID detectors to select p(e, e’ π^+)X events
- Use excellent momentum resolution to produce accurate missing mass
- Use missing mass to select p(e,e’ π^+)n events



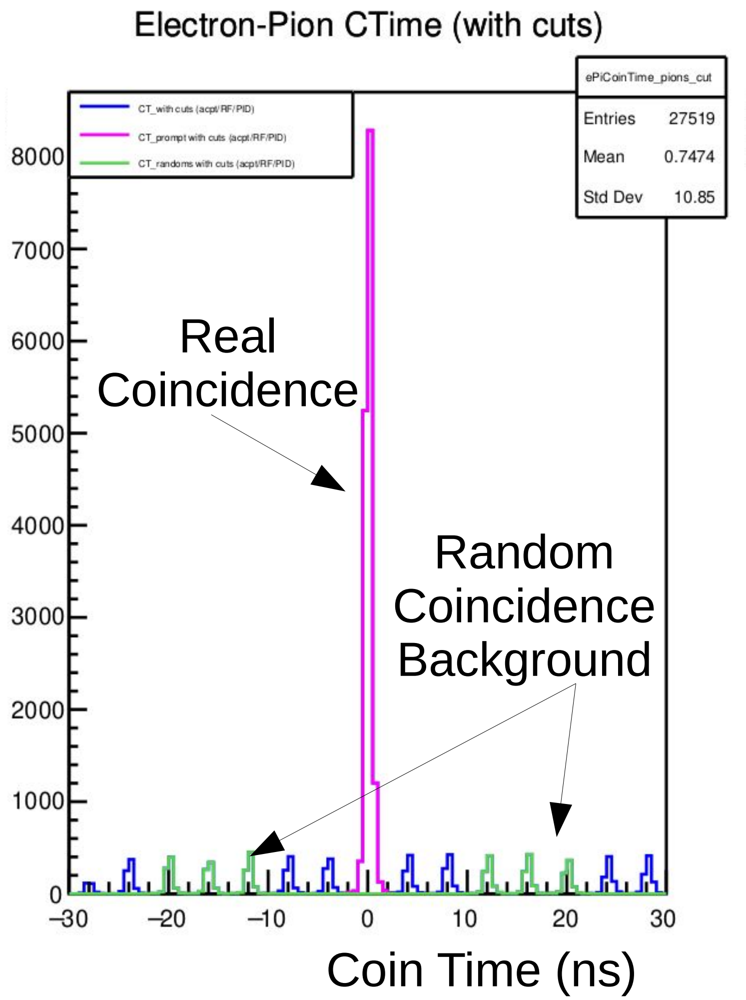
Missing Mass Definition:

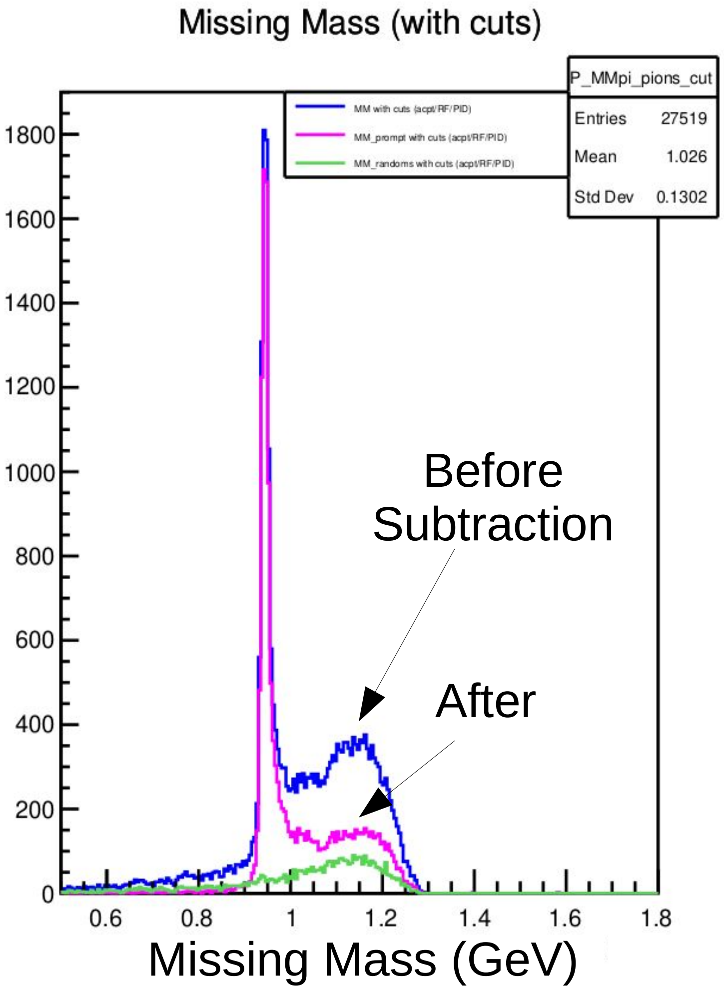
$$m_X^2 = \left(E_e - E_{e'} - E_\pi + E_p\right)^2 - P_X^2$$

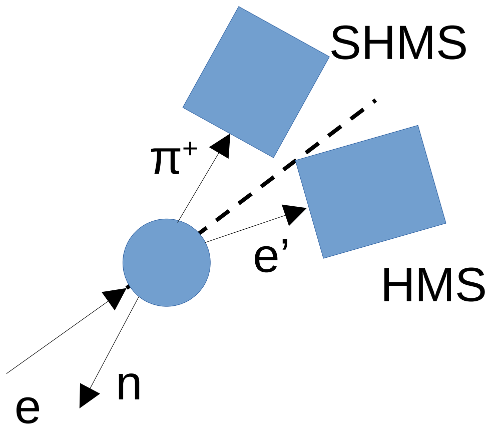


Background Removal

Since we take the coincidence of the e’ and π^+ we can subtract the random background under main peak by using the average of several background peaks







π and e’ detected in coincidence

Analysis Timeline

Analysis is underway, a rough outline of tasks:

- Detector Calibrations (3 months)
- Rate Dependence Studies (5 months)
- p(e,e’ p’) Elastic Cross Sections (8 months)
- LT Separations (1-2 months/setting)

Total time estimate is 2-3 years for LT Separated data, finishing 2025

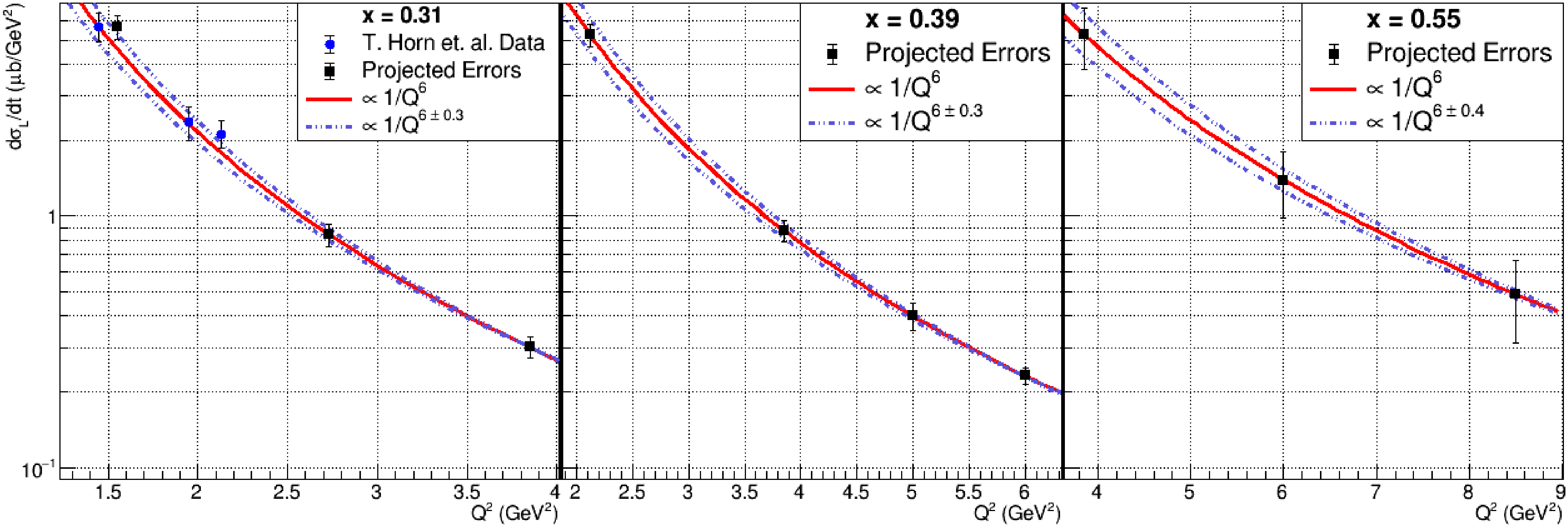
Work is divided between 3 grad students:
Nathan Heinrich, Muhammad Junaid, and Jacob Murphy

Projected Scaling Results

PionLT collected data to do scaling studies at 3 values of x_B and t:

The $x_B = 0.31$ data overlaps with data from the previous study, and will extend the reach significantly.

The other points at $x_B = 0.39$, and 0.55 will provide additional tests of the factorizability.



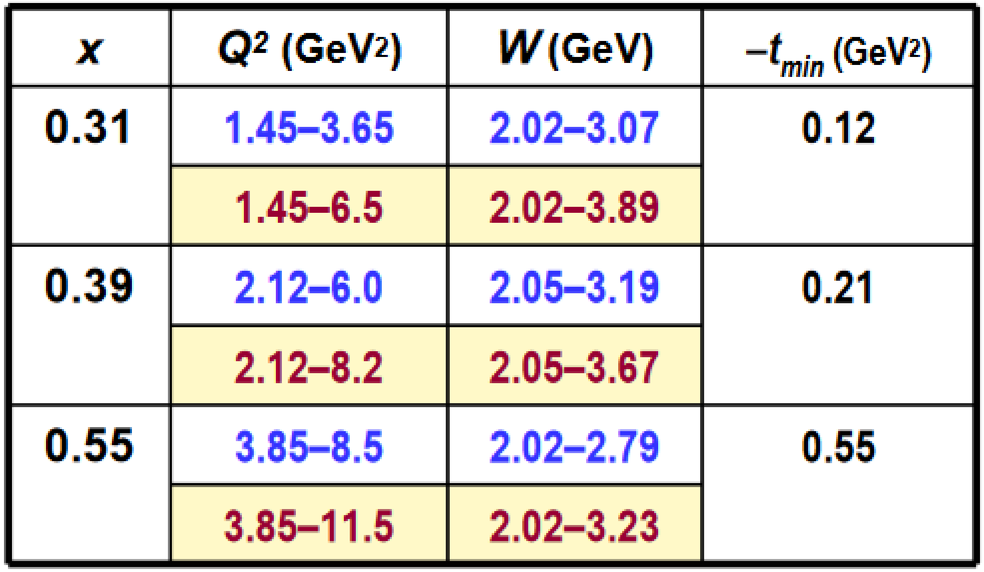
Y-Positions Arbitrary

Impact of 22 GeV

The JLab 22 GeV upgrade would provide an extended Q^2 reach, greatly improving the kinematic reach:

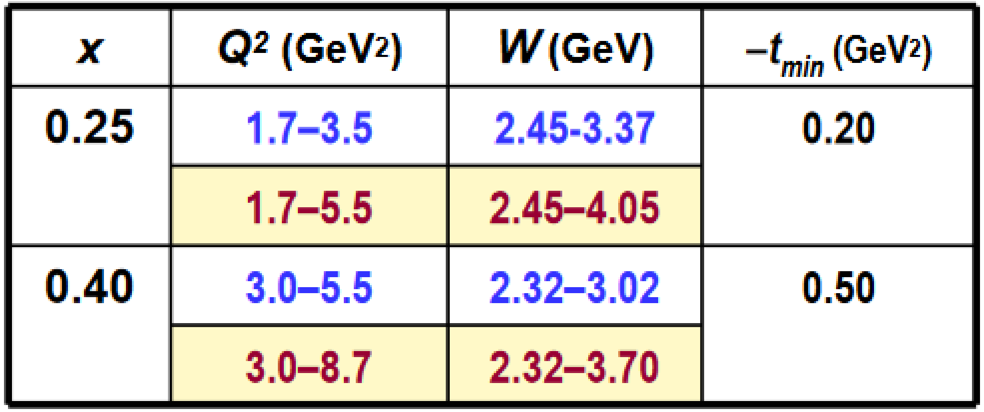
Current Reach:

With 22 GeV:



x	Q^2 (GeV^2)	W (GeV)	$-t_{min}$ (GeV^2)
0.31	1.45–3.65	2.02–3.07	0.12
	1.45–6.5	2.02–3.89	
0.39	2.12–6.0	2.05–3.19	0.21
	2.12–8.2	2.05–3.67	
0.55	3.85–8.5	2.02–2.79	0.55
	3.85–11.5	2.02–3.23	

This extends to the KaonLT, our sister experiment:



x	Q^2 (GeV^2)	W (GeV)	$-t_{min}$ (GeV^2)
0.25	1.7–3.5	2.45–3.37	0.20
	1.7–5.5	2.45–4.05	
0.40	3.0–5.5	2.32–3.02	0.50
	3.0–8.7	2.32–3.70	

To hear more about future work at Jlab 22 GeV, See Stephen Kay’s talk tomorrow

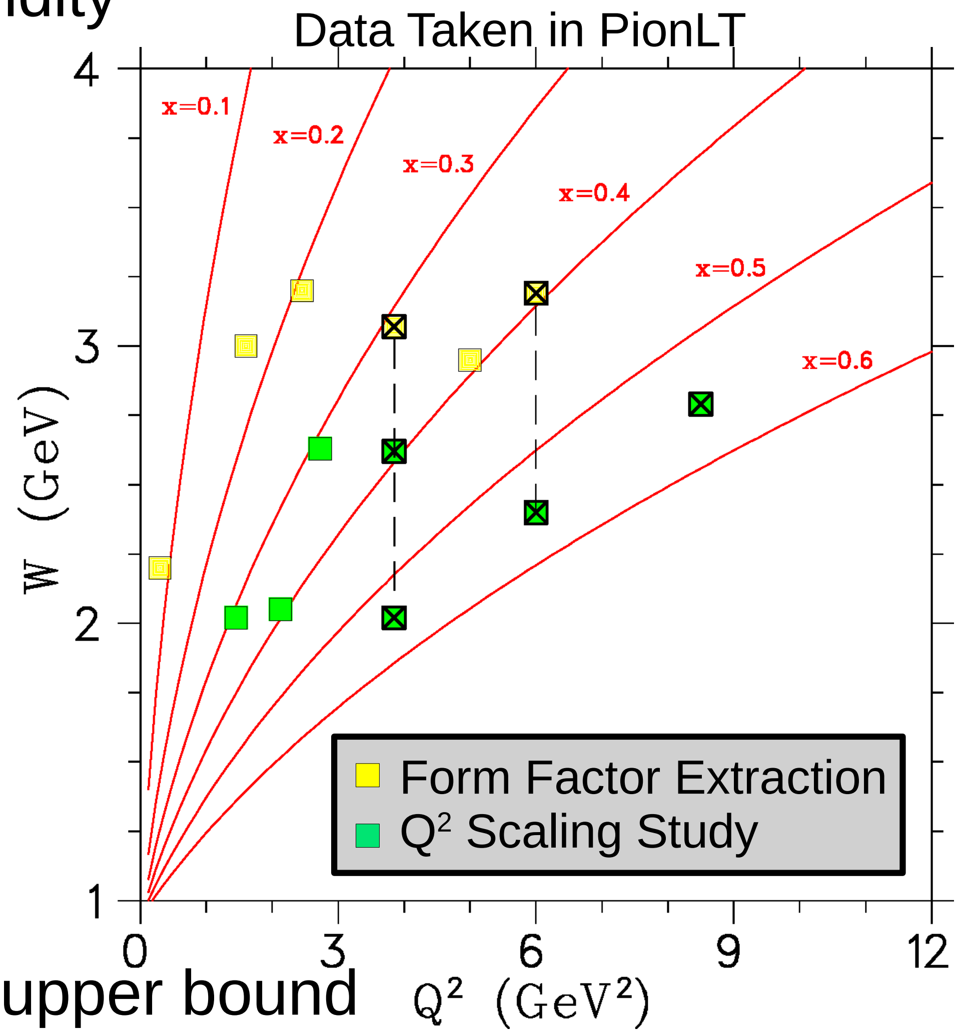
Summary

Covered the pion GPD factorization validity study from the PionLT experiment.

GPDs are the next step in the understanding of hadronic structure.

Factorization studies are crucial if the field is to understand GPDs, as GPDs are only accessible in the factorization regime.

PionLT will cover a wide range Q^2 (from 1.5 to 8.5 GeV^2).



These data will provide a conservative upper bound on the start of factorization for meson production.

Thank You

Nathan Heinrich[1], Jacob Murphy[2], Muhammad Junaid[1], Garth Huber[1], Stephen Kay[1],
Dave Gaskell[3], Tanja Horn[3,4], Julie Roche[2]

Special thanks to all the shift takers!

1: University of Regina, 2: Ohio University, 3: Jefferson Lab, 4: Catholic University

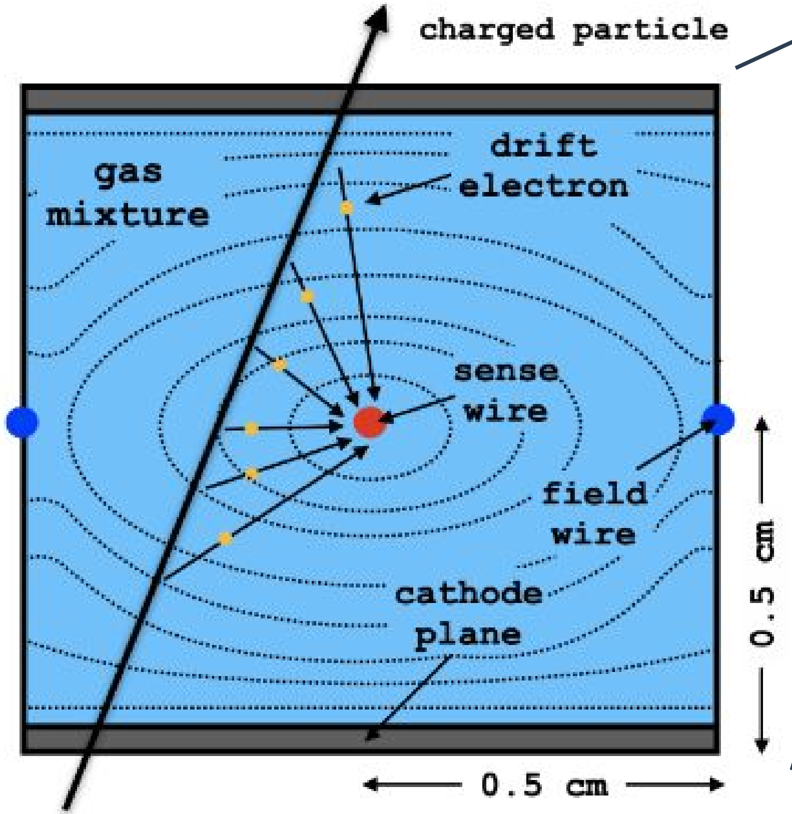
NSF: #2209199 J.Roche
NSF PHY 2012430 T.Horn

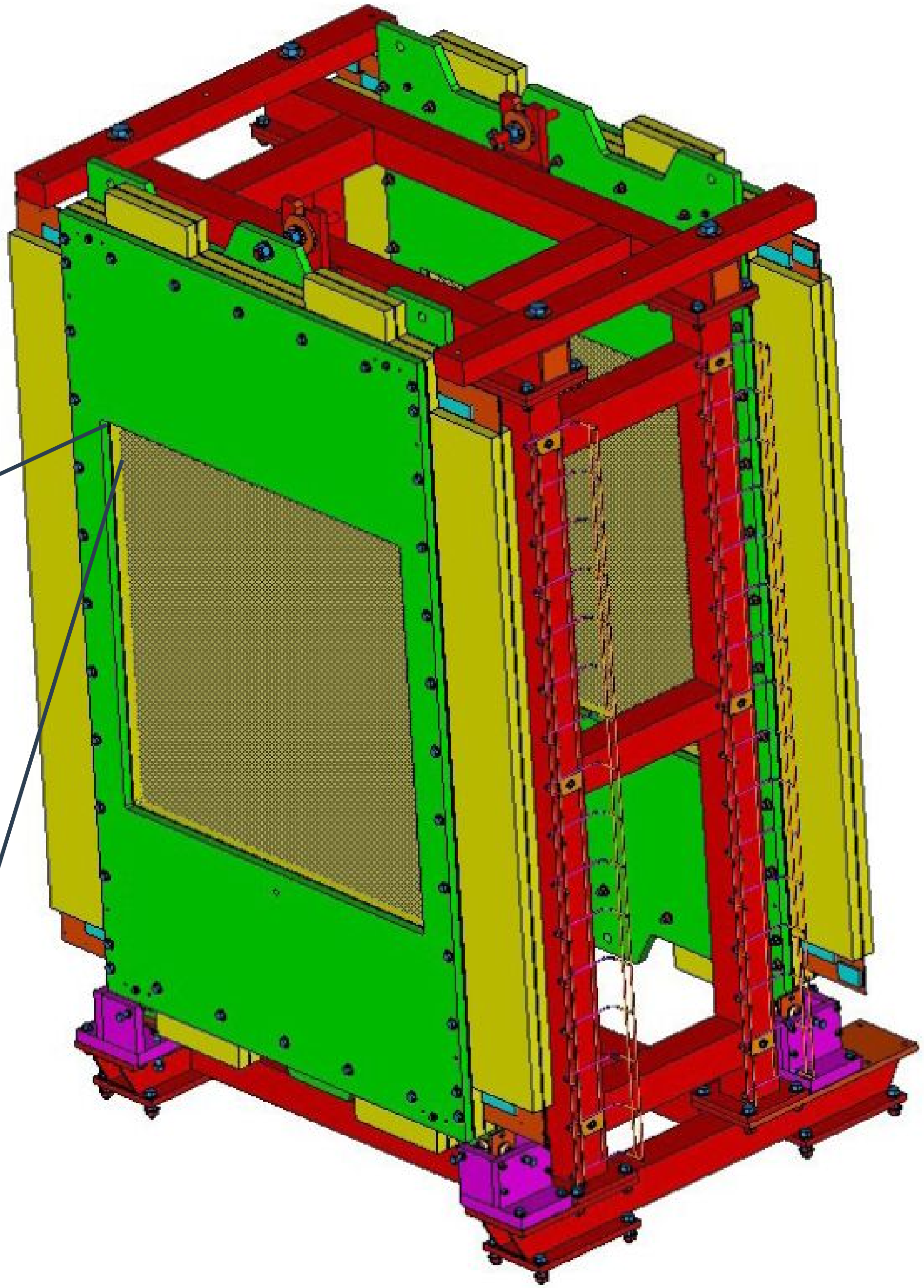
NSERC grant:
SAPIN-2021-00026

Questions?

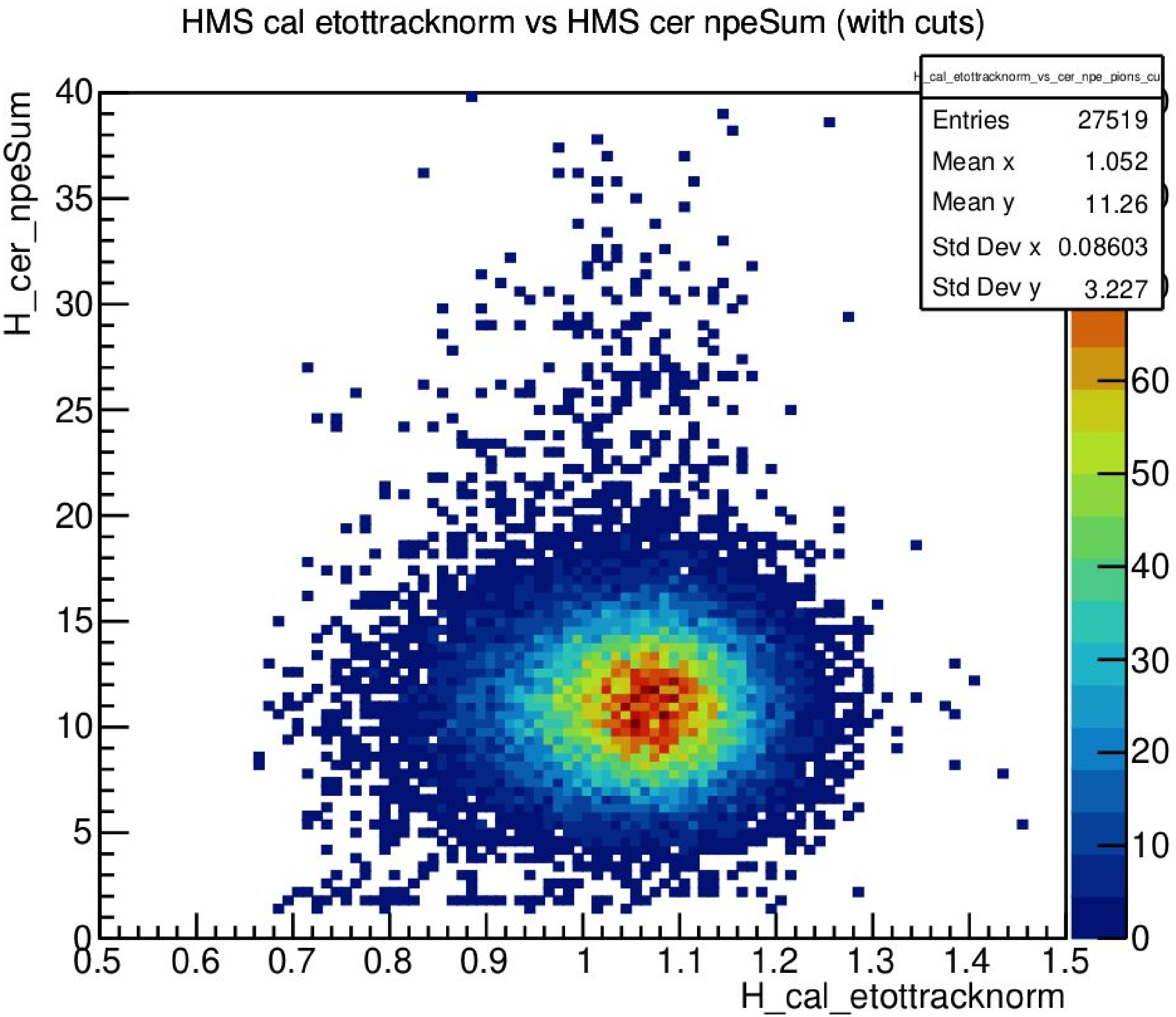
I acknowledge financial support from The Gordon and Betty Moore Foundation and the American Physical Society to present this work at the GHP 2023 workshop

DC Diagram

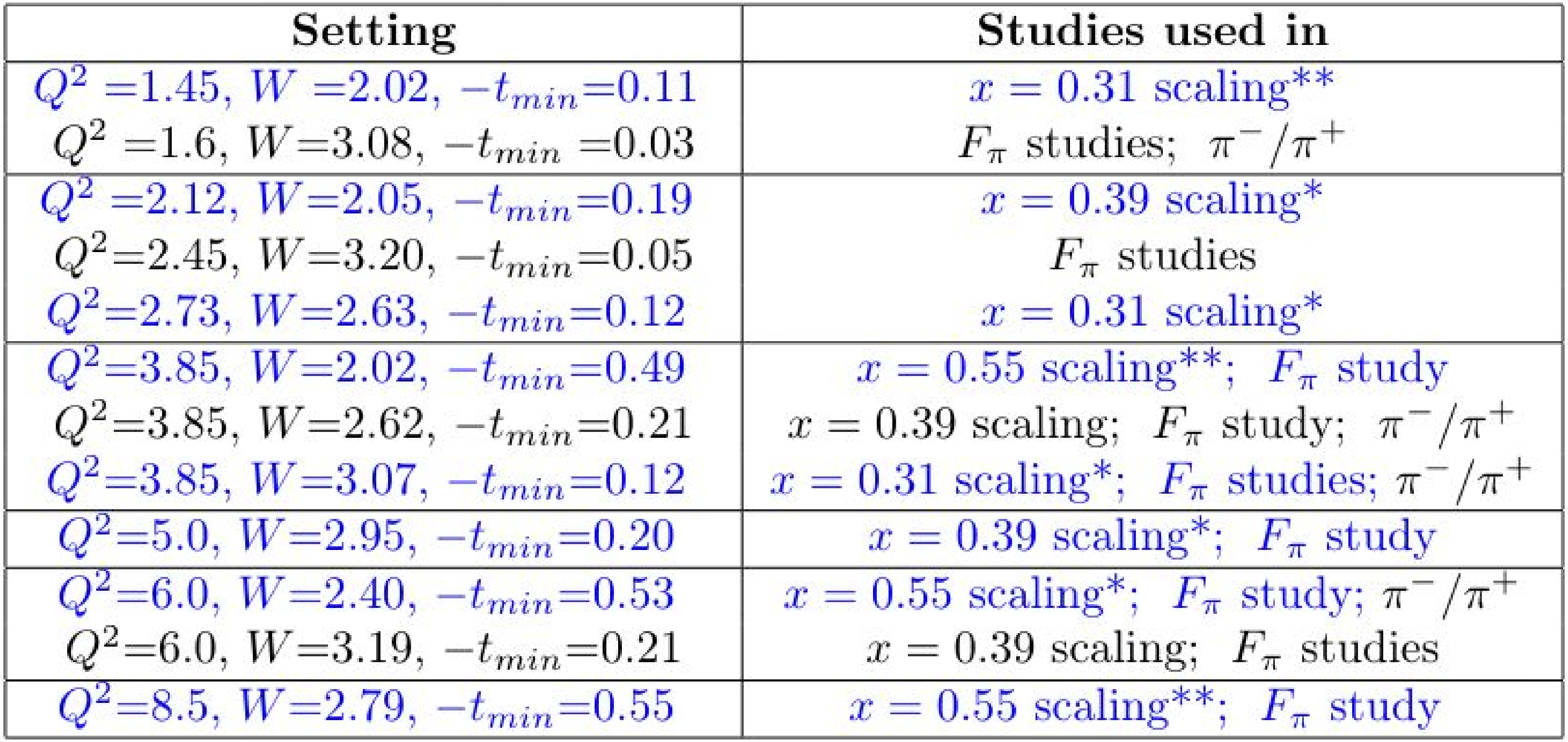

charged particle
gas mixture
drift electron
sense wire
field wire
cathode plane
0.5 cm
0.5 cm



HMS PID


HMS cal etottracknorm vs HMS cer npeSum (with cuts)
H_cal_etottracknorm_vs_cer_npe_pions_cu
Entries 27519
Mean x 1.052
Mean y 11.26
Std Dev x 0.08603
Std Dev y 3.227
H_cer_npeSum
0
5
10
15
20
25
30
35
40
0.5
0.6
0.7
0.8
0.9
1
1.1
1.2
1.3
1.4
1.5
H_cal_etottracknorm
0
10
20
30
40
50
60

Kinematic reach

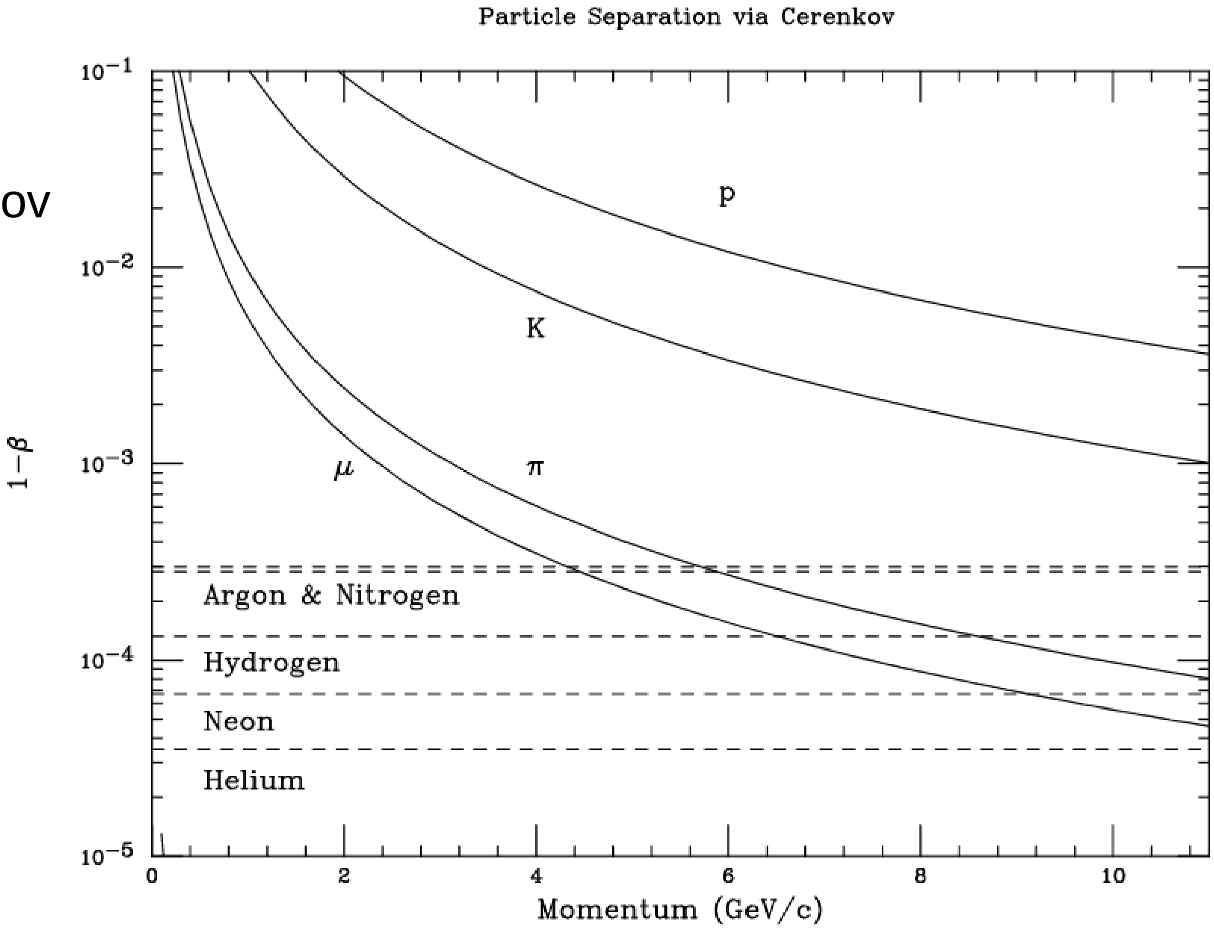


Setting	Studies used in
$Q^2=1.45$, $W=2.02$, $-t_{min}=0.11$	$x=0.31$ scaling**
$Q^2=1.6$, $W=3.08$, $-t_{min}=0.03$	F_π studies; π^-/π^+
$Q^2=2.12$, $W=2.05$, $-t_{min}=0.19$	$x=0.39$ scaling*
$Q^2=2.45$, $W=3.20$, $-t_{min}=0.05$	F_π studies
$Q^2=2.73$, $W=2.63$, $-t_{min}=0.12$	$x=0.31$ scaling*
$Q^2=3.85$, $W=2.02$, $-t_{min}=0.49$	$x=0.55$ scaling**; F_π study
$Q^2=3.85$, $W=2.62$, $-t_{min}=0.21$	$x=0.39$ scaling; F_π study; π^-/π^+
$Q^2=3.85$, $W=3.07$, $-t_{min}=0.12$	$x=0.31$ scaling*; F_π studies; π^-/π^+
$Q^2=5.0$, $W=2.95$, $-t_{min}=0.20$	$x=0.39$ scaling*; F_π study
$Q^2=6.0$, $W=2.40$, $-t_{min}=0.53$	$x=0.55$ scaling*; F_π study; π^-/π^+
$Q^2=6.0$, $W=3.19$, $-t_{min}=0.21$	$x=0.39$ scaling; F_π studies
$Q^2=8.5$, $W=2.79$, $-t_{min}=0.55$	$x=0.55$ scaling**; F_π study

Threshold Cherenkovs

Aerogel set to have Kaons cherenkov
Heavy Gas set for Pions
Nobel Gas set for electrons

$$\frac{1}{n} \leq \beta$$

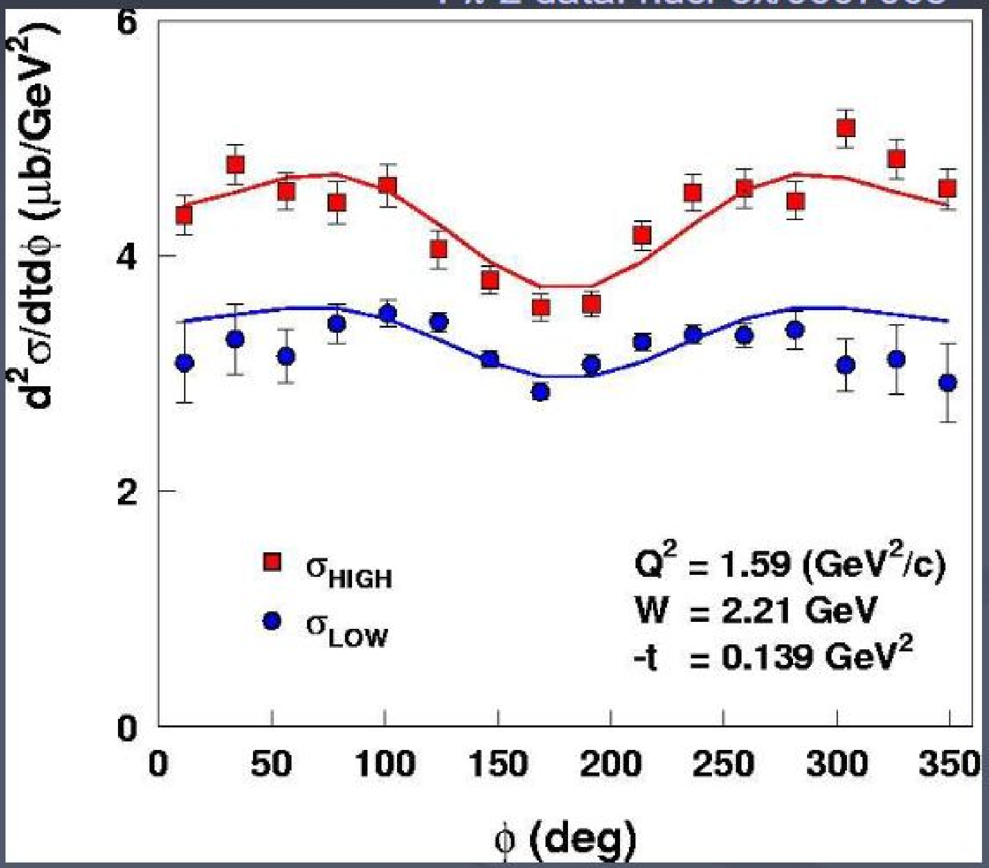


Experimental Cross Section Determination

- Compare experimental yields to Monte Carlo of the experiment:
  - *p(e,e'π^+)n* model based on pion electroproduction data.
  - Radiative effects, pion decay, energy loss, multiple scattering
  - COSY model for spectrometer optics.

$$\left(\frac{d\sigma(\overline{W},\overline{Q}^2,t,\phi)}{dt}\right)_{\exp} = \frac{\langle Y_{\exp}\rangle}{\langle Y_{MC}\rangle}\left(\frac{d\sigma(\overline{W},\overline{Q}^2,t,\varphi)}{dt}\right)_{MC}$$

Fπ-2 data: nucl-ex/0607005



Only Statistical Uncertainties Shown.

- Extract σ_L by simultaneous fit using measured azimuthal angle (φ_π) and knowledge of photon polarization (ε).

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