GPD Factorization in Pion Electroproduction: PionLT Luminosity Studies

Nathan Heinrich
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Jefferson Lab
Thomas Jefferson National Accelerator Facility

University of Regina

Motivation

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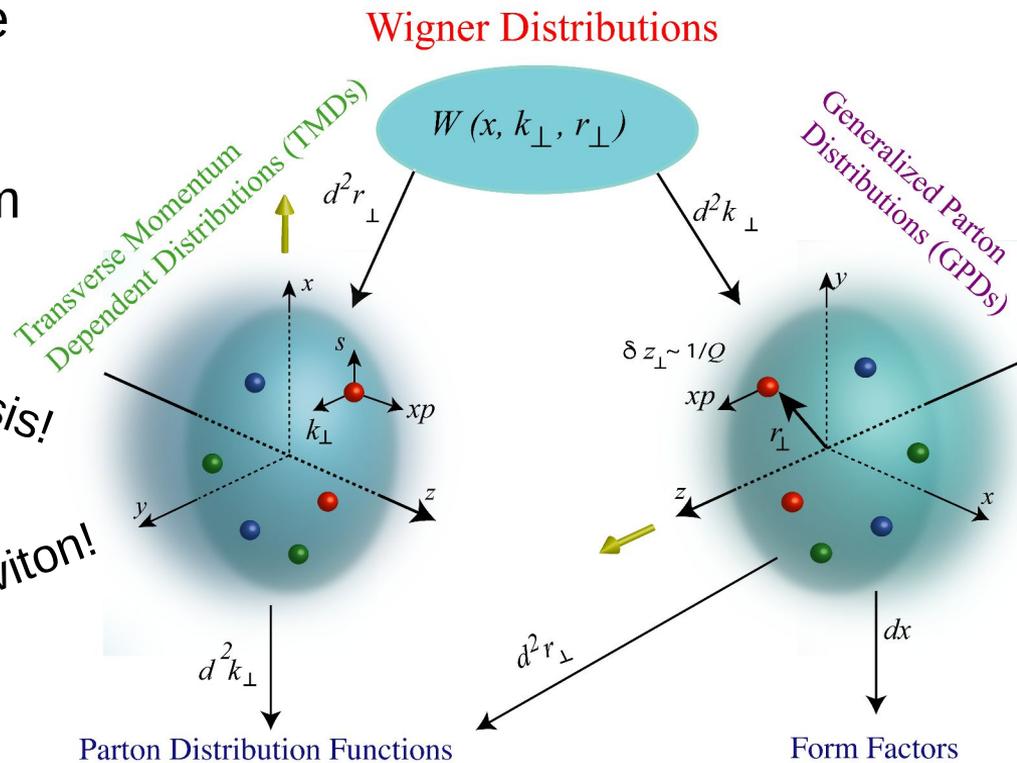Want to better understand Hadron structure (Thus the Strong Force)

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!

Wigner Distributions

$W(x, k_\perp, r_\perp)$

Transverse Momentum
Dependent Distributions (TMDs)

Generalized Parton
Distributions (GPDs)

$d^2 r_\perp$

$d^2 k_\perp$

x

s

xp

$k_\perp$

z

y

$\delta z_\perp \sim 1/Q$

y

xp

$r_\perp$

z

x

$d^2 k_\perp$

$d^2 r_\perp$

dx

Parton Distribution Functions

Form Factors

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

$H^{q,g}(x, \xi, t)$
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

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
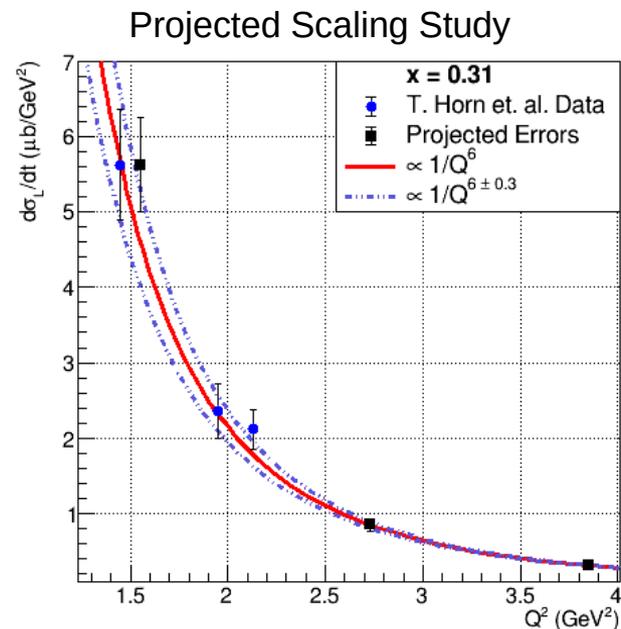
This is shown by the "Handbag Diagram"

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

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

Require LT Separation

Hard Probe

Factorization

Non-perturbative part
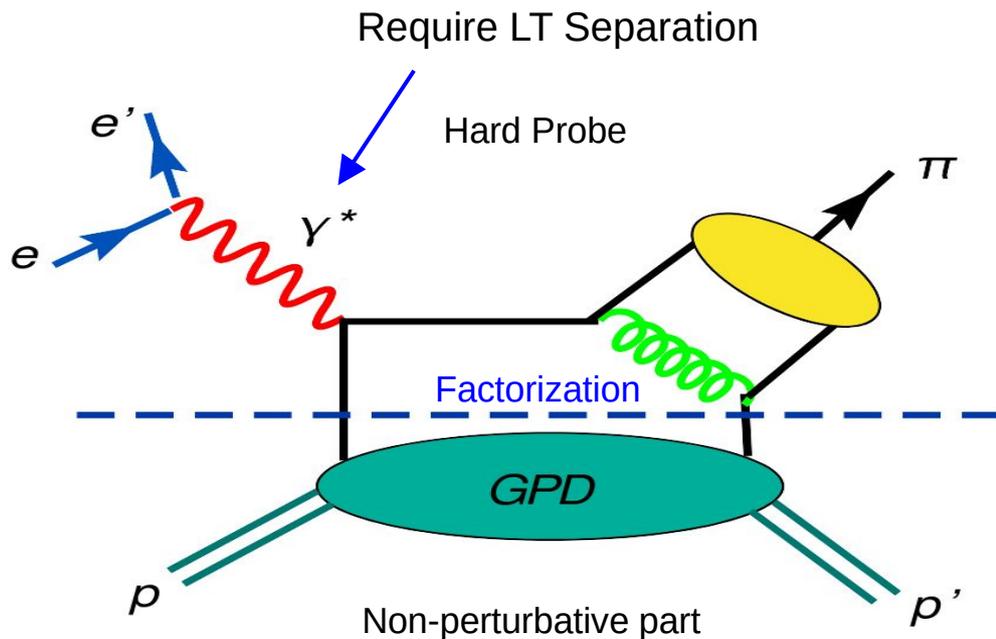
Factorizability

- 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 = 0.31	
•	T. Horn et. al. Data
▪	Projected Errors
—	$\propto 1/Q^6$
·-·-·	$\propto 1/Q^{6 \pm 0.3}$

X_B - Bjorken scaling variable, and represents longitudinal momentum fraction

# 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

Scattering Plane Reaction Plane

$-Q^2=(p_e-p_{e'})^2$

$W^2=(p_\gamma+p_p)^2$

$t=(p_\gamma-p_\pi)^2$
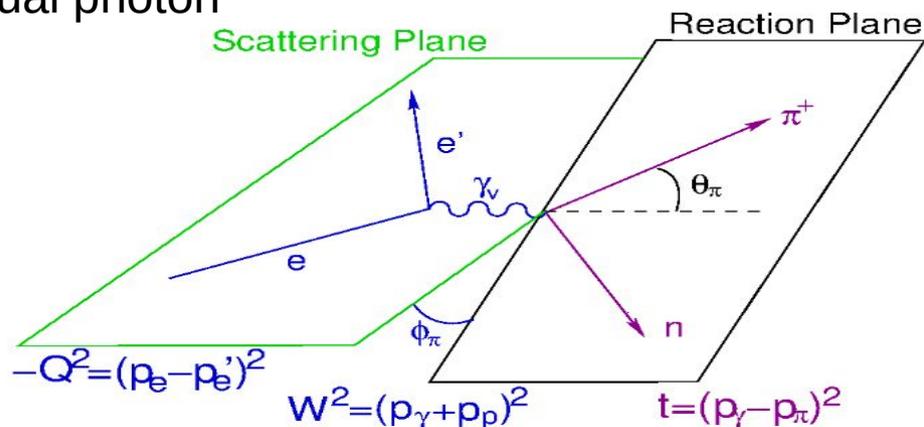
Virtual-photon polarization:

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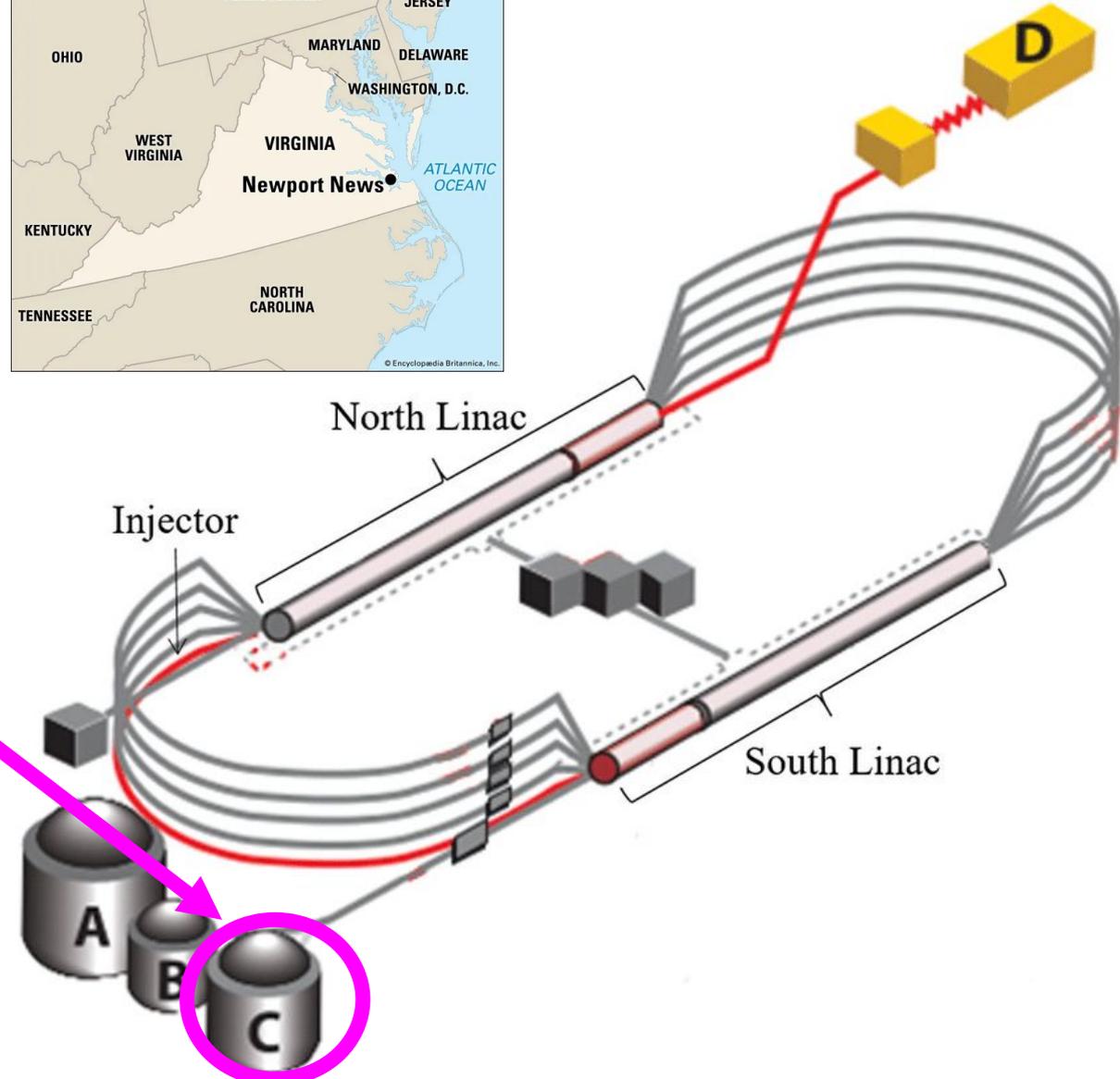
Jefferson Lab

Located in Newport News, Virginia

Electron Accelerator
- Up to 12GeV beam
- Continuous beam of up to 200 uA
- Supports 4 Experiment Halls

PionLT Experiment took place in Hall C
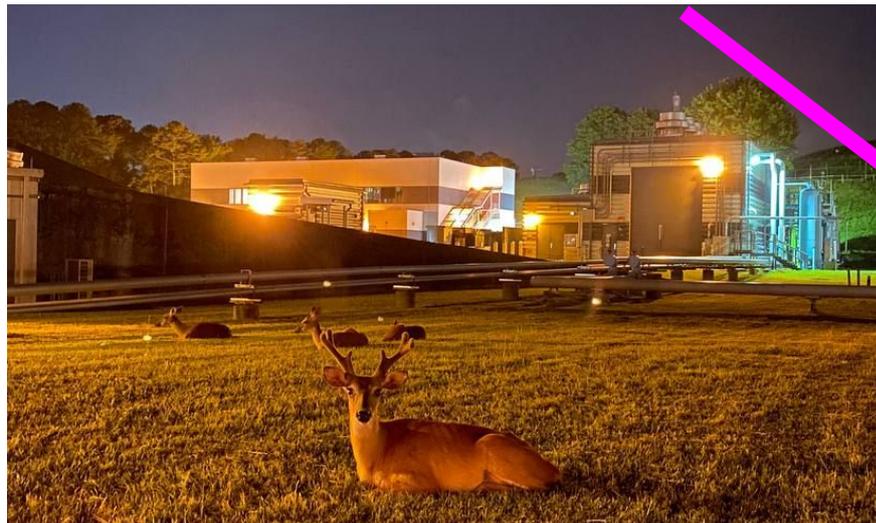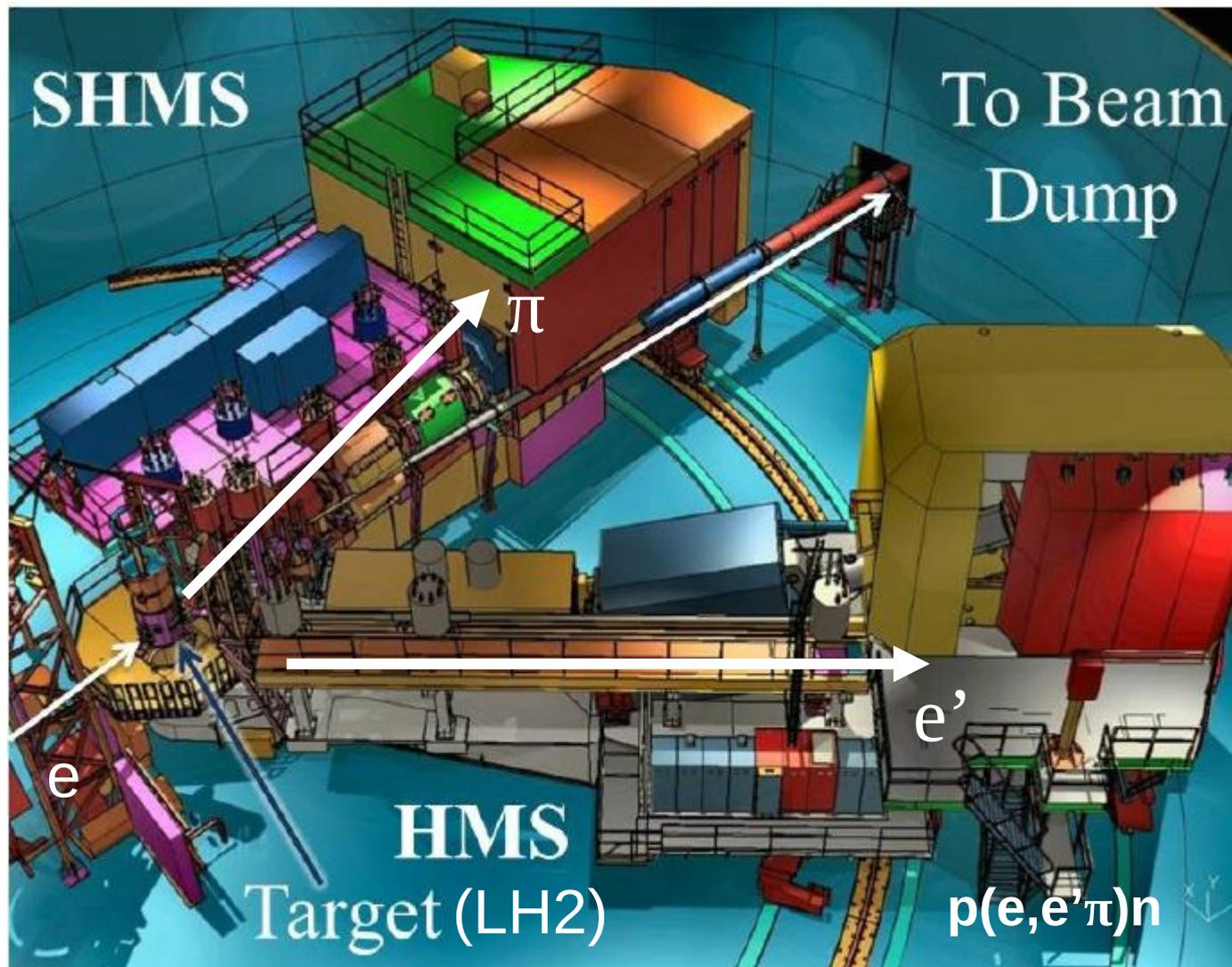
Hall C

Use the spectrometers in Hall C to detect pions and electrons in coincidence

Both spectrometers have:

Superconducting Magnets:
- Choose desired momenta

Rotate on Rails:
- Choose Angles in phase space

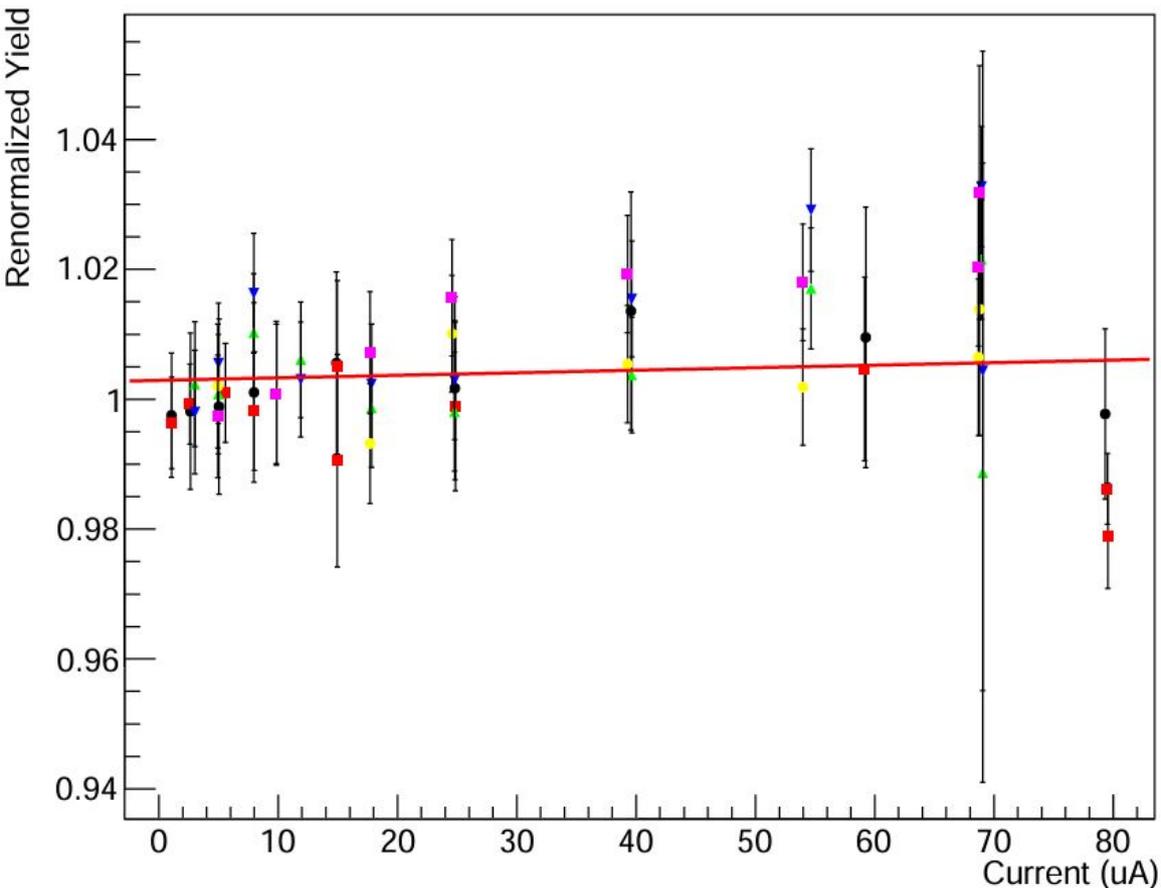PID detectors:
- Selection of particle type
    from background

Luminosity Analysis

Need to understand and remove any rate dependence in data.

Important as to do a LT Separation we need to combine settings with different physics and background rates.

1) Carbon Target – Understand Detectors

2) LH2 Singles – Understand target boiling

3) Physics Coincidences – Ensure no unknown effects.

Carbon Singles - Flat

Carbon Data Combined

Carbon Target shouldn't 'boil' so if detectors are understood there will be no rate dependence in Yield:

$$Yield = \frac{Events}{(Charge)*(\prod Efficiencies)}$$

With charge, tracking and live time corrections applied slope of combined Carbon singles settings:
    0.39 ± 0.50 %/100uA

Consistent with no slope,
Data is well understood.

LH2 Singles Lumi - Boiling
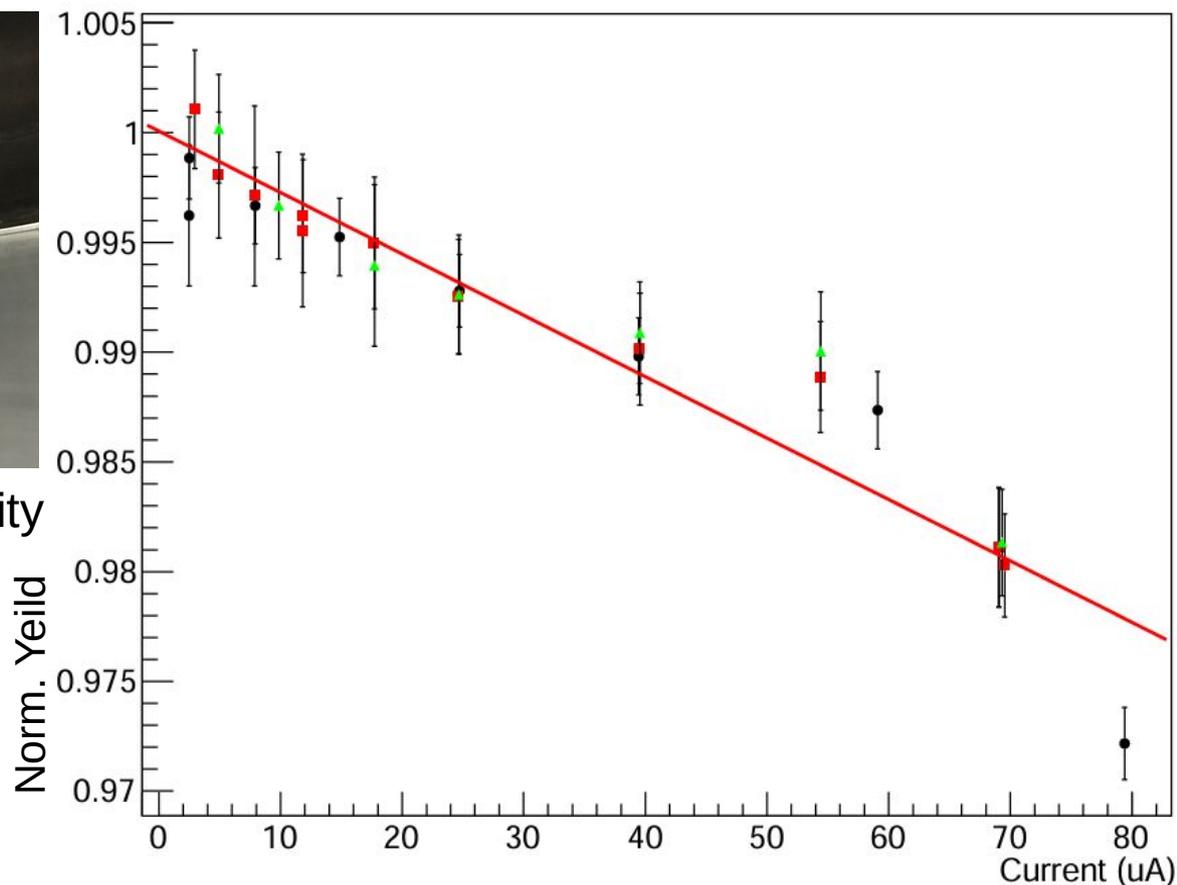
After ensuring that carbon data is understood move to Liquid Hydrogen target
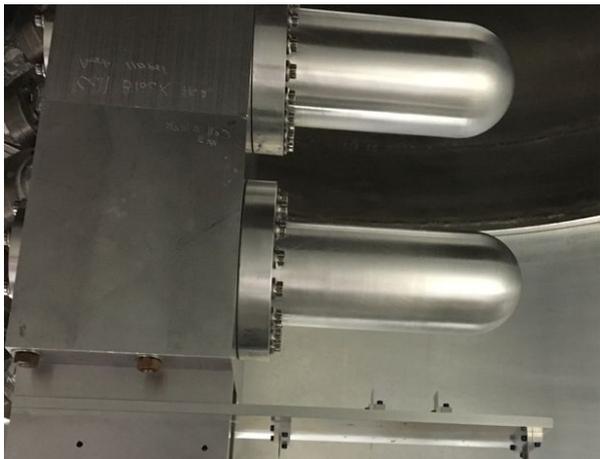
Here we expect "boiling" or change in density with current (beam heating)

Acquire boiling coefficient:
2.8 ± 0.17 ± 0.69 %/100uA
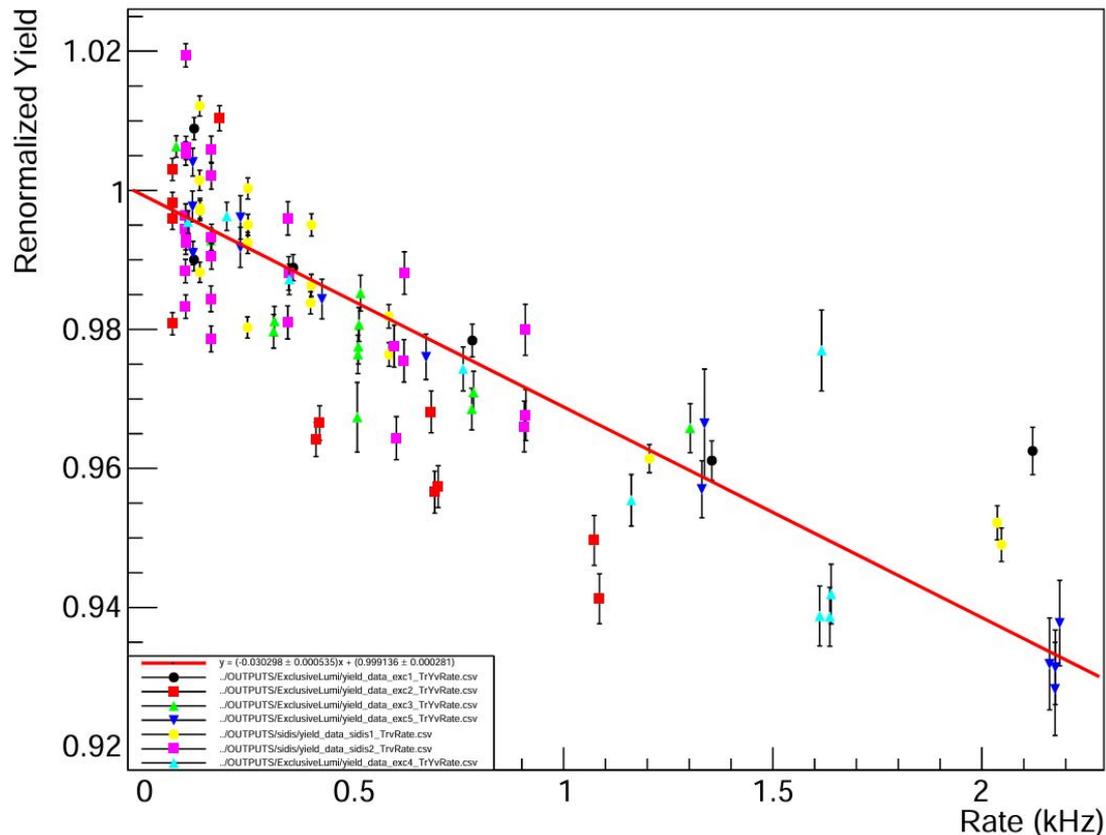   (Stat)   (Sys)

LH2 Physics Coin

Moving to coincidence between HMS and SHMS spectrometers (called Coin), specifically using data similar to what is used for physics studies.

Theoretically should have no slope

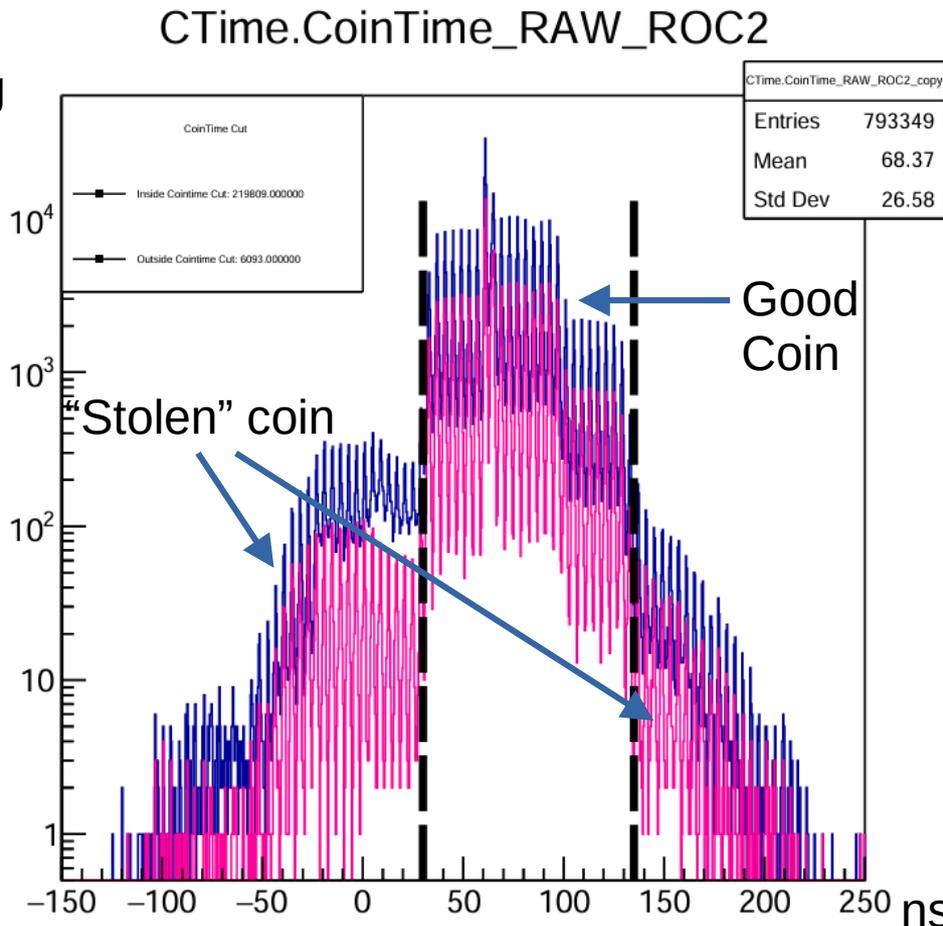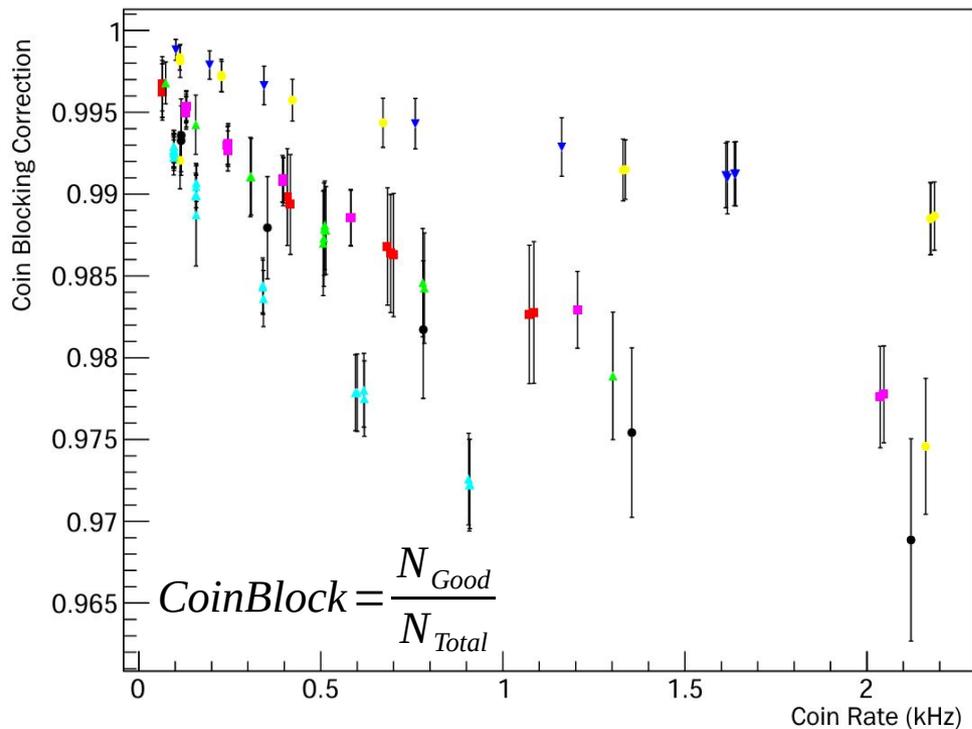With all corrections applied find additional rate dependence.

Still find additional effect coming from Coincidence Blocking

CoinRate Data Combined

# Coin Blocking Correction – 12 GeV Era

Coin Blocking is where noise events "steal" the coin time, Causing the event to be lost.
Fixed with by cutting on raw coin time and correcting

$$CoinBlock = \frac{N_{Good}}{N_{Total}}$$

CTime.CoinTime_RAW_ROC2

CTime.CoinTime_RAW_ROC2_copy	
Entries	793349
Mean	68.37
Std Dev	26.58

CoinTime Cut

Inside Cointime Cut: 219809.000000

Outside Cointime Cut: 6093.000000
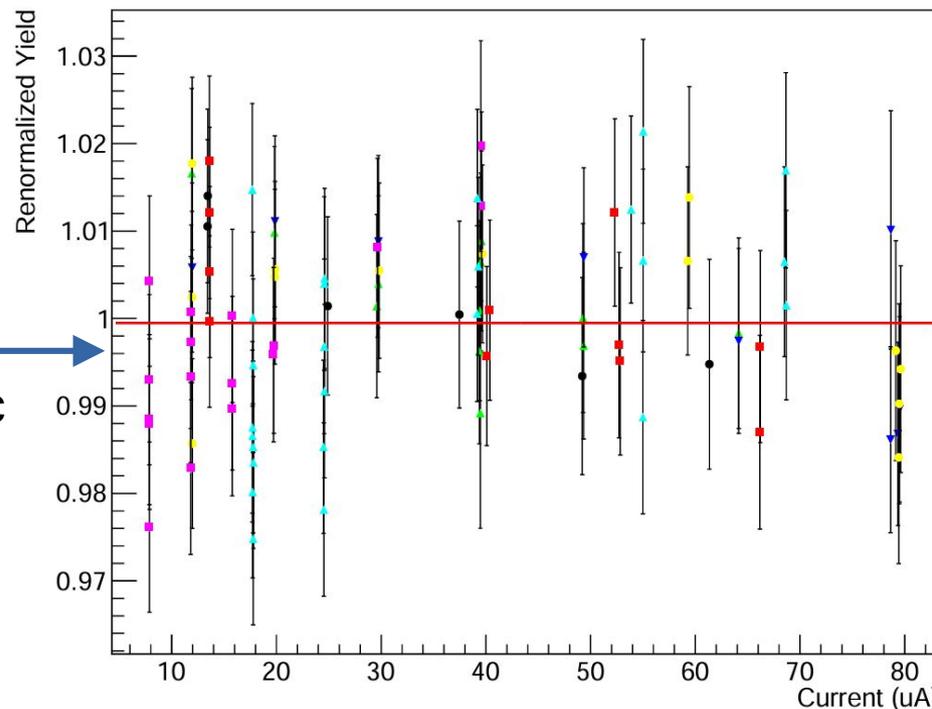
Good Coin

"Stolen" coin

ns

Coin Lumi Flat

After correcting for Coin Blocking plot is very nearly flat, but not within errors listed. So uncertainty must be under estimated.
To correct this, Add a small systematic uncertainty of 0.94% to Total Live Time
so that a constant fit has $\chi^2 = \sim 1$
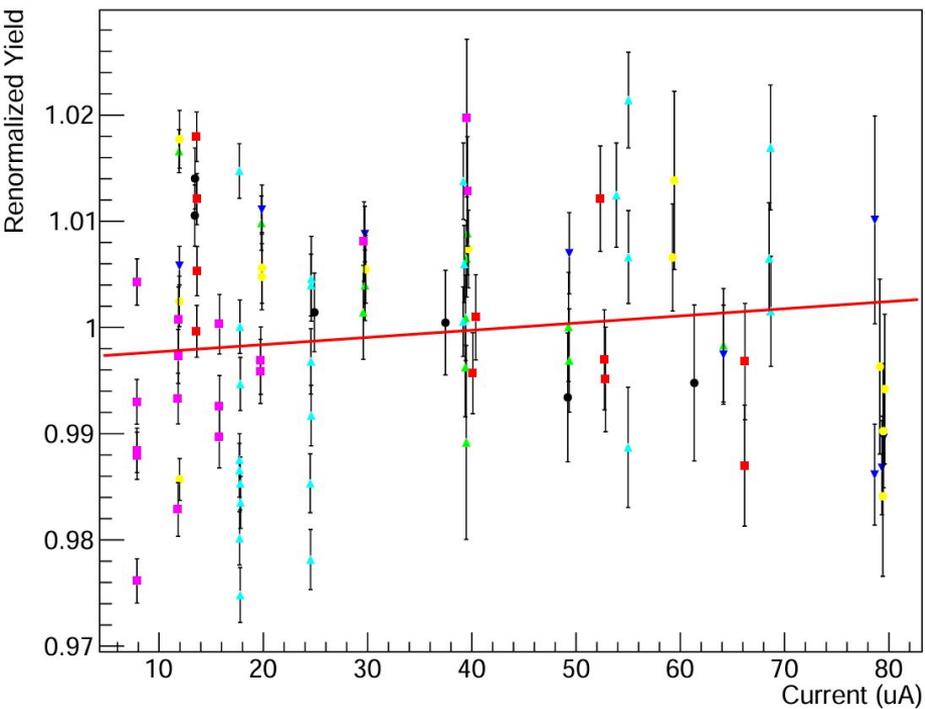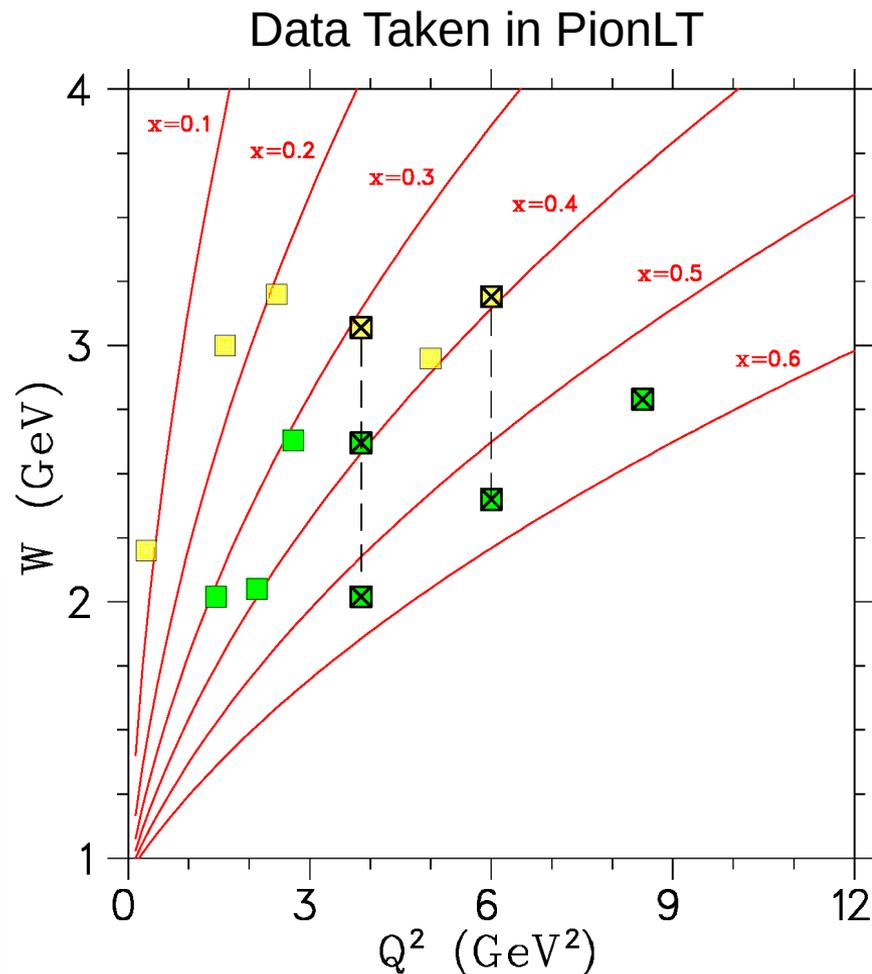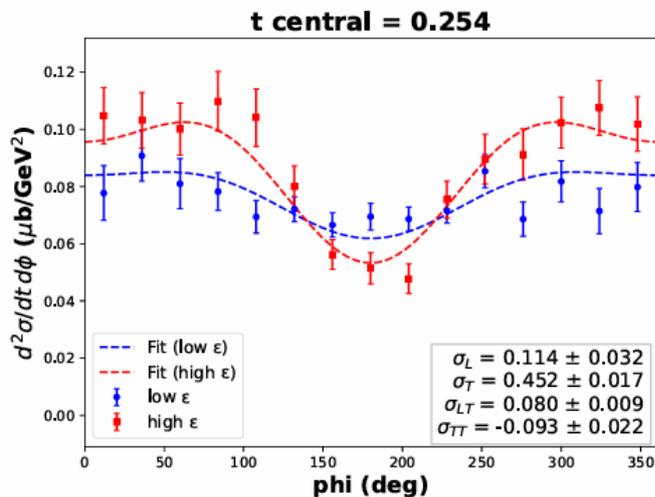

Add

Systematic

Conclusion

Recently concluded of Lumi study allows us to reliably extract cross sections.

The PionLT experiment has begun LT separation of cross-sections

Pion Production can access GPDs via LT Separations
GPDs are the exciting new frontier of proton structure
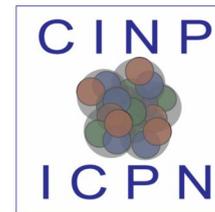
See Junaid's Talk
for details about
LT Separation

t central = 0.254

$\sigma_L = 0.114 \pm 0.032$
$\sigma_T = 0.452 \pm 0.017$
$\sigma_{LT} = 0.080 \pm 0.009$
$\sigma_{TT} = -0.093 \pm 0.022$

- - - Fit (low ε)
- - - Fit (high ε)
low ε
high ε

Data Taken in PionLT

Thank You

Questions?

University of Regina

NSERC CRSNG

Jefferson Lab
Thomas Jefferson National Accelerator Facility

CINP ICPN

Canadian Institute of Nuclear Physics

Institut canadien de physique nucléaire

Solving the Spin Crisis

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

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

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

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

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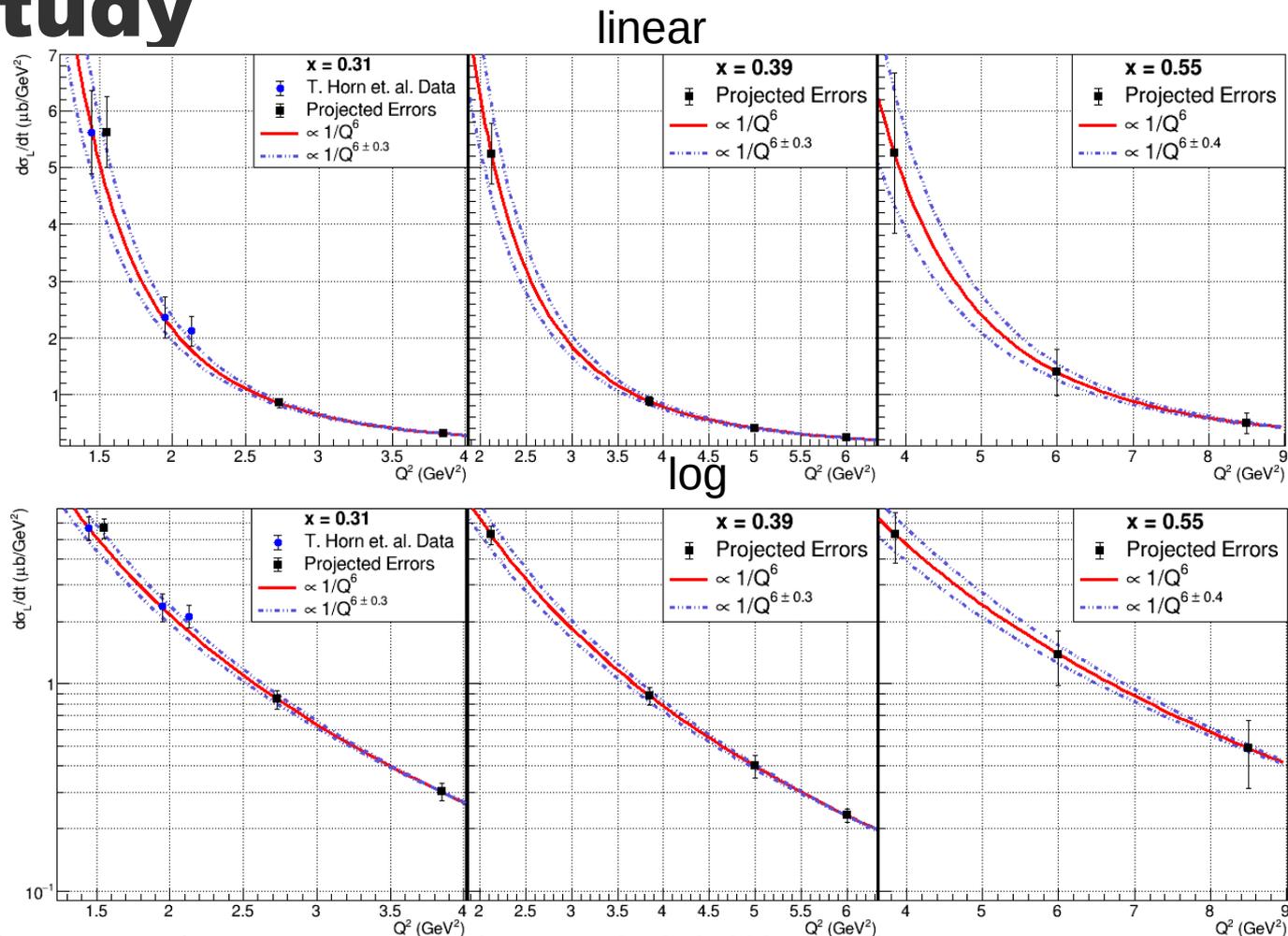
Allows extraction of Pressure, shear, and mass distribution from GPDs
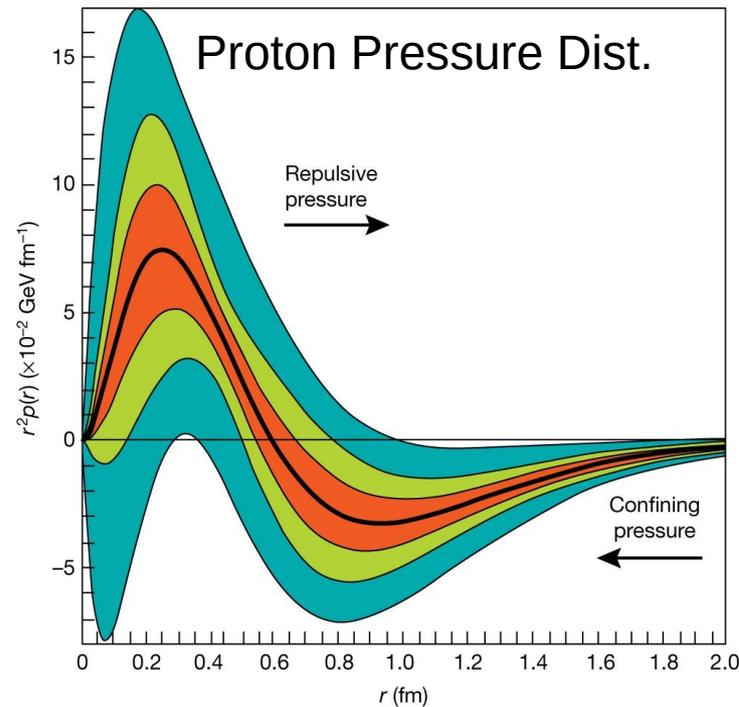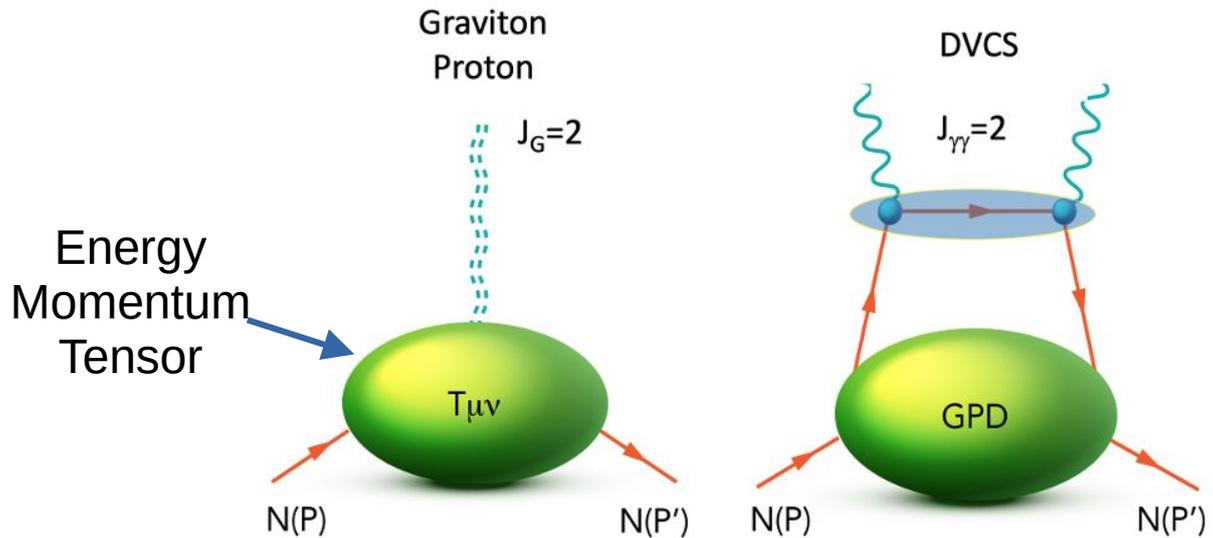
Scaling study

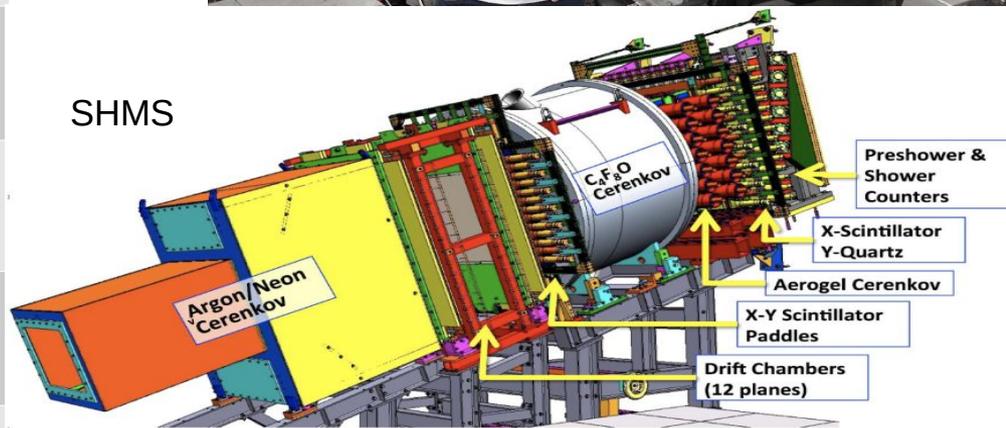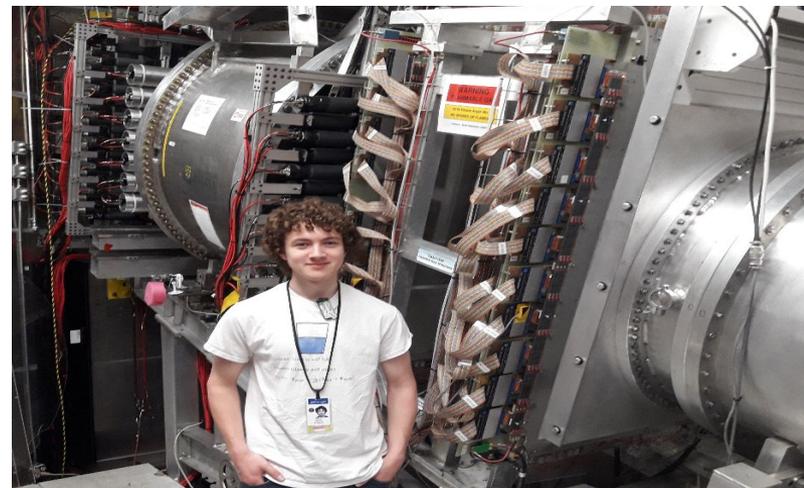Factorization regime will have characteristic $1/Q^6$ scaling of σ_L with fixed x_B

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

linear

log

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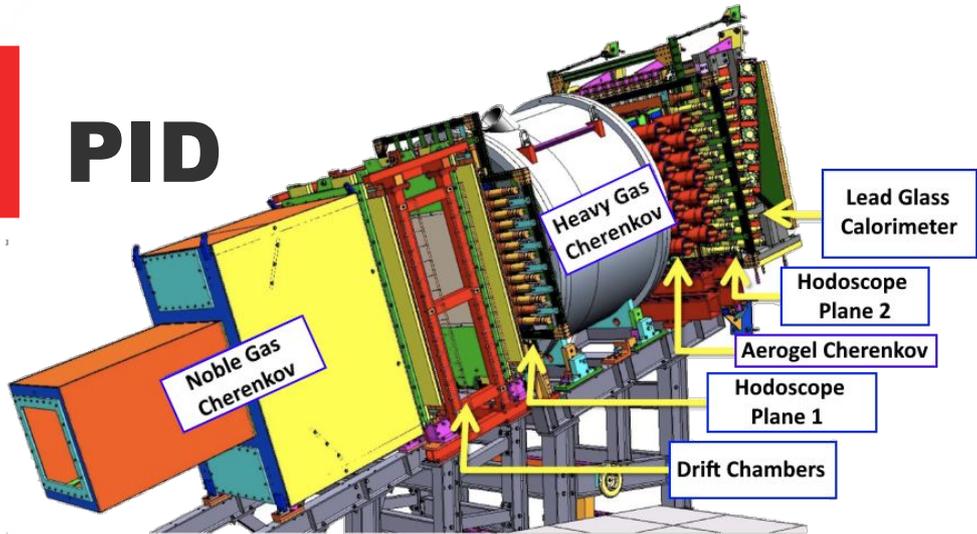
Detector Stack

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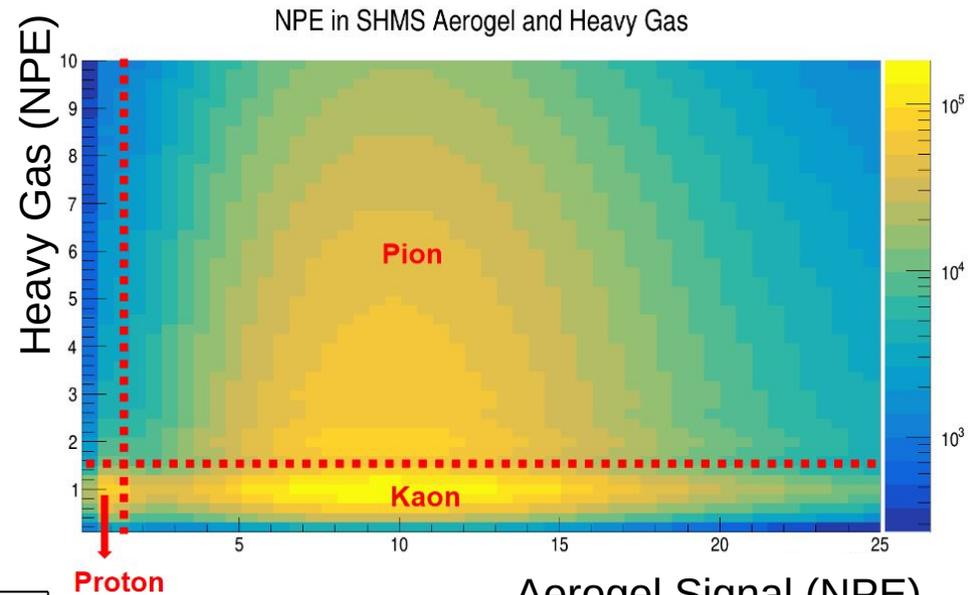Which give high momentum resolution and particle Identification

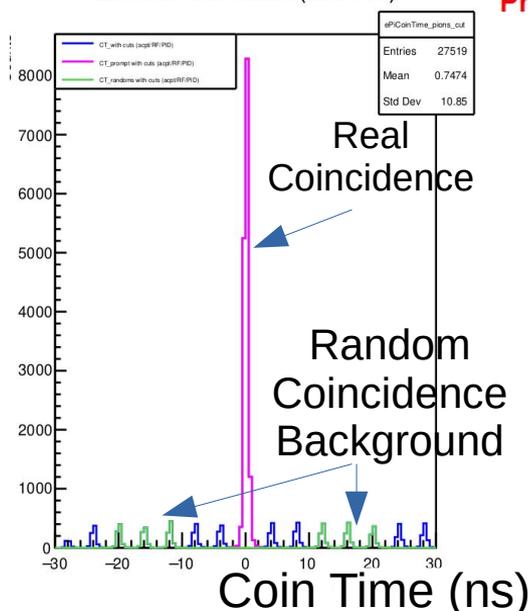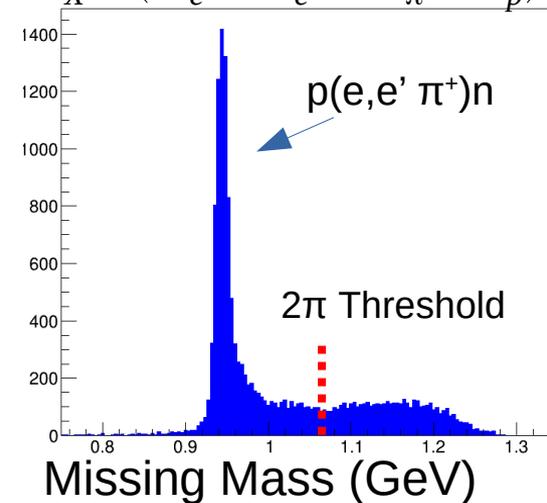| Detector	Purpose	Notes
Aerogel Cerenkov	Particle ID,K^+/p discrimination	n = 1.011, 1.015, 1.03, 1.05
Heavy Gas Cerenkov (HGC)	Particle ID, Trigger, $\pi^\pm$/$K^\pm$ discrimination	C_4F_{10} –Vary pressure to set n at $K^\pm$ threshold
Noble Gas Cerenkov	Particle ID, Trigger. e^+/π^+ at high momentum	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

PID

SHMS Detector Stack

NPE in SHMS Aerogel and Heavy Gas

Heavy Gas (NPE)

Pion

Kaon

Proton

Aerogel Signal (NPE)

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

Electron-Pion CTime (with cuts)

ePiCoinTime_pions_cut	
Entries	27519
Mean	0.7474
Std Dev	10.85

- CT_with cuts (acpt/RF/PID)
- CT_prompt with cuts (acpt/RF/PID)
- CT_randoms with cuts (acpt/RF/PID)

Real Coincidence

Random Coincidence Background

Coin Time (ns)

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

p(e,e' π⁺)n

2π Threshold

Missing Mass (GeV)

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

MC = 270.21+/-0.51

Data = 268.73+/-1.17

Ratio = 0.995+/-0.005

Stat. uncertainty only