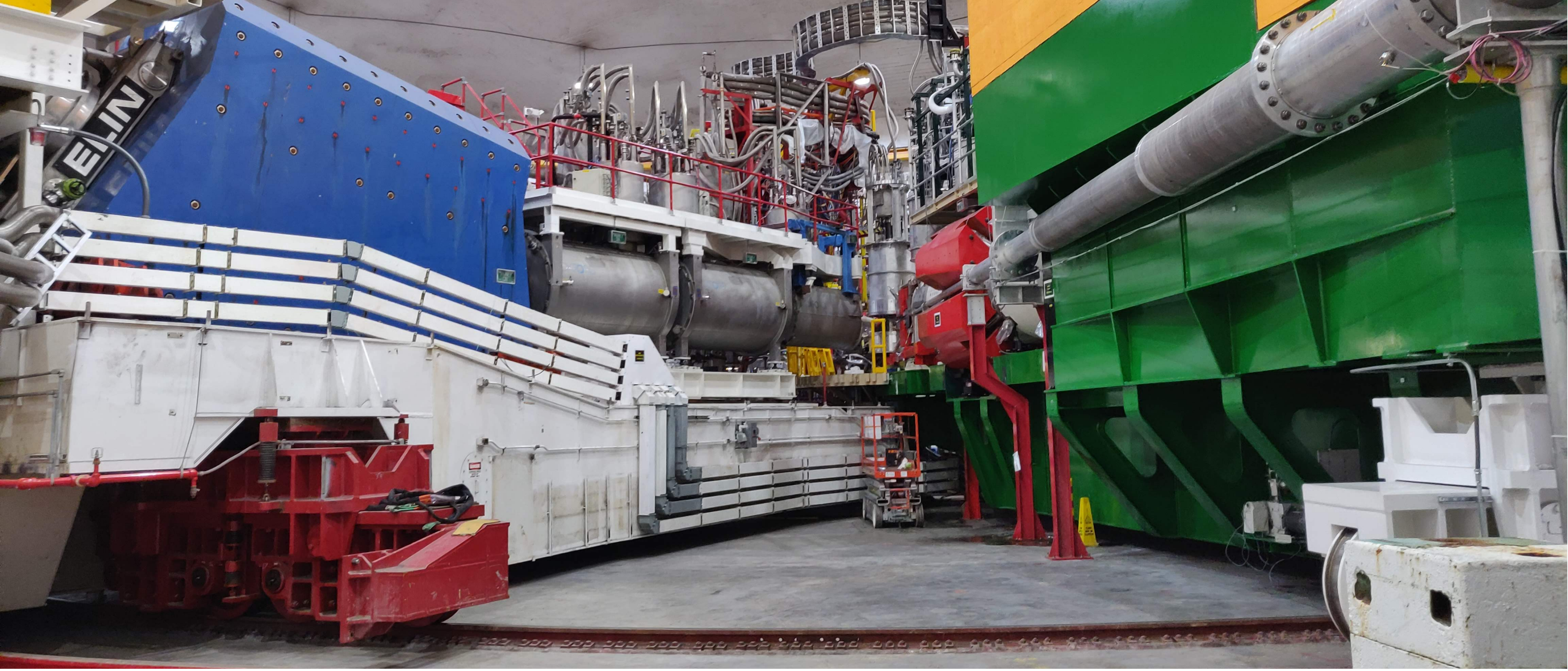

Update On GPD Factorization Validity Studies For Meson Production

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Introduction

This talk will cover Generalized Parton Distributions (GPDs) studies from the recent PionLT experiment.

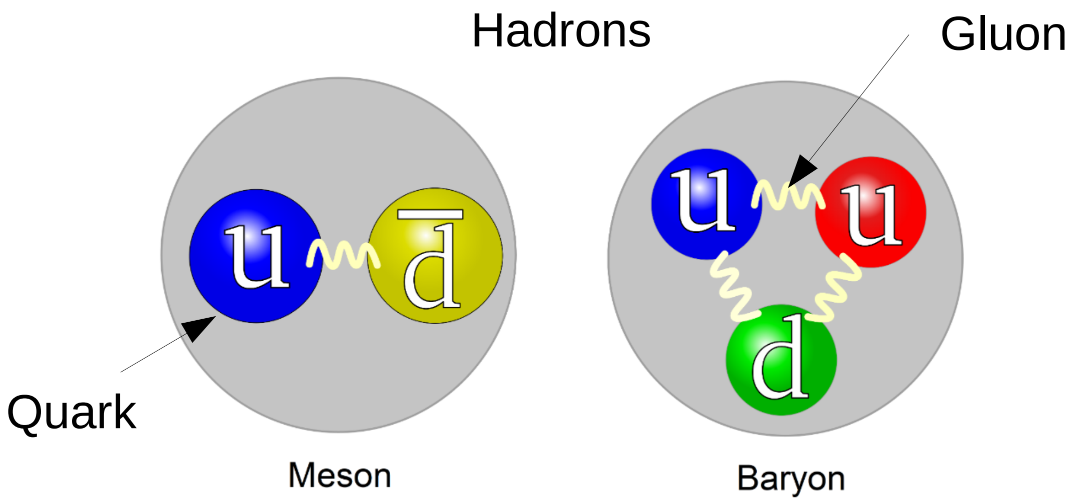
PionLT is an experiment that recently finished collecting data at Jefferson Lab, Hall C.

This talk will answer the following questions:

- What are GPDs and why do we care?
- What is a Longitudinal-Transverse (LT) separation?
- What are Jefferson Lab and Hall C?

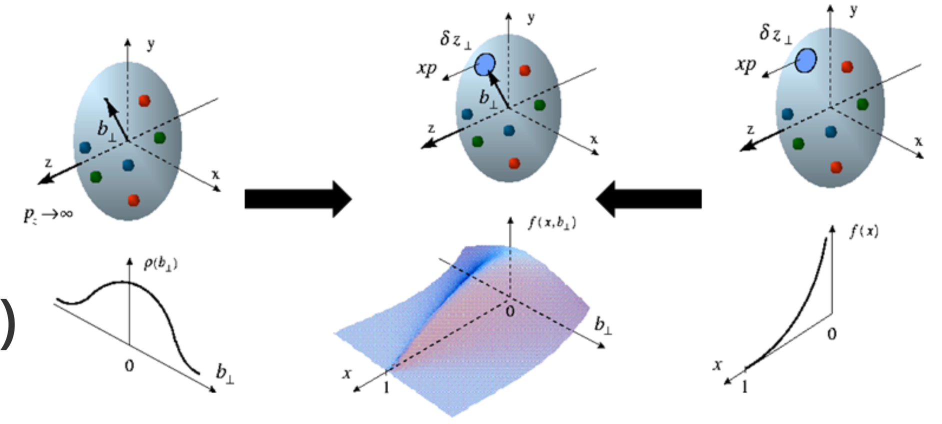
Motivation

- The goal is to the better understand Quantum Chromo-Dynamics (QCD) in the strong coupling regime.
- In particular QCD Struggles to predict the behavior of light quark systems, which make up visible matter
- Thus the main interest is to describe hadrons in terms of quarks and gluons
- One method of understanding bound systems is by using Generalized Parton Distributions (GPDs)



What are GPDs

- GPDs unify momentum-space parton densities (from inclusive deep-inelastic scattering), with spatial densities (eg. form factors).
- They are a generalization of Parton Distribution Functions (PDFs) to model different parton configurations
- GPDs thus describe 3 of the 6 degrees of freedom (1 spatial and 2 momentum)



Form factors - Transverse charge and current densities

Generalised Parton Distributions - Correlated quark momentum and helicity distributions in transverse space

Parton Distribution Functions - Quark longitudinal helicity and momentum distributions

Accessing GPDs

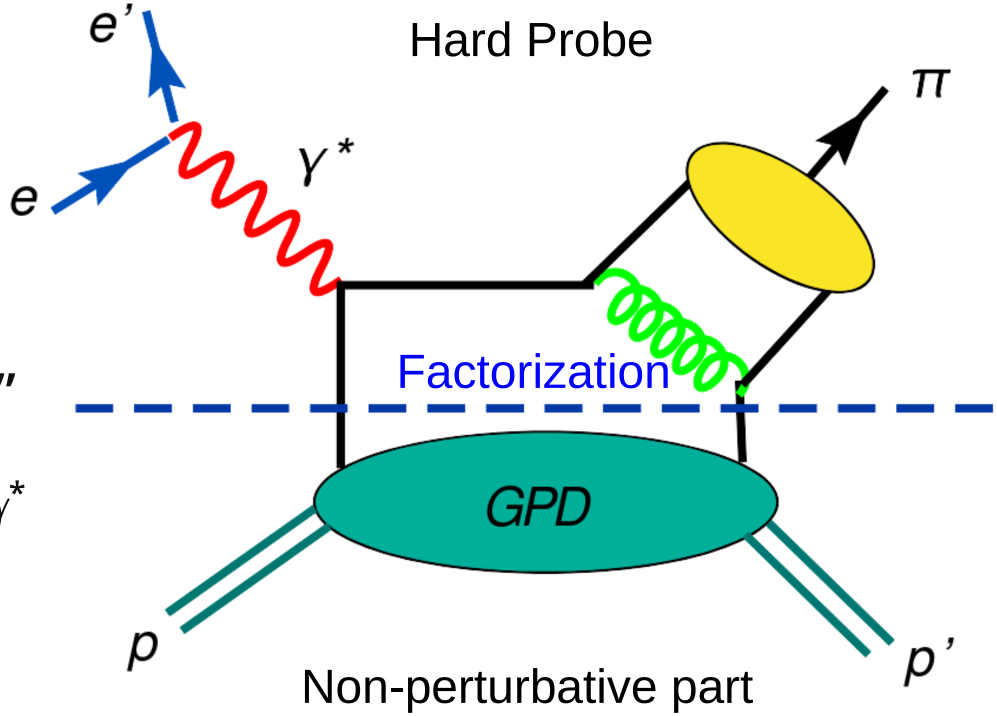
Using a recently proven factorization theorem to separate the process amplitude into two parts:

- 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].

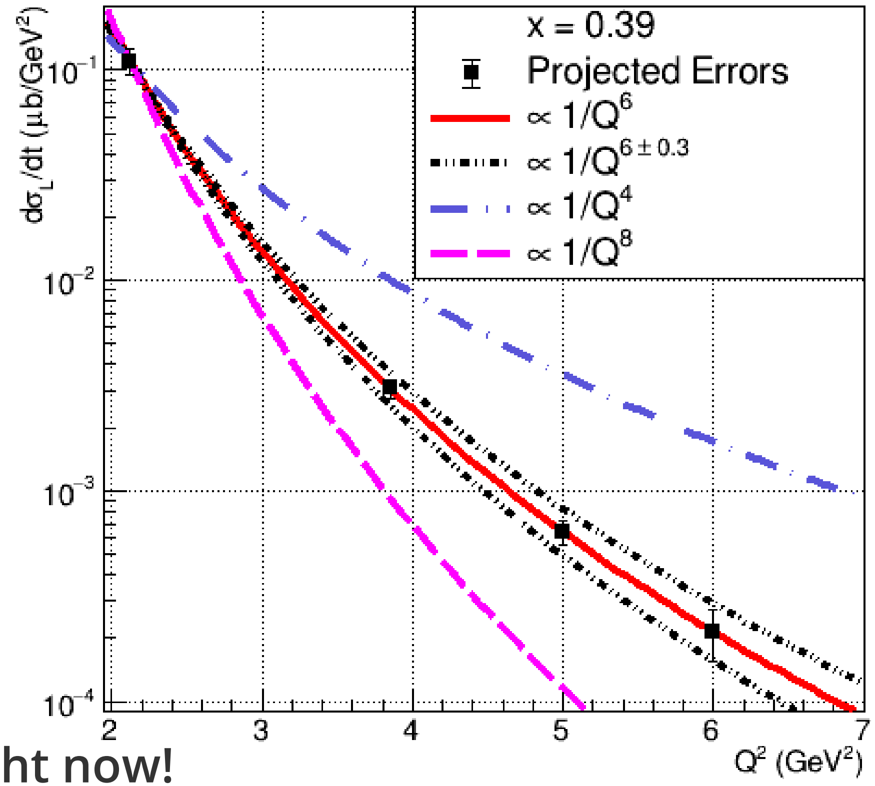


Factorization Validity

- 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 it will have major validity implications for all meson production GPD experiments in this Q^2 regime.
  - Some experiments of this type are running right now!

Projected Scaling Study

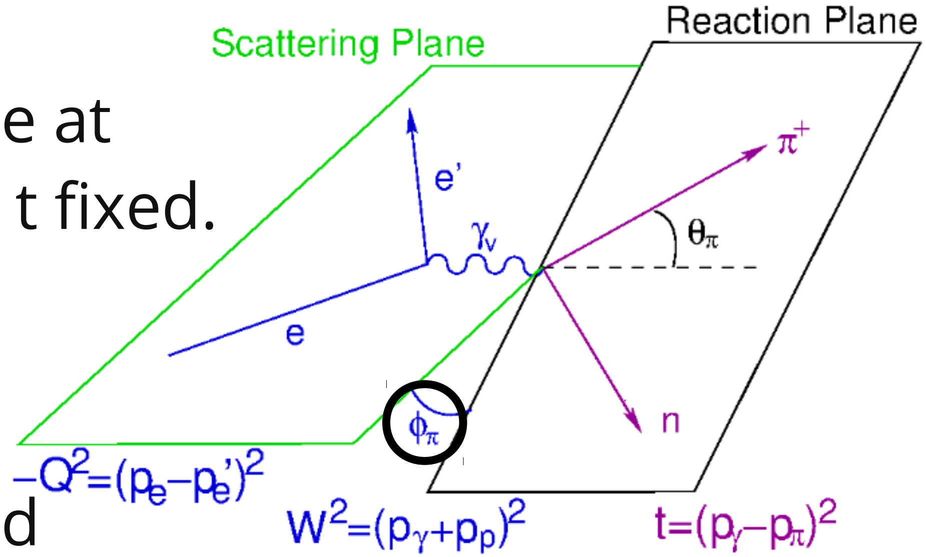


X_B - Bjorken scaling variable, and represents longitudinal momentum fraction

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
- Longitudinal component is not allowed for real photons, only existed due to γ being virtual.



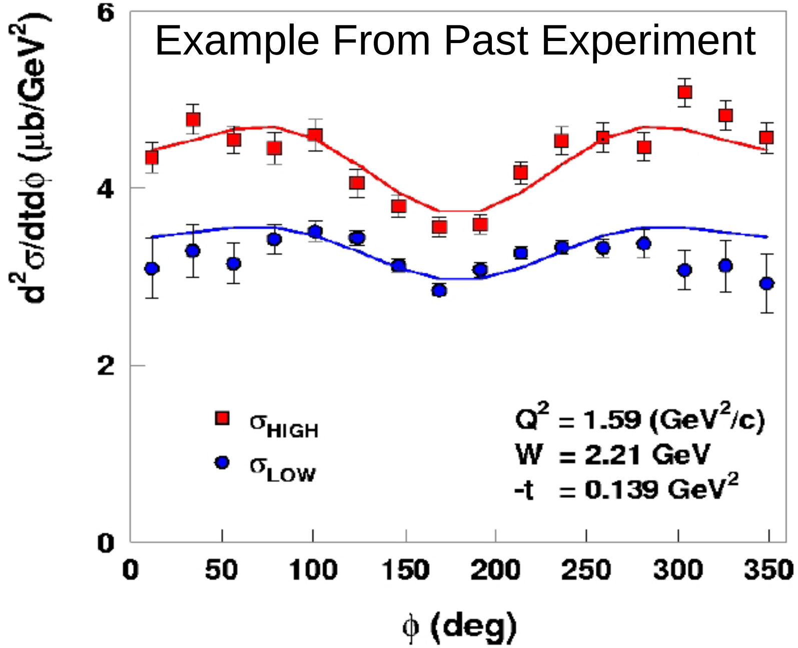
Virtual-photon polarization:

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

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:

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

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

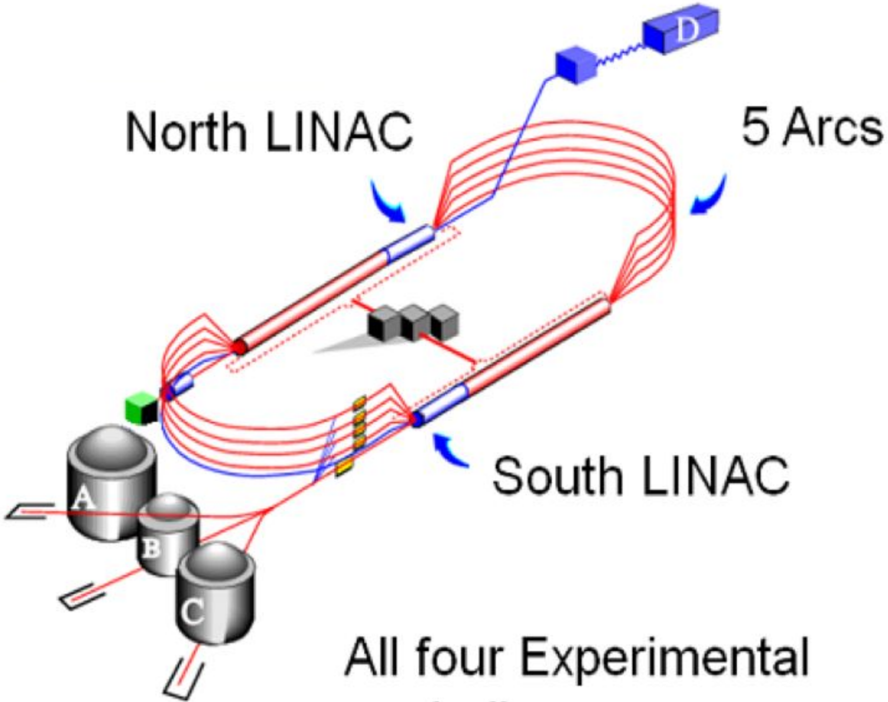
This means we must keep excellent control of our systematic errors

Virtual-photon polarization:

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

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! $(\Delta\epsilon \propto \Delta E_{Beam})$



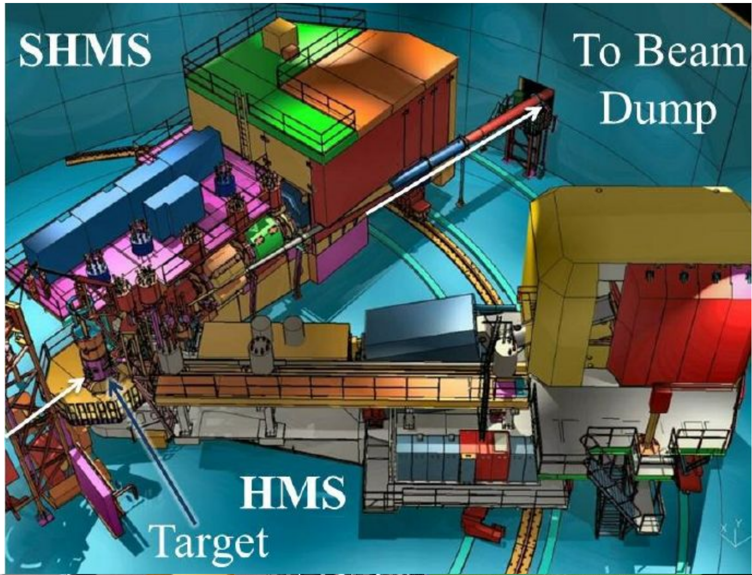
All four Experimental halls can run simultaneously

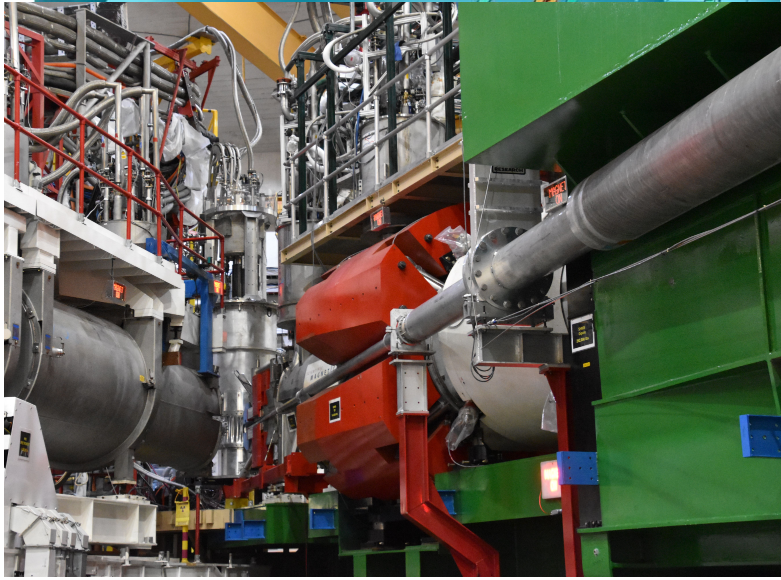
Hall C

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)

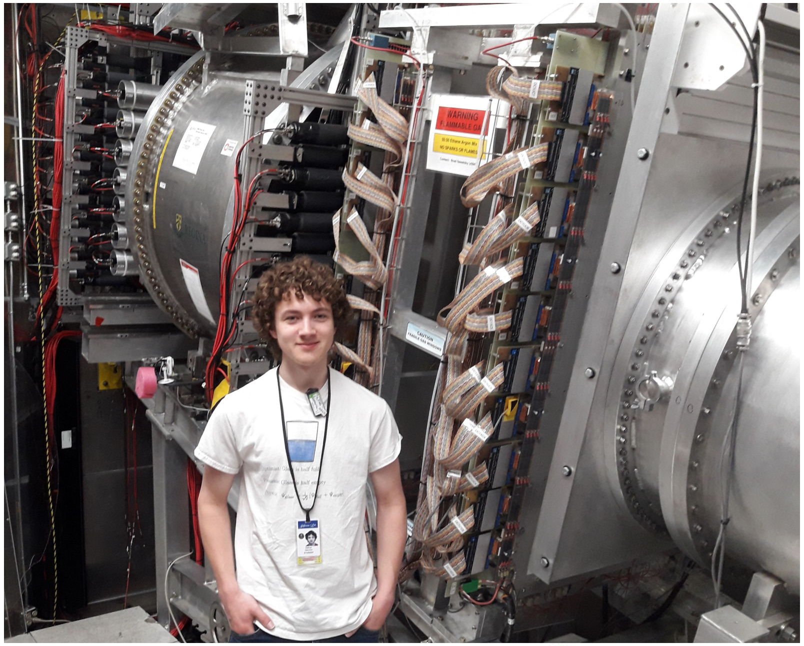
Spectrometer	Angle Range (Degrees)	Momentum Range (GeV/c)
HMS	10.5 - 90	0.5 - 7
SHMS	5.5 - 40	0.5 - 11





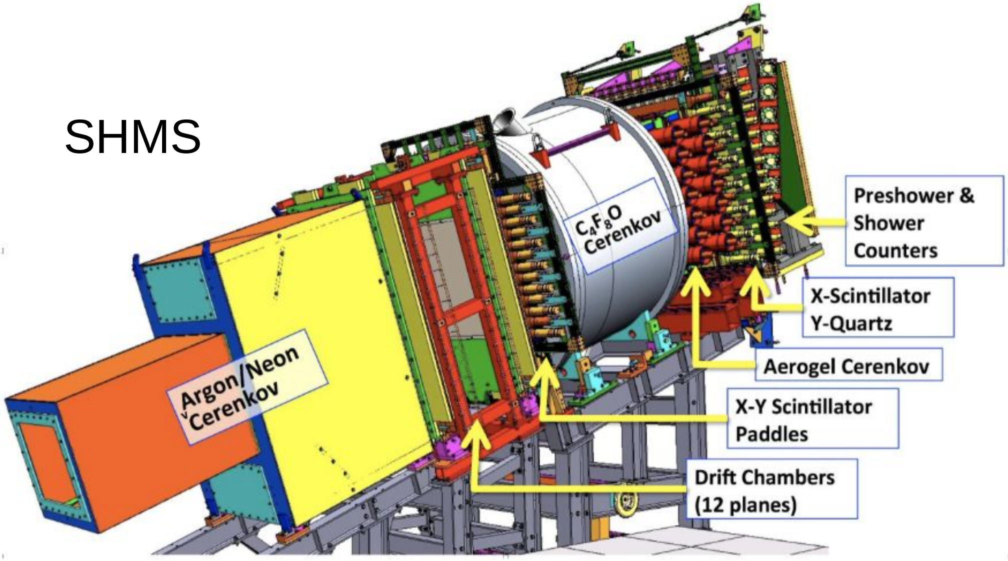
Detector Stack

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



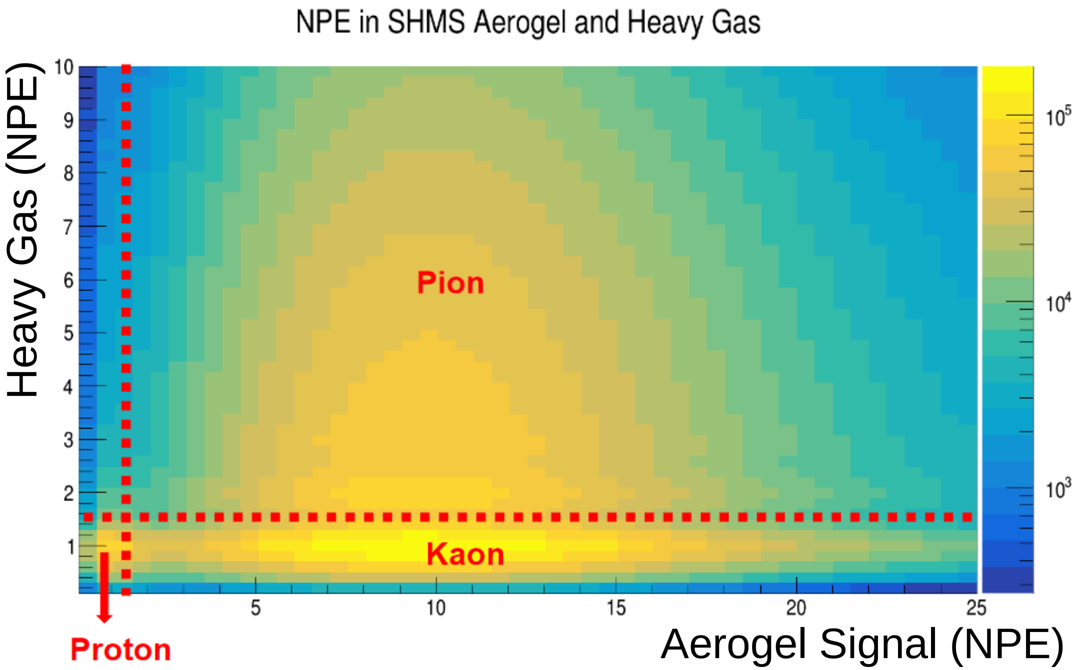
Detector	Purpose	Notes
Aerogel Cerenkov	Particle ID,K^+/p discrimination	n = 1.011, 1.015, 1.03, 1.05
Heavy Gas Cerenkov (HGC)	Particle ID, Trigger, $\pi^\pm/K^\pm$ discrimination	C_4F_{10} –Vary pressure to set n at $K^\pm$ threshold
Noble Gas Cerenkov	Particle ID, Trigger. e^+/π^+ at high momentum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

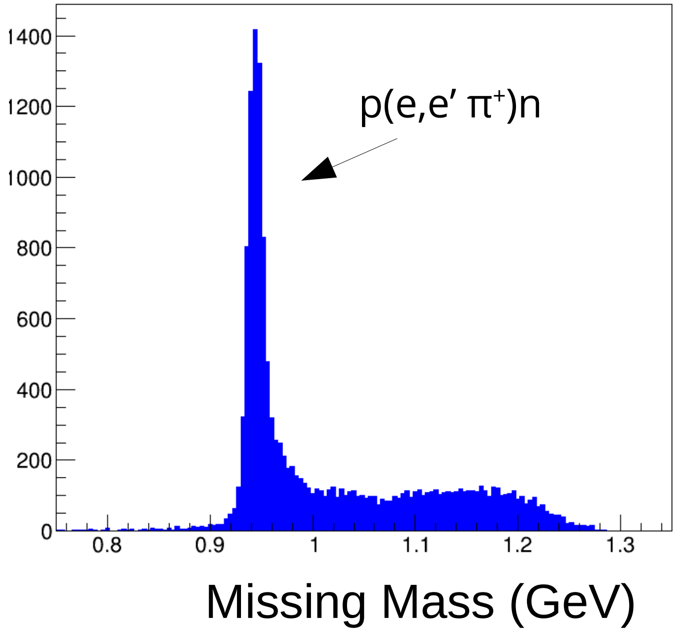
SHMS



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



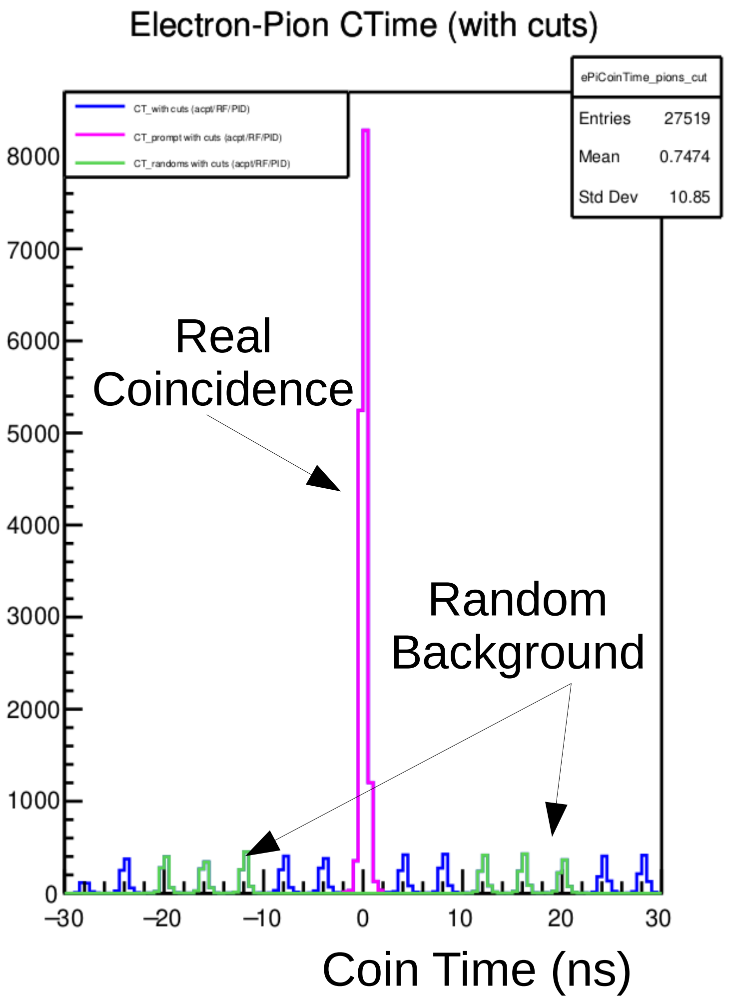


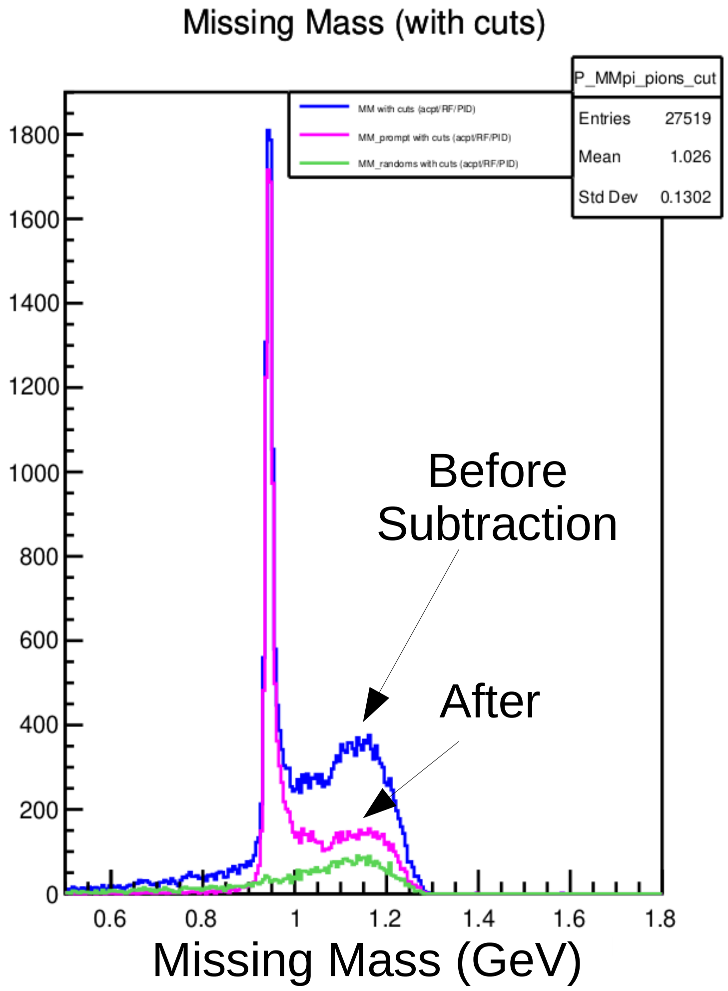
Missing Mass Definition:

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

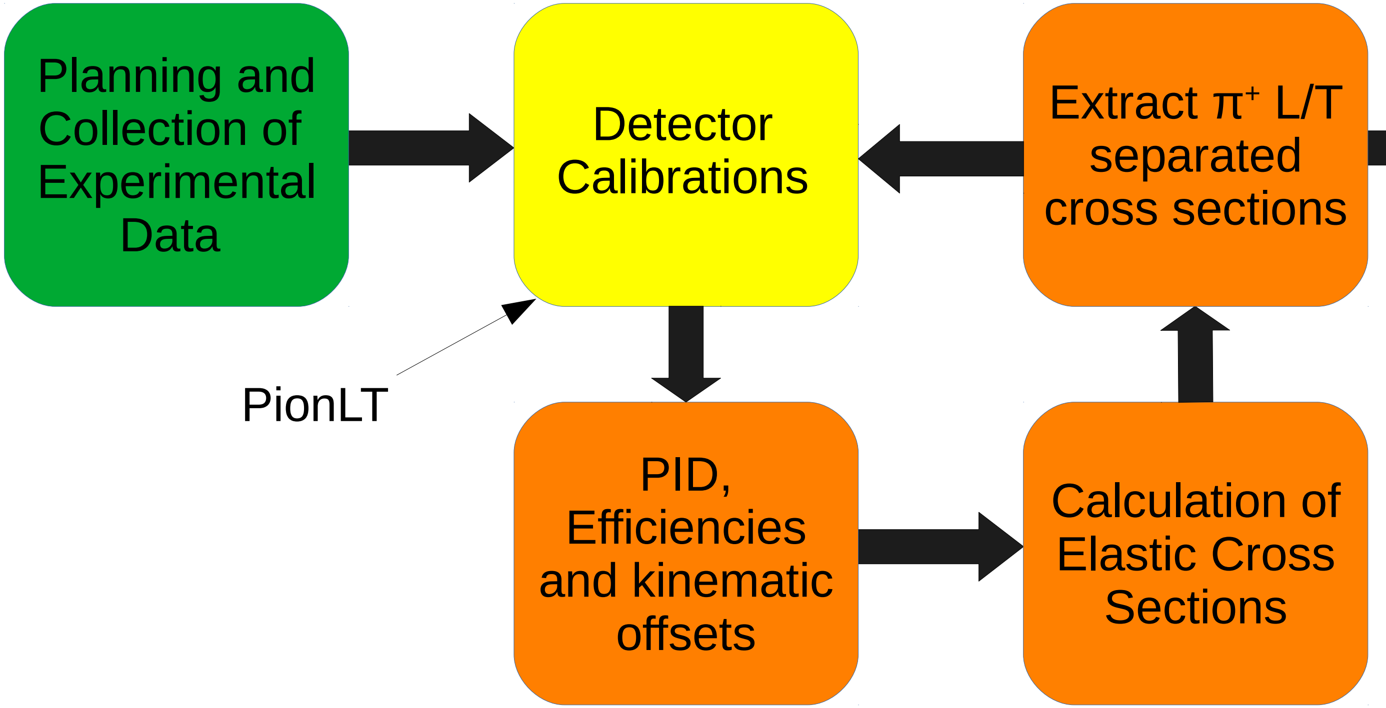
Background Removal

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





Step to Extract Cross Sections



Planning and Collection of Experimental Data

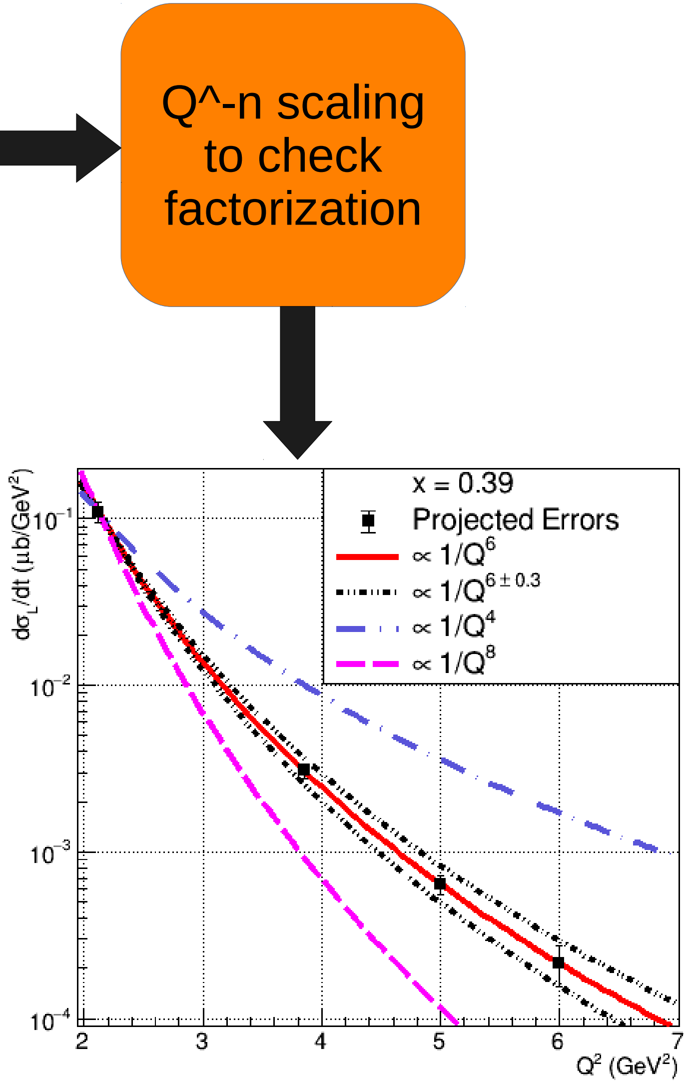
Detector Calibrations

Extract π^+ L/T separated cross sections

PID, Efficiencies and kinematic offsets

Calculation of Elastic Cross Sections

PionLT



Q^-n scaling to check factorization

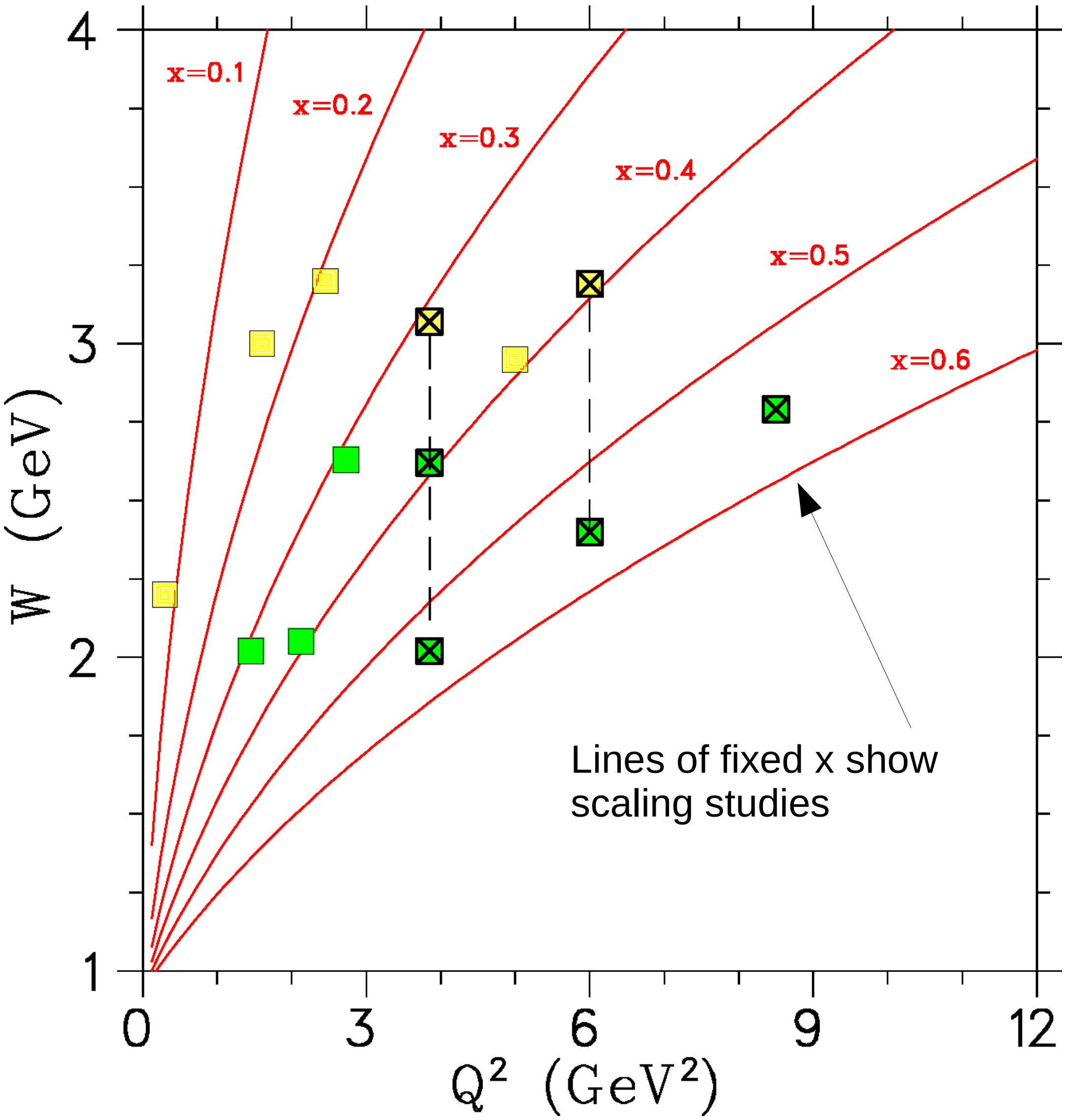
In order to reduce systematic uncertainties to an acceptable level, multiple passes through the analysis may be required.

After performing the LT separation finding the Q^2 dependence is simply a matter of fitting it.

Outlook\Summary

- Took data for three separate scaling studies
    - At x=0.31, 0.39, and 0.55
- Plot shows the LT separated data points taken in PionLT
    - PionLT is highly optimized, many data points serve multiple purposes
        - e.g. Form Factor extraction, and beam spin asymmetries
- Analysis is ongoing
- Expect publications sometime in 2025

Data Taken in PionLT



Lines of fixed x show scaling studies

Thank You

Questions?

NSERC grant:
SAPIN-2021-00026

NSERC CRSNG

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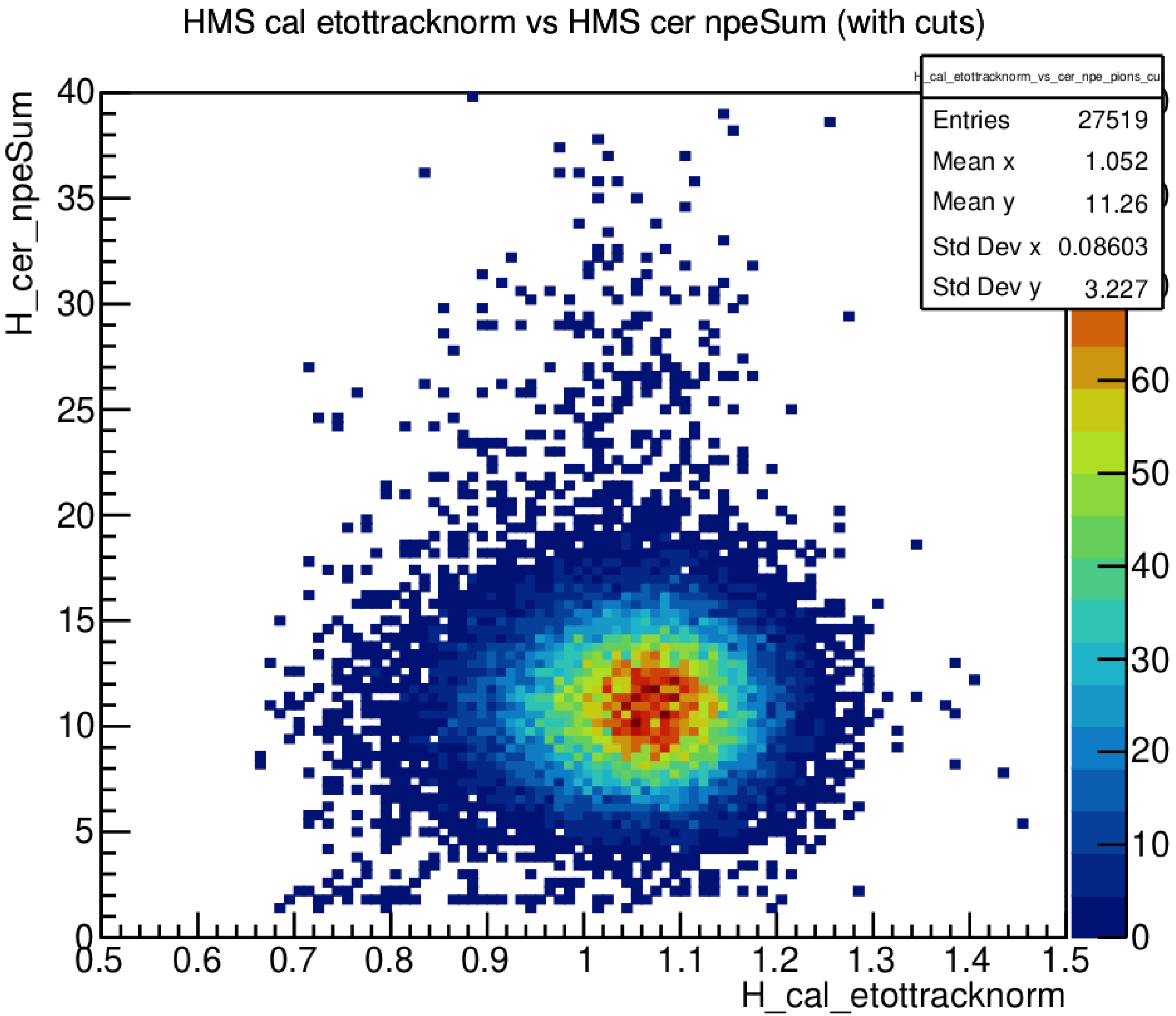
HMS PID

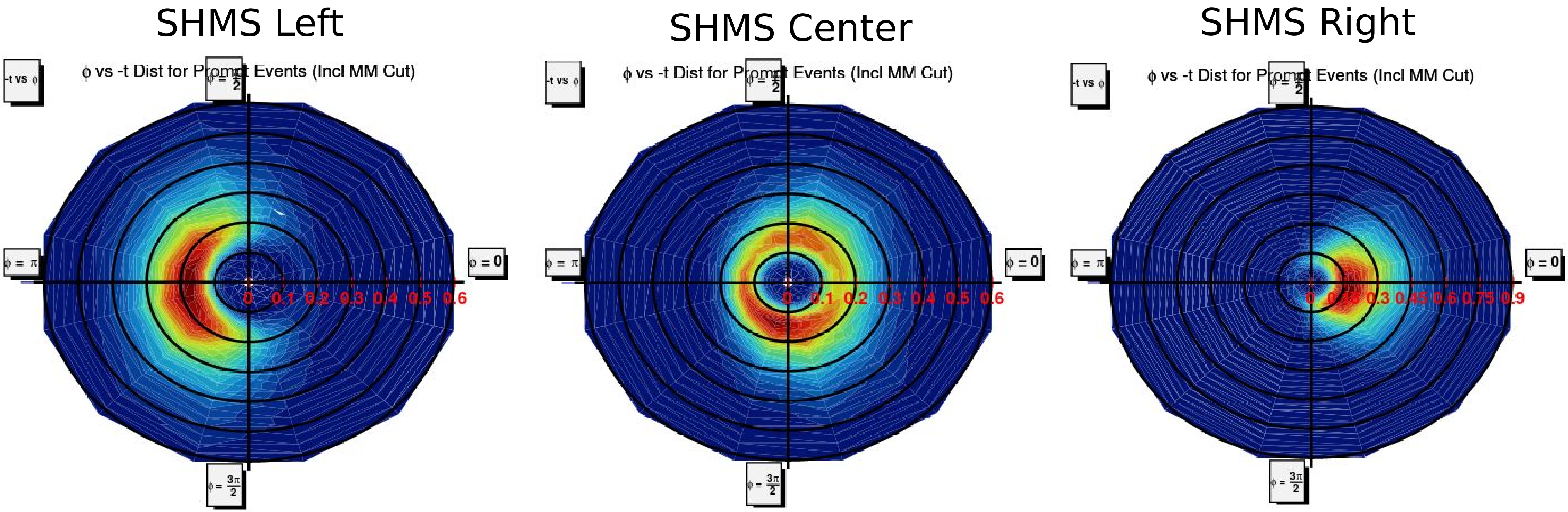

HMS cal etottracknorm vs HMS cer npeSum (with cuts)
H_cal_etottracknorm_vs_cer_npe_pions_cu
Entries 27519
Mean x 1.052
Mean y 11.26
Std Dev x 0.08603
Std Dev y 3.227
H_cer_npeSum
0
5
10
15
20
25
30
35
40
0.5
0.6
0.7
0.8
0.9
1
1.1
1.2
1.3
1.4
1.5
H_cal_etottracknorm
0
10
20
30
40
50
60

ϕ Coverage

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

This is done to determine the variation of **σ_L, σ_T, σ_{LT}, and σ_{TT}.**

To control systematics an excellent understanding of the spectrometers is required

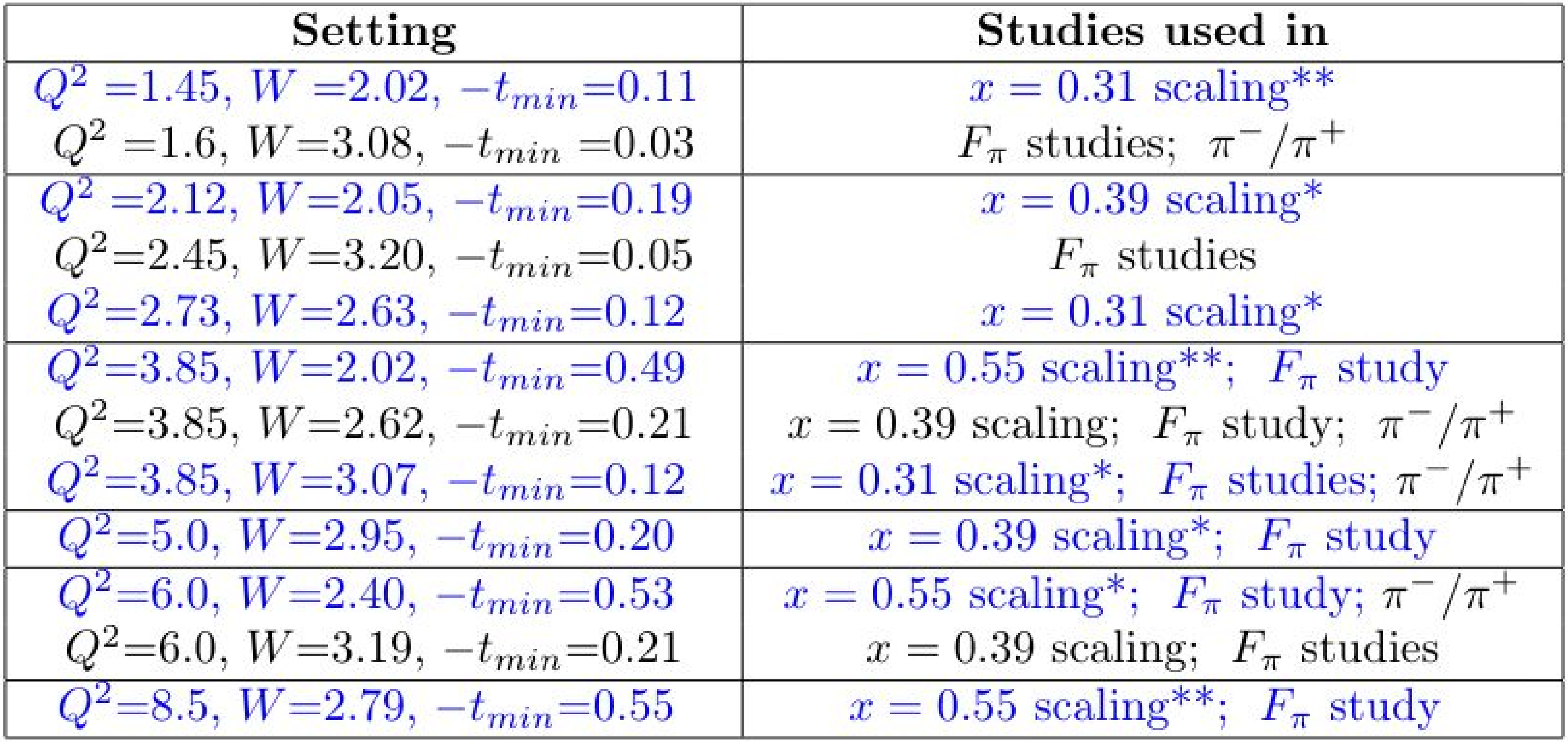

SHMS Left

SHMS Center

SHMS Right

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

Kinematic reach

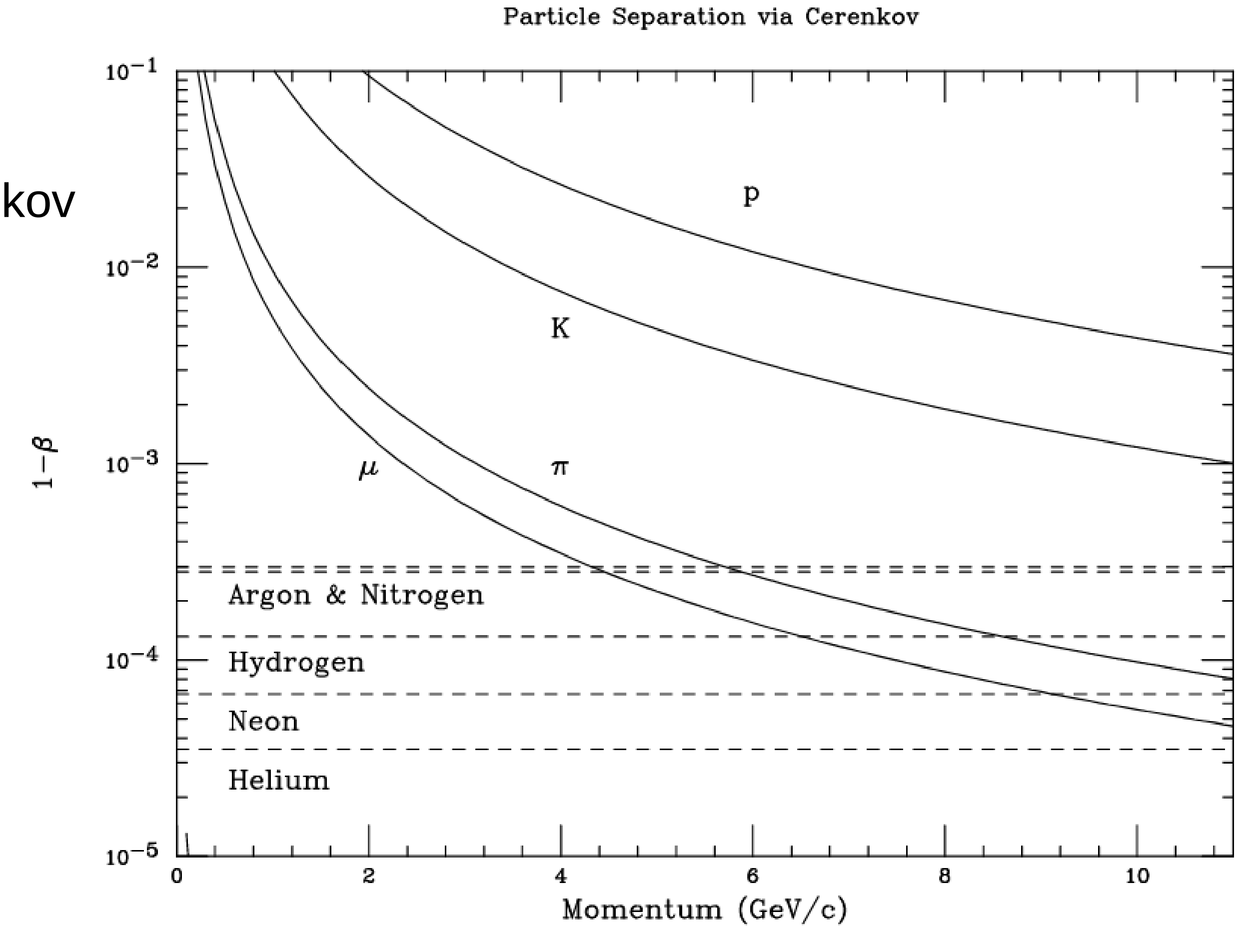


Setting	Studies used in
Q^2 =1.45, W =2.02, $-t_{min}$=0.11	$x = 0.31$ scaling**
Q^2 =1.6, W=3.08, $-t_{min}$ =0.03	F_π studies; π^-/π^+
Q^2 =2.12, W=2.05, $-t_{min}$=0.19	$x = 0.39$ scaling*
Q^2=2.45, W=3.20, $-t_{min}$=0.05	F_π studies
Q^2=2.73, W=2.63, $-t_{min}$=0.12	$x = 0.31$ scaling*
Q^2=3.85, 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

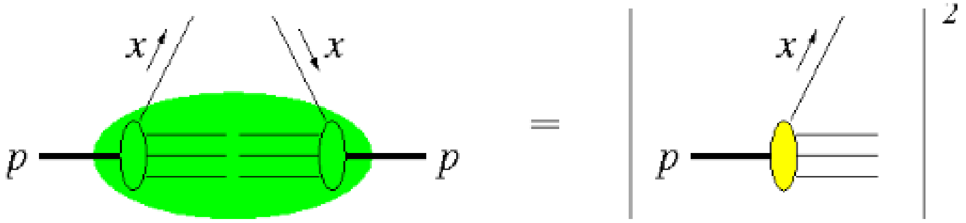
Aerogel set to have Kaons cherenkov
Heavy Gas set for Pions
Nobel Gas set for electrons

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

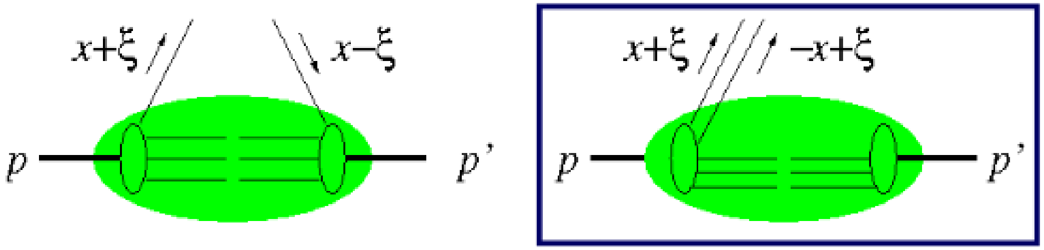


GPDs in Deep Exclusive Meson Production

PDFs : probability of finding a parton with longitudinal momentum fraction x and specified polarization in fast moving hadron.



GPDs : interference between partons with $x+\xi$ and $x-\xi$, interrelating longitudinal momentum & transverse spatial structure of partons within fast moving hadron.



A special kinematic regime is probed in Deep Exclusive Meson Production, where the initial hadron emits $q\overline{q}$ or gg pair.

- No counterpart in usual PDFs.
- Since GPDs correlate different parton configurations in the hadron at quantum mechanical level,
  - GPDs determined in this regime carry information about $q\overline{q}$ and gg-components in the hadron wavefunction.

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Generalized Parton Distributions (GPDs)

- **GPDs interrelate the longitudinal momentum and transverse spatial structure of partons within a fast moving hadron.**
- **GPDs are universal quantities and reflect nucleon structure independently of the probing reaction.**

- At leading twist–2, four quark chirality conserving GPDs for each quark, gluon type.
- Because quark helicity is conserved in the hard scattering regime, the produced meson acts as helicity filter.
  - Pseudoscalar mesons → $\tilde{H}$ $\tilde{E}$
  - Vector mesons → 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

- Additional chiral–odd GPDs (H_T E_T $\tilde{H}_T$ $\tilde{E}_T$) offer a new way to access the transversity–dependent quark–content of the nucleon.

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Links to other nucleon structure quantities

- First moments of GPDs are related to nucleon elastic form factors through model-independent sum rules:

$$\left.\begin{aligned} \sum\nolimits_q e_q \int_{-1}^{+1} dx\, H^q(x,\xi,t) &= F_1(t) \\ \sum\nolimits_q e_q \int_{-1}^{+1} dx\, E^q(x,\xi,t) &= F_2(t) \end{aligned}\right\}$$

Dirac and Pauli elastic nucleon form factors. *t* -dependence fairly well known.

$$\sum\nolimits_q e_q \int_{-1}^{+1} dx\, \tilde{H}^q(x,\xi,t) = G_A(t)$$

Isovector axial form factor. *t* –dep. poorly known.

$$\sum\nolimits_q e_q \int_{-1}^{+1} dx\, \tilde{E}^q(x,\xi,t) = G_P(t)$$

Pseudoscalar form factor. Very poorly known.

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