

**Measurement of the Deeply Virtual Neutral Pion  
Electroproduction Cross Section at the Thomas  
Jefferson National Accelerator Facility at 10.6 GeV**

by

Robert Johnston

Submitted to the Department of Physics  
in partial fulfillment of the requirements for the degree of

Interdisciplinary PhD in Physics and Statistics

at the

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

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**Abstract**

Deeply virtual exclusive reactions provide unique channels to study both transverse and longitudinal properties of the nucleon simultaneously, allowing for a 3D image of nucleon substructure. This presentation will discuss work towards extracting an absolute cross section for one such exclusive process, deeply virtual neutral pion production, using 10.6 GeV electron scattering data off a proton target from the CLAS12 experiment in Jefferson Lab Hall B . This measurement is important as exclusive meson production has unique access to the chiral odd GPDs, and is also a background for other exclusive processes such as DVCS, making the determination of this cross section crucial for other exclusive analyses.

Thesis Supervisor: Richard Milner  
Title: Professor of Physics

# Acknowledgments

To Be Completed. Currently this will serve as a to-do list:

input list of figures

input list of tables

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# Chapter 1

## Introduction

### 1.1 Exploring Structure through Scattering

Humanity interested in the structure of reality, atomic theory, subatomic, subnuclear, structure of this thesis. The rest of this chapter discusses these advancements, and describes the theoretical background for this experiment. Chapter 2 describes the experiment, Chapter 5 the analysis, etc. Chapter 8 summarizes this work and discusses how this analysis will proceed in the near future and a path for future experiments. The appendix includes numerous technical details and supplemental plots.

As we increase the resolution (resolve features over smaller spatial distances), what we see is dependent on what resolution scale we are at. An exception to this case is if we are investigating point-like particles, which would have an identical response across all resolution scales

GPDs combine the kinematics of both elastic form factors and parton distributions. Andrey references 5, 6, and 7

#### 1.1.1 Discovery of the Proton

Yimin has good references for this part

### 1.1.2 Electron as a Nucleon Probe

Include discussion of wavelength and momentum transfer (but in practice, limiting factor to resolution is lens system)

1961 hofstadter nobel prize (Andrey reference 1) Andrey refrence 2 Friedman Kendall Tayleor scaling

Andrey thesis good write ups

Sangbaek: proton has properties Describe with QFT, words about QCD role of experiment in studying proton structure - proton discovery - neutron discovery - pointlike consitutents - development of quark model - scaling behavior and asymptotic freedom - details about scattering experiments from first principles - words about elastic scattering (mott scattering) - Plot of elastic form factors, discussion of  $G_E$  and  $G_M$ , Rosenbluth formula - Mention TPEX - discussion of inelastic scattering - Structure funcitons - Discussion of spin and sum rules

Now discussion of DVEP: GPDs, Wigner functions relationships all the way around some annoying math Handbag diagram Lepton hadron plane Status of experiments and future (EIC mapping)

invariant mass is  $W$

Understanding the structure of matter has been a fundamental research pursuit for centuries.

Proton not a point mass - it has structure

### 1.1.3 Structure of our World

- atomic theory - discovery of proton / nucleon - proton structure measurements - lepton scattering experiments, HERA, etc



## 1.2 Theoretical Background

### 1.2.1 GPDs and Deeply Virtual Scattering

There are 8 GPDs, 4 correspond to helicity conserving (chiral even) processes and 4 correspond to are helicity flipping (chiral odd) processes:  $H$ ,  $E$ ,  $\tilde{H}$ , and  $\tilde{E}$  for chiral even, and  $H_T$ ,  $E_T$ ,  $\tilde{H}_T$ , and  $\tilde{E}_T$  for chiral odd.  $\tilde{E}_T = 2^* \tilde{H}_T + E_T$  is commonly used

Nucleon Polarization	Quark Polarization		
	U	L	T
U	$H$		$\tilde{E}_T$
L		$\tilde{H}$	
T	$E$		$H_T, \tilde{H}_T$

Why do the structure combine in the way they do with the coefficients of cos phi terms and epsilons?

And the structure functions can be written as:

$$\frac{d\sigma_L}{dt} = \frac{4\pi\alpha}{kQ^2} \left\{ (1 - \xi^2) |\langle \tilde{H} \rangle|^2 - 2\xi^2 \Re [\langle \tilde{H} \rangle^* \langle \tilde{E} \rangle] - \frac{t'}{4m^2} \xi^2 |\langle \tilde{E} \rangle|^2 \right\} \quad (1.1)$$

$$\frac{d\sigma_T}{dt} = \frac{2\pi\alpha\mu_\pi^2}{kQ^4} \left\{ (1 - \xi^2) |\langle H_T \rangle|^2 - \frac{t'}{8m^2} |\langle \tilde{E}_T \rangle|^2 \right\} \quad (1.2)$$

$$\frac{d\sigma_{LT}}{dt} = \frac{4\pi\alpha\mu_\pi}{\sqrt{2}kQ^3} \xi \sqrt{1 - \xi^2} \frac{\sqrt{-t'}}{2m} \Re \{ \langle H_T \rangle^* \langle \tilde{E} \rangle \} \quad (1.3)$$

$$\frac{d\sigma_{TT}}{dt} = \frac{4\pi\alpha\mu_\pi^2}{kQ^4} \frac{-t'}{16m^2} \langle \tilde{E}_T \rangle^2 \quad (1.4)$$

and epsilon is...

and  $t'$  stands for  $t - t_0$  where  $t_0 = \frac{-4m^2\xi^2}{1-\xi^2}$

Where the skewness parameter is  $\xi = \frac{x_B}{2-x_B}$  or whatever

The bracket  $\langle \tilde{F} \rangle$  is the convolution of a GPD and an appropriate subprocess amplitude:  $\langle \tilde{F} \rangle = \Sigma_\lambda \int_{-1}^1 d\bar{x} H_{0\lambda,0\lambda}(\bar{x}, \xi, Q^2, t=0) \tilde{F}(\bar{x}, \xi, Q^2, t)$

Where  $\lambda$  is the unobserved helicities of the partons participating in the subprocess

And  $k$  is the phase space factor given as  $k = 16\pi (W^2 - m^2) \sqrt{\Lambda(W^2, -Q^2, m^2)}$

Where  $\Lambda(W^2, -Q^2, m^2)$  is the Källén function and  $\mu_{pi}$  is the reduced pion mass given as  $\mu_{\pi^0} = \frac{m_{\pi^0}^2}{m_u + m_d}$   $m_u$  and  $m_d$  are respective masses of up and down quarks.

Include proton pressure distribution plot

The cross section for DV $\pi^0$ P has been theoretically linked to GPDs, which describe the 3D structure of the nucleon.

$$\frac{d^4\sigma_{\gamma^*p \rightarrow p'\pi^0}}{dQ^2 dx_B dt d\phi_\pi} = \Gamma(Q^2, x_B, E) \frac{1}{2\pi} \left\{ \left( \frac{d\sigma_T}{dt} + \epsilon \frac{d\sigma_L}{dt} \right) + \epsilon \cos(2\phi) \frac{d\sigma_{TT}}{dt} + \sqrt{2\epsilon(1+\epsilon)} \cos(\phi) \frac{d\sigma_{LT}}{dt} \right\} \quad (1.5)$$

$$\Gamma(Q^2, x_B, E) = \frac{\alpha}{8\pi} \frac{Q^2}{m_p^2 E^2} \frac{1-x_B}{x_B^3} \frac{1}{1-\epsilon} \quad (1.6)$$

In addition to collinear momentum distribution of partons inside the nucleon, GPDs also encode the distribution of partons in the plane transverse to the nucleon's momentum in the infinite momentum frame [58]. Moreover, their relation to energy-momentum tensor (EMT) form factors allow us to access the EMT densities, the distribution of energy, angular momentum, pressure, and shear forces inside the nucleon [15].

Only valence quarks contribute electroproduction of uncharged pions.

### 1.2.2 The Handbag Approach

DVMP is sensitive to chiral odd GPDs, distinguishing it from DVCS as a GPD probe because why? Because something involving photon helicity and pion helicity, I forget exactly though

### 1.2.3 The Goloskokov-Kroll Model

## 1.3 Overview of Experimental Status

### 1.3.1 Previous Experimental Results

### 1.3.2 Overview of this Analysis

Hi ([Bedlinskiy et al., 2014](#)) see more in section [1.1](#) just a test



# References

Bedlinskiy, I., Kubarovsky, V., Niccolai, S., Stoler, P., Adhikari, K. P., Anderson, M. D., . . . Zonta, I. (2014). Exclusive  $\pi^0$  electroproduction at  $w > 2$  gev with clas. *Physical Review C - Nuclear Physics*, 90. Retrieved from <https://arxiv.org/pdf/1405.0988.pdf> doi: 10.1103/PhysRevC.90.025205



# Appendix A

## A.1 Full Cross Section Data

To be completed





# Appendix B

## B.1 Cross check between Andrey Kim and Bobby Johnston

As an additional cross check, Bobby calculated a  $DV\pi^0P$  beam spin asymmetry and compared to Andrey Kim's results. This check will not comment on any acceptance, luminosity, or virtual photon flux factor calculations, but does validate exclusive event selection criteria. By examining figure [B-1](#) we can see that agreement is reasonable, especially considering Bobby's calculation does not have sideband subtraction included.

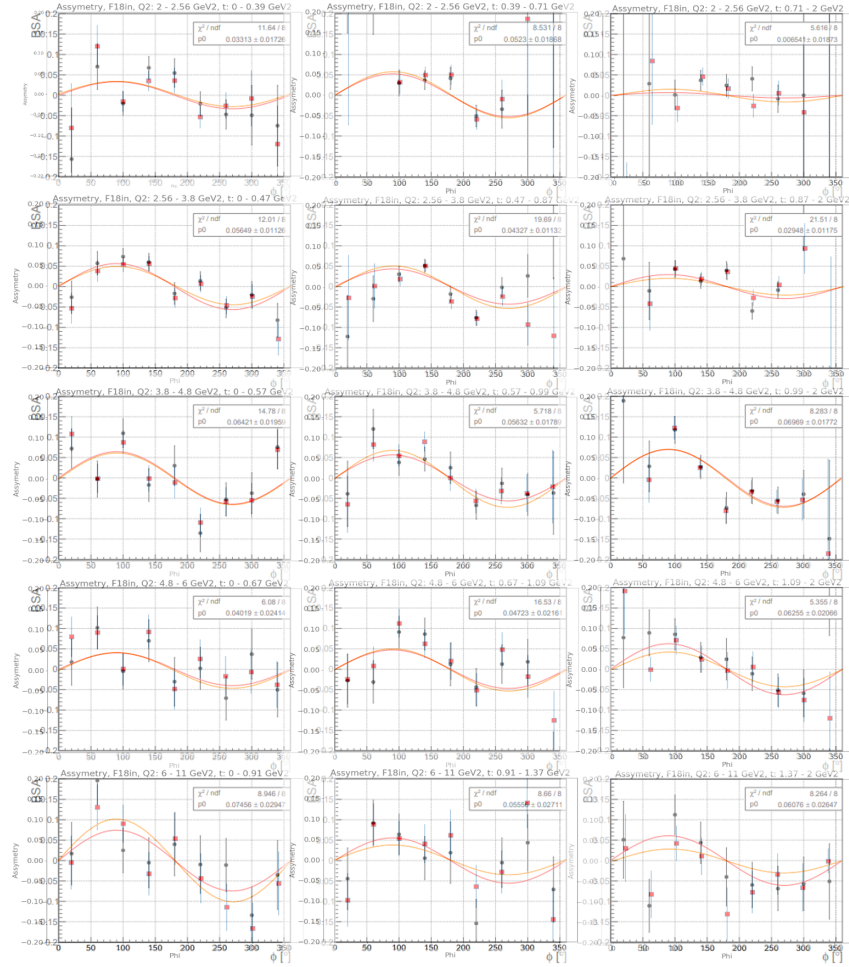


Figure B-1: Overlay comparison of Andrey Kim's results (black datapoints, red fit line) and Bobby's results (red datapoints, orange fit line).