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
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Author . . . .
Department of Physics
May 5, 2023

Certified by . . . .
Richard Milner
Professor of Physics
Thesis Supervisor

Accepted by . . . .
Lindley Winslow
Associate Department Head of Physics

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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.

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Chapter 1

Introduction

People have tried to understand the nature of the world around us for millennia, with discerning the structure of matter being a central effort in this quest. Famously, the Greek philosophers Leucippus and Democritus ($\sim$ 5th century BCE) are credited with the concept of "atomism" - the belief that matter is composed of tiny indivisible particles called atoms (from the Greek $\alpha\tau o\mu o\sigma$, roughly translating to "uncuttable" [1]. Even further back, there are Indian records from as early as the 8th century BCE conceptualizing the world as being built from tiny fundamental particles [2].

Scientific progress on this front stalled until the early 1800s, when chemists explored how different elements combined in to form compounds in specific, repeatable, small integer ratios. John Dalton formulated this idea as the Law of Multiple Proportions, which paved the way for early scientific atomic theory [3]. In 1897, J.J. Thomson discovered the first subatomic particle, the electron, by studying cathode rays[4]. Accordingly, he devised a model of the atom which had electrons embedded in a ball of positively charged material, called the Thomson, or Plum Pudding, Model[5].

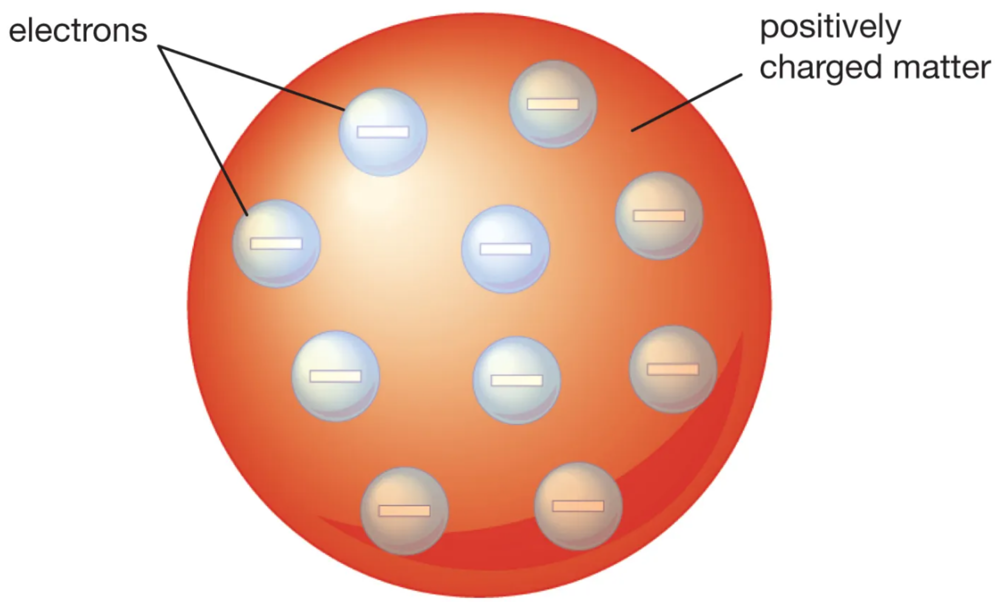

Figure 1-1: J.J. Thomson's Plum Pudding Model of the atom [6]

With the idea that the atom was a composite object, scientist began experimentation to study its exact structure. This was the start of what has been the 120 years of particle scattering studies to probe first atomic, then nuclear structure.

The rest of this chapter details the findings of previous scattering experiments and provides a background on Generalized Parton Distributions and Deeply Virtual Exclusive Processes, the topic of this work. Chapter 2 describes the experimental setup of the CLAS12 detector and data taking conditions. Chapter 3 discusses data analysis procedures to reconstruct particles and classify events from detector level information. Simulations and computational pipelines for this work are presented in chapter 4. The analysis procedure for combining experimental and simulated data into a differential cross section with correction factors is discussed in chapter 5. Chapter 6 displays and discusses results and uncertainties. Chapter 7 summarizes this work and lays a path for finalizing the measurement. The appendicies include numerous technical details and supplemental plots.

1.1 Exploring Structure through Scattering

1.1.1 Discovery of the Proton

Gieiger Marsden -, low energy scattering Yimin has good references for this part of proton discovery

1.1.2 Electron as a Precision probe

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

- neutron discovery (see Sangbaek) - pointlike consitutents 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

- 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 Ge and Gm, Rosenbluth formula - Mention TPEX - discussion of inelastic scattering - Structure funcitons - Discussion of spin and sum rules - Proton not a point mass - it has structure - proton structure measurements - lepton scattering experiments, HERA, etc 1961 hofstadter nobel prize (Andrey reference 1) Andrey refrence 2 Friedman Kendall Tayleor scaling

1.2 Theoretical Background

Discussion of Form Factors and genralized proton structure, Wigner Functions

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

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

1.2.1 GPDs and Deeply Virtual Scattering

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

$$\frac{d^4\sigma_{\gamma^* p \to p'\pi^0}}{dQ^2 dx_B dt d\phi_\pi} = \Gamma(Q^2, x_B, E)\frac{1}{2\pi}\left\{\left(\frac{d\sigma_T}{dt} + \epsilon\frac{d\sigma_L}{dt}\right) + \epsilon cos(2\phi)\frac{d\sigma_{TT}}{dt} + \sqrt{2\epsilon(1+\epsilon)}cos(\phi)\frac{d\sigma_{LT}}{dt}\right\} \tag{1.1}$$

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 $\tilde{E}_T$

$\bar{E}_T$= 2*$\tilde{H}_T$+$E_T$is commonly used

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

Table 1.1: GPDs Across Nucleon and Quark Polarizations

Why do the scrtucture combine in the way they do with the coefficents of cos phi terms and epsilons?

And the structure functions can be written as:

$$\frac{d\sigma_L}{dt} = \frac{4\pi\alpha}{kQ^2}\left\{\left(1-\xi^2\right)|\langle\tilde{H}\rangle|^2 - 2\xi^2\Re\left[\langle\tilde{H}\rangle^*\langle\tilde{E}\rangle\right] - \frac{t'}{4m^2}\xi^2|\langle\tilde{E}\rangle|^2\right\} \tag{1.2}$$

$$\frac{d\sigma_T}{dt} = \frac{2\pi\alpha\mu_\pi^2}{kQ^4}\left\{\left(1-\xi^2\right)|\langle H_T\rangle|^2 - \frac{t'}{8m^2}|\langle\bar{E}_T\rangle|^2\right\} \tag{1.3}$$

$$\frac{d\sigma_{LT}}{dt} = \frac{4\pi\alpha\mu_\pi}{\sqrt{2}kQ^3}\xi\sqrt{1-\xi^2}\frac{\sqrt{-t'}}{2m}\Re\left\{\langle H_T\rangle^*\langle\tilde{E}\rangle\right\} \tag{1.4}$$

$$\frac{d\sigma_{TT}}{dt} = \frac{4\pi\alpha\mu_\pi^2}{kQ^4}\frac{-t'}{16m^2}\langle\bar{E}_T\rangle^2 \tag{1.5}$$

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: $\langle\tilde{F}\rangle = \Sigma_\lambda \int_{-1}^{1} d\bar{x} H_{0\lambda,0\lambda}\left(\bar{x},\xi,Q^2,t=0\right)\tilde{F}\left(\bar{x},\xi,Q^2,t\right)$

Where λ is the unobserved helicites of the partons participaing in the subprocess

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

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

Include proton pressure distribution plot

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

In addition to collinear momentum distribution of partons inside the nucleon, GPDs also encode the distribution of partons in the plane transverse to the nucleons 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 GDP probe because why? Because something involving photon helicity and pion helicity, I forget exactly though

1.3 Overview of Experimental Status

1.3.1 Previous Experimental Results

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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.

Fig B-1 shows an overlay comparison of Andrey Kim's results (black datapoints, red fit line) and Bobby's results (red datapoints, orange fit line

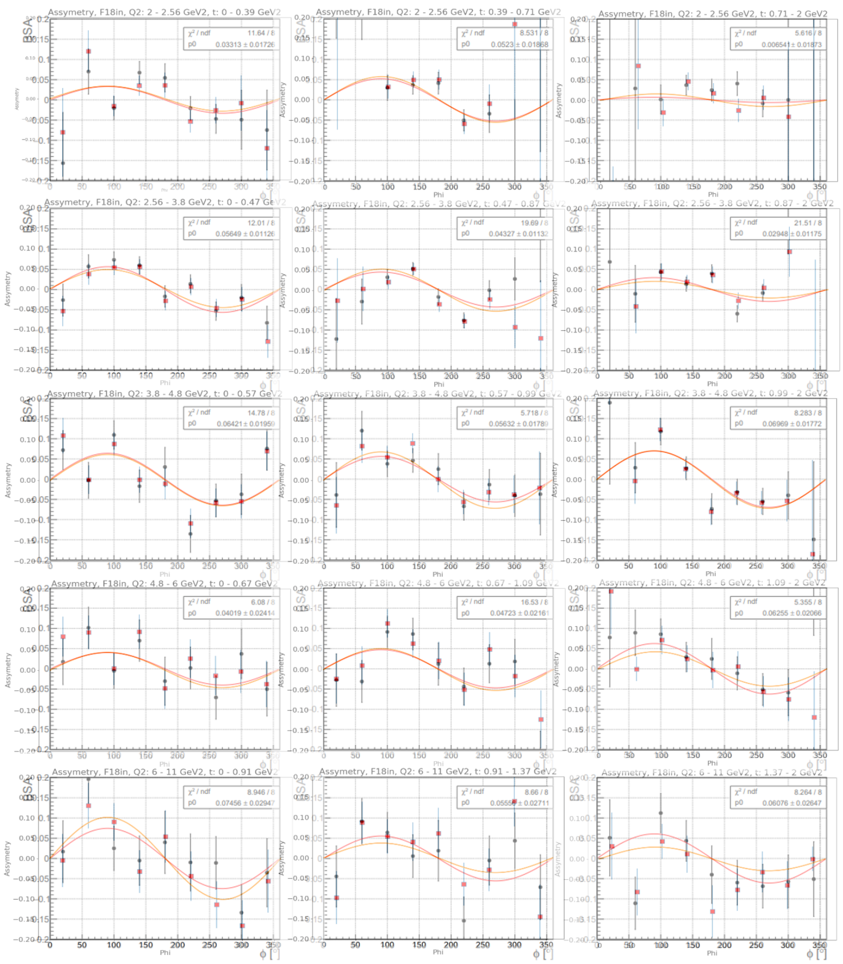

Figure B-1: BSA Cross Check Results