

**Measurement of the Chiral-Odd Generalized  
Parton Distribution Functions and  
Non-Parametric Analysis 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

June 2023

© Massachusetts Institute of Technology 2023. All rights reserved.

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



**Measurement of the Chiral-Odd Generalized Parton  
Distribution Functions and Non-Parametric Analysis 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  
on May 5, 2023, in partial fulfillment of the  
requirements for the degree of  
Interdisciplinary PhD in Physics and Statistics

**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

# Contents

|  |           |
|--|-----------|
| <b>List of Figures</b>                               | <b>7</b>  |
| <b>1 Introduction</b>                                | <b>9</b>  |
| 1.1 Background - Structure of the Proton . . . . .   | 9         |
| 1.2 Deeply Virtual Neutral Pion Production . . . . . | 9         |
| 1.2.1 The Handbag Approach . . . . .                 | 9         |
| 1.2.2 The Goloskokov-Kroll Model . . . . .           | 9         |
| 1.2.3 Status of Measurements . . . . .               | 9         |
| 1.2.4 Analysis Overview . . . . .                    | 9         |
| <b>2 Experimental Setup</b>                          | <b>11</b> |
| 2.1 Experiment Overview . . . . .                    | 11        |
| 2.2 Accelerator Beamline . . . . .                   | 11        |
| 2.2.1 Overview of Jefferson Lab . . . . .            | 11        |
| 2.2.2 Electron Source . . . . .                      | 11        |
| 2.2.3 Polarimeters . . . . .                         | 11        |
| 2.2.4 Accelerator . . . . .                          | 11        |
| 2.2.5 Target . . . . .                               | 11        |
| 2.3 CEBAF Large Acceptance Spectrometer . . . . .    | 11        |
| 2.3.1 Forward Detector . . . . .                     | 11        |
| 2.3.2 Central Detector . . . . .                     | 11        |
| 2.4 Experiment Running and Data Taking . . . . .     | 11        |

|          |   |           |
|----------|---|-----------|
| <b>3</b> | <b>Simulations</b>                                  | <b>13</b> |
| 3.1      | Simulation Infrastructure . . . . .                 | 13        |
| 3.1.1    | Motivation for massive simulations . . . . .        | 13        |
| 3.1.2    | OSG, MIT Tier 2, submission pipeline . . . . .      | 13        |
| 3.2      | Generator Details . . . . .                         | 13        |
| 3.2.1    | AAO . . . . .                                       | 13        |
| 3.2.2    | AAONORAD . . . . .                                  | 13        |
| 3.2.3    | AAORAD . . . . .                                    | 13        |
| 3.3      | Simulation Pipeline . . . . .                       | 13        |
| <b>4</b> | <b>Analysis</b>                                     | <b>15</b> |
| 4.1      | General Analysis Overview . . . . .                 | 16        |
| 4.2      | Data Pre-Processing . . . . .                       | 16        |
| 4.2.1    | Energy Loss Corrections . . . . .                   | 16        |
| 4.2.2    | Momentum Corrections . . . . .                      | 16        |
| 4.2.3    | Simulation:Experiment Resolution Matching . . . . . | 16        |
| 4.3      | Particle Identification . . . . .                   | 16        |
| 4.4      | Event Selection . . . . .                           | 16        |
| 4.4.1    | Rigid Event Selection . . . . .                     | 16        |
| 4.4.2    | Classifier Based Event Selection . . . . .          | 16        |
| 4.5      | Luminosity . . . . .                                | 16        |
| 4.6      | Configuration and Kinematics . . . . .              | 16        |
| 4.7      | Binning . . . . .                                   | 16        |
| 4.8      | Acceptance Correction . . . . .                     | 16        |
| 4.9      | Radiative Corrections . . . . .                     | 16        |
| 4.10     | Binning Corrections . . . . .                       | 16        |
| 4.11     | Overall Normalization Corrections . . . . .         | 16        |
| 4.12     | Error Analysis . . . . .                            | 16        |
| <b>5</b> | <b>Results</b>                                      | <b>17</b> |
| 5.1      | General Analysis Overview . . . . .                 | 18        |

|                   |   |           |
|-------------------|---|-----------|
| 5.2               | Data Pre-Processing . . . . .                               | 18        |
| 5.2.1             | Energy Loss Corrections . . . . .                           | 18        |
| 5.2.2             | Momentum Corrections . . . . .                              | 18        |
| 5.2.3             | Simulation:Experiment Resolution Matching . . . . .         | 18        |
| 5.3               | Particle Identification . . . . .                           | 18        |
| 5.4               | Event Selection . . . . .                                   | 18        |
| 5.4.1             | Rigid Event Selection . . . . .                             | 18        |
| 5.4.2             | Classifier Based Event Selection . . . . .                  | 18        |
| 5.5               | Luminosity . . . . .  | 18        |
| 5.6               | Configuration and Kinematics . . . . .                      | 18        |
| 5.7               | Binning . . . . .   | 18        |
| 5.8               | Acceptance Correction . . . . .                             | 18        |
| 5.9               | Radiative Corrections . . . . .                             | 18        |
| 5.10              | Binning Corrections . . . . .                               | 18        |
| 5.11              | Overall Normalization Corrections . . . . .                 | 18        |
| 5.12              | Error Analysis . . . . .                                    | 18        |
| <b>References</b> |   | <b>21</b> |
| <b>A</b>          |   | <b>23</b> |
| A.1               | Full Cross Section Data . . . . .                           | 23        |
| <b>B</b>          |   | <b>25</b> |
| B.1               | Cross check between Andrey Kim and Bobby Johnston . . . . . | 25        |





# Chapter 1

## Introduction

### 1.1 Background - Structure of the Proton

### 1.2 Deeply Virtual Neutral Pion Production

#### 1.2.1 The Handbag Approach

#### 1.2.2 The Goloskokov-Kroll Model

#### 1.2.3 Status of Measurements

#### 1.2.4 Analysis Overview

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



# Chapter 2

## Experimental Setup

### 2.1 Experiment Overview

### 2.2 Accelerator Beamline

#### 2.2.1 Overview of Jefferson Lab

#### 2.2.2 Electron Source

#### 2.2.3 Polarimeters

#### 2.2.4 Accelerator

#### 2.2.5 Target

### 2.3 CEBAF Large Acceptance Spectrometer

#### 2.3.1 Forward Detector

#### 2.3.2 Central Detector

### 2.4 Experiment Running and Data Taking



# Chapter 3

## Simulations

### 3.1 Simulation Infrastructure

#### 3.1.1 Motivation for massive simulations

#### 3.1.2 OSG, MIT Tier 2, submission pipeline

### 3.2 Generator Details

#### 3.2.1 AAO

#### 3.2.2 AAONORAD

#### 3.2.3 AAORAD

### 3.3 Simulation Pipeline





# Chapter 4

## Analysis

### 4.1 General Analysis Overview

### 4.2 Data Pre-Processing

#### 4.2.1 Energy Loss Corrections

#### 4.2.2 Momentum Corrections

#### 4.2.3 Simulation:Experiment Resolution Matching

Kinematics Correction of Experimental Data

Smearing Simulated Data

### 4.3 Particle Identification

### 4.4 Event Selection

#### 4.4.1 Rigid Event Selection

#### 4.4.2 Classifier Based Event Selection

### 4.5 Luminosity

### 4.6 Configuration and Kinematics





# Chapter 5

## Results

### 5.1 General Analysis Overview

### 5.2 Data Pre-Processing

#### 5.2.1 Energy Loss Corrections

#### 5.2.2 Momentum Corrections

#### 5.2.3 Simulation:Experiment Resolution Matching

Kinematics Correction of Experimental Data

Smearing Simulated Data

### 5.3 Particle Identification

### 5.4 Event Selection

#### 5.4.1 Rigid Event Selection

#### 5.4.2 Classifier Based Event Selection

### 5.5 Luminosity

### 5.6 Configuration and Kinematics

Methods General analysis technique event selection Configuration and kinematics region Cross section extraction Simulation pipeline acceptance correction Radiative corrections Monte carlo estimators

Data post processing energy loss correction for charged particles electron energy loss detector regions for proton energy loss correction details of the two band issue proton energy loss correction biases for higher momentum protons benchmarks for corrections Resolution matching kinematics correction of experimental data smearing the simulation data

Results CLAS12 quality assurance Event selection revisited multidimensional binning signal yields and acceptance corrections radiative corrections normalization and the modified cross section error analysis unpolarized cross sections polarized cross sections conclusions



# 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.

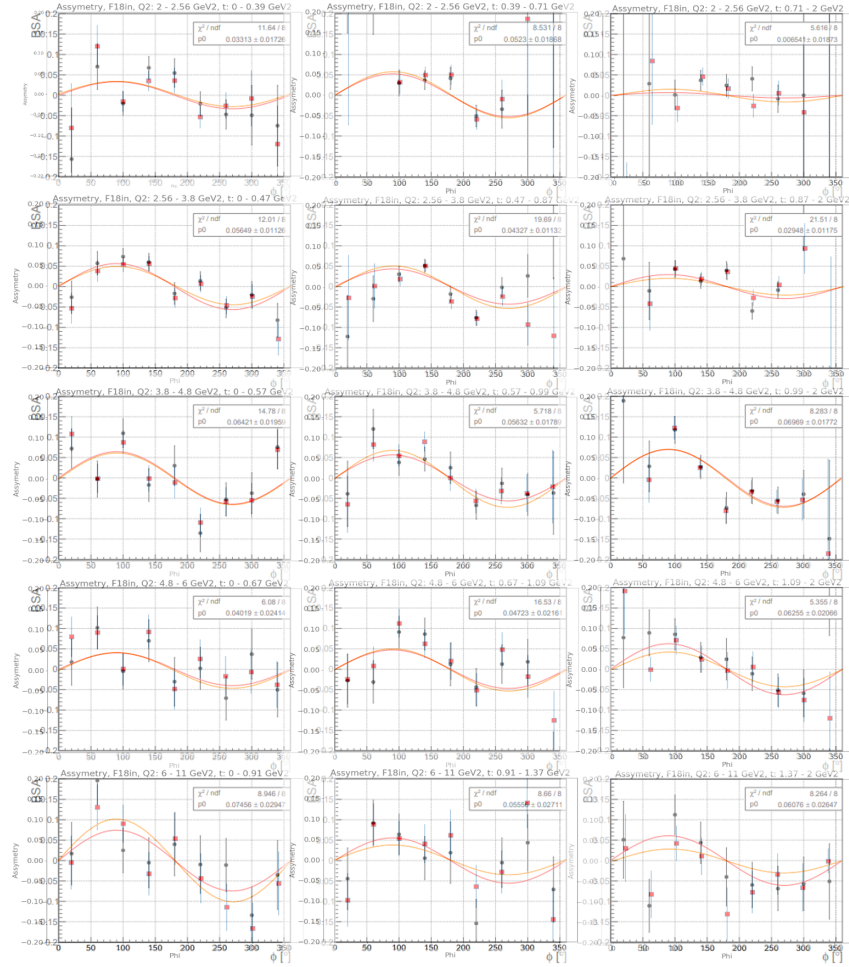


Figure B-1: Overlay comparison of Andrey Kim's results (black datapoints, red fit line) and Bobby's results (red datapoints, orange fit line).