STUDY OF THE TWO PION PHOTOPRODUCTION ON DEUTERIUM

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ABSTRACT

Understanding the structure of baryons in terms of the fundamental interaction of the constituent quarks and gluons is one of the primary challenges in strong interaction physics. This interaction is governed by Quantum Chromodynamics (QCD), which is a theory for understanding the dynamics of strong. QCD displays the asymptotic freedom of hadrons at very short distances and also the confinement of quarks and gluons inside hadrons. However, solutions of this QCD theory in the non-perturbative domain of the interaction are extremely difficult to achieve, mainly because confinement happens on the hadronic scale on which the coupling constant is large and prevents any perturbative approach. Thus leaving us with strategies such as lattice QCD or formulating QCD sum rules to get around this problem.

In exclusive hadron production the γN interaction is recognized for being a powerful method for investigating hadrons and the mysteries that still exist within the strong interaction. From reactions with the nucleon, the strong interaction can be investigated through the transition amplitudes to the N and Δ resonances. More specifically, if an electromagnetic interaction is well known then the intermediate resonance states may be evaluated through meson photoproduction. To gain more detailed insight into this interaction, we look to probe the baryon structure of the nucleon and the photo-excited resonance decays through photon scattering off a deuteron producing two pions in the final state. This photoproduction process off the deuteron will be used to investigate known baryon resonances in the two pion channel.

The two pion final state will be investigated for unraveling new information into the photo-coupling strengths. We want to explore final state interactions, search for

properties of known resonances, and to explore the possibility of seeing missing states that are predicted by quark models but have not yet been found experimentally. Using the CEBAF Large Acceptance Spectrometer (CLAS), the hadronic products are detected in coincidence with the incident scattered photon on a deuterium target. This makes it possible to measure the single differential cross sections and the decay angular distributions for the production of two pion final states. The measured cross sections will contribute significantly to a better understanding of the coupling strengths that govern the baryonic and mesonic resonances which will push the knowledge of the strong interaction to a next level.

We use CLAS to study the two pion channel from the eg3 data set, for resonance production, specifically investigating the exclusive reaction of $\gamma d \rightarrow p\pi^+\pi^-n$, and comparing the relevant cross sections to already existing data sets. The eg3 data set provided an excellent data set for investigating photo-induced baryonic and mesonic resonances. It contains a large photon tagging range from 1.1 to 5.5 GeV in the study of photo-coupling strengths, as well as an available two pion reaction channel for resonant decay study. These measurements provide unique and coherent results from tagged photons over a broad range of energy, and represent the only two pion production data above 5 GeV at this present time. We found that the data produced good comparable single-differentials cross sections to other existing CLAS (gll dataset) two pion differential cross sections, and an excellent comparable total cross section to published (ELSA and ABBHHM) two pion total cross sections.

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CHAPTER 1

INTRODUCTION

One of four types of interactions (gravitational, electromagnetic, weak and strong interactions) governs every physical phenomenon. The gravitational is the weakest interaction but seemingly the most effective to the universe by the natural eye's view. The electromagnetic interaction takes place between charged particles, which is witnessed through how atoms are structured. The weak interaction has the shortest range of all interactions, and is best for describing mechanisms such as beta decay. The final interaction is the strong force, which is responsible for holding hadrons together. All these interactions have fundamental exchange particles and they couple to specific particles with specific strengths known as coupling constants. Within any realm of physical matter, atleast one of these forces will be the governing mechanism to dictate how its interactions will proceed with other physical matter.

The study of nuclear physics centers around two main problems. The first is the hope of understanding properties of the force that holds the nucleus together. Second, is the attempt to describe the behavior of systems of many particles, such as nuclei are. These problems are related, since the properties of a system of many particles are to a large extent determined by the force that binds them together. But other aspects of such a system come about simply because many particles are interacting. These interactions are understood at large distances through the predictions of nuclear models, and at short distances by the principles of Quantum Chromodynamics (QCD). QCD is the theory of strong interaction that binds quarks and gluons for the formation of hadrons such as protons and neutrons. It also controls the formation of nuclei, where it describes gluonic mediators between quarks that make up hadronic

particles. The problematic aspect arises in understanding the transition between the different distance scales. At low energies (few 10 MeV) the hadrons look like particles with no structure. At medium energies (few 100 MeV) the hadron substructure can be investigated and many nucleon resonant states exist. At higher energies (few GeV) the complex structure of quarks and gluons within the hadron can be seen. And at even higher energies (few 10 GeV), the strong coupling constant of the strong force becomes much smaller than 1, and seemingly QCD theory can be treated perturbatively [Shende(2007)]. This higher energy region of transition is the focus of nuclear study, that connects to phenomena through experimental exploration that perturbative QCD has predicted. However, perturbative approximations often fail because the QCD interaction is so strong and confinement limits any perturbative approach to the theory. Consequently, few precise predictions can be made from the theory of QCD. This has led to the introduction of a non-perturbative approximations, such as lattice QCD that is based on discretizing four-dimensional space-time onto a lattice of points which can be simulated on a computer.

The fundamental degrees of freedom of QCD, quarks and gluons, are already well established even though they cannot be observed as free particles, but only in color neutral bound states (confinement)[Kharzeev(2002)]. There still lacks foundational evidence from experimental data that attributes the dominant degrees of freedom to elementary quarks and gluon fields, making constituent quarks and pions more relevant in the interpretation of data. The γN interaction is recognized for being a powerful method for investigating hadrons and the mysteries that still exist within the strong interaction. From reactions with the nucleon, the strong interaction can be tested through the transition amplitudes to the N and Δ resonances. In that the excitation and decay of a resonance are sensitive to the dynamics of quarks within the hadron, the testing of the photocouplings of baryon resonances is vital to understanding nonperturbative QCD. Photoproduction experiments are complimentary to electroproduction experiments, at least on the level of low Q^2 experiments.

For some time now, electron scattering has been a major tool used for probing the structure of nucleons in exclusive reactions. Studies of exclusive reactions, where intacting hadrons appear in the initial and final state, are necessary to understand the dynamical processes of the resonance decay productions. Detectors with large acceptances and adequate resolution have been utilized for years now to deal with the need to explore a large phase space in the experimental final states. Not only high acceptance and resolution, but high luminosity in an electron beam environment was also a main requirement. Due to the nature of these specifications, only the simplest reactions were able to be investigated.

The CLAS detector at Jefferson National Accelerator Facility has quickly proven to incorporate all the necessary requirements for exploring leading-edge nuclear physics. Providing such pros as large acceptances combined with a good resolution and particle detection capabilities, and also operating at high luminosities in an electron beam environment have opened many new paths into investigating hadron structure in exclusive reactions. We look to investigate the exclusive reaction of $\gamma d \rightarrow p\pi^+\pi^-n$, extracting and comparing the relevant cross sections to published and preliminary data sets.

1.1. QUANTUM CHROMODYNAMICS

Quantum Chromodynamics (QCD), is a quantum field theory that describes the strong interaction between quarks at short distances. QCD also controls the formation of nuclei by mediating the forces between hadrons. The fundamental properties of QCD cannot be directly tested at the confinement scale, but a wealth of indirect evidence supports this theory. The problem is that QCD is a nonlinear theory that is not analytically solvable. For quantum field theories for weaker forces, i.e. electromagnetism, using perturbation expansion approximations in the strength of the interaction gives accurate results. However, since the QCD interaction is strong at

Symbol	u	c	t
Name	Up	Charm	Top
Charge(e)	+2/3	+2/3	+2/3
Mass(MeV/c^2)	1.5-3.0	1250 ± 90	$1.725 \pm 0.023 \times 10^5$
Symbol	d	s	b
Name	Down	Strange	Bottom
Charge(e)	-1/3	-1/3	-1/3
Mass(MeV/c^2)	3-7	95 ± 25	4200 ± 70

TABLE 1.1. Properties of current quarks

[**Amsler(2008)**].

intermediate distances, the perturbative approximations consequently fail leaving few predictions of the theory with precision.

QED has been tested by experiments with unprecedented precision, but this is not the case for Quantum Chromodynamics (QCD) [**Greiner(1994)**]. QCD describes the interactions between quarks, the building blocks of matter, in that they are the elementary particles that make up baryons. The complication is due to the strong force carriers, the gluons, that have the ability to interact with each other, unlike the electro-weak force carriers. When valence quarks, the basic elements of hadrons, are close to each other, and thus have high momenta according to Heisenberg’s uncertainty principle, their interaction can be calculated by perturbative QCD (pQCD) [**Greiner(1994)**].

Table 1.1 summarizes the properties of the six current quarks. Currently, we know of six types or “flavors” of quark: up, down, strange, charm, top, and bottom. In addition to having “flavor,” quarks can carry one of three possible charges. These charges are distinguished as “color” being analogous to electric charge in electromagnetic interaction. Color is of three varieties, arbitrarily designated as red, blue, and green, and, analogous to positive and negative charges, three anticolor varieties. Similarly as positively and negatively charged particles form electrically neutral atoms, colored quarks form particles with no net color. Quarks interact by emitting and absorbing massless particles called gluons, each of which carries a color-anticolor pair.

FIGURE 1.1. The pseudo-scalar meson nonet

The strong force between quarks and gluons is believed to be explained by QCD based on $SU(3)$ color symmetry, and the strength of these interactions is measured by the coupling constant α_s . Because a ground state meson is made of a quark of spin $1/2$ and an anti-quark of spin $1/2$, its spin component can be 0 or 1. The flavor composition has nine states, $SU(3)_{quark} \otimes SU(3)_{antiquark} = 8 \oplus 1$. Therefore, there are totally two nonets with different spins shown in Figure 1.1 and Figure 1.2.

A similar situation happens again for ground state baryons that are made of three light quarks. The total spin can now be $1/2$ and $3/2$ and the flavor decomposition is $SU(3) \otimes SU(3) \otimes SU(3) = 10 \oplus 8 \oplus 8 \oplus 1$. The octet with spin $1/2$ and the decuplet with spin $3/2$ are shown in Figure 1.3 and Figure 1.4. The constituent quark model (CQM) predicts the light hadron ground states well. Hadrons, composite particles, can have excited states due to their internal degrees of freedom, and the CQM has had some successes as well as failures in describing these excited states.

The coupling constant for QCD appears to increase with distance, which is why we never see an isolated quark, since they are always bound together by the strength of the coupling between them. This phenomenon is known as confinement within

FIGURE 1.2. The vector meson nonet

FIGURE 1.3. The baryon octet

QCD. Perturbative calculations are therefore only possible at short distances (or large energies).

In order to solve QCD at intermediate distances, K. Wilson [Wilson(1974)] introduced lattice gauge theory in 1974, in which the space-time continuum is discretized

FIGURE 1.4. The baryon decuplet

and a discrete version of the gauge theory is derived that keeps the gauge symmetry intact. This discretization onto a lattice, which is typically hypercubic, gives a nonperturbative approximation to the theory that can be successively improved by increasing the lattice size and decreasing the lattice spacing, and it provides a simple and natural way of regulating the divergences which plague perturbative approximations. It also makes the gauge theory amenable to numerical simulation by computers.

1.2. BARYON SPECTROSCOPY

Baryons have historically played a central role in the development of the theory of the strong interaction. The low-lying baryons were crucial to the motivation for the fractionally charged quark model and soon after its proposal baryon spectroscopy [Gell-Mann(1964)] played a major role in the development of quark models in dynamical theories [Capstick and Isgur(1986)].

From the experimental point of view the main difference between nuclear and nucleon structure studies results from the large, overlapping widths of the nucleon

resonances, which makes it difficult to study individual resonances. Most nucleon resonances have been identified in pion scattering reactions that profit from large hadronic cross sections. However, investigating nucleon resonances only in the $N\pi$ -channel has two disadvantages in that no use is made of the rich information connected to electromagnetic transition amplitudes and experimental bias may arise for nucleon resonances that couple only weakly to the $N\pi$ -channel, which might explain part of the "missing resonance" problem, where many more excited resonance states are predicted that have yet to be measured in experimental investigation.

Nucleon resonances, excited states of the nucleon, are characterized in the following nomenclature: $L_{2I,2J}(W)$. L is the orbital angular momentum of the nucleon - pion (or other pseudoscalar meson) pair from the decay of the resonance in spectral notation (S,P,D,F corresponding to $L=0,1,2,3$). The isospin and total angular momentum of the resonance are I and J , and W stands for its mass in units of MeV/c^2 . The isospin $I=1/2$ resonances are called N^* states, and isospin $I=3/2$ resonances are called Δ states. As an example, the first excited state of the nucleon, the well-known Δ -resonance is notated: $P_{33}(1232)$ corresponding to an $I=3/2$, $J=3/2$ state at $1232 MeV/c^2$ decaying into a nucleon - pion pair with relative orbital angular momentum of $L=1$. The nucleon ground state is $P_{11}(939)$.

By emitting mesons, nucleon resonances can decay to the nucleon ground state through the strong interaction. Δ -resonances ($I=3/2$) can decay to the nucleon ground state ($I=1/2$) by emitting pions ($I=1$) but not through the emission of eta-mesons ($I=0$), though both decays are possible for the $I=1/2$ N^* -resonances. Due to the decay via the strong interaction the lifetimes of the resonances are very small (typically $10^{-23}s$) and their energy widths are correspondingly large. Typical widths of nucleon resonances are on the order of $100 - 300 MeV/c^2$, so that most resonances overlap with their neighbors.

Table 1.2 lists the CQM [**Capstick and Roberts(1993)**] predicted excited nucleon (p, n) states with masses, angular momenta, and parities and compares them

J^P	M_{CQM}	M_{PDG}	Rating	J^P	M_{CQM}	M_{PDG}	Rating
$1/2^-$	1460	1535	****	$1/2^+$	1540	1440	****
$1/2^-$	1535	1650	****	$1/2^+$	1770	1710	***
$1/2^-$	1945	2090	*	$1/2^+$	1880		
$1/2^-$	2030			$1/2^+$	1975		
$1/2^-$	2070			$1/2^+$	2065	2100	*
$1/2^-$	2145			$1/2^+$	2210		
$1/2^-$	2195						
$3/2^-$	1495	1520	****	$3/2^+$	1795	1720	****
$3/2^-$	1625	1700	***	$3/2^+$	1870		
$3/2^-$	1960	2080	**	$3/2^+$	1910		
$3/2^-$	2055			$3/2^+$	1950		
$3/2^-$	2095			$3/2^+$	2030		
$3/2^-$	2165						
$3/2^-$	2180						
$5/2^-$	1630	1675	****	$5/2^+$	1770	1680	****
$5/2^-$	2080			$5/2^+$	1980	20000	**
$5/2^-$	2095	2200	**	$5/2^+$	1995		
$5/2^-$	2180						
$5/2^-$	2235						
$5/2^-$	2260						
$5/2^-$	2295						
$5/2^-$	2305						
$7/2^-$	2090	2190	****	$7/2^+$	2000	1990	**
$7/2^-$	2205			$7/2^+$	2390		
$7/2^-$	2255			$7/2^+$	2410		
$7/2^-$	2305			$7/2^+$	2455		
$7/2^-$	2355						
$9/2^-$	2215	2250	****	$9/2^+$	2345	2220	****
$11/2^-$	2600	2600	***				
$11/2^-$	2670						
$11/2^-$	2700						
$11/2^-$	2770						
$13/2^-$	2715						

TABLE 1.2. N^* spectrum predicted by the Constituent Quark Model

[Close and Li(1990)].

with experimentally found resonances, whose evidence is ranked by the increasing number of stars [Amsler(2008)]. Some predictions match well with the results of the experiments, but most of the predicted states are not found experimentally and are often called “missing resonances”. It could be that the prediction is wrong or

that they are not found because most experiments used pion scattering off nucleons, and the missing states may not have strong πN coupling.

For baryon spectrum calculations, the knowledge of the quark configuration of each state is a requirement. The quark configuration determines the energy spectrum and is then used in calculating the photo-coupling amplitudes. Since the photo-couplings require a more detailed knowledge of the wave function than is needed for the calculation of energy, the couplings provide a more stringent test of the quark model.

Koniuk and Isgur [**Koniuk and Isgur(1990)**] did a systematic calculation of the photo-couplings using a simple, nonrelativistic, electromagnetic transition operator. Close and Li [**Close and Li(1990)**] introduced an expansion of the transition operator to be consistent with the hyperfine interaction. Warns, Schroder, Pfeil and Rollnik [**Warns(1990)**] also calculated the couplings in a relativistic quark model that includes configuration mixing. All these methods have attempted to find an adequate description and calculation of photo-couplings. Comparing the calculations of these groups, one finds some large differences in their results. As pointed out [**Capstick and Roberts(1993)**], these calculations suffer from the truncation of the model space at the $N = 2$ band of the harmonic-oscillator, where this led them to calculate the couplings within the relativized model of Capstick and Isgur, which includes harmonic-oscillator basis functions to at least $N=7$. While the spectroscopy of the excited states is similar to that of Koniuk and Isgur, the resulting wave functions is found to be quite different.

1.3. PRESENT WORK

The photoproduction of mesons, where a nucleon is excited electromagnetically into a resonant state and subsequently decays hadronically via the emission of mesons, is viewed by many as the ideal complementary tool to unveiling new and exciting physics. In photoproduction reactions, the first extended resonance studies focused

FIGURE 1.5. Photoabsorption cross section on the free proton and experiemental decomposition into meson production channels measured at MAMI, ELSA, GRAAL, and JLAB. The curve indicates the sum of the meson production cross sections and describes the total absorption [Schadmand(2004)].

on single pion production. However, recently neutral meson photoproduction has moved into the center of interest of the physics community due to the development and optimization of high sensitivity, high resolution photon detectors. Reactions involving neutral mesons have the advantage that non-resonant background contributions are less important, where for charged mesons the problem of background contributions is much larger.

In the present work, we look to investigate photoproduction on deuterium producing two pions in the final state. In our reaction the photon scatters off the proton inside the deuteron leaving the neutron as a spectator in the reaction. Figure 1.5 shows the current knowledge of the contributions of different channels to the total photoabsorption cross-section, where many contributing overlapping resonances. This

FIGURE 1.6. Feynman Diagrams of two pion channel processes. [Ignatov(2009)]

suggests that the search for unambiguous evidence for additional states is a complex matter to say the least.

What we ultimately would like to learn is how the properties of nucleons and their excited states are connected to the properties of QCD. We investigate differential cross sections, production observables, and other particle decay information from direct measurements of photoproduction reactions. To gain an overall understanding of how nucleons are connected to QCD properties, a connection must be made between the measured observables and QCD. This connection is done with the help of reaction models. The reaction model in Figure 1.6 [Ignatov(2009)] can be used to extract the properties of the investigated resonances, such as quantum numbers (spin, parity, isospin), the excitation energy, the decay widths (or lifetimes) for all possible decay channels, and their electromagnetic couplings to photons. The extracted nucleon properties can then be compared to QCD-based hadron models which establish the connection to QCD. Therefore, a phenomenal model reaction will be used to make this connection for photo-induced data to analyze our differential cross section.

1.3.1. Previous Measurements. The world data on double pion production in the nucleon resonance excitation region were rather scarce before the data from CLAS became available. The reaction $\gamma p \rightarrow p\pi^+\pi^-$ was analyzed at an early stage by Luke and Soding aiming to extract the dominant production mechanisms

FIGURE 1.7. Total cross-sections for $p\pi^+\pi^-$ for SAPHIR data with model fits. [Barth, Braun, and Wu(2005)]

[Luke and Soding(1971)]. The total cross section was seen to be small between threshold at $E_\gamma = 310$ MeV and 400 MeV, and it then rose to a maximum at 650 MeV (Figure 1.7) [Schadmand(2004)]. This rise reflects the $\gamma p \rightarrow \Delta\pi$ threshold smeared by the width of the Δ resonance, and it is accompanied by a strong peak at the mass of the Δ in the invariant mass distribution of $p\pi^+$. In the $p\pi^-$ distribution this peak was missing, and for this reason, an important contribution is assigned to the $\gamma p \rightarrow \Delta^{++}\pi^-$ channel while the $\gamma p \rightarrow \Delta^0\pi^+$ is considered almost negligible. Our data follows the trend witnessed in their data. As discussed in the data analysis chapter, we found that the strong contributing resonances to the two pion channel were the Δ^{++} and ρ .

The photoproduction of ρ^0 -mesons and Δ -baryons at photon energies up to 2.6 GeV have been studied with the SAPHIR detector at the electron stretcher ELSA [Barth, Braun, and Wu(2005)]. Total (Figure 1.8 and Figure 1.9) and differential cross-sections were obtained. For the reactions $\gamma p \rightarrow \Delta^{++}\pi^-$ and $\gamma p \rightarrow \Delta^0\pi^+$ new data on cross-sections were presented by Barth et al. [Ripani(2000)] performed a phenomenological analysis of $\Delta^{++}\pi^-$ photo- and electro-production data. Contrary to the others they implement all established N^* and Δ^* resonances between 1440 and

1950 MeV. The total reaction amplitude in this model is evaluated as coherent superposition of resonant and Born terms with absorption correction for initial and final states. According to the authors the resonance contributions and their interference terms play a non negligible role [Barth, Braun, and Wu(2005)].

FIGURE 1.8. Total cross-section for $\gamma p \rightarrow \Delta^{++}\pi^{-}$ together with theoretical calculations from [Ripani(2000)]. — full model, --- : model with reggeized π -exchange, - - -: as before with modified contact term (see [Wu(2000)]).

They published measurements of cross-sections for the reaction $\gamma p \rightarrow p\pi^{+}\pi^{-}$ in the photon energy range $0.5 \text{ GeV} < E_{\gamma} < 2.6 \text{ GeV}$ using the SAPHIR spectrometer at ELSA. The observed final state gives access to the sub-channels

$$(1) \gamma p \rightarrow \pi^{-}\Delta^{++},$$

FIGURE 1.9. Total cross-sections comparison for Δ^{++} (top) and Δ^0 (bottom) production using SAPHIR data. [Barth, Braun, and Wu(2005)] The solid curve is from [Murphy(1996)]

$$(2) \gamma p \rightarrow \pi^+ \Delta^0, \text{ and}$$

$$(3) \gamma p \rightarrow \rho^0 p.$$

At CLAS, an isobar model for an analysis of double charged pion production induced by real and virtual photons in the entire N excitation region was developed by the collaboration of Jefferson Lab and Moscow State University (MSU). This approach relates the N photo-couplings and hadronic parameters to measured integrated, single and multi-differential cross sections for the $p\pi^+\pi^-$ final state [Moiseev(2005)]. This allows for the extraction of N photo-couplings and, in part, hadronic decay parameters from a fit to the analyzed data. In the JLab-MSU (or JM) model, the contributions

FIGURE 1.10. Description of CLAS charged double pion differential cross sections at $W = 1.51$ GeV within the framework of the JM model. The full calculations are shown by the solid lines. The contributions from $\pi^-\Delta^{++}$ and $\pi^+\Delta^0$ isobar channels are shown by the dashed and dotted lines, respectively. The contributions from direct charged double pion production processes are shown by the dot-dashed lines. α_i angular distributions were calculated with the JM parameters fit to the other 6 differential cross sections. [Barth, Braun, and Wu(2005)]

from the isobar channels $\Delta^{++}\pi^-$, $\Delta^0\pi^+$, $p\rho$, and $D_{13}(1520)\Delta^+$ were taken into account and examined [Moiseev(2005)].

The remaining mechanisms of the unknown dynamics were parametrized as 3-body phase space with the amplitude dependent on the photon energy and virtuality only. A combined analysis of recent CLAS photo- and electroproduction data allowed a considerable improvement of this approach [Moiseev(2005)].

FIGURE 1.11. Resonant (dot-dashed line) and non-resonant (dashed lines) contributions to the charged double pion differential cross sections at $W = 1.51$ GeV and $Q^2 = 0.425$ GeV². [Barth, Braun, and Wu(2005)]

By studying the kinematical dependencies of the differential cross sections and their couplings, they were able to establish the presence and strength of the relevant reaction mechanisms. Additionally this approach is intended to establish all significant mechanisms seen in the observables of charged double pion production to isolate the resonant parts of the amplitudes, and to derive the couplings of nucleon to nucleon resonance transitions from fits of all measured observables combined.

For N^* studies in pion photoproduction, as in electroproduction, information is needed on the mechanisms contributing to each of these channels in order to properly account for the impact of coupled-channel effects on the exclusive channel cross section. Thus we look to produce final state photo-induced cross sections for an adequate

FIGURE 1.12. Kinematic variables for the $\gamma p \rightarrow p \pi^+ \pi^-$ reaction (choice 2). The top plot shows the π^- spherical angles θ_{π^-} and ϕ_{π^-} , while the bottom plot shows the angle $\alpha_{(\pi^- p)(\pi^+ p')}$ of the plane defined by the momenta of the final $p\pi^+$ pair with respect to the plane comprised by the momenta of the initial proton p and π^- . [Fedotov and Mokeev(2008)]

study of the coupled-channel effects, where at the end of our analysis we will have photo-induced one dimensional differential cross sections that can be analyzed using a photoproduction version of the JLab-MSU model. Figure 1.10 and Figure 1.11 depict these cross sections needed to be produced.

The JLab-MSU model adopted the following set of variables to describe the 3-body final state as the polar angle and angle between the planes are referenced by Figure 1.12:

- invariant mass of the first pair of particles M_{12} ;
- invariant mass of the second pair of particles M_{23} ;
- the first particle solid angle Ω ; and
- the angled between two planes: one of them (plane A) is defined by the 3-momenta of the real photon and the initial proton, and the second plane (plane B) is defined by the 3-momenta of the two other hadrons (see Figure 1.12)

We adopt the following variable assignments to describe the 3-body final state:

- invariant mass of the $p\pi^+$ pair, invariant mass of the $\pi^+\pi^-$ pair, the final proton spherical angles θ_p and ϕ_p and the angle $\alpha_{(pp')(\pi^+\pi^-)}$ between the two planes: B, composed by the momenta of the $\pi^+\pi^-$ pair, and A, composed by the momenta of the initial and final protons (choice 1);
- invariant mass of the $\pi^+\pi^-$ pair, invariant mass of the $p\pi^-$ pair, π^- spherical angles θ_{π^-} and ϕ_{π^-} and the angle $\alpha_{(p\pi^-)(p'\pi^+)}$ between the two planes: B, composed by the momenta of the final state particle p' and π^+ pair, and A, composed by the initial state proton p and π^- (choice 2);
- invariant mass of the $p\pi^+$ pair, invariant mass of the $p\pi^-$ pair, π^+ spherical angles θ_{π^+} and ϕ_{π^+} and the angle $\alpha_{(p\pi^+)(p'\pi^-)}$ between the two planes: B, composed by the momenta of the final state particle p' and π^- and A, composed by the momenta of the initial state proton p and π^+ (choice 3)[**Fedotov and Mokeev(2008)**];

For our usage of the model, the selected double pion events were collected in bins of W (the kinematic range of the reaction) that are fully inside the kinematically allowed area. The shapes of the cross sections for the different mechanisms are substantially

different in the various observables, but highly correlated to the reaction dynamics. Moreover, we found no need to implement additional mechanisms beyond the ones already included in JLab-MSU. Therefore, the successful description of all nine single-fold differential charge double pion cross sections will allow us to identify all significant contributing processes and access their dynamics at the phenomenological level.

1.4. THEORY

The quark model was introduced about 30 years ago by Gell-Mann as a description of the $SU(3)$ symmetry observed in the hadron spectrum [Gell-Mann(1964)]. The model was then used to describe the nucleon in terms of a non-relativistic motion of three constituent quarks. Constituent quark models (CQM) have been developed to describe the whole spectrum for the excited nucleon states. To adequately calculate the baryon spectrum, a knowledge of the quark configuration for each state is needed. Once the configuration is determined utilizing the energy spectrum, the configuration can be used to calculate photo-coupling amplitudes and the decay of the state.

Knowledge of the nucleon and its excited states relies on QCD-inspired models. Constituent quark models do a good job of explaining experimental results but predict more resonances than have been seen. In models involving the quark and diquark, the degrees of freedom are limited and they do a better job in predicting the observed states. Thus, the discovery or observation of additional predicted states would imply new avenues into the challenge of missing states.

1.4.1. Harmonic Oscillator Model. Many excited states have been observed through πN and γN scattering experiments, having different spin and parity. To describe excited baryons including the masses of the baryon decuplet, one must introduce dynamics for the constituent quarks [UMD].

In the simplest model the constituent quarks are put in a harmonic oscillator potential with additional spin-spin and spin-orbit dependent interactions arising from gluon exchange terms. The choice of this potential is mainly due to its simplicity in

separating out the center-of-mass motion. In the framework of the constituent quark model the simplest excitations of the nucleon are described by a spin-flip or an orbital excitation of one quark. The wavefunctions are composed of space, spin, flavor, and color parts, where the total wavefunction and the color part must be antisymmetric.

As a first approximation, the quarks are treated as moving non-relativistically, then atomic and nuclear physics ideas are carried over [Faiman(1969)]. The most common starting place to formulate a model within these parameters is the harmonic oscillator (which forms the basis for the shell model). It conveniently becomes a reasonable and common choice for the potential between quarks, at least for the low-lying energy states.

In this basis for the shell model, the particle is moving in a central three-dimensional, harmonic-oscillator potential, this being a familiar scenario in the constituent quark framework of models [Faiman(1969)]. The Hamiltonian

$$H = \frac{1}{2M}p^2 + \frac{1}{2}M\omega^2r^2, \quad (1)$$

has energy levels

$$E = (l + 2k + \frac{3}{2})\omega \quad (2)$$

where l is the orbital angular momentum quantum number, and $k=0,1,2,\dots$ is associated with the number of nodes in the radial wave function, and the position vector $\vec{R}$ of the center of mass and the two relative coordinates $\vec{\lambda}, \vec{\psi}$ are:

$$\vec{R} = \frac{1}{3}(\vec{r}_1 + \vec{r}_2 + \vec{r}_3), \quad (3)$$

$$\lambda = \frac{1}{\sqrt{6}}(\vec{r}_1 + \vec{r}_2 - \vec{r}_3), \quad (4)$$

$$\psi = \frac{1}{\sqrt{2}}(\vec{r}_1 - \vec{r}_2). \quad (5)$$

FIGURE 1.13. Low-lying energy levels predicted by a simple harmonic oscillator quark model.

The resulting energy spectrum is shown in Figure 1.13. The harmonic oscillator model predicts a spectrum of baryons that is consistent with quantum numbers observed, but the difficulty in concluding whether the data follows this general trend comes in with the mass splitting. Thus it leaves a need to extend the model to incorporate mass-splitting potentials in addition to the basic forces of the harmonic-oscillator, which are included in Figure 1.13.

In comparing the data and the model predictions, there are more theoretical states than what has been observed experimentally. Two possibilities exist: either the other resonances are too broad and too weak to be seen, or the models with the 3-quarks do not represent appropriately the correct number of degrees of freedom in spectroscopy [UMD]. For example, other literature suggest that a quark-diquark system represents the low-energy excitations of baryons much better.

The harmonic oscillator model provides a vast achievement in classifying a large array of resonant states discovered in the last twenty or so years. These resonant states can be understood in terms of simple excitations of a three-quark system, but the three-quark system quickly predicts a large number of states with high spin. Since the number of states in subsequent bands increases rapidly, the separation of

FIGURE 1.14. The energy-levels of baryon resonances (shown as bars) in simple harmonic oscillator potential mixed by residual and hyperfine interactions. The PDG resonances are shown by shaded boxes with 3 and 4 states shaded darker than 1 and 2 star states.[UMD]

the center-of-mass motion obviously becomes very laborious and in any case, the whole situation becomes confused by configurations mixing [Faiman(1969)]. Thus the harmonic oscillator model is not as useful as other models when dealing with higher spin states.

1.4.2. Soliton Models. Two other models of pion photoproduction, the Skyrme model and the algebraic model, received attention due to the nucleons spin content measurement raising questions about the validity of the constituent quark model used an algebraic framework to study a collective string-like model of the nucleon [Bijker(1994)]. In this approach, in which both internal (spin-flavor-color) and spatial degrees of freedom of hadrons are treated algebraically, hadron spectroscopy is examined. The new ingredient is the introduction of a space symmetry and a spectrum generating algebra for the radial excitations. The algebraic approach unifies

State, J^P	Predicted Mass (MeV)	Experiment
N $1/2^+$	960	939
Δ $3/2^+$	1230	1232
Λ $1/2^+$	1115	1116
Σ $1/2^+$	1190	1193
Σ $1/2^+$	1370	1384
Ξ $1/2^+$	1305	1318
Ξ $1/2^+$	1505	1533
Ω $1/2^+$	1635	1672

TABLE 1.3. Table of Ground State Baryons. [Capstick and Isgur(1986)]

the harmonic oscillator quark model with collective string-like models of baryons [Bijker(2000)]. Since the quark model and the algebraic model consider resonant excitations as bound states in the continuum, background reaction channels must be subtracted to find the photo-coupling amplitudes. On the other hand, other Skyrme models describe the nucleon as a soliton and computes all aspects of the reaction, including background, where the results can be compared directly with partial-wave amplitudes. A skyrmion is known as a mathematical model used to model baryons with a non-trivial classical solution for the non linear sigma model. Skyrme’s innovation was to provide a model in which the fundamental fields consist of just pions. The nucleon is then obtained, in the initial approximation, as a certain classical configuration of the pion fields [Schechter(2000)]. To avoid the contradiction of making Fermi fields out of Bose fields, the classical field is arranged to possess a non-zero ”winding number”, thus such objects are solutions to the classical field equations with localized energy density [Rajaraman]. This model is just one particular choice for the non linear sigma model, but it has the great advantage of being only of second order in time derivatives, and hence, of succumbing to the traditional methods of Hamiltonian quantum mechanics. Furthermore, it possesses soliton solutions, or Skyrmions, of finite extent.

In the framework of the Skyrme model, one can calculate many static properties of baryons such as magnetic moments, g-factors and charge radii. Despite some glaring exceptions, these typically agree with experiment to within 30%, when the adjustable

State, J^P	Predicted Mass (MeV)	Experiment	Status
$N^* 1/2^-$	1460	1520-1560	****
	1535	1620-1680	****
$\Delta^* 3/2^-$	1555	1600-1650	****
$N^* 3/2^-$	1495	1510-1530	****
	1625	1670-1730	***
$\Delta^* 3/2^-$	1620	1630-1740	****
$N^* 5/2^-$	1630	1660-1690	****
	(b)		
$N^* 1/2^-$	1945,2030,2070,2145,2195		
$\Delta^* 1/2^-$	2035,2140		
$N^* 3/2^-$	1960,2055,2095,2165,2180		
$\Delta^* 3/2^-$	2080,2145		
$N^* 5/2^-$	2080,2095,2180		
$\Delta^* 5/2^-$	2155,2165		
$N^* 7/2^-$	2090		

TABLE 1.4. Table of negative-parity S=0 excited baryons. (a) States in the N=1 band and (b) predictions for other states below 2200 MeV.[**Capstick and Isgur(1986)**]

parameters of the model are chosen to give the nucleon and delta masses correctly [**Bijker(1994)**].

The Skyrme model cannot be compared directly with quark and algebraic models, because it calculates the full multipole amplitude, not just the resonant part. The amplitudes are in fair agreement with other calculations and the data, except for the $P_{11}(1440)$ where the Skyrme results are much larger.

There are large disagreements between the algebraic and quark models for some amplitudes. For example, the algebraic model predicts a negative value for the amplitude of the D_{33} (1700), while the quark model predicts a positive amplitude of about the same magnitude [**Bijker(1994)**]. The magnitudes of the results of the quark model and the algebraic model are in reasonable agreement, with a few exceptions for which some of the quark model amplitudes are much smaller than those of the algebraic model. Table 1.4 and Table 1.5 shows the negative- and positive-parity predicted excited states in the skyrme model.

State, J^P	Predicted Mass (MeV)	Experiment	Status
$\Lambda^* 1/2^-$	1550	1400-1410	****
	1615	1660-1680	****
	1675	1720-1850	***
$\Sigma^* 1/2^-$	1630	1610-1635	**
	1675	1730-1800	***
	1695		
$\Lambda^* 3/2^-$	1545	1520	****
	1645	1685-1695	****
	1770		
$\Sigma^* 3/2^-$	1655	1665-1685	****
	1750	1900-1950	***
	1755		
$\Lambda^* 5/2^-$	1775	1810-1830	****
$\Sigma^* 5/2^-$	1755	1770-1780	****
	(b)		
$\Lambda^* 1/2^-$	2015,2095,2160,2195,2235,2280		
$\Sigma^* 1/2^-$	2110,2155,2165,2205,2260,2275		
$\Lambda^* 3/2^-$	2030,2110,2185,2230,2290		
$\Sigma^* 3/2^-$	2120,2185,2200,2215,2265,2290		
$\Lambda^* 5/2^-$	2180,2225,2240,2295		
$\Sigma^* 5/2^-$	2205,2250,2270,2280		
$\Lambda^* 7/2^-$	2150,2230		
$\Sigma^* 7/2^-$	2245		

TABLE 1.5. Table of positive-parity S=0 excited baryons. (a) States in the N=1 band and (b) predictions for other states below 2200 MeV. [Capstick and Isgur(1986)]

1.4.3. Diquark Model. In the framework of phenomenological constituent quark models (CQMs), many works have been initially realized with a non-relativistic approach giving satisfactory results for the static properties of the nucleon and of its excited states [Gutierrez(2009)]. In the ordinary quark model, hadrons are $q\bar{q}$ or qqq states of mesons or baryons. However, the diquark possibility was first mentioned by Gell-Mann where he suggested the idea q-q bound states could be formed within the baryon. This idea allows us to reduce a 3-body problem to a 2-body one.

FIGURE 1.15. Predicted (black) and measured (grey) states from the diquark model [Gutierrez(2009)].

Quark/diquark models have been proposed for the study of the baryonic spectroscopy [Gutierrez(2009)] to avoid the problem of missing resonances. The presence of a coherent diquark structure has been suggested within baryons. This structure has been studied as a computational tool for baryon calculations and also as a solution for scaling violations in deep inelastic scattering. Treating the diquark as an s-wave bound state of two quarks reduces the problem of three-body quark excitations to a two-body quark-diquark excitations. Using perturbative QCD, the spin-dependent excitation levels of the quark-diquark system can be calculated as in Figure 1.15.

From the spectrum of this model, the differences are seen with respect to the conventional symmetric quark model spectrum. First, the spin-orbit mass splitting is easily handled in the quark-diquark frame, where it is cancelled in order to obtain a good fit to the mass spectrum in the conventional model. Also, a unified description of spin-dependent forces in mesons and baryons is obtained through this model because the model parameters needed for the fit in the diquark model are essentially the same as those used in the meson spectrum.

The model gives a good description in the lower part of the spectrum. However, for high energy states discrepancies have been found with respect to experimental

data [Yao(2006)]. This fact can be due to the non-relativistic treatment or other field effects that have not been taken into account by the model.

1.5. SUMMARY

There are many known resonances within the γN excitation spectrum that have significant $N\pi\pi$ couplings. These states are the focus of our analysis to validate and solidify the existing data set. Thus, we look to produce known resonances and states to finally gauge the coupling strength of the two pion channel.

CHAPTER 2

EXPERIMENT AND DETECTOR

The data presented here was obtained from Hall B at Thomas Jefferson National Accelerator Facility (TJNAF), also known as Jefferson Laboratory or JLab, in Newport News, Virginia. A picture of JLab is shown in Figure 2.1. There are currently three experimental halls, denoted as A, B, and C. The Continuous Electron Beam Accelerator Facility (CEBAF) can deliver high-intensity beam to three experimental halls with independent beam parameters simultaneously. A demonstration layout is shown in Figure 2.2. All of the three halls have fixed targets. Hall A and Hall C have fixed-angle detectors for detecting hadrons and electrons, and Hall B has a spherical detector of large acceptance covering almost 4π of solid angle.

2.1. EXPERIMENT

A layout of the accelerator facility is shown in Figure 2.2. CEBAF came on-line in 1996, delivering a high quality electron beam which could be used in the study of hadronic physics at Jefferson Lab (JLab). New technology used in JLab's CEBAF allows for an extremely high luminosity continuous beam of electrons that partially counteracts the problem of low interaction rates. CEBAF is designed to deliver a beam of high-luminosity electrons with 100% duty factor to three experimental halls, A, B, and C, where each hall provides a different experimental program [Mecking(2003)]. The accelerator's layout is in a race-track configuration that has two parallel 80 m long linear accelerators (linacs) connected by a set of five recirculating arcs at one end, and four similar arcs at the other end. Any number of arcs can be used at a given time, allowing for the extraction of the electron beam

FIGURE 2.1. Picture of TJNAF.

at different energies, with the maximum energy being obtained when the machine is run in five-pass mode. Meaning that the beam circulates five times (passes) where it gains approximately 1 GeV with each pass. CEBAF's three experimental halls are the end stations to simultaneously receive beam at either the same energy or at different energies, which are multiples of 0.2 times the end-point energy (if five-pass beam is used in one of the halls). The almost 100% duty cycle, where continuous comes into play for the electron beam, is made possible by the use of superconducting niobium RF cavities.

Several of these cavities are housed in a single cryomodule, see Figure 2.3, and these cryomodules then form the backbone of the linacs. Each cryomodule has a gradient of 5 MeV per meter, so that each linac can boost the energy of the electrons by 400 MeV. This gives an 800 MeV electron energy increase at each pass, corresponding

FIGURE 2.2. Layout of Thomas Jefferson National Accelerator Facility, showing injector, linear accelerators, recirculation arcs and three halls.

to a maximum energy of 4 GeV in five-pass mode. However the performance of the cavities has exceeded the design specifications, allowing for gradual energy upgrades, with the highest energy reached to date being 5.7 GeV. Further upgrades are planned for the future, which should result in much higher beam energies, designed to push this maximum electron energy up to 12 GeV. A feature of CEBAF is that it is capable of delivering a continuous electron beam, which means that electrons are delivered to each hall in well defined beam buckets separated by 2.0005 ns. At the time of this experiment (eg3 data run), a polarized electron beam was initially produced at the injector by a laser source. The initial electrons from the gun are accelerated to 45 MeV and are then passed through a rotating disc with three slits in it. This separates the electrons into three bunches; the time interval between each bunch is determined by the frequency of the disc. The size of each gap can be enlarged or reduced, thus controlling the number of electrons per bunch. By extracting every third bunch and directing it to a different hall, it is possible to deliver beams of three different currents to the different halls. The range in currents is 100 pA to 100 μ A, and the bunch separation obtained from the 499 MHz frequency for each hall is 2.005 ns. The eg3

experimental run was conducted in Hall B; a schematic of the hall is also shown in Figure 2.5. For photon experiments like eg3, a metal foil is placed in the path of the electron beam and the resulting photons are tagged in the bremsstrahlung tagger (see Sec. 2.10). The photon beam then impinges on the liquid-deuterium target, which is situated in the center of the CEBAF Large Acceptance Spectrometer (CLAS) located downstream in the hall. The CLAS, tagger, and target are discussed in the ensuing sections.

2.2. CONTINUOUS ELECTRON BEAM ACCELERATOR FACILITY

CEBAF delivers electron beams to the three experimental halls. The main advancement of the accelerator facility is the adoption of superconducting radio frequency (SRF) cavities, which allow for continuous, high-gradient acceleration. Before CEBAF, the usual cavities were made of copper. The electric resistance of the material heated up the cavities. Therefore, a significant cooling time was needed between two operations. With the usage of the SRF cavities, the accelerator can deliver "continuous" electron beams.

The electron beam starts from the injector. The electrons are generated by shining a pulsed laser on a GaAs photocathode and then accelerated to 45 MeV by going through 2 and 1/4 SRF cavities. The laser pulses generate electron bunches for each experimental hall every 2 ns. The injector system then cleanly separate the bunches before recirculating them through the linear accelerators (LINACs) of CEBAF Figure 2.2.

The basic element group of the LINAC is the SRF Cavities as shown in Figure 2.3. There are 168 SRF Niobium Cavities in each LINAC. Each cavity is cooled with liquid Helium to $-271^{\circ}C$ to maintain the superconductivity of the material. The RF electromagnetic standing waves in the cavities accelerate the electron beams. The illustration is shown in Figure 2.4. This acceleration is independent of the speed of the electron once they have 45 MeV provided by the injector. There are two

FIGURE 2.3. Picture of CEBAF's SRF cavities.

FIGURE 2.4. The acceleration gradient is provided by the electric field formed from standing waves.

LINACs and each LINAC can accelerate the electron beam by 600 MeV, so that each electron gains 1.2 GeV after one loop. The recirculation arcs shown in Figure 2.2 bend the electron beam in the loop. There are 5 routines corresponding to 5 passes. After that, each electron in the beam has gained up to 6 GeV energy before entering each experimental hall initiated by extraction elements Figure 2.2. This acceleration

process also helps to focus electrons in the beam so that each bunch has a width of only about several picoseconds.

2.3. CLAS

Hall B is the smallest of the three experimental halls at JLab. It houses a series of experimental detectors, but the centerpiece device is the CEBAF Large Acceptance Spectrometer (CLAS). The primary focus of the CLAS detector is optimal charged particle measurement with sufficient momentum resolution and geometrical coverage specifically in the laboratory frame that enables the usage of polarized targets by maintaining a magnetic-free region around the target.

A description of the CEBAF Large Acceptance Spectrometer (CLAS) is best begun with a discussion of the original design goals for the detector. The physics program in Hall B is broad and includes the study of the baryon and meson structure and spectroscopy, gluonic degrees of freedom, and multi-nucleon correlations. In order to achieve all of these physics objectives, as well as to take advantage of the availability of a high quality, high luminosity electron beam, the CLAS detector was designed to have the following features [Mecking(2003)].

- ◊ Homogeneous coverage over a large angular and momentum range for charged particles, photons, and neutrons.
- ◊ Good momentum and angular resolution.
- ◊ High luminosity and counting rate.
- ◊ Good particle identification: separation of electrons, pions, kaons, protons, and deuterons in the momentum range of interest as well as the separation of photons and neutrons.
- ◊ Homogeneous magnetic field that does not penetrate the target region.
- ◊ Sufficient space in the target region for the use of polarized targets and their associated equipment.
- ◊ Azimuthal symmetry around the beam axis. [Philips(2002)]

FIGURE 2.6. Picture of CLAS.

The CLAS detector is designed and currently runs at energies of up to 6 GeV, but with recent approval it will be upgraded to energies of 12 GeV. The Forward Detector detects neutral and charged particles from angles of 5 degrees up to 40 degrees. Presently, it consists of 6 main sub-detectors for the precise detection of particles. Each segment, more commonly referred to as a sector, spans 60 degrees in azimuthal angle around the z-axis that is defined by the beam direction. This segmentation, which is necessary for high-luminosity operation, enables CLAS to accommodate high counting rates.

Each sector consists of drift chambers (DC) to determine the charged particle paths, gas Cherenkov counters (CC) for electron discrimination, time-of-flight (TOF) scintillators for nucleon and meson identification, and an electromagnetic calorimeter (EC) for identifying showering electrons and photons. A two-level trigger system was incorporated for conversion of data and readout capabilities, and a data acquisition system collects and stores all information for analysis.

Figure 2.10 shows a side view of CLAS together with typical track segments of a charged particle and the energy deposition of neutral particles from a real event, obtained from the run-time event display CLAS Event Display (CED).

FIGURE 2.7. Design sketch of Components of CLAS.

What follows is a brief description of the separate components that make up the CLAS detector.

2.4. TOROIDAL MAGNET

The magnetic field for the spectrometer is provided by a toroidal magnet to best achieve the design goals of the CLAS detector. The toroidal magnet allows a field free region around the target, and it is an efficient way of providing a large field volume. For good momentum resolution, it provides a magnetic field that is always transverse to the particle momentum. In addition, the determination of the azimuthal angle is independent of the determination of the polar angle and the momentum, providing another independent kinematic variable. The magnetic field within CLAS is generated by a system of six superconducting coils arranged into a toroidal geometry around the beamline [Mecking(2003)]. This configuration effectively creates six different sectors in CLAS, and the presence of the magnetic coils reduces the acceptance only minimally.

FIGURE 2.8. Longitudinal cut of the Torus magnetic field map.

FIGURE 2.9. Transversal cut of the Torus magnetic field map.

Figure 2.8 and Figure 2.9 characterize the torus magnetic field map. This immediately illustrates one of the main disadvantages of a toroidal magnet; the lack of complete ϕ -coverage due to the presence of the coils themselves. The coils are designed with 4 layers and 54 turns of aluminum-stabilized NbTi/Cu superconductor and are cooled to temperatures of 4.5 K by forcing super-critical helium through cooling tubes located at the edge of the windings. The other disadvantage of the

toroidal field is that it is inhomogeneous, making the reconstruction of particle trajectories more complicated than in the case of uniform fields. These disadvantages are, however, minimal in comparison with the tremendous benefits provided by a toroidal magnet. The toroidal geometry also has the advantage that it preserves a central field free region that can be utilized for the operation of a polarized target. The normal polarity of the field is such that negative particles are bent inwards towards the beam axis, and positive particles are bent outward. The maximum field strength is 2 T.

2.5. DRIFT CHAMBERS

The drift chambers in CLAS are designed to provide good tracking resolution and efficiency while maintaining a large acceptance [Mestayer(2007)]. The main purpose of the drift chambers is to determine particle trajectories, and to provide some particle identification via determination of the particle momentum (in conjunction with the velocity obtained from the TOF counters). Figure 2.10 shows a cross sectional view of the arrangement of the drift chambers. There are three chambers in each sector, see (Figure 2.11), referred to as Regions 1, 2, and 3 [Mestayer(2007)]. Each sector contains three large multi-layer chambers at different radial locations giving a total of 18 drift chamber modules. A particle leaving the target first encounters Region 1, which is a low-magnetic-field region, prior to reaching the toroidal magnets. It then enters Region 2, which is a high-field region within the toroid, and finally passes through Region 3, which lies outside the outer coils of the toroid.

Each region consists of two super-layers, each of which is in turn made up of six layers. A layer contains many wires, arranged so as to make hexagonal cells. A cell is defined by six field wires, each made of gold-plated aluminum, having a diameter ranging from 15 - 45 μm depending on the region, and maintained at high voltage. In the center of each cell is a sense wire, made of gold-plated tungsten and having a diameter of 20 μm . The drift chambers are filled with a gas mixture of 90% Ar and 10% CO_2 . A charged particle traversing the chambers ionizes the gas, and the

FIGURE 2.10. Sketch of the two-dimensional side view of CLAS and the Drift Chambers with charged particles of a real event.

FIGURE 2.11. Cross-sectional view of CLAS illustrating the layout of the three drift chamber regions.

resulting ions drift towards the nearest sense wire giving rise to a signal pulse. The drift time can be used to infer the position of the particle within the cell, using a known time-to-distance correlation function. The hit positions obtained from several sense wires along the particle trajectory can then be combined to provide a track or

FIGURE 2.12. View of CLAS illustrating the third region drift chamber.

trajectory. This is illustrated in Figure 2.12. The polar angle coverage provided by the chambers is $8^\circ < \theta < 142^\circ$, while the azimuthal coverage per sector is 50° , giving a total of 300° (out of 360°). The missing azimuthal coverage is due to the presence of the magnet coils, and while strictly not constant in θ , the angles quoted here are a reasonable estimate. Overall, CLAS covers $\sim 74\%$ of 4π .

2.6. CHERENKOV COUNTERS

The main purpose of the Cherenkov counters (CCs) is to identify electrons, and to separate them from other charged particles, especially pions [Adams et. al(2000)]. Cherenkov radiation is the photon emission from charged particles that cross through a medium with a velocity greater than the speed of light in that medium. The photons are radiated in a cone centered around the path of the charged particle. The dependence of the emission angle of the Cherenkov radiation on particle velocity is exploited by ring image Cherenkov counters which can provide the most accurate measurement of particle velocities.

The Cherenkov detector aims at maximizing the coverage of each sector up to a polar angle of 45° . Each sector is divided into 18 regions of θ , and each θ -segment is divided into two sub-modules by the symmetry plane bisecting each sector.

FIGURE 2.13. A schematic diagram of the array of optical modules in one of the six sectors.

FIGURE 2.14. Diagram of one Cherenkov counter segment spanning a sector in CLAS.

The Cherenkov Counters as shown pictured in Figure 2.13, are located outside Region 3 of the drift chambers. These detectors are generally not operational during tagged photon runs but were operational for the eg3 data set.

2.7. TIME OF FLIGHT SCINTILLATORS

The Time of Flight (TOF) system is designed to decipher the flight time of particles produced from incident radiation reactions. Charged particle identification is an important part of the physics program. If a *particle's* start position and momentum

FIGURE 2.15. Schematic view of one time of flight wall sector.

are known by taking the path length information to where it was detected in TOF, then one can calculate the velocity of that particular particle. The time of flight system at CLAS uses the start to arrival time of a particle to determine its flight time. The system was purposed to include good time resolution to adequately identify particles and also obtain good segmentation to provide flexible triggering and pre-scaling. The time of flight system is subdivided into two groups, which are parameterized by the scattering angle of the reaction particle. At polar angles of up to 40° , TOF is comprised of what are known as the small (forward) angle counters. At these angles, the scattering angle is minimal and the particle inherits more momentum. From 41° and above, these are known as the large angle counters. One important advantage of the reconstructed angles is depending on the orientation of the magnetic field, the bending angle provides immediate information as to the charge of particles within the reaction [Smith(1999)].

The TOF system is equipped for a resolution of $\sigma = 120$ ps at the small angles and 250 ps at angles of 90° and larger. These specifications are required by the fact that at small angles, the most energetic particles are produced requiring a better resolution where this lessens with each increment in θ angle. Using off-line analysis, the final time resolution for particles is achieved by correcting leading-edge discriminator based time measurements with pulse-height information for the introduced time-walk.

FIGURE 2.16. Sketch of a Photomultiplier Tube.

Thus, the system is required to give signals that represent a uniform response to selected particles that reach the time of flight detectors. The TOF system is not only used to determine the particles velocity but can also be used for energy-loss measurements. Energy loss in the counter is proportional to pulse-height information, which means there is a separate way to identify slow particles. If multiple scattering particles dominate the tracking resolution, then the particles distinct energy loss can also give a better measurement of the particle's energy. In addition to excellent timing resolution and segmentation, the TOF system has to be able to operate in a high-rate environment.

The timing resolution of each counter in the TOF system was measured with cosmic rays and for the shortest scintillators the resolution was found to be 80 ps and 150 ps for the longer counters which are positioned at smaller angles and would give an average of 120 ps [Smith(1999)]. Each counter has its signal readout by a QDC and a pipeline TDC, and can be used to generate prompt signals for the CLAS level 1 trigger. The TOF system was also used during the analysis to calculate the velocity of particles passing through CLAS by measuring the flight time between the start counter and itself. This calculated velocity, along with measured momentum from the drift chamber system, allows the particle's mass to be determined using the relation $m = p/v$. As will be discussed in chapter 4, the TOF mass is used for the initial particle identification.

2.8. ELECTROMAGNETIC CALORIMETER

The Electromagnetic Shower Calorimeters (ECs) [**Amarian and Asryan(2000)**] are primarily used to provide the electron trigger for CLAS in electron beam experiments, and for the reconstruction of π^0 s from their decay photons. They can also be used for pion rejection and neutron detection (including neutron/photon discrimination). Each sector in CLAS has a calorimeter that covers scattering angles from 8° to 45° . In two sectors this coverage is extended to 90° by the Large Angle Calorimeters (LACs). Since the LACs were not used in this two pion analysis, only a brief description is provided here. The LACs are electromagnetic calorimeters with a rectangular shape, having an area of $3.6 \times 3.9 \text{ m}^2$. Alternate layers of scintillator strips are oriented perpendicular to each other in a square grid to provide the geometrical location of the hit, and in order to better determine the location of a shower, both ends of the scintillator strips are read out. The EC in each sector was constructed in the shape of an equilateral triangle, in order to match the hexagonal geometry of CLAS. Each calorimeter consists of 13 identical submodules, with each submodule made up of three layers of 2-mm-thick lead plates, interleaved with layers of 10-mm-thick, 10-cm-wide scintillator strips. The three layers of scintillator strips in a submodule are rotated 120^{circ} relative to each other, so that each layer is parallel to one side of the triangle. These three layers within each submodule are referred to as the U-, V-, and W-planes, and they enable stereoscopic readout, which is necessary to resolve multiple-particles in the EC.

Figure 2.17 shows the layout of EC. The layers are arranged in a projective geometry, which means that in the direction away from the target, each layer has a slightly larger area than the previous one. This minimizes shower leakage at the edges of the detector. The active volume of the EC is thus a (truncated) triangular pyramid, having a base of 8 m^2 , with a projected apex at the CLAS target 5 m away [**Amarian and Asryan(2000)**]. Of the thirteen submodules, five constitute the inner portion of the EC nearest to the target, while the other eight make up

FIGURE 2.17. Exploded view of one of the six CLAS electromagnetic calorimeter modules. .

the outer portion. The inner and outer portions are read out independently, thus providing longitudinal sampling of the showers. The CLAS EC is thus a sampling calorimeter, which serves to provide better particle identification for electrons. When an electron enters the EC it interacts with the scintillator-lead layers and loses energy by radiating a bremsstrahlung photon. This photon then induces the production of a e^+e^- pair which leads to more bremsstrahlung, thus producing an electromagnetic shower. To reconstruct a valid hit in the EC, the energy deposition is required in all three planes of a module. The energy and time of the hit can then be calculated by measuring the path lengths from the particle hit position to the readout edge.

2.9. TARGET

A liquid deuterium target was chosen for the experiment. The target has a 4 cm wide diameter, providing sufficient coverage of the beam line in case the photon beam is slightly off-center. The target length was chosen to be 40 cm, allowing for a large event rate while maintaining an acceptable tagger rate. The density of the target was 0.179 g/cm^3 , the areal density 0.358 g/cm^2 , a thickness of 20mm. While the background due to accidental coincidences from unrelated events increases with target length, it is not significant enough to negate the advantage of having a high event rate.

The target met these requirements, and thus was used for eg3. It has a slightly conical shape and a rounded endcap with a thin aluminum window at the front.

2.10. START COUNTER

The purpose of the start counter (ST) is to provide the start signal for an event that occurs in the target. To serve this function, the ST consists of a collection of scintillator paddles that completely surround the target [Taylor(2000)]. The scintillator paddles are constructed in a V-shaped arrangement. In this way, each paddle provides coverage in CLAS, resulting in a hexagonal tube around the length of the target. The tube tapers to a hexagonally shaped cone at the downstream end of the target, where the paddles are bent inward so as to provide coverage for small angles. This design also enables the PMTs at each end of the scintillator to be situated upstream of the target so as to avoid interfering with the particles originating from the target, as well as to be out of the way of the photon beam which could potentially damage them. The paddles are only 3mm thick to minimize multiple scattering, and each section (covering one sector) is 60 cm long. The signal obtained from the ST is used in conjunction with the signals from the TOF paddles, the photon tagger, to provide the start time for each event.

FIGURE 2.18. The CLAS start counter surrounding the target cell.

2.11. THE PHOTON TAGGER

The Photon Tagger is the main component in photon beam production in Hall B [Sober et al(1999)]. The photon beam is made by directing the electron beam on a foil producing photons by the bremsstrahlung process. The bremsstrahlung recoil electrons are then deflected downwards by a uniform dipole magnetic field onto the Tagger focal plane, where energy and timing information are extracted. The bremsstrahlung photons are nearly collinear with the incident electron beam and pass through a hole in the magnet yoke, after which they are collimated, and then impinge on the target which sits in the center of the CLAS.

The photons themselves are not detected, instead they are tagged by matching them with the electrons that produced them. Photons that are produced with between 20% and 95% of the incident electron beam energy (E_0) are capable of being tagged by the detector [Sober et al(1999)].

The tagger magnet's field strength is set such that electrons near energy E_0 will curve and strike a shielded beam dump below Hall B. However, electrons that radiate energetic photons have significantly lower energy, thus curving more in the magnetic

field to strike the scintillator hodoscope. This hodoscope consists of two layers of scintillators, the E-counters to determine the radiated photon's energy and the T-counters to determine its timing.

The E-counters are used to determine the momentum of the recoiling electrons simply by measuring which path the electron goes, because the path of electrons in the magnetic field is solely determined by the momentum. The E-counters are 384 partially-overlapping scintillators each 20 cm long and 4 mm thick, providing 757 channels for energy measurement [Sober et al(1999)]. The widths of these counters vary from 6 to 18 mm such that each spans a constant energy interval of $0.003 E_0$. From the overlapping scintillator paddles, the energy of the incident electron beam, and the applied magnetic field, the photon energy can be determined with a resolution of $0.001 E_0$ [Sober et al(1999)].

The T-counters are 61 scintillator paddles, each 2 cm thick, which provide a time resolution of 110 ps. The first 19 paddles correspond to photon energies of $0.75 E_0$ and greater, and are much narrower than the others. This allows experiments to run with a high photon beam flux while maintaining adequate electron-photon matching at low photon energies. Within each group, the T-counters vary in width to maintain the same counting rate in each paddle to account for the $1/E$ energy distribution of the bremsstrahlung photons.

The signals from T-counters are sent to the Master OR (MOR) and an array of FASTBUS TDCs after passing through discriminators. The MOR signal is part of the trigger system, which decides whether it should write the digitized information from all detectors into the data stream or discard them. The TDC array generates the timing digitization. The E-counter signals are also sent through a discriminator and then forwarded to a multi-hit TDC. The timing information of both E-counters and T-counters is sent to the data stream. The offline software establishes the position and timing coincidence between them.

For eg3, a 15 μm thick gold foil was used as the radiator. Corresponding to 5×10^{-4} radiation lengths, this relatively thick radiator was used to provide as large a photon flux as possible for up to 5 GeV photoproduction. At electron energies of 4.5 GeV and higher the electron photon matching in the tagger is still good due to the narrow T-counters despite the high number of deflected electrons.

The time resolution from the tagger system is good enough to determine from which beam bunch the recoil electron come. In the off-line analysis, the time is corrected according to the beam bunch (RF correction), which is obtained from the accelerator and the most accurate time information available in the data. It is also corrected to the time when the photon reaches the target in order to serve as the start time of the event.

2.12. TRIGGER SYSTEM

The trigger system for CLAS is essential to decide when a particular event will be written into the data stream to eventually be analyzed. A variety of processes such as electronic noise and cosmic rays passing through a detector element could produce a signal in a subsystem that does not correspond to a physics event. The CLAS trigger is therefore required to determine which set of signals correspond to a real physics process of interest. The CLAS trigger uses logic signals derived from the various detector subsystems to decide on whether to initiate the digitization and readout of ADCs and TDCs or perform a fast clear/reset. Depending on the event rates in the detectors and the system live time the trigger can be configured to be highly specific to a signal state configuration of particles or relatively open ended [Mecking(2003)]. This is implemented by 3 components: level 1 trigger, level 2 trigger and trigger supervisor. In brief, the level 1 trigger is initiated by the data from the start counter and is configured to make a decision based on some combination of tagger master OR, TOF and start counter information. It uses a lookup table to identify true charged particle tracks by checking for a match between hits in the TOF

and hits in the start counter which correspond to the same sector. The level 2 trigger uses tracking information from the drift chambers, looking for suitable particle tracks before declaring an event valid. The system is designed to give fast information on a physics event of interest in conjunction with the level 1 trigger, as well as providing a more stringent constraint on which events are read out [Mecking(2003)]. For example, a combination of noise and background events could trigger an event at level 1 but no correlated track would be present in the drift chambers and this would cause level 2 to send a fast clear signal to all TDCs. This event would then not be read into the data stream. The trigger supervisor takes all level 1 and level 2 trigger inputs and produces all common start and stop signals, busy gates and resets required by the detector electronics.

2.13. DATA ACQUISITION

The CLAS data acquisition system (DAQ) builds events into a format that can be used for analysis using the CODA system [Mecking(2003)]. The DAQ receives data from the various detector systems that is digitized in VME and FASTBUS crates in the hall before being collected by VME readout controllers [Mecking(2003)]. These digitized values are then tabulated in such a way that each event is associated with a unique identity number. These data arrays, or event fragments, are then buffered and sent to an online acquisition computer (CLON10). At this point the event builder on CLON10 assembles the fragments and converts them into a BOS format [Pasyuk(2007)]. The event builder then passes the completed events on to the event transporter which transfers them to shared memory where they can be used for data monitoring or online analysis. Finally, the event recorder picks up all the events for permanent storage on the RAID array. From here the data can be transported to the JLab tape silo, where it becomes available for off-line analysis.

CHAPTER 3

EVENT SELECTION

The data used for analysis was obtained in Hall B from December 2004 to January 2005 over a running time period of 40 days. The liquid deuterium target, which was positioned 50 cm upstream of the CLAS center, was 40 cm long and 4 cm in diameter. The data of the eg3 experiment was processed with the standard CLAS offline software packages [Gothel(2004)].

The electron beam energy averaged measurements of 5765.5 MeV and 5768.3 MeV, respectively. The electron-beam energy was measured by its deflection in the magnetic field of the tagging system after it passes through a radiator with a nominal thickness of 5×10^{-4} radiation lengths. The standard electron beam current was chosen to be 30 nA, and it was limited by the drift chamber performance. The trigger required a hit in the tagger in the energy range from 4.5 to 5.5 GeV. The Level-1 trigger configuration demanded trigger bits five and six, where trigger bit five was prescaled and required a coincidence in the TOF system with the start counter (ST) in the same sector in at least two sectors. Trigger bit six required TOF with ST in coincidence in at least three sectors. The CLAS Level-2 trigger was not utilized in this experiment.

This chapter describes the steps taken after event reconstruction (cooking) of the data. It is dedicated to the quasi-free reaction of the photon scattering off protons by producing $p\pi^+\pi^-(n)$ for the final state particles. The purpose of the event selection is to determine a series of conditions, under which a good data sample can be produced that will lead to an error-controlled cross section for extraction.

3.1. EXCLUDED RUNS

Data taking in Hall B is grouped into runs. Run numbers are from 45255 to 46351. The first good run starts at 45552. The runs before it are mostly commissioning runs or questionable for various other reasons. Most runs are using a beam current of 30 nA and there are four high luminosity runs at 35 nA. However, they are treated the same in the analysis process, because the normalization is done on the photon flux, which is calculated independent of the beam current. The set criteria for choosing a run as a golden run was the luminosity of the beam current for that run. The run needed to have at least a 30nA luminosity and no other detector problems during the run. Such as bad runs had low luminosity, or frequent trips of the Drift Chambers, or DAQ problems during the run.

A good run query program can be obtained by doing the following as ordered: `cvs co eg3_ runs, cd eg3_ runs, make lib, make exe, eg3_ runs`. The data is stored in Dbhost "mysql://clasdb.jlab.org" with Dbname "eg3_ offline", DbTabl1 "Pass2v1" and DbTabl2 "GoldenRuns". Compared with the all-cooked-run list, the golden-run list has all 15 hydrogen runs removed and 8 bad deuteron runs removed. The golden runs are listed below: 45552, 45553, 45554, 45555, 45556, 45557, 45558, 45563, 45566, 45568, 45569, 45570, 45571, 45572, 45576, 45577, 45578, 45579, 45580, 45581, 45582, 45598, 45599, 45600, 45601, 45602, 45603, 45605, 45606, 45607, 45608, 45609, 45612, 45613, 45614, 45621, 45622, 45623, 45624, 45625, 45626, 45627, 45804, 45807, 45808, 45809, 45810, 45811, 45812, 45814, 45815, 45816, 45817, 45818, 45847, 45848, 45851, 45852, 45860, 45862, 45863, 45864, 45866, 45868, 45869, 45870, 45872, 45873, 45874, 45876, 45891, 45893, 45894, 45895, 45896, 45897, 45902, 45903, 45904, 45905, 45906, 45907, 45911, 45912, 45913, 45914, 45916, 45917, 45918, 45919, 45920, 45921, 45922, 45923, 45924, 45925, 45926, 45927, 45928, 45929, 45930, 45931, 45932, 45933, 45934, 45935, 45936, 45937, 45938, 45939, 45942, 45943, 45944, 45945, 45946, 45947, 45948, 45976, 45977, 45978, 45981, 45983, 45984, 45985, 45986, 45987, 45988, 45993, 45995, 45996, 46000, 46001, 46002, 46003, 46004, 46005, 46009, 46011, 46012, 46013, 46014,

46015, 46016, 46017, 46018, 46019, 46020, 46021, 46022, 46023, 46024, 46025, 46028, 46029, 46030, 46035, 46036, 46037, 46038, 46046, 46047, 46057, 46058, 46062, 46063, 46064, 46065, 46066, 46069, 46071, 46072, 46073, 46074, 46077, 46078, 46085, 46086, 46087, 46088, 46089, 46093, 46094, 46096, 46097, 46098, 46099, 46100, 46101, 46104, 46113. The runs from 45552 to 45627 are performed before Christmas 2004 and the rest are after that.

3.2. CHARGED PARTICLES

For the experimental and simulated data (discussed in Chapter 5), only the events with 2 positive and 1 negative final state particles are selected for the proton channel $p\pi^+\pi^-$. All charged particles are required to have good time-based tracking.

3.3. EVENT PHOTON SELECTION

FIGURE 3.1. β^2 versus p for all charged particles detected in CLAS. The low p , high β red band are the pions, the other red band are the protons, and the kaons lie between them. Standard particle identification cuts are placed on this distribution by the seb software package.

The eg3 experiment was first proposed for pentaquark study. Being that the eg3 experiment has a beam of high-intensity, this provides the opportunity to study events out of the triggered photon energy range. On the other hand, it also causes problems

FIGURE 3.2. tau versus momentum for positive (left) and negative charged particles (right) from the result of the improved particle identification.

in particle identification, because there are many photons recorded in each event and many particles produced as in Figure 3.1. Here at the low momentum is shows the pions in the high β red band. The other red band are the protons, and the kaons lie between them. Standard particle identification cuts are placed on this distribution to distinguish between the particles. But the standard CLAS offline software does not give satisfactory results for concise particle identification, so a method must be developed to ensure the results are adequate.

The method developed was a channel-specific particle identification (PID) method requiring vertex time cuts involving the two π s. For the analysis, we skimmed (pre-selected exclusive events to our reaction) the eg3 data set, requiring an exclusive data set of 3 particles (two positive tracks and one negative track). The skim contained all particles that fulfilled a 2-ns vertex timing cut between the final state particles

and additionally for the fastest-pion vertex time a tagger cut of 2-ns see Figure 3.3. The fast pion vertex timing cut acts on the TOF timing difference of the fastest pion calculated back to the vertex. The method requires three charged particles reconstructed by the standard cooking software and assumes the faster of them to be the pions. The start time at the target center is calculated from TOF time, vertex position, momentum and trajectory length established by the cooking software and the pion mass as

$$T_{tc} = T_{TOF} - \frac{l_{track}}{\beta c} - \frac{Z_{vt} - Z_{target}}{c}, \quad (6)$$

where T_{tc} is the start time at the target center, T_{TOF} is the TOF time of the particle, l_{track} is the trajectory length, $\beta = \frac{v}{c}$ is calculated from the momentum and the pion mass, Z_{vt} is the vertex position and Z_{target} is the target center position, which is -50 cm. The photon, whose time at the target center is closest to the time T_{tc} , is selected according to the vertex timing restraints, respectively.

For this analysis, the event selection begins with the identification of the $p\pi^+\pi^-$ final state that feeds the Δ^{++} production and where the measured proton and π^+ originate from the $\Delta^{++}(1232)$ decay in the photon-deuteron reaction. Events from the eg3 data set are preselected to contain these Δ^{++} particles. In that, the events have at least one negative (charge conservation) and two positive particles as identified by time-based tracking, this condition is satisfied for the required proton, π^+ , and π^- final state. Figure 3.2 (a) shows $\tau = 1/\beta$ versus momentum in GeV of the two positive tracks and the one negative track for the $p\pi^+\pi^-$ skim set. These are two of several histograms that are used to verify the track selection parameters applied in the skim. Two others are shown in Figure 3.7, displaying the TOF squared mass of all positive and negative particles. As shown in the plots, we clearly see the squared mass distribution of the proton, π^+ , and π^- .

FIGURE 3.3. 2ns vertex timing cuts between all particles (left) and fastest pion with tagger time (right) difference. The vertex timing cut between all particles (left) was an absolute cut on 2ns. The timing cut between the particles vertex time and the photons tagger time for choosing the right photon for each event. The idea behind this is that if the photon was triggering a good event, then it must be found within the 2ns vertex photon time window for optimal particle identification.

3.4. MULTIPLE PHOTON HITS

The beam intensity of eg3 is so strong that there are sometimes more than one electron that generate Bremsstrahlung photon events in one beam bunch (see Figure 3.5). For those photons from different bunches, the above described process can distinguish them. However, a pure timing method cannot distinguish those photons from the same bunch, since they correspond to the same start time. This is because in each single electron beam bucket every 2 ns, there can be more than one electron having radiated a photon and thus more than one photon detected by the photon tagger. However, these photons usually have different energies. It is very unlikely that they have very close energy.

FIGURE 3.4. The experimental data fits of $MM(p + \pi^+ \pi^-)$ are shown.

Therefore, a selection based on the missing mass , $\gamma d \rightarrow p \pi^+ \pi^- (n)$ (Figure 4.4) ,is applied so that the photon both in time and giving closest missing mass to spectator neutron is selected. The error of this method is studied by plotting the number of photons that satisfy both the timing and energy requirement. The energy requirement is that the missing mass calculated from the photon energy must be within 3σ of the spectator peak. The histogram is shown in Figure 3.6, where the ratio of multiple-photon to single-photon events is below 0.1% and hence negligible in this study.

3.5. PARTICLE IDENTIFICATION

After an event photon is selected, its time is regarded as the event start time t_0 . We use the event start time, particle TOF time, flight path and momentum to calculate the particle TOF mass as defined by

$$\tau = \frac{1}{\beta} = \frac{t_{TOF} - t_0 - (Z_{vt} - Z_{target})/c}{l_{track}/c} \quad (7)$$

$$m_{TOF}^2 = p^2(\tau^2 - 1) \quad (8)$$

FIGURE 3.5. The number of photons in the beam bunch corresponding to the event start time. This shows that the ratio of events of multiple photons to those of a single photon is about 45%.

FIGURE 3.6. The number of photons in the beam bunch corresponding to the event start time giving the correct missing mass within 3σ cut. The ratio of multiple to single photons is extremely low.

This quantity is always distributed around the PDG particle mass and broadened with increasing momentum when the CLAS time resolution starts to decrease. Protons are easily identified as their TOF mass distribution are well separated from those of pions.

FIGURE 3.7. Histograms show the mass plots of the two positive particles (top) and one negative particle (bottom) for the particle identification of the skim.

We also incorporated a missing mass squared cut from 0.7 GeV^2 to 1.2 GeV^2 to ensure exclusivity of our 3 particle selection, which is optimal for resonance production. The only additional cuts besides the skim cuts are a refined neutron missing mass cut to identify $\gamma d \rightarrow p \pi^+ \pi^- (n)$, missing momentum cuts (discussed in Chapter 4) to further enrich exclusive and quasi-free events, and proton momentum cuts (discussed in Chapter 4) to eliminate low-momentum protons that do not originate from Δ^{++} or ρ decays. Figure 3.8 displays the momentum distributions of each charged particle

from the experiment and simulation. The proton momentum cut was applied at 2 GeV which is presented in Chapter 4. These cuts were loosely implemented to reduce the number of good events discarded.

FIGURE 3.8. Momentum distribution of the final state particles proton, π^+ , and π^- for experiment (top row) and an isotropic phase space simulation (bottom row).

3.6. THE RECONSTRUCTION OF Δ^{++}

When analyzing the $p\pi^+\pi^-$ channel, only events with two positive charged particles and one negative charged particle were selected. The invariant mass of the $p\pi^+$ pair, whose invariant mass includes the mass of Δ^{++} , is shown in Figure 3.9. A Gauss-convoluted Breit-Wigner plus a third-order polynomial fit is used to fit the peak Figure 3.10. The fitted peak is at 1.22 GeV, and the width is 120 MeV. Events within a cut of 3σ around the peak position are selected as candidates of Δ^{++} events.

FIGURE 3.9. Δ^{++} distributions of mass, momentum, theta and theta versus momentum.

After this cut, the invariant mass of Δ^{++} is calculated for each event and plotted against the W of all detected particles, $p\pi^+\pi^-$, see Figure 3.11, which shows the strength of the Δ^{++} and Δ^0 resonance contributions to the two-pion channel.

FIGURE 3.10. Invariant mass of $p\pi^+$ around $\Delta(1232)$. The red line is a Gaussian fit with a fitted peak position at 1.22 GeV and a fitted width of about 120 MeV.

Similarly, the invariant mass of $p\pi^-$ is calculated for each event and plotted against the W of all detected particles, $p\pi^+\pi^-$, see Figure 3.12.

3.7. THE RECONSTRUCTION OF ρ

The invariant mass of the $\pi^+\pi^-$ pair, whose invariant mass peaks at the mass of ρ , is shown in Figure 3.13 and Figure 3.14. A Gaussian-convoluted Breit-Wigner plus third-order polynomial fit is used to fit the peak. The fitted peak is at 0.73 GeV, and the σ width results in 150 MeV. Events within a cut of 3σ around the peak position are selected as candidates of ρ events.

FIGURE 3.11. Invariant mass of Δ^{++} (y) versus W of $p\pi^+\pi^-$ (x).

FIGURE 3.12. Invariant Mass of Δ^0 versus W of final state particles.

After this cut, the invariant mass of ρ is calculated for each event and plotted versus the W of all detected particles, $p\pi^+\pi^-$, see Figure 3.15, which shows the strength of the ρ resonance contribution to the two-pion channel.

FIGURE 3.13. ρ distributions of mass, momentum, theta and theta vs momentum.

3.8. SUMMARY

After applying the series of event selection conditions as described above, exclusive events of $\gamma d \rightarrow p\pi^+\pi^-(n)$ for the $\Delta^{++}(1232)$ and for the $\rho(770)$ channel have been enriched and will be used to optimize the simulated t-slopes in the corresponding channels. Figure 3.16 shows Δ^{++} versus ρ displaying the strength of their resonances but also the coupling strength between the two. Likewise, Figure 3.17 shows Δ^0 versus ρ displaying the resonance strengths of each as well.

FIGURE 3.14. Invariant mass of $\pi^+\pi^-$ around $\rho(770)$. The red line is a Breit-Wigner with a fitted peak position on .770 GeV and yellow is a second-order polynomial background fit.

FIGURE 3.15. Invariant mass of ρ (y) versus W (x) of final state particles.

FIGURE 3.16. Invariant mass of Δ^{++} (y) versus Invariant Mass of ρ (x).

FIGURE 3.17. Invariant mass of Δ^0 (y) versus Invariant Mass of ρ (x).

CHAPTER 4

DATA ANALYSIS

The Data Analysis chapter describes all procedures and corrections applied to the data for cross section extraction. There are a series of corrections and cuts that must be applied to the experimental and/or simulated data to produce adequate cross sections.

4.1. FIDUCIAL VOLUME CUTS

Some kinematic regions of the data have very low acceptance, which may introduce large uncertainty on the acceptance. The low acceptance, a property of the detector, leaves a fiducial volume that cannot be reproduced by GEANT Simulation (GSIM) and needs to be cut away [Egiyan(2009)]. This study was performed sector by sector by Paul Mattione. Because eg3 has a long target, the work studied the effect of the vertex position, which means the process groups particles into three groups according to their position where they are produced. The trajectory the particle travels depends on the momentum of the particle. Therefore, the work also groups particles according to their momentum.

The fiducial volume cuts are regions of the detector that need to be cut away where those kinematic regions have very low acceptance. They are a function of the momentum and the charge of the particle since the curvature of the particle in a constant magnetic field (the torus was run at a constant inverse field throughout eg3) varies only with the momentum and the charge of the particles. To summarize, the particles in the study are grouped according to four variables: charge as positive or negative, three groups of vertex positions, six sectors, and momentum. For each

FIGURE 4.1. An example of the fiducial study of protons in sector 1 at middle vertex position. Top left to bottom right is the order of increasing momentum of protons. Each histogram except the lower right one shows the distribution of ϕ versus θ and black line is the fiducial cut produced. The last plot displays the minimum θ cut value versus momentum.

group, the θ versus ϕ distribution is plotted, and a cut is produced according to the edges of uniform acceptance in ϕ . One example is shown in Figure 4.1, which shows the fiducial study of protons in sector 1 at the middle vertex position. Each histogram shows the distribution of ϕ versus θ of protons, and the black line is the fiducial cut produced on each kinematic region. The bottom right histogram displays the momentum-dependent lowest angle cut, corresponding to the forward-most angle that protons can be detected efficiently.

The study is performed on protons and negative pions only. However, the results of the study can be extended to any positive charged particles, by using the proton cuts, and to any negative charged particles, by using π^- cuts. The reason is that the trajectories of particles do not depend explicitly on the mass of the particles if the energy loss can be neglected. Therefore, the fiducial cut needs to be done after the energy loss correction.

We made cuts to the data for the geometrical fiducial volumes. These cuts were made to both simulation and experimental data, where we chose the areas of uniform

detector response that can be reproduced by GSIM [Mattione(2007)]. The fiducial cuts were studied and formulated for 7-momentum bins of positive and negative particles. These cuts were done in the laboratory frame for selected angular ranges. This program has become the conventional way in which fiducial cuts are done in eg3.

4.2. ENERGY LOSS CORRECTIONS

Charged particles detected in CLAS may lose a portion of their energy while passing through the target and the detector. This energy loss due to ionization must be accounted for and is corrected in the data set. The correction depends not only on the material traversed by the particle, but also the velocity and charge it carries. The momenta of the charged particles in CLAS are determined by tracking them through the magnetic field with drift chambers. The present CLAS tracking code does not account for energy losses along the track. It returns some effective momentum between the Region 1 and Region 3 drift chambers.

The energy loss software package (Eloss) has been developed to take into account and correct for some of those energy losses. For a given particle and reconstructed momentum it finds the corrected momentum at the vertex. It is made up of a set of subroutines that determine the path-length of the particle in each of the materials along the track starting from the air gap between the region 1 drift chambers, start counter, scattering chamber, target cell wall, and target material between the target wall and the vertex. Eloss works for any charged particle with a charge equal to e that is heavier than the electron in the momentum range $0.05 < p/m < 50$. Eloss corrections have been applied to the eg3 data set according to the Eloss procedure [Pasyuk(2007)]. The energy loss corrections are applied to all particles involved in this analysis.

FIGURE 4.2. The photon energy correction for eg3, as a function of energy due to the gravitational sag in the tagger.

4.3. PHOTON ENERGY CORRECTION

Due to gravity, there is a slight sag in the tagger scintillator paddles away that produces a mismatch between the actual position of a deflected electron and the nominal paddle it hits (see Figure 4.2). A correction has been excluded in the calibration database and was applied during reconstruction (cooking) [Mattione(2007)].

In the study of $\gamma d \rightarrow pp\pi^-$ reaction, it was discovered that the reconstructed eg3 photon energy has been too low by 7.71 MeV [Mattione(2007)]. It is likely that the magnetic field strength in the tagger has been underestimated. This would again cause an energy mismatch between the deflected electron energy and the E-counter it struck. An inaccurate field strength will give a wrong tagger energy calibration because it will affect how electron bends and its hit position, while the energy is determined by the hit position alone. The procedure was done with an exclusive channel and compared the photon energy in the tagger bank with the sum of final state particles. The correction is applied to the photon energy obtained from Tagger.

4.4. MOMENTUM CORRECTIONS

After energy loss corrections are applied, there still exist systematic shifts in the particle momentum determined by CLAS using the standard reconstruction software. These shifts are likely due to the residual effect of imperfect knowledge of the magnetic field and imperfect drift chamber alignment. These shifts can lead to changes in the measured masses of particles and widen the peaks when determining their momenta.

A procedure was developed to determine the necessary momentum corrections based on particle vertex after energy loss corrections [Mattione(2007)]. The resulting momentum corrections are small but have been systematically applied to all charged particles (see Figure 4.3).

FIGURE 4.3. For (A) protons and (B) π^- s, the total momentum correction due to inelastic scattering in the target and various detector materials as a function of momentum.

4.5. MISSING MASS CUT

In calculating the missing nucleon mass square, the event photon energy information is needed. As mentioned before in the multi-hit photon section, there are about 20% of events in the eg3 data that have more than one event photon candidate in the Tagger according to our event photon selection method based only on the timing. Therefore, we loop through all of the event photon candidates in an event and test their energy matching with respect to the missing nucleon mass. A surviving event has at least one event photon candidate satisfying the missing nucleon mass cut. For most of these multi-hit events, there is one and only one event photon candidate surviving the cut, and we keep the exclusive event and assign that photon as the event photon. In some rare situations, a few percent, there is more than one event photon candidate satisfying the cut. We keep these events and the event photon is picked randomly. We do not have any other way to distinguish them in these cases, but this will not create much of a problem, because their energies are anyhow very close to each other.

The exclusivity of our reaction is ensured by cutting on the missing nucleon mass squared. 3σ cuts are applied in individual photon energy bins to accommodate the decreasing CLAS resolution at high energies.

There are 44 energy bins for the proton channel. Each of the missing nucleon mass square histograms is fitted by a convoluted Gaussian Breit-Wigner plus a polynomial background. The fitting functions and resulting means and widths with errors are plotted in Figure 4.4 for this channel. It is clear that the peaks become wider when the photon energy increases.

The same quantities for the simulated data are fitted by the same functions. The results are shown in Figure 4.5 also for the $p + \pi^+\pi^-$ channel. The resolution of the simulated data follows the same trend of the experimental data. The peaks also widen at higher energies.

FIGURE 4.4. The experimental data fits of $MM(p + \pi^+\pi^-)$ are shown.

FIGURE 4.5. The simulated data fits of $MM(p\pi^+\pi^-)$ are shown.

4.6. MISSING MOMENTUM CUT

Because we are studying quasi-free production, the neutron in the deuteron is assumed to serve as a spectator. However, it is difficult to tell if the neutron is involved in the reaction, especially in the rescattering process, in which the final state particles interact with each other (FSI). However, it is known that the proton inside

FIGURE 4.6. Simulated data, the fits of $MM(p\pi^+\pi^-)$ are shown in the upper pad.

the deuteron exhibits a Fermi motion causing smearing of the momentum. Therefore, if the missing momentum, which is supposed to be the momentum of the missing neutron, exhibit the anticipated Fermi smearing, it is more certain that the neutron serves only as a spectator. Since the simulation includes only events with spectator neutrons, cutting away the > 0.2 GeV region, where the only significant deviations from experiment exist, enhances the desired events and suppresses the events with FSI. This is seen by comparing the missing momentum from data with the missing momentum from simulation, because the simulation is well controlled with neutrons serving simply as spectators see Figure 4.7 and Figure 4.8. To enhance the quasi-free process, a cut on missing momentum of 0.2 GeV is applied.

4.6.1. Minimum Proton Momentum Cut. When charged particles travel through the CLAS detector, their trajectories are bent under the magnetic field. When the momentum is so low that the trajectory is not well described by a simple

FIGURE 4.7. Comparison between missing momentum from measured and from simulation data. The red line is from measured data and the blue line from simulation data. They are scaled by a global factor to match each other.

parameterized fitting procedure or even not recognized by the pattern recognition in the cooking procedure, the particles are lost. The lowest momentum under which a proton can not be reconstructed by the cooking program is the threshold of detection. However, even above the threshold, in the area close to the threshold, protons are usually thrown away intentionally. The reason is that protons in that region are very difficult to simulate actively. This is due to two reasons. There is a relatively large amount of energy loss during the ionization process when the proton travels. The other reason is that the acceptance is low near the threshold and a small error would introduce a large relative error.

The way to determine which of the protons to cut away is to plot the momentum distribution of protons and cut on the rising edge. The momentum distribution of the measured protons is shown in Figure 4.9, and a momentum cut of 0.45 GeV is generated according to the distribution.

FIGURE 4.8. $MMom(p\pi^+\pi^-)$ for all exclusive, Δ^{++} , and ρ experimental data (red) and simulation (green). The simulated data are normalized to the experimental data for the comparison. The black line shows where the cuts are.

FIGURE 4.9. Momentum distribution of the measured protons. A momentum cut at 0.45 GeV is applied according to this distribution.

4.7. UN-TRIGGERED T-COUNTER CORRECTION

The eg3 data set contains a higher tagged energy range than the g11 data set. The g11 data set goes up to 5 GeV where eg3 goes up to 5.7 GeV photon energy. To compare the data sets for the full tagged region that overlaps, we must find a correction factor for the eg3 data for the untriggered tagged region below 4.5 GeV, which causes a step in the yield at 4.5 GeV, where the tagged triggered region begins. The eg3 energy range spans from 1.1 to 5.5 GeV, where the untriggered tagged range is from 1.1 to 4.47 GeV, and the triggered tagged range is from 4.48 to 5.5 GeV. Due to accidental coincidences with the tagger, considerable data was acquired in the untriggered region between 2 to 5 GeV. So a correction factor must be found to make the data consistent with the triggered region.

Looking into the correction factor for the untriggered region, if we have an untriggered tagged photon that initiates a good event, it will only be recorded if an accidental tagged photon in the trigger range occurs within the coincidence time window of the hardware trigger. The hardware trigger is based on the Tagger-Or (MOR) and the Start-Counter-Or (STOR) in ASYNC. Thus, we need to know the width

of the coincidence gate that triggers an event, for in this gate width an accidental untriggered event is allowed as well.

FIGURE 4.10. Coincidence rate versus Delay.

From the hardware trigger gate, Figure 4.10, we estimate an effective width of the overlap coincidence of $T=26.7ns$, which was extracted from an early eg3 test run. The probability for k accidental tagged photons in the trigger window T in dependence of the average rate is given by the Poisson distribution:

$$P_k = \frac{(aT)^k e^{-aT}}{k!} \quad (9)$$

that we also use for the photon flux determination. Thus the probability P for one or more accidental tagged photons in the trigger range is

$$P = 1 - P_0 . \quad (10)$$

If we take the average rate of electrons in the trigger range for a nearby eg3 run $a = 13.5 \times 10^6 Hz$, which can be extracted from the photon flux corrected files, then we can estimate a correction factor for the run

$$\frac{1}{P} = 3.30 \pm 0.03. \quad (11)$$

After extracting the correction factor, it should be applied to the data set for each event. We stress again that this correction factor has to be a constant value according to the underlying probability theory and we checked that it is indeed run number independent. We now search for a method to extract the overall factor from all runs of the data set. Once the correction factor is applied we have a smooth distribution from the untriggered tagged region into the triggered tagged region.

In principle, the theoretical method would be followed to calculate the trigger correction for our data set if we could determine the effective coincidence window with T for all runs from the data simultaneously with the average rate, but we chose to use an instantaneous and still fundamental approach to calculate the trigger correction factor. We began to study the photon flux-normalized events in terms of the E-counters by plotting the photon E-counter spectrum normalized by the gflux for different skims. Since the overall factor is channel dependent but has to be constant, we want to investigate the data using the finest possible binning based on the E-counters. Figure 4.11 was created by using a skim from eg3 devoted to the Lambda production.

This skim required at least two charged particle tracks with a narrow mass constraint of 1.098 to 1.133 GeV around the Lambda invariant mass. We chose Lambda production to extract the correction factor being that this is one of the cleanest (low background) channels of the eg3 data set, where we can see the jump from the un-triggered to triggered range in the plot. From this, we obtain a ratio in terms of the un-triggered range of E-counters to the triggered range of E-counters, which gives us the constant correction factor for the tagged un-triggered region.

The first 20 T-counters in the tagger system were included in the eg3 trigger system, while all T-counters are on. Thus, events caused by photons associated with

FIGURE 4.11. Normalized gflux entries versus EID (top), which are the populated E-counter bins. The fit of the aforementioned to calculate ratio of triggered to untriggered tagged regions (bottom) to obtain overall correction factor.

scattered electrons hitting counters 21 - 60 can only be recorded when there is at least one recoiling electron that hits one of the first 20 T-counters during the trigger time window. This causes a discontinuity around 4.5 GeV that must be corrected.

There are several ways to do it. However, we use a practical way of plotting the photon flux-normalized yield of mixed-channel (inclusive reaction dataset) events as shown in Figure 4.12. The histogram excludes those events with multiple good photon hits (see 3.4) because multiple photons will wash out the jump and lead to a wrong or misleading un-triggered correction value. The histogram is fitted with a second-order polynomial function with a scaling factor on the high end. The fit gives the factor as 5.7. The same histogram corrected by the factor is shown in Figure 4.13 and shows no discontinuity. The estimated uncertainty is about 5%.

FIGURE 4.12. Normalized yield of mixed-channel events versus E-counter logic paddles. The jump happens at the edge of the triggered and un-triggered region. A second order polynomial function with a jump factor is used to fit the histogram and drawn in red. It gives a factor of 5.7.

FIGURE 4.13. Corrected normalized yield of mixed-channel events versus E-counters. The factor 5.7 is applied. The dependence of normalized yield on logic paddles looks now continuous.

Through further study of this factor, we realized that this factor has to be channel dependent being that the 4.5 factor extracted from the Lambda skim is not adequate for the correction of this date. We found that once we applied this factor to the $p\pi^+\pi^-$ skimmed data set, it still left the un-triggered tagged region slightly short. The reason

for this is that the $p\pi^+\pi^-$ is an exclusive skimmed data set where we require only three charged particle tracks (two positive and one negative), where as the Lambda was an inclusive skim requiring at least three charged particles. Therefore, we extracted the correction factor from our corresponding normalized yield plots to be a constant value, which raises the un-triggered tagged region up to adequately meet the triggered tagged region.

4.8. TRIGGER EFFICIENCY

As documented in the eg3 run group proposal, the energy region of interest to eg3 is dominated by multi-pion production. In order to run at the highest luminosity, a trigger scheme was developed, which reduces the rates to a level that can be accommodated by the present DAQ system [Gothe(2004)]. It was found during the Φ^{--} analysis that the yields for four-track events in the three sector trigger were reduced by 20% due to the lack of coincidence between the start counter and the tagger Master OR signals [Egiyan(2009)].

In extracting the Δ^{++} cross section, our first results were drastically off from g11 data and existing published results. In this analysis, we investigated every parameter and process taken and we found that a critical step was missing in the overall analysis of our data. We discovered a discrepancy in the trigger efficiency of our data. For the Φ^{--} analysis, this efficiency was studied for events with 4 track in exactly 3 sectors of the detector.

FIGURE 4.14. Normalized yield for Λ versus run number for trigger bit 5 and trigger bit 6 events.

The normalized rates of $K\Lambda$ (4-track, 3-sector events) are plotted versus run number of the data set in Figure 4.14. Here, the red points are trigger bit 6 (3-sector tracks required) uncorrected, the blue points are trigger bit 6 corrected for trigger inefficiency, and the green points are trigger bit 5 (2-sector tracks required). The trigger correction for the 4 track, 3 sector events were obtained by the following procedure. Events not in the beam trip interval were utilized, contained a good Λ candidate: $\Delta T \leq 0.9$ ns, $DOCA \leq 3.5$ cm. It was also required to have at least 3 time based tracks (2 of these are already required for Λ) with a hit in the SC and ST. At least 3 different sectors have to have one of these tracks which is to pick up the first term in bit 6. The events were histogrammed with weights according to the prescale factor (weight is set to 1 for histograms where all bits are taken). Once these requirements were satisfied, then the photon in tagger trigger range was matched within 1 ns window or the photon is assumed if the event is reconstructed. These events were then fit with a gaussian plus a second-order polynomial function. From this, we see that with the 4 track efficiency corrections the 2 sector and 3 sector plotted yields are now in agreement and the correction for trigger bit6 is valid.

From this, we see that with the 4-track efficiency corrections the 2-sector and 3-sector plotted yields are now in agreement and the correction for trigger bit 6 is valid. The Λ channel was used for this correction due to the fact that the eg3 data set was proposed for the study of the Φ^{--} . This correction was applied to the data set as a whole and adequate for all reaction channels studied from the set.

This would normally be the entire story to a trigger efficiency study, but the eg3 data set unveiled a critical inconsistency amongst the number of particle tracks we are attempting to correct, which is again channel dependent. In the present study, we performed an efficiency study on our skimmed data set, which is based on the 3 particle tracks of the proton, π^+ , and π^- , respectively.

We found through this study Figure 4.15 a discrepancy in correction to the trigger efficiency of our Δ^{++} cross section. For the Φ^{--} analysis, this efficiency was studied

for 4 tracks in 3 sectors in the detector but our analysis requires 3 tracks in 3 sectors. In extracting the Δ^{++} cross section, our first results were drastically off from g11 CLAS data and existing published results. In our analysis, we investigated every parameter and process taken to extract the cross section results to recover the missing factors for obtaining a reasonable agreement. What we found through this study is a critical step in the overall analysis of our data. We found a needed correction to the trigger efficiency of our Δ^{++} cross section. For the Φ^{--} analysis, this efficiency was studied for 4 track in 3 sectors in the detector. However, this analysis requires exactly 3 tracks in 3 sectors, which is the same number as that required in by the trigger (see Figure 4.14).

FIGURE 4.15. Normalized Λ yield versus beam current for 3- and 4-track events with atleast 3- or 4-sector requirements for various trigger conditions.

From the information plotted in Figure 4.15, we calculated again as discussed earlier the efficiency corrections for 4-track and 3-track events requiring 3- or 4-sectors.

These values were used to correct the Δ^{++} cross section data for the 3-track in 3-sector requirement, but these corrections yielded wrong results, because they are not based on the correction that had been calculated for the $p\pi^+\pi^-$ channel exclusively, where as the Δ^{++} channel required atleast 3-tracks in 3-sectors, with the proton, π^+ , and π^- , respectively.

The correction for the exclusive 3-track, 3-sector channel was investigated by the plots in Figure 4.16 and Figure 4.17. Figure 4.16 shows trigger bit 5 events, where the normalized yield of Δ^{++} is plotted for each run versus that run number. The assumption here is that trigger bit 5 for the first 40 runs has 100% efficiency, thus all other triggers should be corrected to the corresponding yield. Thus we fit the average yield for trigger bit 5. This fit resulting in the average yield of 0.000211 to be the standard for all triggers. The theory behind this is that because trigger bit 5 has 3-tracks but only a 2-sector trigger, there is a greater probability for the particles being detected than in a 3-track 3-sector trigger as trigger bit 6 requires. Furthermore, in the study of atleast 3-tracks the triggered bit 5, the yield is current independent.

Thus, after obtaining the set point for the efficiency, we calculated the efficiency of the Δ^{++} data set, which requires a 3-track, 3-sector trigger. For each run we obtained the efficiency correction for that run by dividing the trigger bit 5 fit value by the yield of the trigger bit 6 run. Figure 4.16 shows the fit for only the range of trigger bit 5 data.

Likewise, Figure 4.17 shows the trigger bit 6 data. For each run we obtained the efficiency correction for that run by dividing the trigger bit 5 fit value by the yield of the trigger bit 6 run. Again, we point out here that after correcting for the efficiency, the two yields for trigger bit 5 and 6 are assumed to be 100%. The only other correction would come from the simulation, where these conditions are also mandated for events produced. After extracting these efficiency values for each run, we applied these corrections to each run within the analysis code to correct

FIGURE 4.16. Normalized yield for Δ^{++} versus run number for trigger bit 5 events for run numbers 0 to 40 (coincidence of two sectors) and 41 to 189 (coincidence of three sectors). Fit for runs 0 - 40 that took place before the coincidence of Start Counter with Tagger was instituted for triggering.

TABLE 4.1. Trigger Efficiency Corrections

Run Number	Efficiency Correction
0 - 40 (coincidence of two sectors)	1.7
41 - 189 (coincidence of three sectors)	3.1

for the overall trigger inefficiency. Table 4.1 shows the golden run numbers and the corresponding average of efficiency correction values for all runs.

4.9. SUMMARY

After analyzing the series of event selection conditions as described above, we have finally isolated the exclusive and quasi-free enriched events in the $\gamma d \rightarrow p\pi^+\pi^-n$ channel and determined the channel specific correction factors.

FIGURE 4.17. Normalized yield for Δ^{++} versus run number for trigger bit 6 events for run numbers 0 to 40 (coincidence of two sectors) and 41 to 189 (coincidence of three sectors). Fit for runs taken place before and after the coincidence of Start Counter with Tagger was instituted for triggering.

CHAPTER 5

ACCEPTANCE AND NORMALIZATION

In order to calculate the cross section from experimental yields, the acceptance needs to be calculated. For our analysis the components that factor into the acceptance are the detector geometry, the detection efficiency, and the particle reconstruction efficiency. The acceptance was obtained by passing the simulated events (discussed in the next section) through the same reconstruction program used for the measured data, and by calculating

$$Acceptance = \frac{Number\ of\ reconstructed\ events\ in\ a\ bin}{Number\ of\ generated\ events\ in\ the\ same\ bin} . \quad (12)$$

The purpose is to obtain the detector system inefficiency information so that we can correct the yield obtained (measured reconstructed simulated data) to the yield produced (generated thrown simulated data). This inefficiency could come from several sources such as the detector performance, or the software used to produce the raw data or its conversion to cooked data. The inefficiency from the detector performance could come from the geometry of the detector, the electronics' dead time, the hardware noise, unexpected behavior due to cosmic ray background and other things. The data acquisition (DAQ) could have problems more than likely out of the DAQ system's control, for example where it needs to write the data from cache to tape and the cache is full. The cooking program also could introduce inefficiency in such a case where it cannot extract trajectory information from digitization of detector components due to too much background, hardware noise, or limitations of the software. The acceptance is defined as the probability that an event in a certain

kinematics will survive to the analysis stage. After acceptance of the detector system is understood, the number of events actually produced is obtained.

After the acceptance is obtained, the final goal is to determine the cross sections. The cross sections can be compared with theoretical models or confirmed by other experiments. The process where we go from acceptance-corrected yield to cross section is known as normalization. In this process, several things need to be considered such as: the total number of photons incident on the target in photoproduction, the total number of target particles, the fraction of total time when the detector system is ready to take data, decay branching ratios, etc. This chapter describes the acceptance calculation and normalization factors.

5.1. EVENT GENERATOR

For the acceptance, the first and main piece we need is the simulation. Simulations are produced using an event generator. In the event generator step, events are produced as much like real-world events as possible up to our knowledge level. For an unknown production channel, it is typical to produce events according to the phase space distribution, where events are evenly distributed in the phase space (momentum and coordinate space). However, in our case, we know that the channel is probably t channel dominant, but also that there is no adequate two pion model yet produced for any event generator, thus we will use the t -slope phase space event generator, FSGEN.

5.1.1. GSIM. The basis of the acceptance calculation is the GEANT-based simulation (GSIM) of the CLAS detector, which is the CLAS collaboration's standard simulation package. After events are produced by the event generator, they are processed by GSIM. GSIM propagates each of the particles through all CLAS components from the vertex produced by the event generator. The particles travel through the simulated detector where it is possible for them to lose energy due to ionization, decay

with probabilities according to PDG values, and undergo multiple-scattering with detector materials as it would happen in the real detector. The package also simulates the response of each detector component to the incident particles. The digitization signals from each component are collected and stored just like real experimental data.

After the reactions are generated, every event passes through GSIM, the standard Monte Carlo simulation package for the CLAS detector, which is based on the simulation frame work GEANT3 from CERN. There are a few things to be noted here.

1. Energy losses are simulated when particles pass through material. Thus energy loss corrections need to be applied just like for the experimental data.
2. The photon tagger is not simulated. The photon energy information comes directly from the event generator calling E-counter and T-counter entries accordingly.
3. The eg3 trigger condition is not simulated. The trigger condition will be applied to the simulated data later in the analysis process.
4. The inefficiency and resolution of detector components are not fully simulated. They will be compensated for in the next step covered below.

5.1.2. GSIM Post Processing. The GSIM output is then processed by the GSIM Post Processing (GPP) package, which smears the detector signals to be more realistic. The scintillator timing is smeared according to the length of the scintillator. GPP also smears the drift chamber signal according to the average drifting time of ionization electrons to the sensor wires. GPP has a series of parameters allowed to be changed by users to match with the resolution of each experiment.

The output of GSIM is then processed by the cooking program and by the analysis thereafter just like experimental data.

5.1.3. Simulation and Cooking. The simulated data is cooked using the same version of user_ana with the same configuration as the experimental data. However,

the cooking of simulated data does not need all the calibration constants from the real data because the GSIM assumes perfect detectors to simulate CLAS. The only things it needs to know are the target specifications and the start counter geometry configuration, which it finds in the calibration database. So a special runindex "*calib-user.RunindexEG3Sim*" is used for the cooking.

After final reconstruction of the simulated data, the same analysis code that is used for the experimental data, is executed on the simulated data. Then acceptance is calculated as the ratio of the number of reconstructed events over the number of generated events in all analyzed kinematic bins.

5.1.4. Trigger Simulation. The details of the trigger were discussed earlier, and there are mainly two aspects. One is that it triggers on the photon energy above 4.5 GeV; therefore it creates a yield jump around 4.5 GeV, and the other is that it requires tracks in at least three sectors for each event (as discussed in trigger efficiency section). The simulation of this is easily done by requiring that each event reconstructed has tracks coming from at least three sectors.

For all completed simulation files we applied the same cuts and corrections used on the experimental data to calculate the acceptance. These include the vertex timing cuts that were made on the skimmed data, the energy binning correction for conversion from E-counter bins to energy bins, the neutron missing mass squared cut and the proton momentum cuts. All the corrections were also applied to the simulated data in order to achieve reliable acceptance for the selection cuts that were applied as part of the two-pion skim program.

Figure 5.1 shows the simulated GSIM data for two reconstructed Δ^{++} events energy bins, 1.5 GeV and 3.1 GeV, each plot shows the mass distribution. The Breit-Wigner fit is not needed here, since the simulation has no background contribution and hence all events are taken into account.

FIGURE 5.1. Plots of the GSIM simulated Δ^{++} mass spectrum at two fixed photon energies.

5.2. PHOTON NORMALIZATION

Another important piece of the cross section calculation is the number of photons incident on the target at different energies, which is called photon flux (gflux). It is also standard in CLAS analyses to include the detector live time at this stage. The live time is the amount of time when the detector system is ready to record data.

In order to determine the cross section, the data must be normalized to the measured photon flux. This value is normally given by the gflux package, where the number of photons reported by the gflux is already corrected for the data acquisition livetime [Ball(2005)] and no further corrections for the deadtime are needed. Figure 5.2 shows the number of the photons in terms of E-counter bins corresponding to

the data sample, which was analyzed in this work. This analysis uses the full tagger region corresponding to the energy range of 1.1 to 5.5 GeV.

FIGURE 5.2. Number of photons per tagger energy bin versus Ecounter bins.

5.3. DETECTOR SIMULATION

To determine the acceptance with sufficient statistical accuracy, 100 million $\gamma d \rightarrow \Delta^{++}\pi^-n \rightarrow p + \pi^+ + \pi^- + n$ events were generated using the FSGEN event generator with various t-slopes. For an unknown production channel, it is typical to produce events according to the phase space distribution. The phase space distribution is to distribute events evenly in the phase space (momentum and coordinate space). However, in this case, we know that the channel is probably t-channel dominated (see Figure 1.6 diagram 5), so that the t-slope phase space event generator is used

[Lu(2010)]. The incident electron energy was set to 5.776 GeV to match the maximum electron energy in the experiment, and the photon range was set to 1.1 to 5.5 GeV to coincide with the photon energy range of the experimental data.

FIGURE 5.3. The t distribution of events from experimental data for t of π^- (left), t of π^+ , and t of $\pi^+\pi^-$.

A study was done with the simulated events to decide the best t -slope choice for the event generator. Simulations were done using a phase space t -distribution from $t = 0$ to $t = 6$, and after the study it was discovered that the t -distribution varies depending on the energy bin.

(A) $W = 1.7$ to 1.8 GeV

(B) $W = 1.8$ to 1.9 GeV

(C) $W = 1.9$ to 2.0 GeV

(D) $W = 2.0$ to 2.1 GeV

FIGURE 5.4. Δ^{++} cross sections (red) and normalized thrown events (black) for t-slope 1 versus t-min and for W bins from 1.7 - 2.1

(A) $W = 2.1$ to 2.2 GeV

(B) $W = 2.2$ to 2.3 GeV

(C) $W = 2.3$ to 2.4 GeV

(D) $W = 2.4$ to 2.5 GeV

FIGURE 5.5. Δ^{++} cross sections (red) and normalized thrown events (black) for t-slope 1 versus t-min and for W bins from 2.1 - 2.5

(A) $W = 2.5$ to 2.6 GeV

(B) $W = 2.6$ to 2.7 GeV

(C) $W = 2.7$ to 2.8 GeV

(D) $W = 2.8$ to 2.9 GeV

FIGURE 5.6. Δ^{++} cross sections (red) and normalized thrown events (black) for t-slope 1 versus t-min and for Wbins from 2.5 - 2.9

(A) $W = 2.9$ to 3.0 GeV

(B) $W = 3.0$ to 3.1 GeV

(C) $W = 3.1$ to 3.2 GeV

(D) $W = 3.2$ to 3.3 GeV

FIGURE 5.7. Δ^{++} cross sections (red) and normalized thrown events (black) for t-slope 1 versus t-min and for Wbins from 2.9 - 3.3

(A) $W = 3.3$ to 3.4 GeV

FIGURE 5.8. Δ^{++} cross sections (red) and normalized thrown events (black) for t-slope 1 versus t-min and for Wbins from 3.4

In general, a constant t-slope for all energy bins is not sufficient, and since we lack an event generator that can produce events from an incorporated two-pion model (model dependent generator), finding the t-slope for each bin gives the best result for obtaining an adequate model dependent simulation for the two pion data. More simply, we need to plot the normalized experimental yield as a function of t and compare it to the simulated data to find what t-slope to use in the end for the simulated data.

Normally, once all the proper parameters of the simulation are determined, the events would run through GSIM for detector response simulation and the GSIM post processor (GPP) for dead wire drift chamber signal removal and smearing adaptation. After post processing, each file is processed by RECSIS for reconstruction. Then we calculate the acceptance using the same analysis code for the measured data.

This process was still followed, but instead of for one overall simulation, we in turn had to do this process for each of the t-slope sets that were in good agreement for a particular energy bin with the experimental data. Once we had these different sets of t-dependant simulations, we used them in the method described in the next section to create a best-attempt model-dependent simulation.

The t-slope for all events was plotted first, but after further study we found that plotting the distributions in each W bin produced a more precise approach. Thus, the method of using various t-distributions which correspond to the experimental low

t-distributions resulted in the best agreement of simulated with measured two pion data.

(A) $W = 1.7$ to 1.8 GeV (B) $W = 1.8$ to 1.9 GeV

(C) $W = 1.9$ to 2.0 GeV (D) $W = 2.0$ to 2.1 GeV

FIGURE 5.9. Δ^{++} cross sections (red) and normalized thrown events (black) for t -slope 2 versus t -min and for W bins from 1.7 - 2.1

(A) $W = 2.1$ to 2.2 GeV (B) $W = 2.2$ to 2.3 GeV

(C) $W = 2.3$ to 2.4 GeV (D) $W = 2.4$ to 2.5 GeV

FIGURE 5.10. Δ^{++} cross sections (red) and normalized thrown events (black) for t -slope 2 versus t -min and for W bins from 2.1 - 2.5

(A) $W = 2.5$ to 2.6 GeV

(B) $W = 2.6$ to 2.7 GeV

(C) $W = 2.7$ to 2.8 GeV

(D) $W = 2.8$ to 2.9 GeV

FIGURE 5.11. Δ^{++} cross sections (red) and normalized thrown events (black) for t-slope 2 versus t-min and for Wbins from 2.5 - 2.9

(A) $W = 2.9$ to 3.0 GeV

(B) $W = 3.0$ to 3.1 GeV

(C) $W = 3.1$ to 3.2 GeV

(D) $W = 3.2$ to 3.3 GeV

FIGURE 5.12. Δ^{++} cross sections (red) and normalized thrown events (black) for t-slope 2 versus t-min and for Wbins from 2.9 - 3.3

(A) $W = 3.3$ to 3.4 GeV

FIGURE 5.13. Δ^{++} cross sections (red) and normalized thrown events (black) for t-slope 2 versus t-min and for Wbins from 3.4

(A) $W = 1.7$ to 1.8 GeV (B) $W = 1.8$ to 1.9 GeV

(C) $W = 1.9$ to 2.0 GeV (D) $W = 2.0$ to 2.1 GeV

FIGURE 5.14. Δ^{++} cross sections (red) and normalized thrown events (black) for t-slope 3 versus t-min and for Wbins from 1.7 - 2.1

(A) $W = 2.1$ to 2.2 GeV (B) $W = 2.2$ to 2.3 GeV

(C) $W = 2.3$ to 2.4 GeV (D) $W = 2.4$ to 2.5 GeV

FIGURE 5.15. Δ^{++} cross sections (red) and normalized thrown events (black) for t-slope 3 versus t-min and for Wbins from 2.1 - 2.5

clearpage

FIGURE 5.16. Δ^{++} cross sections (red) and normalized thrown events (black) for t-slope 3 versus t-min and for Wbins from 2.5 - 2.9

(A) $W = 2.9$ to 3.0 GeV

(B) $W = 3.0$ to 3.1 GeV

(C) $W = 3.1$ to 3.2 GeV

(D) $W = 3.2$ to 3.3 GeV

FIGURE 5.17. Δ^{++} cross sections (red) and normalized thrown events (black) for t-slope 3 versus t-min and for Wbins from 2.9 - 3.3

(A) $W = 3.3$ to 3.4 GeV

FIGURE 5.18. Δ^{++} cross sections (red) and normalized thrown events (black) for t-slope 3 versus t-min and for Wbins from 3.4

The figures 5.4a to 5.33a show the corrected measured fully normalized yields (left), the generated (thrown) simulated events (middle), and the yields with the generated events (right) fits for t-slopes from 0 to 6, for each 1 GeV width of W bin, which was used to determine the t-slope in best agreement at low t. The closeness of the simulated slope to the experimental slope indicates the appropriate t-slope simulation for that bin. For each test we focused on their correspondence at low t (the rising edge). It was vital to reproduce the slope at low t due to the problem of the holes (or lack of geometrical acceptance) which occur at low t. With this missing information at low t, we had already experienced how dependent it made the determination of the cross sections from the normalized yields on the acceptance so it was a must to mimic the slopes at low t to account for the missing data in the holes.

(A) $W = 1.7$ to 1.8 GeV

(B) $W = 1.8$ to 1.9 GeV

(C) $W = 1.9$ to 2.0 GeV

(D) $W = 2.0$ to 2.1 GeV

FIGURE 5.19. Δ^{++} cross sections (red) and normalized thrown events (black) for t-slope 4 versus t-min and for Wbins from 1.7 - 2.1

(A) $W = 2.1$ to 2.2 GeV

(B) $W = 2.2$ to 2.3 GeV

(C) $W = 2.3$ to 2.4 GeV

(D) $W = 2.4$ to 2.5 GeV

FIGURE 5.20. Δ^{++} cross sections (red) and normalized thrown events (black) for t-slope 4 versus t-min and for Wbins from 2.1 - 2.5

(A) $W = 2.5$ to 2.6 GeV

(B) $W = 2.6$ to 2.7 GeV

(C) $W = 2.7$ to 2.8 GeV

(D) $W = 2.8$ to 2.9 GeV

FIGURE 5.21. Δ^{++} cross sections (red) and normalized thrown events (black) for t-slope 4 versus t-min and for W bins from 2.5 - 2.9

(A) $W = 2.9$ to 3.0 GeV

(B) $W = 3.0$ to 3.1 GeV

(C) $W = 3.1$ to 3.2 GeV

(D) $W = 3.2$ to 3.3 GeV

FIGURE 5.22. Δ^{++} cross sections (red) and normalized thrown events (black) for t-slope 4 versus t-min and for Wbins from 2.9 - 3.3

(A) $W = 3.3$ to 3.4 GeV

FIGURE 5.23. Δ^{++} cross sections (red) and normalized thrown events (black) for t-slope 4 versus t-min and for Wbins from 3.4

To single out only Δ^{++} events in our two pion data, we cut on the invariant mass of Δ^{++} , from 1.0 to 1.3 GeV. With this cut, along with the missing mass neutron cut and missing momentum cut already applied, the most adequate method to separate out these Δ^{++} events is achieved.

(A) $W = 1.7$ to 1.8 GeV

(B) $W = 1.8$ to 1.9 GeV

(C) $W = 1.9$ to 2.0 GeV

(D) $W = 2.0$ to 2.1 GeV

FIGURE 5.24. Δ^{++} cross sections (red) and normalized thrown events (black) for t -slope 5 versus t -min and for W bins from 1.7 - 2.1

(A) $W = 2.1$ to 2.2 GeV

(B) $W = 2.2$ to 2.3 GeV

(C) $W = 2.3$ to 2.4 GeV

(D) $W = 2.4$ to 2.5 GeV

FIGURE 5.25. Δ^{++} cross sections (red) and normalized thrown events (black) for t -slope 5 versus t -min and for W bins from 2.1 - 2.5

(A) $W = 2.5$ to 2.6 GeV

(B) $W = 2.6$ to 2.7 GeV

(C) $W = 2.7$ to 2.8 GeV

(D) $W = 2.8$ to 2.9 GeV

FIGURE 5.26. Δ^{++} cross sections (red) and normalized thrown events (black) for t -slope 5 versus t -min and for W bins from 2.5 - 2.9

(A) $W = 2.9$ to 3.0 GeV (B) $W = 3.0$ to 3.1 GeV

(C) $W = 3.1$ to 3.2 GeV (D) $W = 3.2$ to 3.3 GeV

FIGURE 5.27. Δ^{++} cross sections (red) and normalized thrown events (black) for t-slope 5 versus t-min and for Wbins from 2.9 - 3.3

(A) $W = 3.3$ to 3.4 GeV

FIGURE 5.28. Δ^{++} cross sections (red) and normalized thrown events (black) for t-slope 5 versus t-min and for Wbins from 3.4

The invariant mass of Δ^{++} was produced after the missing mass cut in each energy range. A Breit-Wigner function for the signal plus a second-order polynomial function for background are used to fit each histogram. The integration of the fit function gives the number of events obtained.

(A) $W = 1.7$ to 1.8 GeV (B) $W = 1.8$ to 1.9 GeV

(C) $W = 1.9$ to 2.0 GeV (D) $W = 2.0$ to 2.1 GeV

FIGURE 5.29. Δ^{++} cross sections (red) and normalized thrown events (black) for t -slope 6 versus t -min and for W bins from 1.7 - 2.1

(A) $W = 2.1$ to 2.2 GeV (B) $W = 2.2$ to 2.3 GeV

(C) $W = 2.3$ to 2.4 GeV (D) $W = 2.4$ to 2.5 GeV

FIGURE 5.30. Δ^{++} cross sections (red) and normalized thrown events (black) for t -slope 6 versus t -min and for W bins from 2.1 - 2.5

(A) $W = 2.5$ to 2.6 GeV

(B) $W = 2.6$ to 2.7 GeV

(C) $W = 2.7$ to 2.8 GeV

(D) $W = 2.8$ to 2.9 GeV

FIGURE 5.31. Δ^{++} cross sections (red) and normalized thrown events (black) for t-slope 6 versus t-min and for Wbins from 2.5 - 2.9

(A) $W = 2.9$ to 3.0 GeV

(B) $W = 3.0$ to 3.1 GeV

(C) $W = 3.1$ to 3.2 GeV

(D) $W = 3.2$ to 3.3 GeV

FIGURE 5.32. Δ^{++} cross sections (red) and normalized thrown events (black) for t -slope 6 versus t -min and for W bins from 2.9 - 3.3

(A) $W = 3.3$ to 3.4 GeV

FIGURE 5.33. Δ^{++} cross sections (red) and normalized thrown events (black) for t-slope 6 versus t-min and for Wbins from 3.4

The same was done for ρ , see 5.34a - 5.63a , and for the Δ^0 channel, see 5.64a - 5.93a as the other dominating t-channel contributions to our two pion data set.

(A) $W = 1.7$ to 1.8 GeV

(B) $W = 1.8$ to 1.9 GeV

(C) $W = 1.9$ to 2.0 GeV

(D) $W = 2.0$ to 2.1 GeV

FIGURE 5.34. ρ cross sections (red) and normalized thrown events (black) for t-slope 1 versus t-min and for Wbins from 1.7 - 2.1

(A) $W = 2.1$ to 2.2 GeV

(B) $W = 2.2$ to 2.3 GeV

(C) $W = 2.3$ to 2.4 GeV

(D) $W = 2.4$ to 2.5 GeV

FIGURE 5.35. ρ cross sections (red) and normalized thrown events (black) for t-slope 1 versus t-min and for Wbins from 2.1 - 2.5

(A) $W = 2.5$ to 2.6 GeV

(B) $W = 2.6$ to 2.7 GeV

(C) $W = 2.7$ to 2.8 GeV

(D) $W = 2.8$ to 2.9 GeV

FIGURE 5.36. ρ cross sections (red) and normalized thrown events (black) for t-slope 1 versus t-min and for W bins from 2.5 - 2.9

(A) $W = 2.9$ to 3.0 GeV

(B) $W = 3.0$ to 3.1 GeV

(C) $W = 3.1$ to 3.2 GeV

(D) $W = 3.2$ to 3.3 GeV

FIGURE 5.37. ρ cross sections (red) and normalized thrown events (black) for t-slope 1 versus t-min and for Wbins from 2.9 - 3.3

(A) $W = 3.3$ to 3.4 GeV

FIGURE 5.38. ρ cross sections (red) and normalized thrown events (black) for t-slope 1 versus t-min and for Wbins from 3.4

We continue to show the t-slope determination process for the rho channel. Again displaying the corrected measured normalized yields (left), the generated (thrown) simulated events (middle), and the yields with the generated events (right) fits for t-slopes from 0 to 6 GeV^2 , which was used to determine the t-slope in best agreement at low t with measured ρ channel events. To obtain exclusive ρ events, we cut on the invariant mass of $\pi^+\pi^-$, from 0.67 to 0.85 GeV and follow the procedure analogous to that for the Δ^{++} .

(A) $W = 1.7$ to 1.8 GeV

(B) $W = 1.8$ to 1.9 GeV

(C) $W = 1.9$ to 2.0 GeV

(D) $W = 2.0$ to 2.1 GeV

FIGURE 5.39. ρ cross sections (red) and normalized thrown events (black) for t-slope 2 versus t-min and for Wbins from 1.7 - 2.1

(A) $W = 2.1$ to 2.2 GeV

(B) $W = 2.2$ to 2.3 GeV

(C) $W = 2.3$ to 2.4 GeV

(D) $W = 2.4$ to 2.5 GeV

FIGURE 5.40. ρ cross sections (red) and normalized thrown events (black) for t-slope 2 versus t-min and for Wbins from 2.1 - 2.5

FIGURE 5.41. ρ cross sections (red) and normalized thrown events (black) for t-slope 2 versus t-min and for Wbins from 2.5 - 2.9

FIGURE 5.42. ρ cross sections (red) and normalized thrown events (black) for t-slope 2 versus t-min and for Wbins from 2.9 - 3.3

(A) $W = 3.3$ to 3.4 GeV

FIGURE 5.43. ρ cross sections (red) and normalized thrown events (black) for t-slope 2 versus t-min and for Wbins from 3.4

The invariant mass of ρ is produced after the missing mass cut in each energy range. A Breit-Wigner function for the signal plus a second-order polynomial function for background are used to fit each histograms. The overall fit is shown in red, background in yellow, and signal peak in green. The integration of the fit function yields the number of events obtained.

FIGURE 5.44. ρ cross sections (red) and normalized thrown events (black) for t-slope 3 versus t-min and for Wbins from 1.7 - 2.1

FIGURE 5.45. ρ cross sections (red) and normalized thrown events (black) for t-slope 3 versus t-min and for Wbins from 2.1 - 2.5

(A) $W = 2.5$ to 2.6 GeV

(B) $W = 2.6$ to 2.7 GeV

(C) $W = 2.7$ to 2.8 GeV

(D) $W = 2.8$ to 2.9 GeV

FIGURE 5.46. ρ cross sections (red) and normalized thrown events (black) for t-slope 3 versus t-min and for Wbins from 2.5 - 2.9

FIGURE 5.47. ρ cross sections (red) and normalized thrown events (black) for t -slope 3 versus t -min and for W bins from 2.9 - 3.3

(A) $W = 3.3$ to 3.4 GeV

FIGURE 5.48. ρ cross sections (red) and normalized thrown events (black) for t-slope 3 versus t-min and for Wbins from 3.4

(A) $W = 1.7$ to 1.8 GeV

(B) $W = 1.8$ to 1.9 GeV

(C) $W = 1.9$ to 2.0 GeV

(D) $W = 2.0$ to 2.1 GeV

FIGURE 5.49. ρ cross sections (red) and normalized thrown events (black) for t-slope 4 versus t-min and for Wbins from 1.7 - 2.1

(A) $W = 2.1$ to 2.2 GeV

(B) $W = 2.2$ to 2.3 GeV

(C) $W = 2.3$ to 2.4 GeV

(D) $W = 2.4$ to 2.5 GeV

FIGURE 5.50. ρ cross sections (red) and normalized thrown events (black) for t-slope 4 versus t-min and for Wbins from 2.1 - 2.5

(A) $W = 2.5$ to 2.6 GeV (B) $W = 2.6$ to 2.7 GeV

(C) $W = 2.7$ to 2.8 GeV (D) $W = 2.8$ to 2.9 GeV

FIGURE 5.51. ρ cross sections (red) and normalized thrown events (black) for t -slope 4 versus t -min and for W bins from 2.5 - 2.9

FIGURE 5.52. ρ cross sections (red) and normalized thrown events (black) for t-slope 4 versus t-min and for Wbins from 2.9 - 3.3

(A) $W = 3.3$ to 3.4 GeV

FIGURE 5.53. ρ cross sections (red) and normalized thrown events (black) for t-slope 4 versus t-min and for Wbins from 3.4

This ensures that we are testing the t-slope of exclusive ρ events from the two-pion data. Once we have these events, the simulation is generated and the acceptance is obtained in the normal manner.

(A) $W = 1.7$ to 1.8 GeV

(B) $W = 1.8$ to 1.9 GeV

(C) $W = 1.9$ to 2.0 GeV

(D) $W = 2.0$ to 2.1 GeV

FIGURE 5.54. ρ cross sections (red) and normalized thrown events (black) for t-slope 5 versus t-min and for Wbins from 1.7 - 2.1

(A) $W = 2.1$ to 2.2 GeV

(B) $W = 2.2$ to 2.3 GeV

(C) $W = 2.3$ to 2.4 GeV

(D) $W = 2.4$ to 2.5 GeV

FIGURE 5.55. ρ cross sections (red) and normalized thrown events (black) for t-slope 5 versus t-min and for Wbins from 2.1 - 2.5

FIGURE 5.56. ρ cross sections (red) and normalized thrown events (black) for t-slope 5 versus t-min and for Wbins from 2.5 - 2.9

(A) $W = 2.9$ to 3.0 GeV

(B) $W = 3.0$ to 3.1 GeV

(C) $W = 3.1$ to 3.2 GeV

(D) $W = 3.2$ to 3.3 GeV

FIGURE 5.57. ρ cross sections (red) and normalized thrown events (black) for t-slope 5 versus t-min and for Wbins from 2.9 - 3.3

(A) $W = 3.3$ to 3.4 GeV

FIGURE 5.58. ρ cross sections (red) and normalized thrown events (black) for t-slope 5 versus t-min and for Wbins from 3.4

(A) $W = 1.7$ to 1.8 GeV (B) $W = 1.8$ to 1.9 GeV

(C) $W = 1.9$ to 2.0 GeV (D) $W = 2.0$ to 2.1 GeV

FIGURE 5.59. ρ cross sections (red) and normalized thrown events (black) for t -slope 6 versus t -min and for W bins from 1.7 - 2.1

(A) $W = 2.1$ to 2.2 GeV (B) $W = 2.2$ to 2.3 GeV

(C) $W = 2.3$ to 2.4 GeV (D) $W = 2.4$ to 2.5 GeV

FIGURE 5.60. ρ cross sections (red) and normalized thrown events (black) for t -slope 6 versus t -min and for W bins from 2.1 - 2.5

(A) $W = 2.5$ to 2.6 GeV

(B) $W = 2.6$ to 2.7 GeV

(C) $W = 2.7$ to 2.8 GeV

(D) $W = 2.8$ to 2.9 GeV

FIGURE 5.61. ρ cross sections (red) and normalized thrown events (black) for t -slope 6 versus t -min and for W bins from 2.5 - 2.9

FIGURE 5.62. ρ cross sections (red) and normalized thrown events (black) for t-slope 6 versus t-min and for Wbins from 2.9 - 3.3

(A) $W = 3.3$ to 3.4 GeV

FIGURE 5.63. ρ cross sections (red) and normalized thrown events (black) for t-slope 6 versus t-min and for Wbins from 3.4

And finally, we plotted the corrected measured normalized yields (left), the generated (thrown) simulated events (middle), and the yields with the generated events (right) fits for t-slopes from 0 to 6 GeV^2 , which was used to determine the t-slope in best agreement at low t for Δ^0 . To separate the Δ^0 events in the two-pion data, we cut on the invariant mass of $p\pi^-$, from 1.0 to 1.3 GeV. With this cut, along with the missing mass neutron cut and missing momentum cut already applied, this gives us our most adequate method to separate out these events. We then produced the different t-slope simulations and acceptance, calculated the acceptance-corrected yields for each t for comparison with the thrown simulation to determine the proper t-slope per W bin.

(A) $W = 1.7$ to 1.8 GeV

(B) $W = 1.8$ to 1.9 GeV

(C) $W = 1.9$ to 2.0 GeV

(D) $W = 2.0$ to 2.1 GeV

FIGURE 5.64. Δ^0 cross sections (red) and normalized thrown events (black) for t-slope 1 versus t-min and for Wbins from 1.7 - 2.1

(A) $W = 2.1$ to 2.2 GeV

(B) $W = 2.2$ to 2.3 GeV

(C) $W = 2.3$ to 2.4 GeV

(D) $W = 2.4$ to 2.5 GeV

FIGURE 5.65. Δ^0 cross sections (red) and normalized thrown events (black) for t-slope 1 versus t-min and for Wbins from 2.1 - 2.5

(A) $W = 2.5$ to 2.6 GeV

(B) $W = 2.6$ to 2.7 GeV

(C) $W = 2.7$ to 2.8 GeV

(D) $W = 2.8$ to 2.9 GeV

FIGURE 5.66. Δ^0 cross sections (red) and normalized thrown events (black) for t-slope 1 versus t-min and for Wbins from 2.5 - 2.9

(A) $W = 2.9$ to 3.0 GeV

(B) $W = 3.0$ to 3.1 GeV

(C) $W = 3.1$ to 3.2 GeV

(D) $W = 3.2$ to 3.3 GeV

FIGURE 5.67. Δ^0 cross sections (red) and normalized thrown events (black) for t-slope 1 versus t-min and for Wbins from 2.9 - 3.3

(A) $W = 3.3$ to 3.4 GeV

FIGURE 5.68. Δ^0 cross sections (red) and normalized thrown events (black) for t-slope 1 versus t-min and for Wbins from 3.4

(A) $W = 1.7$ to 1.8 GeV

(B) $W = 1.8$ to 1.9 GeV

(C) $W = 1.9$ to 2.0 GeV

(D) $W = 2.0$ to 2.1 GeV

FIGURE 5.69. Δ^0 cross sections (red) and normalized thrown events (black) for t-slope 2 versus t-min and for Wbins from 1.7 - 2.1

(A) $W = 2.1$ to 2.2 GeV

(B) $W = 2.2$ to 2.3 GeV

(C) $W = 2.3$ to 2.4 GeV

(D) $W = 2.4$ to 2.5 GeV

FIGURE 5.70. Δ^0 cross sections (red) and normalized thrown events (black) for t-slope 2 versus t-min and for Wbins from 2.1 - 2.5

(A) $W = 2.5$ to 2.6 GeV

(B) $W = 2.6$ to 2.7 GeV

(C) $W = 2.7$ to 2.8 GeV

(D) $W = 2.8$ to 2.9 GeV

FIGURE 5.71. Δ^0 cross sections (red) and normalized thrown events (black) for t -slope 2 versus t -min and for W bins from 2.5 - 2.9

FIGURE 5.72. Δ^0 cross sections (red) and normalized thrown events (black) for t-slope 2 versus t-min and for Wbins from 2.9 - 3.3

(A) $W = 3.3$ to 3.4 GeV

FIGURE 5.73. Δ^0 cross sections (red) and normalized thrown events (black) for t-slope 2 versus t-min and for Wbins from 3.4

(A) $W = 1.7$ to 1.8 GeV

(B) $W = 1.8$ to 1.9 GeV

(C) $W = 1.9$ to 2.0 GeV

(D) $W = 2.0$ to 2.1 GeV

FIGURE 5.74. Δ^0 cross sections (red) and normalized thrown events (black) for t-slope 3 versus t-min and for Wbins from 1.7 - 2.1

(A) $W = 2.1$ to 2.2 GeV

(B) $W = 2.2$ to 2.3 GeV

(C) $W = 2.3$ to 2.4 GeV

(D) $W = 2.4$ to 2.5 GeV

FIGURE 5.75. Δ^0 cross sections (red) and normalized thrown events (black) for t-slope 3 versus t-min and for Wbins from 2.1 - 2.5

(A) $W = 2.5$ to 2.6 GeV (B) $W = 2.6$ to 2.7 GeV

(C) $W = 2.7$ to 2.8 GeV (D) $W = 2.8$ to 2.9 GeV

FIGURE 5.76. Δ^0 cross sections (red) and normalized thrown events (black) for t-slope 3 versus t-min and for W bins from 2.5 - 2.9

FIGURE 5.77. Δ^0 cross sections (red) and normalized thrown events (black) for t-slope 3 versus t-min and for Wbins from 2.9 - 3.3

(A) $W = 3.3$ to 3.4 GeV

FIGURE 5.78. Δ^0 cross sections (red) and normalized thrown events (black) for t-slope 3 versus t-min and for Wbins from 3.4

(A) $W = 1.7$ to 1.8 GeV

(B) $W = 1.8$ to 1.9 GeV

(C) $W = 1.9$ to 2.0 GeV

(D) $W = 2.0$ to 2.1 GeV

FIGURE 5.79. Δ^0 cross sections (red) and normalized thrown events (black) for t -slope 4 versus t -min and for W bins from 1.7 - 2.1

(A) $W = 2.1$ to 2.2 GeV

(B) $W = 2.2$ to 2.3 GeV

(C) $W = 2.3$ to 2.4 GeV

(D) $W = 2.4$ to 2.5 GeV

FIGURE 5.80. Δ^0 cross sections (red) and normalized thrown events (black) for t -slope 4 versus t -min and for W bins from 2.1 - 2.5

(A) $W = 2.5$ to 2.6 GeV

(B) $W = 2.6$ to 2.7 GeV

(C) $W = 2.7$ to 2.8 GeV

(D) $W = 2.8$ to 2.9 GeV

FIGURE 5.81. Δ^0 cross sections (red) and normalized thrown events (black) for t-slope 4 versus t-min and for W bins from 2.5 - 2.9

FIGURE 5.82. Δ^0 cross sections (red) and normalized thrown events (black) for t-slope 4 versus t-min and for Wbins from 2.9 - 3.3

(A) $W = 3.3$ to 3.4 GeV

FIGURE 5.83. Δ^0 cross sections (red) and normalized thrown events (black) for t-slope 4 versus t-min and for Wbins from 3.4

(A) $W = 1.7$ to 1.8 GeV (B) $W = 1.8$ to 1.9 GeV

(C) $W = 1.9$ to 2.0 GeV (D) $W = 2.0$ to 2.1 GeV

FIGURE 5.84. Δ^0 cross sections (red) and normalized thrown events (black) for t-slope 5 versus t-min and for W bins from 1.7 - 2.1

(A) $W = 2.1$ to 2.2 GeV (B) $W = 2.2$ to 2.3 GeV

(C) $W = 2.3$ to 2.4 GeV (D) $W = 2.4$ to 2.5 GeV

FIGURE 5.85. Δ^0 cross sections (red) and normalized thrown events (black) for t-slope 5 versus t-min and for W bins from 2.1 - 2.5

(A) $W = 2.5$ to 2.6 GeV (B) $W = 2.6$ to 2.7 GeV

(C) $W = 2.7$ to 2.8 GeV (D) $W = 2.8$ to 2.9 GeV

FIGURE 5.86. Δ^0 cross sections (red) and normalized thrown events (black) for t-slope 5 versus t-min and for W bins from 2.5 - 2.9

FIGURE 5.87. Δ^0 cross sections (red) and normalized thrown events (black) for t-slope 5 versus t-min and for Wbins from 2.9 - 3.3

(A) $W = 3.3$ to 3.4 GeV

FIGURE 5.88. Δ^0 cross sections (red) and normalized thrown events (black) for t-slope 5 versus t-min and for Wbins from 3.4

(A) $W = 1.7$ to 1.8 GeV

(B) $W = 1.8$ to 1.9 GeV

(C) $W = 1.9$ to 2.0 GeV

(D) $W = 2.0$ to 2.1 GeV

FIGURE 5.89. Δ^0 cross sections (red) and normalized thrown events (black) for t -slope 6 versus t -min and for W bins from 1.7 - 2.1

(A) $W = 2.1$ to 2.2 GeV

(B) $W = 2.2$ to 2.3 GeV

(C) $W = 2.3$ to 2.4 GeV

(D) $W = 2.4$ to 2.5 GeV

FIGURE 5.90. Δ^0 cross sections (red) and normalized thrown events (black) for t -slope 6 versus t -min and for W bins from 2.1 - 2.5

(A) $W = 2.5$ to 2.6 GeV

(B) $W = 2.6$ to 2.7 GeV

(C) $W = 2.7$ to 2.8 GeV

(D) $W = 2.8$ to 2.9 GeV

FIGURE 5.91. Δ^0 cross sections (red) and normalized thrown events (black) for t-slope 6 versus t-min and for W bins from 2.5 - 2.9

FIGURE 5.92. Δ^0 cross sections (red) and normalized thrown events (black) for t-slope 6 versus t-min and for Wbins from 2.9 - 3.3

(A) $W = 3.3$ to 3.4 GeV

FIGURE 5.93. Δ^0 cross sections (red) and normalized thrown events (black) for t-slope 6 versus t-min and for Wbins from 3.4

Once all the correct t-slopes are determined for each energy bin, we produce proper simulations with adequate t-slopes for each dominant t-channel of two-pion data that allows us to produce an overall best-to-model result. Of the three dominant t-channels, the Δ^0 's t-slopes varies the least per W bin. This is not to say that they do not change with each bin, but the final extractions ranged only from t-slope = 1 to t-slope = 3. Whereas the t-slopes for the Δ^{++} and ρ ranged both from 2 to 6.

5.4. TWO PION SIMULATION

The steps outlined in the previous sections all display how the simulation process is carried out in a conventional way. Since the ultimate goal of our study is to obtain first results of differential cross sections that will give us an estimate of the photo-coupling strengths to various production processes, it is necessary to treat our simulation in this conventional manner but instead of using one single distribution to describe the physics of our reaction we in turn will use a summed combination. After following the conventional method, we found that the extracted cross sections were heavily dependent upon the acceptance, where the holes at low t were harshly affecting any produced cross section.

To alleviate this problem, we had to devise a method to extract the cross sections with a more realistic sample as a starting point for our simulation because to date there is no model dependent photoproduction event generator available. Our method was to simulate the dominant t-channels, which are corresponding to Δ^{++} , Δ^0 , and ρ , resonance production channels that contribute to the two-pion channel. From these simulations, we plot the t-min distributions of π^- , π^+ , $\pi^+\pi^-$ (see Figure 5.94) and phase space as defined by the two-body equation in the particle data booklet [Amster(2008)].

The idea is then that composing each of these distributions in the various simulations by weighting them according to their most appropriate contribution should give us an adequate model for the experimental data.

FIGURE 5.94. t of π^- (blue), π^+ (red) and $\pi^+\pi^-$ (green) plotted for simulation.

We achieve best results by weighting each of the simulations and adjusting those weights to get the best model for the experimental data. Once this is achieved, these weight factors will be the factors used in producing the simulation for extracting the cross sections. To ensure that these weight factors are best determined, we perform a χ^2 fit of the summed simulated contributions for each t -distribution and minimized the fit of the function defined by the shape of the distributions by simultaneously adjusting the weight factors.

From the plots, the figures 5.96a to 5.110d, we see that the binned fits look very accurate. We also see that the fits are much better for the lower t bins rather than the higher bins. This undoubtedly is due to the fact that we optimized our t -slopes to the lower t -range to account for the hole problem at low t . Plus, to ensure the fit took into account a larger range of the combined fit we started with a short range fit initially which was the best fitting range, then took those parameters and fixed

them, and fit at a larger range. This procedure ensures that the best fit parameters and range are being used.

In each plot, the figures 5.96a to 5.110d, there are three different t-min distributions shown. The top histogram is the t of π^- , the middle is the t of π^+ , and the last is t of $\pi^+\pi^-$. Each histogram shows the measured data (magenta), the combined fit simulated data (blue), the Δ^{++} simulation of that t (black), the ρ simulation of that t (green), the Δ^0 simulation of that t (red) and the phase space simulation of that t (yellow). All of these simulated contributions should and do add up to the combined fit that represents the model for the experimental data.

FIGURE 5.95. Experiment (green) and Simulation (clear) plotted for t of π^- , t of π^+ and t of $\pi^+\pi^-$. The simulated data are normalized to the experimental data for the comparison.

FIGURE 5.96. Simultaneous fit to experimental for t of π^- , t of π^+ , and t of $\pi^+\pi^-$ t -min distribution from the simulations of Δ^{++} , Δ^0 , ρ , and phase space to extract each contribution's weight factor for W bins from 1.8 GeV to 1.9 GeV.

FIGURE 5.97. Simultaneous fit to experimental for t of π^- , t of π^+ , and t of $\pi^+\pi^-$ t -min distribution from the simulations of Δ^{++} , Δ^0 , ρ , and phase space to extract each contribution's weight factor for W bins from 1.9 GeV to 2.0 GeV.

FIGURE 5.98. Simultaneous fit to experimental for t of π^- , t of π^+ , and t of $\pi^+\pi^-$ t -min distribution from the simulations of Δ^{++} , Δ^0 , ρ , and phase space to extract each contribution's weight factor for W bins from 2.0 GeV to 2.1 GeV

FIGURE 5.99. Simultaneous fit to experimental for t of π^- , t of π^+ , and t of $\pi^+\pi^-$ t -min distribution from the simulations of Δ^{++} , Δ^0 , ρ , and phase space to extract each contribution's weight factor for W bins from 2.1 GeV to 2.2 GeV

FIGURE 5.100. Simultaneous fit to experimental for t of π^- , t of π^+ , and t of $\pi^+\pi^-$ t -min distribution from the simulations of Δ^{++} , Δ^0 , ρ , and phase space to extract each contribution's weight factor for W bins from 2.2 GeV to 2.3 GeV

FIGURE 5.101. Simultaneous fit to experimental for t of π^- , t of π^+ , and t of $\pi^+\pi^-$ t -min distribution from the simulations of Δ^{++} , Δ^0 , ρ , and phase space to extract each contribution's weight factor for W bins from 2.3 GeV to 2.4 GeV

FIGURE 5.102. Simultaneous fit to experimental for t of π^- , t of π^+ , and t of $\pi^+\pi^-$ t -min distribution from the simulations of Δ^{++} , Δ^0 , ρ , and phase space to extract each contribution's weight factor for W bins from 2.4 GeV to 2.5 GeV

FIGURE 5.103. Simultaneous fit to experimental for t of π^- , t of π^+ , and t of $\pi^+\pi^-$ t -min distribution from the simulations of Δ^{++} , Δ^0 , ρ , and phase space to extract each contribution's weight factor for W bins from 2.5 GeV to 2.6 GeV

FIGURE 5.104. Simultaneous fit to experimental for t of π^- , t of π^+ , and t of $\pi^+\pi^-$ t -min distribution from the simulations of Δ^{++} , Δ^0 , ρ , and phase space to extract each contribution's weight factor for W bins from 2.6 GeV to 2.7 GeV

FIGURE 5.105. Simultaneous fit to experimental for t of π^- , t of π^+ , and t of $\pi^+\pi^-$ t -min distribution from the simulations of Δ^{++} , Δ^0 , ρ , and phase space to extract each contribution's weight factor for W bins from 2.7 GeV to 2.8 GeV

FIGURE 5.106. Simultaneous fit to experimental for t of π^- , t of π^+ , and t of $\pi^+\pi^-$ t -min distribution from the simulations of Δ^{++} , Δ^0 , ρ , and phase space to extract each contribution's weight factor for W bins from 2.8 GeV to 2.9 GeV

FIGURE 5.107. Simultaneous fit to experimental for t of π^- , t of π^+ , and t of $\pi^+\pi^-$ t -min distribution from the simulations of Δ^{++} , Δ^0 , ρ , and phase space to extract each contribution's weight factor for W bins from 2.9 GeV to 3.0 GeV

FIGURE 5.108. Simultaneous fit to experimental for t of π^- , t of π^+ , and t of $\pi^+\pi^-$ t -min distribution from the simulations of Δ^{++} , Δ^0 , ρ , and phase space to extract each contribution's weight factor for W bins from 3.0 GeV to 3.1 GeV

FIGURE 5.109. Simultaneous fit to experimental for t of π^- , t of π^+ , and t of $\pi^+\pi^-$ t -min distribution from the simulations of Δ^{++} , Δ^0 , ρ , and phase space to extract each contribution's weight factor for W bins from 3.1 GeV to 3.2 GeV

FIGURE 5.110. Simultaneous fit to experimental for t of π^- , t of π^+ , and t of $\pi^+\pi^-$ t -min distribution from the simulations of Δ^{++} , Δ^0 , ρ , and phase space to extract each contribution's weight factor for W bins from 3.2 GeV to 3.3 GeV

What appeared most interesting from the fits is that the dominant t -channel contribution comes from the Δ^0 and ρ rather than the Δ^{++} , which would not be the expected results because of what we have learned from the Clebsch-Gordon couplings. We plotted ρ (y-axis) versus Δ^{++} (x-axis) and ρ (y-axis) versus Δ^0 (x-axis) Dalitz plots for each W bin to demonstrate the measured contributions of each resonance to validate what we see in the fitting histograms.

From the first set of Dalitz plots (ρ versus Δ^{++}), 5.128a - 5.144c show that the Δ^{++} resonance is not dominant for the majority of the W bins. It is present in all but very weak for most of them. Around 1.9 GeV to 2.0 GeV it peaks to a dominant form but other than these few bins we see that these plots indeed validate the results of our combined fitting procedure.

FIGURE 5.111. ρ versus Δ^{++} Dalitz Plot for W bins 1.7 - 1.8

FIGURE 5.112. ρ versus Δ^{++} Dalitz Plot for W bins 1.8 - 1.9

FIGURE 5.113. ρ versus Δ^{++} Dalitz Plot for W bins 1.9 - 2.0

FIGURE 5.114. ρ versus Δ^{++} Dalitz Plot for W bins 2.0 - 2.1

FIGURE 5.115. ρ versus Δ^{++} Dalitz Plot for W bins 2.1 - 2.2

FIGURE 5.116. ρ versus Δ^{++} Dalitz Plot for W bins 2.2 - 2.3

FIGURE 5.117. ρ versus Δ^{++} Dalitz Plot for W bins 2.3 - 2.4

FIGURE 5.118. ρ versus Δ^{++} Dalitz Plot for W bins 2.4 - 2.5

FIGURE 5.119. ρ versus Δ^{++} Dalitz Plot for W bins 2.5 - 2.6

FIGURE 5.120. ρ versus Δ^{++} Dalitz Plot for W bins 2.6 - 2.7

FIGURE 5.121. ρ versus Δ^{++} Dalitz Plot for W bins 2.7 - 2.8

FIGURE 5.122. ρ versus Δ^0 Dalitz Plot for W bins 2.8 - 2.9

FIGURE 5.123. ρ versus Δ^{++} Dalitz Plot for W bins 2.9- 3.0

FIGURE 5.124. ρ versus Δ^{++} Dalitz Plot for W bins 3.0 - 3.1

FIGURE 5.125. ρ versus Δ^{++} Dalitz Plot for W bins 3.1 - 3.2

FIGURE 5.126. ρ versus Δ^{++} Dalitz Plot for W bins 3.2 - 3.3

FIGURE 5.127. ρ versus Δ^{++} Dalitz Plot for W bins 3.3 - 3.4.

For the second set of Dalitz plots (ρ versus Δ^0), they show the dominance of the Δ^0 in most of the W bins. The strong showing of the resonance again validates its strong appearance in the combined fitting.

Again, what we know about the two-pion channel and the strengths of the contributing t-channel productions and driving resonances, i.e. the branching ratios, coupling strengths, etc., we expect a total dominance of Δ^{++} . But we find that the Δ^0 exists as the strongest reconstructed contribution in our t-min distribution fits for extracting the weight factors for our model simulation.

FIGURE 5.128. ρ versus Δ^0 Dalitz Plot for W bins 1.7 - 1.8

FIGURE 5.129. ρ versus Δ^0 Dalitz Plot for W bins 1.8 - 1.9

FIGURE 5.130. ρ versus Δ^0 Dalitz Plot for W bins 1.9 - 2.0

FIGURE 5.131. ρ versus Δ^0 Dalitz Plot for W bins 2.0 - 2.1

FIGURE 5.132. ρ versus Δ^0 Dalitz Plot for W bins 2.1 - 2.2

FIGURE 5.133. ρ versus Δ^0 Dalitz Plot for W bins 2.2 - 2.3

FIGURE 5.134. ρ versus Δ^0 Dalitz Plot for W bins 2.3 - 2.4

FIGURE 5.135. ρ versus Δ^0 Dalitz Plot for W bins 2.4 - 2.5

FIGURE 5.136. ρ versus Δ^0 Dalitz Plot for W bins 2.5 - 2.6

FIGURE 5.137. ρ versus Δ^0 Dalitz Plot for W bins 2.6 - 2.7

FIGURE 5.138. ρ versus Δ^0 Dalitz Plot for W bins 2.7 - 2.8

FIGURE 5.139. ρ versus Δ^0 Dalitz Plot for W bins 2.8 - 2.9

FIGURE 5.140. ρ versus Δ^0 Dalitz Plot for W bins 2.9 - 3.0

FIGURE 5.141. ρ versus Δ^0 Dalitz Plot for W bins 3.0 - 3.1.

FIGURE 5.142. ρ versus Δ^0 Dalitz Plot for W bins 3.1 - 3.2

FIGURE 5.143. ρ versus Δ^0 Dalitz Plot for W bins 3.2 - 3.3

FIGURE 5.144. ρ versus Δ^0 Dalitz Plot for W bins 3.3 - 3.4.

After acquiring all the weight factors for the different binned simulations, see Figure 5.145, we now have the information we need to produce our best-model simulation to the data to calculate and apply acceptance corrections. With an as "good as possible" model dependent simulation, the reconstructed simulated events and the generated thrown events can be produced now by the methods outlined earlier in the chapter.

FIGURE 5.145. The simulation weight factors, $\alpha = t$ of π^- , $\beta = t$ of π^+ , $\gamma = t$ of $\pi^+\pi^-$, and $\delta = t$ of phase space, plotted versus W of data.

Once we have both of these, we calculate the acceptance by dividing the yields of the reconstructed simulated events by the yields of the generated thrown events. This gives us the needed acceptance factor that we in turn apply to the measured experimental data to go about extracting the cross sections. These methods will be discussed further in the next chapter.

CHAPTER 6

CROSS SECTIONS

In scattering theory, the likelihood of a particular reaction happening is defined by the cross section. It is based on the classical picture of a point-like particle hitting a target filled with solids. The probability of a reaction, which means the particle hits a solid, is simply the ratio between the total cross-sectional area of solids and that of the target. In modern scattering theory, it is defined as

$$N_{reaction} = \frac{N_{incoming}N_{target}}{A}\sigma, \quad (13)$$

where $N_{reaction}$ is the number of reaction events, $N_{incoming}$ and N_{target} are the number of incoming particles and the target particles respectively, A is the unit area and σ the cross section. In this study, the cross section is calculated by

$$\sigma = \frac{Y}{aL} \frac{1}{f_{br}}, \quad (14)$$

where Y is the reaction yield, a the acceptance, f_{br} is a factor from the decay branching ratio and L is the integrated luminosity. The integrated luminosity has two parts. One is the photon flux, from the beam aspect. The other comes from the target and is calculated as

$$L_{target} = \frac{\rho l N_a}{m_{mol}}, \quad (15)$$

where ρ is the density of the target, l is the length of the target and 40 cm here, N_a is the Avogadro constant, and m_{mol} is the mass of the target material per mole.

6.1. ENERGY-DEPENDENT LUMINOSITY

The integrated luminosity per photon energy bin $E_{\gamma i}$ is given by

$$L_i = \frac{N_i \rho_D l N_A}{m_{mol}}, \quad (16)$$

where N_i is the integrated number of photons on target in a given photon energy bin, $\rho_D = 0.169g/cm^3$ the density of liquid deuterium, $l = 40cm$ the length of the eg3 target, $N_A = 6.02 \times 10^{23}deuterons/mole$ Avogadro's number, and $m_{mol} = 2.014g/mole$ the molar mass of deuterium.

FIGURE 6.1. Number of photons per tagger energy bin versus corresponding photon Ecounter bins.

The photon flux N_i is obtained with the GFLUX package. The idea of the method is to use the out-of-time photons, which do not produce recorded events, to calculate the rate corresponding to each T-Counter. This rate is then corrected by a factor, which is determined during test runs and that accounts for the photon loss between the tagger and the target. Then the rate is multiplied with the live time, the sum of small intervals during which the rates are consistent with each other within statistical errors. Figure 6.1 shows the number of the photons per photon energy bin corresponding to

the data set analyzed. The typical uncertainties reported by GFLUX package for a single energy bin is on the order of $\sim 2\%$.

The tagger counter efficiency correction, detector livetime correction, and beam trip cuts are automatically taken care of by applying the GFLUX analysis to the experimental data.

6.2. CROSS SECTION CALCULATION

The three-body final state is unambiguously determined by five kinematics variables. Indeed, three final particles could be described by $4 \times 3 = 12$ components of their four-momenta. All these particles are on-shell. So, it gives us three restrictions $E_i^2 - P_i^2 = m_i^2$ ($i = 1, 2, 3$). Energy-momentum conservation impose four additional constraints for the final particle four momentum components [**Fedotov(2010)**]. In the photon scattering process, $\gamma p \rightarrow p\pi^+\pi^-$, we also have the variable W in the hadronic final state kinematics variables. So photon scattering cross sections for double charged pion production should be five-differential: four variables for the final hadrons plus W determined by the photon scattering kinematics. Such five-differential cross sections may be written as

$$\frac{d^5\sigma}{d^4\tau}, \quad (17)$$

where $d^5\tau$ is four-differential phase space, describing the final hadron kinematics. Several sets of four variables for the description of the final hadron kinematics may be used. We adopted the following set of variables as defined by the JM model [**Mokeev(2005)**] discussed in the introduction:

- invariant mass of the first pair of particles M_{12} ;
- invariant mass of the second pair of particles M_{23} ;
- first particle solid angle Ω , but we only use θ because for photoproduction there is no symmetry in ϕ around the axis of the beam;

• and the angle between two planes: where one of them (plane A) is composed by three-momenta of the virtual photons and first hadron and the second plane (plane B) is composed by three-momenta of two other hadrons, see Figure 6.2.[**Fedotov(2010)**]

The selected events were collected in five-dimensional cells corresponding to these variables: W , invariant masses of the first pair of particles M_{12} and second pair of particles M_{23} , solid angle for the first final-state particle, and the angle α between the two planes. The cross sections were estimated in the CM frame, which is determined by the final state particles $p\pi^+\pi^-$. So, four-momenta of the final particles described above, initially measured in the lab frame, were boosted into the CM frame.

We calculated cross sections for various assignment for the first, second, and third final-state hadrons:

- invariant mass of the $p\pi^+$ pair, invariant mass of the $\pi^+\pi^-$ pair, proton spherical angle θ_p and angle $\alpha_{\pi^+\pi^-}$ between planes B (composed by momenta of $\pi^+\pi^-$ pair) and A (composed by initial and final protons);
- invariant mass of the $\pi^-\pi^+$ pair, invariant mass of the π^+p pair, π^- spherical angle θ_{π^-} and angle $\alpha_{p\pi^+}$ between planes B (composed by momenta of $p\pi^+$ pair) and A (composed by initial proton and π^-);
- invariant mass of the $\pi^+\pi^-$ pair, invariant mass of the π^-p pair, π^+ spherical angle θ_{π^+} and angle $\alpha_{p\pi^-}$ between planes B (composed by momenta of $p\pi^-$ pair) and A (composed by initial proton and π^+).

The final-state particle emission angles for the second set of variables is shown in Figure 6.2. The variables $M_{\pi^+\pi^-}$; M_{π^+p} ; θ_{π^-} ; α_{π^+p} were calculated from the three-momenta of the final-state particles $\vec{P}_{\pi^-}$, $\vec{P}_{\pi^+}$, $\vec{P}_{p'}$ in the following way. Since all observables are determined in the lab frame, we first transfer three-momenta of the final-state particles into the CM frame. All three-momenta used below, if not specified otherwise, are defined in the CM frame[Fedotov(2010)]. $M_{\pi^+\pi^-}$, M_{π^+p} , and M_{π^-p} masses are estimated as:

$$M_{\pi^+\pi^-} = \sqrt{(P_{\pi^+} + P_{\pi^-})^2}, \quad (18)$$

$$M_{\pi^+p'} = \sqrt{(P_{\pi^+} + P_{p'})^2}, \quad (19)$$

$$M_{\pi^-p'} = \sqrt{(P_{\pi^-} + P_{p'})^2}, \quad (20)$$

where P_i stands for the final-state particle four-momentum [Fedotov(2010)]. The angle θ_{π^-} between three-momentum of the initial photon and final π^- in the CM frame is calculated as:

$$\theta_{\pi^-} = \arccos \frac{\vec{P}_{\pi^-} \cdot \vec{P}_\gamma}{|\vec{P}_{\pi^-}| |\vec{P}_\gamma|} \quad (21)$$

The calculation of angle α_{π^+p} , between two planes A and B, see Figure 6.2, is more complicated. First we determine two auxiliary vectors $\vec{\gamma}$ and $\vec{\beta}$. The vector $\vec{\gamma}$ is unit vector perpendicular to the three-momentum $\vec{P}_{\pi^-}$, directed toward vector $-\vec{n}_z$ and situated in the plane composed by virtual photon three-momentum and three-momentum $\vec{P}_{\pi^-}$, see Figure 6.2. $\vec{n}_z$ is the unit vector directed along the z-axis, see Figure 6.2. The vector $\vec{\beta}$ is the unit vector perpendicular to three-momentum of π^- , directed toward three-momentum $\vec{P}_{\pi^+}$ and situated in the plane composed by the π^+ and p' three-momenta. Note that three-momenta of π^+ , π^- , and p' are in the same

plane, since in the CM frame their total three-momentum should be equal zero. Then angle between two planes $\alpha_{\pi+p}$ is:

$$\alpha_{\pi+p} = \arccos \vec{\gamma} \cdot \vec{\beta} \quad (22)$$

$\arccos$ function is running between zero and π . From the other hand angle between planes A and B may vary between zero and 2π . To determine α angle in a range between π and 2π we looking at relative direction of the vector $\vec{P}_{\pi^-}$ and vector product $\vec{P}_{\delta}$ for mentioned above auxiliary vectors $\vec{\gamma}$ and $\vec{\beta}$:

$$\vec{\delta} = \vec{\gamma} \times \vec{\beta} \quad (23)$$

If the vector $\vec{\delta}$ is collinear to $\vec{P}_{\pi^-}$, then the $\alpha_{\pi+p}$ angle is determined from (4.9). In a case of anti-collinear vectors $\vec{\delta}$ and $\vec{P}_{\pi^-}$:

$$\alpha_{\pi+p} = 2\pi - \arccos(\vec{\gamma} \cdot \vec{\beta}) \quad (24)$$

Defined above vector $\vec{\gamma}$ may now be expressed through the particle three-momenta as:

$$\vec{\gamma} = a_{\alpha}(-\vec{n}_z) + b_{\alpha} \vec{n} P_{\pi^-}, \quad (25)$$

$$a_{\alpha} = \sqrt{\frac{1}{1 - (\vec{n} P_{\pi^-} (-\vec{n}_z))^2}}, \quad (26)$$

$$b_{\alpha} = (\vec{n} \vec{P}_{\pi^-} (-\vec{n}_z)) a_{\alpha}, \quad (27)$$

where $\vec{n} P_{\pi^-}$ is unit vector directed along $\vec{P}_{\pi^-}$ three-momentum Figure 6.2[Fedotov(2010)]. Taking the scalar products $(\vec{\gamma} \cdot \vec{n} \vec{P}_{\pi^-})$ and $(\vec{\gamma} \cdot \vec{\gamma})$, it is straightforward to verify, that $\vec{\gamma}$ is a unit vector perpendicular to $\vec{P}_{\pi^-}$.

Vector $\vec{\beta}$ may be obtained as:

$$\vec{\beta} = a_\beta \overrightarrow{n_{P_{\pi^+}}} + b_\beta \overrightarrow{n_{P_{\pi^-}}}, \quad (28)$$

$$a_\beta = \sqrt{\frac{1}{1 - \overrightarrow{n_{P_{\pi^+}}} \cdot \overrightarrow{n_{P_{\pi^-}}}}}, \quad (29)$$

$$b_\beta = -(\overrightarrow{n_{P_{\pi^+}}} \cdot \overrightarrow{n_{P_{\pi^-}}}) a_\beta, \quad (30)$$

where $\overrightarrow{n_{P_{\pi^+}}}$ is unit vector directed along $\overrightarrow{P_{\pi^+}}$ [Fedotov(2010)]. Again the taking scalar products $(\vec{\beta} \cdot \overrightarrow{n_{P_{\pi^-}}})$ and $(\vec{\beta} \cdot \vec{\beta})$, it is straightforward to see, that $\vec{\beta}$ is a unit-vector perpendicular to the π^- three-momentum. The angle α_{π^+p} coincides with angles between vectors $\vec{\gamma}$ and $\vec{\beta}$. So, the scalar product $(\vec{\gamma} \cdot \vec{\beta})$ allows us to determine angle α_{π^+p} . The kinematics variables for the other hadron assignments for the first, second, and third final-state particles as described above, were evaluated in a similar way. [Fedotov(2010)]

$$\frac{d\sigma}{dM_{\pi^+\pi^-}} = \int \frac{d^5\sigma}{d^5\tau'} d\tau_{\pi^+\pi^-}, d\tau_{\pi^+\pi^-} = dM_{\pi^-p} d\Omega_{\pi^-} d\alpha_{p\pi^+} \quad (31)$$

$$\frac{d\sigma}{dM_{\pi^+p}} = \int \frac{d^5\sigma}{d^5\tau'} d\tau_{\pi^+p}, d\tau_{\pi^+p} = dM_{\pi^+\pi^-} d\Omega_{\pi^-} d\alpha_{p\pi^+} \quad (32)$$

$$\frac{d\sigma}{d(-\cos\theta_{\pi^-})} = \int \frac{d^5\sigma}{d^5\tau'} d\tau_{\pi^-}, d\tau_{\pi^-} = dM_{\pi^+\pi^-} - dM_{\pi^+p} \Omega_{\pi^-} d\alpha_{p\pi^+} \quad (33)$$

$$\frac{d\sigma}{dM_{\pi^-p}} = \int \frac{d^5\sigma}{d^5\tau'} d\tau_{\pi^-p}, d\tau_{\pi^-p} = dM_{\pi^+\pi^-} d\Omega_{\pi^+} d\alpha_{p\pi^-} \quad (34)$$

$$d^5\tau' = dM_{\pi^-p} dM_{\pi^+\pi^-} d\Omega_{\pi^+} d\alpha_{p\pi^-} \quad (35)$$

Thus our kinematic four-dimensional variables are defined and we are ready to extract them.

FIGURE 6.2

Utilizing a four-dimensional binning with the variables defined above, gives us enough dimensional variables to integrate over, apply four-dimensional acceptances, and extract a single-differential cross sections for each variable. These single-differential cross sections are our ultimate goal to compare eg3 two pion data results to g11 data results off the free proton. Within the analyses of two pion data, the missing piece for any analysis is a good event generator to produce a model-dependent simulation to extract adequate cross sections for the overall channel. This presents excitement for the present analysis, in that these first cross section results will conclude with a best achievable model-dependent result that will lead to a more realistic description of the

two-pion photoproduction off deuterium and hence to less model-dependent future analyses. This is the goal of both g11 and this work, and the difference between the final results of both analyses will reflect the different approaches in correcting for the low t acceptance holes. We discuss this further in the next sections.

6.3. MISSING MASS FITTING, SIDE BAND SUBTRACTION, AND YIELD EXTRACTION

After binning the data, the missing mass of X in $\gamma d \rightarrow p\pi^+\pi^-(X)$ is plotted and fitted with a Gaussian distribution plus a polynomial background. Then a cut of 3σ , where σ is the width of the Gaussian distribution, around the peak position is applied in order to extract yields. The histograms and fits for extracting total cross section are shown in Figure 6.3.

In order to extract the signal out of the background, side-band subtraction must be applied. The side-band subtraction cuts the same 3σ width on both sides of the missing mass peak. After fitting the invariant mass peaks on both side bands, the lower and upper integrations on both side bands are subtracted from the number under the missing mass peak, with the proper weight factor being applied to both the lower and upper side bands. The weight factors are determined by the ratio of the events under the background side bands over those under the peak for the fit of the background. This is applied for all bins of W to extract the signal from the background, where it would be nominal compared to the signal above the background polynomial.

The missing mass and positions of the side bands are plotted and shown in Figure 6.3. The mass is fit with a Gauss function of signal and a second-order polynomial function of background, the following steps applied. The fitting parameters must be adjusted for some bins of W for the subroutine to fit the histograms well.

To apply the missing mass subtraction, the data was binned four-dimensionally within the limits of the missing mass, lower side band, and upper side band regions

FIGURE 6.3. Fits of the missing mass per W bin.

that were determined from the fitting procedure. Once we have the data from these regions, we integrate out our various single differential variables in each region, apply the corresponding weight factors to the lower and upper side bands, and then perform the subtraction of each weighted side band from the missing mass peak. Thus, giving us a background corrected signal of the two pion photoproduction cross section.

6.4. ACCEPTANCE-CORRECTED YIELDS , NORMALIZED THROWN YIELDS, AND ACCEPTANCE-CORRECTED HOLE-CORRECTED YIELDS

To produce the final four-dimensionally integrated nine single-differential variables, we had to devise a method to correct for the holes at low t in n -dimensional

binning. The problem becomes best visible in n-dimensional binning, where all variables are dependent upon one another, which makes it highly complicated to correct for the holes if the variables cannot be separated. Since our calculation is now in four-dimensional space, the challenge becomes how to adequately correct for the holes in t four-dimensionally.

Every aspect of the cross section extraction was done on the n-dimensional binning level. The measured experimental data, reconstructed simulated data, and generated thrown data were all filled n-dimensionally. Following the same steps outlined in previous chapters, we divided the reconstructed simulated data by the generated thrown data to obtain a four-dimensional acceptance correction. This acceptance was then applied to the measured experimental data to achieve an acceptance-corrected four-dimensional yield. Conventionally, we should only have to integrate out each of the nine single-differential variables, apply the luminosity and bin normalizations, and this would give us our single differential cross section results. But we still need to administer a very important and critical correction, that being for the holes at low t.

The concept for correcting is that for the holes in the acceptance-corrected yield we take normalized generated thrown yield (meaning normalized to the accepted-corrected, luminosity and bin corrections applied final cross sections determined where no holes are) and fill the holes in the accepted-corrected yield with the normalized thrown yield for those bins. This means that we are getting the shape of the t directly from the generated thrown events, which would ultimately give a superior method of adjusting for the holes at low t because the corresponding t-slopes are extracted from the measured data in the corresponding channels.

To extend this method to 4-dimensional binning, the equations below show how we obtain the correction for the holes. We take the N_{Thrown}^4 and divide by $N_{sim,rec}^4$, this technical trick see 37 populates the zero-hole elements of the experiment with thrown yield. This process is not-trivial in culmination but presents a straightforward

approach to correcting for the holes. The general premise of the equation is that where ever there is a hole in the experimental data, it populates that hole with thrown events. If $N_{Thrown}^4 = 0$ and $N_{sim,rec}^4 = 0$, then our equation yields 0. If $N_{Thrown}^4 = 0$ and $N_{sim,rec}^4 > 0$, then again the equation yields 0. But if $N_{Thrown}^4 > 0$ and $N_{sim,rec}^4 = 0$, then our equation yields the number of thrown events. This adequately provides a fill of each experimental zero-hole bin with weighted thrown events. In the bins populated by the detector we determine the acceptance corrected yield by

$$N_{ACorr} = \frac{N_{exp}}{N_{acc}} \quad (36)$$

where N_{exp} is the experimental four-dimensional yield and N_{acc} is the four-dimensional acceptance. The division of the two gives the accepted-corrected yield.

$$N_{corr} = \left(\frac{N_{exp}^W}{N_{rec}^W}\right)(N_{thrown}^4 - \left(\frac{N_{thrown}^4}{N_{rec}^4}\right)N_{rec}^4) \quad (37)$$

where N_{exp}^W is the experimental one-dimensional yield and N_{rec}^W is the one-dimensional reconstructed simulated yield. The first term would give the normalization weight factor. N_{thrown}^4 is the four-dimensional thrown yield.

$$N_{Diff} = N_{ACorr} + N_{corr}; \quad (38)$$

where N_{Diff} would give the acceptance-corrected yield with hole correction.

The next series of plots display the acceptance-corrected experimental yields, the generated thrown events normalized (as final cross sections would be), and acceptance-corrected experimental yields with hole corrections. These plots confirm the validity of our approach and how well our corrections perform. In that the Acceptance-corrected Yield plus the normalized thrown events equals approximately the hole-corrected acceptance-corrected yield plots, confirming that our correction for the holes is being applied properly. We plotted the acceptance-corrected yield to show the differential variables with the holes, then took the generated thrown events and normalized them

as we would to obtain cross sections. The summation of those two plots gives us the third plot, which is the acceptance-corrected yield with hole corrections.

(A) Measured Plot 181

(B) T Norm Plot 181

(C) Hole Corr Plot 181

FIGURE 6.4. Accepted-Corrected Integrated Yield, Normalized Thrown Integrated Yield, and Accepted-Corrected Integrated Yield with hole correction for W bin 1.8 to 1.825.

(A) Measured Plot 183

(B) T Norm Plot 183

(C) Hole Corr Plot 183

FIGURE 6.5. Accepted-Corrected Integrated Yield, Normalized Thrown Integrated Yield, and Accepted-Corrected Integrated Yield with hole correction for W bin 1.825 to 1.85.

(A) Measured Plot 186

(B) T Norm Plot 186

(C) Hole Corr Plot 186

FIGURE 6.6. Accepted-Corrected Integrated Yield, Normalized Thrown Integrated Yield, and Accepted-Corrected Integrated Yield with hole correction for W bin 1.85 to 1.875.

(A) Measured Plot 188

(B) T Norm Plot 188

(C) Hole Corr Plot 188

FIGURE 6.7. Accepted-Corrected Integrated Yield, Normalized Thrown Integrated Yield, and Accepted-Corrected Integrated Yield with hole correction for W bin 1.875 to 1.9.

(A) Measured Plot 191

(B) T Norm Plot 191

(C) Hole Corr Plot 191

FIGURE 6.8. Accepted-Corrected Integrated Yield, Normalized Thrown Integrated Yield, and Accepted-Corrected Integrated Yield with hole correction for W bin 1.9 to 1.925.

(A) Measured Plot 193

(B) T Norm Plot 193

(C) Hole Corr Plot 193

FIGURE 6.9. Accepted-Corrected Integrated Yield, Normalized Thrown Integrated Yield, and Accepted-Corrected Integrated Yield with hole correction for W bin 1.925 to 1.95.

(A) Measured Plot 196

(B) T Norm Plot 196

(C) Hole Corr Plot 196

FIGURE 6.10. Accepted-Corrected Integrated Yield, Normalized Thrown Integrated Yield, and Accepted-Corrected Integrated Yield with hole correction for W bin 1.95 to 1.975.

(A) Measured Plot 198

(B) T Norm Plot 198

(C) Hole Corr Plot 198

FIGURE 6.11. Accepted-Corrected Integrated Yield, Normalized Thrown Integrated Yield, and Accepted-Corrected Integrated Yield with hole correction for W bin 1.975 to 2.0.

(A) Measured Plot 201

(B) T Norm Plot 201

(C) Hole Corr Plot 201

FIGURE 6.12. Accepted-Corrected Integrated Yield, Normalized Thrown Integrated Yield, and Accepted-Corrected Integrated Yield with hole correction for W bin 2.0 to 2.025.

(A) Measured Plot 203

(B) T Norm Plot 203

(C) Measured Corr Plot 203

FIGURE 6.13. Accepted-Corrected Integrated Yield, Normalized Thrown Integrated Yield, and Accepted-Corrected Integrated Yield with hole correction for W bin 2.025 to 2.05.

(A) Measured Plot 206

(B) T Norm Plot 206

(C) Hole Corr Plot 206

FIGURE 6.14. Accepted-Corrected Integrated Yield, Normalized Thrown Integrated Yield, and Accepted-Corrected Integrated Yield with hole correction for W bin 2.05 to 2.075.

(A) Measured Plot 208

(B) T Norm Plot 208

(C) Hole Corr Plot 208

FIGURE 6.15. Accepted-Corrected Integrated Yield, Normalized Thrown Integrated Yield, and Accepted-Corrected Integrated Yield with hole correction for W bin 2.075 to 2.1.

(A) Measured Plot 211

(B) T Norm Plot 211

(C) Hole Corr Plot 211

FIGURE 6.16. Accepted-Corrected Integrated Yield, Normalized Thrown Integrated Yield, and Accepted-Corrected Integrated Yield with hole correction for W bin 2.1 to 2.125.

(A) Measured Plot 213

(B) T Norm Plot 213

(C) Hole Corr Plot 213

FIGURE 6.17. Accepted-Corrected Integrated Yield, Normalized Thrown Integrated Yield, and Accepted-Corrected Integrated Yield with hole correction for W bin 2.125 to 2.15.

(A) Measured Plot 216

(B) T Norm Plot 216

(C) Hole Corr Plot 216

FIGURE 6.18. Accepted-Corrected Integrated Yield, Normalized Thrown Integrated Yield, and Accepted-Corrected Integrated Yield with hole correction for W bin 2.15 to 2.175.

(A) Measured Plot 218

(B) T Norm Plot 218

(C) Hole Corr Plot 218

FIGURE 6.19. Accepted-Corrected Integrated Yield, Normalized Thrown Integrated Yield, and Accepted-Corrected Integrated Yield with hole correction for W bin 2.175 to 2.2.

(A) Measured Plot 221

(B) T Norm Plot 221

(C) Hole Corr Plot 221

FIGURE 6.20. Accepted-Corrected Integrated Yield, Normalized Thrown Integrated Yield, and Accepted-Corrected Integrated Yield with hole correction for W bin 2.2 to 2.225.

(A) Measured Plot 226

(B) T Norm Plot 226

(C) Hole Corr Plot 226

FIGURE 6.21. Accepted-Corrected Integrated Yield, Normalized Thrown Integrated Yield, and Accepted-Corrected Integrated Yield with hole correction for W bin 2.25 to 2.275.

(A) Measured Plot 226

(B) T Norm Plot 226

(C) Hole Corr Plot 226

FIGURE 6.22. Accepted-Corrected Integrated Yield, Normalized Thrown Integrated Yield, and Accepted-Corrected Integrated Yield with hole correction for W bin 2.25 to 2.275.

(A) Measured Plot 228

(B) T Norm Plot 228

(C) Hole Corr Plot 228

FIGURE 6.23. Accepted-Corrected Integrated Yield, Normalized Thrown Integrated Yield, and Accepted-Corrected Integrated Yield with hole correction for W bin 2.275 to 2.3.

(A) Measured Plot 231

(B) T Norm Plot 231

(C) Hole Corr Plot 231

FIGURE 6.24. Accepted-Corrected Integrated Yield, Normalized Thrown Integrated Yield, and Accepted-Corrected Integrated Yield with hole correction for W bin 2.3 to 2.325.

(A) Measured Plot 236

(B) T Norm Plot 236

(C) Hole Corr Plot 236

FIGURE 6.25. Accepted-Corrected Integrated Yield, Normalized Thrown Integrated Yield, and Accepted-Corrected Integrated Yield with hole correction for W bin 2.35 to 2.375.

(A) Measured Plot 236

(B) T Norm Plot 236

(C) Hole Corr Plot 236

FIGURE 6.26. Accepted-Corrected Integrated Yield, Normalized Thrown Integrated Yield, and Accepted-Corrected Integrated Yield with hole correction for W bin 2.35 to 2.375.

(A) Measured Plot 238

(B) T Norm Plot 238

(C) Hole Corr Plot 238

FIGURE 6.27. Accepted-Corrected Integrated Yield, Normalized Thrown Integrated Yield, and Accepted-Corrected Integrated Yield with hole correction for W bin 2.375 to 2.4.

(A) Measured Plot 241

(B) T Norm Plot 241

(C) Hole Corr Plot 241

FIGURE 6.28. Accepted-Corrected Integrated Yield, Normalized Thrown Integrated Yield, and Accepted-Corrected Integrated Yield with hole correction for W bin 2.4 to 2.425.

(A) Measured Plot 243

(B) T Norm Plot 243

(C) Hole Corr Plot 243

FIGURE 6.29. Accepted-Corrected Integrated Yield, Normalized Thrown Integrated Yield, and Accepted-Corrected Integrated Yield with hole correction for W bin 2.425 to 2.45.

(A) Measured Plot 246

(B) T Norm Plot 246

(C) Hole Corr Plot 246

FIGURE 6.30. Accepted-Corrected Integrated Yield, Normalized Thrown Integrated Yield, and Accepted-Corrected Integrated Yield with hole correction for W bin 2.45 to 2.475.

(A) Measured Plot 248

(B) T Norm Plot 248

(C) Hole Corr Plot 248

FIGURE 6.31. Accepted-Corrected Integrated Yield, Normalized Thrown Integrated Yield, and Accepted-Corrected Integrated Yield with hole correction for W bin 2.475 to 2.5.

(A) Measured Plot 251

(B) T Norm Plot 251

(C) Hole Corr Plot 251

FIGURE 6.32. Accepted-Corrected Integrated Yield, Normalized Thrown Integrated Yield, and Accepted-Corrected Integrated Yield with hole correction for W bin 2.5 to 2.525.

(A) Measured Plot 253

(B) T Norm Plot 253

(C) Hole Corr Plot 253

FIGURE 6.33. Accepted-Corrected Integrated Yield, Normalized Thrown Integrated Yield, and Accepted-Corrected Integrated Yield with hole correction for W bin 2.525 to 2.55.

(A) Measured Plot 256

(B) T Norm Plot 256

(C) Hole Corr Plot 256

FIGURE 6.34. Accepted-Corrected Integrated Yield, Normalized Thrown Integrated Yield, and Accepted-Corrected Integrated Yield with hole correction for W bin 2.55 to 2.575.

(A) Measured Plot 258

(B) T Norm Plot 258

(C) Hole Corr Plot 258

FIGURE 6.35. Accepted-Corrected Integrated Yield, Normalized Thrown Integrated Yield, and Accepted-Corrected Integrated Yield with hole correction for W bin 2.575 to 2.6.

(A) Measured Plot 261

(B) T Norm Plot 261

(C) Hole Corr Plot 261

FIGURE 6.36. Accepted-Corrected Integrated Yield, Normalized Thrown Integrated Yield, and Accepted-Corrected Integrated Yield with hole correction for W bin 2.6 to 2.625.

(A) Measured Plot 263

(B) T Norm Plot 263

(C) Hole Corr Plot 263

FIGURE 6.37. Accepted-Corrected Integrated Yield, Normalized Thrown Integrated Yield, and Accepted-Corrected Integrated Yield with hole correction for W bin 2.625 to 2.65.

(A) Measured Plot 266

(B) T Norm Plot 266

(C) Hole Corr Plot 266

FIGURE 6.38. Accepted-Corrected Integrated Yield, Normalized Thrown Integrated Yield, and Accepted-Corrected Integrated Yield with hole correction for W bin 2.65 to 2.675.

(A) Measured Plot 268

(B) T Norm Plot 268

(C) Hole Corr Plot 268

FIGURE 6.39. Accepted-Corrected Integrated Yield, Normalized Thrown Integrated Yield, and Accepted-Corrected Integrated Yield with hole correction for W bin 2.675 to 2.7.

(A) Measured Plot 271

(B) T Norm Plot 271

(C) Hole Corr Plot 271

FIGURE 6.40. Accepted-Corrected Integrated Yield, Normalized Thrown Integrated Yield, and Accepted-Corrected Integrated Yield with hole correction for W bin 2.7 to 2.725.

(A) Measured Plot 273

(B) T Norm Plot 273

(C) Hole Corr Plot 273

FIGURE 6.41. Accepted-Corrected Integrated Yield, Normalized Thrown Integrated Yield, and Accepted-Corrected Integrated Yield with hole correction for W bin 2.725 to 2.75.

(A) Measured Plot 276

(B) T Norm Plot 276

(C) Hole Corr Plot 276

FIGURE 6.42. Accepted-Corrected Integrated Yield, Normalized Thrown Integrated Yield, and Accepted-Corrected Integrated Yield with hole correction for W bin 2.75 to 2.775.

(A) Measured Plot 278

(B) T Norm Plot 278

(C) Hole Corr Plot 278

FIGURE 6.43. Accepted-Corrected Integrated Yield, Normalized Thrown Integrated Yield, and Accepted-Corrected Integrated Yield with hole correction for W bin 2.775 to 2.8.

(A) Measured Plot 281

(B) T Norm Plot 281

(C) Hole Corr Plot 281

FIGURE 6.44. Accepted-Corrected Integrated Yield, Normalized Thrown Integrated Yield, and Accepted-Corrected Integrated Yield with hole correction for W bin 2.8 to 2.825.

(A) Measured Plot 283

(B) T Norm Plot 283

(C) Hole Corr Plot 283

FIGURE 6.45. Accepted-Corrected Integrated Yield, Normalized Thrown Integrated Yield, and Accepted-Corrected Integrated Yield with hole correction for W bin 2.825 to 2.85.

(A) Measured Plot 286

(B) T Norm Plot 286

(C) Hole Corr Plot 286

FIGURE 6.46. Accepted-Corrected Integrated Yield, Normalized Thrown Integrated Yield, and Accepted-Corrected Integrated Yield with hole correction for W bin 2.85 to 2.875.

(A) Measured Plot 288

(B) T Norm Plot 288

(C) Hole Corr Plot 288

FIGURE 6.47. Accepted-Corrected Integrated Yield, Normalized Thrown Integrated Yield, and Accepted-Corrected Integrated Yield with hole correction for W bin 2.875 to 2.9.

(A) Measured Plot 291

(B) T Norm Plot 291

(C) Hole Corr Plot 291

FIGURE 6.48. Accepted-Corrected Integrated Yield, Normalized Thrown Integrated Yield, and Accepted-Corrected Integrated Yield with hole correction for W bin 2.9 to 2.925.

(A) Measured Plot 291

(B) T Norm Plot 291

(C) Hole Corr Plot 291

FIGURE 6.48. Accepted-Corrected Integrated Yield, Normalized Thrown Integrated Yield, and Accepted-Corrected Integrated Yield with hole correction for W bin 2.9 to 2.925.

(A) Measured Plot 293

(B) T Norm Plot 293

(C) Hole Corr Plot 293

FIGURE 6.49. Accepted-Corrected Integrated Yield, Normalized Thrown Integrated Yield, and Accepted-Corrected Integrated Yield with hole correction for W bin 2.925 to 2.95.

(A) Measured Plot 296

(B) T Norm Plot 296

(C) Hole Corr Plot 296

FIGURE 6.50. Accepted-Corrected Integrated Yield, Normalized Thrown Integrated Yield, and Accepted-Corrected Integrated Yield with hole correction for W bin 2.95 to 2.9075.

(A) Measured Plot 298

(B) T Norm Plot 298

(C) Hole Corr Plot 298

FIGURE 6.51. Accepted-Corrected Integrated Yield, Normalized Thrown Integrated Yield, and Accepted-Corrected Integrated Yield with hole correction for W bin 2.975 to 3.1.

(A) Measured Plot 301

(B) T Norm Plot 301

(C) Hole Corr Plot 301

FIGURE 6.52. Accepted-Corrected Integrated Yield, Normalized Thrown Integrated Yield, and Accepted-Corrected Integrated Yield with hole correction for W bin 3.0 to 3.025.

(A) Measured Plot 303

(B) T Norm Plot 303

(C) Hole Corr Plot 303

FIGURE 6.53. Accepted-Corrected Integrated Yield, Normalized Thrown Integrated Yield, and Accepted-Corrected Integrated Yield with hole correction for W bin 3.025 to 3.05.

(A) Measured Plot 306

(B) T Norm Plot 306

(C) Hole Corr Plot 306

FIGURE 6.54. Accepted-Corrected Integrated Yield, Normalized Thrown Integrated Yield, and Accepted-Corrected Integrated Yield with hole correction for W bin 3.05 to 3.075.

(A) Measured Plot 308

(B) T Norm Plot 308

(C) Hole Corr Plot 308

FIGURE 6.55. Accepted-Corrected Integrated Yield, Normalized Thrown Integrated Yield, and Accepted-Corrected Integrated Yield with hole correction for W bin 3.075 to 3.1.

(A) Measured Plot 311

(B) T Norm Plot 311

(C) Hole Corr Plot 311

FIGURE 6.56. Accepted-Corrected Integrated Yield, Normalized Thrown Integrated Yield, and Accepted-Corrected Integrated Yield with hole correction for W bin 3.0 to 3.025.

(A) Measured Plot 313

(B) T Norm Plot 313

(C) Hole Corr Plot 313

FIGURE 6.57. Accepted-Corrected Integrated Yield, Normalized Thrown Integrated Yield, and Accepted-Corrected Integrated Yield with hole correction for W bin 3.125 to 3.15.

(A) Measured Plot 316

(B) T Norm Plot 316

(C) Hole Corr Plot 316

FIGURE 6.58. Accepted-Corrected Integrated Yield, Normalized Thrown Integrated Yield, and Accepted-Corrected Integrated Yield with hole correction for W bin 3.15 to 3.175.

(A) Measured Plot 321

(B) T Norm Plot 321

(C) Hole Corr Plot 321

FIGURE 6.59. Accepted-Corrected Integrated Yield, Normalized Thrown Integrated Yield, and Accepted-Corrected Integrated Yield with hole correction for W bin 3.2 to 3.225.

(A) Measured Plot 323

(B) T Norm Plot 323

(C) Hole Corr Plot 323

FIGURE 6.60. Accepted-Corrected Integrated Yield, Normalized Thrown Integrated Yield, and Accepted-Corrected Integrated Yield with hole correction for W bin 3.225 to 3.25.

(A) Measured Plot 326

(B) T Norm Plot 326

(C) Hole Corr Plot 326

FIGURE 6.61. Accepted-Corrected Integrated Yield, Normalized Thrown Integrated Yield, and Accepted-Corrected Integrated Yield with hole correction for W bin 3.25 to 3.275.

6.5. SINGLE-DIFFERENTIAL CROSS SECTIONS

The final single-differential cross sections were extracted from the four-dimensional binning process by integrating out each of the nine variables from the acceptance and hole-corrected, four-dimensional binning, giving us a single differential variable with the luminosity and bin normalizations applied. All nine differential cross sections were extracted and compared to still preliminary g11 JLab cross section data that was extracted using a different approach to correct for the holes at low t . Where we get the t -slope extrapolation into the holes by filling them with the generated thrown events, which are experimental data adapted representation of the slope, the g11 data corrects the holes by interpolating between the surrounding still filled bins. Meaning wherever their holes are, they take the bin content from the next closest bins with data and extrapolate into the neighboring hole bin. We find that a short coming in this method is that because there are many neighboring bins with holes, the extrapolation flattens out or suppresses the true t -slope in the correction. In the plots below, the nine single-differentials are shown for the masses, angles, and angles between the planes. EG3 data is plotted in red versus the g11 data in blue.

Most of the bins are consistent with each other and we see a stronger resonance structure in the g11 mass cross sections. Our data has all the weight factors applied to obtain first results using as good as possible model-dependent simulation. Also, the single-differential polar angle cross sections show the differences in the two methods to correct for the holes. As you can see, the g11 data t slope is typically smaller than for the eg3 data as it is expected due to the different approach. This also shows how well the extracted t slopes allow us to correct the final cross sections with the generated thrown events.

(A) Measured Plot 328

(B) T Norm Plot 328

(C) Hole Corr Plot 328

FIGURE 6.62. Accepted-Corrected Integrated Yield, Normalized Thrown Integrated Yield, and Accepted-Corrected Integrated Yield with hole correction for W bin 3.275 to 3.3.

(A) 1.8 to 1.825

(B) 1.825 to 1.85

FIGURE 6.63. 9 Differential cross sections for bins of W .

(A) 1.85 to 1.875

(B) 1.875 to 1.9

FIGURE 6.64. 9 Differential cross sections for bins of W .

(A) 1.9 to 1.925

(B) 1.925 to 1.95

FIGURE 6.65. 9 Differential cross sections for bins of W .

(A) 1.95 to 1.975

(B) 1.975 to 2.0

FIGURE 6.66. 9 Differential cross sections for bins of W .

(A) 2.0 to 2.025

(B) 2.025 to 2.05

FIGURE 6.67. 9 Differential cross sections for bins of W .

(A) 2.05 to 2.075

(B) 2.075 to 2.1

FIGURE 6.68. 9 Differential cross sections for bins of W .

(A) 2.1 to 2.125

(B) 2.125 to 2.15

FIGURE 6.69. 9 Differential cross sections for bins of W .

(A) 2.15 to 2.175

(B) 2.175 to 2.2

FIGURE 6.70. 9 Differential cross sections for bins of W .

(A) 2.2 to 2.225

(B) 2.225 to 2.25

FIGURE 6.71. 9 Differential cross sections for bins of W .

(A) 2.25 to 2.275

(B) 2.275 to 2.3

FIGURE 6.72. 9 Differential cross sections for bins of W .

(A) 2.3 to 2.325

(B) 2.325 to 2.35

FIGURE 6.73. 9 Differential cross sections for bins of W .

(A) 2.35 to 2.375

(B) 2.375 to 2.4

FIGURE 6.74. 9 Differential cross sections for bins of W .

(A) 2.4 to 2.425

(B) 2.425 to 2.45

FIGURE 6.75. 9 Differential cross sections for bins of W .

(A) 2.45 to 2.475

(B) 2.475 to 2.5

FIGURE 6.76. 9 Differential cross sections for bins of W .

(A) 2.5 to 2.525

(B) 2.525 to 2.55

FIGURE 6.77. 9 Differential cross sections for bins of W .

(A) 2.55 to 2.575

(B) 2.575 to 2.6

FIGURE 6.78. 9 Differential cross sections for bins of W .

(A) 2.6 to 2.625

(B) 2.625 to 2.65

FIGURE 6.79. 9 Differential cross sections for bins of W .

(A) 2.65 to 2.675

(B) 2.675 to 2.7

FIGURE 6.80. 9 Differential cross sections for bins of W .

(A) 2.7 to 2.725

(B) 2.725 to 2.75

FIGURE 6.81. 9 Differential cross sections for bins of W .

(A) 2.75 to 2.775

(B) 2.775 to 2.8

FIGURE 6.82. 9 Differential cross sections for bins of W .

(A) 2.8 to 2.825

(B) 2.825 to 2.85

FIGURE 6.83. 9 Differential cross sections for bins of W .

(A) 2.85 to 2.875

(B) 2.875 to 2.9

FIGURE 6.84. 9 Differential cross sections for bins of W .

(A) 2.9 to 2.925

(B) 2.925 to 2.95

FIGURE 6.85. 9 Differential cross sections for bins of W .

(A) 2.95 to 2.975

(B) 2.975 to 3.0

FIGURE 6.86. 9 Differential cross sections for bins of W .

(A) 3.0 to 3.025

(B) 3.025 to 3.05

FIGURE 6.87. 9 Differential cross sections for bins of W .

(A) 3.05 to 3.075

(B) 3.075 to 3.1

FIGURE 6.88. 9 Differential cross sections for bins of W .

(A) 3.1 to 3.125

(B) 3.125 to 3.15

FIGURE 6.89. 9 Differential cross sections for bins of W .

(A) 3.15 to 3.175

(B) 3.175 to 3.2

FIGURE 6.90. 9 Differential cross sections for bins of W .

FIGURE 6.91. Total cross section of two pion channel.

6.5.1. Total Cross Section. Now that we have the single differential cross sections, we simply integrate each set of nine single-differential cross sections to calculate the total cross section. The same was done for the g11 data single-differential cross sections as well. Figure 6.91 shows the comparison of eg3 total cross section (red) to g11 total cross section (blue), ELSA (black), and ABBHMM (orange) [ABBHMM(1968)] data. The eg3 data set does not include the systematic error. We see good comparison with published data, but have not determined the cause for the high cross section points around 1.9, 2.5 and 3 GeV. Our first theory in which we are still studying is that they are due to a slightly improper missing mass fit for the side band subtraction.

6.5.2. Systematic Error Study. Only statistical errors are shown for all of the plots in this work. The systematic errors are studied by examining how much the variation of the various corrections, cuts, and event selecting condition affect the cross section and decay angle results. There are large contributions from the untriggered

tagger T-Counter correction about 15% and the trigger efficiency correction about 20%. All other corrections and cuts applied to the experimental data only affect the final results slightly and their total systematic error is about 5%. The various event selection conditions have total 5% error. The systematic error of acceptance calculation from the simulation is estimated to be 6% and the normalization by using photon flux has error about 2%. The overall systematic error is about 35% for the results of cross sections and decay angle distributions in our study. This is comparable to other analyses based on the CLAS eg3 data set, like the pentaquark $\Phi^{--}(1862)$ search [**Egiyan(2009)**], the $\Sigma^{*-}(1385)$ cross section [**Lu(2010)**], and the $K^+\Sigma^{*-}$ cross section [**Zhao(2010)**].

CHAPTER 7

SUMMARY

This analysis obtained the first differential and total cross section of $\gamma p(n) \rightarrow p\pi^+\pi^-(n)$ photoproduction in an extended photon beam energy ranging from the production threshold to 5.5 GeV, by using the eg3 data set obtained in the Hall B at Thomas Jefferson National Laboratory. The differential cross sections obtained are consistent in the overlapping kinematic region with the previously published results from a different data set. However, it extends to the region of significantly higher photon energies. The differential cross sections exhibit strong t-channel production characteristics as seen from our method of correcting the data for holes at low t. Two pion differential cross sections show a strong t-channel dominance. The total cross section off the deuteron is similar to the world data and also consistent with the preliminary results from the g11, which was measured on the free proton.

Our results give us a first model-dependent cross section result, where the simulated data was obtained by getting the t-slopes directly from the generated thrown data for the holes at low t, which should be the best achievable first approach. This, we believe, gives us an overall advantage to date among any other two pion extracted cross sections, because of our method of weighting the different t-channel contributions and allowing those weights to make up the overall simulation. Thus, allowing us to produce cross sections that will introduce an advanced method of gaining better model-dependent cross sections by building on the foundation that we have laid.

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