RICE UNIVERSITY

Kinematic Fitting of Detached Vertices

by

Paul Mattione

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APPROVED, THESIS COMMITTEE:

Gordon S. Mutchler, Professor, Chair
Physics and Astronomy

Randall G. Hulet, Professor
Physics and Astronomy

Jabus B. Roberts Jr., Professor
Physics and Astronomy

HOUSTON, TEXAS

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ABSTRACT

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The eg3 experiment at the Jefferson Lab CLAS detector aims to determine the existence of the Ξ_5 pentaquarks and investigate the excited Ξ states. Specifically, the exotic Ξ_5^{--} pentaquark will be sought by first reconstructing the Ξ^- particle through its weak decays, $\Xi^- \rightarrow \pi^- \Lambda$ and $\Lambda \rightarrow p\pi^-$. A kinematic fitting routine was developed to reconstruct the detached vertices of these decays, where confidence level cuts on the fits are used to remove background events. Prior to fitting these decays, the exclusive reaction $\gamma D \rightarrow pp\pi^-$ was studied in order to correct the track measurements and covariance matrices of the charged particles. The $\Lambda \rightarrow p\pi^-$ and $\Xi^- \rightarrow \pi^- \Lambda$ decays were then investigated to demonstrate that the kinematic fitting routine reconstructs the decaying particles and their detached vertices correctly.

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Chapter 1

Pentaquark and Excited Cascade States

Pentaquark states have the potential to revolutionize hadron spectroscopy. All of the hadrons that have been detected and confirmed so far are either baryons or mesons, containing three quarks or one quark and one antiquark respectively, bound together by the strong force. Pentaquarks contain four quarks and one antiquark, so while they are not forbidden by the standard model they would significantly expand our knowledge of the hadron quark structure. However, several high statistic experiments performed over the past several years conflict with the original supporting experiments, casting significant doubt on the existence of the pentaquarks. The eg3 experiment at the Jefferson Lab CLAS detector was performed to search for the Ξ_5 pentaquark states, particularly the Ξ_5^- .

Since the eg3 experiment was designed to search for the cascade pentaquarks, it provides an excellent opportunity to search for the excited Ξ states as well. This area of the standard model remains largely unexplored, as there are many excited Ξ states predicted by $SU(3)$ symmetry that have yet to be discovered. Very little is known even of the ones that have been observed; many have only roughly-defined masses and unknown quantum numbers. The eg3 experiment will attempt to observe more of the Ξ^* states and to better establish those states that have already been detected.

1.1 The Status of Pentaquark Research

In 2003, the LEPS Collaboration at SPring-8 in Japan found evidence for the existence of the Θ^+ pentaquark state [1]. This narrow state was observed at 1540

MeV/c² in the nK^+ invariant mass spectrum, indicating a quark content of four quarks, one antiquark: $uudd\bar{s}$. This state is manifestly exotic, as the established quark model does not permit the existence of positively charged baryons with an anti-strange quark. Since then, several other collaborations have published evidence supporting the existence of the Θ^+ state, including CLAS [2, 3], DIANA [4], HERMES [5], SAPHIR [6], ZEUS [7], SVD [8], and COSY-TOF [9]. Also, the NA49 Collaboration reported evidence for the existence of two additional pentaquark states, the Ξ_5^{--} and Ξ_5^0 , both at a mass of 1860 MeV/c² [10]. The Ξ_5^{--} and Ξ_5^+ pentaquarks, with quark content $ddss\bar{u}$ and $uuss\bar{d}$ respectively, are both exotic states because they have charges forbidden by the Standard Model for baryons containing two strange quarks.

Diakonov, Petrov, and Polyakov predicted the existence of these pentaquark states several years prior to these observations as part of an anti-decuplet of pentaquark states in the chiral soliton model. The two lowest rotational states of this model reproduce the well-known spin- $\frac{1}{2}$ baryon octet and the spin- $\frac{3}{2}$ baryon decuplet, both shown in Figure 1.1. The next rotational state in the chiral soliton model is an anti-decuplet of pentaquarks, shown in Figure 1.2. This group resembles that of the spin- $\frac{1}{2}$ baryon octets, but is expanded to include the exotic Θ^+ , Ξ_5^{--} , and Ξ_5^+ states [12].

The J^{PC} quantum numbers, or the spin, parity, and charge conjugation of the N and Σ pentaquark states are identical to their octet counterparts, while those of the Ξ baryons have not yet been fully measured. This permits the mixing of the N and Σ pentaquark states with the observed $N(1710)$ and $\Sigma(1880)$ excited baryon states, which is integral to the chiral soliton model. However, the mixing of the N and Σ states is not directly observable by experiment; only the detection of the exotic states

Figure 1.1 (A) The spin- $\frac{1}{2}$ baryon octet. (B) The spin- $\frac{3}{2}$ baryon decuplet. The particles are grouped by charge and strangeness [11].

Figure 1.2 The anti-decuplet states and their masses of the chiral soliton model. The states with exotic quantum numbers are shown in red with their quark content. The states in green are mixed with those in the excited spin- $\frac{1}{2}$ baryon octet. The eg3 experiment will attempt to detect the states along the bottom row, particularly the exotic Ξ_5^- and Ξ_5^+ states. [37]

can verify the pentaquark anti-decuplet predicted by the chiral soliton model [13].

Initially, the observed $N(1710)$ octet states were used as a reference to calculate the masses of the unobserved pentaquarks, yielding initial mass predictions of $1530 \text{ MeV}/c^2$ for the Θ^+ and $2070 \text{ MeV}/c^2$ for the Ξ_5 states [12]. While the $1540 \text{ MeV}/c^2$ Θ^+ signal reported by LEPS matched the chiral soliton model well, the NA49 Collaboration observed a signal for the Ξ_5 states at $1860 \text{ MeV}/c^2$ [10]. Thus, the $N(1650\text{-}1690)$ states were used to adjust the model to remove the discrepancy [13].

However, there have been several experiments that did not observe the Θ^+ signal, including those by the CLAS [14, 15, 16, 17], ALEPH [18], BABAR [19], Belle [20], BES [21], FOCUS [22], HERA-B [23], HyperCP [24], PHENIX [25], SPHINX [26], WA89 [27], and HERMES [28] collaborations. Most of these experiments were run with much higher statistics than those supporting the existence of the Θ^+ . Additionally, several collaborations searching for the Ξ_5^- have reported null results, including HERA-B [23], COMPASS [29], CDF [30], and WA89 [31].

The large discrepancy between experimental results may be due to uncertainties or underestimates of the background shapes, yielding statistical significance estimates that were too optimistic. Additionally, the Θ^+ state observed in the various, low-statistic supporting experiments was reconstructed over a relatively broad mass range, much too large to properly coincide with such narrow signals [32].

The existence of the pentaquark states must be significantly reinforced before they become an accepted part of the standard model. The large amount of opposing evidence does not necessarily negate the existence of the Θ^+ and Ξ_5^- , but the

discrepancies between any positive signals and the null results must be satisfactorily explained. Meanwhile, stringent upper limits have been placed on the pentaquark production cross sections. While most of the effort has centered around the Θ^+ pentaquark, the eg3 experiment was designed to resolve the status of the exotic Ξ_5 pentaquark states. This experiment is a part of the CLAS Collaboration's goal of determining whether the pentaquark states exist.

1.2 The Status of Excited Ξ Research

The doubly-strange Ξ states, containing two strange quarks, remain a largely unexplored area of particle physics. While 11 of these cascade states have been observed, only three have fully determined spin and parity, the $\Xi(1321)_{\frac{1}{2}}^+$, $\Xi(1530)_{\frac{3}{2}}^+$, and the $\Xi(1820)_{\frac{3}{2}}^-$ states [33]. SU(3) flavor symmetry predicts that there should be a Ξ^* state for every one of the N^* and Δ^* states, 20 of which are firmly established [34].

The Ξ^* states are difficult to find for several reasons, firstly because they are doubly-strange. Because fixed targets contain only up and down quarks, strange quarks may only be produced in $s\bar{s}$ pair production which is additionally suppressed due to their relatively large mass. Also, while photoproduction of these states are typically studies of the $\gamma p \rightarrow K^+ K^+(X)$ missing mass, they are susceptible to backgrounds introduced by misidentifying pions or protons as kaons. Recent studies at CLAS [35, 36] have reported on the $\Xi^-(1321)$ and $\Xi^-(1530)$ cross sections, but no additional excited cascade states were observed.

The lower mass Ξ^* states decay primarily into $\Xi\pi$, whereas the heavier states

have been observed to decay to $\Lambda\bar{K}$ [32]. Since the eg3 experiment was designed to reconstruct the exotic Ξ_5^- pentaquark through its decay into the Ξ^- , the decays of the missing excited cascade states can be searched for as well.

Chapter 2

The eg3 Experiment

The eg3 experiment was run using the CLAS detector at the Jefferson Lab CEBAF electron beam accelerator. The experiment was run over a period of forty days in December 2004 and January 2005, the goal of which is to determine the existence of the pentaquark cascade states, specifically the Ξ_5^{--} . A 5.75 GeV tagged photon beam incident on a liquid deuterium target was used to search for these states. The production cross sections of the pentaquark states are estimated to be very small, between 0.1 and 10 nb. However, in the missing mass of the $\gamma n \rightarrow K^+ K^+(X)$ system, the Ξ_5^{--} will be indistinguishable from the Ξ_5^- and Ξ^* states. Fortunately, the Ξ_5^{--} can be identified by reconstructing its decay chain $\Xi_5^{--} \rightarrow \pi^- \Xi^-$, $\Xi^- \rightarrow \pi^- \Lambda$, and $\Lambda \rightarrow p \pi^-$. It is difficult to isolate the Ξ^- decays due to the large background from the $\Sigma^-(1385) \rightarrow \pi^- \Lambda$ decay, so kinematic fitting will be used to search for the Ξ_5^{--} .

2.1 Pentaquark Photoproduction and Decays

The primary photoproduction reactions of the doubly-strange Ξ_5^{--} , Ξ_5^- , Ξ_5^0 , and Ξ_5^+ states on protons and neutrons are shown in Tables 2.1 and 2.2 respectively, along with their predicted cross sections. The cross sections have been calculated for the $\gamma n \rightarrow K^+ K^+ \Xi_5^{--}$ and $\gamma p \rightarrow K^0 K^0 \Xi_5^+$ reactions [38]. Their first-order Feynman diagrams are illustrated in Figure 2.1. The cross sections of the other reactions in the tables were estimated by assuming that the same production mechanism dominates, while taking into account the increase in the production threshold in the final states

with an additional pion.

Reaction	Threshold (GeV)	σ (nb) (estimate)
$\gamma p \rightarrow K^+ K^+ \pi^+ \Xi_5^{--}$	4.3	1
$\gamma p \rightarrow K^+ K^+ \Xi_5^-$	3.9	10
$\gamma p \rightarrow K^+ K^0 \Xi_5^0$	3.9	5
$\gamma p \rightarrow K^0 K^0 \Xi_5^+$	3.9	1
$\gamma p \rightarrow K^+ K^0 \pi^- \Xi_5^+$	4.3	0.1 [38]

Table 2.1 Photoproduction of the cascade pentaquark states off of a proton. The cross sections are calculated with $E_\gamma = 5$ GeV and are all estimates, except for the $\gamma p \rightarrow K^0 K^0 \Xi_5^+$ reaction [37].

Reaction	Threshold (GeV)	σ (nb) (estimate)
$\gamma n \rightarrow K^+ K^+ \Xi_5^{--}$	3.9	10 [38]
$\gamma n \rightarrow K^+ K^0 \Xi_5^-$	3.9	5
$\gamma n \rightarrow K^0 K^0 \Xi_5^0$	3.9	1
$\gamma n \rightarrow K^0 K^0 \pi^- \Xi_5^+$	4.3	0.1

Table 2.2 Photoproduction of the cascade pentaquark states off of a neutron. The cross sections are calculated with $E_\gamma = 5$ GeV and are all estimates, except for the $\gamma n \rightarrow K^+ K^+ \Xi_5^{--}$ reaction [37].

Typically, the photoproduction of the Ξ_5 states on a neutron proceed through K^+ exchange, while the cross section on a proton varies with the value of the yet-to-be-determined $g_{K^* N \Xi}$ coupling constant. The cross sections on the proton have been calculated with a best-guess value of $g_{K^* N \Xi} = 1.8$ [37]. All of the cross sections listed in the tables are 10 nb or less, and all were calculated assuming a photon beam energy of 5 GeV. Between the exotic Ξ_5^{--} and Ξ_5^+ production reactions, at 10 nb the $\gamma n \rightarrow K^+ K^+ \Xi_5^{--}$ reaction has the largest cross section and thus is the most promising for study.

The primary decay modes of the Ξ_5 pentaquark states are listed in Table 2.3. The weak decays proceed through the extremely massive, $80.4 \text{ GeV}/c^2$ W^- gauge boson to

Figure 2.1 First-order Feynman diagrams for the pentaquark photoproduction reactions (A) $\gamma n \rightarrow K^+ K^+ \Xi_5^{--}$ and (B) $\gamma p \rightarrow K^0 K^0 \Xi_5^+$ [39].

perform the quark flavor change $s \rightarrow u$. This process has a much longer decay length than electromagnetic decays, resulting in multiple decay vertices several centimeters apart for each decay mode. For example, the decay lengths $c\tau$ of the $\Lambda \rightarrow p\pi^-$ and $\Xi^- \rightarrow \pi^- \Lambda$ decays are 7.89 cm and 4.91 cm, respectively.

Primary Decay	Secondary Decay	Tertiary Decay	Mass Ctr.	Q=0	B.R.
$\Xi_5^{--} \rightarrow \pi^- \Xi^-$	$\rightarrow \pi^- (\pi^- \Lambda)$	$\rightarrow \pi^- \pi^- (\pi^- p)$	Ξ^-, Λ		0.32
$\Xi_5^{--} \rightarrow K^- \Sigma^-$	$\rightarrow K^- (\pi^- n)$		Σ^-	n	0.5
$\Xi_5^- \rightarrow \pi^0 \Xi^-$	$\rightarrow \pi^0 (\pi^- \Lambda)$	$\rightarrow \pi^0 \pi^- (\pi^- p)$	Ξ^-, Λ	π^0	0.21
$\Xi_5^- \rightarrow \pi^- \Xi^0$	$\rightarrow \pi^- (\pi^0 \Lambda)$	$\rightarrow \pi^- \pi^0 (\pi^- p)$	Ξ^0, Λ	π^0	0.11
$\Xi_5^- \rightarrow \bar{K}^0 \Sigma^-$	$\rightarrow (\pi^- \pi^+) (\pi^- n)$		K_s, Σ^-	n	0.06
$\Xi_5^- \rightarrow K^- \Sigma^0$	$\rightarrow K^- (\gamma \Lambda)$	$\rightarrow K^- \gamma (\pi^- p)$	Σ^0, Λ	γ	0.21
$\Xi_5^0 \rightarrow \pi^0 \Xi^0$	$\rightarrow \pi^0 (\pi^0 \Lambda)$	$\rightarrow \pi^0 \pi^0 (\pi^- p)$	Ξ^0, Λ	$2\pi^0$	0.21
$\Xi_5^0 \rightarrow \pi^+ \Xi^-$	$\rightarrow \pi^+ (\pi^- \Lambda)$	$\rightarrow \pi^+ \pi^- (\pi^- p)$	Ξ^-, Λ		0.11
$\Xi_5^0 \rightarrow K^- \Sigma^+$	$\rightarrow K^- (\pi^+ n)$		Σ^+	n	0.09
$\Xi_5^0 \rightarrow \bar{K}^0 \Sigma^0$	$\rightarrow (\pi^- \pi^+) (\gamma \Lambda)$	$\rightarrow \pi^- \pi^+ \gamma (\pi^- p)$	K_s, Σ^0, Λ	γ	0.07
$\Xi_5^+ \rightarrow \pi^+ \Xi^0$	$\rightarrow \pi^+ (\pi^0 \Lambda)$	$\rightarrow \pi^+ \pi^0 (\pi^- p)$	Ξ^0, Λ	π^0	0.32
$\Xi_5^+ \rightarrow \pi^+ \pi^+ \Xi^-$	$\rightarrow \pi^+ \pi^+ (\pi^- \Lambda)$	$\rightarrow \pi^+ \pi^+ \pi^- (\pi^- p)$	Ξ^-, Λ		?
$\Xi_5^+ \rightarrow \bar{K}^0 \Sigma^+$	$\rightarrow (\pi^- \pi^+) (\pi^+ n)$		K_s, Σ^+	n	0.09

Table 2.3 The decay chains of the Ξ_5 states. The decaying particles are listed in the mass constraints column, as the invariant mass of their decays may be used to apply cuts during reconstruction. For the secondary and tertiary decays, the decay products are grouped in parentheses, while the others are spectators that were produced in an earlier decay. Also listed are the number of neutral particles in the final state produced during the decays, and the overall branching ratio of the decay mode. [37]

2.2 Experiment Conditions

With such small predicted cross sections for the pentaquarks, the eg3 experiment was run with a high flux, 5.75 GeV tagged photon beam in order to maximize the number of events. This energy, the maximum provided by the CEBAF accelerator at Jefferson Lab, is large enough to sufficiently exceed the predicted production thresholds of the Ξ_5 pentaquark states. The tagged photon beam was chosen because it provides additional triggering for data acquisition than the virtual photons from the electron beam, allowing for a higher effective luminosity with reduced activity in the detector. The bremsstrahlung photon tagger and the data acquisition triggering are discussed in detail in Sections 3.2.4 and 3.3, respectively.

As the reaction $\gamma n \rightarrow K^+ K^+ \Xi_5^{--}$ is the most likely exotic pentaquark production mechanism, a liquid deuterium target was chosen for the experiment. The target has a 4 cm thick 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. While the background due to accidental coincidences from unrelated physics events increases with target length, it is not significant enough to negate the advantage of having a high event rate.

The target shown in Figure 2.2 for the previously run g11 experiment 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. This window allows the remnants of the photon beam to exit the target with minimal interactions [41].

Figure 2.2 Conical liquid deuterium target used for the eg3 experiment, measuring 40cm in length, and 4cm in diameter at its widest. The beam axis runs along the center of the target. The front of the target is rounded off, and a very thin aluminum window is located at the front for photons that do not strike the deuterium. [40]

However, as the incident photon beam can interact with either the proton or neutron in the deuterium, additional background reactions can distort the missing mass spectrum. For example, high energy pions are commonly misidentified as high energy kaons due to their similarly light masses. As a result, large backgrounds are introduced via the $\gamma p \rightarrow K^+ \pi^+ \Sigma^-$ and $\gamma p \rightarrow \pi^+ \pi^+ \Delta^-$ reactions, which would easily overwhelm the low-count $K^+ K^+ \Xi_5^{--}$ signal. Therefore, the eg3 experiment will attempt to reconstruct the Ξ_5^{--} pentaquark state through its decay chain.

2.3 Decay Reconstruction

Because charged particles are capable of being electromagnetically tracked they are detected at a better resolution than neutral particles. Therefore, the pentaquark decays best-suited for reconstruction are those without any neutral particles in the final state. From Table 2.3, the three-stage $\Xi_5^{--} \rightarrow \pi^- \Xi^-$, $\Xi^- \rightarrow \pi^- \Lambda$, and $\Lambda \rightarrow p \pi^-$ decay chain is the most likely candidate for Ξ_5^{--} reconstruction, resulting in a fully-charged final state of $p \pi^- \pi^- \pi^-$. This decay mode is illustrated in Figure 2.3, showing the detached vertices of the Ξ^- and Λ decays, along with the kaons produced in the

Figure 2.3 The primary decay chain of the Ξ_5^{--} , showing the detached vertices of the weakly decaying Ξ^- and Λ particles. In order to reconstruct the decay, the proton and the pions must be detected, but the kaons may be used for additional cuts as well [37].

initial reaction.

With three π^- 's in the final state of the decay, the CLAS detector was optimized to detect negatively charged particles for the eg3 experiment by setting the torus magnet to bend negatively charged tracks away from the beam line and through the drift chambers. Consequently, positively charged tracks are bent towards the beam line and some of the slow K^+ 's created in the pentaquark photoproduction reactions may escape detection. This choice of field direction supports pentaquark reconstruction through their decay chains but further limits the effectiveness of the missing mass technique. With this field configuration, the liquid deuterium target was moved 50 cm upstream from the center of CLAS because Monte Carlo simulations of Ξ_5^{--} production indicated this position was the best target location for π^- detection. The CLAS torus magnet and drift chambers are discussed in detail in Sections 3.2.1 and 3.2.2, respectively.

In the chosen Ξ_5^{--} decay chain, invariant mass cuts may be placed on the decays $\Lambda \rightarrow p\pi^-$ and $\Xi^- \rightarrow \pi^-\Lambda$ to reduce the background. Unfortunately, the wide $\Sigma^-(1385)$

signal predominates the $\pi^-\Lambda$ invariant mass spectrum, making the selection of the $1321 \text{ MeV}/c^2$ Ξ^- signal from the background more difficult. A cut requiring the detection of the kaons produced in the initial reaction will reduce this background, but many events from the Ξ^- signal will be lost as well since many of the inward-bending kaons escape detection. However, cuts may be placed on the detached vertices of the Λ and Ξ^- weak decays to improve the signal.

As stringent limits have already been placed on the production cross sections of the pentaquarks, they are exceedingly difficult to locate. Therefore, kinematic fitting will be used to place more robust cuts on the Ξ_5^{--} decay chain. Specifically, a fitting routine will be used to simultaneously reconstruct the location of the vertex and the momentum of the decaying particles by taking into account the errors on the track measurements. Confidence level cuts on the fits provide a systematic method of rejecting a large amount of the background while preserving an understood majority of the true events. The details for the analysis and procedure of kinematic fitting are discussed in Chapter 4. Thus, the eg3 experiment will search for the Ξ_5^{--} pentaquark by kinematic fitting its fully-charged decay chain.

Chapter 3

CEBAF and CLAS

The Continuous Electron Beam Accelerator Facility (CEBAF) at Jefferson Lab is capable of providing an electron beam to each of its three detectors at energies up to 6 GeV. The CEBAF Large Acceptance Spectrometer (CLAS) in Hall B is used to study nuclear and hadronic interactions induced by both photon and electron beams. In order to study these interactions, CLAS has been designed to efficiently detect both neutral and charged particles over a large portion of the solid angle.

The large angular acceptance and high luminosity capability of this detector make it well suited for evaluating medium-energy reactions with many-particle final states. CEBAF and CLAS form an ideal environment for investigating the complex decay chains of pentaquarks and excited cascade states in the eg3 experiment.

3.1 The CEBAF Accelerator

The superconducting radio frequency (RF) Continuous Electron Beam Accelerator Facility at Jefferson Lab is an underground, racetrack shaped electron accelerator capable of producing a continuous wave electron beam up to nearly 6 GeV in energy. Beam supplied to detector Halls A and C can range between 1 and 200 μA , and between 1 and 100 nA in Hall-B [42]. The accelerator is illustrated in Figure 3.1.

Electrons are initially produced at an energy of 100 keV using three independent RF-gain-switched lasers directed at a photocathode. The three resultant electron beams are each produced at 499 MHz with a relative 120° phase. These bunches are then interlaced into a 1497 MHz beam, accelerated in two cryomodules up to 45

Figure 3.1 The Jefferson Lab CEBAF Accelerator [43].

MeV, and injected into the accelerator. Each of the two linear accelerators, shown in Figure 3.1, incorporate 160 accelerating cavities and nominally provide 400 MeV of energy to the electrons as they circulate the accelerator. The electrons can circulate the accelerator up to six times, attaining a maximum energy of nearly 6 GeV. Phased RF deflecting cavities are used to separate the electron bunches into the three detector halls, including the CEBAF Large Acceptance Spectrometer (CLAS) in Hall-B. For the eg3 experiment, the accelerator provided a 30 nA, 5.75 GeV electron beam, resulting in a narrow bunch of about 375 electrons every 2 ns [42].

3.2 The CLAS Detector

The Hall B CLAS detector provides efficient detection of particles over a large fraction of the full solid angle. Fast data acquisition and triggering rates allow experiments to typically achieve luminosities on the order of 10^{34} nucleons $\text{cm}^{-2} \text{s}^{-1}$ [43]. The CLAS target can be changed for different experiments and is ordinarily filled with either liquid hydrogen or liquid deuterium.

For the eg3 experiment, a photon beam was produced from the accelerator electrons with the bremsstrahlung photon tagger. Surrounding the target, the start counter was used to match each physics event to the correct photon bunch. Charged particles produced in the target are bent by a toroidal magnetic field and are tracked in the drift chambers. The time-of-flight (TOF) scintillator paddles and photomultiplier tubes (PMTs) provide track timing information. At the forward angles, Cherenkov counters help with charged particle identification and the electromagnetic calorimeters detect neutral particles.

3.2.1 The Torus Magnet

The detector itself is designed around six superconducting coils that produce an azimuthal magnetic field surrounding the beam line. This field bends charged particles through the detector's drift chambers for momentum measurements. As seen in Figure 3.2, the magnetic field from the superconducting torus coils is negligible in the region near the beam line, allowing for the use of polarized targets. The coils are approximately five meters in length, producing a field five meters in diameter. At the maximum coil current of 3860 A the integral magnetic field reaches $2.5 \text{ T} \cdot \text{m}$ in the forward region, dropping to $0.6 \text{ T} \cdot \text{m}$ at a 90° scattering angle [43]. All non-active parts of the detector, such as the Cherenkov counter, photomultiplier tubes, and the drift chamber support structure are confined to the shadow of the torus coils to provide maximum angular resolution.

Figure 3.2 (A) Magnetic field strength in the plane between two of the torus coils. The concentration of violet lines is the projection of one of the coils onto the midplane. (B) Magnetic field vectors in the cross section of CLAS perpendicular to the beam line. The location of the six torus coils are shown in violet for reference [43].

3.2.2 The Drift Chambers

The six superconducting coils split the detector into six separate tracking sectors. In each sector the drift chambers are divided into three regions, each a different distance from the beam line. The chambers span from 8° to 145° in polar angle from the beam line while covering 80% of the azimuthal range. Figure 3.3 illustrates the curved shape and location of the drift chamber regions within the CLAS detector.

In the drift chambers, wire layers are arranged such that the wires form a hexagonal pattern. In this arrangement there are six field wires surrounding each sense wire, as shown in Figure 3.4. For each region of the drift chambers, the wires are grouped into two superlayers, each consisting of six wire layers. The only exception is the second superlayer of Region 1, which consists of only four wire layers due to space constraints. The wires within the first superlayer of each region are aligned

Figure 3.3 (A) Cross section of the CLAS detector along the beam line. Typical charged particle tracks are shown with corresponding hits in the detector equipment. The Torus Magnet is outlined by the dotted line surrounding the Region 2 Drift Chambers. The Cherenkov counters (CC), time-of-flight scintillators (TOF), and electromagnetic calorimeters (EC) are also illustrated. (B) Cross section of the CLAS Detector perpendicular to the beam line. The mini-torus shown in the middle is only used for electron runs. [43]

perpendicular to the magnetic field's bend plane in order to best measure the track curvature. The second superlayer for each region is rotated by a 6° stereo angle with respect to the first in order to provide azimuthal tracking information [43].

To detect the passage of a charged particle through the drift chambers, a strong electric field is created between the field and sense wires of the drift chamber. A gas mixture of 90% argon and 10% CO_2 fills the drift chambers and ionizes when a charged particle passes through. With the field and sense wires kept at average potentials of -680 V and 1360 V respectively, the electrons freed during ionization drift through the gas and are detected by the sense wires. With this gas mixture multiple scattering and flammability concerns are minimized while simultaneously allowing a fairly high saturated drift velocity of $4 \text{ cm}/\mu\text{s}$ or greater. The distance between the path of the charged particle and the sense wires is determined by comparing the sense time and

Figure 3.4 The two superlayers of the Region 3 drift chambers. The highlighted cells indicate where a sense wire has fired, one in the center of each of the hexagonal cells of field wires [43].

drift velocity to the timing information from the time-of-flight scintillators [43].

The design of the drift chambers provides fine track resolution in CLAS. The hexagonal cells of wires have an average spatial resolution of 200–250 μm . With 10–12 wire layers per region, particles are tracked within a region at resolutions of 100 μm in the bend plane of the torus field and 1 mm in the azimuth. Overall, charged particles produced at a momentum of 1 GeV/c are measured with a momentum resolution of $\delta p/p \leq 0.5\%$ and at angular resolutions $\delta\theta$, $\delta\phi$ near 2 mrad [44].

3.2.3 The Time-of-Flight Scintillators

After passing through the drift chambers, particles hit the time-of-flight scintillator paddles. These plastic scintillators span the same solid angle as the drift chambers, between 8° and 142° in polar angle, and nearly the full range of the azimuthal angle. For each sector of the detector there are 57 scintillators, each of which is approximately 5 cm thick [43]. The paddles at the detector’s forward angles are 15 cm wide and those at the large angles are 22 cm wide. The paddles vary in length across the

azimuth of the detector.

When a particle passes through a scintillator it ionizes the material, which in turn radiates photons. Some of these photons are internally reflected down the length of the scintillator, through the light guides, and into the PMTs at each end of the paddle. The PMTs have diameters of either 2 or 3 in and provide a timing resolution of roughly 150 ps, depending on the length of the scintillators [43]. The TOF counters provide timing information that is used both for charged particle identification and tracking in the drift chambers.

3.2.4 The Bremsstrahlung Photon Tagger

The photon beam used in the eg3 experiment is generated from the accelerator's electron beam. When in use, the electron beam strikes a thin radiator and then passes through a magnetic spectrometer known as the tagger. Bremsstrahlung photons produced in the radiator continue down the beam line towards CLAS, whereas electrons are deflected by the magnetic field in the tagger. 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 [45].

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 for determining the radiated photon's energy, and the

Figure 3.5 The Hall-B photon tagger. Typical electron trajectories and shown for different transfers of fractional energies to the photon [45].

T-counters for determining its time of flight.

The E-counters consist of 384 partially-overlapping scintillators, each 20 cm long and 4 mm thick, providing 767 channels for energy measurement. The widths of these counters vary from 6 to 18 mm such that each spans a constant energy interval of $0.003E_0$. 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 $0.001E_0$ [45].

The T-counters consist of 61 scintillator paddles, each 2 cm thick, which provide a timing resolution of 110 ps [45]. The first 19 paddles correspond to photon energies of $0.75E_0$ 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 high energies. Within each group, the T-counters vary in width to maintain the same counting rate in each paddle to account for the $1/E_\gamma$ energy

distribution of the bremsstrahlung photons.

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 Ξ_5 photoproduction. At energies of 4.5 GeV and higher the electron-photon matching in the tagger was excellent due to the narrow T-counters, despite the high number of deflected electrons. Since the predicted Ξ_5 photoproduction thresholds are near 4 GeV, eg3 was able to successfully run with a high photon flux, yielding an effective luminosity of 2×10^{34} nucleons $\text{cm}^{-2} \text{s}^{-1}$.

3.2.5 The Start Counter

In order to obtain correct timing information during a photon run, an event in CLAS has to be matched with the corresponding photon produced in the tagger. In order to do this, the start counter surrounding the target measures the time at which tracks pass through it. The TOF of these tracks is compared to those of the photons in the tagger in order to select the correct 2 ns bunch from the accelerator. This bunched structure of the beam is clearly seen in Figure 3.6 where the electrons, with a 50 ps resolution in the beam, are matched with the 110 ps resolution T-counter hits. Once the correct photon bunch is determined, the photon within the bunch matching the detected event is selected by comparing the time of the photons from the accelerator to the particle times from the TOF scintillators, projecting both to the reconstructed interaction vertex in the target.

The start counter is a collection of 24 single-ended scintillation paddles in a hexagonal orientation surrounding the target, as seen in Figure 3.7. There are four 29 mm

Figure 3.6 Time difference between the RF signal from the accelerator and the T-counters in the tagger, accounting for the electron propagation and cable times. The start counter is used to determine which photon bunch matches the detected event in CLAS [45].

wide paddles on each side of the counter, each only 2.2 mm thick in order to minimize multiple scattering. The start counter can enclose targets up to 40 cm in length, covering the polar angle range $7^\circ \leq \theta \leq 145^\circ$ and nearly the entire azimuth, the same solid angle as the TOF scintillators. The start counter is unnecessary for electron beam experiments and is thus removed [46].

3.2.6 The Cherenkov Counters and Electromagnetic Calorimeters

The Cherenkov counters in the CLAS detector are located after the drift chambers but before the TOF scintillators, as shown in Figure 3.3. They are divided among the sectors of the detector into 216 light collection modules, and cover the forward 45° of the detector. Figure 3.8 is a schematic of one of the counters, and illustrates how Cherenkov radiation is collected by the light cones. These light cones and PMTs are located behind the torus magnetic coils where they will not obstruct particles passing through the detector. The thin counters are designed to provide a high photon

Figure 3.7 The CLAS start counter surrounding the target cell [46].

Figure 3.8 A diagram of one of the Cherenkov counters spanning a sector in CLAS. An electron track and its subsequent radiation is shown being reflected into the light cone and detected by the PMT [43].

yield and a pion momentum threshold of 2.5 GeV/c. The Cherenkov counters provide excellent pion and electron differentiation while minimally degrading the energy resolution [43].

The CLAS detector has electromagnetic calorimeters at both forward and large angles. The calorimeters are used to detect both neutrons and the photons from π^0 and η decays. They are located between drift chambers and the TOF scintillator

paddles, and the forward region extends back to 45° . These forward angle calorimeters are made up of 39 alternating layers of scintillators and lead sheets with a total thickness of 16 radiation lengths. The energy of the tracks passing through the calorimeters is determined by using the scintillator paddles to detect the radiated energy lost in the lead sheets. Successive layers of scintillators are rotated 120° with respect to each other, providing more accurate information on the track position within the calorimeter.

Two of the six sectors of CLAS have large angle calorimeters, each extending back to 75° . Their setup is similar to the forward angle calorimeters, but with only 33 layers and a total thickness of 12.9 radiation lengths. The energy resolutions of the forward and large angle calorimeters are, respectively, [43]

$$\frac{\sigma}{E} = \frac{10.3\%}{\sqrt{E \text{ (GeV)}}}, \quad \frac{\sigma}{E} = \frac{(7.5 \pm 0.2)\%}{\sqrt{E \text{ (GeV)}}}. \quad (3.1)$$

The electromagnetic calorimeters are unable to provide detailed tracking information for neutral particles. This fact, along with the superior solid angle coverage of the drift chambers, results in charged particles being detected at a much better resolution than neutral particles.

3.3 Data Acquisition Triggering in eg3

Event triggering for the data acquisition (DAQ) system is an essential attribute for every experiment in the CLAS detector. With an overall maximum DAQ rate of only several kHz, only a small fraction of the physics events in the detector can be recorded. Triggering on the signals from the different detector equipment is used to

allow physics events of interest to be selected for recording.

There are two stages at which DAQ triggering occurs; the Level 1 trigger acts on the prompt signals from the fast electronics of the various detector components, and the Level 2 trigger acts on the slower track reconstruction in the drift chambers. For the eg3 experiment, two different Level 1 triggers were used to record separate types of events. The first Level 1 trigger was set to record a scaled fraction of the events where there was a coincidence between the start counter (ST) and TOF scintillators in at least two of the sectors, represented as $(ST \times TOF)^2$. This was used to supplement future normalization studies. However, the primary Level 1 trigger was set to record all events that satisfied

$$(ST \times TOF) \times (ST^2 \times TOF) + (ST \times TOF)^3. \quad (3.2)$$

In other words, events were recorded that had three different coincidences between the start counter and the TOF, whether they occurred in two or three separate sectors of the detector. In addition, both Level 1 triggers required that a tagged photon be detected between T-counters 1 and 19, the range of the tagger with the best timing resolution. For the 5.75 GeV beam used in eg3, this corresponds to photons between energies of 4.5 and 5.5 GeV, the energy range of interest for Ξ_5 production. Finally, the Level 2 trigger required the reconstruction of at least three charged tracks in the drift chambers for any event to be accepted and written to the data farm for future analysis.

The tagged photon beam was chosen for a number of reasons, most importantly because the additional triggering on the tagger and start counter allowed for a higher

beam flux and effective luminosity than that of the electron beam. Additionally, during tests with an electron beam there was significantly more activity in the drift chambers, with drift chamber occupancies several times larger than with a photon beam at the same design luminosity of 2×10^{34} nucleons $\text{cm}^{-2} \text{s}^{-1}$. With a 30 nA current and a 5×10^{-4} radiation length gold radiator, this trigger setup allowed the eg3 experiment to record physics events at 4 kHz, nearly the maximum DAQ rate.

Chapter 4

Least Squares Kinematic Fitting

In general, kinematic fitting is used to test the hypothesis that a set of measurements represent a given physics reaction. The fit is a least squares error minimization of the track measurements that must satisfy the specified constraint equations, namely that the tracks have a common vertex and observe four-momentum conservation. In other words, if the system is overdetermined, the track parameters may be fit such that they abide these constraints while minimizing the deviation from their measured values relative to their uncertainties. Because track measurements are Gaussian distributed about their true values, the fit errors from a large data sample follow a χ^2 distribution corresponding to the number of degrees of freedom in the fit. This distribution can be translated into a confidence level of the fit, which can then be cut on to extract signals from the background.

4.1 Lagrangian Multipliers Formalism

The following discussion on Lagrangian multipliers originated from work by Brandt [47] and by Williams [48]. In a general system with vectors of N observables $\mathbf{y}$ and J unknowns $\mathbf{x}$, the Lagrangian multipliers fitting method is used in order to treat all of the parameters equally. The measurements of a system $\boldsymbol{\eta}$ are normally distributed about their true values $\mathbf{y}$ with known error $\boldsymbol{\epsilon}$ such that

$$\mathbf{y} = \boldsymbol{\eta} - \boldsymbol{\epsilon}. \tag{4.1}$$

The errors $\boldsymbol{\epsilon}$ on the measurements $\boldsymbol{\eta}$ are normally distributed by $\boldsymbol{\sigma}_\eta$. These errors,

along with the symmetric matrix ρ of the correlations between the measurements, are stored in the covariance matrix C_η such that the matrix elements are

$$C_{\mu\nu} = \sigma_\mu \rho_{\mu\nu} \sigma_\nu. \quad (4.2)$$

To test a given hypothesis, the vector of K constraint equations $\mathbf{f}(\mathbf{x}, \mathbf{y}) = \mathbf{0}$ is applied to the system. For example, to test whether an event satisfies the decay $\Lambda \rightarrow p\pi^-$, the energy and momentum of the system must be conserved and the p and π^- tracks must have a common vertex ($\mathbf{V}_C$). Specifically,

$$\mathbf{f}(\mathbf{x}, \mathbf{y}) = \begin{pmatrix} E_\Lambda - E_p - E_{\pi^-} \\ \mathbf{p}_\Lambda - \mathbf{p}_p - \mathbf{p}_{\pi^-} \\ (\mathbf{V}_C - \mathbf{V}_p) \times \mathbf{p}_p \\ (\mathbf{V}_C - \mathbf{V}_{\pi^-}) \times \mathbf{p}_{\pi^-} \end{pmatrix} = \mathbf{0}. \quad (4.3)$$

In this case $K = 8$, as only two equations are needed for each cross-product. The third cross-product equation is redundant because it may be derived from the other two.

For constraint equations that are non-linear in the parameters $\mathbf{x}$ and $\mathbf{y}$ an iterative process is used. Before kinematic fitting, first approximations of the unknowns $\mathbf{x}_0$ and the observables $\mathbf{y}_0$ of the system are needed. For the first iteration, one chooses $\mathbf{y}_0 = \boldsymbol{\eta}$ and suitable values for $\mathbf{x}_0$ that correspond to the system. In the above example $\mathbf{x}_0$ would consist of a vertex guess near the two tracks and the p , π^- missing four-momentum for the Λ . For the ν -th iteration, the constraint equations $\mathbf{f}(\mathbf{x}, \mathbf{y}) = \mathbf{0}$ may be Taylor-expanded about $(\mathbf{x}_\nu, \mathbf{y}_\nu)$ to first order, giving

$$f_k(\mathbf{x}_\nu, \mathbf{y}_\nu) + \sum_{j=1}^J \left[\left(\frac{\partial \mathbf{f}_k}{\partial \mathbf{x}_j} \right) \Big|_{\mathbf{x}_\nu, \mathbf{y}_\nu} (\mathbf{x}_{j\nu+1} - \mathbf{x}_{j\nu}) \right] + \sum_{n=1}^N \left[\left(\frac{\partial \mathbf{f}_k}{\partial \mathbf{y}_n} \right) \Big|_{\mathbf{x}_\nu, \mathbf{y}_\nu} (\mathbf{y}_{n\nu+1} - \mathbf{y}_{n\nu}) \right] = 0. \quad (4.4)$$

The above may be written in a less unwieldy format by introducing definitions for the matrices

$$A = a_k^j = \left(\frac{\partial f_k}{\partial x_j} \right) \Big|_{\mathbf{x}_\nu, \mathbf{y}_\nu}, \quad B = b_k^n = \left(\frac{\partial f_k}{\partial y_n} \right) \Big|_{\mathbf{x}_\nu, \mathbf{y}_\nu} \quad (4.5)$$

and for the vectors,

$$\mathbf{c} = \mathbf{f}(\mathbf{x}_\nu, \mathbf{y}_\nu), \quad \boldsymbol{\xi} = \mathbf{x}_{\nu+1} - \mathbf{x}_\nu, \quad \boldsymbol{\delta} = \mathbf{y}_{\nu+1} - \mathbf{y}_\nu. \quad (4.6)$$

Then the Taylor expansion of the constraint equations becomes simply

$$A\boldsymbol{\xi} + B\boldsymbol{\delta} + \mathbf{c} = \mathbf{0}. \quad (4.7)$$

A least squares fit has converged when the weighted sum of squares of the differences between two approximations for the fit parameters is a minimum. In other words, the quantity $\boldsymbol{\delta}^T C_\eta^{-1} \boldsymbol{\delta}$ is minimized. Thus we construct the Lagrangian

$$L = \boldsymbol{\delta}^T C_\eta^{-1} \boldsymbol{\delta} + 2\boldsymbol{\mu}^T (A\boldsymbol{\xi} + B\boldsymbol{\delta} + \mathbf{c}), \quad (4.8)$$

where the constraint equations are scaled by $\boldsymbol{\mu}$, the unknown vector of K Lagrangian multipliers. To minimize the Lagrangian, its derivatives with respect to all unknowns are set equal to zero:

$$\frac{\partial L}{\partial \boldsymbol{\delta}} = 2C_\eta^{-1}\boldsymbol{\delta} + 2B^T\boldsymbol{\mu} = \mathbf{0} \quad (4.9)$$

$$\frac{\partial L}{\partial \boldsymbol{\mu}} = 2(A\boldsymbol{\xi} + B\boldsymbol{\delta} + \mathbf{c}) = \mathbf{0} \quad (4.10)$$

$$\frac{\partial L}{\partial \boldsymbol{\xi}} = 2\boldsymbol{\mu}^T A = \mathbf{0}. \quad (4.11)$$

Solving this system of equations gives

$$\boldsymbol{\xi} = -(A^T C_B A)^{-1} A^T C_B \mathbf{c}, \quad (4.12)$$

$$\boldsymbol{\mu} = C_B(\mathbf{c} - A(A^T C_B A)^{-1} A^T C_B \mathbf{c}), \quad (4.13)$$

$$\boldsymbol{\delta} = -C_\eta B^T C_B(\mathbf{c} - A(A^T C_B A)^{-1} A^T C_B \mathbf{c}), \quad (4.14)$$

where $C_B = (BC_\eta B^T)^{-1}$.

Thus the fit values of the unknowns $\mathbf{x}$ and observables $\mathbf{y}$ for the ν -th iteration are

$$\mathbf{x}_{\nu+1} = \mathbf{x}_\nu + \boldsymbol{\xi}, \quad \mathbf{y}_{\nu+1} = \mathbf{y}_\nu + \boldsymbol{\delta}. \quad (4.15)$$

This process is repeated until the fit parameters have converged satisfactorily. Once solutions for $\mathbf{x}$ and $\mathbf{y}$ have been fit, the covariance matrices for these parameters may be calculated via the propagation of errors. For the unknown parameters $\mathbf{x}$,

$$C_x = \left(\frac{\partial \mathbf{x}}{\partial \boldsymbol{\eta}} \right) C_\eta \left(\frac{\partial \mathbf{x}}{\partial \boldsymbol{\eta}} \right)^T = (A^T C_B A)^{-1}. \quad (4.16)$$

Similarly, for the observables $\mathbf{y}$,

$$C_y = \left(\frac{\partial \mathbf{y}}{\partial \boldsymbol{\eta}} \right) C_\eta \left(\frac{\partial \mathbf{y}}{\partial \boldsymbol{\eta}} \right)^T = C_\eta - C_\eta B^T C_B B C_\eta + C_\eta B^T C_B A C_x A^T C_B B C_\eta. \quad (4.17)$$

Therefore, in a kinematic fit of a physics event, the observed particles become correlated with one another as their errors are no longer separable. However, in the case of the decay $\Lambda \rightarrow p\pi^-$, the errors on the unknown Λ particle $C_\Lambda = C_x$ are self-contained and may be propagated to evaluate the next stage of the event evaluation, such as reconstructing $\Xi^- \rightarrow \Lambda\pi^-$.

4.2 Interpreting Kinematic Fitting Results

The following discussion on the results from kinematic fitting originated from work by Williams [48] and by Frodesen, Skjeggstad, and Tofte [49]. The χ^2 of a kinematic fit is the weighted sum of the errors of the fit,

$$\chi^2 = \boldsymbol{\epsilon}^T C_\eta^{-1} \boldsymbol{\epsilon}. \quad (4.18)$$

For a large sample of events, χ^2 has a probability density function

$$f(\chi^2, n) = \frac{(\chi^2)^{\frac{n}{2}-1} e^{-\frac{\chi^2}{2}}}{2^{\frac{n}{2}} \Gamma(\frac{n}{2})}, \quad (4.19)$$

also known as the χ^2 distribution function with n degrees of freedom. For a kinematic fit with K constraints and J unknowns, the degrees of freedom $n = K - J$, which is known as an nC fit.

Figure 4.1 The χ^2 distribution function as a function of χ^2 , shown for different degrees of freedom n [50].

The weighted sum of the errors, χ^2 , has a known probability distribution and can be used as a measure of how well the measurements fit the constraints. The confidence level of the fit is its integral

$$CL = \int_{\chi^2}^{\infty} f(u, n) du \quad (4.20)$$

and corresponds to the probability of obtaining a larger χ^2 for the same system and similar measurements. For a large sampling of true events, the normally distributed parameters yield a confidence level that is uniformly flat between 0 and 1. If there are background events in the data sample, these will be evidenced as a steep rise near zero confidence. However, if there is an overall overestimation in the errors of the track parameters, the confidence level distribution will not be flat but will rise as it gets closer to 1, indicating a systematic overconfidence in the fitting. The opposite

Figure 4.2 A sample confidence level distribution. The large spike near zero confidence corresponds to background events.

is true of an underestimation of the errors. A sample confidence level distribution is illustrated in Figure 4.2.

While a large χ^2 may indicate a false event, it is also possible that the fit was skewed by one or several bad parameters in the fit. The affect that the individual parameters have on the fit may be examined with the pull distributions. The pulls of the observables are defined as

$$z_j = \frac{\epsilon_j}{\sigma_{\epsilon_j}}, \quad (4.21)$$

and thus show the deviation between the measured and the fit observables, normalized by the uncertainty in the deviation. As $\epsilon = \eta - \mathbf{y}$ and the η and $\mathbf{y}$ parameters are fully correlated,

$$z_j = \frac{\eta_j - y_j}{\sqrt{\sigma_{\eta_j}^2 - \sigma_{y_j}^2}}. \quad (4.22)$$

In a normally distributed sample of entirely true events, the pulls should be Gaussian distributed with mean zero and $\sigma = 1$. If the center of a pull is shifted away from zero then there is a systematic error in η_j . If the width of a pull is either too narrow or too wide then σ_{η_j} has been either overestimated or underestimated, respectively. If such biases are found then the measurables η_j and their errors need to be calibrated before any cuts may be placed on the confidence level of the fit.

In practice, it is usually not possible to find a complete sample of true events to study the pulls. However other cuts, such as invariant mass or track time, may be placed on the system to come sufficiently close. Once the pulls are distributed correctly, the confidence level of the system will be flat, with a sharp rise near zero for the background events. Thus, cutting out events with low confidence level from a kinematic fit is an excellent way of removing the background events while losing only a quantifiable minority of true events.

4.3 The *decaychain* Software Package

The least squares kinematic fitting procedure discussed in this chapter has been implemented in the CLAS *decaychain* package. The package's data classes *DecayParticle*, *DecayStep*, *DecayChain*, and *DecayEvent* are structured to store all pertinent track and fitting information for an event. The executables *DecayRun* and *DecayHistogram* are used for performing and studying the kinematic fits. There are many other programs and macros included that provide support for data analysis, includ-

ing fitting and performing track corrections and cutting on data produced in the DecayEvent format.

The kinematic fitting routine in the *DecayFit.C* file is capable of applying, separately or simultaneously, vertex and four-momentum conservation constraints on any particle reaction. It may be used either to fit a system with all of the tracks present or to reconstruct a track that decays or is missing. During any kinematic fit, the user may choose to treat any parameter or track as missing, even if it was measured. By studying an exclusive reaction, this feature may be used to perform an unbiased comparison between a parameter's fit and detected values. This feature is essential for investigating errors in track measurement.

Before kinematic fitting, the *DecayRun* program in the *decaychain* package imports all track and photon information via *DecayBOS.C* into separate instances of the DecayParticle class. It then constructs DecaySteps for each particle interaction the user wishes to evaluate, and stores them in a DecayChain. Next, *DecayEvaluate.C* loops over all of the tracks that were detected in the event, creating a new DecayChain for each possible combination, and filling them with those particular DecayParticles. The unused tracks are saved in the DecayChains, and all of the DecayChains are stored in a single DecayEvent. Then kinematic fitting is performed in *DecayFit.C* on the DecaySteps, and those DecayChains that fail the user-defined cuts are discarded. The included *DecayHistogram* program can be used to study the results of the fits.

Other support files include *DecayTarget.C* which contains the CLAS geometry information for performing energy loss and covariance matrix corrections and *DecayInformation.C* which contains the charge and mass of many different particles.

Also, *DecayTrackCorrections.C* and *DecayFiducialCuts.C* contain the specific track corrections and fiducial cuts used for each experimental group. Finally, *DecayCutFunctions.C* and *DecayTrackFunctions.C* contain useful functions that are easily accessible.

Chapter 5

Tracking in CLAS

Before studying physics events with kinematic fitting, a brief introduction is given on track reconstruction in the CLAS detector. The measured track parameters and their coordinate system are defined in relation to the standard lab coordinates. Also, the track measurement errors and their sources are examined to determine if they are reasonable for fitting.

5.1 CLAS Coordinate Systems

There are two coordinate systems in CLAS, the sector coordinate system and the lab coordinate system. These two coordinate systems are illustrated in Figure 5.1. The lab coordinate system is defined with the z_{lab} axis collinear with the beam line, the y_{lab} axis as pointing from the floor to the roof of the detector hall, and the x_{lab} axis pointing from the center of CLAS through the middle of Sector 1, parallel to the floor. Additionally, the angle θ_{lab} is defined as the polar angle from the beam line, and ϕ_{lab} is defined as the azimuthal angle from the x_{lab} axis.

However, as the CLAS drift chambers are divided into six separate sectors, tracks are reconstructed in the sector coordinate system. For any given sector, the x_{trk} axis is in the direction of the beam line, the y_{trk} axis points from the center of CLAS through the middle of the sector, and the z_{trk} axis is defined as being in the plane normal to x_{trk} , right-hand rotated 90° clockwise from the y_{trk} axis. The coordinate systems are rotated with respect to each other by a sector dependent angle α , where

Figure 5.1 (A) A cross section of the CLAS detector and its coordinate systems perpendicular to the beam line. The beam line goes into the page, and the sector coordinate system is shown for Sector 3. (B) A cross section of the detector and its coordinate systems along the beam line, through the center of Sectors 1 and 4. The sector coordinate axes are shown for Sector 1. In both plots, the blue lines indicate the path of a charged particle through the detector, and its tracking parameters are illustrated in red [43].

$$\alpha = \frac{\pi}{3}(N_{sector} - 1). \quad (5.1)$$

Thus, to convert from the sector coordinates to lab coordinates,

$$\begin{pmatrix} x_{lab} \\ y_{lab} \\ z_{lab} \end{pmatrix} = \begin{pmatrix} y_{trk} \cos(\alpha) - z_{trk} \sin(\alpha) \\ y_{trk} \sin(\alpha) + z_{trk} \cos(\alpha) \\ x_{trk} \end{pmatrix}. \quad (5.2)$$

Particle tracks are defined by a system of five parameters: q/p , λ_{trk} , ϕ_{trk} , D_0 , and Z_0 . The ratio q/p is the charge of the track divided by its momentum. λ_{trk} is defined as the angle between the track and the sector's x_{trk} - y_{trk} plane, and ϕ_{trk} is defined as the angle in the sector's x_{trk} - y_{trk} plane between the track and the beam line. Note that as they are defined in the same plane, λ_{trk} is essentially a sector-normalized version of ϕ_{lab} . D_0 is the distance of closest approach from the track to the line defined by $x_{trk} = 0$, $y_{trk} = 0$ and Z_0 is the z_{trk} coordinate of the track when

$y_{trk} = 0$. These parameters are illustrated in Figure 5.1. Thus, to convert from the tracking parameters to lab coordinates [48],

$$\begin{pmatrix} p_{x_{lab}} \\ p_{y_{lab}} \\ p_{z_{lab}} \\ x_{lab} \\ y_{lab} \\ z_{lab} \end{pmatrix} = \begin{pmatrix} p(\cos(\lambda_{trk}) \sin(\phi_{trk}) \cos(\alpha) - \sin(\lambda_{trk}) \sin(\alpha)) \\ p(\cos(\lambda_{trk}) \sin(\phi_{trk}) \sin(\alpha) + \sin(\lambda_{trk}) \cos(\alpha)) \\ p \cos(\lambda_{trk}) \cos(\phi_{trk}) \\ -Z_0 \sin(\alpha) \\ Z_0 \cos(\alpha) \\ -D_0 / \sin(\phi_{trk}) \end{pmatrix}. \quad (5.3)$$

And to convert from lab coordinates back to tracking parameters,

$$\begin{pmatrix} \lambda \\ \phi \\ D_0 \\ Z_0 \end{pmatrix} = \begin{pmatrix} \sin^{-1}((p_y \cos(\alpha) - p_x \sin(\alpha))/p) \\ \tan^{-1}((p_x \cos(\alpha) + p_y \sin(\alpha))/p_z) \\ (x \cos(\alpha) + y \sin(\alpha)) \cos(\phi_{trk}) - z \sin(\alpha) \\ y \cos(\alpha) - x \sin(\alpha) - (x \cos(\alpha) + y \sin(\alpha)) \tan(\lambda_{trk}) / \sin(\phi_{trk}) \end{pmatrix} \quad (5.4)$$

where x , y , and z are in the lab coordinate system and the self-explanatory q/p term has been omitted. As the particles in an event may be detected in multiple sectors of CLAS, the lab coordinate system is used during kinematic fitting. Equation 5.3 is used to describe the kinematic fitting constraints in terms of the track measurements and their errors.

5.2 Track Reconstruction and Errors

To reconstruct charged particle tracks, the tracking software fits the hits registered on the drift chamber sense wires to a curved path through all three regions of the drift chamber. The particle charge and momentum are determined from the radius of curvature of the track through the magnetic field. Tracks that are not adequately fit through at least four of the six chamber superlayers are discarded as background.

These are generally caused by either dead, misfiring, or mis-strung wires in the drift chamber, or by noise from cosmic rays. The track direction and location are determined primarily from hits in Region 1, prior to where the track encounters the full strength of the magnetic field. The track is then projected in a straight line path back towards the target to study physics events.

The identity of the detected particle is determined from its momentum and timing measurements. The squared mass of a relativistic particle is related to its momentum and velocity by

$$m^2 = \frac{p^2}{\beta^2}(1 - \beta^2). \quad (5.5)$$

The distribution of β^2 versus p of all detected charged particles is shown in Figure 5.2. The CLAS *seb* software package places cuts on this distribution for particle identification. The pion and proton bands are clearly visible in red, but there is no clear band to identify as kaons. This is primarily due to the fact that kaons have non-zero strangeness, and thus are produced at a significantly lower probability than pions. Thus, often kaons are misidentified as either protons or pions, introducing additional backgrounds to the system.

It is critical for kinematic fitting to have an accurate covariance matrix, so it is important to check that the measured uncertainties are on par with those predicted by the detector's design specifications. Tracking errors are due to a number of factors such as deviations in the uniformity of the magnetic field, the spacing and alignment of the drift chamber wires, and the number of sense wire hits registered for the track.

Figure 5.2 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. Particle identification cuts are placed on this distribution by the *seb* software package. The kaons lie between these two regions with no clear edges upon which to place identification cuts.

Secondary effects include energy loss and multiple scattering while traversing the drift chambers, misaligned wires, and rotations or displacements of the drift chamber regions with respect to each other or the beam line. Finally, tracking errors will occur if a particle decays while traversing the drift chambers.

Firstly, it is more convenient to perform kinematic fits using the parameter p instead of q/p . Using the vector $\boldsymbol{\eta}$ defined as the tracking parameters q/p , λ_{trk} , ϕ_{trk} , D_0 , and Z_0 , and the vector $\boldsymbol{\eta}' = \boldsymbol{\eta}$ except $\eta'_0 = p$, the conversion is simply

$$C'_{\eta} = \left(\frac{\partial \boldsymbol{\eta}'}{\partial \boldsymbol{\eta}} \right) C_{\eta} \left(\frac{\partial \boldsymbol{\eta}'}{\partial \boldsymbol{\eta}} \right)^T, \quad \frac{\partial \boldsymbol{\eta}'}{\partial \boldsymbol{\eta}} = \begin{pmatrix} -p^2/q & 0 & \cdots & 0 \\ 0 & 1 & & \\ \vdots & & \ddots & \\ 0 & & & 1 \end{pmatrix}. \quad (5.6)$$

The more a track bends as it traverses the drift chambers, the better its momentum

Figure 5.3 The momentum uncertainty σ_p of the proton as a function of p in two different angle ranges. The streak of large uncertainty at low momentum is due to a lack of tracking in one or more superlayers. Otherwise, σ_p is largest for fast tracks produced at large angles.

resolution. Therefore, it is expected that the uncertainty in momentum increases with momentum, and decreases with increasing magnetic field strength. While the magnetic field is generally constant with ϕ_{lab} , it decreases with increasing θ_{lab} . As seen in Figure 5.3, the momentum uncertainty σ_p of the proton increases with momentum and θ_{lab} , with magnitude within the design goal of $\delta p/p \leq 0.5\%$.

The uncertainties in the angles λ_{trk} and ϕ_{trk} are primarily dependent on the wire spacing in their respective directions, but also by magnetic field non-uniformities. As mentioned in Section 3.2.2, the CLAS drift chambers were designed to measure tracks to an accuracy of $100 \mu\text{m}$ in the ϕ_{trk} direction and 1 mm in the λ_{trk} direction. The error in λ_{trk} is much larger than ϕ_{trk} because azimuthal tracking is only provided by the 6° rotation of the drift chamber superlayers with respect to each other. As seen in Figure 5.4, ϕ_{trk} is indeed determined more accurately than λ_{trk} by close to a factor of 10, and both angles are near the design resolution of 2 mrad [43].

Figure 5.4 For protons, the uncertainties in (A) λ_{trk} and (B) ϕ_{trk} . The small, secondary peak is due to tracks missing an entire superlayer of hit information.

However, for both angles there is a secondary but significant source of large uncertainty. This comes from particles that pass through holes in the drift chamber and thus have less tracking information on their parameters. Figure 5.5 shows the sense wire hits of particles that are successfully tracked in the Sector 6 drift chamber. Several holes are clearly visible, along with the limited range of the Region 1 superlayers. Some of the larger holes are probably due to cable swaps, causing the track fitting to fail in those regions. Also, holes in the Region 1 drift chamber are inaccessible for maintenance without first removing the outer drift chambers, a complicated procedure that is likely to produce more problems than those that result from the few holes that need to be fixed.

Figure 5.6 illustrates the drastic spike in uncertainty in the track angles as a function of the number of drift chamber wire layer hits. The abrupt change in error represents the lack of information from an entire superlayer of the drift chambers. This occurs primarily because the center of the eg3 target was located 50 cm upstream from

Figure 5.5 Sense wire hits for particles that survive track fitting in the Sector 6 drift chamber. The Region 1 superlayers, represented by wire layers 1-4 and 7-12, don't extend as far backwards as the other regions. Holes in the drift chambers due to dead wires are clearly visible throughout, especially in Region 2 between wire numbers 100 and 130.

the center of the detector, where some of the particles produced at large angles miss the Region 1 drift chambers. This phenomenon is observable in all of the measured track parameters.

The uncertainty in the track location is due not only to the resolution of the wires in the drift chamber, but to the uncertainty in the track angles and the distance from the target as well. By definition, D_0 is heavily correlated with ϕ_{trk} , and Z_0 with λ_{trk} . As seen in Figure 5.7, σ_{Z_0} is many times larger than σ_{D_0} . This is expected given that the drift chamber resolution in that direction is much worse than in the bend plane. Again, the secondary peaks are due to the lack of tracking information in the drift chambers, as illustrated in Figure 5.8.

Figure 5.6 The uncertainty on the proton (A) λ_{trk} and (B) ϕ_{trk} angles as a function of the number of wire layers hit in the drift chamber. The large jumps in uncertainty are from omitting superlayer information that yield bad track fits.

Figure 5.7 The uncertainty on the measurement of the proton track location parameters (A) D_0 and (B) Z_0 . These are highly correlated with the tracking angles, and the better resolution of ϕ_{trk} results in a more accurate measurement of D_0 .

The two separate spikes in σ_{Z_0} vary from sector to sector of the CLAS detector, and thus are probably due to holes in the wires of the drift chambers.

Figure 5.8 The uncertainty on the proton track position parameters (A) D_0 and (B) Z_0 as a function of the number of wire layers hit in the drift chamber. Again, the large increase in uncertainty is due to a lack of information from one or more superlayers.

Chapter 6

The $\gamma D \rightarrow pp\pi^-$ Calibration Reaction

In order to determine if there any corrections that need to be made to the track measurements or covariance matrices, a complete, isolated reaction was studied. All of the particles in the final state of this reaction were charged to ensure good track reconstruction. For a fully-charged final state during photoproduction on deuterium, the photon must strike the neutron and produce only charged particles. However, the proton in the deuterium is bound to the neutron, and the reaction is not kinematically complete if that proton is not detected. Thus, the simplest clean reaction in which both nucleons from the deuterium are detected is $\gamma D \rightarrow pp\pi^-$. Although the photon is striking the neutron to produce the π^- , often times the proton in the deuterium has a large enough momentum to be detected due to Fermi motion. By requiring momentum conservation and a common vertex for the particles in this reaction, kinematic fits were used to calibrate the covariance matrices and determine if any track measurement corrections were needed.

6.1 Standard Energy Corrections

Before analyzing physics events, the CLAS *eloss* software package performs an energy loss correction for charged particles. As charged particles pass through the various target and detector components, the mean energy loss is described by the Bethe-Bloch equation. The *eloss* package applies this correction separately for each of the different materials that the charged particle passes through. The momentum dependence of the total energy loss correction is shown in Figure 6.1 for both protons

Figure 6.1 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. This correction is derived from the Bethe-Bloch formula and performed in the CLAS *eloss* software package.

and π^- 's.

It has been found during past photon beam experiments that an energy correction must be applied to the photon energy from the tagger. This energy correction, shown in Figure 6.2, is required because there is a slight sag in the tagger scintillator paddles due to gravity. This results in a mismatch between the energy of the deflected electron and the scintillator paddle that it struck. This correction is simply an E-counter dependent multiplicative constant to the photon energy, and thus is scalable for all experiments and photon energies.

6.2 Event Selection

Several cuts were placed on the data in order to isolate the $\gamma D \rightarrow pp\pi^-$ reaction. The proton and π^- tracks were identified by the *seb* particle identification software package, as detailed in Section 5.2. In order to select the correct bremsstrahlung photon in the tagger, a time difference cut of $\Delta t_{\gamma\pi^-} < 1.0$ ns was used. This cut

Figure 6.2 The eg3 photon energy correction, as a function of energy, due to the gravitational sag in the tagger.

removes background events due to selecting photons from the wrong electron beam bunch in the tagger. The time differences between the tracks and the photon are shown in Figure 6.3. The track time of the π^- is more accurate than that of the protons because the energy the π^- loses as it traverses the detector has a much smaller effect on its velocity.

Cuts on the missing momentum in the reaction are used to eliminate events with neutral particles in the final state, such as $\gamma D \rightarrow pp\pi^-\pi^0$. Cuts on the missing momentum in the direction of the beam line, missing $p_{zlab} < 50$ MeV/c, and perpendicular to the beam line, missing $p_{transverse} < 50$ MeV/c, were used and are shown in Figure 6.4. Also, fiducial cuts on the track direction are made to discard particles that pass near the torus magnet coils, as their track resolution is significantly decreased due to the non-uniform magnetic field close to the coil surface. With these cuts in place, the $\gamma D \rightarrow pp\pi^-$ channel is largely isolated and can be studied.

Figure 6.3 Time differences between the photon and the particles in the $\gamma D \rightarrow pp\pi^-$ reaction. The time difference between the photon and the π^- has been cut at 1.0 ns to remove events matched with the wrong photon.

Figure 6.4 (A) Missing p_{zlab} after discarding events with $p_{zlab} > 50$ MeV/c in the $\gamma D \rightarrow pp\pi^-$ reaction. The red line at 12 MeV/c highlights an error in the momentum measurements of CLAS and is addressed in Section 6.3 (B) Missing $p_{transverse}$ after discarding events with $p_{transverse} > 50$ MeV/c in the $\gamma D \rightarrow pp\pi^-$ reaction.

6.3 Photon Energy Correction

As can be seen in Figure 6.4(A), the average missing p_{zlab} of the system is approximately 10 MeV/c instead of centered at zero. In Figure 6.5(A), this difference is shown to be independent of photon energy. Meanwhile, Figure 6.5(B) shows the average difference between the missing p_{zlab} and the missing energy to be approximately zero. Since the massless photon has $E = p_{zlab}c$ and doesn't contribute to Figure 6.5(B), it appears that the p_{zlab} of the photoproduced particles are relatively accurate compared to that of the photon. Therefore, a constant energy increase of 10.2 MeV is applied to the photon energy from the tagger. This study will be revisited in Section 8.2, after corrections to the particle momenta have been kinematically fit.

It is uncertain what causes this constant shift, although it is likely that the magnetic field strength in the tagger has been underestimated. This would cause an energy mismatch between the deflected electron energy and the E-counter it struck that could account for the difference.

(A)

(B)

Figure 6.5 (A) The average missing $p_{z_{lab}}$ of $\gamma D \rightarrow pp\pi^-$ fit as a constant of photon energy. (B) The difference between the missing $p_{z_{lab}}$ and missing energy. This indicates that the missing $p_{z_{lab}}$ is due to an error in measurement of the photon energy.

Chapter 7

Covariance Matrix Corrections

As charged particles pass through the liquid deuterium target, the scattering chamber surrounding it, the start counter, the drift chambers, and the air between them, they lose energy and multiple scatter. The effect that these collisions have on the particle are probabilistic in nature. Although a particle's mean scattering angle is zero and its mean energy loss can be calculated with the Bethe-Bloch equation, the individual true values of these effects are unknown. However, with many collisions these effects become normally distributed and were taken into account by increasing the track parameter errors in the covariance matrix. After the errors due to energy loss and multiple scattering were determined, the covariance matrix was updated by adding them in quadrature to the errors in measurement. In other words,

$$\sigma_{total}^2 = \sigma_{measurements}^2 + \sigma_{corrections}^2. \quad (7.1)$$

First, the uncertainty in the photon energy was determined from the energy resolution of the E-counters in the photon beam tagger. Next, the known functional form of the uncertainty in the multiple scattering angle was converted to the λ_{trk} and ϕ_{trk} tracking angles. The magnitude of the scattering error corrections for these angles was manually fine-tuned by kinematically fitting the $\gamma D \rightarrow pp\pi^-$ reaction with four-momentum conservation constraints and the momentum of the protons and π^- treated as unknown. Then, the correction to the track momentum error, due to a combination of energy loss and multiple scattering effects, was fit as a function of β^2

and θ_{lab} . Finally, the errors in the track location parameters D_0 and Z_0 were converted from the multiple scattering angles and fine-tuned by studying a kinematic fit of the $\gamma D \rightarrow pp\pi^-$ interaction vertex.

After applying these corrections, a simultaneous fit of the vertex and four-momentum of the $\gamma D \rightarrow pp\pi^-$ reaction yielded a nearly flat confidence level distribution with a sharp rise near zero confidence. The widths of the pull distributions from the fit were nearly equal to one. However the pull means were off-center, indicating corrections to the tracking measurements needed to be made.

7.1 Tagged Photon Variance

The photon tagger is capable of detecting electrons scattered from the radiator with energies between 20% and 95% of the electron beam energy E_0 . With 767 channels for measurement, this corresponds to an energy resolution of $0.001E_0$, or about 5.75 MeV for eg3. Assuming a uniform probability distribution amongst the channels, the variance in the photon energy measurement is [48]

$$\sigma_{\gamma_E}^2 = \frac{1}{0.002E_0} \int_{-0.001E_0}^{0.001E_0} E^2 dE = 11.1 \text{ MeV}^2. \quad (7.2)$$

The characteristic half-angle of the bremsstrahlung photon beam is [45]

$$\theta_c = m_e c^2 / E_0 = 8.9 \times 10^{-5} \text{ rad}. \quad (7.3)$$

As seen in the following section this is negligible compared to the uncertainties on the track angles due to multiple scattering. Thus, all photons are assumed to traverse the CLAS detector rigidly parallel to the beam line with an energy variance of 11.1

MeV².

7.2 Track Angle Variance Corrections

Increases to the uncertainty of the track angles of charged particles are needed due to the multiple scattering of the track off of nuclei in the target and surrounding material. The variance in the scattering angle ($\sigma_{\theta_{scatter}}^2$) is proportional to the function

$$\sigma_{\theta_{scatter}}^2 \propto \frac{1}{p^2 \beta^2} \sum_i \frac{x_i}{X_{0i}}, \quad (7.4)$$

where the summation is over the different materials that the track passes through. For each material, x is the charged particle's path length through it and X_0 is its radiation length. This quantity is converted to the uncertainty on the track angles via the propagation of errors, yielding

$$\sigma_{\lambda_{trk} \text{ corr}}^2 \propto \sigma_{\theta_{scatter}}^2, \quad \sigma_{\phi_{trk} \text{ corr}}^2 \propto \frac{1}{\cos^2(\lambda_{trk})} \sigma_{\theta_{scatter}}^2. \quad (7.5)$$

The magnitudes of $\sigma_{\lambda_{trk} \text{ corr}}^2$ and $\sigma_{\phi_{trk} \text{ corr}}^2$ were manually fine-tuned from the confidence level and pull distributions of the four-momentum conserving kinematic fit of the $\gamma D \rightarrow pp\pi^-$ reaction with the track momentum treated as unknown. The values of the track momenta were removed from the fit because their errors were still unknown. This kinematic fit has one degree-of-freedom, known as a 1C fit. The same multiple scattering error correction applies to all charged particles, regardless of their mass or the sign of their charge.

To check that the errors in the track angles follow this functional form, initial ad hoc corrections to the particle momentum uncertainty were applied. The $\gamma D \rightarrow pp\pi^-$

Figure 7.1 In the left plot, $\Delta\lambda_{trk}$ for the π^- is shown versus $(\beta p)^{-1}\sqrt{\sum_i(x_i/X_{0_i})}$. $\sigma_{\Delta\lambda_{trk}}$ is fit on the right as a linear function of $(\beta p)^{-1}\sqrt{\sum_i(x_i/X_{0_i})}$. The width of $\Delta\lambda_{trk}$ is larger at low $(\beta p)^{-1}\sqrt{\sum_i(x_i/X_{0_i})}$, which corresponds to large angles for the eg3 cylindrical target, due to the increased errors in the tracking measurements from holes in the drift chambers.

reaction was then kinematically fit with the track angles of the π^- treated as unknown, a 2C fit. The difference between the fit and measured values of the π^- tracking angles are shown in Figures 7.1 and 7.2 versus the predicted scattering angle uncertainty $(\beta p)^{-1}\sqrt{\sum_i(x_i/X_{0_i})}$. The bins of $(\beta p)^{-1}\sqrt{\sum_i(x_i/X_{0_i})}$ in these distributions were fit to Gaussians, with their widths shown in those figures as well. As expected, the widths of $\Delta\lambda_{trk}$ and $\Delta\phi_{trk}$ are linear in the scattering correction term. The final covariance matrix uncertainties in the π^- tracking angles are shown in Figure 7.3 as a function of $\beta p\sqrt{\sin(\theta_{lab})}$, where the sin term approximates the summation $\sum_i(x_i/X_{0_i})$ for the nearly cylindrical eg3 target.

7.3 Track Momentum Variance Corrections

The σ_p for charged tracks was increased in order to account for the uncertainty in the energy loss from both inelastic scattering with electrons and elastic scattering from the nuclei in the target and detector material. With these separate effects

Figure 7.2 In the left plot, $\Delta\phi_{trk}$ for the π^- is shown versus $(\beta p)^{-1}\sqrt{\sum_i(x_i/X_{0i})}$. $\sigma_{\Delta\phi_{trk}}$ is fit on the right as a linear function of $(\beta p)^{-1}\sqrt{\sum_i(x_i/X_{0i})}$. The slight bump at low $(\beta p)^{-1}\sqrt{\sum_i(x_i/X_{0i})}$ is due to increased errors in the tracking measurements by the drift chambers.

Figure 7.3 The total uncertainty as a function of $\beta p\sqrt{\sin(\theta_{lab})}$ of the π^- tracking angles (A) λ_{trk} and (B) ϕ_{trk} . These uncertainties increase with multiple scattering, or decreases in $\beta p\sqrt{\sin(\theta_{lab})}$. The uncertainty in λ_{trk} is larger than that of ϕ_{trk} due to larger measurement errors in the azimuthal direction. The clusters of high uncertainty in each plot are from tracks that pass through holes in the drift chambers.

entangled, the combination was fit to the functional form

$$\sigma_p^2{}_{corr} = \sum_i \left[\rho_i x_i \frac{Z_i}{A_i} \right] (D_0 + D_1 \beta^2 + D_2 \beta^4) (D_3 + D_4 \theta_{lab} + D_5 \theta_{lab}^2), \quad (7.6)$$

where the D 's are the fit constants. The summation is over the different materials that the track passes through, where for each material ρ is its density, x is the path length through it, and Z/A is the ratio of its atomic numbers. The elastic scattering contribution is expected to be different for heavy and light particles, so the D constants were fit separately for protons and pions.

In order to fit the correction to the data, the reaction $\gamma D \rightarrow pp\pi^-$ was fit requiring four-momentum conservation and treating all of the particle momenta as unknown, a 1C fit. The momentum was fit as unknown in order to remove the any biases that the ad hoc momentum uncertainties introduce to the fit. For protons, the quantity $\Delta p / \sqrt{\sum_i (\rho x_i Z_i / A_i)}$ was histogrammed against β^2 and θ_{lab} where Δp is the difference between the fit and measured momentum. Because there were very few pions with low β^2 they were histogrammed against $\sqrt{p}$ and θ_{lab} instead.

The quantity $\Delta p / \sqrt{\sum_i (\rho x_i Z_i / A_i)}$ in each bin of β^2 , θ_{lab} and $\sqrt{p}$, θ_{lab} was fit to a Gaussian, and the square of the widths of the Gaussians are shown in Figure 7.4. These widths were fit using Equation 7.6, where the fit for the π^- was performed by converting $\beta^2 = p^2 / (p^2 + m^2)$. Although the widths truly represent $\sigma_p{}_{total}$ they are a suitable initial estimate as $\sigma_p{}_{measurement}^2$ is small except at large p and θ_{lab} .

After $\sigma_p^2{}_{corr}$ was fit for both light and heavy particles the kinematic fit was performed again, this time with the track momenta present. With the track momenta

Figure 7.4 The left plot is $\sigma_{\Delta p}^2 / [\sum_i (\rho x_i Z_i / A_i)]$ versus β^2 and θ_{lab} for the proton, and the right is $\sigma_{\Delta p}^2 / [\sum_i (\rho x_i Z_i / A_i)]$ versus $\sqrt{p}$ and θ_{lab} for the π^- . $\sigma_{\Delta p}^2 / [\sum_i (\rho x_i Z_i / A_i)]$ was derived by first scaling the difference between the measured and kinematic fit track momenta, then squaring the width of the Gaussian fit to each bin of β^2 , θ_{lab} and $\sqrt{p}$, θ_{lab} .

reintroduced into the system, the $\sigma_{p\ corr}^2$ was manually fine-tuned to account for the measurement errors that were ignored earlier. It was noted in previous work [48] that an additional factor of I_{max}/I , the ratio between the maximum and used current in the CLAS torus magnet, is needed as a multiplier to the original $\sigma_{p\ measurement}$. However it was found for the eg3 experiment that this factor was not needed, so it appears that the error in the tracking that was causing the miscalculation of $\sigma_{p\ measurement}$ in the past has been corrected. The final σ_p is shown versus p in Figure 7.5 for the proton and π^- for different ranges of θ_{lab} .

7.4 Track Location Variance Corrections

Due to multiple scattering errors, the uncertainty in the track location was increased as well. These corrections were found by projecting the uncertainty in scattering angle from Equation 7.4 across a distance L and converting it to the D_0 and Z_0 tracking coordinates. L is defined as the distance along the track between the

Figure 7.5 The final σ_p versus p in different θ_{lab} ranges for (A) protons and (B) π^- 's. The final uncertainty increases with p and θ_{lab} and is several MeV/c larger than the measured errors, which are shown in Figure 5.3 for the proton. The uncertainty in the proton momentum is larger than that of the pion due to its lower β and increased energy loss. The streaks of high uncertainty at low p are due to holes in the drift chambers.

interaction vertex and the last point that the particle multiple scatters before it is detected in the drift chambers. Since charged particles scatter negligibly in air, the last scattering point is typically the location where the particle exits the CLAS start counter. The functional form of the correction to the D_0 variance due to multiple scattering is

$$\sigma_{D_0 \text{ corr}}^2 \propto L^2 \left(\frac{x_{trk}}{\Delta x_{trk}} \cos^2(\phi_{trk}) + 1 \right) \sigma_{\theta_{scatter}}^2, \quad (7.7)$$

where x_{trk} is the x_{trk} component of the interaction vertex and Δx_{trk} is the distance along the x_{trk} axis between the interaction vertex and the last point that the particle multiple scatters. Similarly, the functional form of the Z_0 variance correction due to multiple scattering is

$$\sigma_{Z_0 \text{ corr}}^2 \propto L^2 \left(\frac{\tan^2(\lambda_{trk})}{\sin^2(\phi_{trk})} - 4\sin^2(\lambda_{trk}) + 1 \right) \sigma_{\theta_{scatter}}^2. \quad (7.8)$$

The magnitudes of these corrections were determined manually by studying the kinematic fit of the $\gamma D \rightarrow pp\pi^-$ reaction with simultaneous constraints of four-momentum conservation and a common vertex. These corrections were found to be comparable in scale with those of the tracking angles. However, because the uncertainties in the measurements of D_0 and Z_0 were so large the corrections are not significant. The final covariance matrix uncertainties in the π^- track location parameters are shown in Figure 7.6 as a function of $\beta p \sqrt{\sin(\theta_{lab})}$. Although some scattering dependence is visible for D_0 , the track errors are typically dominated by the measurement uncertainties.

Figure 7.6 The total uncertainty as a function of $\beta p \sqrt{\sin(\theta_{lab})}$ of the π^- -tracking location parameters (A) D_0 and (B) Z_0 . The uncertainties are dominated by the error in measurement and increase little with multiple scattering, or decreases in $\beta p \sqrt{\sin(\theta_{lab})}$. The uncertainty in Z_0 is a factor of 10 larger than that of D_0 due to the larger error in measurement in the azimuthal direction. The cluster of high uncertainty visible in σ_{Z_0} is from tracks that pass through holes in the drift chambers.

7.5 Fitting with the Corrected Covariance Matrix

With the covariance matrix has been fine-tuned, the $\gamma D \rightarrow pp\pi^-$ reaction was kinematic fit requiring both a common vertex and momentum conservation, a 7C fit. The confidence level from the kinematic fit is shown in Figure 7.7 and is mostly flat with a sharp rise near zero confidence. As seen in Figure 7.8 the reconstructed vertex position corresponds with the location of the target, with the spread due to the background found at low confidence level.

The pull distributions for the different particles in the kinematic fit are shown in Figures 7.9 and 7.10. Because the pulls are only normally distributed in data samples containing only true events, a 2% confidence level cut has been placed on them to remove most of the background. The means and widths of the pulls are listed in Tables 7.1 and 7.2, respectively. The widths of the pulls are all near one, but some

Figure 7.7 The confidence level distribution for kinematic fitting $\gamma D \rightarrow pp\pi^-$ with constraints on the vertex and four-momentum.

Figure 7.8 The position of the reconstructed vertex in the $\gamma D \rightarrow pp\pi^-$ reaction (A) along the beam line, and (B) its perpendicular distance from the beam line. The reconstructed vertex location corresponds with that of the target, which is 2 cm in radius and spans from -70 to -30 cm along the beam line. There are less production vertices at the back of the target due to the lower tracking acceptance at the back of the drift chambers.

of the means are shifted significantly from the center. This indicates that there are several biases in the measurements that need to be investigated and corrected.

Track	p	λ_{trk}	ϕ_{trk}	D_0	Z_0
p_{slow}	0.003	0.244	-0.065	0.123	-0.276
p_{fast}	-0.049	0.289	-0.045	0.132	-0.331
π^-	0.040	0.214	-0.044	0.099	-0.214
γ	0.065				

Table 7.1 The means of the pull distributions of the track parameters in the simultaneous vertex and four-momentum fit of the $\gamma D \rightarrow pp\pi^-$ reaction. These means indicate that corrections to the track measurements are needed, especially to the Z_0 and λ_{trk} parameters.

Track	p	λ_{trk}	ϕ_{trk}	D_0	Z_0
p_{slow}	0.955	0.941	0.910	0.951	0.985
p_{fast}	0.948	0.922	0.910	0.938	0.964
π^-	0.945	1.053	0.947	0.984	1.057
γ	1.323				

Table 7.2 The widths of the pull distributions of the track parameters in the simultaneous vertex and four-momentum fit of the $\gamma D \rightarrow pp\pi^-$ reaction. These widths are all near one, with the exception of the photon energy.

Figure 7.9 The pull distributions of the track parameters of the (A) slow and (B) fast protons in a kinematic fit of $\gamma D \rightarrow pp\pi^-$, simultaneously requiring a common vertex and four-momentum conservation.

Figure 7.10 The pull distributions of the track parameters of the (A) photon and (B) π^- in a kinematic fit of $\gamma D \rightarrow pp\pi^-$, simultaneously requiring a common vertex and four-momentum conservation.

Chapter 8

CLAS Measurement Corrections

After correcting the covariance matrix the pull distributions showed that there were biases in the data. The kinematic fitting routine was then used to fit corrections to these measurements. Skews in the track measurements were attributed to a number of causes, including non-uniformities in the magnetic field, energy losses in the drift chambers, rotations and displacements of the drift chamber regions with respect to each other, and rotations of the drift chambers with respect to the beam line.

The measurement corrections were determined by performing multiple kinematic fits of the $\gamma D \rightarrow pp\pi^-$ calibration reaction, each time treating a different observable as unknown. When a measurement is treated as unknown, its bias is removed from the system and its value can be fit from the constraints on the reaction. The mean difference between an observable's fit and measured values is the correction that must be applied to the parameter. As particles of opposite charge bend in opposite directions through the drift chambers, the errors on the track measurements were fit separately for the protons and the π^- .

The correlated nature of the track measurements precludes the kinematic fitting routine from deriving perfect corrections to the tracks. This is because only a limited number of observables may be treated as unknown during a fit and it is not possible to remove all of the biases from a fit simultaneously. However, the corrections derived from fitting the $\gamma D \rightarrow pp\pi^-$ reaction with different parameters treated as unknown were accurate enough to result in pull means that were negligibly different from zero.

From the pull distributions in Figures 7.9 and 7.10, it appears that the skews on the track parameters λ_{trk} and Z_0 supply the largest bias during the kinematic fit. As these parameters are highly correlated they must be isolated to fit the error on each. Since ϕ_{trk} and D_0 are similarly correlated, the angle corrections must be found in a four-momentum conservation fit, where the track location biases cannot influence the results. However, studies of the pulls in the four-momentum conservation fit indicated that the error in the track momentum was larger than that of the angles so it was corrected first, followed by the photon energy, the angles, and finally the track location.

8.1 Particle Momentum Corrections

To fit the charged particle momentum corrections, the $\gamma D \rightarrow pp\pi^-$ reaction was fit requiring four-momentum conservation with the track momenta of the protons and π^- treated as unknown. With four equations and three unknowns, the system was still overdetermined with one degree of freedom, a 1C fit. The average difference between the fit momentum and the detected momentum after *eloss* corrections was be studied for each particle in each sector of the detector. This average difference in momentum Δp is plotted versus p , ϕ_{lab} , and θ_{lab} in Figures 8.1, 8.2, and 8.3, respectively.

The error in the measured momentum is significant in all sectors of the detector and appears to be largest when examined versus ϕ_{lab} . These skews in the charged particle momentum are sometimes as large as 10-15 MeV/c and may be attributed to misalignments of the drift chambers, energy loss in the drift chambers, and non-uniformities in the magnetic field.

Figure 8.1 The average difference in GeV/c between the fit and detected momentum after $e\text{loss}$ corrections as a function of p in the six sectors of CLAS for the (A) proton and (B) π^- .

Figure 8.2 The average difference in GeV/c between the fit and detected momentum after e_{loss} corrections as a function of the sector-normalized ϕ_{lab} in the six sectors of CLAS for the (A) proton and (B) π^- .

Figure 8.3 The average difference in GeV/c between the fit and detected momentum after e_{loss} corrections as a function of θ_{lab} in the six sectors of CLAS for the (A) proton and (B) π^- .

To determine the momentum of a charged particle traversing the drift chambers, the radius of curvature of the track is measured. The radius of curvature of a charged particle in a magnetic field is

$$r = \frac{\left| \int \vec{B} \times d\vec{l} \right|}{p}. \quad (8.1)$$

Therefore the errors in momentum measurement were examined in terms of $\Delta(1/p)$, the difference between the inverse of the fit momentum and the inverse of the detected momentum after *eloss* corrections. Although $\int \vec{B} \times d\vec{l}$ varies with track direction and momentum, its value was not readily available for the kinematic fitting analysis. Therefore, during the fitting of the momentum corrections the p and θ_{lab} dependence of $\int \vec{B} \times d\vec{l}$ were assumed to be absorbed to first order in the fitting constants of Equations 8.2 and 8.4. Since particles of opposite charge were bent in opposite directions through the CLAS magnetic field, the momentum corrections were fit separately for the protons and π^- . This method of using kinematic fitting to determine momentum corrections was first performed by M. Williams, D. Applegate, and C.A. Meyer [51].

The ϕ_{lab} -dependent measurement corrections were fit first as they appeared to be the largest source of error. These drift chamber misalignments and magnetic field non-uniformities were studied by splitting up the tracks in each sector into 10 bins in ϕ_{lab} . These bins each span 5° of the sector azimuth except at the edges, where the last bin on each side is 10° . This is because data near the edge of the sector is sparse due to the decreased tracking resolution near the torus magnets. For each sector and ϕ_{lab} bin in the CLAS detector, these errors in momentum measurement were fit to

$$\Delta \frac{1}{p} = A_0 + A_1 \frac{1}{p}, \quad (8.2)$$

where the fit constants A represent the entangled contributions of the ϕ_{lab} -dependent measurement errors. The fit of the mean $\Delta(1/p)$ for the protons and π^- in the different ϕ_{lab} bins are illustrated in Figures 8.4 through 8.9, one for each sector of the detector.

Next, the error in momentum due to energy loss in the drift chambers was studied as a function of p . As seen in Figure 8.10, the Δp versus p distributions were cleaned up considerably by the ϕ_{lab} -dependent corrections. For the proton, the change in momentum was fit in Figure 8.10(A) as

$$\Delta p = B_0 e^{-B_1(p+B_2)}, \quad (8.3)$$

where the B 's are the fitting constants. The functional form of this equation is an inexact but adequate representation of the Bethe-Bloch energy loss equation at low energies. This correction is not charge dependent, but was not fit for the low mass π^- as its energy loss was negligible, as seen in Figure 8.10(B).

Finally, the θ_{lab} dependent drift chamber misalignments were studied as a function of θ_{lab} . Figure 8.11 shows the mean $\Delta(1/p)$ versus θ_{lab} fit to the polynomial

$$\Delta \frac{1}{p} = \sum_{i=0}^7 C_i \theta_{lab}^i, \quad (8.4)$$

where the C 's are the fit constants. This fit is limited in range in θ_{lab} , as the error bars on the mean $\Delta(1/p)$ are too large at the backward angles to be reliable.

Figure 8.4 The fit to the mean $\Delta(1/p)$ versus $1/p$ for the 10 ϕ_{lab} bins in Sector 1 for the (A) protons and the (B) π^- . These errors are due to the ϕ_{lab} -dependent drift chamber misalignments and non-uniformities in the magnetic field. Units are in $(\text{GeV}/c)^{-1}$.

Figure 8.5 The fit to the mean $\Delta(1/p)$ versus $1/p$ for the 10 ϕ_{lab} bins in Sector 2 for the (A) protons and the (B) π^- . These errors are due to the ϕ_{lab} -dependent drift chamber misalignments and non-uniformities in the magnetic field. Units are in $(\text{GeV}/c)^{-1}$.

Figure 8.6 The fit to the mean $\Delta(1/p)$ versus $1/p$ for the 10 ϕ_{lab} bins in Sector 3 for the (A) protons and the (B) π^- . These errors are due to the ϕ_{lab} -dependent drift chamber misalignments and non-uniformities in the magnetic field. Units are in $(\text{GeV}/c)^{-1}$.

Figure 8.7 The fit to the mean $\Delta(1/p)$ versus $1/p$ for the 10 ϕ_{lab} bins in Sector 4 for the (A) protons and the (B) π^- . These errors are due to the ϕ_{lab} -dependent drift chamber misalignments and non-uniformities in the magnetic field. Units are in $(\text{GeV}/c)^{-1}$.

Figure 8.8 The fit to the mean $\Delta(1/p)$ versus $1/p$ for the 10 ϕ_{lab} bins in Sector 5 for the (A) protons and the (B) π^- . These errors are due to the ϕ_{lab} -dependent drift chamber misalignments and non-uniformities in the magnetic field. Units are in $(\text{GeV}/c)^{-1}$.

Figure 8.9 The fit to the mean $\Delta(1/p)$ versus $1/p$ for the 10 ϕ_{lab} bins in Sector 6 for the (A) protons and the (B) π^- . These errors are due to the ϕ_{lab} -dependent drift chamber misalignments and non-uniformities in the magnetic field. Units are in $(\text{GeV}/c)^{-1}$.

Figure 8.10 The mean Δp versus p , updated with the ϕ_{lab} -dependent corrections, in the six sectors of CLAS for the (A) proton and (B) π^- . These errors are due to the energy loss of the track as it traversed the drift chambers, and were not fit for the π^- as they were negligible. Units are in GeV/c.

Figure 8.11 The fit to the mean $\Delta(1/p)$ in $(\text{GeV}/c)^{-1}$ as a function of θ_{lab} in the six sectors of CLAS for the (A) proton and (B) π^- . These corrections are not fit to the tracks that traverse the backmost angles of the detector as the data is too sparse in these regions to be confident of the mean $\Delta(1/p)$.

After performing these fits, the mean difference between the fit and corrected momentum is shown versus p , ϕ_{lab} , and θ_{lab} in Figures 8.12, 8.13, and 8.14 respectively. All of the distributions are mostly flat, indicating that the momentum corrections have been fit properly.

8.2 Final Photon Energy Correction

After performing the track momentum corrections, the missing $p_{z_{lab}}$ in the $\gamma D \rightarrow pp\pi^-$ reaction is shown in Figure 8.15(A), indicating that a final correction to the photon energy was needed. This missing $p_{z_{lab}}$ of -2.5 MeV/c is seen in Figure 8.15(B) to be independent of photon energy. Combining this with the result from Section 6.3 yields a final increase of 7.7 MeV to the photon energy.

8.3 Angle Corrections

Corrections to the track angles λ_{trk} and ϕ_{trk} were needed due to rotations and displacements of the drift chamber regions with respect to each other, rotations of the drift chambers with respect to the beam line, and some localized effects. These corrections are different for particles of different charges because they bend through drift chambers in different directions. Although the magnitudes of these corrections are relatively small, these errors result in significant displacements of the tracks when projected back towards the interaction vertex.

To fit the charged particle λ_{trk} and ϕ_{trk} angle corrections, the $\gamma D \rightarrow pp\pi^-$ reaction was fit requiring four-momentum conservation with various combinations of the angles treated as unknown. Because there aren't enough constraints to simultaneously treat all of the angles as unknown the π^- angles were corrected first, followed by the proton

Figure 8.12 The average difference in GeV/c between the fit and corrected momentum as a function of p in the six sectors of CLAS for the (A) proton and (B) π^- .

Figure 8.13 The average difference in GeV/c between the fit and corrected momentum as a function of the sector-normalized ϕ_{lab} in the six sectors of CLAS for the (A) proton and (B) π^- .

Figure 8.14 The average difference in GeV/c between the fit and corrected momentum as a function of θ_{lab} in the six sectors of CLAS for the (A) proton and (B) π^- .

Figure 8.15 (A) Missing $p_{z,lab}$ after performing momentum corrections to the particles and discarding events with $p_{z,lab} > 50$ MeV/c in the $\gamma D \rightarrow pp\pi^-$ reaction. (B) The average missing $p_{z,lab}$ of $\gamma D \rightarrow pp\pi^-$ fit as a constant of photon energy. This was combined with the results from Section 6.3 to give a final photon energy increase of 7.7 MeV.

λ_{trk} angles, and finally the proton ϕ_{trk} angles. The differences between the fit and measured values of these angles were fit and corrected as a function of the track direction.

8.3.1 λ_{trk} Corrections

The average difference between the fit and detected values of the particle λ_{trk} angles is shown versus λ_{trk} and ϕ_{trk} in Figures 8.16 and 8.17, respectively. The errors are more pronounced when versus λ_{trk} , especially for the π^- . Although these differences are typically less than 10 mrad, these result in significant deviations of the track location near the interaction vertex.

Biases in λ_{trk} due to displacements and rotations of the drift chamber regions were fit as a function of both λ_{trk} and ϕ_{trk} . A correction for the large dip in the π^- tracking error at low ϕ_{trk} was fit as well. This error could possibly be due to non-uniformities in the magnetic field, which is strongest at the forward angles. This effect is not observed in the protons because they are bent inwards toward the beam

Figure 8.16 The average difference between the fit and detected λ_{trk} angles versus λ_{trk} in the six sectors of CLAS for the (A) protons and (B) π^- . Units are in radians.

Figure 8.17 The average difference between the fit and detected λ_{trk} angles versus ϕ_{trk} in the six sectors of CLAS for the (A) protons and (B) π^- . Units are in radians.

line and the low angle tracks escape detection.

Figure 8.18 shows the mean $\Delta\lambda_{trk}$ versus λ_{trk} and ϕ_{trk} for each sector and particle. The mean $\Delta\lambda_{trk}$ at the backward angles of each sector are unreliable due to the lack of statistics in those regions. The correction to λ_{trk} was fit with the function

$$\Delta\lambda_{trk} = (A + B\phi_{trk}) \sin(\lambda_{trk}) + (C + D\phi_{trk}) \cos(\lambda_{trk}) + E + Fe^{-G(\phi_{trk}+H)}. \quad (8.5)$$

The constants A and C represent the errors due to displacements of the drift chamber regions with respect to each other along the y_{trk} and z_{trk} axes, respectively. The constants B , D , and E represent the errors due to rotations of the drift chamber regions with respect to each other or the beam line about the z_{trk} , y_{trk} , and x_{trk} axes, respectively. The exponential term with the constants F , G , and H is used to perform a phenomenological fit to the error in tracking the π^- at the forward end of the drift chambers. This correction term rapidly approaches zero as ϕ_{trk} increases.

After applying the λ_{trk} corrections to their measured values, the final mean $\Delta\lambda_{trk}$ of the particles are shown in Figures 8.19 and 8.20 versus λ_{trk} and ϕ_{trk} , respectively. These distributions are much improved, although the lack of statistics precludes successful fitting at the backmost ϕ_{trk} angles. Also, there is a wide bump in the ϕ_{trk} distribution in Sector 5 that could not be fit, but it appears to coincide with observed holes in the drift chamber wires.

8.3.2 ϕ_{trk} Corrections

The mean difference between the fit and detected values of the ϕ_{trk} angles is shown versus λ_{trk} and ϕ_{trk} in Figures 8.21 and 8.22, respectively. The measurement errors

Figure 8.18 The mean $\Delta\lambda_{trk}$ fit as a function of λ_{trk} and ϕ_{trk} for the sectors of the CLAS detector for the (A) protons and the (B) π^- . A manual increase of 20 mrad was introduced to $\Delta\lambda_{trk}$ for presentation purposes.

Figure 8.19 The final mean $\Delta\lambda_{trk}$ shown versus λ_{trk} in the six sectors of the CLAS detector for the (A) protons and (B) π^- .

Figure 8.20 The final mean $\Delta\lambda_{trk}$ shown versus ϕ_{trk} in the six sectors of the CLAS detector for the (A) protons and (B) π^- .

on ϕ_{trk} were not as large as those for λ_{trk} . However, versus λ_{trk} the errors are as large as 5 mrad and needed to be corrected.

The correction to ϕ_{trk} was fit as a function of both track angles for displacements and rotations of the drift chamber regions. The mean $\Delta\phi_{trk}$ was fit for each particle and sector with the function

$$\Delta\phi_{trk} = (A + B\lambda_{trk}) \cos(\phi_{trk}) + (C + D\lambda_{trk}) \sin(\phi_{trk}) + E \quad (8.6)$$

as shown in Figure 8.23. The constants A and C represent the errors due to displacements of the drift chamber regions with respect to each other along the y_{trk} and x_{trk} axes, respectively. The constants B , D , and E represent the errors due to rotations of the drift chamber regions with respect to each other or the beam line about the x_{trk} , y_{trk} , and z_{trk} axes, respectively. This equation was derived from earlier work by A. Klimenko and S. Kuhn [52].

After applying the ϕ_{trk} corrections to their measured values, the mean $\Delta\phi_{trk}$ of the particles is shown in Figures 8.24 and 8.25 versus the λ_{trk} and ϕ_{trk} angles, respectively. These distributions are not completely flat but are much improved over the originals. Again, the correction is not applied at the backmost angles of the detector, as the lack of statistics makes the fit in this region unreliable.

8.4 Position Corrections

As mentioned previously, biases in the track angles cause errors when projecting the track location back to the target. Corrections to the D_0 and Z_0 parameters were derived directly from the correction to the track angles and the known geometry of

Figure 8.21 The average difference between the fit and detected ϕ_{trk} angles versus λ_{trk} in the six sectors of CLAS for the (A) protons and (B) π^- .

Figure 8.22 The average difference between the fit and detected ϕ_{trk} angles versus ϕ_{trk} in the six sectors of CLAS for the (A) protons and (B) π^- .

Figure 8.23 The mean $\Delta\phi_{trk}$ fit as a function of λ_{trk} and ϕ_{trk} for the sectors of the CLAS detector for the (A) protons and (B) π^- . A manual increase of 20 mrad was introduced to $\Delta\phi_{trk}$ for presentation purposes.

Figure 8.24 The corrected mean $\Delta\phi_{trk}$ shown versus λ_{trk} in the six detectors of the CLAS detector for the (A) protons and (B) π^- .

Figure 8.25 The corrected mean $\Delta\phi_{trk}$ shown versus ϕ_{trk} in the six detectors of the CLAS detector for the (A) protons and (B) π^- .

the CLAS detector.

Specifically, it was assumed that the track location was known at the point the track intersected the first superlayer of drift chambers. The distance L to this point from the $y_{trk} = 0$ point on the particle track is a piecewise function due to the separate flat and curved surfaces of the Region 1 drift chamber, as seen previously in Figure 3.3(A). If $D_0 \geq 57.88 \cos(\phi)$ then the track struck the flat portion of the drift chambers and the distance L is given by

$$L = \frac{57.88}{\cos(\lambda) \sin(\phi)}, \quad (8.7)$$

where all of the λ and ϕ angles in this section are in the tracking coordinate system. However, if $D_0 < 57.88 \cos(\phi)$ then the track struck the circular portion of the drift chambers and the distance L is given by

$$L = \frac{1}{\cos(\lambda)} \left(\sqrt{12306.40 - (53.05 \cos(\phi) - D_0)^2} - D_0 \cos(\phi) - 53.05 \sin(\phi) \right). \quad (8.8)$$

Thus, by projecting the track from the drift chamber intersection point back towards the target at the new angles, the corrected value for the parameter D_0 is

$$D_{0_{corr}} = L \cos(\lambda_{orig}) (\sin(\phi_{orig}) \cos(\phi_{corr}) - \cos(\phi_{orig}) \sin(\phi_{corr})) + D_{0_{orig}} \frac{\sin(\phi_{corr})}{\sin(\phi_{orig})}, \quad (8.9)$$

where the subscripts *orig* and *corr* indicate the measured and corrected values of the parameters, respectively. The change in D_0 is illustrated for each sector in Figure 8.26 versus D_0 for both protons and pions. These changes are centered around zero,

but there are a significant number of tracks that are corrected by a full centimeter or more.

Similar to D_0 , the correction for Z_0 is

$$Z_{0_{corr}} = Z_{0_{orig}} + L \sin(\lambda_{orig}) - L \cos(\lambda_{orig}) \sin(\phi_{orig}) \tan(\lambda_{corr}) / \sin(\phi_{corr}). \quad (8.10)$$

The correction for Z_0 is shown in Figure 8.27 versus D_0 for both protons and pions. Again, although these corrections are distributed about zero a significant number of tracks had relatively large changes. After applying these corrections, a kinematic fit of these parameters showed that additional corrections to D_0 and Z_0 were unnecessary.

8.5 Kinematic Fit with Corrections

After applying all of the corrections to the tracking parameters, a simultaneous kinematic fit on the $\gamma D \rightarrow pp\pi^-$ reaction was performed with four-momentum and vertex constraints. This fit was without any parameters treated as unknown to confirm that these track corrections improved the pull means. With these corrections, the tracking errors determined in Chapter 7 had to be slightly reduced to adjust for the improved values of the parameters.

The confidence level of the fit is shown in Figure 8.28. The pull distributions of the two protons are shown in Figure 8.29 and the pulls of the photon and π^- are shown in Figure 8.30. The means and widths of the pull distributions are found in Tables 8.1 and 8.2, respectively. The pulls are after a 2% confidence level cut to remove the majority of the background from the distributions. The confidence level is nearly flat, and the widths of the pulls are mostly all near one. The means of the

Figure 8.26 ΔD_0 versus D_0 in each sector of CLAS due to corrections in the tracking angles for the (A) protons and (B) π^- .

Figure 8.27 ΔZ_0 versus D_0 in each sector of CLAS due to corrections in the tracking angles for the (A) protons and (B) π^- .

Figure 8.28 The final confidence level of a simultaneous momentum conservation and common vertex fit of the $\gamma D \rightarrow pp\pi^-$ reaction, a 7C fit.

pulls have significantly improved and are all near zero, indicating that the biases in the data have been removed.

Track	p	λ_{trk}	ϕ_{trk}	D_0	Z_0
p_{slow}	0.005	-0.001	0.005	-0.015	0.011
p_{fast}	0.019	0.082	-0.067	0.099	-0.084
π^-	-0.023	-0.046	-0.017	0.010	0.053
γ	0.054				

Table 8.1 The means of the pull distributions of the track parameters in the simultaneous vertex and four-momentum fit of the $\gamma D \rightarrow pp\pi^-$ reaction. These means are all close to zero, indicating that most of the biases in the track measurements have been removed.

Figure 8.29 The pull distributions of the track parameters for the (A) slow and (B) fast protons in $\gamma D \rightarrow pp\pi^-$, simultaneously requiring a common vertex and four-momentum conservation.

Figure 8.30 The pull distributions of the track parameters of the (A) photon and (B) π^- in $\gamma D \rightarrow pp\pi^-$, simultaneously requiring a common vertex and four-momentum conservation.

Track	p	λ_{trk}	ϕ_{trk}	D_0	Z_0
p_{slow}	0.968	0.954	0.921	0.949	0.974
p_{fast}	0.955	0.932	0.910	0.938	0.944
π^-	0.907	1.063	0.932	0.980	1.073
γ	1.345				

Table 8.2 The widths of the pull distributions of the track parameters in the simultaneous vertex and four-momentum fit of the $\gamma D \rightarrow pp\pi^-$ reaction. These widths are all near one, with the exception of the photon energy.

Chapter 9

Testing $\Lambda \rightarrow p\pi^-$ Reconstruction

With the tracking covariance matrix and measurements corrected, the kinematic fitting routine was tested by reconstructing $\Lambda \rightarrow p\pi^-$ decays in the eg3 dataset. These results are preliminary and are only meant to be an initial demonstration of the kinematic fitting routine.

To select events, particle identification cuts from the *seb* software package were placed on the proton and π^- along with very loose invariant mass cuts about the $1.116 \text{ GeV}/c^2$ Λ mass. For events with more than one proton or π^- , the pair of tracks that have the least time difference are chosen. A plot of this time difference is shown in Figure 9.1(A). To remove some of the background, the time difference is fit to a Gaussian and events with $\Delta t_{p\pi^-} > 0.95 \text{ ns}$ (2.5σ) were cut. For a small fraction of the eg3 dataset, the $p\pi^-$ invariant mass after the time difference cut is shown in Figure 9.1(B). There are 44263 events in the fit Λ peak, with a signal-to-background ratio of 1.59. This time difference cut will be used throughout the rest of this chapter, as well as in Chapter 10 during Ξ^- reconstruction.

The signal of the Λ was studied further by requiring that the proton and π^- tracks share a common vertex. This requirement can be met by either performing a kinematic fit or examining the distance-of-closest-approach (DOCA) between the two tracks. Both of these methods are used in comparison to examine an initial test of the kinematic fitting routine.

Figure 9.1 (A) The time difference between the proton and π^- tracks after a loose invariant mass cut. This difference is fit to the Gaussian shown in blue, and cuts were chosen to be placed at 0.95 ns (2.5σ) which are shown by the vertical red lines. (B) The $p\pi^-$ invariant mass after cutting out events with $\Delta t_{p\pi^-} > 0.95$ ns. The Λ peak has been fit to a Gaussian in blue on top of the linear background fit shown in green. Between the vertical red lines, there are 44263 events in the fit Λ peak, with a signal-to-background ratio of 1.59.

9.1 Kinematic Fit of the Λ Decay Vertex

The confidence level of the $\Lambda \rightarrow p\pi^-$ common vertex kinematic fit is shown in Figure 9.2(A). Events with confidence level $< 5\%$ were cut, removing a large portion of the background while retaining most of the true events. The invariant mass of the $p\pi^-$ system after this cut is shown in Figure 9.2(B). The background was cleaned up considerably as there are 31567 events in the signal with a 1.95 signal-to-background ratio. This is a loss of about 28% of the signal but that is because there are a large number of events where the tracks happened to have the correct invariant mass but did not come close to intersecting. With a confidence level cut of 10% only an additional 2595 events are removed from the signal, a 5.8% loss of the original signal. This closely matches the predicted 5% difference, indicating that the kinematic fitting routine performed as expected.

The position of the reconstructed vertex is shown along the z_{lab} axis in Figure 9.2(C), and its distance perpendicular to the beam line is shown in Figure 9.2(D). The location of these reconstructed vertices corresponds to the eg3 target, which is 2 cm in radius and is located between -70 and -30 cm on the CLAS z_{lab} axis. However, the Λ decay vertex distribution extends past the front edge of the target because the Λ particle has a $c\tau$ of 7.89 cm [32]. Also, the small peak in the vertex distribution at $z_{lab} = -16$ cm corresponds to the front edge of the target vacuum chambers.

9.2 The $p\pi^-$ Distance of Closest Approach

The DOCA between the proton and π^- is shown in Figure 9.3(A). With a 5% confidence level cut chosen, a DOCA cut of 2.5 cm was selected for comparison as it cuts a roughly similar number of events. After applying the DOCA cut, the resulting invariant mass is plotted in Figure 9.3(B). There are 34654 events in this signal, yielding a 2.07 signal-to-background ratio. This is relatively the same as the 1.95 ratio from the confidence level cut, despite the confidence cut losing a significant portion of its original signal. A cut of $1.112 \text{ GeV}/c^2 < p\pi^-_{invariant\ mass} < 1.12 \text{ GeV}/c^2$, illustrated by the red lines in Figure 9.3(B), will be placed on the Λ in Chapter 10 for reconstructing Ξ^- decays.

9.3 Combined Kinematic Fit

Finally, the $\Lambda \rightarrow p\pi^-$ decay was kinematically fit with the combined constraints of a common vertex and four-momentum conservation. The confidence level of this fit is shown in Figure 9.4(A). This distribution is mostly flat, with a sharp rise near zero confidence. Choosing a 5% confidence level cut, the resulting invariant mass

Figure 9.2 (A) The confidence level of the kinematic fit of a common vertex to the proton and π^- tracks. The red line indicates the 5% confidence level cut that was used. (B) The $p\pi^-$ invariant mass after placing the 5% confidence cut. Between the red lines, there are 31567 events in the signal, with a 1.95 signal-to-background ratio. (C) The kinematic fit vertex along the z_{lab} axis, where the peak at -16 cm is due to photoproduction on the front edge of the target vacuum chambers. (D) The perpendicular distance between the reconstructed vertex and the beam line.

Figure 9.3 (A) The distance-of-closest-approach between the proton and π^- tracks. The red line indicates the 2.5 cm DOCA cut that was used. (B) The $p\pi^-$ invariant mass after placing the 2.5 cm DOCA cut. Between the red lines there are 34654 events in the signal with a 2.07 signal-to-background ratio. Also, these lines define the invariant mass region that is cut to select Λ 's when examining the $\Xi^- \rightarrow \pi^- \Lambda$ decay in Chapter 10.

spectrum is shown in Figure 9.4(B). This cut heavily suppresses the background, and a Gaussian fit to the signal yields a width of $1.7 \text{ MeV}/c^2$. Although there are 53768 events in this distribution, some of the background still remains in the system. The background in this signal is heavily cut dependent and remains to be studied in detail.

Figure 9.4 (A) The confidence level of the kinematic fit of a common vertex and four-momentum conservation of the $\Lambda \rightarrow p\pi^-$ decay. The red line indicates the 5% confidence level cut that was used. (B) The $p\pi^-$ invariant mass after placing the 5% confidence cut. There are 53768 events in this distribution, but the shape of the background is no longer clear. However, the Gaussian portion of the signal is a narrow $1.7 \text{ MeV}/c^2$ at the predicted $1.116 \text{ GeV}/c^2$ mass, showing that the kinematic fitting routine reconstructed the Λ correctly.

Chapter 10

Testing $\Xi^- \rightarrow \Lambda\pi^-$ Reconstruction

With the Λ particles reconstructed, the $\Lambda\pi^-$ invariant mass was studied to search for the Ξ^- . The two different methods of Λ reconstruction, kinematic fitting and cuts on the track DOCA and invariant mass, are extended to the Ξ^- search. With both the production and decay vertices of the Λ , the resolution of the detached vertex reconstruction is examined. The results from these searches are preliminary, and are meant only to serve as a demonstration of the kinematic fitting.

The *seb* software package is used for particle identification and the detection of a proton and at least two π^- 's are required, where the π^- 's that are matched with the proton and the Λ are the combination with the least time difference that passes all of the cuts on the system. A plot of the time difference between the Λ and π^- is shown in Figure 10.1 for a small fraction of the eg3 dataset. Here the Λ 's have been reconstructed using the combined kinematic fit from Section 9.3. This distribution has been fit to a Gaussian, and a time difference cut of $\Delta t_{\Lambda\pi^-} > 0.6$ ns (2σ) is used throughout the rest of this chapter.

10.1 Testing the Λ Reconstruction

With the time difference cut applied, the $\Lambda\pi^-$ system was examined using both Λ reconstruction methods. Using the entire eg3 dataset, Figure 10.2(A) illustrates the $\Lambda\pi^-$ invariant mass from a 5% confidence level cut on the Λ reconstruction performed in Section 9.3. This results in a signal of 6263 events with a signal-to-background ratio of 0.09. Cuts of $p\pi^-_{DOCA} < 2.5$ cm and $1.112 \text{ GeV}/c^2 < p\pi^-_{invariant \text{ mass}} < 1.12$

Figure 10.1 The time difference between the reconstructed Λ and the measured π^- . This distribution has been fit to a Gaussian, and the vertical red lines illustrate the cuts placed at 0.6 ns (2σ).

GeV/c^2 on Λ reconstruction yield the invariant mass plot in Figure 10.2(B). This signal contains 6869 events and a signal-to-background ratio of 0.10 between the red lines.

Both of these signals are dominated by the $\Sigma^-(1385)$ state, which also decays into $\Lambda\pi^-$. The Ξ^- signals from the two Λ reconstruction methods are similar, but in this preliminary study their cuts have not yet been optimized for Ξ^- reconstruction.

10.2 The $\Lambda\pi^-$ Distance of Closest Approach

The DOCA between the Λ and π^- tracks is illustrated in Figure 10.3(A). A DOCA cut of 2.5 cm is shown in the plot, which roughly cuts a similar number of events as the 5% confidence level cut performed in Section 10.3. Figure 10.3(B) shows the $\Lambda\pi^-$ invariant mass with the 2.5 cm DOCA cut and contains 5681 events in the signal with a signal-to-background ratio of 0.12. However, this cut does not remove much of the background from the $\Sigma^-(1385) \rightarrow \Lambda\pi^-$ decay, providing negligible improvement to

Figure 10.2 (A) The $\Lambda\pi^-$ invariant mass with the Λ 's reconstructed via kinematic fitting. There are 6263 events in the signal between the vertical red lines yielding a 0.09 signal-to-background ratio. (B) The $\Lambda\pi^-$ invariant mass with the Λ 's reconstructed via invariant mass and DOCA cuts. There are 6869 events in the signal between the vertical red lines giving a 0.10 signal-to-background ratio. In both plots, the Ξ^- signal has been fit as a Gaussian shown in blue on top of a linear background shown in green.

the Ξ^- signal.

10.3 Kinematic Fit of the Ξ^- Vertex

The confidence level from fitting a common vertex to the Λ and π^- is shown in Figure 10.4(A). Events with confidence level $< 5\%$ were cut from the data and the resulting $\Lambda\pi^-$ invariant mass is shown in Figure 10.4(B). However, the Ξ^- signal was not much improved, as there are only 4714 events in the signal and a 0.11 signal-to-background ratio. This is because the $\Lambda\pi^-$ invariant mass system is still dominated by the background from the $\Sigma^-(1385) \rightarrow \Lambda\pi^-$ decay. Although there are much less events in this signal than the one from applying a DOCA cut, the DOCA cuts chosen throughout have been somewhat arbitrary as there is no clear location to place the cuts in their smooth distributions. The reconstructed vertex is shown along z_{lab} in Figure 10.4(C), and its perpendicular distance from the beam line is visible in

Figure 10.3 (A) The distance-of-closest-approach between the Λ and π^- tracks, with a 2.5 cm cut illustrated by the vertical red line. (B) The $\Lambda\pi^-$ invariant mass after the 2.5 cm DOCA cut. Between the red lines there are 5681 events in the signal, with a 0.12 signal-to-background ratio.

Figure 10.4(D).

The reconstructed vertex resolution can be viewed by studying the distance between the production and decay vertices of the Λ particle. The z_{lab} component of this distance is shown in Figure 10.5 versus the invariant mass of the $\Lambda\pi^-$ system. This demonstrates that the kinematic fitting routine reconstructed the detached vertices properly, as the decay distance is several centimeters in the forward direction for most of the Λ 's produced in the $\Xi^-(1321)$ and $\Sigma^-(1385)$ decays instead of distributed about zero.

Figure 10.4 (A) The confidence level of the kinematic fit of a common vertex to the Λ and π^- tracks. The red line indicates the 5% confidence level cut that was used. (B) The $\Lambda\pi^-$ invariant mass after placing the 5% confidence cut. Between the red lines, there are 4714 events in the signal, resulting in a 0.11 signal-to-background ratio. (C) The kinematic fit vertex location along the z_{lab} axis. (D) The perpendicular distance between the reconstructed vertices and the beam line.

Figure 10.5 The difference between the Ξ^- and Λ reconstructed vertices in the z_{lab} direction versus the invariant mass of the $\Lambda\pi^-$ system. This represents the distance in the direction of the beam line that the Λ traverses before decaying. The large peak in the middle is from the Λ 's produced in $\Sigma^-(1385)$ decays, and the Ξ^- signal is visible at its mass of $1.321 \text{ GeV}/c^2$.

Chapter 11

Summary

The eg3 experiment aims to determine the existence of the exotic Ξ_5^- pentaquark by investigating its $\Xi_5^- \rightarrow \pi^- \Xi^-$, $\Xi^- \rightarrow \pi^- \Lambda$, $\Lambda \rightarrow p \pi^-$ decay chain. The kinematic fitting routine was developed to provide robust reconstruction of the detached vertices of the Ξ^- and Λ weak decays. Prior to kinematic fitting, the $\gamma D \rightarrow pp \pi^-$ reaction was studied to perform corrections to the tracking measurements and calibrate the tracking covariance matrices of the charged particles detected in CLAS.

After performing these corrections, preliminary studies of the Λ and Ξ^- decays illustrate that the kinematic fitting routine reconstructs their detached vertices well. Confidence level cuts on the kinematic fits were shown as an excellent method of removing the background in the $\Lambda \rightarrow p \pi^-$ decay. However, the vertex fit showed little improvement in the reconstruction of the Ξ^- due to the background from the $\Sigma^-(1385)$ state. This preliminary reconstruction analysis demonstrates that the kinematic fitting routine effectively reconstructs the detached vertices in the weak decays. Additionally, the placement of the confidence level cuts used in the analysis needs to be investigated to determine how to maximize the number of Ξ^- events. After reconstructing the Ξ^- , a confidence level cut on the kinematic fit of the $\Xi^- \pi^-$ vertex will be used to search for the Ξ_5^- pentaquark state.

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