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Electroproduction of hyperons at low momentum transfer

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FLORIDA INTERNATIONAL UNIVERSITY

Miami, Florida

ELECTROPRODUCTION OF HYPERONS AT LOW
MOMENTUM TRANSFER

A dissertation submitted in partial fulfillment of the
requirements for the degree of
DOCTOR OF PHILOSOPHY

in

PHYSICS

by

Armando R. Acha

2011

To: Dean Kenneth Furton
College of Arts and Sciences

This dissertation, written by Armando R. Acha, and entitled Electroproduction of Hyperons at Low Momentum Transfer, having been approved in respect to style and intellectual content, is referred to you for judgment.

We have read this dissertation and recommend that it be approved.

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Date of Defense: November 10, 2011

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Florida International University, 2011

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DEDICATION

To my parents Ivanna and Armando,
and my dearest wife Thamara.

ABSTRACT OF THE DISSERTATION
ELECTROPRODUCTION OF HYPERONS AT LOW
MOMENTUM TRANSFER

by

Armando R. Acha

Florida International University, 2011

Miami, Florida

Professor Pete E.C. Markowitz, Major Professor

A high resolution study of the $H(e, e'K^+)\Lambda, \Sigma^0$ reaction was performed at Hall A, TJNAF as part of the hypernuclear experiment E94-107. One important ingredient to the measurement of the hypernuclear cross section is the elementary cross section for production of hyperons, Λ and Σ^0 . This reaction was studied using a hydrogen (i.e. a proton) target. Data were taken at very low Q^2 (~ 0.07 (GeV/c) 2) and $W \sim 2.2$ GeV. Kaons were detected along the direction of $\mathbf{q}$, the momentum transferred by the incident electron ($\theta_{CM} \sim 6^\circ$). In addition, there are few data available regarding electroproduction of hyperons at low Q^2 and θ_{CM} , and the available theoretical models differ significantly in this kinematical region of W . The measurement of the elementary cross section was performed by scaling the Monte Carlo cross section (MCEEP) with the experimental-to-simulated yield ratio. The Monte Carlo cross section includes an experimental fit and extrapolation from the existing data for electroproduction of hyperons. Moreover, the estimated transverse component of the electroproduction cross section of $H(e, e'K^+)\Lambda$ was compared to the different predictions of the theoretical models and existing data curves for photoproductions of hyperons. None of the models fully describe the cross-section

results over the entire angular range. Furthermore, measurements of the Σ^0/Λ production ratio were performed at $\theta_{CM} \sim 6^\circ$, where data are not available. Finally, data for the measurements of the differential cross sections and the Σ^0/Λ production were binned in Q^2 , W and θ_{CM} to understand the dependence on these variables. These results are not only a fundamental contribution to the hypernuclear spectroscopy studies but also an important experimental measurement to constrain existing theoretical models for the elementary reaction.

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The Thomas Jefferson National Accelerator Facility (TJNAF) has unique experimental facilities. It is able to produce a high intensity electron beam up to $200\text{ }\mu\text{A}$ with beam energies up to 6 gigaelectronvolts (GeV). The high-resolution spectrometers in Hall A, among the different pieces of equipment, allow the study of sub-nuclear dynamics in the intermediate-energy range (i.e., energies of several GeV). It is at these energies that a hadronic description and a quark description of nuclear reactions compete in terms of describing observations.

Quantum Hadrodynamics (QHD) constitutes a phenomenological description that uses degrees of freedom like mesons and baryons (e.g., pions, kaons, protons, neutrons, Deltas, Lambdas, Sigmas, etcetera) to describe how particles interact. Properties and strengths of interactions of those particles are determined empirically through measurements of photoproduction, electroproduction, hadron-hadron scattering, or radiative capture [1] and utilizing the symmetry relations (e.g., crossing symmetry and duality) between related reactions and the different experiments.

On the other hand, Quantum Chromodynamics (QCD) constitutes a quark description of nuclear reactions. QCD considers hadrons to be composed of a small number of more fundamental particles. These more fundamental particles are 6 quarks and 8 gluons. Therefore, QCD uses fewer particles to describe nuclear phenomena and, in principle, QHD parameters could be deduced from QCD [2]. However, calculations in QCD theory are quite difficult at few GeV energies, in particular due to the fact that for a given quark-gluon interaction the strength of the QCD coupling grows greater than unity

as the transferred momentum is decreased, which constitutes an obstacle for carrying out calculations in QCD. Solutions of problems via QCD are limited to approximate methods like perturbation theory (valid for momentum transfers above some non-determined but large threshold) [2].

1.1 Mesons, baryons and hyperons

Hadrons are made of fundamental particles called quarks and/or antiquarks that interact through the strong force according to the standard model. Hadrons are classified into two different groups: baryons and mesons. Baryons are composed of three quarks (qqq) or three anti-quarks ($\bar{q}\bar{q}\bar{q}$) and mesons are composed of quark-antiquark pairs ($q\bar{q}$). Most of the mass constituting matter and basically everything on Earth is made of up (u) and down (d) quarks, with no strange (s) or other quarks (although virtual strange and other quarks are calculated to briefly coalesce from the vacuum before vanishing again). The lightest meson that contains strangeness is the kaon (K^+), which is composed of an up quark and a strange antiquark ($u\bar{s}$). When baryons contain strange quarks they are called hyperons. Examples of hyperons are Λ , Σ^0 (uds).

In experiment E94-107, Lambda (Λ) or Sigma (Σ^0) hyperons were produced together with a kaon K^+ . The Λ and Σ^0 particles have the same quark content. They are composed of up, down and strange quarks (uds). However, the Λ and Σ^0 particles differ in their masses and also in their isospin. The lighter Λ hyperon is an isoscalar ($I=0$) singlet, whereas the heavier Σ^0 is an isovector ($I=1$) triplet member [3].

Table 1 shows a selection of some of the lightest mesons and baryons composed of up, down and strange quarks and antiquarks as well as some of their main properties.

Particle	Quarks	Mass (MeV)	Charge	Isospin $ I, I_z\rangle$	Spin	Parity
up quark	u	$\approx 1 - 5$	$+\frac{2}{3}e$	$ \frac{1}{2}, +\frac{1}{2}\rangle$	$\frac{1}{2}$	+
down quark	d	$\approx 3 - 9$	$-\frac{1}{3}e$	$ \frac{1}{2}, -\frac{1}{2}\rangle$	$\frac{1}{2}$	+
strange quark	s	$\approx 60 - 170$	$-\frac{1}{3}e$	$ 0, 0\rangle$	$\frac{1}{2}$	+
π^-	$\bar{u}d$	139.57	$-1e$	$ 1, -1\rangle$	0	-
π^+	$u\bar{d}$	139.57	$+1e$	$ 1, +1\rangle$	0	-
K^+	$u\bar{s}$	493.68	$+1e$	$ \frac{1}{2}, +\frac{1}{2}\rangle$	0	-
K^-	$s\bar{u}$	493.68	$-1e$	$ \frac{1}{2}, -\frac{1}{2}\rangle$	0	-
p	uud	938.27	$+1e$	$ \frac{1}{2}, +\frac{1}{2}\rangle$	$\frac{1}{2}$	+
n	udd	939.57	0	$ \frac{1}{2}, -\frac{1}{2}\rangle$	$\frac{1}{2}$	+
Λ	uds	1115.68	0	$ 0, 0\rangle$	$\frac{1}{2}$	+
Σ^0	uds	1192.64	0	$ 1, 0\rangle$	$\frac{1}{2}$	+

Table 1: Properties of the lightest mesons and baryons [4].

Another interesting piece of information relevant to experiment E94-107 is how these hyperons decay. The Λ particle decays via the weak decay either into a proton and a negative pion or into a neutron and a neutral pion. Strangeness in either decay is not conserved. The characteristic long lifetime of a weak decay is observed to be on the order of 10^{-10} seconds. The neutral Σ^0 particle decays via the strong interaction into a Λ particle and a γ -ray conserving in this case the strangeness number with consequently a much shorter lifetime on the order of 10^{-20} seconds [5]. Table 2 shows the main properties of the hyperons involved in experiment E94-107:

Hyperons	Masses (MeV)	Lifetime (s)	Principal decays
Λ	1115.6	2.63×10^{-10}	$p\pi^-, n\pi^0$
Σ^0	1192.5	6×10^{-20}	$\Lambda\gamma$

Table 2: Main properties of the hyperons involved in experiment E94-107 [6].

1.2 Hypernuclear physics and the elementary reaction

Hyperons are particles that contain strangeness in their structure and are not common on Earth. On Earth, the mass comprising the majority of matter is made of “ordinary” nuclear material that contains protons and neutrons, referred to as nucleons. These nucleons sit inside the nuclei with separate nuclear orbital angular momenta, energy levels and quantum numbers (collectively describing their quantum states) and the Pauli exclusion principle prevents any two of these particles from being in the same

quantum state. Creating a bound hyperon in the nucleus, called a hypernucleus, constitutes a different kind of matter and since a hyperon differs in structure from nucleons, it follows a separate exclusion principle. Therefore, a hyperon can have the orbital angular quantum numbers of already populated levels inside the hypernucleus. Spectroscopy experiments allow us to extract information about these energy levels where the hyperon can sit and from this we can study the way hyperons and nucleons interact inside the hypernuclei [7].

In the process of understanding hypernuclear spectroscopy experiments, it is essential to experimentally study the elementary process that creates these hyperons. One method is by studying electroproduction of hyperons, Λ and Σ^0 particles, on a hydrogen target which contains only one proton (the simplest nucleus). The ratio of the two cross sections (hypernuclear and hydrogen) is proportional to the overlap of the hypernuclear wave function with the wave function of the target, which provides crucial information on the hypernuclear system. However, this elementary process is itself not very well understood so the experimental results are of great importance for theoreticians to constrain their different models. Theoretical efforts are hard in this area of research because of the additional strangeness feature in hypernuclei that increases the degrees of freedom and also greatly increases the difficulties in performing analytical calculations.

The use of an electron beam as a probe is particularly desirable because electron interactions are well understood via the theory of Quantum Electrodynamics (QED), avoiding many of the complications that arise from the influence of the strong interactions as happens in experiments utilizing hadron-hadron scattering [8, 9]. The elementary electroproduction reaction is given by:

$$e + p \rightarrow e' + K^+ + (\Lambda \text{ or } \Sigma^0).$$

In this case an incident electron scatters off a proton by radiating a virtual photon (electromagnetic probe). The scattered electron (e') and the ejected kaon (K^+) are then detected in coincidence. A convenient kinematics is then chosen to ensure the creation either of a Lambda (Λ) or Sigma (Σ^0) particles represented by Y in Figure 1:

Figure 1: General view of the kinematics of the elementary reaction.

1.3 Kaon electroproduction in E94-107

The aim of this dissertation is the study of Λ and Σ^0 electroproduction from a ^1H target at very forward kaon scattering angles (θ_K) and low 4-momentum transfer squared (Q^2), which is an important region for understanding hyperon electroproduction via $^1\text{H}(e,e'K^+)\Lambda$ and $^1\text{H}(e,e'K^+)\Sigma^0$. My study is also an important part of the more general hypernuclear program in Hall A. Figure 2 shows the main kinematic variables for the elementary reaction:

$$e + p \rightarrow e' + K^+ + Y(\Lambda \text{ or } \Sigma^0),$$

Figure 2: View of the elementary reaction kinematics.

where the four momenta involved are:

$$e = (E, \vec{p}_e), \text{ for the incident electron,} \quad (1)$$

$$e' = (E', \vec{p}'_e), \text{ for the scattered electron,} \quad (2)$$

$$p = (M_p, \vec{0}), \text{ for the target nucleon,} \quad (3)$$

$$k = (E_K, \vec{p}_K), \text{ for the produced kaon,} \quad (4)$$

$$Y = (E_Y, \vec{p}_Y), \text{ for the unobserved residual system.} \quad (5)$$

Other kinematics variables including a few Lorentz invariants are defined as:

$$q = (\nu, \vec{q}), \text{ is the four-momentum transfer of the virtual photon,} \quad (6)$$

$$\nu = E - E', \text{ is the energy of the virtual photon,} \quad (7)$$

$$\vec{q} = (\vec{p}_e - \vec{p}'_e), \text{ is the three-vector-momentum of the virtual photon,} \quad (8)$$

$$q^2 = (e - e')^2 = -4EE' \sin^2\left(\frac{\theta_e}{2}\right) = -Q^2, \quad (9)$$

is the square of the four-momentum transfer carried by the virtual photon,

$$W^2 = (q + p)^2 = M_p^2 + 2M_p\nu - Q^2, \quad (10)$$

is the mass squared of the system recoiling against the electron (i.e. the photon-proton system),

$$t = (q - k)^2 = q^2 + m_K^2 - 2qk, \quad (11)$$

is a Mandelstam variable for the four-momentum transfer squared,

$$s = (e + p)^2 = M_p^2 + 2M_pE, \quad (12)$$

is a Mandelstam variable for the square of the energy,

$$u = (k - p)^2, \quad (13)$$

is a Mandelstam variable for the crossed four-momentum squared,

$$x = \frac{Q^2}{2M_p \nu}, \quad (14)$$

is the Bjorken scaling variable (interpreted in the quark parton model, as the fraction of the target nucleon's momentum carried by the struck quark).

The laboratory five-folded differential electroproduction cross section can be conveniently expressed in terms of the center-of-momentum (CM) cross section. Therefore, it allows comparisons with previous or similar measurements taken at different kinematics [10, 11, 12]:

$$\frac{d^5\sigma}{dE' d\Omega'_e d\Omega_K} = \Gamma \frac{d\cos\theta_K^*}{d\cos\theta_K} \frac{d^2\sigma}{d\Omega_K^*}, \quad (15)$$

where Γ is the virtual-photon flux factor given by:

$$\Gamma = \frac{\alpha}{2\pi^2} \frac{(W^2 - M_p^2)}{2M_p^2} \frac{E'}{E} \frac{1}{Q^2} \frac{1}{(1-\varepsilon)}, \quad (16)$$

and $\frac{d\cos\theta_K^*}{d\cos\theta_K}$ is the Jacobian between the $\text{CM}(\theta_K^*)$ and the laboratory (θ_K) angle between the virtual photon and the kaon. φ is the angle between the scattering and reaction planes as shown in Figure 2. $d\Omega'_e = d\cos\theta_e d\varphi$ is the electron lab-frame solid angle, $d\Omega_K = d\cos\theta_K d\varphi$ is the kaon lab-frame solid angle and $d\Omega_K^* = d\cos\theta_K^* d\varphi$ is the kaon center-of-momentum (CM) solid angle. $\frac{d^2\sigma}{d\Omega_K^*}$ represents the CM cross section and ε is the virtual photon longitudinal polarization:

$$\varepsilon = \frac{1}{1 + 2\left(1 + \frac{\mathbf{v}^2}{Q^2}\right)\tan^2\left(\frac{\theta_e}{2}\right)}, \quad (17)$$

the cross section for kaon electroproduction in the CM frame can be written as follows [12, 13, 14]:

$$\frac{d^2\sigma}{d\Omega_K^*} = \left(\frac{d^2\sigma_T}{d\Omega_K^*}\right) + \varepsilon\left(\frac{d^2\sigma_L}{d\Omega_K^*}\right) + \varepsilon\left(\frac{d^2\sigma_{TT}}{d\Omega_K^*}\right)\cos(2\varphi) + \sqrt{2\varepsilon(\varepsilon+1)}\left(\frac{d^2\sigma_{LT}}{d\Omega_K^*}\right)\cos(\varphi), \quad (18)$$

or in more compact notation:

$$\frac{d^2\sigma}{d\Omega_K^*} = \sigma_T + \varepsilon\sigma_L + \varepsilon\cos(2\varphi)\sigma_{TT} + \sqrt{2\varepsilon(\varepsilon+1)}\cos(\varphi)\sigma_{LT}, \quad (19)$$

and where:

σ_T is the cross section that results from the transverse component of the virtual photons,

σ_L is the cross section that results from the longitudinal component of the virtual photons,

σ_{LT} is the cross section that results from the interference between the transverse and longitudinal components of the virtual photons,

σ_{TT} is the cross section that results from the interference between the two different states of the transverse components of the virtual photons.

The quantities $\sigma_T, \sigma_L, \sigma_{TT}$ and σ_{LT} completely characterize the dependence of the cross section for scattering electrons off of the nucleon (nucleus). They are functions of the independent kinematical variables Q^2 , W and t .

It is interesting to point out that if Equation (19) is integrated in φ over $(0, 2\pi)$ the interference terms vanish. In practical terms this means that if the experiment is carried out in such way that the acceptance has complete coverage in φ then the interference terms vanish. Further, if data could then be taken at different ε holding the other variables constant, a Rosenbluth technique can be used to separate σ_L and σ_T [13]. However, this is not the case in E94-107, as will be shown in Chapter 4, because in this experiment the angular acceptance is not uniform in φ . Consequently, the results from E94-107 include all four of these response functions.

1.4 Theoretical models

Various theoretical models have been created in an attempt to describe kaon production and radiative kaon capture while maintaining consistency with SU(3) symmetry constraints on the coupling constants [15]. Most of these models have been constructed for energies of just a few GeV. These energies are low enough that the models can be formulated under the effective rules of Quantum Hadrodynamics (QHD). Moreover, when these models are tested at slightly higher energies they are consistent with perturbative Quantum Chromodynamics (pQCD) [1]. The most important models in this energy regime are isobaric models and Regge models.

1.4.1 Isobaric models

In isobaric models, the kaon production amplitudes are calculated from tree-level QHD Feynman diagrams. In other words, the models include only one-particle exchange. The tree level Feynman diagrams are for s , t and u channels. Figure 3 shows the three channels of processes. Basically, in the s channel one considers the virtual photon (q) as being absorbed by the proton (p) which then decays emitting a meson (K^+) and a hyperon (Y). The proton could also go through an intermediate resonance state before the emission as shown in Figure 3. The t channel represents the virtual photon being scattered by a (virtual) K^+ meson or one of its resonances so that a K^+ and a hyperon are emitted. The u channel treats the scattering as the virtual photon being absorbed by a hyperon (or hyperon resonance), which then emits a K^+ and another hyperon.

Different models include different couplings between the particles and different resonances. When these different model calculations are performed limits are taken on the properties of the propagators. The strengths of the couplings are empirical degrees of freedom determined by fitting the experimental data. A model described in Reference [16] uses a sum over s -channel nucleonic resonances up to spin $5/2$, u -channel hyperonic resonances (spin $1/2$) and the t -channel kaonic resonances $K^*(892)$ and $K1(1270)$. In another model, called the WJC model [15], a different selection of s and u channels resonances is used. In these models, each vertex in the diagrams shown in Figure 3 is associated with a particular coupling constant.

Figure 3: Feynman diagrams in isobaric models for kaon electroproduction.

All the isobaric models start by including only spin $\frac{1}{2}$ baryonic resonances. These resonances can be different for each model and the coupling constants are obtained by performing phenomenological fits to the data. There are not enough data available to fully constrain the coupling constants. New data (especially at forward kaon angles where there are very few data) are important to discriminate between which of the isobaric models is best able to describe the experimental observations. J.C. David, G. Fayard, G.H. Lamot and B. Saghai [16] compared four different isobaric models called AS [17], WJC [15], SL [16] and MBH [18]. To perform the fits they started with the available data with energy range from threshold to 2.1 GeV, and by extending the AS model to higher energies and focusing on the $K^+\Lambda$ photoproduction channel they included the spin- $\frac{3}{2}$ nucleonic resonances. The $K^+\Lambda$ electroproduction channel was also studied and in this case spin- $\frac{5}{2}$ nucleonic resonances were included resulting in the Saclay-Lyon (SL) model. See Table 3 for the $K\Lambda$ channels. In the case of the $K^+\Sigma$ channels, the fits were done adding up to isospin- $\frac{3}{2}$ nucleonic resonances. The resulting SL model is shown. See Table 4 and Reference [16].

Particle	Coupling	AS	WJC	SL
Λ	$g_{KAN}/\sqrt{4\pi}$	-4.17 ± 0.75	-2.38	-3.16 ± 0.01
Σ	$g_{K\Sigma N}/\sqrt{4\pi}$	1.18 ± 0.66	0.27	0.91 ± 0.10
K^*	$G_V/4\pi$	-0.43 ± 0.07	-0.16	-0.05 ± 0.01
	$G_T/4\pi$	0.20 ± 0.12	0.08	0.16 ± 0.02
$K1$	$G_{V1}/4\pi$	-0.10 ± 0.06	0.02	-0.19 ± 0.01
	$G_{T1}/4\pi$	-1.21 ± 0.33	0.17	-0.35 ± 0.03
$N1$	$G_{N1}/\sqrt{4\pi}$	-1.41 ± 0.60		-0.01 ± 0.12
$N4$	$G_{N4}/\sqrt{4\pi}$		-0.04	
$N6$	$G_{N6}/\sqrt{4\pi}$		-0.06	
$N7$	$G_{N7}^a/4\pi$			-0.04 ± 0.01
	$G_{N7}^b/4\pi$			-0.14 ± 0.04
$N8$	$G_{N8}^a/4\pi$			-0.63 ± 0.10
	$G_{N7}^b/4\pi$			-0.05 ± 0.56
$L1$	$G_{L1}/\sqrt{4\pi}$		-0.07	-0.31 ± 0.06
$L3$	$G_{L3}/\sqrt{4\pi}$	-3.17 ± 0.86		1.18 ± 0.09
$L5$	$G_{L5}/\sqrt{4\pi}$			-1.25 ± 0.20
$S1$	$G_{S1}/\sqrt{4\pi}$			-4.96 ± 0.19

Table 3: Isobaric model coupling constants and resonances for $K\Lambda$ channels [16].

Particle	Coupling	MBH	WJC	SL
Λ	$g_{KAN}/\sqrt{4\pi}$	0.51	-2.38	-3.23±0.17
Σ	$g_{K\Sigma N}/\sqrt{4\pi}$	0.13	0.27	0.80±0.10
K^*	$G_V/4\pi$	0.05	0.11	0.02±0.01
	$G_T/4\pi$	0.05	-0.14	-0.07±0.02
$K1$	$G_{V1}/4\pi$		-0.13	-0.05±0.01
	$G_{T1}/4\pi$		0.07	0.23±0.04
$N1$	$G_{N1}/\sqrt{4\pi}$			-0.95±0.11
$N4$	$G_{N4}/\sqrt{4\pi}$	0.08	0.09	
$N6$	$G_{N6}/\sqrt{4\pi}$	0.57	0.47	
$N7$	$G^a_{N7}/4\pi$			-0.04±0.02
	$G^b_{N7}/4\pi$			-0.53±0.06
$N8$	$G^a_{N8}/4\pi$			2.02±0.20
	$G^b_{N7}/4\pi$			3.91±0.57
$L1$	$G_{L1}/\sqrt{4\pi}$		0.46	-0.42±0.03
$L3$	$G_{L3}/\sqrt{4\pi}$			-0.10±0.09
$L5$	$G_{L5}/\sqrt{4\pi}$			6.01±0.23
$S1$	$G_{S1}/\sqrt{4\pi}$			-1.72±0.21
$D1$	$G_{D1}/\sqrt{4\pi}$		-0.03	
$D2$	$G_{D2}/\sqrt{4\pi}$	0.07	-0.06	
$D3$	$G_{D3}/\sqrt{4\pi}$	0.30	-0.51	0.43±0.04
$D4$	$G^a_{D4}/4\pi$			-0.47±0.06
	$G^b_{D4}/4\pi$			-1.88±0.14
$D7$	$G^a_{D7}/4\pi$			0.05±0.01
	$G^b_{D7}/4\pi$			0.29±0.04

Table 4: Isobaric model coupling and resonances for $K\Sigma$ channels [16].

The different coupling constants are values are shown in Tables 3 and 4. The tables show that the fits of the different resonances (i.e., degrees of freedom in the fits) used in the calculations result in disagreements in the coupling constants. One reason for this disagreement is the lack of sufficient data in kaon production to constrain the models.

Additional electromagnetic kaon production data in previously unmeasured regions (i.e., forward kaon angles) are important for improving the results in the theoretical calculations by constraining the model parameters.

1.4.2 Regge models

A different class of models is based on Regge theory [19]. In Regge models the Feynman diagram approach is modified in such a way that at higher energies the standard single particle Feynman propagator $\frac{1}{(t - m^2)}$ is replaced by the Regge propagator that takes into account the exchange of a family of particles with the same intrinsic quantum numbers [20]. As an example, in photoproduction the pseudoscalar hadronic current in the t -channel exchange for the Λ channel is given by:

$$J_{K_{t=exch}}^\mu \propto ie\bar{k}Y_f(k - p_K)^\mu \times P_{Regge}^K \times g_{K\Lambda N}\gamma^5 N_i. \quad (20)$$

In Equation (20) e is the fundamental charge, Y_f is the Lambda spinor, $k^\mu = (q - p_K)^\mu$ is the four-vector of the exchanged kaon and $\bar{k}$ is its Feynman dagger, where p_K^μ is the kaon four-vector and q^μ is the photon four-vector, P_{Regge}^K represents the Regge propagator, $g_{K\Lambda N}$ is the coupling constant at the $p^+ - \Lambda - K^+$ vertex in the diagram and N_i is the proton spinor.

The Regge propagator has the form:

$$P_{\text{Regge}}^K = \left(\frac{s}{s_0} \right)^{\alpha_K(t)} \left(\frac{\pi \alpha'_K(t)}{\sin \pi \alpha_K(t)} \right) \left(\frac{S_K + e^{-i\pi \alpha_K(t)}}{2} \right) \left(\frac{1}{\Gamma(1 + \alpha_K(t))} \right), \quad (21)$$

where s is the Mandelstam variable and s_0 is a mass scale, commonly taken as 1 GeV^2 .

The α_K and α'_K parameters characterize the Regge trajectories shown in Figure 4. S_K with values $+1$ or -1 is the signature of the trajectory and Γ is the Gamma function

$$(\Gamma(x) = \int_0^\infty t^{x-1} e^{-t} dt).$$

Figure 4: Regge trajectories of the form $\alpha = \alpha_0 + \alpha' * t$ for K and K^* [20].

The equation for the Regge propagator (21) reduces to the Feynman propagator when one approaches the first pole of the trajectory. In other words, this occurs when $t \rightarrow m_K^2$. A similar current operator and propagator can be constructed for the pseudovector coupling of the K^* mesons. The only parameters in Regge model described in [19] are the first materialization of the trajectories with the external particles, that is to say $g_{KAN}, g_{K^*AN}, \dots$ which have to be determined to describe all existing high-energy data [20].

An extension from photoproduction to electroproduction can be done by multiplying the gauge invariant t -channel K and K^* diagrams by a form factor. The monopole form factor used in the model [19] is given by:

$$F_{K,K^*}(Q^2) = \frac{1}{1 + \frac{Q^2}{\Lambda_{K,K^*}^2}}, \quad (22)$$

where Λ_{K,K^*}^2 are adjustable parameters known as mass scales. The mass scales can be fit to the high Q^2 behavior of the separated electroproduction cross sections σ_T and σ_L , which is useful in describing the results of Rosenbluth or other response function separation experiments.

1.4.3 Σ^0/Λ production ratio

From previous measurements of the $^1\text{H}(e,e'K^+)\Lambda, \Sigma^0$ reactions it has been observed that the ratio of cross sections Σ^0/Λ for the two channels decreases rapidly as Q^2 is increased. The following Figures 5 and 6 show world data up to 1996 from which it is clear to see that Σ^0/Λ production ratio decreases with Q^2 [11]. The data were taken at a variety of values of W and kaon angles (θ_K). The data have been extrapolated to a common value of $W=2.15$ GeV, using the method found in References [11,13]. The angles (θ_K) were all forward, but have not been extrapolated to 0° .

Figure 5: World data prior to 1996 for $^1\text{H}(e,e'K^+)\Lambda$, $\langle W \rangle = 2.15$ GeV, $\theta_{CM} = 0$ [11].

Figure 6: World data prior to 1996 for $^1\text{H}(e,e'K^+)\Sigma^0$, $\langle W \rangle = 2.15$ GeV, $\theta_{CM} = 0$ [11].

In Figures 5 and 6 there is a photoproduction point ($Q^2 = 0$); these figures suggest that the cross section for electroproduction of kaons at very forward angles and very low Q^2 is larger than the cross section for photoproduction [21], which rises one of the questions that this dissertation tries to answer with the measurements done on $^1\text{H}(e,e'K^+)\Lambda, \Sigma^0$ cross sections at low $Q^2 \sim 0.07$ GeV² and a laboratory kaon angle $\theta = 6^\circ$, corresponding to a center-of-mass (CM) kaon angle of $\theta_{CM} = 6^\circ$.

On the basis of a simple isospin argument, the Σ^0/Λ production ratio should decrease with Q^2 . This argument is formulated in the framework of the quark parton model and is qualitative. The decrease of the Σ^0/Λ ratio is related to the decrease of the ratio F_1^{qn}/F_1^{qp} as Q^2 increases, where F_1^{qp} and F_1^{qn} are the usual structure functions for

deep inelastic electron-nucleon scattering. Nachtmann and Close have shown that the observed Σ^0/Λ ratio decreases with Q^2 using this isospin argument [20, 21, 22, 23, 24]. The previous references also show the Σ^0/Λ ratio depends on the Bjorken scale x , which shows the expected dependence on Q^2 as well [25].

1.5 Physics motivation

The study of Λ and Σ^0 electroproduction from a ^1H target at very forward kaon scattering angles and low 4-momentum transfer squared (Q^2) is one of the objectives in the hypernuclear program at Hall A, JLab, which is an important region for measuring hyperon electroproduction via $^1\text{H}(e, e'K^+)\Lambda$ and $^1\text{H}(e, e'K^+)\Sigma^0$. At small kaon angles and low Q^2 , theoretical models of the Λ cross section vary greatly. The Σ^0 data also provide important information on the Σ^0/Λ ratio at low Q^2 where this ratio changes rapidly as explained in Section 1.4.

Currently existing models are divergent at small kaon (forward) CM angles and the existing data on elementary hyperon production at small forward angles is not enough to fully constrain the models. In addition most of the data have been taken at kaon CM angles larger than 20 degrees. Figure 7 shows that the deviations in the various models become large at small (forward) kaon CM angles. The models contain a number of free parameters (such as, e.g., coupling constants and cut-off masses), which can be constrained by low angle data. Since perturbative QCD is not applicable, the parameters of the models rely upon phenomenological approaches that vary from model to model. The description of the elementary process is, however, poor in the kinematical region

relevant for the hypernuclear calculations (e.g., for photon energies larger than 1.5 GeV and small photon mass $Q^2 \sim 0.06 \text{ (GeV/c)}^2$), which covers very forward kaon angles.

Figure 7: Isobaric model predictions compared with experimental data [26].

Calculations of the cross section for production of hypernuclei in excited states, e.g., to analyze data from the hypernuclear experiments carried out at Jefferson Laboratory, depend on two main ingredients: i) the elementary-production operator and ii) the nuclear and hypernuclear structure information. One has to understand the elementary process, in the relevant kinetical region to learn more about the hypernuclear structure, which is closely connected with the hyperon-nucleon interaction. However, predictions for the hypernuclear production cross sections using various isobaric models for the elementary operator differ by more than 100% at kaon laboratory angles less than 10 degrees and photon energies larger than 1.5 GeV (See Figure 7).

Figure 7 shows predictions of the models discussed above, compared with experimental photoproduction ($Q^2=0$) data from CLAS [27], SAPHIR [28], and LEPS [29] collaborations. An updated version of the hybrid RPR-2 model [30] (Regge-isobar approach) is shown in which the P11(1900) resonance is replaced by the D13(1900) to better describe the latest data. Kaon-MAID, Janssen C, and H2 [31] contain a hadronic form factor (HFF), revealing very sharp damping of the cross section at kaon CM angles smaller than 30° , whereas the cross section in models without a HFF, Saclay-Lyon and Williams-Ji-Cotanch (WJC) [15], continue rising (Figure 7). The CLAS and SAPHIR data suggest a plateau at these forward angles.

The possible damping of the cross section at very forward angles and photon lab energy of 2 GeV can be understood within the Saclay-Lyon A (SLA) and H2 models [31]. The cross section calculated with these models is dominated by the Born terms, particularly by the electric part of the photon exchange, at kaon CM angles smaller than 30 degrees. In this case, the contribution provides a plateau in the cross section as the

angle goes to zero for the SLA results, such a feature would be very similar in both models since the main two coupling constants are almost equal. The situation is different in the H2 model due to a very strong suppression of the photon term by the HFF, which is of the order of $0.2 \mu\text{b}$ in cross section for this energy region. The very strong suppression of the Born terms leads to a pronounced “dip” in the differential cross section at very small angles (see Figure 7 for the results of the H2 model). The Kaon MAID model gives a similar result. In this region, the resonances contribute only by interference with the Born terms so that they cannot fill in the dip.

The strong suppression of the cross section at very forward angles and energies above 1.7 GeV is a common feature of the isobaric models with a HFF. Therefore, the dynamical aspect of the isobaric models requires a more detailed investigation. However, the large bulk of new data cannot discriminate between the models due to a lack of data at very forward angles. These latest data were measured only for CM kaon angles as small as 18 and 26 degrees for the LEPS, SAPHIR and CLAS sets respectively, see Figure 7.

Analysis of CLAS data on the cross section in a wide energy interval [27] shows, besides the forward peaking, a progressive flattening of the slope as the kaon angle goes to zero. The CLAS data, however, only reach to 26 degrees. The question whether the cross section continues rising, forms a plateau or decreases (as is the case for the high-energy data over 5 GeV [20]), as some of the models predict, is therefore another challenging question.

On top of that, there is a need for a better description of the elementary operator at forward angles, to serve as input in the hypernuclear calculations. The scarceness of data

at forward angles can result only in a poor description of the process and therefore in a large uncertainty in the hypernuclear calculations.

Figure 8: Isobaric and RPR2 models predictions compared to data [26], CLAS data from Bradford et al., [27].

Figure 8 shows predictions made by isobaric models and the RPR2 models for photoproduction at different kaon CM angles (θ_{CM}). The theoretical predictions differ at very forward angles and it is here where E94107 measures the cross section at 6 degrees. Although, E94107 is electroproduction, it is performed at very low $Q^2 \sim 0.07 \text{ (GeV/c)}^2$, which allows comparison of photoproduction and electroproduction reactions. By

providing this important point, theoretical models can be discriminated. The main questions that this dissertation answers are:

- a) What are the cross sections for $^1\text{H}(e,e'K^+)\Lambda,\Sigma^0$ at $\theta_K=6^\circ$, $W=2.2$ GeV and $Q^2 \sim 0.07$ (GeV/c) 2 ?
- b) Experiment E94-107 measures the cross section for electroproduction of hyperons that includes longitudinal amplitudes. What is the estimated transverse component of the electroproduction cross section? Which model better describes the data with the new experimental point included in Figure 8?
- c) Does the cross section for photoproduction continue rising as the kaon angle goes to zero or is there a plateau?
- d) What is the ratio of Σ^0/Λ at low Q^2 ? How does this result compare to the existing data?
- e) Which of the models describes the data at forward angles and can therefore be used in the analysis of the hypernuclear data without introducing an additional uncertainty?

Answers to the first four questions are important for understanding the dynamics of the elementary reaction process, while the last question is crucial for the hypernuclear calculations since the elementary amplitude scales the predictions.

2 Experimental apparatus

2.1 Overview of the Jefferson Lab

Experiment E94-107 was performed at the Thomas Jefferson National Accelerator Facility (also known as Jefferson Lab or JLab) located in Newport News, Virginia. The accelerator at Jefferson Lab can provide almost continuous electron beams to the three experimental halls: A, B and C (see Figure 9). The electron beams can reach up to energies of 5.7 GeV with beam currents ranging from 10 nA up to 200 μ A.

Although the beam delivered by the accelerator is considered to be almost continuous it is actually made of pulses of electron packets accelerated by two linear accelerators (linacs) joined at their ends by recirculation arcs. The linacs consist of twenty cryomodules and each cryomodule has eight superconducting niobium cavities, which are kept at a temperature of 2 K during operations.

By shining a 780 nm laser on a GaAs photocathode, polarized electrons are obtained and accelerated up to 45 MeV in the injector towards the first linac. At normal operations 0.4 GeV is added to the beam each time it passes through a linac and after 5 passes the total energy reached would be 4.045 GeV. However, non-standard operation modes are available and energies close to 0.6 GeV can be added to the beam per pass through a linac making a maximum of 5.7 GeV. There are 5 recirculation arcs at one end and 4 at the other end. The recirculation arcs have magnetic fields designed to bend the different energy beams through each arc, which before entering the next linac, get recombined again [32].

Radio waves with a frequency of 1497 MHz are used in the cavities to accelerate the electron pulses, which are separated by a distance of $c/1497 \text{ MHz} = 20 \text{ cm}$, approximately. Normally one third of these pulses are sent to each hall at a frequency of one third of the accelerator frequency. Therefore, the frequency with which the pulses reach one experimental hall is 499 MHz. Subsequently, the time separation between pulses is approximately $1/499 \text{ MHz} = 2 \text{ ns}$. The energies used during this experiment were 3.77 GeV and 3.96 GeV.

Figure 9: The accelerator at TJNAF [32].

The accelerator is now being upgraded and five new cryomodules are being added to each linac as well as a new arc added to one of the ends. The upgrade will allow the accelerator to reach a beam energy of up to 12 GeV.

2.2 The experimental Hall A

Hall A is one of the three experimental halls where physics experiments are carried out. The electron beam enters the hall along the beam line. In order to monitor the beam current and beam position on the target there are two Beam Current Monitors (BCMs) and two Beam Position Monitors (BPMs) along the beam line just upstream of the target scattering chamber. After passing the BCMs and the BPMs the beam reaches the scattering chamber. Inside the scattering chamber the targets are located on a vertical ladder system, which allows remotely changing targets during data taking. A big portion of the beam gets through the target without interacting and continues beyond the scattering chamber to the final part of the beam line to end up in a shielded beam dump.

There are two spectrometers in the hall mounted on a system of rolling bearings so that they can be rotated to different scattering angles. The two spectrometers are designed with the same magnetic components and similar optical properties [32]. Normally, one of them, called the electron spectrometer (right) is used to measure the momentum and direction of the scattered electrons (also π^- , $\mu^- \dots$) and the other, called the hadron spectrometer (left) is used to measure the momentum and direction of scattered positively charged particles (p^+ , π^+ , $K^+ \dots$). These measurements in many cases are done in coincidence to detect particles from the same reaction.

At the end of each spectrometer there is a shielding house (also known as the detector hut) containing a detector package mounted on a support structure along with the electronics associated with the operation of the detectors for data collection. The purpose of the shielding houses is to protect the detectors and electronics by reducing the rates

from particles or radiation that do not pass through the magnetic spectrometers. Figure 10 shows the interior of the Hall A.

Figure 10: Experimental Hall A [33].

2.3 The beam line

2.3.1 Beam energy

There are two independent methods to measure the beam energy. The first method is done in the arc section of the beam line. To measure the energy, a known magnetic field is used to deflect the beam. The bending angle of the beam is 34.3° and the momentum of the beam can be calculated by knowing the magnitude of the magnetic field and the net bend angle through the arc. Therefore,

$$p_{beam} = \frac{c}{\theta} \int \vec{B} \cdot d\vec{l}, \quad (23)$$

where c is the speed of light, $\vec{B}$ the magnetic field, and $d\vec{l}$ is the differential path length of the electrons [32]. The absolute energy resolution using the arc method is 1×10^{-4} GeV. The energy used in E94-107 is 3.77 GeV, implying that in utilizing this method the energy uncertainty is about 0.4 MeV. In this method, the energy spread is measured at a high dispersion point, where the energy spread is:

$$\frac{\sigma_E}{E_{beam}} = \frac{\sigma_\delta}{D}, \quad (24)$$

and σ_δ is the size of the beam due to dispersion D . Moreover, the total beam size is $\sigma_{beam} = \sqrt{\sigma_\beta^2 + \sigma_\delta^2}$, where σ_β is the beam betatron's size. However, for high dispersion point measurements the contribution of σ_β to the beam size can be ignored, so with $\sigma_{beam} > \sigma_\delta$ in Equation (24). Then the upper limit of the energy spread is

$$\frac{\sigma_E}{E_{beam}} < \frac{\sigma_{beam}}{D}, \quad (25)$$

In E94-107 the beamline optics had the dispersion $D = 4$ m and the energy spread was 3×10^{-5} [34].

Another method to measure the beam energy is called the “ep” method. This method is based on the kinematics of elastic scattering of the electron beam off a proton target. To do this measurement two sets of detectors are placed symmetrically about the incident beam direction. Therefore, at either side of the beam the scattered electron and the recoiling protons are detected and, by the two-body kinematics, the energy is

$$E = M_p \frac{\cos(\theta_e) + \frac{\sin(\theta_e)}{\tan(\theta_p)} - 1}{1 - \cos(\theta_p)} , \quad (26)$$

where θ_e and θ_p are the scattering angles of the electrons and protons from the incident electron beam direction and M_p is the mass of the proton [35]. The accuracy of the measurement in the “ep” method is up to $\frac{\delta E}{E} = 2 \times 10^{-4}$. The agreement between the two methods (relative uncertainty) is about 3×10^{-4} .

In addition, in order to have a complete characterization of the beam energy it is also important to measure the beam energy spread as well as the centroid. These measurements are performed by two methods as well. One of the methods is Optical Transition Radiation (OTR) and it consists of a $0.3\mu\text{m}$ thin carbon foil where the transverse beam size is measured by imaging the optical transition radiation on a CCD camera and analyzing the horizontal and vertical projections. The other method is known as the Synchrotron Light Monitor and it uses a synchrotron light interferometer pattern to measure the transverse beam size [36].

2.3.2 The beam current

The precise measurement of the current is needed in order to measure cross sections normalized to the luminosity. To measure the beam current a DC current transformer monitor (DCT) is used (Unser monitor). Since the DC beam current provides no time varying flux component to generate a signal by magnetic induction, an AC flux component is "brought to the beam" via the action of a magnetic modulator circuit. The operation of a magnetic modulator, and hence a DCT, is based on the non-linear characteristics of high-quality tape-wound magnetic cores [37]. The Unser monitor is designed for non-destructive beam current measurements and it provides an absolute reference. The Unser monitor can also be calibrated by setting a known current in a wire that passes through the Unser. The nominal output is of 4 mV/ μ A. However, the Unser monitor tends to drift after several minutes so it is normally used only for calibration purposes.

To monitor the current continuously, two other BCMs are used. They are two resonant cavities located in the beam line about 24.5 m upstream of the target. These BCMs are basically cylindrical resonant cavities made out of stainless steel with a diameter of 15.18 cm and a length of 15.24 cm. Two loop coaxial antennas are inside each cavity and their positions are where the H field reaches its largest magnitude. The resonant frequency of the cavities is adjusted to the frequency of the beam pulses, that is to say 499 MHz. Consequently, the output voltages levels are proportional to the beam current. An analog DC voltage level is obtained from converting the RMS output from the cavities. However, its response is not linear for currents below 5 μ A. Therefore, to

extend the non-linear region of this response, the signals are amplified by 3 and by 10. Furthermore, by knowing the time duration of a run the amount of charge can be measured and then, the charge data is stored in the Experimental Physics and Industrial Control System (EPICS) data stream [38]. Figure 11 shows the charge ratio of the two amplified BCM signals with respect to the non-amplified one.

Figure 11: Charge ratio of the two amplified signals to the non-amplified signal for experiment E94-107.

2.3.3 Beam position monitor and raster

Two BPM devices placed upstream of the target at 1.286 m and 7.524 m are used to monitor the beam position in the horizontal (X) and vertical (Y) directions. Each BPM has two 4-wire antennas arrays of open-ended thin wire strip lines tuned to the fundamental radio frequency of the beam. For currents above 1 μA the beam position can be determined within a precision of less than 100 μm . Adjacent to each of the BPMs are

located the 'superharp' scanners at 7.353 m and at 1.122 m upstream, which are used to calibrated the absolute position of the BPMs [38]. The information obtained by the BPMs is recorded into the EPICS data stream every 3 to 4 seconds with a record of the time at that moment.

The superharp can measure not only the absolute position of the beam centroid but also the profile or spatial extent of the beam. To do this, the superharp has one tungsten wire bent twice to give 3 straight sections, two of which measure the beam profile in the Y direction and the third in the X direction. These wires are mounted into a fork-shaped frame. Therefore, when the frame is moved towards the beam making the wires cross the beam, secondary electrons are emitted producing a signal which is detected and amplified. The positions of the wires are well known allowing reliable absolute positions and widths of the beam in the X and Y directions as well. There is an analog-to-digital converter (ADC) that measures the signal on the wires and also a position encoder which measures the position of the ladder that holds the wires. The proper combination of this information determines the position and profile of the beam in the coordinate system of the hall. The beam position is typically obtained with an accuracy of about 10 μm and the width of the beam is about 100 μm (FWHM).

When data are collected, an intense beam is used to maximize the luminosity. However, an intense beam can destroy the target. To prevent the target from being damaged by the beam, a raster system is used. A raster system is located 24 m upstream of the target. The raster system sweeps the beam to cover an area over the target instead of a fixed point, spreading the heat from the impact of the beam over the covered area and preventing the target from large, local-density fluctuations for liquid targets. The

raster has X- and Y-direction air-core dipoles and they can operate in two different modes, sinusoidal- and amplitude-modulated. The sinusoidal-mode uses purely sine waves with a relative phase of 90° . In the amplitude modulated mode the X and Y magnets are driven at a frequency between 17.7 KHz and 24.4 KHz with a difference of phase of 90° producing a circular pattern. By changing the radius of the pattern a uniform distribution of the beam is obtained. The raster of the beam in experiment E94-107 had a rectangular shape of approximately $2\text{ mm} \times 2\text{ mm}$ shown in the following Figure 12.

Figure 12: Rastered beam size and position in experiment E94-107.

2.4 Target system

The design of the target system allows placing different targets in the same ladder, so it is possible to remotely change targets during the experiment. The different targets that can be selected are solid flat targets and cryotargets (liquid). The targets are mounted on a vertical ladder. The ladder can be moved up and down remotely through a DC stepping motor. The accuracy of the relative position of the targets with respect to the beam line is about 0.020 inches. The accuracy in moving the target from one position to another and moving it back is about 0.006 inches. The solid flat target ladder is usually mounted under a system that holds the containers with the cryotargets. The cryotarget chamber has a vertical assembly of long (~15 cm) horizontal and short (~4 cm) horizontal containers to hold liquid hydrogen (LH_2), Deuterium (LD_2), Helium-4 and others.

Figure 13: Pictures of the target ladder (left) and cryotarget system (right).

The complete target system is installed inside the scattering chamber along with sub-systems for cooling, gas handling, temperature and pressure monitoring. All these variables are monitored remotely from the counting house (control room). Among the solid targets we had ^{12}C (thin~50 mg/cm² and thick~100 mg/cm²), which are used for optics studies. Other solid targets were BeO and Ta. BeO is used to have a visual position of the beam over the target since it glows when the electron beam impacts it and Ta is used for commissioning, since it has a large atomic number and it is useful for the scattering of electrons with a minimum recoiling momentum. Dummy targets are also available, which consist of thick aluminum walls to simulate the cryotarget containers. These dummy targets have thickness 10 times larger than those of the cryotarget containers for the purpose of collecting data in less time. They also have the same radiation length as a full target. Once the information for a dummy target is obtained, a subtraction of the background it produces can be done from the cryotarget that contains the target itself (LH₂ or other) plus the walls of the aluminum container of the cryotarget [39]. The scattering chamber that has the purpose of protecting the targets mechanically and thermally has a cylindrical shape with an inner radius of about 100 cm and a height of 90 cm. The thickness of the wall of the scattering chamber is about 5 cm. Openings for entrance and exit of the beam are at both ends of the chamber. The scattered particles exit the scattering chamber through very thin aluminum windows. Each aluminum window is about 18cm high and the thickness of the aluminum walls is about 40 μm .

The cryotargets are installed with loops that contain a cooling system, a heat exchanger, and a fan system that it set to run at 60 Hz. All this equipment is meticulously

organized to keep the target at a very low temperature and in a narrow range of temperatures. In E94107, the LH_2 target was kept at 19 K.

In E94-107, the solid targets were also used for the different optics studies and commissioning. The LH_2 (April 2004) and the waterfall (June 2005) targets were used for the production data. The waterfall target was installed in 2005, for the second part of the experiment. Technical reasons did not allow having the cryotarget system and the waterfall target simultaneously. The waterfall target was installed in the space occupied by the cryotarget system for the second part of the experiment. The waterfall target has the special feature to allow us to have two different kinds of targets at the same time: oxygen and hydrogen. In other words, we look into the two nuclear reactions: $^1\text{H}(e,e'K^+)\Lambda,\Sigma^0$ and $^{16}\text{O}(e,e'K^+)^{16}_\Lambda\text{N}$ simultaneously. The former represents the elementary production of hyperons and the latter is for hypernuclear spectroscopy studies of the $^{16}_\Lambda\text{N}$ hypernucleus. This dissertation is focused on the elementary production of hyperons at low momentum transfer. The data used in this dissertation comes from the first part of the experiment E94-107 in which a LH_2 cryotarget was used. The study of the elementary reaction is also used to calibrate the hypernuclear spectroscopy study of $^{16}_\Lambda\text{N}$, whose data is obtained in the second part of E94107 using the waterfall target.

The waterfall target consists of water falling with thickness controlled by a system, which through a gear pump magnetically coupled to a DC motor, used to produce a stable water film. By changing the speed of the pump, monitored with a tachometer the thickness can be changed. A cooler is used to control the temperature and the thickness is measured by elastic scattering of electrons off hydrogen [40].

2.5 High resolution spectrometers

The two high resolution spectrometers (HRSs) each have at their entrances two superconducting focusing quadrupole magnets Q1 and Q2 that are followed by a dispersing 6.6 m magnetic dipole, which bends the particle trajectories vertically upwards, with a nominal bending angle of 45° . The magnetic dipoles use a field gradient to further focus the particles that pass through them. A third superconducting quadrupole magnet Q3 does a final focusing before particles get into the detector hut. Therefore, both HRSs have a QQDQ configuration, 12.5° being the minimum forward angle they can go and 125° as the maximum. The dipole magnetic field can be set at a central-momentum value ranging from 0.3 GeV/c to 4 GeV/c. The central-ray particle trajectory is the reference for the symmetry plane of the spectrometer magnets. The optical length of the central ray from the target to the exit window of the spectrometers is 23.4 m (see Figure 14). All these features constitute the standard configuration and the parameters that characterize the HRSs are shown in Table 5 [32]:

HRS General Characteristics:

Momentum range: 0.3 – 4.0 GeV/c

Configuration: QQDQ

Bending angle: 45^0

Optical Length: 23.4 m

Momentum Acceptance: $\pm 4.5 \%$

Dispersion at the focus(D): 11.9 m (without septum), 12.4 m (with septum).

Momentum Resolution $\delta p/p$ (FWHM): 1×10^{-4}

Horizontal Angular Acceptance: ± 30 mrad

Vertical Angular Acceptance: ± 60 mrad

Solid Angle at $\delta p/p = 0, y_0 = 0$: 6 msr

Horizontal Angular Resolution: 0.5 mrad

Vertical Angular Resolution: 1.0 mrad

Angular Determination Accuracy: 0.1 mrad

Table 5: General characteristics of the HRSs of the Hall A.

Figure 14: Profile view of the spectrometers in Hall A [32].

On top of the HRSs are the detector huts with their detector packages that can be moved in and out for maintenance and access. Each detector package contains some standard detectors and some specific detectors designed for this specific experiment. The detector configurations for the experiment E94-107 are shown in Tables 6 and 7 and Figures 15 and 16:

Hadron Spectrometer (HRS-L)

VDC: Two Vertical Drift Chambers

S1: Trigger Scintillator Counters

A1: 1st Aerogel Counter

A2: 2nd Aerogel Counter

RICH: Ring Imaging Cherenkov Detector

S2: Trigger Scintillator Counter

Table 6: Hadron arm detector configuration for E94-107.

In experiment E94-107 The HRS-L was configured to analyze positively charged particles like K^+ , π^+ and p^+ . The VDCs provide information on momentum and position of particles while the two layers of scintillators S1 and S2 provide information on the time of flight. A1 and A2 discriminate K^+ from π^+ and p^+ background. The RICH detector enhances the particle identification (PID) done by A1 and A2. More details are discussed in Section 2.6.

Figure 15: Configuration of the detector package in the HRS-L.

The right HRS has the following configuration:

Electron Spectrometer (HRS-R):
VDC: Two Vertical Drift Wire Chambers
S1: Trigger Scintillator Counters
CER: CO ₂ Gas Cherenkhov counter
S2: Trigger Scintillator Counters
PS: Preshower Counters
SH: Total Shower Counters

Table 7: Electron arm detector configuration for E94-107.

In experiment E94-107 The HRS-R was configured to analyze negatively charged particles as e^- and π^- . The VDCs provide information on momentum and position of particles while the two layers of scintillators S1 and S2 provide information of the time of flight. The CO₂ Gas Cherenkhov counter (CER) discriminates e^- from π^- background. The preshower (PS) and shower (SH) detectors enhances the particle identification (PID) done by CER. More details are discussed in Section 2.6.

Figure 16: Configuration of the detector package in the HRS_R.

2.5.1 Septum magnets

Experiment E94-107 required very forward scattering angles of $\sim 6^\circ$. Since the HRSs cannot go further than 12.5° a new pair of magnets were inserted in front of the two spectrometers and after the scattering chamber to be able to horizontally bend trajectories of scattered particles at forward angles ($\sim 6^\circ$) towards the entrance of the spectrometers located at 12.5° without significantly affecting the optics and momentum resolution of the two HRSs and in this way ensure good resolution in the missing mass spectra (see Figure 17). An important consideration in the design of the septa is maximizing the angular acceptance to match the solid angle of the spectrometers of around 4.5 msr.

Figure 17: Picture of one of the septum magnets during fabrication.

The design of the septa allows complete angular coverage over the full range from 6° to 12.5° to smoothly overlap the standard HRS minimum angle for all momenta up to 4 GeV/c. In particular, there are two important parameters, they are the distance (d) that the target chamber was moved upstream in order to provide enough space to insert the septa, 80 cm, and the distance (T) from the septum gap to the beam line which was minimized to be 2.5 cm (see Figure 18) [41]. The optics was studied and the results were as expected and are described in Section 3.2.

Figure 18: Layout of the septum magnet insertion [41].

2.6 Detector stack packages

The two high-resolution spectrometers are very similar except for some detectors used for PID. The position of the detectors in the detector stacks is shown in Figure 15 and Figure 16. The detectors used in experiment E94107 are listed in Tables 6 and 7.

2.6.1 Scintillator counters

Each HRS uses two layers of scintillators called S1 and S2. These layers are made of thin plastic scintillators (polyvinyl toluene, PVT) to minimize hadron absorption. They are separated 2 m along the flight path. The S1 consists of six overlapping paddles with dimensions $36\text{ cm} \times 30\text{ cm} \times 0.5\text{ cm}$ and the S2 consists of six paddles with dimensions $60\text{ cm} \times 37\text{ cm} \times 0.5\text{ cm}$. At both ends of each counter (paddle) there are photomultiplier tubes (PMT) attached through light couplers. The PMTs are Burle 8575 and their time resolution is 200 ps per plane [32].

The set of two layers S1 and S2 in each detector stack allows measuring the time it takes for charged particles to travel the distance in between. Therefore, using the time of flight (TOF), the velocity of particles can be measured. In order to prevent light leakage, the scintillators are wrapped in one layer of aluminum foil and two layers of Tedlar (polyvinyl fluoride). The active area for S1 is $170\text{ cm} \times 35\text{ cm}$ and for S2 is $220\text{ cm} \times 54\text{ cm}$ and the scintillator paddles overlap by 5mm to maximize coverage of the area through which particles go (see Figure 19). The first scintillator plane (S1) is located at 1.5 m from the center of the first vertical drift chamber (VDC) and the second

scintillator plane (S2) is located at 3.5 m from the center of the first plane of the VDC. Triggers are generated by the PMT signals from the scintillator planes and are sent to all other detectors and data acquisition system.

Figure 19: View of S1 looking upstream.

2.6.2 Vertical drift chambers (VDC)

The VDCs are the HRS tracking detectors. They provide measurements of position and angle for both electrons (HRS-R) and hadrons (HRS-L) at the focal planes of the respective spectrometers [32, 42]. The VDC consists of two planes separated by a distance of 33.5 cm in each HRS detector stack. However, because of the 45° angle of the central ray, the distance along the central ray is about 47.4 cm. Each of the VDC planes

are composed of two wire planes U and V. The distance between the two U and V planes is 26 mm. The wires of the U plane are perpendicular to the wires of the V plane. Both U and V wires make an angle of 45° with the dispersive and transverse directions in the spectrometer. The VDC wires are in a chamber filled with a mixture of gases: Argon (62%) and Ethane (38%). The gas mixture flows through the chambers at 10 liters/hour. Details are shown in Figure 20.

Figure 20: Details of the vertical drift chambers [32].

As charged particles pass through the gas chamber they produce ionization. In addition, each VDC has three high voltage planes (cathodes) at -4KV. The cathode planes

and the U and V wire planes are parallel and alternated so each wire plane is in between two cathode planes. The resulting electric field configuration is shown in Figure 21.

When electrons are produced by ionization they drift to the wires. That time is measured by a Time to Digital Converter (TDC), which is started by the triggered wire and stopped by a signal from the trigger supervisor. The trigger supervisor is the electronic device that controls the Hall A data acquisition system.

Figure 21: Electric field and equipotential lines inside the VDC [43].

Figure 21 shows a diagram of the distribution of electric field lines and equipotential lines in a VDC making most of the drift of the electrons produced by ionization along the perpendicular direction of the planes. If the drift distance and the drift time through the TDCs are obtained then the drift velocity of the electron in the gas mixture can be determined. The drift chamber TDCs measure the time that the wire detected the electrons created by the ionization of the chamber gas relative to the time of

the trigger. Then using the scintillator TDCs to determine the time that the particle passed through the focal plane (relative to the trigger), the time it took for the electrons created by the ionizing particles to drift to the wire can be determined. The drift time is converted into a drift distance and, taking into account the distance from all the wires that fired when a particle passed through the VDC, the trajectory of the particle can be obtained. Position is determined with a resolution of 225 μm (FWHM) and the angular resolution is approximately 0.3 mrad (FWHM) [44].

2.6.3 Gas threshold Cherenkov detector

A CO₂ gas threshold Cherenkov detector was used in the right HRS to distinguish electrons from negative pions and it is located in between the S1 and S2 scintillator planes in the HRS-R detector stack as shown in Figure 16. The detector contains CO₂ at atmospheric pressure with an index of refraction (n) of 1.00041. The length of the particle path in the gas radiator is about 130 cm. The threshold speed of particles is $\beta_{th}=1/n=0.999590$. Consequently, the threshold momentum given by $p_{th} = \frac{m_0 c}{\sqrt{1-\beta^2}}$, with m_0 as the rest mass, is 4.8 GeV/c for negative pions and 17 MeV/c for electrons [45]. Therefore, the CO₂ gas threshold Cherenkov detector with a momentum range from 0.30 GeV/c to 4.0 GeV/c is an excellent tool for particle identification (PID) as described in Chapter 4.5.

Figure 22: CO₂ gas threshold Cherenkov detector, JLab PHY98-06.

The detector is made of steel with thin entrance and exit windows made of Tedlar. It has a 10 spherical mirror arranged as shown in Figure 22 [46]. The mirrors are very light and represent a thickness no more than 0.23 g/cm^2 for the particles passing through. Each mirror is individually coupled to PMTs (Burle 8854), which are located at the focal point of the mirrors (45cm from the mirrors). All the electric signals resulted from the light collected by the PMT, are sent to ADCs. Although pions are not supposed to emit Cherenkov radiation they can still interact with the material, knocking out electrons, that in turn produce Cherenkov radiation. As a result, a small amount of light caused by negative pions will also be observed. However, the light produced as a result of pion interactions will produce fewer numbers of photoelectrons on average compared to those produced by electrons. Consequently, electrons can be distinguished from negative pions.

The average number of photoelectrons produced by a 1.56 GeV electron in the CO₂ gas threshold Cherenkov detector is of ~ 14 p.e. [47].

2.6.4 Lead glass preshower and shower counters

There are two lead glass counters in the electron arm (HRS-R). The preshower counter consists of an array of $2 \times 24 = 48$ blocks of lead glass transversely oriented with respect to the directions of the scattered electrons (Figure 23). The shower counter consists of $5 \times 20 = 100$ blocks of lead glass oriented parallel to the direction of the scattered electrons [32].

Figure 23: HRS_R shower and preshower counters [32].

Each lead glass block in the preshower is $10\text{cm} \times 10\text{cm} \times 35\text{cm}$ and in the shower is $14.5\text{cm} \times 14.5\text{cm} \times 35\text{cm}$. They are made of DF6 lead glass with a density of 5.18 g/cm^3 .

These detectors provide additional PID and are located behind the second scintillator plane S2. The signal detected by the lead glass counters is linearly proportional to the energy deposited by the incoming particle. The longitudinal distribution of the energy deposited in the counter can be used to identify the incident particles because, due to the longer hadronic mean free path, hadronic showers do not develop while electromagnetic showers do. Hadrons produce a low ADC signal while electrons produce a high ADC signal. The resolution of the detector comes from separating the tails of the two ADC signals. To improve this resolution a double layer of lead glass counters is used, because electrons will deposit most of their energy in the first layer while hadrons will deposit more of their energy in the second. The proper combination of the two lead glass layers enhances the detection of electrons or pions.

2.6.5 Aerogel threshold Cherenkov counters

The aerogel threshold Cherenkov counters are located in the hadron arm (HRS-L) inside the detector stack. There are two aerogel threshold Cherenkov counter detectors called A1 and A2. The purpose of using A1 and A2 in experiment E94-107 is to discriminate kaons from pions and protons. The detectors A1 and A2 form the basic hadron PID procedure, which is further enhanced with a Ring Imaging Cherenkov detector described in Chapter 2.6.6. The A1 and A2 have similar designs. Both are diffusion box types of Cherenkov threshold detectors with different threshold momenta for the different particles.

The A1 has 24 PMTs Burle RCA 8854 with high quantum efficiencies in UV and visible ranges of the electromagnetic spectrum (see Figure 24). The PMTs are aligned at both sides of the diffusion box, which is internally covered with millipore paper with high reflectivity (more than 95%). A 9 cm thickness layer of silica aerogel over a honeycomb structure resides at the bottom and constitutes the Cherenkov radiator. The refractive index of the silica aerogel in A1 is $n_1=1.015$.

Figure 24: A1 silica aerogel Cherenkov detector.

The A2 detector was designed with similar characteristics (see Figure 25), but it has 26 Photonics XP 4572 PMTs and 5 cm of silica aerogel with a refractive index of $n_2=1.055$ [32, 48].

Figure 25: A2 silica aerogel Cherenkov detector.

The PMTs in A2 are different because they do not need to be so sensitive since the number of photoelectrons produced is greater. The greater the refractive index the smaller the threshold momenta and the greater number of photons produced by Cherenkov radiation.

In order to use A1 and A2 to discriminate kaons from protons and pions, we took advantage of the different threshold momenta of the particles in the two detectors. Figure 26 shows the threshold momenta for kaons, protons and pions in both detectors [49].

Figure 26: Threshold momenta for different particles in A1 and A2 [48] and private communication with R. Feuerbach.

In experiment E94-107 three different momenta were set in the hadron spectrometer (HRS-L). These momenta were in the range from 1.82 GeV/c to 1.96 GeV/c. According to the graph shown in Figure 26 for kaons, pions and protons we observe that pions fire both detector A1 and A2, protons fire neither A1 nor A2, and kaons fire A2 but not A1.

Particle	Condition for identification
Pions (π^+)	A1 & A2
Kaons (K^+)	$\overline{A1}$ & A2
Protons (p^+)	$\overline{A1}$ & $\overline{A2}$

Table 8: PID conditions for different particles in A1 and A2.

Specific details and results of the PID procedure are shown in Section 4.1. The average number of photoelectrons (p.e.) obtained per events was of up to 8 p.e. in A1 and of up to 30 p.e. in A2.

Figure 27: Picture showing from left to right; A2, A1 and S1, in the hadron arm. Particles traverse the stack from lower right to upper left.

2.6.6 Ring imaging Cherenkov detector (RICH)

The RICH detector uses the geometrical features of the distribution of the Cherenkov radiation as a tool to identify particles. Basically, Cherenkov radiation is emitted by charged particles moving faster than the speed of light in the medium. The geometrical distribution can be described by $\cos \theta_c = 1/\beta n$. This angle is shown in Figure 28.

Figure 28: Cherenkov radiation geometrical distribution [50].

Therefore, at different speeds the opening angle of the Cherenkov cone will be different. In the case of experiment E94-107, pions, kaons and protons have different speeds. Their Cherenkov radiation will exhibit different cone angles θ_c .

The Hall A RICH detector has a Neoceram container with Freon (C_6F_{14}) radiator, which has a high refractive index of 1.28. The exit window of the Neoceram container is made of fused quartz. This design enhances well-defined light cones of focusing Cherenkov radiation with cone angles θ_c as different as possible for the three different particles. The Cherenkov radiation goes through an environment of dry methane (CH_4). The RICH detector detects the Cherenkov light on a photosensitive plane made of three pads of CsI, and reconstructs the Cherenkov angle of light emitted by the incident particle [51]. After that, the information of the detection of the ring as well as the middle point of ionization are translated into electronic signals. Figure 29 shows schematically the details of the components of the RICH. Figure 30 shows a picture of the RICH at the detector stack.

Pions are expected to be faster than kaons, and kaons to be faster than protons. Therefore, the detected rings produced by pions will have bigger radii than the ones produced by kaons and the detected rings produced by kaons will have bigger radii than the ones produced by protons.

The RICH detector significantly increased the signal to noise ratio. The enhancement in the PID was very important in E94-107 for targets like carbon, beryllium and oxygen. In the case of hydrogen the time of flight provided by the scintillators and the aerogel detectors were enough to have a good PID without losing statistics. In the case of hydrogen, the RICH detector can be used to easily determined the aerogel detector efficiencies as will be described in Section 4.4.

Figure 29: Schematic view of the Hall A operation [50, 51].

Figure 30: Picture of the RICH detector in the HRS-L detector stack, with the A2 just below it.

2.7 Data acquisition

2.7.1 Data acquisition system

All the data obtained when running the experiment comes as electronic signals, which have to be properly combined, recorded and monitored to ensure the data quality. The CEBAF On-line Data Acquisition system (CODA) is a special software developed by Jefferson Lab to readout nuclear physics experiments. In order to readout the data coming from the experiment, the acquisition system uses hardware Read Out Controllers (ROC's), an event builder (EB), and an online analyzer. The information about an event,

such as the run number, information from the detectors, spectrometer magnets settings, angles of scattered particles, scalers data, target temperature and pressure, spectrometers positions, and beam; energy, current and profile, are transferred to the recording computers by the ROC's. After that, the information is combined and organized by the EB and then is incorporated into a common event format [52]. Then the online analyzer system is used to analyze the data and save it to the hard drives, and later, transferred to storage devices such as tapes. The online analyzer is a very important tool since it allows us to take a preliminary view of the output of the experiment to ensure that the detectors and electronic equipment are working properly while acquiring the data.

A single Run Control process controls a network of computers used to run the CODA acquisition system. The Run Control function runs the ROC subsystems, the EB, the EA, and the ER. The ADCs, TDCs and scalers in FASTBUS and VME crates monitor and process signals coming from the detectors. Three independent ROC's, each of them reading/recording part of the information associated with an event, allow the system to have over 20 front-end crates (FASTBUS and VME), with a FASTBUS interface that can read out up to 10000 detector channels.

Finally, the EB receives the data from the ROC's and checks for any missing data. Then, the EB writes the data for each event onto disk.

2.7.2 Trigger electronics

The primary trigger signals come from the scintillators' PMT anode signals. The signals from the detectors are sent to the ADCs and to a discriminator. If the discriminator senses a signal greater than its threshold, whose leading edge lies within a narrow time window, then it sets an output. The VME settable registers control the time window width and offset.

The discriminator time-over-threshold signals are compared to signals coming from other scintillator detectors. In the case of coincidence experiments, a coincidence is formed between the spectrometer arms. The main trigger is formed when both scintillator planes S1 and S2 fire. Therefore, there must be a hit in both PMTs of one paddle in S1 and one in S2. The coincidence between spectrometers is an overlap AND circuit. The right spectrometer single triggers are called T1 and the ones in the left spectrometer are called T3, while the coincidence triggers are called T5. The aerogel Cherenkov detectors produced a trigger, T6, when a kaon was detected. T7 is created by having T5 and T6 in coincidence (coincident kaons). The main configuration of the triggers is in Table 9:

TRIGGERS	
T1	Electron or right HRS (T1) (S1 and S2)
T2	Electron or right HRS (T2)
T3	Hadron or left HRS (T1) (S1 and S2)
T4	Hadron or left HRS (T2)
T5	HRS R & HRS L coincidence
T6	Aerogel
T7	Aerogel and coincidence
T8	Pulser

Table 9: Main configuration of triggers in E94-107.

Additional T2 and T4 triggers are formed when only 3 PMTs fire in the right arm and in the left arm respectively, and they constitute looser triggers. The T2 and T4 triggers are useful for the Scintillators' efficiencies analysis described in Section 3.4.

The delays for the trigger system in Hall A can be configured remotely through CAMAC modules. Sometimes during an experiment the delays need to be adjusted for the timing of triggers that change with particle momenta and particle identification (PID). However, these delays are relevant for coincidence setups only. The signals from the detectors are sent to the Memory Logic Units (MLUs). The output of the MLUs for the experiment is ORs and ANDs of all detectors for which they fired. The MLUs in each spectrometer arm generated a logical output (S-ray) when both PMTs of a scintillator paddle in S1 and in S2 of an adjacent or coincident paddle fired.

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In Figure 31 a schematic of the single arm triggers in either the electron or hadrom spectrometer is shown. T5 constitutes the coincidence trigger and T7 the kaon coincidence trigger. A T5 is obtained each time a single arm S-ray triggers a logical AND unit. There is a time window setup of approximately 100 ns for the coincidence to be accepted as such. Furthermore, the number of events for every trigger type is recorded by a running scaler, which is read and logged by the data acquisition system (DAQ) every 10 seconds. Although, all triggers can fire the DAQ, it is T7 that has the priority and the

3 Calibration, corrections and efficiency measurements

A brief description of coordinate systems, optics calibration and some of the corrections and efficiency measurements without PID software analysis are presented in this section, which are important pieces of information that later, will be used in Section 4 to extract the cross section for the reactions $^1\text{H}(e, e'K^+)\Lambda, \Sigma^0$. To obtain this information specific programming codes have been created that not only provide efficiencies but also particle tracking reconstruction.

3.1 Coordinate systems

3.1.1 Hall A coordinate system (HCS)

Usually, the origin of the HCS is at the center of the hall, as defined by the intersection of the electron unrastered beam and the vertical symmetry axis of the target lifter assembly on the hall's spectrometer pivot. However, as a result of the insertion of the septum magnets the optical center was moved 80 cm upstream from the its normal position. A top view of the HCS is shown in Figure 33. The z axis is along the beam line and points in the direction of the beam dump, y is vertically upward, and $\hat{x} = \hat{y} \times \hat{z}$ [32].

Figure 33: Top view of the Hall A coordinate system.

3.1.2 Target coordinate system (TCS)

The TCS is referenced by the line passing through the target along the central momentum of either of the spectrometers. The line defines, at the target, the z axis of the TCS for a given spectrometer. Consequently, each spectrometer has its own TCS. The x axis is the line crossing perpendicularly both, the electron beam line and the z axis, and it points downward (see Figure 34). The xz plane determines the y axis of the TCS. The triplet $\hat{x}$, $\hat{y}$ and $\hat{z}$ is right handed. Variables referring to the coordinates at the target are designed by the subscript "tg". Therefore, variables x_{tg} and y_{tg} are defined as the x and y

coordinates of the point of intersection of a particle trajectory with the $z_{tg} = 0$ plane. The variables θ_{tg} and ϕ_{tg} are defined as [32]:

$$\tan \theta_{tg} = \frac{dx_{tg}}{dz_{tg}} \quad (27)$$

$$\tan \phi_{tg} = \frac{dy_{tg}}{dz_{tg}} \quad (28)$$

Figure 34: Target coordinate system in Hall A (top view).

The relative momentum δ_{tg} is defined by $\delta_{tg} = \frac{(p - p_0)}{p_0}$, where p is the particle momentum and p_0 is the spectrometer central momentum.

3.2 Optics calibration

In Hall A, conventionally the two HRS are an identical pair of QQDQ magnetic spectrometers with optical properties that are point-to-point in the dispersive direction. However, for E94-107 septum magnets were added, making each spectrometer arrangement into a Septum + QQDQ, which required a recalibration of the optics. The main purposes of the optics calibration are to improve the accuracy in reconstructing the variables at the target from the variables observed at the VDC detectors (at the focal plane) and to independently establish the spectrometer resolution [54].

The optics database is a set of tensor elements defining the transport tensor which links the coordinates measured at the focal plane of the spectrometers with the angular, spatial coordinates at the target, and the momentum. The focal plane coordinates are described by the four quantities; x_{fp} , y_{fp} , θ_{fp} , ϕ_{fp} . A detailed description of the coordinate systems used is given in [55, 56]. When the left-right symmetry of the spectrometers with respect to their vertical mid-planes holds then the relationship between the focal plane and target coordinates could be written in a first-order approximation as a simple matrix given by:

$$\begin{pmatrix} \delta \\ \theta \\ y \\ \phi \end{pmatrix}_{tg} = \begin{pmatrix} \langle \delta | x \rangle & \langle \delta | \theta \rangle & 0 & 0 \\ \langle \theta | x \rangle & \langle \theta | \theta \rangle & 0 & 0 \\ 0 & 0 & \langle y | y \rangle & \langle y | \phi \rangle \\ 0 & 0 & \langle \phi | y \rangle & \langle \phi | \phi \rangle \end{pmatrix} \begin{pmatrix} x \\ \theta \\ y \\ \phi \end{pmatrix}_{fp}, \quad (29)$$

where x_{tg} is determined independently by BPM measurements.

However, the insertion of the septum magnets destroys the symmetry of the spectrometers with respect to their vertical mid-planes so the matrix (29) gets replaced with one that is more complicated (e.g., has more non-zero elements). Thus, the target variables are given by:

$$y_{tg} = \sum_{ijkl} Y_{ijkl} x_{fp}^i \tan^j(\theta_{fp}) y_{fp}^k \tan^l(\phi_{fp}), \quad (30)$$

$$\tan(\theta_{tg}) = \sum_{ijkl} T_{ijkl} x_{fp}^i \tan^j(\theta_{fp}) y_{fp}^k \tan^l(\phi_{fp}), \quad (31)$$

$$\tan(\phi_{tg}) = \sum_{ijkl} P_{ijkl} x_{fp}^i \tan^j(\theta_{fp}) y_{fp}^k \tan^l(\phi_{fp}), \quad (32)$$

$$\delta_{tg} = \sum_{ijkl} D_{ijkl} x_{fp}^i \tan^j(\theta_{fp}) y_{fp}^k \tan^l(\phi_{fp}), \quad (33)$$

and the tensor elements; Y_{ijkl} , T_{ijkl} , P_{ijkl} , D_{ijkl} are polynomial expansions on x_{fp} up to the fifth order ($i + j + k + l \leq 5$) [57].

The database optimization starts with sets of data from elastic scattering on a thin ^{12}C target. Generally, 5 open collimator measurements are performed at $\Delta p/p$ values stepping between -4.5% and +4.5% of the spectrometer central momentum, so that the elastic peak moves across the focal plane. The sieve slit is used to optimize the reconstruction of the angular coordinates. It is positioned behind the target at the entrance of the septum magnets. Each slit has 49 holes of different sizes in well-defined x_{sieve} and y_{sieve} positions as shown in Figure 35.

Figure 35: Picture of the sieve used in Hall A.

An iterative procedure is performed in analysis to obtain the best tensor elements for the optics database. Optics tensor elements for both spectrometers have been optimized over the full ranges many times prior to the insertion of the septum magnets making the process well understood. However the E94-107 setup is the first optimized setup with both septum magnets included. Furthermore, the LH_2 cryotarget used in E94-107 was only 4 cm long. The modest length target together with the kinematics of E94-107 (which was carried out at very forward angles), made the target look quite thin from the point of view of the magnetic spectrometers. Thus, the iterative process of optimization converged faster to the optimal values for the tensor elements

Worthy of note, the spectrometer optics is very sensitive to the values of the magnetic fields in Q2 and Q3. Since the quadrupoles are set by current and not by field, a cycling procedure is required because of the hysteresis effects in the magnets [58]. Figure 36 shows the angular reconstruction of the sieve slit plotting the axes in millimeters.

Figure 36: Sieve slit design (left), sieve reconstruction, before optimization (central) and after optimization (right) (Dec 2003) [57].

The optics optimization analysis was performed at the same spectrometer settings as the experiment. The result of the δ optimization for the kinematics settings of E94-107 corresponded to an average momentum resolution of $\delta p/p = 1.8 \times 10^{-4}$ FWHM on the left arm and $\delta p/p = 1.6 \times 10^{-4}$ FWHM on the right arm. By selecting the central hole of the sieve slit, a slightly improved resolution of 1.4×10^{-4} was obtained on both HRS arms as was expected for the HRS [32]. The elastic scattering peak width includes the incident beam energy spread, yielding a measured sigma of 1.2×10^{-4} (not FWHM, see Figure 37).

Figure 37: Hall A momentum resolution with septum magnets after optics optimization on a thin ^{12}C target (Hall A electronic logbook, December 2003).

3.3 Kaon absorption

Particles traverse different materials along the path from the target up to the detector stack. Consequently, some kaons are absorbed [59]. Dr. Joerg Reinhold developed a program using the kaon-proton cross-section information in the Particle Data Book [60] and on the basis of the eikonal approximation [61] to calculate the kaon absorption depending on the kaon momentum [62]. The program was written in Fortran and it basically determines the ratio of the real to the imaginary part of the kaon nucleon scattering amplitude for forward angles by fitting the K^+ absorption data on ^{12}C from the Particle Data Book [60]. The kaon absorption is proportional to this ratio.

In order to run the program it needed to be adapted to the conditions of experiment E94-107. The program requires detailed information on the thickness of the different materials the kaons traverse on the way to the final detector, including the density and the atomic weight of these materials.

Figure 38 shows how the absorption of kaons decreases as momentum increases. These results show a slowly varying uncertainty, which is sensible considering the small momentum acceptance of $\pm 4\%$ ($\delta p/p$) in the magnetic spectrometer. The program containing the list of all materials is in Appendix A.

During experiment E94-107 three slightly different momenta were set in the hadron arm (HRS-L) to allow some acceptance studies as will be shown in Section 4. Therefore, the kaon absorption coefficients and the associated uncertainties were calculated for those three momenta as shown in Table 10:

KIN	Kaon Momentum (GeV/c)	Variation in momentum		absorption	Variation in absorption		uncertainty
		-4%	4%		-4%	4%	
KIN_1	1.8665	1.7918	1.9412	0.03585	0.03736	0.03450	0.00143
KIN_2	1.8218	1.7489	1.8947	0.03672	0.03821	0.03541	0.00140
KIN_3	1.9600	1.8816	2.0384	0.03415	0.03559	0.03283	0.00138

Table 10: Kaon absorption and uncertainties in E94-107.

Figure 38: Kaon absorption vs. kaon momentum in E94-107. The errors reflect the $\pm 4\%$ variations on $\delta p/p$.

3.4 Scintillators' efficiencies

The trigger types must be considered carefully to determine the scintillator efficiencies. The basic triggers are T1 (electron arm) and T3 (hadron arm). They are formed by the overlap of the S1 and S2 scintillator planes. The description of the scintillators is in Section 2.6.1. The triggers T1 and T3 are formed when the 4 photomultipliers (PMTs) of the two overlapping paddles of scintillators fire in their respective spectrometers. The less stringent T2 (electron arm) and T4 (hadron arm) are formed when only 3 PMTs fire instead. In this sense T2 and T4 are looser triggers than

T1 and T3. The T5 triggers are formed by the T1 and T3 in coincidence. In addition, there is also T6 trigger formed by the aerogel detectors (see Section 2.6.5) when there is a positive identification of a kaon, and finally there is T7 trigger that is formed by having T6 and T5 triggers, in other words kaons in coincidence.

Imposing a pre-scale factor to a certain trigger determines the number of events that will be rejected in between storing the event with that particular trigger type. The pre-scale factors are labeled as PS1, PS2, ... to PS7. Consequently, the trigger T7 that is formed by the most interesting events has a $PS7 = 1$. Nevertheless, all T5, T6 and T7 are analyzed to maximize our statistics. As a consequence, other particles like protons and pions will be also counted and particle identification cuts are needed to discriminate kaons from protons and pions (see Section 4.1). In order to obtain the scintillators' efficiencies the ratio of all events that fired 4 PMTs to all events that fired at least 3 PMTs is considered. Therefore, on the basis of the previous lines the following equations are used to evaluate the scintillator efficiencies in the electron arm (E_e) and in the hadron arm (E_H):

$$E_e = \frac{PS1 \cdot T1 + PS5 \cdot T5 + PS7 \cdot T7}{PS1 \cdot T1 + PS2 \cdot T2 + PS5 \cdot T5 + PS7 \cdot T7} \quad (34)$$

$$E_H = \frac{PS3 \cdot T3 + PS5 \cdot T5 + PS6 \cdot T6 + PS7 \cdot T7}{PS3 \cdot T3 + PS4 \cdot T4 + PS5 \cdot T5 + PS6 \cdot T6 + PS7 \cdot T7} \quad (35)$$

The total efficiency then can be measured just by multiplying the Equations (34) and (35) [63].

$$E_{\text{Scint}} = E_e \times E_H \quad (36)$$

It is also important that a “good” sample of events is being used when measuring the efficiencies. To obtain good events, geometrical cuts are used on the active area of the scintillators (to avoid the edges) and a projected particle track can be required to pass through that active area. Although, this ensures a better determination of the scintillators’ efficiencies there is a negative effect, which is to decrease in statistics. Usually in doing analysis physicists try to optimize these competing requirements. However, in E94-107 with the hydrogen cryotarget the number of electron-kaon coincidence events was fairly small so instead a larger number of good events was obtained by not imposing particle ID cuts on the detectors (see Section 2.6.2). The results of the scintillators’ efficiencies run by run are graphically shown in Figure 39 and in full details in Appendix B.

Figure 39: Scintillators’s efficiencies per run number in E94-107.

The summary of results is shown in Table 11. The run numbers are grouped into three different kinematics (momentum setting of the hadron). See Section 4.9 for details on how uncertainties were determined.

Run Number	Scint_eff	Uncert.
KIN_1 $p_K=1.8665 \text{ GeV/c}$		
2485	0.93576	0.00002
2486	0.93556	0.00002
2487	0.93493	0.00002
2488	0.93589	0.00003
2489	0.93546	0.00003
2490	0.93573	0.00003
2491	0.93544	0.00003
2492	0.93501	0.00003
KIN_2 $p_K=1.8218 \text{ GeV/c}$		
2496	0.93326	0.00003
2497	0.93249	0.00003
2498	0.93307	0.00003
2499	0.93257	0.00003
2500	0.93280	0.00003
2501	0.93342	0.00003
2503	0.81533	0.00065
2504	0.93262	0.00003
2505	0.93273	0.00003
2506	0.93251	0.00004
2507	0.93278	0.00003
2508	0.93243	0.00003
KIN_3 $p_K=1.9600 \text{ GeV/c}$		
2509	0.93490	0.00002
2510	0.93585	0.00002
2511	0.93474	0.00002
2512	0.93466	0.00002
2513	0.93511	0.00002
2514	0.93511	0.00002
2515	0.93431	0.00002
2516	0.93400	0.00003
2517	0.93474	0.00002
2518	0.93536	0.00002
2519	0.93518	0.00002
2520	0.93561	0.00002
2521	0.93515	0.00002

Table 11: Scintillators' efficiencies and uncertainties per run number.

3.5 Vertical drift chamber efficiencies

The VDCs are the first detectors that particles get through in the detector stacks. The main reason to have these VDC detectors in front of the rest of detectors is to minimize undesired multiple scattering. Detector inefficiencies cause particles to not fire triggers, which are then missed from the data sample. Inefficiencies in the drift chambers (hardware) or tracking algorithms (software) both separately reject events. Even if a trigger is formed there will be some events where the information is too incomplete to reconstruct a particle track. The main source of these types of inefficiencies is events in which too many or too few wires fire in the drift chambers. It is usual for VDC detectors that any real particle going through the VDCs would produce three or more hits in each of the four planes. Therefore, a cut was applied to the number of wires that give a signal for a given event (multiplicity variable) in all four planes (U1, U2, V1, V2) for both hadron and electron arms. The cut applied was such that events that fired between 2 and 20 wires in each of the 4 wire planes were considered for the analysis.

The VDC efficiency represents the ratio of good events to the sum of good events and undetected events. The cross section requires the true number of events so the inverse of the efficiency is used as a correction factor for the yield to determine the cross section (see Section 4.8).

The number of particles that hit all planes is determined by means of the multiplicities on each individual plane for any VDC by:

$$N_{1234} = M_1 \cdot M_2 \cdot M_3 \cdot M_4 \quad (37)$$

where the multiplication represents the logical AND operator. M_k represents multiplicity and the indices 1, 2, 3 and 4 denote the planes U1, V1, U2 and V2, respectively. The generic equation of the number of planes hit in any of the 3 VDC planes can be taken as:

$$N_{ijk} = M_i \cdot M_j \cdot M_k, (i < j < k) \quad (38)$$

The tracking efficiency is determined by dividing the number of good 1-track particles by the number of hits in all planes given by (37). The number of good 1-track particles is the number of particles with a single track that made the detector fire. Therefore the efficiency for tracking can be expressed as (for any arm) [64]:

$$E_{\text{VDC}}^T = \frac{M_1 \cdot M_2 \cdot M_3 \cdot M_4 \cdot 1_{\text{Track}}}{M_1 \cdot M_2 \cdot M_3 \cdot M_4} \quad (39)$$

The following plots in Figures 40 and 41 show the histograms of number of counts vs. number of hit wires per plane in the left arm and the right arm, and two peaks can be observed. The VDCs were set in such a way that when one particle is detected traversing them, is because around 5 wires get hit. Therefore, with less likelihood, when two particles are detected traversing them, is because around 10 wires get hit.

Figure 40: Number of hits on the left VDC planes for run 2509. Peak at 5 wires reflects one detected particle, peak at 10 wires reflects two detected particles simultaneously.

The single plane firing efficiency ($E_{\text{VDC}_i}^F$) represents the probability a plane has been fired and it is defined as the ratio of the particles that fired all planes to those that fired at least three planes but without taking into account the plane for which the firing efficiency is being determined.

$$E_{\text{VDC}_i}^F = \frac{N_{ijkl}}{N_{ijk}} \quad (40)$$

Therefore, the total efficiency in the VDC either in the hadron arm or the electron arm can be define as the product (dependent probabilities) given by:

$$E_{\text{VDC}}^{\text{F}} = \prod_{k=1}^4 E_{\text{VDC}_k}^{\text{F}} \quad (41)$$

Once the firing efficiency and the tracking efficiency for each arm are determined then the total VDC efficiency for each arm can be measured as the product:

$$E_{\text{VDC}}^{\text{e}} = E_{\text{VDC}}^{\text{e,F}} \times E_{\text{VDC}}^{\text{e,T}} \quad (42)$$

$$E_{\text{VDC}}^{\text{H}} = E_{\text{VDC}}^{\text{H,F}} \times E_{\text{VDC}}^{\text{H,T}} \quad (43)$$

where e denotes electron arm and H denotes hadron arm.

Finally, the total VDC efficiency with the hadron VDC detector and the electron VDC detector combined results from multiplying (42) and (43)

$$E_{\text{VDC}} = E_{\text{VDC}}^{\text{e}} \times E_{\text{VDC}}^{\text{H}} \quad (44)$$

Figure 42 shows the VDC efficiencies plotted vs. the run number in E94-107. The uncertainty bars are very small and can barely be seen in the graph. In addition, Tables 12 and 13 show a summary of the main VDC efficiencies with their uncertainties. See Section 4.9 for details on how uncertainties are determined. Extra information on the VDC analysis can be found in Appendix C.

Figure 41: Number of hits on the right VDC planes for run 2509. Peak at 5 wires reflects one detected particle, peak at 10 wires reflects two detected particles simultaneously.

Figure 42: VDC efficiencies in E94-107.

RUN	VDC eff.	VDC eff. R	VDC eff. L	R tracking	L tracking	R firing eff.	L firing eff.
KIN_1	p=1.8665 GeV/c						
2485	0.7344	0.8049	0.9124	0.8311	0.9329	0.9685	0.9780
2486	0.7329	0.8042	0.9114	0.8302	0.9318	0.9686	0.9781
2487	0.7332	0.8038	0.9121	0.8299	0.9326	0.9686	0.9781
2488	0.7383	0.8074	0.9144	0.8336	0.9335	0.9687	0.9795
2489	0.7394	0.8085	0.9146	0.8339	0.9340	0.9694	0.9792
2490	0.7402	0.8088	0.9152	0.8349	0.9341	0.9687	0.9798
2491	0.7360	0.8057	0.9135	0.8318	0.9328	0.9686	0.9793
2492	0.7402	0.8086	0.9154	0.8343	0.9344	0.9691	0.9797
KIN_2	p=1.8218 GeV/c						
2496	0.6947	0.7747	0.8968	0.8028	0.9172	0.9650	0.9778
2497	0.6946	0.7750	0.8963	0.8031	0.9170	0.9650	0.9775
2498	0.6958	0.7761	0.8966	0.8041	0.9173	0.9652	0.9775
2499	0.6940	0.7748	0.8957	0.8031	0.9167	0.9649	0.9771
2500	0.6945	0.7748	0.8965	0.8029	0.9170	0.9649	0.9776
2501	0.6910	0.7721	0.8949	0.8002	0.9158	0.9649	0.9772
2502	0.6938	0.7748	0.8954	0.8028	0.9164	0.9651	0.9771
2503							
2504	0.6926	0.7733	0.8956	0.8015	0.9165	0.9649	0.9772
2505	0.6949	0.7759	0.8957	0.8039	0.9166	0.9651	0.9772
2506	0.6957	0.7761	0.8965	0.8038	0.9173	0.9655	0.9774
2507	0.6942	0.7749	0.8958	0.8033	0.9164	0.9647	0.9775
2508	0.6942	0.7748	0.8960	0.8032	0.9168	0.9647	0.9773
KIN_3	p=1.9600 GeV/c						
2509	0.7002	0.7749	0.9036	0.8030	0.9241	0.9651	0.9777
2510	0.7013	0.7756	0.9042	0.8036	0.9251	0.9652	0.9775
2511	0.6982	0.7732	0.9031	0.8014	0.9237	0.9647	0.9777
2512	0.7009	0.7756	0.9036	0.8036	0.9245	0.9652	0.9774
2513	0.7006	0.7754	0.9036	0.8038	0.9244	0.9647	0.9774
2514	0.7008	0.7751	0.9041	0.8032	0.9250	0.9650	0.9774
2515	0.7003	0.7749	0.9036	0.8032	0.9244	0.9648	0.9775
2516	0.6960	0.7713	0.9024	0.7998	0.9237	0.9644	0.9770
2517	0.6990	0.7740	0.9031	0.8021	0.9241	0.9650	0.9773
2518	0.6983	0.7732	0.9031	0.8012	0.9240	0.9651	0.9774
2519	0.6991	0.7739	0.9034	0.8021	0.9243	0.9648	0.9774
2520	0.7024	0.7766	0.9044	0.8044	0.9253	0.9654	0.9774
2521	0.7030	0.7771	0.9046	0.8048	0.9254	0.9655	0.9775

Table 12: VDC efficiencies in E94-107 for the three different kinematics. Firing and tracking efficiencies for left (L) and right (R) arms.

RUN	L firing eff uncertainty	R firing eff uncertainty	L track eff uncertainty	R track eff uncertainty	VDC eff L uncertainty	VDC eff R uncertainty	VDC eff uncertainty
KIN_1							
2485	0.0001	0.0002	0.0003	0.0004	0.0003	0.0004	0.0004
2486	0.0001	0.0002	0.0003	0.0004	0.0003	0.0004	0.0004
2487	0.0001	0.0002	0.0003	0.0004	0.0003	0.0004	0.0004
2488	0.0002	0.0002	0.0003	0.0005	0.0003	0.0005	0.0005
2489	0.0001	0.0002	0.0003	0.0004	0.0003	0.0004	0.0004
2490	0.0001	0.0002	0.0003	0.0004	0.0003	0.0004	0.0004
2491	0.0001	0.0002	0.0003	0.0004	0.0003	0.0004	0.0004
2492	0.0001	0.0002	0.0003	0.0004	0.0003	0.0004	0.0004
KIN_2							
2496	0.0002	0.0002	0.0003	0.0004	0.0003	0.0004	0.0005
2497	0.0002	0.0002	0.0003	0.0004	0.0003	0.0004	0.0005
2498	0.0002	0.0002	0.0003	0.0004	0.0003	0.0004	0.0005
2499	0.0002	0.0002	0.0003	0.0004	0.0003	0.0004	0.0005
2500	0.0001	0.0002	0.0003	0.0004	0.0003	0.0004	0.0005
2501	0.0002	0.0002	0.0003	0.0004	0.0003	0.0005	0.0005
2502	0.0002	0.0002	0.0003	0.0004	0.0003	0.0004	0.0005
2503							
2504	0.0002	0.0002	0.0003	0.0004	0.0003	0.0004	0.0005
2505	0.0002	0.0002	0.0003	0.0004	0.0003	0.0004	0.0005
2506	0.0002	0.0003	0.0004	0.0007	0.0005	0.0007	0.0007
2507	0.0002	0.0002	0.0003	0.0004	0.0003	0.0004	0.0005
2508	0.0002	0.0002	0.0003	0.0004	0.0003	0.0004	0.0005
KIN_3							
2509	0.0001	0.0002	0.0003	0.0004	0.0003	0.0004	0.0005
2510	0.0002	0.0002	0.0003	0.0004	0.0003	0.0004	0.0005
2511	0.0001	0.0002	0.0003	0.0004	0.0003	0.0004	0.0005
2512	0.0002	0.0002	0.0003	0.0004	0.0003	0.0004	0.0005
2513	0.0002	0.0002	0.0003	0.0004	0.0003	0.0004	0.0005
2514	0.0002	0.0002	0.0003	0.0004	0.0003	0.0004	0.0005
2515	0.0002	0.0002	0.0003	0.0004	0.0003	0.0004	0.0005
2516	0.0002	0.0002	0.0003	0.0004	0.0003	0.0004	0.0005
2517	0.0002	0.0002	0.0003	0.0004	0.0003	0.0004	0.0005
2518	0.0002	0.0002	0.0003	0.0004	0.0003	0.0004	0.0005
2519	0.0002	0.0002	0.0003	0.0004	0.0003	0.0004	0.0005
2520	0.0002	0.0002	0.0003	0.0004	0.0003	0.0004	0.0005
2521	0.0002	0.0002	0.0003	0.0004	0.0003	0.0004	0.0005

Table 13: VDC efficiency uncertainties in E94-107 for the three different kinematics. Firing and tracking efficiency uncertainties for left (L) and right (R) arms.

3.6 Deadtime correction

In general for most of the detector systems, there is a minimum amount of time that must separate two events in order for the two to be recorded as separate events. In some cases, processes in the detectors themselves may set the limiting time, and in other cases the limit may arise in the associated electronics. This minimum time separation is usually called the deadtime of the system. Conversely, the livetime is the total time a detector system runs minus the deadtime. Therefore, $\text{deadtime} = 1 - \text{livetime}$, where deadtime and livetime are taken as ratios with respect to total time.

In E94-107, the scalers (counters) and event stream are used to determine the deadtime correction for the analysis of the experiment by computing the ratio of accepted triggers to input triggers [65]. Information on the livetime is registered automatically on the end-of-the-run statement at the end of each run. The livetime registered accounts for both deadtimes combined; the electronics deadtime and the computer deadtime. In general it is important to compute these two different deadtimes separately to avoid errors in the deadtime correction. The scalers are normally used to compute the livetime for three different situations; $\text{livetime}[+]$, $\text{livetime}[-]$ and $\text{livetime}[0]$. The $\text{livetime}[+]$ and $\text{livetime}[-]$, refer to the two opposite longitudinal electron polarizations as determined by the circular laser polarization of the laser used to produce electrons, that later, are sent to the accelerator through injector. The $\text{livetime}[0]$ refers to the sum of the two polarizations, or a net zero polarization. The different polarization of the laser knock out electrons which are produced with different polarizations and then have their spin turned longitudinal (or anti-longitudinal). However, when electrons go through the accelerator's

arcs the magnetic precession can change the direction of the electron polarization. Therefore, to determine the livetime (1-deadtime) the information on the scalers was averaged and the related systematic uncertainty was estimated by taking the standard deviation of the three different measurements. The correction factor will be the inverse of the livetime as described above.

KIN_1	liveTIME(%)			Correction Factor			
	[0]	[+]	[-]	Mean (%)	Stand. D.(%)	1/Mean	Uncertainty
RUN							
2485	91.51	91.7	91.69	91.63	0.1069	1.0913	0.0013
2486	91.44	91.61	91.66	91.57	0.1153	1.0921	0.0014
2487	91.42	91.63	91.62	91.56	0.1185	1.0922	0.0014
2488	88.92	89.09	89.18	89.06	0.1320	1.1228	0.0017
2489	89.08	89.29	89.29	89.22	0.1212	1.1208	0.0015
2490	89.19	89.43	89.36	89.33	0.1234	1.1195	0.0015
2491	88.58	88.84	88.72	88.71	0.1301	1.1272	0.0017
2492	89.09	89.34	89.28	89.24	0.1305	1.1206	0.0016
KIN_2							
RUN							
2496	86.99	87.18	87.18	87.12	0.1097	1.1479	0.0014
2497	87	87.17	87.22	87.13	0.1153	1.1477	0.0015
2498	87	87.28	87.07	87.12	0.1457	1.1479	0.0019
2499	86.83	86.99	87.05	86.96	0.1137	1.1500	0.0015
2500	86.95	87.25	87.03	87.08	0.1553	1.1484	0.0020
2501	86.51	86.7	86.71	86.64	0.1127	1.1542	0.0015
2502							
2503	97.87	100	95.45	97.77	2.2765	1.0228	0.0238
2504	86.68	86.86	86.87	86.80	0.1069	1.1520	0.0014
2505	86.94	87.09	87.14	87.06	0.1041	1.1487	0.0014
2506	86.87	87.03	87.09	87.00	0.1137	1.1495	0.0015
2507	86.77	86.96	86.93	86.89	0.1021	1.1509	0.0014
2508	86.84	87	87.07	86.97	0.1179	1.1498	0.0016
KIN_3							
RUN							
2509	88.4	88.58	88.6	88.53	0.1102	1.1296	0.0014
2510	88.8	88.96	89.04	88.93	0.1222	1.1244	0.0015
2511	87.99	88.11	88.27	88.12	0.1405	1.1348	0.0018
2512	88.69	88.85	88.91	88.82	0.1137	1.1259	0.0014
2513	88.36	88.57	88.53	88.49	0.1115	1.1301	0.0014
2514	88.34	88.48	88.59	88.47	0.1253	1.1303	0.0016
2515	88.27	88.42	88.51	88.40	0.1212	1.1312	0.0016
2516	88.7	88.98	88.82	88.83	0.1405	1.1257	0.0018
2517	88.12	88.37	88.22	88.24	0.1258	1.1333	0.0016
2518	88.05	88.23	88.25	88.18	0.1102	1.1341	0.0014
2519	88.11	88.32	88.26	88.23	0.1082	1.1334	0.0014
2520	88.5	88.67	88.69	88.62	0.1044	1.1284	0.0013
2521	88.52	88.67	88.75	88.65	0.1168	1.1281	0.0015

Table 14: Livetime (%) and deadtime correction factors in E94-107 [66].

As shown in Table 14 the uncertainty on the livetime (1-deadtime) is quite small (see Figure 43). Therefore, this estimate will not imply a significant contribution in the overall uncertainty since it is very small compared to the uncertainties obtained from the aerogel threshold Cherenkov detector analysis in Section 4.4.

Figure 43: Livetime in E94-107 per run number.

3.7 Target density

In many experiments an important factor to consider during analysis is the target density fluctuation with the beam current fluctuation, raster size changes and fan speed. The density fluctuation can be observed by using luminosity monitors when colliding the electron beam on different targets since the luminosity is proportional to the density. D.S.

Armstrong et al., showed that for the hydrogen cryotarget used in E94-107 and for currents of up to 100 μA , the target density remains constant (see Figures 44 and 45). Consequently, for E94-107 analysis there is no boiling correction to perform [67].

Figure 44: LH_2 cryotarget density fluctuations vs. beam current, showing three data sets of independent measurements [67].

Figure 45: LH_2 cryotarget fluctuation vs. raster size, showing three data sets of independent measurements in arbitrary units [67].

Although, the LH2 cryotarget density does not show dependence on beam currents around 100 μA [67] as used in E94-107, a small uncertainty was assigned to account for the minimum variations among the different measurements reported by D. Armstrong et al., [67]. The assigned target density uncertainty is 1% (see Table 48).

4 Data analysis

This section describes the data analysis used to determine all necessary pieces of information to extract the cross sections (which are given in Section 4.8) from the experimental measurements, and later, to do some data binning to observe the trend of the cross sections with respect to the main variables for the elementary reaction.

As mentioned before in previous chapters, three slightly different kinematic settings were used. They differ in the momentum setting of the left (kaon) spectrometer arm as shown in Table 15.

Kinematics	L-arm momentum
KIN_1 (runs 2485-2492)	$p=1.8665 \text{ GeV}/c$
KIN_2 (runs 2496-2508)	$p=1.8218 \text{ GeV}/c$
KIN_3 (runs 2509-2521)	$p=1.9600 \text{ GeV}/c$

Table 15: Kinematics in E94-107.

4.1 Particle identification

In E94-107 the aerogel threshold Cherenkov detectors (A1 and A2) were the primary detectors used to discriminate kaons from other hadrons, e.g., pions and protons. As discussed in Section 2.6.5 concerning the PID conditions, Table 16 shows the cuts utilized in the aerogel detectors.

Particle	A1 cut (channels)	A2 cut (channels)
K^+	<10	>20
π^+	>10	>20 and <1100
p^+	<10	<20

Table 16: Applied aerogel cuts for PID in E94-107.

The typical collected aerogel detector signals are plotted in Figures 46 (for A1) and 47 (for A2).

Figure 46: A1 ADC signal in run 2485, showing the 1st, 2nd and 3rd photoelectron peaks, and A1 cut (dashed line) according to Table 16.

Figure 47: A2 ADC signal in run 2485, showing the 1st photoelectron peak, and the two A2 cuts (dashed line) according to Table 16.

In Figure 46 the single photoelectron (1st) peak was calibrated to the ADC channel 100, which yields approximately 4.5 photoelectrons in A1 for pions. It is worth remarking on the extreme sensitivity of the PMTs used in A1 that allow the second and the third photoelectron peaks to be distinguished. In Figure 47 the 1st peak was calibrated to the ADC channel 50, which gives approximately 14 photoelectrons in A2 for kaons. Moreover, by variously combining the cuts shown in Table 16, the three different particles can be selected. The extra cut in A2 for pions (π^+) was found to give a clearer identification of pions, which might result a reduction of signal created by delta electrons in A2 (see Section 2.6.5).

On the other hand, for the LH₂ target, the RICH detector played the role of an extra detector that was also used for PID. The presence of the RICH detector allowed clean samples of pions, kaons and protons to be determined, which could then in turn be used to measure the efficiency for A1 and A2. However the use of the RICH detector did result in a small loss in efficiency. The result is that the RICH was used to determine the efficiencies for A1 and A2 but not in the actual extraction of the cross sections. The cuts used for the RICH were as shown in Table 17.

Particle	RICH PID cuts (Cherenkov cone angles)
K^+	$0.621 \text{ rad} < \theta_c < 0.660 \text{ rad}$
π^+	$0.665 \text{ rad} < \theta_c < 0.695 \text{ rad}$
p^+	$0.498 \text{ rad} < \theta_c < 0.570 \text{ rad}$

Table 17: RICH PID cuts in E94-107.

Table 17 shows the cuts imposed at the different angles of the emitted Cherenkov radiation cones for the three different particles. In addition, two more common cuts for all particles that are related to the minimum ionizing point in the center of the Cherenkov rings and the tracking of the particles in the RICH wire chambers include are shown in Table 18.

Number of photoelectrons (n.p.e.) > 2
$50 \text{ mm} < x_{tracking} < 1900 \text{ mm}, 50 \text{ mm} < y_{tracking} < 300 \text{ mm}$

Table 18: Additional RICH cuts used in E94-107.

Table 18 shows several cuts combined in the RICH. The first cut (line 1) on the minimum number of photoelectrons produced at the point the particle is going through the detector, which served to ensure that a particle has been detected. The second cut (line 2) on the x and y tracking variables sets the area over the detector where detected particles will be accepted as such. The RICH detector has its own wire tracking system that locates the position of the particle going through the detector. The values of the RICH cuts were provided by F. Cusanno, which have been extensively used in the analysis of the carbon, oxygen, and beryllium targets by the Hall A hypernuclear collaboration [58]. On the other hand, the particles that are identified in the left arm must be in coincidence with electrons in the right arm. However, in the right arm there are not only electrons but also negative pions that pass through the spectrometer. To discriminate electrons from negative pions an additional PID cut is used for the CO_2 gas Cherenkov detector. The typical ADC signal of the gas Cherenkov detector in the right arm is shown in Figure 48:

Figure 48: CO₂ gas Cerenkov ADC signal in run 2485, showing “Rcer” PID cut according to Equation 45 to discriminate electrons from negative pions.

From Figure 48, the large peak corresponds to electrons while the small peak close to the pedestal corresponds to negative pions (π^-) [68]. Negative pions are more massive than electrons and for this reason they have a lower velocity (at the same momenta) compared to the electrons. Therefore, negative pions produce fewer numbers of photons, which is better shown in Section 4.5. Consequently, the following cut, named “Rcer”, was used to discriminate electrons from negative pions in the right arm:

$$\text{Rcer} > 200 \text{ channels.} \quad (45)$$

The next step is to then identify the different particles in the coincidence time of flight (TOF) spectrum. “Coincidence” here means that a particle in the left spectrometer

was detected in the same time window as a particle in the right spectrometer. For this purpose, two different methods were used. Firstly, only the aerogel PID cuts and CO₂ Cherenkov PID (Equation 45) cut were used. Later, aerogel cuts, RICH PID cuts and CO₂ Cherenkov PID cut were used. The two different procedures were performed in order to verify that the RICH PID cuts work as well as the aerogel PID cuts. The following Figures from 49 to 57 show the coincidence TOF spectra (or CT spectra) using aerogel PID cuts and CO₂ gas Cherenkhov PID cut. The y axis denotes counts while the x axis shows time in nanoseconds. Path length corrections were included in these analyses.

Figure 49: CT spectrum (ns) for particles identified as kaons (KIN_1).

Figure 50: CT spectrum (ns) for particles identified as kaons (KIN_2).

Figure 51: CT spectrum (ns) for particles identified as kaons (KIN_3).

Figure 52: CT spectrum (ns) for particles identified as pions (KIN_1).

Figure 53: CT spectrum (ns) for particles identified as pions (KIN_2).

Figure 54: CT spectrum (ns) for particles identified as pions (KIN_3).

Figure 55: CT spectrum (ns) for particles identified as protons (KIN_1).

Figure 56: CT spectrum (ns) for particles identified as protons (KIN_2).

Figure 57: CT spectrum (ns) for particles identified as protons (KIN_3).

Similar TOF spectra are shown in Appendix D, which include not only the aerogel cuts and CO₂ Cherenkov PID cut but also the RICH cuts. In general, it can be seen that both detectors can satisfactorily identify the three different observed particles in the hadron arm. The bump structure of the of the TOF spectra represents accidental coincidences from incident electrons which arriving every 2 ns at the target. Therefore, a width of ± 1 ns was assigned to the coincidence time for all particles on the basis of the resolution shown in the CT spectra. It is also important to remark that the obtained coincidence times for all particles are basically the same if the RICH cuts are used or not. Essentially, the main difference between using only the aerogel cuts and whether the RICH cuts are included or not is that the RICH reduces the statistics significantly. The coincidence times are summarized in Table 19.

CTOF	KAONS (ns)	PIONS (ns)	PROTONS (ns)
KIN_1	140.7	137.8	148.3
KIN_2	140.7	137.6	148.6
KIN_3	140.5	137.9	147.6

Table 19: Coincidence times for each particle in each kinematics.

4.2 Missing mass spectra

The missing mass is the mass that the recoiling undetected third particle in the reaction must have in order to conserve energy and momentum. Sometimes, to make calculations simpler it is convenient to add a constant to the missing mass. In a similar

way missing energy is defined. The missing mass in the ${}^1\text{H}(e,e'K^+)Y$ reaction of producing hyperons can be reconstructed by using all the cuts described in the previous chapter. Combining energy and momentum conservation yields:

$$M_{\Lambda,\Sigma^0}^{\text{missing}} = \sqrt{(e - e') + p - K} \quad (46)$$

$$E_{\Lambda,\Sigma^0}^{\text{missing}} = \omega - T_K - T_p = M_\Lambda + M_K - M_p \quad (47)$$

where $e(e')$ is the four-momentum of the incident (scattered) electron, p is the four-momentum of the target proton, K is the four-momentum of the kaon, M_{p^*} is the rest mass of the proton, M_{K^*} is the rest mass of the kaon, M_{Λ,Σ^0} is either the rest mass of the Lambda particle or the Sigma particle, $\omega = E_e - E_{e'}$ is the energy of the virtual photon, T_K is the kinetic energy of the kaon, and T_p is the kinetic energy of the proton (=0 in the laboratory frame). $M_{\Lambda,\Sigma^0}^{\text{missing}}$ and $E_{\Lambda,\Sigma^0}^{\text{missing}}$ are missing mass and energy when a Lambda particle is created or a Sigma particle is created. In principle, it is also possible to create heavier, more excited strange baryons. However, the experimental kinematics limited the possible baryons to the lowest two hyperons.

In Figures 58, 59 and 60, the tails sloping off toward higher missing mass from each of these peaks are caused by the effects of radiative processes. In these processes, the incident electron, scattered electron, or produced kaon loses some energy by radiating a photon. As a result, there is some extra energy and momentum missing from what is measured leading to an apparent increase in the calculated missing mass (tails towards the right of the spectra).

A cut was placed on the missing mass in order to separate the Λ and Σ^0 reaction channels in the analysis (Section 4.8) to select either Λ or Σ^0 particles. It can be easily verified that the expected missing energies are $E_{\Lambda}^{missing} = 670.99$ MeV and $E_{\Sigma^0}^{missing} = 747.89$ MeV. The tails of the missing mass spectrum were included to keep as many hyperons as possible in the analysis statistics. The cuts are shown in Table 20.

$0.6611 \text{ GeV} < M_{\Lambda}^{missing} < 0.7111 \text{ GeV}$
$0.6880 \text{ GeV} < M_{\Sigma^0}^{missing} < 0.7880 \text{ GeV}$

Table 20: Applied cuts on missing masses.

The cuts in Table 20 were obtained after examining the missing mass spectra for the different kinematics. Although the cuts seem wide, the Lambda and the Sigma peaks are quite far apart as shown in Figures 58 and 59.

Figure 58: Missing mass spectrum for KIN_1.

Figure 59: Missing mass spectrum for KIN_2.

Figure 60: Missing mass spectrum for KIN_3.

The peaks in the Figures 58, 59 and 60 are quite separated as expected but the observed background still has to be subtracted. The background is primarily caused by kaons and electrons that came from different scattering events and are therefore not true coincidences. The three different momentum settings in the left arm (Table 15) produced three different missing mass spectra. KIN_1 and KIN_2 allow selection either of Λ or Σ^0 . For KIN_3 only Λ s are seen. Regarding the three different kinematics in Table 15, the produced hyperon selections in Table 20, and the peaks shown in Figures 58, 59 and 60 that five different combinations are obtained as stated in Table 21.

Analysis	Combination
L_KIN_1	KIN_1 and Λ selected
L_KIN_2	KIN_2 and Λ selected
L_KIN_3	KIN_3 and Λ selected
S_KIN_1	KIN_1 and Σ^0 selected
S_KIN_2	KIN_2 and Σ^0 selected

Table 21: Particle/kinematics combinations for analyses.

The missing mass spectra obtained including the RICH PID cuts (see Appendix E) were qualitatively similar to the ones shown in this section that do not contain the RICH PID cuts. The spectra obtained with RICH PID cuts (Table 17), certainly show less background but in the general analysis (Section 4.8) the statistics were lower. Although the spectra get corrected for the RICH efficiency, the inclusion of the RICH causes a larger statistical uncertainty than is desirable. The RICH was a needed detector for PID on the oxygen target to reduce the larger backgrounds and be able to resolve the core excited state peaks, but higher luminosity was needed in return [69]. It will be shown in Section 4.7 that the aerogel PID cuts with no RICH PID are background free and the

increased statistics provide a reduced statistical uncertainty in the measurement. However, utilizing the RICH as an extra detector then becomes very useful to determine the aerogel detector analysis (see Section 4.4).

4.3 Background subtraction

The missing mass spectra shown in Section 4.2 require background subtraction. The background shape was determined by selecting a region in the CTOF spectra (see Figures 49-57) far from the coincident peak. A cut of $160\text{ ns} \leq \text{CTOF} \leq 180\text{ ns}$ was used. The region is also sufficiently far from the proton and pion coincidence peaks that the tails of those peaks do not contribute should any of those events leak through the PID cuts. The missing mass analysis is done over this window and then divided by 10 to find the average of the background in a 2 ns window. After that, the background is subtracted from the missing mass spectra, which has a 2 ns window, resulting in background free spectra as shown in Figures 61, 62 and 63.

Figure 61: Background subtracted spectrum for KIN_1.

Figure 62: Background subtracted spectrum for KIN_2.

Figure 63: Background subtracted spectrum for KIN_3.

It is important to note that there was no need to do “dummy” target subtraction. Although in principle the aluminum target walls can contribute with $(e, e'K^+)$ events, the yields due to the aluminum walls are so small that they are negligible compared to the out-of-time (or accidental coincidence) background. In addition, the Λ and Σ^0 peaks are well enough separated that there was also no need to estimate any overlapping of the Σ^0 peak and the tail of the Λ peak [70].

Similarly, the missing mass spectra analysis was repeated including the RICH PID cuts (Table 17). The spectra are similar. However, for reasons explained later in Section 4.7 and 4.8 the RICH was not used to measure the cross section as a result of the low efficiency of the RICH (about 75 % to 85 %) for the LH_2 cryotarget. See at the end of Section 4.4 and Appendix G.

4.4 Aerogel Cherenkov detectors analysis

It is also necessary to determine the efficiency of the aerogel detectors A1 and A2 to be able to extract the cross section for the elementary reaction. These two detectors provided the primary PID for these measurements. However, it is important to be precise when describing how aerogel detector A1 was used, since it must not fire (i.e., produce Cherenkov photons) when a kaon passes through. Therefore, in case of A1 we refer to the inefficiency of the detector (see Section 2.6.5). In other words, the inefficiency of A1 will tell us how good the detector is in *not* firing when kaons pass through it. Physically, when kaons traverse the detector they might knock out electrons, which would be energetic enough to fire the aerogel.

The analysis of the aerogel detectors is not totally trivial. They are diffusion boxes, in which the Cherenkov light produced may scatter several times before being detected, and because the experiment is performed with three different momenta and two different hyperons being selected, the analysis of the aerogel detectors efficiencies must be considered separately according to the different combination of kinematics and particle (hyperon) selection (see Table 21). These different kinematics results in different kaon momenta or equivalently velocities. Having different momenta set and selecting different particles effectively selects different kaon momenta in the aerogel diffusion boxes. Therefore, the efficiency of the aerogel boxes will depend not only on the momentum set in the hadron arm but also on the hyperon selected. For this reason, five different results for the aerogel efficiencies are expected, each averaged over the range of kaon momenta used.

The analysis of either A1 or A2 relies on the use of other detectors to select a clean sample of kaons. The RICH detector was used in this case along with the second aerogel to select a clean sample of kaons using the cuts shown in the RICH analysis as detailed in Table 17. In order words, if A1 is being analyzed a tight cut is applied to A2 or vice versa and always with the RICH cuts for kaons. The tight cuts in A1 and A2 applied are shown in Table 22.

Detector	Aerogel cuts for efficiency analysis. (channels)
A1	$100 < A2 < 300$
A2	$A1 < 10$

Table 22: Aerogel tight cuts used for efficiency analysis.

On top of the mentioned cuts in the previous lines, background subtraction is applied (see Section 4.3) and additional tight cuts in the missing mass. Basically, these two tight cuts are narrow regions placed around the hyperon mass peaks in the missing mass spectra. The cuts are shown in Table 23.

Hyperon selected	Missing mass cut for Aerogel analysis (GeV)
Λ	$0.6682 < M_{\Lambda}^{missing} < 0.6736$
Σ^0	$0.7462 < M_{\Sigma^0}^{missing} < 0.7488$

Table 23: Hyperon selection tight cut for the aerogel analysis.

Tables 24-33 and Figures 64-73 are a sequence showing the results for both aerogel detector analyses with the five possible combinations (Table 21).

KAONS		A1sum	A2>100 and A2<300	Inefficiency	
RICH+A2: A1 CUT (<)	569	79	561		
	RICH+AERO	counts ACCIDENTAL			
	TOTAL	(*10)	TRUE	normalized	uncertainty
-10	0	0	0	0.0000	0.0000
0	0	0	0	0.0000	0.0000
5	516	65	509	0.9073	0.0122
10	518	65	511	0.9109	0.0120
25	521	66	514	0.9162	0.0117
50	528	66	521	0.9287	0.0109
75	535	68	528	0.9412	0.0099
100	544	69	537	0.9572	0.0085
125	553	74	545	0.9715	0.0070
150	559	74	551	0.9822	0.0056
175	559	75	551	0.9822	0.0056
200	559	75	551	0.9822	0.0056

Table 24: A1 inefficiency dependence on A1 cut for L_KIN_1.

Figure 64: A1 inefficiency dependence on A1 cut for L_KIN_1.

KAONS		A1sum		A2>100 and A2<300	
RICH+A2: A1 CUT (<)	305	55	299		
	RICH+AERO	counts ACCIDENTAL		inefficiency	
	TOTAL	(*10)	TRUE	normalized	uncertainty
-10	0	0	0	0	0.0000
0	0	0	0	0	0.0000
5	270	50	265	0.8863	0.0184
10	275	50	270	0.9030	0.0171
25	277	51	271	0.9064	0.0168
50	280	51	274	0.9164	0.0160
75	285	52	279	0.9331	0.0144
100	292	52	286	0.9565	0.0118
125	299	53	293	0.9799	0.0081
150	302	55	296	0.9900	0.0058
175	303	55	297	0.9933	0.0047
200	303	55	297	0.9933	0.0047

Table 25: A1 inefficiency dependence on A1 cut for L_KIN_2.

Figure 65: A1 inefficiency dependence on A1 cut for L_KIN_2.

KAONS		A1sum	A2>100 and A2<300
RICH+A2: A1 CUT (<)	406	64	399
	RICH+AERO	counts ACCIDENTAL	inefficiency
	TOTAL	(*10)	TRUE normalized uncertainty
-10	0	0	0 0 0.0000
0	0	0	0 0 0.0000
5	354	55	348 0.8722 0.0167
10	362	55	356 0.8922 0.0155
25	364	56	358 0.8972 0.0152
50	372	57	366 0.9173 0.0138
75	378	58	372 0.9323 0.0126
100	390	58	384 0.9624 0.0095
125	399	60	393 0.9850 0.0061
150	400	60	394 0.9875 0.0056
175	401	60	395 0.9900 0.0050
200	401	61	394 0.9875 0.0056

Table 26: A1 inefficiency dependence on A1 cut for L_KIN_3.

Figure 66: A1 inefficiency dependence on A1 cut for L_KIN_3.

KAONS		A2sum	A1<10		
RICH+A1:	985	188	966		
A2 CUT					
(>)	RICH+AERO	counts		efficiency	
	TOTAL	ACCIDENTAL	TRUE	normalized	uncertainty
		(*10)			
-10	985	188	966	1.0000	0.0000
0	979	163	962	0.9959	0.0021
10	979	160	963	0.9969	0.0018
20	978	159	962	0.9959	0.0021
100	911	145	896	0.9275	0.0083
200	682	112	670	0.6936	0.0148
300	393	80	385	0.3986	0.0158
400	216	54	210	0.2174	0.0133
500	103	30	100	0.1035	0.0098
600	49	17	47	0.0487	0.0069
700	38	11	36	0.0373	0.0061
800	31	7	30	0.0311	0.0056
900	26	7	25	0.0259	0.0051
1000	19	6	18	0.0186	0.0044

Table 27: A2 efficiency dependence on A2 cut for L_KIN_1.

Figure 67: A2 efficiency dependence on A2 cut for L_KIN_1.

KAONS		A2sum	A1<10		
RICH+A1: A2 CUT (>)	484	108	473		
	RICH+AERO	ACCIDENTAL		efficiency	
	TOTAL	(*10)	TRUE	normalized	uncertainty
-10	484	108	473	1.0000	0.0000
0	481	103	470	0.9937	0.0037
10	481	102	470	0.9937	0.0037
20	481	101	470	0.9937	0.0037
100	448	97	438	0.9260	0.0120
200	315	73	307	0.6490	0.0219
300	173	47	168	0.3552	0.0220
400	80	29	77	0.1628	0.0170
500	38	20	36	0.0761	0.0122
600	22	16	20	0.0423	0.0093
700	12	12	10	0.0211	0.0066
800	10	9	9	0.0190	0.0063
900	10	1	9	0.0190	0.0063
1000	7	0	7	0.0148	0.0056

Table 28: A2 efficiency dependence on A2 cut for L_KIN_2.

Figure 68: A2 efficiency dependence on A2 cut for L_KIN_2.

KAONS		A2sum	A1<10		
RICH+A1:	809	159	793		
A2 CUT					
(>)	RICH+AERO	counts			
		ACCIDENTAL			
	TOTAL	(*10)	TRUE	normalized	uncertainty
-10	809	159	793	1.0000	0.0000
0	806	136	792	0.9987	0.0013
10	805	134	791	0.9975	0.0018
20	802	133	788	0.9937	0.0028
100	751	123	738	0.9306	0.0090
200	614	98	604	0.7617	0.0151
300	389	68	382	0.4817	0.0177
400	207	46	202	0.2547	0.0155
500	105	23	102	0.1286	0.0119
600	51	16	49	0.0618	0.0086
700	25	9	24	0.0303	0.0061
800	18	6	17	0.0214	0.0051
900	14	5	13	0.0164	0.0045
1000	12	4	11	0.0139	0.0042

Table 29: A2 efficiency dependence on A2 cut for L_KIN_3.

Figure 69: A2 efficiency dependence on A2 cut for L_KIN_3.

KAONS(Sigma)		A1sum	A2>100 and A2<300		
RICH+A2:	70	22	67		
A1 CUT (<)	RICH+AERO	ACCIDENTAL			
	TOTAL	(*10)	TRUE	normalized	uncertainty
-10	0	0	0	0	0.0000
0	0	0	0	0	0.0000
5	65	20	63	0.9403	0.0289
10	67	20	65	0.9701	0.0208
25	68	20	66	0.9851	0.0148
50	68	21	65	0.9701	0.0208
75	68	21	65	0.9701	0.0208
100	68	21	65	0.9701	0.0208
125	69	21	66	0.9851	0.0148
150	69	21	66	0.9851	0.0148
175	70	21	67	1.0000	0.0000
200	70	21	67	1.0000	0.0000

Table 30: A1 inefficiency dependence on A1 cut for S_KIN_1.

Figure 70: A1 inefficiency dependence on A1 cut for S_KIN_1.

KAONS(Sigma)		A1sum	A2>100 and A2<300		
RICH+A2:	163	121	150		
A1 CUT (<)	RICH+AERO	counts ACCIDENTAL	inefficiency		
	TOTAL	(*10)	TRUE	normalized	uncertainty
-10	0	0	0	0	0.0000
0	0	0	0	0	0.0000
5	140	104	129	0.8600	0.0283
10	142	104	131	0.8733	0.0272
25	144	105	133	0.8867	0.0259
50	146	105	135	0.9000	0.0245
75	149	106	138	0.9200	0.0222
100	153	109	142	0.9467	0.0183
125	157	110	146	0.9733	0.0132
150	160	111	148	0.9867	0.0094
175	160	111	148	0.9867	0.0094
200	161	111	149	0.9933	0.0066

Table 31: A1 inefficiency dependence on A1 cut for S_KIN_2.

Figure 71: A1 inefficiency dependence on A1 cut for S_KIN_2.

KAONS(Sigma)	A2sum	A1<10			
RICH+A1:	115	53	109		
A2 CUT (>)	RICH+AERO	counts	efficiency		
	TOTAL	ACCIDENTAL	TRUE	normalized	uncertainty
		(*10)			
-10	115	53	109	1.0000	0.0000
0	114	41	109	1.0000	0.0000
10	114	40	110	1.0092	0.0092
20	114	40	110	1.0092	0.0092
100	98	38	94	0.8624	0.0330
200	57	24	54	0.4954	0.0479
300	31	18	29	0.2661	0.0423
400	15	9	14	0.1284	0.0320
500	7	8	6	0.0550	0.0218
600	5	6	4	0.0367	0.0180
700	5	4	4	0.0367	0.0180
800	5	4	4	0.0367	0.0180
900	3	3	2	0.0183	0.0129
1000	3	3	2	0.0183	0.0129

Table 32: A2 efficiency dependence on A2 cut for S_KIN_1.

Figure 72: A2 efficiency dependence on A2 cut for S_KIN_1.

KAONS(Sigma)		A2sum	A1<10		
RICH+A1:	275	241	250		
A2 CUT (>)	RICH+AERO	counts		efficiency	
	TOTAL	ACCIDENTAL	TRUE	normalized	uncertainty
		(*10)			
-10	275	241	250	1.0000	0.0000
0	272	206	251	1.0040	0.0040
10	272	201	251	1.0040	0.0040
20	272	199	252	1.0080	0.0057
100	244	183	225	0.9000	0.0190
200	166	129	153	0.6120	0.0308
300	102	79	94	0.3760	0.0306
400	61	43	56	0.2240	0.0264
500	27	29	24	0.0960	0.0186
600	17	24	14	0.0560	0.0145
700	10	15	8	0.0320	0.0111
800	8	11	6	0.0240	0.0097
900	6	7	5	0.0200	0.0089
1000	3	4	2	0.0080	0.0056

Table 33: A2 efficiency dependence on A2 cut for S_KIN_2.

Figure 73: A2 efficiency dependence on A2 cut for S_KIN_2.

In a similar way a RICH efficiency analysis was performed selecting tight cuts in the aerogels to ensure a clean sample of kaons according to Table 22 for the three different kinematics (see Table 19). The efficiencies are quite less than 100%. The RICH low efficiencies cause a significant correction factor to the data as well as decreasing the statistics and increasing the statistical uncertainty. Therefore the RICH was instead taken as an extra detector to be used for the aerogel analysis but not for the cross section analysis. See Appendix G.

4.5 Gas threshold Cherenkov detector analysis

The CO₂ gas Cherenkov is located in the right arm (see Section 2.6.3) and the purpose of it is to discriminate electrons from negative pions (π^-). To perform the analysis of the efficiency of this detector, positive pions (π^+) in the left arm in coincidence with electrons in the right arm were used, which means the coincidence time for pions was selected (Table 19) for the three different kinematics (Table 15). The analysis also includes background subtraction (Section 4.2), RICH PID cut for pion selection (Table 17) and special tight cuts in the aerogels to select a clean sample of positive pions (π^+) in the left arm given in Table 34.

Detector	Pion tight cut (channels)
A1	>100
A2	>500

Table 34: Tight cuts applied to A1 and A2 to select clean sample of pions [68].

In addition to the previously mentioned cuts, it is also important to be sure that we have a clean sample of electrons in the right arm. To have a clean sample of electrons we made used of two extra detectors in the right arm; the shower and the preshower. If we plot shower ADC signal vs. the preshower ADC signal a so-called “banana” plot (because of its obvious resemblance) is obtained, where two “areas” with counts are seen. Electrons release more energy in the preshower and shower counters (counts at higher ADC channels) because of their lighter masses than negative pions, then it is possible to differentiate negative pions (π^-) from electrons (e^-). Plotted is the energy deposited in the first layer or preshower versus the energy deposited in the rest of the detector [68]. The “banana” plots for the three different kinematics with the cuts applied to select electrons (preshower ADC > 500 and shower ADC > 500) in the right arm are shown in Figures 74, 75 and 76.

Figure 74: "Banana" plot for KIN_1, showing shower and preshower detector cuts.

R.sh. asum_c:R.ps. asum_c

Figure 75: "Banana" plot for KIN_2, showing shower and preshower detector cuts.

R.sh. asum_c:R.ps. asum_c

Figure 76: "Banana" plot for KIN_3, showing shower and preshower detector cuts.

The use of pions instead of kaons has the advantage that the statistics are much larger, which gives a smaller statistical uncertainty on the measurement of the gas Cherenkov detector efficiency. The details of efficiency analysis for the different kinematics are shown in Tables 35-37 and Figures 77-79. More details of uncertainties calculations are shown in Section 4.9.

coin PIONS		RCERsum	A1>100, A2>500		
RICH+A1+A2:	48175	118212	36353		
A2 CUT (>)	RICH+AERO	counts	efficiency		
		ACCIDENTAL			
	TOTAL	(*10)	TRUE	normalized	uncertainty
-10	48175	118212	36353	1.0000	0.0000
0	47547	117456	35801	0.9848	0.0006
10	47539	117445	35794	0.9846	0.0006
200	47386	117093	35676	0.9814	0.0007
400	46172	113832	34788	0.9569	0.0011
600	41691	102408	31450	0.8651	0.0018
800	32793	80673	24725	0.6801	0.0024
1000	21820	54203	16399	0.4511	0.0026
1200	12700	31424	9557	0.2629	0.0023
1400	6596	16371	4958	0.1364	0.0018
1600	3251	8019	2449	0.0674	0.0013
1800	1549	4015	1147	0.0316	0.0009
2000	802	2048	597	0.0164	0.0007

Table 35: CO₂ gas Cherenkov detector efficiency at different cuts in KIN_1.

Figure 77: CO₂ gas Cherenkov detector efficiency at different cuts in KIN_1.

coin PIONS		RCERsum	A1>100, A2>500		
RICH+A1+A2:	48895	137776	35117		
A2 CUT (>)	RICH+AERO	counts		efficiency	
	TOTAL	ACCIDENTAL	TRUE	normalized	uncertainty
		(*10)			
-10	48895	137776	35117	1.0000	0.0000
0	48264	136934	34570	0.9844	0.0007
10	48260	136928	34567	0.9843	0.0007
200	48115	136507	34464	0.9814	0.0007
400	46809	132647	33544	0.9552	0.0011
600	41924	118820	30042	0.8555	0.0019
800	32917	92906	23626	0.6728	0.0025
1000	22054	62221	15831	0.4508	0.0027
1200	12727	35832	9143	0.2604	0.0023
1400	6590	18550	4735	0.1348	0.0018
1600	3261	9100	2351	0.0669	0.0013
1800	1670	4471	1222	0.0348	0.0010
2000	886	2237	662	0.0189	0.0007

Table 36: CO₂ gas Cherenkov detector efficiency at different cuts in KIN_2.

Figure 78: CO₂ gas Cherenkov detector efficiency at different cuts in KIN_2.

coin PIONS		RCERsum	A1>100, A2>500		
RICH+A1+A2:	30775	117191	19055		
A2 CUT (>)	RICH+AERO	counts		efficiency	
	TOTAL	ACCIDENTAL	TRUE	normalized	uncertainty
		(*10)			
-10	30775	117191	19055	1.0000	0.0000
0	30263	116459	18617	0.9770	0.0011
10	30260	116457	18614	0.9769	0.0011
200	30159	116089	18550	0.9735	0.0012
400	29341	112762	18064	0.9480	0.0016
600	26439	101015	16337	0.8574	0.0025
800	20659	78573	12801	0.6718	0.0034
1000	13724	52079	8516	0.4469	0.0036
1200	7788	29880	4800	0.2519	0.0031
1400	3976	15196	2456	0.1289	0.0024
1600	1893	7416	1151	0.0604	0.0017
1800	925	3690	556	0.0292	0.0012
2000	461	1865	274	0.0144	0.0009

Table 37: CO₂ gas Cherenkov detector efficiency at different cuts in KIN_3.

Figure 79: CO₂ gas Cherenkov detector efficiency at different cuts in KIN_3.

4.6 Monte Carlo simulation

Another important ingredient to extract the cross section from the data for hyperon production in the elementary reaction is to simulate the experiment using Monte Carlo method. The standard Hall A Monte Carlo simulation (MCEEP) was convenient for this purpose.

4.6.1 MCEEP description

The MCEEP code was originally developed to simulate and calculate the cross section of the exclusive coincidence electron-nucleon reaction ($e, e'N$) [74]. However, later it was enhanced to also simulate and calculate the coincidence ($e, e'K^+$) [73] reaction cross section [72]. The MCEEP simulation includes: averaging over a theoretical model over the experimental acceptance; radiative and kaon decay corrections, Fermi motion, physics weighting, a realistic description of the beam, target, and detectors as well as an absolute normalization for the simulated events [72].

Among the capabilities of the MCEEP simulation is the effect of the raster of the beam and the three-dimensional interaction of the target with the beam; therefore the length of the targets is also required input in the simulation.

The MCEEP simulation also takes into account radiative corrections and realistic multiple scattering. Both internal and external radiative corrections (particle radiation before and after the vertex of the reactions) are performed.

An event constitutes any combination of variables that satisfies the conditions for the reaction studied in the laboratory system of reference. The events are generated randomly within the spectrometer experimental acceptance. Each event is characterized by assigning a random momentum and two orientation angles to an emerging particle. The characterization of particles is performed for particles in both spectrometers (i.e., electrons and hadrons). Therefore, a single event includes six coordinates; a momentum and two angle coordinates for a hadron (left arm) and similarly for an electron (right arm). These variables can be weighted not just by phase space but if the user wishes they can also be weighted by the physics model cross section embedded in the MCEEP simulation.

The MCEEP simulation was used to calculate the yield (Y_{MCEEP}) of kaon electroproduction for the reaction $(e, e' K^+)$ by determining the cross section event by event. The kaon electroproduction cross sections were extracted by comparison of the simulated yield with the measured yield for both hyperons Λ and Σ^0 . Therefore in this case, MCEEP was used to calculate the yield considering the scattering-to-discrete states of the residual system, which in this case are the hyperons Λ and Σ^0 . A cut was applied in the simulation to select each of the two hyperons. The missing mass cuts in the MCEEP used were the same as in the data analysis shown in Table 20. The yield in MCEEP is then obtained by integrating the cross section over a five-fold acceptance volume:

$$Y_{\text{MCEEP}} = L \int \frac{d^5\sigma}{\Delta V dE' d\Omega_e d\Omega_{K^+}} dE' d\Omega_e d\Omega_{K^+}. \quad (48)$$

In Equation (48) L is the luminosity given by:

$$L = \frac{\rho \ell_T N_A Q}{eA} . \quad (49)$$

In Equation (49) ρ and ℓ_T are the target density and length, N_A is Avogadro's number, Q is the total integrated beam charge, e is the fundamental charge constant of the electron, and A is the atomic weight.

The integration in (48) is performed over the electron (Ω_e), kaon (Ω_{K^+}) solid angles, and over the electron final energy E' .

4.6.2 Radiative corrections

There are some corrections that have to be considered for the one-photon exchange diagram for the $(e, e'N)$ reaction. Charged particles interact with the Coulomb field of the nucleus by radiating real photons through the scattering process, which is called internal bremsstrahlung. When a similar process occurs with nuclei other than the one involved in the scattering process then it is called external bremsstrahlung, and the correction in this case is done by using the Bethe-Bloch formula for the energy loss by collisions [72]. The emission and reabsorption of virtual photons are taken into consideration in the simulation. It implies the emission of real low energy photons (soft photons), whose energies are small compared to the energy of the incoming and outgoing electrons.

The radiated photons affect the cross section by affecting the energy and momentum transfer in the reaction. The correction makes the simulation more realistic giving a better comparison with the experiment. Another type of correction included is the Schwinger correction, which considers real and virtual photons for the contribution of the radiative tail. The latter correction is also enhanced with an extra multiphoton correction that accounts for multiple photon emission and reabsorption [72].

4.6.3 Physics models

In the MCEEP simulation the phase-space variables are weighted by the physics model. The simulation allows the usage of different models by opting for the kind of reaction the user is interested in. In the case of $(e, e' K^+)$ reactions the option is the “700”. For the “700” option the physics model embedded was initially based on experimental fitting to the existing data prior to 1980 [11]. In this experimental fitting the cross section is parameterized by a couple of scaling factors given by [11]:

$$\frac{d^2\sigma}{d\Omega_{K^+}^*} \sim f(Q^2) \times f(W), \quad (50)$$

where these scaling factors are given by the equations:

$$f(Q^2) = \frac{1}{(Q^2 + X)^2} \quad \text{and,} \quad (51)$$

$$f(W) = \frac{|\bar{p}_{K^*}|}{W(W^2 - m_p^2)}, \quad (52)$$

where $X=2.67$ (GeV/c)² for the Λ channel and $X=0.79$ (GeV/c)² for the Σ^0 channel. However, in the later experiment carried out about ten years ago it was found the scaling with W at low W was incorrect as shown by the solid line in Figure 80.

Figure 80: Cross sections as functions of W with different scaling functions, $f(W)$, overlaid [75].

The embedded scaling functions in the MCEEP were provided by Bebek (solid line in Figure 80) while analysis results done in JLab experiment by D.M. Koltenuk for experiment E91-016 shows a better scaling function for the simulation [75]. The improved scaling function performed for the Λ channel is given by:

$$f(W) = \frac{C_1 |\vec{p}_{K^+}|}{W(W^2 - m_p^2)} + \frac{C_2 (1.72)^2 (0.10)^2}{(W^2 - (1.72)^2)^2 + (1.72)^2 (0.10)^2}, \quad (53)$$

here $C_1=4023.9 \text{ GeV}^2 \text{ nb/sr}$ and $C_2=180.0 \text{ GeV}^2 \text{ nb/sr}$. The corrected Equation (53) was estimated by considering possible resonance contributions to the cross section at lower W that modify Equation (52).

Another scaling function was also taken into account later to correct the ones used initially in MCEEP. The scaling function is used to estimate the behavior of the cross section with θ_{CM} . On the basis of the results by Brauel et al., [76], the scaling function can be shown to be [25]:

$$\frac{f(\theta_{CM})}{\langle f(\theta_{CM} = 0^0) \rangle} = \frac{e^{-\xi|t|}}{e^{-\xi|t_{\min}|}} = e^{-\xi(t-t_{\min})}, \quad (54)$$

with Mandelstam t ,

$$-t = -Q^2 + m_{K^+}^2 - 2E_{K^+}^* \nu^* + 2|\vec{q}^*| |\vec{p}_{K^+}^*| \cos(\theta_{CM}), \quad (55)$$

here $-t \rightarrow -t_{\min}$ when $\theta_{CM} \rightarrow 0^0$. The variables used in the equations of Section 4.6.3 were previously defined in Chapter 1.3. The starred variables refer to the CM frame.

MCEEP contains the latest corrections and it will be shown later in the next sections that it does a very good job in the comparison with the yields. One of the reasons

is that, experiment E94-107 is performed at a higher $W \approx 2.2$ GeV where the model does a good job of describing the data compared to the data shown in Figure 80. However, the later corrections do not change the results by much in the kinematical region of experiment E94-107.

4.7 Spectrometer acceptance corrections

As was shown in Table 21 there are five cases to study that combine three different momenta in the hadron arm and two hyperon channels. The acceptance correction is performed for each of these cases with the purpose of excluding undesired events because of the edges of the entrance to the spectrometers where the acceptance changes rapidly. By comparing the MCEEP yield versus the measured yield it is possible to find the correction for the acceptance.

The MCEEP runs with many statistics, but the results must be scaled down so the amount of charge is the same as in the real experiment in order to get the same yields, which can be performed by giving the proper running time in MCEEP, and the proper luminosity so the integrated charges match. However, since the MCEEP simulation does not include detector efficiencies, for the purpose of comparing both yields the running time was deliberately changed to make the yields the same.

There were several details that must be taken into account when adapting the MCEEP input file to a particular experiment. Among them, the need to make sure that the coordinate y_{tg} matches the experimental value. Resolution spreading of the VDC resolution was adjusted so that the MCEEP y_{tg} distribution matched y_{tg} for real data. It

was found that the missing mass peak was off by about 1~2 MeV. The reason for this was because of some small uncertainty in the accelerator (EPICS) data stream reading of the beam energy [38]. The database was corrected for that small amount of energy and the data were analyzed again. Because this experiment had essentially a point target (only 0.4 cm thick as seen by the spectrometers), the complexity of this correction procedure was reduced. By comparing both the measured yield versus the MCEEP yield with their integrals normalized it can be seen whether the two match. Then a small cut in the angular variables was applied watching carefully how all other variables vary. The idea is to apply the minimum cuts to have a good match and in this way avoid reducing the statistics by too much.

The comparison (histograms) of the two yields for the five different cases are shown in the next pages. The variables have been plotted such that in the first two rows the left or kaon spectrometer variables are to the left and the right or electron spectrometer variables are to the right while the last row show some of the reconstructed physics and coincidence variables. The angles in the first row are in radians and the y_{lg} is in meters. The reconstructed variables are: missing energy in GeV, the square of invariant mass W in GeV^2 , the square of the four-momentum transfer Q^2 $(\text{GeV}/c)^2$ and θ_{CM} in radians. They are shown such that dash lines represent the MCEEP yield and solid lines represent the measured yield.

From Figure 81 to 85 the comparison between MCEEP yield and measured yield are shown with areas made equal (for comparison purposes), then from Figure 86 to 90 the comparison is shown after cuts made to the angles and/or momenta to make the acceptance correction. The kinematic/particle selections are given in Table 21.

The histograms shown in Figures 81-85 and 86-90 show a comparison between the MCEEP simulation (dashed line) and the real data (solid line). The first two rows are the simulated and reconstructed target variables for both spectrometers, where kaon refers to the left arm and electron refers to the right arm, so that;

$$\text{kaon } \phi = \phi_k \text{ (rad),} \quad \text{kaon } \theta = \theta_k \text{ (rad),}$$

$$\text{electron } \phi = \phi_e \text{ (rad),} \quad \text{electron } \theta = \theta_e \text{ (rad),}$$

$$\text{kaon } dp/p = (\delta p/p)_K, \quad \text{kaon } y = (y_{tg})_K,$$

$$\text{electron } dp/p = (\delta p/p)_e, \quad \text{electron } y = (y_{tg})_e,$$

the third row shows some of the reconstructed variables (see Section 1.3 for variable definitions);

$$\text{missing energy} = E_{miss} \text{ (GeV),} \quad \text{invariant mass } W^2 = W^2 \text{ (GeV}^2\text{),}$$

$$4 \text{ momentum transfer } Q^2 = Q^2 \text{ (GeV}^2\text{),} \quad \text{theta in CM} = \theta_{CM} \text{ (rad).}$$

In Figures 91 to 95 extra reconstructed variables are shown;

$$\text{Mandelstam } t = t \text{ (GeV}^2\text{),} \quad \phi_x = \phi \text{ (rad),}$$

$$\cos(\phi_x) = \cos(\phi), \quad \sin(\phi_x) = \sin(\phi),$$

$$\text{Electron } p = p_e \text{ (GeV/c),} \quad \text{Kaon } p = p_K \text{ (GeV/c),}$$

$$\text{Theta } Kq = \theta_K \text{ (rad),} \quad \text{Theta_Lambdaq} = \theta_Y \text{ (rad),}$$

$$\text{Omega} = E - E' \text{ (GeV),} \quad \text{Theta_lab } q = \text{angle}(\vec{p}_e, \vec{q}) \text{ (rad),}$$

$$\text{Electron scattering angle} = \theta_e \text{ (rad),} \quad \text{Epsilon} = \epsilon.$$

Figure 81: Yields comparison for L_KIN_1 before corrections (description: page 138).

Figure 82: Yields comparison for L_KIN_2 before corrections (description: page 138).

Figure 83: Yields comparison for L_KIN_3 before corrections (description: page 138).

Figure 84: Yields comparison for S_KIN_1 before corrections (description: page 138).

Figure 85: Yields comparison for S_KIN_2 before corrections (description: page 138).

After empirically trying cuts into the angles and in last instance to momentum, it was observed that the following cuts in Table 38 make the most appropriate acceptance variable corrections, providing the best matching between the simulated and real yields.

Kin/particle	ϕ_K (rad)	θ_K (rad)	ϕ_e (rad)	θ_e (rad)	$(\delta p/p)_K$	$(\delta p/p)_e$
L_KIN_1	[-0.02,0.02]	[-0.045,0.045]	[-0.03,0.016]	[-0.045,0.045]	[-0.04,0.04]	[-0.04,0.04]
L_KIN_2	[-0.017,0.02]	[-0.045,0.045]	[-0.03,0.015]	[-0.045,0.045]	[-0.04,0.04]	[-0.04,0.04]
L_KIN_3	[-0.018,0.02]	[-0.045,0.045]	[-0.03,0.016]	[-0.045,0.045]	[-0.04,0.04]	[-0.04,0.04]
S_KIN_1	[-0.02,0.02]	[-0.045,0.045]	[-0.03,0.016]	[-0.045,0.045]	[-0.04,0.00]	[-0.04,0.01]
S_KIN_2	[-0.017,0.02]	[-0.045,0.045]	[-0.03,0.015]	[-0.045,0.045]	[-0.04,0.04]	[-0.04,0.04]

Table 38: Acceptance variable corrections for all kinematics/particle selections.

It can be seen in Table 38 that the corrections were basically small cuts at the border of the angle ranges and that there was no need to apply cuts on the $\delta p/p$ variable other than the regular cut of $[-0.04, 0.04]$ for full acceptance except for the case of Σ^0 particle selected, in which there was a need for a hard cut in the $\delta p/p$.

The cuts shown in the above table were applied to both the MCEEP simulation and in the measurement of the experimental yield and compared again to make sure the corrections were producing well matched yields. The following histograms show the simulated and measured yield normalized.

Figure 86: Yields comparison for L_KIN_1 after corrections (description: page 138).

Figure 87: Yields comparison for L_KIN_2 after corrections (description: page 138).

Figure 88: Yields comparison for L_KIN_3 after corrections (description: page 138).

Figure 89: Yields comparison for S_KIN_1 after corrections (description: page 138).

Figure 90: Yields comparison for S_KIN_2 after corrections (description: page 138).

After observing good agreement between the MCEEP yield and the measured yield for the spectrometer variables (with the acceptance correction cuts applied as in Table 38) more histograms for other variables were obtained. Figures 91 to 95 show additional variables described in page 138 (see Figure 2, and Section 1.3).

Another important distribution to consider is the yield around the angle between the reaction plane and the scattering plane (φ in Equation (19)). From the distribution, it can be seen if there are contributions from the interference terms of the cross section in the measured cross section. If the distribution is homogenous around φ then the interference terms cancel out in Equation (19). To perform this comparison the Mandelstam variable t is used, and the simulated and real yields are plotted on the reconstructed variable $t\cos(\varphi)$ vs. $t\sin(\varphi)$ (GeV)². The results are shown in Figures 96-100. The distributions are not homogeneous and they have a semi “donut” shape and the MCEEP yields are normalized to match data yield. The MCEEP simulated yield matched very well with the measured yield. For a description of the variables shown in Figures 96-100 see page 138.

Figure 91: More yields comparison for L_{KIN_1} after corrections (see page 138).

Figure 92: More yields comparison for L_KIN_2 after corrections (see page 138).

Figure 93: More yields corrections for L_KIN_3 after corrections (see page 138).

Figure 94: More yields comparison for S_KIN_1 after corrections (see page 138).

Figure 95: More yields comparison for S_KIN_2 after corrections (see page 138).

Figure 96: Yields distributions on φ for L_KIN_1 after corrections. For a description see page 138 and Section 1.3.

Figure 97: Yields distributions on φ for L_KIN_2 after corrections. For a description see page 138 and Section 1.3.

Figure 98: Yields distributions on φ for L_KIN_3 after corrections. For a description see page 138 and Section 1.3.

Figure 99: Yields distributions on φ for S_KIN_1 after corrections. For a description see page 138 and Section 1.3.

Figure 100: Yields distributions on ϕ for S_KIN_2 after corrections. For a description see page 138 and Section 1.3.

A good agreement is observed for the Λ channel. However, the quality of the agreement for the Σ^0 channel is harder to discern as a result of the relatively poor statistical precision of the data.

The number of Λ and Σ^0 particles found were:

Kinematics/particle	Number of hyperons
L_KIN_1	1380 Λ
L_KIN_2	563 Λ
L_KIN_3	2506 Λ
S_KIN_1	481 Σ^0
S_KIN_2	866 Σ^0

Table 39: Total measured experimental yield.

4.8 Cross-section measurements

To obtain the measurements of the cross sections it is necessary to know the integral of the electron charge and the number of potential scattering centers. The measurement of the charge is performed using the beam current monitors described in Section 2.3.1. Table 40 shows the total charge used in E94-107 (cryotarget) for each run.

Run	Charge (C)	Uncertainty (C)	Uncertainty (%)
2485	0.0503	0.0002	0.40
2486	0.0499	0.0002	0.40
2487	0.05	0.0003	0.60
2488	0.0398	0.0003	0.75
2489	0.0399	0.0001	0.25
2490	0.0403	0.0002	0.50
2491	0.0391	0.0002	0.51
2492	0.0397	0.0002	0.50
2496	0.0411	0.0003	0.73
2497	0.0428	0.0003	0.70
2498	0.043	0.0004	0.93
2499	0.0425	0.0004	0.94
2500	0.0428	0.0004	0.93
2501	0.0374	0.0003	0.80
2503	0		
2504	0.0425	0.0004	0.94
2505	0.0428	0.0004	0.93
2506	0.0171	0.0002	1.17
2507	0.0426	0.0005	1.17
2508	0.0426	0.0004	0.94
2509	0.0471	0.0004	0.85
2510	0.047	0.0004	0.85
2511	0.0467	0.0004	0.86
2512	0.047	0.0004	0.85
2513	0.0473	0.0004	0.85
2514	0.0471	0.0004	0.85
2515	0.0471	0.0004	0.85
2516	0.0461	0.0004	0.87
2517	0.0469	0.0004	0.85
2518	0.0467	0.0004	0.86
2519	0.0468	0.0005	1.07
2520	0.0474	0.0004	0.84
2521	0.0473	0.0003	0.63

Table 40: Charges and uncertainties in E94-107 from BCM measurements.

Figure 101: Charge ratio among different BCM.

The uncertainties in Table 40 were obtained by comparing the three BCMs during the experiment and, therefore, represent a systematic uncertainty (for details see Section 4.9).

Former JLab graduate student, J. Cha [77] did a fit to the experimental data obtained at JLab on Λ electroproduction in the late 90's (Experiment E91-016), from which later, a program was developed by the hypernuclear collaboration to find out what the cross section should be for different values of Q^2 , W and θ_{CM} and by including the scaling factors described in Section 4.6.3. The program is called KFIT3s.f and by introducing the beam energy value (E), momentum transfer squared (Q^2), invariant mass (W), left spectrometer momentum (p_K) and the angle between the virtual photon and the kaon particle (θ_K) (see Section 1.3) gives the corresponding cross section on the basis of a fit of the available experimental data [77]. See Appendix H for details of KFIT3s.f.

Instead of using Equation (15) directly for the cross-section measurements, a different approach was used. Since the MCEEP simulation was used for the acceptance correction cuts by comparing the MCEEP yield to the measured yield, the average values of the variables taken from the MCEEP output summary were used as input to KFITs3.f to get the expected cross sections (cross-section values from Cha's fit [77]). Then, the ratio of the corrected measured yield to the MCEEP yield and the ratio of the measured cross section in E94-107 to the expected cross section from KFIT3s.f are considered to be the same. The measured yield is corrected by a correction factor, where the correction factor is calculated as the inverse of the product of all the detectors efficiencies and inefficiencies [68]. Therefore, the equations are:

$$\frac{d\sigma_{\text{exp}}}{d\Omega} = Y_{\text{ratio}} \frac{d\sigma_{\text{expected}}}{d\Omega}, \quad (56)$$

with,

$$Y_{\text{ratio}} = \frac{Y_{\text{exp}}^{\text{corrected}}}{Y_{\text{MCEEP}}}, \quad (57)$$

$$Y_{\text{exp}}^{\text{corrected}} = Y_{\text{exp}} F_{\text{correction}}, \quad (58)$$

$$F_{\text{correction}} = \frac{1}{E_{\text{VDC}} \cdot E_{\text{SCINT}} \cdot I_{\text{A1}} \cdot E_{\text{A2}} \cdot E_{\text{CO}_2} \cdot L \cdot A}, \quad (59)$$

where E_{VDC} , E_{SCINT} , E_{A2} , E_{CO_2} are detector efficiencies, I_{A1} is the A1 inefficiency, L is the livetime factor and A is the absorption factor.

It is also typical to express the yield as the yield per unit of charge, which can be simply obtained by just dividing the yield obtained, either from the simulation or from the experiment, by the total charge (Table 40) for each kinematics (Table 15). However, the ratio in (57) remains the same. The experimental yields are in Table 39.

The correction factors are shown in Table 41.

Kinematics particle	Correction Factor	VDC	A1	A2	CO2	Deadtime	Scint_eff	Absorp.
L_KIN_1	1.8751	1.3577	1.0978	1.0042	1.0190	1.1089	1.06900	1.0372
L_KIN_2	2.0931	1.4406	1.1074	1.0064	1.0189	1.1497	1.07200	1.0381
L_KIN_3	2.0709	1.4285	1.1208	1.0063	1.0272	1.1299	1.06950	1.0354
S_KIN_1	1.7373	1.3577	1.0308	0.9909	1.0190	1.1089	1.06900	1.0372
S_KIN_2	2.1335	1.4406	1.1450	0.9921	1.0189	1.1497	1.07200	1.0381

Table 41: Correction factors for all kinematics/particles.

In the case of the VDC, deadtime, and scintillator correction factors, it is important to remark that because the analyses were performed run by run, the combined efficiency (or correction factor as the inverse) is previously weighted by the charge of each run by the equation:

$$E = \frac{\sum Q_i E_i}{\sum Q_i} \quad (60)$$

Table 42 shows the input values to the KFITS3.f program that were taken from the MCEEP summary output (Appendix I). In Table 42, the average values for the beam energy value (E), momentum transfer squared (Q^2), invariant mass (W), left spectrometer momentum (p_K) and the angle between the virtual photon and the kaon particle (θ_K) are shown.

kinematics/particle	E (GeV)	Q^2 (GeV/c) ²	W (GeV)	p_K (GeV/c)	θ_K (degrees)
L_KIN_1	3.7758	0.0750	2.2140	1.8934	2.2420
L_KIN_2	3.7807	0.0770	2.2060	1.8721	2.2230
L_KIN_3	3.7758	0.0740	2.2290	1.9319	2.3300
S_KIN_1	3.7758	0.0730	2.2320	1.8293	2.3340
S_KIN_2	3.7807	0.0750	2.2250	1.8122	2.3040

Table 42: KFITS3.f input values from the MCEEP simulation.

In Table 43, the output values (expected cross sections) from KFITS3.f are shown after entering input values shown in Table 42.

kinematics/particle	Expected C.S. ($\mu\text{B/sr}$)
L_KIN_1	0.5800
L_KIN_2	0.5829
L_KIN_3	0.5728
S_KIN_1	0.5424
S_KIN_2	0.5449

Table 43: Expected cross sections for all kinematics/particle selections (from KFITS3.f).

The corrected experimental yields are obtained by multiplying the experimental yields shown in Table 39 by the correction factors shown in Table 41. The simulated and corrected experimental yields, as well as the ratios (see Equation (57)), are shown in Table 44.

kinematics/particle	MCEEP yield	Experimental Yield (corrected)	Ratio
L_KIN_1	2597	2588	0.9963
L_KIN_2	1299	1178	0.9068
L_KIN_3	4710	5190	1.1020
S_KIN_1	1836	836	0.4552
S_KIN_2	3698	1848	0.4996

Table 44: Yields and ratios for all kinematics/particle selections.

From Tables 43, 44, and Equation (56) the measured experimental cross sections were obtained as shown in Table 45.

kinematics/particle	Measured Cross Section ($\mu\text{B}/\text{sr}$)	Average experimental Q^2 (GeV/c) ²	Average experimental W (GeV)	Average experimental θ_{CM} (rad)
L_KIN_1	0.5779	0.0710	2.2160	0.1089
L_KIN_2	0.5286	0.0719	2.2080	0.1092
L_KIN_3	0.6312	0.0699	2.2310	0.1134
S_KIN_1	0.2469	0.0691	2.2320	0.1108
S_KIN_2	0.2723	0.0711	2.2250	0.1145

Table 45: Experimental cross sections in E94-107. Experimental average variable values are listed. Uncertainties discussed in Section 4.9.

When the analysis is performed with the inclusion of the RICH detector, it causes the statistics to decrease. However, after correcting for RICH efficiency, the cross sections were similar, but also using the RICH produced a larger statistical uncertainty. The RICH performs very well in reducing the background, something crucial for resolving hypernuclear energy states with different targets or nuclear core states. In this analysis since the Λ and Σ^0 peaks are quite evident above the background the RICH is not really necessary.

4.9 Uncertainty measurements

The origin of the many of the uncertainties in this work is statistical in nature. However, the uncertainties in the cross-section measurements produced when analyzing the efficiencies, inefficiencies, or correcting factors of the detectors, absorption and deadtime, called systematic uncertainties, are taken separately from the statistical ones that comes from the yields themselves, because later, when the data are binned in different variables to study the cross-section measurement trends, the statistical uncertainties depend on the number of counts for each bin while the systematic uncertainties remain the same. The efficiencies of the different detectors follow binomial or Poisson distributions because of the dependence between the numerator and denominator of the general detector efficiency (ε_{det}) formula:

$$\varepsilon_{det} = \frac{N_{det}}{N_{tot}}, \quad (61)$$

where N_{det} and N_{tot} are the detected events and the total number of events (detected and undetected). In this case the uncertainty of the efficiency ($\delta\epsilon_{\text{det}}$) is given by the formula:

$$\delta\epsilon_{\text{det}} = \sqrt{\frac{\epsilon_{\text{det}}(1 - \epsilon_{\text{det}})}{N_{\text{tot}}}}, \quad (62)$$

After obtaining the uncertainties for the different efficiency analyses, the standard method for uncertainties propagation is used:

$$\delta\epsilon_{\text{det}} = \sqrt{\sum \left(\frac{\partial\epsilon_{\text{det}}}{\partial x_i} \right)^2 (\delta x_i)^2}, \quad (63)$$

where $\frac{\partial\epsilon_{\text{det}}}{\partial x_i}$ is the partial derivative with respect to a generic variable and δx_i is variation of the generic variable. Because systematic uncertainties result from the uncertainties in the measurements of the detector efficiencies, inefficiencies, and scaling factors, and because they propagate as shown above, they are straightforward to tabulate as shown in Table 46. After obtaining the uncertainties in the correction factors, it is simple to get the systematics uncertainties in the cross sections. The systematics uncertainties are obtained by multiplying the experimental yield by the uncertainties of the correction factors according to Equation (63) instead of the correction factors, and following the same method as when calculating the experimental cross section (see Section 4.8). It is

important to note that the uncertainties obtained per run in sections 3.3, 3.4 and 3.5 were weighted by the charge by the following equation:

$$\delta\epsilon_{\text{det}} = \frac{\sum Q_i \delta\epsilon_i}{N \sum Q_i}, \quad (64)$$

where N is the number of runs for a particular kinematics/particle selected. Table 46 shows the uncertainties in each correction factor for each detector that contribute for the total uncertainty in the total correction factor.

Kinematics particle	Uncertainty:	SYSTEMATIC UNCERTAINTIES IN THE CORRECTION FACTORS FROM DETECTORS AND ELECTRONICS						
Uncertainty in:	Correction FACTOR	VDC	A1	A2	CO ₂	Deadtime	Scint_eff	Absorp.
L_KIN_1	0.1110	0.0008	0.0145	0.0021	0.0007	0.0002	0.00003	0.0016
L_KIN_2	0.1738	0.0010	0.0210	0.0037	0.0007	0.0001	0.00003	0.0016
L_KIN_3	0.1465	0.0009	0.0195	0.0028	0.0012	0.0001	0.00003	0.0015
S_KIN_1	0.2814	0.0008	0.0221	0.0090	0.0007	0.0002	0.00003	0.0016
S_KIN_2	0.2632	0.0010	0.0356	0.0056	0.0007	0.0001	0.00003	0.0016

Table 46: Systematic uncertainties from detectors and electronics in the correction factors.

Regarding Table 46 and proceeding as the explanation in the above paragraphs the contribution from detectors and electronics for the systematic uncertainties in the cross-section measurements were calculated and are shown in Table 47.á

kinematics/particle	Systematic Uncertainties ($\mu\text{B}/\text{sr}$)
L_KIN_1	0.0078
L_KIN_2	0.0103
L_KIN_3	0.0112
S_KIN_1	0.0058
S_KIN_2	0.0086

Table 47: Systematic uncertainties from detectors and electronics in the experimental cross sections.

In addition to the systematic uncertainties shown in Table 47, the integrated beam current uncertainty and the target density uncertainty that reflect the uncertainty in the luminosity has to be included in the overall systematic uncertainties. The integrated beam current uncertainties are calculated from Table 40. The target density uncertainties are taken as the estimates described in Section 3.7. These additional uncertainties are shown in Table 48.

Kinematics	Target density	Integrated beam current
	Uncertainty (%)	Uncertainty (%)
KIN_1 (2485-2492)	1.00	0.18
KIN_2 (2496-2508)	1.00	0.28
KIN_3 (2509-2521)	1.00	0.24

Table 48: Uncertainties in target density and integrated beam current.

The statistical uncertainties comes from the experimental yields themselves and they are different for each bin done later in Section 4.10. In the case of the five different kinematics/particle selected, the uncertainty in the yield is given by the square root of the uncorrected experimental yield (Table 39), which then correcting the uncertainties and following the same procedure to calculate the cross section as done using the Equation (56), this produces the following results shown in Tables 49 and 50.

kinematics/particle	Statistical Uncertainties ($\mu\text{B}/\text{sr}$)
L_KIN_1	0.0156
L_KIN_2	0.0223
L_KIN_3	0.0126
S_KIN_1	0.0113
S_KIN_2	0.0093

Table 49: Statistical uncertainties in the experimental cross sections.

Kinematics /particle	SYSTEMATICS ($\mu\text{B}/\text{sr}$)	STATISTICAL ($\mu\text{B}/\text{sr}$)	TOTAL ($\mu\text{B}/\text{sr}$)	Syst. Unc. (%)	Stat. Unc. (%)	Total %
L_KIN_1	0.0104	0.0156	0.0187	1.79	2.69	3.24
L_KIN_2	0.0123	0.0223	0.0255	2.33	4.21	4.82
L_KIN_3	0.0137	0.0126	0.0186	2.16	2.00	2.94
S_KIN_1	0.0065	0.0113	0.0130	2.63	4.56	5.28
S_KIN_2	0.0093	0.0093	0.0131	3.41	3.40	4.82

Table 50: Summary of uncertainties in E94-107 (Tables 47, 48 and 49 included).

In addition, having a large number of entries (hundreds of thousands) in the MCEEP simulation makes the statistical uncertainties in the simulation results too small to be considered.

4.10 Data binning

The purpose of binning the data over the narrow range of kinematics covered in this experiment is to observe the trend or slope of the cross sections when a particular variable changes. In particular the interesting variables are: momentum transfer squared (Q^2), invariant mass (W) and kaon angle in the CM frame (θ_{CM}). As a result of the limited statistics in experiment E94-107, it was decided to bin the data in three approximately equal parts for each variable, producing three cross-section measurements

for each kinematics/particle selection for each of the five kinematics/particle (Table 21) selections. Given three different variables, a total of forty five cross-section measurements were obtained resulting from the binning. The ranges for the variables taken for the binning, mentioned in the previous paragraph are shown in Tables 51, 52 and 53.

Kinematics /particle	Q1 (GeV/c) ²	Q2 (GeV/c) ²	Q3 (GeV/c) ²
L_KIN_1	[0.0400,0.0593]	[0.0593,0.0756]	[0.0756,0.1200]
L_KIN_2	[0.0400,0.0666]	[0.0666,0.0789]	[0.0789,0.1200]
L_KIN_3	[0.0400,0.0613]	[0.0613,0.0762]	[0.0762,0.1200]
S_KIN_1	[0.0400,0.0568]	[0.0568,0.0677]	[0.0677,0.1200]
S_KIN_2	[0.0400,0.0599]	[0.0599,0.0700]	[0.0700,0.1200]

Table 51: Ranges for binning the data in Q^2 for each kinematics/particle selection. The bins in Q^2 were labeled; Q1, Q2 and Q3.

Kinematics /particle	W1 (GeV)	W2 (GeV)	W3 (GeV)
L_KIN_1	[2.1794,2.2112]	[2.2112,2.2218]	[2.2218,2.2694]
L_KIN_2	[2.1794,2.2036]	[2.2036,2.2091]	[2.2091,2.2694]
L_KIN_3	[2.1794,2.2268]	[2.2268,2.2382]	[2.2382,2.2694]
S_KIN_1	[2.1863,2.2303]	[2.2303,2.2369]	[2.2369,2.2583]
S_KIN_2	[2.1863,2.2205]	[2.2205,2.2359]	[2.2359,2.2583]

Table 52: Ranges for binning the data in W for each kinematics/particle selection. The bins in W were labeled; W1, W2 and W3.

Kinematics /particle	T1 (rad)	T2 (rad)	T3 (rad)
L_KIN_1	[0.0000,0.0923]	[0.0923,0.1283]	[0.1283,0.2550]
L_KIN_2	[0.0000,0.0892]	[0.0892,0.1194]	[0.1194,0.2550]
L_KIN_3	[0.0000,0.0942]	[0.0942,0.1312]	[0.1312,0.2550]
S_KIN_1	[0.0000,0.0860]	[0.0860,0.1206]	[0.1206,0.2550]
S_KIN_2	[0.0000,0.0916]	[0.0916,0.1280]	[0.1280,0.2550]

Table 53: Ranges for binning the data in θ_{CM} for each kinematics/particle selection. The bins in θ_{CM} were labeled; T1, T2 and T3.

Another piece of information needed is the input average values from the MCEEP simulation to be used as input to the program KFITS3.f that calculates the “point” cross section for each bin (see Section 4.8). The point cross sections are multiplied by the ratio of the corrected measured yield to the MCEEP simulated yield (see Equations from (56) to (60)). MCEEP values were used as input to KFITS3.f instead of real data because the statistical uncertainties in the simulation (high number of entries) were neglectable compared to the significant statistical experimental uncertainties (see Table 50), and a good matching between the simulated and experimental yields was obtained after acceptance corrections (see Section 4.7). Detailed information of the MCEEP summary outputs and the comparison of the MCEEP histograms and the experimental histograms are in Appendix J.

The MCEEP values are listed for the binned data in the variables Q^2 , W and θ_{CM} in Tables 54 to 56, where variations on the average values of the unbinned variables are observed, because when binning in one variable no cuts were applied in the other variables to keep statistics as high as possible, otherwise the statistical uncertainties increases too much.

Binned Kinematics /particle	Beam Energy (E) (GeV)	Q^2 (GeV/c) ²	W (GeV)	p_K (GeV/c)	θ_K (degrees)
Q1_L_KIN_1	3.7758	0.0540	2.2200	1.8961	2.6400
Q2_L_KIN_1	3.7758	0.0670	2.2170	1.8944	2.4010
Q3_L_KIN_1	3.7758	0.0880	2.2110	1.8917	1.9800
Q1_L_KIN_2	3.7807	0.0590	2.2100	1.8724	2.5580
Q2_L_KIN_2	3.7807	0.0730	2.2070	1.8723	2.3100
Q3_L_KIN_2	3.7807	0.0910	2.2030	1.8718	1.9490
Q1_L_KIN_3	3.7758	0.0550	2.2350	1.9348	2.7110
Q2_L_KIN_3	3.7758	0.0690	2.2310	1.9326	2.4420
Q3_L_KIN_3	3.7758	0.0880	2.2250	1.9298	2.0270
Q1_S_KIN_1	3.7758	0.0530	2.2370	1.8317	2.7540
Q2_S_KIN_1	3.7758	0.0620	2.2340	1.8302	2.5790
Q3_S_KIN_1	3.7758	0.0830	2.2290	1.8284	2.1330
Q1_S_KIN_2	3.7807	0.0550	2.2310	1.8174	2.6990
Q2_S_KIN_2	3.7807	0.0650	2.2270	1.8139	2.5150
Q3_S_KIN_2	3.7807	0.0850	2.2220	1.8099	2.0950

Table 54: MCEP average values for data binning in Q^2 . The bins in Q^2 were labeled; Q1, Q2 and Q3.

Binned Kinematics /particle	Beam Energy (E) (GeV)	Q^2 (GeV/c) ²	W (GeV)	p_K (GeV/c)	θ_K (degrees)
W1_L_KIN_1	3.7758	0.0790	2.2030	1.8682	2.0910
W2_L_KIN_1	3.7758	0.0750	2.2160	1.8997	2.2410
W3_L_KIN_1	3.7758	0.0700	2.2290	1.9232	2.4550
W1_L_KIN_2	3.7807	0.0840	2.1990	1.8625	2.0060
W2_L_KIN_2	3.7807	0.0750	2.2060	1.8746	2.2330
W3_L_KIN_2	3.7807	0.0690	2.2150	1.8815	2.4750
W1_L_KIN_3	3.7758	0.0780	2.2170	1.9064	2.1600
W2_L_KIN_3	3.7758	0.0730	2.2320	1.9382	2.3760
W3_L_KIN_3	3.7758	0.0680	2.2440	1.9645	2.5420
W1_S_KIN_1	3.7758	0.0780	2.2230	1.8122	2.1520
W2_S_KIN_1	3.7758	0.0730	2.2340	1.8337	2.3510
W3_S_KIN_1	3.7758	0.0670	2.2420	1.8496	2.5700
W1_S_KIN_2	3.7807	0.0780	2.2090	1.7782	2.1330
W2_S_KIN_2	3.7807	0.0740	2.2280	1.8194	2.3420
W3_S_KIN_2	3.7807	0.0700	2.2430	1.8544	2.5130

Table 55: MCEP average values for data binning in W . The bins in W were labeled; W1, W2 and W3.

Binned Kinematics /particle	Beam Energy (E)	Q^2 (GeV/c) 2	W (GeV)	p_K (GeV/c)	θ_K (degrees)
T1_L_KIN_1	3.7758	0.0800	2.2120	1.8922	1.4010
T2_L_KIN_1	3.7758	0.0730	2.2150	1.8944	2.4110
T3_L_KIN_1	3.7758	0.0700	2.2180	1.8940	3.3650
T1_L_KIN_2	3.7807	0.0820	2.2040	1.8728	1.3630
T2_L_KIN_2	3.7807	0.0750	2.2070	1.8725	2.2880
T3_L_KIN_2	3.7807	0.0720	2.2080	1.8709	3.2340
T1_L_KIN_3	3.7758	0.0790	2.2260	1.9299	1.4850
T2_L_KIN_3	3.7758	0.0720	2.2300	1.9330	2.4540
T3_L_KIN_3	3.7758	0.0680	2.2330	1.9335	3.3920
T1_S_KIN_1	3.7758	0.0800	2.2290	1.8278	1.3410
T2_S_KIN_1	3.7758	0.0730	2.2310	1.8294	2.2400
T3_S_KIN_1	3.7758	0.0680	2.2340	1.8304	3.2110
T1_S_KIN_2	3.7807	0.0800	2.2210	1.8083	1.4280
T2_S_KIN_2	3.7807	0.0730	2.2260	1.8139	2.3730
T3_S_KIN_2	3.7807	0.0690	2.2280	1.8152	3.3210

Table 56: MCEEP average values for data binning in θ_{CM} . The bins in θ_{CM} were labeled; T1, T2 and T3.

The method followed to obtain the cross sections was the same as explained in Section 4.8. The results have been listed in Tables 57, 58 and 59. The first column indicates the different bins, the second the yield in each bin, the third column indicates the average value of the variable on which the binning was performed, then follows the measured cross section, and the four final columns are the uncertainties, which were obtained by the procedure explained in Section 4.9. The results are shown graphically in Chapter 5, Section 5.1.

Binned Kinematics /particle	Binned Yield	Average Q^2 (GeV/c) ²	Cross Section (μB/sr)	Systematic Uncert. (μB/sr)	Statistical Uncert. (μB/sr)	Total Uncert. (μB/sr)	Total Uncer. (%)
Q1_L_KIN_1	399	0.0540	0.7280	0.0104	0.0364	0.0379	5.20
Q2_L_KIN_1	450	0.0670	0.5004	0.0104	0.0236	0.0258	5.15
Q3_L_KIN_1	531	0.0880	0.5672	0.0104	0.0246	0.0267	4.71
Q1_L_KIN_2	245	0.0590	0.6210	0.0123	0.0397	0.0416	6.69
Q2_L_KIN_2	135	0.0730	0.4806	0.0123	0.0414	0.0432	8.99
Q3_L_KIN_2	181	0.0910	0.4683	0.0123	0.0348	0.0369	7.88
Q1_L_KIN_3	881	0.0550	0.7177	0.0137	0.0242	0.0278	3.87
Q2_L_KIN_3	788	0.0690	0.5774	0.0137	0.0206	0.0247	4.28
Q3_L_KIN_3	837	0.0880	0.6110	0.0137	0.0211	0.0252	4.12
Q1_S_KIN_1	128	0.0530	0.3313	0.0065	0.0293	0.0300	9.06
Q2_S_KIN_1	149	0.0620	0.2775	0.0065	0.0227	0.0236	8.51
Q3_S_KIN_1	203	0.0830	0.1995	0.0065	0.0140	0.0154	7.74
Q1_S_KIN_2	225	0.0550	0.2883	0.0093	0.0192	0.0213	7.40
Q2_S_KIN_2	215	0.0650	0.2694	0.0093	0.0184	0.0206	7.65
Q3_S_KIN_2	425	0.0850	0.2670	0.0093	0.0130	0.0160	5.99

Table 57: Cross-section results for data binning in Q^2 , summed over the other variables. The bins in Q^2 were labeled; Q1, Q2 and Q3.

Binned Kinematics /particle	Binned Yield	Average W (GeV)	Cross Section (μB/sr)	Systematical Uncert. (μB/sr)	Statistical Uncert. (μB/sr)	Total Uncert. (μB/sr)	Total Uncert. (%)
W1_L_KIN_1	513	2.2030	0.5274	0.0104	0.0233	0.0255	4.84
W2_L_KIN_1	382	2.2160	0.5699	0.0104	0.0292	0.0310	5.44
W3_L_KIN_1	484	2.2290	0.6503	0.0104	0.0296	0.0314	4.82
W1_L_KIN_2	179	2.1990	0.4534	0.0123	0.0339	0.0361	7.95
W2_L_KIN_2	192	2.2060	0.5930	0.0123	0.0428	0.0445	7.51
W3_L_KIN_2	191	2.2150	0.5539	0.0123	0.0401	0.0419	7.57
W1_L_KIN_3	958	2.2170	0.5865	0.0137	0.0189	0.0233	3.98
W2_L_KIN_3	737	2.2320	0.6555	0.0137	0.0241	0.0277	4.23
W3_L_KIN_3	811	2.2440	0.6721	0.0137	0.0236	0.0273	4.06
W1_S_KIN_1	212	2.2230	0.2520	0.0065	0.0173	0.0185	7.33
W2_S_KIN_1	129	2.2340	0.2947	0.0065	0.0259	0.0267	9.06
W3_S_KIN_1	138	2.2420	0.2073	0.0065	0.0176	0.0188	9.05
W1_S_KIN_2	348	2.2090	0.2819	0.0093	0.0151	0.0177	6.29
W2_S_KIN_2	259	2.2280	0.2626	0.0093	0.0163	0.0188	7.15
W3_S_KIN_2	258	2.2430	0.2712	0.0093	0.0169	0.0193	7.11

Table 58: Cross-section results for data binning in W , summed over the other variables. The bins in W were labeled; W1, W2 and W3.

Binned Kinematics /particle	Binned Yield	Average θ_{CM} (deg.)	Cross Section ($\mu\text{B}/\text{sr}$)	Systematical Uncert. ($\mu\text{B}/\text{sr}$)	Statistical Uncert. ($\mu\text{B}/\text{sr}$)	Total Uncert. ($\mu\text{B}/\text{sr}$)	Total Uncert. (%)
T1_L_KIN_1	484	3.6600	0.5191	0.0104	0.0236	0.0258	4.97
T2_L_KIN_1	451	6.2900	0.5767	0.0104	0.0272	0.0291	5.05
T3_L_KIN_1	444	8.7730	0.6602	0.0104	0.0313	0.0330	5.00
T1_L_KIN_2	186	3.5530	0.4665	0.0123	0.0342	0.0363	7.79
T2_L_KIN_2	142	5.9590	0.4700	0.0123	0.0394	0.0413	8.78
T3_L_KIN_2	235	8.4170	0.6481	0.0123	0.0423	0.0441	6.80
T1_L_KIN_3	840	3.8920	0.5885	0.0137	0.0203	0.0245	4.16
T2_L_KIN_3	784	6.4290	0.5599	0.0137	0.0200	0.0242	4.33
T3_L_KIN_3	881	8.8790	0.7745	0.0137	0.0261	0.0295	3.81
T1_S_KIN_1	145	3.5550	0.2705	0.0065	0.0225	0.0234	8.66
T2_S_KIN_1	165	5.9310	0.2625	0.0065	0.0204	0.0214	8.16
T3_S_KIN_1	170	8.4930	0.2184	0.0065	0.0167	0.0179	8.21
T1_S_KIN_2	297	3.7780	0.2756	0.0093	0.0160	0.0185	6.71
T2_S_KIN_2	227	6.2740	0.2051	0.0093	0.0136	0.0165	8.03
T3_S_KIN_2	341	8.7760	0.3452	0.0093	0.0187	0.0209	6.05

Table 59: Cross-section results for data binning in θ_{CM} summed over the other variables. The bins in θ_{CM} were labeled; T1, T2 and T3.

5 Results and conclusions

In the beginning of this dissertation, Section 1.5 posed the following Question a):

What are the cross sections for $^1\text{H}(e,e'K^+)\Lambda,\Sigma^0$ at $\theta_{CM}=6^\circ$, $W=2.2$ GeV and $Q^2 \sim 0.07$ (GeV/c) 2 ? The answer is in Section 5.1, where the results from E94-107 are summarized as well as shown graphically.

In Section 5.2, discussions of the results and conclusions are presented to answer Questions b), c), d) and e).

5.1 Results

The results for the Λ channel (Table 45) corresponding to the three first rows of Table 42 are plotted vs. their average kaon momentum and shown in Figure 102.

Similarly the results for the Σ^0 channel corresponding (Table 45) to the last two rows of Table 42 are plotted vs. their average kaon momentum and shown in Figure 103. In both cases, the inner error bars represent the statistical uncertainties, while the outer error bars represent the total uncertainties (statistical and systematical uncertainties). It is important to mention that the average of the other variables like Q^2 and W are not quite equal but they are close (e.g., typically a few MeV in W) because of the very small acceptance in the Hall A spectrometers. Therefore to answer Question a), the cross sections for $^1\text{H}(e,e'K^+)\Lambda,\Sigma^0$ at $\theta_{\text{CM}}=6^\circ$, $W=2.2$ GeV and $Q^2 \sim 0.07$ (GeV/c) 2 are shown in Figures 102 and 103 for each kinematics/particle selection (Table 21).

Figure 102: Λ -channel measured cross section vs. average kaon momentum for unbinned data. $W=2.2$ GeV, $Q^2 \sim 0.07$ (GeV/c) 2 and $\theta_{\text{CM}}=6^\circ$. Inner error bars represent statistical uncertainties only, and outer error bars represent total uncertainties (statistical and systematic uncertainties).

Figure 103: Σ^0 channel measured cross sections vs. average kaon momentum for unbinned data. $W=2.2$ GeV, $Q^2 \sim 0.07$ (GeV/c) 2 and $\theta_{\text{CM}}=6^\circ$. Inner error bars represent statistical uncertainties only, and Outer error bars represent total uncertainties (statistical and systematic uncertainties).

The results from the binned data in Q^2 , W and θ_{CM} that are listed in Tables 57, 58 and 59 are shown in Figures 104, 105 and 106. The results are organized for the five different kinematics/particle selections as described in Table 21. The error bars represent total uncertainties; the combined systematic and statistical uncertainties.

Figure 104: Cross sections vs. Q^2 in E94-107. Error bars represent total uncertainties (statistical and systematic uncertainties). Average variable values are listed in Table 57.

Figure 105: Cross sections vs. W in E94-107. Error bars represent total uncertainties (statistical and systematic uncertainties). Average variable values are listed in Table 58.

Figure 106: Cross section vs. θ_{CM} in E94-107. Error bars represent total uncertainties (statistical and systematic uncertainties). Average variable values are listed in Table 59.

Figure 104 shows that the Λ channel cross section slightly decreases with Q^2 , but Figure 106 shows that it slightly increases in θ_{CM} . However, according to Figure 105 the trend appears almost flat in W . These results are expected according to the scaling factors mentioned in Equations (51) and (54). Note also that the change in W is very small, a possible reason for observing an almost flat trend.

On the other hand, Figures 104, 105 and 106 show that all the trends for the Σ^0 channel are almost flat. Although, it is difficult to conclude from the binning in Q^2 , it can arguably be said that there is a slight decrease when Q^2 increases. The Σ^0 channel results are less understood than the Λ channel. There are not much data available and less

knowledge about it. One of the scopes of my dissertation is to provide extra data that could be useful for future model construction.

5.2 Conclusions

The results of experiment E94-107 are shown in Section 5.1. In this section several comparisons of the results from E94-107 with the existing data and the available models are performed. Furthermore, Questions b), c), d) and e) in Section 1.5 are answered. These questions are:

- b) What is the estimated transverse component of the electroproduction cross section? Which model better describes the data with the new experimental point included in Figure 8?
- c) Does the cross section for photoproduction continue rising as the kaon angles goes to zero or is there a plateau?
- d) What is the ratio of Σ^0/Λ at low Q^2 ? How does this result compare to the existing data?
- e) Which of the models describes the data at forward angles and can therefore be used in the analysis of the hypernuclear data without introducing an additional uncertainty?

In order to compare E94-107 results with the existing data and considering that small variations in $\delta p/p$ were done over a fairly small acceptance, the results for the different Λ channels (Table 45) and their uncertainties (Table 50) were averaged by the charge for each of the channels (see Equation (60) and (64)). The result obtained is then

$0.5858 \pm 0.0208 \frac{\mu\text{b}}{\text{sr}}$ and is shown graphically in Figure 107.

Figure 107: E94-107 electroproduction result with $Q^2 \sim 0.07 \text{ (GeV/c)}^2$, $W=2.2 \text{ GeV}$ and $\theta_{\text{CM}}=6^\circ$ compared to photoproduction data and models, all of them with $W=2.2 \text{ GeV}$. Error bars in E94-107 result represent total uncertainty (statistical and systematic uncertainties). CLAS data from Bradford et al., [27].

As shown in Figure 107, the cross section for electroproduction obtained $\theta_{\text{CM}} = 6^\circ$ from experiment E94-107 is greater than any value of the cross section for

photoproduction predicted by the models. There is also a lack of experimental data for angles less than $\theta_{\text{CM}} = 20^\circ$. However, any comparison has to take into account that the cross section for electroproduction in Equation (19), even at low Q^2 , contains extra terms (longitudinal contributions) that make it different from the (strictly transverse) cross section for photoproduction. The cross section for photoproduction does not have either longitudinal or longitudinal-transverse interference terms as is shown in (19) for the electroproduction cross section. In order to proceed with a better comparison, it is required to estimate how significant are the contributions for longitudinal and interference terms in the electroproduction cross section for the E94-107 kinematics. Experiment E94-107 was run not at the same kinematic conditions of the experiment E91-016 [77]. However, we are in a kinematical region in W where there are no resonances dominating and where previous measurements by Bradford et al. [27] have shown that the interference terms are negligible. Therefore, only the longitudinal contribution needs to be estimated. Figure 108 shows the existing data on electroproduction of Λ hyperons at JLab. The data include Halls A, B and C (a short description of the experimental halls at JLab is in Section 2.1). Figure 108 shows the different measurements of the cross sections vs. Q^2 for different invariant masses W . For comparison purposes, the data have been scaled in W . Consequently, it can be estimated that over the entire range in Q^2 , the ratio $\frac{\sigma_L}{\sigma_T}$ is not more than 0.5. In other words,

$$\frac{\sigma_L}{\sigma_T} < 0.5 \text{ and with Equation (19) it can be stated that: } \frac{d^2\sigma}{d\Omega^*_K} \approx \sigma_T + \varepsilon\sigma_L. \text{ Observing the}$$

E94-107 kinematic settings for the virtual photon's polarization, Figures 91, 92 and 93

show that the average polarization is $\varepsilon = 0.710 \pm 0.010$ for this experiment. Therefore, the estimated contribution by transverse amplitudes to the electroproduction cross section is conservatively greater than 0.740 ± 0.003 of the measured cross section. Furthermore, the minimum value that the corresponding photoproduction cross section for E94-107 can reach is given by multiplying 0.740 ± 0.003 times the weighted measured electroproduction cross sections and their uncertainties by the charge for each kinematics as shown in Equation (60).

Figure 108: Longitudinal to transversal component ratios of electroproduction cross section for JLab experiments. Data shown are at different θ_{CM} and W (on the range 1.5 - 1.8 GeV).

Consequently, to answer Questions b) and c), it can be stated that the transverse component of the electroproduction cross section in E94-107 would have a minimum possible value of $0.432 \pm 0.015 \frac{\mu\text{b}}{\text{sr}}$. However, since an actual longitudinal-transverse separation was not performed, the ratio $\frac{\sigma_L}{\sigma_T}$ in Figure 108 has an assigned uncertainty of 0.2 (for low Q^2). The assigned uncertainty produces a larger uncertainty on the estimate of the transverse component of the cross section. Nevertheless, the overestimate of the uncertainty comes from directly comparing electroproduction and photoproduction results. This larger uncertainty is ± 0.05 . Figure 109 shows the transverse component of the electroproduction cross section in E94-107 with inner error bars because of the uncertainties in E94-107 only, and outer error bars that include the assigned uncertainty obtained from Figure 108 in addition to the uncertainty in E94-107.

Figure 109: Estimate of the transverse component of the electroproduction cross section in E94-107 ($Q^2 \sim 0.07$ (GeV/c) 2 , $W=2.2$ GeV and $\theta_{CM}=6^\circ$) compared to photoproduction data and models, all of them with $W=2.2$ GeV. Inner error bars in E94-107 estimate represent E94-107 uncertainty only. Outer error bars represent total uncertainty (E94107 uncertainty and assigned uncertainty from Figure 108). CLAS data from Bradford et al., [27].

As a conclusion for Question e), the obtained cross section for transversely polarized photons exceeds most of the predicted values by the different theoretical models and shows that the transverse component of the electroproduction cross section rises when $\theta_{CM} \rightarrow 0^\circ$, except in the WJC and Saclay-Lyon A models. However, the WJC and Saclay-Lyon A models do not describe correctly the experimental measurements at higher θ_{CM} .

In order to answer Question d) in Section 1.5 the results taken from the data

binning in Q^2 were used to find the $\frac{\Sigma^0}{\Lambda}$ ratios. From Table 57, it was obtained Table 60.

Binning in Q^2	Kinematics /particle combination	Cross section ratios	Uncertainties
Q1:	S_KIN_1/L_KIN1	0.4551	0.0475
Q2:	S_KIN_1/L_KIN1	0.5546	0.0552
Q3:	S_KIN_1/L_KIN1	0.3517	0.0319
Q1:	S_KIN_2/L_KIN2	0.4643	0.0463
Q2:	S_KIN_2/L_KIN2	0.5605	0.0662
Q3:	S_KIN_2/L_KIN2	0.5701	0.0564

Table 60: $\frac{\Sigma^0}{\Lambda}$ ratios in E94-107.

Tables 54 and 60 were used to generate Figure 110, where the solid circles correspond to KIN_1 and the solid square to KIN_2, both for different binned data in Q^2 as shown in Table 60.

From the $\frac{\Sigma^0}{\Lambda}$ cross-section ratios for the different kinematics listed in Table 45, the weighted by the charge (Equation (60)), average value for the $\frac{\Sigma^0}{\Lambda}$ cross-section ratio was determined to be 0.4761 ± 0.0313 (see Figure 111). The ratio would be the slightly greater for the transverse components of the cross section since the Σ^0 longitudinal responses appear to be smaller than the Λ . Figure 110 shows the results of $\frac{\Sigma^0}{\Lambda}$ cross-section ratio after binning the data in Q^2 .

Figure 110: $\frac{\Sigma^0}{\Lambda}$ cross section ratio results from E94-107. Values listed in Table 60. Average variable values listed in Tables 54 and 57.

Figure 111 shows the $\frac{\Sigma^0}{\Lambda}$ photoproduction cross-section ratio data available from Hall B published by Bradford et al, [27]. The E94-107 $\frac{\Sigma^0}{\Lambda}$ electroproduction cross-section ratio has been added at a very small angle $\theta_{\text{CM}} = 6^\circ$. It can be seen that the E94-107 contribution fits well on the trend of the data, which was obtained at the same invariant mass $W \approx 2.2 \text{ GeV}$.

CLAS Ratio of $\Sigma^0:\Lambda^0$, $W=2.207$ GeV

Figure 111: $\frac{\Sigma^0}{\Lambda}$ photoproduction cross-section ratio data from Hall B, Jlab (Bradford et al., [27]) and E94-107 contribution at $\theta_{CM}=6^\circ$, with $Q^2=0.07$ (GeV/c) 2 and $W=2.2$ GeV.

Furthermore, the Kaon Maid model that includes hadronic form factors in the calculations differs from the data for θ_{CM} less than 20° , as was shown in Figure 112.

Kaon Maid Ratio of $\Sigma^0:\Lambda^0$ vs. Q^2

Figure 112: Kaon Maid model for $\frac{\Sigma^0}{\Lambda}$ cross-section ratio vs. Q^2 , with $W=2.2$ GeV and $\theta_{CM}=0^0$.

The Kaon maid model also predicts a $\frac{\Sigma^0}{\Lambda}$ cross-section ratio of about 0.15 to 0.2 for $Q^2 \approx 0.07$ (GeV/c)², which is too low (see Figure 112) compared to E94107 result (see Figure 111).

In conclusion, none of the models completely describe well the results of the photoproduction cross sections. The results of my research are important experimental measurements that will probably contribute to improve the existing theoretical models (see Section 1.5).

Finally, it is also important to remark that in the case of the Σ^0 channel, the MCEEP simulation was run using a similar model as in the case of the Λ channel. In particular, the model assumed a similar cross section dependence on the kinematic variables in averaging the cross section over the experimental acceptance. Nevertheless, the MCEEP-to-measured yield distributions for the Σ^0 channel showed a good agreement. Currently, although we have highlighted that there are still many adjustments to do to describe the Λ channel mechanisms, the Σ^0 channel is even less known. The results of my work will probably contribute to a better understanding of the elementary reaction $H(e, e'K^+)\Lambda, \Sigma^0$ as more data become available.

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Appendices

A Kaon absorption program (by J. Reinhold).

```
program absorb
  implicit none
  real siga(0:20),NovrN,NovrN0(0:20),R,Ns,Rabs(0:20),p,dens,A,t,Ntar,
  integer i
  real sigKA
c   write(*,*)'momenta,  absorp coef,  absorp coef Reinhold'
  write(*,*)'momenta,  absorp coef'
  do p=1.,2.6,0.01
c   /* function calls for the various materials for a given momentum */

c   /* first do hydrogen target */
  A=1.01                                /* atomic weight, hydrogen */
  t=4.00                                /* thickness in cm */
  dens=0.0723                           /* density in gm/cm^3 */
  siga(0)=0.804*(p**(-0.99))*26.2*(A**0.79) /* cross section in mb */
  NovrN0(0)=6.022*dens*t*siga(0)/A      /* fraction (number) absorbed */
  Rabs(0)=6.022E-4*dens*t*sigKA(1.,p)/A

c   /* second: target walls second */    /* aluminum */
  A=26.98
  t=0.0102
  dens=2.70
  siga(1)=0.804*(p**(-0.99))*26.2*(A**0.79)
  NovrN0(1)=6.022*dens*t*siga(1)/A
  Rabs(1)=6.022E-4*dens*t*sigKA(27.,p)/A

c   ! third: VDC detectors

c   /* kevlar (approx)*/
  A=(5.*12.01 + 4.*1.01 + 2.*16.00)/11.0
  t=0.0381
  dens=0.74
  siga(3)=0.804*(p**(-0.99))*26.2*(A**0.79)
  NovrN0(3)=6.022*dens*t*siga(3)/A
  Ntar=6.022E-4*dens*t/(5.*12.01 + 4.*1.01 + 2.*16.00)
  Rabs(3)=Ntar*(5.*sigKA(12.,p)+4.*sigKA(1.,p)+2.*sigKA(16.,p))

c   /* wire chambers (2 each), fourth */
c   /* tungsten */
  A=183.85
  t=0.0000212*2. + 0.00085*2
  dens=19.30
  siga(4)=0.804*(p**(-0.99))*26.2*(A**0.79)
  NovrN0(4)=6.022*dens*t*siga(4)/A
```

```

Ntar=6.022E-4*dens*t/A
Rabs(4)=Ntar*sigKA(184.,p)

c    /* cathode (mylar) fifth */
A=(5.*12.01 + 4.*1.01 + 2.*16.00)/11.0
t=0.0044*2.
dens=1.39
sig(5)=0.804*(p**(-0.99))*26.2*(A**0.79)
NovrN0(5)=6.022*dens*t*sig(5)/A
Ntar=6.022E-4*dens*t/(5.*12.01 + 4.*1.01 + 2.*16.00)
Rabs(5)=Ntar*(5.*sigKA(12.,p)+4.*sigKA(1.,p)+2.*sigKA(16.,p))

c    /* Ar-ethane air sixth */
A=(39.95 + (2.*12.01 + 6.*1.01)/8.)/2.
t=10.16*2.
dens=((1.356 + 1.780)/2.)*1.E-3
sig(6)=0.804*(p**(-0.99))*26.2*(A**0.79)
NovrN0(6)=6.022*dens*t*sig(6)/A
Ntar=6.022E-4*dens*t/(39.95 + 2.*12.01 + 6.*1.01)
Rabs(6)=Ntar*(sigKA(40.,p)+2.*sigKA(12.,p)+6.*sigKA(1.,p))

c    /* scintillators (2 each), seventh */

c    /* mylar */
A=(5.*12.01 + 4.*1.01 + 2.*16.00)/11.0
t=.00254*2.
dens=1.39
sig(7)=0.804*(p**(-0.99))*26.2*(A**0.79)
NovrN0(7)=6.022*dens*t*sig(7)/A
Ntar=6.022E-4*dens*t/(5.*12.01 + 4.*1.01 + 2.*16.00)
Rabs(7)=Ntar*(5.*sigKA(12.,p)+4.*sigKA(1.,p)+2.*sigKA(16.,p))

c    !eight /* aluminum */
A=26.98
t=0.0000480*2.
dens=2.70
sig(8)=0.804*(p**(-0.99))*26.2*(A**0.79)
NovrN0(8)=6.022*dens*t*sig(8)/A
Ntar=6.022E-4*dens*t/A
Rabs(8)=Ntar*sigKA(27.,p)

c    !ninth /* polystyrene */
A=(1.01 + 12.01)/2.
t=1.125*2.
dens=1.032
sig(9)=0.804*(p**(-0.99))*26.2*(A**0.79)
NovrN0(9)=6.022*dens*t*sig(9)/A
Ntar=6.022E-4*dens*t/(12.01+1.01)

```

```
Rabs(9)=Ntar*(sigKA(12.,p)+sigKA(1.,p))
```

```
c  /* tedlar (mylar) tenth */
    A=(5.*12.01 + 4.*1.01 + 2.*16.00)/11.0
    t=.00254*2.
    dens=1.39
    sig(10)=0.804*(p**(-0.99))*26.2*(A**0.79)
    NovrN0(10)=6.022*dens*t*sig(10)/A
    Ntar=6.022E-4*dens*t/(5.*12.01 + 4.*1.01 + 2.*16.00)
    Rabs(10)=Ntar*(5.*sigKA(12.,p)+4.*sigKA(1.,p)+2.*sigKA(16.,p))
```

```
c  /* AEROGEL A1 Cherenkov, eleventh */ /*AEROGEL A1 */
    A=(12.01 + 2.*16.00)/3.
    t=9.00
    dens=0.074
    sig(11)=0.804*(p**(-0.99))*26.2*(A**0.79)
    NovrN0(11)=6.022*dens*t*sig(11)/A
    Ntar=6.022E-4*dens*t/(12.01 + 2.*16.00)
    Rabs(11)=Ntar*(sigKA(12.,p)+2.*sigKA(16.,p))
```

```
c  /* AEROGEL A2 Cherenkov, twelveth */ /*AEROGEL A2 */
    A=(12.01 + 2.*16.00)/3.
    t=5.00
    dens=0.074
    sig(12)=0.804*(p**(-0.99))*26.2*(A**0.79)
    NovrN0(12)=6.022*dens*t*sig(12)/A
    Ntar=6.022E-4*dens*t/(12.01 + 2.*16.00)
    Rabs(12)=Ntar*(sigKA(12.,p)+2.*sigKA(16.,p))
```

```
c  /* kevlar (approx) thirteenth*/
    A=(5.*12.01 + 4.*1.01 + 2.*16.00)/11.0
    t=0.0381*2
    dens=0.74
    sig(13)=0.804*(p**(-0.99))*26.2*(A**0.79)
    NovrN0(13)=6.022*dens*t*sig(13)/A
    Ntar=6.022E-4*dens*t/(5.*12.01 + 4.*1.01 + 2.*16.00)
    Rabs(13)=Ntar*(5.*sigKA(12.,p)+4.*sigKA(1.,p)+2.*sigKA(16.,p))
```

```
c  ! RICH
c  !Neoceram+quartz SiO2
    A=(28.086 + 2.*16.00)/3.
    t=0.90
    dens=2.20
    sig(14)=0.804*(p**(-0.99))*26.2*(A**0.79)
    NovrN0(14)=6.022*dens*t*sig(14)/A
    Ntar=6.022E-4*dens*t/(28.086 + 2.*16.00)
    Rabs(14)=Ntar*(sigKA(28.,p)+2.*sigKA(16.,p))
```

```

c      !Freon C6F14
      A=(6.*12.01 + 14.*18.998)/20.
      t=1.5
      dens=1.68
      siga(15)=0.804*(p**(-0.99))*26.2*(A**0.79)
      NovrN0(15)=6.022*dens*t*siga(15)/A
      Ntar=6.022E-4*dens*t/(6.*12.01 + 14.*18.998)
      Rabs(15)=Ntar*(6.*sigKA(12.,p)+14.*sigKA(19.,p))

c      !methane
      A=(12.01 + 4.*1.01)/5.
      t=10.0
      dens=0.0004
      siga(16)=0.804*(p**(-0.99))*26.2*(A**0.79)
      NovrN0(16)=6.022*dens*t*siga(16)/A
      Ntar=6.022E-4*dens*t/(12.01 + 4.*1.01)
      Rabs(16)=Ntar*(sigKA(12.,p)+4.*sigKA(1.,p))

c      !rohacell:polymethacrylimide ~aprox !~ -C2H7N02- rich electronics
      A=(2.*12.01 + 7.*1.01 + 1.*14.007 + 2.*16.00)/12.
      t=4.0
      dens=0.03
      siga(17)=0.804*(p**(-0.99))*26.2*(A**0.79)
      NovrN0(17)=6.022*dens*t*siga(17)/A
      Ntar=6.022E-4*dens*t/(2.*12.01 + 7.*1.01 + 1.*14.007 + 2.*16.00)
      Rabs(17)=Ntar*(2.*sigKA(12.,p)+7.*sigKA(1.,p))
      Rabs(17)=Rabs(17)+Ntar*(1.*sigKA(14.,p)+2.*sigKA(16.,p))

c      !18th !/* aluminum rich */ rich electronics
      A=26.98
      t=0.1
      dens=2.70
      siga(18)=0.804*(p**(-0.99))*26.2*(A**0.79)
      NovrN0(18)=6.022*dens*t*siga(18)/A
      Ntar=6.022E-4*dens*t/A
      Rabs(18)=Ntar*sigKA(27.,p)

c      /* air, ninth */ /* air */
      A=(0.80*14.01 + 0.20*16.00)
      t=25.0
      dens=1.29E-3
      siga(19)=0.804*(p**(-0.99))*26.2*(A**0.79)
      NovrN0(19)=6.022*dens*t*siga(19)/A
      Ntar=6.022E-4*dens*t/(8.*14.01 + 2.*16.00)
      Rabs(19)=Ntar*(8.*sigKA(14.,p)+2.*sigKA(16.,p))

c      /* now sum the cross sections and N/N0 */
      NovrN = 0.0

```

```

R=0.0
Ns=1.
do i=0,19
  NovrN = NovrN + NovrN0(i)
  R=R+Rabs(i)
  Ns=Ns*(1.-Rabs(i))
enddo
write(*,*) p,NovrN*1E-4
enddo
stop
end

```

```

C*****
  real function sigKA(A,p)
  implicit none
  real A,p
  integer i,ndat
  real pi,r02,xKpN,beta
C   parameter(pi=4.*atan(1.),ndat=205,r02=1.2*1.2E1)
  parameter(pi=3.1415927,ndat=205,r02=1.2*1.2E1)
  real pdat(205),xkpp(205)
C *****
C * total kaon-proton cross section from *
C * R.M. Barnett et al., Physical Review D54, 1 (1996) *
C * http://pdg.lbl.gov/~sbl/kpp_total.dat *
  data pdat/
1  0.178, 0.265, 0.321, 0.351, 0.366, 0.405, 0.440,
2  0.451, 0.475, 0.475, 0.506, 0.522, 0.536, 0.566,
3  0.569, 0.588, 0.589, 0.592, 0.593, 0.596, 0.618,
4  0.620, 0.627, 0.643, 0.644, 0.657, 0.668, 0.686,
5  0.698, 0.713, 0.717, 0.727, 0.757, 0.768, 0.770,
6  0.786, 0.817, 0.823, 0.846, 0.864, 0.864, 0.881,
7  0.891, 0.900, 0.904, 0.916, 0.938, 0.942, 0.951,
8  0.969, 0.969, 0.970, 0.970, 0.985, 0.992, 1.020,
9  1.029, 1.043, 1.055, 1.060, 1.084, 1.090, 1.094,
1 1.125, 1.130, 1.140, 1.144, 1.160, 1.170, 1.189,
2 1.194, 1.207, 1.210, 1.238, 1.245, 1.250, 1.293,
3 1.295, 1.300, 1.320, 1.345, 1.347, 1.380, 1.395,
4 1.408, 1.440, 1.445, 1.450, 1.468, 1.480, 1.495,
5 1.550, 1.563, 1.596, 1.600, 1.646, 1.690, 1.696,
6 1.700, 1.746, 1.750, 1.796, 1.800, 1.850, 1.896,
7 1.900, 1.945, 1.950, 1.960, 1.970, 1.996, 2.000,
8 2.050, 2.096, 2.100, 2.150, 2.196, 2.200, 2.260,
9 2.300, 2.350, 2.396, 2.400, 2.450, 2.473, 2.500,
1 2.530, 2.550, 2.550, 2.600, 2.650, 2.700, 2.750,
2 2.760, 2.800, 2.830, 2.850, 2.900, 2.950, 3.000,
3 3.050, 3.100, 3.150, 3.200, 3.200, 3.240, 3.250,
4 3.300, 3.700, 4.000, 4.200, 4.750, 5.000, 5.500,
5 6.000, 7.000, 7.000, 8.000, 8.200, 8.500, 10.000,
6 10.000, 10.000, 10.000, 10.900, 11.500, 12.000, 12.500,
7 13.400, 14.000, 15.000, 15.000, 16.000, 16.000, 16.900,
8 18.000, 19.000, 20.000, 20.000, 25.000, 30.000, 32.000,

```



```

9 35.000, 35.000, 40.000, 42.500, 45.000, 50.000, 50.000,
1 52.200, 55.000, 70.000, 100.000, 100.000, 120.000, 147.000,
2 150.000, 170.000, 200.000, 200.000, 240.000, 240.000, 280.000,
3 280.000, 310.000/

```

```
data xkpp/
```

```

1 11.400, 13.000, 14.000, 12.200, 13.200, 13.690, 12.810,
2 16.300, 12.700, 13.580, 13.020, 15.200, 12.090, 13.200,
3 12.700, 12.600, 16.300, 14.360, 13.050, 13.040, 12.650,
4 12.910, 12.180, 12.500, 12.880, 12.430, 13.100, 11.250,
5 12.600, 11.140, 11.100, 12.450, 12.650, 11.650, 13.000,
6 12.800, 13.200, 12.970, 13.450, 14.070, 13.210, 13.900,
7 14.390, 13.100, 14.230, 14.200, 14.590, 15.570, 14.950,
8 15.630, 15.280, 15.250, 15.400, 16.200, 15.970, 16.100,
9 15.690, 17.390, 16.950, 16.400, 17.040, 17.600, 17.120,
1 17.550, 18.080, 18.020, 18.090, 17.950, 18.100, 18.060,
2 18.470, 19.850, 18.580, 18.110, 18.540, 20.710, 18.440,
3 18.610, 17.900, 19.330, 18.440, 18.270, 18.640, 18.270,
4 17.970, 18.100, 18.040, 18.200, 17.940, 18.040, 17.930,
5 17.700, 17.660, 17.750, 17.710, 17.860, 17.500, 17.850,
6 17.730, 17.800, 17.830, 17.800, 17.980, 17.770, 17.810,
7 17.790, 17.410, 17.750, 19.400, 16.900, 17.600, 17.630,
8 17.720, 17.510, 17.560, 17.570, 17.540, 17.600, 17.100,
9 17.440, 17.520, 17.550, 17.560, 17.480, 17.250, 17.490,
1 17.470, 17.100, 17.440, 17.500, 17.470, 17.410, 17.410,
2 17.410, 17.400, 16.700, 17.300, 17.340, 17.300, 17.190,
3 17.140, 17.080, 17.150, 17.130, 17.130, 17.130, 17.500,
4 17.140, 21.000, 17.600, 17.100, 21.300, 17.200, 17.900,
5 17.000, 17.200, 18.400, 17.300, 17.200, 18.700, 17.300,
6 17.200, 17.300, 18.800, 18.100, 19.000, 17.300, 18.300,
7 17.500, 17.400, 17.310, 18.500, 17.100, 17.000, 18.800,
8 17.100, 17.300, 17.420, 17.500, 17.680, 17.720, 18.400,
9 17.800, 17.820, 18.050, 17.910, 17.880, 18.060, 18.370,
1 18.280, 18.170, 18.520, 18.700, 18.880, 19.140, 19.520,
2 19.360, 19.640, 19.910, 19.900, 20.220, 20.280, 20.450,
3 20.640, 20.670/

```

```
c *****
```

```
c *** find Kp x-section at momentum p ***
```

```

c do i=1,ndat
  i=1
  do while(i.lt.ndat)
    if(pdat(i).eq.p)then
      xKpN=xkpp(i)
      i=ndat+1
    endif
    if(pdat(i).gt.p)then
      xKpN=xkpp(i-1)+(xkpp(i)-xkpp(i-1))*(p-pdat(i-1))/
&      (pdat(i)-pdat(i-1))
      i=ndat+1
    endif
    i=i+1
  enddo
enddo

```

```

enddo
if(abs(A-1.).lt.0.1)then
  sigKA=xKpN
else
c   *** calculate KA x-section using the eikonal approximation of
c   *** W.Weise, Il Nuovo Cimento 102A(1989)265.

c   *** J.Reinhold, 5/27/98:
c   *** beta determined by fit to K-12C absorption data from:
c   *** R.J.Abrams et al., Phys.Rev.D 4(1971)3235.

  beta=0.82119-0.11274*p

  sigKA=A*xKpN*(1.-(3./8.)*(xKpN/(pi*r02))*
& . (1.-beta*beta)*A**(1./3.))
endif
return
end

```

B Scintillators' efficiencies measurement details.

Run Number	ps1	ps2	ps3	ps4	ps5	ps6	ps7
<u>KIN_1</u>							
2485	12000	1200	4150	900	3	1200	1
2486	12000	1200	4150	900	3	1200	1
2487	12000	1200	4150	900	3	1200	1
2488	12000	1200	4150	900	2	1200	1
2489	12000	1200	4150	900	2	1200	1
2490	12000	1200	4150	900	2	1200	1
2491	12000	1200	4150	900	2	1200	1
2492	12000	1200	4150	900	2	1200	1
<u>KIN_2</u>							
2496	24000	1200	4150	900	3	1200	1
2497	24000	1200	4150	900	3	1200	1
2498	24000	1200	4150	900	3	1200	1
2499	24000	1200	4150	900	3	1200	1
2500	24000	1200	4150	900	3	1200	1
2501	24000	1200	4150	900	3	1200	1
2503	24000	1200	4150	900	3	1200	1
2504	24000	1200	4150	900	3	1200	1
2505	24000	1200	4150	900	3	1200	1
2506	24000	1200	4150	900	3	1200	1
2507	24000	1200	4150	900	3	1200	1
2508	24000	1200	4150	900	3	1200	1
<u>KIN_3</u>							
2509	24000	1200	4150	900	3	1200	1
2510	24000	1200	4150	900	3	1200	1
2511	24000	1200	4150	900	3	1200	1
2512	24000	1200	4150	900	3	1200	1
2513	24000	1200	4150	900	3	1200	1
2514	24000	1200	4150	900	3	1200	1
2515	24000	1200	4150	900	3	1200	1
2516	24000	1200	4150	900	3	1200	1
2517	24000	1200	4150	900	3	1200	1
2518	24000	1200	4150	900	3	1200	1
2519	24000	1200	4150	900	3	1200	1
2520	24000	1200	4150	900	3	1200	1
2521	24000	1200	4150	900	3	1200	1

Table 61: Trigger prescale factors.

Run Number	T1	T2	T3	T4	T5	T6	T7
<u>KIN_1</u>							
2485	17821	3913	18281	4599	777095	9663	273646
2486	17646	3891	18098	4565	776592	9528	273042
2487	17656	3939	18155	4625	776468	9580	273438
2488	13411	2982	13831	3444	875464	7264	202469
2489	13475	2979	13747	3480	874590	7403	203680
2490	13631	2981	14018	3544	875133	7577	202925
2491	13126	2890	13386	3390	875909	7041	203265
2492	13479	2946	13727	3524	875026	7257	203867
<u>KIN_2</u>							
2496	6577	3213	14091	3604	779226	7401	257549
2497	6881	3371	14727	3829	806462	7727	265597
2498	6914	3307	14798	3847	806804	7856	267715
2499	6784	3336	14598	3784	805625	7688	267277
2500	6892	3358	14731	3814	806086	7751	268173
2501	5941	2872	12747	3269	717090	6710	237256
	6581	3231	14054	3621	777492	7496	259602
2503	46	46	46	46	46	46	46
2504	6795	3294	14556	3799	807394	7684	267053
2505	6915	3350	14659	3817	806885	7763	268460
2506	2740	1345	5843	1517	323935	3056	107991
2507	6799	3326	14550	3769	805201	7751	267190
2508	6733	3288	14674	3830	805526	7734	267515
<u>KIN_3</u>							
2509	7811	3797	14930	3674	799028	7924	273103
2510	7847	3773	15115	3653	798667	8049	273161
2511	7619	3781	14655	3591	799770	7923	271664
2512	7810	3830	14989	3694	798016	7981	273985
2513	7819	3791	15033	3691	799469	8085	273578
2514	7742	3760	14861	3644	798998	7953	272847
2515	7733	3826	14918	3692	799050	7951	273484
2516	7633	3811	14694	3650	798514	7856	274656
2517	7697	3796	14817	3639	798433	7960	273477
2518	7656	3772	14843	3583	799360	7852	273450
2519	7688	3730	14824	3632	798556	7949	273963
2520	7882	3816	15051	3650	796565	8087	274800
2521	7797	3757	15025	3696	797052	8058	274063

Table 62: Trigger events.

Run Number	E eff	H eff	Scint eff	Uncert. E	Uncert. H	Uncert. Scint
<u>KIN_1</u>						
2485	0.97877	0.95606	0.93576	0.00001	0.00002	0.00002
2486	0.97868	0.95594	0.93556	0.00001	0.00002	0.00002
2487	0.97844	0.95553	0.93493	0.00001	0.00002	0.00002
2488	0.97850	0.95645	0.93589	0.00001	0.00002	0.00003
2489	0.97862	0.95590	0.93546	0.00001	0.00002	0.00003
2490	0.97885	0.95595	0.93573	0.00001	0.00002	0.00003
2491	0.97872	0.95579	0.93544	0.00001	0.00002	0.00003
2492	0.97886	0.95520	0.93501	0.00001	0.00002	0.00003
<u>KIN_2</u>						
2496	0.97653	0.95569	0.93326	0.00001	0.00002	0.00003
2497	0.97646	0.95497	0.93249	0.00001	0.00002	0.00003
2498	0.97701	0.95503	0.93307	0.00001	0.00002	0.00003
2499	0.97638	0.95513	0.93257	0.00001	0.00002	0.00003
2500	0.97659	0.95516	0.93280	0.00001	0.00002	0.00003
2501	0.97678	0.95561	0.93342	0.00001	0.00003	0.00003
2503	0.95239	0.85609	0.81533	0.00020	0.00065	0.00065
2504	0.97671	0.95486	0.93262	0.00001	0.00002	0.00003
2505	0.97672	0.95496	0.93273	0.00001	0.00002	0.00003
2506	0.97642	0.95503	0.93251	0.00002	0.00004	0.00004
2507	0.97650	0.95522	0.93278	0.00001	0.00002	0.00003
2508	0.97655	0.95483	0.93243	0.00001	0.00002	0.00003
<u>KIN_3</u>						
2509	0.97660	0.95730	0.93490	0.00001	0.00002	0.00002
2510	0.97684	0.95803	0.93585	0.00001	0.00002	0.00002
2511	0.97613	0.95760	0.93474	0.00001	0.00002	0.00002
2512	0.97639	0.95725	0.93466	0.00001	0.00002	0.00002
2513	0.97666	0.95746	0.93511	0.00001	0.00002	0.00002
2514	0.97662	0.95750	0.93511	0.00001	0.00002	0.00002
2515	0.97619	0.95709	0.93431	0.00001	0.00002	0.00002
2516	0.97599	0.95698	0.93400	0.00001	0.00002	0.00003
2517	0.97627	0.95746	0.93474	0.00001	0.00002	0.00002
2518	0.97629	0.95808	0.93536	0.00001	0.00002	0.00002
2519	0.97665	0.95755	0.93518	0.00001	0.00002	0.00002
2520	0.97669	0.95795	0.93561	0.00001	0.00002	0.00002
2521	0.97680	0.95736	0.93515	0.00001	0.00002	0.00002

Table 63: Scintillators' efficiencies and uncertainties.

C Details about VDC analysis.

RUN	R4 efficiency	R3 efficiency	R2 efficiency	R1 efficiency	L4 efficiency	L3 efficiency	L2 efficiency	L1 efficiency
p=1.8665								
KIN_1	GeV/c							
2485	0.9922	0.9937	0.9912	0.9911	0.9901	0.9959	0.9958	0.9960
2486	0.9924	0.9936	0.9913	0.9910	0.9901	0.9960	0.9958	0.9960
2487	0.9922	0.9935	0.9912	0.9912	0.9902	0.9961	0.9959	0.9958
2488	0.9921	0.9937	0.9913	0.9912	0.9913	0.9961	0.9960	0.9960
2489	0.9923	0.9938	0.9915	0.9914	0.9911	0.9962	0.9958	0.9960
2490	0.9924	0.9935	0.9913	0.9912	0.9914	0.9962	0.9961	0.9960
2491	0.9924	0.9936	0.9911	0.9912	0.9913	0.9961	0.9959	0.9958
2492	0.9924	0.9937	0.9914	0.9913	0.9914	0.9962	0.9960	0.9959
p=1.8218								
KIN_2	GeV/c							
2496	0.9914	0.9928	0.9903	0.9900	0.9904	0.9958	0.9957	0.9956
2497	0.9912	0.9930	0.9903	0.9900	0.9904	0.9959	0.9955	0.9956
2498	0.9914	0.9930	0.9902	0.9901	0.9903	0.9958	0.9956	0.9956
2499	0.9914	0.9929	0.9901	0.9900	0.9903	0.9956	0.9955	0.9955
2500	0.9913	0.9928	0.9903	0.9899	0.9904	0.9958	0.9956	0.9956
2501	0.9913	0.9929	0.9903	0.9899	0.9902	0.9958	0.9955	0.9955
2502	0.9914	0.9929	0.9903	0.9900	0.9902	0.9957	0.9956	0.9955
2503								
2504	0.9912	0.9930	0.9901	0.9901	0.9902	0.9957	0.9955	0.9956
2505	0.9915	0.9929	0.9901	0.9901	0.9901	0.9957	0.9957	0.9955
2506	0.9914	0.9930	0.9905	0.9902	0.9904	0.9959	0.9955	0.9954
2507	0.9913	0.9929	0.9900	0.9900	0.9903	0.9958	0.9957	0.9955
2508	0.9913	0.9927	0.9901	0.9901	0.9902	0.9958	0.9956	0.9955
p=1.9600								
KIN_3	GeV/c							
2509	0.9914	0.9929	0.9902	0.9901	0.9902	0.9960	0.9958	0.9956
2510	0.9913	0.9930	0.9903	0.9901	0.9901	0.9958	0.9956	0.9957
2511	0.9911	0.9928	0.9902	0.9901	0.9900	0.9959	0.9957	0.9958
2512	0.9913	0.9930	0.9903	0.9901	0.9900	0.9959	0.9958	0.9956
2513	0.9913	0.9928	0.9901	0.9900	0.9900	0.9958	0.9956	0.9958
2514	0.9914	0.9929	0.9903	0.9900	0.9900	0.9959	0.9957	0.9957
2515	0.9913	0.9928	0.9902	0.9900	0.9900	0.9960	0.9956	0.9957
2516	0.9912	0.9927	0.9900	0.9900	0.9897	0.9959	0.9956	0.9955
2517	0.9914	0.9929	0.9901	0.9902	0.9899	0.9957	0.9958	0.9957
2518	0.9913	0.9930	0.9904	0.9900	0.9900	0.9958	0.9957	0.9957
2519	0.9912	0.9928	0.9902	0.9902	0.9900	0.9959	0.9956	0.9957
2520	0.9913	0.9930	0.9903	0.9903	0.9899	0.9959	0.9959	0.9956
2521	0.9915	0.9930	0.9903	0.9903	0.9900	0.9959	0.9958	0.9957

Table 64: VDC firing plane efficiencies for different plane combinations in the left(L) or right (R) arms (see Section 3.5).

RUN	# Events	RU1	RV1	RU2	RV2	LU1	LV1	LU2	LV2
KIN_1 p=1.8665 GeV/c									
2485	1002110	943860	943609	949489	947896	972091	971617	969785	964094
2486	1000709	942500	942444	948262	947084	970948	970480	968635	962877
2487	1000762	942582	942096	947845	946393	970598	970420	968620	962890
2488	737738	697667	697380	701781	700484	717724	717493	716460	712977
2489	1003256	950607	950304	956165	954643	978059	977614	976084	971137
2490	1004127	950541	950171	955729	954673	978389	978183	976700	971947
2491	1002629	950597	949972	955798	954634	977875	977706	976310	971598
2492	1003334	950509	950340	956102	954602	977611	977472	976017	971416
KIN_2									
2496	969408	915223	915067	921763	920367	950558	950463	948809	943697
2497	1003161	946821	946749	953578	951650	983486	983131	981520	976083
2498	1004753	948125	948018	954980	953302	984983	984692	983069	977697
2499	1002517	946096	945727	953042	951280	982721	982506	980630	975390
2500	1004037	947467	947476	954196	952510	984238	984024	982216	976906
2501	891242	841502	841345	847566	846018	873776	873551	872218	867331
2502	968900	913759	913668	920545	918928	949384	949181	947503	942289
2503	46	0	0	0	0	0	0	0	0
2504	1003623	947373	946999	954297	952324	984192	983838	982221	976761
2505	1005176	949012	948544	955497	953961	985350	985157	983393	977783
2506	403281	380776	380761	383548	382861	395357	395297	394606	392413
2507	1001755	945240	944856	952149	950495	982005	981792	980199	974797
2508	1002766	946919	946424	953413	951651	983174	983026	981259	975790
KIN_3									
2509	1003722	947145	946861	953719	951858	982270	982121	980185	974495
2510	1003801	946955	946669	953739	951850	982123	981841	980043	974398
2511	1002591	946031	945739	952894	950968	981538	981156	979371	973606
2512	1003558	946872	946622	953545	951419	981988	981856	980016	974284
2513	1004075	947392	947035	954046	952203	982618	982165	980366	974726
2514	1003080	946460	946387	953337	951516	981696	981453	979518	973809
2515	1003835	946828	946848	953408	951530	982325	982005	980354	974549
2516	1003819	947321	947007	953809	952090	982364	982168	980508	974487
2517	1002734	946140	945592	952751	951017	981338	981152	979070	973350
2518	1002785	946189	946157	953289	951243	981420	981148	979240	973606
2519	1003331	946740	946278	953197	951383	981889	981620	979942	974195
2520	1002094	945609	945258	952042	950128	980475	980356	978460	972611
2521	1002432	946103	945731	952879	951133	980993	980916	978993	973241

Table 65: VDC single plane number of hits in the left (L) or right (R) arms (see Section 3.5).

RUN	R123	R124	R234	R134	R1234	L123	L124	L234	L134	L1234	Both1234
KIN_1	p=1.8665 GeV/c										
2485	922453	921042	923407	923317	915212	959784	954158	954066	954259	950276	869572
2486	921093	919950	922415	922114	914078	958614	952916	952915	953092	949115	868533
2487	920983	919714	921844	921857	913772	958458	952786	953057	952952	949038	868188
2488	681938	680870	682541	682531	676562	709205	705740	705862	705873	703021	647121
2489	929641	928240	930464	930401	922501	966197	961291	961458	961600	957591	882223
2490	928833	927812	929983	929891	921779	966884	962212	962413	962341	958546	881836
2491	928741	927646	929894	930003	921687	966264	961606	961941	961797	957882	882049
2492	929452	928209	930495	930378	922371	966136	961485	961806	961679	957842	882535
KIN_2	p=1.8218 GeV/c										
2496	892256	891030	893505	893288	884601	938512	933413	933601	933533	929527	849391
2497	923205	921572	924317	924008	915087	970574	965205	965488	965563	961216	878101
2498	924700	923158	925935	925760	916731	972154	966804	966968	967000	962732	879618
2499	922207	920781	923528	923431	914276	969629	964441	964579	964513	960207	876946
2500	923682	922296	924988	924626	915691	971416	966120	966307	966268	962056	878656
2501	820260	818967	821469	821113	813145	862304	857430	857703	857670	853828	780103
2502	890903	889601	892166	891965	883276	936862	931699	931895	931815	927680	847386
2503	0	0	0	0	0	0	0	0	0	0	0
2504	923607	921940	924630	924663	915494	971295	965871	966025	966067	961753	878558
2505	924996	923724	926290	926345	917156	972485	966951	967143	967016	962820	879773
2506	371319	370715	371771	371661	368123	390176	388023	388233	388171	386432	353243
2507	921370	919966	922638	922617	913393	969397	964066	964320	964211	960024	876851
2508	922779	921466	923890	923853	914736	970351	964887	965240	965157	960868	877792
KIN_3	p=1.9600 GeV/c										
2509	923291	921849	924520	924422	915345	969671	963994	964349	964224	960140	877113
2510	923391	921838	924486	924311	915356	969191	963628	963790	963821	959627	876641
2511	922170	920638	923115	923031	913999	968925	963185	963277	963394	959266	876040
2512	923186	921596	924262	924127	915157	969399	963663	963872	963732	959673	876786
2513	923382	921919	924513	924479	915307	969692	964047	964099	964207	960012	876588
2514	922901	921446	924143	923909	914921	968933	963216	963402	963393	959239	876353
2515	922898	921421	924036	923888	914831	969587	963799	964060	964102	959905	876254
2516	923028	921625	924202	924171	914918	969545	963548	963898	963818	959592	876039
2517	922184	920800	923328	923374	914253	968485	962842	962933	962835	958748	875715
2518	922724	921135	923924	923517	914661	968632	962991	963073	963128	958963	876161
2519	922720	921245	923657	923694	914597	969246	963466	963672	963722	959529	876048
2520	922090	920511	922997	922987	914068	967842	962032	962247	962035	958050	875476
2521	922677	921228	923788	923731	914795	968503	962743	962947	962770	958773	876498

Table 66: VDC number of hits for each plane combination indicated in top row in the left (L) or right (R) arms (see Section 3.5).

RUN	0Track L	1TrackL	2TrackL	3TrackL	4TrackL	Good0 TrackL	Good1 TrackL	Good2 TrackL	Good3 TrackL	Good4 TrackL
KIN_ 1	p=1.8665 GeV/c									
2485	33883	901107	54843	11314	813	1662	886487	51483	10088	513
2486	33375	898959	56013	11370	838	1512	884389	52512	10158	505
2487	33675	899566	55389	11205	779	1583	885062	51869	10006	473
2488	21654	666633	40529	8243	568	963	656297	38000	7360	370
2489	27771	908742	55057	10757	785	1361	894395	51744	9558	488
2490	27991	909380	54811	10951	814	1348	895386	51422	9826	511
2491	26945	907752	55784	11211	779	1353	893524	52463	10021	473
2492	27982	909067	54338	11068	723	1370	895040	50975	9965	446
KIN_ 2	p=1.8218 GeV/c									
2496	21110	866910	65953	14091	1144	1467	852571	62090	12599	741
2497	22006	896255	68636	14882	1138	1411	881425	64351	13230	731
2498	22083	898055	68371	14859	1168	1395	883066	64256	13225	714
2499	22322	895323	68827	14749	1087	1419	880228	64652	13171	663
2500	22352	897054	68413	14808	1174	1500	882238	64218	13274	739
2501	19416	795381	61898	13261	1085	1211	781965	58052	11849	692
2502	21823	864721	66720	14295	1139	1387	850119	62637	12757	713
2503	46	0	0	0	0	0	0	0	0	0
2504	22140	896408	68878	14807	1183	1501	881463	64714	13223	780
2505	22330	897673	69004	14760	1174	1427	882554	64793	13198	783
2506	8825	360495	27413	5995	474	543	354455	25792	5318	296
2507	22079	894549	68965	14822	1121	1485	879726	64763	13295	694
2508	22039	895943	68595	14788	1191	1473	880961	64415	13192	753
KIN_ 3	p=1.9600 GeV/c									
2509	24356	902303	62737	13131	1010	1404	887278	58908	11817	665
2510	24640	902821	62054	13116	964	1402	887724	58204	11629	613
2511	24183	900853	63067	13292	1008	1406	886053	59240	11876	637
2512	24594	902249	62282	13281	960	1472	887216	58435	11881	608
2513	24425	902739	62741	12989	1000	1382	887465	58900	11574	635
2514	24461	902351	61855	13238	991	1417	887286	58030	11824	626
2515	24598	902400	62526	13113	1006	1408	887376	58695	11751	613
2516	24322	901722	63124	13441	1004	1374	886366	59117	12060	620
2517	24444	901271	62642	13189	1011	1385	885985	58873	11800	651
2518	24409	901285	62764	13095	1026	1470	886060	58970	11729	677
2519	24125	902063	62651	13316	954	1409	886857	58769	11851	583
2520	24524	901780	61597	13088	933	1420	886500	57775	11705	584
2521	24346	902220	61701	13045	961	1347	887273	57823	11680	601

Table 67: Number of events with specific number of tracks in the the left arm (see Section 3.5).

RUN	0Trac kR	1TrackR	2TrackR	3Track R	4Track R	Good0 Track R	Good1 TrackR	Good2 TrackR	Good3 TrackR	Good4 TrackR	Good1 Track
KIN_ 1	p=1.8665 GeV/c										
2485	42694	777671	125442	41567	9869	5120	760610	113926	31607	3481	674702
2486	42501	776021	125576	41689	9979	5311	758897	114038	31889	3509	672538
2487	42725	775576	125951	41530	10054	5011	758365	114449	31870	3592	672564
2488	28018	576503	91932	30476	7184	3179	563951	83520	23110	2500	503765
2489	36309	786304	124636	41304	9850	4311	769307	113392	31556	3533	687568
2490	37041	786854	124280	41150	9832	4155	769603	113005	31204	3379	688243
2491	35426	783948	126432	41851	10007	4286	766659	114929	31793	3592	684600
2492	36545	786438	124530	41225	9889	4288	769573	113269	31432	3432	688551
KIN_ 2	p=1.8218 GeV/c										
2496	34455	727842	140798	48308	12117	5085	710138	127526	36815	4507	625814
2497	35958	753236	145659	49656	12516	5307	734884	131973	37699	4663	647149
2498	36085	755461	145125	49598	12281	5176	737120	131666	37669	4509	648981
2499	35761	752819	145619	49637	12524	5264	734211	131741	37884	4603	645877
2500	36064	753703	145751	50086	12380	5217	735208	132205	37958	4578	647183
2501	31216	667216	131246	44979	11179	4654	650696	118932	34249	4080	572212
2502	35107	727125	140882	48080	11786	5094	709138	127593	36531	4389	623961
2503	46	0	0	0	0	0	0	0	0	0	0
2504	35677	752466	146234	50469	12682	5260	733753	132799	38370	4761	645908
2505	36256	755646	145237	49747	12284	5366	737314	131467	37944	4514	648607
2506	14256	303174	58463	19882	4999	2135	295885	52863	15185	1821	260581
2507	35849	752446	145364	49619	12359	5269	733750	131623	37673	4535	646132
2508	35733	753454	145417	49852	12274	5325	734681	131743	37868	4509	646710
KIN_ 3	p=1.9600 GeV/c										
2509	36512	753489	145882	49583	12296	5307	735009	132236	37733	4530	651411
2510	36750	753880	144913	50056	12169	5323	735587	131347	38094	4447	652189
2511	35834	751233	146946	50277	12238	5334	732496	133075	38146	4425	648632
2512	36614	753795	145229	49525	12329	5181	735419	131609	37796	4575	651461
2513	36685	754568	144884	49462	12532	5317	735740	131343	37663	4686	651623
2514	36397	753295	145300	49937	12078	5367	734890	131736	37959	4389	651465
2515	36653	753547	145588	49523	12377	5309	734786	131909	37669	4589	651076
2516	36059	750374	147875	50652	12612	5454	731743	133931	38436	4734	647648
2517	36394	751879	145829	50138	12362	5381	733282	132214	38169	4643	649574
2518	36013	751272	146699	50438	12234	5380	732787	133003	38393	4537	648835
2519	36502	752269	146298	49742	12585	5367	733589	132535	37821	4728	649932
2520	36760	753587	144492	49274	11936	5303	735274	131038	37423	4435	652029
2521	36575	754524	144013	49333	12152	5355	736271	130700	37444	4490	653126

Table 68: Number of events with specific number of tracks in the right arm (see Section 3.5).

D CTOF spectra using aerogel detectors and RICH.

Figure 113: CT spectrum (ns) for particles identified as kaons (KIN_1).

Figure 114: CT spectrum (ns) for particles identified as kaons (KIN_2).

Figure 115: CT spectrum (ns) for particles identified as kaons (KIN_3).

Figure 116: CT spectrum (ns) for particles identified as pions (KIN_1).

Figure 117: CT spectrum (ns) for particles identified as pions (KIN_2).

Figure 118: CT spectrum (ns) for particles identified as pions (KIN_3).

Figure 119: CT spectrum (ns) for particles identified as protons (KIN_1).

Figure 120: CT spectrum (ns) for particles identified as protons (KIN_2).

Figure 121: CT spectrum (ns) for particles identified as protons (KIN_3).

E Missing mass spectra (see Section 4.2) with RICH PID cuts included (Table 17).

Figure 122: Missing mass spectrum with RICH PID cuts for KIN_1.

Figure 123: Missing mass spectrum with RICH PID cuts for KIN_2.

Figure 124: Missing mass spectrum with RICH PID cuts for KIN_3.

F Subtracted missing mass spectra (see Section 4.3) with RICH PID cuts (Table 17).

Figure 125: Background subtracted spectrum with RICH PID cuts for KIN_1.

Figure 126: Background subtracted spectrum with RICH PID cuts for KIN_2.

Figure 127: Background subtracted spectrum with RICH PID cuts for KIN_3.

G RICH efficiencies for the three different kinematics.

KAONS	Skeb.emiss	AERO:	857	347	822		
Ro min	Ro max	R mean	Delta R	R interval			
0.621	0.66	0.6405	0.039	0.004875			
#interval	R min	R max	AERO + RICH TOTAL	ACCIDENTAL (*10)	TRUE	Normalized	Uncertainty
-3	0.635625	0.645375	318	35	314	0.3820	0.0169
-2	0.63075	0.65025	470	55	464	0.5645	0.0173
-1	0.625875	0.655125	513	64	506	0.6156	0.0170
0	0.621	0.66	518	65	511	0.6217	0.0169
1	0.616125	0.664875	520	66	513	0.6241	0.0169
2	0.61125	0.66975	522	69	515	0.6265	0.0169
3	0.606375	0.674625	522	72	514	0.6253	0.0169

Table 69: RICH efficiency for KIN_1.

Figure 128: RICH efficiency for KIN_1.

KAONS	Skeb.emiss	AERO:	394	206	373		
Ro min	Ro max	R mean	Delta R	R interval			
0.621	0.66	0.6405	0.039	0.004875			
#interval	R min	R max	AERO + RICH TOTAL	ACCIDENTAL (*10)	TRUE	Normalized	Uncertainty
-3	0.635625	0.645375	190	34	186	0.4987	0.0259
-2	0.63075	0.65025	257	46	252	0.6756	0.0242
-1	0.625875	0.655125	272	50	267	0.7158	0.0234
0	0.621	0.66	275	50	270	0.7239	0.0231
1	0.616125	0.664875	275	51	269	0.7212	0.0232
2	0.61125	0.66975	275	52	269	0.7212	0.0232
3	0.606375	0.674625	277	54	271	0.7265	0.0231

Table 70: RICH efficiency for KIN_2.

Figure 129: RICH efficiency for KIN_2.

KAONS	Skeb.emiss	AERO:	816	326	783			
Ro min	Ro max	R mean	Delta R	R interval				
0.621	0.66	0.6405	0.039	0.004875				
#interval	R min	R max	AERO + RICH TOTAL	ACCIDENTAL (*10)	TRUE	Normalized	Uncertainty	
	-3	0.635625	0.645375	199	34	195	0.2490	0.0155
	-2	0.63075	0.65025	322	44	317	0.4049	0.0175
	-1	0.625875	0.655125	356	54	350	0.4470	0.0178
	0	0.621	0.66	362	55	356	0.4547	0.0178
	1	0.616125	0.664875	363	55	357	0.4559	0.0178
	2	0.61125	0.66975	364	56	358	0.4572	0.0178
	3	0.606375	0.674625	364	57	358	0.4572	0.0178

Table 71: RICH efficiency for KIN_3.

Figure 130: RICH efficiency for KIN_3.

H KIT3s.f program (JLab Hall A collaboration).

```

program kfit
c empirical fit to electroproduction data by Jinseok Cha, similar to Brauel
c on linux compile with: f77 -o kfit3 kfit3.f
c LAST REVISED: 28-Mar-08, changed inputs to pk and thetacm

      implicit none
      real*8 pi,degrad,alpha,me,mp,mk,mlam,mk2,mp2,ml2
      parameter(pi=3.141592653589,degrad=pi/180.,alpha=1./137.0359895)
      parameter (me=0.000511,mp=0.938272,mk=0.493646,mlam=1.192642)
      parameter (mk2=mk*mk,mp2=mp*mp,ml2=mlam*mlam)

      real*8 Ebeam,W,QQ,t                                ! initial conditions
      real*8 omega,qvec,thq,epsi                          ! virtual photon
      real*8 Ek,pk,thk,thgk,betak,gammak,survive         ! kaon
      real*8 Ee,pe,thedeg,the,qcm,omcm                  ! scattered electron
      real*8 bcm,gcm,s,pcm,tmin,tmax
      real*8 pkx,pkz,pkxcm,pkzcm,thgkcm,pkcm,gtptr,qdotk
      real*8 phi,cosphi
      real*8 dum1,dum2,dum3,dum4,dum5,dum6,dum7
      integer iq2,iread,iang
      real*8 Sigma_eep,jac,rate,lumin,accept,time,Sigma

c *** kinematic input -- E_0 (GeV), Q2 (GeV/c)^2, W (GeV), t (GeV/c)^2 ***
      write(*,*) 'beam energy (GeV)'
      read(*,*) Ebeam
      write(*,*) 'Q2 +(GeV/c)^2 and W (GeV)'
      read(*,*) QQ,W
      write(*,*) 'Pk (GeV/c), Kaon final momentum'
      read(*,*) pk
      write(*,*) 'th qk lab (deg), '
      read(*,*) thgk
      thgk = thgk*degrad

c *** scattered electron ***
      Ee = Ebeam - (((W*W) +QQ - mp2)/(2.*mp))
      the = 2.*asin(sqrt(QQ/(4.*Ebeam*Ee)))
      thedeg=the/degrad
      pe=sqrt(Ee*Ee - me*me)

c *** virtual photon ***
      omega = Ebeam-Ee
      qvec = sqrt(QQ+omega*omega)
      thq = atan(Ee*sin(the)/(Ebeam-(Ee*cos(the))))
      qvec = sqrt(QQ+omega*omega)
      epsi = 1./(1.+2.*(1.+omega**2./QQ)*tan(the/2.)**2.)

c *** photon-proton center-of-mass system ***
      bcm = qvec/(omega+mp)
      gcm = 1./sqrt(1.-bcm*bcm)
      s = W*W

```

```

pcm = qvec*mp/W
c *** photon in CM ***
qcm = -gcm*bcm*omega +gcm*qvec
omcm = gcm*omega-gcm*bcm*qvec

c *** kaon ***
tmin=((-QQ-mk2-mp2+mL2)/(2.0*W))**2.0
# -( sqrt( ((W*W -QQ -mp2)/(2.*W))**2. +QQ)
# -sqrt( ((W*W+mk2 -mL2)/(2.*W))**2. -mk2))**2.
tmax=((-QQ-mk2-mp2+mL2)/(2.0*W))**2.0
# -( sqrt( ((W*W -QQ -mp2)/(2.*W))**2. +QQ)
# +sqrt( ((W*W+mk2 -mL2)/(2.*W))**2. -mk2))**2.

c *** kaon with respect to photon ***
Ek=sqrt(pk*pk + mk*mk)
qdotk = qvec*pk*cos(thgk);
t= -QQ+mk2-(2*Ek*omega) + (2*qdotk);
c/*t=(gamma - k)2*/

if (t.eq.0) then
  t= tmin - 1.0E-9
endif

cosphi=-1
if (cosphi.eq.1) then
  thk=-(thq-thgk)
elseif (cosphi.eq.-1) then
  thk = -(thq+thgk)
endif
pkx = pk*sin(thgk)
pkz = pk*cos(thgk)
pkxcm = pkx
pkzcm = -gcm*bcm*Ek +gcm*pkz
pkcm = sqrt(pkxcm*pkxcm + pkzcm*pkzcm)
thgkcm = atan(pkxcm/pkzcm)
jac=pk*pk*W/pkcm/abs((mp+omega)*pk - Ek*qvec*cos(thgk))

c
phi=3.1415
if (cosphi.eq.1) then
  phi=0.
elseif(cosphi.eq.-1) then
  phi=pi
endif

call eekeek(QQ,W,tmin,phi,epsi,sigma,t,pkcm)
sigma=sigma*(2.+epsi)/3. !INCLUDE EPSILON INTO D

SIGMA
*** Virtual photon flux ***
gtpr = alpha/2./(pi**2)*Ee/Ebeam*(s-mp**2)/2./mp/QQ
# /(1.-epsi)
sigma_eep=sigma*gtpr*jac !d5 sigma/dE'd0omega_e

```



```

d0omega_k (ub/sr2/GeV)
c      SIGMA_EEP=GTPR*JACOB*DSIGMA*(2+EPSILON)/3

      write(*,*) '-----'
      write(*,*) '          Kinematics          '
      write(*,*) '          tmin= ',tmin,'          tmax= ',tmax
      write(*,*) '          Q2 =',QQ,' W=',W,'          t=',t
      write(*,*) 'theta_cm=',thgkcm/degrad, ' E=',Ebeam,' Ee =',Ee
      write(*,*) 'theta_e =',thedeg,' Pk=',pk,'theta_k=',thk/degrad
      write(*,*) '-----'
      gammak= Ek/.494
      betak= sqrt(1- (1.0/(gammak*gammak)) )
      survive= exp(-1.0*25.0/(3.711*betak*gammak))      !25 meters TOF dist.
      lumin=(7.5e-5/1.6e-19)*(0.0708*15*6.022e23)/(1.e30)!75 mikes*LH2 15 cm

target
      accept=(0.060*.130*pi/4)*(0.060*.130*pi/4)*(0.08*Ee)!HRSH, HRSE solid
angles,HRSE mom bite
      rate= sigma_eep*lumin*accept*survive
      time=(10000./3600.)/rate
      write(*,*) '          Cross Sections          '
      write(*,*) 'gtp= ',gtp,' epsilon= ',epsi, ' Gamma= ',gtp
      write(*,*) ' Jacobian= ',jac, ' d sig/d0omega',sigma, '(uB/sr)'
      write(*,*) '++++++ sigma_eep= ', sigma_eep,'ub/sr^2/GeV'
      write(*,*) 'survive= ',survive,' rate= ',rate,' time= ',time
      write(*,*) 'measured sigma_eep [fm^2/MeV/sr^2]=',
&      survive*sigma_eep*1E-7
      end

      subroutine eekeek(Q2,W,tmin,phi,epsi,sigma,t,pkcm)
      implicit none
      real*8 Q2,mp,mp2,pkcm,phi,sigma,tmin,t,epsi
      real*8 f,g,h,i,W
c      real*8 p1g, p2g, p3g, p4g
c      real*8 p1h, p2h
      real*8 p1i, p2i, p3i
      parameter(p1i=.438, p2i=-.048, p3i=0.008)
      parameter (mp=.938272, mp2=mp*mp)

c
c FROM MCEEP:
C---CALCULATE VIRTUAL PHOTOPRODUCTION CROSS SECTION IN fm^2/sr
C f(Q^2) gives dsig/d0 = 3.832/(Q2+2.67)^2 in uB/sr at W=2.15, t=tmin
c      FQ=3.832E-4/((QMU2_G+2.67)**2)
c g(W) gives i) phase space divided by phase space for W=2.15
c (g(W)~pkcm/(s-mp^2)/W) plus ii) a resonance at 1.72 GeV
c      GW=(PKCM/(SG-MPG*MPG)/(W/1000.))/8.4810E-2
c      #      + S2G/(SG*1.4369 +(SG-1.72)**2.D0)
c
c
c
c h(tmin-t) falls exponentially
c      HT=exp(-.2144*(TMIN-T))

```

```

c i(phi)
c      IP=1-.01096*COS(PHI_X)+.0018*cos(2*PHI_X)
c
c
c      DSIGMA=FQ*GW*HT*IP
c      SIGMA_EEP=GTPR*JACOB*DSIGMA*(2+EPSILON)/3
c
c      f=3.832D0*((Q2+2.67D0)**(-2.D0))
c      write(*,*) 'f after is: ',f
c
c      g=(pkcm/(W*W-mp2)/W)/( 0.682352458165202/(2.15*2.15-mp2)/2.15)
c      write(*,*) 'g without the resonance: ',g
c g(W) gives phase space divided by phase space for W=2.15
c      g=(.959*g)+ (5.32512E-3/((W*W-2.9584)+2.9584E-2))
c
c g(W) here I add the resonance at 1.72, according to Koltenuk / Bebek
c      GW=(PKCM/(SG-MPG2)/WG)/(0.682352458165202/(2.15*2.15-MPG2)/2.15)
c      #      + S2G/(SG*1.4369 +(SG-1.72)**2.D0)
c      g=(pkcm/(W*W-mp2)/W)/( 0.682352458165202/(2.15*2.15-mp2)/2.15)
c      #      + W*W/(W*W*1.4369 +(W*W-1.72)**2.D0)
c      write(*,*) 'g with the 1.72 Resoance: ',g
c      GW=(PKCM/(SG-MPG*MPG)/(W/1000.))/8.4810E-2
c      #      + S2G/(SG*1.4369 +(SG-1.72)**2.D0)
cc h(tmin-t)
c      h=p1h*exp(p2h*(tmin-t))
c      h=1
c      h=exp(-0.2144*(tmin-t))
c i(phi)
c      i=1
c      i=1-.01096*cos(phi)+.0018*cos(2*phi)
c
c      sigma=f*g*h*i
c      write(*,*) 'debugging: f,g,h,i=',f,g,h,i
c      write(*,*) 'pkcm',pkcm
c      return
c
end

```

I MCEEP summary outputs (see Section 1.3). In addition to variable definitions shown in page 138, some extra variables are defined here as [72]:

Phi_Q = ϕ_q , the horizontal angle of $\vec{q}$ with respect to the “laboratory” coordinate system,

Theta_Q = θ_q , the vertical angle of $\vec{q}$ with respect to the “laboratory” coordinate system,

P_recoil = p_r , the momentum of the recoiling nuclear system,

Theta_pq = θ_{pq} , the angle between the emerging hadron and $\vec{q}$.

Variable	Central	Average	Centroid	Minimum	Maximum	Units
Scatt.Angle (θ_e)	6	6.383	6.25	5.084	8.1	deg
Omega ($E-E'$)	2201.9	2184.218	2183.286	2137.1	2262.951	MeV
Q-vector ($ \vec{q} $)	2216.636	2201.364	2199.751	2148.715	2284.471	MeV/c
Q_mu ² (Q^2)	0.065	0.075	0.072	0.045	0.123	(GeV/c) ²
Phi_Q (ϕ_q)	4.256	4.5	4.412	3.392	5.809	deg
Theta_Q (θ_q)	0	0.02	0.017	-1.958	1.941	deg
X (Bjorken_x)	0.016	0.018	0.018	0.011	0.03	
Long. Pol. (ϵ)	0.707	0.712	0.712	0.685	0.728	
P_f (p_k)	1866.5	1893.401	1894.794	1793.095	1942.697	MeV/c
P_recoil (p_r)	355.565	319.597	317.134	288.912	401.737	MeV/c
Theta_pq (θ_{pq})	1.744	2.242	2.295	0.004	5.12	deg
Phi_x (φ)	180	178.885	178.924	0.316	359.355	deg
M_miss (E_{miss})	711.449	676.428	674.767	665.478	711.088	MeV
W (W)	2.224	2.214	2.215	2.187	2.253	GeV
Theta_CM (θ_{CM})	4.574	5.85	5.984	0.012	13.314	deg

Table 72: MCEEP output summary for L_KIN_1.

Variable	Central	Average	Centroid	Minimum	Maximum	Units
Scatt.Angle (θ_e)	6	6.399	6.269	5.143	7.961	deg
Omega ($E-E'$)	2206.8	2166.055	2164.294	2141.997	2234.68	MeV
Q-vector ($ \vec{q} $)	2221.522	2183.692	2181.264	2153.982	2251.989	MeV/c
Q_mu ² (Q^2)	0.065	0.077	0.074	0.048	0.118	(GeV/c) ²
Phi_Q (ϕ_q)	4.247	4.613	4.53	3.547	5.798	deg
Theta_Q (θ_q)	0	0.008	0.007	-1.944	1.933	deg
X (Bjorken_x)	0.016	0.019	0.018	0.011	0.029	
Long. Pol. (ϵ)	0.706	0.718	0.719	0.697	0.727	
P_f (p_k)	1821.8	1872.116	1873.267	1798.927	1896.159	MeV/c
P_recoil (p_r)	404.433	322.69	319.605	291.693	399.243	MeV/c
Theta_pq (θ_{pq})	1.753	2.223	2.273	0.013	5.092	deg
Phi_x (φ)	180	179.818	179.828	0.455	358.641	deg
M_miss (E_{miss})	746.166	678.067	675.97	665.993	711.086	MeV
W (W)	2.226	2.206	2.206	2.189	2.24	GeV
Theta_CM (θ_{CM})	4.624	5.789	5.912	0.033	13.191	deg

Table 73: MCEEP output summary for L_KIN_2.

Variable	Central	Average	Centroid	Minimum	Maximum	Units
Scatt.Angle (θ_e)	6	6.384	6.254	5.084	8.052	deg
Omega ($E-E'$)	2205.84	2218.397	2218.332	2160.721	2266.817	MeV
Q-vector ($ \vec{q} $)	2220.513	2234.926	2234.205	2172.898	2289.335	MeV/c
Q_mu ² (Q^2)	0.065	0.074	0.071	0.045	0.116	(GeV/c) ²
Phi_Q (ϕ_q)	4.238	4.337	4.251	3.365	5.634	deg
Theta_Q (θ_q)	0	0.036	0.032	-1.899	1.891	deg
X (Bjorken_x)	0.016	0.018	0.017	0.011	0.028	
Long. Pol. (ϵ)	0.706	0.701	0.701	0.684	0.72	
P_f (p_k)	1960	1931.92	1933.421	1882.035	1993.133	MeV/c
P_recoil (p_r)	268.293	315.932	314.303	287.012	402.521	MeV/c
Theta_pq (θ_{pq})	1.762	2.33	2.385	0.01	5.201	deg
Phi_x (φ)	180	177.98	178.151	0.807	358.808	deg
M_miss (E_{miss})	645.778	674.245	673.129	663.403	711.086	MeV
W (W)	2.226	2.229	2.23	2.199	2.256	GeV
Theta_CM (θ_{CM})	4.588	6.102	6.242	0.027	13.579	deg

Table 74: MCEEP output summary for L_KIN_3.

Variable	Central	Average	age	Centroid	Minimum	Maximum	Units
Scatt.Angle (θ_e)	6	6	380	6.251	5.084	8.046	deg
Omega ($E-E'$)	2201.9	2223	782	2223.151	2181.544	2263.018	MeV
Q-vector ($ \vec{Q} $)	2216.636	2240	191	2238.919	2194.112	2285.487	MeV/c
Q_mu ² (Q^2)	0.065	0	73	0.07	0.045	0.117	(GeV/c) ²
Phi_Q (Φ_q)	4.256	4	309	4.226	3.382	5.536	deg
Theta_Q (θ_q)	0	0	32	0.029	-1.853	1.856	deg
X (Bjorken_x)	0.016	0	18	0.017	0.011	0.028	
Long. Pol. (ϵ)	0.707	0	699	0.7	0.685	0.714	
P_f (p_k)	1866.5	1829	292	1830.312	1792.225	1870.92	MeV/c
P_recoil (p_r)	355.565	420	120	418.251	393.478	502.623	MeV/c
Theta_pq (θ_{pq})	1.744	2	334	2.391	0.02	5.346	deg
Phi_x (φ)	180	178	69	178.254	0.657	359.334	deg
M_miss (E_{miss})	711.449	751	7	749.954	741.363	788.011	MeV
W (W)	2.224	2	232	2.232	2.206	2.254	GeV
Theta_CM (θ_{CM})	4.574	6	178	6.325	0.052	14.13	deg

Table 75: MCEEP output summary for S_KIN_1.

Variable	Central	Average	Centroid	Minimum	Maximum	Units
Scatt.Angle (θ_e)	6	6.396	6.271	5.141	8.087	deg
Omega ($E-E'$)	2206.8	2208.21	2208.473	2141.995	2267.936	MeV
Q-vector ($ \vec{Q} $)	2221.522	2225.054	2224.666	2153.687	2290.744	MeV/c
Q_mu ² (Q^2)	0.065	0.075	0.072	0.046	0.12	(GeV/c) ²
Phi_Q (Φ_q)	4.247	4.409	4.323	3.411	5.762	deg
Theta_Q (θ_q)	0	0.028	0.024	-1.944	1.935	deg
X (Bjorken_x)	0.016	0.018	0.017	0.011	0.029	
Long. Pol. (ϵ)	0.706	0.705	0.705	0.684	0.727	
P_f (p_k)	1821.8	1812.211	1814.328	1749.396	1886.249	MeV/c
P_recoil (p_r)	404.433	421.678	419.558	393.671	502.013	MeV/c
Theta_pq (θ_{pq})	1.753	2.304	2.357	0.004	5.265	deg
Phi_x (φ)	180	178.194	178.361	0.917	359.525	deg
M_miss (E_{miss})	746.166	751.405	750.269	741.646	788.038	MeV
W (W)	2.226	2.225	2.225	2.189	2.256	GeV
Theta_CM (θ_{CM})	4.624	6.091	6.226	0.011	13.925	deg

Table 76: MCEEP output summary for S_KIN_2.

VITA

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- 1992-2001 Member of the Theoretical Physics Research Group, “Universidad Nacional de Ingeniería”, Professional School of Physics, National University of Engineering, Lima, Peru.
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CONTRIBUTED TALKS AND POSTER PRESENTATIONS

1. Kaon Electroproduction at low Q^2 and $W = 2.2 \text{ GeV}$ off hydrogen. A. Acha, P. Markowitz, ... et al., contributed talk at the April meeting of the American Physical Society (APS), Denver, Colorado, 2-5 May 2009.
2. Electroproduction of Hyperons at Low Momentum Transfer. A. Acha, P. Markowitz, ... et al., contributed talk at the 75th Annual Meeting of the Southeastern Section of the APS (SESAPS), Raleigh, North Carolina, 30 Oct- 1 Nov 2008.
3. Hypernuclear Spectroscopy in Hall A: The elementary reaction ${}^1H(e, e'K^+)\Lambda, \Sigma^0$. A. Acha, F. Cusanno, ... et al., contributed talk at the Hall A Collaboration Meeting, Jefferson Lab (Thomas Jefferson Accelerator Facility), Newport News, Virginia, 13-14 Dec 2007.
4. High Resolution 1P-Shell Hypernuclear Spectroscopy at JLAB, HALL A (E94-107) A. Acha, P. Markowitz, ... et al., contributed talk at the 73rd Annual Meeting of the Southeastern Section of the APS (SESAPS), Williamsburg, Virginia, 9-11 Nov 2006.
5. High Resolution 1p-shell Hypernuclear Spectroscopy at JLab, Hall A (E94-107) A. Acha, ... et al., Southeastern University Research Association (SURA) Poster Presentation, Users Group Workshop and Annual Meeting 2006, Jefferson Lab (TJNAF), Newport News, Virginia, 12-14 Jun 2006.
6. Particle Identification for JLab Experiment E94-107. A. Acha, P. Markowitz, ... et al., contributed talk at the 72nd Annual Meeting of the Southeastern Section of the APS (SESAPS), Gainesville, Florida, 10-12 Nov 2005.