

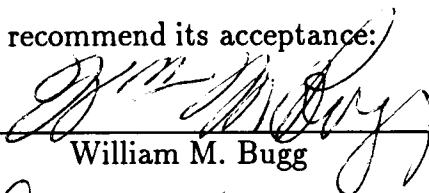
To the Graduate Council:

I am submitting herewithin a dissertation written by Murali Pisharody, entitled "Light-Quark Meson Photoproduction at a Mean Energy of 120 GeV/c." I have examined the final copy of this dissertation for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Doctor of Philosophy with a major in Physics.



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LIGHT-QUARK MESON PHOTOPRODUCTION
AT A MEAN ENERGY OF 120 GEV/C

A DISSERTATION
PRESENTED FOR THE
DOCTOR OF PHILOSOPHY
DEGREE
THE UNIVERSITY OF TENNESSEE, KNOXVILLE

BY
MURALI PISHARODY
DECEMBER 1993

Dedication

This work is dedicated to my parents.

Acknowledgements

I am indebted to many for their help in the course of this work and would especially like to single out a few people to express my gratitude:

Though the entire E687 collaboration needs to be acknowledged, only a few people are mentioned here. Joel Butler, spokesperson for the collaboration, whose dedicated work on the experiment ensured its success, and who along with Paul Lebrun initiated the data reduction scheme. Special acknowledgements to Gary Grim, Luca Cinquini, Matt Nehring, Rodney Greene, Joe Swiatek, Gavin Blackett, and Barbara Caccianiga who were my partners in PASS1-ing. Will Johns, Brian O'Reilly, Carlo Dallapiccola, John Cumalat, and Gianluigi Boca were very helpful in many thankless ways, especially in their assistance which provided a good understanding of the detector. The entire collaboration owes a great deal to Ray Culbertson and Jim Wiss who were responsible for developing some of the crucial physics analysis packages used in the experiment.

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Abstract

The purpose of this work is to investigate the following photoproduction reaction channels:

$$\gamma N \rightarrow \pi^+ \pi^- \pi^+ \pi^- N'$$

$$\gamma N \rightarrow K^+ K^- \pi^+ \pi^- N'$$

$$\gamma N \rightarrow \mu^+ \mu^- \pi^+ \pi^- N'$$

$$\gamma N \rightarrow K^+ K^- K^+ K^- N'$$

where N and N' are nucleons appropriate for charge conservation. The data used for this analysis came from reconstructed tapes condensed from about 500 million triggered events written out by the E687 fixed target photoproduction experiment at FERMILAB during its 1990 and 1991 runs.

Aside from the usual broad enhancement in the $\rho'(1600)$ region, the neutral 4π channel shows evidence for a narrow peak in the vicinity of ~ 2.1 GeV. The resonant substructures in this channel are also investigated. The neutral dipion mass spectrum shows clear enhancements corresponding to $\rho(770)$, $f_2(1270)$, and $\rho_3(1690)$, and a $J/\psi(3097)$ signal presumably through the misidentification of muons as pions. Also, a clear $a_2(1320)$ peak is observed in the $\rho\pi^\pm$ mass spectrum of the $(3\pi)^\pm$ substructure. The dipion spectrum of the $K^+K^-\pi^+\pi^-$ channel displays statistically significant signals of $\rho(770)$ and $f_0(975)$ resonances. Only a clear $\phi(1020)$ peak is found in the dikaon spectrum of this channel (a bias was introduced on the dikaon mass during the original data skimming phase of the experiment). Evidence

for a possible non- $q\bar{q}$ state with a mass ~ 1930 MeV is found in the $\phi\rho$ mass spectrum and an apparent enhancement at ~ 2300 MeV is observed in the ϕf_0 mass spectrum. The $J/\psi\pi^+\pi^-$ ($J/\psi \rightarrow \mu^+\mu^-$) mass spectrum shows a clear $\psi'(3685)$ resonance, the radially excited state of $J/\psi(3097)$. Finally, an investigation of the dikaon spectrum in the neutral $4K$ channel shows peaks corresponding to $\phi(1020)$, $f'_2(1525)$, and a statistically weak enhancement near ~ 1.2 GeV perhaps due to the $f_0(1240)$. The overall neutral $4K$ mass spectrum, as well as the $\phi\phi$ spectrum, show no evidence for any resonant structures.

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Chapter 1

Introduction

1.1 Brief Historical Review

One of the major achievements of physics in this century has been the revelation that the atom is not indivisible or elementary at all but has a complex structure. After the accidental discovery of radioactivity by Becquerel in 1896, which provided the tool with which atoms could be probed, Rutherford, in 1911, showed that the atom consists of a small, dense nucleus which is surrounded by a cloud of electrons. Subsequently, it was shown that the nucleus itself can be broken down into discrete constituents called protons and neutrons which are held together by the strong force acting over a very short range. Since then a great many different particles have been identified. With the advent of high energy accelerators during the 1950s and 1960s, which enabled high energy particles (mesons and protons) to be fired at nuclear targets, new varieties of matter which live only of the order of 10^{-23} seconds were discovered. But it eventually became apparent that those particles too are complex rather than elementary. Then in 1964, independent observations by Gell-Mann and Zweig of recurring patterns among the strongly interacting particles known at that time resulted in the establishment of the idea of a more fundamental variety of matter called quarks which formed these particles

and ultimately the nucleus. They discovered that hadrons, particles that interact through the strong nuclear force, fall into patterns according to properties such as electric charge and strangeness. These patterns are called the 'Eightfold Way'[1]. It was also observed that these patterns would arise naturally if all of the nuclear particles were made of just three varieties of quarks which were called 'up', 'down', and 'strange' (u , d , and s respectively, for short). Studies at the Stanford Linear Accelerator Center (SLAC) in the late 1960's where high energy electrons were fired at protons and neutrons essentially confirmed this hypothesis. The energy and angular distributions of the scattered electrons indicated that some of them were interacting with pointlike, electrically charged objects within the protons and neutrons.

Originally there were supposed to be just these three kinds of quarks. All of the known hadrons in 1968 could be interpreted as combinations of these quarks and their antiparticle equivalents ($\bar{u}$, $\bar{d}$, and $\bar{s}$). Quarks combine in two ways to form hadrons. Three quarks bind together to constitute a baryon, a member of the subclass of hadrons that includes the proton and the neutron. Bound states of a quark and an antiquark form the mesons-the lightest and the most common of which is the pion. It has turned out that these quarks in the "ordinary" hadrons are quite light. Somewhat later, Bjorken at SLAC, and Glashow at Harvard speculated that there might be a fourth quark flavor, which they named charm (c)[2]. In 1970 Glashow and his colleagues[3] had argued on purely theoretical grounds that such a charm quark must exist and should be substantially heavier than the other already known quarks. This hypothesis was soon supported by Applequist and Politzer of Harvard by showing that a charmed quark and its antiquark might form a nonrelativistic bound state which they called charmonium, in analogy to positronium. The breakthrough came in 1974 when such a nonrelativistic quark system was found with the discovery of an extraordinary meson J/ψ having a mass of 3095 MeV. This meson was found almost simultaneously by two groups of experimenters: one at the Brookhaven National Laboratory and the other at

Table 1: The Lepton particle Family.

Particle Name	Symbol	Mass at Rest (MeV)	Electric Charge
Electron Neutrino	ν_e	< 0.0073	0
Electron	e^-	0.511	-1
Muon Neutrino	ν_μ	< 0.27	0
Muon	μ^-	105.6	-1
Tau Neutrino	ν_τ	< 35.0	0
Tau	τ^-	1784.0	-1

SLAC. The discovery of J/ψ stimulated a search for still heavier quarks which became known as the bottom (b) and the top (t). In 1976 Eichten and Gottfried of Cornell University suggested that bottomonium $b\bar{b}$ and toponium $t\bar{t}$ should form nonrelativistic systems similar to charmonium but with a considerably richer spectrum of bound states. The first bottomonium state was discovered in 1977 at the Fermi National Accelerator Laboratory near Chicago and was called the Υ . This meson had a mass of about 9,460 MeV. The toponium has not been yet detected, but the current theory (standard model) requires the existence of the t quark.

The other class of particles that appear to be structureless and indivisible, and therefore fundamental, are known as leptons, all of which have spin 1/2. They may be charged or neutral. The charged leptons have electromagnetic as well as weak interactions while the neutral leptons only interact weakly. Neither the charged nor the neutral leptons are affected by the strong force. Six distinct flavors of leptons have been identified so far (see Table 1) of which the electron is the most common. For each lepton there is a corresponding antilepton with the same mass and spin as their respective particles but opposite values for other properties such as electric charge. There exists "lepton-type" conservation laws which follow automatically in the standard model if the neutrinos are massless.

Table 2: The Quark Family.

Quark	Mass at Rest	Electric Charge	Isospin z-component
up (u)	2 to 8(MeV)	+2/3	+1/2
down (d)	5 to 15(MeV)	-1/3	-1/2
charm (c)	1.3 to 1.7(GeV)	+2/3	0
strange (s)	0.1 to 0.3(GeV)	-1/3	0
bottom (b)	4.7 to 5.3(GeV)	-1/3	0
top (t)	> 91(GeV)	+2/3	0

1.2 Quark Model

Table 2 gives the masses and additive quantum numbers of the quarks[4]. They are spin 1/2 fermions with baryon number 1/3. The convention is that the “strangeness” of the quark has the same sign as its electric charge. The “free” quark masses given in the table are a conservative estimate of the range of masses as given in Reference[4]. Quarks also possess a new form of charge called “color” which is in some ways similar to the electrical charge but with some subtle and far-reaching differences. It is this color charge of the quarks which controls their interactions with each other.

Quantum Electrodynamics (QED) is the theory of electromagnetic forces, acting on fundamental spin-1/2 particles of matter such as electrons and quarks and involving the transmission of spin-1 ‘gauge bosons’ called photons. By analogy, Quantum Chromodynamics (QCD) is the theory of Strong forces acting on the fundamental spin-1/2 quarks involving a transmission of spin-1 gauge bosons known as the ‘gluons’. Unlike QED, which has a U(1) (1×1 matrices) structure, QCD has an SU(3) (3×3 unitary matrix) structure due to the three color charges involved. In close analogy with the U(1) of QED (U(1) of QED describes the group of symmetries of the theory that is associated with the conservation of electric charge and the masslessness of the photon), SU(3) of QCD describes a group of

symmetries of the theory that is associated with the conservation of color charge and the masslessness of the gluons. This SU(3) theory leads to rich structures and, as yet unsolved, complexities of detail. At extremely short ranges, QED and QCD forces are very similar whereas they differ drastically¹ at long ranges of the order of 1 fm. This is believed to be the reason why isolated free quarks have never been seen.

1.3 Mesonic spectra

All the known mesons can be categorized as the bound states of a quark q and an antiquark $\bar{q}$ (of possibly different flavor). Since quarks are spin 1/2 particles, the $q\bar{q}$ pair couple to a total spin singlet ($S=0$) or a spin triplet ($S=1$). They interact[5] through some potential, $V(r)$, and have quantized orbital angular momentum L . The total spin of the system is $J=L+S$. We can therefore construct the J^{PC} for all possible mesonic states in this model². The meaning of these names is the description of how such a particle behaves under the operations of space inversion and rotation. In fact, this behavior is also dependent not just upon spin but also upon parity. Something that is immediately evident is that some of the J^{PC} choices are not permitted. These include $0^{--}, 0^{+-}, 1^{-+}, 2^{+-}, 3^{-+}, \dots$ Such forbidden J^{PC} states may exist outside the known $q\bar{q}$ model³. For a state with $^{2S+1}L_J$, the allowed $q\bar{q}$ states may be written as $^1(L \text{ even})_J, ^1(L \text{ odd})_J, ^3(L \text{ even})_J$, or $^3(L \text{ odd})_J$.

We can see that there are nine possible $q\bar{q}$ combinations if we consider only the u , d , and s quarks. These combinations group themselves into an octet and a singlet in the following way:

$$3 \otimes 3 = 8 \oplus 1 \tag{1}$$

¹QCD theory implies that when colored objects like quarks are less than a fermi apart the forces between them are almost nonexistent, and, in contrast, grow in strength as they are pulled apart from one another (asymptotic freedom).

² P is the parity of the system given by $P = (-1)^{L+1}$. A state $q\bar{q}$ of a quark and its own antiquark is an eigen state of charge conjugation $C = (-1)^{L+S}$.

³see the section on Non- $q\bar{q}$ States.

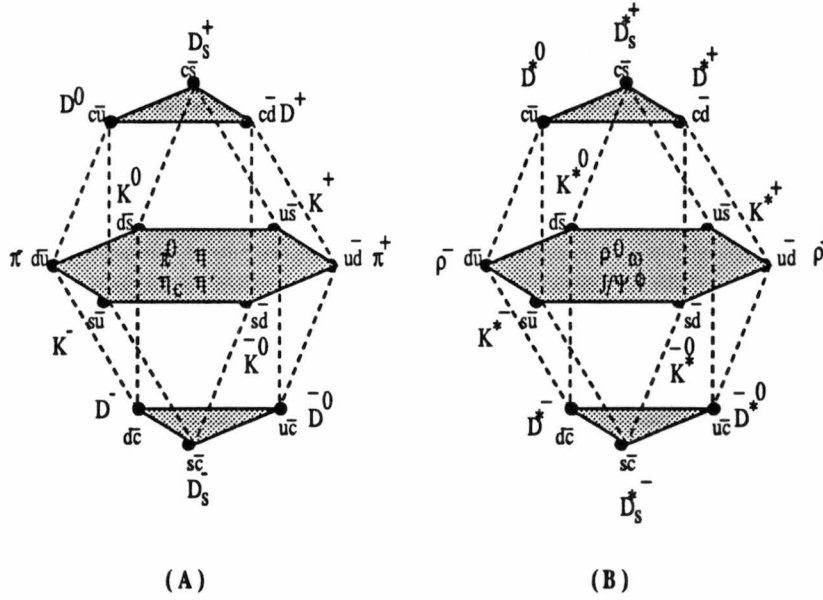


Figure 1: SU(4) hexadecuplets for A) Pseudoscalar Mesons B) Vector Mesons.

Mixing of the states with the same IJ^P and additive quantum numbers are allowed. The charm quark can be added then to this scheme which extends the symmetry to SU(4). Such SU(4) hexadecuplets for the pseudoscalar and vector mesons made up of u, d, s , and $c q\bar{q}$ combinations are shown in Figure 1[4]. The meson nonets lie in the central planes in each case to which the $c\bar{c}$ members have been added. The mixtures of $u\bar{u}, d\bar{d}, s\bar{s}$, and $c\bar{c}$ states form the neutral mesonic states which occupy the center of the central planes in Figure 1. The addition of a bottom quark into such a scenario makes the figure four-dimensional.

In addition to the $S, P, D, \dots$ orbital excitations of the meson spectrum, the quark model also predicts radial excitations of the states, which are characterized by a principal quantum number $n = 1, 2, 3, \dots$. A typical treatment of such radially excited states, which arises from the potential model of quark theory, is given by Graham and O'Donnell[6].

The calculation of mesonic properties can be achieved through four main quantitative techniques: Potential models[5], Bag models[7], QCD sum rules[8], and

Lattice gauge theories[9]. Some of these models yield quite detailed predictions for the masses, widths, branching ratios, etc, but the real test of each model lies in its independence from random parameters which are required for all of the above models.

1.4 Non- $q\bar{q}$ States

QCD implies that the quark can change its color charge upon radiating a gluon. Thus unlike photons, gluons carry color themselves, as a consequence of which, they feel the color forces directly, and can interact with themselves. The existence of such gluon self coupling in QCD suggests that, in addition to the conventional $q\bar{q}$ mesonic states, there may be bound states including gluons: glueballs (gg or ggg) [10] or hybrids ($q\bar{q}g$)[11, 12]. There may also be $q\bar{q}q\bar{q}$ multiquark states [13, 14, 15]. Interestingly, all the models previously mentioned for the mesonic states can be adjusted to accommodate the existence of these gluonic hadrons and multiquark states. But there are problems in extracting the parameters in each model since there are no clear data to compare to the predictions of these models.

Glueballs are pure glue isoscalar states. The gg glueball states cannot have any of the “exotic” J^{PC} values which are allowed for $q\bar{q}g$ hybrids. Rather, they exist with $\gamma\gamma$ like J^{PC} values such as $J^{PC}(gg) = 0^{++}, 0^{-+}, 2^{++}, 2^{-+}, 3^{++}, 4^{++}, 4^{-+}, 5^{++}$, etc. Currently, these states, if they exist, have proved impossible to disentangle from the ordinary broad $I=0$ $q\bar{q}$ mesonic states. Exotic glueballs with values of J^{PC} which are forbidden to $q\bar{q}$ states could also exist but only in the ≥ 3 gluon sector. The bag model estimate for such three gluon states is that their mass is in excess of ≥ 2.5 GeV. Gluonic hadrons have been studied using models such as the MIT bag model, flux tube models[16, 17], constituent gluon models[18], and Lattice gauge theory. Among the expected signatures for a glueball state are:

- The candidate state should not fit into a conventional $q\bar{q}$ nonet. This means either the available slot in the nonet is already filled or the state should

possess J^{PC} quantum numbers not permitted in the quark model.

- It should have relatively copious production in gluon rich reactions such as $p\bar{p}$ annihilations, double Pomeron exchange (DPE) reactions, $J/\psi \rightarrow \gamma X$ decays, or any reaction where a final state meson is produced with disconnected quark lines (According to the Okubo-Zweig-Iizuka (OZI) rule[19], decay processes where the quark diagrams have connected lines are greatly favored over those with disconnected lines). The observation of such an OZI forbidden transition would require a suppressed decay mode of a $q\bar{q}$ state.
- Production should be relatively suppressed in normal (quark line connected) hadronic processes.
- The state should have a small 2γ width since the γ couples to electric charge which is absent from the glueball constituents.
- The state should be an SU(3) singlet in color and flavor and its decay should be flavor symmetric.

The $\iota(1440)$ and $\theta(1720)$ (now called $\eta(1440)$ and $f_0(1710)$ respectively) are considered to be two classic glueball candidates from the J/ψ radiative decay experiments⁴.

The existence of these non- $q\bar{q}$ states in QCD and the absence of analogous “photonballs” in QED can be understood as due to the threefold nature of color charge (SU(3)) as opposed to the U(1) structure of QED. QED shows that an electron remains as an electron upon radiating a photon. The photon, therefore, does not carry away electrical charge and hence feels no direct electromagnetic attraction to other photons.

In contrast to the gluonium states, the $q\bar{q}g$ hybrid states, where both quarks and gluons are present in the dominant basis state, may have unique J^{PC} exotic

⁴Though early references considered $f_0(1710)$ as a glueball candidate, some recent studies indicate this to be unlikely and assign it to be a vector-molecule[20, 21].

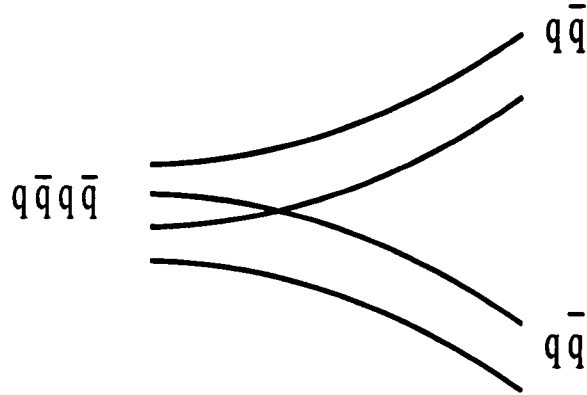


Figure 2: Fall-apart decay of a $q^2 \bar{q}^2$ state.

quantum numbers such as $0^{--}, 0^{+-}, 1^{-+}, 2^{+-}, 3^{-+}$... etc. Thus these states would be unambiguous signatures for non- $q\bar{q}$ states. The isovector sector of the meson spectrum is preferred by most of the hybrid-searchers in order to avoid confusion with the large number of isoscalar states. Also, the exotic $J^{PC} = 1^{-+}$ quantum states are favored in this sector because this state happens to occur in the lightest bag-model hybrid multiplet[22, 23, 24].

The possible existence of a multiquark state, $q\bar{q}q\bar{q}$, was first discussed in detail by Jaffe[13] using the MIT bag model. Among these $q\bar{q}q\bar{q}$ states, some are theoretically predicted to decay to vector meson pairs dominantly (“fall-apart” decays, the rearrangement into color singlets) and their masses are just about the threshold of the corresponding vector meson pairs. This means that their hadronic decay width will be large. These multiquark states might be observed as mass bumps in the invariant mass spectra of the final states of interest. Fall-apart decay would not be possible if the multiquark cluster had a mass lower than the threshold of the two-meson system. This makes the question of the existence of such bound states interesting. The fall-apart decay is pictorially depicted in Figure 2. Only a very few $q^2 \bar{q}^2$ states are expected to be stable enough to be detected experimentally. The $S^*(975)$ and $\delta(980)$ (currently known as $f_0(975)$ and $a_0(980)$ respectively)

are considered to be classic examples of such states. But the experimentally observed narrow widths of these two states, uncharacteristic of the fall-apart decay, have recently prompted the proposal of an alternate theory [14, 15], which concludes that the f_0 and a_0 are $K\bar{K}$ bound states ($K\bar{K}$ molecule) analogous to the deuteron. This theory is supported by the fact that their mass is just below the $K\bar{K}$ threshold. Their small widths, large branching ratio into $K\bar{K}$ final states, and small production cross sections in two-photon interactions contribute to this conclusion[25]. However, a detailed investigation of the $f_0(975)$ mass distribution carried out recently seems to contradict the $K\bar{K}$ molecule hypothesis[26]. Investigations on the inclusive production of $f_0(975)$ mesons in the Υ energy region by the ARGUS collaboration at DESY reported the production features of this meson to be consistent with an ordinary meson, though a $K\bar{K}$ coalescence model, within the precision obtained, was not excluded[27]. Another way out of the narrow width dilemma was proposed by Jaffe[13], where he assigns the two states to $\frac{1}{\sqrt{2}}(u\bar{u} \pm d\bar{d})s\bar{s}$ bound states. The stability of these states, as observed by their relatively narrow widths, may then be explained as due to the limited number decay modes they can undergo without violating the OZI rule.

No state has so far unambiguously been identified as a glueball, hybrid or multiquark state. But there is evidence for good *prima facie* candidates which do not fit well with the $q\bar{q}$ model. Such suspected states will be examined later in this work in the $K^+K^-\pi^+\pi^-$ reaction channel. Some new theoretical studies predict considerable resonant anomaly in the $\gamma\gamma \rightarrow \rho^0\phi \rightarrow K^+K^-\pi^+\pi^-$ cross section[28, 29]. Since no ordinary $q\bar{q}$ resonances can occur in this sector without breaking the OZI rule, the anomaly is suspected to be due to two four-quark flavor states in the M.I.T bag model⁵ with $I = 1$, $J^P = 2^+$ and masses around 1.95 GeV. The bag model calculations show these four-quark states to have large coupling values with the $\phi\rho$ channel. Thus an experimental observation of a large resonant cross section in the $\phi\rho$ final state near it's threshold would be evidence in favor

⁵The M.I.T bag model predicts four scalar and two tensor $U(3)$ multiplets of the four-quark mesons[13].

of these four-quark structures. The $K^{*0}\bar{K}^{*0}$ final state has also been suggested as a good place to look for evidence of multiquark states. The possible existence of a multiquark state decaying through the $\phi\pi$ mode, forbidden by the OZI rule for any $q\bar{q}$ state, has been predicted by Close and Lipkin [30]. The $J^{PC} = 1^{--}, I = 1$ candidate $C(1480)$ meson, recently observed in the $\pi^-p \rightarrow \phi\pi^0n$ channel, would appear to offer evidence supporting this prediction[31, 32, 33, 34, 35]. The $f_0(975)$ resonance is also observed in the dipion mass spectrum of the $\phi\pi^+\pi^-$ sector in the present work. This state has also been observed in previous experiments in the $\pi^+\pi^-$ spectrum of the doubly OZI forbidden decay, $\psi \rightarrow \phi\pi^+\pi^-$ [36].

1.5 The structure of the Photon

When the initial experiments on meson photoproduction from nucleons were conducted, the photon was thought to be structureless. Although the radiative corrections took into account the materialization of the photons into e^+e^- pairs through an interaction with the coulomb field, this was not usually thought of as a manifestation of photonic structure. Over the years, it gradually became clear that, in reality, the photon has an internal hadronic structure and the manifestation of such a structure occurs only at energies that are high enough to excite this degree of freedom. Indeed, when the available photon energies have risen to the multi-GeV range, the similarities between photon interactions with hadrons and other hadron interactions have become increasingly apparent. The most obvious similarity of photon and hadron interactions is in the behavior of the total hadronic and total photon cross sections[37]. Both have sharp resonances at low energies, leveling out approximately above 3 GeV to become structureless. The photon total cross sections were also found to be smaller than the hadronic cross sections by approximately the fine structure constant ($\alpha \simeq 1/137$). Typically, the total elastic cross section accounts for about 15% to 20% of the total cross section in pure hadronic interactions. But the elastic part of the total photon cross section, the nucleon

Compton scattering, is much smaller ($<1\%$). Such a difference, however, is found to be compensated for by the process of diffractive photoproduction. The most striking feature of this diffractive photoproduction is the copious production of neutral vector mesons V such as ρ^0 , ω , and ϕ .

To a first approximation, a real photon can be thought of as a fundamental pointlike particle. However, through its direct coupling to quarks, the photon has a probability to fluctuate into a quark-antiquark pair. The Vector Dominance Model (VDM), which will be discussed in the next section, postulates such a $\gamma \leftrightarrow V$ transition in its theory. Since the present work is devoted mainly to the photoproduction of vector mesons, only the VDM aspects of the theory are considered.

1.6 The Vector Dominance Model (VDM)

The Vector Dominance Model (VDM) was first introduced by Sakurai[38]. It has been successfully used for years to describe the diffractive interactions of the photon. This model tries to explain the striking similarities between the purely hadronic and photon-hadron interactions, at a crude level, by considering the physical photon $|\gamma\rangle$ state to be a superposition of a bare photon $|\gamma_B\rangle$, and a small (of order of $\sqrt{\alpha}$) hadronic component $\sqrt{\alpha}|h\rangle$. The bare photon component $|\gamma_B\rangle$ accounts for a negligible portion of the interaction at high energies whereas the hadronic component $\sqrt{\alpha}|h\rangle$ undergoes the conventional hadronic interactions. This component will also have the same quantum numbers of the photon, $J^{PC} = 1^{--}$, $Q=B=S=0$. It is then possible to express the photon as[37]:

$$|\gamma\rangle \cong \sqrt{Z_3}|\gamma_B\rangle + \sqrt{\alpha}|h\rangle \quad (2)$$

with Z_3 being the normalization constant. According to VDM, the vector mesons ρ^0 , ω , and ϕ will comprise the dominant hadronic component of the physical

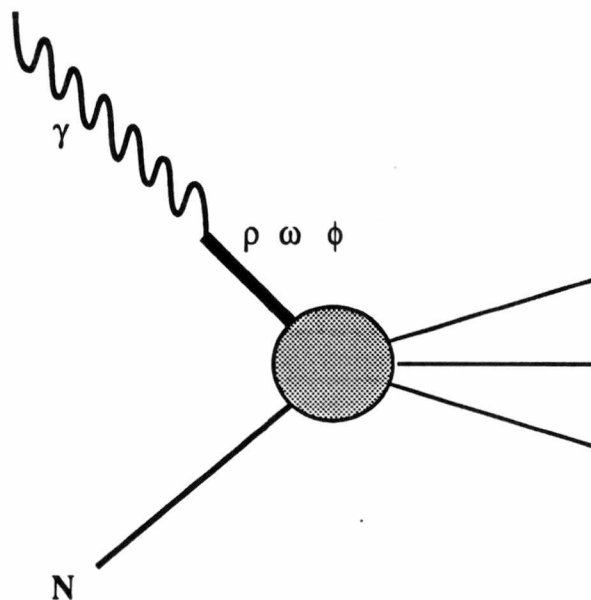


Figure 3: Vector Dominance Model (VDM) picture of photoproduction.

photon⁶. Only this component of the physical photon participates in hadronic interactions.

As mentioned in the previous section, the VDM approach places emphasis on the fluctuation of the ‘bare’ photon into a vector meson state V which then undergoes the interaction. The mechanism of such a $\gamma \leftrightarrow V$ transition, as postulated by the VDM model, is shown in Figure 3. In the photoproduction of a vector meson from a nucleon, the high-energy photon is assumed to transform into the Vector meson before interacting with the target to produce a multiparticle final state.

With the assumption of the diagonal approximation⁷, we can show that the amplitude of the vector meson photoproduction is related to the amplitude of vector meson scattering off the nucleon (of the target) by,

$$T_{\gamma v} = \frac{e}{\gamma_v} T_{vN} \quad (3)$$

⁶This set of vector mesons in VDM is augmented by ρ' , ω' , and ϕ' in the Generalized Vector Dominance theory (GVD)[39, 40].

⁷That the photon’s hadronic constituents are not mixed by the scattering process.

where e is the electric charge and γ_v is the dimensionless constant describing the coupling of the photon to the vector meson V . Replacing N with the proton target, we get the relationship between the amplitudes of vector meson photoproduction and vector meson elastic scattering as,

$$T_{\gamma p \rightarrow vp} = \frac{e}{\gamma_v} T_{vp \rightarrow vp} \quad (4)$$

This implies that the forward differential cross sections are related as,

$$\frac{d\sigma}{dt}(\gamma p \rightarrow vp) = \frac{e^2}{\gamma_v^2} \frac{d\sigma}{dt}(vp \rightarrow vp) \quad (5)$$

From the Optical theorem, the elastic and total cross sections are related as,

$$\left. \frac{d\sigma^{el}}{dt} \right|_{t=0} = \frac{(1 + \eta^2)}{16\pi} \sigma_{tot}^2 \quad (6)$$

where η is the ratio of the real to imaginary forward scattering amplitude. Using this relation, the total photoproduction cross section can be determined by measuring the elastic meson photoproduction cross section for individual vector mesons. The coupling constant γ_v can be calculated from the leptonic width ($\Gamma(v \rightarrow l^+ l^-)$) of the vector meson and could be compared to those obtained from the photoproduction experiments. (see Table I of Reference[37]).

1.7 Photoproduction of Vector Mesons

Elementary particle interactions are generally thought to be due to various types of exchanges between the projectile and the target. The quantities that can be exchanged include momentum, charge, strangeness etc. In the photoproduction process, virtual particles are mediated in the form of One Pion Exchange (OPE), Pomeron exchange (vacuum exchange) ⁸[43], etc. Because of the light pion mass, charge exchange processes appear to be dominated by one pion exchange processes

⁸The Pomeron exchange concept was introduced in the late 1950s to account for elastic and diffractive scattering processes in which there is no exchange of quantum numbers.

(OPE). Such interactions have been observed experimentally through the production of $\rho^-(770)$, $a_2^+(1320)$, and $a_2^-(1320)$ associated with Δ^{++} [41, 42]. The charge exchange interaction cross sections diminish with increasing interaction energies. The scattering process in which the Pomeron is the exchanged particle is known as diffractive scattering. The products of such a diffractive reaction are mostly found to conserve the s channel helicity (*SCHC*)⁹. The ratio of the vector meson cross section to the total photoproduction cross section is similar to the ratio of the elastic cross section in hadronic interactions to the total hadronic cross section:

$$\frac{\sigma(\gamma N \rightarrow VN)}{\sigma(\gamma N_{total})} \sim \frac{\sigma_{elastic}(VN \rightarrow VN)}{\sigma_{total\ hadronic}(VN)} \quad (7)$$

In addition, both seem to display similar forwardly peaked t distributions (t being the invariant momentum transfer squared).

A very useful kinematic variable that has been used in many diffractive and charge exchange photoproduction analyses is t' which is related to the invariant momentum transfer t as:

$$t' = (t - t_{min})|_{CM} \quad (8)$$

where t_{min} is the kinematical minimum of t . The t' distribution shows a steep exponential decrease in case of a Pomeron exchange process and a somewhat shallower exponential fall for an OPE type of reaction. Heavier mass exchange mechanisms are expected to demonstrate even flatter t' distributions.

A way of summing all the different angular-momentum states of the exchanged system (a $q\bar{q}$ system) was suggested in Regge theory[44, 45]. Instead of the exchange of a single particle, we can consider the effect of exchanging a whole “Regge trajectory” of particles, which are made of the same $q\bar{q}$ pair with different values of angular momenta. Regge theory can be used to describe high energy diffractive scattering processes by making use of the so called Pomernanchuk trajectory concept. Here, diffractive elastic scattering process is visualized through the exchange of Regge poles (see Figure 4) where the leading trajectory (known as the

⁹*SCHC* suggests that the helicities are conserved in the meson center of mass. This implies that when the photon converts into a vector meson it passes on it's helicity.

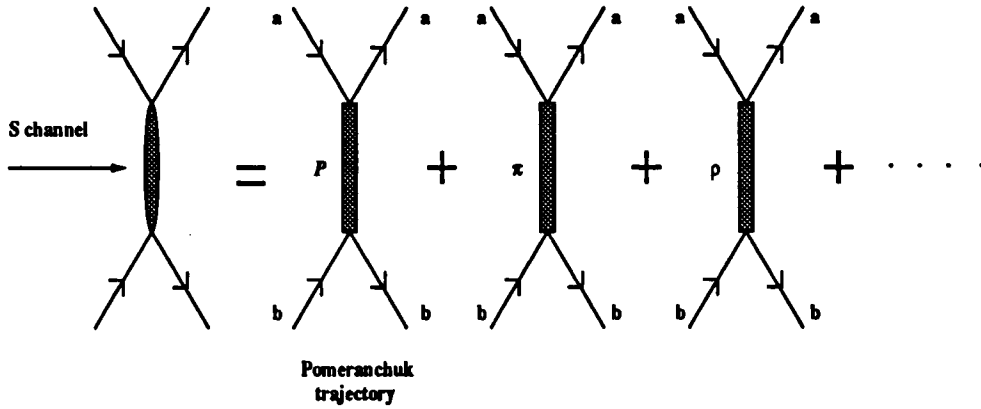


Figure 4: Regge pole exchange series.

Pomeranchuk trajectory) has the quantum numbers of the vacuum (Pomeron exchange). This leading trajectory therefore accounts for the diffractive processes. Higher terms appearing in the trajectory sum correspond to π (OPE type of reactions), ρ , a_2 , ..., etc exchange mechanisms. Though the OPE reactions have been observed, there is no unambiguous evidence for the existence of ρ or higher order exchanges in photoproduction reactions. The theory shows that the Pomeranchuk trajectory dominates all the others at $t = 0$. This is confirmed experimentally where diffractive interactions are indeed found to be peripheral (low t value).

1.7.1 The $\rho'(1600)$ Vector Meson

Indications of the existence of possible vector meson states, other than ρ , ω and ϕ , were reported in $\gamma p \rightarrow \pi^+ \pi^- \pi^+ \pi^- p$ and in $e^+ e^- \rightarrow 4\pi + \text{neutrals}$ reaction channels in the early 1970s[46, 47]. The first strong evidence for the photoproduction of the heavy vector meson analogous to the ρ^0 , known as $\rho'(1600)$, was obtained by the LBL-SLAC 82" Hydrogen Bubble Chamber group[48] in their experiment with a 9.3 GeV linearly polarized photon beam. (This vector meson is called ρ' primarily because it has the quantum numbers of the ρ , and also because higher mass vector mesons predicted by quark and other models have typically been called ρ' .) They observed a broad enhancement in the 4π invariant mass near 1.5 GeV

in the channel $\gamma p \rightarrow \pi^+ \pi^- \pi^+ \pi^- p$. They determined that the parameters of the observed state were consistent with a vector meson state having quantum numbers $I^G(J^{PC}) = 1^+(1^{--})$. The apparent mass and width of the resonance were 1430 ± 50 MeV and 650 ± 100 MeV respectively. Since then many groups have confirmed its existence in various $\gamma p \rightarrow \pi^+ \pi^- \pi^+ \pi^- p$ photoproduction experiments[49, 50, 51, 52, 53] and $e^+ e^- \rightarrow \pi^+ \pi^- \pi^+ \pi^-$ experiments[54, 55, 56, 57], albeit, often, with different values for the mass and width. The enhancement has also been observed in the photoproduction reaction $\gamma p \rightarrow \pi^+ \pi^- p$ [51, 58, 59, 60] and $e^+ e^- \rightarrow \pi^+ \pi^-$ reaction[61, 62].

Recent studies of this heavy vector meson conducted on the data from the annihilation reactions $e^+ e^- \rightarrow \pi^+ \pi^-, 2\pi^+ 2\pi^-$, and $\pi^+ \pi^- \pi^0 \pi^0$, and from the photoproduction reactions $\gamma p \rightarrow \pi^+ \pi^- p, 2\pi^+ 2\pi^- p$, and $\pi^+ \pi^- \pi^0 \pi^0 p$ have replaced what used to be called the $\rho'(1600)$ region with two $I = 1, J^P = 1^-$ states called ρ'_1 and ρ'_2 with masses of 1.465 ± 0.025 GeV and 1.700 ± 0.025 GeV with widths of 0.235 ± 0.025 GeV and 0.220 ± 0.025 GeV respectively[63, 64, 4]. This new hypothesis was prompted from theoretical studies[65] on the 2π and 4π electromagnetic form factors and $\pi\pi$ scattering in the $\rho'(1600)$ region, which concluded that there is no natural way to understand the elastic 2π and inelastic 4π electromagnetic form factors within the framework of the ρ and a single ρ' . The most logical explanation for this problem was to postulate two resonances in this region, which remains the favored interpretation of the data relating to the $\rho'(1600)$ region.

An analysis of the $\rho'(1600)$ region in the reaction $\gamma p \rightarrow \pi^+ \pi^- \pi^+ \pi^- p$ channel will be undertaken in this work. This will include an investigation of the 2π and 3π substates of the 4π mass spectrum.

1.7.2 The $\psi'(3685)$ Vector Meson

The production of the well established radially excited state of $J/\psi(3097)$ known as the $\psi'(3685)$ or $\psi(2S)$ has been observed and investigated in many $e^+ e^-$ experimental results. The decay of $\psi(2S)$ to $J/\psi \pi^+ \pi^-$ accounts for about 32% of its

total hadronic decay mode. It has been observed in this particular reaction channel in e^+e^- [66, 67] and photoproduction[68] results. A recent search for hidden charm resonance states decaying into J/ψ or ψ' along with pions, using 300 GeV/c pions and protons on a natural Li target, has also reported seeing the $\psi(2S)(3685)$ [69]. A study of this state will comprise a portion of this work.

1.8 Decay Angular Distributions

The study of angular distributions of meson states is often a useful way to extract it's angular momentum and parity J^P . The decay angles θ and ϕ are defined as the polar and azimuthal angles of the analyzing vector, which describes the decay of the vector meson. These angles can be calculated in a suitable co-ordinate system, and their distributions in turn will be able to suggest the decaying vector meson's quantum numbers. One such co-ordinate system is the Helicity co-ordinate system of the vector meson. The definition of this particular co-ordinate system for the photoproduction of vector mesons, with an example of a two body decay, is shown in Figure 5. The z axis of this frame is the direction of the vector meson in the total γp_{cm} system, which implies:

$$\hat{z} = \frac{\hat{v}}{|\hat{v}|} \quad (9)$$

where $\hat{v}$ is the vector meson velocity in the overall γp center of mass. The x and y axes are then defined as:

$$\hat{y} = \frac{\hat{k} \times \hat{z}}{|\hat{k} \times \hat{z}|} \quad (10)$$

$$\hat{x} = \frac{\hat{y} \times \hat{z}}{|\hat{y} \times \hat{z}|} \quad (11)$$

where $\hat{k}$ is the photon direction in the overall center of mass. In the case of a two-particle decay, the analyzing vector is taken to be one of the decay products. For a three-particle decay, one analyzing vector that can be used is the normal to the decay plane. There is no good, unambiguous decay angle analyzer in the channel

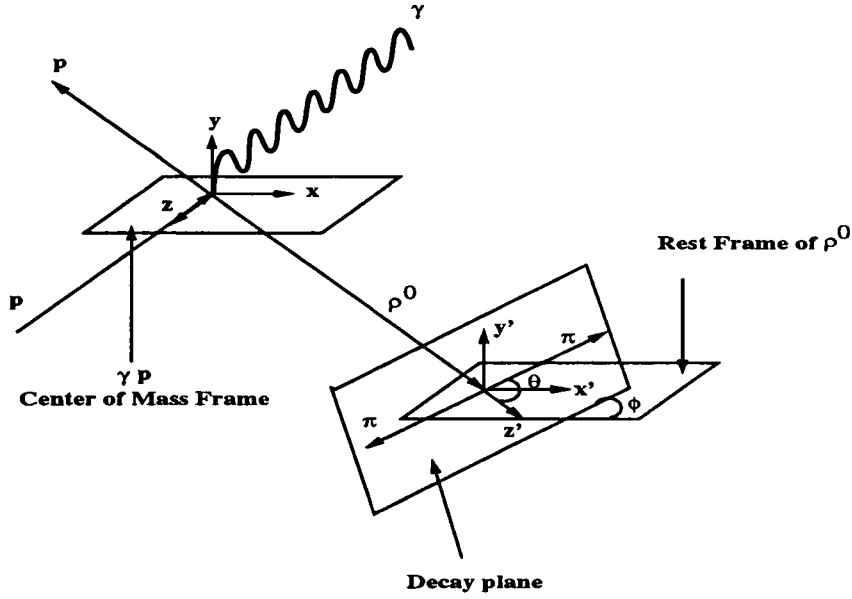


Figure 5: The Helicity frame of ρ^0 for its 2-pion decay.

$\gamma p \rightarrow \pi^+ \pi^- \pi^+ \pi^- p$ though it has been suggested that the analyzer $\hat{P}_{++} = \hat{P}_{\pi^+} + \hat{P}_{\pi^-}$ in the helicity system of (4π) could be useful in the spin parity analysis[70].

Another co-ordinate system of interest is the Gottfried-Jackson (GJ) frame, which is similar to the Helicity system except for the direction of the $\hat{z}$ axis. In the GJ frame the $\hat{z}$ axis is chosen to be the direction of the incident photon in the rest frame of the meson under consideration. This choice of co-ordinates is useful in charge exchange reactions where OPE is often presumed to be the exchange mechanism.

Chapter 2

Experiment E687

Experiment E687 was conducted in the Wide Band Laboratory situated in the east Proton beam line at Fermi National Accelerator Laboratory, Batavia, Illinois. The main purpose of E687 is the study of the production and decay of charm particles, with low background, using a high intensity, high energy photon beam. The use of high energy photon beams, rather than either proton or pion beams, has been recognized as a good method for the investigation of charmed particles since the relative rate of interactions producing charm particles to the total rate of producing multiparticle hadronic final states is about 1% in photoproduction as compared to about 0.1% with production using hadron beams. From the 500 million interactions collected by the experiment over its 1990-91 fixed target runs, approximately 100,000 charm decays have been reconstructed with much higher statistics than any previous experiment. The large data sets acquired also opened the way to previously inaccessible physics topics such as searches for $D^0 \bar{D}^0$ mixing, doubly Cabibbo-suppressed decays, and other rare charm decays.

A thorough description of the E687 Spectrometer can be found in Reference[71]. Here we will review the features and components of the spectrometer which are important to the work described in this thesis. The data used for this analysis were taken during the 1990-91 fixed target experimental runs.

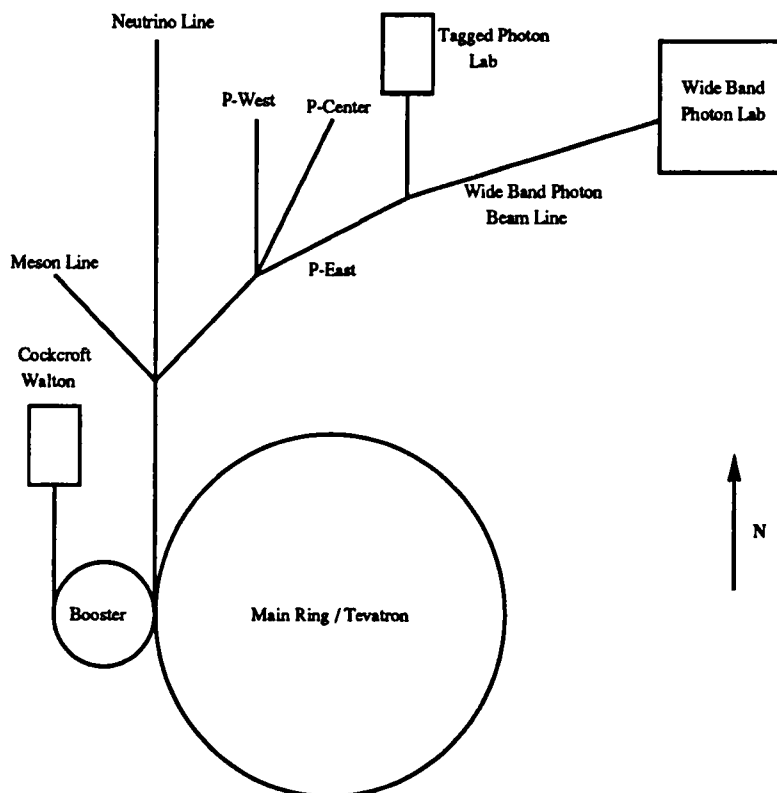


Figure 6: Schematic of FNAL.

2.1 The Wideband Photon Beam

The photon beam is produced by the conventional “bremsstrahlung method”. A brief description of the various steps starting from the primary proton beam to the photons used at the experimental target of E687 is given below:

1. The experimental photon beam is derived from an 800 GeV/c proton beam. A schematic of the Fermilab National Accelerator layout is shown in Figure 6. A Cockcroft-Walton accelerator accelerates protons obtained from ionized hydrogen to 750 KeV/c which is then injected into a Linac. The 1 GeV/c protons from the Linac then enter a booster ring which accelerates them to 8 GeV/c. The beam is then transported into a 1 kilometer radius Main Ring made of iron electromagnets and is accelerated to 150 GeV/c before being

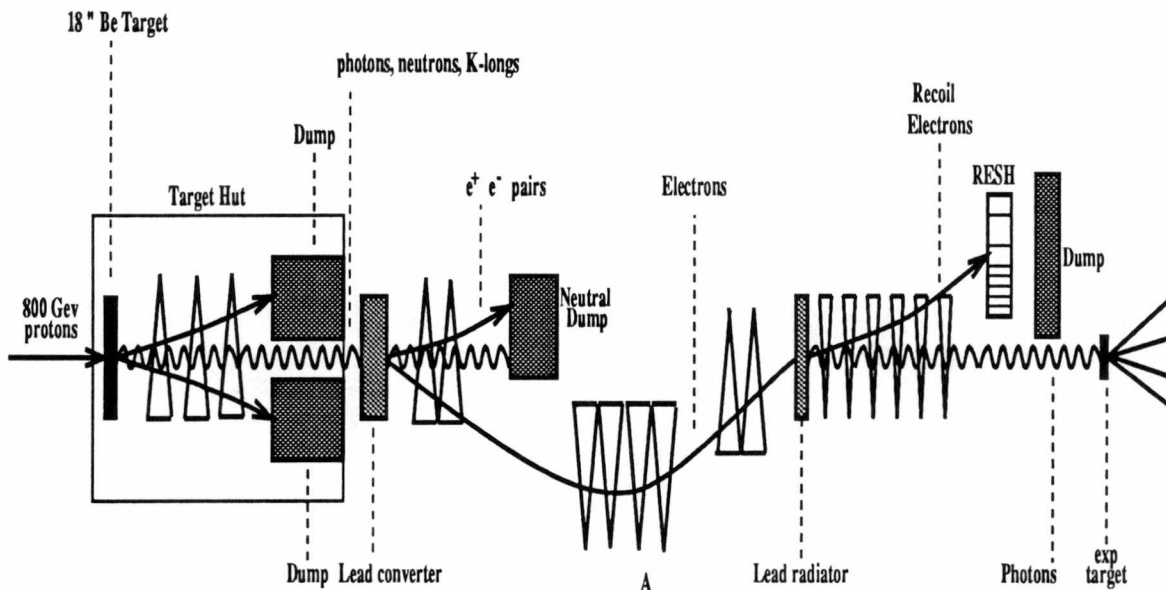


Figure 7: The Wide Band Photon beam line.

injected into the Tevatron which is located directly beneath the Main Ring. The Tevatron is a ring of superconducting magnets of 1 kilometer radius where the proton beam is accelerated to a final energy of 800 GeV/c which is then used for the fixed target experiments.

2. The schematic layout of the Wide Band Photon Beam from the photon production target to the experimental target is shown in Figure 7. The 800 GeV/c Protons interact with the "primary production target" made of Beryllium. This interaction produces both neutral and charged particles. A series of dipole magnets placed after the target sweep the charged products into a dump leaving the neutrals such as γ , π^0 , n , and K_L^0 . The neutral pions produced undergo immediate decay into two photons. These neutrals then go straight through between the charged particle dumps.
3. The photons in this beam then interact with a Lead converter of 0.6 radiation lengths where they produce electron-positron pairs.

4. The electrons from this conversion process are then captured by a conventional beam transport system comprised of dipoles and quadrupoles. They are deflected from zero degrees while the neutral hadrons, neutrons and K_L^0 's, along with unconverted photons, travel straight ahead at zero degrees and are absorbed in a "neutral dump".
5. The captured electron beam which is transported around the neutral dump is then passed through a thin Lead radiator foil of 0.27 radiation lengths to produce photons by bremsstrahlung. The electron/photon beam from the radiator then passes through a series of sweeper magnets which deflect the electrons into a Recoil Electron Shower Counter (RESH) while the photons continue on to the experimental target.

The photon beam derived this way has certain advantages and disadvantages. The advantage is that such a beam will have a very low neutral contamination as compared to other methods of producing high energy photon beams. Thus the problem of a neutral particle mimicing a photon in a subsequent interaction is reduced to a relatively small effect. The disadvantage to this type of beam is that this multi-step process degrades the final energy of the photon beam.

2.1.1 Beam Tagging

The Wideband beam has a simple photon energy tagging system. This system determines the energy of the interacting photon on an event-by-event basis. If the incident energy of the electron is E_{beam} , the recoil electron (after bremsstrahlung) energy is E_{recoil} , and the energy of the photons produced when the incident electron beam undergoes multiple bremsstrahlung is $E_{\gamma'}$, then the interacting photon's energy is given by

$$E_{\gamma} = E_{\text{beam}} - E_{\text{recoil}} - E_{\gamma'} \quad (12)$$

The incoming electron beam momentum, prior to reaching the radiator, is measured by inserting pairs of microstrip detector planes upstream and downstream

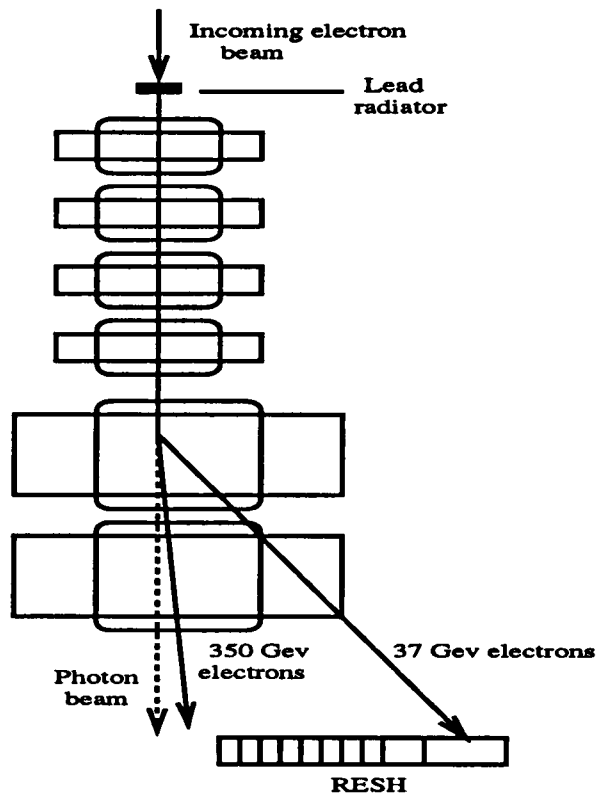


Figure 8: Schematic of Recoil Electron Tagging System.

of the already existing secondary beamline dipoles located at the position marked "A" in Figure 7. An additional plane placed in the small gap between the magnets resolves ambiguities resulting from spurious tracks. The energy of the recoiling electron after the radiator is measured with a recoil electron shower hodoscope (RESH) which consists of 10 segmented electromagnetic calorimeter modules made of lead-lucite. These modules are oriented transverse to the photon beam direction as shown in Figure 8 and Figure 9. As can be seen from Figure 9, RESH 1 is the innermost counter and RESH 10 lies furthest from the beam. The energy of the photons produced through multiple bremsstrahlung processes and that of non-interacting ones which pass through the spectrometer is measured by a Beam Gamma Monitor(1990 run) or by Beam Calorimeter(1991 run). BGM was located at the downstream end of the hadron calorimeter during the 1990 run period. It

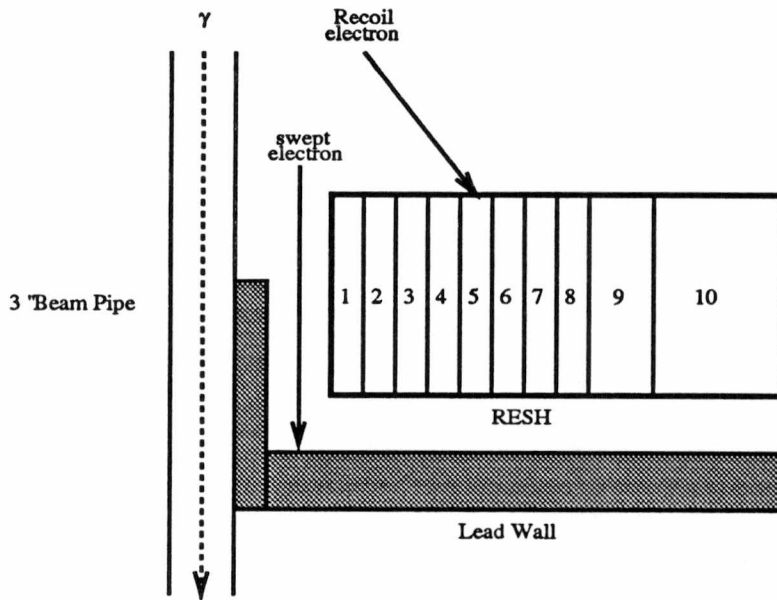


Figure 9: The recoil electron shower hodoscope (RESH).

was replaced by BCAL in the 1991 run period at the very downstream end of the spectrometer, after the muon counters. Both were centered on the photon beam.

2.2 E687 Spectrometer

The Fermilab Wideband Photon Spectrometer is schematically shown in Figure 10. It is designed for high rate capability and has large acceptance for charged and neutral hadrons, muons, electrons, and photons. The main components of the E687 spectrometer are a microstrip detection system, two analysis magnets capable of bending the tracks vertically, a proportional wire chamber system, a Čerenkov particle identification system, a muon detection system, an electromagnetic calorimetry system, and hadronic calorimeters for energy measurement and triggering purposes.

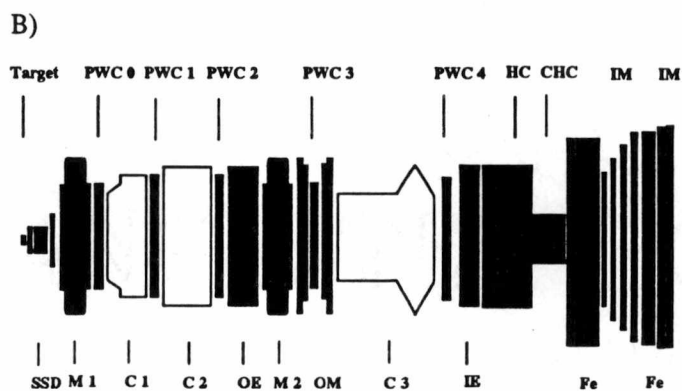
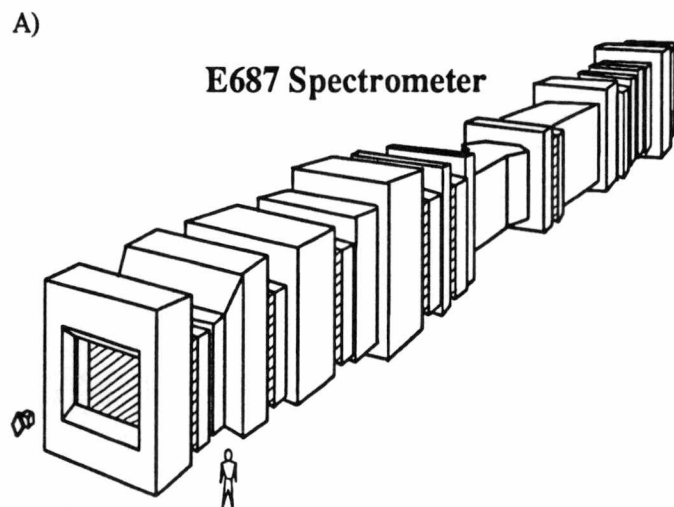


Figure 10: A) The E687 spectrometer.B) 2-dim view of the detector.

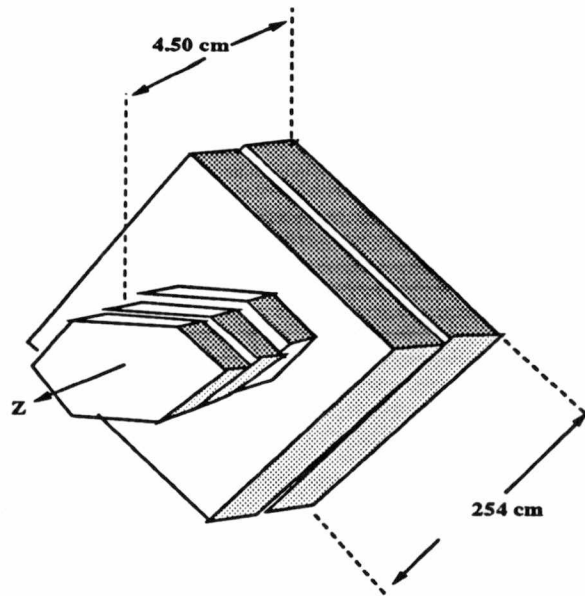


Figure 11: Beryllium experimental target.

2.2.1 The Experimental Target

Two different targets were used in the experiment during the run period: a beryllium and an active silicon target. The beryllium target was employed for the major part of the data taking. The silicon target was used for only 10% of the data taking.

The beryllium target, shown in Figure 11, is composed of five blocks, with a thickness of 8 mm each, separated by thin air gaps. The downstream three blocks have a six sided shape. This is designed to match the high resolution region of the first station of the microstrip detectors which is described in the next section. The total length of the target system is about 4.5 cm which corresponds to a radiation length of 11.5% and an interaction length of about 10%.

2.2.2 Tracking

The charged particle tracking for E687 is accomplished by two separate systems. Tracking in the region between the target and the first magnet is carried out by a system of silicon microstrip detectors (SSD) which provide good track and vertex

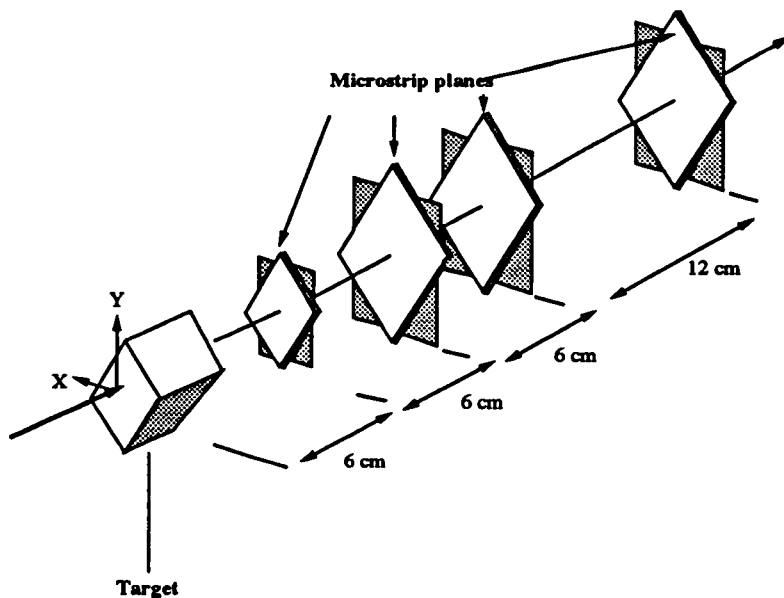


Figure 12: Silicon microstrip detector.

resolution for charged particles produced in the primary interaction and subsequent decays. A multi-wire proportional chamber system (PWC0, PWC1, PWC2, PWC3, PWC4) is used to track charged particles downstream of the two analysis magnets. This system determines the sign of the charge and its momentum.

Silicon Microstrip Detector

The silicon microstrip detector (SSD) is located directly downstream of the experimental target as shown in Figure 12. The system[72] is designed to achieve the very high position accuracy that is required to separate decay vertices of particles containing heavy flavors from the interaction vertex.

The system consists of twelve microstrip planes grouped together in four stations of three detectors. Each station has three coordinates; i , j , and k . The stations are oriented as: i at -135° , j at -45° and k at -90° with respect to the horizontal x axis of the spectrometer reference frame.

The central region of the system which covers the very forward region of the production cone has a resolution twice as good as the outer region. Most of the

energetic tracks, which are spatially quite close to each other, cross this region¹. The first station, which is most crucial in determining the extrapolated error to the production vertex in the target, has twice the position accuracy of the others. The parameters of the silicon microstrip detector system are given in Table 3. In order to ensure correct alignment, all the detectors are mounted on a high precision granite support. Each strip is read out by means of a front-end preamplifier and a charge integrating Flash ADC. The overall detection efficiency of the microstrip detector system is calculated to be greater than 99%.

Multiwire Proportional Chamber System

The multiwire proportional chamber (MPWC) system for E687 consists of 20 signal planes grouped into five stations with four planes per station. The locations of these five stations, labeled PWC0, PWC1, PWC2, PWC3, and PWC4 from upstream to downstream are shown in Figure 10 (for convenience, these stations will be referred to as P0, P1, P2, P3, and P4 respectively). P0, P1, and P2 are located between the two analysis magnets M1 and M2 with P0 just downstream of M1. There were two types of PWC chambers: the smaller aperture Type 1 chambers (P0 and P3) which are located immediately downstream of each of the analysis magnets and the larger aperture Type 2 chambers (P1, P2 and P4). Each of these two types of stations has hit information in 4 views. The X view wires measure horizontal position of a track while the Y wires measure the vertical position. The U and V view wires are rotated at 11.3° from the Y view (see Figure 13) and are used to reduce the ambiguity of the hits.

The Type 1 stations have an active area of approximately 30 in. $\times$ 50 in. The anode wires are 0.8 mil diameter gold-plated tungsten with a wire spacing of about 80 mils and with an anode-cathode halfgap of 0.235 in. Cathode wires are made of 2.5 mil diameter Cu-Be. The Type 2 stations have an active area of 60 in. $\times$ 90 in. The anode planes are 1.0 mil gold-plated tungsten wire with a spacing of 120 mils and a halfgap of 0.240 in. The cathode wires are made of 3.5 mil Cu-Be.

¹These tracks are less affected by the Multiple coulomb Scattering.

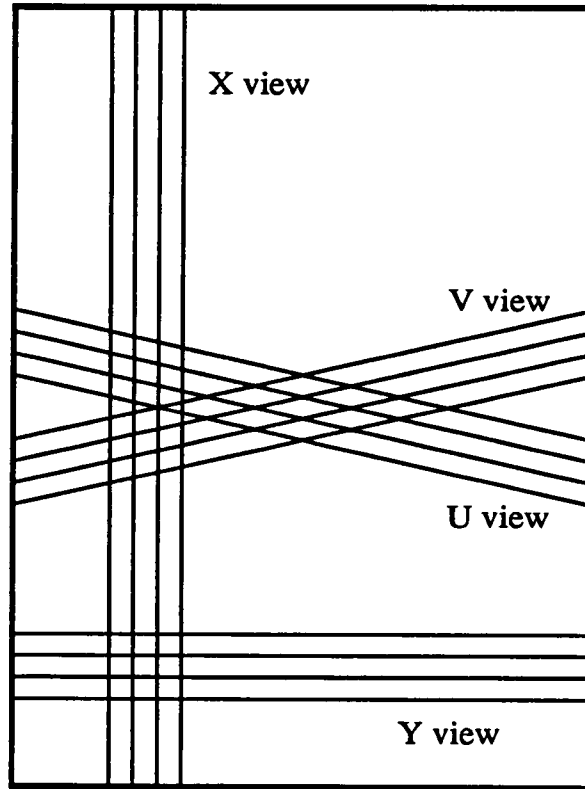


Figure 13: Orientation of PWC wires Looking downstream.

Table 3: Silicon Microstrip Detector parameters.

Station	No.channels	Active area (cm ²)	Center region (cm ²)	Pitch (inner) (μ m)	Pitch (outer) (μ m)	Z position (cm)
1	2064	3.5×2.5	3.5×1.0	25	50	4.6
2	2064	5.0×5.0	5.0×2.0	50	100	10.6
3	2064	5.0×5.0	5.0×2.0	50	100	10.6
4	2064	5.0×5.0	5.0×2.0	50	100	28.6

The entire PWC system for E687 consists of a total of 13424 instrumented wires. A 65/35 argon-ethane gas mixture is used for the system. The mixture is bubbled through ethyl alcohol at 0°C before being distributed to the chambers. Using this gas mixture, operating voltages of 3.30-3.50 kV for Type 1 planes and 3.00-3.30 kV for Type 2 planes produced good efficiency.

Signals from each anode wire are amplified and discriminated by preamplifiers mounted on the chambers. Type 1 chambers use eight channel preamplifier cards with single-ended MECL II outputs, while the Type 2 chambers use 16 channel preamplifier cards with complementary MECL 10K outputs. The signals from the preamplifiers after discrimination are sent to the counting room via 200 to 350 ns delay cable where they are reshaped before being sent to the LeCroy 4290 TDC system. This system recorded time information for every wire using the common stop mode. Once the signal is digitized, it is read out through a TDC readout controller. This controller reformats the information and sends it to a LeCroy 1892 buffer memory. The required time for a complete readout cycle is approximately 300 to 400 μ s for a typical hadronic event.

Analysis Magnets

Momentum analysis of charged tracks is carried out by measuring their deflection in two large aperture dipole magnets (M1 and M2). The two magnets are identical except for the details of the magnetic shield plates on their ends. The charged tracks are bent vertically in the field. The maximum p_t kick of the magnets is about 1 GeV/c. M1 is operated at a p_t kick of 0.4 GeV/c and M2 at 0.85 GeV/c with M1 and M2 bending the tracks in opposite directions. The ratio of the kicks is arranged in such a way that charged tracks return to their initial undeflected position toward the downstream end of the spectrometer, near the inner electromagnetic calorimeter (IE). This particular arrangement thus provided an essentially unchanged beam profile at the end of the spectrometer. Table 4 summarizes the magnet parameters.

Table 4: Analysis magnet specifications.

Central field	14.0 kG
Max. p_t kick	0.97 GeV/c
Total length	104 in
Aperture	30" $\times$ 50"
Max. current	2500 A

2.2.3 Čerenkov system

The charged particle identification is accomplished in part by three multicell threshold Čerenkov counters labeled C1, C2, and C3 in Figure 10. Used together, these three counters provided identification of charged particles with momenta in the range of 6 to 116 GeV/c. The characteristics of the counters are shown in Table 5. Counter C1 provided information for medium momentum tracks, C2 for lowest momentum tracks, and C3 for the highest momentum tracks. The Čerenkov light produced in the cells by particles traveling faster than the speed of light in the refractive gas media is reflected off mirrors, situated at the downstream ends of the counters, into light collection cones. The captured light is then directed to the photomultiplier tubes (PMTs) which are mounted well away from the beam. Signals from the PMTs are read into both a latch system and the LeCroy 1885 Fastbus ADC system for digitization. From the digitized ADC pulse heights of the cells and from the momentum information of the particles, possible particle identification hypotheses were derived.

2.2.4 Calorimetry

E687 has both electromagnetic and hadronic calorimeter systems in order to measure the energy of charged as well as neutral particles. The electromagnetic energy deposited is measured by two lead-scintillator calorimeters: the "Inner Electromagnetic" or IE calorimeter covering the small angle region; and the "Outer

Table 5: Čerenkov counter properties.

Counter	Gas	Threshold (GeV/c)			Number of cells
		pion	kaon	proton	
C1	He-N ₂	6.7	23.3	44.3	90
C2	N ₂ O	4.5	16.2	30.9	110
C3	He	17.0	61.0	116.2	100

Electromagnetic" or OE calorimeter covering the wide angle region. The hadron calorimetry covers only the inner detector. This region is covered by two separate devices: the main Hadron Calorimeter (HC) and the Central Hadron Calorimeter (CHC).

Electromagnetic Calorimeters

The IE provided the γ and e detection for the angular region of 2 mrad to 26 mrad in the X and Y direction respectively. It is located approximately 24 m downstream from the target and has lateral dimensions of 122 cm $\times$ 122 cm. The IE calorimeter consists of thick sheets of lead interleaved with planes of circular scintillating fibers. A central aperture of 10.2 cm $\times$ 10.2 cm in IE allows noninteracting particles from upstream to pass through and strike the BGM/BCAL at the end of the spectrometer. The OE, located about 9 m from the target, has an angular acceptance of 28 mrad to 142 mrad in the X direction and 49 mrad to 114 mrad in the Y direction for neutral particles coming from the target region. The OE consists of alternating layers of lead absorber and plastic scintillator detector. They are oriented in alternating X-Y directions in order to determine the actual position of the shower. It's external dimensions are 255 cm $\times$ 205 cm, with an internal rectangular aperture of 51 cm $\times$ 88 cm which allows particles to enter the inner part of the spectrometer.

Both the IE and OE signals are read out through PMTs and are digitized by LeCroy 1885 Fastbus ADCs.

Hadronic Calorimeters

The main Hadron Calorimeter (HC), located downstream of the IE, is an iron gas sampling calorimeter covering an angular region from 5 to 30 mrad. It consists of 28 planes of 1.75 inch thick iron and 28 sense planes interleaved between the iron planes for a total of 8 interaction lengths. There are proportional tubes connected to each of the sense planes which are read out through capacitive pads. The pads are put together in 8 concentric circles with each circular section containing 24 pads as shown in Figure 14. The whole calorimeter is separated into three sections along the beam line with pads in each section ganged together longitudinally to provide a tower geometry. The central part of HC had a 6 inch diameter hole which allows the noninteracting particles to pass through. The HC served two main purposes:

1. to provide a trigger for hadronic event energy above a specified threshold value thereby rejecting electromagnetic events.
2. to measure hadron energy deposited in case of multi-hadronic events.

The other hadronic calorimeter is the Central Hadronic Calorimeter (CHC) which covers the central 5 mrad of the spectrometer. CHC is located downstream right after the BGM and before the muon filter during the 1990 run period. The BGM was removed during 1991 period and the CHC was placed immediately after the HC. The counter consists of 16 planes of 1.5 inch thick depleted uranium, sandwiched between two 3/32 inch thick iron pieces interspersed with polystyrene scintillator detector. The whole calorimeter is about 6.4 interaction lengths long. The scintillators are read out through PMTs. The CHC is also used in the hadronic energy trigger.

2.2.5 Muon System

The spectrometer has two muon systems[73]: one to identify muons produced at less than 40 mrad, known as Inner Muon system (IM), and the other for wide angle

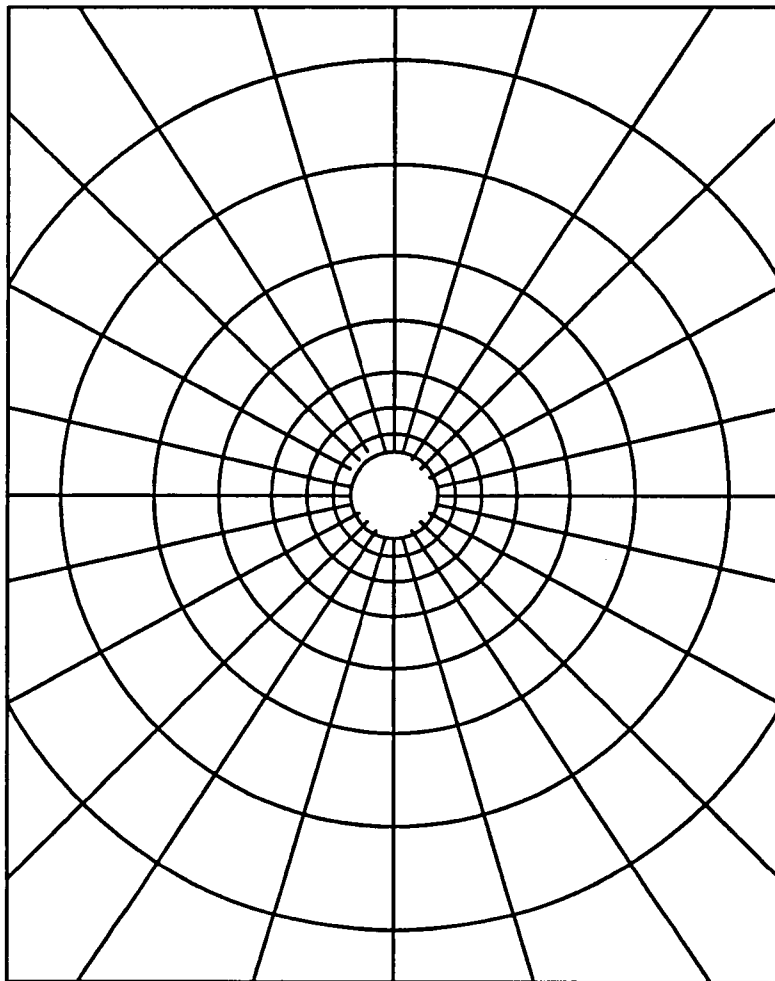


Figure 14: The hadron calorimeter pad arrangement.

muons extending to 125 mrad called Outer Muon system (OM). IM is located at the downstream end of the spectrometer and OM at the downstream end of the analysis magnet M2 (see Figure 10). The inner muon detector consists of two slabs of iron absorber with three scintillator hodoscope planes and four planes of proportional tubes. The outer muon system has an iron absorber which is the iron of magnet M2 with two scintillator hodoscope planes and two proportional tube planes. The fast muon identification information used for triggering purposes is provided by scintillation hodoscopes mentioned above mounted behind M2 (called OMV and OMH) and those mounted behind the muon filter steel downstream of the HC (called IM1V, IM1H, and IM2H). The proportional tubes are used to localize the muon trajectory.

2.2.6 Triggering System

One of the major problems in photoproduction experiments is the high rate of e^+e^- pair production relative to hadronic production. For the typical luminosities achieved during the E687 experimental run, the pair production rate would be such that the Data Acquisition system (discussed in the following section) could be overwhelmed. The main objective of a triggering system is to effectively reject such electromagnetic events while efficiently retaining the hadronic interactions. Triggering in E687 was accomplished in a two step process. The first level is a fast trigger named the MASTER GATE. The next level is a higher level trigger, known as the Second Level Trigger, which operates on latched signals and pulse heights from various parts of the spectrometer which are integrated and stored when the Master Gate occurs.

Master Gate

The Master Gate is designed to detect the presence of two charged tracks in the spectrometer while rejecting events with only e^+e^- pair conversions. A large portion of the events which are electromagnetic in nature are vetoed with this trigger with minimal biases. The Master Gate is derived from logically combining

signals from several scintillation counters. A brief description of each of these counters (see Figure 15) is given below:

1. A0 and A1. These were small scintillator counters placed directly in the experimental photon beam line before the target. They served the purpose of suppressing charged particles in the beam by vetoing against them. They also ensure that the photon initiates the interaction in the target.
2. TM. TM consists of two counters TM1 and TM2. It is situated at about 2.5 meters upstream of the experimental target. Both these counters are used to veto against muons in the halo associated with the beam.
3. TR1 and TR2. Both these scintillator counters are located inside the target hut. They detect the presence of a charged particle from the target. The smaller counter TR1 is mounted directly in front of the first station of microstrip planes while TR2 is placed immediately downstream of the last station of the microstrip planes.
4. OH Hodoscope. This scintillation counter is mounted on the upstream face of the OE calorimeter and consists of 24 scintillator paddles joined horizontally. OH fires on wide angle tracks not going through the aperture of magnet M2.
5. H×V Hodoscope. This counter consists of 24 horizontal scintillator paddles and 12 vertical scintillator paddles in two different sections separated by about 7 cm. It is placed just downstream of the PWC plane P4. It is designed to detect the presence of one or more charged tracks outside of the pair-region. The logic module accepting the signals from this counter interprets the hit pattern on the paddles for consistency with one or two track crossings.

The Master Gate logic is then formed using the signals from individual scintillator counters and the one used for about 70% of the run was:

$$MG = (TR1 \cdot TR2) \cdot \{ (H \times V)_{2body} + OH \cdot (H \times V)_{1body} \} \cdot \overline{(A0 + A1)}$$

Approximately for 20% of the run, the veto counters TM1 and TM2 were used in addition to A0 and A1. For the remainder of the run, the veto was chosen as $\overline{(A0 \cdot A1)}$ instead of $\overline{(A0 + A1)}$.

Second Level Trigger

It is not practically possible to record every event satisfying the Master Gate. We have to take into account the dead times of the detectors, data acquisition rate limit, processing times and data storage facilities. In order to simplify the problems, several Second Level Trigger sets are used based on specific physics goals. Most of these triggers are formed using factors such as event energy detected in the HC, the presence of certain amount of energy deposition in the RESH, two muon detection, prescaled e^+e^- pairs, etc. An event which satisfied the Master Gate starts the readout and processing of individual detector pulse height information the results of which are then latched into "buslines"-signals. Higher level logical selections could then be made from these signals. The second level decision is made within about $1 \mu s$ after the Master Gate. Some of the Second Level Trigger sets are: Energy Trigger, Inner-Inner and Inner-Outer Muon, Pair Trigger, and Master Gate. The Energy Trigger, which is used predominantly throughout the experimental run, requires that the following conditions be satisfied:

1. The hadronic energy of the event, which is the sum of HC and CHC energy, be greater than 35 GeV.
2. A minimal presence of RESH energy.
3. At least one hit outside the central pair region in the chamber P0.

The two Muon triggers are used in order to study the J/ψ production and the Master Gate and Pair triggers are designed for efficiency and normalization studies. If an event did not satisfy any of the Second Level Trigger sets, then a fast clear is issued and the Data Acquisition System (DAQ) is reset and readied for a new Master Gate event.

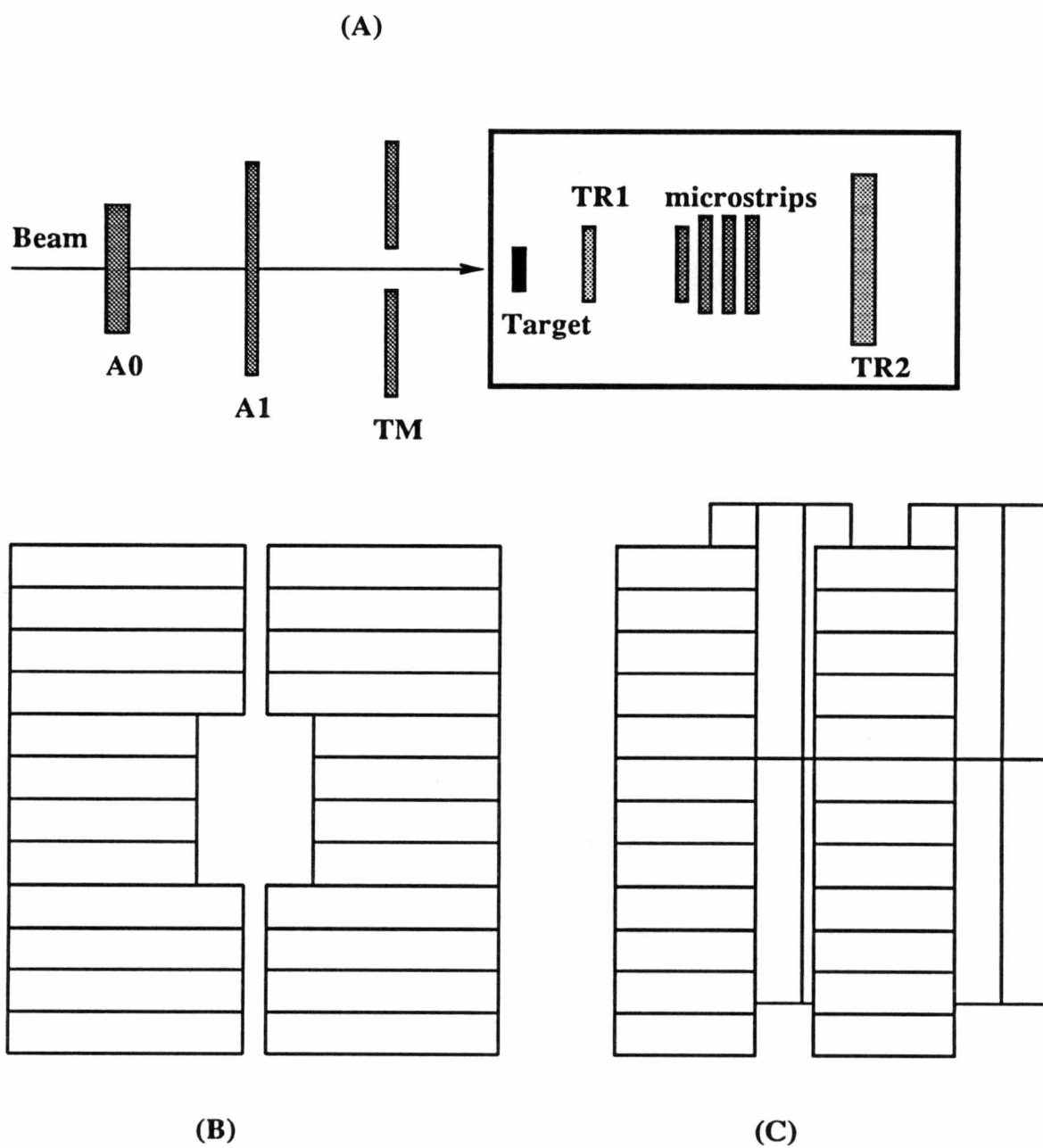


Figure 15: A) MG counters in target region. B) OH counter. C) H $\times$ V counter.

2.2.7 Data Acquisition

The beam for the experiment is delivered in *spills* of 20 seconds duration. Each such spill is followed by a 40 second interval called *inter-spill* period during which no beam is delivered to the experimental hall. At the beginning of each 20 sec beam spill, the DAQ system is set for accepting events. The Master Gate is generated approximately 300 ns after an interaction has occurred in the target. The Master Gate then initiates latching or digitization of the signals from various detectors as well as the Second Level Trigger formation. The analog signals from the detectors are recorded by LeCroy 1185 ADC's, LeCroy TDC's, Milano MIDA ADC's, and latches made by Fermilab. An artificially generated dead time of about 1 μ s is created after the Master Gate which allows the Second Level Trigger electronics to make a decision without forming any additional Master Gates. If the second level logic is not satisfied, a fast clear is sent out to all the recording modules and the DAQ system is reset for a new Master Gate event. If an event meets the Second Level Trigger requirement, the readout of all the digitized detector signals and latches is initiated. These signals are read out into four Fastbus memory buffers. During the readout, a busy signal is generated which prevented new Master Gates and Second Level Triggers. Once the signals are read out into the buffers, the busy signal is dropped and the electronics are reset for the next event. The contents of these memory buffers are read out with "PANDA", a specialized data acquisition system run on a local DEC VAX computer, which concatenates the data, adds run, spill, and event identifiers and write the event to Exabyte 8 mm tapes. Since no beam is available during the inter-spill cycle, this gives the DAQ enough time to finish the procedure of logging data to the tape before the next spill cycle arrives. Up to four Exabyte 8200 8 mm tape drivers are used in parallel to write the data to tapes. Typically 3000 to 4000 Second Level Triggers are recorded for each 20 second spill time. During the data taking, monitoring, run control, and online event display programs are run through a UNIX Hoist. Several SUN and DEC workstations are employed to run this on-line software through the

Hoist. A database system keeps track of the ADC pedestal responses and any geometrical changes in the detector subsystems. An outline of the DAQ system for the experiment is depicted in Figure 16[74].

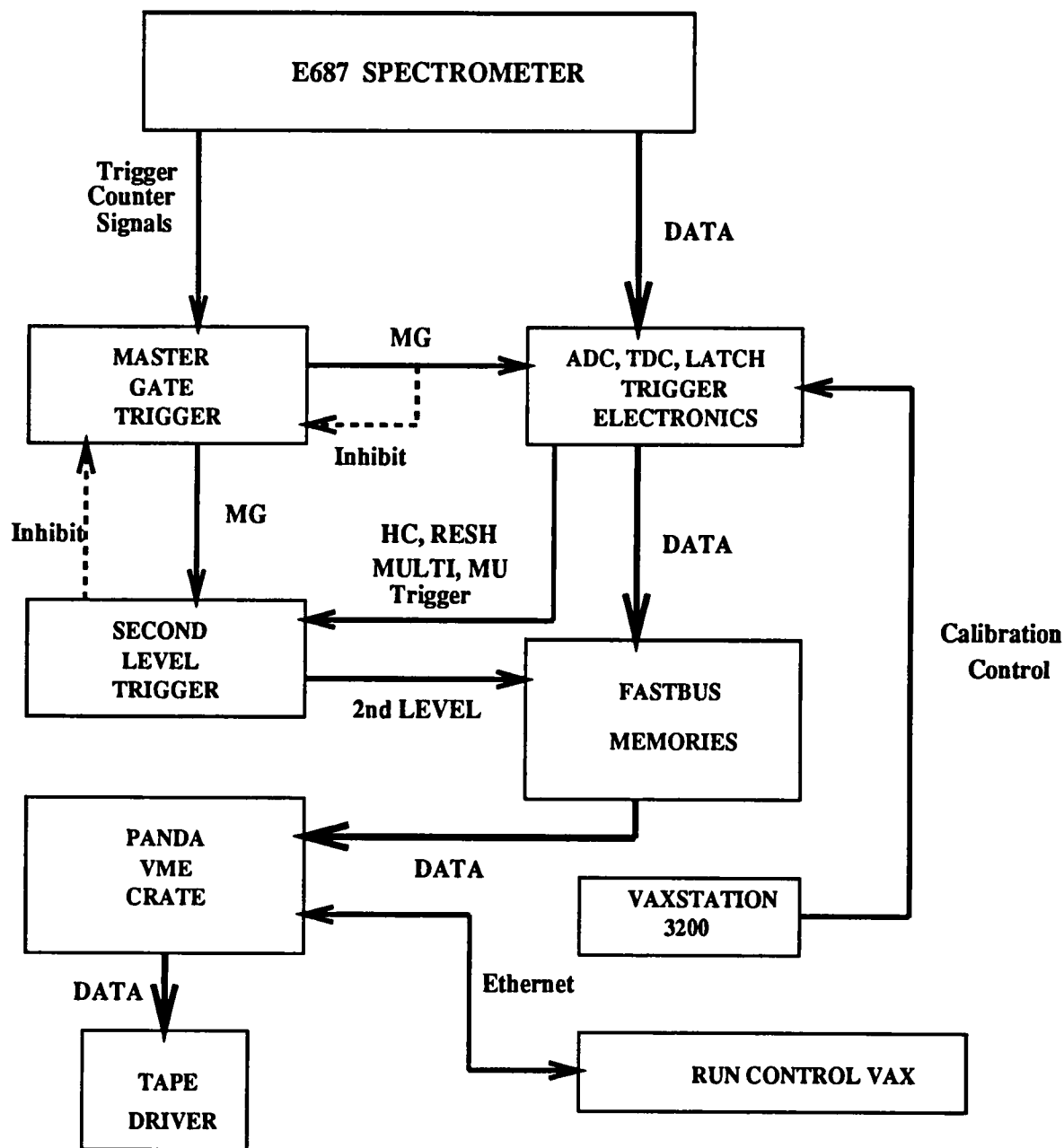


Figure 16: E687 Data Acquisition System.

Chapter 3

Data Reconstruction and Reduction

This chapter is an overview of the techniques used for the data reconstruction and reduction including tracking, neutral vee reconstruction, particle identification, and vertex reconstruction. The data used for this work came from the 1990 and 1991 fixed target runs. A total of about 500 million triggered events were written onto the magnetic tapes during these two separate runs. Each of these events contained digitized ADC and TDC pulse height information from the detectors and also the latched trigger bits. The general E-687 data reconstruction and reduction scheme consisted of the following steps:

1. The first step was to process the “raw” data tapes and convert them into the so called “reconstructed” tapes. This was achieved through the E-687 reconstruction program package known as PASS 1. This package of routines produced the reconstructed tapes in which information such as particle trajectories, momenta, and identification codes were embedded by means of performing the following analyses:
 - Microstrip track reconstruction.
 - PWC track reconstruction.

- Microstrip and PWC track linking.
- Vertexing.
- Neutral vee finding.
- Čerenkov particle identification.
- Muon identification.
- Calorimetry data reduction which includes RESH analysis, BGM or BCAL analysis, IE and OE calorimeter analysis and Hadron calorimeter analysis.

This reconstruction procedure was carried out on the Fermilab ACP (Advanced Computer Project) farms which are basically several RISC UNIX workstations running under a Cooperative Process Software called CPS. The procedure took about 10 months to complete for the combined 1990-1991 data tapes. About 25% of the original data was lost in this special reconstruction procedure due to problems such as tape read errors, etc.

2. Following the PASS 1 reconstruction procedure, a “skimming” of the reconstructed data was performed. This was carried out in order to subdivide the data sample into smaller sets based on physics criteria and also to reduce the data sample to a manageable size. During the skimming phase, various physics states were edited from the reconstructed data sample and written out to new sets of “skim” tapes.

The physics analysis of the present work was done using the above mentioned highly compressed data summary skim tapes.

3.1 Reconstruction of the Tracks

The track reconstruction was achieved through a multi-step process which made use of tracking information from two separate detector systems: the Microstrip

detector system (SSD) and the PWC detector system. The raw responses from these two detectors were first analyzed through independent procedures. Then the fitted track parameters from the two systems were linked together thus providing specifications regarding the complete trajectory of charged particles passing through the spectrometer.

The track reconstruction analysis dealt with four main categories of tracks:

1. "5-chamber" tracks. These were the tracks which hit chamber P0 and passed through the second analysis magnet M2. Within this category, if the track had hits in P3 but not in P4, which is the most downstream wire chamber, it was called a "4-chamber" track.
2. Stubs. These were "3-chamber" tracks which passed through P0, P1, and P2. Stubs are mainly low-momentum or wide-angle tracks striking the upstream face or the pole tips of magnet M2.
3. Unlinked SSD tracks. This category consisted of low-momentum and/or wide angled tracks which did not even pass through the first analysis magnet M1.
4. "Vee" tracks. This included tracks from decays downstream of the first chamber which did not register hits in P0. These were mainly from neutral vees decaying into two charged tracks between P0 and P2 and neutral vees decaying between P3 and P4. Another source of such a track could be from track segments which join with other track segments with a finite angle between them-so called "kinks".

The major points in reconstructing the tracks from SSD and PWC systems are discussed below.

3.1.1 Microstrip track reconstruction

The approach to microstrip tracking is based on a projection finding algorithm in the three separate views, the efficiency of which critically depended on the degree of parallelism among the different planes of the same view.

The first step was to analyze the validity of the hits based on the amount of charge they released in the strips through ionization. This was done to reduce the dimension of clusters of adjacent hits. The final positions of hits were based on the interpolation of the deposited charge on the strips. Projection finding was then performed with wide cuts. Each projection was required to have at least three hits per view. Hit sharing was allowed among the projections, with the exception that the three downstream hits of four-station projections were not made available to projections having only three hits. Projections are then formed into tracks provided they match in space. These tracks were kept if they have a global χ^2 per degree of freedom lower than a certain value. If the space tracks shared one of two projections, they were arbitrated on the basis of their χ^2 values. At this point those hits which did not fall into the class of the reconstructed space tracks were used for the purpose of identifying wide-angle or highly multiple coulomb scattered track segments.

As a result of employing such a conservative arbitration in the reconstruction algorithm, clusters of very closely spaced tracks were often generated. These were later eliminated and reduced to single equivalent tracks on the basis of the number of shared hits and their degrees of freedom.

The efficiency of this tracking algorithm as a function of track momentum was evaluated to be greater than 99% at 10 GeV/c, and 90% at 2.5 GeV/c. This was determined through a Monte Carlo simulation of the microstrip system which included both live and dead strips.

3.1.2 PWC track reconstruction

Two major classes of tracks were considered by the PWC track reconstruction program: 5 or 4-chamber tracks and "stubs", which are tracks passing through 3 chambers. In each case a track is required to have hits in the first chamber, P0. The stubs are formed from hits in the first three chambers, P0, P1, P2.

The tracking program formed projections from hits in all four views, X, Y, U and V. The U, V and Y view projections were done by making use of the PWC information alone while in the X view, hits were formed from the SSD "seed" by searching for PWC hits which match the SSD track extensions. The projections were then followed by a matching of them to form three dimensional space track candidates. X-hits not selected by the extended microstrip tracks were then matched with unused U, V, and Y projections to form additional tracks.

A least squares fit was performed on all candidate tracks. The fit parameters were the intercepts and slopes of the track in both X and Y views at the M2 bend plane. In the case of 5-chamber tracks, the bend angle through M2 was the parameter of fit. A χ^2 per DOF cut was applied to each of the tracks to pass the fit. The tracks were not allowed to have more than four missing hits among all the PWC chambers and also no more than two in any chamber. As in the case of SSD tracking, arbitration between tracks with shared projections had to be done.

Apart from this main routine, several additional tracking routines were designed to recover track topologies that were overlooked. These include linked and unlinked SSD tracks with hits in P0 and P1 only, and 3-chamber extensions into P3 and P4. In addition, a microstrip extension algorithm was used to recover the low momentum tracks which pass through M1 and exit the PWC system before passing through at least three chambers.

Monte Carlo generated tracks were used to study the efficiency of the PWC tracking algorithm. The overall efficiency was determined to be greater than 98% for tracks with momentum greater than 5 GeV/c. Spurious reconstructed tracks occurred at the 0.5% level with this algorithm. A limit of 30 was set on the number

of charged tracks per event in order to reduce the time for reconstructing an event.

3.1.3 Microstrip and PWC track linking

Linking is the process of matching the PWC tracks to the SSD tracks. This procedure is important in the data analysis since the reconstructed PWC tracks are often not of high enough spatial resolution to resolve some of the interesting decay vertices. However, the SSD tracks are very precise but they do not have momentum assignments and thus cannot be used to analyze quantities such as invariant mass etc. Linking the tracks thus provided the momentum information for tracks recorded in the microstrip detector which then passed through M1 into the spectrometer. For some categories of tracks, the use of the microstrip segment in the momentum calculation improves the track momentum resolution. A knowledge of the track momentum is essential in order to calculate accurately the vertex resolution on an event-by-event basis. It is also necessary to achieve high resolution for the impact parameters at the target and for the z coordinates of the interaction point and of any secondary decay vertices. A failure in linking some PWC tracks could also be significant in some cases since these could be candidates for vee and kink decay products.

Linking was carried out by comparing the extrapolated positions of SSD and PWC tracks at the bend plane of M1. Here, differences between slopes and intercepts between the candidate links are calculated in X and Y views. A certain number of wire spacings in each view were set as windows for the link. Combinations falling within the specified windows were then subjected to a global least squares fit using all the hits from the SSD and from the PWC. In order to allow proper linkage of Bethe-Heitler pairs created in the target or microstrips, the algorithm allowed an SSD track to link to two PWC tracks but not vice versa. Thus PWC tracks could only link to a single SSD track.

The charged particle momentum was determined by measuring the deflection of the tracks in the magnetic field of M1 or M2. The momentum was accurately

determined for linked tracks using M1 since the SSD reconstructed tracks provided higher resolution. M2 was used in the case of unlinked, 5-chamber tracks.

3.1.4 Vertex reconstruction

Since the major physics goal of the E687 experiment was to study states containing heavy quarks, it was necessary to maximize the ability to separate tracks coming from the primary interaction vertex from those coming from secondary decays which occurs a distance of the order of a few hundred microns downstream. The silicon microstrip detectors provided the experiment a very efficient way to separate tracks that originate from the primary vertex from those coming from a secondary decay. Two different and complementary vertexing algorithms had been used for the purpose of reconstructing the vertices. A “stand alone” algorithm which uses only the microstrip information to determine vertex assignments and an independent “candidate driven” algorithm which makes use of a charm candidate as a seed to find the primary vertex. The stand-alone algorithm was implemented as a part of the PASS-1 analysis package while the candidate driven algorithm was used at the SKIM level and subsequent analyses. Only the “stand alone” technique is discussed here.

Stand Alone vertex algorithm

This algorithm attempts to reconstruct the whole vertex topology of the event by operating in a “stand-alone” fashion where none of the downstream information such as the momentum of linked PWC tracks was used. It begins with the hypothesis that all tracks belong to a single vertex and then uses an iterative procedure to remove tracks giving the single largest χ^2 contribution until an acceptable χ^2 is obtained. The algorithm then proceeds to utilize the removed tracks to form additional vertices. A track that is not assigned to a vertex is not used in the subsequent analysis.

Since this technique did not make use of a specific decay mode, it was able to pick up decays with missing neutrals. Furthermore, no biases were introduced into

initial selection of candidates by assumptions about final states. The built-in bias of this algorithm towards including poorly separated tracks in the primary vertex resulted in the loss of poorly resolved secondary vertices. But the background was effectively reduced in such a process. The stand-alone technique becomes inefficient for short lifetime neutral decays as the decay vertex is unlikely to be resolved from the primary vertex.

3.1.5 Reconstruction of Neutral Particles

Neutral particles (such as K^0 's, Λ^0 's, etc.) decay into two charged prongs (hence the name "vees") and usually could be detected in the PWC and/or the SSD. By virtue of their longer mean lifetime (compared to neutral particles such as ρ^0 , ϕ , etc), a typical vee decays downstream of the SSD. Thus all unused tracks that intersect in pairs downstream of the target were analyzed for possible decay products whose origin was a neutral particle such as a K^0 or Λ^0 . The PASS-1 phase of the data reduction process dealt with four general decay regions of these "vees":

1. *SSD vees* which decay upstream of the microstrip detector. This category of neutral particle decays were found by looping over pairs of linked tracks having zero net charge and fitting for their vertex. In order to reduce the number of such candidates to a reasonable level, these secondary vertices were required to be greater than $20 \sigma_z$ from the primary vertex and point back to within 1 mm of the primary in the transverse direction.
2. *MIC vees* which decay inside the microstrip detector. This particular region was dealt with by an algorithm which took the unlinked PWC tracks and extrapolated them back into the SSD detector. The fourth SSD station was used as the "seed" station and all unused triplets in this region are tested with the candidate PWC extrapolated track. If a triplet was matched with a PWC track in such a test, the parameters of the track were recalculated.

Such a passed track was then projected upstream to the next SSD station where the search for unused triplets was continued. Since, for each candidate PWC track, more than one candidate triplet (or pair of triplet) may be found, arbitration among these triplets was based on the χ^2 from a global fit to all hits associated with the track. All combinations of pairs of candidate tracks with opposite charge were then tested for “distance of closest approach” (DCA), and an appropriate cut was made based on DCA hypothesis. This cut removed almost all the spurious tracks. If a candidate track still made more than one combination, only the one with minimum DCA was retained.

3. *M1 vees* decayed between the SSD’s and the PWC chamber P0. These generally fell into three subcategories:

- *Track-Track vees* which were built of two 5-chamber tracks.
- *Stub-Stub vees* which were formed of two 3-chamber tracks.
- *Track-Stub vees* which paired a 5-chamber track with a 3-chamber one.

The basic idea of the algorithm was the same for all three topologies. The X-view was used to get an estimate of the x-z location of the vee vertex and an iterative procedure based on the particle tracing formalism was used to determine the y coordinate of the vertex and the momentum of all non-5-chamber tracks. A fit employing the full covariance matrices of the tracks was then applied to the candidates from all three topologies. The resulting χ^2 per DOF then indicated how well the vee candidates satisfied the neutral decay hypothesis.

4. *Reconstruction vees* decayed in the region of the spectrometer between chambers P0 and P2. No magnetic trace was required for their detection since the decay region was essentially field-free. This made the reconstruction vee pattern recognition conceptually simple. The algorithm used to reconstruct such a neutral particle decay topology proceeded as follows: the program

first searched for vees decaying between P0 and P1, then for vees between P1 and P2. Single track projections were found in the X view. The X hits were then matched up with U, V, Y hits to form track candidates followed by single track fits with a loose χ^2 cut. Tracks of opposite charge were then paired up to make the vee candidates. To achieve better vee resolution and signal-to-background ratio, these candidates were then fit imposing the constraint that the two tracks of a vee must have a common vertex in three dimensions. An arbitration algorithm was used on the candidates with an acceptable fit which insured that no X-projection was used in more than one vee.

3.1.6 Kinks

The term “kink” refers to a topology where a charged particle traverses the SSD system and then decays into a single charged track and a missing neutral particle. The decay volume is from the end of the microstrip detector system to the the first PWC chamber P0.

The kink reconstructing routines were executed after all other PWC tracking, SSD tracking, and vee routines were called. The tracks used for this reconstruction were the SSD tracks which did not link and which did not point into the M1 aperture. Vee candidate tracks were also not considered as potential kinks. An intersection in the X view of the SSD track and the main spectrometer track between the SSD and P0 determined the decay point of a successful kink candidate. Then the momenta of both the parent and daughter tracks were calculated using each of the six possible decay hypothesis that can be reconstructed from the kink topology (see Table 6). The parent and the daughter tracks were required to have the same charge and the daughter momentum had to be less than that of the parent. The X and Z positions of the decay point were at first determined by intersecting the SSD and PWC tracks in the X projection. Two separate techniques were used depending on whether the PWC track is a 5-chamber or a 3-chamber track. In the

Table 6: Topologies of KINK decays.

Particle	Mode
π^-	$\mu^- \nu$
K^-	$\mu^- \nu, \pi^- \pi^0$
Σ^+	$p \pi^0, n \pi^+$
Σ^-	$n \pi^-$
Ξ^-	$\pi^- \Lambda^0$
Ω^-	$K^- \Lambda^0$

case of a 5-chamber track the momentum of the daughter was calculated from the bend angle in M2 and the Y position of the decay was determined from the trace of the daughter track. If the decay happened in the M1 field region, the parent momentum was uniquely determined. If the decay occurred upstream of M1, then there was a two-fold ambiguity in the momentum of the parent track. In the case of a 3-chamber track the decay was required to occur in the region upstream of M1. The X and Z positions of the decay point were then determined from the intersection of the SSD and PWC tracks in the X view. The Y position was calculated from the SSD track at this Z location, and the daughter's momentum was determined by tracing the track to decay vertex. Once again, there was a two-fold ambiguity in the parent momentum.

3.1.7 Charged particle identification

Charged particle identification was achieved using several detectors of the spectrometer. Charged particles such as electrons, pions, kaons, and protons were identified using the Čerenkov system. Both the Muon system and the Hadron Calorimeter (HC) were used for the muon identification. The electromagnetic particles, electrons and photons, were identified by the electromagnetic calorimetry system.

Čerenkov Identification

Charged tracks passing through the Čerenkov counters can be categorized as either electrons, pions, kaons, protons (antiprotons) or muons (Čerenkov interprets the muons as pions). These four particles comprised the majority of all tracks emitting Čerenkov light in the experiment. They all have different threshold momenta at which they begin to radiate (see Table 5 in chapter 2). Thus, using the known momentum of a particular track in an event and the gas properties in each Čerenkov counter, a hypothesis is established concerning its light deposition in the counters for each of the four presumed identities.

The first step in the approach was to determine which cells in each of the counters were “on”. A cell was called “on” if the pulse height exceeds a threshold, typically several counts above the pedestal (minimum background level). The tracks were then projected into each of the three counters in order to determine the relevant cells for each of the tracks. The cells examined were the one struck by the track and all the adjacent cells. For each of these cells the light yield based on photoelectron calibration of the counters was calculated. The amount of light expected in a particular cell is a function of the particle hypothesis, particle momentum and the geometric overlap of the particle’s Čerenkov cone with the cell. If the actual pulse height from any cell predicted to have light emission from this track exceeds a low noise level the counter was said to be “on” for that track. If there was more than one track that could have contributed a significant amount of light in that cell or cells, the counter was flagged “confused” for that track. If the total light yield in all of the associated cells for a given track was less than half the predicted yield, the counter was flagged “off” for the track under consideration provided it was not previously called “on”. Also, the counter was set to “confused” if it was neither “on” nor “off” for a track[75]. The nature of this algorithm was biased towards calling the counter “on”, which in turn means that tracks were more likely to be assigned to light particle categories and less likely to be falsely assigned to a heavy particle category.

Table 7: Čerenkov particle ID codes.

ISTATP	Identity	Momentum(GeV/c)
0	Inconsistent	> 0.0
1	e definite	0.0 to 17.4
2	π definite	4.5 to 17.4
3	e, π ambiguous	4.5 to 61.7
4	K definite	16.0 to 44.5
6	π ,K ambiguous	16.0 to 17.4
7	e, π ,K ambiguous	16.0 to 44.5,61.7 to 117.4
8	p definite	16.0 to 44.5,61.7 to 117.4
12	K,p ambiguous	4.5 to 61.7
14	π ,K,p ambiguous	0.0 to 17.4
15	Confused	> 0.0

Once the response to a track was determined for each counter, a 4-bit particle ID word for each counter is generated based on the counter response and particle momentum. The logical AND of these three ID words from the three counters was then performed to make the final particle identification called ISTATP for each track. The various possible Čerenkov ID's and momentum ranges for their validity are given in Table 7. A scatter plot of particle momentum verses ISTATP identification from a typical data tape is also shown in Figure 17.

A certain subset of the over-specified tracks could be recovered by ignoring information from the counters which were "off" when the particle had a momentum above the proton threshold. There could be cases where the identification remains ambiguous between light and heavy particles leading to the under-specification of the tracks. The high momentum tracks were often under-specified because they exceed the highest threshold in one or more counters. Therefore, the counter thresholds determine a range for the momentum of each particle type beyond which the system was incapable of making specific identification.

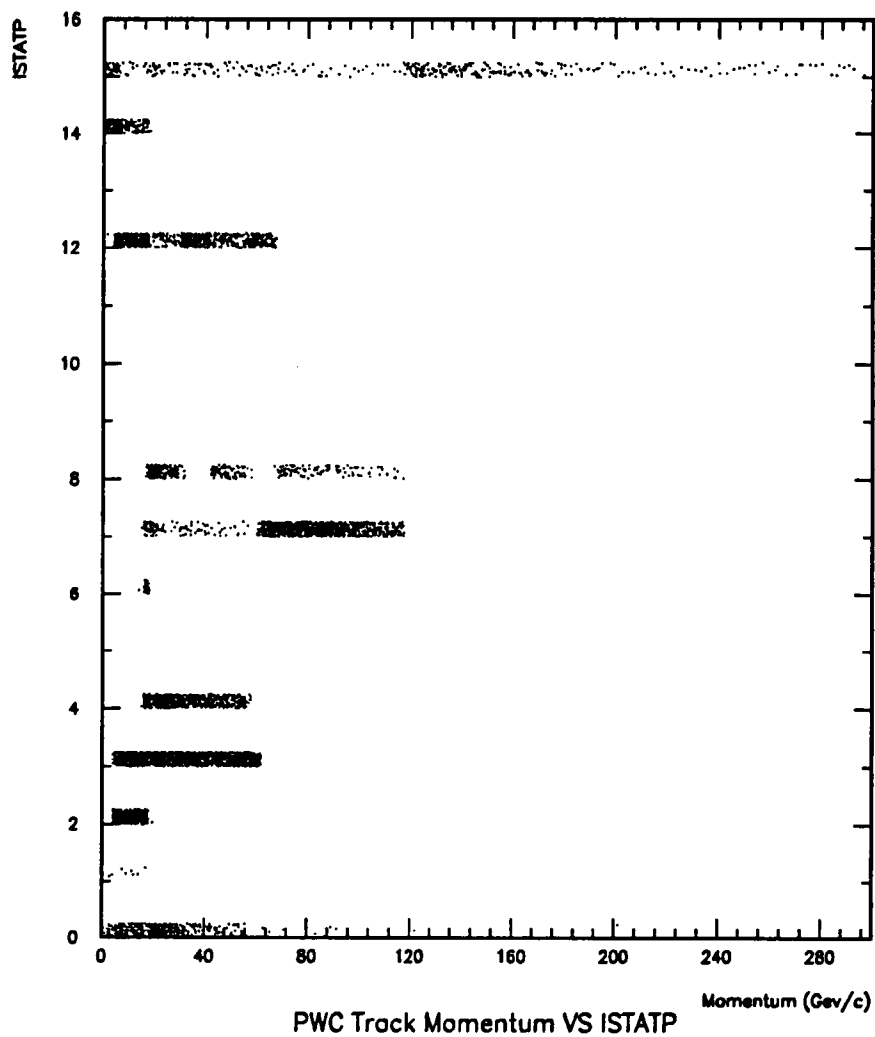


Figure 17: A typical Track momentum vs ISTATP plot.

Muon Identification

Identification of the muons was achieved by using both the muon system and the HC. The basic idea of the algorithm was to project tracks into the muon system and search for corresponding hits, taking into account multiple scattering process[77]. HC was also used for additional muon identification purposes. The tracks were extrapolated to the HC and the pattern of the hits and pulse heights for HC pads along the projected tracks were analyzed for consistency with the muon hypothesis. The efficiency for detecting muons was calculated to be approximately 84% for muons passing through the HC. This was achieved through analyzing a sample of J/ψ decaying to $\mu^+\mu^-$ events[73].

Electromagnetic Calorimetry

Apart from the Čerenkov system, additional identification of electrons was accomplished through the use of the IE and OE calorimetry systems. The algorithm projected tracks into the calorimeters reconstructing the electromagnetic showers. The ratio of the observed energy to momentum as calculated by the tracking system was required to be greater than 0.8. The efficiency studies are reported elsewhere[76].

3.1.8 Skimming

The number of reconstructed PASS1 output tapes was quite large for the purpose of certain specific physics analyses. In order to reduce the data set to a manageable sample size, several editing schemes known as “skims” were devised. In this process, sub-samples of events containing fewer background events were created while saving as many of the interesting events as possible. Some of these schemes were decay topology dependent. Others were completely general methods, where the background events were carefully removed. There were three skim categories run on the 1990-1991 reconstructed data tapes: MOM skim, QT skim, and TINY skim. The MOM skim process picked out all the major detector response blocks from the reconstructed tapes and wrote them out in a convenient format. It did

not have any specific physics oriented cuts employed. Almost all the detector information was preserved in these MOM output tapes. The QT scheme wrote out a smaller record from the reconstructed tapes but with sufficient information for most general physics analyses. The TINY skim routine had only two sets of data records written out. The QT and TINY skims had certain specific physics cuts embedded in them. A ϕ mass cut, for example, was employed in the data written out through the QT skim procedure by requiring the invariant mass of $K^+K^- \leq 1.1$ GeV. If there were more than one K^+K^- combinations present in an event, at least one pair was required to have $M(K^+K^-) \leq 1.1$ GeV.

A total of 113 QT skim tapes from the 1990 and 1991 experimental runs were used for the present analysis in this thesis.

Chapter 4

Analysis of the Data

4.1 Sample Selection

As mentioned in Chapter 3, a total of 113 QT skim tapes, 52 from the 1990 run and 61 from 1991 run, were used for this analysis. Initially, a personal subskim was run on all these QT tapes which generated a reduced event sample that could be conveniently used for later analysis purposes. Various cuts were applied through this subskim, a summary of which is given in Table 8. As shown, this subskim wrote out a total of 111,437 four track events from the combined 1990-91 QT tapes. All the physics analysis was carried out on this subskimmed data set. Additional important cuts were performed on this data during the analysis stage. The main ones of these were:

- No repeated events (“washing” the sample)
- The z of the event vertex is constrained to the target region
- The net charge of the four tracks is zero
- Partial or complete track identification from the Čerenkov system

Apart from these, cuts relevant to the reaction channel under study were also imposed. These include: (a) an opening angle cut to differentiate between $\pi^+\pi^-$

Table 8: Cuts used in the Subskimming of the 113 QT tapes.

cut #	Description of the cuts	1990 Data (52 tapes)	1991 Data (61 tapes)	Combined (113 tapes)
1	QT Events	61,828,877	64,716,015	126,544,892
2	No RESH pileup & Tagged > 0.0 GeV	21,584,038	26,904,411	48,488,449
3	$E_\gamma \geq 0.0$ GeV	20,147,702	25,209,279	45,356,981
4	1 SSD or 1 PWC Vertex	12,859,117	16,470,834	29,329,951
5	No neutral Vees and/or Kinks	7,555,737	10,028,082	17,583,819
6	$SSD_{trks} = PWC_{trks} = 4$	224,804	343,717	568,521
7	IE Neutrals=0	119,240	195,244	314,484
8	OE Neutrals=0	98,643	120,827	219,470
9	HC+CHC Energy > 5.0 GeV	87,450	109,219	196,669
10	IE/OE no e ID's	53,454	64,866	118,320
11	Čerenkov not e	51,676	62,123	113,799
12	All Tracks Linked	50,592	60,845	111,437

and e^+e^- pairs in 4π and $2K2\pi$ channels, (b) a fast ($\pi^+\pi^-$) elimination cut in the 4π sector to separate the high momentum ρ^0 's assumed to be coming from the $\rho^0 N^*$ channel¹, and (c) a t' cut, if appropriate, to choose the peripheral events. A summary of all these cuts on the subskimmed data is given in Table 9. During the Čerenkov ID cut, all tracks not positively identified as either proton, electron or kaon, except the kaon-proton ambiguous, were chosen as pions. The kaon definite and kaon-proton ambiguous tracks were chosen to be kaons. In ISTATP terms these selections corresponds to:

- ISTATP = 0, 2, 3, 6, 7, 14, and 15 *pions*
- ISTATP = 4 and 12 *kaons*

As can be seen from Table 9, 36315 events were rejected after the Čerenkov selection criterion. These belonged to four-track neutral charge events from channels

¹This will be discussed in a later section.

Table 9: Summary of all the Final Cuts imposed on the Subskimmed data. Note that all the $\mu^+\mu^-\pi^+\pi^-$ events are obtained from the $\pi^+\pi^-\pi^+\pi^-$ sample.

Criterion	Event Sample		
Initial Number	111,437		
No Duplicate Events	107,036		
z_{vtx} in Target	101,692		
$Q_{4tracks}^{tot}=0$	92,629		
Definitive Čerenkov 56314 events=A+B+C	A $\pi^+\pi^-\pi^+\pi^-$ ($\mu^+\mu^-\pi^+\pi^-$)	B $K^+K^-\pi^+\pi^-$	C $K^+K^-K^+K^-$
Čerenkov	38,327	17,484	503
Opening Angle	33,604	17,207	—
Fast ρ^0 cut	31,921	—	—

of no interest. Since the reaction channels involving pions are contaminated by electron-positron pairs that survived previous $e\pi$ discrimination cuts, the opening angle cut was employed to reduce the e^+e^- contamination in our sample. This was determined by taking the scalar product of all possible neutral pairs identified as pion tracks. The event was then selected if the angle between all the pairs is greater than 5.4 mrad. Below this angle, the pair invariant mass shows significant e^+e^- contamination. The $\pi^+\pi^-$ mass combinations from the 4π channel, before and after this opening angle cut, are shown in Figure 18. An obvious cleanup in the lower mass region is visible. In subsequent acceptance calculations for each reaction channel, such an opening angle cut, if employed, is incorporated into the Monte Carlo to account for the rejected events.

4.2 The Experimental Beam

The incident tagged electron energy, the RESH energy profile, the BGM/BCAL energy, and the interacting photon energy, as obtained from the subskimmed data

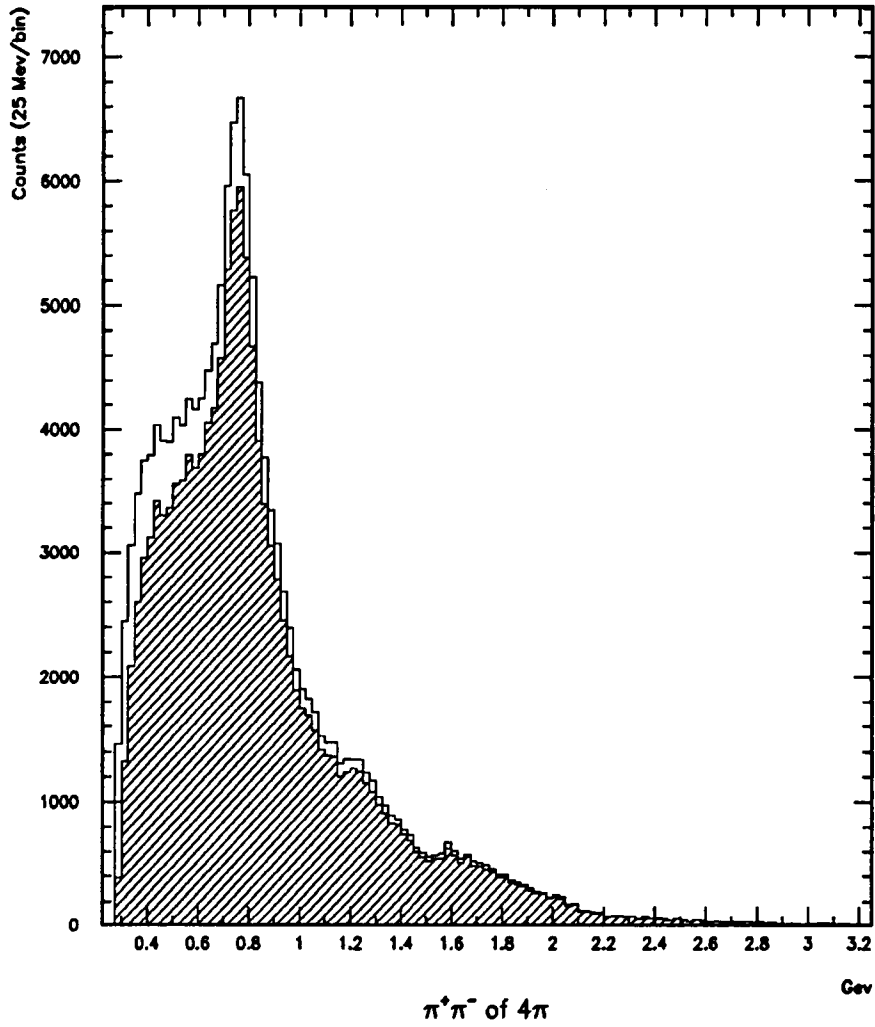


Figure 18: Effect of the opening angle cut as described in text in the dipion spectrum of the $\gamma N \rightarrow \pi^+\pi^-\pi^+\pi^-N'$ channel. The unhatched histogram is before the cut and the hatched one after the cut.

sample, are shown in Figure 19. As mentioned before, the interacting photon energy is determined from these three beam quantities. However, some events were found to have their total PWC track energy greater than the incident photon energy as determined by the tagging system. This could be mainly due to the discontinuous nature of the RESH energy profile though measurement errors associated with the BGM/BCAL counters are also not ruled out. In such cases, however, the total track energy was substituted for the incident photon energy. Since a reliable t' distribution requires reasonable information regarding the incident photon beam direction, a procedure to determine the average beam direction over the entire run period was also developed. In this method, the x and y projections of the tracks onto two separate z planes in the detector were summed on an event by event basis and averaged over the entire data set. The polar angles, θ and ϕ , were then determined from this average and were taken to represent the actual direction of the incident photon. The mean of such averaged values for θ and ϕ was calculated from various runs and was chosen as the mean direction of the photon beam.

4.3 The Analysis Channels

The following photoproduction reaction channels will be investigated in this chapter:

$$\gamma N \rightarrow \pi^+ \pi^- \pi^+ \pi^- N'$$

$$\gamma N \rightarrow K^+ K^- \pi^+ \pi^- N'$$

$$\gamma N \rightarrow \mu^+ \mu^- \pi^+ \pi^- N'$$

$$\gamma N \rightarrow K^+ K^- K^+ K^- N'$$

where N and N' are nucleons appropriate for charge conservation.

The errors involved in determining the invariant masses of the reaction channels $\pi^+ \pi^- \pi^+ \pi^-$, $K^+ K^- \pi^+ \pi^-$, and $K^+ K^- K^+ K^-$ are shown in Figure 20. The source of these errors in the invariant mass may be attributed to the finite resolution

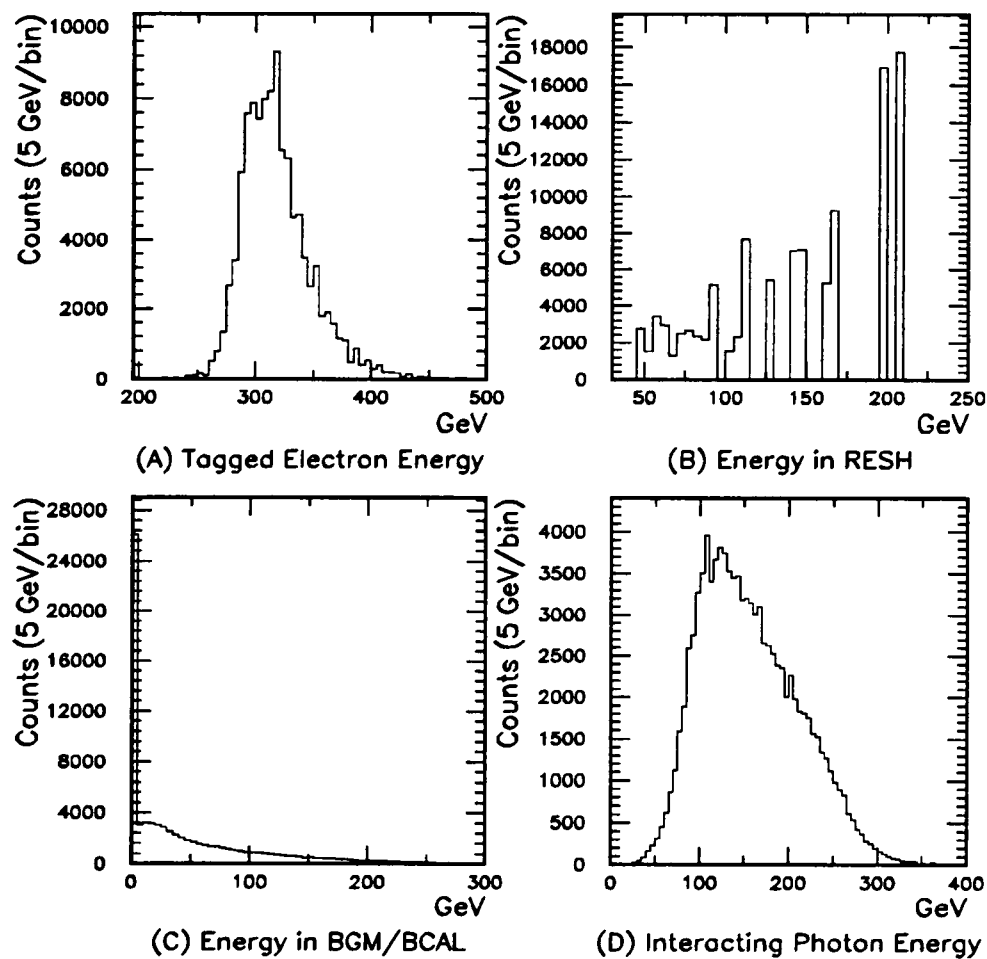


Figure 19: The Beam quantities: A) The Tagged electron energy. B) The recoil electron energy in RESH. C) The non-interacting energy as seen by BGM/BCAL. D) The interacting photon energy.

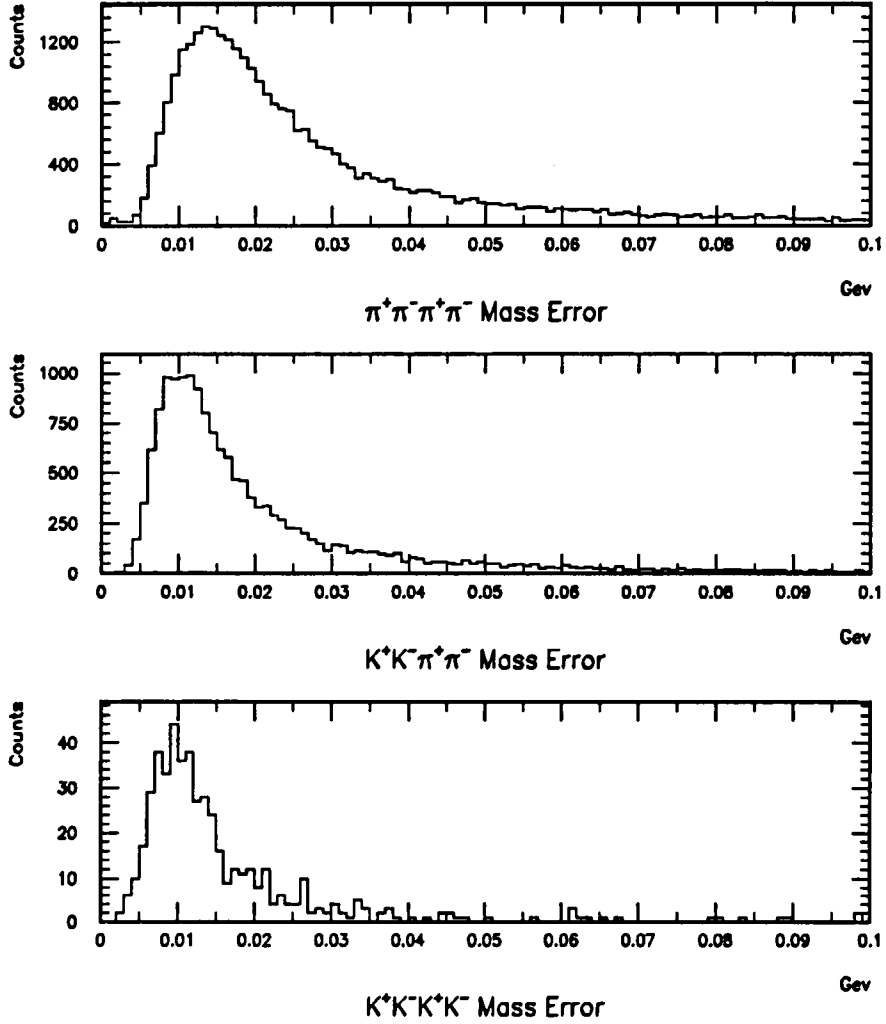


Figure 20: The mass errors in the $\pi^+\pi^-\pi^+\pi^-$, $K^+K^-\pi^+\pi^-$, and $K^+K^-K^+K^-$ reaction channels.

of the detector. From Figure 20, it can be seen that the resolution in the 4π channel is about 13 MeV, while that in the $4K$ channel is approximately 9 MeV. The resolution in the $K^+K^-\pi^+\pi^-$ sector (~ 11 MeV) appears to be intermediate between that of other two channels.

4.3.1 The $\pi^+\pi^-\pi^+\pi^-$ Reaction Channel

The $\pi^+\pi^-\pi^+\pi^-$ invariant mass is shown in Figure 21. A broad enhancement in the 1.6 GeV region, which has been historically associated with the $\rho'(1600)$, is visible. Apart from this enhancement, a narrow structure can also be seen around 2.1 GeV. A similar structure has also been reported by the TASSO collaboration at PETRA in their four pion data from the reaction $\gamma\gamma \rightarrow \pi^+\pi^-\pi^+\pi^-$ [78, 79].

The selection technique employed to obtain the mass spectrum in Figure 21 is described as follows: Events containing a neutral dipion mass in the $\rho^0(770)$ mass region, defined as $0.60 \text{ GeV} \leq \rho^0(770) \leq 0.90 \text{ GeV}$, having a lab momentum greater than 80% that of the incident photon beam are excluded from the analysis. Such a procedure should minimize the residual effects of diffractively produced inelastic $\rho^0 N^*$. (see Figure 22). The mass spectrum of these rejected 4π events containing such fast ρ 's is shown in Figure 23 where no signal is present in the ρ' region.

Figure 24 shows the $t'_{\gamma \rightarrow 4\pi}$ distribution for events in the ρ' mass region of Figure 21. The steep exponential nature of the peripheral production mechanism at low t' values is evident here. An exponential function of the form $e^{-b|t'|}$ with $b = 5.2 \pm 0.34 \text{ GeV}^{-2}$ is found to be the best fit for this t' distribution at its low values.

The broad nature of the enhancement at 1.6 GeV makes it difficult to disentangle the resonance structure in that region. Though a cut to select the low values of the t' shown in Figure 24 helped in removing some of the non-peripheral background, this was found to be less reliable than at lower energies mainly due to the uncertainty in the energy of the incident photon beam arising from the digitized nature of the RESH recoil electron response (see Figure 19(B)). Previous results on the mass and width of ρ' vary from 1.43 GeV to 1.62 GeV and 310 MeV to 650

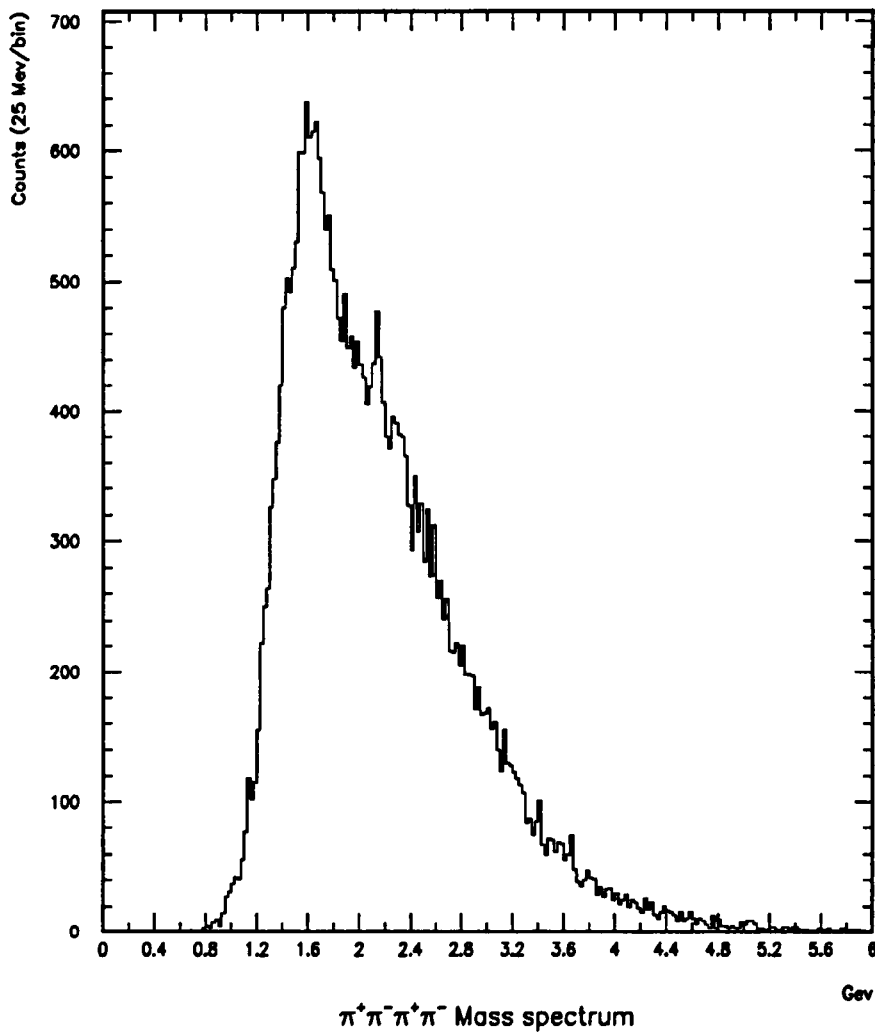


Figure 21: The 4π mass spectrum from the $\gamma N \rightarrow \pi^+\pi^-\pi^+\pi^-N'$ reaction channel. A broad $\rho'(1600)$ enhancement and a narrow peak at 2.1 GeV are seen. A cut removing fast ρ^0 was employed as described in the text.

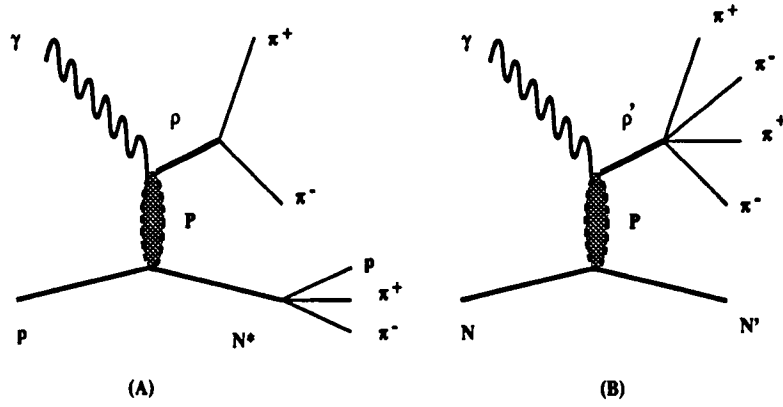


Figure 22: (A) The inelastic diffractive photoproduction of ρ^0 associated with N^* . (B) The elastic diffractive ρ' photoproduction.

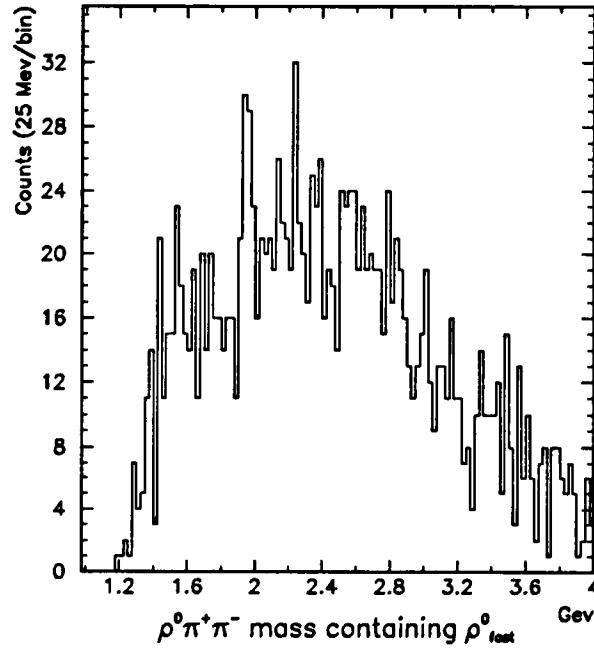


Figure 23: The $\rho^0 \pi^+ \pi^-$ mass containing 'fast' ρ^0 's in any of the dipion combinations. No significant $\rho'(1600)$ signal can be seen. These events were purged in the spectrum shown in Figure 21.

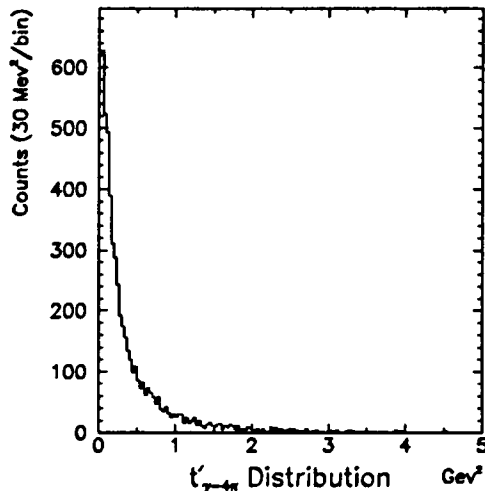


Figure 24: The t' distribution of the ρ' mass region after the fast ρ^0 cut.

MeV respectively[48, 49, 50, 51, 52, 53]. The spectrum in Figure 21 near this region cannot be described by a single Breit-Wigner shape. The $\rho'(1600)$ has also been observed in the $\pi^+\pi^-$ final state in many previous experiments[51, 58, 59, 60]. In this dipion channel, the ρ' resonance was observed above a less complicated background with a much narrower width (the width in the 4π final state averages some 100 MeV larger than the width in the 2π decay mode). Thus if the true width of the $\rho'(1600)$ is assumed to be that obtained from the dipion data, the width of four-pion distribution seen around 1.6 GeV here would indicate contributions from other than this resonance alone. The current status of this resonance was discussed in Chapter 1.

An interesting feature of Figure 21 is the presence of a narrow structure at ~ 2.1 GeV. A Breit-Wigner fit to this region with a polynomial background is shown in Figure 25. The peak is of greater than 3 standard deviations in statistical significance (3σ) and yields a mass and width of 2.145 ± 0.007 GeV and 0.045 ± 0.022 GeV respectively. These values are in good agreement with the ones obtained by the TASSO collaboration for a similar enhancement[78, 79]. No other evidence

for such a structure has been reported. Though the Particle Data Group table contains several states near 2.1 GeV, none of them has been observed to decay into four pions. In order to further investigate this narrow enhancement region for any substructural features, a region from 1.9 GeV to 2.30 GeV in Figure 25 is chosen and divided into eight 50 MeV mass bands. The dipion invariant mass in each of these bands is then plotted separately. A $\rho(770)$ signal is seen in all the plots. The signal to background ratios from these plots are then estimated by fitting each of the plots to a Breit-Wigner over a quadratic background. The resultant ratios are given in Table 10. The ratios appear to be more or less uniform, within the errors, throughout the selected 4π mass region. Thus this ~ 2.1 GeV enhancement in the 4π mass spectrum does not appear to possess decay channels that involve the $\rho(770)$'s.

The neutral dipion subsystem of the $\gamma p \rightarrow \pi^+\pi^-\pi^+\pi^-p$ channel is strongly dominated by ρ^0 production as can be seen in Figure 26. Signals corresponding to the $f_2(1270)$ ($\rightarrow \pi^+\pi^-$) and an enhancement at 1.6 GeV are also clearly visible. The most likely candidate for this higher mass peak is the $\rho_3(1690)$ which has also been observed in the neutral dipion mass spectrum of the $\pi^+\pi^-\pi^\pm$ channel in this same experiment[80]. The $J/\psi(3097)$ is also visible in the same spectrum (Figure 27²), presumably through the misidentification of muons as pions. A detailed analysis regarding this resonance will be presented in the $\mu^+\mu^-\pi^+\pi^-$ channel section. A fit to the spectrum in Figure 26 employing a polynomial background distribution and Breit-Wigner resonances representing the $\rho(770)$, $f_2(1270)$, and $\rho_3(1690)$ is shown in Figure 28. The masses and widths, with their associated errors, are in good agreement with those listed in the PDG table[4] except that the value obtained for the mass of ρ_3 appears to be a little light. In particular we find nearly exact agreement for the $f_2(1270)$ mass and width with the PDG table values. Recently Apsimon *et al*[81], in a central production experiment, have found values for the $f_2(1270)$ and $f_0(975)$ masses which were significantly lower

²This Figure is the same as Figure 26 with the y axis chosen in a logarithmic scale.

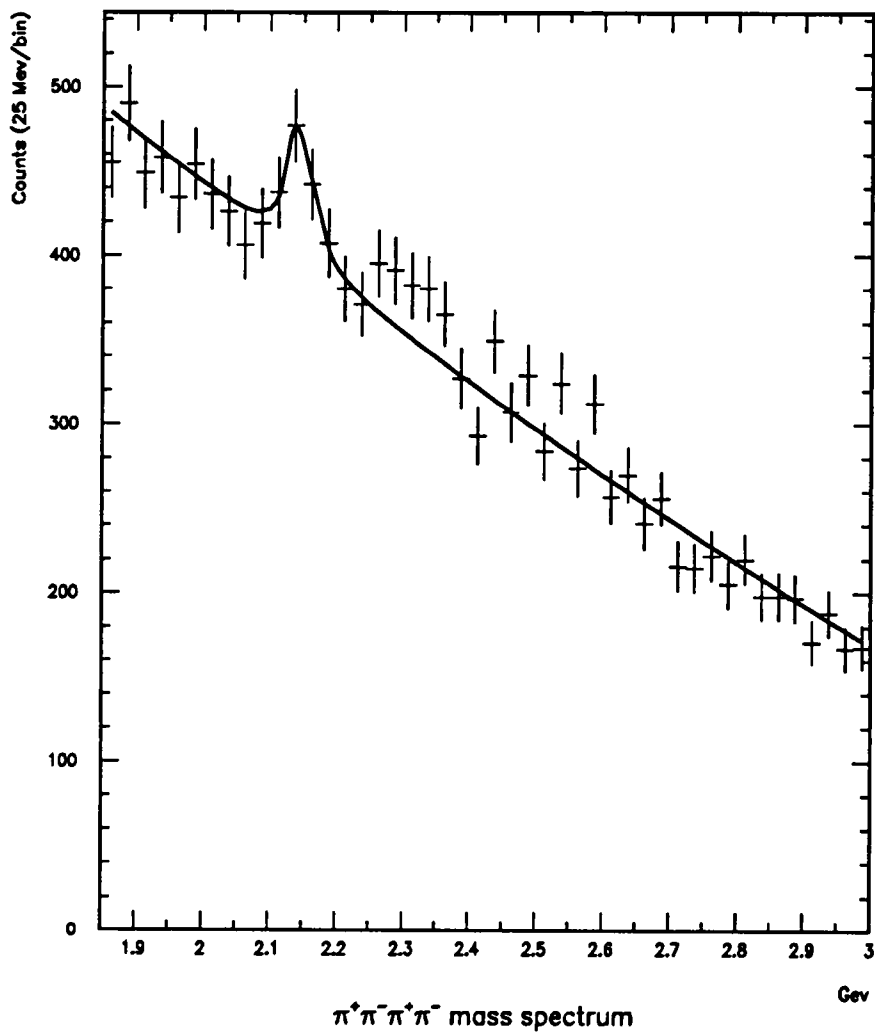


Figure 25: The 4π mass spectrum above the 2 GeV region. The narrow resonance is fit with a Breit-Wigner superposed over a polynomial background. Fit results are described in the text. A fast ρ cut is applied here.

Table 10: The signal to background ratios in the dipion mass spectra from eight different 50 MeV mass bands of the region $1.9 \text{ GeV} \leq m_{4\pi} \leq 2.30 \text{ GeV}$ of Figure 25.

Mass band (GeV)	ρ 's from dipion spectrum	Background from dipion spectrum	Signal/Background from dipion spectrum
1.90 - 1.95	672 ± 86	3160	0.213 ± 0.027
1.95 - 2.00	1208 ± 144	2552	0.473 ± 0.056
2.00 - 2.05	716 ± 90	2880	0.249 ± 0.033
2.05 - 2.10	672 ± 110	2792	0.241 ± 0.039
2.10 - 2.15	748 ± 90	3088	0.242 ± 0.029
2.15 - 2.20	551 ± 81	3017	0.183 ± 0.027
2.20 - 2.25	429 ± 80	2807	0.153 ± 0.029
2.25 - 2.30	560 ± 87	3312	0.203 ± 0.031

than the values quoted in the PDG table. A summary of our fit parameters is given in Table 11.

The origin of the $\rho(770)$ signal could be the inelastic diffractive photoproduction process ($\gamma p \rightarrow \rho^0 N^*$) and/or the decay of heavier states such as the $\rho'(1600)$, $a_2(1320)$, $\pi_2(1670)$ etc. There is no apparent evidence of any skewing of this dipion mass distribution which one would expect for diffractively produced ρ^0 which indicates the absence of a γ - ρ -Pomeron vertex and suggests that these ρ^0 's are the decay products of heavier state(s). The presence of $f_2(1270)$ is also likely to be due to the decay of a higher mass meson, since it's direct photoproduction, via Pomeron or OPE exchange, would violate charge conjugation invariance. It can be produced through the interaction of the photon with the coulomb field of the nucleus by means of virtual photon exchange (Primakoff effect) but the cross section for such a process is expected to be very small. The absence of an f_2 signal in the reaction $\gamma p \rightarrow \pi^+ \pi^- p$ appears to justify this assumption. The $\rho_3(1690)$ on the other hand could be photoproduced by either pion or Pomeron exchange. Although Donnachie *et al* [63], in their analysis of photoproduced 4π states, assume an incoherent contribution from the $\rho_3(1690)$ meson to account for

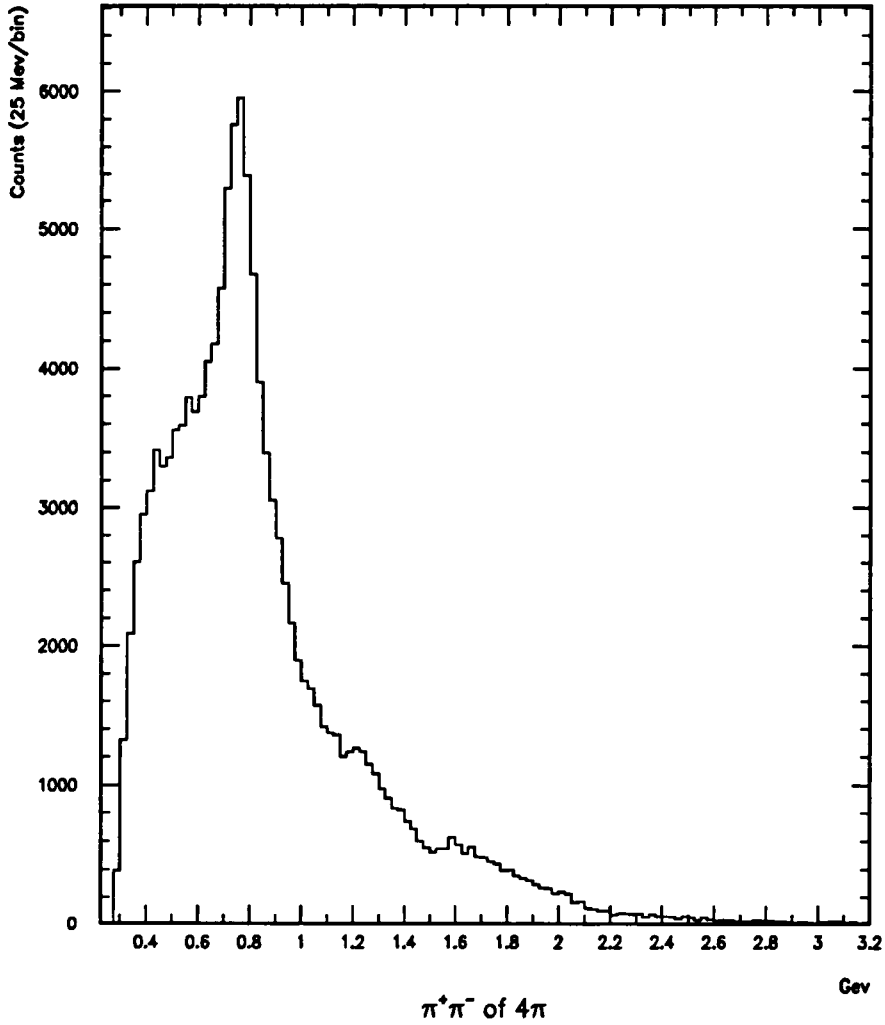


Figure 26: The neutral dipion mass spectrum in the $\gamma N \rightarrow \pi^+ \pi^- \pi^+ \pi^- N'$ channel (4 per event). No cuts are applied. The $\rho^0(770)$, $f_2(1270)$, and $\rho_3(1690)$ peaks are visible.

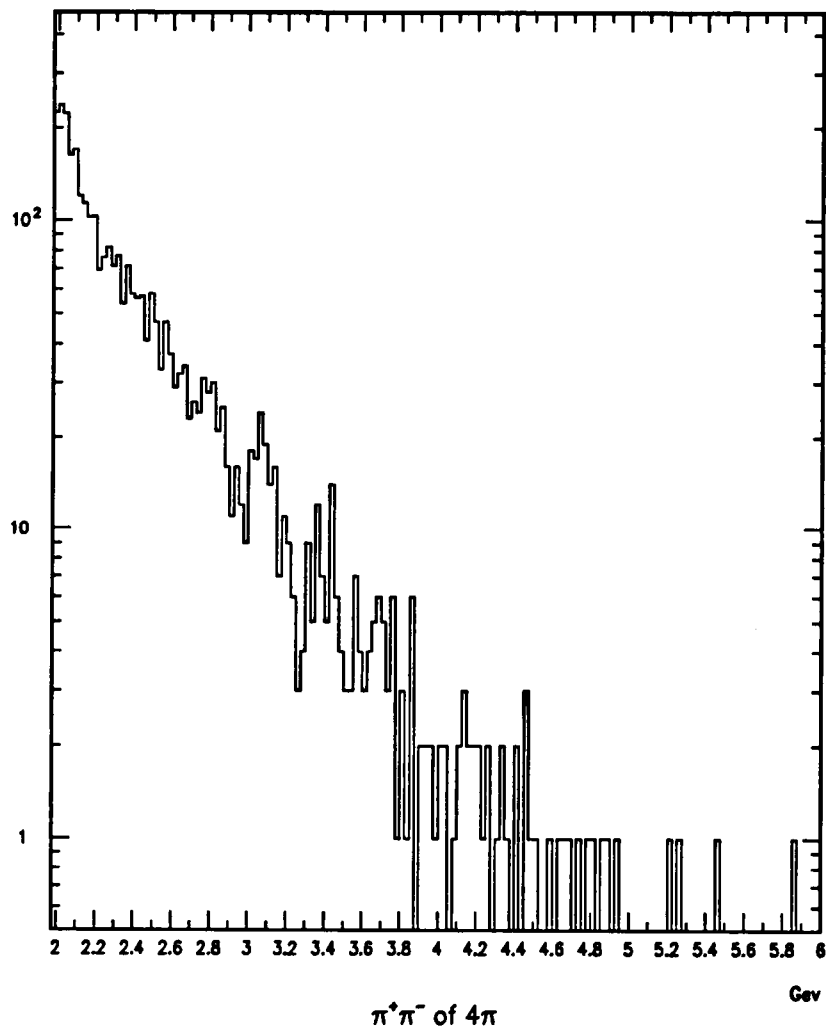


Figure 27: The neutral dipion combinations above the 2 GeV region in the $\gamma N \rightarrow \pi^+ \pi^- \pi^+ \pi^- N'$ channel (4 per event) with the y axis in logarithmic scale. The $J/\psi(3097)$ can be seen. No cuts are applied.

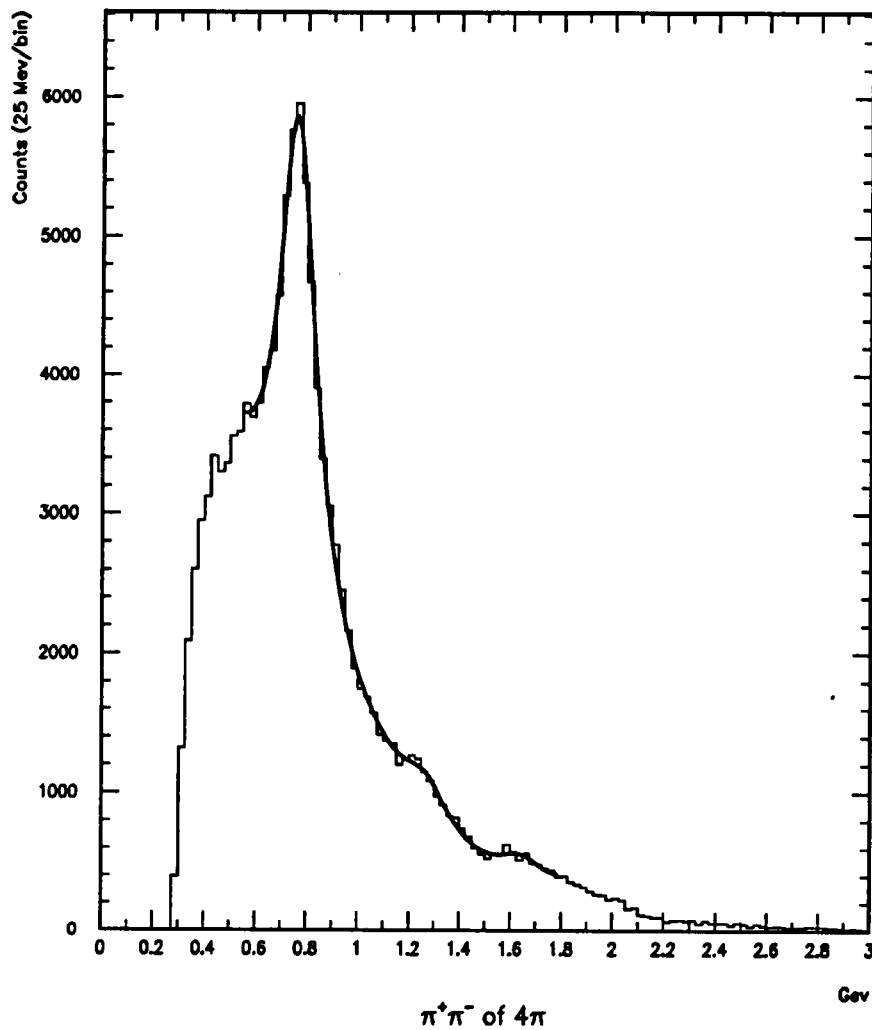


Figure 28: The neutral dipion mass spectrum in the 4π channel with the fit described in the text. Signals of $\rho(770)$, $f_2(1270)$, and $\rho_3(1690)$ are visible. No cuts are applied here.

Table 11: The fit parameters of the dipion mass spectrum in the 4π channel.

Resonance	Yield	Mass (GeV)	Width (GeV)
$\rho(770)$	39784 ± 967	0.761 ± 0.001	0.176 ± 0.004
$f_2(1270)$	3882 ± 574	1.269 ± 0.007	0.210 ± 0.025
$\rho_3(1690)$	2650 ± 739	1.640 ± 0.010	0.223 ± 0.038

it's diffractive production cross section in this channel, the experimental evidence for it's photoproduction in either the elastic or inelastic channels is marginal at best. The presence of $\rho_3(1690)$ therefore, may also be indicative of a higher mass state. In order to check this hypothesis, the $(3\pi)^\pm$ mass spectrum from the 4π channel was investigated. The $\rho\pi^\pm$, $f_2\pi^\pm$ and $\rho_3\pi^\pm$ mass spectra are shown in Figure 29. Although the $\rho\pi^\pm$ mass spectrum (A) is substantially enhanced at low mass region, there is a prominent enhancement (shoulder) at the $a_2^\pm(1320)$ region. The $f_2\pi^\pm$ (B) and $\rho_3\pi^\pm$ (C) mass spectra appear to be dominated by relatively large backgrounds. This is expected as the $f_2(1270)$ and $\rho_3(1690)$ signals themselves (see Figure 28) are produced with poor *signal to noise* ratios compared to the $\rho^0(770)$ region. However, there appears to be an excess of events present around ~ 2.05 GeV in the $\rho_3\pi^\pm$ mass spectrum (C) which may be indicative of the $a_3(2050)(\rightarrow \rho_3\pi)$ meson. No such structure is evident in the $f_2\pi^\pm$ spectrum (B) though it peaks near the $\pi_2(1670)(\rightarrow f_2\pi)$ region. The dominance of large backgrounds in these two mass spectra does not lend itself to further detailed investigation as such. A Monte Carlo simulation to understand the shape of the phase space distributions in these two plots (B) and (C) will be presented in Chapter 5.

Most of the $a_2(1320)$'s in the $\rho\pi$ mass spectrum in Figure 29 (A) may be understood as being produced mainly through one-pion charge exchange (OPE) processes[41] as shown in Figure 30 rather than being from the decay of photoproduced heavier neutral meson. No such heavy meson has been convincingly seen to decay into $a_2^\pm\pi^\mp$ state and our $a_2^\pm\pi^\mp$ mass spectrum gives no indication any such heavy state. The observed large radiative width of $a_2(1320)$ ($\Gamma(a_2 \rightarrow \pi\gamma) \sim 300$

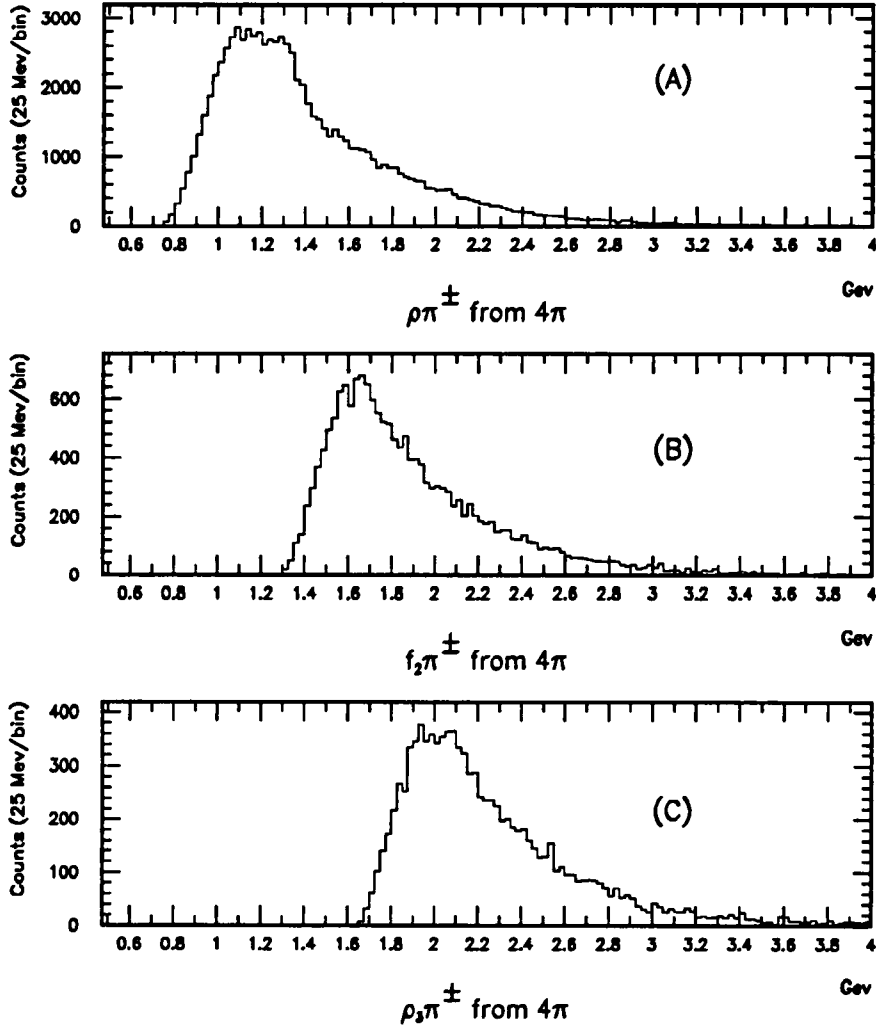


Figure 29: The $\rho\pi^\pm$, $f_2\pi^\pm$, and $\rho_3\pi^\pm$ mass spectra from the 4π channel. The masses were taken as $0.60 \leq \rho \leq 0.90$, $1.15 \leq f_2 \leq 1.35$, and $1.50 \leq \rho_3 \leq 1.75$ for the respective particles. A bump near the $a_2(1320)$ region can be seen in (A). The $\rho_3\pi^\pm$ spectrum (C) shows an excess of events present near the $a_3(2050)$ mass and the $f_2\pi^\pm$ spectrum (B) appears to peak at the $\pi_2(1670)$ mass.

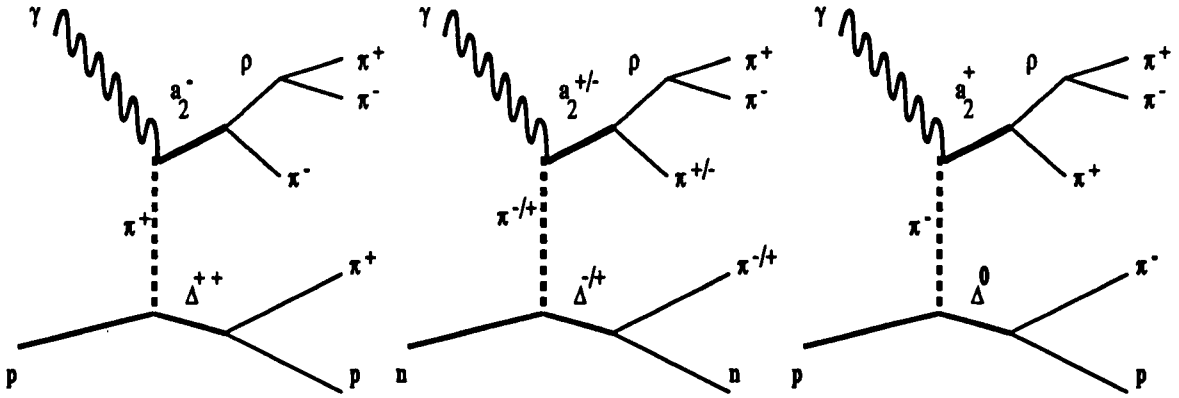


Figure 30: Feynman diagrams for the possible OPE processes that photoproduce $a_2^\pm(1320)$ along with Δ resonances contributing to the 4π final state. As shown, such reactions proceed through charged pion exchanges.

keV) would also appear to justify the possibility of the formation of $a_2^\pm \pi^\mp$ final state through such OPE mechanisms ($\gamma p \rightarrow a_2 \Delta$). Although the cross section for the OPE type reaction becomes small at high energies such as were used in the present experiment (since its energy dependence is given by $\sim 1/E_\gamma^n$, where E_γ is the photon energy and n is a number between 1 and 2), some contribution from these processes could still be expected, as was seen from a Monte Carlo study of the charge exchange channel modeled with an OPE cross section at high energies. In OPE photoproduction processes, such as the ones depicted in Figure 30, a major part of the incident photon's momentum is imparted to the $a_2(1320)$ meson (t -channel). Thus the pions from the decay of $a_2(1320)$ will have higher momentum than those from the Δ decay. In Figure 31 we plot the $\rho\pi^\pm$ mass spectra from the 4π , rejecting the slowest pion among the four pion tracks. The $a_2^\pm(1320)$ resonances are very clearly visible. The smooth curve superposed in the $\rho\pi^\pm$ plot represents a Breit-Wigner fit to the peak region with a cubic background. The fit yields an $a_2(1320)$ peak of $\sim 7.4\sigma$ significance with a mass and width in good agreement with those from the PDG table[4]. Apart from the $a_2(1320)$, a bump near ~ 1.7 GeV is also seen in Figure 31 which is suggestive of the $\pi_2(1670)(\rightarrow \rho\pi)$

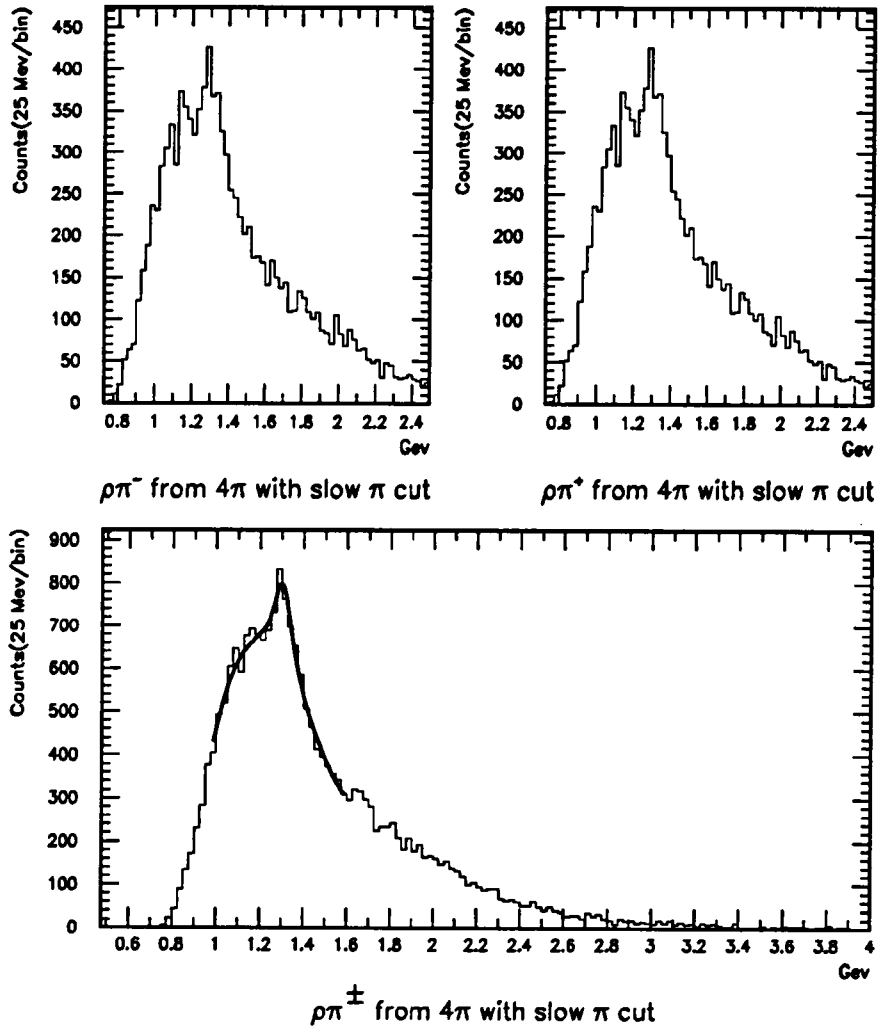


Figure 31: The $\rho\pi^-$, $\rho\pi^+$ and $\rho\pi^\pm$ mass spectra from the $3\pi^\pm$ sector of the 4π channel with the slowest pion among the four tracks being rejected. The $a_2^\pm(1320)$ resonances can be seen. The fit shown in the $\rho\pi^\pm$ mass spectra is described in the text.

meson. The fit parameters of the $a_2(1320)$ peak are summarized in Table 12. However, similar plots made for the $f_2\pi^\pm$ and $\rho_3\pi^\pm$ mass spectra are still dominated by large backgrounds as in Figures 29 (B) and (C) and offer no further clear evidence of $\pi_2(1670)$ and $a_3(2050)$ mesons.

Apart from the OPE processes, another possible source of $a_2(1320)$'s could perhaps be attributed to the "Deck-type" reactions[82] $\gamma p \rightarrow (a_2 \rightarrow 3\pi)\pi p$ which proceeds through pion-pomeron coupled exchange process. The $a_2^\pm\pi^\mp$ final state from such a process would also not be expected to contain any structural features.

In order to investigate the features of the subresonances of the high mass 4π system, we separately plot the $\pi^+\pi^-$ and $\pi^+\pi^-\pi^\pm$ mass spectra in Figure 32 for the 4π mass lying in the region $2.05 \leq m_{4\pi} \leq 3.05$ GeV. The neutral dipion plot shows clear signals from $\rho^0(770)$, $f_2(1270)$, and $\rho_3(1690)$ resonances. The fit shown represents three Breit-Wigners superimposed over a third order polynomial background. The fit results are summarized in Table 12. Figure 32 also shows the $(3\pi)^\pm$ mass spectra from this high mass 4π region. The only clearly delineated enhancement is a signal apparently corresponding to the $a_2(1320)$ meson. A similar investigation of the same high mass 4π mass region ($2.05 \leq m_{4\pi} \leq 3.05$ GeV) from the reaction $\gamma p \rightarrow p\pi^+\pi^-\pi^+\pi^-$ was conducted by Aston *et al*[53] previously. Apart from an $a_2(1320)$ resonance, their results showed evidence for a signal at ~ 1.76 GeV in the $3\pi^\pm$ mass spectrum of the 4π channel. This latter enhancement is not evident in our $(3\pi)^\pm$ mass spectrum (Figure 32) due to the presence of background in that region. The $a_2(1320)$ signal in Figure 32 becomes clearer by selecting a ρ ($0.6 \leq m_{\pi^+\pi^-} \leq 0.9$ GeV) as shown in Figure 33. A Breit-Wigner fit with a cubic background to the $\rho\pi^\pm$ plot yields an $a_2(1320)$ peak of 5.2σ significance with a mass and width of 1.300 ± 0.006 GeV and 0.138 ± 0.025 GeV respectively. These values are consistent with those obtained from the fit to Figure 31 (see Table 12). No structures could be identified in the $f_2\pi^\pm$ and $\rho_3\pi^\pm$ mass spectra in this high mass 4π region.

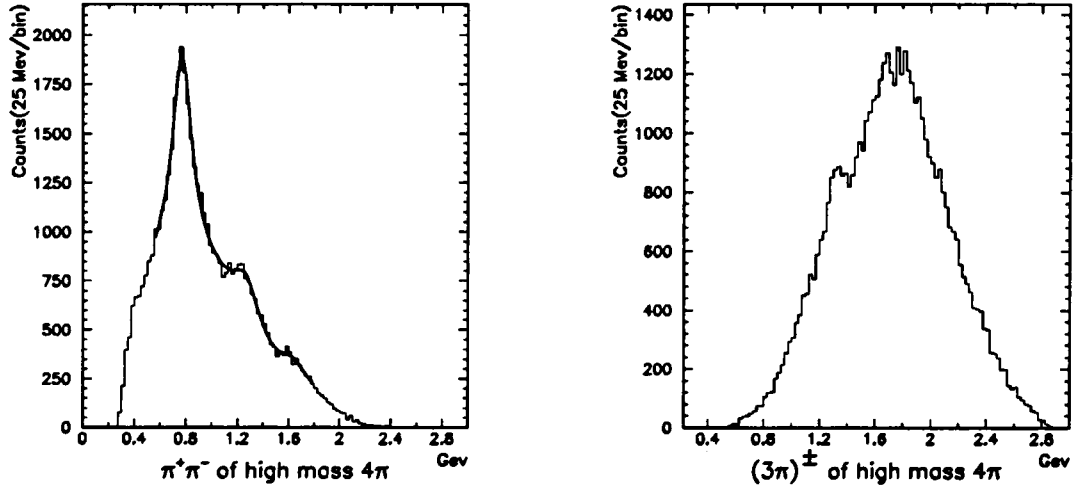


Figure 32: The $\pi^+\pi^-$ and $\pi^+\pi^-\pi^\pm$ mass spectra for the 4π mass lying in the region $2.05 \leq m_{4\pi} \leq 3.05$ GeV. The neutral dipion spectrum on the left displays the $\rho^0(770)$, $f_2(1270)$, and $\rho_3(1690)$ resonances. The fit shown is described in the text. The $\pi^+\pi^-\pi^\pm$ spectrum on the right shows an $a_2(1320)$ enhancement. No other clear structures are visible.

Table 12: Summary of the fit parameters obtained from Figure 31 and Figure 32.

Figure	Resonance	Yield	Mass (GeV)	Width (GeV)
31	$a_2^\pm(1320)$	1446 ± 195	1.305 ± 0.005	0.106 ± 0.016
32	$\rho(770)$	11778 ± 946	0.766 ± 0.002	0.183 ± 0.012
	$f_2(1270)$	4068 ± 779	1.267 ± 0.008	0.256 ± 0.033
	$\rho_3(1690)$	2825 ± 852	1.640 ± 0.012	0.286 ± 0.048

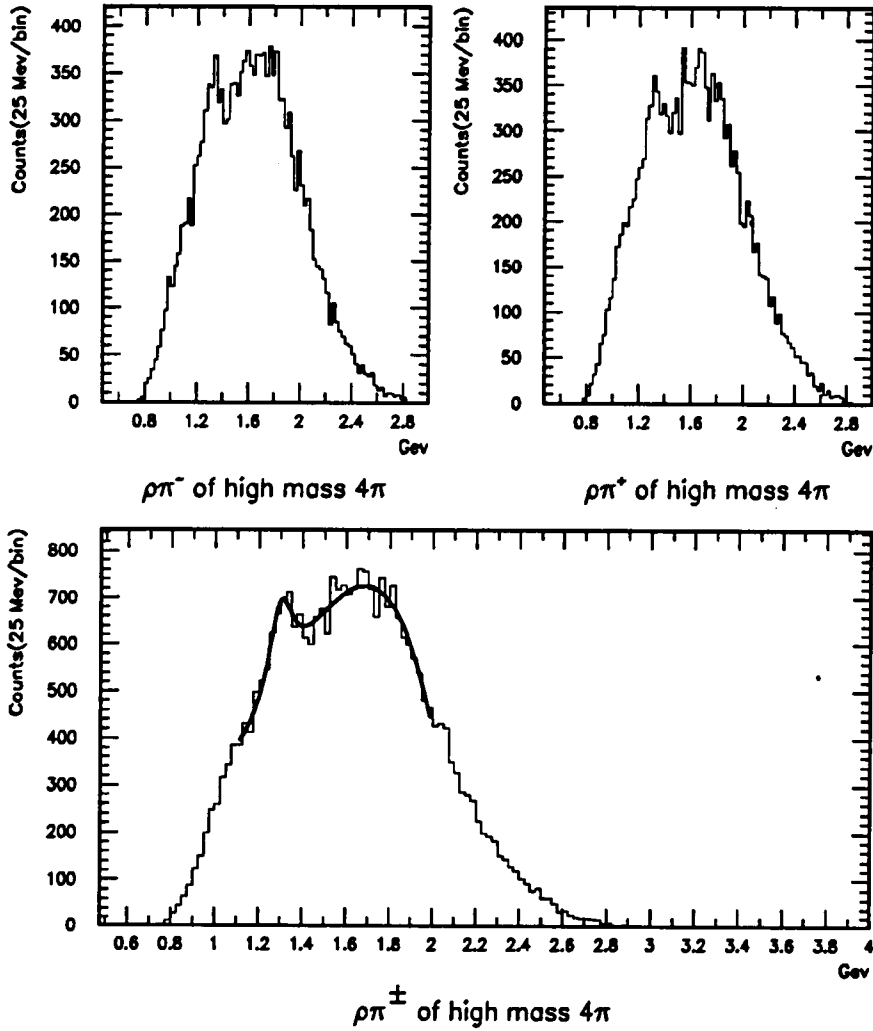


Figure 33: The $\rho\pi^-$, $\rho\pi^+$ and $\rho\pi^\pm$ mass spectra from the for the 4π mass lying in the region $2.05 \leq m_{4\pi} \leq 3.05$ GeV. The $a_2(1320)$ resonance can be seen. The fit shown in the $\rho\pi^\pm$ mass spectra is described in the text.

4.3.2 The $K^+K^-\pi^+\pi^-$ Reaction Channel

Since a ' ϕ ' mass ($M_{K^+K^-} < 1.1$ GeV) cut was employed on the data tapes used for this analysis, this channel is effectively the study of $\phi\pi^+\pi^-$ sector. The selection criteria used for kaons and pions are given in an earlier section. Our selection criteria for the tracks differ slightly from the ones originally used during the skimming stage. The K^+K^- mass from this data sample is shown in Figure 34. The $\phi(1020)$ is clearly visible with a sharp drop at around 1.1 GeV as the result of the introduction of the mass cut on the kaon pairs during skimming. The presence of any events at all beyond 1.1 GeV in Figure 34 may be understood as being due to the difference in the track selection criteria used in the present analysis and in the original skim procedure as mentioned above. The fit shown represents a Breit-Wigner superimposed on a quadratic background. Parameters of the fit are listed on the figure itself. Throughout this section, the ' $\phi(1020)$ mass region' will always be chosen as the region $1.01 \leq m_{K^+K^-} \leq 1.03$ in Figure 34. The $\pi^+\pi^-$ mass spectrum, opposite to the K^+K^- pair, is shown in Figure 35. Here, (A) contains the neutral dipion combination opposite to the dikaons and (B) has those $\pi^+\pi^-$ combinations when the K^+K^- lies between the $\phi(1020)$ mass region and 1.1 GeV. Clear $\rho(770)$ signals are observed in both the figures. The enhancement around 975 MeV, which appears as a shoulder in the full data (A), is missing in the data (B) which require that the K^+K^- mass not be in the ϕ region. This enhancement becomes a clear $f_0(975)$ peak when we plot the dipion spectrum with the requirement that the opposite kaon pair lie in the $\phi(1020)$ mass region. This is shown in Figure 36. The $f_0(975)$ production therefore seems to be associated with ϕ production. A recent study of the hadronic J/ψ decays involving ϕ and ω production, by the DM2 collaboration at the DCI storage ring, reported the observation of a clean, large $f_0(975)$ signal in the $\pi^+\pi^-$ mass spectrum of the OZI forbidden decay $J/\psi \rightarrow \phi\pi^+\pi^-$ [36]. We see no evidence for J/ψ photoproduction in the $\phi\pi^+\pi^-$ final state (Figure 37, discussed below). The fit in Figure 36 consists of two Breit-Wigners superposed over a quadratic background. The parameters of

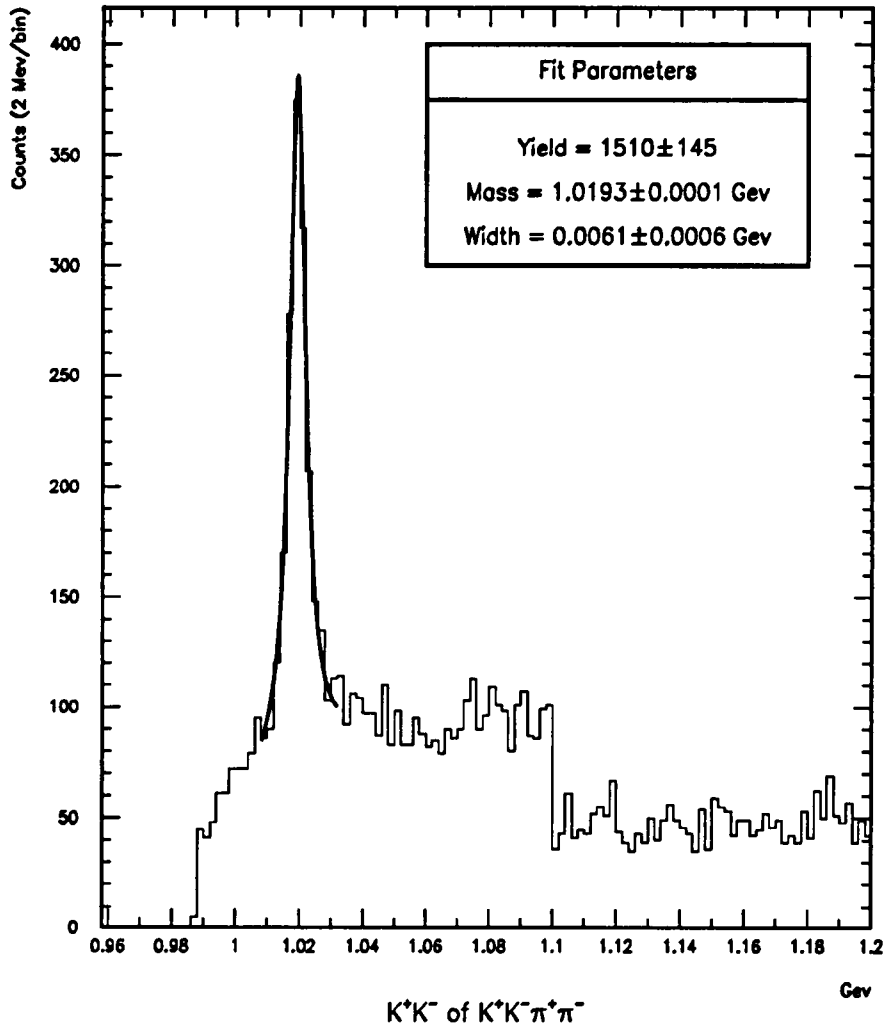
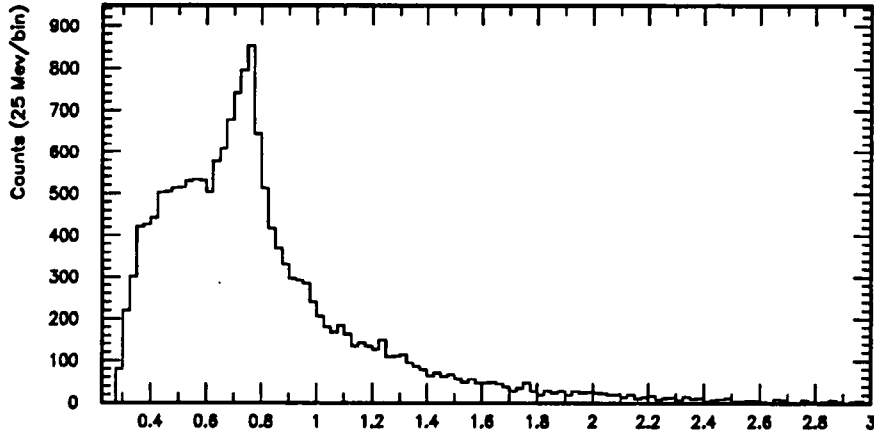
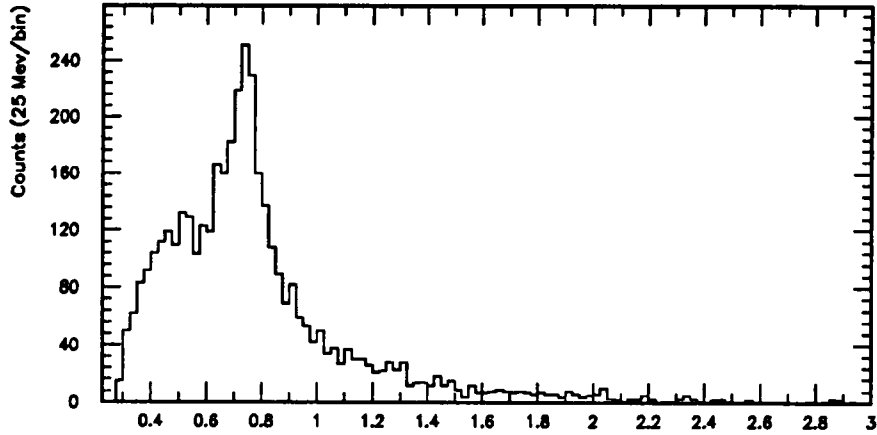


Figure 34: The K^+K^- invariant mass spectrum of the $K^+K^-\pi^+\pi^-$ channel. The sharp $\phi(1020)$ and the discontinuity at 1.1 GeV are visible. The results of the fit described in text are also shown.



(A) $\pi^+\pi^-$ of $K^+K^-\pi^+\pi^-$



(B) $\pi^+\pi^-$ of $K^+K^-\pi^+\pi^-$

Figure 35: (A) The $\pi^+\pi^-$ invariant mass spectrum of the $K^+K^-\pi^+\pi^-$ channel regardless of the K^+K^- mass. $\rho(770)$ and a shoulder near 975 MeV are seen. (B) The $\pi^+\pi^-$ invariant mass spectrum of the $K^+K^-\pi^+\pi^-$ channel when the K^+K^- mass lies outside the $\phi(1020)$ mass region. The ϕ mass was selected in the region $1.01 \leq m_\phi \leq 1.03$ from the kaon pair.

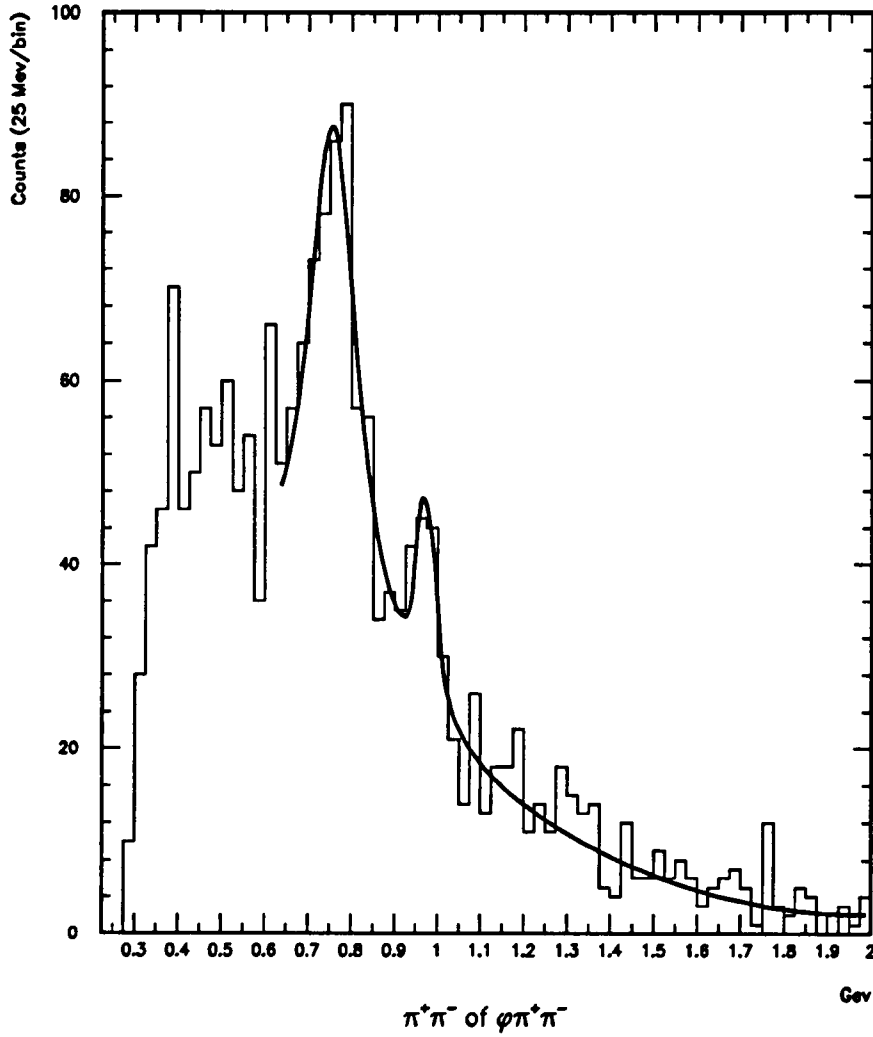


Figure 36: The $\pi^+\pi^-$ invariant mass spectrum of the $\phi\pi^+\pi^-$ channel. The kaon pair was required to lie inside the $\phi(1020)$ mass region (1.01 - 1.03 GeV). Signals corresponding to $\rho(770)$ and $f_0(975)$ are clearly visible. The fit shown is described in the text.

Table 13: The fit parameters of the dipion mass spectrum in the $\phi\pi^+\pi^-$ channel.

Resonance	Yield	Mass (GeV)	Width (GeV)
$\rho(770)$	527 ± 63	0.756 ± 0.007	0.140 ± 0.022
$f_0(975)$	74 ± 24	0.974 ± 0.006	0.045 ± 0.022

the fit are given in Table 13. The masses and widths of both resonances are in good agreement with their respective values from the PDG table[4]. A brief review on the current status of the $f_0(975)$ was outlined in Chapter 1.

The $\phi\pi^+\pi^-$ invariant mass spectrum is shown unhatched in Figure 37. A significant enhancement near 1.9 GeV is present. Although the $\phi\pi^+\pi^-$ mass spectrum from the $K^+K^-\pi^+\pi^-$ final state of previous photoproduction analyses were claimed to be structureless[83, 84], a narrow enhancement near 2.1 GeV in the $\phi\pi^+\pi^-$ final state, produced in inclusive 400 GeV p - N interactions, has been reported elsewhere[85]. One would not expect to observe an ordinary $q\bar{q}$ meson in this channel as it would represent an OZI violating decay mode. However results have been obtained from a study of the OZI rule in exclusive photoproduction reactions[86] when the full extent of suppression expected from theoretical predictions does not seem to occur³. By requiring the effective mass of the dipions to lie outside the $\rho(770)$ mass region, we obtain the hatched histogram in Figure 37 where the 1.9 GeV enhancement is absent. This indicates that the enhancement is associated with the reaction $\gamma N \rightarrow \phi\rho^0 N$. The effective mass spectrum of the $\phi\rho^0$ system is shown in Figure 38. The peak at 1.9 GeV region is now quite pronounced as the background due to non- ρ^0 dipion events is significantly reduced. A scatter plot of the K^+K^- and $\pi^+\pi^-$ masses shown in Figure 39 displays significant overlapping between the ϕ and ρ^0 bands. The smooth curve in Figure 38 is a Breit-Wigner fit to the peak region over a polynomial background multiplied by

³Theoretically, the reaction $e^+e^- \rightarrow \phi\pi\pi$ should be strongly suppressed. As the reaction proceeds through a single photon, coherent photoproduction should be closely related to this process and should be subject to a similar suppression.

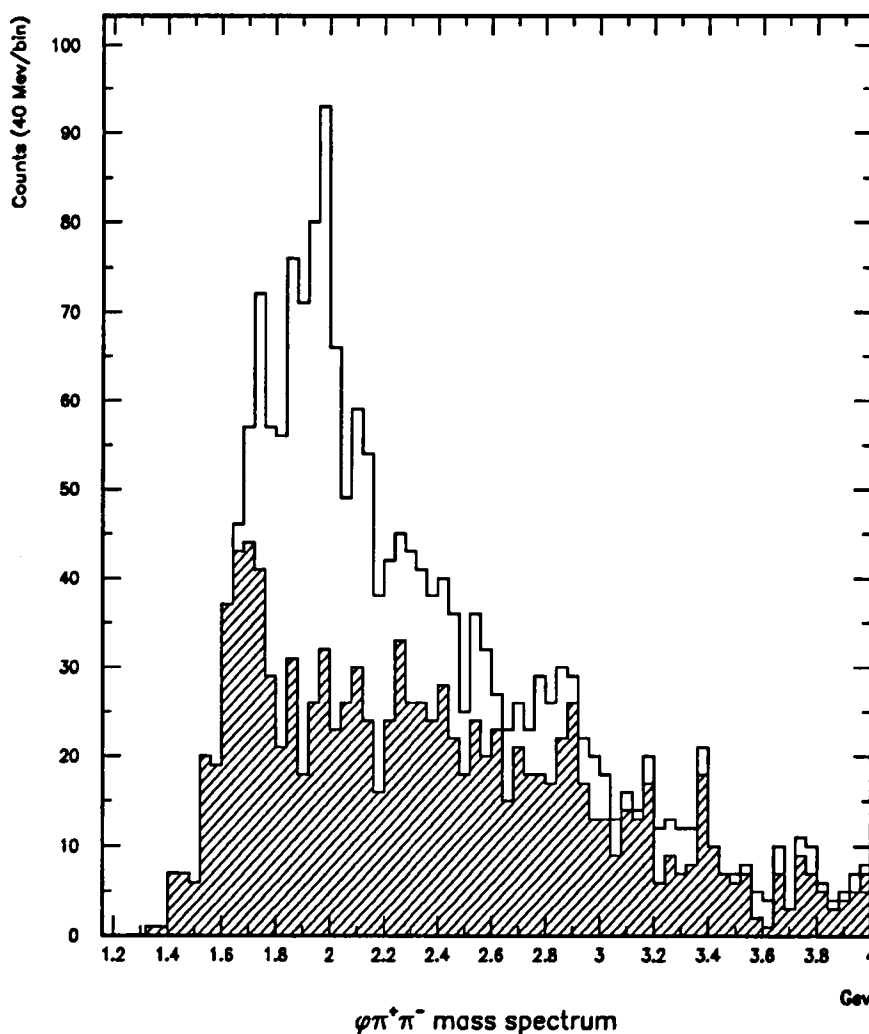


Figure 37: The $\phi\pi^+\pi^-$ invariant mass spectrum of the $K^+K^-\pi^+\pi^-$ channel. Unhatched histogram represents all $\phi\pi^+\pi^-$ events regardless of the effective mass of the $\pi^+\pi^-$ pair. An enhancement at ~ 1.9 GeV is clearly visible. The hatched histogram contains the same events with an additional constraint that the effective mass of the pion pair be outside the $\rho^0(770)$ mass region. The previously mentioned peak at ~ 1.9 GeV is absent here. The $\rho^0(770)$ mass region is defined as $0.60 \leq m_{\pi^+\pi^-} \leq 0.90$.

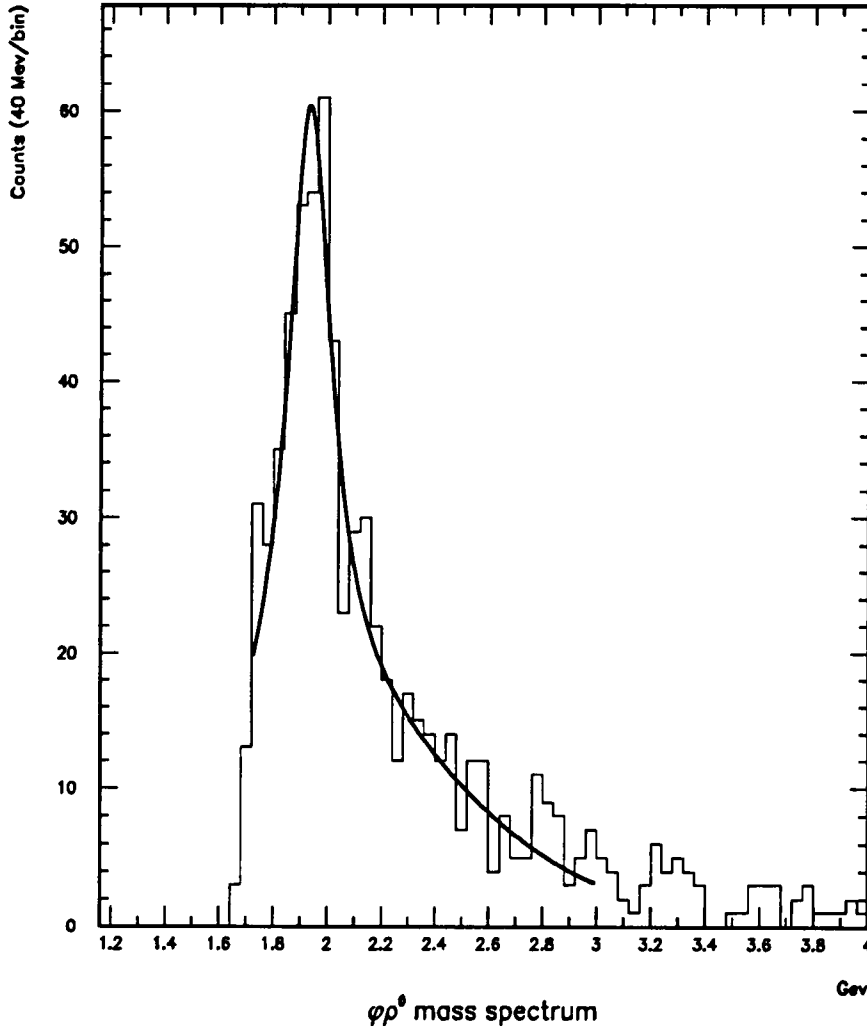


Figure 38: The $\phi\rho^0$ invariant mass spectrum of the $K^+K^-\pi^+\pi^-$ channel. The clear peak at 1.9 GeV can be seen with less background than in $\phi\pi^+\pi^-$. The fit description of the enhancement is given in the text. The $\phi(1020)$ and $\rho^0(770)$ mass regions were defined as $1.01 \leq m_\phi \leq 1.03$ and $0.60 \leq m_{\rho^0} \leq 0.90$ respectively.

Table 14: The fit parameters of the $\phi\rho^0$ mass spectrum .

Resonance	Yield	Mass (GeV)	Width (GeV)
Y	330 ± 45	1.932 ± 0.012	0.190 ± 0.023

a rising exponential function. This exponential function is introduced to account for the rapidly rising nature of the background at low mass. The fit values are given in Table 14. As discussed in Chapter 1, this enhancement is suggestive of the presence of an $I = 1$ four-quark tensor state predicted by M.I.T bag model which has a mass of ~ 1.95 GeV and which has been assumed to be responsible for producing the resonant anomaly in the $\gamma\gamma \rightarrow \phi\rho^0$ channel[28, 29]. The MIT bag model calculations also predict the existence of a $J^P = 2^+ q^2\bar{q}^2$ state in the same mass region which may decay to $\rho^0\phi$ but could also decay to $K^{*0}\bar{K}^{*0}$ and $\omega\phi$. Enhancements near 1.95 GeV have been seen in the $K^{*0}\bar{K}^{*0}$ channel in previous analyses[87]. Although in our $K^+K^-\pi^+\pi^-$ data sample the neutral kaon pairs are all required to be ϕ 's, some $K^{*0}(892)$ production is found in both $K^\pm\pi^\mp$ mass spectra. This is expected because the K^+ and/or K^- in the defined ϕ band could be from the $K^{*0}(892)$ region as both the $\phi(1020)$ and $K^{*0}(892)$ resonances peak approximately at their respective thresholds resulting in some overlap. A scatter diagram of $M(K^+\pi^-)$ vs $M(K^-\pi^+)$ did exhibit these K^{*0} bands with an accumulation of events where the bands overlap indicating evidence for associated $K^{*0}\bar{K}^{*0}$ production. The projection from this scatter plot showed a clear enhancement also at the 1.95 GeV mass region. Thus the nature of the enhancement in Figure 38 as to whether it is produced through $K^{*0}\bar{K}^{*0}$ and/or $\phi\rho^0$ appears to be ambiguous. In an attempt to resolve this ambiguity, we studied the $K^\pm\pi^\mp$ mass spectrum for the 1.95 GeV peak region of Figure 38. A significant number of K^{0*} 's were seen present in this spectrum. Thus the enhancement at 1.95 GeV appears to be mainly from the $\phi\rho^0$ channel with a lesser contribution from the K^{*0} associated production. The skim tape bias on the K^+K^- mass does not permit us to make

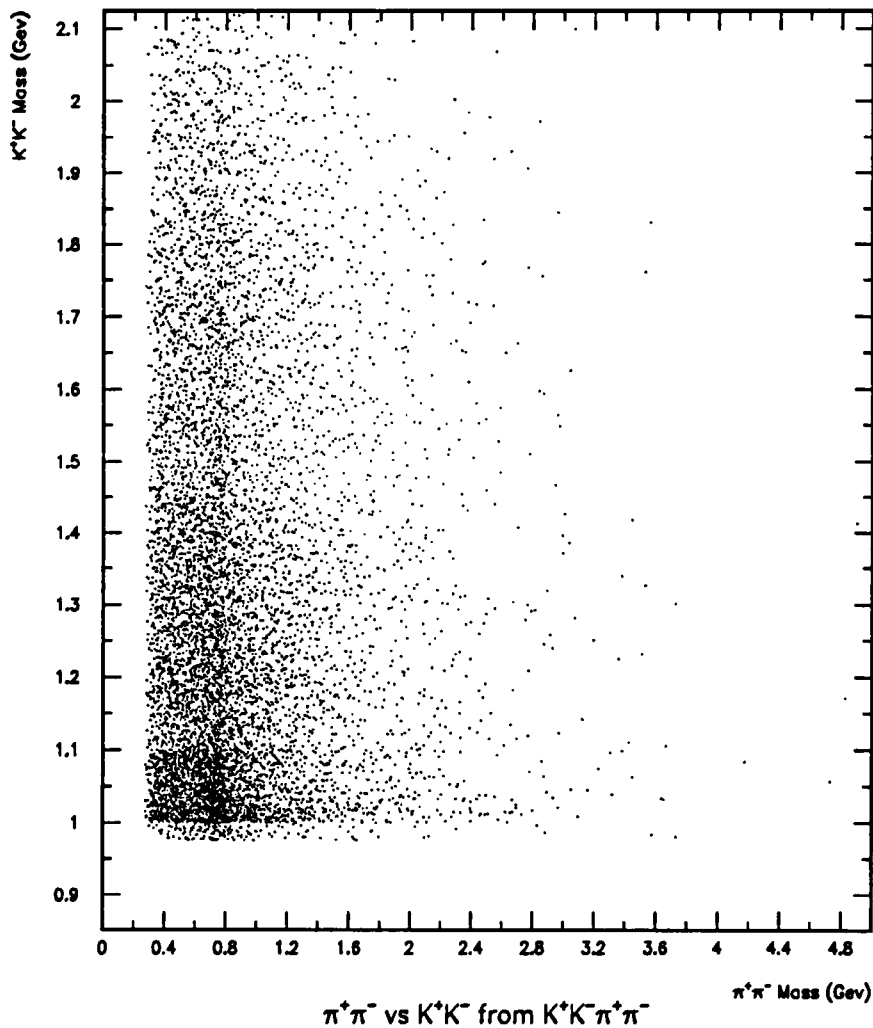


Figure 39: The $\pi^+\pi^-$ vs K^+K^- mass scatter plot from the $K^+K^-\pi^+\pi^-$ channel. Bands corresponding to $\rho^0(770)$ and $\phi(1020)$ are visible. Considerable overlapping between the bands can be seen as evidence for $\phi\rho^0$ production.

a stronger statement here.

In Figure 40, we plot the ϕf_0 mass spectrum from the $\phi\pi^+\pi^-$ channel. An apparent enhancement near the 2.3 GeV region is present. A Breit-Wigner fit to the peak region with a cubic background embedded along with a rapidly rising exponential yields a statistically significant signal of $\sim 3.1\sigma$ standard deviations, with a mass and width of 2.303 ± 0.030 GeV and 0.250 ± 0.047 GeV respectively. No such enhancement has been reported before in this channel. To check for a possible $K^{*0}\bar{K}^{*0}$ contamination in this region, we followed the same logic as discussed for the $\phi\rho^0$ channel in the previous section. The $K^\pm\pi^\mp$ mass spectrum for the 2.3 GeV enhancement region in Figure 40 was analyzed. No K^{*0} signal was found in this region. This observation suggests that the 2.3 GeV structure in Figure 40 is from the $\phi f_0(975)$ channel alone with no contribution from $K^{*0}\bar{K}^{*0}$.

As mentioned in Chapter 1, the possibility that the recently reported $C(1480)$ meson in the $\phi\pi$ channel could be a four-quark state has been investigated by Close and Lipkin[33]. The $\phi\pi$ system is characterized both by nonzero isotopic spin(u and d quarks) and by hidden strangeness ($s\bar{s}$ quarks). Since the coupling between a quarkonium $q\bar{q}$ state and a $\phi\pi$ system is suppressed by the OZI rule, states strongly coupled with this system may have exotic quark structures.

The $\phi\pi^\pm$ mass spectrum from the $\phi\pi^+\pi^-$ channel of the present experiment shows no unambiguous sign of any enhancement in this possibly exotic $C(1480)$ region. Falvard *et al*[36] have reported a possible contribution of $J/\psi \rightarrow C^\pm(1480)\pi^\mp \rightarrow \phi\pi^+\pi^-$ in their data. Although their $\phi\pi^\pm$ mass spectrum is in agreement with the hypothesis that the $J/\psi \rightarrow \phi\pi^+\pi^-$ decay only proceeds through $J/\psi \rightarrow \phi X (X \rightarrow \pi^+\pi^-)$, an excess of events were found around 1.5 GeV in the spectrum with the mass and width consistent with the $C(1480)$ parameters which enabled them to provide an upper limit on the branching ratio as:

$$BR(J/\psi \rightarrow C^\pm(1480)\pi^\mp)BR(C^\pm(1480) \rightarrow \phi\pi^\pm) \leq 1.5 \times 10^{-4}.$$

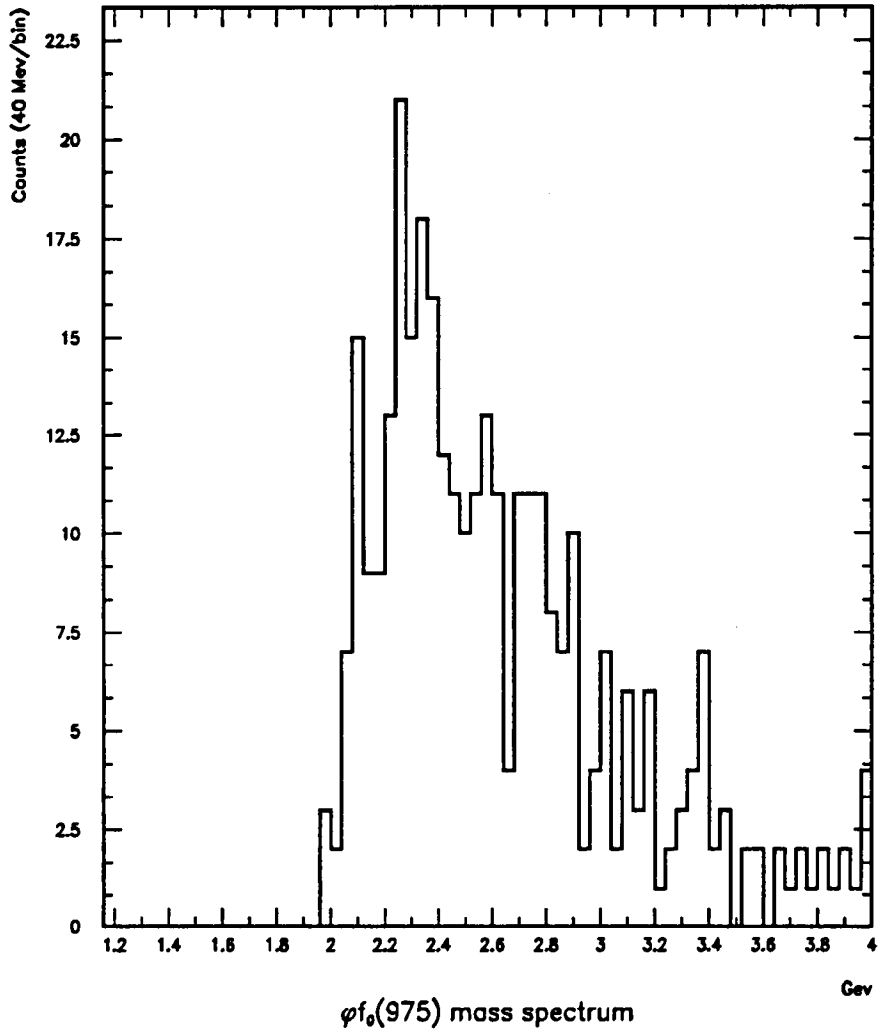


Figure 40: The $\phi f_0(975)$ invariant mass spectrum of the $K^+K^-\pi^+\pi^-$ channel. The $\phi(1020)$ and $f_0(975)$ mass regions were defined as $1.01 \leq m_\phi \leq 1.03$ and $0.91 \leq m_{f_0} \leq 1.25$ respectively.

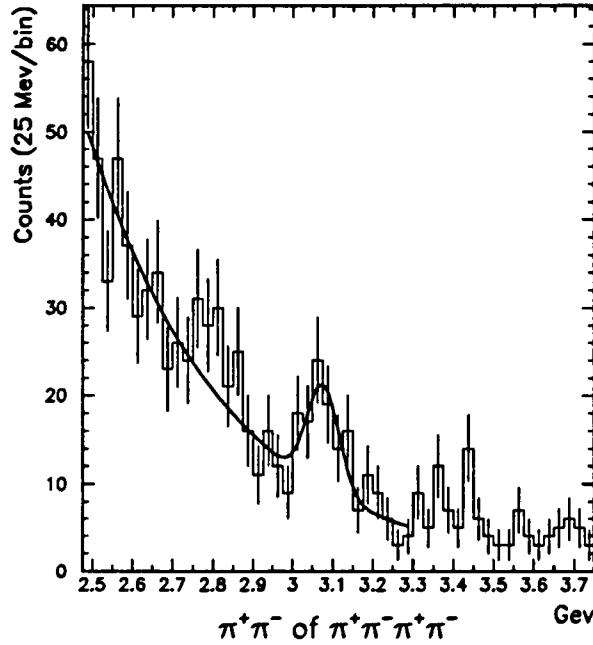


Figure 41: The $\pi^+\pi^-$ mass spectrum in the J/ψ mass region from the $\pi^+\pi^-\pi^+\pi^-$ channel. The J/ψ resonance, resulting from the misidentification of muons as pions, can be seen fit with a Gaussian over a decaying exponential background.

4.3.3 The $\mu^+\mu^-\pi^+\pi^-$ Reaction Channel

As mentioned in Chapter 1, the neutral dipion mass spectrum from the 4π channel exhibits a statistically significant J/ψ resonance (see Figure 27). Since the decay of J/ψ to $\pi^+\pi^-$ is quite weak, its presence in this channel is almost certainly due to the misidentification of muons as pions. Since the pion rest mass is small and close to that of the muon, the kinematics of the $\pi^+\pi^-$ decay of the J/ψ can be closely approximated by incorrectly identified $\mu^+\mu^-$. A Gaussian fit for the J/ψ resonance region in the dipion mass spectrum superposed over a decaying exponential background is shown in Figure 41. The fit parameters are summarized in Table 15. This 3.6σ resonance peak contains approximately 47 ± 13 events.

Table 15: The fit parameters of the dipion mass spectrum in the J/ψ mass region.

Resonance	Yield	Mass (GeV)	Width (GeV)
$J/\psi(3097)$	47 ± 13	3.076 ± 0.012	0.039 ± 0.011

No clear signal from $\psi'(3685)(\rightarrow \mu^+\mu^-)$ is observed (see ref.[68]). This is to be expected as the $\text{BR}(\psi' \rightarrow \mu^+\mu^-)$ is only about 0.8% as compared to $J/\psi \rightarrow \mu^+\mu^-$ which is around 6.0%.

The presence of J/ψ in this channel could be due to the elastic photoproduction of it's radially excited higher mass vector meson counterpart, the $\psi'(3685)$ or $\psi(2S)$ which decays into $J/\psi\pi^+\pi^-$ with a large branching ratio (32.4%). It has been observed previously in this sector by another photoproduction experiment[68]. The reconstruction of $J/\psi\pi^+\pi^-$ from the 4π channel is carried out in the following manner: any $\pi^+\pi^-$ combination out of 4π (4 per event) with an effective mass in the J/ψ region (taken between 3.0 and 3.2 GeV) is reconstructed as a $\mu^+\mu^-$ pair by reassigning the muon mass to the $\pi^+\pi^-$ tracks. Thus we get the $J/\psi\pi^+\pi^-(J/\psi \rightarrow \mu^+\mu^-)$ channel from the four tracks when any one of the four neutral dipion mass combinations is between 3.0 GeV and 3.2 GeV. In Figure 42, we plot the $J/\psi\pi^+\pi^-$ invariant mass thus obtained. The sharp $\psi'(3685)$ is seen here well above the background. The fit used consists of a Gaussian superposed over a polynomial background. The results of the fit are given in Table 16. They are in good agreement with previous photoproduction results[68]. Our mass is about 1σ greater than the mass given by the PDG group[4] while our width reflects our experimental resolution in this mass region. The resonance appears with a statistical significance slightly greater than three standard deviations (3σ). No enhancement is observed in the 3.836 GeV region, where a state was seen by the E705 collaboration in their $J/\psi\pi^+\pi^-$ final state obtained from $\pi^\pm\text{Li}$ interactions[69]. However, there does appear to be an excess of events in the vicinity of 4.1 GeV, but because of the statistical weakness of the signal no quantitative statements can be made.

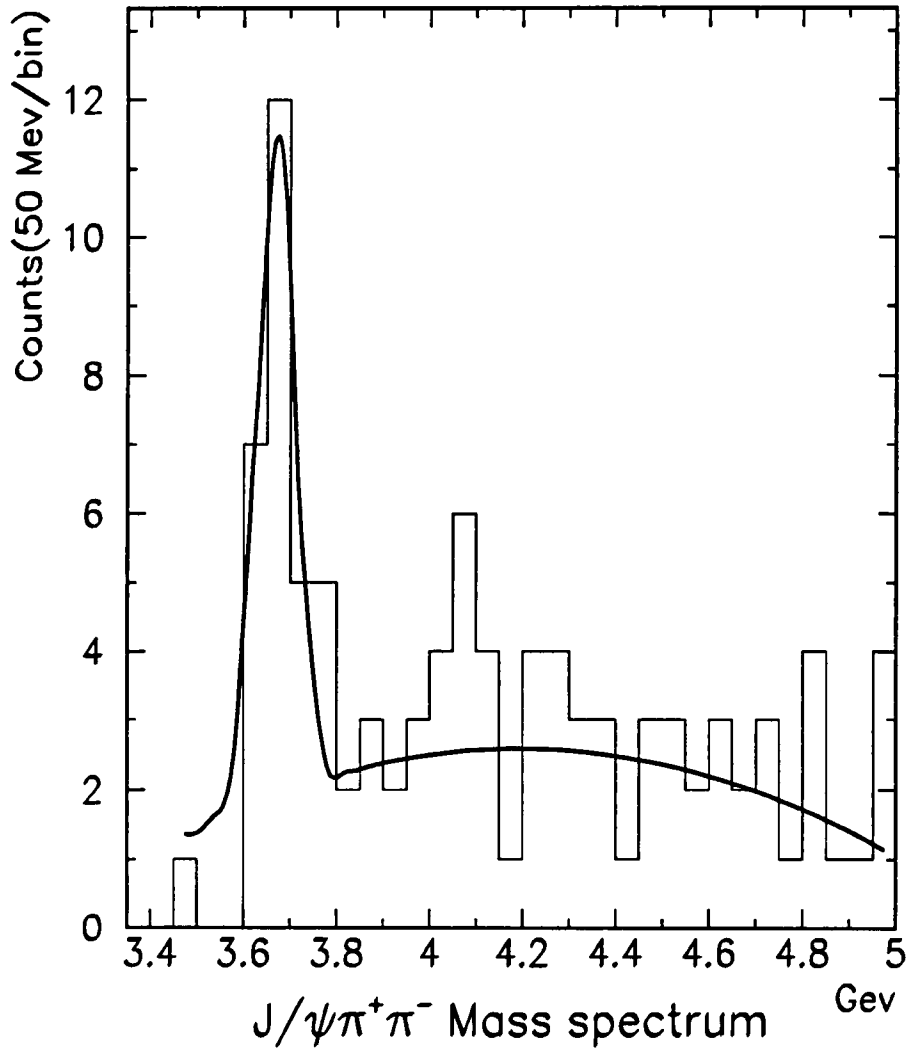


Figure 42: The $J/\psi\pi^+\pi^-$ mass spectrum from the $\mu^+\mu^-\pi^+\pi^-$ channel. The sharp $\psi'(3685)$ resonance is clearly seen. The smooth fit shown is a Gaussian over a polynomial background.

Table 16: The fit parameters of the $J/\psi\pi^+\pi^-$ mass spectrum.

Resonance	Yield	Mass (GeV)	Width (GeV)
$\psi'(3685)$	19 ± 6	3.668 ± 0.013	0.039 ± 0.018

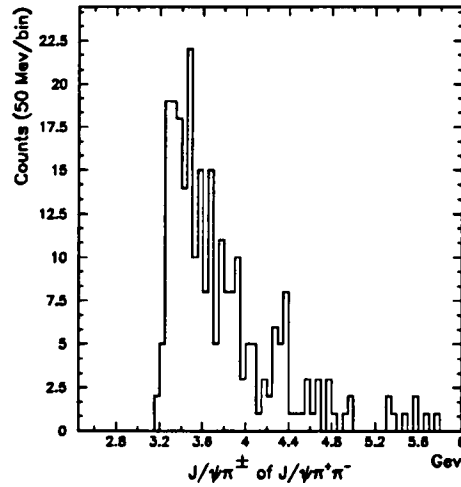


Figure 43: The $J/\psi\pi^\pm$ mass spectrum from the $J/\psi\pi^+\pi^-$ channel. No apparent structures are visible.

of the statistical weakness of the signal no quantitative statements can be made.

We have also searched for evidence of a signal in our $J/\psi\pi^\pm$ mass spectrum of the $J/\psi\pi^+\pi^-$ channel. As shown in Figure 43, the spectrum shows no evidence for any structure that is statistically significant.

4.3.4 The $K^+K^-K^+K^-$ Reaction Channel

Because of the requirement, introduced during the skimming stage, that in an event containing four kaon identified tracks at least one K^+K^- pair should be in the K^+K^- mass region less than 1.1 GeV, this channel is effectively the ϕK^+K^-

sector. Thus we plot the $K^+K^-K^+K^-$ invariant mass spectrum as shown in Figure 44 (A) and the same $K^+K^-K^+K^-$ invariant mass spectrum with the additional requirement that at least one K^+K^- pair mass lie in the selected $\phi(1020)$ band (defined as $1.01 \leq m_{K^+K^-} \leq 1.03$) as shown in Figure 44(B). No interesting features are observed in either plots. Figure 45 shows the neutral K^+K^- combination mass (4 per event) from the $4K$ channel. A narrow $\phi(1020)$ dominates the spectrum. The fit shown is a Breit-Wigner with a flat background. No sudden decrease in this spectrum occurs at 1.1 GeV as happened in the case of the dikaon spectrum from $K^+K^-\pi^+\pi^-$ channel. This is because the skim requirement imposed on our sample required only one of the K^+K^- mass combination to have mass less than 1.1 GeV. No other mass restrictions were applied to the events. We plot the opposite K^+K^- mass as shown in Figure 46. Since one neutral dikaon pair is already required to be a ϕ , this opposite pair plot is essentially unbiased. Apart from a few $\phi(1020)$'s two other enhancements are visible here. The first peak after the ϕ in the vicinity of 1.2 GeV may be indicative of the not so well established $f_0(1240)$, which is the only entry, in the PDG table[4], in this mass region, for which a decay to $K\bar{K}$ is listed. It's only previous observation was in the amplitude analysis of the reaction $\pi^-p \rightarrow K_s^0 K_s^0 n$ at 23 GeV/c[88]. The resonance at 1.5 GeV is consistent with the well established $f_2'(1525)$ which has been observed before in the K^+K^- mass spectrum from the ϕK^+K^- channel produced in e^+e^- annihilation experiments[36]. Neither of these mesons has been reported in photoproduction experiments. The fit in Figure 46 consists of three Breit-Wigners over a polynomial background which is embedded with a rising exponential function. The $\phi(1020)$ peak sitting on a rapidly rising background is found to be best described by means of such a background. Table 17 summarizes the fit parameters obtained. The $\phi(1020)$ and $f_2'(1525)$ peaks are found to have a statistical significance greater than 4σ . The PDG table[4] quotes a significant $f_0(975)$ branching ratio to $K\bar{K}$ state ($\sim 22\%$). The $f_0(975) \rightarrow \pi^+\pi^-$ branching ratio is also given as $\sim 78\%$. From these BR values, along with the observation of 74 ± 24 $f_0(975)$ events in the dipion

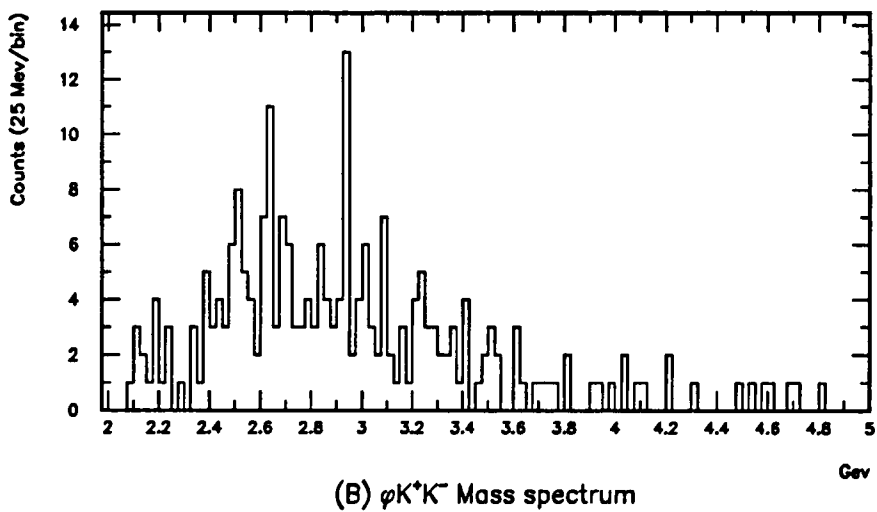
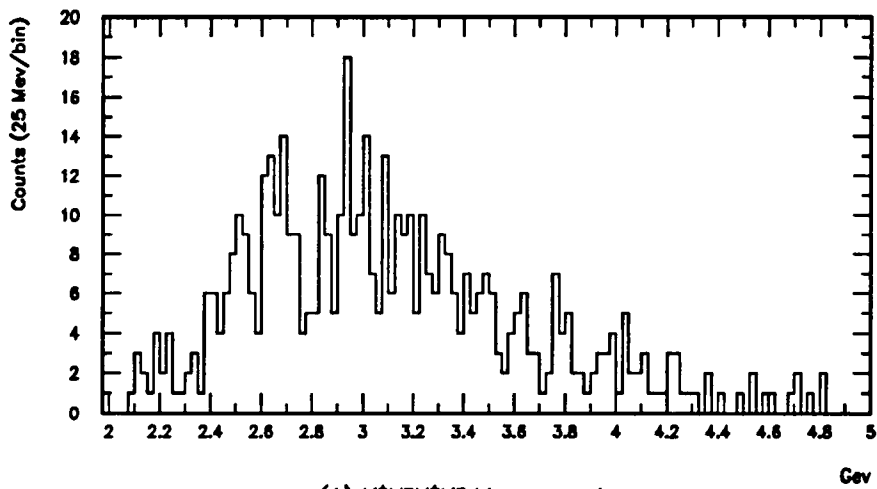


Figure 44: (A) The $K^+K^-K^+K^-$ mass spectrum. (B) The same spectrum with the requirement that at least one ϕ be present in the four possible K^+K^- pairs. The ϕ band was chosen in the region $1.01 \leq m_{K^+K^-} \leq 1.03$. No apparent structures are observed in either one of these spectra.

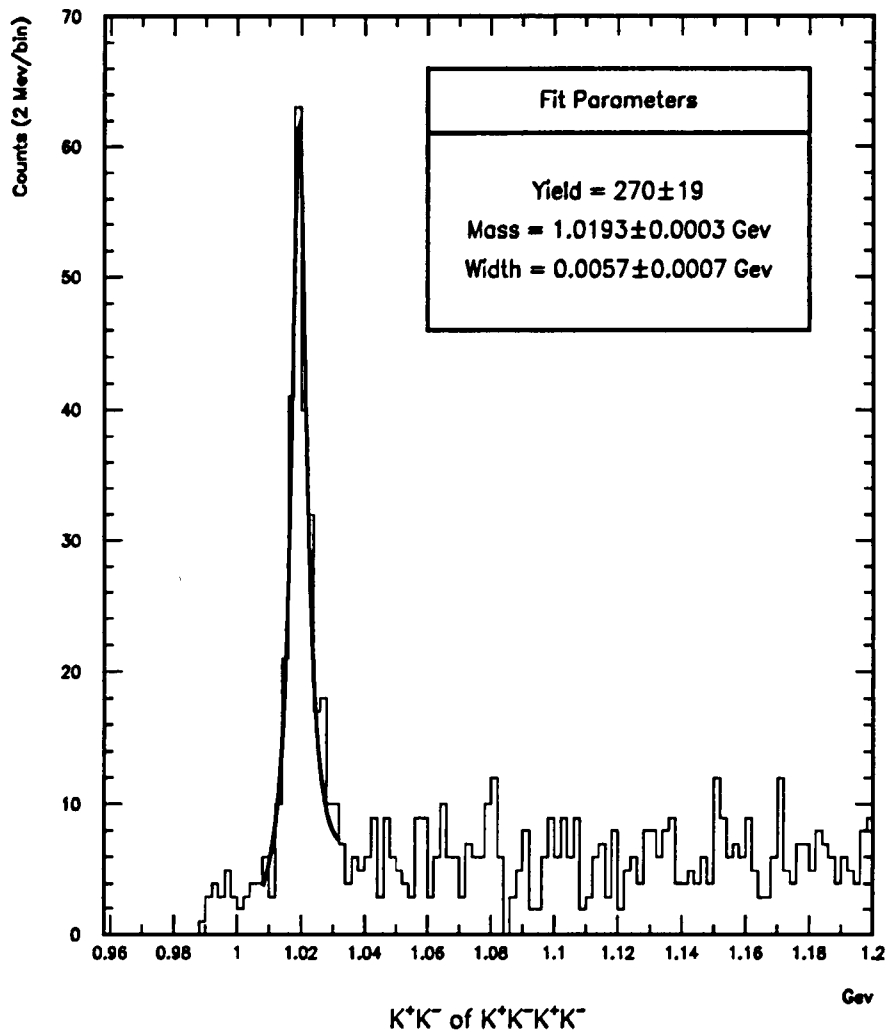


Figure 45: The K^+K^- mass spectrum from $K^+K^-K^+K^-$ channel. A sharp $\phi(1020)$ signal is seen. Results of the fit described in the text are shown.

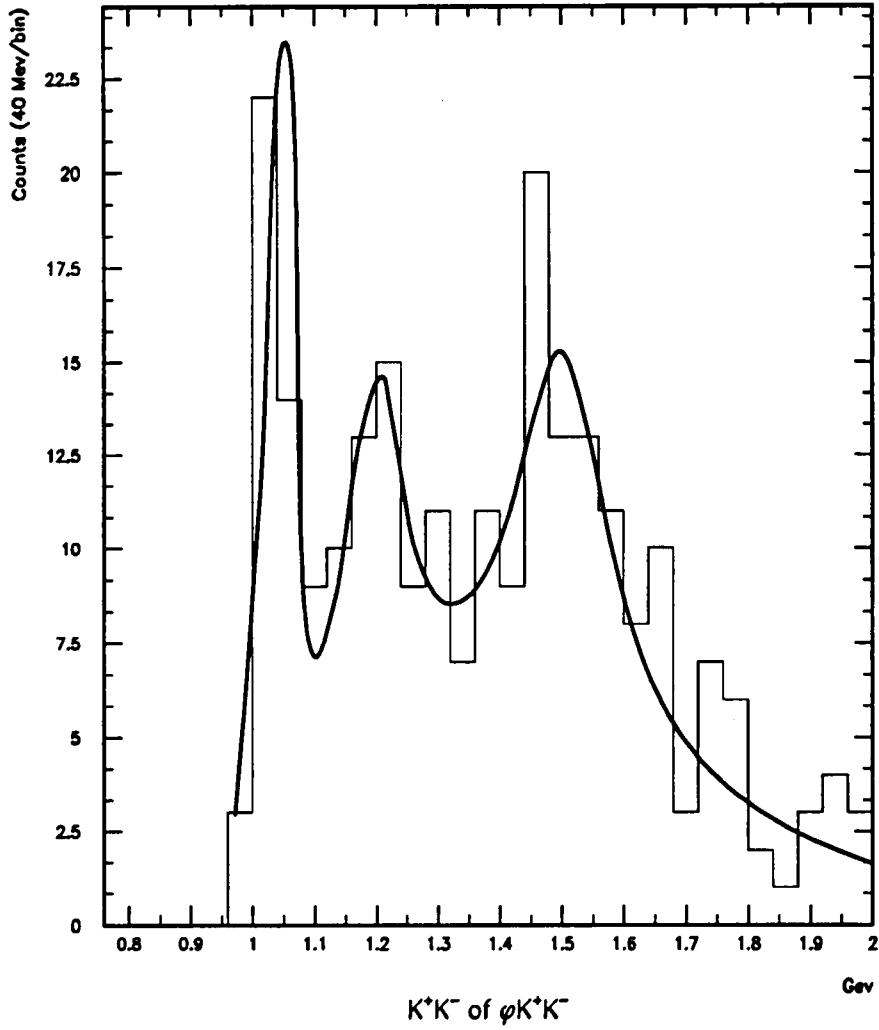


Figure 46: The K^+K^- effective-mass spectrum for the second pair when the first pair falls in the ϕ mass band. Apart from the clear signals of $\phi(1020)$ and $f_2'(1525)$, an enhancement near 1.2 GeV is also evident. The only resonance in this region that decays to a K^+K^- pair is the not so well established $f_0(1240)$. The fit shown is described in the text.

Table 17: The fit parameters of the K^+K^- mass spectrum opposite to the ϕ in the ϕK^+K^- channel.

Resonance	Yield	Mass (GeV)	Width (GeV)
$\phi(1020)$	83 ± 20	1.036 ± 0.003	0.010 ± 0.019
$f_0(1240)$	37 ± 14	1.200 ± 0.020	0.100 ± 0.060
$f_2'(1525)$	77 ± 15	1.500 ± 0.023	0.182 ± 0.050

mass spectrum of the $\phi\pi^+\pi^-$ channel (see Figure 36 and Table 13), we should expect to see roughly 21 ± 7 $f_0(975)$'s in Figure 46 (since the $f_0(975)$ peaks close to 1 GeV, significantly different behavior is to be expected for it's K^+K^- and $K_s^0\bar{K}_s^0$ decays). No evidence for the $f_0(975)$ signal is seen in our plot (Figure 46).

In Figure 47 we plot the scatter diagram of the invariant masses of the K^+K^- pairs. Though the statistics are weak, it is clear that there is no significant enhancement in the $\phi\phi$ overlap region.

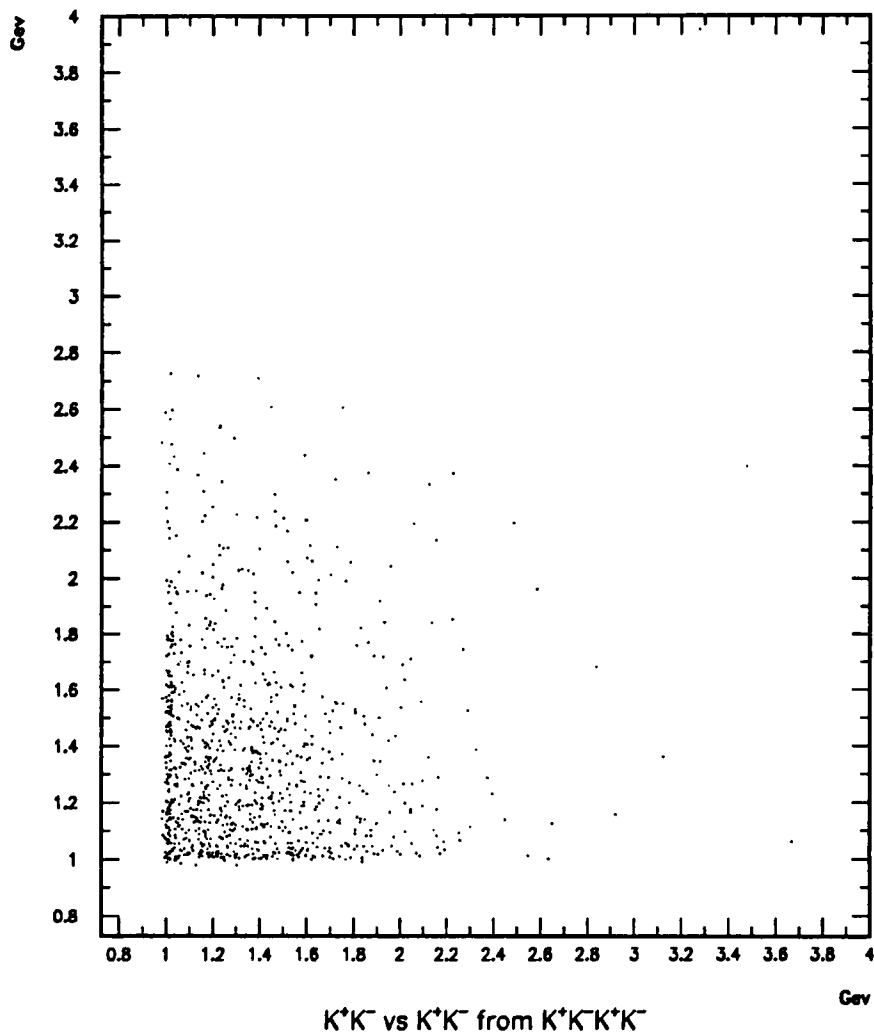


Figure 47: The K^+K^- vs K^+K^- mass scatter plot from the $4K$ channel. Only the bands corresponding to $\phi(1020)$'s are clearly seen. No evidence for the associated $\phi\phi$ or $\phi f'_2$ production are visible.

Chapter 5

Monte Carlo Simulations

5.1 The Super Rogue (SROGUE)

A Monte Carlo program called SROGUE, developed by the E687 collaboration, is used in order to study the geometrical, triggering and reconstruction efficiencies. This stand-alone program is used specifically for this detector. The SROGUE package consists of the following major components: GENERIC, an event generator; CHAT, an interactive specification file for defining a physics problem to GENERIC; and ROGUE which handles the detector simulation. GENERIC deals with the incident electron beam and its bremsstrahlung conversion in the lead radiator to produce the interacting photon beam. GENERIC also generates the particles of interest, from the photon interaction on the target, as specified by the user through the CHAT specification file and performs the decays of all unstable particles. The information from GENERIC is then fed into ROGUE, which simulates the detector components and transports the final state particles, produced by GENERIC, through them, generating appropriate responses as if the detector system is actually tracing the particles. The reconstruction and user routines are then run on this 'raw' data output from ROGUE, generated in accord with various trigger setups that were originally used over the run period.

GENERIC

The incident electron beam generated by GENERIC is parametrized to follow the electron energy profile obtained from BGM/BCAL detectors during the real electron beam calibration runs. It is then allowed to pass through the lead radiator producing bremsstrahlung photons. The electrons are also allowed to undergo multiple coulomb scattering in the radiator. The bremsstrahlung photons emerging from the radiator are then treated through the experimental target, where the creation of an event by a photon is determined by a step function over the target length. The vertex position of the event is randomized within the target volume the limit of which was determined by the photon beam spread. Multiple bremsstrahlung photons from the radiator is not used to create an event inside the experimental target. The energy of the recoiled electron from the radiator is simulated in RESH and additional energy such as noninteracting photons and/or multibremsstrahlung photons appearing in BGM/BCAL are properly tagged and kept. As mentioned before, the particles of interest, as specified by the CHAT file, are produced by GENERIC in the photon interaction. This CHAT file can be constructed either by hand or by means of an interactive program. The decay mode of the generated particle, if unstable, is also specified in this file. Generally, the CHAT file only deals with one of the decay mode at a time.

In order to study the acceptance of the apparatus as a function of the invariant mass of the final particle state in each reaction channels of interest, the particle mass is generated flat with an $e^{-10|t'|}$ distribution in the C.M frame, and with a flat angular distribution. Analysis of the production of a specific vector meson is carried out by generating it's mass with a non-relativistic Breit-Wigner or Gaussian profile and a $\sin^2\theta$ function for their angular distribution in the helicity frame. This implies that the vector mesons are created with the helicity of the incident photon.

ROGUE Detector

ROGUE traces each final state particle produced by GENERIC through the

spectrometer and simulates the response of the detector components to the particles as well as the response of the particles to the spectrometer (such as multiple coulomb scattering, magnetic deflection, etc.). It 'walks' each particle to specified 'stopping locations' until one of the following condition is met: the particle uses up it's decay path, fails to clear an aperture, or leaves the spectrometer volume. These stopping locations could be: SSD or PWC, in which case 'hits' are simulated; or Čerenkov detectors, in which case photons are generated and tracked to the PMT's. ROGUE also takes into account multiple coulomb scattering, and the aperture of a device to determine if the particle is accepted by it. It can also simulate PWC chamber inefficiencies by dropping the number of hits, and add hits to simulate noise. The triggering setups for the 1990-91 runs are also simulated in ROGUE for different periods of run.

5.2 Mass Acceptance and Phase Space Studies

The detector acceptance, as a function of the invariant mass, is determined through SROGUE by taking the ratio of the reconstructed events to the Monte Carlo generated events. These SROGUE generated events have no weights attached to them and are not produced according to a uniform population of the respective channel phase space. Thus the estimated acceptance ratio is an approximate calculation. The acceptance curves obtained in this way for the $\pi^+\pi^-\pi^+\pi^-$ and $K^+K^-\pi^+\pi^-$ channels, after all the relevant analysis cuts have been applied, are shown in Figure 48.

Apart from the SROGUE, another Monte Carlo routine known as SAGE is also used in order to investigate the phase space available in certain reaction channels under study. SAGE is a set of subroutines that generate Monte carlo events with preferred phase space density distribution. In our study, SAGE is used to generate events that correspond to a uniform population of phase space.

As discussed in Chapter 4, the presence of what appears to be an excess number

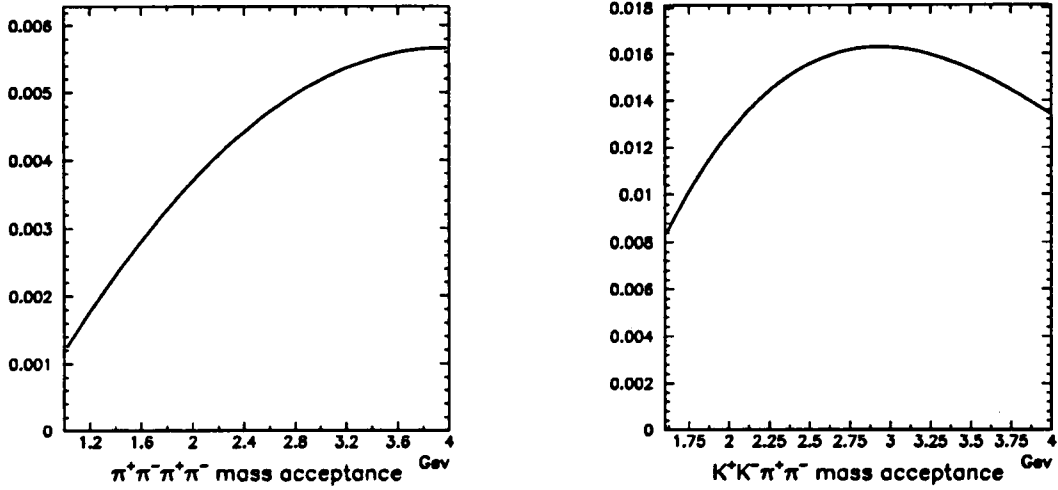


Figure 48: The mass acceptance curves as determined from SROGUE for the $\pi^+\pi^-\pi^+\pi^-$ and $K^+K^-\pi^+\pi^-$ channels. All the analysis cuts have been accounted for in the monte carlo runs.

of events near ~ 2.05 GeV in the $\rho_3\pi^\pm$ mass spectrum (see Figure 29) is investigated through a SAGE phase space study. A photon interaction energy distribution, closely resembling that of the real situation, is modeled and the $\gamma p \rightarrow \pi^+\pi^-\pi^+\pi^-p$ phase space profile is simulated. The $\rho\pi^\pm$, $f_2\pi^\pm$, and $\rho_3\pi^\pm$ mass spectra from this phase space distribution is then formed by selecting the respective mass regions, similar to those used in the data analysis, for ρ , f_2 , and ρ_3 . Although no detector simulation is involved, these plots provided a general idea regarding the shape of the phase space present in the spectra. A comparison of the $\rho_3\pi^\pm$ spectrum obtained this way with the actual $\rho_3\pi^\pm$ spectrum from the data (Figure 29 (C)) showed reasonable agreement on the general shape of the background, except near the ~ 2.05 GeV region, where an excess of events were present in the actual data. This is suggestive of the evidence for the presence of the $a_3(2050)(\rightarrow \rho_3\pi)$ meson¹ which has been observed previously in a charge exchange channel analysis[80]. A

¹The $a_3(2050)$ is the only meson with a $\rho_3\pi$ decay mode that is listed in the PDG table[4].

similar study involving the $f_2\pi^\pm$ spectrum from Monte Carlo showed differences in the general phase space profile near the ~ 1.7 GeV region where the spectrum peaks in the actual data (Figure 29 (B)). Such an observation, along with the fact that the origin of $f_2(1270)$ in the dipion spectrum (Figure 28) can only be interpreted as arising from the decay of a heavier meson (for reasons discussed in Chapter 4, p72), suggests the presence of $\pi_2(1670)(\rightarrow f_2\pi)$ in the $f_2\pi^\pm$ mass spectrum.

Chapter 6

Summary and Conclusions

We have studied the photoproduction of mesons in the $\pi^+\pi^-\pi^+\pi^-$, $K^+K^-\pi^+\pi^-$, $J/\psi\pi^+\pi^-$, and $K^+K^-K^+K^-$ channels. The neutral 4π invariant mass spectrum shows the familiar broad $\rho'(1600)$ enhancement and a narrow peak at ~ 2.1 GeV. The enhancement in the $\rho'(1600)$ region does not lend itself to further detailed analysis due to its broad nature. The interesting feature of this channel is the presence of clear signals due to the $\rho(770)$, $f_2(1270)$, and $\rho_3(1690)$ resonances in the neutral dipion subspectrum. The masses and widths obtained for these states agreed very well with those quoted in the Particle Data Group guide. That these $\rho(770)$ mesons are most likely to be the decay product of higher mass state(s) is consistent with the lack of any skewing in the $\rho(770)$ mass region of the dipion spectrum, which is always seen in diffractive ρ photoproduction. Since, owing to charge conjugation invariance, the $f_2(1270)$ can be photoproduced neither through Pomeron exchange (diffractive) nor through OPE (charge exchange), its presence virtually demands it to be the decay product of a higher mass meson. Although the $\rho_3(1690)$ meson could be photoproduced either diffractively or through charge exchange process, the analyses of this experiment represent its only observation in forward photoproduction. Because there has never been any indication of its photoproduction in the reaction $\gamma p \rightarrow p\rho_3 \rightarrow p\pi^+\pi^-$, its origin in this experiment is likely to be as the decay product of a more massive state. A detailed examination

of the $\rho\pi^\pm$ mass spectrum revealed the presence of the $a_2(1320)$ meson, most likely being produced along with Δ 's through an OPE mechanism. The $\rho_3\pi^\pm$ mass spectrum shows evidence for an excess of events in the $a_3(2050)(\rightarrow \rho_3\pi)$ region. The $f_2\pi^\pm$ spectrum on the other hand contains no readily identifiable structure but appears to peak broadly near what is the $\pi_2(1670)(\rightarrow f_2\pi)$ region. The presence of large backgrounds in these two spectra, however, does not permit us to make a stronger statement.

Another interesting aspect of the neutral 4π mass spectrum is the presence of an unusual narrow peak at ~ 2.1 GeV. A fit to this peak region yields a signal of 3.1σ significance, with the fit parameters very close to those obtained for a similar unexplained enhancement observed by the TASSO collaboration in their 4π mass spectrum from the $\gamma\gamma \rightarrow \pi^+\pi^-\pi^+\pi^-$ channel. This enhancement could not be identified with any of the states given in the PDG table in the ~ 2.1 GeV vicinity as none has been observed to decay into a neutral 4π state. If this enhancement represents a new particle, its relatively high mass and narrow width suggests it is a state with unusual properties.

The $K^+K^-\pi^+\pi^-$ reaction channel is effectively the $\phi\pi^+\pi^-$ sector because of the restriction, $M_{K^+K^-} < 1.1$ GeV (ϕ mass cut), employed on such events in the original data tapes used. The dikaon mass spectrum in this channel contains a sharp $\phi(1020)$ resonance. The dipion mass spectrum of the accompanying pions shows clear signals due to the $\rho(770)$ and $f_0(975)$ resonances-both with a statistical significance exceeding 3σ . The absence of $f_0(975)$ signal in the dipion spectrum when the dikaon mass is required to be outside the $\phi(1020)$ band (ϕ band = $1.01 \leq m_{K^+K^-} \leq 1.03$ GeV) shows that they are produced only with the $\phi(1020)$'s. The most interesting feature of this channel is the presence of a 7σ enhancement at ~ 1.93 GeV in the $\phi\rho$ mass spectrum. Since no ordinary $q\bar{q}$ states can exist in this OZI forbidden channel, this enhancement is suggestive of a non- $q\bar{q}$ state. The MIT bag model does predict an isovector four-quark tensor state at a mass of ~ 1.95 GeV, which could decay into $\phi\rho$ and $K^{*0}\bar{K}^{*0}$. Our enhancement at ~ 1.93

GeV could thus be consistent with the presence of this four-quark state mainly decaying into a $\phi\rho$ final state. A previously unobserved structure (3σ effect) at ~ 2.3 GeV is also seen in the $\phi f_0(975)$ mass spectrum of this channel.

Apart from the $\rho(770)$, $f_2(1270)$, and $\rho_3(1690)$ signals, the neutral dipion mass spectrum from the neutral 4π channel displays a reasonably good (3σ) $J/\psi(3097)$ resonance. Since the branching ratio for $J/\psi \rightarrow \pi^+\pi^-$ is very small, these events are almost certainly due to muons which are misidentified as pions. The $J/\psi\pi^+\pi^-$ ($J/\psi \rightarrow \mu^+\mu^-$) mass spectrum reconstructed from the neutral 4π sample displays a clear $\psi'(3685)$ peak, the fit parameters of which are consistent with those obtained from the only other previous ψ' photoproduction result[68].

No clear structure could be delineated from the overall neutral $4K$ mass spectrum. The dikaon mass spectrum contains a narrow $\phi(1020)$ signal. An examination of the K^+K^- invariant mass spectrum for the second dikaon pair, when the first pair falls in the defined $\phi(1020)$ mass band, revealed clear signals from $\phi(1020)$ and $f'_2(1525)$ resonances along with a statistically weaker enhancement at ~ 1.2 GeV. This latter peak could represent the unconfirmed $f_0(1240)$ meson. Although there appears to be a small amount of $\phi\phi$ production, we found no evidence that an intermediate state ("glueball") was responsible for this.

BIBLIOGRAPHY

Bibliography

- [1] Murray Gell-Mann. "Symmetries of Baryons and Mesons." *Phys.Rev.*, **125**, 1067 (1962).
- [2] J.D.Bjorken and S.L.Glashow. "Elementary Particles and SU(4)." *Phys.Lett.*, **11**, 255 (1964).
- [3] S.L.Glashow, J.Illiopoulos, and L.Maiani. "Weak Interactions with Lepton-Hadron Symmetry." *Phys.Rev.*, **D2**, 1285 (1970).
- [4] Particle Data Group. "Review of Particle Properties." *Phys.Rev.*, **D45**, (1992).
- [5] N.Isgur and S.Godfrey. "Mesons in a Relativized Quark Model with Chromodynamics." *Phys.Rev.*, **D32**, 189 (1985).
- [6] R.H.Graham and P.J.O'Donnell. "Light-Quark Spectroscopy and Radial Excitations." *Phys.Rev.*, **D19**, 284 (1979).
- [7] N.Hasenfratz and J.Kuti. "The Quark Bag Model." *Phys.Reports.*, **40C**, 75 (1978).
- [8] M.Shifman. "QCD and Resonance Physics. Theoretical Foundations." *Nuc.Phys.*, **B147**, 385 (1979).
- [9] K.G.Wilson. "Confinement of Quarks." *Phys.Rev.*, **D10**, 2445 (1974).

- [10] S.Meshkov *et al.* DOE-ER-01545-382., *unpublished*, (1986).
- [11] F.E.Close. "Gluonic Hadrons." *Rep.Prog.Phys.*, **51**, 833 (1988).
- [12] T.Barnes. "(A Few) Open Questions in Hadron Spectroscopy." *Invited contribution to the workshop on Future Directions in Particle and Nuclear Physics at Multi-GeV Hadron Beam Facilities.*, Brookhaven, March 1993.
- [13] R.L.Jaffe. "Multiquark Hadrons. Phenomenology of $Q^2\bar{Q}^2$ Mesons." *Phys.Rev.*, **D15**, 267 (1977).
- [14] N.Isgur and J.Weinstein. "Do Multiquark Hadrons Exist?" *Phys.Rev.Lett.*, **48**, 659 (1982).
- [15] N.Isgur and J.Weinstein. " $qq\bar{q}\bar{q}$ System in a Potential Model." *Phys.Rev.*, **D27**, 588 (1983).
- [16] N.Isgur, J.Paton, and R.Kokoski. "Gluonic Excitations of Mesons: Why They are Missing and Where to Find Them." *Phys.Rev.Lett.*, **54**, 869 (1985).
- [17] N.Isgur and J.Paton. "A Flux Tube Model for Hadrons." *Phys.Lett.*, **124B**, 247 (1983).
- [18] A.LeYaounc, *et al.* " $q\bar{q}g$ Hybrid Mesons in $\psi \rightarrow \gamma + \text{Hadrons}$." *Z.Phys.*, **C28**, 309 (1985).
- [19] F.E.Close. *An Introduction to Quarks and Partons.* Academic Press, San Diego, CA., 1983.
- [20] N.Törnqvist. "Possible Large Deuteronlike Meson-Meson States Bound by Pions." *Phys.Rev.Lett.*, **67**, 556 (1991).
- [21] E.S.Swanson. "Inter-Meson Potentials from the Constituent Quark Model." *Ann.Phys.*, **220**, 73 (1992).

- [22] T.Barnes and F.E.Close. "A Light Exotic $q\bar{q}g$ Hermaphrodite Meson?" *Phys.Lett.*, **116B**, 365 (1982).
- [23] T.Barnes and F.E.Close. " $q\bar{q}g$ Hybrid Mesons in the MIT Bag Model." *Nucl.Phys.*, **B224**, 241 (1983).
- [24] M.S.Chanowitz and S.R.Sharpe. "Hybrids: Mixed States of Quarks and Gluons." *Nucl.Phys.*, **B222**, 211 (1983).
- [25] T.Barnes. "Two-Photon Decays Support the $(K\bar{K})$ -Molecule Picture of the $S^*(975)$ and $\delta(980)$." *Phys.Lett.*, **165B**, 434 (1985).
- [26] D.Morgan and M.R.Pennington. " $f_0(S^*)$: Molecule or Quark State?" *Phys.Lett.*, **258B**, 444 (1991).
- [27] H.Albrecht, *et al.* "Inclusive Production of $\eta'(958)$ and $f_0(975)$ Mesons in the Υ Energy Region." *DESY 92-174.*, 1992.
- [28] N.N.Achasov, S.A.Devyanin, and G.N.Shestakov. "Two Photon Production of Four-Quark States." *Phys.Lett.*, **108B**, 134 (1982).
- [29] N.N.Achasov, S.A.Devyanin, and G.N.Shestakov. "To Search for Four-Quark States in $\gamma\gamma$ -Collisions." *Z.Phys.*, **C16**, 55 (1982).
- [30] F.E.Close and H.J.Lipkin. " $\phi\pi$ Production by Photons as a Signature for Four-Quark States." *Phys.Rev.Lett.*, **41**, 1263 (1978).
- [31] S.I.Bityukov, *et al.* "Study of a Possible Exotic 1.5 GeV Meson decaying into $\phi\pi^0$." *Phys.Lett.*, **188B**, 383 (1987).
- [32] S.I.Bityukov, *et al.* "Observation and Study of the Vector Meson $C(1480)$ which Decays by the Channel $\phi\pi^0$." *Sov.J.Nucl.Phys.*, **46**, 273 (1987).
- [33] F.E.Close and H.J.Lipkin. "New Experimental Evidence for Four-Quark Exotics. The Serpukhov $\phi\pi$ Resonance and the GAMS $\eta\pi$ Enhancement." *Phys.Lett.*, **196B**, 245 (1987).

- [34] N.N.Achasov and A.A.Kozhevnikov. "Is the Resonance $C(1480)$ in the $\phi\pi^0$ Mass Spectrum a New Meson?" *Phys.Lett.*, **207B**, 199 (1988).
- [35] V.P.Kubarovskii, L.G.Landsberg, and V.F.Obraztsov. "Once More on the Nature of the $C(1480)$ Meson." *Sov.J.Nucl.Phys.*, **48**, 837 (1988).
- [36] A.Falvard, *et al.* "Study of Hadronic J/ψ Decays Involving ϕ and ω Production." *Phys.Rev.*, **D38**, 2706 (1988).
- [37] T.H.Bauer, R.D.Spital, and D.R.Yennie. "The Hadronic Properties of the Photon in High-Energy Interactions." *Rev.Mod.Phys.*, **50**, 261 (1978).
- [38] J.J.Sakurai. "Theory of Strong Interactions." *Ann.Phys.*, **11**, 1 (1960).
- [39] V.N.Gribov. "Interaction of Gamma Quanta and Electrons with Nuclei at High Energies." *Sov.Phys.*, **JTEP 30**, 709 (1970).
- [40] S.J.Brodsky and J.Pumplin. "Photo-Nucleus Total Cross Sections." *Phys.Rev.*, **182**, 1794 (1969).
- [41] G.T.Condo, *et al.* "Charge Exchange Photoproduction of the $a_2^-(1320)$ in Association with Δ^{++} at 19.3 GeV/c." *Phys.Rev.*, **D41**, 3317 (1990).
- [42] G.T.Condo, *et al.* "Further Results from Charge Exchange Photoproduction." *To be published.*, 1993.
- [43] F.E.Low. "Model of a Bare Pomeron." *Phys.Rev.*, **D12**, 163 (1975).
- [44] L.Bertocchi. "Theoretical Aspects of High Energy Phenomenology." *Proc. Heidelberg Int.Conf. on Elementary Particles.*, North-Holland, Amsterdam, 1968.
- [45] S.C.Frautschi. *Regge Poles and S-Matrix theory.* Benjamin, New York, NY., 1963.
- [46] M.Davier, *et al.* *SLAC-PUB-666.*, unpublished, (1969).

- [47] G.Bacci, *et al.* "Multihadronic Cross Sections from e^+e^- Annihilation at C.M Energies between 1.4 and 2.4 GeV." *Phys.Lett.*, **38B**, 551 (1972).
- [48] H.H.Bingham, *et al.* "Observation of a Four-Pion Vector Meson State of Mass ≈ 1.5 GeV Produced by Linearly Polarized 9.3 GeV Photons." *Phys.Lett.*, **41B**, 635 (1972).
- [49] M.Davier, *et al.* "The Reaction $\gamma p \rightarrow \pi^+\pi^-\pi^+\pi^-p$ at High Energy and Photon Dissociation into Four Pions." *Nucl.Phys.*, **B58**, 31 (1973).
- [50] G.Alexander, *et al.* "The Study of High Energy Photoproduction with Positron Annihilation Radiation. The Reaction $\gamma p \rightarrow p\pi^+\pi^-\pi^+\pi^-$." *Phys.Rev.*, **D8**, 1965 (1973).
- [51] M.S.Atiya, *et al.* "High-Energy Photoproduction of $\rho'(1600)$." *Phys.Rev.Lett.*, **43**, 1691 (1979).
- [52] P.Schacht, *et al.* "Resonance Production in the Reaction $\gamma p \rightarrow p\pi^+\pi^-\pi^+\pi^-$ in the Energy Range $E_\gamma = 3.0-18.0$ GeV." *Nucl.Phys.*, **B81**, 205 (1974).
- [53] D.Aston, *et al.* "The Reaction $\gamma p \rightarrow p\pi^+\pi^-\pi^+\pi^-$ for Photon Energies from 25 to 70 GeV." *Nucl.Phys.*, **B189**, 15 (1981).
- [54] M.Conversi, *et al.* "The Possible Existence of a Vector Meson $\rho'(1250)$." *Phys.Lett.*, **52B**, 493 (1974).
- [55] G.Cosme, *et al.* "Hadronic Cross Sections Study in e^+e^- Collisions from 1.350 GeV to 2.125 GeV." *Nucl.Phys.*, **B152**, 215 (1979).
- [56] G.Bacci, *et al.* "Measurement of the $e^+e^- \rightarrow \pi^+\pi^-\pi^+\pi^-$ Cross Section in the $\rho'(1600)$ Energy Region." *Phys.Lett.*, **95B**, 139 (1980).
- [57] A.Cordier, *et al.* "Study of the $e^+e^- \rightarrow \pi^+\pi^-\pi^+\pi^-$ Reaction in the 1.4-2.18 GeV Energy Range." *Phys.Lett.*, **109B**, 129 (1982).

- [58] F.Bulos, *et al.* "Photoproduction of High-Mass Di-Pion Pairs at 15 Bev". *Phys.Rev.Lett.*, **26**, 149 (1971).
- [59] K.Abe, *et al.* "Study of the $\rho'(1600)$ Mass Region Using $\gamma p \rightarrow \pi^+\pi^-p$ at 20 GeV". *Phys.Rev.Lett.*, **53**, 751 (1984).
- [60] D.Aston, *et al.* "Observation of the $\rho'(1600)$ in the Channel $\gamma p \rightarrow \pi^+\pi^-p$ ". *Phys.Lett.*, **92B**, 215 (1980).
- [61] V.E.Balakin, *et al.* "Measurement of the Electron-Positron Annihilation Cross Section in $\pi^+\pi^-$, K^+K^- Pairs at the Total Energy 1.18-1.34 GeV." *Phys.Lett.*, **41B**, 205 (1972).
- [62] B.Esposito, *et al.* "Momentum Analysis of Kaon and Pion Pairs Produced from Time-Like Photons at 1.6 GeV Energy." *Phys.Lett.*, **67B**, 239 (1977).
- [63] A.Donnachie and H.Mirzaie. "Evidence for Two ρ' (1600) Resonances." *Z.Phys.*, **C33**, 407 (1987).
- [64] A.B.Govorkov. "The Radial Excitation Spectrum of the ρ and ω Mesons and the Possible Existence of ρ_g and ω_g Hybrids." *Sov.J.Nucl.Phys.*, **48**, 150 (1988).
- [65] C.Erkai and M.G.Olsson. "On the Consistency of Electromagnetic Form Factors and $\pi\pi$ Scattering in the $\rho'(1600)$ Region." *Z.Phys.*, **C31**, 615 (1986).
- [66] G.S.Abrams, *et al.* "Decay of $\psi(3684)$ into $\psi(3095)$." *Phys.Rev.Lett.*, **34**, 1181 (1975).
- [67] D.Coffman, *et al.* "Direct Measurement of the J/ψ Leptonic Branching Fraction." *Phys.Rev.Lett.*, **68**, 282 (1992).
- [68] R.Barate, *et al.* "Measurement of J/ψ and ψ' Real Photoproduction on Lithium-6 at a Mean Energy of 90 GeV." *Z.Phys.*, **33**, 505 (1987).

- [69] L.Antoniuzzi, *et al.* "Search for Hidden Charm Resonance States Decaying into J/ψ or ψ' Plus Pions." *FERMILAB-PUB-92/265-E.*, 1993.
- [70] G.Smadja. "Symmetrization of Simple 4-Pion Decays." *LBL-991.*, unpublished, (1972).
- [71] The E687 Collaboration. "Description and Performance of the Fermilab E687 Spectrometer." *Nucl.Inst.Methods in Phys.Research.*, **A320**, 519 1992.
- [72] G.Bellini, *et al.* "The Microstrip Vertex Detector for the E687 Experiment at Tevatron" *Nucl.Inst.Methods.*, **A252**, 366 1986.
- [73] H.Mendez. *Measurement of the J/ψ Photoproduction Cross Section.* Ph.D. thesis, Cinvestav-IPN, Mexico, 1990.
- [74] B.G.Cheon . "Recent Charm Photoproduction Results from E687". *E687 internal memo.*, 1992.
- [75] J.E.Wiss, *et al.* Čerenkov Group Report. *E687 internal memo.*, 1988.
- [76] S.Bianco, *et al.* "Energy Calibration and Electron Identification in OE and IE." *E687 internal memo.*, 1989.
- [77] R.Yoshida. *High Energy Photoproduction of the J/ψ (J/ψ).* Ph.D. thesis, Northwestern University, 1990.
- [78] D.Lüke. "Recent Results from TASSO at PETRA." *Journal De Physique, suppl.*, **43**, C3-47 (1982).
- [79] D.L.Burke. "Photon-Photon Collisions." *Journal De Physique, suppl.*, **43**, C3-513 (1982).
- [80] G.R. Blackett. *Semi-Inclusive Production of Light Mesons by High Energy Photoproduction.* Ph.D. thesis, University of Tennessee, 1993.

- [81] R.J.Apsimon, *et al.* "Production of $f_2(1270)$ and $f_0(975)$ Mesons by Photons and Hadrons of Energy 65 - 175 GeV." *Z.Phys.*, **C56**, 185 (1992).
- [82] R.T.Deck. "Kinematical Interpretation of the First $\pi - p$ Resonance" *Phys.Rev.Lett.*, **13**, 169 (1964).
- [83] D.Aston, *et al.* "Observation of a Threshold Enhancement in the Reaction $\gamma p \rightarrow K^+ K^- \pi^+ \pi^-$ at γ Energies of 20-70 GeV." *Phys.Lett.*, **92B**, 219 (1980).
- [84] M.Atkinson, *et al.* "Search for a ϕ' Vector Meson in Diffractive Photoproduction $K^+ K^- \pi^+ \pi^-$." *Z.Phys.*, **C30**, 541 (1986).
- [85] D.R.Green, *et al.* "Observation of a Narrow Enhancement in $\phi K K$ and $\phi \pi \pi$ Final States Produced in 400-GeV p - N Interactions." *Phys.Rev.Lett.*, **56**, 1639 (1986).
- [86] M.C.Goodman, *et al.* "Study of the Okubo-Zweig-Iizuka Rule in Exclusive Photoproduction Reactions." *Phys.Rev.*, **D22**, 537 (1980).
- [87] T.A.Armstrong, *et al.* "A Study of the Centrally Produced $K^{*0} \bar{K}^{*0}$ Final State in the Reaction $pp \rightarrow p_f(K^+ K^- \pi^+ \pi^-) p_s$ at 300 GeV/c." *Z.Phys.*, **C46**, 405 (1990).
- [88] A.Etkin, *et al.* "Evidence for Two New 0^{++} Mesons and a Possible Scalar Decuplet." *Phys.Rev.*, **D25**, 2446 (1982).

Vita

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