Decay search for the supersymmetric R(0) (gluon gluino) hadron via the channel R(0) going to positive pion negative pion photino

Kevin Michael Hern
College of William & Mary - Arts & Sciences

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Decay Search for the Supersymmetric $R^0 (g\bar{g})$ Hadron via the Channel $R^0 \rightarrow \pi^+\pi^-\gamma$

A Dissertation
Presented to The Faculty of the Department of Physics
The College of William and Mary

In Partial Fulfillment
Of the Requirements for the Degree of
Doctor of Philosophy

By
Kevin Michael Hern
July 1999
APPROVAL SHEET

This dissertation is submitted in partial fulfillment of the requirements for the degree of

Doctor of Philosophy

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Robert E. Welsh

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Carl Carlson

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Richard Kiefer

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This work is dedicated to the memory of my father:

Stephen Charles Hern

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Abstract

There has been recent theoretical interest in supersymmetry breaking scenarios in which the gauginos are light compared to the squarks. One prediction of these light gluino models is the existence of the $R^0$ hadron ($g\bar{g}$). Brookhaven National Laboratory AGS Experiment 935 (E935) searched for light gluinos through the appearance of $\pi^+\pi^-$ pairs with invariant mass $M_{\pi\pi} > 545$ MeV/$c^2$ in a high flux neutral beam. The search has yielded one candidate event. This event is consistent with the anticipated background of 1.4 events due to interactions of neutrons in the beam with the residual gas in the evacuated decay region. Depending on the mass of the photino, we set an upper limit on the flux ratio of production of the hypothetical $R^0$ relative to that of the $K^0_L$ for $R^0$ particles in the mass and lifetime ranges of $0.91$ GeV/$c^2 < M_{R^0} < 2.0$ GeV/$c^2$ and $4 \times 10^{-10} \text{ s} < \tau < 1 \times 10^{-3} \text{ s}$ respectively.
Decay Search for the Supersymmetric $R^0 (g\bar{g})$ Hadron

via the Channel $R^0 \rightarrow \pi^+\pi^-\gamma$
Chapter 1

Introduction

This dissertation describes the search for a light gluino bound state undertaken at Brookhaven National Laboratory (BNL). BNL experiment 935 (E935) was proposed in December of 1996 [1] to run in the B5 beamline of the Alternating Gradient Synchrotron (AGS) and was approved for 1300 hours in a high-intensity 24 GeV/c proton beam in 1997. The E935 collaboration [2] comprises 12 individuals from four universities: the University of California at Irvine, the University of Richmond, Rensselaer Polytechnic Institute, and the College of William and Mary. Yunan Kuang of the College of William and Mary is the spokesperson. The detector system is derived from the BNL E871 [3] [4] [5] search for rare dilepton decays of the long-lived neutral kaon system.

E935 was run during the 1997 high-energy physics (HEP) running cycle of the AGS. The experiment was online 24 hours a day, seven days a week for eight weeks. Data were uploaded onto 124 4mm data tapes, each with a capacity of 2.0 Gigabytes of information. The data were then uploaded to data storage carts at the computing center of the Stanford Linear Accelerator Center (SLAC). Final data processing took place at the SLAC computer farm.

The search for a light gluino bound state has been motivated by recent speculations on a class of supersymmetric models which leave the gauginos massless at tree level [6] [7] [8].

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These models predict the existence of the $R^0$ hadron, a gluon-gluino ($g\bar{g}$) bound state with a mass on the order of the kaon mass. It is somewhat remarkable that such a light particle has not yet been convincingly ruled out by experiment. Farrar [9] has argued that the current generation of rare kaon decay experiments and experiments designed to measure the direct CP-violating parameter ratio $\epsilon'/\epsilon$ are ideally suited to look for light gluinos.

The discovery of the $R^0$ particle in the parameter space consistent with Farrar's predictions could provide experimental confirmation of supersymmetry as well as offer a solution to the cold dark matter problem. Either of these reasons on its own justifies a search for these hypothetical hadrons.

In the event that no $R^0$ candidate event is observed above the background predicted by Standard Model processes, the results of this experiment can be used to constrain theoretical models of supersymmetry breaking.
Chapter 2

Physics Motivation

2.1 The Standard Model

2.1.1 Overview

A crowning achievement of 20th century theoretical particle physics is the Standard Model (SM) of the strong and electroweak interactions originally put forth by Weinberg, Salam, and Glashow [10] [11] [12] [13].

The content of the SM describes all observed particles and their properties. Interactions between the spin-$\frac{1}{2}$ fermions are communicated via the exchange of gauge-mediating bosons of integer spin. Among the hadrons, all baryons are composed of three quarks and all mesons are quark-antiquark pairs. There are three families of quarks:

\[
\begin{pmatrix}
  u \\
  d
\end{pmatrix}, \quad
\begin{pmatrix}
  c \\
  s
\end{pmatrix}, \quad
\begin{pmatrix}
  t \\
  b
\end{pmatrix}
\]

and three families of leptons:
Each quark and lepton also has a corresponding anti-partner.

The gauge mediating bosons are the massless photon $\gamma$ and the massive vector bosons $W^\pm$ and $Z^0$ which mediate the electromagnetic and weak sectors of the electro-weak force, respectively. An octet of massless, colored gluons $g$ mediates the strong force in the quark sector; leptons do not experience the strong color force.

The Standard Model is a renormalizable Yang-Mills $SU(3)_C \otimes SU(2)_L \otimes U(1)_Y$ gauge theory. The gauge bosons correspond to the generators in the theory. The left-handed fermion fields are weak isodoublets and the right-handed fermion fields are weak singlets.

Quantum Chromodynamics (QCD) is the current theory of the strong interaction in the Standard Model. QCD is a gauge theory built on color invariance under a local $SU(3)_c$ = $SU(3)_{color}$ [14].

The $SU(2)_L \otimes U(1)_{Y}$ symmetry is broken in nature. The Standard Model prescription for spontaneously breaking the $SU(2)_L \otimes U(1)_{Y}$ symmetry is through the Higgs mechanism. Under the Higgs mechanism, a complex weak scalar doublet $\Phi$ is introduced into the theory:

$$\Phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix}$$

The non-zero vacuum expectation value (VEV) of the scalar doublet breaks the weak-hypercharge symmetry down to an unbroken $U(1)_{EM}$: electromagnetism. In spontaneously breaking $SU(2)_L \otimes U(1)_Y$, the real field of the neutral component of the complex Higgs scalar doublet acquires a vacuum expectation value. The physical spin-0 remaining
after this process is the Higgs boson, which has yet to be observed. It is the Yukawa coupling of the fermions to the Higgs component with a $V_{EV}$ (Higgs boson) that gives rise to the fermion masses. In addition, the other Higgs field couplings give mass to the vector bosons $W^\pm$ and $Z^0$ while leaving the photon massless. The discovery of these vector gauge bosons at CERN at 80 and 91 GeV/c$^2$, as predicted by Standard Model calculations, is considered one of the great triumphs of modern experimental physics [15–17].

2.1.2 Physics Beyond the Standard Model

The SM accurately describes all electro-weak phenomena down to scales of approximately $10^{-16}$ cm. However, there are theoretical and, at some level, aesthetic reasons to believe that the SM is not the fundamental theory of nature. First, the gravitational force is noticeably absent from the Standard Model. However, the development of a renormalizable, quantum theory of gravity is a formidable task. The search for a grand unified theory (GUT), which reduces to the Standard Model at low energy scales, continues to engage many theoretical physicists.

Next, recent evidence by the Superkamiokande collaboration [18] of neutrino oscillations implies that neutrinos have mass, whereas in the SM the neutrinos are strictly massless. Furthermore, the Standard Model does not provide a natural explanation as to why the fermion masses range from nearly massless neutrinos to the top quark with mass approximately 180 GeV/c$^2$ [19,20]. This imbalance in fermion masses is referred to as the fermion mass hierarchy problem.

The most serious problem arises in the Higgs sector of the Standard Model. Loop corrections to the mass of the Higgs boson are quadratically divergent [21] with a cut off at the GUT scale ($10^{16}$ GeV). To remedy these difficulties, the Higgs mass requires a cancellation of these divergences over at least 14 orders of magnitude to all orders in perturbation theory. This large cancellation requires extremely fine tuning of the model parameters in the Higgs sector of the SM and is referred to as the gauge hierarchy problem.
There are two proposed solutions to the gauge hierarchy problem. The first solution proposes to replace the Higgs field with a fermion-fermion bound state. This conjecture is the idea behind technicolor theories, although no completely satisfactory technicolor theory has emerged. The second solution to the gauge hierarchy problem is to introduce an additional, softly-broken symmetry between bosons and fermions into the Standard Model Lagrangian. This type of symmetry is referred to as supersymmetry.

2.2 Supersymmetry

2.2.1 Introduction to Supersymmetry

Supersymmetry (SUSY) is a relativistic symmetry between fermions and bosons. The idea of supersymmetry follows from the work of Gol'fand and Likhtman [22]. Shortly afterward, Volkov and Akulov [23] developed a theory invariant under a non-linear realization of SUSY, followed by Wess and Zumino [24], who introduced the first linear SUSY representation in terms of a quantum field theory.

The Minimal Supersymmetric Standard Model (MSSM) provides a general Lagrangian that is the minimal extension to the Standard Model that is invariant under a SUSY transformation (fermions ↔ bosons), up to a soft, symmetry-breaking term.

The realization of the MSSM implies that every particle has a corresponding super-partner with equal mass but with opposite spin statistics: the super-partners of the fermions are bosons and, conversely, the super-partners of the bosons are fermions. These bosonic (scalar) super-partners to the Standard Model fermions are named sleptons and squarks, respectively. The fermionic partners to the SM gauge bosons are named by appending the suffix -ino to the name of the gauge boson, yielding the following gauginos: the photino, Wino, Zino, gluino and Higgsino. Symbolically, all super-partners are denoted by the inclusion of a tilde over the symbol of the SM partner. Therefore, a selectron is denoted \( \tilde{e} \), the photino \( \tilde{\gamma} \), and similarly for the entire super-partner spectrum. In addition, two Higgs
doublets:

\[ H_U = \begin{pmatrix} H_u^0 \\ H_u^+ \end{pmatrix}, \quad H_D = \begin{pmatrix} H_d^+ \\ H_d^0 \end{pmatrix} \] (2.1)

are required to break \( SU(2)_L \otimes U(1)_Y \) in a SUSY theory [21]. The fermion masses are generated by Yukawa couplings to these Higgs doublets. This coupling implies, after three Higgs fields are absorbed to give mass to the \( W^\pm \) and \( Z^0 \), that there are five physical Higgs bosons \( (h, H_u^0, H_d^0, H^\pm) \). Each complex Higgs scalar gives rise to a fermionic super-partner yielding four Higgsino fermions: \( \tilde{H}_u^0, \tilde{H}_d^0, \tilde{H}^\pm \). The \( \tilde{H}^\pm \) and \( \tilde{W}^\pm \) couple to give rise to four massive chargino states, \( \tilde{\chi}_1^\pm, \tilde{\chi}_2^\pm \). The \( \tilde{\tau}, \tilde{Z}^0, \tilde{H}_u^0, \tilde{H}_d^0 \) couple to generate four physical neutralino states \( \tilde{\chi}_1^0, \tilde{\chi}_2^0, \tilde{\chi}_3^0, \tilde{\chi}_4^0 \). The full particle content of the MSSM is as follows:

<table>
<thead>
<tr>
<th>Standard Model Fermions (Spin ( \frac{1}{2} ))</th>
<th>Supersymmetric Bosons (Integer Spin)</th>
</tr>
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<tbody>
<tr>
<td>( \begin{pmatrix} u \ d \end{pmatrix}, \begin{pmatrix} c \ s \end{pmatrix}, \begin{pmatrix} t \ b \end{pmatrix} )</td>
<td>( \begin{pmatrix} \tilde{u} \ \tilde{d} \end{pmatrix}, \begin{pmatrix} \tilde{c} \ \tilde{s} \end{pmatrix}, \begin{pmatrix} \tilde{t} \ \tilde{b} \end{pmatrix} )</td>
</tr>
<tr>
<td>( \begin{pmatrix} \tilde{u} \ \tilde{d} \end{pmatrix}, \begin{pmatrix} \tilde{c} \ \tilde{s} \end{pmatrix}, \begin{pmatrix} \tilde{t} \ \tilde{b} \end{pmatrix} )</td>
<td>( \begin{pmatrix} \tilde{\nu}<em>e \ \tilde{\nu}</em>\mu \ \tilde{\nu}<em>\tau \end{pmatrix}, \begin{pmatrix} \tilde{\nu}<em>e \ \tilde{\nu}</em>\mu \ \tilde{\nu}</em>\tau \end{pmatrix} )</td>
</tr>
</tbody>
</table>

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The SUSY mass eigenstates arising from the gauge and Higgs sectors of SM are denoted as follows:

Standard Model Bosons (Integer Spin) \hspace{1cm} \text{Supersymmetric Fermions (Spin } \frac{1}{2} \text{)}

\((e)\) (8 species) \hspace{1cm} \((\tilde{g})\) (8 species)

\((W^\pm, H^\pm) \implies (\tilde{\chi}_1^\pm, \tilde{\chi}_2^\pm)\)

\((\gamma, Z^0, H_u^0, H_d^0) \implies (\tilde{\chi}_1^0, \tilde{\chi}_2^0, \tilde{\chi}_3^0, \tilde{\chi}_4^0)\)

and the last Higgs boson

\((h)\)
2.2.2 Solution to the Gauge Hierarchy Problem

A direct consequence of the MSSM is that for each loop diagram which arises in a SM calculation, there is an additional loop diagram corresponding to that particle's super partner, as shown schematically in Fig. 2.1. Since the particle-super partner pairs have opposite spin statistics, the loop diagrams have opposite signs. If SUSY was an exact symmetry in nature, the masses of the particle-super particle pairs would still be degenerate and these loop diagrams would cancel exactly. Since SUSY is a broken symmetry, this cancellation removes the leading divergent terms from renormalization calculations.

SUSY renders the gauge hierarchy problem natural by providing a series of these elegant cancellations of the divergent loop diagrams which arise from radiative corrections. The leading quadratic divergences from the self-energy diagrams are canceled by a corresponding diagram from the particle's super-partner, leaving mild logarithmic divergences [25]. These types of cancellation arise throughout SUSY calculations and give SUSY theories an
elegance and computational power that are extremely attractive from a theoretical point of view.

2.2.3 R-Parity and Proton Decay

The effective Lagrangian $\mathcal{L}$ for the MSSM can be derived from the superpotential $W$ of the theory. This superpotential can be written in its most general form as $\mathcal{W} = W_0 + W_L + W_Z$ [26], where

$$W_0 = y_{ij}^U Q^i u^j H_U + y_{ij}^D Q^i d^j H_D + y_{ij}^E L^i e^j H_D + \mu H_U H_D$$  \hspace{1cm} (2.2)

$$W_L = \lambda_{ijk} Q^i d^j L^k + \lambda_{ijk}^\prime e^i L^j L^k + \mu L^i H_U L^j$$ \hspace{1cm} (2.3)

and

$$W_Z = \lambda_{ijk}^\nu u^i d^j d^k.$$ \hspace{1cm} (2.4)

$Q^1$ is the superfield corresponding to the quark doublet $(u_d)^L$ and $Q^2$ and $Q^3$ correspond to the second and third generations; $H_{U,D}$ are the superfields related to the doublets defined in Eq. 2.1; $L^i$ are the superfields corresponding to the lepton left doublets; $u^i$, $d^i$ and $e^i$ are the superfields corresponding to the up-type quark singlets, down-type quark singlets and lepton singlets, respectively; and the $y_{ij}^{U,D,E}$ are coupling parameters.

While $W_0$ preserves global baryon and lepton conservation, as in the Standard Model, $W_Z$ and $W_L$ allow either baryon or lepton number violation, respectively. If either $W_Z$ or
is non zero, however, the lifetime of the proton is predicted to be on the order of \(10^{-12}\) sec [25]. This potential for disaster in supersymmetric theory is solved by one of two *ad hoc* assumptions, described below.

The first solution is to introduce a discrete symmetry into the theory. The action of this symmetry, called \(R\)-parity, is to assign a value of +1 to all SM particles and −1 to all super-partners. In addition to solving the proton-decay problem, this assumption has an added benefit: \(R\)-parity implies that the lightest supersymmetric particle (LSP) is absolutely stable to all orders. The relic LSPs from the formation of the universe could provide an excellent candidate for cold dark matter [27, 28].

The second solution is to set either \(W_Y\) or \(W_L\) equal to zero, but not both. These "\(R\)-parity violating" supersymmetric extensions to the standard model are an area of active research, but are beyond the scope of this treatise.

### 2.2.4 Other Consequences of the MSSM

In some SUSY breaking scenarios, the MSSM can explain features of the fermion hierarchy by incorporating a large \(R_u^0 - \tilde{t}_l\) coupling at the grand unified scale. This coupling, run down to the weak scale, forces \(M_{H_u}^2 < 0\) [21]. Thus, the mass ratio of the top quark to bottom quark, \(M_t/M_b\), can be predicted by the MSSM whereas it is introduced as a parameter to the SM [21].

Finally, the renormalization group running of the gauge coupling constants \(\alpha_i\), using a minimal supersymmetric model, results in a convergence of the couplings at a single point near the GUT scale, as shown in Fig. 2.2. This indirect evidence supports the notion that grand unified theories which incorporate supersymmetry will one day lead to a fundamental theory of nature. In addition, the best candidates thus far for quantum gravity theories are string theories which incorporate space-time supersymmetry.
2.2.5 Summary

Many questions and problems regarding SUSY models remain although they are deemed tractable. For instance, the MSSM introduces 43 physical CP-violating phases which need to be made unnaturally small in order to fit observation [26]. Some SUSY models solve this SUSY-CP problem naturally, as will be discussed in the next section. Furthermore, no SUSY predicted super-partners have been observed experientially.

The lack of super-partners near the masses of the known fermions implies that supersymmetry must be a broken symmetry. Therefore, the MSSM Lagrangian contains a soft breaking term used to break SUSY at the weak scale. The exact method which breaks supersymmetry and the phenomenological implications are open questions and active areas of theoretical research.
2.3 The $R^0$ Hadron

As mentioned previously, an immediate implication of R-parity conservation is that the lightest supersymmetric particle (LSP) is stable. It has been argued [6][29][30][31] that there are some schemes for breaking SUSY for which the gauginos have zero or negligible mass at tree level and trilinear scalar couplings. These models can be constructed to solve automatically the SUSY-CP problem; namely, the neutron electric dipole moment naturally stays below current experimental limits in these models. (The lightest neutralino is a nearly pure mass eigenstate of the photino [28] in these scenarios and will be referred to as the photino from here on.) The gauginos acquire calculable, low-scale masses through higher order radiative corrections of top-stop (the super partner to the top quark) and electroweak gauge Higgs and Higgsino loops [32,33]. After these corrections are applied, the photino acquires a mass in the range $0.1 < M_\tilde{\gamma} < 1.5$ GeV/c$^2$ and the gluino acquires a mass between $0.1 < M_{\tilde{g}} < 1.0$ GeV/c$^2$ [9][27].

Models with exact R-parity in which the tree level gauginos are nearly massless the gluino is the lightest super-partner (LSP) and the photino is the lightest R-odd color singlet have the consequence that the parameter regime in which relic photinos could account for the cold dark matter has not been excluded by experiment and is within the reach of searches at current accelerators [27].

In these light gluino models, the gluino would express itself in a color octet binding to a gluon ($\tilde{g}g$), a quark-antiquark pair ($\tilde{g}q\bar{q}$), or another gluino ($\tilde{g}\tilde{g}$) [6][34]. The lightest of these states is the spin-$\frac{1}{2}$ ($\tilde{g}g$) bound state called the $R^0$ hadron, or glueballino, with a predicted mass in the range of $1.3 < M_{R^0} < 2.2$ Gev/c$^2$ [9].

In order that the photino account for the cold dark matter, the ratio of $R^0$ to $\tilde{\gamma}$ masses should be between $1.2 < \tau \equiv (M_{R^0}/M_{\tilde{\gamma}}) < 1.55$ [27]. This parameter $\tau$ is critical in that the relic abundance of photinos depends on it exponentially [27]. The $R^0$ is expected to decay, via an intermediate squark, into a photino and quark-antiquark pair, as shown in...
Figure 2.3: One Feynman diagram for $R^0 (g\bar{g})$ decay into a photino and $q\bar{q}$ pair via an intermediate squark.

Fig. 2.3. The $R^0$ lifetime $\tau_{R^0}$ is given by [9]:

$$\tau_{R^0} \geq (10^{-10} - 10^{-7}) \left[ \frac{M_{\text{squark}}}{100 \text{ GeV}/c^2} \right]^4 \text{s.} \quad (2.5)$$

Since the masses of the squarks are large, the $R^0$ should have a long lifetime [9], comparable to that of the long-lived neutral kaon. Thus, production beams in experiments designed to study the rare decay modes of the neutral kaon or the CP-violating parameter ratio $\epsilon'/\epsilon$ are likely venues to search for these light gluino bound states, as stated earlier.

### 2.3.1 $R^0$ Production

There are three primary processes which contribute to $R^0$ production in $pN$ collisions [35]:

(a) Quark and sea-antiquark annihilation: $q\bar{q} \rightarrow g\bar{g}$, shown in Fig. 2.4

(b) Gluon fusion: $gg \rightarrow g\bar{g}$, shown in Fig. 2.5, and
Figure 2.4: One Feynman diagram for $q\bar{q} \rightarrow \tilde{g}\tilde{g}$ gluino production.

(c) $gq \rightarrow \tilde{g}\tilde{q}$, shown in Fig. 2.6.

Since the energies and transverse momenta involved are small, the validity of using perturbative QCD comes into question [35]. As long as the internal propagators stay far off shell, pQCD is valid. Only in the case of the $u$ channel does the diagram have a singular region. The exclusion of this region in the cross section calculation results in a 5% uncertainty [35].

The dominant process in a 24 GeV/c proton accelerator such as Brookhaven’s Alternating Gradient Synchrotron is quark and sea-antiquark annihilation, although other processes may be competitive [35]. Carlson [36] has calculated the differential cross section for $R^0$ production for $q\bar{q} \rightarrow \tilde{g}\tilde{g}$ for a 24 GeV/c proton beam at E935’s 3.75° production angle for three different values of the $R^0$ mass (1.0, 1.5, 2.0 GeV/c$^2$). The cross sections are shown in Fig. 2.7. The inclusion of only quark and sea-antiquark annihilation provides a conservative estimate to the total production cross section.

The cross sections for production of the $R^0$ for other values of the $R^0$ mass were obtained by an interpolation of the cross sections provided by Carlson. The procedure used

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Figure 2.5: One Feynman diagram for $gg \rightarrow \tilde{g}\tilde{g}$ gluino production.

Figure 2.6: One Feynman diagram for $gq \rightarrow \tilde{g}q$ gluino production.
Figure 2.7: The double differential $R^0$ production cross section as functions of the $R^0$ momentum for $q\bar{q}$ annihilation in $pN$ interactions. The solid points were calculated by Carlson [36] and the open points are from the interpolation procedure described in Section 2.3.1. The table in the upper right corner shows the differential cross section after integrating the double differential cross section over $R^0$ momentum in $pN$ interactions.
was as follows [1]: set

\[ \frac{d^3\sigma}{d^3p} = f(p, M_{R^0}) \]  

(2.6)

for a given momentum \( p \) and

\[ f(p, M_{R^0}) = e^{a + b M_{R^0} + c M_{R^0}^2}, \]

(2.7)

in which \( a, b, \) and \( c \) are determined from the three \( R^0 \) masses \( (m_1, m_2, m_3) \) from Carlson:

\[
\begin{align*}
  a + bm_1 + cm_1^2 &= \ln f(p, m_1) \\
  a + bm_2 + cm_2^2 &= \ln f(p, m_2) \\
  a + bm_3 + cm_3^2 &= \ln f(p, m_3)
\end{align*}
\]  

(2.8)

The differential cross section for a given \( R^0 \) mass is then interpolated from neighboring points in momenta \( p_1 \) and \( p_2 \) from:

\[ f(p, M_{R^0}) = \frac{(p - p_1)}{(p_2 - p_1)} f(p_2, M_{R^0}) \frac{(p - p_2)}{(p_1 - p_2)} f(p_1, M_{R^0}) \]  

(2.9)

Fig. 2.7 shows the results of this interpolation as well as the calculated cross sections from Carlson. The maximum mass of an \( R^0 \) particle produced in a 24 GeV/c proton beam is approximately 2.48 GeV/c^2.

2.3.2 \( R^0 \) Decay Modes

An \( R^0 \) hadron is expected to decay into a photino and \( q \bar{q} \) pair via an intermediate squark, as previously shown in Fig. 2.3. The dominant \( R^0 \) hadron two-body, three-body, and four-body decay channels are [9]:

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<table>
<thead>
<tr>
<th>Particle</th>
<th>C-eigenvalue</th>
</tr>
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<tbody>
<tr>
<td>g</td>
<td>-1</td>
</tr>
<tr>
<td>$\bar{g}$</td>
<td>-1</td>
</tr>
<tr>
<td>$\tilde{\gamma}$</td>
<td>-1</td>
</tr>
<tr>
<td>$\eta$</td>
<td>+1</td>
</tr>
<tr>
<td>$\pi^0$</td>
<td>+1</td>
</tr>
<tr>
<td>$\rho$</td>
<td>-1</td>
</tr>
<tr>
<td>$\omega$</td>
<td>-1</td>
</tr>
</tbody>
</table>

Table 2.1: Table of C-eigenvalues for the particles in the two-body final state decay channels of the $R^0$ hadron.

- two-body final states:
  \[ R^0 \rightarrow \pi^0\tilde{\gamma}, \quad R^0 \rightarrow \eta\tilde{\gamma}, \quad R^0 \rightarrow \omega\tilde{\gamma}, \quad R^0 \rightarrow \rho\tilde{\gamma} \]

- three-body final states:
  \[ R^0 \rightarrow \pi^0\pi^0\tilde{\gamma}, \quad R^0 \rightarrow \pi^+\pi^-\tilde{\gamma}. \]

- four-body final states:
  \[ R^0 \rightarrow \pi^+\pi^-\pi^0\tilde{\gamma}, \quad R^0 \rightarrow \pi^+\pi^-\eta\tilde{\gamma}. \]

The four-body decay modes are suppressed due to phase space considerations. The $R^0 \rightarrow \pi^0\tilde{\gamma}$ decay occupies approximately 90% of the allowed phase space [9], but is suppressed by the approximate C-invariance of SUSY QCD, and thus is not the dominant decay channel. The C-eigenvalues for the particles in the two-body final state decay channels are listed in Table 2.1.

The C-eigenvalues for the $R^0$ and $\tilde{\gamma}$ are $C(R^0) = +1$ and $C(\tilde{\gamma}) = -1$ [9]. Therefore, the $R^0 \rightarrow \pi^0\tilde{\gamma}$ and $R^0 \rightarrow \eta\tilde{\gamma}$ are suppressed relative to the three-body decay channels because they violate $C$ [9]. If kinematically allowed, $R^0 \rightarrow \rho\tilde{\gamma}$ would be the dominant decay channel, while the $\omega$ channel is G-parity suppressed. The dominant three-body decay channel is $R^0 \rightarrow \pi^+\pi^-\tilde{\gamma}$, which conserves $C$. This decay also accounts for approximately 90% of all three-body decays [9]. Furthermore, $\rho$ decays into $\pi^+\pi^-$ almost 100% of the time. Thus, it is anticipated that the final state of an $R^0$ decay should contain a $\pi^+$, a $\pi^-$.
and a $\tilde{\gamma}$.

### 2.4 Earlier Direct Searches for Light Gluinos

It is remarkable that the existence of a particle only four times that of the mass of the $K_L^0$ and of comparable lifetime to that of the $K_L^0$ has yet to be convincingly excluded. There has been some debate as to the extent of this exclusion using indirect phenomenological analysis of the running of the gauge coupling constants $\alpha_s$ and multi-jet analysis at LEP [37] [38] [39] [40]. These debates highlight the necessity for direct experimental searches for states containing light gluinos.

Previous decay searches for the $R^0$ hadron have been performed at Fermilab by the KTeV Collaboration [41] and at CERN by the NA48 Collaboration [42]. The results from these two experiments are not directly comparable because of the assumptions used in each decay search. The NA48 work involved searching for $R^0 \rightarrow \eta\tilde{\gamma}$ decay assuming a 100% branching fraction for this channel [42]. The KTeV Collaboration searched for $R^0 \rightarrow \rho\tilde{\gamma}$ decay by the appearance of a $\pi^+\pi^-$ pair with an invariant mass $M_{\pi\pi} > 648$ MeV/c$^2$, assuming 100% branching fraction for this decay channel [41] and using 5% of data collected by the collaboration in 1996. In light of the uncertainty of SUSY QCD C-invariance as discussed in Section 2.3.2, the NA48 and KTeV results are complementary, but not directly comparable.

It is important to discuss the extent to which the KTeV search has already excluded light gluino hadrons. Specification of the masses of the $R^0$ and $\tilde{\gamma}$ as well as of the lifetime of the $R^0$ defines the available phase space for an $R^0$ particle. KTeV cites limits to the existence of the $R^0$ for $1.2 < M_{R^0} < 4.6$ GeV/c$^2$ in the lifetime region of $2 \times 10^{-10}$ to $7 \times 10^{-4}$ s, with a dependence on the photino mass [41]. However, the invariant mass cut $M_{\pi\pi} > 648$ MeV/c$^2$ applied to their data has the effect that KTeV is insensitive for $M_{R^0} < 648 \frac{r}{(r-1)}$ MeV/c$^2$, where $r \equiv \frac{M_{\rho\tilde{\gamma}}}{M_{\tilde{\gamma}}}$ was defined previously. The reason for this loss
in sensitivity is that an $R^0$ with a mass less than 648 $\frac{r}{(r-1)}$ MeV/c$^2$ cannot produce a $\gamma$ and $\pi^+\pi^-$ pair with an invariant mass of at least 648 MeV/c$^2$.

The work described here, BNL E935, proposed to search for light gluinos via the decay channel $R^0 \rightarrow \pi^+\pi^-\gamma$. The goal of E935 was to extend the excluded mass region and lifetime regime and thereby probe a larger portion of the $r$ parameter space. The E935 experimental acceptance for $R^0 \rightarrow \rho\gamma \rightarrow \pi^+\pi^-\gamma$ is slightly better than that for $R^0 \rightarrow \pi^+\pi^-\gamma$ decay, overall [1]. Therefore, E935 conservatively assumes $R^0 \rightarrow \pi^+\pi^-\gamma$ even if the $\rho$ channel is kinematically allowed and also assumes 100% branching into this decay mode.
Chapter 3

The E935 Detector

3.1 Experimental Overview

A decay search for the $R^0$ hadron involves very real challenges in its experimental design and implementation. The need for a pure, high flux neutral production beam, similar to those used in high precision rare kaon decay experiments, is paramount. In addition, excellent tracking and good particle identification are necessary in order to reduce background contamination. The $R^0$ decay search in particular has physics backgrounds which are inherent to the neutral beam itself. These backgrounds can mimic the two-pion signal and must be suppressed.

The E935 experimental apparatus, shown in Fig 3.1, is organized into three sections: neutral beam production, dual-arm spectrometer, and the particle identification and trigger subsystems. The important design features of E935 are

- High ($10^{-6}$ torr) vacuum in the decay region to suppress background.
- Two independent momentum measurements for each particle track to provide accurate kinematic information.
- High-precision tracking near the exit of the decay volume.
Figure 3.1: Schematic overview of the E935 detector system.

- Beam stop positioned in the middle of the detector system to absorb the neutral beam.
- "Parallel track" trigger and magnetic field strengths designed to suppress the acceptance of $K_L^0$ decays.
- Good particle identification to reject semi-leptonic kaon decays.

3.2 Beamline

E935 ran in the B5 beamline at the Alternating Gradient Synchrotron (AGS) at Brookhaven National Laboratory (BNL). An overview of the AGS is shown in Fig. 3.2. The neutral beam was a secondary beam resulting from protons interacting with a platinum (Pt) target. The AGS accelerated $60 \times 10^{12}$ protons to 24.4 GeV/c during nominal operation. This primary proton beam was then extracted in slow extraction beam mode (SEB) and
shared among the experimental target stations. The B5 beamline typically received $11 \times 10^{12}$ protons per pulse (11 Tera protons per pulse, or Tp) incident on the platinum target. Each stochastic spill was 1.2-1.6 s long with a pulse rate of one spill every 3.2-3.6 s. Proton intensity was limited by administrative limits on another target which shared the B line and precautionary measures designed to prevent the melting of the target.

### 3.2.1 Production Target

The design goals of the B5 production target were as follows: a small transverse cross section to localize the decay origin, good heat dissipation to allow high incident intensities, and a low Z heat sink to minimize off-axis production of neutral particles.

The E935 production target consisted of a 15-segment Pt target (3.15 mm wide, 2.54 mm high) on a 7.24 mm wide beryllium (Be) stem attached to a water cooled Be heatsink. Each segment was 8.3 mm long separated by 1.1 mm. The Pt was brazed to the beryllium stem by a Ag-Cu-Li alloy (approximately 92.5% Ag, 7.5% Cu, 0.025% Li) [43]. Two thermocouples were attached to the target to monitor the target temperature. Prior to the target’s use in E935, two of the 15 segments had broken off. The effective targeting length
corresponds to 1.32 nuclear interaction lengths. The original configuration was designed to withstand 20 Tp per pulse of incident beam, although it never received more than 15 Tp.

One of the principal backgrounds to the $R^0$ search results from neutron interactions in the residual gas in the decay volume. To reduce this background, the target was oriented at $3.75^\circ$ relative to the neutral beam channel to reduce the neutron flux to $8\pm3$ times that of the kaon flux [44] [45].

### 3.2.2 Pitching Magnets and Collimators

A schematic of the AGS B5 beamline is given in Fig. 3.3. The first of two dipole pitching magnets is located downstream of the target. This magnet (B5P4) sweeps out the charged particles generated by the primary beam. The magnet contains a series of fifteen 2.3 mm thick Pb foils to convert photons in the beam into $e^+e^-$ pairs which are then swept out by the magnet [45] [46].
The neutral beam next passed through a set of three precision, lead-lined, brass collimators. The collimators defined the beam size (64 μsr) with horizontal-vertical dimensions of 4 x 16 mrad², thus insuring a small divergence in the neutral beam [47].

The collimators end at the aperture for the second pitching magnet (B5P5). This magnet sweeps out charged particles generated off of the collimators and from K⁰_S decays.

3.3 Vacuum Decay Region

The neutral beam enters the vacuum decay region 10 m downstream of the production target. The trapezoidally shaped decay region spanned a length of 11 m. The upstream end had a rectangular cross section of 10 cm in x and 16 cm in y while the downstream cross section was 193 cm in x and 86.4 cm in y. The tank was constructed of 5 cm thick battleship steel encased in borated concrete.

The upstream end of the decay tank was attached to the B5 beamline by a flange assembly. The downstream face of the decay tank consisted of a two-layer Kevlar-Mylar window. The 0.432 mm ballistic grade Kevlar layer provided the strength against the pressure gradient. The 0.127 mm Mylar layer ensured a vacuum seal. The window was held in place by a O-ring flange bolted to the tank assembly. Directly downstream of this window was a Mylar bag which was continuously flushed with dry nitrogen in order to prevent helium leakage into the vacuum tank and to reduce fluctuations in the vacuum level due to changes in the ambient barometric pressure and humidity. The nitrogen bag was deflated and a safety shutter was lowered in front of the window whenever access to the experimental area was necessary in order to protect personnel should the window fail and implode.

Monte Carlo simulations of beam neutron-residual air interactions predicted that a vacuum pressure of 1 x 10⁻⁶ torr was necessary to limit the level of background events from neutron-residual gas interactions to one event in 100 hours of 15 Tp running inten-
The AGS Vacuum Group coupled three Model-8 On-Board cryogenic vacuum pumps from CTI-Cryogenics [48] (4,000 l/s water vapor, 2,500 l/s H₂) to the top of the tank assembly; each unit was connected through a separate six-inch port. There was a slight conductance loss since two of the pumps sat atop six inches of access pipe. The third pump was 12 inches above the tank assembly to provide room to attach a combined mechanical/turbo roughing pump. The AGS Vacuum Group also improved the vacuum seal of the upstream flange. There was some consideration of coating the interior of the decay tank with AEROGLAZE [49], a low out-gassing polyurethane material, to help lower the vacuum pressure further, but this was not implemented.

The pressure inside the decay tank was brought down to less than 1×10⁻⁴ torr by the combined mechanical-turbo pump system, after which the cryogenic pumps were turned on. These pumps ran continuously during the entire data taking period except during two periods when the vacuum was purposely degraded in order to take data at “spoiled vacuum” levels. These sets of “spoiled vacuum data” were used to measure the background level arising from neutron-residual gas interactions mentioned above.

The pressure in the vacuum tank was read out continuously by a thermocouple gauge (down to 1×10⁻³ torr) and then by a cold cathode gauge. Both gauges were attached to a three-inch port aligned next to the six-inch ports. The pressure was hand-recorded every two to four hours as part of the monitoring of the experimental equipment and read out to the data stream with every spill. In addition, a SRS Residual Gas Analyzer (RGA) was installed in another three-inch port and used to analyze the residual gas in the vacuum tank. A partial pressure analysis showed that the primary constituents of the vacuum were nitrogen and water vapor at a nominal 2.5×10⁻⁶ torr and 4.0×10⁻⁶ torr partial pressure, respectively, as indicated in Fig 3.4. The nominal vacuum running pressure was maintained at 6×10⁻⁶ torr, as shown in Fig. 3.5.
Figure 3.4: Partial pressure readout of the SRS residual gas analyzer on 4/1/97. The partial pressure and percent content of the major constituent gases are shown.

<table>
<thead>
<tr>
<th>Spectrum Analysis</th>
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<tr>
<td>Neon</td>
</tr>
<tr>
<td>Argon</td>
</tr>
<tr>
<td>Carbon dioxide</td>
</tr>
<tr>
<td>MP Oil</td>
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</tbody>
</table>

Figure 3.5: Plot of the vacuum pressure versus run number under nominal running conditions.

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3.4 Beam Stop

Located inside the first of the two spectrometer magnets, approximately 2.0 m downstream of the vacuum decay tank, is the neutral beam stop, shown in Fig. 3.6. The unusual placement of the beam stop ensures that the neutral beam is absorbed before reaching the trigger and particle identification subsystems. This placement lowers the rates in these detector elements significantly, which in turn permits a higher beam intensity with less likelihood of being overwhelmed by secondary tracks generated when neutrons or undecayed kaons strike hard material.

The design of this compact beam plug (for BNL E871) posed some engineering difficulties. First, the plug had to have a small transverse cross section in order not to affect the geometric acceptance of tracks originating from the decay region. Secondly, the plug material had to be non-magnetic so that it would not affect the magnetic field of the first spectrometer magnet. Finally, the beam stop was required to be about 2.6 m in length in order to be fully contained within the first magnet.

The core of the beam stop is tungsten. The short hadronic interaction length of tungsten ensured the absorption of beam neutrons and secondary particles generated from
them. Borated Polyethylene was incorporated to capture thermalized neutrons generated in the plug. Finally the beam stop was encased in 6.4 mm of lead to stop photons released during hadronic interactions and neutron capture. A detailed description of the design and performance of the beam plug is given in [50].

3.5 Spectrometer

The active elements of the E935 detector system begin immediately downstream of the vacuum decay tank and consist first of a dual-arm spectrometer and then the particle identification and trigger subsystems. An illustration of the spectrometer is shown in Fig. 3.7.

In order to provide highly accurate momentum measurements, the E935 spectrometer system was designed to be redundant. The spectrometer used six tracking stations, containing a total of 22 tracking planes, in conjunction with two analyzing dipole magnets. The use of two analyzing magnets provides two independent measurements of the
track kinematics. The tracking planes were designed to measure momentum in both the horizontal (x-planes) and the vertical (y-planes) directions.

The 22 tracking planes were organized into six tracking stations with chamber modules on each side of the beam axis. All chambers except for the two associated with station 3 contained both x-planes and y-planes; station 3 housed only x-planes. The first four stations, counting downstream from the decay tank, were straw drift chambers (SDCs), and the last two stations were conventional drift chambers (DCHs). The use of straw chambers in the upstream portion of the spectrometer was necessitated by the high flux of charged daughters exiting the decay tank and beam stop.

3.5.1 Spectrometer Magnets

The two spectrometer magnets, shown in Fig. 3.8, were located between tracking chambers and provided two independent momentum measurements for each track. Both magnets were dipole fields oriented in the vertical (y) direction. The upstream magnet (D02 or 96D40) was located between tracking stations 2 and 3 and housed the beam plug. This magnet bent negatively-charged decay daughters in the left arm and positively-charged decay daughters in the right arm inward, towards the beam line. This magnet provided a nominal $p_T$ kick of $-416$ MeV/c towards the beam line. Particles of positive charge on the left or of negative charge on the right were swept out of the detector system.

The downstream magnet (D03 or 100D40) was positioned between tracking stations 4 and 5. This second magnet was polarized in the direction opposite to that of the 96D40 and provided a smaller $p_T$ kick of $+173$ MeV/c. This magnet bent tracks accepted by the 96D40 magnet away from the beam line.

The magnetic fields were monitored by Hall probes. The fields were mapped onto a two-inch grid, using the FNAL Ziptrak system, prior to installation of the tracking chambers [45].

The benefits of this dual magnet configuration are two-fold. The first effect is to
Figure 3.8: Schematic overview of the E935 magnets.
complement the beam stop in decreasing the occupancy of the downstream chambers and of the trigger and particle identification systems. The second effect is to impart a total \( p_T \) kick of \(-243\) MeV/c which bends most charged decay products of the neutral kaon inward towards the beam line. Conversely, the two-pion tracks from an \( R^0 \) decay would be rendered more toward parallel to, or bent away from, the beamline, depending on the ratio of the \( R^0 \) and \( \gamma \) masses, and thus on the available energy in the interaction. These effects, coupled with the outbend trigger settings, balance the need for good acceptance of high invariant mass \( R^0 \) events without overloading the trigger system with \( K_L^0 \rightarrow \pi^+\pi^- \) decays.

### 3.5.2 Straw Chambers

The first four tracking stations that the decay daughters traverse are straw drift chambers. Each station had a tracking module on either side of the beam axis. Each module, except those associated with station 3, contained three layers of vertical (\( x \) measuring) and two layers of horizontal (\( y \) measuring) straws referred to as \( x \)-planes and \( y \)-planes, respectively. The extra layer of straws in the \( x \)-planes provides redundant position measurements which decrease tracking errors in the \( xz \) plane. This is essential for good momentum resolution. An illustration of the layout for \( x \) and \( y \) measuring planes for both straw and drift chamber planes is shown schematically in Fig 3.9.

Each straw cell consisted of a 5.0 mm straw tube made of two 12.5 \( \mu \)m Kapton layers with a 0.1 \( \mu \)m copper-plated cathode on the inner winding. The anode was a gold-plated tungsten sense wire held under tension (70 g) by brass pins. The pins held the wire in the center of the straw by a “V” shaped groove in the plastic feedthrough’s. For historical reasons, one of of the straw chambers (SDC 4LY) used a copper-plated Mylar cathode.

The signal from the sense wire was read out to a six channel amplifier board connected directly to the brass end pins. The amplifier-discriminator circuit had a typical discriminating threshold of 1.5 \( \mu \)A. The digital signal was sent, as a 30 ns pulse, over low-loss Ansley cables to 6-bit, 1.75 ns least-count time-to-digital converters (TDCs).
The straw chambers were designed to handle high rates (100's of kHz) from charged particles exiting the decay tank and particles escaping the beam stop. To accommodate these rates, a fast-gas, 50:50 mixture of CF$_4$/C$_2$H$_6$, was used. This admixture provided a drift velocity of 110 μm/ns.

The high voltage on the straws was ramped up to 1950 V in-spill and ramped down to 1850 V out-of-spill by a CAEN SY127 power supply. Low voltage power (±5 V, +6 V) was provided to the amplifier cards by power supplies rack-mounted inside of the experimental area.

### 3.5.3 Drift Chambers

The last two tracking stations comprised conventional drift chambers (DCH). The drift planes were hexagonal cells (1.016 cm) with six field wires surrounding one (anode) sense wire. In addition, guard wires outside of the drift cells were kept at ground potential to help shape the electric field near the cell edges. The cathode (field) wires were maintained at -2500 V while the sense wire was at ground. As in the SDCs, there are three layers of $x$...
measuring planes and two layers of \( y \) measuring planes. The geometry for the \( x \) measuring and \( y \) measuring planes is shown in Fig 3.9.

The sense wires consisted of 20 \( \mu m \) gold-plated tungsten wires, under 40 g tension, and soldered to pins on the outside of the chambers. The field and guard wires were 109 \( \mu m \) aluminum wires. The drift gas used in the chambers was a 49:49:2 admixture of argon, ethane (\( \text{C}_2\text{H}_6 \)) and ethanol which provided a drift velocity of 50 \( \mu \text{m/ns} \).

As in the straw chambers, the signal from a sense wire was read out to a preamplifier card attached directly to the pins. The digital output was sent over Ansley cables to 6-bit, 2.5 ns least-count TDCs. Low voltage power supplies for the chambers were located in the experimental area.

For a more detailed discussion of the design and construction of the chambers, the reader is referred to [51] and [47].

### 3.6 Trigger Scintillation Counters

The first of two banks of scintillation counters was located at \( z = 29.94 \) m as measured from the target. These trigger scintillation counters (TSCs) consisted of two stations of Bicron BC-408 scintillation bars and form the basis of the hardware trigger [52]. The configuration of the TSCs is illustrated in Fig. 3.10.

The first station contains two modules, one located along each side of the beam line. The scintillator bars in these first two modules were mounted only vertically to provide \( x \) measurement information. There are 32 counters in each module and each scintillator counter was 3.2 cm wide, 0.5 cm thick, and 1.653 m long. Adjacent counters were offset slightly in \( z \) and overlapped 0.29 cm to ensure complete coverage in the \( xy \) plane, as shown in Fig. 3.11. The center-to-center distance of two adjacent counters was only 2.75 cm.

The second TSC station was located 2.91 m downstream from TSC station 1 and consisted of four modules, two on each side of the beamline. The first module a particle
Figure 3.10: Schematic of the Trigger Scintillation Counters.

Figure 3.11: Overlapping Geometry of the Trigger Scintillation Counters.
Figure 3.12: Layout of the Trigger Scintillation Counters in TSC2 showing the slat geometry.

traverses, on either side of the beam line, was identical to that in the first station except the scintillation counters were 1.897 m long. The next two modules, one on either side of the beam line, housed horizontally aligned $y$ measuring counters. Each of the 64 counters in each module measured 3.0 cm wide, 0.5 cm think and 1.009 m long. Here, the $y$ measuring slats were offset 0.28 cm to eliminate acceptance loss which would result if the counters were edge to edge, as illustrated in Fig. 3.12. The center-to-center distance remained 2.75 cm for these counters as well.

Attached to both ends of the $x$ measuring counters are Hamamatsu R1398 photomultiplier tubes (PMTs) through a light guide as shown in Fig. 3.13. In order to maximize acceptance, the two $y$ measuring modules were positioned as close as possible to the beam line. Therefore, each of the $y$ measuring slats contained only a single PMT.

The signals from the PMTs were sent on coaxial cable to LeCroy 4413 discriminators in the counting house. The output of the discriminators was sent to both the trigger
hardware and to “fast” time-to-digital converters (FTDCs) as described in Section 3.9

3.7 Particle Identification Systems

In order to reduce the background arising from $K_L^0$ semi-leptonic decays, E935 employed a series of lepton-rejection schemes. Electron rejection was based on signals in veto from a threshold hydrogen Čerenkov counter (CER) and a lead glass calorimeter (PBG). Muons were vetoed using a muon hodoscope array (MHO) interspersed inside of a muon filter stack composed of marble, iron and aluminum. The tagging of pion candidate events is covered in Section 4.4.

3.7.1 Hydrogen Čerenkov Counter

The threshold hydrogen Čerenkov counter was located between the two TSC stations. The Čerenkov counter was used, as a veto, in the online Level 1 (L1) pion trigger as well as for rejecting electrons offline.

The Čerenkov counter consisted of $2.8 \text{ m}^3$ of gaseous hydrogen at a pressure of $3''$ $\text{H}_2\text{O}$ over atmospheric pressure, encased in a $2.75 \text{ m}$ deep aluminum enclosure, as shown schematically in Fig 3.14.
The upstream, two-layer window was constructed from a 0.127 mm Mylar layer and a 0.0381 mm Tedlar layer. The two layers were separated by 1” through which dry N$_2$ flowed. The window was kept intentionally thin to reduce the probability of producing “knock-on” electrons. The downstream face was covered by 32 rectangular spherical mirrors arranged in two $4 \times 4$ grids on each side of the beamline separated by a 0.0381 mm black Tedlar sheet. Two sizes of mirrors were used in the Čerenkov counter. The larger mirrors were of dimension $25.80 \times 46.57$ cm$^2$. These mirrors were arranged vertically into two columns along the beamline (one beam left, one beam right), as well as along the two farthest away from the beamline (one beam left, one beam right). The narrow mirrors were $23.05 \times 46.57$ cm$^2$ and were positioned in the four central columns, two to a side.

Each mirror (focal length 2.9 m) focused light onto a Burle 8854 photomultiplier tube, shown in Fig 3.15. The geometry of this setup is shown in Fig. 3.16. Signals from the PMTs were split to LeCroy 4413 discriminators and analog to digital converters (ADCs). The discriminator outputs were sent to FTDCs and to the Level 1 trigger, while the ADC outputs were used offline.
Figure 3.15: Schematic diagram of Burle 8854 photomultiplier tube.

Figure 3.16: Schematic view of hydrogen Čerenkov counter enclosure showing the mirror and photomultiplier tube geometry.
### Table 3.1: Čerenkov response thresholds for electrons, muons and pions.

<table>
<thead>
<tr>
<th>Particle Type</th>
<th>Threshold Momentum</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electron</td>
<td>0.03 GeV</td>
</tr>
<tr>
<td>Muon</td>
<td>6.3 GeV</td>
</tr>
<tr>
<td>Pion</td>
<td>8.3 GeV</td>
</tr>
</tbody>
</table>

Čerenkov light is generated when a charged particle traverses a medium at a speed $v$ greater than the speed of light in that medium ($\beta \equiv \frac{v}{c} > \frac{1}{n}$). The Čerenkov light is emitted in a cone at an angle $\theta_c$ with respect to the particle's momentum given by

$$\sin^2 \theta_c = 1 - \frac{1}{\beta^2 n^2}$$ \hspace{1cm} (3.1)

Particles of different masses will emit Čerenkov radiation at different momenta in the same medium. The Čerenkov threshold for a given medium is

$$\beta_t = \frac{1}{n} = \frac{p}{\sqrt{p^2 + m^2 c^2}}$$ \hspace{1cm} (3.2)

For atmospheric hydrogen ($n = 1.00014$), the Čerenkov threshold momenta for electrons, pions and muons are given in Table 3.1 [43].

#### 3.7.2 Lead Glass Array

The second system used for electron rejection was the lead glass electromagnetic calorimeter (PbG). The PbG complemented the Čerenkov counter in rejecting electrons during offline analysis.

The PbG consisted of two layers of Schott F2 lead glass blocks. The upstream layer comprised the converter block layer and the downstream layer served as absorber blocks. The converter layer was composed of 36 blocks measuring 10.9 cm (x), 90 cm (y), and 10 cm (z) each and stacked in two rows with 18 blocks in each row, as shown in Fig 3.17. The converter block thickness corresponds to 3.5 radiation lengths. The downstream back blocks consisted of 168 blocks of dimensions 15.3 cm (x), 15.3 cm (y), 32.2 cm (z) which
corresponds to 10.5 radiation lengths, and are also shown in Fig 3.17. The PBG array was enclosed in a light-tight, air-conditioned hut. Each block had a PMT attached at one end. The PMT signals were read out to ADCs.

3.7.3 Muon Hodoscope

The last particle identification element was the muon hodoscope (MHO). The MHO consisted of 86 Bicron (BC408) scintillator counters organized into six planes, denoted X0, Y0, X1, Y1, X2, Y2. These planes were positioned within a muon filter consisting of iron, marble and aluminum as shown in Fig. 3.18.

The first element of this stack downstream of the PbG array was a large, 30.5 cm thick Fe block used to stop electrons or pions (hadrons) which were not absorbed in the PbG. The longitudinal position of each active MHO plane corresponded to a specific momentum range of a minimum ionizing muon as shown in Table 3.2.
Figure 3.18: Schematic diagram of the MHO range stack layout.

<table>
<thead>
<tr>
<th>Plane Name</th>
<th>Z Position (m)</th>
<th>Momentum (GeV/c)</th>
</tr>
</thead>
<tbody>
<tr>
<td>X0</td>
<td>35.36</td>
<td>1.0</td>
</tr>
<tr>
<td>Y0</td>
<td>35.45</td>
<td>1.0</td>
</tr>
<tr>
<td>X1</td>
<td>35.04</td>
<td>0.75</td>
</tr>
<tr>
<td>Y1</td>
<td>36.44</td>
<td>1.5</td>
</tr>
<tr>
<td>X2</td>
<td>38.29</td>
<td>2.8</td>
</tr>
<tr>
<td>Y2</td>
<td>46.01</td>
<td>5.8</td>
</tr>
</tbody>
</table>

Table 3.2: Location of the MHO planes in terms of distance from the target and in terms of muon momentum loss.
As in the case of the TSCs, each of the x-measuring planes had a Phillips XP2262 PMT attached to each end of the scintillator slat, while the y-measuring planes had only a single PMT, as shown in Fig 3.19. The signals from these PMTs were sent to LeCroy 4413 discriminators and from there to 8-bit TDCs. The second and third MHO planes (X0 and Y0 respectively) also had their discriminator signals sent to the Level 1 trigger. Lastly, the first MHO plane (X1) also had its signals sent both to discriminators and to ADCs.

3.8 Data Acquisition System

3.8.1 Level 0 Trigger

The Level 0 (L0) hardware trigger required a coincidence of signals in all three TSC planes (TSC1X, TSC2X, TSC2Y). Each side of the detector was treated separately in the trigger system. Since the spectrometer magnet settings had the net effect of preferentially bending daughters from $K_L^0$ decays toward or across the beam axis, a "parallel" trigger was used to reduce the rates from $K_L^0$ decays while retaining acceptance for $R^0$ decays. $R^0$ decays could, depending on the $R^0$ and $\gamma$ parameters, have a large transverse momentum $p_t$ in the decay. A hit in a TSC2 x-plane was required to lie between one slat inward (toward
the beam line) and two slats outward (away from the beam line) from a hit in a TSC1 x-plane, as shown in Fig. 3.20. This requirement meant that a particle's trajectory was between $| \frac{d \phi}{dz} | < 20$ mrad inbend and $| \frac{d \phi}{dz} | < 30$ mrad outbend with respect to the beam axis. These criteria defined the “parallel” trigger.

### 3.8.2 Level 1 Trigger

The Level 1 (L1) hardware trigger placed a L0 trigger in coincidence with signals from the CER and MHO particle identification (PID) detectors. The “pion” trigger was a L0 trigger, spatially correlated to and in time with veto signals from both the CER counter and the MHO X0 plane. The $z$ position of the X0 plane corresponded to the maximum range for a 1 GeV/c muon. A “minimum bias” (mb) trigger was a L0 with no requirements from the PID subsystems. “Minimum bias” triggers were used predominantly to check detector calibrations. The trigger used during data taking was a “pion-left, pion-right” $(\pi \pi)$ trigger.
In addition, one out of every 1000 "minimum bias-left, minimum bias-right" (mb/mb) was passed. Calibration triggers were written out for each spill. These included ADC pedestal triggers, the PBG reference tube and laser triggers, and the 50 Hz trigger.

3.8.3 Level 3 Software Trigger

Historically, a Level 2 trigger was designed, but never implemented. The Level 3 (L3) software trigger ran on all events from L1 but passed all L1 "minimum bias" triggers unconditionally. L3 performed basic pattern recognition of spectrometer tracks, requiring a track in each side of the spectrometer based on chamber hit-clusters. In addition, a vertex distance of closest approach of less than 50 cm and a calculated invariant mass $M_{\pi\pi} > 460$ MeV/c$^2$ were required for each event.

3.8.4 Data Upload Process

If an event was passed by L1, gates were sent to the TDCs and ADCs and a signal was sent to the "Readout Supervisor" (RS) which coordinated event processing. The RS coordinated the upload of data from the L1 trigger, the ADCs, and the TDCs to the processors, which ran the code for the L3 software trigger, and finally to the host computer [53].

E935 employed a custom-designed readout architecture known as FASTERBUS. FASTERBUS is a parallel pipelined system able to upload 250 Mb/sec of data into dual port memory modules. The corresponding events were then processed by the L3 trigger code [54]. The FASTERBUS architecture allowed "flash" digitization of the time and charge information from the TDC and ADC modules in less than 200 ns. The data were buffered, read out in parallel, and transferred to dual port memory modules. The data were subsequently processed by a set of seven Silicon Graphics V35 processors which ran the L3 trigger code. Finally, events passing the L3 "event quality" trigger were uploaded to a host IBM RS/6000 53H computer via a dedicated ethernet line [55]. These events were then written to tape for offline analysis.
3.9 Front End Electronics

3.9.1 Amplitude-to-Digital Converters

The 12-channel, 8-bit, amplitude-to-digital converters (ADCs) were constructed from a Sony CX20052A 20 MHz flash ADC converter chip [56]. There were ADCs on the CER, PBG and the X1 plane of the MHO. The ADCs employed a bilinear circuit: for small pulses, the response was 150 fC/count and for large pulses, the response was 470 fC/count. This bilinear circuit provided a large dynamic range while maintaining good resolution for weak pulses.

3.9.2 Time-to-Digital Converters

E935 employed three types of time-to-digital converters. The straw and conventional drift chambers used 6-bit TDCs. The SDCs, with their faster drift gas and small cell size, used 32 channel, 1.75 ns least count TDCs. The conventional drift chambers used 2.5 ns least count TDCs [57]. Both drift chambers received their start pulses from emitter-coupled logic (ECL) signals from the L1 trigger system. The stop signals were provided by the signals from the detectors.

The phototube-based systems (TSC, CER, PBG and MHO) required better timing resolution than that associated with the drift chambers. These systems used 8-bit, 220 ps "fast" TDCs (FTDCs) [58]. A Sony CX20052A 20 MHz flash ADC converter chip formed the basis of each TDC channel [43].
Chapter 4

Analysis Software

4.1 Offline Software Overview

The offline analysis of the $R^0$ decay channel involved:

- Finding good $\pi\pi$ events which have a topology that is inconsistent with known processes.
- Calculating the kaon flux from the $K^0_L \rightarrow \pi^+\pi^-$ normalization sample.
- Evaluating potential sources of background for the event channel.

The data were processed in two different production passes in order to filter the full data set of 0.18 Terabytes down to a more manageable size. This process required the cutting of the data based upon high efficiency selection criteria.

The first pass employed a pattern-finding algorithm to make fast and reliable estimates on tracking parameters. The second pass performed a mathematical fit to the data which was used to calculate event kinematics and associate the detector response to these tracks. Through each production phase, events were organized into analysis streams in order to separate normalization events from possible signal data.
The E935 analysis software package, sometimes simply referred to as “the offline,” was a custom package written for the E871 rare kaon decay search and its predecessor, E791. The code is written in the programming language MORTRAN. The offline was designed around a primary executable loop which automatically executes each logical stage of the analysis. More complete and accurate information about an event is obtained at the end of each of these stages. All of the derived detector responses, calculated kinematics, or raw information were accessible through a set of standard common blocks. The user accessed the data at various stages in the event processing. At each stage the information available is more robust, ranging from raw detector responses to kinematically determined invariant mass and to full particle identification. The offline code was open source code to all of the collaborators; however, changes to the major objects followed a rigid standardization process. Each major revision was locked in an update MOD. Once a MOD was released, it became the new standard. Users could override a standard MOD object in a specific job in order to check code or test a new algorithm, but this procedure remained local to their job unless it eventually was incorporated into a new MOD.

The Monte Carlo package ran within the standard offline. A Monte Carlo simulation follows a standard flow:

- A primary event particle is generated and its decay simulated.

- The decay daughters are transported through the detector while incorporating physics information such as multiple scattering and decays.

- The detector responses are simulated, allowing for the inclusion of random and correlated noise.

- A raw event buffer is generated to look exactly like a data event.

At this point, Monte Carlo events and data events are treated exactly the same way. Thus, generated Monte Carlo events can seamlessly run through an analysis job to compare di-
rectly the effects of any analysis cuts to a simulated process.

At the end of data collection, the data were organized into 200 MB blocks, called runs, and written to 4mm tapes by the acquisition system. The offline unpacked the raw events from each run, derived the detector responses from ADC and TDC data and associated these responses with a reconstructed track.

4.2 Pattern Recognition

The reconstruction of each event began with the pattern recognition algorithm (PATREC). The task of PATREC was to sift through the raw hit clusters in the drift chambers and, from these clusters, reconstruct three dimensional tracks which would then be passed to the kinematic fitting algorithm. PATREC also provided loose kinematic information and an initial guess for the event time which were used to reduce the number of events in the data streams. This section is an overview of the pattern recognition algorithm used in E935. A detailed account is given in [59].

An ideal track passing through the drift chambers would leave a cluster of three hits as it traversed a chamber's $z$ measuring plane (a triplet) and a two-hit cluster as it traversed a $y$ measuring plane (a doublet). However, the presence of multiple tracks, broken or inefficient wires, and electronic cross-talk provided a less than ideal environment for finding tracks in the chambers. The initial task of PATREC was to remove events if any of the drift chamber planes contained no hits.

The next task of PATREC was to determine the event time. The chambers' TDCs receive their starts from the TSCs through the L1 hardware. Jitter in the L1 electronics can cause the apparent event time to deviate from the actual event time. The calculated event time is used as a global offset to reduce this trigger jitter which can be several nanoseconds. This offset used the time sums from good $y$-hit doublets and $x$-hit triplets.

PATREC then organized hit groups in a plane into clusters. A cluster is a set of
contiguous wire hits in different layers of a given chamber plane. A cluster was allowed to have a missing hit resulting in a doublet in $x$ or a singlet in $y$. Furthermore, a cluster was allowed to contain more than three hits in a plane. However, if a cluster became too large (20 hits in $x$ or 10 hits in $y$), it was broken down into smaller clusters.

Clusters were then organized into a list of two-dimensional cluster sets. To take advantage of the lower rates in the downstream portion of the spectrometer, PATREC began with clusters in DC6 and worked forward toward SDC1. The algorithm then added cluster sets which were within a predetermined spatial window. This window varied from $-180$ mm to $+200$ mm in $x$, and $\pm 130$ mm in $y$ in DC5 down to $\pm 55$ mm in $x$ and $\pm 60$ mm in $y$ in SDC1 [43]. If a cluster set could not be found in a single plane, the event was rejected. These cluster lists are called proto-tracks.

As discussed earlier, a given cluster can have a large number of hits associated with it. In order to find the most likely set of wire hits through which a track passed, the wires in each cluster were subdivided into smaller wire sets referred to as segments. PATREC then searched through the segment sets to determine the true path, under the assumption that the angle determined for a segment will not deviate appreciably from the angle determined from the above proto-track. The path of a track is determined by minimizing a local $\chi^2$ defined as:

$$
\chi^2 = \sum_{i=1}^{N} \frac{(\delta_i - doca)^2}{\sigma_i^2},
$$

where the sum is over the number $N$ of wires, $\delta_i$ is the drift distance of the $i$th wire, $doca$ is the distance of closest approach of the hypothetical track to the wire and $\sigma_i$ is the wire resolution. In the ideal cases, this procedure determines the actual track position through a cluster. However, in the case of missing hits or non-Gaussian effects, there is an ambiguity as to which side of a wire the actual track traversed. This ambiguity was addressed by the introduction of a PATREC “score”. This score is similar to a negative log-likelihood function and takes into account the local $\chi^2$ and the probability that a hit was either a noise
hit or a missing hit from a broken or inefficient wire [53]. The hypothesis with the lowest score determined the actual track position. If the next best score was $e^{-4}$ less probable than the best score, it was kept as an alternative. Up to three alternatives could be kept.

These sets were used to form full two dimensional tracks in $x$ and $y$ separately. The $x$-momenta, for the front and back of the spectrometer, were calculated separately and required to match to within 10%. The front and back $y$ tracks were required to meet in the center of each magnet. These full two dimensional tracks were then paired into three dimensional tracks and the recalculated front and back momenta were again required to match to within 10%.

The final step pairs the three-dimensional tracks from each side of the detector to find a vertex distance of closest approach. This $V_{\text{doca}}$ was required to be less than 10 cm and the $z$ position of the $V_{\text{doca}}$ was required to lie between 9.0 m and 21.0 m. In the case of multiple vertices, the vertices were arranged in order of increasing $V_{\text{doca}}$. The best vertex from a pair of tracks had the smallest $V_{\text{doca}}$. The track times of the hits associated with the best vertex determined the new event time $T_0$ to replace the original estimate obtained from PATREC.

4.3 QT Fitting Algorithm

The three-dimensional tracks from PATREC are used as input for the fitting algorithm, known historically as QT. Instead of minimizing a total $\chi^2$ for the entire track as is traditionally done by a mathematical fitting routine, QT iteratively determines a track's parameters as it swims a track through the spectrometer. This section is an overview of the QT algorithm. Details are given in [60] and [45].

The QT fitter treats the front and back halves of the spectrometer separately. In the front of the spectrometer, QT starts with the PATREC information in SDC1 and swims the track forward to SDC3. In the downstream half of the spectrometer, QT starts with
PATREC information in DCH6 and swims the track upstream to SDC4. The calculation begins with values of the track momenta, hit positions, and track direction cosines from PATREC and the three-dimensional magnetic field maps. QT steps the particle through the spectrometer in 20-cm increments, using a fourth-order Runge-Kutta algorithm to solve for the particle's equation of motion. The track parameters at each iteration were adjusted to bring the projected track hit positions in each chamber to within a 10 μm tolerance. A track which could not meet this requirement failed QT [47].

After an iteration through all of the track hypotheses for the front and back halves of the spectrometer, the fit track segments for the front and back are paired. There are six degrees of freedom for each proto-track pair, three each for x and y:

- Front-to-back momentum match: \( \frac{(p_f - p_b)}{p_{\text{average}}} \)
- Position in x and y and slope match at SDC3: \( \delta x_3, \delta y_3, \delta \theta x_3, \delta \theta y_3 \)
- The y position in SDC4: \( \delta y_4 \)

A reduced track chi-squared \( \chi^2_v \) was formed for each full track from the square of the deviations of each degree of freedom.

Next, the tracks on the left and right halves of the spectrometer were paired and the tracks projected to the vacuum decay tank to form a vertex. In much the same way as PATREC, QT calculated a vertex distance of closest approach, \( V_{\text{doca}} \), and the vertex was taken as the midpoint of the doca line segment. In addition, QT calculated a vertex chi-squared \( \chi^2_v \)

\[
\chi^2_v = \frac{V^2_{\text{doca}}}{(z_{\text{SDC1}} - z_v)^2 (\sigma_{\theta L}^2 + \sigma_{\theta R}^2)}
\]  

(4.2)

where \( z_v \) is the z position of the vertex, \( z_{\text{SDC1}} \) is the z position of the SDC1 and the resolutions of the first chamber plane for the left and right tracks are \( \sigma_{\theta L} \) and \( \sigma_{\theta R} \), respectively.
In the instances where an event had multiple vertices, the vertices were sorted by a figure of merit:

\[ f_{QT} = x_v^2 + w \times (x_{vL}^2 + x_{vR}^2) \]  (4.3)

where \( x_v^2 \) is the vertex \( x^2 \), \( x_{vL}^2 \) and \( x_{vR}^2 \) are the track reduced \( x^2 \)'s described previously, and \( w = 1.25 \) is an empirically chosen weighting factor.

The usefulness of the QT algorithm is derived from the fact that all vertex information is determined by hit positions in the first two tracking chambers while the dominant component of error in the momentum measurements arises from multiple scattering [60].

4.4 Particle Identification

Excellent particle identification is paramount in a rare decay search such as that described in this work. The E935 trigger was designed to maximize rejection of events involving electrons and muons, but inefficiencies allow some events with these particles to pass into the data stream. A misidentification of a muon or electron as a pion can cause an otherwise benign \( K_{\mu3} \) or \( K_{e3} \) decay to mimic an \( R^0 \rightarrow \pi^+\pi^-\gamma \) decay. Approximately 66% of \( K_L^0 \)'s in the neutral beam decay into these two modes. Therefore, all electron identification systems were made redundant while muon identification was supplemented with an invariant mass cut. A pion candidate in the E935 detector system has a track with hits consistent with a hardware L0 trigger with no associated hits in any of the particle identification detectors.

Offline particle identification begins with calls to the track-to-counter association software (TKC). The design goal of TKC is to flag every hit in the TSCs and particle identification subsystems as either associated with a particular track or not. The TKC software can use tracks generated by PATREC or QT fitting. The first data reduction pass, discussed fully in Chapter 5, used PATREC tracks while all subsequent analysis used only
tracks which passed the fitting algorithm. Particle identification hits include, where available, both TDC and ADC information for a given detector. The detectors were calibrated using minimum bias data and special runs.

4.4.1 Track-to-Counter Association Overview

In general, the TKC software projects a track from the spectrometer downstream to the detectors and determines if a hit lies within a spatial window which allows for multiple scattering as the track traverses intervening material. The TKC routines returned a series of logical flags to characterize a track's response in a given detector. The hit information for each track is stored for use by the particle identification routines. The raw detector responses are coupled with calibration offsets and the particle momenta to derive energy deposition, timing and pulse height information.

4.4.2 Software Trigger Parallelism

The TSC track-to-counter association routine checks to see if a given track could have resulted in a L0 trigger. The routine returns three flags to characterize the track: good, possible and fail. A track fails TSC TKC if it fails the L0 "parallelism" requirement, whereas a good TSC is both spatially and temporally consistent with a L0 trigger. A possible TSC satisfies the parallelism requirement, but fails to have good timing information associated with one or more of its hits.

It may seem unnecessary, at first, to re-apply the hardware trigger in offline, since a hardware trigger was already required for an event to have made it into the offline data. However, a hardware trigger could have been generated by noise, accidental responses, or a pile-up of tracks from simultaneous decays. In addition, the TKC routines treat the beam-left and beam-right sides of the detector systems independently. As discussed previously in Section 3.5, the majority of pions from $K_L^0 \rightarrow \pi^+\pi^-$ are bent across the beam line. In these instances, a hardware trigger could be generated as the crossing track completes the
Figure 4.1: An example of a $K^0_L \rightarrow \pi^+\pi^-$ cross-over event. This event was accepted by the minimum bias trigger.

parallel requirement of the TSC counter on the opposite side of the beamline, as shown in Fig. 4.1. These cross over events fail TSC track-to-counter association. A more detailed description of the implementation of TSC particle identification can be found in [61].

4.4.3 Electron Identification

The Čerenkov track-to-counter association took TDC timing and ADC pulse height information and compared it to a simulated Čerenkov cone from an incident electron. The TKC routine compares the actual hit information to generate two flags that characterize the track: possible electron and good electron. In addition, the Čerenkov pulse height, in units of photo-electrons (p.e.), was returned by the Čerenkov TKC routine. A track which returned a possible Čerenkov electron had hits which matched the track both spatially and
temporally. A *good* electron passed a pulse height threshold requirement as well as the *possible* electron criteria.

The lead glass array provided electron identification information redundant to that of the Čerenkov counter. The projected tracks are used to determine which converter blocks and which absorber blocks are to be associated with the track. Blocks within a 15 cm radius of the projected track position are associated with a track. The ADC information from these blocks, corrected by calibration information, is then used to calculate the energy deposited in the converter blocks and in the absorber blocks, as well as the sum of these two.

Electrons are identified by their measured energy deposition-to-momentum ratio, \( \frac{E_C}{p} \), and the fraction of their energy deposited in the converter block, \( \frac{E_C}{E_T} \). An electron entering the PbG array produces a large electromagnetic shower which is almost wholly contained in the array. Therefore, the total energy deposited is approximately equal to its momentum, \( \frac{E_C}{p} \approx 1 \). The electron energy resolution is momentum-dependent and can be expressed as [62]:

\[
\frac{\sigma_E}{p} = 0.015 + \frac{0.062}{\sqrt{p(\text{GeV})}}.
\]

(4.4)

Muons, and pions for the most part, deposit energy as minimum ionizing particles at E935 energies and thus would not be readily distinguishable from one another in the lead glass array. Pions which deposit energy in the PbG array can produce hadronic showers. These showers begin farther downstream than electromagnetic showers and more of the shower energy escapes the array, resulting in a ratio \( \frac{E}{p} \ll 1 \). Low momentum pions, however, can charge exchange, producing \( \pi^0 \)s. The \( \pi^0 \) produces photons which then create electromagnetic showers. If the \( \pi^0 \) carries away most of the original pion momentum, these showers can mimic those of electrons. For this reason, a small correction to the \( \frac{E_C}{p} \) cut using the converter energy fraction, \( \frac{E_C}{E_T} \), was used to differentiate between electrons and pions since the pion will leave minimum ionizing energy in the converter. Thus, a contour
Figure 4.2: $E_\text{local}/E_\text{total}$ versus $E_T/p$ plane showing the contour cut used to reject electrons. The electrons appear predominantly around $E_T/p = 1.0$

cut in the $E_\text{local}/E_\text{total}$ versus $E_T/p$ plane is used to identify electrons offline. A plot of $E_\text{local}/E_\text{total}$ versus $E_T/p$, given in Fig 4.2, shows the form of this cut. The electron identification efficiency of this cut was 97.88% [63]. A detailed account of the lead glass track-to-counter association and particle identification can be found in [63].

4.4.4 Muon Identification

The muon hodoscope TKC routine projects tracks to the X0 and Y0 trigger planes, both of which are located downstream of the 30.5 cm thick iron filter. The TKC routine returns possible, good, and not muon flags. If a track has no track-associated hits in any of the first three MHO planes, the track is classified as a not muon. If the track has at least one acceptable hit in the X0 or Y0 modules, it is classified as a possible muon. A good muon has track-associated hits in X1, X0 and Y0 as well as good temporal information for
all of these hits.

Pions from $K_L^0 \rightarrow \pi^+\pi^-$, or from $R^0 \rightarrow \pi^+\pi^-\gamma$, which decay into muons would be rejected by either the muon trigger veto or in offline. In addition, a pion can “punch through” the hadron filter and either hadronically shower or pass through to the X0 and Y0 trigger planes. Since these pions are rejected they must be accounted for in order to calculate correctly both the sensitivity of the detector to an $R^0$ decay and the kaon flux from $K_L^0 \rightarrow \pi^+\pi^-$ decays used in normalization.

### 4.5 Monte Carlo Simulation Packages

Two Monte Carlo simulation packages were employed during various stages of the E935 analysis: the standard offline Monte Carlo [64] and the GEANT Detector Description and Simulation Tool [65].

The majority of these simulations used the offline Monte Carlo code developed by the E871 and E791 collaborations to study rare kaon processes. The first three stages of the standard offline analysis software were specifically set aside for this offline package. In particular, calculations of the detector acceptance of the $R^0 \rightarrow \pi^+\pi^-\gamma$ decay needed extensive modeling for all of the possible parameter combinations. The acceptance for $K_L^0 \rightarrow \pi^+\pi^-$ decays was also calculated using this standard offline Monte Carlo.

Monte Carlo generation of a primary particle (either an $R^0$ or $K_L^0$) begins with the random placement of the generation vertex in the target. Next, a random point 10.0 m downstream of the target is chosen, within the neutral beam divergence, to define the direction of the primary particle as it left the target. A random momentum is assigned for the primary particle and weighted by the interpolated $R^0$ cross section calculated by Carlson [36], in the case of $R^0$'s, or by the parameterized Skubic cross section for $K_L^0$ production [66] [67]. The production cross section is weighted by the probability that the particle will decay in the region between $9.0 \, m < z < 21.0 \, m$. The decay daughters are
generated assuming an isotropic angular distribution in the center-of-mass frame.

The standard Monte Carlo simulates Molière scattering and energy loss as a particle traverses the detector material [68], whereas pion hadronic interactions are not simulated. Thus the GEANT simulation package was used to supplement the standard Monte Carlo. A correction for pions lost upstream of the lead glass array was calculated based on the results of a GEANT simulation of the spectrometer, TSC banks and Čerenkov Counter [69].
Chapter 5

Data Collection and Reduction

5.1 Overview

E935 ran during the 1997 HEP program of the AGS. Production-quality data were collected from April 10, 1997 until May 31, 1997. Production was continuous except for one week of down time. By the end of this period, 124 raw 4mm tapes were written out totaling 0.18 Terabytes of raw data.

During the night of May 15 through to the morning of May 16, the vacuum level in the decay volume was intentionally degraded and data were taken. To downgrade the vacuum, the three cryogenic vacuum pumps were shut down as was the RGA to protect its filament. Next, the turbo vacuum pump was turned off leaving just the mechanical rough-pump to maintain the vacuum in the decay volume. The vacuum pressure in the decay region, as measured by both thermocouple gauges, rose from $1.6 \times 10^{-3}$ to $9.0 \times 10^{-3}$ torr during this "spoiled vacuum" data collection. The data were organized into 38 runs, each approximately 50 MB in length.

A second "spoiled vacuum" study was initiated during the entire day of May 31. Data were taken between the vacuum levels of $6.1 \times 10^{-2}$ torr and $8.2 \times 10^{-1}$ torr. Fourteen full, 200 MB long runs were dedicated to this spoiled vacuum period.
The full analysis of the data addressed several issues. First, in order to accommodate the sheer volume of data collected, the dataset needed to be reduced to a manageable size. Next, the tracks for each event needed to be reconstructed and mathematically fit. Then, the particle identification of each track had to be determined. Lastly, the final sensitivity of the experiment had to be determined. To accomplish these tasks, the offline analysis was organized into several stages:

1. The primary goals of the first production, Pass 1, were to upload data to storage carts and to supply preliminary pattern recognition.

2. The second data reduction pass, Pass 2, mathematically fit the data.

3. Candidate events were selected.

4. The normalization stream was analyzed.

5. The "spoiled vacuum" data were studied.

This chapter covers the first two production passes and the organization of the data for the final analysis which is covered in Chapter 6.

5.2 Pass 1 Data Reduction

All offline data analyses were performed using the computer farm at the Stanford Linear Accelerator Center (SLAC). The first production pass, Pass 1, ran on the computer farm for two weeks in June 1997 with a one-week interruption due to a tape loading problem.

Pass 1 was designed as much for data characterization as for data reduction. Histograms depicting quantities describing detector performance and trigger statistics over the course of the entire data taking period were generated. These histograms, or strip charts, were used to check for detector anomalies, gave an overview of the detector calibration and highlighted large scale changes from nominal running conditions. In this manner, run 31065
was determined to have been taken with the wrong magnetic field configuration, and the run was removed from further data analysis. The "spoiled vacuum" runs were processed in exactly the same manner as the other Pass 1 events.

The processing of an event by Pass 1 depended on the L1 and L3 trigger bits for the event. L1 calibration triggers were passed. All L1 minimum bias and L1 \( \pi \pi \) events were required to pass MOD 14 pattern recognition. In addition, L1 \( \pi \pi \) events had to have at least one vertex with a reconstructed \( \pi \pi \) invariant mass greater than 485 MeV/c\(^2\) and pass a "CER possible electron" veto. Pathological events with both physics and calibration data in the same event were passed as were raw events. The L1 \( \pi \pi \) trigger statistics for the first analysis pass were:

- Total L1 \( \pi \pi \) events read: 128,917,728
- Total L1 \( \pi \pi \) events reconstructed: 86,047,933
- Total L1 \( \pi \pi \) events written out: 38,836,986

The data were written to storage carts for subsequent analysis. A total of 778 runs was successfully processed by Pass 1.

5.3 Pass 2 Data Reduction

The primary purposes of the second analysis pass, Pass 2, were to fit the data using the QT kinematic fitter and to organize the data in streams for subsequent analysis. Pass 2 was run in the early fall of 1997 and then completely rerun shortly thereafter when a new version of the analysis code, MOD 15, was made available and the detector calibrations were finalized.

It was determined that the runs prior to run 30600 did not contain the proper ADC calibration pedestal triggers for the PBG or CER. Subsequently, only those runs after 30600...
were subject to Pass 2 and the rest of the data analysis. A total of 576 runs was processed by Pass 2.

Pedestal events and other calibration events from L1 were derived and then removed from the data. All L1 minimum bias events, prescaled by a factor of 10, were required to have at least one vertex pass MOD 15 pattern recognition and MOD 15 QT event fitting. The L1 ππ events were required to have at least one vertex pass MOD 15 pattern recognition and MOD 15 QT event fitting. The "CER possible electron" veto was re-applied to these events. The "signal stream" bit was assigned to L1 ππ events which satisfied the following requirements:

1. Contain at least one vertex with a reconstructed ππ invariant mass, calculated by MOD 15 PATREC, greater than 540 MeV/c².
2. Pass QT fitting with an invariant mass greater than 545 MeV/c².
3. Satisfy a "CER possible electron" veto.

Those events passing the MOD 15 pattern recognition, QT fitting and "CER possible electron" veto, but failing the mass cut were prescaled by P=100 and assigned a "ππ prescale stream" bit. These events formed the basis for the normalization sample. The "spoiled vacuum" data were analyzed in exactly the same manner as the other Pass 2 runs.

The Pass 2 output was reduced to the point that runs could be combined into "composite runs." Each composite run was composed of approximately 20 of the original data runs. Each period of "spoiled vacuum" data was organized into a separate composite run, one for each period. The total data set was under 3 GB in size. The output statistics for Pass 2 L1 ππ triggers were as follows:

- Total L1 ππ events read: 27,297,684
- Total L1 ππ events reconstructed: 25,835,947
• Total L1 $\pi\pi$ events written out: 880,930

Detector calibrations coming out of Pass 2 were verified. The data were written to storage carts for subsequent analysis.

5.4 Data Organization for the Production Analysis

The data out of Pass 2 were organized in analysis runs with each composite run containing a mixture of events from the minimum bias stream, the $\pi\pi$ prescaled-normalization stream, and the high-mass signal stream, as well as a few pathological events. Subsequent analysis warranted a further paring of the data. A computer job was written to strip out events based on their Pass 2 stream bits. These data streams were organized into separate files called data summary tapes (DSTs).

Events from the standard data runs with the Pass 2 $\pi\pi$ prescale stream bit were stripped from the composite runs and organized into three data files. These data were referred to as the "normalization sample." Those events from the "spoiled vacuum" runs with the Pass 2 $\pi\pi$ prescale stream were organized into two separate files to keep them apart from the standard data, but were otherwise stripped in the same way as were the standard data runs.

Those events obtained during nominal running conditions which were assigned the Pass 2 "high mass signal stream" bit were stripped from the composite runs and organized into a single data file. These data were referred to as either "high mass stream" or "signal stream" during subsequent analysis. The data from the "spoiled vacuum" running periods with the the Pass 2 "high mass signal stream" bit were stripped from the standard data in the same manner but stored in two separate data files.

The structure of the data after they were organized into the "normalization" and "high mass" streams were:

• Total prescaled "normalization" events organized into three data files (DSTs).
Figure 5.1: A plot of the $\pi\pi$ invariant mass distribution for two composite runs. The low mass $M_{\pi\pi} < 545$ MeV/c$^2$ stream has a prescale factor $P=100$ applied to it.

- Total high mass "signal" events organized into a single data file (DSTs).
- Two data files (DSTs) for the "normalization" events from the "spoiled vacuum" runs.
- Two data files (DSTs) for the high mass "signal" events from the "spoiled vacuum" runs.

Minimum bias and pathological events were not part of the subsequent analysis. A plot of the $\pi\pi$ invariant mass distribution for two composite runs is shown in Fig. 5.1. The effect of the prescale factor applied to the low mass $\pi\pi$ normalization stream is apparent.
Chapter 6

Candidate Event Selection

6.1 Overview of the Analysis

The production passes were designed to reduce the data to a manageable size through the application of highly efficient selection criteria. The goals of the analysis were to develop a set of selection criteria, or cuts, which each event must satisfy in order to be considered a signal candidate, and to determine the experimental sensitivity in terms of the ratio of the calculated flux at the production target of hypothetical $R^0$ hadrons to that of neutral kaons.

The mis-identification of the lepton in a semi-leptonic kaon decay, tracking or event reconstruction errors, large-angle pion scattering, and beam neutron interactions could each produce signals which mimic an $R^0$ event. A thorough understanding of all of these potential background levels was paramount in the search for an unambiguous $R^0$ decay event. The $R^0 \rightarrow \pi^+\pi^−\gamma$ signal in the E935 detector system was, in essence, a two-pion event which could not be explained by any previously known physics process or accidental circumstance.

Events in the $\pi\pi$ “normalization” DST, the “high mass” spoiled vacuum DST, and Monte Carlo simulations of $R^0$ decays with different parameter sets of $R^0$ mass and lifetime were studied extensively in order to determine the optimal cuts to place on the high mass
"signal" stream.

Though many of the final selection criteria are interrelated, they are organized here into categories which emphasize the dominant feature they are designed to address. Those cuts which serve a dual purpose are described as such. An overview of all of the selection criteria is given and then each cut and its efficiency are presented in detail. The plots which accompany each description contain sample subsets of the high mass signal stream and low mass normalization stream. Unless indicated otherwise, each graph contains the raw output from Pass 2, with no addition cuts applied. The final cuts applied to the data can be summarized by the following categories:

- **Fiducial Volume Cuts**: Those cuts designed to reject events based on track location and vertex reconstruction with respect to the active elements of the detector system and neutral beam.

- **Vertex Quality Cuts**: Those cuts which reject events based on the quality of the reconstructed vertices.

- **Event Quality Cuts**: Those cuts that remove poorly reconstructed tracks after track reconstruction and fitting.

- **Particle Identification Cuts**: Those criteria which define the two-pion candidate sample.

- **Kinematic Cuts**: Those cuts specific to the kinematic differences between a hypothetical $R^0$ decay and possible background.
6.2 Fiducial Volume Cuts

6.2.1 Vertex $z$

The first fiducial volume cut requires that the distance $z_v$ of the reconstructed vertex in the $z$ direction lie within a restricted part of the decay region. The motivation behind this cut is twofold: first, the magnetic fringe field of the pitching magnet upstream of the decay volume extends into the decay region. This fringe field can have the effect of increasing the opening angle between two tracks originating in the upstream portion of the decay tank. From the invariant mass formula:

$$M_{12}^2 = (E_1 + E_2)^2 - (|\mathbf{P}_1|^2 + |\mathbf{P}_2|^2 + 2|\mathbf{P}_1||\mathbf{P}_2|\cos(\theta_{\text{open}}))$$

(6.1)

an increase in this opening angle from the actual angle of the decay will increase the calculated mass of the event. This increase could move the mass of a $K^0_L \rightarrow \pi^+\pi^-$ event to a value above the mass threshold of 545 MeV/c$^2$ and into the signal region. In addition, if the neutral beam scrapes off of the upstream flange or interacts in the upstream window itself, $\Lambda$ hyperons can be produced which promptly decay into a $\pi^-p$ pair. The increase in accepted high mass events in the upstream portion of the decay tank is shown in Fig. 6.1.

The second motivation for this cut is that neutrons from the neutral beam or pions from $K^0_L$ decays can interact hadronically in the downstream window of the decay tank. The beam neutrons can produce low-momentum $\pi^+\pi^-$ pairs as can be verified by looking at the downstream ($z \sim 20.5$ m) portion of Fig. 6.1. Almost all of the pions originating from the downstream “beam spot” are “soft” in that they have momenta less than 1.0 GeV/c. Fig. 6.2 shows the same vertex distribution for a subset of $K^0_L \rightarrow \pi^+\pi^-$ normalization events. The $\Lambda$ peaks (low-$z$) and fringe field effects as well the peak from events originating from within the downstream window are absent.
Figure 6.1: Vertex $z$ distribution for a subset of raw signal stream events. The increase in accepted events originating in the upstream end (low $z$) of the decay volume is apparent. The downstream peak ($z \sim 20.5$ m) results from hadronic interactions within the downstream window. The vertical lines show the $z$ position of the vertex cuts.

Figure 6.2: Vertex $z$ position for an event sample from the $\pi\pi$ prescale stream. Notice the absence of a downstream (high $z$) peak. There is no increase in the number of events upstream (low $z$) from fringe field effects.
Figure 6.3: Schematic representation of an event where one particle scatters in the downstream window of the decay region. The reconstructed vertex moves out of the neutral beam channel and downstream toward the window. The angles and distances are greatly exaggerated.

6.2.2 Beam Divergence

If a pion from a $K_L^0$ decay scatters outward in the downstream window, its reconstructed vertex will move downstream and possibly out of the beamline, as indicated in Fig. 6.3. The next set of fiducial cuts required that the reconstructed vertices originate from within the neutral beam. As shown in Fig. 6.4, there is a halo of events surrounding the fiducial location of the neutral beam in the high mass signal stream as compared to the low mass normalization sample. This plot of the vertex distribution in the $xz$ plane for the high mass stream also shows the "beam spot" in the downstream window. Also apparent are the interactions near the upstream window.

A similar plot, Fig. 6.5, for the $yz$ vertex distribution shows the increase in accepted events in the upstream portion of the decay volume and events originating from the walls of the decay tank.

We define the beam divergence by the two quantities $\Theta_x$ and $\Theta_y$: 
Figure 6.4: Vertex position in the $xz$ plane for a subset of signal stream events and normalization stream events are shown on the left and right, respectively. The upstream end (low $z$) for the signal stream shows the illumination of the upstream window and flange. The downstream end (high $z$) shows the same “neutral beam spot” in the downstream window. Here, $\pi\pi$ events originate from hadronic interactions within the downstream window.

\[
\Theta_x = \frac{x_v - x_t}{z_v - z_t}
\]

and

\[
\Theta_y = \frac{y_v - y_t}{z_v - z_t}
\]

where $x_v, y_v, z_v$ are the vertex coordinates and $x_t, y_t, z_t$ are the coordinates of the target. Figs. 6.6 and 6.7 show the $\Theta_x$ and $\Theta_y$ distributions, respectively, for the signal and $\pi\pi$ prescale streams.

Finally, an event was rejected if either track projected to any material other than the active elements of the detectors. The positions of the magnets, beam-stop and other hard materials were known from surveys. The effect of this cut is incorporated into the acceptance calculations.
Figure 6.5: Vertex position in the $yz$ plane for a subset of signal stream events and normalization stream events on the left and right, respectively. The upstream end (low $z$) of the signal stream shows a shadow from the upstream pitching magnet as well as tracks originating off of the upper and lower edges of the decay tank as charged particles are pitched into the vacuum tank itself. The downstream end (high $z$) shows events originating from hadronic interactions at the downstream window.

Figure 6.6: Sample distributions for the beam divergence $\Theta_x$ of the high mass signal stream (left) and the $\pi\pi$ prescale stream (right). Vertical lines show the location of the applied cuts.
Figure 6.7: Beam divergence $\Theta_y$ for the high mass signal stream (left) and the $\pi\pi$ prescale stream (right). The peaks in the high mass signal stream correspond to events generated off of the walls of the decay volume. Vertical lines show the location of the applied cuts.

### 6.3 Vertex Quality Cuts

It is possible for a pion from, for example, a $K_L^0 \rightarrow \pi^+\pi^-$ decay, to scatter away from the beam axis while the vertex remains in the neutral beam. However, the reconstructed tracks from downstream scattering with a large momentum component out of the plane normal to $\vec{p}_T \times \vec{p}_Z$ (the decay plane, with $\vec{p}_T$ and $\vec{p}_Z$ the momentum vectors of the positively and negatively charged particles, respectively) will not intersect and thus form a good vertex. In the case of planar scattering (i.e., scattering in the plane of the decay), the two tracks can reconstruct to a good, although incorrect, vertex. These latter events have the corresponding opening angle of their decay, and thus their calculated masses, artificially increased. The detector does not have the ability to track events upstream of the downstream vacuum window and therefore the presence of these events represents a serious background.
6.3.1 Vertex Distance of Closest Approach

Finite chamber wire resolution results in the reconstruction of tracks that will not intersect exactly at the original vertex position. Therefore, criteria were designed to characterize the quality of a reconstructed vertex. The first quantity is the vertex distance of closest approach $V_{doca}$ of the two tracks. The $V_{doca}$ uses a puncture plane approximation to measure the distance between the two tracks. The puncture plane approximation calculates the distance between the two tracks in the $xy$ plane. This approximation relies on the fact that the $doca$ vector between two tracks is predominantly in a plane perpendicular to the $z$ axis. The vertex position is defined as the midpoint of the $doca$ line segment in the $xy$ plane.

The vertex $doca$ criterion tightens the cuts already made in the pattern recognition and fitting algorithms. Based on a fit to the $V_{doca}$ distribution for the $\pi\pi$ prescale stream, the two tracks were required to be within $|V_{doca}| < 8.5$ mm of each other. The efficiency of this cut is $96.30 \pm 0.27\%$, measured using the $\pi\pi$ normalization sample. Fig. 6.8 shows the vertex $doca$ distributions for both the signal and $\pi\pi$ data streams.

6.3.2 Vertex $\chi^2$

The puncture plane approximation introduces a slight $z$ dependence in the vertex $doca$ distribution. The vertex chi-square $\chi^2_v$, given by Eq. 4.2, was designed to account for both the finite resolution of the spectrometer and the $z$ dependence of the vertex $doca$ in the puncture plane approximation. The QT $\chi^2_v$ was a more stringent cut than the vertex $doca$. The vertex $\chi^2$ was required to be $\chi^2_v < 3$ and is shown in Fig. 6.9 for both the signal and $\pi\pi$ prescale stream. The efficiency of this cut, measured by the $\pi\pi$ prescale stream, was $94.79 \pm 0.26\%$.

The vertex $doca$ and $\chi^2_v$ criteria are highly correlated because of the inclusion of the vertex $doca$ in the minimized $\chi^2_v$ function. The combined efficiency of these two cuts was...
Figure 6.8: The vertex $doca$ distributions for the high-mass signal stream (left) and for the $\pi\pi$ prescale stream (right). The applied cut is shown as a vertical line. Notice the difference in horizontal scales.

Figure 6.9: The vertex $\chi^2$ distributions for the high-mass signal stream (left) and for the $\pi\pi$ prescale stream (right). The applied cut is shown as a vertical line.
dominated by the $\chi^2$ cut and measured to be 93.70 ± 0.26%.

6.4 Event Quality Cuts

The selection criteria which characterize the quality of a reconstructed event are described in the following sections.

6.4.1 Track $\chi^2$

The track chi-square per degree of freedom $\chi^2$, described in Section 4.3, measured the quality of event reconstruction by the QT fitting algorithm. The $\chi^2$ for both tracks in signal stream and in the $\pi\pi$ prescale stream are shown in Fig. 6.10. The $\chi^2$ for both tracks was required to be $\chi^2 < 10$. This cut had an efficiency of 93.60± 0.26% measured from the $K^0_L \rightarrow \pi^+\pi^-$ normalization sample.
6.4.2 Front-Back Momentum Match

E935 used the two independent momentum measurements by the spectrometer magnets to address the following pathological events:

- A track subject to a large-angle scattering in the spectrometer.
- A pion which decays in the spectrometer with the decay muon mis-identified.
- A crossover event which reconstructs as an event with two non-crossing tracks.

Each of these cases can yield tracks with different values for the momentum calculated for the front (upstream) portion of the spectrometer and for the back (downstream) portion. The front-to-back momentum match is defined in terms of the ratio of the difference in the measured track momenta \( \Delta P = (p_f - p_b) \) to their average momenta, \( P_{ave} = (p_f + p_b)/2 \). The cut imposed was \( |\frac{\Delta P}{P_{ave}}| < 0.05 \). Fig. 6.11 shows the front-to-back momentum match for the high mass signal stream and the normalization stream. The efficiency of the front-to-back momentum match requirement was 99.47 ± 0.25%.

6.4.3 Momentum Cut

A pion track with a momentum greater than the hydrogen Čerenkov counter's pion threshold should have generated photo-electrons in the Čerenkov counter and thus a veto signal in the hardware trigger. A cut on tracks with momentum greater than the Čerenkov counter pion threshold \( p > 8.3 \text{ GeV/c} \) was imposed. Fig. 6.12 shows the momentum distributions for both tracks of the signal stream and \( \pi\pi \) prescale stream. The efficiency of this criterion will be factored into the calculated acceptance for each \( R^0 \) parameter set.

6.4.4 Extra Track Cut

A particle which hadronically showers in the downstream window or two kaons decaying in time coincidence could produce extra tracks in the spectrometer for some events.
Figure 6.11: The front-to-back momentum match for the high-mass signal stream and for the normalization stream. The signal stream is shown on the left, the $\pi\pi$ prescale stream is on the right. The applied cut is shown as vertical lines in each graph.

Figure 6.12: The momentum distributions of the high-mass signal stream and of the normalization stream are shown. The signal stream is shown on the left, the $\pi\pi$ prescale stream is on the right. The vertical lines show the applied cut. The peak at 1 GeV/c in the high mass sample is due to soft pions originating at the downstream window of the decay tank.
Figure 6.13: The offline trigger requirement for the high-mass signal stream and for the normalization stream. Each plot shows the track angle at DC6 of the negatively-charged track versus that of the positively-charged track. The signal stream is shown on the left, the $\pi\pi$ prescale stream is on the right. The interior of the box in each graph shows those events which were consistent with the geometric requirement of the hardware trigger.

The presence of a distinct extra track introduces an ambiguity as to which proto-tracks are to be associated with an event. A distinct track is defined as any track in the spectro­meter which does not share any PATREC segments with any other PATREC track. Any event with a distinct extra track was removed from further consideration. The efficiency of rejecting an event with a distinct extra track, based upon the $K_L^0 \rightarrow \pi^+\pi^-$ stream, was $95.17 \pm 0.26\%$.

### 6.4.5 Offline Trigger Requirement

The hardware "parallel" trigger imposed a strict angular requirement in the $xz$ plane on accepted tracks. However, as previously discussed, events which cross over the beam line or tracks from coincidence decays can be accepted by the hardware trigger. One signature of these events, as illustrated in Fig. 6.13, is that the measured angle in the $xz$ plane is outside of the 20 mrad (inbend) $< \frac{\Delta \theta}{\Delta \phi} <$ 30 mrad (outbend) window imposed by the trigger.
The maximum geometric trigger window, measured at DC6, was re-imposed on the data. The efficiency of this trigger requirement was $97.62 \pm 0.26\%$ from the $\pi\pi$ prescale stream.

### 6.4.6 Track Time Cuts

The track times of both tracks were required to be consistent with that of a two-pion signal. Two pions originating from the same decay, even if their momenta differ by 8.0 GeV/c, should arrive at the TSCs within 0.5 ns of each other. However, a neutron from the neutral beam which interacts with a constituent of the residual gas in the decay volume could produce a $\pi^- p$ pair from a reaction such as:

$$n + n \rightarrow n + p + \pi^-$$  \hspace{1cm} (6.4)

The proton's speed does not approach the speed of light until its momentum is approximately 4.0 GeV/c or more. The difference in $\beta = \frac{v}{c}$ of the two tracks versus the momentum of the positively charged track for data taken under conditions of degraded vacuum is shown in Fig. 6.14. Low momentum protons from $n + n$ interactions can be suppressed by imposing a track time match at the TSCs. This cut also rejects accidental coincidences in the hardware trigger. Fig. 6.15 shows the difference in track times measured at the TSC modules for both the high mass and normalization samples.

The track times were required to match to within 1.75 ns of each other. The efficiency of this cut was $96.76 \pm 0.26\%$ measured from the normalization stream.
Figure 6.14: The difference in track $\beta$ versus the momentum of the positively charged track for a subset of the signal stream taken under degraded vacuum conditions. Pions in the E935 system travel at essential $\beta = 1$. Low momentum protons travel at $\beta < 1$. Thus the increase in $\Delta \beta$ for low momentum positively charged tracks is evidence of protons.

Figure 6.15: The TSC track time requirement for the high-mass signal stream and for the normalization stream. Each plot shows the difference in track times measured at TSC modules. The signal stream is shown on the left, the $\pi\pi$ prescale stream is on the right. The vertical lines show the applied cut.
6.5 Kinematic Cuts

6.5.1 Invariant Mass Cut

For the case in which only the two charged tracks of the $R^0 \rightarrow \pi^+\pi^-\gamma$ decay are reconstructed, the two body invariant mass in given by

$$M_{12}^2 = (E_1 + E_2)^2 - (P_1 + P_2)^2$$ (6.5)

This invariant mass formula can be approximated in the laboratory frame in the limit of kinetic energies much greater than rest energies and small opening angle between the two tracks by:

$$M_{12}^2 \sim m_1^2 \left( 1 + \frac{p_2^{lab}}{p_1^{lab}} \right) + m_2^2 \left( 1 + \frac{p_1^{lab}}{p_2^{lab}} \right) + p_1^{lab} p_2^{lab} \theta_{open}$$ (6.6)

The approximations in Eq. 6.6 are valid for pions accepted by E935.

The mis-identification of a lepton as a pion from a $K_L^0 \rightarrow \pi e \nu$ ($K_{e3}$) or a $K_L^0 \rightarrow \pi \mu \nu$ ($K_{\mu3}$) decay incorrectly assigns the lepton the mass of a pion. For $K_{\mu3}$, this mis-identification can increase the calculated invariant mass by $\geq 34$ MeV/c$^2$. For $K_{e3}$, this increase can be $\geq 139$ MeV/c$^2$. Thus a benign semi-leptonic kaon decay could mimic an $R^0$ signal.

In order to address these backgrounds from $K_L^0$ semi-leptonic decays, electron identification was made redundant and used both the Čerenkov counter and the lead glass array. Muon identification consisted only of signals from the muon hodoscope planes. Thus to facilitate muon rejection, an invariant mass cut of $M_{\pi\pi} > 545$ MeV/c$^2$ as calculated in the QT fitting algorithm, was imposed upon the signal stream in Pass 2. This cut had the effect of adding a level of redundancy to lepton identification.

The 545 MeV/c$^2$ invariant mass cut implies that for any given value of $M_{R^0}$, there is a kinematic constraint on the value of $r \equiv \frac{M_{R^0}}{M_{\gamma}}$:
\[ M_{R^0} \left( 1 - \frac{1}{r} \right) > 545 \text{ MeV/c}^2 \] (6.7)

Eq. 6.7 places a strict limit on the sensitivity of the experiment to various combinations of \( R^0 \) parameters.

6.5.2 Transverse Momentum in the Decay Plane

From Eq. 6.6, it can be seen that the value of the opening angle between two decay daughters has a large effect on the calculated invariant mass for the decay. Since there is no tracking in the decay volume, the opening angle between the two charged tracks is determined entirely by the particle trajectories through the first two tracking stations. Any interactions which occur upstream of these chambers can cause an increase in the measured opening angle and thus in the calculated invariant mass.

Gaussian multiple scattering of a pion in \( K_L \rightarrow \pi^+\pi^- \) decay can be safely ignored since effects from it would not cause an increase in the invariant mass above the 545 MeV/c\(^2\) cut. However, non-Gaussian effects, such as hadronic scattering of a pion, are a source of serious background. Fortunately, vertex reconstruction requirements reduce the acceptance for these non-Gaussian interactions. A track which scatters with a large component of momentum out of the decay plane will increase the \( V_{doca} \) substantially. However, this background becomes important when the track scatters in the plane of the decay. Vertex reconstruction will not identify these events.

To address the problem of in-plane scattering, a cut was made on the component of the transverse momentum in the plane of the decay, denoted \( p_T \). The transverse momentum \( p_T \) is defined as the vector difference between the parent particle's momentum and the vector sum of the momenta of the daughters of the decay, measured in the laboratory, as shown in Fig. 6.16.

The peak of the transverse momentum distribution for a particle from \( K_{e3} \) decay

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Figure 6.16: The transverse momentum $p_T$, defined for a final state in which only two of the particles are observed. An example kaon with incident momentum $P_K$ decays into two observed particles with momenta $p_1$ and $p_2$ as shown. The transverse momentum $p_T$ is the difference between the vector sum of momenta of the daughter particles $p_1 + p_2$, and the initial kaon momentum $P_K$. Adapted from [45].

is 229 MeV/c; for $K^0_L \rightarrow \pi^+\pi^-$ decay, 206 MeV/c; and for $K_{\mu3}$ decay, 216 MeV/c [70]. Fig. 6.17 shows the $p_T^\parallel$ distribution of the positively-charged and negatively-charged tracks in a subset of the $\pi\pi$ prescale stream. As expected, the $K^0_L \rightarrow \pi^+\pi^-$ stream is peaked at $p_T^\parallel = 206$ MeV/c for both tracks. Fig. 6.18 shows the distribution in $p_T^\parallel$ for both positivelycharged and negatively-charged tracks for both the $K^0_L \rightarrow \pi^+\pi^-$ normalization stream and the high mass signal stream.

The $p_T^\parallel$ for both tracks was required to be $> 229$ MeV/c. The effect of this cut will be factored into the calculated acceptance for each $R^0$ parameter set. The $R^0$ acceptance calculation will be described in Section 8.2.1.

6.6 Particle Identification Cuts

The $\pi\pi$ prescale stream was studied extensively to assess the detector performance for a two-pion signal. The following is a summary of the criteria applied to both the
Figure 6.17: The transverse momentum in the plane of the decay of the positively-charged track (dashed) and the negatively-charged track (solid) for a subset of raw $K^0_L \rightarrow \pi^+\pi^-$ normalization stream events. The peak of the distribution is expected to be at $p_T^\parallel = 206$ MeV/c.

Figure 6.18: The transverse momentum in the plane of the decay of the positively-charged track versus that of the negatively-charged track. The high-mass signal region is shown on the left, the $\pi\pi$ prescale stream is on the right. The applied cut required both tracks to have $p_T^\parallel > 229$ MeV/c.
\( K_L^0 \to \pi^+\pi^- \) and the high mass signal streams.

### 6.6.1 Čerenkov Counter

Since \( K_{\ell3} \) decays constitute almost 40% of all long-lived kaon decays, and the geometric trigger requirements preferentially accepted this mode, a hard electron veto in the Čerenkov counter was applied. An event was rejected if any photo-electrons from the Čerenkov counter were associated with either track. This rejection re-imposes the Čerenkov veto applied in the trigger. The efficiency of this cut was 96.25 ± 0.26%, as measured by the \( \pi\pi \) prescale stream. However, this value is misleading since the Čerenkov “possible electron” veto had already been applied to all tracks in the stream. This cut implies an 8.3 GeV/c momentum cut since all pions above 8.3 GeV/c momentum should yield Čerenkov photo-electrons.

### 6.6.2 Lead Glass Array

As discussed in Section 3.7.2, the lead glass array used a contour cut to identify electrons. Event selection with the lead glass array employed a logical NOT “possible electron” and NOT “good electron” from the PBG track-to-counter association routine. The efficiency of this requirement was 97.91 ± 0.26%.

Since a NOT “possible electron” could consist of tracks which fail to strike any of the active elements of the lead glass array, a fiducial cut requiring a track to deposit some energy in the converter blocks was imposed. Therefore, the converter fraction \( \frac{E_C}{E_T} \) was required to be non-zero. The efficiency of this requirement was calculated to be 83.98 ± 0.28% measured with \( K_L^0 \to \pi^+\pi^- \) events. This value of the efficiency is misleading in that it is a combination of both fiducial volume considerations as well as of the inherent efficiency of the array itself.
6.6.3 Muon Hodoscope

The trigger veto on muons was re-applied offline by requiring that each track return a logical NOT "good $\mu$" and NOT "possible $\mu$" from the MHO track-to-counter association routine. The efficiency of this requirement was 97.19 ± 0.26 % measured with events in the $\pi\pi$ prescale stream. This efficiency calculation, however, does not take into account the number of $\pi\pi$ events which were vetoed in the trigger.

6.7 Summary of the Selection Criteria

Fiducial volume, vertex quality, event quality, and kinematic and particle identification selection criteria have thus been determined. Table 6.1 is a summary of these selection criteria and their efficiencies.

After the application of all of the above cuts to the signal stream, one event remains. This event is shown in Fig. 6.19, a plot of the $p_T^\parallel$ plane with all criteria, except the $p_T^\parallel$ cut, applied. In order to assess the significance of this event, the experimental sensitivity and anticipated background need to be determined.
<table>
<thead>
<tr>
<th>Description of Cut</th>
<th>Efficiency (%)</th>
<th>Data Stream</th>
</tr>
</thead>
<tbody>
<tr>
<td>$</td>
<td>\Theta_X</td>
<td>&lt; 2 \text{ mrad}$</td>
</tr>
<tr>
<td>$</td>
<td>\Theta_Y</td>
<td>&lt; 10 \text{ mrad}$</td>
</tr>
<tr>
<td>$10.6 \text{ m} &lt; V_Z &lt; 19.5 \text{ m}$</td>
<td>Acceptance</td>
<td>–</td>
</tr>
<tr>
<td>$\text{Vertex } \chi_2^2 &lt; 3$</td>
<td>94.79 ± 0.26</td>
<td>$\pi\pi$</td>
</tr>
<tr>
<td>$\text{Vertex doca }</td>
<td>V_d</td>
<td>&lt; 8.5 \text{ mm}$</td>
</tr>
<tr>
<td>$\text{Combined } V_d \text{ and } \text{Vertex } \chi_2^2$</td>
<td>93.70 ± 0.26</td>
<td>$\pi\pi$</td>
</tr>
<tr>
<td>$\text{Track } \chi_2^2 &lt; 10$</td>
<td>93.60 ± 0.26</td>
<td>$\pi\pi$</td>
</tr>
<tr>
<td>$</td>
<td>\Delta P</td>
<td>&lt; 5%$</td>
</tr>
<tr>
<td>No Extra Distinct Track</td>
<td>95.17 ± 0.26</td>
<td>$\pi\pi$</td>
</tr>
<tr>
<td>$\frac{dE}{dz}_{DC6} \rightarrow 20 \text{ mrad inbend } / 30 \text{ mrad outbend}$</td>
<td>97.62 ± 0.26</td>
<td>$\pi\pi$</td>
</tr>
<tr>
<td>$P &lt; 8.3 \text{ GeV/c}$</td>
<td>Acceptance</td>
<td>–</td>
</tr>
<tr>
<td>$</td>
<td>\Delta T</td>
<td>_{TSC} &lt; 1.75 \text{ ns}$</td>
</tr>
<tr>
<td>$E_C / E_T \neq 0$</td>
<td>83.98 ± 0.28</td>
<td>$\pi\pi$</td>
</tr>
<tr>
<td>Good TSC</td>
<td>96.76 ± 0.26</td>
<td>$\pi\pi$</td>
</tr>
<tr>
<td>No CER Photo-Electrons</td>
<td>96.25 ± 0.26</td>
<td>$\pi\pi$</td>
</tr>
<tr>
<td>No “Good e” and No “Possible e” From PBG</td>
<td>97.91 ± 0.26</td>
<td>$\pi\pi$</td>
</tr>
<tr>
<td>No “Good \mu” and No “Possible \mu” From MHO</td>
<td>97.19 ± 0.26</td>
<td>$\pi\pi$</td>
</tr>
<tr>
<td>$M_{\pi\pi} &gt; 545 \text{ MeV}$</td>
<td>Acceptance</td>
<td>–</td>
</tr>
<tr>
<td>$P_T^{ll} &gt; 229 \text{ MeV}$</td>
<td>Acceptance</td>
<td>–</td>
</tr>
</tbody>
</table>

Table 6.1: Values of the final cuts applied to the signal stream and their respective efficiencies. All efficiencies were measured from the $\pi\pi$ prescale stream except those whose effects were folded into the values of the $R^0$ acceptance.
Figure 6.19: The final signal data in the $p_T^\parallel$ plane. All cuts except the $p_T^\parallel > 229$ MeV/c$^2$, shown as a dashed box, are applied. The signal region is the upper right quadrant.
Chapter 7

Experimental Sensitivity

7.1 Overview

In order to determine the sensitivity of E935 to possible $R^0 \rightarrow \pi^+\pi^-\gamma$ events, the flux for hypothetical $R^0$ production must be determined relative to some well measured process. Given a theoretical model of $R^0$ production, the anticipated flux ratio of $R^0$ events to the normalization mode can be determined.

The decay $K_L^0 \rightarrow \pi^+\pi^-$ was chosen as the normalization process. Since the $\pi\pi$ prescale stream was treated in a manner identical to that of the high mass signal stream, except for a prescale based on the reconstructed invariant mass of the event, the events in the $\pi\pi$ prescale data stream, at the end of Pass 2, were used as the normalization data sample.

The minimum bias data stream, taken simultaneously with the $\pi\pi$ trigger data, was used for an approximate confirmation of the normalization counting. However, large hardware and software prescales on the minimum bias sample left this sample with minimal statistics.

Both the anticipated tracks from hypothetical $R^0$ events and the tracks from the normalization $K_L^0 \rightarrow \pi^+\pi^-$ sample are two-charged pion tracks. Thus the primary differ-
ence between the behavior of pions from $K_L^0 \rightarrow \pi^+\pi^-$ events and from hypothetical $R^0$ events arises from differences in the momentum distributions of the decays.

The following sections describe the calculation of the kaon flux from the number of $K_L^0 \rightarrow \pi^+\pi^-$ events counted in the normalization data stream.

7.2 Normalization Sample

As discussed in Chapter 5, L1 $\pi\pi$ events which passed mod15 PATREC, QT fitting, and a CER "possible electron" veto, but did not have at least one vertex which passed a PATREC $M_{\pi\pi} > 540$ MeV/c$^2$ and a QT $M_{\pi\pi} > 545$ MeV/c$^2$, were prescaled by 100 and assigned the $\pi\pi$ prescale stream bit at the end of Pass 2. This event stream forms the basis for all subsequent normalization analysis.

All selection criteria discussed in Chapter 6 were applied to this data stream with the exception of the kinematic $\pi\pi$ invariant mass $M_{\pi\pi} > 545$ MeV/c$^2$ and $p_T^\pi > 229$ MeV/c cuts. Thus the $K_L^0 \rightarrow \pi^+\pi^-$ prescale events were required to pass the same particle identification requirements as the signal stream, as well as the same event and vertex quality criteria. A total of 83,696 prescaled $K_L^0 \rightarrow \pi^+\pi^-$ events pass all of these selection criteria.

A background subtraction was applied to these remaining events to remove mis-identified semi-leptonic kaon decays from the final flux calculation. Two procedures for the background subtraction were performed and compared. The first method fits the $K_L^0 \rightarrow \pi^+\pi^-$ peak in $M_T$. The second method fits the $K_L^0 \rightarrow \pi^+\pi^-$ distribution in $p_T^\pi$, the square of the transverse momentum.

7.2.1 Kaon Counting in the $M_{\pi\pi}$ Distribution

The first background subtraction was performed on the $K_L^0 \rightarrow \pi^+\pi^-$ peak in $M_{\pi\pi}$. A $p_T^\pi < 10$ (MeV/c)$^2$ cut was applied to the prescaled $K_L^0 \rightarrow \pi^+\pi^-$ events. A total of 78,819 events remains in the data sample, as shown in Fig. 7.1.
Figure 7.1: The $\pi\pi$ invariant mass plot for the $\pi\pi$ prescale stream. A $p_T^2 < 100 \text{ (MeV/c)}^2$ cut is applied.

The peak was fit to a Gaussian plus a flat background. The background was measured to be 13.45 events per 0.16 MeV/c$^2$ bin. The signal region was defined as the region between $\pm 5\sigma$ of the fit $K_L^0$ peak; namely $491.02 \text{ MeV/c}^2 < M_{\pi\pi} < 504.27 \text{ MeV/c}^2$ ($1\sigma = 1.33 \text{ MeV/c}^2$). The number of events in this region was 78,205 of which 1,117.8 were determined to be background. Hence, fitting the normalization distribution in $M_{\pi\pi}$ gives $77,087.2 \pm 279.7$ prescaled $K_L^0 \rightarrow \pi^+\pi^-$ events.

7.2.2 Kaon Counting in the $p_T^2$ Distribution

As a consistency check, a background subtraction from fitting the $K_L^0 \rightarrow \pi^+\pi^-$ distribution in $p_T^2$ was also performed. First, a requirement that the calculated invariant mass $M_{\pi\pi}$ lie within $\pm 5\sigma$ of the fit $K_L^0$ peak ($1\sigma = 1.33 \text{ MeV/c}^2$), and thus a cut of $491.02 \text{ MeV/c}^2 < M_{\pi\pi} < 504.27 \text{ MeV/c}^2$, was applied. After this invariant mass requirement was applied, 81,330 prescaled events remained, as shown in Fig. 7.2.

The region for which $p_T^2 > 150 \text{ (MeV/c)}^2$ was fit to a flat line. The number of events in the signal region, defined as $p_T^2 < 100 \text{ (MeV/c)}^2$, was 78,205. Of these events, 436.8 were
determined to be background. Thus, a fit to the normalization distribution in $p_T^2$ resulted in a total of $77,768.2 \pm 279.65$ $K^0_L \rightarrow \pi^+\pi^-$ events.

This second method agrees to within 1% of the kaon counting in $M_{\pi\pi}$. The number of kaons counted from fitting the distribution in $M_{\pi\pi}$, namely 77,087, will be used in the remainder of this paper.

### 7.2.3 $K^0_S$ Contamination

Although the proper lifetime $\tau_S$ of the $K^0_S$ is 2.676 cm [70] and the decay region begins a distance of almost 11 m downstream of the target, some $K^0_S$ decays can enter into the number of detected $\pi\pi$ events. Kaons produced when protons interact in the target are $K^0$ and $\bar{K}^0$ eigenstates. The relative production of these states is given in terms of a dilution factor $D(p_K)$ defined as [71]:

$$D(p_K) = \frac{N_{K^0} - N_{\bar{K}^0}}{N_{K^0} + N_{\bar{K}^0}}.$$  \hspace{1cm} (7.1)
Christianson, et al. [71] fit this dilution factor for kaons at AGS energies and found a parameterization of $D(p_K)$ such that:

$$D(p_K) = 1 - 1.5e^{-0.17p_K}, \quad (7.2)$$

where $p_K$ is in GeV/c. The probability for a $K^0$ to decay into a $\pi^+\pi^-$ pair after a time $t$ can be written as:

$$| \langle \pi\pi | \hat{H}_{\text{weak}} | K^0(t) \rangle |^2 \sim e^{-t/\tau_S} + |\eta_{+-}|^2 e^{-t/\tau_L}$$

$$+ 2 |\eta_{+-}| e^{-(t/\tau_S + t/\tau_L)/2} \cos(\Delta m_K \tau - \phi_{+-})$$

(7.3)

where $\Delta m_K$ is the $K_L^0 - K_S^0$ mass difference and $|\eta_{+-}|$ and $\phi_{+-}$ are related by the ratio of amplitudes [70]:

$$\eta_{+-} = \frac{A(K_L^0 \to \pi^+\pi^-)}{A(K_S^0 \to \pi^+\pi^-)} = |\eta_{+-}| e^{i\phi_{+-}} \quad (7.4)$$

Multiplying the last term in Eq. 7.3 by the factor $D(p_K)$ and dividing by the second term in Eq. 7.3 gives the correction factor $f_{K_S}$ for the $K_S^0$ contamination:

$$f_{K_S} = 1 + |\eta_{+-}|^{-2} \exp\left(\frac{(1 - \frac{\tau_L}{\tau_S}) \frac{m_K}{p_K} \frac{z}{2}}{}\right)$$

$$+ 2 |\eta_{+-}|^{-1} (1 - 1.5e^{-0.17p_K}) \exp\left(\frac{(1 - \frac{\tau_L}{\tau_S}) \frac{m_K}{p_K} \frac{z}{2}}{}\right) \cos\left(\frac{m_K \frac{z}{p_K} \Delta m_K - \phi_{+-}}{2}\right)$$

(7.5)
In Eq. 7.5, the proper time as a function of the kaon momentum $p_K$, kaon mass $m_K$, and distance $z$ traversed prior to decay has been used:

$$ cT = \frac{m_K z}{p_K} \quad (7.6) $$

The kaon momentum and decay vertex location from $K_L^0 \rightarrow \pi^+\pi^-$ Monte Carlo events which satisfy all of the analysis cuts applied to the normalization stream were used to calculate the $f_{K_S}$ correction factor. When the proper lifetime of the event is less than approximately 50 cm, the $K_S^0$ correction factor becomes significant [45]. Those Monte Carlo events with $cT < 50$ cm were weighted by the correction factor to find an average correction $f_{K_S} = 1.00045$.

7.3 Experimental Acceptance for $K_L^0 \rightarrow \pi^+\pi^-$ Decays

7.3.1 Geometric and Selection Acceptance

The experimental acceptance $A_{\pi\pi}$ for $K_L^0 \rightarrow \pi^+\pi^-$ was calculated in Monte Carlo simulations. The acceptance was determined from a comparison of the number of events which was geometrically accepted by the trigger and passed all of the $K_L^0 \rightarrow \pi^+\pi^-$ normalization analysis criteria to the number of generated events. Events were also required to pass the $-1/2$ trigger parallelism. $K_L^0 \rightarrow \pi^+\pi^-$ events were generated in the $z$ range from 9.5 to 22.0 m with primary kaon momentum between 1.7 and 20.0 GeV/c. The value of the acceptance was calculated to be

$$ A_{\pi\pi} = 0.123\% \quad (7.7) $$

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Of the number of $K^0_L$ originating at the target, only a fraction decayed in the $z$ range given above. This decay fraction $D_{F_K}$ was calculated simultaneously with the acceptance and determined to be

$$D_{F_K} = 9.21\%$$ (7.8)

### 7.3.2 Pion Loss Due to Hadronic Interactions in the Spectrometer

Pions may interact in the material upstream of the TSCs and thus not satisfy the parallel trigger requirement. The standard Monte Carlo package does not simulate hadronic processes, and thus a correction to the experimental acceptance calculations was needed in order to account for the effect of the loss of such events in the kaon flux measurement.

In order to calculate this correction to the standard offline Monte Carlo simulation, a GEANT [65] Monte Carlo simulation of the pion loss due to hadronic interactions in the E935 detector system was developed [69]. The momentum distributions of the accepted Monte Carlo events were weighted by the pion loss probability for positively-charged and negatively-charged pions determined in this GEANT simulation. Fig. 7.3 shows the pion loss as a function of pion momentum for both positive and negative pions as determined by the GEANT simulations.

The procedure described determined the probability that an event would be lost by either track failing the trigger parallelism due to a hadronic interaction in the spectrometer. The correction factor for pion loss from hadronic interactions for the accepted $K^0_L \rightarrow \pi^+\pi^-$ events was determined to be $f_{\pi\pi}(K) = 0.9648$. 

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7.3.3 Pion Loss Due to "Pion Punch Through"

Although the iron hadronic filter immediately downstream from the lead glass array was designed to absorb hadrons impinging upon it, some pions or their interaction products will pass through the filter. Furthermore, these pions could reach the one GeV/c MHO trigger plane and would thus be vetoed by the hardware trigger. This "pion punch through" was not simulated in the standard offline Monte Carlo package. Therefore a GEANT Monte Carlo simulation [65] was developed to determine the number of pions which "punched through" to the first trigger plane.

The lead glass array, muon hodoscopes and muon range-finding stack were simulated in the GEANT study. A series of simulations was developed for both negatively charged and positively charged pions to cover the momentum range between 0.5 and 8.0 GeV/c. Monochromatic pions were generated 2.0 cm upstream of the lead glass array and tracked through the simulated detectors. An event was considered to be vetoed by the MHO if any charged particle struck the MHO X0 scintillation plane within ± 25.4 cm of the initial track.

Figure 7.3: The pion loss as a function of pion momentum for pions interacting in the upstream portion of the detector system determined from GEANT Monte Carlo simulations.
Figure 7.4: The pion loss as a function of pion momentum for pions in the downstream portion of the detector system that penetrate to the trigger plane of the MHO, as determined from GEANT Monte Carlo simulations.

position (± 1 MHO X0 slat). The percentage of monochromatic pions which was deemed vetoed by the MHO trigger as a function of incident pion momentum is shown in Fig. 7.4 for both positively charged and negatively charged pions.

In a manner similar to the calculation for the correction for pion loss in the spectrometer, the momenta distribution for the $K_L^0 \rightarrow \pi^+\pi^-$ acceptance Monte Carlo simulation was weighted by the "pion punch through" loss as a function of momentum in order to determine a correction $f_{ML}(K)$ for $K_L^0$ events lost because of the MHO veto in the trigger. The correction for $K_L^0 \rightarrow \pi^+\pi^-$ events lost due to "pion punch through" to the MHO trigger plane was $f_{ML}(K) = 0.798$.

7.4 Experimentally Determined Kaon Flux

The total $K_L^0$ flux at the target production angle of 3.75° was determined from the number of $K_L^0 \rightarrow \pi^+\pi^-$ events, corrected for both pion loss and $K_S^0$ contamination, and from the experimental acceptance. The number of $K_L^0$ which originated from the target at
Table 7.1: Table of factors which are used to determine the total number of kaons originating at the production target.

\[
N_{K_L}^0 = \frac{P N_{\pi \pi}}{Br[K_L^0 \to \pi^+ \pi^-] f_{\pi \pi}(K) f_{\pi \pi}(K) A_{\pi \pi} DF_K}
\]  

(7.9)

where P is the software prescale factor applied in Pass 2 and \( Br[K_L^0 \to \pi^+ \pi^-] \) is the branching ratio \cite{70}

\[
Br[K_L^0 \to \pi^+ \pi^-] = 2.067 \times 10^{-3}
\]  

(7.10)

The values of the factors in Eq. 7.9 are given in Table 7.1. The total number of \( K_L^0 \)'s originating at the target at a targeting angle of 3.75° was determined to be:

\[
N_{K_L^0} = 4.27 \times 10^{13}
\]  

(7.11)
7.5 Theoretical Cross Section for Kaon Production

The theoretical cross section for production of neutral kaons was determined by a parameterization of the \( pBe \) cross section from the work of Skubic, et al. [66]. Their results were extrapolated down to 24 GeV AGS energies by Feynman scaling [64]. These data were used to calculate the double differential production cross section from beryllium at 3.75° targeting angle. This double differential cross section was then integrated over the momentum distribution of kaons produced in Monte Carlo, which ranged from 1.7 to 20.0 GeV/c. The differential cross section thus calculated was then scaled to \( pN \) scattering by a factor of \( (1/A_{Be})^{3/2} = (1/4.33) \). The \( pN \) differential cross section was 30.4 mb/ster at 3.75°.

For reference, the \( pN \) cross section was scaled to \( pPt \) scattering by a factor of \( A_{Pt}^{2/3} \) to yield an estimated production cross section for neutral kaons from a Pt target of \( \frac{d\sigma}{d\Omega} = 148.65 \) mb/ster.

7.6 Kaon Absorption in the Pt Target

In order to convert the differential production cross section into a flux, it is necessary to correct for the absorption in the target of incident protons as well as for outgoing \( K^0_L \)'s. As a particle traverses matter, there is a probability that the particle will scatter, exchange quanta or be absorbed. At shallow targeting angles, the primary proton beam passes through a significant amount of material and is attenuated by 1.4 proton interaction lengths. The \( K^0_L \) flux, at small production angles, is given by [67]:

\[
\frac{K^0_L}{(Tp \ \mu ster)} = \frac{d\sigma}{d\Omega} \left( \frac{mb}{ster} \right) \times 10^{-21} \times \left( \frac{N_{Av}\lambda_p}{A} \right) \times C(K^0) \tag{7.12}
\]

where \( N_{Av} \) is Avogadro's number, \( A \) is atomic weight of the target material, \( \lambda_p \) is the proton interaction length in the target material in \( g/cm^2 \), \( 10^{-21} \) is the conversion factor in order to have the correct units, and \( C(K^0) \) is the transmission correction factor which accounts for
the attenuation of the incident proton beam as well as the attenuation of the exiting kaon beam in the target. This “thick target transmission correction factor” for a material $X$ is given by [67, 72]:

$$C(K^0)_X = \left( \frac{\lambda_K}{\lambda_p - \lambda_K} \right) \left( e^{-n} - e^{-n \frac{\lambda_p}{\lambda_K}} \right)$$

(7.13)

where $\lambda_p$ and $\lambda_K$ are the respective absorption lengths of the proton and kaon in units of $g/cm^2$ and $n$ is the length of the target in proton interaction lengths.

The interaction length of a particle in matter can be determined from its total absorption cross section $\sigma_{abs}$. For a substance with atomic weight $A$ the interaction length is the particle’s mean free path in the substance:

$$\lambda_{particle} = \frac{A}{N_A \sigma_{abs}}$$

(7.14)

Thus, the interaction length for the kaon can be written in terms of the proton mean free path as:

$$\lambda_{K^0} = \left( \frac{\sigma(pN)_{abs}}{\sigma(K^0N)_{abs}} \right) \lambda_p$$

(7.15)

The absorptive cross section for neutral kaons in matter is determined by averaging those of the two charged kaon states:

$$\sigma(K^0)_{abs} = \frac{1}{2} \left( \sigma(K^+)_{abs} + \sigma(K^-)_{abs} \right) = 24 \text{ mb}$$

(7.16)

over the momentum range from 1.0 to 20 GeV/c for a Pt target. The cross sections for the charged kaon states in $pp$ and $pn$ interactions, found in [70], are complicated functions of the particle momentum. The interaction length for the neutral kaon is determined to be $\lambda_{K^0}$.

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1.6 \lambda_p [72]. The proton interaction length is given in the Review of Particle Properties published by the Particle Data Group (PDG) for various target materials [70]. The mean free path for protons in a Pt target is \lambda_p = 189.7 \text{ g/cm}^2. The thick target correction factor [Eq. 7.13] for kaons produced by a primary proton beam incident on a 1.4 proton interaction length Pt target is \( C(K^0)_{Pt} = 0.454 \).

7.7 Spoiled Vacuum Analysis

The next step in the analysis was to determine the number of background events in the high mass signal region expected from neutrons interacting with the residual gas in the decay volume. This measurement used the two series of "spoiled vacuum data" discussed in Section 5.1. For this measurement, the ratio of the number of signal stream events which pass all selection criteria to the number of normalization \( K_L^0 \rightarrow \pi^+\pi^- \) decay events was determined as a function of pressure in the decay region. This ratio of the number of high-mass events to the number of \( K_L^0 \rightarrow \pi^+\pi^- \) events was then extrapolated down to the vacuum level at nominal running conditions.

The justification for this background extrapolation was that the expected number of high-mass events per \( K_L^0 \rightarrow \pi^+\pi^- \) decay scales linearly with the pressure in the decay volume. Previous Monte Carlo simulations [1] explored this linear relationship of the number of high-mass events as a function of vacuum level. A preliminary comparison was made of the first series of "spoiled vacuum" data to the second series of "spoiled vacuum" data. However, the first set of data was not actually used in subsequent analysis because of the low statistics of the sample. Both series of "spoiled vacuum" data are shown in Fig. 7.5.

Following a study of the second series of "spoiled vacuum" data, it was determined that the high-statistics sample taken when the pressure in the decay tank was maintained at 0.32 torr (runs 31418 through 31420) would form the basis of the linear fit through the origin, as shown schematically in Fig. 7.6.
Figure 7.5: The number of high mass events per $K_L^0 \rightarrow \pi^+\pi^-$ as a function of the vacuum pressure for data taken under "spoiled vacuum" conditions. The data from the first series of degraded vacuum runs have been combined into three data points at approximately $10^{-2}$ torr. All analysis cuts have been applied to both the normalization and signal streams in this graph. The $K_L^0 \rightarrow \pi^+\pi^-$ sample has been multiplied by the prescale factor $P=100$, from Pass 2.

Figure 7.6: Schematic representation of background extrapolation to nominal running pressure. Point $A$ represents the "spoiled vacuum" data. Point $B$ represents the extrapolation to the running vacuum level at $6 \times 10^{-6}$ torr.
The number of signal events passing all selection criteria per $K^0_L \rightarrow \pi^+\pi^-$ event was extrapolated to the nominal running pressure ($6 \times 10^{-6}$ torr). This ratio of signal events per $K^0_L \rightarrow \pi^+\pi^-$ at nominal running conditions, multiplied by the number of $K^0_L \rightarrow \pi^+\pi^-$ counted, $N_{\pi\pi} = 77,087$, yields the total number of anticipated high mass background events generated over the period of running. The details of this analysis are described in the following sections.

### 7.7.1 Analysis of the Spoiled Vacuum Data

The $\pi\pi$ prescale stream and high-mass signal stream of the "spoiled vacuum" runs were analyzed in exactly the same manner as were the data taken during actual running vacuum conditions. The three runs corresponding to a vacuum level of 0.32 torr taken on the final day of running (31418, 31419, 31420) were full 200 MB data runs at stable vacuum conditions. The total number of these spoiled vacuum events in the high-mass signal region after all analysis cuts were applied was measured to be $SV_{HM} = 333$, as indicated in Fig. 7.7. The distribution for these same data taken during the 0.32 torr degraded vacuum period, in
Figure 7.8: The $p_T$ distribution for the high-mass signal stream of the spoiled vacuum data. All analysis cuts, except the $p_T$ requirement, have been applied.

$p_T$ for the positively-charged track versus the negatively-charged track, is shown in Fig. 7.8.

The total number of $K_L^0 \rightarrow \pi^+\pi^-$ events for the above three runs was also determined. For this measurement, the method for background subtraction followed the same procedure as described earlier in this chapter. After a 100 (MeV/c)$^2$ cut in $p_T^2$ was applied, 339 prescaled $K_L^0 \rightarrow \pi^+\pi^-$ events remained in the normalization region, as shown in Fig. 7.9. There was not enough of a distinct background to attempt a background subtraction. Therefore, all events within $\pm 5\sigma$ of the $K_L^0$ mass peak were counted as $K_L^0 \rightarrow \pi^+\pi^-$ decays. From these data, it was determined that $SV_{\pi\pi} = 337 \pm 18$ is the number of $K_L^0 \rightarrow \pi^+\pi^-$ events. As a reminder, these data were subject to a prescale factor $P=100$ coming out of Pass 2. The $K_S^0$ correction to this number is negligible.

In a manner similar to the earlier background subtraction, the $K_L^0 \rightarrow \pi^+\pi^-$ distribution was also studied in $p_T^2$. The number of events between $\pm 5\sigma$ of the kaon mass was determined to be 349, as shown in Fig. 7.10. After examining the region $p_T^2 > 150(\text{MeV}/c)^2$, it was determined that there were not enough data in this region to perform a reliable
7.7.2 Extrapolation to the Running Vacuum Level

At this point, the number of anticipated high-mass background events arising from beam neutron-residual gas interactions under nominal vacuum conditions can be calculated. Following Fig. 7.6, the line from point $A$ through the origin is

$$Y \left( \frac{(High\ mass\ signal\ events)}{(K^0_L \rightarrow \pi^+\pi^- \times P)} \right) = m \times (torr)$$

(7.17)

where $P = 100$ is the prescale factor applied in Pass 2. Thus,

$$m = \left( \frac{SV_{HM}}{SV_{\pi\pi} \times P} \right) \left( \frac{1}{0.32 \text{ torr}} \right)$$

(7.18)

or
Figure 7.10: $P_T^2$ distribution for the $\pi\pi$ data stream of the spoiled vacuum runs. A $491 \frac{MeV}{c^2} < M_{\pi\pi} < 504 \frac{MeV}{c^2}$ cut was applied.

$$m = \frac{333}{(337 \times 100)(0.32)} = 0.0309 \quad (7.19)$$

The number of anticipated high mass background events at the running vacuum level (point $B$ of Fig. 7.6) of $x = 6 \times 10^{-6}$ torr is thus:

$$Anticipated\ Background = [m \, (6 \times 10^{-6} \, torr)](N_{\pi\pi} \times P) \quad (7.20)$$

or

$$Anticipated\ Background = [((0.0309)(6 \times 10^{-6}))(77,087 \times 100)] \quad (7.21)$$

which yields:

$$Anticipated\ Background = 1.4 \pm 0.2 \quad (7.22)$$
and thus this calculation implies an anticipated background of 1.4 events in the signal region for the duration of running at the nominal vacuum condition of $6 \times 10^{-6}$ torr.
Chapter 8

$R^0$ Sensitivity

8.1 Overview

Analysis of the spoiled vacuum data indicates that 1.4 events in the signal region, after all selection criteria were applied, could be attributed to interactions of neutrons in the neutral beam with the residual gas in the vacuum decay region. After all selection criteria were applied to data taken at the nominal running pressure of $6 \times 10^{-6}$ torr, one event remained as a possible signal event, as shown in Fig. 6.19. The final task remaining in the analysis is the calculation of the experimental limit on $R^0$ production in $pN$ collisions normalized to the $K_L^0 \rightarrow \pi^+\pi^-$ decay.

The results of the E935 light gluino search will be given in terms of a limit on the $R^0$ to $K_L^0$ flux ratio. The flux ratio is determined from Eq. 7.12 written as a ratio of $R^0$ production to $K_L^0$ production:

$$\text{Number of } \frac{R^0}{K_L^0} = \left( \frac{\frac{d\sigma}{dt}(R^0)}{\frac{d\sigma}{dt}(K_L^0)} \right) \times \frac{C(R^0)_{Pt}}{C(K^0)_{Pt}} \quad (8.1)$$

If we assume $C(R^0)_{Pt} = C(K^0)_{Pt}$, then Eq. 8.1 reduces to the ratio of differential cross sections:
Number of $\frac{R^0}{K^0_L} = (\frac{d\sigma_R}{d\Omega})/(\frac{d\sigma_K}{d\Omega})$ \hfill (8.2)

The experimentally determined flux ratio written out with all of the calculated correction factors is:

\[
(\frac{d\sigma_R}{d\Omega})/(\frac{d\sigma_K}{d\Omega}) = N_{ob} \left( \frac{A_{fK} \times DfK \times f_{K_L} \times f_{\pi\pi}(K) \times f_{ML}(K)}{P \times N_{\pi\pi}} \right) \left( \frac{Br[K^0_L \rightarrow \pi^+\pi^-]}{Br[R^0 \rightarrow \pi^+\pi^-]} \right) \left( \frac{1}{A_{R^0}} \right) \hfill (8.3)
\]

where the first factor in parenthesis multiplied by $Br[K^0_L \rightarrow \pi^+\pi^-]$ is $\frac{1}{N_{K^0_L}}$, which was determined in Chapter 7. $N_{ob} = 1$ is the number of observed events as determined in Chapter 6. $Br[R^0 \rightarrow \pi^+\pi^-]$ is the branching fraction for $R^0 \rightarrow \pi^+\pi^-\gamma$, and $A_{R^0}$ is the combined geometric acceptance for $R^0 \rightarrow \pi^+\pi^-\gamma$ in the detector and the efficiency of selection criteria applied to the $R^0$ decay. Under the assumption that $Br[R^0 \rightarrow \pi^+\pi^-\gamma] = 100\%$, this equation reduces to:

\[
(\frac{d\sigma_R}{d\Omega})/(\frac{d\sigma_K}{d\Omega}) = \left( \frac{N_{ob}}{N_{K^0_L}} \right) \left( \frac{1}{A_{R^0}} \right) \hfill (8.4)
\]

Incorporation of the experimentally measured number of kaons [Eq. 7.11] and one signal candidate event into Eq. 8.4 yields

\[
(\frac{d\sigma_R}{d\Omega})/(\frac{d\sigma_K}{d\Omega}) = 2.34 \times 10^{-14} \left( \frac{1}{A_{R^0}} \right) \hfill (8.5)
\]

where all $R^0$ parameter-dependent factors are contained in $A_{R^0}$. Therefore, the final task in the analysis is to determine the experimental acceptance of $R^0 \rightarrow \pi^+\pi^-\gamma$ events in the E935 detector system. Since the topology of a two-pion event from an $R^0 \rightarrow \pi^+\pi^-\gamma$ decay depends on the choice of $R^0$ parameters $M_{R^0}$, $M_{\gamma}$, $\tau \equiv M_{R^0}/M_{\gamma}$, and $\epsilon \tau$, the acceptance factor $A_{R^0}$ must be determined for each $R^0$ parameter set.
The conservative approach in the calculation of the limit on $R^0$ production is to evaluate the limit based on one event. In this discussion, it is assumed that the branching ratio $\text{Br}[R^0 \rightarrow \pi^+\pi^-\gamma]$ is 100%. As discussed in Chapter 2, if the $R^0 \rightarrow \rho\gamma$ channel is not inhibited by energy balance, it would be the dominant decay channel. The acceptance for $R^0 \rightarrow \rho\gamma \rightarrow \pi^+\pi^-\gamma$ increases the acceptance over the channel $R^0 \rightarrow \pi^+\pi^-\gamma$ by a few percent [1]. Thus it is conservative to set an upper limit based solely on the $R^0 \rightarrow \pi^+\pi^-\gamma$ channel.

8.2 Determination of the $R^0$ Experimental Sensitivity

The E935 experimental sensitivity $A_{R^0}$ to $R^0 \rightarrow \pi^+\pi^-\gamma$ was determined in Monte Carlo. This $R^0$ Monte Carlo simulation was based on the standard offline MC used for the $K_L^0 \rightarrow \pi^+\pi^-$ acceptance calculations. $R^0$ events were generated in MC stage 1, and swum through the detector. The charged daughters were required to satisfy the -1/+2 trigger parallelism criterion and to avoid striking any hard material in the spectrometer. Details of the Monte Carlo event generation were given in Chapter 4 and references cited therein. The $R^0 \rightarrow \pi^+\pi^-\gamma$ events which satisfied these geometric requirements were then fit using the QT algorithm and required to pass the same criteria as were the data, as described in Chapter 6.

As discussed in Chapter 2, in order for light photinos, $\tilde{\gamma}$, to be dark matter candidates, the ratio of the $R^0$ mass to $\tilde{\gamma}$ mass, $r = \frac{M_{R^0}}{M_{\tilde{\gamma}}}$, should be in the range of 1.4 to 2.2. Consistent with the cold dark matter postulate, the basis of the $R^0$ simulation used $r = 1.4, 1.5, 2.0, 2.2,$ and $2.5$. It was also required that the quantity $M_{R^0}(1 - \frac{1}{r})$ be at least 545 MeV/c$^2$ in order to permit decay into two pions with invariant mass greater than the applied mass cut, $M_{\pi\pi} > 545$ MeV/c$^2$.

The $R^0$ Monte Carlo simulation suffered from the same limitations as the $K_L^0 \rightarrow \pi^+\pi^-$ simulation in that the offline MC did not calculate corrections for hadronic inter-
actions. Correction factors for the pion loss $f_{\pi\pi}(R)$ in the spectrometer and for pion loss $f_{ML}(R)$ in the MHO trigger were determined for each set of $R^0$ parameters based on the momentum distribution of accepted $R^0 \rightarrow \pi^+\pi^-\gamma$ MC events. The overall $R^0$ acceptance, $A_{R^0}$, thus reflects those events satisfying both geometric and selection requirements together with corrections for pion loss. The $R^0$ acceptance must also include the appropriate $R^0$ decay fraction $DF_{R}$. The acceptance is written as:

$$A_{R^0} = \text{(geometric and selection acceptance)} \times DF_{R^0} \times f_{\pi\pi}(R) \times f_{ML}(R)$$  \hspace{1cm} (8.6)$$

where the $R^0$ decay fraction $DF_{R^0}$ is a function of the $R^0$ and $\gamma$ masses and $R^0$ lifetime $\tau$. This decay fraction was calculated in Monte Carlo. The quantity $f_{\pi\pi}(R)$ is the correction for pion loss from hadronic interactions in the spectrometer and $f_{ML}(R)$ is the correction for pion loss in the MHO trigger. The geometric acceptance incorporates the geometric constraints of the detector configuration and the parallelism requirement trigger. Those events which topologically satisfy these requirements were then subject to the selection criteria detailed in Chapter 6. The number of $R^0$ events passing the geometric requirements imposed by the configuration of the detector system, passing the parallelism and particle identification requirements of the trigger, and satisfying the selection criteria imposed on data were then normalized to the number of $R^0$ events generated in Monte Carlo to yield the $R^0$ geometric and selection acceptance.

8.2.1 Calculating the $R^0$ Acceptance

The total acceptance $A_{R^0}$ of $R^0 \rightarrow \pi^+\pi^-\gamma$ events, as given in Eq. 8.6, was determined for each $R^0$ parameter set. First, a value of the mass ratio parameter $r$ was chosen. The mass of the $R^0$ was then varied from the kinematic limit imposed by the invariant mass requirement, $M_{R^0} (1 - \frac{1}{2}) > 545 \text{ MeV/c}^2$, to approximately 2.0 GeV/c$^2$. The choice of 2.0 GeV/c$^2$ arose a posteriori from the fact that the predicted flux of $R^0$ events begins to
Figure 8.1: Theoretical prediction of the $R^0/K_L$ flux ratio versus $M_{R^0}$, based on Carlson [36] and Skubic [66].

decrease rapidly as $M_{R^0}$ approaches 2.1 GeV/c$^2$, as shown in Fig. 8.1. This decrease arises from the fact that the 24 GeV proton beam of the AGS cannot produce an $R^0$ with mass greater than 2.48 GeV/c$^2$.

For each combination of $R^0$ and $\bar{\gamma}$ masses, the $R^0$ lifetime $c\tau$ was varied from $10^{-10}$ to $10^{-5}$ s. The $R^0$ Monte Carlo events were required to satisfy the geometric requirements imposed by the trigger as well as the same selection criteria that were imposed on the data. The number of events which satisfied all of these criteria divided by the number of events generated defined the combined geometric and selection acceptance. The decay fraction $DF_{R^0}$ for the fraction of $R^0$ events which decays in the decay volume was also determined in Monte Carlo. The correction factors $f_{\pi\pi}(R)$ and $f_{ML}(R)$ for pions lost because of pion interactions in the spectrometer and for pion loss in the trigger, respectively, were determined in a manner similar to those corrections for $K_L^0 \rightarrow \pi^+\pi^-$ decays, as described in Chapter 7. The total acceptance, decay fraction, and pion loss corrections are listed in Appendix A in Tables A.1 to A.8 for various values of the mass ratio $\tau$.

The total acceptance for $R^0 \rightarrow \pi^+\pi^-\bar{\gamma}$ decays is summarized graphically for various
$R^0$ parameter combinations in Fig. 8.2. This figure shows the total acceptance as a function of $R^0$ mass for mass ratio $r = 2.2$ for various values of the $R^0$ lifetime $\tau$.

Fig. 8.3 shows the topology of hypothetical $R^0$ events with $r=2.2$, $M_{R^0} = 1.0$ GeV/$c^2$ and $\tau = 1 \times 10^{-8}$ s in $p_T^\parallel$ prior to the application of the $p_T^\parallel > 229$ MeV/$c$ cut. A comparison of this plot to the corresponding plot from the spoiled vacuum analysis, Fig. 7.8, shows the similar topology of the $R^0$ decay to that of the beam-neutron interactions.

### 8.3 Determining the Experimental $R^0$ to $K^0_L$ Flux Ratio

With the parameter-dependent acceptance determined, the experimentally observed sensitivity of E935 to $R^0 \rightarrow \pi^+\pi^-\gamma$ can be obtained. As discussed in Chapter 6, one event remained in the signal region after all selection criteria were applied to the data. An expected 1.4 background event was determined from the extrapolation of the spoiled vacuum runs, as was described in Chapter 7.

The experimental $R^0$ to $K^0_L$ flux ratio must be computed for each combination of $R^0$ parameters. As an example, the $R^0$ to $K^0_L$ flux ratio for one of the parameters sets which
Figure 8.3: Transverse momentum in the decay plane for $R^0 \rightarrow \pi^+ \pi^- \tilde{\gamma}$ with $r=2.2$, $M_{R^0} = 1.0 \text{ GeV/c}^2$ and $\tau = 1 \times 10^{-8} \text{ s}$. All criteria except the $p_T^{\parallel} > 229 \text{ MeV/c}$ cut have been applied.

has a high calculated $R^0$ acceptance is computed below. This calculation uses the following parameters from Table A.7 to set an upper limit on the $R^0$ production cross section:

- $r = 2.5$
- $M_{R^0} = 1.0 \text{ GeV/c}^2$
- $M_{\tilde{\gamma}} = 0.4 \text{ GeV/c}^2$
- $c\tau = 3.0 \text{ m}$ (corresponding to $\tau = 10^{-8} \text{ s}$)

The total calculated acceptance for this set of parameters is:

- $A_{R^0} = 2.97 \times 10^{-5}$

The conservative approach to the calculation of the limit on $R^0$ production is to evaluate the limit based on one candidate event in the signal region rather than attempt a background subtraction. In this case, Eq. 8.5 must be modified to
incorporate the statistical probability that the one candidate event in the signal region is a background event when the anticipated level of background is 1.4 events. The correction factor \( \lambda = 3.1389 \) is derived in Appendix B. Therefore, Eq. 8.5 becomes:

\[
\left( \frac{d\sigma_R}{d\Omega} \right) / \left( \frac{d\sigma_K}{d\Omega} \right) = \lambda \times \left( 2.34 \times 10^{-14} \right) \left( \frac{1}{A_{R^0}} \right),
\]

(8.7)

and thus the experimental sensitivity to the production of this hypothetical \( R^0 \), at 90\% confidence level (C.L.), is given by:

\[
\left( \frac{d\sigma_R}{d\Omega} \right) / \left( \frac{d\sigma_K}{d\Omega} \right) = 7.35 \times 10^{-14} \left( \frac{1}{A_{R^0}} \right),
\]

(8.8)

Hence, the experimental \( R^0 \) to \( K^0_L \) flux ratio for \( A_{R^0} = 2.97 \times 10^{-5} \) is:

\[
\text{Experimental} \quad \frac{R^0}{K^0_L} \text{ Flux Ratio} = \left( \frac{d\sigma_R}{d\Omega} \right) / \left( \frac{d\sigma_K}{d\Omega} \right) = 2.47 \times 10^{-9}
\]

(8.9)

Similar determinations of the \( R^0 \) to \( K^0_L \) experimental flux ratio were made for different \( R^0 \) parameter combinations. Values of the experimental flux ratio for \( \tau = 2.2 \) as a function of \( R^0 \) lifetime for several values of \( M_{R^0} \) are shown in Fig. 8.4.

In this analysis, it has been assumed that the branching ratio \( Br[R^0 \rightarrow \pi^+\pi^-\tilde{\gamma}] \) is 100\%. As discussed in Chapter 2, if the \( R^0 \rightarrow \rho\tilde{\gamma} \) channel is not inhibited by energy balance, it would be the dominant decay channel. The acceptance for \( R^0 \rightarrow \rho\tilde{\gamma} \rightarrow \pi^+\pi^-\tilde{\gamma} \) increases the acceptance over the channel \( R^0 \rightarrow \pi^+\pi^-\tilde{\gamma} \) by a few percent [1]. Thus it remains conservative to set an upper limit based on the \( R^0 \rightarrow \pi^+\pi^-\tilde{\gamma} \) channel.

The experimentally determined flux ratio must be compared to a theoretical model of \( R^0 \) production in order to exclude the existence of the hypothetical \( R^0 \) particle for this parameter set at 90\% C.L.
Figure 8.4: The experimental $R^0$ to $K^0_L$ Flux Ratio for $r=2.2$ as a function of $R^0$ lifetime for various values of $M_{R^0}$.

8.4 Determining the Theoretical $R^0$ to $K^0_L$ Flux Ratio

In order to compare the experimentally determined flux ratio to the theoretically predicted production cross section, the calculations of the differential cross sections determined from interpolating the pQCD results from Carlson et al. [35,36], detailed in Chapter 2, were used.

The interpolation procedure detailed in Chapter 2 of the pQCD results from Carlson et al. [35,36] provided the double differential cross section for the production of the hypothetical $R^0$ particle in $pN$ interactions. This double differential cross section was then integrated over the momentum range from 1.7 to 12 GeV/c. As also discussed in Chapter 2, this cross section incorporates only $q\bar{q}$ annihilation. Table 8.1 shows the differential cross sections for various values of the $R^0$ mass. These values can be scaled to $pPt$ interactions by multiplying by $A^{2/3}$, where $A$ is the atomic weight of the target ($A_{Pt} = 195.1$), assuming that the $R^0$ absorption rate in the target was equal to the absorption for the neutral kaon. This last assumption is addressed in
Table 8.1: $R^0$ production differential cross section in $pN$ collisions for various values of the $R^0$ mass.

<table>
<thead>
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<th>$M_{R^0} (GeV)$</th>
<th>$\frac{d\sigma}{d\Omega} (\mu b/\text{ster})$</th>
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</tr>
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</tr>
<tr>
<td>2.2</td>
<td>$1.03 \times 10^{-14}$</td>
</tr>
</tbody>
</table>

8.4.1 $R^0$ Absorption in the Target

In this analysis, it has been assumed that the $R^0 N$ interaction length is equal to the $K^0 N$ interaction length, $\lambda_{K^0} = 1.6 \lambda_p$ [72], where $\lambda_p = 189.7 \text{ g/cm}^2$ is the proton interaction length in Pt. In a manner similar to that of the kaon, as developed in Chapter 7, the $R^0$ hadron can also interact in the production target.

Nussinov has argued [73] that the total $R^0 N$ inelastic cross section $\sigma'(R^0 N)$ should be between 7 mb and 40 mb and that $\sigma(R^0 N) \leq \sigma(MN)$ for $E_{lab} \leq 10 \text{ GeV}$, where $\sigma(MN)$ is the meson-nucleon cross section. These arguments imply that the $R^0$ interaction rate in matter could lie in the range of 18% to 100% of the proton interaction rate. This range places the $R^0$ mean free path between 5.5 $\lambda_p$ and 1.0 $\lambda_p$. Under the assumption that the $R^0 N$ cross section is less than the $KN$ cross section, the ratio of the $R^0$ and $K_L$ thick-target correction factors for a 1.4 interaction length...
Pt production target would lie in the range

\[ 1 \leq \left( \frac{C(R^0)_{Pt}}{C(K^0)_{Pt}} \right) \leq 1.43 \]  

(8.10)

This range of values implies that fewer generated $R^0$ particles are re-absorbed in the target compared to generated $K^0_L$'s. In the preceding development, it was assumed that the thick target correction factors for the $R^0$ and $K^0_L$ were equal, and thus canceled in the $R^0$ and $K^0_L$ flux ratio. However, it is noted that the theoretical flux ratio could be 1.4 times larger than stated, solely on the basis of re-absorption in the target.

8.4.2 Theoretical $R^0$ to $K^0_L$ Flux Ratio

The kaon production differential cross section in $pPt$ interactions, calculated in Chapter 7, is \( (\frac{d\sigma}{d\Omega})_{Pt} = 148,650 \ \frac{\mu b}{ster} \). The theoretical cross section for $R^0$ production, from Table 8.1, was scaled to $pPt$ interactions by the factor $A^{2/3}$ where $A$ is the atomic weight of $Pt$ ($A_{Pt} = 195.1$). The differential cross section in $pPt$ interactions for an $R^0$ with mass $M_{R^0} = 1.0$ GeV/c$^2$ was determined to be \( (\frac{d\sigma}{d\Omega})_{Pt} = 45.37 \ \frac{\mu b}{ster} \).

With the conservative assumption described in the previous section that the $R^0$ to $K^0_L$ mean free paths are equal, the ratio of the $R^0$ to $K^0_L$ production cross sections [Eq. 8.2] defines the predicted $R^0$ to $K^0_L$ theoretical flux ratio for the E935 apparatus. Thus, the theoretical flux ratio for an $R^0$ hadron with mass $M_{R^0} = 1.0$ GeV/c$^2$ is:

\[ \text{Theoretical: } \frac{(\frac{d\sigma_R}{d\Omega})}{(\frac{d\sigma_K}{d\Omega})} = 45.37 \frac{\mu b}{ster}/148,650 \frac{\mu b}{ster} \]  

(8.11)

or,
Theoretical: \( \left( \frac{d\sigma_R}{d\Omega} \right) / \left( \frac{d\sigma_K}{d\Omega} \right) = 3.05 \times 10^{-4} \) \hspace{1cm} (8.12)

The theoretical flux ratio can be determined for each value of the \( R^0 \) mass. Fig. 8.1 shows this theoretical prediction for the \( R^0 \) to \( K^0_L \) flux ratio as a function of \( R^0 \) mass.

### 8.5 Final Results

The experimental sensitivity, given by Eq. 8.9, is smaller than the theoretically predicted flux ratio of Eq. 8.12 for the same 1.0 GeV/c^2 value of \( M_{R^0} \). Therefore E935 sets an upper limit on the \( R^0 \) to \( K^0_L \) flux, for an \( R^0 \) hadron with \( M_{R^0} = 1.0 \text{ GeV/c}^2 \), \( M_\gamma = 0.4 \text{ GeV/c}^2 \) (corresponding to \( \tau = 2.5 \)), and \( c\tau = 3.0 \text{ m} \) (corresponding to \( \tau = 10^{-8} \text{ s} \)) at 90% CL at \( 2.47 \times 10^{-9} \)

Calculations for the experimental sensitivity have been done for the same values of \( M_{R^0} = 1.0 \text{ GeV/c}^2 \) and \( M_\gamma = 0.4 \text{ GeV/c}^2 \) (corresponding to \( \tau = 2.5 \)) for various values of the \( R^0 \) lifetime \( \tau \). The results are shown in Fig. 8.5.

The experimental flux ratios for a series of \( R^0 \) and \( \gamma \) masses for a fixed value of \( c\tau = 3.0 \text{ m} \) (\( \tau = 10^{-8} \text{ s} \)) were also determined. Fig. 8.6 shows a plot of the flux ratio as a function of \( R^0 \) mass.
Figure 8.5: The experimental $R^0$ to $K^0_L$ flux ratio for $r = \frac{M_{R^0}}{M_\pi} = 2.5$, $M_{R^0} = 1.0$ GeV/c$^2$ and $M_\pi = 0.4$ GeV/c$^2$, as a function of $R^0$ lifetime. (Theory predicts the flux ratio to be: $\left(\frac{d\sigma_R}{dt}\right) / \left(\frac{d\sigma_K}{dt}\right) = 3.05 \times 10^{-4}$, and is shown as a horizontal dot-dashed line in the graph.)
Figure 8.6: The $R^0$ to $K^0_L$ experimental flux ratio as a function of $R^0$ mass for various values of the ratio parameter $r \equiv \frac{M_{R^0}}{M_{\tau}}$. 

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Chapter 9

Conclusions

9.1 Improvements Over Previous Light Gluino Searches

The experiment described in this report was successful in extending the excluded parameter space available for the $R^0$ hadron. This extended exclusion region places further restrictions on supersymmetric models which contain light gluinos.

The KTeV [41] collaboration had set the best upper limit on the $R^0$ to $K_L^0$ flux ratio under the assumption that the $Br[R^0 \rightarrow \rho^{0}\gamma]$ decay was 100%. The most stringent restriction to the original KTeV search was their 648 MeV/$c^2$ mass cut. This cut restricted their sensitivity to the region for which $M_{R^0}(1-\frac{1}{r}) > 648$ MeV/$c^2$. E935 extended the larger $r$ parameter region with a 545 MeV/$c^2$ invariant mass cut and greater sensitivity to longer $R^0$ lifetimes. Thus for $r=2.2$, KTeV was kinematically restricted to regimes for which $M_{R^0} > 1.2$ GeV/$c^2$ while, for the same value of $r$, E935 can claim sensitivity down to 999.2 MeV/$c^2$ and to $R^0$ lifetimes as high as $\tau = 1\times10^{-3}$ s, as is shown in Fig. 9.1.

During the writing of this dissertation, the KTeV collaboration submitted a paper detailing a further analysis of their data [74], the results of which complement the conclusions of the E935 search.
Figure 9.1: The $R^0$ mass-lifetime region excluded by this analysis at 90% CL for $r=2.2$. The $R^0$ mass-lifetime region excluded by the KTeV collaboration is also shown. The KTeV data are obtained from a graph in their Phys. Rev. Lett. [41].
The NA48 [42] collaboration also searched for light gluinos. NA48 searched for the C-suppressed \( R^0 \rightarrow \eta \gamma \) decay mode of the \( R^0 \). In addition, NA48 used a \( K^0_S \) neutral beam to probe short (\( 10^{-9} \) s to \( 10^{-10} \) s) \( R^0 \) lifetimes. Both E935 and NA48 assumed 100% branching fractions for their respective decay channels. Under the assumption of a 100% branching fraction, the results presented in this work are comparable to the NA48 results. Fig. 9.2 shows the sensitivity of E935 compared to the sensitivity of NA48. For longer lifetime hypothetical \( R^0 \)’s, the sensitivity of E935 is better than that of NA48. Moreover, since the \( R^0 \rightarrow \eta \gamma \) decay channel is expected to be suppressed relative to the \( R^0 \rightarrow \pi^+\pi^-\gamma \), Fig. 9.2 underestimates the E935 sensitivity relative to that of NA48.

9.2 Implications for Future Light Gluino Searches

Useful information can be obtained from this search for any future work on an \( R^0 \rightarrow \pi^+\pi^-\gamma \) investigation. The anticipated primary background for the E935 \( R^0 \) search was \( \pi^-p \) production from neutron interactions with residual gas molecules in the vacuum decay tank. However, the actual background which yielded the largest restriction in phase space was hadronic scattering in the downstream window of the decay tank. The engineering difficulties involved to develop a detector to provide tracking upstream of this window are substantial. Nevertheless, advances in computational power and improvements to simulation packages such as GEANT [65] suggest that backgrounds can be studied in much greater detail prior to a future search.

Although E935 was kinematically sensitive to the lower mass regime for the ratio parameter \( r \leq 1.4 \), the small theoretical production cross section for \( R^0 \) hadrons with mass of 2.0 GeV/c\(^2\) or greater at AGS energies proved to be a limiting factor for E935. An improvement in the experimental acceptance by lowering this invariant
Figure 9.2: The E935 sensitivity to $R^0$ production versus the sensitivity of the NA48 collaboration. The horizontal (dot-dashed) line is the theoretical production limit for the E935 search. The diagonal line is the NA48 limit using their $K_S^0$ beam. The NA48 data are obtained from a graph in their Phys. Lett. B [42].
mass cut even more, along with increasing the geometric acceptance, are logical methods to improve the sensitivity to lower values of the mass ratio $r$ in any future light gluino searches. However, a lowering of the invariant mass cut would introduce an additional background from mis-identified $K_{\mu 3}$ which in turn would require improved muon identification.

A further drawback to increasing the level of sensitivity of the results from this experiment was the lack of a detector able to provide pion-proton discrimination. The inclusion of a Čerenkov counter designed to tag protons, for instance, would allow a longer period of SEB running before the background from lower-rate neutron processes resulting in two charged pions in the final state becomes substantial.

Finally, while the use of a blanket veto in the 1.0 GeV/c MHO plane ($X0$) for muon rejection in the trigger succeeded in reducing the trigger rates substantially, this veto also resulted in the rejection of approximately 20% of all $K_L^0 \rightarrow \pi^+\pi^-$ decays. While pions which decay to muons in flight would still be lost, a more efficient trigger design and muon rejection scheme could also increase the experimental sensitivity to $R^0$ production. Such a design would allow the invariant mass requirement to be lowered substantially and thus increase the sensitivity to the low $r$ region of the $R^0$ parameter set.

### 9.3 Summary of the E935 Search for $R^0 \rightarrow \pi^+\pi^-\gamma$

E935 observed no candidate $R^0$ events inconsistent with the background levels expected. The search reported in this work extended the phase space excluded by the KTeV collaboration [41] down to an $R^0$ mass of 910 MeV/$c^2$ for $r=2.5$ and with sensitivity to $R^0$ hadrons with lifetimes spanning seven orders of magnitude from $4 \times 10^{-10}$ s to $< 1 \times 10^{-3}$ s. From a cosmological perspective, smaller values of the
mass ratio parameter $r$ and lower-mass $R^0$ hadrons are more interesting [27] [28] [40] in that the photino could account for the cold dark matter of the universe. In addition, the experimental sensitivity to $R^0$ production for a 2.0 GeV/c$^2$ mass $R^0$ hadron and a photino with mass of approximately 1.43 GeV/c$^2$ ($r=1.4$) falls just outside of the theoretically predicted flux from $q\bar{q}$ annihilation. In principle, higher order corrections to the production cross section calculation as well as the inclusion of gluon fusion and other processes could allow E935 to claim exclusion to $R^0$ hadrons in the region of primary interest [40]: $1.4$ GeV/c$^2 < M_{R^0} < 2.2$ GeV/c$^2$ for $r \leq 1.4$, to which KTeV is completely insensitive.
Appendix A

Tables of $R^0$ Acceptance Factors

The factors used in the $R^0$ acceptance calculations are presented here. The factors are $r \equiv M_{R^0}/M_\gamma$; $M_{R^0}$, the mass of the $R^0$ hadron in GeV/c$^2$; $M_\gamma$, the mass of the photino in GeV/c$^2$; $\tau r$, the $R^0$ lifetime times the speed of light in a vacuum in meters; $DF_{R^0}$, the fraction of $R^0$ produced at the target which decay in the decay volume $9.5 \text{ m} < z < 22.0 \text{ m}$; $f_{\pi\pi}(R)$, the correction factor for pions lost in the spectrometer; and $f_{ML}(R)$, the correction factor for pions lost due to the MHO trigger veto. $A_{R^0}$ [Eq. 8.6] is the total $R^0$ acceptance from geometric and selection criteria requirements and incorporates these correction factors.
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Table A.1: Total $R^0$ acceptance for various $R^0$ lifetimes with the mass ratio parameter $r = \frac{M_{R^0}}{M_\gamma} = 1.4$ for all entries.
Table A.2: Total $R^0$ acceptance for various $R^0$ lifetimes with the mass ratio parameter $r = \frac{M_{R^0}}{M_\tau} = 1.5$ for all entries.
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<td>0.9</td>
<td>1.5</td>
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<td>0.962</td>
<td>0.837</td>
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</tr>
<tr>
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<td>0.9</td>
<td>3.0</td>
<td>0.2721</td>
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<td>0.847</td>
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<tr>
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<td>0.9</td>
<td>15.0</td>
<td>0.1689</td>
<td>0.960</td>
<td>0.855</td>
<td>7.21x10^{-6}</td>
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<td>30.0</td>
<td>0.0986</td>
<td>0.960</td>
<td>0.856</td>
<td>4.01x10^{-6}</td>
</tr>
<tr>
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<td>0.9</td>
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<td>0.0224</td>
<td>0.960</td>
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</tr>
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<td>2.0</td>
<td>1.0</td>
<td>1.5</td>
<td>0.1483</td>
<td>0.962</td>
<td>0.829</td>
<td>5.48x10^{-6}</td>
</tr>
<tr>
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<td>1.0</td>
<td>3.0</td>
<td>0.2685</td>
<td>0.961</td>
<td>0.837</td>
<td>9.94x10^{-6}</td>
</tr>
<tr>
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<td>1.0</td>
<td>15.0</td>
<td>0.1752</td>
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</tr>
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<td>2.0</td>
<td>1.0</td>
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<td>0.848</td>
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<td>0.0235</td>
<td>0.961</td>
<td>0.848</td>
<td>7.18x10^{-7}</td>
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Table A.3: Total $R^0$ acceptance for various $R^0$ lifetimes with the mass ratio parameter $r = \frac{M_{R^0}}{M_{\bar{R}}} = 2.0$ for all entries.
Table A.4: Total $R^0$ acceptance for various $R^0$ lifetimes with the mass ratio parameter $r = \frac{M_{R^0}}{M_\gamma} = 2.2$ for all entries.
<table>
<thead>
<tr>
<th>$r$</th>
<th>$M_{R^0}$</th>
<th>$M_\Delta$</th>
<th>$\Delta T$ (m)</th>
<th>$D F_{R^0}$</th>
<th>$f_{XX}(R)$</th>
<th>$f_{ML}(R)$</th>
<th>$A_{R^0}$</th>
</tr>
</thead>
<tbody>
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<td>2.2</td>
<td>1.199</td>
<td>0.545</td>
<td>0.03</td>
<td>$3.307\times10^{-17}$</td>
<td>0.965</td>
<td>0.795</td>
<td>1.30\times10^{-22}</td>
</tr>
<tr>
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<td>0.545</td>
<td>0.15</td>
<td>$4.907\times10^{-5}$</td>
<td>0.963</td>
<td>0.825</td>
<td>4.75\times10^{-9}</td>
</tr>
<tr>
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<td>1.199</td>
<td>0.545</td>
<td>0.3</td>
<td>0.0034</td>
<td>0.960</td>
<td>0.849</td>
<td>6.04\times10^{-7}</td>
</tr>
<tr>
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<td>1.199</td>
<td>0.545</td>
<td>1.5</td>
<td>0.1859</td>
<td>0.956</td>
<td>0.884</td>
<td>3.40\times10^{-5}</td>
</tr>
<tr>
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<td>1.199</td>
<td>0.545</td>
<td>3.0</td>
<td>0.2715</td>
<td>0.955</td>
<td>0.891</td>
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</tr>
<tr>
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<td>0.545</td>
<td>15.0</td>
<td>0.1543</td>
<td>0.955</td>
<td>0.897</td>
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<td>0.545</td>
<td>30.0</td>
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<td>0.955</td>
<td>0.898</td>
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</tr>
<tr>
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<td>0.545</td>
<td>150.0</td>
<td>0.0202</td>
<td>0.955</td>
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</tr>
<tr>
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<td>0.545</td>
<td>300.0</td>
<td>0.0102</td>
<td>0.955</td>
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</tr>
<tr>
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<td>0.545</td>
<td>900.0</td>
<td>0.0035</td>
<td>0.955</td>
<td>0.899</td>
<td>3.45\times10^{-7}</td>
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<tr>
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<td>0.545</td>
<td>1500.0</td>
<td>$2.081\times10^{-3}$</td>
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<td>0.898</td>
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</tr>
<tr>
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<td>0.545</td>
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<td>0.899</td>
<td>1.04\times10^{-8}</td>
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<tr>
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<td>1.199</td>
<td>0.545</td>
<td>150000.0</td>
<td>$2.081\times10^{-5}$</td>
<td>0.956</td>
<td>0.899</td>
<td>2.04\times10^{-9}</td>
</tr>
<tr>
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<td>300000.0</td>
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<td>0.899</td>
<td>1.03\times10^{-9}</td>
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</tr>
<tr>
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<td>0.68</td>
<td>0.03</td>
<td>$1.329\times10^{-20}$</td>
<td>0.967</td>
<td>0.774</td>
<td>1.69\times10^{-26}</td>
</tr>
<tr>
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<td>0.15</td>
<td>$1.064\times10^{-5}$</td>
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<td>0.789</td>
<td>4.58\times10^{-10}</td>
</tr>
<tr>
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<td>0.805</td>
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<td>0.1674</td>
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<td>0.839</td>
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<td>0.960</td>
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<td>300.0</td>
<td>0.0221</td>
<td>0.960</td>
<td>0.858</td>
<td>1.22\times10^{-6}</td>
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<td>0.0112</td>
<td>0.960</td>
<td>0.859</td>
<td>6.11\times10^{-7}</td>
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<td>1500.0</td>
<td>$2.275\times10^{-3}$</td>
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<td>0.859</td>
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<td>0.960</td>
<td>0.850</td>
<td>6.21\times10^{-8}</td>
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<td>15000.0</td>
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<td>0.859</td>
<td>1.26\times10^{-8}</td>
</tr>
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<td>0.68</td>
<td>30000.0</td>
<td>$1.141\times10^{-4}$</td>
<td>0.960</td>
<td>0.859</td>
<td>6.23\times10^{-9}</td>
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<td>150000.0</td>
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<td>0.859</td>
<td>1.25\times10^{-9}</td>
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<td>300000.0</td>
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<td>0.859</td>
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<td>1.71\times10^{-5}</td>
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Table A.5: Total $R^0$ acceptance for various $R^0$ lifetimes with the mass ratio parameter $r = \frac{M_{R^0}}{M_\Delta} = 2.2$ for all entries, continued.
<table>
<thead>
<tr>
<th>( r )</th>
<th>( M_{R^0} )</th>
<th>( M_\gamma )</th>
<th>( c \tau ) (m)</th>
<th>( DF_{R^0} )</th>
<th>( f_{\pi R}(R) )</th>
<th>( f_{M_\gamma R}(R) )</th>
<th>( A_{R^0} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.2</td>
<td>1.76</td>
<td>0.8</td>
<td>0.03</td>
<td>( 1.26 \times 10^{-23} )</td>
<td>0.967</td>
<td>0.766</td>
<td>( 4.67 \times 10^{-30} )</td>
</tr>
<tr>
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<td>1.76</td>
<td>0.8</td>
<td>0.15</td>
<td>( 2.956 \times 10^{-6} )</td>
<td>0.966</td>
<td>0.776</td>
<td>( 5.74 \times 10^{-11} )</td>
</tr>
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<td>0.3</td>
<td>0.0009</td>
<td>0.965</td>
<td>0.789</td>
<td>( 3.60 \times 10^{-8} )</td>
</tr>
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<td>0.8</td>
<td>1.5</td>
<td>0.1618</td>
<td>0.962</td>
<td>0.822</td>
<td>( 9.17 \times 10^{-6} )</td>
</tr>
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<td>1.76</td>
<td>0.8</td>
<td>3.0</td>
<td>0.2725</td>
<td>0.962</td>
<td>0.832</td>
<td>( 1.42 \times 10^{-5} )</td>
</tr>
<tr>
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<td>0.8</td>
<td>15.0</td>
<td>0.1678</td>
<td>0.961</td>
<td>0.841</td>
<td>( 7.32 \times 10^{-6} )</td>
</tr>
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<td>30.0</td>
<td>0.0978</td>
<td>0.961</td>
<td>0.842</td>
<td>( 4.22 \times 10^{-6} )</td>
</tr>
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<td>0.0222</td>
<td>0.961</td>
<td>0.843</td>
<td>( 9.26 \times 10^{-7} )</td>
</tr>
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<td>0.843</td>
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<td>0.842</td>
<td>( 4.69 \times 10^{-8} )</td>
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<td>( 9.46 \times 10^{-9} )</td>
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<td>0.842</td>
<td>( 9.29 \times 10^{-10} )</td>
</tr>
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<td>( 1.145 \times 10^{-5} )</td>
<td>0.961</td>
<td>0.842</td>
<td>( 4.74 \times 10^{-10} )</td>
</tr>
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<td>( 1.03 \times 10^{-11} )</td>
</tr>
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<td>1.5</td>
<td>0.1495</td>
<td>0.963</td>
<td>0.812</td>
<td>( 5.75 \times 10^{-6} )</td>
</tr>
<tr>
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<td>0.9</td>
<td>3.0</td>
<td>0.2689</td>
<td>0.963</td>
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<td>( 9.95 \times 10^{-6} )</td>
</tr>
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<td>( 7.10 \times 10^{-7} )</td>
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<td>3000.0</td>
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<td>30000.0</td>
<td>( 1.205 \times 10^{-4} )</td>
<td>0.960</td>
<td>0.851</td>
<td>( 3.98 \times 10^{-9} )</td>
</tr>
<tr>
<td>2.2</td>
<td>1.98</td>
<td>0.9</td>
<td>150000.0</td>
<td>( 2.411 \times 10^{-5} )</td>
<td>0.960</td>
<td>0.852</td>
<td>( 8.07 \times 10^{-10} )</td>
</tr>
<tr>
<td>2.2</td>
<td>1.98</td>
<td>0.9</td>
<td>300000.0</td>
<td>( 1.206 \times 10^{-5} )</td>
<td>0.960</td>
<td>0.852</td>
<td>( 3.98 \times 10^{-10} )</td>
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<tr>
<td>2.2</td>
<td>2.20</td>
<td>1.0</td>
<td>3.0</td>
<td>0.2609</td>
<td>0.964</td>
<td>0.806</td>
<td>( 8.20 \times 10^{-5} )</td>
</tr>
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</table>

Table A.6: Total \( R^0 \) acceptance for various \( R^0 \) lifetimes with the mass ratio parameter \( r = \frac{M_{R^0}}{M_\gamma} = 2.2 \) for all entries, continued.
<table>
<thead>
<tr>
<th>r</th>
<th>$M_{R^0}$</th>
<th>$M_\gamma$</th>
<th>$c\tau$ (m)</th>
<th>DF$_{R^0}$</th>
<th>$f_{\tau\tau}(R)$</th>
<th>$f_{ML}(R)$</th>
<th>$A_{R^0}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.5</td>
<td>0.92</td>
<td>0.368</td>
<td>3.0</td>
<td>0.2711</td>
<td>0.956</td>
<td>0.908</td>
<td>1.54x10^{-6}</td>
</tr>
<tr>
<td>2.5</td>
<td>0.95</td>
<td>0.38</td>
<td>3.0</td>
<td>0.2712</td>
<td>0.955</td>
<td>0.907</td>
<td>9.30x10^{-6}</td>
</tr>
<tr>
<td>2.5</td>
<td>1.0</td>
<td>0.4</td>
<td>0.015</td>
<td>5.469x10^{-27}</td>
<td>0.965</td>
<td>0.800</td>
<td>2.54x10^{-33}</td>
</tr>
<tr>
<td>2.5</td>
<td>1.0</td>
<td>0.4</td>
<td>0.03</td>
<td>6.076x10^{-15}</td>
<td>0.965</td>
<td>0.800</td>
<td>7.36x10^{-20}</td>
</tr>
<tr>
<td>2.5</td>
<td>1.0</td>
<td>0.4</td>
<td>0.15</td>
<td>0.0001</td>
<td>0.963</td>
<td>0.830</td>
<td>1.34x10^{-8}</td>
</tr>
<tr>
<td>2.5</td>
<td>1.0</td>
<td>0.4</td>
<td>0.3</td>
<td>0.0056</td>
<td>0.961</td>
<td>0.851</td>
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<td>1.0</td>
<td>0.4</td>
<td>1.5</td>
<td>0.1975</td>
<td>0.957</td>
<td>0.892</td>
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</tr>
<tr>
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<td>0.4</td>
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<td>0.2714</td>
<td>0.956</td>
<td>0.901</td>
<td>2.97x10^{-5}</td>
</tr>
<tr>
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<td>1.0</td>
<td>0.4</td>
<td>15.0</td>
<td>0.1467</td>
<td>0.955</td>
<td>0.909</td>
<td>1.19x10^{-5}</td>
</tr>
<tr>
<td>2.5</td>
<td>1.0</td>
<td>0.4</td>
<td>30.0</td>
<td>0.0845</td>
<td>0.955</td>
<td>0.910</td>
<td>6.55x10^{-6}</td>
</tr>
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<td>0.4</td>
<td>150.0</td>
<td>0.0190</td>
<td>0.955</td>
<td>0.911</td>
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</tr>
<tr>
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<td>0.4</td>
<td>300.0</td>
<td>0.0096</td>
<td>0.955</td>
<td>0.911</td>
<td>7.08x10^{-7}</td>
</tr>
<tr>
<td>2.5</td>
<td>1.0</td>
<td>0.4</td>
<td>1500.0</td>
<td>1.951x10^{-3}</td>
<td>0.955</td>
<td>0.911</td>
<td>1.38x10^{-7}</td>
</tr>
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<td>0.4</td>
<td>3000.0</td>
<td>9.770x10^{-4}</td>
<td>0.955</td>
<td>0.911</td>
<td>7.15x10^{-8}</td>
</tr>
<tr>
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<td>1.0</td>
<td>0.4</td>
<td>15000.0</td>
<td>1.957x10^{-4}</td>
<td>0.955</td>
<td>0.911</td>
<td>1.45x10^{-8}</td>
</tr>
<tr>
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<td>1.0</td>
<td>0.4</td>
<td>30000.0</td>
<td>9.781x10^{-5}</td>
<td>0.955</td>
<td>0.911</td>
<td>7.24x10^{-9}</td>
</tr>
<tr>
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<td>0.4</td>
<td>150000.0</td>
<td>1.948x10^{-5}</td>
<td>0.955</td>
<td>0.912</td>
<td>1.42x10^{-9}</td>
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<td>0.4</td>
<td>300000.0</td>
<td>9.744x10^{-6}</td>
<td>0.955</td>
<td>0.911</td>
<td>7.19x10^{-10}</td>
</tr>
<tr>
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<td>0.44</td>
<td>3.0</td>
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<td>0.958</td>
<td>0.880</td>
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<td>1.2</td>
<td>0.48</td>
<td>3.0</td>
<td>0.2715</td>
<td>0.959</td>
<td>0.862</td>
<td>4.32x10^{-5}</td>
</tr>
</tbody>
</table>

Table A.7: Total $R^0$ acceptance for various $R^0$ lifetimes with the mass ratio parameter $r = \frac{M_{R^0}}{M_\gamma} = 2.5$ for all entries.
Table A.8: Total $R^0$ acceptance for various $R^0$ lifetimes with the mass ratio parameter $r = \frac{M_{R^0}}{M_4} = 2.5$ for all entries, continued.
Appendix B

Calculation of the 90 % Confidence Level Upper Limit

In order to have confidence at the 90% level (C.L.) that the number of observed events $N_{ob}$ in a data sample is statistically relevant for an anticipated background $N_{bg}$ it is necessary to calculate the number of signal events which should have been recorded. The upper limit $\lambda$ on the number of signal events at $\delta$ confidence level in the presence of an anticipated background $N_{bg}$, with $N_{ob}$ observed events, is given by the Poisson probability for a process with signal plus background [70]:

$$\frac{e^{-(\lambda+N_{bg})} \sum_{n=0}^{N_{ob}} \frac{(\lambda+N_{bg})^n}{n!}}{e^{-N_{bg}} \sum_{n=0}^{N_{ob}} \frac{(N_{bg})^n}{n!}} = 1 - \delta$$

(B.1)

In the case for which one event was observed, $N_{ob} = 1$, and with an estimated background of $N_{bg} = 1.4$ events, the desired $\delta = 90\%$ confidence level is obtained for a value of $\lambda$ given by:

$$\frac{e^{-(\lambda+1.4)(\lambda + 2.4)}}{e^{-1.4(2.4)}} = 0.1$$

(B.2)
There are two solutions to this transcendental equation. The physical (positive) solution is:

\[ \lambda = 3.1389 \]  \hspace{2cm} (B.3)

Therefore, at 90 % C.L., the $R^0$ flux is multiplied by $\lambda = 3.1389$. 

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Bibliography


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[49] AEROGLAZE is a registered trademark of Lord Corporation.


Vita

Kevin Michael Hern