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**Study of Photonic Final States in e^+e^- Collisions
at $\sqrt{s}$ of 161 and 172 GeV using the OPAL detector
at LEP**

by

Michael A. Donkers

A thesis submitted to
the Faculty of Graduate Studies and Research
in partial fulfillment of
the requirements for the degree of
Master of Science

Ottawa-Carleton Institute for Physics
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September, 1997

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**Study of Photonic Final States in e^+e^- Collisions at
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Thesis Supervisor

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Date 19th Sept 97

Abstract

Photonic final states events, with and without missing energy, have been studied in e^+e^- collisions using the OPAL detector at LEP. The data sample was collected at center of mass energies of 161 and 172 GeV corresponding to a total integrated luminosity of 7.90 and 8.21 pb^{-1} respectively. In the data collected at 161 GeV, 20 events were selected with missing energy with a cross section of $3.78 \pm .86$ pb compared to a Standard Model prediction of 4.79 pb. At 172 GeV, 21 events were selected with a cross section of $3.86 \pm .86$ pb consistent with the Standard Model prediction of 4.31 pb. Upper limits on the cross section at 95% confidence are set on the production of new particles. The cross section measured for photons with no missing energy is consistent with that predicted by quantum electrodynamics for two photon production. Using the combined photons with no missing energy data from 161 and 172 GeV, 95% CL lower limits are placed on the mass scale of new physics of $\Lambda_+ > 166.9$ GeV and $\Lambda_- > 192.8$ GeV.

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Chapter 1

Introduction

One of the greatest scientific successes of the second half of the 20th century is the Standard Model [1] of particle physics. The Standard Model is a relativistic quantum field theory which describes much of what we know about fundamental particles and their interactions. Predictions made by the Standard Model have been tested with very high precision and no major discrepancies have been found [2]. With increasingly more precise measurements being taken, the agreement between experiment and the Standard Model continues to improve.

Even with all of the strengths of the Standard Model, it has some major weaknesses. For instance, it cannot explain the mechanism involved in electroweak symmetry breaking. It does not explain how the fundamental forces of the universe may be unified, the origin of only three generations of particles or the origin of the large number of parameters involved in the Standard Model.

In order to overcome some of the shortcomings of the Standard Model many extensions to it have been proposed, such as supersymmetry [3], technicolour [4] and others. Two of these extensions will be explored in this thesis: supersymmetry and compositeness [5]. Each of these extensions tries to explain some aspect not handled by the Standard Model. The extensions have various experimental signatures that one could look for to find evidence for new physics. A problem when looking for signals that

would indicate new physics is that many Standard Model processes can produce similar signals, making it difficult to separate the two processes. Therefore, one would look for a signal where the Standard Model background is a minimum.

One search for supersymmetry can be carried out by looking for signals with photons and missing energy. The Standard Model background to this signal is the process of radiative neutrino production. The advantage to looking in this mode for a supersymmetric signal is that radiative neutrino production events produce a relatively clean signal. Therefore, any signal that is greater than that expected from the Standard Model process is likely to be a candidate for new physics. A search for compositeness is performed by looking at the Standard Model process of two photon production which, in that context, is a purely quantum electrodynamical (QED) process.

Chapter 2 will deal with the theory of the Standard Model, as well as some of its shortcomings. It will conclude with a discussion in how supersymmetry and compositeness can overcome some of the weaknesses of the Standard Model, as well as, outline how one would look for new physics above the Standard Model background. Chapter 3 deals with a description of the experiment used to measure the Standard Model signal, notably the LEP accelerator and the OPAL detector. The final chapters deal with the cuts required to keep the signal events free from other physics and non physics backgrounds, followed by a discussion on the results found.

Chapter 2

Standard Model

High energy particle physics deals with the study of the fundamental constituents of matter and their interactions. These fundamental particles can be put into one of two classes, depending on the spin of the particle, either fermions with half integral ($1/2, 3/2, \dots$) spin or bosons with integral ($0, 1, 2, \dots$) spin. This classification also determines the underlying symmetry of the particle's wavefunction under exchange of identical particles, symmetric for bosons and anti-symmetric for fermions.

The nature of the interaction between fundamental particles is described by the four fundamental forces of nature: electromagnetism and gravity, which are long range forces; and the strong and weak force, which have very short ranges. A further classification of fundamental particles can be made on the type of interaction which they experience. Fermions that experience all the forces except the strong force are known as leptons, whereas fermions that are strongly interacting are known as quarks. Leptons can be further classified into particles that interact through both the electromagnetic and weak forces, the electron, muon and tau particles and the partners of these particles that only interact through the weak force, the electron, muon and tau neutrinos.

Quarks are not found in nature as free particles, due mainly to the nature of the strong force, but are found in bound states of two's or three's, collectively known as hadrons. Bound systems of two quarks, or more precisely, a quark-antiquark pair form

a meson with an integral total spin and thus are bosons. A bound system of three quarks forms a baryon with half integral spin and thus a fermion. Like the leptons, quarks come in three pairs, up and down, strange and charm and bottom and top, for a total of six flavours.

The interactions themselves are described by quantum field theory, which characterizes the interaction between two particles as an exchange of a quanta known as a gauge boson. The electromagnetic force is “mediated” by the exchange of a photon, the weak force by three possible gauge bosons, the Z^0 and $W^\pm$, and the strong force by eight gluons. The gravitational force also has a mediating boson called the graviton, however at the distance scales involved in high energy physics, the gravitational force is negligible in comparison to other forces of the Standard Model.

particle	spin	charge	mass
e^-	1/2	-1	.511 MeV
ν_e	1/2	0	0
μ^-	1/2	-1	105.7 MeV
ν_μ	1/2	0	0
τ^-	1/2	-1	1777 MeV
ν_τ	1/2	0	0
u up	1/2	2/3	~ 5 MeV
d down	1/2	-1/3	~ 10 MeV
s strange	1/2	-1/3	~ 200 MeV
c charm	1/2	2/3	~ 1.3 GeV
b bottom	1/2	-1/3	~ 4.3 GeV
t top	1/2	2/3	175 ± 6 GeV
γ	1	0	0
Z^0	1	0	91.2 GeV
$W^\pm$	1	± 1	80.5 GeV
gluons	1	0	0
graviton	2	0	0

Table 2.1: Fundamental Particles within the Standard Model

2.1 Gauge Theory and Local Symmetry

The Standard Model is a gauge theory based on relativistic quantum mechanics describing particle interactions as interactions between quantized fields. The interactions take place between matter (fermionic) fields, usually denoted as ψ , and gauge (force) fields, denoted as A_μ . The gauge theory requires the underlying Lagrangian to be invariant under a local gauge transformation. An example of a simple transformation showing local phase invariance is given in the following.

$$\psi(x) \rightarrow \psi(x)' = e^{iq\theta(x)}\psi(x) \quad (2.1)$$

where q is the charge of a fermion and $\theta(x)$ is continuous over the parameter x . The transformation has the effect of adding a constant phase to the overall wavefunction of the field. The exponential effectively is a rotation in the internal space of the wavefunction of the field.

There is a simultaneous transformation on the gauge field A_μ

$$A_\mu(x) \rightarrow A_\mu(x)' = A_\mu(x) - \partial_\mu\theta(x) \quad (2.2)$$

which is necessary in order to assure that the terms containing derivatives, (eg. $\psi^*\partial_\mu\psi$), remain invariant under the transformation. The derivatives themselves must then be replaced by Covariant Derivatives.

$$\partial_\mu \rightarrow D_\mu = \partial_\mu - iqA_\mu \quad (2.3)$$

such that $\psi^*D_\mu\psi$ is now invariant.

The arbitrariness of the gauge field A_μ , due to a transformation, Eqn(2.2), is lifted by putting a constraint on the field, which will fix the gauge function $\partial_\mu\theta(x)$, for example, $\partial_\mu A^\mu = 0$, which is known as the Lorentz gauge. The choice of constraint will not affect the underlying physics of the particular interaction being investigated.

The infinite set of simple transformations of the type in Eqn(2.1) form a unitary group called $U(1)$. The quantum theory of the electromagnetic interaction, quantum

electrodynamics (QED), is invariant under such $U(1)$ transformations. Within QED, the field A_μ is consistent with Maxwell's equations and ψ is the wavefunction of a free charged particle. The gauge invariance of QED leads to the conservation of electromagnetic current as well as the requirement that the gauge boson which mediates the electromagnetic interaction, the photon, be massless.

More complicated phase transformations are also possible, involving both charged and neutral gauge bosons, such as transformations in isospin space associated with the special unitary group $SU(2)$. This symmetry group involves non-commuting operators, Pauli matrices τ , and therefore is non-Abelian. The wavefunction ψ will be invariant under such a transformation.

$$\psi \rightarrow \psi' = e^{ig\tau \cdot \Theta} \psi \quad (2.4)$$

where g is constant and Θ is an arbitrary vector. The covariant derivative can then be defined as

$$D_\mu = \partial_\mu - ig\tau \cdot \mathbf{W}_\mu \quad (2.5)$$

where $\mathbf{W}_\mu$ is a vector field analogous to A_μ for QED. The $SU(2)$ symmetry group is the underlying symmetry of the weak force, in particular, $SU(2)_L$, since the weak force is only experienced by fermions in the left-handed helicity state. Within the weak force left-handed fermions are grouped into isospin doublets representing the weak eigenstates.

$$\begin{pmatrix} \nu_e \\ e^- \end{pmatrix}_L, \begin{pmatrix} \nu_\mu \\ \mu^- \end{pmatrix}_L, \begin{pmatrix} \nu_\tau \\ \tau^- \end{pmatrix}_L, \begin{pmatrix} u \\ d' \end{pmatrix}_L, \begin{pmatrix} c \\ s' \end{pmatrix}_L, \begin{pmatrix} t \\ b' \end{pmatrix}_L$$

The remaining right-handed fermions are grouped into singlets.

$$(\bar{e})_R, (\bar{\mu})_R, (\bar{\tau})_R, \begin{pmatrix} (u)_R \\ (d)_R \end{pmatrix}, \begin{pmatrix} (c)_R \\ (s)_R \end{pmatrix}, \begin{pmatrix} (t)_R \\ (b)_R \end{pmatrix}$$

As in the case for the $U(1)$ transformation in QED, $SU(2)$ also requires the gauge bosons that mediate the weak force to be massless in order to maintain the gauge invariance of the underlying Lagrangian. This condition is contradictory to experiment which shows that the mass of the three weak bosons are on the order of 100 GeV.

2.2 Electroweak Model

In 1968 a model (known as the electroweak model) was proposed by Weinberg [6] that would unify the electromagnetic and weak forces. This model is based on the $SU(2)_L \times U(1)_Y$ symmetry group, where $SU(2)_L$ is the group of weak isospin and $U(1)_Y$ is the symmetry group of weak hypercharge (Y). The electroweak model requires four gauge bosons, three for $SU(2)_L$ and one for $U(1)_Y$, however, in the simplest form of the model these bosons are expected to be massless.

The Higgs mechanism [7, 8], in which spontaneous symmetry breaking of the electroweak symmetry occurs, gives mass to the weak gauge bosons ($W^\pm, Z^0$) while leaving the photon massless. Within the mechanism, one introduces a scalar Higgs field (spin - 0) that forms a weak isospin doublet. The potential associated with the Higgs scalar has non-zero minima. At one of these minima the symmetry of the potential is broken and the Higgs field acquires a vacuum expectation value. The gauge bosons (as well as quarks and leptons) couple to the Higgs scalar doublet thereby acquiring a mass. The Higgs mechanism predicts the existence of a electrically neutral scalar boson but gives no prediction of its mass.

The Standard Model of the electroweak interaction has been tested against experiment with very high precision, showing very good agreement between observation and predictions made by the Standard Model. The four main parameters of the electroweak model are the weak coupling constant g , the mass of the neutral weak gauge boson M_Z , the Weinberg angle θ_W and the mass of the Higgs boson M_H . The Weinberg angle is a parameter that connects the two coupling constants of the $SU(2)_L \times U(1)_Y$ symmetry group g and g' such that $\tan \theta_W = \frac{g'}{g}$. M_H is the only parameter to be left undetermined. It is hoped that the next generation of particle colliders will be able to produce the Higgs boson, thus enabling its mass and width to be measured.

Despite its great success in explaining observed high energy phenomena, the Standard Model of Electroweak interactions has some difficulties. For instance, even though the Higgs mechanism involves spontaneous symmetry breaking, it is not completely

understood how it occurs. The standard model does not provide an explanation for the origin of the large number of other parameters involved in the theory, for example, particle masses, coupling constants and parameters in the Kobayashi-Maskawa mixing matrix. Likewise, the standard model offers no explanation for the fact that only three generations of particles are observed.

Motivation to look for physics beyond the Standard Model comes primarily from computations of the Higgs mass when radiative corrections are included. One loop self interactions of the Higgs boson lead to quadratic divergences as the internal momentum becomes large. In order to cancel the quadratically divergent terms fine tuning of the cutoff parameter Λ is required to better than one part in 10^{16} . Here Λ refers to the energy scale in which the Standard Model breaks down due to form factor effects or the introduction of new degrees of freedom.

2.3 Physics Beyond the Standard Model

Many theories have been proposed, as extensions to the Standard Model, in order to deal with many of its shortcomings. One of the most popular of these theories is Supersymmetry, which ascribes to every fermion a bosonic superpartner and to every boson a fermionic superpartner, thus creating a symmetry between bosons and fermions. In this way, fermionic contributions to quadratically divergent terms of the Higgs mass are completely balanced with scalar (boson) terms. This balance between fermion and scalar terms leads to a natural cancellation of the quadratic divergence without having to appeal to the fine tuning of any parameters. Another appealing feature of Supersymmetry includes natural unification of interactions at a mass scale of $M_U \sim 10^{16}$ GeV. Within Supersymmetry a way for the unification of gravity with the other interactions is easily achieved. A model of electroweak symmetry breaking automatically comes out of theory describing the coupling of the Higgs field to the top quark.

There is no single theory of Supersymmetry. The Minimal Supersymmetric Model

(MSSM) [9], Gauge-Mediated Supersymmetry [10], and R-parity violating [11] Supersymmetry are the supersymmetric models most often referred to. Of these three, the MSSM theory is the simplest of the models with the fewest number of new particles and interactions. An important value of this model is called R-parity, where $R = (-1)^{3B+L+2S}$, where B is defined as the baryon number, L is the lepton number and S is the spin of a particle of interest. Within the MSSM R-parity is conserved in all reactions, with regular Standard Model particles having an R-parity of +1 and their superpartners having an R-parity of -1. Conservation of R-parity has two important consequences: first, superparticles must be created in pairs; and second, the lightest supersymmetric particle (LSP) must be stable.

The main candidate for the LSP in the MSSM scenario is the lightest neutralino, $\tilde{\chi}_1^0$. The neutralinos are particles that are unique to supersymmetry, they are the neutral supersymmetric partners of the electroweak gauge and Higgs bosons. Within supersymmetry there are expected to be two Higgs fields giving rise to two Higgs doublets. The physical eigenstates of the doublets comprise five bosons, two neutral scalars (H^0, h^0) one neutral pseudoscalar (A^0) and two charged bosons (H^+, H^-). The supersymmetric partners of the Higgs bosons, called Higgsinos, form superpositions with the superpartners of the electroweak gauge bosons, the gauginos (Winos, Zino, and photino), to form a set of four neutral fermions (neutralinos) $\tilde{\chi}_{1,2,3,4}^0$ and four charged fermions (charginos) $\tilde{\chi}_{1,2}^\pm$.

Supersymmetry cannot be an exact symmetry of nature, otherwise we would be able to observe supersymmetric particles that have identical properties (mass, charge, etc.) to their Standard Model partners differing just in their spin. Clearly no particle has been observed with spin 1 and the mass and charge of the electron, therefore supersymmetry must be a broken symmetry. It is difficult for the symmetry to be broken at the weak scale, so it is expected that SUSY symmetry is broken by a "hidden" sector at a scale much greater than M_W . The symmetry is broken most naturally via interactions involving gravity, in which the scale at which symmetry breaking occurs would be

expected to be on the order of the Planck mass $\sim 10^{19}$ GeV. Unfortunately, this gravity-mediated SUSY breaking runs into a problem requiring fine tuning of parameters to avoid difficulties at lower energies.

Gauge mediated supersymmetry is a SUSY model which breaks supersymmetry at a lower energy scale $\sim 10 - 100$ TeV. Unlike in gravity mediated models, symmetry breaking occurs via strong gauge interactions. This mechanism leads to the existence of a Goldstino, which is the longitudinal component of the gravitino. The mass of the gravitino is expected to be small, on the order of a few eV, making the gravitino the LSP.

In both models, gravity and gauge mediated supersymmetry, the LSP is stable and weakly interacting. In R-parity conserving supersymmetry all supersymmetric particles must eventually decay to the LSP. Cosmological bounds demand that this LSP be neutral and thus must be weakly interacting. Therefore a key experimental signature indicating supersymmetry would be the measurement of missing energy in an event. A dominant supersymmetric signal of this type would be the decay of the next-to-lightest supersymmetric particle, ($\tilde{\chi}_2^0$ for MSSM or $\tilde{\chi}_1^0$ gauge mediated) which is expected to decay by the emission of a photon, ie $X \rightarrow Y\gamma$. This type of signal could be observed in e^+e^- collisions through the reaction $e^+e^- \rightarrow XX \rightarrow YY\gamma\gamma$ or $e^+e^- \rightarrow XY \rightarrow YY\gamma$. This type of signal only has one Standard Model background source, radiative neutrino production, $e^+e^- \rightarrow \nu\bar{\nu}\gamma$. In this type of event one would only expect to see evidence of the photon, since the neutrinos and neutralinos are weakly interacting and thus would only be observed as missing energy.

Within R-parity violating models of supersymmetry, the value of R is no longer conserved. Consequently, the LSP can decay to ordinary particles through observable modes reducing the missing energy signature of SUSY. R-parity violation also has consequences for other modes that might be employed in a search, in that new parameters are introduced into the superpotential of the SUSY Lagrangian. These new parameters describe couplings and interactions between particles, therefore the new parameters

may alter super particle production cross-sections and decays.

A second theory that deals with problems of the Standard Model, known as compositeness, has also received a great deal of attention. The theory of compositeness contends that the fundamental particles of the Standard Model are composed of even smaller constituents, much in the same way a nucleus is composed of protons and neutrons which in turn are composed of quarks. A large appeal of the compositeness idea is that it may be able to explain the existence of fermion masses and mixing as well as the existence of the three generations of fermions

Nuclei and nucleons can appear as excited states due to their composite nature, the same is expected to be true if “fundamental” fermions are composite. One would expect to see excited leptons and quarks produced in collision experiments. These excited states would be unstable and therefore would decay to the ground state of the fermion, most likely through the emission of a photon. The production of an excited neutrino with a ground state neutrino would produce a signal like that mentioned above for radiative neutrino production, ie. $e^+e^- \rightarrow \nu^*\bar{\nu} \rightarrow \nu\bar{\nu}\gamma$.

Compositeness can also be observed indirectly by its effect on production cross sections, in particular in the QED process of two photon production. Normally this process occurs via an exchange of an electron between an electron-positron pair resulting in the emission of two photons. The differential cross-section for this process can be shown to be [12]

$$\left(\frac{d\sigma}{d\Omega}\right)_{\text{Born}} = \frac{\alpha^2}{s} \left(\frac{1 + \cos^2 \theta}{1 - \cos^2 \theta}\right). \quad (2.6)$$

where α is the electromagnetic coupling constant, s refers to the square of the center of mass energy. Similarly two photon production can also proceed via the exchange of an excited electron. The effect of the excited electron can be parameterized by a mass scale $\Lambda_{\pm}$ which modifies Eqn(2.6) to [13]

$$\left(\frac{d\sigma}{d\Omega}\right)_{\Lambda_{\pm}} = \frac{\alpha^2}{s} \left(\frac{1 + \cos^2 \theta}{1 - \cos^2 \theta}\right) \left(1 \pm \frac{s^2}{2\Lambda_{\pm}^4}(1 - \cos^2 \theta)\right). \quad (2.7)$$

where θ corresponds to the angle the photons make with the beam line, and Λ_+ cor-

responds to the case of the $+$ sign and the Λ_- to the $-$ sign in Eqn(2.7). A fit of the data to Eqn(2.7) should then be able to either determine $\Lambda_{\pm}$ or put 95% Confidence Limits on its lower bound.

Chapter 3

LEP and the OPAL detector

The Large Electron-Positron (LEP) accelerator located at CERN in Geneva, Switzerland accelerates and collides high energy beams of positrons and electrons. The electron-positron pair interact with each other through an electroweak process with a center of mass energy equal to the sum of the energy of the two beams. This electroweak interaction allows the four LEP experiments ALEPH, DELPHI, L3, and OPAL to make precision electroweak and quantum chromodynamic measurements thus enabling them to test the Standard Model.

3.1 The LEP Accelerator

LEP accelerates counter-rotating beams of electrons and positrons through a circumference of 27 km and brings them into collision at four interaction points, each occupied by one of the LEP experiments. The large radius of LEP is required to reduce the amount of synchrotron radiation emitted. The beams are kept in a circular orbit by means of a series of dipole magnets. In order to increase the luminosity, the beams are tightly focused at each collision point, by the use of superconducting quadrupole magnets with very strong magnetic field gradients. The dimensions of each beam, at the interaction point, are of the order of $10\mu\text{m}$ and $250\mu\text{m}$ in the vertical and horizontal

planes respectively.

The electron-positron beams are initially accelerated by using two linacs of 200 MeV and 600 MeV respectively, which is followed by a 600 MeV Electron-Positron Accumulator(EPA). The EPA injects the beams into the CERN Proton Synchrotron(PS) which accelerates them to 3.5 GeV. The PS then injects the beams into the Super Proton Synchrotron(SPS) at CERN which produces a further acceleration to 20 GeV. The beams are finally injected to the LEP accelerator where the final acceleration phase takes place. Fig 3.1 shows the various stages and accelerators used in the acceleration of the electron-positron beams at LEP.

LEP accelerates the electron-positron beams through the use of RF cavities, which also restores energy lost to synchrotron radiation. Initially, the acceleration system consisted of 128 copper cavities, powered by sixteen 1 MW klystrons, each cavity having a operating frequency of 352.2 MHz, allowing for an operating RF voltage of 400 MV per revolution. The beams of electrons and positrons are circulated around the LEP ring in bunches, typically four bunches per beam, with approximately 10^{11} particles per bunch, from which a beam luminosity can be determined, as follows.

$$\mathcal{L} = \frac{I^2 n_b}{4\pi e^2 f_0 \sigma_x \sigma_y} \quad (3.1)$$

where I is the bunch current, n_b is the number of bunches, σ_x and σ_y are the vertical and horizontal dimensions of each bunch at the interaction point, and f_0 is the revolution frequency of the bunches.

The initial stage of LEP, now known as LEP 1, ran from 1989 to 1995 and achieved a center of mass energy of 91 GeV, equivalent to the mass of the Z^0 , which allowed extensive study of Z physics. The operational luminosity for the first half of this period was of the order of $11 \times 10^{30} \text{cm}^{-2} \text{s}^{-1}$, and $23 \times 10^{30} \text{cm}^{-2} \text{s}^{-1}$ for the second half when LEP ran with 8 bunches per beam. Over the entire lifetime of LEP 1 a total integrated luminosity of 169.5 pb^{-1} was collected, corresponding to several million Z^0 events.

In late 1995 an ambitious project to upgrade the LEP accelerator began, which saw the replacement of many of the copper RF cavities with superconducting RF cavities. These superconducting cavities are able to operate with much higher accelerating gradients than the copper ones, allowing LEP to achieve much higher center of mass energies, as well as higher luminosities (eventually up to $1 \times 10^{32} \text{cm}^{-2} \text{s}^{-1}$). An intermediate stage, known as LEP 1.5, had center of mass energies reaching 130, 136 and finally 140 GeV, with a total integrated luminosity of 5.5 pb^{-1} .

The final phase of the LEP upgrade, known as LEP 2, started in 1996 with the continued installation of new superconducting RF cavities. LEP 2 started with a center of mass energy on the W pair production threshold of 161 GeV and shortly thereafter

increased to 172 GeV, where a totals 10.3 and 10.5 pb^{-1} of data were collected respectively. The center of mass energy reached 184 GeV in early 1997 and will subsequently increase to 192 GeV in 1998, with further increases expected in 1999 and 2000. By the end of the LEP 2 run, circa 2000, a total 500 pb^{-1} of data is hoped to be collected by each experiment. Following this LEP will be replaced with the first of the next generation of particle accelerators, the Large Hadron Collider (LHC), which is expected to start physics runs early in the next century.

3.2 The OPAL Detector

The OPAL detector [14] is a multipurpose detector that has an acceptance that covers almost the entire solid angle of 4π . The idea behind the design of the detector was to enable it to efficiently and accurately identify particles and reconstruct events that occur in reactions that arise from electron-positron collisions.

The basic layout of the OPAL detector can be seen in Fig 3.2. In the central part of the detector lies the central tracking chambers, which operate within a 4 bar pressure vessel. The pressure vessel is contained within a solenoid that provides a 0.435 T magnetic field which allows the momentum of charged particles to be determined. Outside of the solenoid is a time of flight counter followed by a lead glass electromagnetic calorimeter with presampler. A hadron calorimeter lies outside the electromagnetic calorimeter followed by four layers of muon chambers. At forward angles close to the beam line lies the forward detector and silicon-tungsten detector, which are electromagnetic calorimeters primarily used to measure luminosity.

3.2.1 The Electromagnetic Calorimeter

The main detector utilized for this analysis is the Electromagnetic (EM) Calorimeter, see Fig 3.3. The primary use of the calorimeter is to identify and measure the energies and positions of photons, electrons and positrons with energies ranging from a

Figure 3.2: Cut Away diagram showing layout of the OPAL detector

few hundred MeV up to 100 GeV. Electromagnetic showers initiated by electrons and photons produce Čerenkov light within lead glass blocks. By measuring the amount of Čerenkov light produced, the energy of the particle can be determined. The use of lead glass blocks gives excellent energy resolution ($\sigma_E/E \sim 5\%/\sqrt{E}$) as well as spatial resolution (~ 1 cm), by using the centroid of clusters spread over several blocks.

The EM Calorimeter consists of three overlapping parts, a barrel and two endcaps covering 98% of the solid angle. The barrel EM calorimeter lies outside the solenoid covering the full azimuthal angle and polar angle where $|\cos\theta| < 0.82$. The barrel

Figure 3.3: Cross Section of Electromagnetic Calorimeter. Barrel and Endcaps

region has a cylindrical geometry containing 9440 lead glass blocks with a thickness of $24.6 X_0$. Each lead glass block is approximately $10 \text{ cm} \times 10 \text{ cm}$ in cross-section and 37 cm in depth and is tilted so as to point toward the interaction region. The Čerenkov light produced in each block is viewed by phototubes which are shielded from the small magnetic fields.

The endcap regions have a dome shaped geometry with 1132 lead glass blocks of thickness $\sim 20.5 X_0$ in each, covering the full azimuthal angle and the polar angle between $0.81 < |\cos \theta| < 0.98$. Unlike in the barrel, the blocks in the endcap are oriented parallel to the beamline because of geometrical constraints. Since the endcap is located inside the solenoid the Čerenkov light is measured using vacuum photo triodes which are able to operate in the full field of the magnet.

3.2.2 The Forward Detectors

The Forward and Silicon-Tungsten detectors are detectors that extend the EM calorimeter's reach as close as possible to the beam-line, primarily to allow for the measurement of forward scattered electrons. This measurement of Bhabha scattered electrons and positrons can then be used to determine the luminosity of a particular data sample.

The Forward detector is actually a composite of four detectors, two of which are used for the analysis, the Forward Calorimeter and the Gamma Catcher. The Forward calorimeter is a lead-scintillator sandwich sampling calorimeter of $24X_0$ that covers the polar region between 47 and 120 mrad. The Gamma Catcher is a ring of lead-scintillator detector ($7X_0$) that covers the region between the Forward Calorimeter and the EM Endcap; that is, it covers the region from 142 to 200 mrad. The Silicon-Tungsten detector is a sampling calorimeter composed of 19 layers of silicon and 18 layers of tungsten, covering the angles between 25 mrad to 59 mrad.

3.2.3 The Tracking Chambers

The main tracking chambers consist of the Central Vertex detector and the Central Jet chamber. The Vertex detector is a cylindrical drift chamber, 1 m long and 470 mm in diameter, located between the beam pipe and the Jet chamber (see Fig 3.2). Precise measurements of ionization drift time to axial wires allows precision measurement of position in the $r - \phi$ plane, which aids in the identification of secondary vertices. This allows for identification of non-physics beam related events, such as those events arising from interactions between the beam and the beam-wall or between the beam and gases within the beam line.

The Jet chamber is also a cylindrical drift chamber designed to give good space and track resolution. The chamber, which surrounds the vertex detector and the beam line, is 4 m long and has an inner radius of .5 m and extends to an outer radius of

3.7 m. The chamber is able to measure three dimensional coordinates (r, ϕ, z) through the determination of wire position, drift time and charge division. The energy loss, dE/dx , of the particle in the chamber gas can also be determined (from the total charge measurement) which allows particle determination. The measurement of multiple points (up to 159) along a track, as well as, good double track resolution give a very good tracking efficiency, which allows for the identification of all events with charged particles.

3.2.4 Hadron Calorimeter and Muon Detector

The hadron calorimeter measures the energy of hadrons leaving the electromagnetic calorimeter and helps in the identification of muons. The calorimeter covers nearly the entire solid angle (97%) and consists of three parts: the barrel, endcaps and poletips. The detector is composed of alternating layers of detectors and iron slabs, which provide at least 8 interaction lengths in the barrel region. Since the EM calorimeter, just inside the hadron calorimeter, provides an additional 2.2 interaction lengths the total hadron energy must be determined by combining the signals from both the hadron calorimeter and the EM calorimeter.

The muon detector is designed to unambiguously identify muons. The detector itself is the outermost layer of the OPAL detector. It consists of four layers of drift chambers in the barrel and four layers of limited streamer tubes which are aligned perpendicular to the beam line in the endcap. The efficiency of detecting an isolated muon with energies above 3 GeV is essentially 100 %.

3.2.5 The Trigger and Data Acquisition Systems

An event will only be recorded by the data acquisition system if it satisfies certain trigger conditions. The trigger system [15] is designed to provide good efficiency at selecting various physics processes, as well as, good rejection of backgrounds, like cosmic rays. At LEP, bunch crossings occur every $22.2\mu\text{s}$, which corresponds to a crossing

rate of 45 kHz. Between 1992 and 1994 LEP ran with 8 bunches per beam doubling the crossing rate to 90 kHz. For the 1995 run LEP returned to four bunch trains per beam. The trigger system uses fast information from the subdetectors to select potential electron-positron interactions, thereby reducing the rate to less than 5 Hz, which is much more manageable for the data acquisition system.

Trigger signals from the OPAL detector are divided into 144 overlapping bins, 6 bins in θ and 24 bins in ϕ . Different trigger signals within each subdetector are then combined by the central trigger logic processor. Trigger signals from each subdetector can be identified as either “stand alone” signals which include things like total energy or track multiplicities, which have relatively high thresholds and “low threshold” signals that are input into the $\theta - \phi$ binning. A decision, to accept or reject an event is formed in the central trigger logic by the combination of stand alone and $\theta - \phi$ triggers.

Once the trigger has selected a potentially interesting event after a beam crossing, the data from the subdetectors can then be collected and the event reconstructed. The data acquisition system [16] begins with a read out from each of the individual subdetectors separately from its own front-end electronics into a local system crate (LSC). The sub-event data from each of the LSC's is then passed on to an Event Builder, which collects each subevent, merges the data and passes the full event to one or more destinations. After an event is built it is sent to a filter which performs a fast analysis of each event, acting as a second-level software trigger. By partially reconstructing the event, the filter classifies the full event into various physics categories, backgrounds can optionally be accepted or rejected; as well, junk events which pass the initial trigger ($\sim 15 - 35\%$ of events) can be further rejected. The data from the filter is then written to disk in files 20 Mbyte long, each containing 2000 events. The raw data then undergoes full event reconstruction by a farm of HP workstations, where it gets converted into physical quantities, like particle energies or momenta. Datafiles of the reconstructed events are then concatenated and permanently stored on disk and backed up on cartridge for offline analysis.

Chapter 4

Event Selection

Events with a purely photonic signal have a distinct signature. All the information about the event is determined from the electromagnetic calorimeter. Events corresponding to radiative neutrino production (or photons with weakly interacting final state particles) are expected to produce at least one high energy electromagnetic cluster. The energy of the invisible particles can be deduced to be the difference between the total center of mass energy and the energy deposited by the photons. The Standard Model process that produces photons and missing energy is due mostly to Z^0 decays to

Figure 4.1: Feynman diagrams for $e^+e^- \rightarrow \nu\bar{\nu}\gamma$

neutrino pairs accompanied by initial state photon radiation along with a non-negligible amplitude from the t-channel $W^\pm$ exchange diagram, as seen in Fig 4.1.

The energy of the radiated photons due to the diagram involving the Z^0 decay then is expected to peak at

$$E_\gamma = \frac{s - M_Z^2 + m_\gamma^2}{2\sqrt{s}}, \quad (4.1)$$

where $\sqrt{s}$ is the center of mass energy. M_Z is the mass of the Z boson and m_γ is the mass of the photon (taken to be zero). At 161 GeV this corresponds to an energy of about 55.7 GeV. However, lower energy photons are also expected from the production of neutrinos from the W t-channel exchange.

Events with photons and no missing energy are expected to be characterized by two electromagnetic clusters which are back to back, each having an energy approximately equal to the beam energy, E_{beam} . The Standard Model diagram for this process is shown in Fig 4.2.

Figure 4.2: Feynman diagram for $e^+e^- \rightarrow \gamma\gamma$

The largest source of background to both types of photonic events is expected to be due to Bhabha scattering, $e^+e^- \rightarrow e^+e^-$. In particular, those Bhabha events (see Fig 4.3) in which a photon is radiated and is detected in the electromagnetic calorimeter, but the final state electrons and positrons are directed down the beamline and thus

escape detection contribute to the background. These type of events would be observed as a photon and missing energy. Bhabha events with no radiated photons can also be a large source of background, since the cross section is very forward peaked. At forward angles electrons can escape detection as charged particles, leaving only clusters in the electromagnetic calorimeter, thus mimicking the signal of back to back photons.

Figure 4.3: Feynman diagrams for radiative Bhabhas scattering, where the photon can be radiated in the initial or final state.

4.1 Monte Carlo Simulation

Essential to any analysis is a study of Monte Carlo simulated data, not only to understand various backgrounds which may affect the analysis, but to understand how these events appear to the detector. Central to OPAL is the Monte Carlo program GOPAL [17] which simulates the OPAL detector. GOPAL uses the GEANT [18] package to simulate detector elements as well as to track particles as they pass through the detector. Events can then be reconstructed using the same OPAL reconstruction routines used on actual data.

Physical processes are simulated through the use of Monte Carlo generators in which the 4-momenta of particles produced in a particular process are generated. These

4-vectors are then passed to GOPAL which simulates the detector response to these particles. The energy deposited, positions and charges of the simulated particles as well as other detector parameters are then determined and recorded. The original Monte Carlo generator information such as particle energies, momenta and particle types are also recorded in a separate bank.

Several Monte Carlo generators are used in this analysis. The expected Standard Model signals are simulated using the Monte Carlo generators NUNUGPV [19] for $e^+e^- \rightarrow \nu\bar{\nu}\gamma$ events and RADCOR [20] for $e^+e^- \rightarrow \gamma\gamma$ events. The main backgrounds, Bhabha events, are investigated using TEEGG [21] which generates radiative Bhabha scattering events with one or both electrons scattered at small angles and BHWIDE [22] for Bhabha scattering events with both electrons scattered at wide angles. Other possible sources of background are also examined, $e^+e^- \rightarrow \mu^+\mu^-(\gamma)$ and $e^+e^- \rightarrow \tau^+\tau^-(\gamma)$ with KORALZ [23] and $e^+e^- \rightarrow e^+e^-\ell^+\ell^-$ (lepton final states from two photon collisions) using Vermaseren [24]. Physics beyond the Standard Model can also be simulated this way, in particular supersymmetry, through SUSYGEN [25].

4.2 Selection Criteria

Events with a purely photonic signal (with or without missing energy) are expected to be classified as low particle multiplicity events in the OPAL detector, meaning that the event does not have a large number of good tracks and energetic electromagnetic clusters. In fact, photonic events are not expected to have any charged tracks associated with the events, except for the case when a photon converts into an electron-positron pair before leaving the tracking chambers. A cut that removes events with a charged track is an efficient means of rejecting backgrounds such as Bhabha events with the final state electron detected in the tracking chamber. The fraction of photon events lost is expected to be less than 10%.

A potentially large source of background that is not investigated by Monte Carlo

is cosmic rays, in particular cosmic muons, since the detector is located below ground. A great deal of the background can be removed by imposing a cut on signals from the muon detector, so that any event with a signal consistent with a muon can be rejected.

4.2.1 Photons with Missing Energy

Radiative Bhabha scattering remains the largest source of background to photonic final state events, even after a cut on charged tracks. This is because the cross section is very forward peaked and electrons that scatter at small angles avoid detection. Should a photon be radiated and detected in the EM Calorimeter one would see an energetic EM cluster and missing energy due to the undetected electrons. Events with missing energy where the direction of the missing momentum vector, ($\vec{p} = -(\vec{p}_{\gamma_1} + \vec{p}_{\gamma_2})$), is down the beamline should be rejected by requiring, $|\cos \theta_{\vec{p}}| < 0.9$. This requirement is necessary since it is impossible to determine whether the missing energy is due to neutrinos or some background process that escapes detection. A typical event display of the OPAL detector showing a cluster in the EM calorimeter and significant missing energy is shown in Fig 4.4

Bhabha scattering radiated photons are forward peaked and have a relatively low energy compared with that of radiative neutrino photons as seen in Fig 4.5. A cut on the scaled energy (photon energy normalized to the beam energy) of a particular event of $x_{\gamma} > 0.07$ accompanied by a cut on clusters with a large forward angle, requiring $|\cos \theta_{\gamma}| < 0.9$, will remove a vast majority of the Bhabha background. However, even with these cuts a significant background will remain. The freedom to adjust these cuts is limited, since a larger cut on x_{γ} will further restrict the search space in which one could look for new physics. A $|\cos \theta_{\gamma}|$ cut is also constrained by the fact that photons from radiative neutrino production are forward peaked like the photons from radiative Bhabha scattering, hence, a lower cut on the photon angle would reduce the efficiency to observe the signal.

Further cuts must be made on the electrons and positrons of the Bhabha back-

```

Run:event 7226: 17872 Date 960713 Time 134817 Ctrk(N= 0 Sump= 0.0) Ecal(N= 7 SumE= 43.1) Hcal(N= 0 SumE= 0.0)
Ebeam 80.679 Evis 42.9 Emiss 118.5 Vtx ( -0.03, 0.08, 0.50) Muon(N= 0) Sec Vtx(N= 0) Fdet(N= 0 SumE= 0.0)
Bz=4.027 Bunchlet 1/1 Thrust=***** Aplan=***** Oblat=***** Spher=*****

```

Figure 4.4: OPAL event display of a typical $e^+e^- \rightarrow \nu\bar{\nu}\gamma$ event (beamline is pointed out of the page). Notice the large cluster in the EM calorimeter with a large visible energy ($E=42.9$ GeV) from a photon and significant missing energy ($E_{miss}=118.5$ GeV) from undetected particles.

ground. Because the final state electrons (and positrons) are forward peaked they can escape detection by the tracking chambers. The electrons, however, will interact and therefore deposit energy in the forward detectors, namely the Gamma Catcher. Forward

Figure 4.5: Comparison between photons from radiative neutrino Monte Carlo events and the expected background due to radiative Bhabha scattering events. The scaled energy is defined as the energy of the photon divided by the beam energy, $x_\gamma = E_\gamma/E_{\text{beam}}$. Only events with no reconstructed tracks are shown.

Calorimeter and the Silicon-Tungsten detector(Fig 4.6).

The activity in these detectors due to photons from neutrino events is very small, so tight cuts can be applied to the forward detectors. A cut on the maximum deposited energy in either the Forward Calorimeter or the Gamma Catcher is set at 5 GeV. A

similar cut is set on the maximum energy deposited in the Silicon-Tungsten detector at 10 GeV. Tighter cuts are constrained by noise in the detectors that could produce a signal large enough to cut upon should the energy cuts be too low. This would result in significant loss of signal due to the rejection of events based on noise in the detector. therefore cuts must allow for the rejection of background and still maintain a

Figure 4.6: Comparison between energy deposited in the forward detectors by radiative neutrino Monte Carlo events and radiative Bhabha scattering Monte Carlo events with no reconstructed tracks and the x_γ and $|\cos\theta_\gamma|$ cuts applied. Arrows indicate where cuts will be applied.

Figure 4.7: Energy measured in EM calorimeter and the Forward detectors in random beam crossings events. These events allow the noise of the detectors to be measured.

good selection efficiency. The cuts on the forward detectors correspond to an efficiency loss of $\sim 1.52\%$ due to noise, with the major contribution coming from noise in the Silicon-Tungsten detector (Fig 4.7c).

At high energies the radiation of a second energetic photon in the initial state becomes more likely, so it is advantageous to look for events with one or two high energy photons. Three energetic photons being produced is much less likely, so that a

cut on the number of photons detected for a given event can be set at three. Fig 4.7a shows where a lower bound on the energy of a photon is set. A cluster is required to have an energy greater than .5 GeV to be accepted as a photon. If a much lower energy cut was used, many events would be rejected for having too many clusters, as a result of noise in the EM calorimeter.

Figure 4.8: Energy of clusters in endcap beyond $|\cos \theta| < 0.9$

The portion of the EM calorimeter endcap beyond the $\cos \theta$ cut may also be used as part of the Forward detectors. As seen in Fig 4.5b EM clusters arising from the Bhabha background are more likely to occur in this region than those from radiative neutrino production. The energy of the individual clusters in this region is seen in Fig 4.8 which compares Monte Carlo Bhabha events to Monte Carlo radiative neutrino events. A relatively low cut on the energy of these clusters of $E_{\text{end}} < 8$ GeV completely removes all background events from this region.

Care must be taken in examining clusters in the EM Calorimeter, in particular clusters that occur in the region where the barrel part of the calorimeter meets the endcap. The energy of clusters is not reconstructed very well as is seen in Fig 4.9 where

the difference between the Monte Carlo generated energies and that measured by the detector is plotted against the polar angle of the photon. Throughout most of the range of the polar angle there is good agreement between the Monte Carlo energy and the measured energy. In the region, $0.73 < |\cos \theta_\gamma| < 0.82$, denoted as the overlap region, there are large differences. These differences are due mostly to the fact the photons entering this region have traversed through more material than at any other point. In order to have a sample of well understood events, events containing a cluster with energy greater than 0.5 GeV in this region are rejected.

Figure 4.9: The difference between the true energy and the measured energy of a photon generated by the Monte Carlo over the entire range of the detector. The overlap region is indicated.

4.2.2 Non-Physics Backgrounds

As mentioned above, a potentially significant background can be expected for non-physics sources. Cosmic muons and beam halo muons that are not detected by the muon

```

Run event 4110 169966 Date 930530 Time 12926 Cirk(Nu: 0 Surp= 0 0) Ecali(Nu: 4 SumEx 10 0) Hcal(Nu: 5 SumEx 2 2)
Ebeam 45 443 Evis 11 6 Emiss 79 7 Vls ( 0 03, 0 08, 0 41) Muon(Nu: 0) Sec Vls(Nu: 0) Fdet(Nu: 0 SumEx 0 0)
Bz=4 029 Bunchlet 1/1 Thrust=0 9509 Aplane=0 0054 Oblat=0 1562 Spher=0 0597

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Run event 4050 9066 Date 930518 Time 15312 Cirk(Nu: 0 Surp= 0 0) Ecali(Nu: 4 SumEx 15 1) Hcal(Nu: 0 SumEx 0 0)
Ebeam 45 644 Evis 14 8 Emiss 76 5 Vls ( 0 04, 0 08, 0 17) Muon(Nu: 0) Sec Vls(Nu: 0) Fdet(Nu: 0 SumEx 0 0)
Bz=4 028 Bunchlet 1/1 Thrust=***** Aplane=***** Oblat=***** Spher=*****

```

Figure 4.10: Event displays of cosmic muon(a) (display looking down the beam line) leaving a large cluster in the ϕ direction in the EM Calorimeter, and beam halo muon(b) (display looking perpendicular to the beamline) leaving a large cluster in the θ direction in the EM calorimeter.

chambers are of particular concern. Muons can traverse much of the OPAL detector without being observed, they typically deposit very little energy in the Calorimeters and do not leave good tracks in the tracking chambers. A typical event display of a cosmic and beam halo muon is seen in Fig 4.10. Muons that deposit more than 500 MeV in the EM calorimeter will be accepted as a photon.

Figure 4.11: Cluster extent in θ and ϕ of typical high energy EM clusters in the EM barrel region from high energy single electron events.

Figure 4.12: Cluster extent in θ and ϕ of a typical high energy EM cluster versus $|\cos\theta_\gamma|$, the endcap begins at $|\cos\theta_\gamma|=0.82$, showing that the angular size of clusters is over estimated in the endcap.

Fortunately, there are some tell-tale signs of the presence of a non-physics muon in an event. Muons striking the EM calorimeter on trajectories that do not originate from the interaction point will typically leave long trails of blocks in the polar or azimuthal directions. Clusters from particles originating from the interaction point are contained within a smaller region. A cut on the total extent of a cluster in the polar and azimuthal directions will remove most of the muon events of the type shown in Fig 4.10. In order to understand what spatial extent a typical EM cluster is expected to have at high energies, clusters created by single electrons were employed (Fig 4.11). Typical high energy clusters in the EM calorimeter do not extend more than 300 mrad in the polar or azimuthal directions so that the cut can be made on the cluster extent of $\Delta\theta < 0.3$ rad and $\Delta\phi < 0.3$. Cuts on the extent of a cluster can only be applied to clusters within the barrel region, since the spatial extent is over estimated within the endcap, as seen in fig 4.12.

Figure 4.13: Number of central tracks and total energy in the hadron calorimeter in 82500 random beam crossing events. The bin with zero tracks is suppressed.

Although muons are very penetrating and thus will not easily interact with the detectors, a measurable amount of their energy may be deposited in the hadron calorimeter.

After scanning several events similar to the one shown in Fig 4.10a, a cut requiring the

```
Run:event 4068:101076 Date 930522 Time 71253 Ctrk(N= 5 Sump= 0.0) Ecal(N= 5 SumE= 5.8) Hcal(N= 5 SumE= 2.5)
Ebeam 45.683 Evis 2.6 Emiss 88.8 Vtx ( -0.05, 0.08, 0.36) Muon(N= 0) Sec Vtx(N= 0) Fdet(N= 0 SumE= 0.0)
Bz=4.027 Bunchlet 1/1 Thrust=0.9986 Aplan=0.0000 Oblat=0.0528 Spher=0.0037
```

Figure 4.14: Cosmic that passes cluster extent cuts. Cluster is small, with relatively few blocks, however, it is energetic enough to pass the scaled energy requirements. The track in the central detector is not considered a good track but is typical of the type of track left by a cosmic muon.

total energy deposited in the hadron calorimeter be less than 2 GeV was made. Also cosmic muons will not leave good charged tracks. However, they may produce some

activity in the tracking chambers, so that a cut can be made on any event with activity in the central detectors. Therefore, an event is rejected if there is any track, regardless of quality, measured by the central detectors. These cuts are sensitive to the noise in the two detectors and contribute $\sim 2.75\%$ loss of efficiency. Fig 4.13 shows the plots of the number of tracks measured by the central detector as a result of noise within the detectors, as well as the total energy measured by the hadron calorimeter coming from noise clusters.

Figure 4.15: Number of blocks in a high energy cluster from single electron and $e^+e^- \rightarrow \nu\bar{\nu}\gamma$ Monte Carlo data with $|\cos\theta_\gamma|$ and x_γ cuts included. It is expected a large number of blocks will be included in an individual cluster resulting from a photon or electron.

A final cut can be made on EM clusters to remove cosmic backgrounds. In particular those cosmic events of the type seen in Fig 4.14 in which the muon is not detected in the muon detector or leaves a measurable track in the central detectors is of greatest concern. EM clusters resulting from a cosmic ray of this type typically involve no more than one or two lead glass blocks, whereas EM clusters from photons and electrons are composed of several blocks, see Fig 4.15. A cut on the number of blocks in a high energy cluster requiring it be greater than or equal to four was made.

4.2.3 Photons with no Missing Energy

The main requirement for determination of QED two photon events is the presence of two high energy clusters. This type of event is much less sensitive to backgrounds than the case for photons with missing energy because of its distinctive topology (Fig 4.16). There still are backgrounds which must be dealt with. Here again, Bhabha scattering can be a major source of background when the final state electrons scatter at small enough angles to escape detection in the tracking chamber but still deposit energy in the forward parts of the EM calorimeter. Backgrounds of this type can be dealt with most effectively by placing a cut on the polar angle of the cluster (Fig 4.17). A cut of $|\cos \theta_\gamma| < 0.97$ removes backgrounds due to this type of Bhabha scattering. Another potential source of background comes from $e^+e^- \rightarrow \nu\bar{\nu}\gamma$ in which two photons are radiated in the initial state. These photons, however, typically will be radiated at random opening angles between them, so that a cut on the acoplanarity angle (π minus the opening angle in azimuth), of $\phi_{\text{acop}} < 0.04$ rad, will enable a differentiation between two photons with missing energy and photons without missing energy, as seen in Fig 4.18.

Like photons from radiative neutrino production, there is an increased likelihood for additional energetic photons to be produced in QED photon production as the center of mass energy increases. When only two energetic photons are produced, the polar angle each photon makes with the beamline is expected to be roughly equivalent, so that the scattering angle of each event is easily determined, ie.

$$\cos \theta^* = \frac{1}{2}(|\cos \theta_{\gamma_1}| + |\cos \theta_{\gamma_2}|). \quad (4.1)$$

If there is a third photon produced, this is no longer the case and determination of the scattering angle becomes much more complicated. Therefore, in order to simplify the calculations, events with no missing energy will be restricted to having only two observed photons. Two photon events are also subject to cuts that remove non-physics backgrounds, as well as, the forward detector cuts to remove Bhabha scattering events

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Run:event 7220: 79539 Date 960712 Time 31833 Clrk(N= 0 Sump= 0.0) Ecal(N= 12 SumE=165.2) Hcal(N= 2 SumE= 1.3)
Ebeam 80.685 Evis 165.7 Emiss -4.3 Vtx ( -0.03, 0.08, 0.41) Muon(N= 0) Sec Vtx(N= 0) Fdel(N= 2 SumE= 0.0)
Bz=4.027 Bunchlet 1/1 Thrust=0.9927 Aplan=0.0000 Oblat=0.0114 Spher=0.0001

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Figure 4.16: Event display of a typical QED two photon production event. This event type has a distinctive topology with two high energy EM clusters that are back to back in the ϕ direction

discussed previously.

Figure 4.17: Cosine distribution of the most energetic EM cluster comparing QED two photon production (open histogram) to that from Bhabha scattered electrons(positrons) (hatched histogram).

Figure 4.18: Comparison of acoplanarity angle, ϕ_{acop} , between photons from QED production (open histogram) and radiative neutrino production (hatched histogram)

4.3 LEP 1 Analysis

The physics backgrounds have been explored by the analysis of Monte Carlo data with selection cuts set accordingly. Unfortunately, backgrounds from non-physics sources can make their way into this analysis. The largest sources of this type for the missing energy channel arise from cosmic and beam backgrounds. Cosmic backgrounds are not modeled using Monte Carlo techniques and so it is difficult to predict their effect on an analysis before hand. One method of determining the extent to which a cosmic background is problematic is to run the analysis over a control sample, recorded at lower energies in which the same cosmic background is present, but where it is a much smaller fraction of the signal cross section. Cuts then can be amended to the analysis to remove any background events that passed the original selection criterion.

The data sample chosen as a cross check of the selection criterion is the data collected at OPAL while LEP was running with $\sqrt{s} = 91$ GeV, known as the Z^0 or LEP 1 run. Photonic data from this run was originally analyzed to determine Standard Model parameters like the number of light neutrino species and the invisible Z decay width, as well as putting “low” energy limits on the size of the mass scale of new physics due to compositeness. The physics signal for photons with and without missing energy and background cross section are small at this energy and so the data set provides a good test for the high energy analysis.

4.3.1 Data Sample and Luminosity Determination

The total data sample from the LEP 1 period is not employed since the silicon-tungsten detector was not installed until 1993. Each sub-detector utilized in the analysis is required to be online and working well, with no readout or voltage problems. The LEP 1 data sample which satisfies this criteria corresponded to a total of 46.2 pb^{-1} and a livetime of 95.7 days, all with a center of mass energy on the Z peak, collected during 1993 and 1994. Data collected during the period of LEP 1 also contains events off of

the Z peak, ie with $\sqrt{s} \approx M_Z \pm 2$ GeV. These events are excluded from the analysis to keep the data and Monte Carlo center of mass energies consistent.

The integrated luminosity of this data set was determined using the subroutine ROCROS [26]. This routine scans the data set and looks at events determined to be forward angle Bhabha scattering events. Events will only be presented to ROCROS if each detector is working properly as mentioned above. The events passed to ROCROS are identified by activity measured by the Silicon-Tungsten detector or by the Forward Detector. The contribution to the total luminosity is determined by taking the inverse of a precisely calculated cross-section for the determined center of mass energy. A running sum is kept which then corresponds to the total luminosity when the entire data set has been analyzed. A determination of the systematic and statistical error of the luminosity is also performed as the luminosity is calculated. The total error on the luminosity determined in this way is typically much less than 1%. This method is also used to determine luminosity at higher energies.

4.3.2 Hot Zones

When looking for clusters in the EM Calorimeter one must be careful of clusters that arise from noise in specific channels of the calorimeter, these are referred to as hot clusters. A standard OPAL analysis subroutine is used to identify persistent hot clusters in both the hadron and the electromagnetic calorimeter so they can be removed from the analysis.

An initial analysis of the data collected at LEP 1 with all of the above cuts applied, showed a large discrepancy between what was observed and what was expected (Fig 4.19). Much of the excess is found in the endcaps of the EM calorimeter as seen in Fig 4.20. In particular a large part of the excess appears in three distinct regions of the EM endcap. Typically, one would expect the clusters to be distributed randomly in both angular directions, but the clusters in these "hot zones" seem to have a preferential direction in θ and ϕ . This characteristic suggests that the regions are due to some noise within

Figure 4.19: Energy distribution of most energetic EM cluster showing the discrepancy between data and Monte Carlo for photons with missing energy

the endcap of the EM calorimeter.

An interesting feature of the hot zones is that each event has two high energy clusters. The clusters themselves are separated by very small amounts in both θ and ϕ as seen in Fig 4.21. The opening angle between these two clusters then would be very small so that a cut on the cosine of the opening angle should remove these events from the data set. From Fig 4.21c it is seen that a relatively loose cut of $|\cos \theta_{\text{open}}| < 0.99$ removes this background.

4.3.3 Endcap Excess

Despite removing the excess clusters in the hot zones with an opening angle cut, a relatively large excess of data events still exists over that predicted by Monte Carlo. This

Figure 4.20: Box scatter plot of the Z^0 data showing the positions of the clusters in θ and ϕ , indicating evidence of three hot zones. The area of each box is proportional to the number events contained in each region

excess again seems to be located within the endcap of the EM calorimeter (Fig 4.22). A cut on the scaled transverse energy, the energy of the endcap EM cluster multiplied by $\sin \theta$ normalized to the beam energy, of $x_T > 0.2$ will remove the last of the excess from data set. This cut only needs to be applied to the endcap region since this is where the excess exists. If this cut were applied to all clusters within the EM calorimeter there would be a significant loss of signal events. Therefore, any event having clusters with $|\cos \theta_c| > 0.82$ and $x_T < 0.2$ is rejected.

With all of the cuts made, the agreement between Monte Carlo and observed data is improved dramatically, compare Fig 4.19 and Fig 4.24a. No new cuts were required to be introduced for events with two photons and no missing energy as there is good agreement between the Z^0 and the Monte Carlo (Fig 4.24b).

Figure 4.21: Distribution of the separation of cluster in (a) azimuth ($\phi_1 - \phi_2$), and (b) the polar angle ($\theta_1 - \theta_2$) and (c) $|\cos \theta_{\text{open}}|$ for all events with two high energy photons.

4.4 Summary

After a thorough Monte Carlo study of expected signal and backgrounds, cuts have been developed to limit the influence of the background on future datasets. Cosmics and other non-physics related backgrounds have been taken into consideration with several

Figure 4.22: The $|\cos \theta_\gamma|$ distribution showing an excess of expected events over Monte Carlo prediction

Figure 4.23: The scaled transverse energy distribution, x_T , of events within the endcap

cuts to be applied both to events with and without missing energy. Also potential machine backgrounds have also been fully explored with analysis of data collected on the Z-peak. The amount of data collected with $\sqrt{s} = M_Z$ corresponded to 46.2 pb^{-1} for a total livetime of 95.77 days. This compares to a livetime of 24.2 days at 161 GeV

Figure 4.24: Energy distribution (a) for most energetic photon of data (points) and Monte Carlo events (hatched histogram) for $e^+e^- \rightarrow \nu\bar{\nu}\gamma$ and (b) $|\cos\theta_\gamma|$ distribution for $e^+e^- \rightarrow \gamma\gamma$

and 18.9 days at 172 GeV of the LEP 2 run. Since no significant cosmic background was observed in the 95.77 days of the Z-peak data sample there is not expected to be a significant cosmic background to the two LEP 2 data sets. Therefore, with all of the cuts applied, the total background at the higher center of mass energies is expected to be negligible, on the order of two or three percent, see Tables 4.1 and 4.2.

Process	MC Generator	$e^+e^- \rightarrow \nu\bar{\nu}\gamma$	$e^+e^- \rightarrow \gamma\gamma$
$e e(\gamma)$	TEEGG	0.28 ± 0.16	0.21 ± 0.16
$e e$	BHWIDE	$0.08 \pm .08$	0.25 ± 0.08
$\mu\mu$	KORALZ	$0.02 \pm .007$	0.003 ± 0.002
$\tau\tau$	KORALZ	$0.002 \pm .002$	0.002 ± 0.002
$e e \mu\mu$	Vermaseren	$0.05 \pm .05$	$0.05 \pm .05$
$e e \tau\tau$		$0.05 \pm .05$	$0.05 \pm .05$
$e e e e$		0.10 ± 0.10	$0.05 \pm .05$
$e^+e^- \rightarrow \gamma\gamma$	RADCOR	$0.06 \pm .02$	39.1 ± 0.40
$e^+e^- \rightarrow \nu\bar{\nu}\gamma$	NUNUGPV	25.9 ± 0.36	0.04 ± 0.01
Total Background		$.642 \pm 0.22$	$.655 \pm .20$
Total Signal		25.9 ± 0.36	39.1 ± 0.40

Table 4.1: Total expected background events from Monte Carlo analysis at $\sqrt{s} = 161$ GeV compared to total expected number of signal events. Entries in left most column correspond to final state particles produced in processes that may produce a potential background to photonic final state events.

Process	MC Generator	$e^+e^- \rightarrow \nu\bar{\nu}\gamma$	$e^+e^- \rightarrow \gamma\gamma$
$e e(\gamma)$	TEEGG	0.33 ± 0.19	0.21 ± 0.15
$e e$	BHWIDE	$0.03 \pm .03$	0.33 ± 0.10
$\mu\mu$	KORALZ	$0.01 \pm .003$	0.001 ± 0.001
$\tau\tau$	KORALZ	$0.001 \pm .001$	0.001 ± 0.001
$e e \mu\mu$	Vermaseren	$0.05 \pm .05$	$0.05 \pm .05$
$e e \tau\tau$		$0.05 \pm .05$	$0.05 \pm .05$
$e e e e$		0.10 ± 0.10	$0.05 \pm .05$
$e^+e^- \rightarrow \gamma\gamma$	RADCOR	$0.01 \pm .007$	35.5 ± 0.40
$e^+e^- \rightarrow \nu\bar{\nu}\gamma$	NUNUGPV	23.6 ± 0.30	0.003 ± 0.003
Total Background		$.581 \pm 0.23$	$.695 \pm .2$
Total Signal		23.6 ± 0.30	35.5 ± 0.40

Table 4.2: Total expected background events from Monte Carlo analysis at $\sqrt{s} = 172$ GeV compared to total expected number of signal events

Chapter 5

Analysis at $\sqrt{s}=161$ and 172 GeV

With selection criterion and background rejection cuts set and the expected backgrounds reduced to negligible levels, it is possible to move the analysis to higher energies. The high energy data set to be analyzed was collected by OPAL in 1996 when LEP ran at the center of mass energies of 161 GeV and 172 GeV. The total amount of data collected passing the detector status requirements corresponds to $7.90 \pm .03 \pm .04 \text{ pb}^{-1}$ and $8.21 \pm .03 \pm .04 \text{ pb}^{-1}$, where the first error is systematic and the second error is statistical.

The energies of 161 and 172 GeV are the highest center of mass energies achieved to date for e^+e^- collisions. These new energies allow for the exploration of potential new physics beyond energies previously explored. New physics can be seen in either case of photons with or without missing energy. When looking at the missing energy case one looks for new physics in an excess signal in the various photon distributions, in particular the energy spectrum. In the case of photons with no missing energy the signal of new physics is expected to be seen as a modification to the differential cross-section of the Standard Model QED two photon production (see eqn 2.7).

5.1 Results for Photons and Missing Energy

After applying all of the selection cuts described above for data at 161 and 172 GeV, the energy spectrum of the most energetic photon in the event was produced for both energies (Fig 5.1). The data at 161 GeV contained 20 selected events compared to 25.9 expected from the Monte Carlo simulation of the $e^+e^- \rightarrow \nu\bar{\nu}\gamma$ process. Likewise, 21 events were observed at 172 GeV compared to 23.6 events expected from Monte Carlo.

Figure 5.1: Energy spectrum of most energetic photon, comparing data (points) and Monte Carlo (histogram) for 161 and 172 GeV data sets.

The Standard Model cross-section that this data corresponds to, is determined by the equation.

$$\sigma = \frac{N_{\text{obs}}}{\mathcal{L}\epsilon} \quad (5.1)$$

where N_{obs} is the number of events observed, $\mathcal{L}$ corresponds to the integrated luminosity and ϵ is the efficiency of selecting a photon with missing energy event. The selection efficiency is determined by taking the ratio of the number of Monte Carlo events selected using the event selection criterion to the number that is generated within the fiducial volume. Here the fiducial volume is defined as the region where $x_\gamma > 0.07$, $|\cos \theta_\gamma| < 0.9$ and the overlap region is excluded.

Systematic errors due to backgrounds and inefficiency due to noise have also been determined and are displayed in Table 5.1. The noise background corresponds to the random inefficiency mentioned in Table 5.1, it is determined through the use of random

	161 GeV	172 GeV
selection efficiency	$67.6 \pm 1.34\%$	$66.9 \pm 1.18\%$
random inefficiency	3.41%	3.41%
physics backgrounds	2.48%	2.46%
luminosity uncertainty	.56%	.56%

Table 5.1: Selection efficiency, inefficiency due to noise as determined from random beam crossings, the physics backgrounds and the uncertainty in the luminosity.

beam crossing events. The OPAL detector records a random beam crossing event regularly with a frequency of about 4 Hz. The information contained within these events show the activity in any particular subdetector when there are no physics events to be measured. If this activity is high enough it could produce a signal that could be cut by the selection criterion. The random inefficiency is simply the ratio of the number

of random beam crossing events with a signal in a particular subdetector that would fail the selection cuts to the total number of random beam crossing events analyzed. Therefore, the random inefficiency corresponds to the probability a good event would be rejected due to noise. This probability corresponds to a reduction in the overall selection efficiency.

The background errors come from the estimate of total expected background compared to the total expected signal determined from the Monte Carlo studies done previously, see Table 4.1 and 4.2. This error corresponds to the amount of background expected in the selected data. The systematic error for the luminosity is also included as determined by ROCROS as mentioned above. The table shows that uncertainties will be dominated by statistical errors, since there are relatively few events observed.

With 20 events and the given selection efficiency for 161 GeV a total observed production cross-section of 3.78 ± 0.86 pb is found. This can be compared with a Standard Model prediction of 4.79 ± 0.12 pb, based on the Monte Carlo simulation of the $e^+e^- \rightarrow \nu\bar{\nu}\gamma$ process. Similarly for data at 172 GeV, 21 events observed corresponds to 3.86 ± 0.86 pb which compares to a 4.31 ± 0.09 pb Standard Model prediction for radiative neutrino production. There is no direct evidence in either Fig 5.1 or the cross section calculations that would indicate the presence of new physics at 161 or 172 GeV.

These cross sections have been determined assuming the background from cosmics and noise is zero based on the LEP 1 analysis. The number of cosmics is determined by looking at the number of events in the Z-peak data with $E_\gamma > 0.07 \times 161$ (0.07×172). These events correspond to potential cosmic events that would be a background to events with $\sqrt{s} = 161$ GeV ($\sqrt{s} = 172$ GeV) in the LEP 1 data. After determining the number of Monte Carlo events expected with the E_γ cut, a 95% CL can be set on the number of backgrounds due to cosmics. In order to determine the number of potential cosmics at 161 GeV the 95% CL of the number of cosmics is divided by the total livetime of the LEP 1 analysis and multiplied by the livetime of the 161 GeV (172 GeV) giving less than 2.6 cosmics at 95% confidence and less than 1.3 at 172 GeV.

Figure 5.2: Distribution of the missing mass of an event for the center of mass energies 161 and 172 GeV, comparing Monte Carlo to data.

Limits have been set on the production cross section for various mass combinations of $\tilde{\chi}_1^0$ and $\tilde{\chi}_2^0$. These confidence limits on the production cross-section are based on the SUSYGEN Monte Carlo for the supersymmetric process $e^+e^- \rightarrow \tilde{\chi}_1^0 \tilde{\chi}_1^0 \gamma$. These different mass combinations have the effect of adjusting the energy of the photon that is radiated in the decay thus affecting the missing mass of the event. Therefore scanning the spectrum of missing mass (total mass of all invisible particles in an event) in regions defined by the mass combinations one can set an upper limit on the number of events

Figure 5.3: Missing mass distribution for the case when $M_{\chi_2^0} + M_{\chi_1^0} = 150$ and $M_{\chi_2^0} - M_{\chi_1^0} = 15$. The region defined by this mass combination requires events to have a missing mass greater than 135 GeV. Data was generated using the SUSYGEN Monte Carlo for a center of mass energy of 161 GeV.

in the region due to non-Standard Model processes. The missing mass in radiative neutrino events is due to the neutrinos and therefore is expected to peak at the Z mass as seen in Fig 5.2. This is not necessarily the case for non-Standard Model processes in which the missing mass will be determined from the mass of the invisible particles. A scan of the missing mass spectrum from the various supersymmetry Monte Carlos for neutralino decays reveal that the data tends to peak in a particular region, as shown in Fig 5.3. Having determined the number of events in the 161 and 172 GeV data in these particular regions, as well as the expected number of Standard Model background events, an upper limit on the number of events observed can be set, thus allowing an upper limit on the production cross section for a given region to be determined. The 95% confidence limit on the number of events in a particular region was determined

Figure 5.4: Missing mass distribution for the case of the decay of a 140 GeV excited neutrino. The region defined by this mass distribution requires events to have a missing mass less than 85 GeV.

following the method outlined in [27] for Poisson processes with backgrounds.

$$1 - \varepsilon = 1 - \frac{e^{-(B+\mu_{n0})} \sum_{j=0}^n \frac{(B+\mu_{n0})^j}{j!}}{e^{-B} \sum_{j=0}^n \frac{B^j}{j!}} \quad (5.2)$$

where B is the number of Standard Model background events, n is the number of observed events and μ_{n0} is the desired upper limit on the signal in a particular region. The value of μ_{n0} is adjusted until Eqn 5.2 registers a probability of 95%. Once the number of events in a region is determined with the Standard Model background subtracted, the cross section is determined at the 95% confidence limit. The number of events selected in each bin is compared with the number expected from the Standard Model radiative neutrino production in Tables 5.2 and 5.3.

Systematic errors can be included by using the method described in [28]. The

confidence limit on the cross section is then given by

$$\bar{\sigma} = \frac{\mu_{n0}}{S} \left[1 + \frac{(\mu_{n0} + B - n) \mu_{n0} \sigma_r^2}{(\mu_{n0} + B) 2} \right] \quad (5.3)$$

where n is the number of events observed in a missing mass region. μ_{n0} for a given n corresponds to the 95% confidence limit defined by Poisson statistics. B refers to the number of expected background events. S corresponds to $\mathcal{L}\epsilon$ from eqn 5.1 and σ_r is the systematic uncertainty in S . The limits on the production cross-section is shown in Tables 5.4 and 5.5.

Confidence limits may also be set on production of an excited neutrino which decays to a standard neutrino by radiating a photon. Examination of the Monte Carlo [29] for the production of a single excited neutrino shows that missing mass also extends over different regions for different masses of the excited neutrino, as seen in Fig 5.4. Eqn 5.3 gives the 95% confidence upper limit for the production cross-section at both $\sqrt{s}$ of 161 and 172 GeV. The results are shown in Tables 5.6 and 5.7.

$M_{\tilde{\chi}_2^0} + M_{\tilde{\chi}_1^0}$ GeV	$M_{\tilde{\chi}_2^0} - M_{\tilde{\chi}_1^0}$ GeV	Selection Efficiency %	Number Selected	Number Expected
160	5	-	-	-
	15	83.2	0	2.6
	53.3	93.2	7	4.02
	160	91.4	0	0.03
150	5	82.0	1	3.7
	15	82.3	1	6.05
	50	90.5	13	12.92
	150	88.3	0	.61
130	5	70.2	1	3.87
	15	81.6	1	6.12
	43.3	87.4	13	13.25
	130	87.7	12	14.16
110	5	70.8	1	4.16
	15	73.3	3	8.14
	36.7	86.9	19	23.01
	110	88.1	19	18.23
90	5	67.7	1	5.29
	15	70.0	3	8.0
	30	74.7	19	23.01
	90	83.8	19	21.09

Table 5.2: Table showing selection efficiency for the various SUSYGEN neutralino mass combinations, the number of events observed and the number of events expected from the Standard Model background in each missing mass region for the given mass combination at $\sqrt{s}=161$. There were no Monte Carlo events generated within the fiducial volume for the first entry so the selection efficiency is essentially zero.

$M_{\tilde{\chi}_2^0} + M_{\tilde{\chi}_1^0}$ GeV	$M_{\tilde{\chi}_2^0} - M_{\tilde{\chi}_1^0}$ GeV	Selection Efficiency %	Number Selected	Number Expected
170	5	-	-	-
	15	83.2	2	1.97
	56.7	90.5	1	2.13
	160	N/A	-	-
160	5	75.8	2	2.35
	15	80.8	5	4.53
	53.3	88.7	4	5.57
	160	88.5	0	0.59
150	5	74.0	2	2.35
	15	79.0	5	5.07
	50	84.8	5	6.21
	150	88.1	9	13.16
130	5	71.3	3	3.54
	15	78.2	7	5.54
	43.3	86.3	10	13.46
	130	89.5	10	15.73
110	5	65.4	4	4.33
	15	73.4	7	6.04
	36.7	83.9	11	14.64
	110	86.9	13	18.20
90	5	65.3	4	4.33
	15	68.6	8	7.03
	30	77.3	18	22.68
	90	84.0	13	18.74

Table 5.3: Table showing selection efficiency for the various SUSYGEN neutralino mass combinations for 172 GeV. The Monte Carlo with the sum of the masses 170 GeV and the difference 160 GeV was unavailable so the selection efficiency could not be determined.

	$M_{\chi_2^0} + M_{\chi_1^0}$				
$M_{\chi_2^0} - M_{\chi_1^0}$	160	150	130	110	90
5	-	0.57	0.66	0.65	0.67
15	0.47	0.54	0.55	0.75	0.79
53.3	1.81	-	-	-	-
50	-	1.59	-	-	-
43.3	-	-	1.60	-	-
36.7	-	-	-	1.46	-
30	-	-	-	-	1.69
160	0.43	-	-	-	-
150	-	0.45	-	-	-
130	-	-	1.31	-	-
110	-	-	-	2.02	-
90	-	-	-	-	2.12

Table 5.4: 95 % CL on the cross section for $e^+e^- \rightarrow \chi_1^0 \chi_1^0 \gamma$ production at 161 GeV in pb.

	$M_{\chi_2^0} + M_{\chi_1^0}$					
$M_{\chi_2^0} - M_{\chi_1^0}$	170	160	150	130	110	90
5	-	0.86	0.89	1.04	1.31	1.31
15	0.81	1.28	1.22	1.71	1.70	1.91
56.7	0.55	-	-	-	-	-
53.3	-	0.85	-	-	-	-
50	-	-	0.99	-	-	-
43.3	-	-	-	1.11	-	-
36.7	-	-	-	-	1.18	-
30	-	-	-	-	-	1.53
170	-	-	-	-	-	-
160	-	0.45	-	-	-	-
150	-	-	0.99	-	-	-
130	-	-	-	0.94	-	-
110	-	-	-	-	1.12	-
90	-	-	-	-	-	1.13

Table 5.5: 95 % CL on the cross section for $e^+e^- \rightarrow \chi_1^0 \chi_1^0 \gamma$ production at 172 GeV in pb.

	M_{ν^*} GeV	Selection Efficiency %	Number Observed	Number Expected	Cross Section pb
ν_e^*	80	87.8	19	21.1	1.79
	100	93.0	19	19.6	2.00
	120	90.6	14	17.0	1.42
	140	89.3	6	7.3	1.14
	155	90.0	0	0.2	0.48
ν_μ^*	80	82.2	19	21.1	1.89
	100	88.4	19	19.6	2.00
	120	90.9	14	17.0	1.41
	140	90.8	11	7.3	1.41
	155	89.7	0	0.6	0.49

Table 5.6: Table showing selection and 95% confidence upper limit on production cross section of an excited neutrino of various masses for $\sqrt{s}=161$ GeV.

	M_{ν^*} GeV	Selection Efficiency %	Number Observed	Number Expected	Cross Section pb
ν_e^*	80	86.5	17	21.3	1.36
	110	89.2	14	18.2	1.20
	140	90.1	11	15.7	1.03
	170	92.0	0	0.6	0.43
ν_μ^*	80	82.9	17	21.3	1.42
	110	89.4	14	18.2	1.20
	140	89.9	11	15.7	1.03
	170	91.1	0	0.6	0.43

Table 5.7: Table showing selection and 95% confidence upper limit on production cross section of an excited neutrino of various masses for $\sqrt{s}=172$ GeV.

5.2 Results for Photons and no Missing Energy

Results from the analysis of the 161 and 172 GeV data sets for photons with no missing energy can be seen in Fig 5.5, which shows the distribution of the photon scattering angle comparing Monte Carlo to data. Results are consistent with that expected from the Standard Model, with 46 events observed at 161 and 32 events observed at 172 GeV. This compares to a Standard Model prediction of 39.1 and 35.5 events respectively. The ratio of the number of selected events to the number of expected

Figure 5.5: Distribution of the photon scattering angle comparing data (points) to Monte Carlo (histogram) for QED two photon production at $\sqrt{s}$ of 161 and 172 GeV. Distributions were divided into 6 bins to perform a binned likelihood fit.

events at 161 GeV is 1.17 ± 0.17 . Similarly, this ratio at 172 GeV is determined to be 0.90 ± 0.15 . Both are consistent with the Standard Model expectations.

The events in Fig 5.5 are divided into six bins as in Table 5.8. The efficiency for selecting events in each of the bins was determining by comparing the number of Monte Carlo events in each bin and dividing it by the number calculated from the QED cross section over the angular size of the bin using Eqn 2.6. Table 5.8 shows the angular dependence of the selection efficiency.

Bin Width ($\cos \theta$)	Selection Efficiency for 161 GeV	Selection Efficiency for 172 GeV
(0..3)	$53.9 \pm 1.6\%$	$53.5 \pm 1.8\%$
(.3..5)	$50.8 \pm 1.7\%$	$50.8 \pm 1.8\%$
(.5..6)	$48.1 \pm 2.0\%$	$48.5 \pm 2.2\%$
(.6..73)	$53.0 \pm 1.6\%$	$49.6 \pm 1.6\%$
(.82..9)	$44.7 \pm 1.1\%$	$47.3 \pm 1.2\%$
(.9..97)	$13.0 \pm 0.36\%$	$12.7 \pm 0.39\%$

Table 5.8: Selection efficiencies per $\cos \theta$ bin. The gap in the binning is due to the exclusion of the overlap region. Bins were chosen to ensure that they contain at least three events.

In order to put limits on new physics, a fit is performed using a binned likelihood function for Poisson statistics.

$$\mathcal{L} = \prod_{i=1}^m \frac{\mu_i^{n_i} e^{-\mu_i}}{n_i!} \quad (5.1)$$

where m is the number of bins, n_i is the number of events in a given bin and μ_i is the number of events expected per bin with the influence of new physics, due to the influence of the t-channel exchange of an excited electron on QED two photon production. The data in Fig 5.5 were arranged into six bins such that there was at least three events per bin. The expected number of events per bin for a given value of the mass scale characterizing the effect of the excited electron, $\Lambda_{\pm}$, was determined by

using the number of Monte Carlo events per bin,

$$\mu_i = \frac{\mathcal{L}}{\mathcal{L}_{MC}} N_i^{MC} \frac{\beta_i(\lambda)}{\beta_i(0)} \quad (5.2)$$

with

$$\beta(\lambda) = \frac{\alpha^2}{s} \int_{x_l}^{x_h} \left(\frac{1 + \cos^2 \theta}{1 - \cos^2 \theta} \right) \left(1 \pm \frac{s^2 \lambda}{2} (1 - \cos^2 \theta) \right) d(\cos \theta) \quad (5.3)$$

where $\beta(\lambda)$ is the integral over each bin width, $(x_h - x_l)$, of the differential cross section. $\lambda = 1/\Lambda_{\pm}^4$ and $\mathcal{L}$ and $\mathcal{L}_{MC}$ are the integrated luminosities of the data set and the Monte Carlo respectively. The ratio of β 's in Eqn 5.2 will determine the amount that N_i^{MC} will increase or decrease due to λ . The advantage of using the Monte Carlo data to determine the expected number of events per bin is that the angular dependence of efficiency is implicitly included in the calculations.

The negative log of the likelihood function, Eqn 5.1, can be minimized so as to determine the parameter λ . Once the value of λ is determined a 95% confidence lower limit is set. It should be noted that in all cases the value of λ is free to become negative in the fit; however, this is an unphysical region. The unphysical regions were excluded from the 95% confidence level determination by using the Bayesian approach outlined in [27], in which the probability distribution is normalized to include only values of λ that are in the physically allowed region ($\lambda > 0$). Results showing minimums and 95% confidence limits are shown in Table 5.9. The likelihood distributions over the physically allowed region is shown in Fig 5.6 for each Λ value along with the 95% confidence region. The measured differential cross section is compared with the theoretical differential cross sections for the cases in which $\Lambda_{\pm}$ is taken at its 95% CL lower bound as well as the Standard Model ($\Lambda_{\pm} = \infty$) differential cross section in Figs 5.7 and 5.8. The cross section was determined using Eqn 5.1 for each of the six $\cos \theta$ bins.

A comparison between the limits in Table 5.9 and limits set by other experiments at LEP 1.5 and LEP 2 is shown in Table 5.10.

 Figure 5.6: Likelihood distributions for the determination of 95% CL on Λ_+ and Λ_- .

Data Set	Minimum Value (GeV^{-1})		95% CL Lower Bound (GeV)	
	λ_+^{min}	λ_-^{min}	Λ_+	Λ_-
161 GeV	6.99×10^{-10}	-6.99×10^{-10}	141.7	178.4
172 GeV	-7.20×10^{-11}	7.20×10^{-11}	163.5	176.9
161 + 172 GeV	2.2×10^{-10}	-2.2×10^{-10}	166.9	192.8

Table 5.9: Minima and 95% Confidence Limits on $\Lambda_{\pm}$.

Experiment	$\sqrt{s}$ GeV	Λ_+ GeV	Λ_- GeV
ALEPH [30]	130-136	169	132
OPAL [31]	130-136	152	142
L3 [32]	130-136	131	167
L3 [33]	161-172	207	205
This Analysis	161-172	166.9	192.8

Table 5.10: Comparison to previous 95% confidence lower limits on mass scale characterizing the effect of the excited electron. $\Lambda_{\pm}$.

Figure 5.7: Comparison of differential cross sections for the 95% confidence level lower limit on $\Lambda_{\pm}$ for 161 GeV

Figure 5.8: Comparison of differential cross sections for the 95% confidence level lower limit on $\Lambda_{\pm}$ for 161 and 172 GeV data sets.

Chapter 6

Conclusions

The processes in which e^+e^- annihilation events with a purely photonic final state are produced, with and without missing energy, have been thoroughly examined using the OPAL detector at LEP. The data was collected with center of mass energies of 161 and 172 GeV and total integrated luminosities of 7.90 and 8.21 pb^{-1} respectively during the initial phase of the LEP 2 run.

The collected data samples were kept relatively clean from all sources of background, both physics and non-physics related. Cuts and selection criterion have been chosen to minimize noise from detectors and still maintain good background rejection. Backgrounds from cosmic rays and beam related backgrounds were studied by analyzing a data set, namely the data collected over the later half of the LEP 1 run on the Z-peak, in which the backgrounds were well understood. Additional cuts were required to remove various machine backgrounds, however, no significant increase in backgrounds due to cosmic rays was observed. Total expected background from all sources contributed on the order of a few percent to the overall errors. The overall error therefore is dominated by statistical errors.

A scan of the energy spectrum of photons produced with missing energy shows a peak in the data at about 55 GeV for 161 GeV data and about 65 GeV for 172 GeV. These

peaks are consistent with that which is expected from the Standard Model radiative neutrino production. No other significant peak is seen in the energy spectrum that would directly indicate new physics.

Selection efficiency for $e^+e^- \rightarrow \nu\bar{\nu}\gamma$ events was found to be 67.6% at 161 GeV and 66.9% at 172 GeV. With the determination of the selection efficiency a total production cross section of 3.78 ± 0.86 pb was found for $\sqrt{s} = 161$ GeV which compares to a Standard Model prediction of 4.79 ± 0.12 pb. The cross section for events with $\sqrt{s} = 172$ GeV was found to be 3.86 ± 0.86 pb which is consistent with the Standard Model prediction of 4.31 ± 0.09 pb. for the given fiducial acceptance.

The differential cross section for the data with two coplanar photons with no missing energy shows no clear departure from that predicted for QED two photon production, $e^+e^- \rightarrow \gamma\gamma$. The ratio of the number of observed events to the number expected of 1.17 ± 0.17 and 0.90 ± 0.15 at 161 and 172 GeV respectively, is consistent with the Standard Model expectation.

A comparison of the data to that expected from the Standard Model showed no inconsistencies, so no direct evidence for physics beyond the Standard Model was observed. With no direct evidence observed, 95% confidence levels for production cross section and mass scale have been set. Production cross section limits have been set for a variety of mass combinations of neutralinos as defined by SUSYGEN, as well as, for various masses for excited neutrinos.

A lower bound has been put on the size of the mass scale, $\Lambda_{\pm}$, allowed in a compositeness contribution to the QED two photon production differential cross section. Using the combined data sets for coplanar photons with no missing energy of 161 and 172 GeV the lower bound on Λ_+ at 95% confidence is 166.9 GeV. The lower bound on Λ_- at 95% confidence is 192.8 GeV. These limits compare well with or exceed previously published limits with a center of mass of 130 - 136 GeV, although not as good as L3 at higher energy

The future holds great promise for the discovery of new physics. The continued

upgrade of the LEP accelerator will continue to increase the center of mass energy of the electron-positron collisions to higher bounds, allowing us to look for particles with rest mass higher than current accelerators can attain. The LEP upgrade will also come with a significant increase in luminosity allowing much more data to be taken so that processes with small cross sections (which are below current sensitivities) can be more easily observed. Following the LEP runs, the first of the next generation of colliders, the LHC, will come online, colliding protons on protons at the highest center of mass energies achieved by any particle collider.

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IMAGE EVALUATION TEST TARGET (QA-3)

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