A study of isolated photons in Z0 hadronic decays using the DELPHI detector at LEP

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A study of isolated photons in $Z^0$ hadronic decays
using the DELPHI detector at LEP

by

Randall R. Holmes

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CHAPTER 1. PHYSICS INTEREST

Introduction

One of the primary purposes of the first phase of the Large Electron Positron (LEP) collider physics program is to test the neutral current sector of the Standard Model (SM) [1] by studying the properties and decay channels of the $Z^0$ boson. In this work we present an analysis of isolated energetic photons in decays of the $Z^0$ to a $q\bar{q}$ system or $Z^0$ decays having a $q\bar{q}\gamma$ event topology. The SM predicts numerous sources from which such decays can arise. We consider in detail the production mechanism where a photon is radiated directly from a primary final state quark, which we refer to as final state radiation (FSR) [2].

Also of interest at LEP are the search for the Higgs boson [3] (predicted by the SM to impart mass to the known particles) and searches for new particles not predicted by the SM. Evidence for these particles can arise directly by the observation of a new decay channel, or indirectly by measuring deviations in the expected properties of the $Z^0$ (hence the motivation for precision studies of the $Z^0$). Both the Higgs boson, $H^0$, and a number of hypothesized new particles have decay modes that give rise to a $q\bar{q}\gamma$ event topology. This analysis considers the possibility that discrepancies between the data and the predictions of SM processes for $Z^0 \rightarrow q\bar{q}\gamma$ event topologies might arise from these undiscovered particles.

In the following chapter we discuss the major contributions to isolated photon production at LEP as predicted by the SM. Also given is a theoretical overview of the new processes that are considered in this study.

Chapter 2 gives an overview of the LEP machine and the Detector with Lepton, Photon and Hadron Identification (DELPHI) used to record the data for this study. An overview of the major components of the DELPHI system are presented, followed
The gauge fields for the SU(2) x U(1) portion of the SM are also initially massless and are denoted as $W_\mu^i, i = 1, 2, 3$ for SU(2) and $B_\mu$ for U(1). The strengths of the gauge coupling constants are $g_2$ and $g_1$ for SU(2) and U(1) respectively. The particles are given mass by introducing into the theory a complex iso-doublet of scalar fields. By choosing a vacuum expectation value for the scalar fields, the original SU(2) x U(1) gauge invariance symmetries are broken. The effect of breaking the symmetry is a mixing of the gauge fields to produce three massive gauge bosons ($W^+, W^-, Z^0$) and one massless gauge boson (the photon, $A$) as observed in nature. The observed bosons are expressed in terms of the original fields by

\[
\begin{align*}
A_\mu &= B_\mu \cdot \cos \theta_W + W_\mu^3 \cdot \sin \theta_W \\
Z_\mu &= -B_\mu \cdot \sin \theta_W + W_\mu^3 \cdot \cos \theta_W \\
W_\mu^\pm &= \frac{(W_\mu^1 \mp i \cdot W_\mu^2)}{\sqrt{2}}
\end{align*}
\]  

(1.1)

where $\tan \theta_W = g_1/g_2$ is a measure of the mixing in the neutral sector of the theory. In addition, the couplings $g_1$ and $g_2$ can be related to the ordinary electromagnetic interaction coupling (in natural units) through the mixing angle,

\[
\begin{align*}
g_1 &= \frac{e}{\cos \theta_W} \\
g_2 &= \frac{e}{\sin \theta_W}
\end{align*}
\]  

(1.2)

The mechanism which gives mass to the gauge bosons also gives rise to an additional massive scalar particle, the Higgs boson, $H^0$. Experimental observation of the $H^0$ would confirm the mass generation mechanism. In Chapter 4 we set limits on $H^0$ production.

Because the first phase of the LEP program is a study of the production and properties of the $Z^0$, we now focus on the part of the Lagrangian that contains the $Z^0$ couplings to fermions,

\[
L_f = -\frac{g_2}{4 \cdot \cos \theta_W} \sum_{f = \text{fermions}} f \gamma^\mu (\bar{\nu}_f - a_f \gamma_5) f Z_\mu
\]  

(1.3)

where $\gamma^\mu, \gamma_5$ are the Dirac matrices which appear in the description of spin-1/2 particles. The sum is over all fermions, $f$, in the theory which includes the leptons and their associated neutrinos ($e, \nu_e, \mu, \nu_\mu, \tau, \nu_\tau$) and the six quark flavors ($u, d, c, s, t, b$).
Final State Radiation in Hadronic Events

Photon production in the decay of the $Z^0$ to hadrons can arise from a number of known sources in the SM. A list of potential photon sources include:

1. prompt photon radiation from primary quarks that are directly coupled to the $Z^0$, or FSR.

2. photons that radiate off the incoming $e^\pm$, referred to as initial state radiation (ISR).

3. secondary quark radiation (SQR). This is different from FSR since the radiating quark is first produced from gluon pair production, where the gluon is radiated from the primary quark.

4. hadrons which electromagnetically decay, thus producing photons. This phenomenon is dominated by $\pi^0$ decay to two photons. This process will be referred to as a QCD source of photons since hadrons arise from partons through QCD processes.

5. bremsstrahlung from charged hadrons in the final state.

6. $Z^0$ decays to $\tau^+\tau^−\gamma$ and where at least one of the taus decays to three hadrons.

Diagrams representing the above contributions are shown in Figure 1.1.

For the first part of this analysis we are interested in separating isolated photons due to FSR from the rest of the sources. This process is represented by the diagram 1 in Figure 1.1 where the photon originates from a primary quark. The matrix element for final state bremsstrahlung radiation of photons off quarks is given in first order QED (Born approximation) by [6, 7]

\[
\frac{d\sigma}{dx_\gamma \cdot dx_q} = \frac{d\sigma}{dx_\gamma \cdot dx_Q} \propto \frac{x_q^2 + x_\gamma^2}{(1 - x_q) \cdot (1 - x_\gamma)} \cdot \sum_f e_f^2 \cdot c_f
\]

where $x_i = 2 \cdot E_i / E_{cm}$ represents the energy of the three final state partons ($i = \gamma, q, Q$) as a fraction of the center of mass energy with the normalization $x_\gamma + x_q + x_Q = 2$. The sum is over all quark flavors where $e_f$ is the charge of quark flavor...
Figure 1.1: Known contributions to events with a $q\bar{q}\gamma$ topology.
\( f \), and \( c_f \) is the weak coupling of the quark to the \( Z^0 \). Equation 1.8 indicates that divergencies can arise if one or both of the quark energies approaches 1. Since this is a three-body final state, if either \( x_q \rightarrow 1 \) or \( x_{\bar{q}} \rightarrow 1 \) then the photon must be collinear with the other antiquark or quark to conserve energy and momentum. If both \( x_q \rightarrow 1 \) and \( x_{\bar{q}} \rightarrow 1 \) then \( x_{\gamma} \rightarrow 0 \) and the photon is soft. Divergencies of this nature can be avoided by requiring the photon to have an energy larger than some minimum energy and to have a large angle of emission with respect to the quark. Therefore this study uses only isolated energetic photons.

By including the lowest order QED radiative corrections in the width of the \( Z^0 \), the partial width for FSR is given by [8]

\[
\Gamma_{q\bar{q}\gamma} = N_C \cdot \frac{G_F M_Z^2}{24\pi\sqrt{2}} \cdot \frac{3\alpha}{4\pi} \left( \sum_{f=1}^{N_q=5} e_f^2 \cdot c_f \right)
\]  

(1.9)

where the summation is over the quark flavors. In this expression \( N_C \) is the number of quark colors, \( G_F \) is the Fermi constant, and \( \alpha \) is the value of the fine structure constant at \( \sqrt{s} = 91 \) GeV \( (\alpha = 1/128) \). The dependence of \( \Gamma_{q\bar{q}\gamma} \) on the square of the quark charge gives a different mixture of quark types for a sample of FSR hadronic events than for the entire hadronic event sample where there is no dependence on the charge of the quarks (see 1.6). This contrast in dependence of \( \Gamma_{q\bar{q}\gamma} \) and \( \Gamma_{\text{had}} \) on the quark charge, \( e_f \), can be used to determine the weak couplings of the up-type and down-type quarks [7, 9, 10].

The effects of QCD alter the above formula and hence the production of photons. At low emission angles of the photon, corresponding to low \( M_{q\gamma}^2 \), it is possible for gluons to radiate from the quark prior to photon radiation. This introduces higher order QCD corrections in an \( M_{q\gamma}^2 \) region where it is not clear that perturbative QCD can be applied [6]. This provides additional motivation for restricting this study to isolated energetic photons where one expects only the lowest order QED and QCD corrections to be important.

A potentially large source of background photons to FSR is initial state bremsstrahlung radiation (ISR) as shown in diagram 2 of Figure 1.1. This contribution has been well studied from a theoretical point of view and has been calculated to order \( \alpha^3 \) for QED and weak virtual corrections [11]. The cross section to emit a photon
with fractional energy \( x_\gamma = E_\gamma / E_{\text{beam}} \) at center of mass energy \( \sqrt{s} \) is

\[
\frac{d\sigma}{dx_\gamma} = \sigma_0(s') \cdot \frac{\alpha}{\pi} \cdot \frac{1 + x_\gamma^2}{x_\gamma^2} \cdot \left( \ln \left[ \frac{s}{m_E^2} \right] - 1 \right)
\]  

(1.10)

where \( \sigma_0(s') \) is the Born cross section, evaluated at the reduced \( e^+e^- \) center of mass, \( \sqrt{s'} \), after radiating a photon. The energy spectrum of the ISR photons is dominated by soft photons. The radiated photons are also produced predominantly in the forward direction of the \( e^\pm \) beam. The cross section is actually divergent for very soft photons \( (x_\gamma \to 0) \) or collinear photons \( (\theta_{e\gamma} \to 0) \). Hence the contribution of ISR photons can be reduced to a negligible level by using only ‘energetic’ photons ‘far’ away from the beam axis. The terms ‘energetic’ and ‘far’ will be given substance in Chapter 3.

The interference term between FSR and ISR is complicated but can be important. At low energies the interference term is responsible for charge asymmetries [2]. However, at the peak of the \( Z^0 \) resonance the interference term is expected to be small [6, 7], about 0.5% of the total \( q\bar{q}\gamma \) cross section, and is negligible.

Secondary quark radiation (SQR) (see diagram 3 in Figure 1.1) is another possible source of photons. However, since SQR occurs at least two steps down in the cascade process the photon energy spectrum is quite soft compared to FSR. In addition this process is suppressed because the branching of the gluon is dominated by \( g \to gg \) as opposed to \( g \to q\bar{q} \). Therefore, SQR is a negligible (< 1%) contribution to energetic isolated photon production compared to FSR.

One of the most serious backgrounds to FSR comes from hadronic production of \( \pi^0 \) as illustrated by diagram 4 in Figure 1.1. At high energies the two photons from the \( \pi^0 \) decay cannot easily be separated experimentally, and hence fake a single photon. While neutral pions are commonly produced in \( Z^0 \) events, the \( \pi^0 \) energy spectrum decreases rapidly with increasing energy. More important the \( \pi^0 \) have a limited transverse momentum with respect to the jet axis, and hence are found primarily in the jet of particles produced from the hadronization of the quarks. Therefore, requiring the photon to have a large angle of emission with respect to the jet, or to be isolated from other particles, should reduce this background process considerably. Large angle pions can also be produced by gluon bremsstrahlung events. Again,
requiring the photon to be isolated from other particles can make this background manageable.

Another possible source of photons is bremsstrahlung radiation from charged hadrons, represented by diagram 5 in Figure 1.1. The probability of bremsstrahlung from charged particles is inversely proportional to square of the particle mass. Hence, this process is suppressed due to the relatively high mass of the hadrons. In addition these photons are found primarily in the direction of the charged particle and are not isolated. It is a negligible effect in this study.

Decays of the $Z^0 \rightarrow \tau^+ \tau^- \gamma$ can also fake a $q\bar{q}\gamma$ topology when one of the $\tau^\pm$ decays to three charged particles and begins to look like a hadronic event (see diagram 6 in Figure 1.1). Reliable $e^+e^- \rightarrow \tau^+\tau^-$ event generators exist to study the magnitude of this contribution to the $q\bar{q}\gamma$ event topologies expected in the data.

The $H^0$ Boson with $M_H < M_Z$

In the previous subsection we outlined the known, or observed SM processes that can contribute to a $q\bar{q}\gamma$ final state. However, the SM also allows the $q\bar{q}\gamma$ final state to occur through the rare decay of the $Z^0$ to a photon and a SM Higgs boson, $H^0$, where the $H^0$ decays into a $q\bar{q}$ pair [12, 13, 14],

$$e^+e^- \rightarrow Z^0 \rightarrow \gamma H^0 \downarrow H^0 \rightarrow q \bar{q}. \quad (1.11)$$

This decay is forbidden at lowest order, but can occur through the higher order processes shown in Figure 1.2. The relative decay rate for this process is given by [15]

$$\frac{\Gamma(Z^0 \rightarrow H^0 \gamma)}{\Gamma(Z^0 \rightarrow \mu^+\mu^-)} = \frac{\alpha^2}{8\cdot\pi^2\cdot\sin^2\theta_W} \left(1 - \frac{M_H^2}{M_Z^2}\right)^3 \frac{|A_f + A_W|^2}{1 + (1 - 4\cdot\sin^2\theta_W)^2} \quad (1.12)$$

where $A_f$ and $A_W$ are the contributions from the fermion and $W$ boson loops respectively. The contribution to the decay width from the fermion loop is small and goes to zero in the limit of massless fermions. The top quark mass, $m_t$, enters into the width through the fermion loop, but has an effect of less than 5% when $m_t$ is
Figure 1.2: The Feynman diagrams for the $e^+e^- \rightarrow Z^0 \rightarrow H^0 \gamma$ process. Only higher order diagrams contribute to this process, and include (a) fermion loops and (b) $W$ boson loops. The dominant contribution to the decay width comes from the $W$ boson loops.
varied between 60 and 200 GeV. The fermion loops give a constant contribution in the limit of infinitely massive fermions and is expressed as

\[ m_f \lim_{m_f \to \infty} A_f = \sum_f 2 \cdot N_c \cdot Q_f \cdot (T_f^3 - 2 \cdot Q_f \cdot \sin^2 \theta_W) \]

where \( N_c, Q_f, \) and \( T_f^3 \) are the number of colors, electric charge, and third component of weak isospin respectively for each fermion (\( f \)). The limiting value for a charged lepton is 0.03, and for up (down) type quarks is 0.29 (0.26).

The dominant contribution to the decay width comes from the \( W \) boson loops. An approximate formula for \( A_W \) is

\[ A_W = -(4.55 + 0.31 \cdot (M_H^2 / M_Z^2)) \]

and is the primary contribution for even small \( H^0 \) masses. Neglecting the fermion loop contributions, a good approximation of equation 1.12 is

\[ \frac{\Gamma(Z^0 \to H^0 \gamma)}{\Gamma(Z^0 \to \mu^+ \mu^-)} \approx 6.94 \times 10^{-5} \cdot \left(1 - \frac{M_H^2}{M_Z^2}\right)^3 \left(1 + 0.07 \cdot \frac{M_H^2}{M_Z^2}\right)^2 \]

where \( \alpha = 1/128 \) and \( \sin^2 \theta_W = 0.229 \). The corresponding cross section for the process \( e^+ e^- \to Z^0 \to H^0 \gamma \) is displayed in Figure 1.3. The coupling of the Standard Model \( H^0 \) to fermion pairs is a function of \( m_f^2 \), so that the branching ratio of the \( H^0 \) to quarks is over 90%.

In Chapter 4 we place limits on the production rate of \( e^+ e^- \to Z^0 \to H^0 \gamma \) where the \( H^0 \) decays to two quarks.

Non-Standard Model Physics Processes

In the previous section we have discussed how the \( q\bar{q}\gamma \) final state arises in the Standard Model. However, processes beyond the SM can also contribute to this final state. In the following we discuss two such processes; (a) a composite, or radiatively excited, quark state and (b) a composite, non-point like \( Z^0 \) boson.
Excited Quark

An extension of the Standard Model (SM) that has been of interest is the possibility that elementary fermions are composite particles consisting of more fundamental constituents. A typical consequence of compositeness in the fermion sector is the existence of excited states of the observed fermions [16, 17]. The simplest extension of compositeness is to assume that the excited fermions are similar to the ordinary fermions. In particular an excited quark, q*, is a triplet of color and a weak isospin doublet of SU(2) × U(1). Thus, the coupling of excited quarks to the gauge bosons is of the same form as found in the SM.

The possible decay processes of the Z^0 to excited quarks are \( e^+e^- \rightarrow Z^0 \rightarrow q \, q^* \) and \( e^+e^- \rightarrow Z^0 \rightarrow q^* \, q^* \). For this study, only the former decay will be considered. The \( q\bar{q}\gamma \) topology is formed by the decay sequence

\[
\begin{align*}
  e^+e^- & \rightarrow Z^0 \rightarrow q \, q^* \\
  q^* & \rightarrow q \, \gamma.
\end{align*}
\]

(1.16)

The excited quark should be produced at LEP energies if \( m_{q^*} < M_Z - m_q \). Of particular interest for a \( q\bar{q}\gamma \) topology search is the mass range where \( m_{q^*} > E_{\text{beam}} \) since direct \( Z^0 \rightarrow q^* \, q^* \) production is excluded in this kinematic range. (If \( m_{q^*} \) were below half the collision energy direct \( q^* \, q^* \) production would increase the \( Z^0 \) width, \( \Gamma_Z \), and would have been clearly observed in the hadronic width of the 1990 LEP data.)

In Chapter 4 we place limits on the production rate of \( e^+e^- \rightarrow Z^0 \rightarrow q \, q^* \) where the \( q^* \) radiates a photon.

Composite Z^0 Boson

The idea of compositeness can also be extended to the boson sector [17] of the SM. In particular the \( Z^0 \) may not be a fundamental particle but instead may consist of more elementary particles. If the \( Z^0 \) were a composite particle made up of charged constituents, it could decay directly into a photon and hadrons. New interactions that can account for this decay include;
1. $Z^0$ decay into a photon and an off-mass-shell $Z^0$, referred to here as a $Z^*$, which would produce a broad spectrum of photon energies,

2. anomalous three- and four-boson couplings [17, 18] which would also produce a broad spectrum of photon energies,

3. $Z^0$ decay into a photon and a scalar partner, $S$, which would result in a monochromatic photon energy if the width of the $S$ is not too large [19].

In Chapter 4 we place limits on the production rate of a composite $Z^0$ for each of the above cases.
The luminosity is expressed in units of $\text{cm}^{-2}\text{s}^{-1}$ and is given by the formula:

$$L = \frac{N^2 k f}{4\pi\sigma_x\sigma_y}$$

(2.1)

where $N$ is the number of electrons or positrons in a bunch, $k$ is the number of bunches in each beam, $f$ is the frequency of revolution, and $\sigma_x$ and $\sigma_y$ are the horizontal and vertical r.m.s beam radii at the collision point. As implied, a 'beam' of electrons is actually one or more bunches of electrons, each bunch being several centimeters long and a few millimeters in diameter. LEP currently runs with 4 bunches and during 1990 maintained a typical operating luminosity of about $3 \times 10^{30} \text{cm}^{-2}\text{s}^{-1}$. This is below the design luminosity of $1.7 \times 10^{31} \text{cm}^{-2}\text{s}^{-1}$, so that the $Z^0$ production rate can be expected to increase in the near future. Indeed, part of the LEP physics program includes the possibility of running at high luminosity within the next few years of operation. Design values for other LEP parameters of interest are shown in Table 2.1 [23].

The LEP tunnel has a circumference of 26.7 km and lies at a depth which varies from 50 to 175 m below-ground. The main LEP tunnel is actually in the shape of an octagon with rounded corners and eight straight sections. At the center of each straight section is a possible collision point for the $e^+e^-$ beams. Four of the collision points include large experimental halls that house the detectors used to record interaction products of the $e^+e^-$ collisions. Figure 2.1 shows a schematic of the LEP tunnel and the location of the four LEP detectors, ALEPH, DELPHI, L3 and OPAL [24].

The LEP collider is a complex of accelerators which culminates with collisions in the LEP tunnel. The injection of electrons and positrons into the LEP ring takes advantage of two existing facilities at CERN, the 450 GeV Super Proton Synchrotron (SPS) and its injector the 28 GeV Proton Synchrotron (PS). Both are used used in the fixed target $p$ beam program and the $pp$ program. These facilities were modified for LEP operation by the addition of the LEP Pre-Injector (LPI), which consists of two LEP Injector Linacs (LIL), and an Electron/Positron Accumulation Ring (EPA). Two transfer lines were also installed between the SPS and LEP. Figure 2.2 shows an overview of the machines used to accumulate and accelerate $e^+$ and $e^-$ bunches [21].
Figure 2.2: The LEP injection system for accumulation of electron and positron bunches. The electrons and positrons are accelerated to a nominal energy of 20 GeV before injection into the LEP accelerator.
Table 2.1: Design parameters for the Large Electron Positron (LEP) collider at CERN laboratory.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum beam energy</td>
<td>60 GeV</td>
</tr>
<tr>
<td>Injection energy</td>
<td>20 GeV</td>
</tr>
<tr>
<td>Luminosity</td>
<td>$1.7 \times 10^{31} \text{ cm}^{-2} \text{s}^{-1}$</td>
</tr>
<tr>
<td>Circumference</td>
<td>26.66 Km</td>
</tr>
<tr>
<td>Interaction regions</td>
<td>4</td>
</tr>
<tr>
<td>Particles per bunch</td>
<td>$4.16 \times 10^{10}$</td>
</tr>
<tr>
<td>Bunches per ring</td>
<td>4</td>
</tr>
<tr>
<td>Average beam current</td>
<td>3 mA</td>
</tr>
<tr>
<td>Filling time</td>
<td>0.25 mA/min</td>
</tr>
<tr>
<td>Acceleration period</td>
<td>80 s</td>
</tr>
<tr>
<td>Bunch length</td>
<td>1.2 cm</td>
</tr>
<tr>
<td>Beam radius</td>
<td>Horizontal: 300 $\mu$m</td>
</tr>
<tr>
<td></td>
<td>Vertical: 12 $\mu$m</td>
</tr>
<tr>
<td>Maximum magnetic field</td>
<td>0.135 T</td>
</tr>
</tbody>
</table>

Production of electrons and positrons starts at the LIL. Since positrons are the anti-matter of electrons and not found readily in nature, they are the more difficult to produce. Positron production starts by first producing electrons with an $e^-$ gun and accelerating them through the 200 MeV Linac. The electrons then strike a tungsten target, creating positrons which are separated from other particles by magnetic fields. The positrons are then accelerated through the 600 MeV Linac and 'stored' in the EPA. The EPA accumulates positrons in 8 bunches by collecting many bursts of positrons from the 600 MeV Linac. The positrons are then transferred to the PS (in 4 or 8 bunches) where they are accelerated to 3.5 GeV. From the PS the positrons go to the SPS for acceleration up to an energy of 20 GeV. Finally the positrons are injected into the four bunches of LEP. The electrons for LEP are produced in the same fashion, except that the tungsten target is not needed, the $e^-$ gun supplies the electrons directly. The entire cycle of injecting 4 positron bunches followed by 4 electron bunches into LEP takes approximately 15 seconds and is called an SPS
supercycle. Many SPS supercycles are needed (about 50) to produce the desired number of particles, $1.6 \times 10^{12}$, in each $e^+$ and $e^-$ beam. This corresponds to a current of about 3 mA for each beam at the end of a LEP 'fill'.

When $e^+$ or $e^-$ bunches are injected into LEP they must be kept in a circular orbit with energy 20 GeV until the fill is complete. In addition the beam cross sectional area must be kept small and the energy loss due to synchrotron radiation must be compensated for. The beams are kept in a circular trajectory by 3304 dipole magnets of 5.75 m each. An additional 64 dipole magnets are located at the 8 interaction regions and another 24 dipole magnets at the injection point of LEP. The beams are focussed in the plane perpendicular to the beam by 816 quadrupole magnets and 501 sextupole magnets. Two superconducting quadrupoles at each of the four interaction regions give the beam a final 'squeeze' to reduce $\sigma_x$ and $\sigma_y$ as much as possible before collision.

The energy loss due to synchrotron radiation is compensated for by a Radio Frequency (RF) system that operates at 352.21 MHz. This system also accelerates each beam from 20 to 45 GeV after a sufficient beam intensity has been reached. The RF system consists of 128 coupled cavity units, each containing a five-cell acceleration cavity coupled to a single-cell spherical storage cavity on the side. The accelerating cavities are located at two of the interaction points directly opposite each other. Each five cell acceleration cavity can run at a maximum accelerating gradient of 1.47 MV/m, hence each of the 2.12 m cavities can give a maximum energy of 3.1 MeV to an electron or positron. Figure 2.3 shows a schematic of the magnet and RF cavity positions in the LEP ring [22].

Once the electron and positron beams have been accelerated to the desired energy, nominally 45.6 GeV, the beams collide at the interaction points where the four LEP detectors are located. The duration of one LEP fill for useful physics interactions is typically about 4 hours. The data for this analysis have been recorded by the DELPHI detector. To gain an understanding of the size and complexities of this experiment, an overview of the DELPHI detector is presented below.
Figure 2.3: Position of the LEP magnets and RF cavities. The dipole magnets keep the trajectory of the beams circular. The quadrupole and sextupole magnets focus the beams. The $e^+$ and $e^-$ are accelerated by the RF cavities from an energy of 20 GeV up to a nominal energy of 45.6 GeV.
The Detector with Lepton, Photon and Hadron Identification - DELPHI

The Detector with Lepton, Photon and Hadron Identification, DELPHI, is a general purpose detector composed of 16 detector sub-systems and a superconducting solenoid. Figure 2.4 shows a general overview of how these sub-systems are arranged to form DELPHI [25]. (The following detector description uses a cylindrical coordinate system where the $z$-axis is parallel to the $e^-$ beam direction and whose origin is at the center of the detector.) As seen in this figure, DELPHI can be considered as a cylindrical barrel region and two end-cap regions. The barrel region covers from $40^\circ$ to $140^\circ$ in the polar angle. The two endcaps, or forward regions, overlap the barrel region and extend down to polar angles of about $10^\circ$ and $170^\circ$. A 5.2 m long superconducting solenoid is located at a radius of 2.6 m. The solenoid produces a uniform magnetic field of 1.2 T parallel to the beam axis within the cylindrical region it surrounds. By measuring the curvature of charged particle trajectories within this region, the momenta of charged particles can be determined. Detailed schematics of the longitudinal and transverse cross section of the DELPHI detector are shown in Figures 2.5 and 2.6 [25].

The DELPHI sub-detectors can be divided into several classes based on their primary function, such as charged and neutral particle detection, particle identification, and triggering. In most instances, the sub-systems contribute information to more than one class. The following sections describe the purpose of each class and how the detectors within the class accomplish their function. The most important properties of the subdetectors, i.e., resolutions, will also be presented. More information on DELPHI particle detection techniques and detector performance in general can be found in references [25, 26, 27].

**Charged Particle Detection**

The uniform magnetic field of 1.2 T, produced parallel to the $e^+e^-$ beam by the DELPHI solenoid, changes the direction of charged particles with momentum components perpendicular to the beam. Hence, the momenta of the charged interaction products can be determined. This section describes the DELPHI subdetectors that are designed primarily for charged particle detection. The descriptions are intended
Figure 2.5: Longitudinal view of the DELPHI detector.
to be short summaries. Some additional emphasis is placed on the TPC since this subdetector is the primary tracking device for the barrel region of the DELPHI detector and our analysis is very dependent on it. A summary of the primary parameters and performance of each tracking detector is given in reference [25].

**Vertex Detector (VTX)** This detector is designed to determine the vertex of a $Z^0$ decay by providing accurate $R\phi$ - resolution. Precise vertex information is especially useful for the study of short-lived states, in particular b-quark physics.

The VTX consists of two cylinders of Si-strip detectors concentric to the incident beam and located at average radii of 9 and 11 cm with a length of 24 cm. Each cylinder has 24 azimuthal modules that span the full length of the VTX, with an overlap of about 10% in $\phi$ between the modules. A module consists of four Si-detectors along the $\theta$-direction, each 300 $\mu$m thick with a 25 $\mu$m diode pitch. Each detector has a sensitive length of 59 mm and a width 25.6 mm or 32 mm for the inner or outer cylinders respectively. The readout strips are located on the Si-detector parallel to the beam and have a 50 $\mu$m pitch, hence there are 512 readout channels per detector on the inner cylinder and 640 readout channels per detector on the outer shell. Detector pairs are wire-bonded together in series, giving the VTX a total of 54254 readout channels.

Relative alignment of the modules before installation was done to an accuracy of 10 $\mu$m in 3 dimensions. By using tracks that cross the overlap region in both cylinders, a preliminary value of 7 $\mu$m was obtained for the $R\phi$ - resolution of the VTX alone. Using tracks from $Z^0$ events, internal alignment with other detectors has reached an accuracy of $\sigma_{R\phi}=14$ $\mu$m leading to a vertex reconstruction error of 90 $\mu$m in $(x,y)$.

**Inner Detector (ID)** The ID serves two functions, redundancy for vertex reconstruction and a source for fast trigger information. The ID consists of two cylinders concentric to the beam axis to accomplish each of its functions.

The primary function of the inner-most cylinder is to provide additional $R\phi$ information for charged track reconstruction. The inner cylinder is a drift chamber with a jet-chamber geometry. Sense wire planes running parallel to the beam direction
are located in the middle of each sector. Ionized electrons are drifted to these planes with a drift velocity proportional to $R$ (thus the trigger information for each $R\phi$ point of a track is kept in the same narrow time-window). Wire grids on both sides of the sense planes provide a varying drift field of $1 - 2$ kV/m. The gas used for ionization and drifting is CO$_2$/C$_4$H$_{10}$/C$_3$H$_7$OH. This jet-chamber geometry provides 24 $R\phi$ points per track.

The outer-most cylinder of the ID primarily provides fast trigger information, and is also important for resolving left/right ambiguities in the jet-chamber. The outer cylinder consists of 5 cylindrical layers of MWPC. Each layer is 8 mm deep and contains 192 sense wires spaced about 8 mm apart and interleaved with field wires. The wires run parallel to the beam for a length of approximately 50 cm. Each layer also has circular cathode strips that lie at a 5 mm pitch and are proportional to $R$ to give a fixed angular resolution. The sense wires resolve left/right ambiguities in the jet-chamber. Fast trigger information is provided by both the cathode strips and the sense wires.

Cosmic ray and beam tests have measured an average single wire resolution of $\sigma_{R\phi}=90$ $\mu$m in the jet-chamber. The efficiency of the jet-chamber is typically 20 points/track during LEP data runs. The outer layer wire resolution has been measured to be $\sigma_z=600$ $\mu$m in beam tests and is less than 1 mm for data runs. Single track efficiency for the outer layers is greater than 95%.

**Time Projection Chamber (TPC)** The TPC is the primary tracking device of DELPHI, and its main function is detection of charged tracks. Normally track reconstruction starts with the TPC information. The TPC can also provide particle identification by measuring the energy loss per unit distance, $dE/dX$, of the charged particles passing through its volume. This information is particularly useful for $e^-\pi$ separation below 8 GeV. Above this energy, the HPC (see page 57) is used to separate electrons from pions.

The TPC uses the principle of time projection to obtain 3-dimensional spatial information for a charged track. The TPC volume is a large cylinder with the $z$-axis parallel to the beam axis. A uniform electric and magnetic field lie within this volume, parallel to each other and the beam axis. A charged particle passing through
the gas liberates electrons via ionization. These electrons are caused to drift towards a sensitive region by the electric field. Transverse diffusion of the charge is kept low due to the presence of the parallel magnetic field. The sensitive region is located at the end of the drift region and is segmented in the plane transverse to the beam, providing spatial track information in the $R\phi$ plane. Using the known drift-velocity of electrons in the gas and the measured drift time, the track position in the $z$-direction can be determined.

The DELPHI TPC has an inner radius of 35 cm and an outer radius of 111 cm. It is split into two halves with respect to the interaction point, each extending to 134 cm in the $\pm z$-direction. Hence the TPC covers a polar angle of $20 \leq \theta \leq 160$. The gas used in this volume is an Ar/CH$_4$ (80/20\%) mixture. For a nominal electric drift field of 150 V/cm the drift velocity of the ionized charge is $v_D = 66.94 \pm 0.07 \text{ mm/}\mu\text{s}$ at a temperature of $T = 22^\circ \text{C}$.

The sensitive region at each end of the TPC consists of an end-cap that is divided into six sectors. Each sector has 192 sense wires spaced 4 mm apart and covered by 16 circular cathode pad rows. Individual cathode pads are about 7.5 mm in length and 8 mm in height ($R$), adjusted to give a constant surface area and a multiple of 16 pads per row. A total of 1680 pads are found on each TPC sector. The energy loss of the charged track, $dE/dX$, is obtained from the sense wire pulses. The cathode pads determine the $R\phi$ position of the track.

Preliminary spatial resolutions of the DELPHI TPC during LEP operation are $\sigma_{R\phi} = 180 - 280 \mu\text{m}$ depending on $\phi$ and $z$, and $\sigma_z < 900 \mu\text{m}$. Two track separation is about 1.5 cm. Resolution for $dE/dX$ is currently $\sigma = 6.2\%$ for muons at 45 GeV and $\sigma = 7.5\%$ for pions between 280 and 400 MeV.

**Ring Imaging Cherenkov Device - (RICH)** The RICH sub-detector system is designed to identify the various species of charged particles which are produced in the interaction. It relies on the principle of Cherenkov radiation, light emitted by charged particles passing through a medium at a speed faster than light travels through the medium. This causes a 'cone' of photons to be emitted at an angle $\theta$
Muon Chambers - Barrel (MUB)  As its name implies, the purpose of the MUB is to distinguish muons from other charged particles. Since muons only interact weakly with matter, muon identification is accomplished by placing a device sensitive to charged particles behind several interaction lengths of matter. Thus most of the ordinary hadronic matter is absorbed in this material.

The DELPHI MUB consists of two concentric cylinders located at radii of about 445 and 485 cm. Hence, the inner cylinder lies behind the first 90 cm of iron in the barrel hadron calorimeter (and lies entirely after the lead of the barrel electromagnetic calorimeter). The second cylinder is located behind an additional 20 cm of hadron calorimeter iron. The first cylinder consists of 2x24 azimuthal planks, each containing 3 layers of staggered drift chamber planes. The second cylinder consists of overlapping planks, each containing 2 layers of staggered drift chamber planes. Each plank is about 3.65 m in length and covers half the detector in the $\phi$-direction. The drift chamber planes are 20.8 cm wide by 2.6 cm high and contain a single sense wire in the center. They operate in a proportional mode using a gas mixture of $\text{Ar}/\text{CH}_4/\text{CO}_2$ (85.5/8.5/6%).

Resolutions from test beams and cosmics are $\sigma_{R\phi} \sim 1$ mm and $\sigma_z \sim 10$ mm. Resolutions from measurements of extrapolated tracks during LEP operation are $\sigma_{R\phi} = 4$ mm and $\sigma_z \sim 10$ mm. Individual chamber efficiencies are estimated at about 95%.

Forward Chamber A (FCA)  The main function of the FCA is to provide tracking ability, and hence improved momentum resolution, at low polar angles. The FCA also provides fast trigger information for the forward region. These functions are accomplished by placing planes of wire chambers, rotated with respect to each other, at the ends of the cylindrical volume of the DELPHI detector.

The FCA is located at each end of the TPC and stands perpendicular to the beam axis. Each detector consists of 3 chambers split into half-discs with a radial coverage of $30 < R < 103$ cm. Each chamber has two staggered layers constructed from conductive plastic that form 15 mm square cells with the anode wire located in the center. The chambers are rotated at an angle of 120° with respect to each other, thus giving stereo spatial information for charged tracks. In addition the outer
surfaces of each double layer are reinforced with 0.7 mm G10 sheets that carry a pattern of 58 mm wide cathode strips, rotated at 60° with respect to the anode wires. The cathode strips provide improved local pattern recognition. The chambers are operated in limited streamer mode in a gas mixture of Ar/i-C_4H_{10}/C_2H_5OH (48.75/48.75/2.5%).

Spatial resolution from test beams are $\sigma_x \sim 150$ $\mu$m for the anode wire signal. Efficiencies for the double layers were $\varepsilon \sim 97\%$. Preliminary results from LEP operation are $\sigma_x \sim 300$ $\mu$m for the anode signal and a double layer efficiency of $\varepsilon \sim 95\%$.

**Forward Chamber B (FCB)** The FCB provides additional tracking ability in the forward region, and hence substantially improved momentum resolution. The FCB also provides trigger information for low polar angles. Like the FCA, this is accomplished by placing wire chambers, rotated with respect to each other, at the ends of the DELPHI detector.

The FCB is located between the forward RICH and the FEMC on each arm of DELPHI at a $z$-distance of about 267 cm. The chamber consists of 2 half discs on each end with a radial coverage of $53 < R < 195$ cm. An FCB chamber contains 12 wire planes 1.1 cm apart (in $z$), separated by cathode plates. Pairs of planes are rotated with respect to each other by 120°. Each pair of wire planes is also staggered with respect to each other. Sense wires are 2 cm apart and are separated by field wires. The gas mixture used is Ar/C_2H_6/C_2H_5OH (50/48/2%).

Test beam results for spatial resolution are $\sigma_x < 150$ $\mu$m and efficiency $\varepsilon = 97\%$ for the individual wires. Double layer efficiency is near 100%. Preliminary results from LEP operation are $\sigma = 250$ $\mu$m and $\varepsilon = 80\%$ per plane, averaged over all planes. This includes effects from dead regions. Combined information from the 12 planes gives $\sigma_x = \sigma_y = 120$ $\mu$m.

**Muon Chambers - Forward (MUF)** The MUF works on the same principle as the MUB; i.e., place wire chambers after many radiation lengths of material to detect the only particles likely to reach it, namely muons.

The DELPHI MUF consists of 2 planes of wire chambers (lying perpendicular
to the beam axis), the first located at \( z = 463 \text{ cm} \) and behind 85 cm of HAF iron, and the second located after another 20 cm of iron at \( z = 500 \text{ cm} \). Each plane covers an area of \( 9 \times 9 \text{ m}^2 \) and is made up of 4 quadrants, each covering \( 4.4 \times 4.4 \text{ m}^2 \). Each quadrant consists of 2 layers of orthogonal drift chambers. The drift chambers are 435.4 cm long, 18.8 cm wide and 2 cm high with an anode wire located in the center and running the length of the chamber. The drift chambers are operated in limited streamer mode with a mixture of \( \text{Ar}/\text{CO}_2/\text{i-C}_4\text{H}_{10} \) (14/70/14\%) and 2\% i-propanol.

Resolutions from cosmic tests are \( \sigma_{x,y} = 1 \text{ mm} \) for the drift time measurement and \( \sigma_{DL} = 2 \text{ mm} \) for the delay line information. Using halo muons from the LEP beams, the efficiency per layer was found to be \( 89 \pm 3\% \), averaged over all layers. This includes an 8\% inefficiency due to structural deadspaces. Spatial resolution for muons hitting all four detector layers is \( \sigma = 3 \text{ mm} \) (averaged over 16 detectors on one end-cap).

**Combined Track Detection** One of the primary objectives of detecting the charged particles is to determine the particle momentum to a high degree of accuracy. This is accomplished by combining the information from each of the independent subdetectors to determine vertex positions and track trajectories of the charged particles. Combining subdetector information is especially important for determining high momentum resolution.

Pattern reconstruction of tracks starts by finding tracks in each subdetector. The individual subdetector tracks are then fitted together to find the particle trajectory through the entire DELPHI detector. An important consideration for achieving precise track reconstruction is the relative alignment between subdetectors. The alignment relies on a precise structural survey of the detector components, and in particular on calibration with cosmic events.

Using the combined tracking information of the ID, TPC, and OD in the barrel region, the momentum resolution for 45.6 GeV muons has been measured to be \( \Delta p/p = 7\% \). This indicates an overall momentum resolution of \( \Delta p/p = 0.0015 \times p \) (GeV) for the barrel region. For the forward region, using the combined tracking of the ID, TPC, and OD \((20^\circ < \theta < 35^\circ)\), the momentum resolution for 45.6 GeV muons has a preliminary value of \( \Delta p/p = 17\% \).
Neutral Particle Detection

The main function of neutral particle subdetectors is to measure the position and energy of neutral particles. Neutral particle detectors aim at measuring energies by causing the neutral particles to deposit their full energy within the detector. The response of the detector, or output signal, is a function of the incident particle energy, hence the particle energy can be determined. For this reason these devices are called calorimeters. Electromagnetic calorimeters are optimized for detection of photons (and electrons). Hadron detectors are designed to enhance detection of hadrons (neutrons, pions, kaons, etc.). While the most important function of these detectors is to identify neutral particles, they also play an important role in charged particle detection and identification. For example, charged tracks from $Z^0 \rightarrow e^+e^-$ and $Z^0 \rightarrow \mu^+\mu^-$ are not distinguishable, yet the energy each type of track leaves in the HPC are very different.

Below are brief descriptions of the detectors used for neutral particle detection. A summary of performance for neutral particle detectors is given in reference [25]. Since this analysis involves a study of photons, emphasis is placed on the DELPHI barrel electromagnetic calorimeter, the HPC.

High-density Projection Chamber (HPC) The HPC [28] measures the position and energy of photons, identifies electrons, and provides information regarding the position and energy of charged particles. The HPC also provides information for fast triggering.

The HPC detector forms a cylindrical shell (z-axis parallel to the beam) just inside the superconducting coil in the radial region $208 < R < 260$ cm and subtends a polar angle of $43 < \theta < 137^\circ$. The shell consists of 144 modules collected together in lines of 3 modules (in z-direction) by 24 azimuthal lines on each half of the detector. Hence each module covers approximately $15^\circ$ in $\phi$ and has a space of 1 cm to its azimuthal neighbors. A single set of 24 azimuthal modules can be thought of as a ‘ring’ covering a solid angle of $2\pi \Delta \theta$. The middle-rings are separated from the inner-rings and outer-rings by a z-distance of 1 cm. The two inner-rings are separated by a z-distance of 7.5 cm (centered at $\theta = 90^\circ$) caused by structural support.

The HPC is a gas sampling calorimeter that uses the principle of time projection
to obtain 3-dimensional spatial information of neutral particles [29]. Each HPC module contains a series of lead wire converters separated by gaps filled with an ArCH₄ gas mixture. A uniform electric field (parallel to the beam axis) is established in the module volume using a passive resistor chain soldered to the lead wires, forming a voltage divider network. Particles incident on the module interact with the lead converters primarily through electromagnetic processes. Hence photons pair produce and $e^- (e^+)$ bremsstrahlung radiate as they pass through the lead converters, thus producing a cascade shower of electrons, positrons, and photons. The charged particles in the shower ($e^+e^-$) ionize the Ar gas as they pass through the detector. (Since the ratio of mean energy loss due to radiation as compared to ionization for a particle of energy $E$ and mass $M$ is roughly proportional to $E \cdot m_e/M^2$, radiation is only important for $e^\pm$. Other charged particles (muons and pions) will generally not produce a cascade shower, but leave only a line of constant ionization charge and are referred to as minimum ionizing particles, or mips.) The electrons released from the ionization are drifted parallel to the beam axis by the uniform electric field towards a sensitive region at the end of the module. Transverse diffusion is low because of the small Lorentz angle due to the magnetic field. The sensitive region is segmented in the plane perpendicular to the drift direction (and hence the beam-axis). The segmentation provides $R \phi$ spatial information for the shower, while the drift time and known drift-velocity of the ionized electrons provides spatial information in the $z$-direction. The energy of the incident particle is proportional to the amount of ionized charge produced by a shower. Hence, photon energy can be determined by measuring the amount of charge detected in the sensitive region.

Each module of the HPC is in the shape of a trapezoid, as viewed along the $z$-axis, with bases of 51.9 and 63.8 cm. The modules of the inner and middle rings are 90 cm long (drift direction) and the modules of the outer rings are 65 cm long. The 46.5 cm depth of a module contains 40 lead converters (18 radiation lengths) spaced by 8 mm gas gaps. Scintillator planes are located in a single 18 mm gap behind 4.5 radiation lengths of lead for fast trigger information.

The sensitive region is a plane of proportional wires that lies at the end of each module, perpendicular to the drift direction. The wires are capacitively coupled to a plane of 128 cathode pads. The cathode pads are organized into 9 active layers to
determine the longitudinal development of the shower. The pad size is small in the first few rows to accurately determine the position of an incident particle and avoid saturation at the shower maximum. Pad size is larger in the later rows since there is little positional information and saturation is not a problem. Figure 2.7 shows the pad layout for a module. This pad pattern determines the $R \phi$ granularity.

The energy and $z$-coordinate of the shower are determined by digitizing the induced signal on the pads using an 8-bit flash analog to digital converter (FADC) operating at a frequency of 15 MHz [30]. The FADC operates in a bilinear mode resulting in a dynamic range of $\sim 800:1$. In this way the FADC digitization can distinguish low energy showers for minimum ionizing particles, and does not saturate for high energy showers. The FADC samples the charge $\sim 255$ times over the 90 cm drift length, leading to a fine spatial resolution of $\sim 3.5$ mm in the $z$-direction. For the given number of modules, pads and time samplings, over 4 million space cells are available for position and energy measurement. The instrumentation of these cells is accomplished with 18432 electronic channels, one per cathode pad. A zero-suppression circuitry has been implemented in the electronics readout so that the output data is kept at a modest level.

Shower reconstruction of test beam data measured an angular resolution of the HPC alone (without vertex constraints) to be $(\sigma_\theta = 36/\sqrt{E} + 2.5)$ mrad for theta and $(\sigma_\phi = 97/\sqrt{E} + 10)$ mrad for phi. The energy resolution from test beam data is $(\sigma_E/E = \left[(23/\sqrt{E})^2 + (1.1)^2\right]^{1/2})\%$, where $E$ is expressed in GeV. Measurement of the HPC energy resolution during LEP operation has been more difficult to assess. The energy resolution of bhabha events in the HPC indicates a poorer energy resolution than expected from beam tests. It has been suggested that the deterioration is due to the interactions of the incident particle with the detector material in front of the HPC, for example radiation, pair production or scattering. A study of the HPC resolution has been done using Bhabha events $(E(e^\pm) \sim 45$ GeV) and about 700 Compton scattered events where the scattered $e^\pm$ produces an electromagnetic shower in the HPC (primarily $3 < E(e^\pm) < 15$ GeV) and the scattered photon is detected in the forward calorimeter. From this study the energy resolution of the HPC is consistent with $(\sigma_E/E = \left[(26/\sqrt{E})^2 + (7)^2\right]^{1/2})\%$. 
Forward Electromagnetic Calorimeter (FEMC) The forward electromagnetic calorimeter provides for detection of neutral particles in the forward region, $10^\circ < \theta < 36.5^\circ$ and $143.5^\circ < \theta < 170^\circ$. The FEMC consists of two 5 m disks with a radial coverage of $46 < R < 240$ cm and located on the $z$-axis at $\pm(233 - 285$ cm).

Each disk contains 4532 lead glass blocks that are shaped (front face $5 \times 5$ cm$^2$, back face $5.6 \times 5.6$ cm$^2$, longitudinal depth of 20 radiation lengths) and arranged to project towards the interaction point. The projected direction has a slight offset from the interaction point, $3^\circ$, to minimize the effects of the 'cracks' between blocks.

Test beam results show an energy resolution of $\sigma_E/E = [(5/\sqrt{E} + 0.35)^2 + (6/E)^2]^{1/2}$% where $E$ is in GeV and the last term is due to amplification noise. As with the HPC, the energy resolution during LEP operation shows a degradation from the test beam results due to material in front of the FEMC. The resolution of bhabha events at $E = 45$ GeV is observed to be $\sigma_E/E = 4\%$.

Hadron Calorimeter - Barrel (HAB) The purpose of the hadron calorimeter is to measure the energy and position of hadronic particles that reach the HAB after passing through the rest of the detector with minor interactions. The hadron calorimeter is particularly important for the detection of neutrons since they typically pass through most of the HPC before initiating a hadronic shower. This is accomplished by providing many interaction lengths of iron (large atomic number $A$) in which the hadronic particles can interact. The iron in the HAB also provides for the return flux of the magnetic field.

The HAB is a cylindrical shell that lies outside the superconducting coil at $320 < R < 479$ cm and subtends the polar angle $43 < \theta < 137^\circ$. The hadron calorimeter is a gas sampling calorimeter that consists of 24 azimuthal sectors, each composed of 20 layers of limited streamer mode detectors (installed in 2 cm gaps) separated by 5 cm thick iron plates. The detector gas used is a low i-butane mixture composed of AR/CO$_2$/i-butane (10/60/30%). A single detector 'plank' consists of a plastic cathode forming a row of 8 square cells ($9 \times 9$ mm$^2$) with a wire anode in each cell. The sampling gaps in the HAB contain 19,032 planks that vary in length between 40 and 410 cm.

The readout of the HAB is accomplished by placing segmented copper clad
boards along the length of the detector planks which pickup the streamer charges. The pads are coupled together to form ‘towers’ projecting back to the interaction point. Pads from five adjacent layers are combined to produce 4 superlayers of towers, where each tower covers an angular region of $\Delta \theta = 2.96^\circ$ and $\Delta \phi = 3.75^\circ$. Typical dimensions of the towers are $25 \times 25 \times 35$ cm$^3$.

The performance of the HAB has been studied using LEP data from hadron and muon decays of the $Z^0$. The momentum of charged hadrons is measured in the TPC and compared to the energy deposited by the hadron in the HAB. This study indicates a resolution of $\sigma_E/E \sim 120\%/\sqrt{E}$. The efficiency of single muon detection is about 80%.

**Hadron Calorimeter - Forward (HAF)** The forward hadron calorimeter provides for detection of neutral hadrons in the forward regions of DELPHI, subtending the angles $11^\circ < \theta < 48^\circ$ and $132^\circ < \theta < 169^\circ$. The HAF is located at $\pm(340 - 489)$ cm on the $z$-axis and has a radial coverage of $65 < R < 460$ cm.

The HAF is very similar to the HAB, using the same type of detector planks to form 19 sampling layers interspersed with iron plates. The segmented pads of 4 or 7 adjacent layers form superlayers of towers (projecting to the interaction region) that cover the solid angle $\Delta \theta = 2.62^\circ$ and $\Delta \phi = 3.75^\circ$. A maximum of 4 such superlayers are formed.

Performance is similar to the HAB, with an energy resolution of $\sigma_E/E \sim 120\%/\sqrt{E}$.

**Luminosity Monitors**

The integrated luminosity for each run is determined by counting the number of bhabha events, $(e^+e^- \rightarrow e^+e^-)$, and using the bhabha cross section, $\sigma_B$, for the angular acceptance of the SAT ($43 < \theta < 135$ mrad). In this very forward region, $\sigma_B$ is determined primarily by QED processes. Since the QED couplings have been calculated to a high degree of accuracy the integrated luminosity, $L$, is determined from the expression

$$L = \frac{N_{ev} - N_{bk}}{\varepsilon_B \cdot \sigma_B}$$

(2.3)
Very Small Angle Tagger (VSAT)  The very small angle tagger consists of two blocks each at \( z = \pm 7.7 \) m, where each block is mounted to the vertical side (inner and outer circumference) of the beam pipe. Each block is a W-Si calorimeter stack, \( 3 \times 5 \times 10 \) (24 radiation lengths deep) \( \text{cm}^3 \), subtending a polar angle of \( 5 < \theta < 7 \) mrad and an azimuthal angle of \( \pm 45^\circ \) around the horizontal axis. Each stack consists of 12 W-plates, 2 radiation lengths thick, separated by full area (3 \( \times \) 5 cm) Si-detectors for energy measurement. For positional information, two Si-detectors with 32 vertical strips (1 mm pitch) are inserted after 5 and 9 radiation lengths, and one Si-detector with 48 horizontal strips is placed behind 7 radiation lengths.

The information from the Si-strips is used to reject showers near the edge of the detector and to correct for energy leakage. After selecting bhabha events where the energy deposited in diagonally opposite VSAT blocks satisfies the circular energy cut, \( (E_b - E_c^+) + (E_b - E_c^-)^2 < (E_b - 37)^2 \), the energy resolution is found to be 5% at 45 GeV, or \( \sigma E / E \sim 35\% / \sqrt{E} \). The bhabha rate of events with an \( e^\pm \) tagged in each VSAT is about 10 times the \( Z^0 \) rate on the peak.

Trigger/Veto Detectors

Almost all the detector sub-systems have some secondary function as a trigger for physics events. However, there are two DELPHI detectors, the time-of-flight counters and the forward hodoscope, that are designed primarily for triggering on physics events or rejecting high rates from background events.

Time-of-flight counter (TOF)  The time-of-flight sub-system is located in the barrel region of DELPHI and serves as a fast trigger for physics events. The TOF has a dual role with respect to cosmic events, with the capability to veto cosmics during beam crossings or to trigger on cosmics during LEP operation. Triggering on cosmic events is important because they are used extensively for internal alignment of the DELPHI detector sub-systems.

The TOF consists of a single layer of 172 scintillating counters forming a cylindrical shell located just outside the solenoid. Each counter (355 \( \times \) 19 \( \times \) 2 cm\(^2\)) covers half the length of DELPHI, subtending a polar angle of \( 41^\circ < \theta < 139^\circ \), with a 6 cm dead space at \( \theta = 90^\circ \). The scintillator used for the counters is NE110. The scintil-
lator is connected on both ends to a photomultiplier via plexiglass light guides folded back by 180°. This geometry reduces the dead zone in the center of the detector. The effective attenuation length of the scintillator is 135 cm and the effective light propagation is 16 cm/ns. Signal loss in the light guide is 78%.

Time resolution as measured with cosmic events is \( \sigma_t = 1.2 \text{ ns} \), corresponding to a resolution of \( \sigma_Z = 20 \text{ cm} \) on the axial position of a track. The rate of cosmic events using a back-to-back coincidence of the TOF is 3.5 Hz, with a detection efficiency of 99.9% for mips.

**Forward Hodoscope (HOF)** The forward hodoscope sub-system is located in the DELPHI end-caps and provides a trigger for forward \( Z^0 \) decays, and a veto against beam-gas events. However, the HOF can also act as a trigger for beam related muons that are very useful for alignment purposes in the forward region.

The HOF is mounted on each end of DELPHI just in front of the second muon chamber. Each hodoscope consists of a single layer of scintillator counters covering a total surface area of \( \sim 140 \text{ m}^2 \). The layer is divided into quadrants, each containing 28 counters. The counters have dimensions of \( 1 \times 20 \times 450 \text{ cm}^3 \) and are mounted with some overlap to avoid crack affects. The scintillators are coupled to a single photomultiplier via bent light guides. The effective attenuation length of the scintillator is 150 cm and loss of signal in the light guides is less than a factor of 3.

Time resolution as measured with beam related muons is \( \sigma_t = 5 \text{ ns} \) averaged over the whole counter. Detection efficiency is \( \sim 95\% \) for mips.

**Hadron Trigger** The DELPHI trigger system is complicated and has many details. For this study, only the hadron trigger is of importance and will be presented as an overview. More details are available elsewhere [25, 31].

The DELPHI trigger had two levels for LEP operation in 1990. The 1st level trigger decision is made 3 \( \mu \text{s} \) after the beam crossing and the 2nd level decision after 42 \( \mu \text{s} \). Since a beam crossing occurs every 22 \( \mu \text{s} \) the detector is 'dead' during the first beam crossing after a positive first level decision. A typical 1st level trigger rate of 400 Hz leads to a deadtime of about 1%. The 2nd level trigger was typically about 2 Hz.
The following four sub-trigger components were used for 1st level triggering of hadronic events. The term octant used below refers to eight equal sectors that are created conceptually by splitting the DELPHI detector with three planes lying in the $x - y$, $y - z$, $z - x$-planes and which intersect at the center of the detector.

- A 'track trigger' was made by coincidences of the ID and OD tracking chambers. A positive trigger from each detector is provided if 3 out of 5 detector layers recorded a signal. The track trigger requires a positive response from at least two OD quadrants, in coincidence with any signal from the ID.

- A 'scintillator trigger' was made by coincidences of the HPC and TOF scintillation counters. The HPC counters are sensitive to showers of 2 GeV or more. The TOF counters are sensitive to minimum ionizing particles and also shower leakage from the calorimeter. A positive scintillation trigger is formed by the OR of the following criteria:
  - A signal in at least 2 TOF octants.
  - A signal in at least 2 HPC octants.
  - A coincidence of any TOF octant with any HPC octant.

- A redundant trigger in the barrel region was formed by a coincidence of any TOF octant with any OD octant.

- A 'forward majority' trigger was formed by coincidence of at least two of the following conditions:
  - A coincidence of HOF signals from back-to-back quadrants.
  - At least one track detected by coincidences between the forward tracking chambers FCA and FCB.
  - A coincidence of one OD quadrant with any ID signal.
  - At least 3.0 GeV energy deposition in the FEMC.

The efficiency of these combined subtriggers for hadronic events was over 99.5%. A study also was made for data recorded with trigger components missing. This was
done by using events with all trigger components operating and artificially removing part of the trigger pattern. A correction of 0.2% to 2.5% was needed for less than 5% of the data. This is a negligible effect for this analysis.

Event Reconstruction of Detector Data

The goal of a complicated detector like DELPHI is to correctly reconstruct the $Z^0$ decay products so that physical parameters of nature can be extracted. The decay of the $Z^0 \rightarrow \ell^+\ell^-$ has four 'common' decay modes that can be separated from each other relatively clearly by their event topology: $Z^0 \rightarrow e^+e^-$, $Z^0 \rightarrow \mu^+\mu^-$, $Z^0 \rightarrow \tau^+\tau^-$, and $Z^0 \rightarrow q\bar{q}$. We give an example of a reconstructed event for each decay mode in the following to illustrate the capabilities of the DELPHI detector.

Figure 2.8 shows the $Z^0 \rightarrow e^+e^-$ decay as reconstructed in the DELPHI detector. Because the $Z^0$ is created at rest and the $e^\pm$ are stable we observe two back to back charged tracks in the TPC. Upon entering the electromagnetic calorimeter (HPC) the $e^\pm$ showers and deposits its energy in the calorimeter. This large energy deposition is illustrated in the graphical reconstruction by the long rectangular structures in the HPC. The $e^\pm$ is stopped by the electromagnetic calorimeter and little or no energy is detected beyond it. (The graphics seems to indicate energy beyond the HPC but this is not the case, it is only a reflection of the graphical representation of large energy deposits in the HPC.)

Figure 2.9 shows the decay of a $Z^0$ to two muons where one of the muons has also radiated a photon. The muons are observed by the charged tracks in the TPC and the photon can be seen as a single deposit in the HPC with no charge track leading to it. The momentum sum of the photon and the nearest muon exactly balance the momentum of the opposite muon, again indicating the back to back nature of $Z^0 \rightarrow \ell^+\ell^-$ at LEP. The muons leave only a small amount of energy in the HPC as opposed to the $e^\pm$ case (see Figure 2.8). In addition the muons pass through the hadron calorimeter and out to the muon chamber. Thus $Z^0 \rightarrow \mu^+\mu^-$ decays can be separated from $Z^0 \rightarrow e^+e^-$ decays.

Figure 2.10 shows the decay of a $Z^0 \rightarrow \tau^+\tau^-$ where one $\tau$ has decayed to three pions and the other $\tau$ has decayed to a muon and neutrinos. The pions are identified as such because they leave little energy in the electromagnetic calorimeter
Figure 2.8: Reconstructed tracks of a $Z^0 \rightarrow e^+e^-$ event. The back to back tracks recorded in the TPC are 'linked' to the energy deposited in the HPC. The graphical display of this event indicates that a large amount of energy has been deposited in the HPC by the charged particles, and no signals are observed in the muon detector or hadron calorimeter.
Figure 2.9: Reconstructed tracks of a $Z^0 \rightarrow \mu^+\mu^-$ event. Back to back tracks recorded in the TPC are 'linked' to the energy deposited in the HPC. In contrast to Figure 2.8, only a small amount of energy is deposited in the HPC by the charged particles, and signals are also observed in the HAB and MUB.
Figure 2.10: Reconstructed tracks of a $Z^0 \rightarrow \tau^+\tau^-$ event. The taus quickly decay to a three particle final state, where two of the particles are often undetectable neutrinos. Hence the charged tracks are not necessarily back to back, in distinct contrast to the leptonic decay of the $Z^0$ to $e^+e^-$ and $\mu^+\mu^-$. This event shows one tau decaying to a leptonic final state (muon) and the other tau decaying to a three charged particle state.
Figure 2.11: Reconstructed tracks of a $Z^0 \rightarrow q\bar{q}$ event. The high multiplicity of charged and neutral tracks easily distinguishes the $Z^0$ hadronic decays from the $e^+e^-$ and $\mu^+\mu^-$ leptonic decays. There is typically a small misidentification of $\tau^+\tau^-$ events as hadronic events and vice versa.
Figure 2.12: Reconstructed tracks of a $Z^0 \rightarrow q\bar{q}\gamma$ event. The two jets of particles from the quarks are clearly separated in this example. The photon in the electromagnetic calorimeter is observed to be isolated and highly energetic.
CHAPTER 3. ANALYSIS TECHNIQUES

This chapter discusses the analysis used in this thesis. A description of the data used for this analysis is given, along with an overview of the procedures and computer programs used to create these data. The criteria for selecting isolated photons in hadronic events from this data is also discussed.

The events of interest for this study must have a $q\bar{q}\gamma$ topology. Therefore, the selection of a hadronic event is described, followed by the selection criteria for hadronic events which have a photon consistent with the physics processes of interest. (In one sense, all hadronic events could be considered to have a $q\bar{q}\gamma$ event topology since nearly every hadronic decay of a $Z^0$ will produce a photon somewhere, either in a jet of particles or away from the jets.) The physics channel we are interested in studying in the first part of this analysis is final state radiation (FSR). A detailed discussion is given describing the criteria used to separate events due to FSR from the known background sources, i.e., ISR, SQR, QCD processes, and $\tau^+\tau^-$ events. In the second part of this analysis, the identical FSR criteria are used to estimate the efficiency for selecting isolated photons due to the existence of the $H^0$ boson, an excited quark, or an excited $Z^0$ boson.

Data Description

The data used for this analysis was recorded during 1990 by the DELPHI detector at LEP. Over 130,000 $e^+e^- \rightarrow Z^0$ events were detected by DELPHI in the 1990 energy scan, corresponding to a total integrated luminosity of about 5.7 $pb^{-1}$.

The first step in the analysis of the raw data from the DELPHI detector is to reconstruct the tracks of the charged and neutral particles in each event using the DELPHI Data Analysis Program (DELANA) [32]. The data structure of DELANA
output is referred to by the collaboration as TANAGRA [33] 'data'. TANAGRA data contains a great deal of information about each particle track, including details of intermediate steps in reconstructing the tracks. For example, the TANAGRA data includes the spatial location of each point in the TPC used to reconstruct the trajectory of a charged track. This detailed information is not needed for most physics analysis, only the reconstructed momentum of the track and its starting point in the detector. Therefore, a reduced data set is produced from TANAGRA data using a program called PXDST [34]. This reduced data set is called Data Summary Tape (DST) data and the details of its contents are specific to DELPHI, though the concept of DST data is common in experimental high energy physics. DST data contains a summary of the particle track reconstruction process, such as track positions, particle energies and momenta, errors on these quantities, etc. [34]. Data from the intermediate steps of track reconstruction is generally not put on the DST structure.

In addition to the raw data, DELAN A is used to process simulated pseudo-raw data produced by a Monte Carlo simulation of both the physics processes and the detector response. While the specifics of implementing Monte Carlo simulation programs may vary greatly from one experiment to another, the procedural steps are generally the same. Using a theoretical model of the physics process, the primary interaction is generated and the final particle content of the event at the interaction point is generated. The event generator is separate from the detector simulation and rather modular so that it is relatively easy to change generators. This is necessary because event generators calculate specific physics processes. The generator used by DELPHI for the process $e^+e^- \rightarrow q\bar{q}$ is a combination of two different generators, DYMU3 [35, 36] for calculation of initial state radiation contributions, and the JETSET [37, 38] generator for parton production and fragmentation of the quarks into observable particles. (A description of what is included in the generators for DELPHI will be discussed shortly.) The output of these generators is a list of stable particles produced at the interaction point.

Next, the particles at the interaction point are passed through a detailed simulation of the DELPHI detector called DELSIM [39]. The DELSIM program includes physics processes (such as particle interactions with the detector material and parti-
particle decays for short lived particles) and the response of the detector to the particles passing through it (such as the drifting of ionization charge and the characteristics of the electronics response). The final output of the Monte Carlo detector simulation is a set of pseudo-raw data for each event having the same data structure as the data from a real event. DELSIM output also includes information about the event generation and track simulation processes.

The pseudo-raw data is processed through the DELANA and PXDST codes in the same manner as the real data. The final product is called simulated data and contains the same data structure as the TANAGRA and DST data described earlier. Therefore, distributions of any physical quantities analyzed in the real data can also be analyzed using the Monte Carlo simulation and compared to the real data. The simulated TANAGRA and DST data also contain information relevant to the simulation, such as the generated decay chain of the partons for an $e^+ e^- \rightarrow q\bar{q}$ event. This information is often useful for evaluating track reconstruction quality, or for determining acceptances and efficiencies in physics analysis.

To compare the number of energetic isolated photons in the data to what we expect from SM sources requires a detailed Monte Carlo simulation of the physics processes and the detector response. For this study the generation of the known primary physics interactions ($H^0$ production is excluded) and resulting final state particles is accomplished using a combination of the DYMU3 event generator [35] and the JETSET 7.2 parton shower fragmentation model [37]. Initial state radiation is modelled with DYMU3. Final state radiation is included in the JETSET 7.2 event generator [38]. However, interference between ISR and FSR is not included in the generation. At the $Z^0$ peak the interference term is expected to be small, about 0.4% of the total $q\bar{q}\gamma$ cross section, and is negligible. This is not so true for $\sqrt{s}$ slightly off the $Z^0$ peak, where the interference term can become significant. For a given quark type the variation in the contribution to the total cross section of the interference term can range between -10% to +5% [6, 7]. For both up and down type quarks the interference at $s < M_Z^2$ and at $s > M_Z^2$ changes sign. Hence the effect is not so serious if an equal amount of data is recorded at $\sqrt{s}$ above and below the $Z^0$ peak. Since more than 75% of the data is taken on the $Z^0$ peak (interference suppressed) and the data above and below the $Z^0$ peak is roughly equal, the lack of
an interference term in the Monte Carlo is not expected to be an important problem. The higher order QCD corrections are implemented in JETSET in two parts, one perturbative in which the quarks and gluons are generated according to perturbative QCD, and another non-perturbative part in which the partons fragment into colorless hadrons. The perturbative QCD part used for this analysis is the parton shower (PS) approach available in JETSET 7.2 [38]. The parton shower method uses a combination of the Leading Logarithm Approximation (LLA) and the first order QCD matrix element. For the non-perturbative part (the transformation of partons into hadrons) JETSET produces hadrons along color flux tubes stretched between the outgoing partons according to the Lund string model. Emitted gluons act as 'kinks' or excitations of the string. The string may break and produce a new $q\bar{q}$ pair. This process stops when only on-mass-shell hadrons remain. The Lund parton shower fragmentation model has been found to be in good agreement with the LEP data for a number of event variables [40, 41].

In addition to the generation of hadrons, short-lived hadrons are allowed to decay, for example $\pi^0 \rightarrow \gamma\gamma$. The $\pi^0$ decay in particular provides a sizeable background to FSR when the two photons overlap and appear as one photon in the detector.

Using the simulation programs described above, a total of 90822 events were generated for the $e^+e^- \rightarrow q\bar{q}$ physics channel. In addition, a sample of $e^+e^- \rightarrow \tau^+\tau^-$ events was also used to study the background contribution to our data from this channel. A small fraction of the $\tau^+\tau^-$ events have the same event topology as hadronic events, and some of these events have a $q\bar{q}\gamma$ event topology satisfying the criteria for FSR. The event generator used for $e^+e^- \rightarrow \tau^+\tau^-$ simulation was KORALZ [42, 36].

Selection Criteria for Physics Analysis

This section describes the criteria used to identify candidate events for bremsstrahlung radiation from quarks and possible new physics processes described in Chapter 1. The objective of the selection criteria is to obtain a data sample with a clear $e^+e^- \rightarrow q\bar{q}\gamma$ event topology. Comparisons are made between data and simulation, and acceptance criteria for FSR and background are also discussed.
of the above criteria for finding charged tracks has been determined to be greater than 99% overall. Background from spurious tracks has been found to be less than 0.1%.

Once the charged tracks have been selected, they may be used to calculate event characteristics. By placing criteria on selected event characteristics, hadronic events can be well separated from other sources of event triggers. A primary distinction between hadronic \( Z^0 \) decays and lepton \( Z^0 \) decays is the number of charged tracks in the events. Hadronic \( Z^0 \) decays have on average 21 charged tracks per event. Decays of the \( Z^0 \) to \( e^+e^- \) and \( \mu^+\mu^- \) ideally have two tracks. Decay of the \( Z^0 \) to \( \tau^+\tau^- \) has a 1-1 prong event topology 74% of the time and a 3-1 prong event topology about 24% of the time. In addition, background from cosmic events is primarily a two-track phenomenon. These backgrounds can be reduced to a negligible level by requiring a minimum charged track multiplicity.

Sources of high multiplicity events include beam-gas interactions (the beam interacts with residual gas left in the beam pipe) and 2-photon interactions. However, the tracks from these processes are produced in a very forward direction and typically have a total energy far below that of the available center of mass energy. Hence these events can be rejected by imposing a minimum energy constraint and demanding the event does not have a 'forward' topology.

To reduce these backgrounds, the following selection criteria were required:

(a) At least 3 charged tracks in one hemisphere.
   (A hemisphere is defined by the plane perpendicular to the beam direction and passing through the center of the interaction point.)

(b) \( \Sigma P_T^2 > 9 \text{ (GeV/c)}^2 \).

The multiplicity cut removes cosmic events and leptonic events (with the exception of a small fraction of \( \tau^+\tau^- \) events). The \( P_T^2 \) cut rejects contamination from beam gas and two photon interactions. The overall efficiency of these criteria for identifying true hadronic events was determined to be \( \epsilon_{had} = (94.3 \pm 1.0)\% \). Background from \( \tau^+\tau^- \) decays was found to be \( (1.3\pm0.3)\% \). Beam gas and two photon interactions contributed less than 0.1% each to the background.
the simulation to the data as described above. The agreement is very good. Figure 3.2 shows the $\cos \theta_T$ for the data and simulation where $\theta_T$ is the polar angle between the thrust axis and the beam axis. Excellent agreement is observed in all but the most forward regions.

Photon Definition

The selection of $e^+e^- \rightarrow q\bar{q}\gamma$ events requires that the photon in the data be strictly defined. For this analysis, a neutral, electromagnetic shower in the HPC is defined to be a photon. The terms neutral and electromagnetic are described more fully in the following paragraphs.

A neutral shower is defined to be a reconstructed track element (TE) [33] in the HPC that is not linked to a charged track. The complete procedure for linking a charged track to an HPC TE, or shower, requires an extended discussion that is beyond the scope of this thesis (see [46] for details). In essence a shower in the HPC is linked to an extrapolated charged track if the spatial separation between the two is less than 4 cm. at the entrance of the HPC.

The HPC pattern recognition also attempts to distinguish electromagnetic showers (i.e., photons and electrons) from hadronic showers (i.e., neutrons and pions) by studying the longitudinal and transverse structure of the shower. A general description of the procedure is outlined here and additional material is available in [47]. The method used to separate the two classes of showers is a statistical one known as canonical discriminant analysis. Given two classes of observations with measurements on $N$ variables, the canonical discriminant analysis finds a linear combination of the $N$ variables (hence finding $N$ coefficients) that maximizes the multiple correlation with the classes. The variable defined by this linear combination is called the canonical variable and can show substantial differences between the classes even if the original $N$ variables do not.

To implement this technique, Monte Carlo samples of electrons and pions were produced at different energies and angles. A set of $N$ variables was selected to describe the longitudinal and transverse shape of the showers. Examples of these variables are: the total shower energy, the energy deposited in each layer, the layer number where the maximum energy is found, the fraction of energy deposited in the
Figure 3.1: The thrust value, $T$, for events satisfying the hadronic criteria.
Figure 3.2: The $\cos\theta_T$ for events satisfying the hadronic criteria. $\theta_T$ is the angle between the thrust axis and the $e^+e^-$ beam direction.
maximum layer, the fraction of energy deposited in the last two layers of the shower, etc. For each energy and angle, the statistical package SAS [48] was used to find the set of \( N \) coefficients, or weights, that leads to the best separation of the two classes of showers. These weights are used by the HPC pattern recognition program to calculate the associated canonical variable. The distribution of the canonical variable for \( E = 8 - 12 \text{ GeV} \) is shown in Figure 3.3. The two classes of showers are well separated by this procedure. By placing a cut on the canonical variable, one can establish the fraction of electromagnetic showers to be identified. The pattern recognition places a restriction on the value of the canonical variable such that the fraction of e-m showers retained is 95%. Showers that satisfy this criterion are labeled as electromagnetic. For showers of greater than 5 Gev, the probability of misidentifying hadronic showers as e-m showers is less than 1%.

The events of interest in this study correspond to the final state radiation of a photon by a quark. One background process contributing to events with a \( q\bar{q}\gamma \) topology is due to initial state radiation by the incident electron or positron. Such events are produced primarily in the forward/backward direction (parallel to the beam axes). By requiring the photon to be contained within the barrel region of the detector, \( 45^\circ \leq \theta \leq 135^\circ \), the background from initial state radiation is reduced to a negligible level. Thus we do not use showers identified by the forward electromagnetic calorimeter (FEMC) in this analysis.

Geometrical constraints were also applied to the starting position of the electromagnetic shower in the HPC to ensure proper reconstruction. Because of mechanical supports in the middle of the detector the photon was rejected if it was found in the angular region \( 88^\circ \leq \theta \leq 92^\circ \). Another class of photons not well understood at the time of this analysis are those that span the space between the inner and middle rings of the HPC modules. Hence photons that spanned two modules were rejected for this study. This corresponds to photons with an extrapolated \( z \)-coordinate (extrapolation to entrance of the HPC module, \( R = 208 \text{ cm} \)) of \( 75 < | z_{ext} | < 92 \text{ cm} \). Figure 3.4 and Figure 3.5 show \( \theta \gamma \) and \( z_{ext} \) for the photons with \( E_\gamma \geq 8 \text{ GeV} \) after these fiducial criteria have been applied. (The significance of the \( E_\gamma \geq 8 \text{ GeV} \) criterion will be discussed later.)

To further ensure proper energy and position reconstruction, criteria are also
Figure 3.4: The polar angle $\theta_\gamma$ for photons with $E_\gamma \geq 8$ GeV. The data is represented by the crosses and the simulation by the histogram.
applied to photons that start showering at the 24 azimuthal boundaries of the HPC modules. Photons were rejected for this analysis if the shower started within ±1° of an HPC module boundary. Figure 3.6 shows the $\phi$ distribution of photons with $E_\gamma \geq 8$ GeV calculated modulo $15^\circ$, and after applying the $\phi$ criteria. Conceptually this overlays the $\phi$ distribution in each of the 144 modules. The 12 peaks and valleys observed in the data and simulation correspond to the cathode pads located in the first row.

A final fiducial requirement is placed on the starting position of the photon in the HPC with respect to the six TPC sector boundaries. It is possible for an energetic charged track to traverse a crack in the TPC, failing to leave a signal but producing a shower in the HPC. Therefore, a photon is rejected if it is closer than ±1° to the boundary of a TPC sector.

The number of hadronic events that have at least one photon with $E_\gamma \geq 8$ GeV and satisfying all the fiducial requirements is 15235 in the data as compared to 17608 in the Monte Carlo. Figure 3.7 and 3.8 shows the thrust and angular distribution of the thrust axis for these events. The number of photons with $E_\gamma \geq 8$ GeV and satisfying the fiducial requirements is 16672, and is predicted to be 19573 from the simulation.

The simulation does a good job in reproducing the shape of the thrust, $T$, and $\cos \theta_T$ distributions, but overestimates the absolute number of photons satisfying the cuts. In what follows we present evidence that this discrepancy is dominated by photons that fail our isolation criteria, i.e., photons within jets. These are the vast majority of all photons in hadronic events. Simulation of the detector response to such photons is a difficult task. The large amount of hadronic energy deposition due to the high multiplicity jets also makes electromagnetic shower identification and energy measurements difficult for photons within jets. We expect these discrepancies to be reduced in the future as our understanding of the response of the electromagnetic calorimeter increases.

Figure 3.9 shows the energy distribution of all photons satisfying the fiducial requirements for the data and simulation. Figure 3.10 shows the transverse momentum of the photon with respect to the thrust axis, $P_\perp$, for those photons with $E_\gamma \geq 8$ GeV and within the fiducial criteria.
Figure 3.6: The azimuthal angle modulo $15(\phi_{\gamma})$ for photons with $E_{\gamma} \geq 8$ GeV. Crosses represent data and the histogram represents simulation.
Figure 3.7: The thrust value, $T$, for events with a photon of $E_{\gamma} \geq 8$ GeV and satisfying the fiducial criteria.
Figure 3.9: The photon energy distribution, $E_\gamma$, for photons satisfying the fiducial criteria.
Figure 3.10: The photon $P_{t}$ distribution for photons with $E \geq 8$ GeV and satisfying the fiducial criteria.
The shape of both distributions are reproduced well by the simulation, particularly for higher energy photons. As expected, some discrepancy is also evident. In Figure 3.10 the difference is especially worse for low $P_\perp$ photons. These are photons that are generally aligned with the thrust axis. Hence, photons within jets show the greatest discrepancy between data and simulation as was discussed earlier.

Photons from Final State Radiation

The selection criteria described up to now have been made so that only well reconstructed electromagnetic showers are used in the analysis. At this point additional criteria are needed to separate FSR $q\bar{q}\gamma$ events from other events which have a $q\bar{q}\gamma$ topology. Other known physics processes which have a $q\bar{q}\gamma$ topology were outlined in Chapter 1: initial state radiation (ISR), secondary quark radiation (SQR), QCD processes, charged hadrons, and $\tau^+\tau^-$ events. Figure 3.11 shows the energy spectrum of photons from FSR, ISR, SQR, and QCD ($\pi^0$ only) predicted by JETSET 7.2 [7]. The photon has been required to be in the polar region $|\cos \theta| < 0.8$. Detector simulation has not been included in this calculation. At low energies SQR and ISR are significant $q\bar{q}\gamma$ processes relative to FSR. For this analysis the photon is required to have an energy of 8 GeV or more. This cut suppresses ISR relative to FSR by over an order of magnitude, and for this analysis ISR is further reduced since a more restricted polar region used is, $|\cos \theta| \leq 0.707$. The SQR contribution is suppressed by more than two orders of magnitude relative to FSR. Hence, ISR and SQR will be essentially negligible in this study. However, background from two photon production in $\pi^0$ decay still dominates the signal from FSR by over two orders of magnitude.

The vast majority of photons from $\pi^0$ decay are found in jets since the $\pi^0$ originates from the quark fragmentation process. Due to the limited transverse momentum in the fragmentation process, the $\pi^0$ (and hence the photon) are produced predominantly in the original quark direction. Photons from FSR originate from the decay process $Z^0 \rightarrow q\bar{q}$ where one quark radiates a photon. These photons have a much broader angular distribution with respect to the quark direction. Therefore, the background contribution from $\pi^0$ decay can be reduced by placing isolation criteria on the photons. Figure 3.12 shows the angle between the photon and the nearest charged track of more than 0.5 GeV/c for the data and the simulation. The
Figure 3.11: The energy spectrum for the known physics processes that may have a $q\bar{q}\gamma$ topology. The plot is produced from a Monte Carlo generation of $10^6 e^+e^- \rightarrow q\bar{q}$ events using JETSET 7.2 [7]. The photon is required to be in the angular range $|\cos \theta| \leq 0.8$. 
agreement between the data and simulation for the 'charged track isolation angle' (CTIA) is good, with the exception of the low CTIA region. This region of CTIA discrepancy consists of non-isolated photons, or photons in jets, as discussed earlier. Figure 3.13 shows the Monte Carlo prediction for the angle between the photon and the nearest charged track of more than 0.5 GeV/c for photons originating from background processes and for photons originating from FSR. The CTIA distribution for the background processes is strongly concentrated at low values since the photons are produced in the fragmentation process. However, while the CTIA distribution for FSR photons is also peaked at lower values of the isolation angle, a significant fraction of FSR photons are distributed throughout the entire region. Therefore, requiring the photon to be isolated will reduce the background from QCD processes considerably while retaining a reasonable fraction of FSR photons.

For this analysis the photon is required to be at least 20° away from all charged tracks with momentum greater than 0.5 GeV/c. The direction of the photon (or neutral particle) is defined by the starting position of the reconstructed shower (TE) in the HPC, using the interaction point as the origin of the photon. The direction of a charged particle is determined by use of its reconstructed momentum vector. The number of events remaining after this cut is 519.0 in the data compared to 471.9 in the Monte Carlo. The Monte Carlo includes contributions from all known processes, FSR, ISR, SQR, QCD processes and tau background. The simulation predicts that 128.6 of the remaining events are from FSR and 343.3 are from the background processes. Over 90% of the background events are due to photons from $\pi^0$ decay and the rest are essentially from $\tau^+\tau^−$ events.

It is also possible for background photons to be produced in neutral jets. A fraction of these photons can be excluded by also placing isolation criteria on the photons with respect to neutral showers in the HPC. Figure 3.14 shows the angle between the photon and the nearest neutral track in the HPC of more than 2.0 GeV for the data and simulation. (The CTIA criteria is not included.) The structure of the 'neutral track isolation angle' (NTIA) for the simulation is in good agreement with the data. Again, some differences are observed for photons that are not isolated, i.e., that are located in the low NTIA region. Figure 3.15 shows the NTIA distribution for the Monte Carlo background processes and for FSR alone. Like the CTIA case,
Figure 3.12: The charged track isolation angle (CTIA) for photons from the data and the simulation. The photons satisfy the energy and fiducial criteria described in the text. The CTIA is the angle between the photon and the nearest charged track with momentum greater than 0.5 GeV/c.
photons from background processes are sharply concentrated at low isolation angles while FSR photons are distributed throughout the range of isolation angles.

However, unlike the CTIA distribution, the NTIA distribution has a larger fraction of events distributed at high values of the NTIA (140° < θ < 180°). There are a number of reasons for this. Recall that only the HPC is used for neutral particle detection, while charged particles are detected in the polar region 20° ≤ θ ≤ 160°. Hence there are fewer neutrons with which to calculate isolation angles and the neutrons that are used tend to be further away. The HPC also has a much larger aggregate dead region than the TPC in the azimuth angle. The HPC has 24 cracks that are about ±1° wide each, while the TPC has only 6 cracks that are about ±1° each. Furthermore, the dead region of the TPC affects primarily high momentum particles. Unlike photons, a low momentum charged particle is bent in the magnetic field, thus crossing the boundary of two TPC sectors and generally leaving enough signal in each sector so that the charged track can be reconstructed.

The large fraction of background events at high NTIA values is not a serious problem as the CTIA and NTIA are highly correlated. Figure 3.16 and 3.17 show scatter plots of the CTIA versus the NTIA for the for FSR events and background processes respectively. The CTIA criteria rejects nearly all the background events with a high NTIA value. This is simply a reflection of the fact that most of the photons are produced in jets containing both charged and neutral particles. Figure 3.18 shows the NTIA distribution for FSR and background as predicted by the Monte Carlo after placing the CTIA criteria on the photon. Based on these plots, this analysis further reduces non-FSR events by using photons that are at least 20° away from all neutral tracks with an energy greater than 2.0 GeV.

Table 3.1 shows a summary of the criteria used to separate FSR events from events with similar qqγ topologies. A total of 308 events from the real data satisfy the selection criteria while the simulation predicts 302.3 normalized events. The number of events the Monte Carlo attributes to FSR is 126.3 and the remaining events are due to background processes.

A number of systematic errors arise when applying these criteria using a Monte Carlo technique. Ideally one would like to generate many simulation data samples that are each about the size of the data sample, and then compare results between
Figure 3.15: The neutral track isolation angle (NTIA) for photons from Monte Carlo FSR events and Monte Carlo background events. The photons satisfy the energy and fiducial criteria described in the text. The NTIA is the angle between the photon and the nearest neutral track with momentum greater than 2.0 GeV/c.
Figure 3.16: The CTIA vs. NTIA distribution for photons from Monte Carlo FSR events. The photons satisfy the energy and fiducial criteria described in the text.
Figure 3.17: The CTIA vs. NTIA distribution for photons from Monte Carlo background events. The photons satisfy the energy and fiducial criteria described in the text. The CTIA and NTIA are highly correlated reflecting the fact that most photons are found in jets containing both charged and neutral particles.
Figure 3.18: The NTIA distribution for photons from Monte Carlo FSR events and Monte Carlo background events after applying the CTIA criteria.
Table 3.1: Summary of selection criteria for a FSR photon.

<table>
<thead>
<tr>
<th>Selection</th>
<th>Criteria</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fiducial</td>
<td>$45^\circ \leq \theta \leq 88^\circ$</td>
</tr>
<tr>
<td></td>
<td>$92^\circ \leq \theta \leq 135^\circ$</td>
</tr>
<tr>
<td></td>
<td>$\phi &gt; \pm1^\circ$ from all HPC boundaries</td>
</tr>
<tr>
<td></td>
<td>$\phi &gt; \pm1^\circ$ from all TPC boundaries</td>
</tr>
<tr>
<td>Energy</td>
<td>$E(\gamma) \geq 8\text{GeV}$</td>
</tr>
<tr>
<td>Isolation</td>
<td>$CTIA(&gt;0.5\text{GeV}/c) &gt; 20^\circ$</td>
</tr>
<tr>
<td></td>
<td>$NTIA(&gt;2.0\text{GeV}/c) &gt; 20^\circ$</td>
</tr>
</tbody>
</table>

The samples. This approach was not feasible because of the tremendous computing time needed. Systematics were arrived at by varying the criteria slightly over an appropriate range of values.

The error due to the HPC acceptance of a photon depends upon the fiducial criteria and the requirement that a shower in the HPC be an electromagnetic shower. Systematic errors due to the fiducial cuts were studied by comparing the number of photons in the data and the Monte Carlo as a function of the fiducial criteria. The error due to requiring the photon to be an electromagnetic shower was also studied in the same manner. Based on these studies a systematic uncertainty of 3% is assigned to the HPC acceptance after applying fiducial and shower class criteria to the photon.

Another source of error is that due to the uncertainty in the energy resolution of the HPC. Monte Carlo studies have consistently found a lower energy resolution than that suggested by the data from $e^+e^- \rightarrow e^+e^-$ events. An estimate of the difference can be found by using the simple view that the number of photons above some energy is a product of the HPC resolution and the falling energy spectrum of the photon. By estimating the difference in the number of events found for an optimistic and pessimistic HPC energy resolution, a 3% systematic uncertainty is assigned to the acceptance of a photon with $E_\gamma \geq 8\text{ GeV}$.

The isolation requirements produces the largest source of uncertainty. Studies of the data and simulation have been done over a range of isolation angles at different photon energy criteria. Tracks of varying minimum energy were also used to study
the CTIA and NTIA. Based on comparing data and simulation from these studies, a systematic uncertainty of 7% was assigned to the isolation requirements.

A set of criteria has now been established to select isolated energetic photons. The motivation for these selection criteria is to separate $q\bar{q}\gamma$ event topologies due to FSR from background events that have a similar event topology. The results of this selection criteria are presented in the following chapter.
CHAPTER 4. RESULTS

This chapter discusses the results obtained from the study of events with isolated photons using the criteria applied in Chapter 3. Results for final state radiation are presented first by comparing data and simulation for the known process that contribute $q\bar{q}\gamma$ event topologies. This includes a measurement of the cross section for final state radiation, and a determination of the sum of the up-type and down-type quark coupling constants. Based on these results, it is possible to place upper limits on the cross section times branching ratio for the rare and new processes; (a) $\sigma(e^+e^- \rightarrow Z^0 \rightarrow H^0 \gamma) \cdot \text{BR}(H^0 \rightarrow q\bar{q})$, (b) $\sigma(e^+e^- \rightarrow Z^0 \rightarrow q q^*) \cdot \text{BR}(q^* \rightarrow q \gamma)$, and (c) $\sigma(e^+e^- \rightarrow Z^0 \rightarrow Z^* \gamma) \cdot \text{BR}(Z^* \rightarrow q\bar{q})$. 

Data and Monte Carlo

In Chapter 3 a number of criteria were demanded of the data in order to separate FSR events from background events. Table 4.1 shows a summary of the number of events remaining after each criteria is applied. The number of events is shown for the real data and for the Monte Carlo prediction, where the simulation includes the known processes contributing to a $q\bar{q}f$ event topology: FSR, ISR, SQR and $\pi^0$ decay to two photons, and tau decays. The event count for simulation is further split into two categories, FSR and non-FSR processes.

After applying this set of criteria to the real data, a total of $308 \pm 17.5 \text{(stat.)} \pm 25.2 \text{(syst.)}$ events remain. The first error is statistical and the second systematic, where the systematic error is the quadrature sum of the error due to HPC acceptance and energy resolution, the isolation criteria and the background subtraction. The Monte Carlo simulation predicts a total of $302.3 \pm 18.2 \text{(stat.)}$ events, $126.3 \pm 11.9 \text{(stat.)}$ from FSR and $176.1 \pm 13.8 \text{(stat.)}$ from other processes (over 90% due to $\pi^0$ decay.
Table 4.1: Number of *events* surviving successive criteria and the contributions expected from simulation.

<table>
<thead>
<tr>
<th>Selection</th>
<th>DATA Observed</th>
<th>MC Total</th>
<th>MC FSR</th>
<th>MC ISR + QCD + τ</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hadronic Z's</td>
<td>97264</td>
<td>97264</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Normalized</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$E_\gamma &gt; 8$ GeV</td>
<td>19919</td>
<td>22492</td>
<td>239</td>
<td>22234</td>
</tr>
<tr>
<td>$45^\circ &lt; \theta_\gamma &lt; 88^\circ$</td>
<td>18884</td>
<td>21646</td>
<td>239</td>
<td>21407</td>
</tr>
<tr>
<td>$92^\circ &lt; \theta_\gamma &lt; 135^\circ$</td>
<td>16579</td>
<td>19729</td>
<td>215</td>
<td>19514</td>
</tr>
<tr>
<td>$z_{ext}$ fiducial cut</td>
<td>15235</td>
<td>17608</td>
<td>197</td>
<td>17411</td>
</tr>
<tr>
<td>$\phi$ fiducial cut</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CTIA($&gt;0.5$GeV) &gt; 20°</td>
<td>519.0</td>
<td>471.9</td>
<td>128.6</td>
<td>343.3</td>
</tr>
<tr>
<td>NTIA($&gt;2$GeV) &gt; 20°</td>
<td>308.0</td>
<td>302.3</td>
<td>126.3</td>
<td>176.0</td>
</tr>
<tr>
<td>$P_\perp (\gamma) &gt; 5$GeV</td>
<td>202.0</td>
<td>189.5</td>
<td>116.1</td>
<td>73.4</td>
</tr>
</tbody>
</table>

alone). Figure 4.1 shows the photon energy distribution of the events for the real data, the simulated data of all processes, and the simulated data for FSR only. The error on the data is statistical only. Figure 4.2 shows the ratio of the number of events in the data to the number in the simulation. The error bars in this Figure include all statistical and systematic errors. The discrepancy in the first two energy bins is rather large, but still within 1.5 \(\sigma\) of the combined statistical and systematic error. Good agreement is observed for the remainder of the photon energy spectrum. Hence the data are consistent with the Monte Carlo for both the event count and the photon energy distribution.

Another quantity of interest for comparison is the transverse momentum of the photon relative to the thrust axis, $P_\perp$. The interest in this quantity arises from the possibility of reducing the background contribution (primarily $\pi^0$ decay) in the event sample. Unlike photons from FSR, the $\pi^0$ decay photons originate from the fragmentation process, and are therefore produced primarily in the quark direction. One might expect the $P_\perp$ distribution of the FSR photons to be broader than for $\pi^0$
Figure 4.1: Energy distribution of isolated photons meeting energy and isolation criteria described in the text.
Figure 4.2: Ratio of the event count for the data as compared to the simulation. All known processes are included in the simulation. The photons satisfy the criteria described in the text. Statistical and systematic errors are included in the error on the ratio.
photons. Figure 4.3 shows the $P_{\perp}$ distribution of the photon for the data, simulation (all $q\bar{q}\gamma$ processes), and FSR only events. The data are in rather good agreement with the Monte Carlo over the full $P_{\perp}$ spectrum. The large contribution below 5 GeV/c is due almost entirely to two-photon decay of the $\pi^0$, hence the background to FSR can be greatly reduced by rejecting events with $P_{\perp}$ less than 5 GeV.

If the photon is required to have a $P_{\perp}$ of at least 5 GeV the number of isolated photon events in the data is reduced to $202 \pm 14.2$ (stat.) compared to $189.5 \pm 14.4$ (stat.) events in the simulation. The Monte Carlo simulation predicts $116.1 \pm 11.4$ (stat.) of these events are due to FSR and $73.4 \pm 8.7$ (stat.) are background. Hence the background is reduced by a factor of 2.40 while the number of FSR events is reduced by a factor of only 1.09.

This result is promising for reducing the background. However, the $P_{\perp}$ criterion only slightly affects the comparison of data to simulation. Figure 4.4 and Figure 4.5 show the photon energy distribution and photon energy ratio respectively after requiring the photon $P_{\perp}$ to be at least 5 GeV. The shape of the energy spectrum does not change significantly from the energy distribution before the $P_{\perp}$ criterion (see 4.1 and 4.2). In particular there is no significant improvement in the agreement between data and Monte Carlo in the first two energy bins. In the following analysis, results will be presented for both cases; without the $P_{\perp}$ criterion applied and including the $P_{\perp}$ criterion.

**Final State Radiation**

The study of FSR in the data requires that the background processes are known along with their associated error. Table 4.1 shows the number of non-FSR $q\bar{q}\gamma$ events predicted by the Monte Carlo and separated by production mechanism. The Monte Carlo predicts the number of events due to all background processes with a $q\bar{q}\gamma$ final state is $176.1 \pm 13.8$ (stat.) before applying the photon $P_{\perp}$ requirement. The dominant background comes from decay of a $\pi^0$ into two photons. Background from $\tau^+\tau^-$ events is expected to be $\sim 5\%$. Subtracting the Monte Carlo prediction of background from the data sample gives the number of isolated FSR photon events in
Figure 4.3: Transverse momentum distribution, $P_T$, with respect to the event thrust axis for data, simulation, and FSR only. The simulation includes all $q\bar{q}\gamma$ processes. The photons must satisfy the energy and isolation criteria described in the text.
Figure 4.4: Energy distribution of isolated photons after applying the photon $P_\perp$ criterion.
Figure 4.5: Ratio of the event count for the data as compared to the simulation. All known processes are included in the simulation. The $P_{\perp}$ criterion has been applied to both event samples. Statistical and systematic errors are included in the error on the ratio.
Figure 4.6: Photon energy distribution for FSR from the data and for FSR as predicted by the Monte Carlo. The photon $P_\perp$ criterion has not been applied.
Figure 4.7: Photon $P_T$ distribution for FSR from the data and for FSR predicted by the Monte Carlo.
Again the observation is adequately explained by the Standard Model simulation.

The energy distribution for FSR photons is shown in Figure 4.8 for the data and for the Monte Carlo after the $P_\perp$ criteria has been included. The two energy distributions are consistent. There is little change in the shape of the FSR energy distribution compared to the previous result without the $P_\perp$ demand (see 4.6).

In summary, we conclude that the number of energetic isolated photons found in the data is consistent with that predicted by Standard Model processes. There is no convincing evidence for an excess source of isolated photons. In particular the data sample selected is relatively rich in $qq\gamma$ events due to the process of FSR. These measurements supplement the findings of other experiments at LEP [9, 10, 49, 50] and experiments at lower center of mass energies [51].

For the remainder of the analysis only the results found without the photon $P_\perp$ criterion will be used.

**Quark Weak Coupling Constants**

As an alternative comparison with Standard Model predictions, we can use these data to calculate the sum of the electroweak couplings of the up-type (charge +2/3) and down-type (charge -1/3) quarks.

Recall from equation 1.9 in Chapter 1 that the partial width for final state radiation of photons off quarks is dependent on the charge and weak couplings of the quarks,

$$\Gamma_{qq\gamma} \propto S_{qq\gamma}$$  \hspace{1cm} (4.5)

where we use the notation

$$S_{qq\gamma} = \left(\sum_{f=1}^{N_q=5} e_f^2 \cdot c_f \right)$$  \hspace{1cm} (4.6)

for the sum of the quark coupling constants, $c_f$, and quark charges, $e_f$. Since the same cuts have been applied to the data and to the Monte Carlo, the proportionality of equation 4.5 holds true for both samples so that

$$\frac{(S_{qq\gamma})_{\text{exp}}}{(N_{qq\gamma})_{\text{exp}}} = \frac{(S_{qq\gamma})_{\text{MC}}}{(N_{qq\gamma})_{\text{MC}}}.$$  \hspace{1cm} (4.7)
The indices 'exp' and 'MC' refer to experimental values and Monte Carlo values respectively. \((N_{qq\gamma})_{exp}\) is the uncorrected number of FSR events in the data after all cuts have been applied, and after the predicted number of background events (ISR + QCD + \tau) have been subtracted. \((N_{qq\gamma})_{MC}\) is the number of FSR events predicted by the Monte Carlo, after being submitted to the same cuts as the data and normalized to the total number of hadronic events in the data. Thus, the earlier result on the number of events is transformed to a quantity that can be calculated, namely the sum of the quark weak coupling constants. If the couplings of each up-type quark are equal and each down-type quark are equal, as is true in the Standard Model and is assumed in the simulation, then the sum in equation 4.9 can be expressed as

\[
S_{qq\gamma} = \frac{1}{9} \cdot (3 \cdot c_{1/3} + 8 \cdot c_{2/3})
\]

where the up-type quarks have charge +2/3 and the down-type quarks have charge -1/3. All three down-type quarks contribute to the summation, while only two up-type quarks contribute since the \(t\) quark mass is known to be above the kinematically allowed region at LEP. Using our previous results on the number of FSR events found in the data and the number predicted by Monte Carlo, the sum of the quark couplings, \(S_{qq\gamma}\), is found to be

\[
S_{qq\gamma} = \frac{N_{Q=5}}{\sum_{f=1}^{N_{Q=5}}} e_{f}^{2} \cdot c_{f} = 1.58 \pm 0.26(\text{stat.}) \pm 0.13(\text{syst.})
\]

where the statistical error includes both the number of events observed in the data and the limited number of generated Monte Carlo events. For \(\sin^{2} \theta_{W} = 0.229\) the SM predicts \(S_{qq\gamma} = 1.52\). Thus the data are in good agreement with the Standard Model.

Cross Section Measurement

The determination of the FSR cross section in this thesis will be limited to the FSR cross section of photons with energy of at least 8 GeV, and in the angular region of \(45^\circ \leq \theta \leq 135^\circ\). With regard to this statement, this subsection presents the results for the differential cross section measurement of final state radiation. The differential
cross section is measured with respect to the photon energy, and also with respect to the photon $P_\perp$. The total cross section is obtained in three different ways. First, a simple count of FSR events is used to arrive at a total cross section measurement. Next, the two differential cross section measurements are each summed over to arrive at the value for the total FSR cross section.

Determination of the cross section for final state radiation requires that the number of events from FSR is known after correcting for background and acceptances. For the case where the number of FSR events are just counted the background subtraction and efficiency scaling are applied globally with respect to energy and $P_\perp$. For the differential cross sections, the background subtraction and efficiency scaling are applied bin by bin.

After applying all the selection criteria described in Chapter 4, the number of isolated photon events due to FSR in the data has been found to be $131.9 \pm 22.8$ (stat.)$ \pm 10.8$ (syst.). This number of events must be corrected for the acceptances of the selection criteria. These acceptances are arrived at using the Monte Carlo simulation of FSR only. Let $N_{1\text{FSR}}$ be the number of generated FSR photons that have a generated energy and angular distribution such that:

1. $45^\circ \leq \theta(\gamma) \leq 135^\circ$.
2. $E(\gamma) \geq 8$ GeV.

Next, let $N_{2\text{FSR}}$ be the number of generated FSR photons that have reconstructed properties such that the photon passes all the selection criteria described in Chapter 4. Then the product of all acceptances is

$$\epsilon_{\text{FSR}} = \frac{N_{2\text{FSR}}}{N_{1\text{FSR}}}$$

(4.10)

where the corrections included in this acceptance are:

- Loss of photons due to pair production and multiple scattering in the material before the HPC.
- Loss of photons due to the fiducial criteria on $\phi(\gamma)$ and $z_{\text{ext}}(\gamma)$.
- Loss of events due to the isolation criteria imposed on the photon.
From the simulation sample used, $N_{FSR} = 285$ and $N_{FSR}^2 = 112$. Thus the overall acceptance is determined to be $(39.3 \pm 6.1)\%$.

The resulting number of corrected FSR events is $335.7 \pm 56.7 (\text{stat.}) \pm 37.0 (\text{syst.})$. The first error is statistical only and the second error is due to the systematic error described earlier. This number represents the corrected final state bremsstrahlung events with a photon energy $E_\gamma \geq 8$ GeV and polar angle between $45^\circ$ and $135^\circ$.

The cross section is computed by normalizing to the measured hadronic cross section on the $Z^0$ peak. DELPHI has measured the hadronic cross section to be $30.89 \pm 0.17$ pb. at a center of mass energy of $91.22$ GeV [31]. The number of hadronic events from the data, 97264, was corrected for by subtracting the background and correcting for the efficiency as described in Chapter 3. The resulting number of corrected hadronic events is $101596 \pm 1168.7$. The cross section for FSR can then be written as

$$\sigma_{FSR} = \sigma_{\text{had}} \left( \frac{N_{FSR}^c}{N_{\text{had}}^c} \right)$$

(4.11)

where $N_{FSR}^c$ and $N_{\text{had}}^c$ are the corrected number of FSR events and hadronic events respectively. Hence the cross section for final state radiation in the kinematic region specified above is

$$\sigma_{FSR} = 101.7 \pm 17.2 (\text{stat.}) \pm 11.2 (\text{syst.}) \text{ pb.}$$

(4.12)

Another method for determining the total cross section for final state radiation is to measure the differential cross section relative to some physical quantity of the photon. The total cross section can then be found by summing up the differential cross sections. Figure 4.9 shows the differential cross section for final state radiation relative to the photon energy, $E_\gamma$, and Figure 4.10 shows the differential cross section relative to the transverse momentum of the photon, $P_{\perp}$. The background subtraction and normalization are computed bin by bin with the same method as described in the previous paragraphs. The total cross sections determined from each of the differential cross sections is in good agreement with the earlier result. These results are actually more meaningful since they rely on the Monte Carlo distributions of the photon energy and transverse momentum to agree with the data. The agreement between the two differential cross sections is a reflection of the fact that the photon energy
Figure 4.9: Differential cross section for FSR with respect to photon energy $E_\gamma$. 
Figure 4.10: Differential cross section for FSR with respect to transverse momentum of photon $P_{\perp}$.  

$$d\sigma/dP_T \ [\text{pb/GeV}]$$

$$P_T(\gamma) \ [\text{GeV}]$$
1. The quark momenta must first be estimated. Using all final state particles in the event, with the exception of the isolated photon, the Lund jet-finding algorithm [37] is invoked with default parameters. The jets found by Lund are ordered from increasing to decreasing momenta.

2. The event is then forced to have two jets, each jet being a first order estimate of the quark direction. Two jets are forced by first using the two highest momenta jets from Lund as jet 1 and jet 2. Then each particle not part of jet 1 or jet 2 is vectorally added to the jet it is closest to. The 4-momenta of the photon and two jets at this point are referred to as the unscaled 4-momenta.

3. In general the photon and two-quark 4-momenta will not sum to the center of mass 4-momenta because of measurement errors and missing particles, for example neutrinos. Most of the missing 4-momenta is expected to arise from the two jet reconstruction, since the photon 4-momenta is well measured by the electromagnetic calorimeter. Therefore, energy-momentum conservation is demanded by first scaling the energy of the two jets equally so that the photon and two jet energy equals the center of mass energy,

$$E_{cm} = E_{\gamma} + \alpha \cdot (E_{\text{jet}1} + E_{\text{jet}2})$$

where $\alpha$ is the energy scale factor for jet 1 and jet 2. The momentum of the jets is also scaled appropriately assuming a negligible quark mass,

$$\vec{P}'_{\text{jet}1} = \alpha \cdot \vec{P}_{\text{jet}1} \quad \text{and} \quad \vec{P}'_{\text{jet}2} = \alpha \cdot \vec{P}_{\text{jet}2}.$$  \hspace{2cm} (4.14)

4. Next, conservation of momentum is accomplished by fixing the photon momentum and moving the two jet momenta equally so that the sum of the photon and two jet momenta is identically zero, the center of mass momentum. If the missing momenta is $\Delta \vec{P}$ then

$$\Delta \vec{P} = -(\vec{P}_{\gamma} + \vec{P}'_{\text{jet}1} + \vec{P}'_{\text{jet}2})$$

and the new jet momenta are

$$\vec{P}''_{\text{jet}1} = \vec{P}'_{\text{jet}1} + \frac{1}{2} \cdot \Delta \vec{P}$$

$$\vec{P}''_{\text{jet}2} = \vec{P}'_{\text{jet}2}$$

\hspace{2cm} (4.16)
\[
\vec{P}_{jet2}' = \vec{P}_{jet2} + \frac{1}{2} \cdot \Delta \vec{P}.
\] (4.17)

The two jet energies are also scaled appropriately.

5. Finally a global rescaling is done so that the sum of the photon and two jet energies is equal to the center of mass energy,

\[
E_{cm} = \beta \cdot (E\gamma + E''_{jet1} + E''_{jet2})
\] (4.18)

where \( \beta \) is the global rescaling factor. The 4-momenta of the photon and two jets after this procedure are now conserved and are referred to as the scaled 4-momenta.

The validity of this rescaling method was studied using a Monte Carlo sample of isolated FSR photons. Hence the generated 4-momenta of the photon and two quarks are known and can be compared to the unscaled and scaled 4-momenta. Figure 4.11 shows the ratio \( R^u(P) = |\vec{P}_{jet1}'| / |\vec{P}_{jet1}^g| \) where \( \vec{P}_{jet1}' \) and \( \vec{P}_{jet1}^g \) are the unscaled reconstructed momenta and the generated momentum of jet 1 (the higher energy quark) respectively. The ratio after scaling, \( R^s(P) = |\vec{P}_{jet1}^s| / |\vec{P}_{jet1}^g| \) where \( \vec{P}_{jet1}^s \) is the scaled momentum of jet 1, is also shown. One observes that the scaling algorithm significantly improves the momentum magnitude and resolution of the first jet. The same ratios, \( R^u(P) \) and \( R^s(P) \), are also shown in Figure 4.12 for jet 2 (the lower energy quark) and in Figure 4.13 for the photon. Again, the momentum magnitude and resolution of jet 2 are considerably improved after the scaling procedure. The photon momenta changes very little because it is not altered until the final step of the scaling procedure.

A final check of the scaling algorithm was made by studying the invariant mass distributions for the \( q\bar{q} \) and \( q\gamma \) systems using the sample of Monte Carlo FSR events. The invariant mass of the \( q\bar{q} \) system can be expressed in terms of the photon energy and the center of mass energy (beam energy), \( E_{cm} \),

\[
M^2(q\bar{q}) = (\vec{P}_{jet1}' + \vec{P}_{jet2}')^2 = (\vec{P}_{cm} - \vec{P}_{\gamma})^2 = E_{cm}^2 \cdot (1 - \frac{2E_{\gamma}}{E_{cm}})
\] (4.19)
Figure 4.11: Ratios of unscaled, $R^u(P)$, and scaled, $R^s(P)$, momentum for jet 1. The ratios are defined by $R^u(P) = \frac{|\vec{P}_{jet1}^u|}{|\vec{P}_{jet1}^g|}$ and $R^s(P) = \frac{|\vec{P}_{jet1}^s|}{|\vec{P}_{jet1}^g|}$. 
Figure 4.13: Ratios of unscaled, $R^u(P)$, and scaled, $R^s(P)$, momentum magnitudes for the isolated photon. The ratios are defined by $R^u(P) = P_{\gamma}^u / P_{\gamma}^0$ and $R^s(P) = P_{\gamma}^s / P_{\gamma}^0$. 
Figure 4.14: Ratios of unscaled, $R^u(M)$, and scaled, $R^s(M)$, $q\bar{q}$ invariant masses. The ratios are defined by $R^u(M) = M^u(q\bar{q})/M^g(q\bar{q})$ and $R^s(M) = M^s(q\bar{q})/M^g(q\bar{q})$. 
Figure 4.16: Ratios of unscaled, $R^u(M)$, and scaled, $R^s(M)$, $q\gamma$ invariant masses for jet 2. The ratios are defined by $R^u(M) = M^u(q\gamma)/M^g(q\gamma)$ and $R^s(M) = M^s(q\gamma)/M^g(q\gamma)$. 
Figure 4.17: The invariant mass of the $q\bar{q}$ system, $M(q\bar{q})$, for the data and the simulation before applying the scaling procedure.
Figure 4.18: The invariant mass of the $q\bar{q}$ system, $M(q\bar{q})$, for the data and the simulation after applying the scaling procedure.
The $M(q\gamma)$ distribution for data and simulation is shown in 4.19 before applying the scaling procedure. Two entries per event are included for the two combinations of photon and quarks, since it is not possible to know a priori which quark-photon pair might originate from the $q^\ast$. Figure 4.20 shows $M(q\gamma)$ for the data and the simulation after scaling. Good agreement is again observed between the data and Monte Carlo before scaling and after scaling. The appearance of a peak at $M(q\gamma) \sim 40$ GeV is a kinematical effect due to the concentration of events with an isolated photon at low energy. Figure 4.21 is a scatter plot of $E(\gamma)$ vs $M(q\gamma)$ for the simulation. This plot shows the correlation between the low energy photons and the invariant mass peak at $M(q\gamma) \sim 40$ GeV. The resolution of the $M(q\gamma)$ distributions are determined by using the Monte Carlo techniques above. The $M(q\gamma)$ mass was calculated from the final reconstructed tracks and compared to the $M(q\gamma)$ mass from the generated partons. The scaled $M(q\gamma)$ resolution was determined to be approximately 4 GeV for the scaled photon/jets compared to about 7 GeV for the unscaled photon/jets. This difference in $M(q\gamma)$ resolution is shown by the different bin widths between Figure 4.19 and Figure 4.20.

To determine the limits on new processes in the next section we will use only the scaled invariant masses of the $q\bar{q}\gamma$ system.

**Upper Limits on New Physics**

The invariant mass distributions are reproduced well by Standard Model processes only (FSR, ISR, QCD, and tau). Since the data show no evidence of structure in the $M(q\bar{q})$ distribution nor in the $M(q\gamma)$ distribution we can place upper limits on the production rate for the new processes described in Chapter 1.

To determine the production rates for the new physics processes requires knowledge of the efficiency of our criteria for selecting $q\bar{q}\gamma$ events originating from the new processes. Monte Carlo techniques were used to determine the selection efficiency for each of the processes considered. The angular distribution used to model the $Z^0 \to H^0 \gamma$ decay was assumed to be $(1 + \cos^2 \theta)$ where $\theta$ is the angle between the $H^0$ and the beam axis [52]. The decay of the $H^0$ to fermions was assumed to be isotropic. The efficiency of the selection criteria as a function of the $H^0$ mass is shown in Figure 4.22.
Figure 4.19: The invariant mass of the $q\gamma$ system, $M(q\gamma)$, for the data and the simulation before applying the scaling procedure. Two entries per event are included, one for each possible $q\gamma$ combination.
Figure 4.21: Scatter plot of $E(\gamma)$ vs $M(\gamma\gamma)$ for the scaled data and the simulation. The peak in $M(\gamma\gamma)$ at $\sim 40$ GeV is a kinematical effect due to the concentration of photons at low energies.
Figure 4.22 also shows the efficiency of the selection criteria for an excited quark, \( q^* \), where our model assumed the angular distribution of \( e^+e^- \rightarrow Z^0 \rightarrow q \, q^* \) to be the same as \( Z^0 \) decay to normal quarks, \((1 + \cos^2 \theta)\), where \( \theta \) is the angle between the \( q^* \) and the beam axis. The decay of the \( q^* \) to a quark and a photon was taken as a bremsstrahlung process with an angular distribution of \( 1/\theta' \) where \( \theta' \) is the angle of photon emission.

The efficiency for a composite \( Z^0 \) is model dependent. For the off-mass-shell \( Z^* \) case, an isotropic angular distribution was used for the \( e^+e^- \rightarrow Z^0 \rightarrow \gamma \, Z^* \) reaction. The decay of the \( Z^* \rightarrow qq \) was assumed to have the same angular distribution as the SM \( Z^0 \), \((1 + \cos^2 \theta)\), where \( \theta \) is the Gottfried-Jackson angle of the \( Z^* \) decay into \( qq \) (the angle of the \( q \) momentum in the \( qq \) rest frame with respect to the \( qq \) momentum in the \( Z^0 \) rest frame.) The efficiency for this process is also shown in Figure 4.22. The treatment of efficiency with regard to determining upper limits on the two additional \( Z^0 \) composite models will be discussed below.

No significant structure is observed in the \( M(q\gamma) \) distribution (see Figure 4.18), thus the upper limit on the product of the cross section, \( \sigma(e^+e^- \rightarrow Z^0 \rightarrow H^0 \gamma) \), times the branching ratio \( BR(H^0 \rightarrow qq) \) can be determined. Figure 4.23 shows this limit as a function of the \( H^0 \) mass. The upper limit has been calculated at the 95% level and is less than 12 pb over the full \( H^0 \) mass range. This limit is an order of magnitude above the predictions of the Standard Model with a single Higgs iso-doublet.

The \( M(q\gamma) \) distribution also shows no evidence of an excited quark resonance (see Figure 4.20). Hence, the upper limit on the cross section, \( \sigma(e^+e^- \rightarrow Z^0 \rightarrow q \, q^*) \), times the branching ratio, \( BR(q^* \rightarrow q \gamma) \) can be determined. Figure 4.23 also shows this limit at the 95% confidence level as a function of the \( q^* \) mass. In particular the limits on a \( q^* \) mass are extended above the region \( M_{q^*} > M_Z/2 \).

The final limit we consider is on a composite \( Z^0 \) that decays to a photon and quarks. A number of different decay modes are possible: (1) \( Z^0 \) decay into a photon and off-mass-shell \( Z^0 \), referred to here as \( Z^* \), (2) anomalous three and four-boson couplings, and (3) \( Z^0 \) decay into a photon and a scalar partner, S. Case (1) and (2) may give a broad range of energies in the \( M(q\gamma) \) distribution. In Figure 4.23 we show the upper limit for the product of the cross section, \( \sigma(e^+e^- \rightarrow Z^0 \rightarrow Z^*) \), times
the branching ratio, $\text{BR}(Z^* \rightarrow q\bar{q})$, for the angular distribution given in Chapter 1. The upper limit is given at the 95% confidence level over the full mass range. The upper limit for case (2) is essentially the same as case (1) since the two cases may differ only by a small change in the angular distribution. Case (3) would give a nearly monochromatic photon, much like the $H^0$ process. Since no sharp peak is observed that deviates from the expected $M(q\bar{q})$ distribution, the limits for case (3) are effectively the same as the $H^0$ limits, since these two also differ only by a small change in the angular distribution.
CHAPTER 5. SUMMARY

We have studied the production mechanisms for isolated energetic photons in hadronic events at the DELPHI detector at LEP. The number of photons found in the data is consistent with the assumption of FSR and other Standard Model processes; ISR, QCD, and $\tau$ decays. In addition, the measured photon energy and $P_{\perp}$ distribution are in agreement with SM expectations. The sum of the quark couplings to the $Z^0$ were determined by these measurements to be

$$S_{\gamma qq} = \sum_{f=1}^{N_q=5} e_f^2 \cdot c_f = 1.58 \pm 0.26(\text{stat.}) \pm 0.13(\text{syst.}). \quad (5.1)$$

The cross section for FSR photons with $E \geq 8$ GeV and in the angular region $45 \leq \theta \leq 135^\circ$ was measured to be

$$\sigma_{FSR} = 101.7 \pm 17.2(\text{stat.}) \pm 11.2(\text{syst.}) \quad \text{pb.} \quad (5.2)$$

There is no evidence of anomalous photon production in the data. This allows us to placed upper limits at the 95% confidence level on the cross section times the branching ratio for three new processes that produce an isolated photon and quarks;

1. $\sigma(e^+e^- \rightarrow Z^0 \rightarrow H^0 \gamma) \cdot \text{BR}(H^0 q\bar{q})$,
2. $\sigma(e^+e^- \rightarrow Z^0 \rightarrow q q^*) \cdot \text{BR}(q^* \rightarrow q \gamma)$,
3. $\sigma(e^+e^- \rightarrow Z^0 \rightarrow Z^* \gamma) \cdot \text{BR}(Z^* \rightarrow q\bar{q})$.

The upper limits for these processes are a function of the mass of the new particle and range from 6 pb. to 20 pb. for the kinematic region studied.
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