Chapter 8

Summary and Conclusions

In this thesis I examined the production of events consisting of one or more photons and characterized by missing transverse energy using the L3 detector at the LEP electron-positron collider. I analyzed 619 pb^{-1} of data collected from 1998 through 2000 at center-of-mass energies $\sqrt{s} = 189 - 208$ GeV, the highest energies ever attained in an e^+e^- collider. Using these data, I selected a high-purity sample of well-reconstructed single- and multi-photon events with missing energy. This allowed me to study the production of neutrinos in e^+e^- collisions and to search for manifestations of new physics processes in a previously inaccessible range.

In this chapter I briefly summarize the main results of this thesis and compare them with results from other experiments. I conclude with a discussion on the potential of the upcoming Large Hadron Collider to probe the same types of physics beyond the Standard Model that I searched for in this thesis.

8.1 Summary of Results

Calibration of the BGO Calorimeter Using an RFQ Accelerator

In order to measure the energy and direction of photons, I used the BGO electromagnetic calorimeter of the L3 detector. A thorough understanding of its performance was essential for my analyses.

The Caltech L3 group pioneered a precise and rapid calibration technique using a pulsed H^- beam from a Radiofrequency Quadrupole accelerator to bombard a lithium target permanently installed inside the BGO calorimeter. The radiative capture reaction ${}^{7}_{3}\mathrm{Li}(\mathrm{p},\gamma){}^{8}_{4}\mathrm{Be}$ produced an intense flux of 17.6 MeV photons which we used to intercalibrate the 11,000 BGO crystals on a crystal-by-crystal basis. I analyzed the calibration data collected during 1997-2000 and determined the statistical precision of the RFQ intercalibration to be approximately 1%.

The absolute calibration of the BGO calorimeter was performed using events from the Bhabha scattering process $\mathrm{e}^+\mathrm{e}^-\rightarrow\mathrm{e}^+\mathrm{e}^-$, which I selected in the data collected by L3 during 1995-2000. I was able to improve the calibration algorithm and achieve a calibration precision of 0.5%, both for the barrel and endcaps of the BGO calorimeter. The BGO energy resolution was measured to be

$$\frac{\sigma_E}{E} = \frac{3.2\,\%}{\sqrt{E}} \oplus 0.85\,\% \;\; (E \text{ in GeV})\,,$$

giving a 1% resolution for photons with energies above 30 GeV. Equally important was the elimination of the resolution tails which substantially increased the sensitivity of my searches for new physics. For comparison, calibrations used during 1989-1996 provided a resolution of approximately 2% with significant resolution tails.

By measuring the effects of the BGO aging and non-linearity, I was able to determine the photon energy scale to a precision better than 0.5%. This significantly reduced the associated systematic uncertainty in my measurements of the cross section of the reaction $\mathrm{e}^+\mathrm{e}^-\rightarrow\nu\bar{\nu}\gamma(\gamma)$. I also found that the detector simulation program substantially underestimated the effects of shower leakage from the BGO into the hadron calorimeter. To address this problem, I developed a dedicated correction procedure.

Beginning in 1997, the RFQ calibration was used in the L3 data reconstruction and was shown to improve the quality of several physics analyses.[1] The experience gained in calibrating the BGO calorimeter is now successfully used for the calibration of the CMS lead tungstate calorimeter [166, 167].

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[1] Including searches for singlet heavy neutrinos in the decay channel $N\rightarrow\mathrm{eW}$, where the implementation of the RFQ calibration facilitated the suppression of the $\mathrm{W}^+\mathrm{W}^-$ background. This work was performed in collaboration with Dr. Sergey Shevchenko (Caltech) and resulted in stringent limits on the masses and couplings of heavy singlet neutrinos [214].

Measurement of Neutrino Production

In order to study neutrino production at LEP, I selected a sample of 2,022 single- and multi-photon events with missing energy. This sample consisted almost purely of events from neutrino pair-production accompanied by the emission of one or more photons, $e^+e^- \rightarrow \nu\bar{\nu}\gamma(\gamma)$. The residual background from other Standard Model processes and cosmic contamination was estimated to be below 1%.

As part of this work, I performed studies of the detector hermeticity, trigger efficiency, photon conversion, and cosmic contamination. In particular, my study of the photon conversion in the dead material in front of the central tracker eliminated the problem of large systematic effects seen by other photonic analyses of L3. I also developed a new anti-cosmic selection scheme by combining information from both the muon chambers and the scintillation counters. This anti-cosmic selection significantly reduced contamination from cosmic ray background while retaining acceptance for the $e^+e^- \rightarrow \nu\bar{\nu}\gamma(\gamma)$ events.

The cross section of the $e^+e^- \rightarrow \nu\bar{\nu}\gamma(\gamma)$ process was determined from the number of selected events. To quantify possible deviations from the Standard Model expectations, I computed the ratio of the measured to expected cross section at each center-of-mass energy. Averaging over the eight measurements yielded

$$\left\langle \frac{\sigma^{meas}_{\nu\bar{\nu}\gamma}}{\sigma^{exp}_{\nu\bar{\nu}\gamma}} \right\rangle = 0.987 \pm 0.022\,(stat) \pm 0.010\,(syst) \pm 0.010\,(theory)\,.$$

In the Standard Model of the electroweak interactions, the reaction $e^+e^- \rightarrow \nu\bar{\nu}\gamma(\gamma)$ proceeds through s-channel Z exchange for all neutrino flavors ($\nu_l = \nu_e, \nu_\mu, \nu_\tau$) and through t-channel W exchange for electron neutrinos only. Separating out the s-channel contributions gives a direct measurement of the invisible Z width, which in turn gives the effective number of light neutrino species N_ν. By performing a likelihood fit to the kinematic distributions of the selected $\nu\bar{\nu}\gamma(\gamma)$ events, I obtained

$$N_\nu = 2.95 \pm 0.08\,(stat) \pm 0.03\,(syst) \pm 0.03\,(theory)\,,$$

in good agreement with the Standard Model prediction of $N_\nu = 3$.

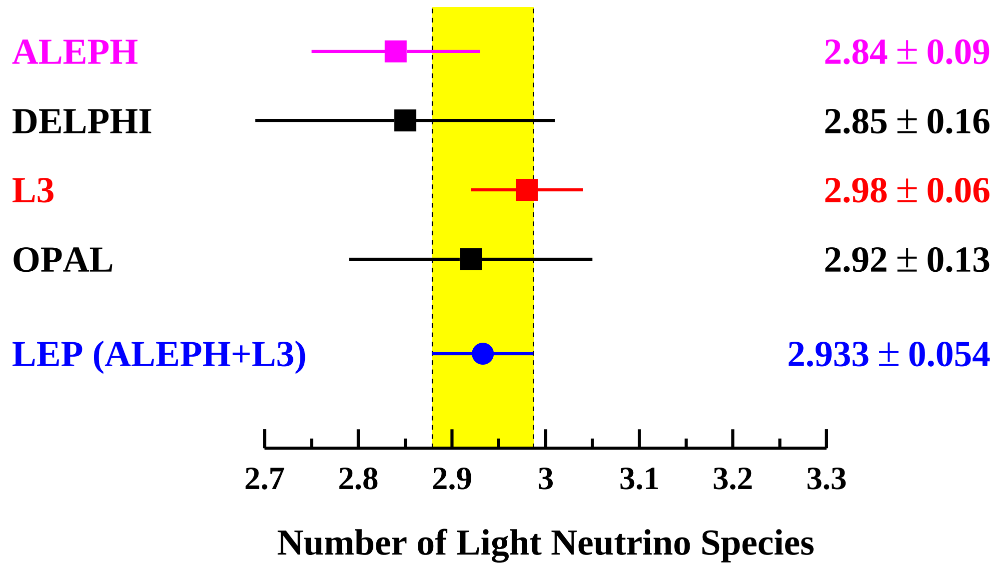

Figure 8.1: Measurements of the number of light neutrino species performed by the four LEP experiments. The error bars show combined statistical and systematic uncertainties. For comparison, the LEP−combined value of N_ν is also shown. In this combination, I considered the theoretical uncertainties to be completely correlated.

I combined my result with the L3 measurements performed at the beginning of LEP2 ($\sqrt{s} = 130 - 183$ GeV) and at LEP1 ($\sqrt{s} \simeq 91$ GeV), obtaining

$$N_\nu = 2.98 \pm 0.05\,(stat) \pm 0.04\,(syst)\,.$$

This result is in agreement with the indirect measurement of invisible Z width performed by L3 at LEP1 ($N_\nu = 2.978 \pm 0.014$ [183]), while being sensitive to different systematic and theoretical uncertainties.

The other three LEP experiments — ALEPH, DELPHI, and OPAL — have also studied the $e^+e^- \rightarrow \nu\bar{\nu}\gamma(\gamma)$ process. In Figure 8.1, I show a comparison of their measurements of N_ν with the result that I obtained in this thesis. OPAL has not the analyzed data collected during 1999-2000 at $\sqrt{s} = 192 - 202$ GeV [215], while the analysis performed by DELPHI suffered from significant systematic errors due to trigger inefficiencies and calorimeter calibration [216]. As a consequence, their measurements were substantially less accurate than my measurement. Compared to

OPAL and DELPHI, the ALEPH collaboration has reported a more precise measurement of N_ν [111]. However, combining my and ALEPH measurements provides little improvement over my result alone (see Figure 8.1).

I also used the selected sample of single- and multi-photon events to measure the size of the t-channel W exchange contributions in the reaction $\mathrm{e}^+\mathrm{e}^- \rightarrow \nu_\mathrm{e}\bar{\nu}_\mathrm{e}\gamma(\gamma)$. These contributions were parameterized by a multiplicative scale factor f_W, defined to be 1 for the Standard Model prediction. Assuming three light neutrino generations, I obtained

$$f_W = 0.99 \pm 0.06\,(stat) \pm 0.02\,(syst) \pm 0.02\,(theory)\,.$$

Contrary to the LEP1 measurement of $f_W = 0.1 \pm 0.5 \pm 0.3$ [173, 217], my measurement clearly established that the W-contributions were observed and were consistent with the expectations from the Standard Model. Therefore, this result can be interpreted as the first direct evidence for the reaction $\mathrm{e}^+\mathrm{e}^- \rightarrow \nu_\mathrm{e}\bar{\nu}_\mathrm{e}\gamma(\gamma)$.

Searches for New Physics

Photonic final states provide a rich hunting ground for new physics at $\mathrm{e}^+\mathrm{e}^-$ colliders. I was able to use my samples of single- and multi-photon events to search for manifestations of Supersymmetry, extra spatial dimensions, and anomalous gauge-boson couplings. I found no evidence for physics beyond the Standard Model and derived limits on the corresponding signal cross sections and model parameters. The main results of my searches are summarized below. All limits are quoted at the 95% confidence level.

Searches for SUSY Signatures

Different mechanisms have been suggested for symmetry breaking in SUSY models [31], which imply three different scenarios: “superlight,” “light,” and “heavy” gravitinos. At LEP, these scenarios could give rise to several distinct single- or multi-photon and missing energy signatures.

In no-scale supergravity models such as the LNZ model [193], the gravitino can become "superlight" (10^{-6} eV $\lesssim m_{\tilde{\mathrm{G}}} \lesssim 10^{-4}$ eV), leading to a sizable cross section for the reaction $\mathrm{e^+e^-} \rightarrow \tilde{\mathrm{G}}\tilde{\chi}_1^0$ with $\tilde{\chi}_1^0 \rightarrow \tilde{\mathrm{G}}\gamma$. I searched for this process and excluded gravitino masses below 10^{-5} eV for neutralino masses below 175 GeV.

Models with superlight gravitinos may also lead to pair-production of gravitinos accompanied by a photon from initial-state radiation, $\mathrm{e^+e^-} \rightarrow \tilde{\mathrm{G}}\tilde{\mathrm{G}}\gamma$ [72]. Even if the masses of all other SUSY particles were above $\sqrt{s}$, this process could still provide a means to detect Supersymmetry at LEP. My search resulted in the following lower limit on the gravitino mass:

$$m_{\tilde{\mathrm{G}}} > 1.35 \times 10^{-5}\ \mathrm{eV}\,,$$

which in turn corresponds to a lower limit on the SUSY breaking scale $\sqrt{F} > 238$ GeV. OPAL [215] and DELPHI [216] have also searched for this process, excluding gravitino masses below 0.87×10^{-5} eV and 1.09×10^{-5} eV, respectively. In addition, the CDF experiment at the Tevatron $p\bar{p}$ collider performed a search for the $q\bar{q} \rightarrow \tilde{\mathrm{G}}\tilde{\mathrm{G}}\gamma$ process and set the following limit: $m_{\tilde{\mathrm{G}}} > 1.17 \times 10^{-5}$ eV [218].

In gravity-mediated SUSY breaking models (SUGRA) the lightest neutralino is expected to be the lightest supersymmetric particle (LSP). This scenario may lead to a new source of multi-photon events from the reaction $\mathrm{e^+e^-} \rightarrow \tilde{\chi}_2^0\tilde{\chi}_2^0$, followed by the decay $\tilde{\chi}_2^0 \rightarrow \tilde{\chi}_1^0\gamma$ [62]. I found no evidence for this process and ruled out most of the SUSY parameter space allowed for the SUGRA interpretation of the rare $\mathrm{ee}\gamma\gamma$ event observed by CDF in 1995 (see Figure 7.11 p. 218).

In models with gauge-mediated SUSY breaking (GMSB) [55], the LSP is always a light gravitino, 10^{-2} eV $\lesssim m_{\tilde{\mathrm{G}}} \lesssim 10^{2}$ eV. If the next-to-lightest supersymmetric particle is the lightest neutralino, it decays predominantly through $\tilde{\chi}_1^0 \rightarrow \tilde{\mathrm{G}}\gamma$, and the reaction $\mathrm{e^+e^-} \rightarrow \tilde{\chi}_1^0\tilde{\chi}_1^0 \rightarrow \tilde{\mathrm{G}}\tilde{\mathrm{G}}\gamma\gamma$ gives rise to a multi-photon plus missing energy signature. My search resulted in the following lower limit on the neutralino mass:

$$m_{\tilde{\chi}_1^0} > 99.5\ \mathrm{GeV},$$

where I assumed the mass relations of the Minimal Gauge Model [194]. This search ruled out the GMSB interpretation of the CDF event, (see Figure 7.10b p. 218).

The other LEP experiments have also searched for this process and reported similar limits [111, 215, 216]. In addition, the Tevatron experiments have investigated the GMSB SUSY scenario by searching for anomalous production of di-photon events with missing energy. They have recently reported the following limits: $m_{\tilde{\chi}_1^0} > 93$ GeV by CDF [219] and $m_{\tilde{\chi}_1^0} > 108$ GeV by D∅ [220].

All of the above results were obtained assuming a negligible neutralino decay length. However, for much of the GMSB parameter space the neutralino has a macroscopic lifetime. In this case, one or both of the neutralinos produced in the reaction $\mathrm{e}^+\mathrm{e}^- \rightarrow \tilde{\chi}_1^0\tilde{\chi}_1^0$ may decay within the sensitive volume of the detector, but at a distance from the primary vertex. I investigated this scenario by searching for events with non-pointing photons not only in the BGO but also in the hadron calorimeter of L3. I found no candidate events in data, excluding neutralino masses below 89 GeV for $\tilde{\chi}_1^0$ proper decay lengths smaller than 100 m. For this scenario, only ALEPH have reported comparable limits [111].

Searches for Extra Dimensions

Models with extra spatial dimensions [77] predict a gravity scale to be as low as the electroweak scale, naturally solving the hierarchy problem. In such models, Kaluza-Klein gravitons could be produced at LEP via the reaction $\mathrm{e}^+\mathrm{e}^- \rightarrow \gamma\mathrm{G}$. Since the energy spectrum of the produced photons was expected to be soft, I extended my single-photon selection to include photons with transverse momenta as low as 1.5 GeV. For comparison, the other analyses performed at LEP had to apply a threshold cut of $P_t^\gamma \geq 5 - 7$ GeV. I found no evidence of extra dimensions, excluding gravity scales as high as 1.5 TeV. These limits are substantially tighter than those derived by other LEP experiments (see Table E.2 p. 304).

I also searched for branons $\tilde{\pi}$, new stable particles expected to be produced by brane fluctuations in extra spatial dimensions [82]. In this model, extra dimensions would manifest themselves at LEP through the reaction $\mathrm{e}^+\mathrm{e}^- \rightarrow \tilde{\pi}\tilde{\pi}\gamma$, leading to a single-photon signature. In the massless branon scenario, my search excluded brane tensions below 180 GeV. This is currently the best limit on branon production.

Measurements of Gauge-Boson Couplings

The existence of anomalous couplings between the photon and heavy gauge bosons would affect both the total cross sections and the differential distributions of the reactions $\mathrm{e}^+\mathrm{e}^- \to \nu\bar{\nu}\gamma$ and $\mathrm{e}^+\mathrm{e}^- \to \nu\bar{\nu}\gamma\gamma$.

In order to constrain possible anomalous quartic gauge couplings, I used the results of my multi-photon analysis. Combining with previous L3 results from studies of the $\mathrm{q\bar{q}}\gamma\gamma$ and $\mathrm{W}^+\mathrm{W}^-\gamma$ final states, I obtained the following limits on the anomalous coupling parameters:

$$-0.010\ \mathrm{GeV}^{-2} < a_0^{\mathrm{Z}}/\Lambda^2 < 0.020\ \mathrm{GeV}^{-2}, \quad -0.029\ \mathrm{GeV}^{-2} < a_{\mathrm{c}}^{\mathrm{Z}}/\Lambda^2 < 0.041\ \mathrm{GeV}^{-2},$$
$$-0.015\ \mathrm{GeV}^{-2} < a_0^{\mathrm{W}}/\Lambda^2 < 0.015\ \mathrm{GeV}^{-2}, \quad -0.046\ \mathrm{GeV}^{-2} < a_{\mathrm{c}}^{\mathrm{W}}/\Lambda^2 < 0.025\ \mathrm{GeV}^{-2},$$

where Λ is the energy scale of new physics. The analysis by OPAL has established similar bounds on the anomalous $\mathrm{ZZ}\gamma\gamma$ couplings $\{a_0^{\mathrm{Z}}, a_{\mathrm{c}}^{\mathrm{Z}}\}$ [221]. However, our limits on the $\mathrm{W}^+\mathrm{W}^-\gamma\gamma$ couplings $\{a_0^{\mathrm{W}}, a_{\mathrm{c}}^{\mathrm{W}}\}$ are more stringent than those obtained by other LEP experiments.

I also used the results of my single- and multi-photon analyses to probe the electromagnetic couplings of the W boson describing the triple-gauge-boson vertex $\mathrm{W}^+\mathrm{W}^-\gamma$. I measured these triple gauge couplings to be

$$\kappa_\gamma = 0.7 \pm 0.5\,(stat) \pm 0.3\,(syst)\,, \qquad \lambda_\gamma = 0.3 \pm 0.7\,(stat) \pm 0.4\,(syst)\,,$$

in good agreement with the Standard Model prediction of $\kappa_\gamma = 1$ and $\lambda_\gamma = 0$.

Combinations with Other LEP Experiments

The LEP collaborations have performed combinations of their results on searches for photonic signatures expected in Supersymmetry. As I discuss in Appendix E, these combinations did not result in a significant improvement over the results of my analyses alone, mainly due to the superior accuracy of the L3 BGO calorimeter which we precisely calibrated with the RFQ accelerator.

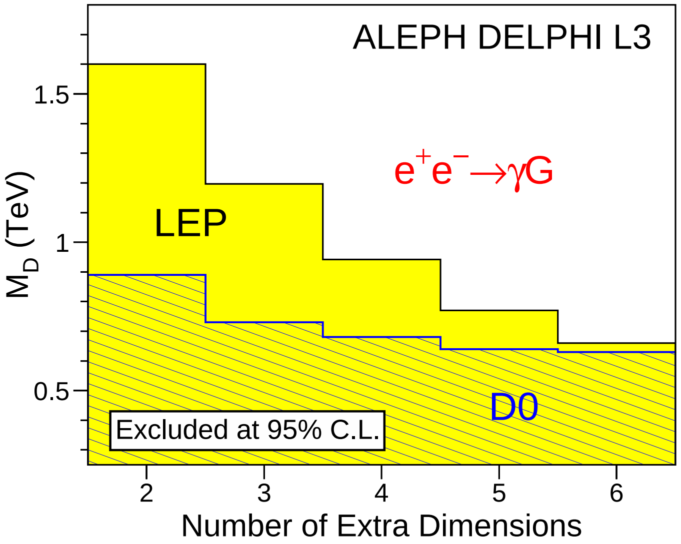

Figure 8.2: Constraints on the fundamental gravitational scale obtained by combining the LEP results on searches for extra spatial dimensions (ALEPH, DELPHI, and L3). Current limits [222] from the DØ experiment at Tevatron are also shown (CDF has quoted similar limits [223]).

As described in Section E.3, I also combined the LEP results on searches for the reaction $e^+e^-\rightarrow\gamma G$, predicted to occur in models with extra spatial dimensions. This LEP−combined search excluded gravity scales below between 1.6 TeV and 0.66 TeV for the number of extra dimensions (n) between 2 and 6. Figure 8.2 shows that for $n < 6$ the LEP limits are the best bounds to date on direct graviton emission in collider experiments.

8.2 Prospects at LHC

The Large Hadron Collider is scheduled to begin operation in 2007, with the first physics runs in early 2008. The LHC will collide proton beams at a center-of-mass energy of 14 TeV. After the first year of data taking, its two main detectors — CMS [224] and ATLAS [225] — are expected to collect about 10 fb^{-1} of integrated luminosity, which will increase to 100 fb^{-1} per year during the second and third years. In this section, I briefly describe the projected physics reach of these experiments with an emphasis on the new physics models I considered in this thesis.

The main motivation for building the LHC is to shed light on the mechanism responsible for electroweak symmetry breaking. The mass of the Standard Model Higgs should be above the current experimental limit from LEP, $M_H > 114.4$ GeV, and below the unitarity limit, $M_H \lesssim 1$ TeV. The CMS and ATLAS experiments have been designed to discover a Higgs boson in this mass range after just one year of physics running [226].

The LHC is also expected to provide a definitive answer on the existence of TeV-scale Supersymmetry. The squark and gluino production cross sections are expected to be as high as several hundred fb. If these SUSY particles are lighter than about 1.5 TeV, they should be discovered within the first few months or even weeks of data taking [226, 227]. The existence of extra spatial dimensions would lead to the emission of a graviton and a hadronic jet: $q\bar{q} \rightarrow g\mathrm{G}$, $qg \rightarrow q\mathrm{G}$, and $gg \rightarrow q\mathrm{G}$. With about 100 fb^{-1} of data, the LHC experiments should be able to detect this process for gravitational scales below $5 - 10$ TeV [228]. Finally, the quartic gauge-boson couplings will be probed by studying the vector-boson fusion processes. This analysis is expected to be sensitive to anomalous quartic couplings as low as 10^{-5} GeV^{-2} [229], improving the current limits from LEP by three orders of magnitude.

8.3 Conclusion

In this thesis I have studied the production of photonic events with missing energy in $\mathrm{e}^+\mathrm{e}^-$ collisions at LEP. The results of my studies were reported in eight publications [149, 200, 202, 208, 230] and three notes from the LEP working groups [231, 232].

Within the accuracy of my measurements, no deviations from the Standard Model predictions were observed. As of this writing, the same holds true for other physics analyses performed at LEP or any other collider experiments. The upcoming Large Hadron Collider will provide the first exciting opportunity to investigate the production of elementary particles at multi−TeV scales. The LHC is bound to either confirm the Standard Model by discovering the Higgs boson or challenge and extend our present understanding of Nature's laws and principles.