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Single- and Multi-Photon Events with Missing Energy in e^+e^- Collisions at LEP

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A brief review of searches for physics beyond the Standard Model using single- and multi-photon events with missing energy at LEP is given here. These include searches for supersymmetry, large extra dimensions, and anomalous neutrino production. Recent results from all four LEP experiments are presented, including improved limits on the new scale of gravity for models with large extra dimensions and the most precise direct measurement of the number of light neutrino species. Status and prospects of the LEP combined searches are also discussed.

Keywords: LEP; single photons; neutrino production; extra dimensions; SUSY.

1. Introduction

Single- and multi-photon events with missing energy were produced at LEP via the Standard Model (SM) reaction $e^+e^- \to \nu\bar{\nu}\gamma(\gamma)$. These experimental signatures are also predicted by a wide variety of theories with physics beyond the Standard Model. In particular, single- and multi-photon events can be used in direct searches for new neutral particles, such as graviton production in models with extra dimensions and neutralino and gravitino production processes in Supersymmetry (SUSY).

Results reviewed here are based on studies of such events by the four LEP collaborations, ALEPH, DELPHI, L3 and OPAL, using the highest center-of-mass energy, $\sqrt{s}$, and luminosity LEP data samples collected in 1998-2000 at $\sqrt{s} = 189 - 208$ GeV with an integrated luminosity of about 650 pb^{-1} per experiment.

2. Neutrino Production

In the SM of the electroweak interactions the reaction $e^+e^- \to \nu\bar{\nu}\gamma(\gamma)$ proceeds through s-channel Z exchange and t-channel W exchange, where the photons are radiated mainly from the incoming electrons and positrons. The distribution of the recoil mass to the photon system, M_{rec}, is expected to peak around the Z mass in the s-channel, whereas photons from the t-channel W exchange are expected to have

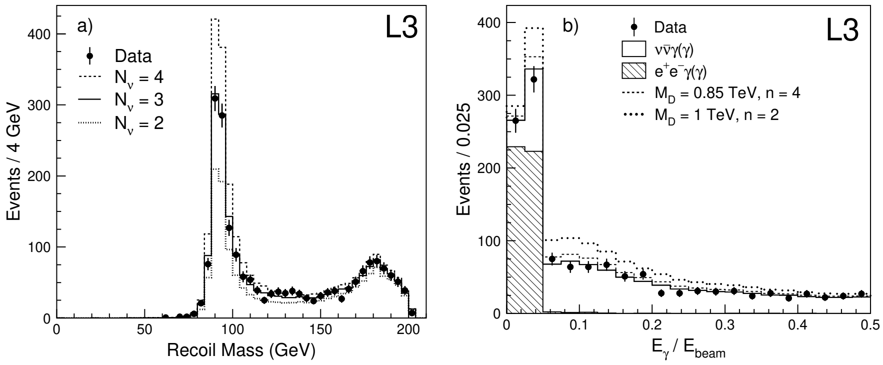

Fig. 1. a) The recoil mass spectrum of the single- and multi-photon events selected by L3 compared to the expected spectra for $N_\nu = 2, 3$ and 4. b) Distribution of the ratio of the photon energy to the beam energy, for the single-photon sample selected by L3. Expected signals from the reaction $\mathrm{e}^+\mathrm{e}^- \to \gamma\mathrm{G}$ are also shown.

a relatively flat energy distribution. A typical selection (L3) of single- and multi-photon events at LEP requires no charged tracks and the transverse momentum of the photon system, P_t^γ, greater than $0.02\sqrt{s}$. The purity of the selected $\nu\bar{\nu}\gamma(\gamma)$ sample is 99% and the selection efficiency is estimated to be about 71%.[1]

The expected total and differential cross sections depend on the number of light neutrino species, N_ν. The M_{rec} spectrum of the single- and multi-photon events selected by the L3 experiment is shown in Figure 1a) together with the expectations for $N_\nu = 2, 3$ and 4. To determine N_ν a maximum likelihood fit is performed to the two-dimensional distribution of M_{rec} *vs.* $|\cos\theta_\gamma|$. Including lower energy data, the number of light neutrino species is determined to be[1]

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

This result is more precise than the present world average of measurements relying on the single-photon method.[2] ALEPH[3] and DELPHI[4] have performed similar measurements of N_ν, which are also consistent with the SM value of $N_\nu = 3$.

3. Searches for Extra Dimensions

Models with large extra dimensions predict a gravity scale, M_D, as low as the electroweak scale, naturally solving the hierarchy problem. Gravitons, G, are then produced in $\mathrm{e}^+\mathrm{e}^-$ collisions through the process $\mathrm{e}^+\mathrm{e}^- \to \gamma\mathrm{G}$, and escape detection, leading to a single-photon signature.

All LEP experiments have performed searches for this reaction using selected samples of single-photon events. Since the photon energy spectrum from the graviton production is expected to be soft, the L3 experiment has also extended its standard single-photon selection to accept photons with P_t^γ as low as $0.008\sqrt{s}$.[1] In the low P_t^γ region the SM background is increased due to the reaction $\mathrm{e}^+\mathrm{e}^- \to \mathrm{e}^+\mathrm{e}^-\gamma(\gamma)$,

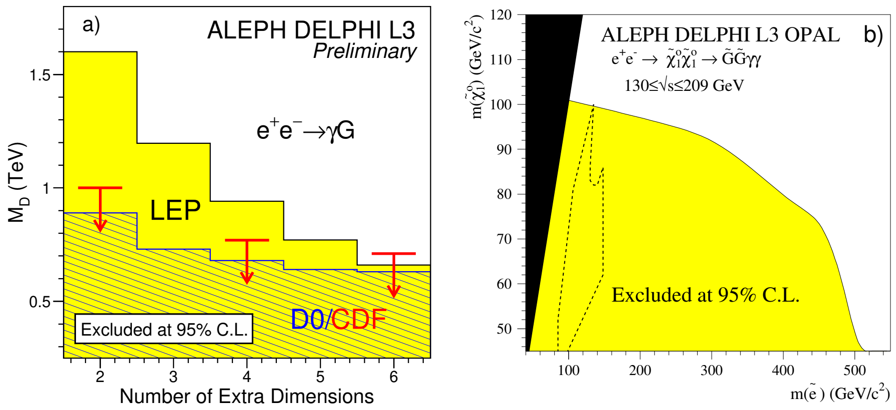

Fig. 2. a) The 95% CL exclusion contours in the M_D *vs.* n plane for the graviton-photon emission at LEP (ADL combined). Current limits from D0 and CDF are also shown. b) Region excluded at 95% CL in the $m_{\tilde{\chi}^0_1}$ *vs.* $m_{\tilde{\mathrm{e}}}$ plane. Overlaid is the region favored by the interpretation of the CDF event in the scalar electron scenario. These results are preliminary.

where both electrons have a very low polar angle and cannot be detected. However, this effect is compensated by a significant increase in the accepted signal cross section. Effects of extra dimensions on the L3 photon energy spectrum are shown in Figure 1b).

A good agreement with the SM expectation is observed and limits on the graviton production are derived from a fit to the photon energy and polar angle distributions. Recently, a combination of direct searches for large extra dimensions at LEP have been performed.[5] Lower limits between 1.6 TeV and 0.66 TeV are set, at the 95% CL, on the parameter M_D for the number of extra dimensions, n, between 2 and 6 (see Figure 2a). These are the best current collider limits for $n < 6$.

The presence of the brane in theories with extra dimensions creates additional degrees of freedom. Brane fluctuations in the extra-space directions would then manifest themselves as new stable particles, called "branons", $\hat{\pi}$. If the brane tension is below the gravity scale, branons can be detected at LEP via the reaction $\mathrm{e}^+\mathrm{e}^- \to \hat{\pi}\hat{\pi}\gamma$, leading to a single-photon signature. The signal properties are similar to those of the graviton production process. L3 has limited branon masses to be above 103 GeV for a scenario with small brane tensions. Alternatively, under the assumption of light branon masses, brane tensions below 180 GeV are excluded.[6]

4. Searches for SUSY

Single- and multi-photon events can be also produced by a variety of processes predicted in different models with supersymmetry (SUSY). These processes involve production and decays of neutralinos and gravitinos. No evidence for such models is observed and corresponding limits on SUSY parameters are given in References.[1,3,4] Combined searches are also performed by the LEP SUSY Working group.[7]

In particular, a search for pair-production of neutralinos, each decaying into a photon and a gravitino, is motivated by an interpretation of the rare $\mathrm{ee}\gamma\gamma$ event observed by CDF. This reaction, $\mathrm{e}^+\mathrm{e}^- \rightarrow \tilde{\chi}_1^0\tilde{\chi}_1^0 \rightarrow \tilde{\mathrm{G}}\gamma\tilde{\mathrm{G}}\gamma$, is predicted by models with gauge-mediated SUSY breaking when the lightest and next-to-lightest supersymmetric particles are gravitino, $\tilde{\mathrm{G}}$, and neutralino, $\tilde{\chi}_1^0$, respectively. The experimental signature of this process is very clean, involving events with two energetic acoplanar photons. No anomalous production of such events has been observed, and Figure 2b) shows the region excluded by LEP in the $m_{\tilde{\chi}_1^0}$ *vs.* $m_{\tilde{\mathrm{e}}}$ plane, where $m_{\tilde{\chi}_1^0}$ and $m_{\tilde{\mathrm{e}}}$ are the neutralino and scalar electron masses. The above interpretation of the rare CDF event is now excluded.

5. Conclusions

Searches for New Physics involving single- and multi-photon events with missing energy have been performed at LEP using the complete LEP data sample. These include searches for large extra dimensions and supersymmetry. No evidence of such models is found. Constraints on various New Physics theories are set by the LEP experiments separately and by preliminary LEP combinations. Several search strategies and results have been briefly reviewed in this paper. Individual references should be consulted for details.

The LEP combinations are expected to be finalized in the near future, and an improvement in sensitivity of the LEP combined searches with single- and multi-photon events is expected. The L3 experiment has also published the selection results in the form of tables,[1] which can be used to test future models involving such photonic final states at LEP.

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