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Search for Anomalous photon events at LEP [1)]

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Abstract

At e^+e^- high energy colliders, events with photons and missing energy can offer the first hint of the emergence of new physics. We report on the results obtained by the four LEP experiments concerning such anomalous events, in the 1996 data at $\sqrt{s} = 161 \div 172$ GeV. No new signal has been found in any of the searched processes and limits have been derived on the parameters of the models.

[1)]Invited talk at the International Europhysics Conference on High Energy Physics, 19-26 August 1997, Jerusalem.

1 Introduction

Events with photons, missing energy and nothing else in the detector can offer the first hint of the emergence of new physics. Near the Z centre of mass, the measurement of the cross section for the single photon process :

$$e^+e^- \rightarrow \gamma + nothing \tag{1}$$

has long been recognised as the direct method for the determination of the number of light neutrino generations and all experimental groups at LEP1 reported studies of the single photon production [1]. In fact, new physics processes, implying weakly interacting particles, could also arise through the same channel. This is particularly true at LEP2 for supersymmetric particles, where R-parity conservation leads to the prediction of an invisible lightest SUSY particle, generally assumed to be the lightest neutralino $\tilde{\chi}^0_1$. These invisible particles, carrying away energy and momentum, the experimental signature of supersymmetry could be a single detected photon with missing energy.

Photons (and new physics) can appear in two different situations:

- the photon is produced in the final state and all the remaining particles are invisible e.g in the radiative decay of neutralino, $e^+e^- \rightarrow \tilde{\chi}^0_2\tilde{\chi}^0_1 \rightarrow \gamma\tilde{\chi}^0_1\tilde{\chi}^0_1$.
- the final state is, either totally invisible e.g in $e^+e^- \rightarrow \tilde{\chi}^0_1\tilde{\chi}^0_1$, or nearly invisible, the particles being too soft to be seen or to trigger the detector, e.g in the production of charginos, mass-degenerate with neutralinos [2]. The photon is an initial state radiation (ISR) photon which is used to tag the event.

In the first case, the photon can have (generally) any energy, depending of the real spectrum of the final state particles. On the contrary, in the last case, the energy spectrum, from ISR emission increases exponentially when decreasing the energy and this detection is highly connected to the low energy detection capability of the detector.

Two photons + missing energy search is more recent and is mainly accountable to the 1995 CDF event $ee\gamma\gamma + \not{E}$, where two high energy electrons and two high energy photons with large missing transverse energy have been observed [3]. In the hypothesis where supersymmetry would be relevant for the explanation of the event topology, through pair production of $\tilde{e}$, the selectron interpretation, or $\tilde{\chi}^{\pm}$, the chargino interpretation, photonic states with 1 or 2 photons and missing energy, would be likely to appear at LEP energies [4, 5].

In this paper, we present the results with data collected in 1996 by the 4 LEP experiments. During this period, the machine delivered about $11pb^{-1}$ at $\sqrt{s} = 161$ GeV and about the same integrated luminosity at $\sqrt{s} = 172$ GeV. All the limits given are at 95 % confidence level and most of the results are preliminary. Published data can be seen in [6]. Except when mentioned, results at both centre of mass energies have been summed up. After a presentation of the obtained data, we discuss some of the interpretations proposed by the collaborations. These kinds of studies will continue to be developed in the coming years, as the LEP collider will reach higher centre of mass energies.

2 Experimental results

2.1 One photon data

Table 1 summarises the data collected for the $\gamma\not{E}$ channel. It shows the angular cuts, the energy cuts, the number of events expected from the Standard Model (SM) and the number of events collected by the 4 experiments. There are 2 columns for L3 as this experiment has a second independent analysis for the selection of low energy photons. The main contribution to the sample comes from the $\nu\bar{\nu}\gamma$ reaction, mainly due to a radiative return to the Z center of mass, followed by the Z decay into 2 neutrinos. The generators used agree at the few % level. Others contributions are negligible, except for radiative low angle Bhabha events in the case of the low energy sample. To illustrate these data, one can see in Figure 1, the recoil (missing) mass spectrum and the photon angular distribution obtained by the ALEPH collaboration and in Figure 2 the missing mass and the low energy photon distribution for the L3 experiment. For this last plot, one can see below 4 GeV, the increasing contribution of radiative low angle Bhabha scattering. Finally in Figure 3 is shown the result of the merging of ALEPH, L3 and OPAL results. It has been produced by the LEP Susy Working Group (LSWG), a group setup to combine and optimise the results of the LEP experiments. In all cases, there is a good agreement between data and Monte Carlo [7, 8].

	ALEPH	DELPHI	L3		OPAL
Angular cuts $\lvert cos\theta \rvert$	< 0.95	< 0.75	< 0.97	< 0.70	< 0.70
Energy cuts	$p_t >$ $0.0375\sqrt{s}$	$E_\gamma > 4$ GeV	$E_\gamma > 10$ GeV	$E_\gamma < 10$ GeV $p_t > 1.3$ GeV$/c$	$E_\gamma > 0.2E_b$
N_{exp}	82	26.4	100	52.7	29.6
Data	77	22	106	55	26

Table 1: Single photon events obtained at $\sqrt{s} = 161 \div 172$ GeV.

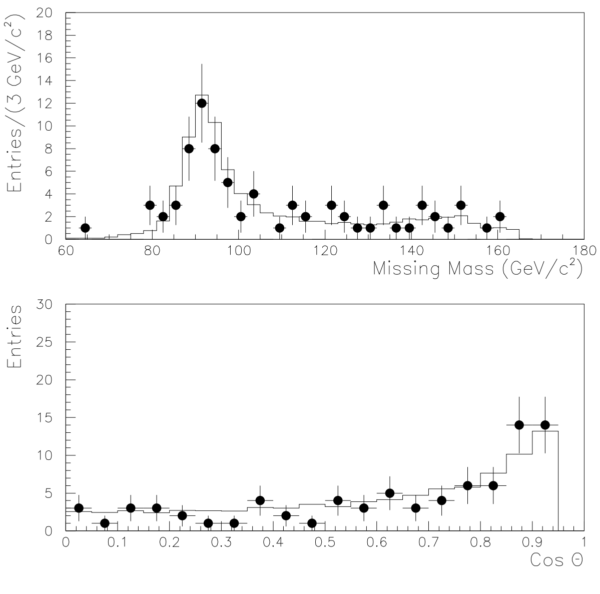

Figure 1: Missing mass spectrum and photon angular distribution obtained by the ALEPH collaboration for the "1γ" data. The simulation (full line) is obtained using the KORALZ generator.

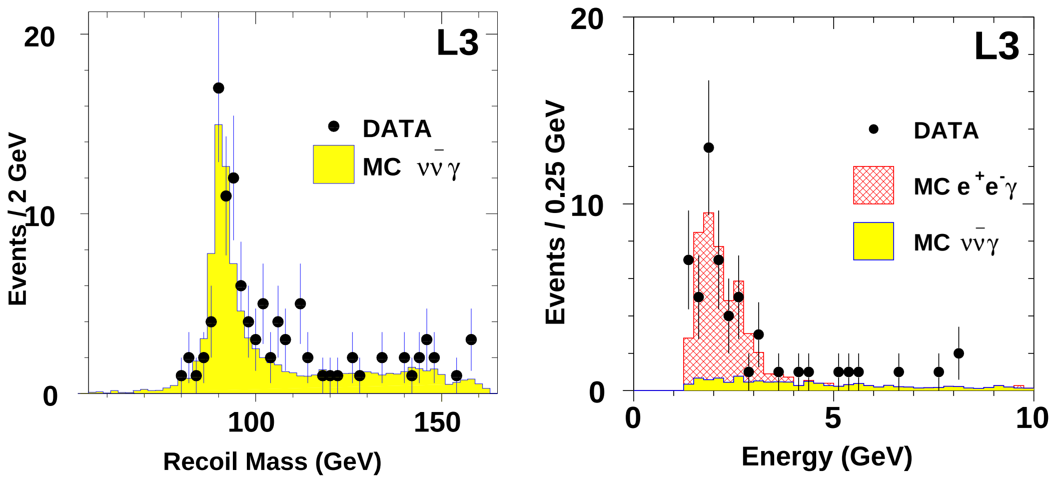

Figure 2: Recoil mass spectrum for the high energy sample and energy spectrum for the soft photon sample obtained by L3 from the "1γ" data. KORALZ(for $\nu\bar{\nu}\gamma$) and TEEGG(for $e^+e^-\gamma$) programs are used for the simulation.

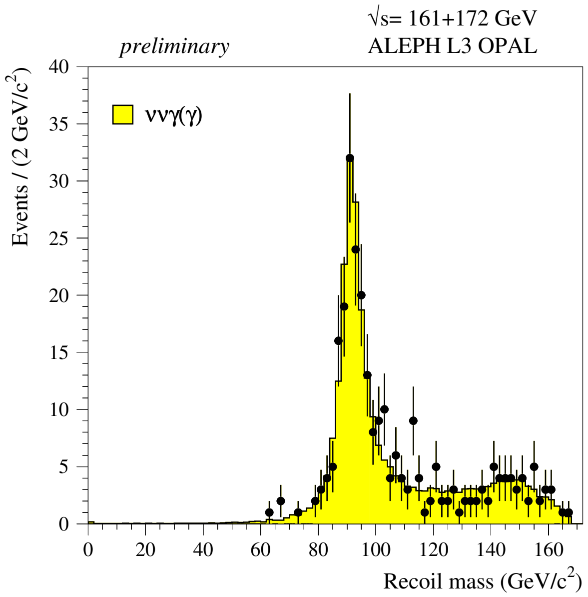

Figure 3: Recoil mass spectrum obtained by combining "1γ" data obtained by ALEPH, L3 and OPAL, compared with the results of the KORALZ Monte Carlo program (from LSWG).

2.2 Two photon data

In Table 2 which gathers the results for the $\gamma\gamma\not{E}$ channel, one can see, respectively, the cuts on the first (most energetic) photon, on the second photon, and the number of expected and collected events. In the last line, the number of events with a missing mass $M_R > 100$ GeV$/c^2$ is given, together with the approximate values of the missing mass of the selected events. These events are the one potentially interesting for new physics. The different selections aim at removing $\gamma\gamma$ events from QED using cuts on acoplanarity and acolinearity. The irreducible contribution of the $\nu\bar{\nu}\gamma\gamma$ reaction, with two radiative photons remains. A correct estimate is essential if one would like to address the significance of such events with large missing energy.

Figure 4, from the LSWG, collects all the events from the 4 experiments together with the cumulative expected contribution of the $\nu\bar{\nu}\gamma\gamma$ process. Due to the low statistics, nothing really puzzling is seen in this figure. There were some concerns about the predictions of the different generators. New results [9] in the working group and the collaborations show a better agreement. For instance, there is agreement on a ratio of around 0.30-0.35, between the cross section for the production of events with recoil mass $M_R > 100$ GeV/c^2 and the total cross section. The experimental ratio is 0.5 ± 0.15.

	ALEPH	DELPHI	L3	OPAL
$1^{st}photon$	$\lvert cos\theta\rvert < 0.95$ $E_\gamma > 1$	$\lvert cos\theta\rvert < 0.73$ $10 < E_\gamma < 1.4E_b$	$\lvert cos\theta\rvert < 0.97$ $E_\gamma > 10$	$\lvert cos\theta\rvert < 0.97$ $E_\gamma > 0.05E_b$
$2^{nd}photon$	$\lvert cos\theta\rvert < 0.95$ $E_\gamma > 1$	$\lvert cos\theta\rvert < 0.90$ $5 < E_\gamma < E_1$	$\lvert cos\theta\rvert < 0.97$ $E_\gamma > 1$	$\lvert cos\theta\rvert < 0.97$ $E_\gamma > 0.05E_b$
N_{exp}	5.0	1.7	7.8	4.3
Data	3	2	6	3
M_R > 100	2 (122,136)	1 (126)	3 (103,101,112)	1 (107)

Table 2: $\gamma\gamma\not{E}$ events obtained at $\sqrt{s} = 161 \div 172$ GeV. Energies and missing masses are expressed in GeV and GeV/c^2 respectively.

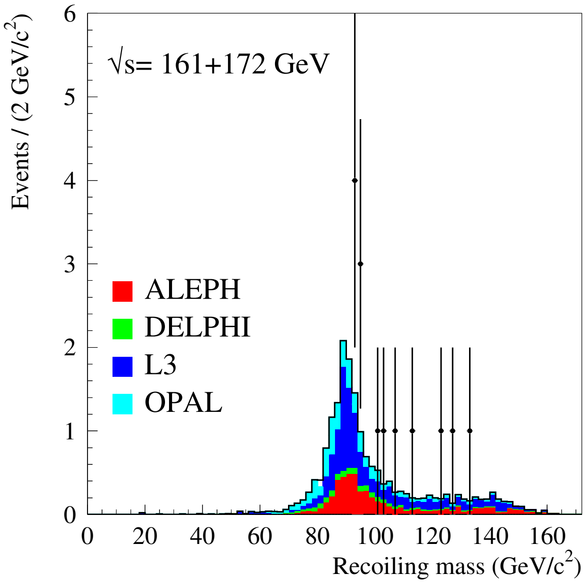

Figure 4: $\gamma\gamma\not{E}$ data. Recoil mass spectrum using the combined data of the 4 LEP experiments, compared with the KORALZ $\nu\bar{\nu}\gamma\gamma$ generator results (from LSWG).

3 Interpretations and limits

The absence of any obvious anomaly in the $\gamma\not{E}$ or $\gamma\gamma\not{E}$ spectra is interpreted by LEP experiments in the framework of supersymmetric models with R-parity conservation and thus the existence of a stable lightest supersymmetric particle (LSP).

In a first class of studies, the neutralino is the LSP and a first example is given by the MSSM interpretation of the CDF event. Such possibility has been studied by the ALEPH collaboration.

Numerous studies have been done using a second class of models where a very light gravitino is the LSP. This happens:

- In Gauge Mediated Supersymmetry Breaking models (GMSB) where supersymmetry breaking is realized at low energy scale ($\sqrt{F}$) and through SM gauge interactions, not through gravity [10].

- In "no-scale" supergravity models, such as the LNZ model [11]. Gravity is still responsible of supersymmetry breaking. It is a one parameter model, so very attractive to experimentalists.

These models imply, always for LNZ, most of the time for GMSB models, the neutralino as the Next Lightest Supersymmetric particle (NLSP), opening channels with very attractive signatures such as single photon + missing energy or acoplanar photons + missing energy. All LEP experiments have presented interpretations in this scenario.

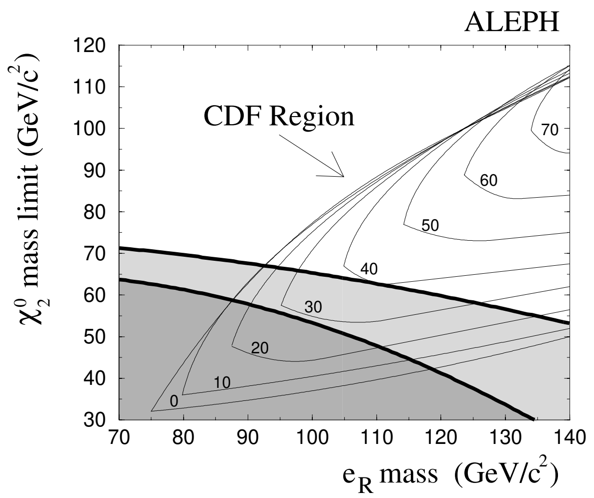

Figure 5: Exclusion plot from $\gamma\gamma\not{E}$ data in the $\tilde{\chi}_1^0$ LSP hypothesis (2). The shaded area is for $m_{\tilde{e}_L}= m_{\tilde{e}_R}$ and the darker area for $m_{\tilde{e}_L} \gg m_{\tilde{e}_R}$. Curves are labelled with $\tilde{\chi}_1^0$ mass values. The excluded area is based on the assumption of a $\tilde{\chi}_2^0$ being a pure photino and $\tilde{\chi}_1^0$ a pure higgsino.

3.1 $\tilde{\chi}_1^0$ as LSP : 2γ data

The CDF event is interpreted, through the production of a pair of selectrons, in the framework of MSSM, with the neutralino as LSP:

$$q\bar{q} \to \tilde{e}\tilde{e} + X \text{ then } \tilde{e}\tilde{e} \to ee\tilde{\chi}_2^0\tilde{\chi}_2^0 \to ee\gamma\gamma\tilde{\chi}_1^0\tilde{\chi}_1^0,$$

in a particular mass scenario, proposed in [12] which is consistent with all existing data. The $\tilde{\chi}_2^0$ has mainly a photino composition and the $\tilde{\chi}_1^0$ is mainly higgsino in order to favour a high radiative branching ratio. As a consequence, the usual relation between the weak-scale gaugino mass parameters M_1 and M_2 no longer exists and instead, $M1/M2 \sim 1$. At LEP, $\tilde{\chi}_1^0\tilde{\chi}_3^0$ and $\tilde{\nu}\tilde{\nu}$ production, if allowed, have high cross section but are invisible, except through an ISR photon;

$\tilde{\chi}_1^0\tilde{\chi}_2^0$ is kinematically favoured, but the cross section is low due to the different neutralino compositions. Then the best possibility is the production of $\tilde{\chi}_2^0\tilde{\chi}_2^0$ which leads to $\gamma\gamma + \not{E}$ events:

$$\mathrm{e^+e^-} \rightarrow \tilde{\chi}_2^0\tilde{\chi}_2^0 \rightarrow \gamma\gamma\tilde{\chi}_1^0\tilde{\chi}_1^0 \tag{2}$$

The channel has been studied by the ALEPH collaboration which has produced cross section limits and an exclusion plot of the CDF allowed region (Figure 5).

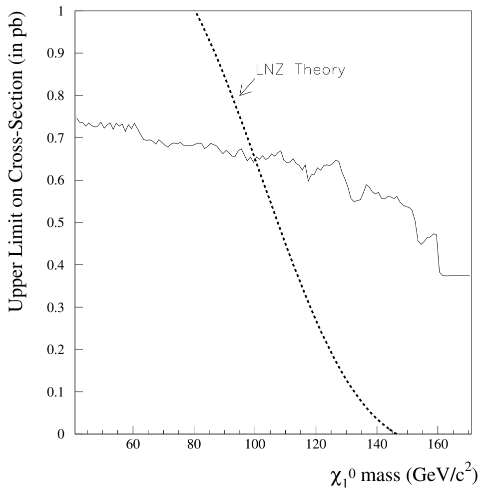

Figure 6: Upper limit cross section in ALEPH for the "1γ" process (3). The dashed line shows the cross section expected from the LNZ model for a gravitino mass of $m_{\tilde{G}} = 10^{-5}$ GeV/c^2. $\sqrt{s} = 161 \div 172$ GeV centre of mass energies are combined assuming a β^8 dependence for the cross section.

3.2 $\tilde{G}$ as LSP : 1γ data

The first example of an interpretation with the gravitino as LSP is in the "single photon" channel. Excess above the SM contribution can be interpreted as a signal for the direct production of gravitino with an accompanying neutralino which decay radiatively to gravitino:

$$\mathrm{e^+e^-} \rightarrow \tilde{\chi}_1^0\tilde{G} \rightarrow \gamma\tilde{G}\tilde{G} \tag{3}$$

The channel has interesting features:

- This is the only process which allows the production of a neutralino with a mass $m_\chi > \sqrt{s}/2$.
- It allows to constrain an important parameter, the mass of the gravitino. The cross section is inversely proportional to the square of the gravitino mass and for a mass around 10^{-5} eV/c^2 one reaches observable cross sections. Such mass also guarantees a prompt decay of the neutralino at the vertex of the interaction [13].

The 4 experiments present results and cross section limits, ALEPH and DELPHI in this specific scenario, the others in the more generic hypothesis

$$\mathrm{e^+e^-} \rightarrow XY \rightarrow YY\gamma \tag{4}$$

for $M_Y = 0$ (OPAL) or for any couple M_X, M_Y (L3). In Figure 6 the ALEPH result is shown and compared with the LNZ model. However, the mass limit obtained for the neutralino is strongly dependent of the assumed gravitino mass. Figure 7 shows the cross section limits for the L3 experiment, for the case $M_Y = 0$ or for any M_X and M_Y. To get a better signal over background ratio and then improve the sensitivity, cuts have been made to avoid the low Q^2 Bhabha events and events with $M_R \sim M_Z$. Using the cross section limit for $M_X = 0$, in the framework of the same LNZ model, it is possible to constraint the gravitino mass versus the neutralino mass. Figure 8 shows the exclusion plot obtained by L3. Note that below $m_{\tilde{\chi}_1^0} < m_Z$, the gravitino mass is constrained by the LEP1 results which have not been introduced here.

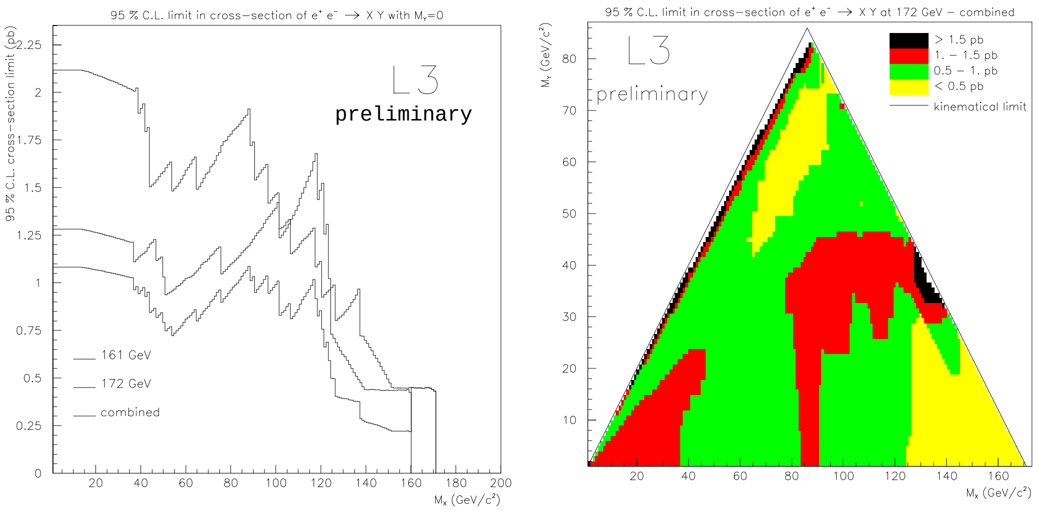

Figure 7: Upper limit cross sections in L3 for the "1γ" process (4), for $M_Y = 0$ (left) or for any M_X and M_Y.

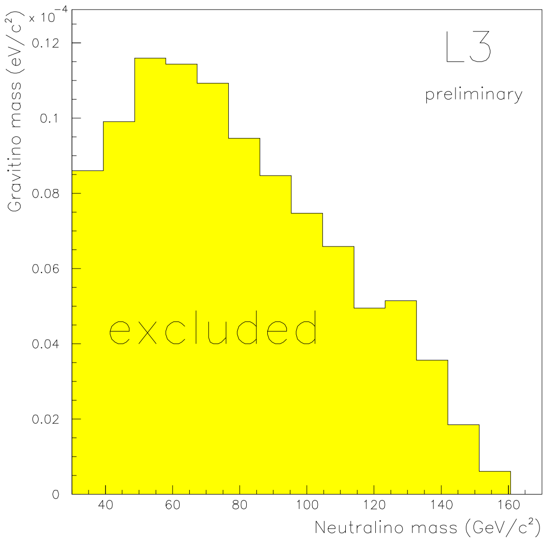

Figure 8: Excluded region in the gravitino-neutralino mass plane obtained by L3, from the "1γ" process (3) in the framework of the "one-parameter" LNZ model.

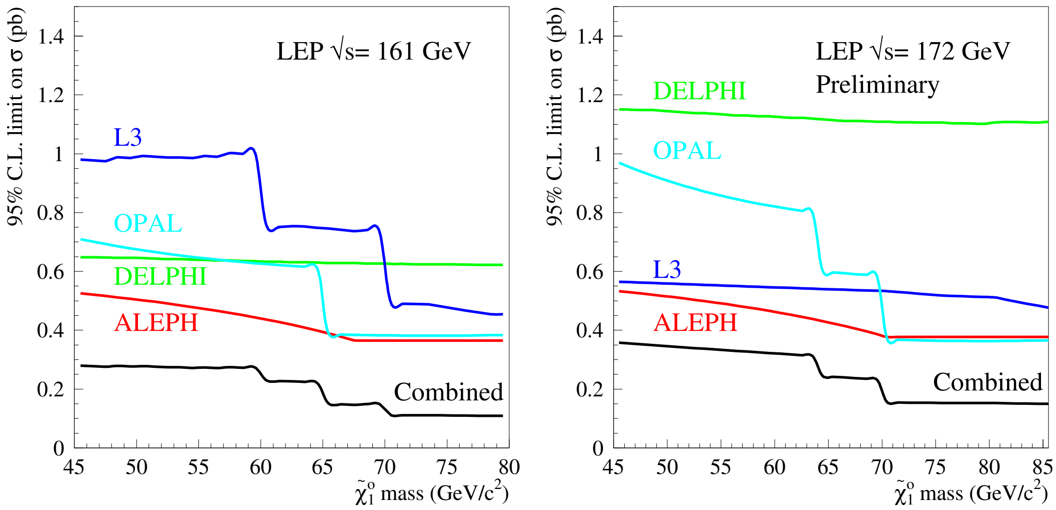

Figure 9: Upper limit cross section for the $\gamma\gamma\not{E}$ process (5) at 161 GeV(left) and 172 GeV(right), from the individual experiments and the combined one (from LSWG).

3.3 $\tilde{G}$ as LSP : 2γ data

In the gravitino LSP scenario, acoplanar photon pairs, at LEP2, come from neutralino pair production followed by the decay to photons and invisible gravitinos:

$$e^+e^- \to \tilde{\chi}^0_1\tilde{\chi}^0_1 \to \gamma\gamma\tilde{G}\tilde{G} \tag{5}$$

Here studies are limited to $m_{\tilde{\chi}^0_1} < \sqrt{s}/2$ and the cross section is independent of the gravitino mass. The CDF event can be explained, again by selectron pair production, with the following decays:

$$q\bar{q} \to \tilde{e}\tilde{e} + X \text{ then } \tilde{e}\tilde{e} \to ee\tilde{\chi}^0_1\tilde{\chi}^0_1 \to ee\gamma\gamma\tilde{G}\tilde{G}.$$

To match the cross section of the event, the neutralino must be mainly gaugino, and to avoid losses of efficiency, it must decay near the centre of the detector. The decay length, L_{decay}, depends on 3 parameters, the photino content of the neutralino, κ_γ, the mass of the neutralino, $m_{\tilde{\chi}^0_1}$, and the mass of the gravitino $m_{\tilde{G}}$:

$$L_{decay} \propto \frac{1}{\kappa_\gamma}\left(\frac{m_{\tilde{\chi}^0_1}}{100 \text{ GeV}}\right)^{-5}\left(\frac{m_{\tilde{G}}}{1 \text{ eV}}\right)^2 \tag{6}$$

To suppress as much as possible, in the 2γ sample, the background from the $\nu\bar{\nu}\gamma\gamma$ channel, further cuts are applied. The 4 experiments have set limits on the production cross section and have given lower limits on the neutralino mass in the frame of the LNZ or GMSB models. The LSWG has combined their results. Cross section limits, for the individual experiments and combined, for 161 GeV and 172 GeV centre of mass energy, are shown in Figure 9. Note that the performance of each experiment is highly dependent on the number of candidates they have and that the limit with the combination is significantly improved. Using models previously mentioned, (with assumptions such as the % of bino content or the mass of the right handed s-electron) one can set limit on the neutralino mass, $m_{\tilde{\chi}^0_1} > 76$ GeV$/c^2$. (Figure 10). The interpretation of the CDF event in the light gravitino scenario leads to a specific area in the $m_{\tilde{\chi}^0_1}$,$m_{\tilde{e}_R}$ plane, rather model independent, seen in Figure 11. The mass limit is given versus

$m_{\tilde{e}_R}$, which controls the dominant t-exchange production diagram. A significant fraction of the allowed region is already excluded.

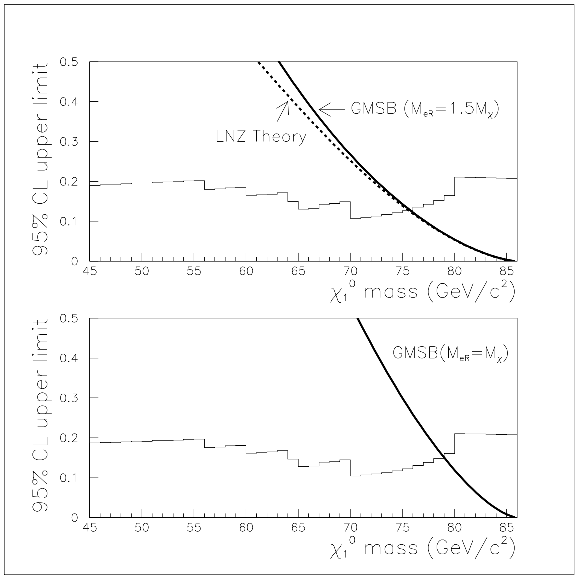

Figure 10: Limit on the neutralino mass from $\gamma\gamma\not{E}$ data, in the $\tilde{G}$ LSP hypothesis (5), using the results from the 4 LEP experiments and both centre of mass energies (from LSWG). In this computation $\tilde{\chi}_1^0$ is pure bino and decays near the interaction point. From these plots, one deduces a lower limit of 76 GeV/c^2 on the neutralino mass.

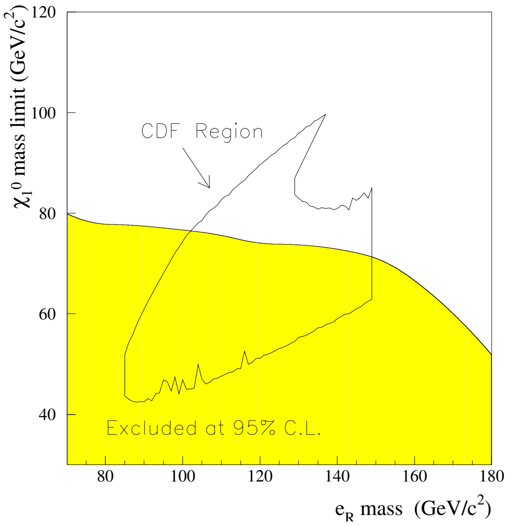

Figure 11: Exclusion mass plot, in the $\tilde{G}$ LSP hypothesis (5), from $\gamma\gamma\not{E}$ data using the results from the 4 LEP experiments (from LSWG). The indicated CDF region is the one which is deduced, assuming the CDF event is due to the production of a pair $\tilde{e}\tilde{e}$.

3.4 $\tilde{G}$ as LSP : the $\tilde{\tau}$ NLSP scenario

No photonic candidate events have still supported the gravitino existence at LEP. However, there exists another possibility, always with the gravitino as LSP [14] . For part of the parameter space, an $\tilde{l}$ and in particular a $\tilde{\tau}$ can be the NLSP leading to the process:

$$e^+e^- \rightarrow \tilde{\tau}\tilde{\tau} \rightarrow \tau\tau\tilde{G}\tilde{G} \tag{7}$$

The $\tilde{\tau}$ could decay inside or outside the detector, depending of the decay length value, which is a function of the $\tilde{\tau}$ mass and the $\tilde{G}$ mass, in a formula analogous to (6). The gravitino mass is linked to $\sqrt{F}$, the supersymmetry breaking scale. In GMSB models, the decay length distribution would be a direct measurement of the scale of supersymmetry breaking. Depending on the value of the decay length, experiments must develop different strategies. If the decay is prompt, at the interaction vertex, the search is identical to the lepton search with missing energy in the conventional MSSM, in the limit case of a vanishing neutralino mass, the gravitino having a near zero mass. Then for an increasing decay length, one has to look for tracks with large impact parameters, then for secondary vertices appearing in the detector (kinks). Finally, if the decay happens outside the detector, one has to search for stable heavy ionising particles (HIP). ALEPH, DELPHI and OPAL have searched for such HIPs and combined their results inside the LSWG, to give an experimental limit on the mass of the $\tilde{\tau}$. In this scenario, $m_{\tilde{\tau}} > 75.6$ GeV$/c^2$ or $m_{\tilde{\tau}} > 76.5$ GeV$/c^2$, depending if the $\tilde{\tau}$ is the supersymmetric partner of the right or left handed τ. Figure 12 shows the results, here for a $\tilde{\mu}$, which is the same as a $\tilde{\tau}$ as the cross section depends only on the mass.

DELPHI has developed specific analyses for all the different signatures and has combined all of them to give cross section limits and an exclusion area in the plane $m_{\tilde{\tau}}, m_{\tilde{G}}$ [15]. No candidate has been observed in any of these searches. The $\tilde{\tau}$ must have a mass higher than 55 GeV$/c^2$ for $m_{\tilde{G}} > 1$ eV$/c^2$ or higher than 65 GeV$/c^2$ for $m_{\tilde{G}} > 40$ eV$/c^2$. The exclusion plot can be seen in Figure 13.

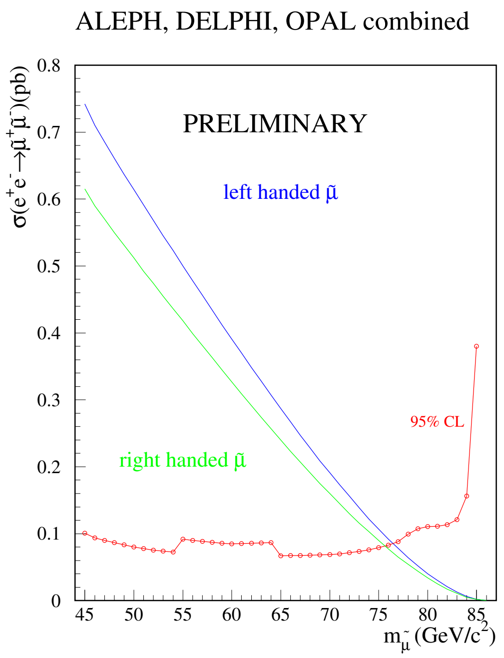

Figure 12: Production cross section for long lived particles and limits set by the combined results of ALEPH, DELPHI and OPAL (from LSWG). The plot applies both in case of a $\tilde{\tau}$ or a $\tilde{\mu}$.

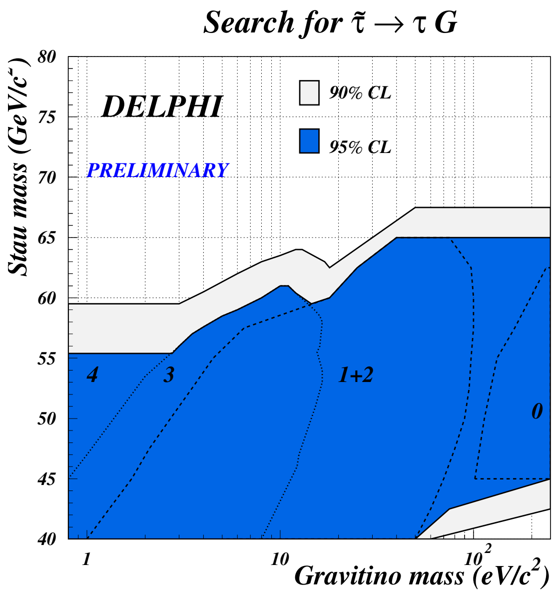

Figure 13: Exclusion plot in the $\tilde{\tau}$-gravitino mass plane assuming the $\tilde{\tau}$ NLSP hypothesis (7). Limits are set by DELPHI using different analyses.

4 Conclusions

No anomaly with respect to standard model predictions has been reported by any experiment. In particular, there is no sign of confirmation of the CDF event at LEP. In the gravitino scenario, a significant fraction of the allowed region has already been excluded. Further data at LEP, will essentially exclude all the domain (if no sign of new physics is found). This is in the hypothesis where the CDF event is due to the production of a pair of selectrons. The other possibility, production of a chargino pair, is already excluded by data from Run 1 at the Tevatron [16]. In the $\tilde{\chi}^0_1$ LSP scenario, the excluded part is still marginal and some regions of the parameter space could stay inaccessible at LEP2, even at its maximum energy.

Supersymmetry breaking at a low scale clearly provides many experimental challenges and opportunities. In both the neutralino NLSP and the $\tilde{\tau}$ NLSP option, LEP2 data have started to set constraints on the mass of the intervening particles. Single photon final state is the best channel to put a lower limit on the gravitino mass. $\gamma\gamma \not{E}$ channel has allowed to set a limit $m_{\tilde{\chi}^0_1} > 76$ GeV$/c^2$ with LNZ or GMSB models, at least for a mainly bino NLSP neutralino. With a $\tilde{\tau}$ as NLSP, searches of $\tilde{\tau}$ decay in the detector have allowed to constrain $m_{\tilde{\tau}}$ for gravitino mass higher than 1 eV. A "stable" $\tilde{\tau}$ have been excluded for masses up to 76 GeV$/c^2$ thanks to the combination of LEP experiment results.

I want to thank all the people from the 4 LEP experiments and from the LSWG who helped me in providing all the information.

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