NEW PARTICLE SEARCHES AT LEP

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Abstract

We briefly survey searches for new particles/effects on the Z resonance at LEP. Emphasis is placed on the searches for supersymmetric particles, excited fermions and composite Z effects. In addition, we very briefly discuss " llV " events, " $ll\gamma\gamma$ " events, searches for lepton flavor violation, and some other exotic physics at the Z .

1. Introduction^(*)

It is generally believed that the Standard Model (SM) is not the final theory of elementary particle interactions. There are several problems which seem to point to physics beyond the SM. These problems include the following: (i) Why are there several generations of fermions? (ii) What is the origin of the fermion mass spectrum? (iii) Related to the previous point: Why are there so many "arbitrary" parameters? (iv) Finally, there are difficulties with the elementary scalar Higgs, a problem often referred to as the "hierarchy" problem.

At this moment there is no model which comes even near to solving a decent fraction of the above problems (for a recent review¹, see ref. [1]), and not even the slightest prediction beyond the SM has been unquestionably confirmed experimentally. New models might just be incomplete, or realized in nature in some, to date, unanticipated way. It is not unreasonable to expect that the physics derived from some of to-days ideas will, at least in part, remain valid after having been incorporated into a realistic model. To-days theoretical predictions can therefore serve as a useful guide in experimental searches for new effects. It is to be expected that most of such searches will not be successful. They will, however, lead to more stringent constraints on theoretical models, constraints which in turn are essential *e.g.*, for the design of future machines and detectors.

Below we will give an experimental review of the search for new particles and effects at LEP. We will seldom try to combine the results of different experiments but rather discuss the result of one of them and just mention the others. Many results discussed below have recently been reviewed elsewhere

[2–5] (see also ref. [6]). We try to use the most recent data; whenever newer results are not available, we will just use the results compiled in the above references.

Higgs searches are not discussed here; this would be a topic in itself, likely to be discussed by another paper.

2. Z Widths

The SM predictions are experimentally confirmed to a very high precision. Before making an effort to search for exotic processes it is thus useful to compare first some of these precisely measured quantities with their predictions. Quantities pre-eminently suited for this purpose are the Z widths. This approach is used, at some point and in some form, by all LEP experiments.

In ref. [5] one uses the averages of the line shape parameters of all the LEP experiments to constrain the maximally allowed anomalous contribution of a process $Z \rightarrow X$, Γ_X , to a partial Z width. The SM expectations of these parameters have uncertainties [5, 7] due to their dependence on the top mass, the Higgs mass and α_s ; these uncertainties considerably limit the sensitivity of the result. The results for the maximally allowed contribution of $Z \rightarrow X$ to the total and the "invisible"²⁾ Z width are (at 95% C.L.)³⁾: $\Gamma_X^t < 25$ MeV and $\Gamma_X^{inv} < 17$ MeV, respectively. The measured values for the total and the invisible widths are (2492 ± 7) MeV and (504.6 ± 5.8) MeV, respectively [7]. If the SM expectations are chosen such as to give the most conservative limits the results are: $\Gamma_X^t < 34$ MeV and $\Gamma_X^{inv} < 17.5$ MeV, respectively.

²⁾ In fact, this "invisible" width limit not only comprises the truly invisible ($\bar{\nu}\nu$ -like) channels but also the (visible) Z decays which are neither standard hadronic events nor colinear lepton pairs [3, 5].

³⁾ Unless explicitly stated otherwise, limits on masses, BR's etc. are henceforth given at 95% C.L.

¹⁾ It is impossible in a short review like this to refer to all the relevant papers. For more details the bibliographies of the references given below should be consulted.

These limits, which are to a large extent independent of the topological and kinematical details of exotic Z decays, are powerful tools to constrain exotic processes whenever their contribution to the Z widths can be calculated explicitly.

3. Supersymmetry

Supersymmetry (SUSY) [8], a symmetry relating fermions and bosons, is interesting for many reasons. It *e.g.*, provides an elegant solution of the hierarchy problem, *i.e.* it protects in a natural way the mass of the elementary SM Higgs from quadratically divergent radiative corrections, which would push the Higgs mass, and the electroweak scale, towards the GUT scale.

A SUSY version of the SM necessarily leads to a vast increase of particles. All the ordinary fields get mass-degenerate superpartners, differing by half a unit of spin. Since such states are not observed, SUSY must be broken, and the superpartners heavy. This mass-splitting, however, cannot be too large since this would reintroduce the hierarchy problem: SUSY states are expected at, or below ~ 1 TeV. It is also important to note that in SUSY models two Higgs-doublets are inevitable. Furthermore, a new discrete symmetry, R (+1 for ordinary particles, -1 for the superparticles), is introduced (which may or may not be conserved).

Searches for SUSY effects at LEP are often performed in the context of the Minimal Supersymmetric SM (MSSM). This model contains the $SU(3) \times SU(2) \times U(1)$ gauge group, and requires a minimum number of fields and parameters. R parity is assumed to be conserved, hence superparticles can only be produced in pairs, and the Lightest SUSY Particle (LSP), presumably the neutralino (χ), is stable. Since χ is only sensitive to (very) weak interactions, it behaves 'neutrino-like' in detectors. SUSY events therefore have, in general, large missing E_T . Table 1 shows the MSSM particle content and nomenclature.

There is mixing among the SUSY weak eigenstates. The most important mixtures are those of the charged higgsinos and the wino (charginos), and those of the neutral higgsinos, the photino and the zino (neutralinos). Three parameters determine the couplings and masses of these mixed states, and therefore their production cross section. One of these parameters is the ratio of the vacuum expectation values of the two Higgs-doublets, v_2/v_1 . Another is the mass parameter μ , related to the higgsino potential. The third parameter, M , is associated with the three SUSY breaking, gaugino mass terms (Due to GUT relations this breaking mechanism has only one degree of freedom.).

3.1 Sfermions

The scalar leptons $\tilde{l}_L$ and $\tilde{l}_R$ are pair-produced: $Z \rightarrow \tilde{l}_L \tilde{l}_L^*$ or $\tilde{l}_R \tilde{l}_R^*$. They decay into their normal lepton partner and a

Table 1

Particles in the MSSM. The SM fermions f with two helicity states obtain two scalar partners $\tilde{f}_L$ and $\tilde{f}_R$. In the text the lightest chargino pair will be denoted as $\chi^\pm$. The neutralinos $\chi, \chi', \dots$ are given in order of increasing mass.

SM	MSSM weak eigenstate	MSSM mass eigenstate
q	$\tilde{q}_L, \tilde{q}_R$ squark	$\tilde{q}_1, \tilde{q}_2$
l	$\tilde{l}_L, \tilde{l}_R$ slepton	$\tilde{l}_1, \tilde{l}_2$
ν	$\tilde{\nu}$ sneutrino	$\tilde{\nu}$
g	$\tilde{g}$ gluino	$\tilde{g}$
$W^\pm$	$\tilde{W}^\pm$ wino	$\chi_{1,2}^\pm$ chargino
$H_1^\pm$	$\tilde{H}_1^\pm$ higgsino	
$H_2^\pm$	$\tilde{H}_2^\pm$ higgsino	
H_1^0	$\tilde{H}_1^0$ higgsino	χ, χ' χ'', χ''' neutralino
H_2^0	$\tilde{H}_2^0$ higgsino	
γ	$\tilde{\gamma}$ photino	
Z	$\tilde{Z}_0$ zino	

neutralino, $\tilde{l} \rightarrow l\chi$, resulting in a clean topology: an acoplanar e^+e^- , $\mu^+\mu^-$ or $\tau^+\tau^-$ pair with missing E_T . None of the LEP experiments [9–12] observes a signal and charged sleptons can easily be excluded up to ~ 45 GeV⁴. Direct searches for squarks ($Z \rightarrow \tilde{q}\tilde{q}^*$, $\tilde{q} \rightarrow q\chi$) at LEP are possible [9], but more stringent limits are obtained from $p\bar{p}$ experiments [15]. Sneutrino presence at Z would give an important contribution to the invisible Z width (via $Z \rightarrow \tilde{\nu}\tilde{\nu}^*$, $\tilde{\nu} \rightarrow \nu\chi$ or $\tilde{\nu} = LSP$). Such a contribution is, however, not observed [9, 11–13] and lower-mass limits are obtained up to ~ 41 GeV.

3.2 Charginos

Whatever the exact field content of these mixed states might be, if light enough, they would be copiously produced at the Z . From the expected contribution of $Z \rightarrow \chi^+\chi^-$ to the Z width, the LEP experiments can therefore easily exclude the $\chi^\pm$ up to ~ 45 GeV. An ALEPH [11] search for the direct decays, $\chi^+ \rightarrow \chi W^{++}$ or $\chi^+ \rightarrow l^+\tilde{\nu}_l$, brings this limit to ~ 47 GeV (for $m_{LSP} \lesssim 41$ GeV).

⁴ It is, however, more accurate to give exclusion plots in the $m_l - m_\chi$ plane; see the above refs. Furthermore, one uses in fact $m_{\tilde{l}_R}$, since one expects $m_{\tilde{l}_R} < m_{\tilde{l}_L}$ from radiative corrections.

3.3 Neutralinos

The neutralino sector is experimentally the most difficult accessible SUSY sector due to the mixing of the gauge fermions. It is, however, also the most interesting subject because the lightest neutralino might be stable and is a good dark matter candidate. Neutralinos are pair produced: for the two lightest ones one has the following possibilities $Z \rightarrow \chi\chi, \chi\chi'$ and $\chi'\chi'$. The dominant χ' decay mechanism is expected to be $\chi' \rightarrow \chi Z^* \rightarrow \chi f\bar{f}$. It may happen, however, that the higher order process $\chi' \rightarrow \chi\gamma$ is also important or even dominant. None of the LEP experiments [11–14] (see also ref. [5]) observes a signal in any of the channels. ALEPH reports a limit on $\text{BR}(Z \rightarrow \chi\chi', \chi'\chi')$ of a few times 10^{-5} , in most of the kinematically accessible domain: this result is independent from the χ' decay modes. More precise interpretations of the neutralino searches are possible within the context of the MSSM⁵. E.g., for $v_2/v_1 \gtrsim 3^6$ one obtains: $m_{\chi} \gtrsim 20$ GeV and $m_{\chi'} \gtrsim 45$ GeV. For lower values of v_2/v_1 these limits decrease and it is impossible to exclude a zero-mass χ from the LEP data alone. Often the results of MSSM gaugino searches are represented in the form of exclusion plots in the M, μ and v_2/v_1 parameter space; it is, at the moment, impossible to exclude all the kinematically allowed regions (see the above refs).

4. Compositeness

A substructure underlying the ordinary fermions and/or gauge bosons is the most drastic and difficult way to resolve the SM problems. This is probably the cause for the large proliferation of such models [16].

Whatever the correct model might be, if any, it is not unreasonable to expect the existence of excited states f^* corresponding to the known fermions f . Excited fermions f^* are assumed to have the same $\text{SU}(3) \times \text{SU}(2) \times \text{U}(1)$ gauge couplings and quantum numbers as their partners f . In fig. 1 we show the expected contribution to the Z width for the process $Z \rightarrow f^*f^*$, where f^* is either a u^*, d^*, l^* or a (Dirac) ν^* , as a function of the f^* mass. Excited quarks can be excluded up to almost $m_Z/2$. However, it is still worthwhile to search directly for excited leptons.

4.1 Searches for excited fermions

In the direct searches for excited fermions one usually assumes that the radiative decay $f^* \rightarrow f\gamma$ is important. Direct searches for the pair produced channels $Z \rightarrow l^*\bar{l}^* \rightarrow l\bar{l}\gamma\gamma$ or $\nu^*\bar{\nu}^* \rightarrow \nu\bar{\nu}\gamma\gamma$ yield negative results, and can easily exclude

FIGURE 1

The expected contribution to the Z width for the process $Z \rightarrow f^*f^*$. The horizontal lines represent the limits on the maximally possible anomalous contribution to the Z total, $\Gamma_X^l(mx)$, and invisible width, $\Gamma_X^{\text{inv}}(mx)$, as described in the text (section 2); we have plotted the most conservative values.

[11, 18, 20] excited leptons up to $\sim m_Z/2$. Direct searches for $Z \rightarrow q^*\bar{q}^*$ [11, 13], including the channels with $q^* \rightarrow qg$, give similar limits.

Searches at LEP of excited fermions beyond $m_Z/2$ are possible if there is a significant Zf^*f coupling. This effective coupling is presumed to be caused by physics at the compositeness scale Λ . Although the exact dynamics of such processes may not be known, its consequences at much lower energy scales can be described by an effective Lagrangian [17]: $\mathcal{L}_{\text{eff}} = \sum_{V=\gamma,Z} \frac{e}{\Lambda} \bar{f}^* \sigma^{\mu\nu} (c_{Vf^*f} - d_{Vf^*f} \gamma_5) f \partial_\mu V_\nu + \text{h.c.}$ One usually assumes $c = d$, which is in part motivated by $g-2$ and dipole-moment measurements. Using $\mathcal{L}_{\text{eff}}$ one can calculate cross sections for $Z \rightarrow f^*f$ in terms of c_{Zf^*f}/Λ and $m_{f^*}^2$. Note that the t -channel contribution for ee^* production (via virtual photon exchange), where one e^+/e^- may disappear in the beam pipe, is also described by $\mathcal{L}_{\text{eff}}$. This process can be used to measure the cross section in terms of $c_{\gamma e^*e}/\Lambda$ and m_e^2 .

Searches for these singly produced excited leptons have been performed by all LEP experiments [11, 13, 18–20]. No signals are observed. In fig. 2 we show, as an example, the L3 exclusion plots in terms of c_{Zl^*l}/Λ vs. $m_{l^*}^2$ and $c_{\gamma e^*e}/\Lambda$ vs. m_e^2 . Hadronic events with hard isolated photons can be used to search for singly produced excited quarks [11, 13, 21, 22]. One can also include [11, 13] the qq^* channels with $q^* \rightarrow qg$. Again

⁵ The process $Z \rightarrow \chi\chi$ is dealt with by the limit on the invisible width.

⁶ One expects $v_2/v_1 > 1$ because of the large mass-splitting between “up-” and “down-type” quarks.

no signal is observed and similar limits as the ones above are obtained. Singly produced excited neutrinos would lead to an enhancement of single photon events if $\nu^* \rightarrow \nu\gamma$ is important; no signal is observed [11, 24], and similar limits as for l^* can be set. L3 also searched for ν^* assuming that $\nu^* \rightarrow W^\pm e^\mp$ is dominant [24].

Limits on excited fermions with masses beyond M_Z , in the above framework and using LEP data, are possible for the e^* . The presence of an e^* would be noted by an anomalous contribution (via t-channel exchange of a virtual excited electron) to the differential cross section for the pure QED process $e^+e^- \rightarrow \gamma\gamma(\gamma)$. All LEP experiments have done these kind of QED tests [3, 11, 25–27] without observing anything significant. Limits are obtained in terms of $\lambda/m_e^* (= \sqrt{2}c_{\gamma ee}/\Lambda)$ and m_e^* . It is in this kind of analysis customary to quote a lower limit for m_e^* at $\lambda = 1$; the latest L3 result pushes this limit to 127 GeV.

FIGURE 2

From L3: 95% C.L. u.l. curves for excited leptons (a) t-channel ee^* , with $\lambda/m_e^* = 1.41 \cdot c_{\gamma ee}/\Lambda$. (b) s-channel ee^* (solid), $\mu\mu^*$ (dashed) and $\tau\tau^*$ (dotted) with $\lambda/m_l^* = 2.23 \cdot c_{Zll}/\Lambda$. The rise of the lines close to ~ 90 GeV is due to the decreasing cross section for $Z \rightarrow ll^*$.

In summary: Excited fermions f^* which couple to the Z in the same way as their f partners can easily be excluded up to $\sim m_Z/2$ by limits on the Z widths and by direct searches. Limits on the existence of these fermions beyond $m_Z/2$ are

only possible in terms of their mass and their effective $Z(\gamma)ff^*$ coupling; for excited leptons one thus finds c_{Zll}/Λ or $c_{\gamma ll}/\Lambda < 1 - 3 \times 10^{-4} \text{ GeV}^{-1}$ for $m_Z/2 \lesssim m_{l^*} \lesssim 85 \text{ GeV}$; and for excited quarks $c_{Zqq}/\Lambda \lesssim 5 - 7 \times 10^{-4} \text{ GeV}^{-1}$ in the same mass range.

4.2 Search for composite Z effects

The cleanest signature for a Z having charged constituents would be an anomalously high $Z \rightarrow \gamma\gamma\gamma$ rate. Model dependent predictions [16] for the BR can be as high as 10^{-4} . SM calculations including fermion loops give $\sim 10^{-9}$. Experimental searches have to deal with the $e^+e^- \rightarrow \gamma\gamma\gamma$ QED background. The upper limits (u.l.) found for $\text{BR} \times 10^5$ are: 1.9 by ALEPH [11]; 14. by DELPHI [25]; 3.0 by OPAL [26]; and 3.1 by L3 [27]. ALEPH [11] and OPAL [21] have also searched for the related Z decay $Z \rightarrow gg\gamma$ (SM prediction [16]: $\text{BR}(Z \rightarrow gg\gamma) \approx 7 \times 10^{-7}$). Again no signal is observed and the BR u.l.'s are $2 - 3 \times 10^{-4}$.

Another consequence of a composite gauge boson sector could be the existence of partners [16] Y of the Z , which could be produced via $Z \rightarrow \gamma Y$. The Y resonance (assumed to be relatively narrow) would subsequently decay into a lepton pair or hadrons. The monochromatic isolated photon produced in these kind of reactions would readily be identified. OPAL [29], DELPHI [30] and L3 [31] (see also ref. [4]) searched for such narrow resonances; u.l.'s on $\text{BR}(Z \rightarrow \gamma Y; Y \rightarrow l^+l^- \text{ or hadrons})$ are in the range of $6 - 30 \times 10^{-5}$.

Finally, L3 [32] searched for energetic single photon events ($E_\gamma > \frac{1}{2}E_{\text{beam}}$) assumed to be due to the electric dipole transition $Z \rightarrow \gamma Z^*$ ($Z^* \rightarrow \nu\bar{\nu}$); no events are observed.

5. Miscellaneous Searches

5.1 " llV " events

In 1991 ALEPH published [40] a study of the process $e^+e^- \rightarrow l^+l^-V$ where V is a e^+e^- , $\mu^+\mu^-$, or $\pi^+\pi^-$ pair (or, more general, any pair of oppositely charged tracks) originating from the vertex. An excess of events in the $\tau^+\tau^-V$ channel was reported. In SM leptonic- Z decay this process could arise through conversion of a virtual photon into a lepton pair or (via a vector-meson intermediate state) into a charged pion pair. In an update of the ALEPH analysis, based on a larger data sample, the significance of the effect is reduced [4, 41]. No $\tau^+\tau^-V$ excess is reported by other LEP experiments [4]. OPAL [42] completed a systematic study of llV events (table 2). Part of their studies consist in using, as far as possible, experimental cuts similar to those used by ALEPH. Nothing unusual is observed. There is a preliminary result from L3 related to this issue, *viz.* a study of four-lepton events from Z decays. A very pure event sample was obtained; again nothing abnormal is observed in the channels containing a $\tau\tau$ pair (table 2).

Table 2

The number of observed events llV events. The numbers in parenthesis are the expected number of events on the basis of SM processes.

$e^+e^- \rightarrow$	eeV	$\mu\mu V$	$\tau\tau V$
ALEPH [40]	10 (7.2)	10 (6.6)	15 (3.2)
ALEPH (1989–91) [4]	18 (18.2)	18 (15.1)	18 (7.4)
DELPHI [4]	11 (9.9)	9 (9.3)	8 (3.9)
OPAL [42]	21 (27.7)	18 (15.3)	11 (9.5)
L3 (prelim.)	17 (15.1)	9 (8.1)	12 (13.9)

5.2 “ $ll\gamma\gamma$ ” events

Recently, L3 [36] reported the observation of four exceptional events in the channel $e^+e^- \rightarrow l^+l^-\gamma\gamma$. These four events, one $e^+e^-\gamma\gamma$ and three $\mu^+\mu^-\gamma\gamma$, have a two-photon invariant mass close to 60 GeV and are well separated from the other events. In fig. 3 we show the L3 two photon invariant mass distribution, $M_{\gamma\gamma}$, for this channel. Standard Model $l^+l^-\gamma\gamma$ events are dilepton events with hard photon radiation in the

FIGURE 3

Two photon invariant mass distribution of the L3 $l^+l^-\gamma\gamma$ events compared to the expectation from the Monte Carlo.

final and/or initial state. The probability, however, for observing four clustering events, all with $M_{\gamma\gamma} > 50$ GeV, is estimated to be of order 10^{-3} [36]; events were considered clustered if they were found in a single mass bin of $\Delta M_{\gamma\gamma} = \pm 2.5$ GeV (corresponding to eight times the $M_{\gamma\gamma}$ measurement error at 60 GeV). Nothing unexpected is observed in the channels $e^+e^- \rightarrow \tau\tau\gamma\gamma$, $q\bar{q}\gamma\gamma$, or $(\nu\bar{\nu})\gamma\gamma$. It is worth quoting from the conclusions of ref. [36]: “... Therefore, a QED fluctuation cannot be ruled out. More data are necessary to ascertain the origin of these events.”

The quickest way to increase the amount of data in to include the (preliminary) results of the other LEP collaborations.

The distributions of DELPHI’s [37] $ll\gamma\gamma$ events show a good agreement with those expected from doubly radiative leptonic decays of the Z. They observe, however, two events (one $ee\gamma\gamma$ and one $\mu\mu\gamma\gamma$) with $M_{\gamma\gamma}$ close to 60 GeV; from standard sources they would expect 0.25 events in a mass bin of 5 GeV. DELPHI concludes: “... The possibility that they [the two events] come from a new particle decaying to two photons cannot be ruled out, and more data will be necessary to verify it.”

ALEPH’s [38] $M_{\gamma\gamma}$ distribution for $ll\gamma\gamma$ shows a tail extending up to 70 GeV (6 events with $M_{\gamma\gamma} > 50$ GeV): one event is observed with $M_{\gamma\gamma} = 59.4 \pm 0.2$ GeV, there is, however, no clustering of events close to that mass point.

OPAL [39] observes, in agreement with the expectation from QED, four events in $e^+e^- \rightarrow ll\gamma\gamma$ with $M_{\gamma\gamma} > 40$ GeV; there is no event with $M_{\gamma\gamma} \approx 60$ GeV. In addition, they find five events with two isolated photons ($M_{\gamma\gamma} > 40$ GeV) in hadronic events; there is no resonant structure.

5.3 Flavor-violating Z decays

The decays $Z \rightarrow e\mu$, $e\tau$ and $\mu\tau$ are strictly forbidden in the SM; in many exotic models, however, these decays are possible. This could be caused by loop contributions, but also tree level couplings could contribute if the ordinary particles mix directly with exotic states [16]. The predicted BR’s can in such cases be of order 10^{-4} . All LEP experiments [11, 33–35] have searched for these decay modes; no signal is observed. The L3 energy/momentum resolution for electrons and muons permits constraining the BR’s down to 1.5×10^{-5} , 3.0×10^{-5} and 2.9×10^{-5} for $Z \rightarrow e\mu$, $e\tau$ and $\mu\tau$, respectively [4].

5.4 Other rare Z decays and effects

At LEP one has searched for $Z \rightarrow \gamma\gamma$, $\pi^0\gamma$, $\eta\gamma$, $\eta'\gamma$, πW , and ρW ; u.l.’s on the BR’s of $10^{-4} - 10^{-5}$ are obtained [2–4].

Searches at LEP [11, 43–45] exclude the simplest leptoquarks up to ~ 45 GeV.

ALEPH [11] has searched for weakly interacting particles, X^0 , in the process $e^+e^- \rightarrow Z^*X^0$ with $Z^* \rightarrow l^+l^-$ and the X^0 escaping the detector or decaying into a virtual W or Z pair; u.l.’s are of order 10^{-5} for $10 < M_{X^0} < 60$ GeV.

ALEPH [46], L3 [47] and DELPHI [48] have searched for exotic heavy leptons; lower limits are in the range of 35 to 45 GeV, depending on the nature of the heavy lepton.

OPAL [49] and L3 [50] have searched for isosinglet neutral heavy leptons, N_l ($l = e, \mu, \tau$); no evidence for signals are observed and $\text{BR}(Z \rightarrow \nu_l N_l) < 3 \times 10^{-5}$ for $3 \text{ GeV} < M_{N_l} < M_Z$ [50].

OPAL [51] and ALEPH [52] searched for CP violation in $e^+e^- \rightarrow \tau^+\tau^-$; no evidence for CP violation is found. ALEPH measures the weak dipole moment of the τ to be $(1.3 \pm 1.4 \pm 0.1) \times 10^{-17} e \cdot \text{cm}$, resulting in an u.l. of $3.7 \times 10^{-17} e \cdot \text{cm}$; OPAL's limit is $7 \times 10^{-17} e \cdot \text{cm}$.

L3 [32] searched, unsuccessfully, for a gravitino ($\tilde{G}$) contribution to the photon energy spectrum of single photon events at the Z ($Z \rightarrow \chi \tilde{G}$; $\chi \rightarrow \tilde{G} \gamma$).

OPAL [53] searched, also unsuccessfully, for free gluons.

6. Conclusions

The LEP experiments have searched for new phenomena at the Z resonance. No clear evidence for exotic phenomena is found. Many limits of "standard" new physics searches now saturate the maximally allowed kinematical regions; these limits are important input for theoretical studies. Higher statistics remains nevertheless important to settle the question of the $l^+l^- \gamma \gamma$ events, to tighten the limits on (or to discover) lepton flavor violation, composite Z effects or Z decays into neutralinos, and finally, to search for hitherto unanticipated exotic phenomena.

Acknowledgements

I thank many colleagues from all four LEP collaborations for providing me with material and suggestions for this report. I am grateful to R.T. Van de Walle for remarks on the final manuscript.

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⁷ "Geneva 91" refers to the Proceedings of the "Joint International Lepton-Photon Symposium and Euro-physics Conference on High Energy Physics", Geneva, 25 July-1 August, 1991. Eds. S. Hegarty, K. Potter, and E. Quercigh.

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