PRAMANA
—journal of
physics

Vol. 51, Nos 1 & 2,
July/August 1998
pp. 77–86

Recent results from large electron positron collider

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Abstract. We summarize here the recent results from the four experiments at the large electron positron collider (LEP). These experiments provide precise measurements of the W and Z boson properties and their couplings to leptons and quarks. These measurements, together with measurements of the top quark and W boson masses in the Tevatron collider provide a stringent test of the standard electroweak theory. Searches for Higgs boson and supersymmetric particles have yielded null results so far giving rise to lower bounds in the parameter space.

Keywords. LEP; W boson properties; Higgs; SUSY Higgs; SUSY particles.

PACS Nos 14.70; 14.80

1. Introduction

After running successfully at centre of mass energies around 91 GeV, LEP entered the high energy phase by the end of 1995 with a brief run (6 pb^{-1}) at energies between 130 and 140 GeV. The year 1996 saw two runs of LEP above the W-pair production thresholds with integrated luminosities of 10 pb^{-1} each at 161 and 172 GeV. During 1997, LEP delivered a total of 73.4 pb^{-1} integrated luminosity in 132 days. The maximum integrated luminosity delivered in a 24 hour period has been recorded to be 1.7 pb^{-1}. The performance of LEP has been exemplary during 1997.

The run in 1997 is split into three centre of mass energies: (1) 2.3 pb^{-1} at $\sqrt{s}=91.2$ GeV which is used to calibrate the detectors; (2) 7.2 pb^{-1} at $\sqrt{s}=130$–136 GeV to review the excess of four jet events reported earlier by ALEPH [1]; (3) 63.8 pb^{-1} at $\sqrt{s}=183$ GeV. Each experiment is expected to have ~ 1000 events from $e^+e^- \to W^+W^-$ or high energy hadronic events.

The four LEP experiments, ALEPH, DELPHI, L3 and OPAL have most of their results finalized for $\sqrt{s} \leq 172$ GeV. The results [2–5] from the runs at $\sqrt{s}=183$ GeV are still preliminary. Results on four fermion production are summarized in § 2. In § 3, we report the measurements on fermion pair production. In § 4, the search results of Higgs boson are discussed and searches for supersymmetry are summarized in § 5.

2. Four fermion production

Four fermion production at $\sqrt{s}=183$ GeV are due to on shell production of W^+W^-/ZZ with each of the boson subsequently decaying to $f\bar{f}$; or due to non-resonant intermediate state (charged or neutral currents). First candidates of on-shell ZZ production have been reported by L3 [4] and OPAL [5] experiments. OPAL reported one candidate in the 4 lepton final state ($e^+e^-\tau^+\tau^-$) with the mass of e^+e^- pair and the recoil mass as 89.5 ± 3.4 GeV and 90.7 ± 3.1 GeV respectively. L3 reported one candidate each in the final states $e^+e^-q\bar{q}$ and $q\bar{q}q\bar{q}$ where it expects to see 0.98 ($0.68 + 0.30$) events from signal and 0.8 ($0.5 + 0.3$) events from background.

At $\sqrt{s} = 161$ GeV, each experiment typically recorded around 30 W^+W^- events with an integrated luminosity of $10\,\mathrm{pb}^{-1}$. The measured cross sections for the process $e^+e^- \rightarrow W^+W^-$ have been averaged over the 4 LEP experiments:

$$\sigma_{W^+W^-} = 3.69 \pm 0.45\,\mathrm{pb}.$$

Assuming the standard model couplings of the W boson, one calculates theoretical cross sections as a function of the W mass. The measured cross section thus gives rise to determination of W mass:

$$m_W = 80.40^{+0.22}_{-0.21} \pm 0.03\,\mathrm{GeV}$$

where the first error is experimental and the second error is uncertainty due to LEP energy calibration.

At centre of mass energies of 172 and 183 GeV, each LEP experiment has recorded approximately 700 W pair events. To determine W mass, the experiments fit the reconstructed invariant mass distributions. These fits have been separately done in the final states $q\bar{q}\ell\nu$ and $q\bar{q}q\bar{q}$. The W mass value obtained from the $q\bar{q}q\bar{q}$ final state has additional uncertainty due to final state interactions (Bose-Einstein correlation and colour reconnection effects). W mass values measured in the 4 LEP experiments have been combined [6] for the semi-leptonic and the hadronic channels:

$$m_W{}^{\mathrm{leptonic}} = 80.27 \pm 0.10 \pm 0.03(\mathrm{LEP})\,\mathrm{GeV},$$
$$m_W{}^{\mathrm{hadronic}} = 80.40 \pm 0.10 \pm 0.10(\mathrm{FSI}) \pm 0.03(\mathrm{LEP})\,\mathrm{GeV}.$$

At the current level of accuracy, there is no difference between the W mass determined in the fully hadronic and in the semi-leptonic channels. One can combine these two measurements and the W mass determined from the cross section measurement at threshold to give the overall W mass determined from LEP2:

$$m_W = 80.35 \pm 0.09\,\mathrm{GeV}.$$

This measurement is compared in figure 1 with the direct measurements from pp colliders [7] and indirect measurements in the framework of the standard model using the precision data from LEP1 and SLD. The two direct measurements agree well within errors giving world average value [6]:

$$m_W = 80.375 \pm 0.064\,\mathrm{GeV}$$

which in turn agrees well with the indirect measurement.

The four LEP experiments have measured W pair cross section in various channels: $q\bar{q}q\bar{q}$, $q\bar{q}e\nu$, $q\bar{q}\mu\nu$, $q\bar{q}\tau\nu$, $\ell\nu\ell\nu$. These measurements can be combined to determine W decay branching ratios. Figure 2 summarizes the hadronic decay branching ratio of W from the four LEP experiments. One sees the four measurements are compatible and can

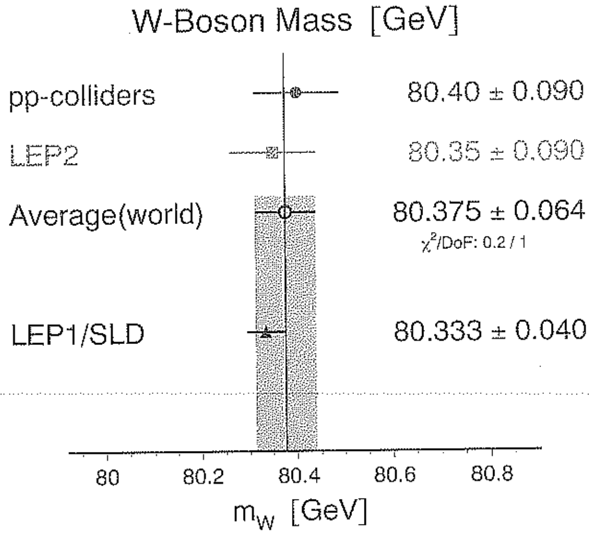

Figure 1. *W* mass measurements from different experiments.

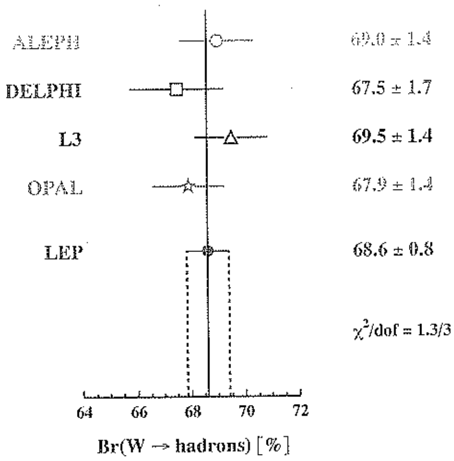

Figure 2. Hadronic decay branching ratio of *W* measured by the four LEP experiments.

be combined to get an overall measurement from LEP. The decay branching ratios of *W* are summarized in table 1.

Figure 3 shows the energy dependence of the cross section for the process $e^+e^- \to W^+W^-$. The measurements from the 4 LEP experiments have been combined and compared with predictions from the standard model. The data are in agreement with the standard model predictions and the predictions without the *ZWW* vertex or only via ν exchange diagram cannot explain the energy evolution.

Table 1. W decay branching ratios in percent by combining the four LEP experiments.

Br ($W \rightarrow e\nu$)	Br ($W \rightarrow \mu\nu$)	Br ($W \rightarrow \tau\nu$)	Br ($W \rightarrow$hadrons)
11.0 ± 0.5	10.3 ± 0.5	10.0 ± 0.6	68.7 ± 0.8

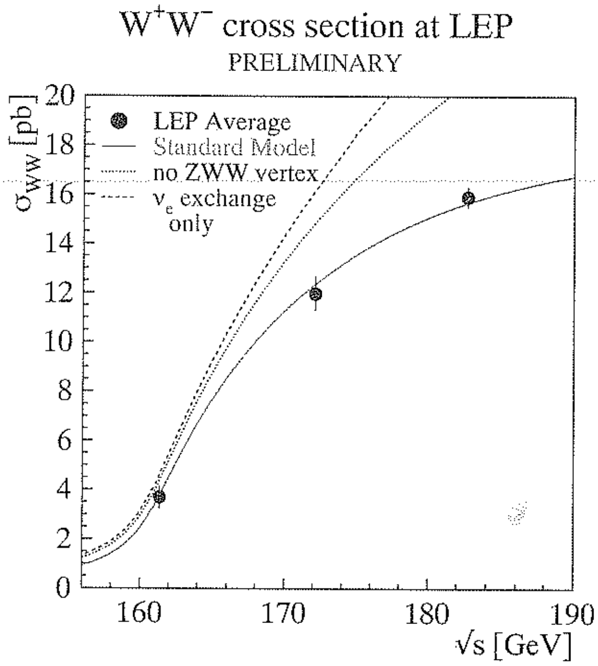

Figure 3. LEP average values of $\sigma(e^+e^- \rightarrow W^+W^-)$ as a function of the centre of mass energy. The measurements are compared with predictions from the standard model (solid line), model with no ZWW vertex (dotted line), model with only t-channel ν-exchange (dashed line).

Thus the cross section measurements for the process $e^+e^- \rightarrow W^+W^-$ gives evidence for the tripe gauge boson vertex (TGV). The most general Lorentz invariant Lagrangian for triple gauge boson vertex gives rise to 14 independent terms, seven each for $WW\gamma$ and WWZ. Assuming electromagnetic gauge invariance, C and P conservation, one ends up with 5 independent parameters. In the standard model framework, these parameters are known. Deviations from the standard model value can be investigated from the cross section measurements together with the production and decay angular distributions of the W. This has been carried out by the 4 LEP experiments. With the present set of observables, one can only test the anomalous triple boson couplings within the framework of a given model. One common set is motivated by $SU(2) \times U(1)$ gauge invariance [8] giving rise to the parameter set: α_{W_ϕ}, α_W and α_{B_ϕ}. The current limits on these parameters by combing the 4 LEP experiments are summarized in table 2. All the anomalous TGV coupling parameters are compatible with 0.

Table 2. The measured values for the anomalous TGV coupling parameters by combining the four LEP experiments.

α_{W_ϕ}	α_W	α_{B_ϕ}
$0.02^{+0.16}_{-0.15}$	$0.15^{+0.27}_{-0.27}$	$0.45^{+0.56}_{-0.67}$

3. Fermion pair production

The four LEP experiments measured cross sections, forward–backward asymmetries, polarization asymmetries in the reaction $e^+e^- \rightarrow f\bar{f}$ at centre of mass energies around Z boson mass with the LEP1 data. These precise measurements together with similar measurements at SLD have been used to determine Z boson parameters and neutral current couplings of quarks and leptons with a high degree of accuracy [6]. Table 3 summarizes the line shape parameters obtained by combining the measurements from 4 LEP experiments and taking the γ-Z interference from the standard model.

If one tries to measure the interference term from the data, one finds a large correlation between m_Z and the interference term. Consequently, the uncertainty in m_Z increases to 12.7 MeV. Cross sections and forward–backward asymmetries for $e^+e^- \rightarrow f\bar{f}$ are measured also with the LEP2 data. At these energies, there is a large contamination of events with a high energy initial state radiation so that the mass of the fermion pair becomes close to m_Z. If these events are removed by imposing a cut on $\sqrt{s'/s} > 0.85$, the resulting cross sections and asymmetries are sensitive to the interference term. A combined fit with LEP1 and LEP2 data yields

$$m_Z = 91.1882 \pm 0.0031\ \text{GeV}$$
$$j^{\text{tot}}_{\text{had}} = 0.14 \pm 0.14$$

Thus one measures m_Z with the same level of precision as in LEP1 without making specific assumption on the standard model.

The radiative return to Z events have been used to carry out a direct determination of the Z mass and width by fitting the s' distribution. This procedure is similar to that for W mass determination at the high energies. This determination provides systematic errors in the direct determination of m_W. The experiments show no significant systematic effect in this procedure.

Table 3. Average line shape parameters assuming lepton universality.

Parameter	Average value
m_Z (GeV)	91.1867±0.0020
Γ_Z (GeV)	2.4948±0.0025
σ^0_h (nb)	41.486±0.053
R_ℓ	20.775±0.027
$A^{0,\ell}_{FB}$	0.0171±0.0010

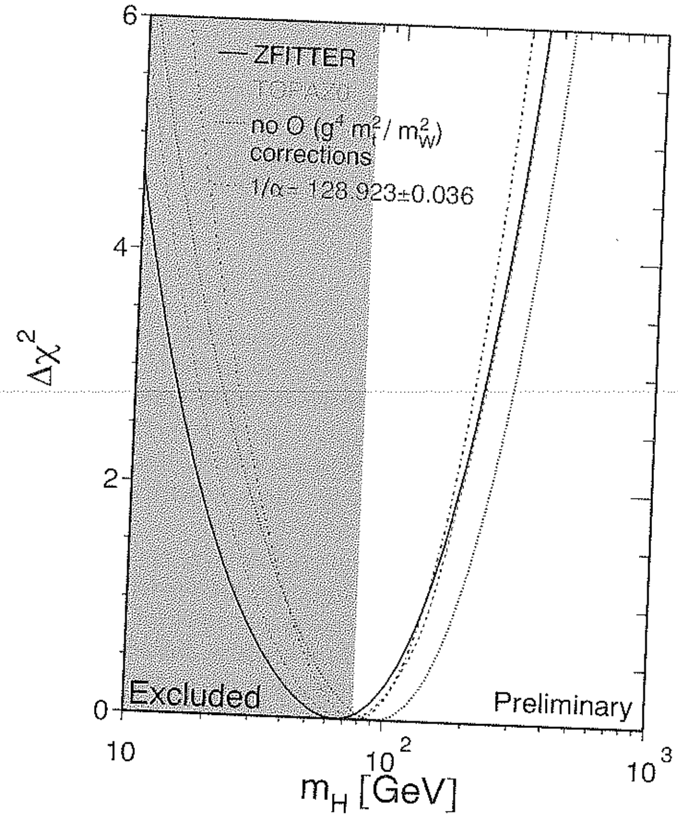

Figure 4. $\Delta\chi^2 = \chi^2 - \chi^2_{min}$ has been plotted as a function of m_H from a fit of the standard model to all data. The band represents an estimate of theoretical error due to missing higher order corrections.

Events with a hard radiated photon accompanied by two jets or with two ν's provide the possibility of measuring anomalous coupling of $ZZ\gamma$ or $Z\gamma\gamma$ vertices. The deviations are usually suppressed by terms of the form $(p_z/E_z)^n$. So sensitivity of measuring these couplings are higher at LEP2 energies. So far there is no evidence of anomaly in $ZZ\gamma$ or $Z\gamma\gamma$ couplings.

All electroweak measurements from LEP have been fitted within the framework of the standard model. The LEP measurements together with those from Tevatron collider have yielded the best fit with the mass of the Higgs boson

$$m_H = 66^{+74}_{-39}\ \text{GeV}$$

Figure 4 shows the variation of χ^2 as a function of Higgs mass. From the plot it is clear that at 95% CL, Higgs boson with mass above 215 GeV can be ruled out.

4. Search for Higgs

In the framework of the standard model, Higgs boson will be produced in e^+e^- interactions with an associated Z. The associated Z will be off mass shell at LEP1 energies and

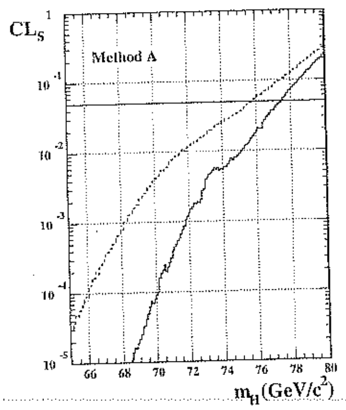

Figure 5. Average expected and observed confidence levels, obtained from combining the results of the four LEP collaborations using one of the statistical methods used by the LEP working group on Higgs boson searches.

will be on shell at LEP2. No evidence of Higgs boson was seen in the LEP1 searches by the 4 LEP experiments and combining the results from the four experiments, one can rule out Higgs boson of mass smaller than 65.6 GeV at 95% CL [9].

The searches have been extended in the LEP2 energies in a variety of channels: (1) $(Z\to q\bar{q})$ $(H\to q\bar{q})$; (2) $(Z\to \nu\bar{\nu})$ $(H\to q\bar{q})$; (3) $(Z\to e^+e^-, \mu^+\mu^-)$ $(H\to q\bar{q})$; (4) $(Z/H\to \tau^+\tau^-)$ $(H/Z\to q\bar{q})$. Still there is no evidence of the Higgs boson in all these searches. The LEP working group for Higgs boson searches [10] has combined the search results up to $\sqrt{s} = 172$ GeV. To combine the results from all the channels at different $\sqrt{s}$ from 4 experiments, the working group has adopted several statistical procedures. Figure 5 shows average expected and observed confidence level in one of these methods as a function of Higgs mass. This gives the most conservative limit of $m_{\rm H} > 77.5$ GeV at 95% CL.

Preliminary results from 183 GeV data [11] suggest a higher mass limit for the standard model Higgs. The limits from the four LEP experiments are summarised in table 4.

In the minimal supersymmetric model (MSSM), one may expect to observe two neutral Bosons below the Z boson mass, the scalar particles h and the pseudoscalar particle A. The h boson can have standard model like decays and the same search strategy can be used there. In addition, h can decay invisibly through a pair of LSP's or to a pair of A's if the A bosons are light enough. In addition h can be produced through the interaction $e^+e^-\to hA$. All these channels have been exclusively looked into. Combining the results from all LEP experiments, one finds that h boson can be ruled out up to 73.6 GeV [9] for all $\tan\beta$ values.

The direct searches from LEP can rule out A up to 75 GeV for $\tan\beta > 1$. For smaller $\tan\beta$ values, no limit on m_A exists. However if one combines the results from charged Higgs searches from CDF, $m_A \geq 75$ GeV for any $\tan\beta$ at 95% CL.

Table 4. Preliminary 95% CL lower bound on Higgs boson mass from the 183 GeV run at LEP.

	ALEPH	DELPHI	L3	OPAL
At 95% CL $m_{\rm H} >$	88.0 GeV	84.4 GeV	87.6 GeV	84.2 GeV

5. Search for supersymmetry

Supersymmetric partners of quarks, leptons and gauge bosons have been searched within the framework of MSSM. The phenomenology depends on the SUSY breaking mechanism as well as on the hypothesis of R-parity conservation. The standard search mode assumes SUSY breaking is gravity mediated and R-parity is conserved.

For R-parity conserving SUSY searches, one utilises some global characteristics like missing momentum, missing mass, acoplanarity, etc. Searches are optimized for each final state for three different topologies depending on the mass difference between the supersymmetric particle and the LSP (lightest supersymmetric particle). At high energies, W-pair events give rise to irreducible background for SUSY searches in the domain of large mass differences. Multidimensional optimisation is carried out to find the set of cut parameters which provides the maximum sensitivity in finding the signal. All the searches have yielded null results and one can get only limits on particle production depending on the parameter space. One has used minimal supergravity model so that the results can be interpreted in terms of five parameters: m_0 (common scalar mass), M_2 (common gaugino mass), $\tan\beta$ (ratio of vacuum expectation values), μ (Higgs mixing parameter), A_0 (common trilinear coupling).

For charginos, the searches have reached almost the kinematic limit. Figure 6 shows the preliminary exclusion limit from L3 for charginos in the limit when it is higgsino like or gaugino like.

One can combine the results from chargino and neutralino searches and in the framework of MSSM obtain a lower bound on the mass of the LSP. One needs to add the results from scalar lepton search to get a lower bound, independent of other SUSY parameters like μ or $\tan\beta$. Using the results from $\sqrt{s} \leq 172$ GeV data, neutralinos with mass below 14 GeV are ruled out at 95% CL.

LEP SUSY working group [12] has combined results from the four experiments to get a better exclusion region for sleptons, stops and sbottoms. Using the 161 and 172 GeV

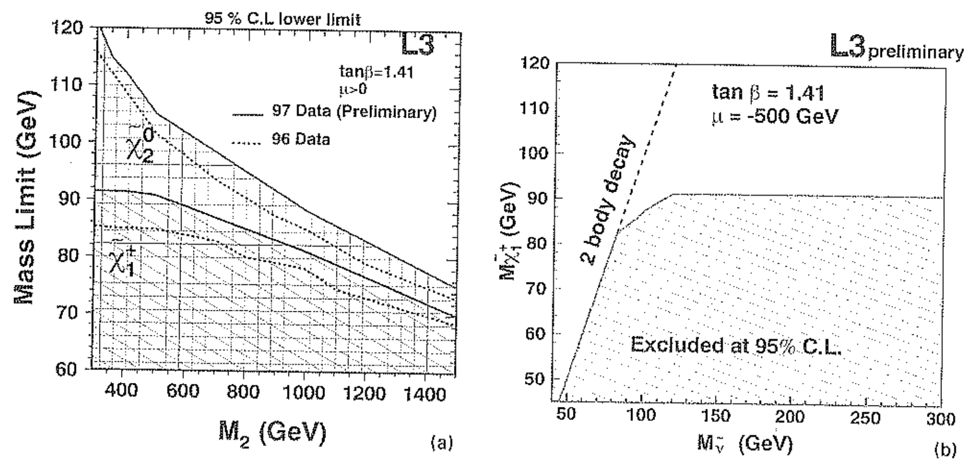

Figure 6. 95% CL exclusion limit for charginos in the scenarios $M_2 \gg |\mu|$ (higgsino like) and $|\mu| \gg M_2$ (gaugino like).

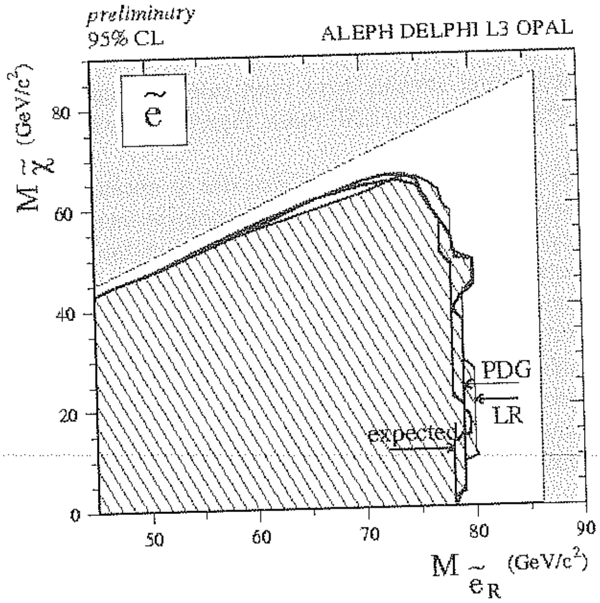

Figure 7. Excluded region for selectron searches by combining the results from the four LEP experiments.

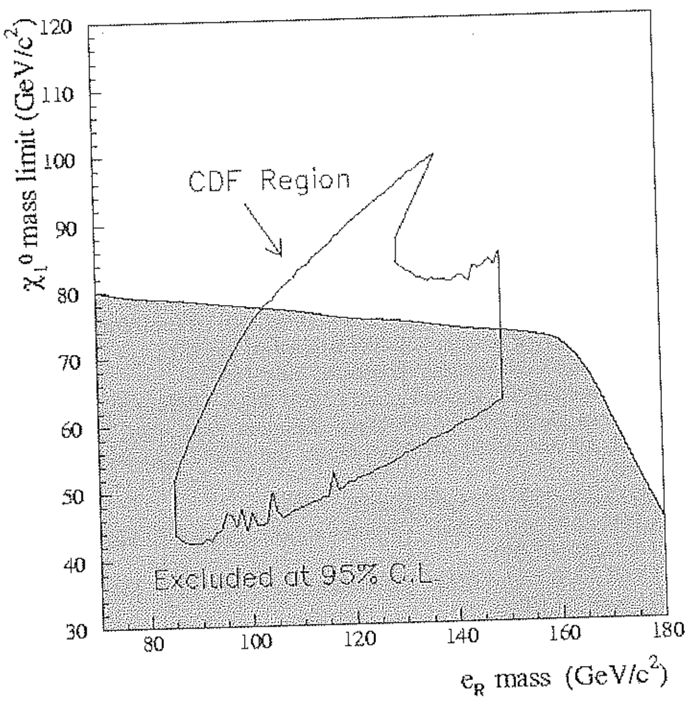

Figure 8. Region defined by the kinematics of the CDF event in its selectron interpretation together with the excluded region from LEP with searches done at energies $\leq$ 172 GeV.

data, right handed selectrons and smuons have been ruled out upto 78 and 70 GeV respectively for most of the values of the LSP mass. Figure 7 shows the exclusion plot selectron searches.

Gauge mediated SUSY breaking scenario will give rise to events with one or more energetic photons with missing energy. Search for these topologies have yielded no excess over the standard model expectations. Combining the results from the 4 LEP experiments [13], one can almost rule out the GMSB explanation of the CDF event with multiple electrons and photons. Figure 8 shows the parameter space in the model required to explain the CDF event and the excluded part of the parameter space from LEP experiments.

Searches have been made with the assumption of no R-parity conservation. There one expects to see multi-lepton or multi-jet events depending on the specific R-parity violating term in the Lagrangian. Absence of such events give rise to better exclusion regions than the corresponding search results in the R-parity conserving scenario.

6. Conclusion

The precision results from LEP has tested the standard model to a high degree of accuracy. Using the precision data, one has put an upper bound on Higgs boson mass at 215 GeV. The direct searches puts a lower bound at 88 GeV. No evidence of any new physics through anomalous couplings of gauge bosons, observation of new particles has been reported as yet. One looks forward to the higher energy and high luminosity runs of LEP to come during the year 1998 and beyond.

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