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Recent results from LEP

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Abstract. Recent results from the LEP collider at CERN are presented: on the identification of $e^+e^- \rightarrow W^+W^-$ and the determination of the W mass and width and limits on its anomalous couplings; the search for the Standard Model and non-minimal Higgs; search for SUSY and other new particles. Fits to all electroweak data leading to predictions of the Higgs mass within the Standard Model are presented.

Keywords. Gauge bosons; Higgs and new particle searches; LEP results; Standard Model.

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1. Introduction

The major goals of LEP2 are precision measurement of the mass and width of the W boson and search for new particles such as the Higgs and SUSY particles. Before 1996 the study of W production and decay was an exclusive domain of the $p\bar{p}$ colliders. In summer 1996 LEP ran at $\sqrt{s}$ = 161.3 GeV, just above the W-pair production threshold, providing 10 pb^{-1} luminosity per LEP experiment. In autumn 1996 LEP provided a similar luminosity at 172 GeV and in 1997 and 1998 integrated luminosities of 55 and 175 pb^{-1} per LEP experiment have been achieved at $\sqrt{s}$ values of 183 and 189 GeV respectively. So far as new particle searches are concerned, because of relatively low backgrounds inherent in e^+e^- interactions, the sensitivity extends practically over the entire allowed kinematic range. Thus these searches became particularly interesting with the advent of LEP2 in 1996 when LEP entered a new energy regime. In this talk LEP results on W properties and Higgs and SUSY searches are presented.

2. Identification of $e^+e^- \rightarrow W^+W^-(\gamma)$

There are many other competing standard model (SM) processes which contribute to the background. The situation is particularly difficult at $\sqrt{s}$ = 161 GeV (threshold) where background $\simeq$ 100 times the signal.

2.1 *Final states detected*

Using the SM branchings $B(W \rightarrow q\bar{q}')$ = 67.6% and $B(W \rightarrow \ell\,\bar{\nu})$ = 10.8% per lepton flavour leads to the following final states:

- $B(W^+W^- \to q\bar{q}^{'} q\bar{q}^{'})$ = 45.6%   4 jets
- $B(W^+W^- \to q\bar{q}^{'} \ell\, \bar{\nu})$ = 14.6%   2 jets, 1 lepton for each lepton flavour
- $B(W^+W^- \to \ell\, \bar{\nu} \bar{\ell^{'}}\, \nu^{'})$ = 10.6%   2 leptons, summed over lepton flavours

$e^+e^- \to W^+W^- \to q\bar{q}' q\bar{q}' \to 4\, jets$

The signal cross section $\simeq$ 1.6, 5.5, 7.2 pb   at 161, 172, 183 GeV and the main background is $\sigma(e^+e^- \to q\bar{q}(\gamma)) \simeq$ 150 pb.

Selection strategy:

- Select high multiplicity events without $\not{E}$
- Reject radiative return to the Z events
- Force events to four jets
- Impose energy-momentum conservation → 4C fit
- *Residual QCD background*: $qq \to qq$ gluon Bremsstrahlung → 4 jets. Neural network or equivalent multidimensional analyses are utilised to distinguish this background and make a best estimate of the signal. Use is made of the fact that

  (a) Bremsstrahlung gluons tend to follow parent quark direction, and
  (b) they mainly have smaller energies.

$e^+e^- \to W^+W^- \to q\bar{q}'\ell\, \bar{\nu} \to 2\, jets + \ell$

The signal cross section for each lepton flavour is $\simeq$ 0.5, 2.1, 2.3 pb   at 161, 172, 183 GeV and the main backgrounds are: $e^+e^- \to q\bar{q}(\gamma))$, 4-fermion, and $e^+e^- \to q\bar{q}\ell^+\ell^-$, with one lepton undetected.

Selection strategy:

- Identify hadronic event with a high energy, isolated lepton
  (e, μ, τ tagging as at LEP I)
- Cluster remaining event into 2 jets
- Determine missing momentum vector ($\vec{p}_\nu$)
- Apply selection cuts on kinematics of the 4 fermion system – angles between lepton and jets
  – magnitude and direction of missing energy
  – energies of lepton and jets
  – hadronic and leptonic invariant masses ($M_{q\bar{q}},\ M_{\ell\bar{\nu}}$)

$e^+e^- \to \ell\, \bar{\nu}\, \ell'\, \bar{\nu'} \to \ell + \ell'\ (\ell/\ell' = e/\mu/\tau)$

Summed over lepton flavours the signal cross section $\simeq$ 0.4, 1.5, 1.7 pb at 161, 172, 183 GeV and the main backgrounds are dilepton events from $e^+e^- \to Z(\gamma)$, Bhabha scattering, and 2 photon processes.

Selection strategy:

- Exclude hadronic events using multiplicity
- Identify 2 leptons (e, μ, τ tagging as at LEP I)
- Apply selection cuts on
  – acoplanarity angle between the 2 leptons
  – missing transverse momentum in event.

2.2 *Systematic errors on WW production cross sections*

Some of the important sources of systematic error on WW production cross section at LEP are:

- Variation of selection cuts around nominal value
- Model parameter variation – signal and backgrounds
- Model to model variation
- W mass dependence
- Differences between data and Monte Carlo
- Limited Monte Carlo statistics.

2.3 $e^+e^- \to W^+W^-$ *cross sections*

Many other background processes proceeding via different intermediate states produce the same final states as WW production. Much of this background is removed by appropriate invariant mass or other cuts, but a Monte Carlo based correction factor ($\sim$ a few percent) is still required specially for some channels.

The LEP average WW production cross section values at 161, 172 and 183 GeV are determined to be 3.69±0.45 [1], 12.0±0.7 and 15.9±0.4 pb [2], the first two being final numbers and the last preliminary. The variation of this cross section as a function of $\sqrt{s}$ is depicted in figure 1. The points represent the data and the curve is the SM expectation. The data at 189 GeV is very preliminary, based on limited statistics available at the time of the Vancouver conference [2]. Later results [3–6] indicate a better agreement with the SM expectation at this energy.

3. Determination of W mass

3.1 W *mass from 161 GeV data; threshold method*

The method is to measure $\sigma(e^+e^- \to W^+W^-)$ and obtain M_W using the predicted dependence of σ with M_W at the given $\sqrt{s}$. While this dependence is obtained within the framework of the SM (GENTLE program) it can be shown that just above WW threshold

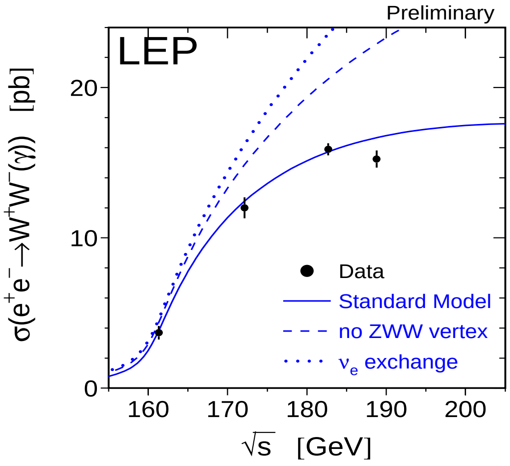


Figure 1. WW cross section as a function of $\sqrt{s}$.

it is the kinematics that controls the cross section behaviour and not any dynamic or physical assumption of the SM. The optimum energy value to obtain the maximum statistical sensitivity is $\sqrt{s} \simeq 2{\cdot}M_W$ + 0.5 GeV. Knowing $M_W{\simeq}$81.2 GeV (from $p\bar{p}$ experiments at CERN and FNAL) the first run of LEP above WW threshold was made at $\sqrt{s}$ =161.3 GeV. Corresponding to a measured LEP average $\sigma(e^+e^- \to W^+W^-)$ = 3.69±0.45 pb one obtained $M_W = 80.40^{+0.22}_{-0.21}$ GeV [1].

3.2 W *mass using reconstructed* W*'s*

Well above threshold the sensitivity of the threshold method decreases and the method is then to reconstruct the W's and fit the reconstructed mass distribution to obtain the W mass (and width) taking properly into account the detector resolution. In principle the procedure is simple after WW events are identified.

- Calculate jet–jet, lepton–neutrino invariant masses. For $qq\ell\nu(\gamma)$ channels life is simpler: no combinatorics and small background.
- Apply beam energy constraints to improve reconstructed mass resolution. This results in a 4C fit for $qqqq$, a 1C fit for $qq\ell\nu(\gamma)$.
- Application of the beam energy constraint leads to an anti-correlation between the 2 reconstructed W masses. To take care of this effect one
  - either, uses the average W mass, $\langle M_W\rangle = 0.5 \times (M_{W1} + M_{W2})$,
  - or, sets M_{W1}=M_{W2} leading to a 5C fit for $qqqq$ and a 2C fit for $qq\ell\nu(\gamma)$
  - or, studies the fitted M_{W1}–M_{W2} correlation in MC and applies a correction

- Use a Breit–Wigner (BW) plus parametrized (or actual) background and fit for M_W and possibly (additionally) Γ_W.

Sources of systematic errors on M_W: The systematic errors on M_W using the reconstruction method are:

- The use of beam energy constraint to improve mass resolution leads to two sources of systematic error
  1. A LEP energy uncertainty, $\Delta E_{\rm LEP} \simeq$ 20 MeV, leads to a mass uncertainty of similar magnitude.
  2. Initial state radiation decreases the effective $\sqrt{s}$. Thus using the nominal value of $\sqrt{s}$ results in an increased M_W. Modelling uncertainties of ISR lead to uncertainty in the fitted M_W of $\simeq$10 MeV.
- Modelling QCD background under the signal: the background also peaks just under the M_W peak and uncertainty in this affects M_W.
- Detector effects: miscalibration of energy of leptons and mismatch between M.C. and data for energies/angles of jets.
- Fit type dependence:
  - Relativistic vs non-relativistic BW
  - different parametrisation for backgrounds
  - variations in fitting procedures (4C, 1C vs 5C, 2C).

These effects at present total to $\simeq$ 30–50 MeV systematic error on M_W.

Theoretical systematics in qqqq: Owing to the short lifetime of the W bosons ‘colour reconnection’, due to the possible gluon exchange between quarks from the decay of the two different W’s, leads to a distortion of the reconstructed W masses. The presently available models give divergent results on this correction and this uncertainty results in a theoretical systematic error on M_W determined using the $qqqq$ final state.

Another similar distortion of the reconstructed W mass distribution could be due to Bose–Einstein correlations between identical bosons (e.g., π°) produced as decay products of the two W’s because the hadronisation regions of the W’s overlap. Here again a good theoretical understanding of this problem is lacking.

Some LEP experiments have carried out more detailed investigation of different models than others. Currently the overall theoretical uncertainty in M_W determination due to both these effects is estimated to be ~90 MeV in the $qqqq$ final state. For a result combining roughly equal numbers of $qqqq$ and $qq\ell\nu(\gamma)$ events the uncertainty will be ~45 MeV.

3.3 M_W *and* Γ_W *from 172 and 183 GeV LEP data*

The preliminary M_W values as determined from reconstructed W’s at 172 and 183 GeV are shown in figure 2 with the LEP average M_W= 80.36±0.09 GeV [2].

L3 and OPAL have carried out fits using both M_W and Γ_W as free parameters (when only M_W is floated Γ_W is taken from the SM at that M_W). The analysis of combined 172 + 183 GeV data by L3 [7] and OPAL [8] leads to Γ_W = 1.97±0.34±0.17 GeV and $1.84 \pm 0.32 \pm 0.20$ GeV respectively.

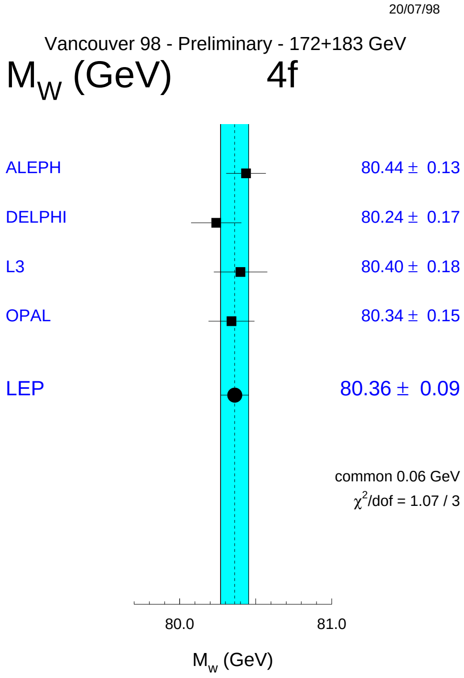


Figure 2. M_W determination at 172–183 GeV at LEP.

4. Indirect determination of M_W and $M_{\rm Higgs}$

Precision electroweak data, including LEP1 and SLD results, can be fitted within the SM framework to obtain an indirect estimation of M_W and $M_{\rm Higgs}$, the still missing piece of the SM zoo. Data available at the time of the Vancouver conference [2], excluding direct M_W results, leads to an indirect estimation of $M_W = 80.367\pm0.029$ GeV. The comparison of different determinations of M_W is depicted in figure 3. The direct measurements agree very well with the indirect determination indicating the validity of the SM, in particular the radiative corrections. Using all data, including directly measured M_W, the best estimate of $M_{\rm Higgs} = 76^{+85}_{-47}$ GeV, the central value being below the direct lower limits set on $M_{\rm Higgs}$ by LEP experiments ($\simeq$90 GeV [9]). Figure 4 depicts the contours of $M_{\rm top}$ vs M_W using direct and indirect data. The preference for low $M_{\rm Higgs}$ is obvious as also the necessity of a more precise determination of M_W to fix $M_{\rm Higgs}$ better.

5. General remarks on searches at LEP2

In order to obtain the best search limits from LEP, various Working Groups (WG's) have been established at CERN to devise methods for combining results from the four individual experiments (Aleph, Delphi, L3 and Opal). Combined LEP results obtained by the

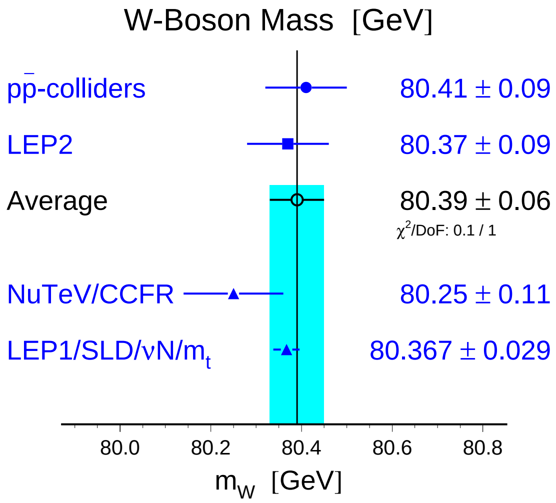


Figure 3. M_W determinations.

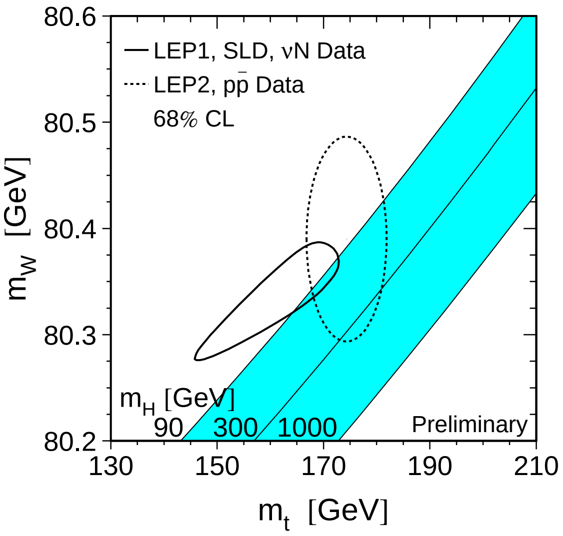


Figure 4. $M_{\rm top}$ vs M_W contours using direct and indirect data.

LEP Higgs WG and the LEP SUSY WG will be presented for data collected up to 183 GeV (1997 run). Preliminary results using the high statistics 189 GeV data (1998 run) were presented by individual experiments at the November 1998 LEPC meeting at CERN. These will also be shown.

6. Search for the Standard Model Higgs

The dominant production process is Higgs-strahlung: $e^+e^- \rightarrow Z^\star \rightarrow H^0\, Z$, with H^0 and Z decaying to fermion–antifermion pairs, the dominant branching of Higgs being $b\,\bar{b}$ (≈84%).

The main final states detected and their signatures are:

- $H^0(\rightarrow b\bar{b})\; Z(\rightarrow q\bar{q}) \sim$ 60%: 4 high multiplicity jets, 2 with b quarks, other 2 giving invariant mass of a Z.
- $H^0(\rightarrow b\bar{b})\; Z(\rightarrow \nu\bar{\nu}) \sim$ 17%: 2 acoplanar hadronic jets (b quarks), no isolated charged leptons, large $\not{p}_T$.
- $H^0(\rightarrow b\bar{b})\; Z(\rightarrow \ell\bar{\ell})$ and $H^0(\rightarrow \tau\bar{\tau})\; Z(\rightarrow q\bar{q}) \sim$ 14%: With two b jets and two isolated charged leptons in the first case and two τ's and two quark jets in the second case, the leptons in the first case and the quarks in the second case giving an invariant mass of the Z.

Using data up to 183 GeV, the individual 95% C.L. lower limits on the mass of the SM Higgs and the combined LEP limit [9] are: 87.9 (A), 85.7 (D), 87.6 (L), 88.3 (O) and 89.8 (LEP) GeV, where A, D, L, O stand for Aleph, Delphi, L3, Opal.

Preliminary results using 189 GeV data lead to 95% C.L. lower limit of 94.1 GeV from Delphi [4] and 95.5 GeV from L3 [5]. Opal [6] have searched for the $H^0 \rightarrow \gamma\gamma$ decay mode in their 189 GeV data and obtained an exclusion region in the M_H vs BR($H^0 \rightarrow \gamma\gamma$) plot. Recall that at low Higgs mass (≤ 140 GeV) this is the classic discovery mode at LHC or upgraded Tevatron.

7. Higgs sector in the MSSM

In the minimum supersymmetric extension of the Standard Model (MSSM) one has five observable Higgs: 2 CP-even neutral, h^0, H^0 with $m_h < m_H$, 1 CP-odd neutral, A^0, and 2 charged Higgs, $H^\pm$. At tree-level MSSM yields the mass relations: $m_h < m_Z < m_H$ and $m_{W^\pm} < m_{H^\pm}$. These are modified significantly by radiative corrections

$$\Delta m_h^2 \sim \frac{m_{\rm top}^4}{m_W^2}\left(\log\frac{m_{\tilde{t}_1}^2\, m_{\tilde{t}_2}^2}{m_{\rm top}^4} + \cdots\right)$$

but still $m_h < 130$ GeV or so. But, the second relation, $m_{W^\pm} < m_{H^\pm}$ is still almost always obeyed.

7.1 *Search for* h^0, H^0

The production mechanisms at LEP are due to complementary processes: $e^+e^- \rightarrow Z^\star \rightarrow h^0Z$ and $e^+e^- \rightarrow Z^\star \rightarrow h^0A^0$ with Z, h^0 and A^0 decaying to fermion–antifermion pairs, the dominant branching of Higgs being $b\,\bar{b}$ or $\tau\bar{\tau}$. Their cross sections in comparison to the cross section for SM Higgs production are

$$\sigma(e^+e^- \to h^0 Z) = \sin^2(\beta-\alpha)\cdot\sigma_{\rm SM},$$
$$\sigma(e^+e^- \to h^0 A^0) = \cos^2(\beta-\alpha)\cdot\bar{\lambda}\cdot\sigma_{\rm SM},$$

$\bar{\lambda}$ being a kinematic factor, $\tan\beta$ the ratio of the vacuum expectation values of the two Higgs doublets and α the Higgs mass mixing angle.

The search channels are then $hA \to b\bar{b}b\bar{b}$, $hA \to (q\bar{q}\tau\bar{\tau},\ \tau\bar{\tau}q\bar{q})$, $AAA \to b\bar{b}b\bar{b}b\bar{b}$ at $\sqrt{s} = 161$ and 172 GeV. At 183 GeV and above new channels including Z open up: $Zh \to q\bar{q}A(\to b\bar{b})A(\to b\bar{b})$, $Zh \to \nu\bar{\nu}A(\to b\bar{b})A(\to b\bar{b})$ and $Zh \to \ell\bar{\ell}A(\to b\bar{b})A(\to b\bar{b})$.

7.2 *Theoretical interpretation*

There are too many parameters in the MSSM to allow easy and transparent exclusion of parameter regions. The LEP experiments use LEP2 workshop benchmarks [10] regarding the parameters to be varied and their allowed ranges. Briefly, take $m_{\rm top} \simeq 175$ GeV (Tevatron), assume SUSY scale $M_{\rm SUSY} = 1$ TeV and vary the parameters M_A up to 1 TeV and $\tan\beta$ up to 50. Within this framework three scenarios are examined with μ being the SUSY Higgs mass parameter:

1. $A = 0$, $\mid\mu\mid << \rm M_{SUSY}$ (NO squark mixing)
2. $A = \sqrt{6}\,M_{\rm SUSY}$, $\mid\mu\mid << M_{\rm SUSY}$ (MAXIMAL squark mixing)
3. $A = M_{\rm SUSY} = -\mu$ (‘TYPICAL’ squark mixing).

7.3 *Results on h^0 and A^0*

Based on data up to 183 GeV 95% C.L. lower limits on m_{h^0} and m_{A^0} from individual experiments (ADLO) and LEP (GeV) are [9]:

	A	D	L	O	LEP
$m_{h^0} >$	72.2	74.4	70.7	70.5	78.8
$m_{A^0} >$	76.1	75.3	71.0	72.0	79.1

Using 189 GeV data, the Delphi 95% MSSM exclusion limits in the m_h vs $\tan\beta$ plane [4] are shown in figure 5. A limit on $m_{A^0} > 83.3$ GeV is obtained. It is interesting to note that the low $\tan\beta$ region ($\tan\beta$ less than about 2) now starts to get excluded experimentally. Opal [6] confirm this observation.

7.4 *Results on charged Higgs bosons*

Within the MSSM the mass of $H^\pm$ is too high to be produced at LEP for almost all sets of MSSM parameters. However, within the general two doublet Higgs model $m_{H^\pm}$ is a free parameter. The production process is $e^+e^- \to H^+H^-$ with the cross section depending only on $m_{H^\pm}$ and not on $\tan\beta$. One assumes that only two decay modes are allowed: $c\bar{s}$ and $\tau\nu$. Thus one investigates the three final states ($c\bar{s}\bar{c}s$), ($c\bar{s}\tau\nu$) and ($\tau\nu\tau\nu$).

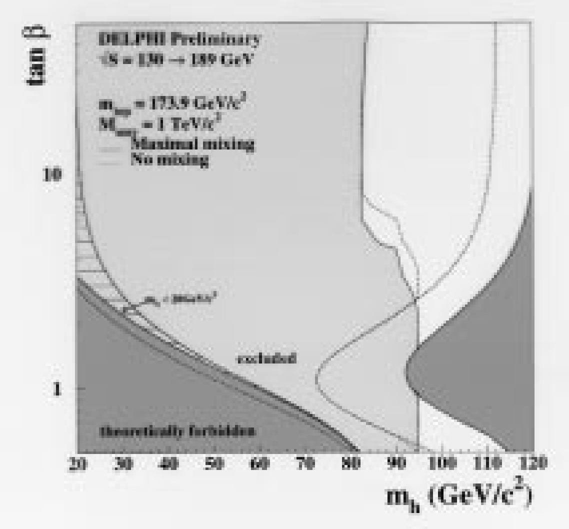


Figure 5. Delphi [4] 95% exclusion limits in $\tan\beta$ vs m_h plane.

The detection efficiency is typically 40–50%. Based on data up to 183 GeV 95% C.L. lower limits on $m_{H^\pm}$ from individual experiments (ADLO) and LEP (GeV) are [9]:

	A	D	L	O	LEP
$m_{H^\pm} >$	59	56.6	57.5	59	68

8. Search for SUSY particles

The SUSY particle spectrum may be summarised as

particle	J	sparticle	J
gauge bosons	1	gauginos	1/2
Higgs	0	Higgsinos	1/2
fermions	1/2	sfermions	0

After electroweak symmetry breaking the gauginos and Higgsinos mix into the physical mass eigenstates consisting of two charginos, $\tilde{\chi}_i^\pm$, $i = 1, 2$ and four neutralinos, $\tilde{\chi}_i^0$, $i = 1, 4$. The parameters relevant to this sector are the gaugino mass, M_2, the higgsino mass, μ, and $\tan\beta$.

In the fermion sector, each quark and lepton has 2 scalar partners of left and right chirality. The scalar mass eigenstates are a mixture of these with the mixing angles being free parameters.

In terms of the baryon and lepton numbers, B and L, and the spin, S, R-parity is defined: $R = (-1)^{3B-L+2S}$ with particles having $R = +1$ and sparticles having $R = -1$.

8.1 *m-SUGRA model*

Many experimental results are interpreted within the framework of the minimal-SUperGRAvity model which reduces the number of parameters to five: m_0 and $m_{1/2}$, the universal scalar and gaugino masses, A_0, the universal trilinear coupling, $\tan\beta$ and the sign of μ, the Higgsino mixing term. Fixing the value of these fixes all the sparticle masses, their mixing angles as well as their production cross sections and decay modes.

8.2 *SUSY signatures under R-parity conservation*

In most scenarios the lighter neutralino, $\tilde{\chi}_1^0$, is the lightest SUSY particle (LSP). Under R-parity conservation SUSY particles are always pair produced and at the end of the decay chain 2 $\tilde{\chi}_1^0$'s always escape detection. Thus the generic SUSY signature is large $\not{p}_T$, large missing energy, missing mass and acoplanarity. Once these basic requirements are met all chargino, neutralino and slepton searches demand one of the three topologies:

1. 2 or more acoplanar leptons,
2. hadrons + 1 or more isolated leptons,
3. high multiplicity hadronic state.

Another important variable for signal topology is Δm, the mass difference between the SUSY particle and the LSP. For low Δm the background is more 2γ-like and for high Δm it is more WW-like.

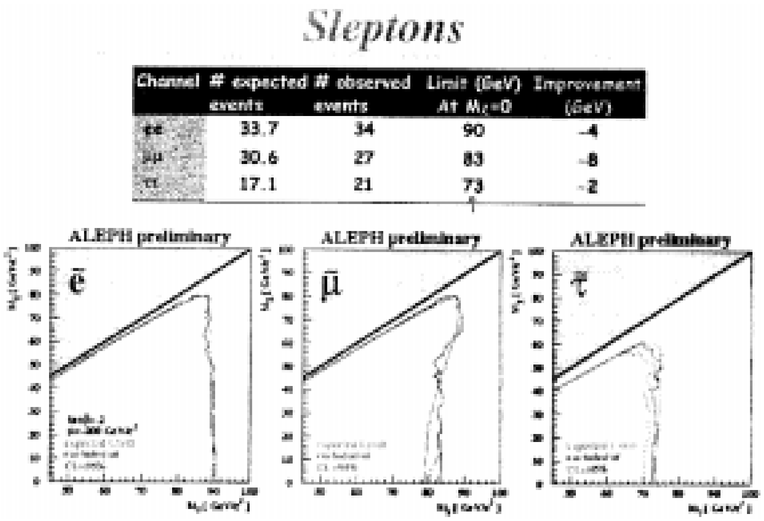
The decay modes searched for stop and sbottom are $\tilde{t} \to c\tilde{\chi}_1^0$: 2 jets, $\tilde{t} \to b\tilde{\chi}_1^+ \to bl\tilde{\nu}$: 2 b jets $+2$ isolated leptons, and $\tilde{b} \to b\tilde{\chi}_1^0$: 2 b jets.

Results on sleptons: For $\tilde{e}_R,\ \tilde{\mu}_R$ and $\tilde{\tau}_R$, the 95% C.L. lower limit on their masses from single experiments (A, D, L, O) are 79–83 GeV, 55–62 GeV and 45–63 GeV respectively using data up to 183 GeV. From a combination of all LEP data [11], the limits become 85 GeV, 71 GeV and 75 GeV respectively. Preliminary analysis of 189 GeV data improves these limits even using a single experiment. Plots from Aleph [3] are shown in figure 6.

Results on stop, sbottom: The kinematics of the events strongly depends on Δm, the best selection efficiency being obtained at $\Delta m \sim$20–30 GeV. Unbalanced 2-jet b- and c-quark tagged events are chosen as candidates. Results are presented at two values of the mixing angle, θ, and using 183 GeV data one obtains the results [11] shown in table 1.

There is considerable improvement in these limits using 189 GeV data. Preliminary plots from Aleph [3] are shown in figure 7.

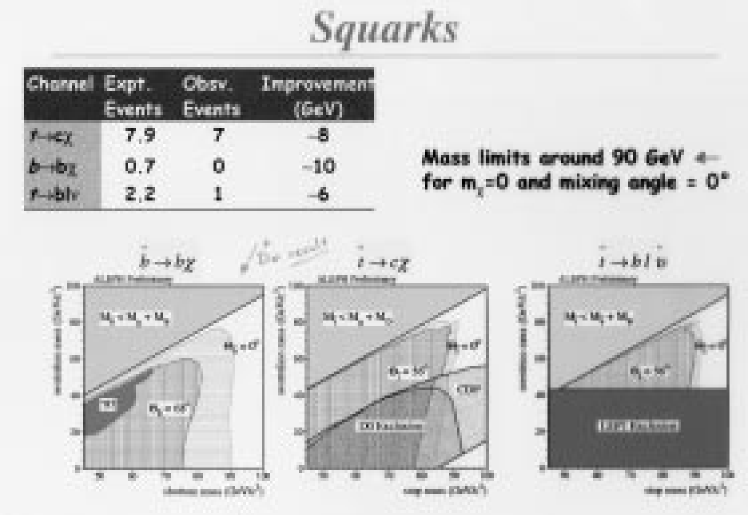
Results on charginos, neutralinos: Delphi, L3 and Opal data at 183 GeV has been combined [11] and the number of candidates is consistent with expectations from standard model processes. Assuming large slepton masses, i.e., dominance of the decay $\tilde{\chi}^\pm \to \tilde{\chi}^0 W^\star$, the 95% C.L. lower limits on chargino mass are 90.1, 89.0 and 81.7 GeV for Δm ($m_{\tilde{\chi}^\pm} - m_{\tilde{\chi}^0}$) values of 5, 4 and 3 GeV respectively. So far as neutralinos are concerned, the lightest one escapes detection and hence limits on its mass are extracted using data from other SUSY searches. The lower limit on the LSP mass, $m_{\tilde{\chi}_1^0}$, is



Sleptons

Channel	# expected events	# observed events	Limit (GeV) At M_χ=0	Improvement (GeV)
ee	33.7	34	90	~4
μμ	30.6	27	83	~8
ττ	17.1	21	73	~2

Figure 6. Aleph [3] results on slepton searches.



Squarks

Channel	Expt. Events	Obsv. Events	Improvement (GeV)
$\tilde{t}\to c\chi$	7.9	7	~8
$\tilde{b}\to b\chi$	0.7	0	~10
$\tilde{t}\to bl\tilde{\nu}$	2.2	1	~6

Mass limits around 90 GeV ←
for m_χ=0 and mixing angle = 0°

Figure 7. Aleph [3] results on squark searches.

determined as a function of $\tan\beta$ [3,5,6] using 189 GeV data and an example of the plots is shown from Opal [6] in figure 8. All experiments find $m_{\tilde{\chi}_1^0} >$ 30–32 GeV or so.

R-parity violating scenario: SUSY, renormalizability and gauge invariance does not imply R-parity conservation. The Lagrangian may contain additional terms:

Table 1. 95% Mass lower limit on stop and sbottom for $\Delta m = 15$ GeV.

	$\tilde{t} \to c\tilde{\chi}_1^0$		$\tilde{t} \to b\tilde{\chi}_1^+ \to b\ell\tilde{\nu}$		$\tilde{b} \to b\tilde{\chi}_1^0$	
	$\theta = 0°$	$\theta = 56°$	$\theta = 0°$	$\theta = 56°$	$\theta = 0°$	$\theta = 56°$
Single Expt.	80–85	72–81	84–85	80–82	78–84	45–68
Combined LEP	86	83	87	85	86	75

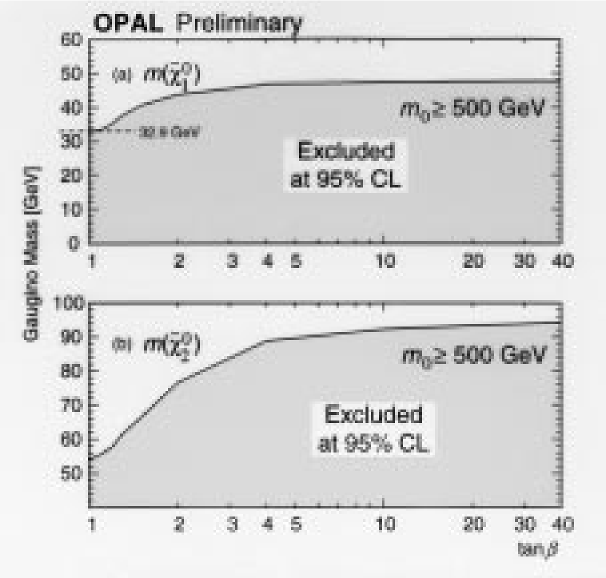


Figure 8. Opal [6] results on chargino, neutralino searches.

$$\lambda_{ijk} L_i L_j \bar{E}_k + \lambda'_{ijk} L_i Q_j \bar{D}_k + \lambda''_{ijk} U_i \bar{D}_j D_k$$

where i, j, k are generation indices; L, Q are left-handed lepton, quark-doublet superfields and $\bar{E}, \bar{D}, \bar{U}$ are right-handed singlet superfields for charged leptons and down,up type-quarks. LLE, $LQ\bar{D}$ terms violate lepton number and $U\bar{D}\bar{D}$ term violates baryon number. An example of such an analysis is from $L3$ [5] where LLE mediated decays were considered corresponding to λ_{122} and λ_{133} terms:

λ_{122}: e, μ in final state (high selection efficiency) with

$$\tilde{\chi}_1^0 \to \bar{\nu}_e \mu^+ \mu^-, \nu_\mu e^+ e^-,\ \nu_e \mu^- \mu^+, \bar{\nu}_\mu e^- \mu^+.$$

λ_{133}: each neutralino decays in one τ (low selection efficiency) with

$$\tilde{\chi}_1^0 \to \bar{\nu}_e \tau^+ \tau^-, \nu_\tau e^+ \tau^-,\ \nu_e \tau^- \tau^+, \bar{\nu}_\tau e^- \tau^+.$$

The selections are similar to 'normal' SUSY, except $\not{E}$ is replaced by jets or leptons. Figure 9 shows L3 results using 189 GeV data. As one notices, the lower limit on LSP mass is still ∼30 GeV. Similar results have been presented by Aleph [3].

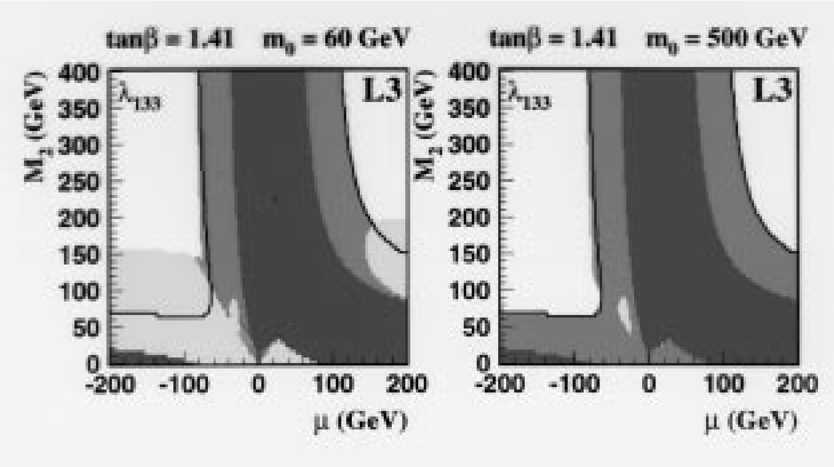


Figure 9. R-parity violation scenario. L3 [5] 98% exclusion limits is in μ vs M_2 plane.

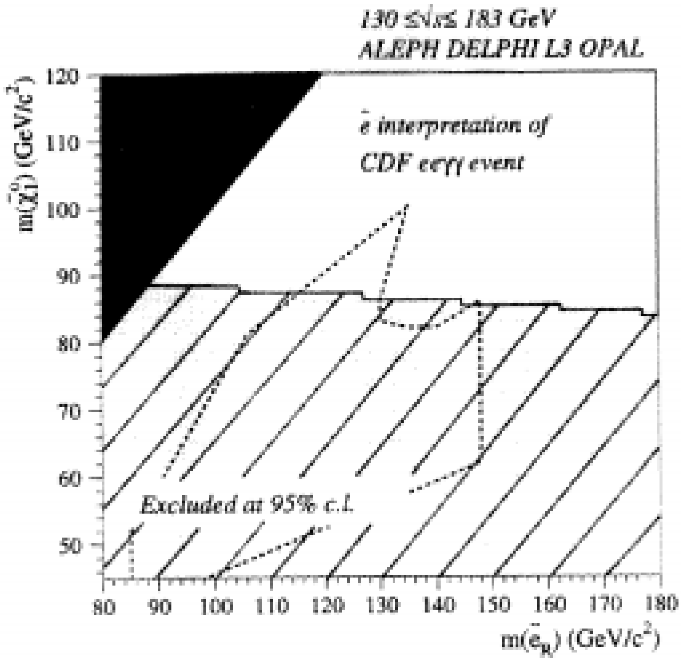


Figure 10. GMSB interpretation of CDF event. LEP combined exclusion [9].

GMSB SUSY scenario: Inspired by the one CDF, $e^+e^-\gamma\gamma\ \not{E}$, event the gauge-mediated symmetry breaking scenario envisages an ultra-light gravitino, $\tilde{G}$, as the LSP and R-parity conservation. The typical reactions at LEP would be $e^+e^- \to \tilde{\chi}\tilde{G} \to \gamma\tilde{G}\tilde{G}$ and $e^+e^- \to \tilde{\chi}\tilde{\chi} \to \gamma\tilde{G}\ \gamma\tilde{G}$, i.e., states involving single or multi photons and nothing else. Such events have been searched for by all the LEP experiments. No deviation from standard model expectations are found either in the number of events or in their energy spectrum [3–6,11]. The favoured parameter space corresponding to the CDF event is now almost excluded by the combined LEP data at 183 GeV [11] as shown in figure 10. Preliminary results using 189 GeV data from Aleph [3] leads to the same conclusion.

9. Summary and outlook

9.1 *W-properties*

- as of summer 98, using $161 \leq \sqrt{s} \leq 183$ GeV data, LEP M_W= 80.37±0.09 GeV, i.e., ΔM_W = 90 MeV. This was based on $\simeq 75$ pb^{-1}/LEP experiment.
- outlook for spring 99 (European winter conferences), after including 189 GeV data, $\simeq 175$ pb^{-1}/LEP experiment,

expectation is that $\Delta M_W \Rightarrow$ 50–60 MeV.

Table 2.

		Up to 183 GeV		Up to 189 GeV One Expt.
		One Expt.	Combined	
SM	Higgs	∼88	89.8	94–95.5
MSSM	h^0	70–74	78.8	82.4
	A^0	71–76	79.1	83.3
Excluded $\tan\beta$				
No Mixing		0.8–2.1		0.6–2.5
Maximal Mixing				1.0–1.5
	$H^\pm$	57–59	68	
SUSY	$\tilde{e}_R$	79–83	85	∼85
	$\tilde{\mu}_R$	55–62	71	∼80
	$\tilde{\tau}_R$	45–63	75	∼72
$\tilde{t}$	$\theta = 0°$	84–85	87	∼88
	$\theta = 56°$	80–82	85	∼86
$\tilde{b}$	$\theta = 0°$	78–84	86	∼90
	$\theta = 68°$	45–68	75	∼75
$\tilde{\chi}^\pm$	$\Delta M = 3$	79–81	81.7	
	$\Delta M = 5$	86–88	90.1	
	$\Delta M = 10$	87–89	91.0	
$\tilde{\chi}^\circ$	R_P cons.	27–33		
	R_P viol.			30.6

– at end of LEP running, end 2000, $\simeq 500$ pb^{-1}/LEP experiment,

$$\text{expected } \Delta M_W \simeq 35 \text{ MeV,}$$
$$\text{if color reconnection, Bose–Einstein correlations are understood,}$$

$$\Delta M_W \simeq 45 \text{ MeV otherwise.}$$

9.2 *New particle searches*

The 95% C.L. lower limits on the mass of various particles searched at LEP are given in table 2 in GeV.

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