THE SEARCH FOR NEW PARTICLES AT LEP

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ABSTRACT

LEP is a fantastic machine to search for new particles because of the very simple initial and final state. In these days LEP has the leading role in all of the searches: Higgs, supersymmetric particles, Technicolor, LeptoQuarks, excited fermions, extra dimensions, and many others.

Particular attention will be given to the Higgs bosons search: production and decay in various models will be reviewed and the results presented. In particular the phenomenology of the Higgs bosons in the Standard Model, the Minimal Supersymmetric Standard Model and more exotic extensions of the standard model will be detailed. The potential for discovery at the end of LEP and for future colliders will be discussed.

In the supersymmetry (SUSY) domain the main results will be review: the limits on the chargino mass and on the lightest supersymmetric particle.

Results of the searches for LeptoQuark, FCNC processes, Technicolor particles, excited leptons and extra dimensions will be summarised.

All the results are as of summer 2000.

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1 Introduction

From 1995 LEP started to run at centre of mass energies higher than the Z mass. From E_{cm}=130 GeV in Autumn 1995, LEP gradually increased the centre of mass energy, reaching $E_{cm} \sim$ 209 GeV in the year 2000.

In Table 1 the centre of mass energies and the luminosity collected by each of the 4 experiments are shown. More than 2 fb^{-1} at E_{cm} larger than 180 GeV have been collected.

year	89-95	95		96		97	98	99				2000
E_{cm}(GeV)	91	130	136	161	172	183	189	192	196	200	202	204-209
Lum(pb^{-1})	175	2.5	2.5	11	11	55	160	30	80	80	40	>220

Table 1. *LEP Centre of Mass Energies and Average Luminosity per Experiment*

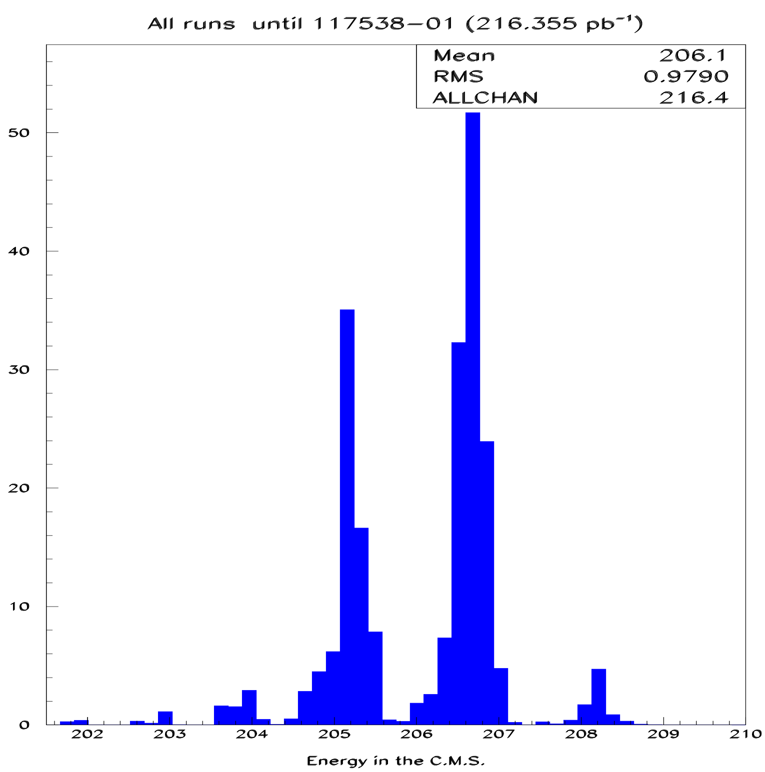

Fig. 1. *Luminosity delivered per experiment as a function of* E_{cm}.

In the year 2000 the running mode of the machine changed in order to exploit the full potential of the machine and reach the maximum energy and luminosity. Instead of running at a fixed $\mathrm{E_{cm}}$, the energy of the beam is increased during a fill when the luminosity starts to decrease. In this way the machine is always at its cryogenic limit. In Figure 1 the luminosity as a function of the centre of mass energy is shown for the 2000 run (as of the end of October). LEP delivered to each experiment $\sim$10 $\mathrm{pb^{-1}}$ at $\mathrm{E_{cm}}$>208 GeV and more than 220 $\mathrm{pb^{-1}}$at $\mathrm{E_{cm}}$>200 GeV.

With increasing energy the phase space available to produce new particles increases. At LEP we try to look everywhere and consider all the models, we investigate each channel and each fluctuation. In direct searches the signal is looked for in the framework of a theoretical model or as an excess in any final state topology. Indirect searches instead take the Standard Model as the null hypothesis and look for any possible deviations.

The four experiments then combined their results in order to increase the kinematical range accessible and to smooth eventual statistical fluctuations.

One of the main physics goal of the four LEP experiments was the search for the Higgs boson. The Higgs boson mass is not predicted by the Standard Model (SM) and as of today only limits from the precise electroweak measurements could be inferred. Results on SM Higgs, MSSM and 2HDM Higgs bosons, and on anomalous couplings will be reviewed and the situation at the end of LEP will be discussed.

In the supersymmetry (SUSY) domain various messenger interactions are investigated by which the symmetry breaking is transmitted from the hidden sector to the "particle" world. The main results will be review: the limits on the mass of the particle with the highest cross section (the chargino) and on the lightest supersymmetric particles will be given.

Finally some other searches like the searches for excited leptons, LeptoQuark, Technicolor particles and single top production will be reviewed.

2 The Standard Model Higgs

The Standard Model has been tested by the experiments at LEP, SLC and Tevatron accelerators to a per mil precision. In the data no significant evidence for departure from the SM has been observed,[1] as shown in Figure 2. This tells us that the theory (SU(2)$\times$SU(1)) describes at the per mil level the coupling of quarks and leptons to photons, Z and W bosons, and (to less accuracy) the triple gauge vertices, or in other words that the gauge symmetry is indeed exact.

Yet, the particles have mass and are not degenerate in mass: this implies that the

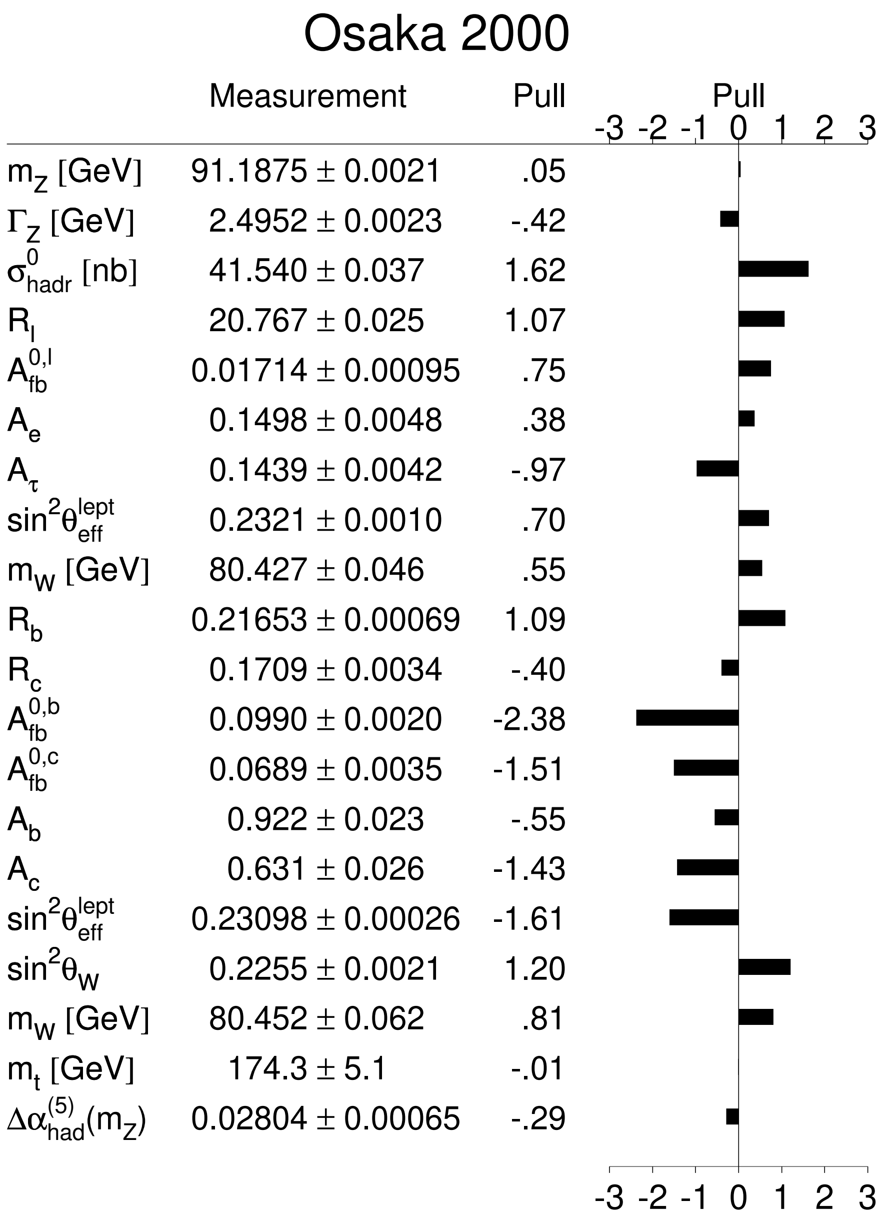

Fig. 2. *Summary of the measurements of the Standard Model parameters from LEP, SLD and $p\bar{p}$ and νN experiments.*

symmetry is broken in the masses. The mechanism that describes the spontaneous breaking of the symmetry is the Higgs mechanism.[2] While the existence of the Higgs boson is well supported by the data on radiative corrections,[1] the value of its mass is not predicted by the theory and only weak limits come from the experiments. In Figure 3 the theoretical bounds on the Higgs mass are shown as a function of Λ, the scale at which new physics can occur. These bounds are derived from general considerations: the lower bound arises from the requirement of vacuum stability after the inclusion of radiative corrections, while the upper bound is a consequence of the requirement that the Higgs quartic coupling does not leave the perturbative domain up to the scale Λ. This means that if we assume the SM to be valid up to the Planck scale the Higgs boson mass should be between 130 $\mathrm{GeV/c^2}$ < m(H) < 180 $\mathrm{GeV/c^2}$.

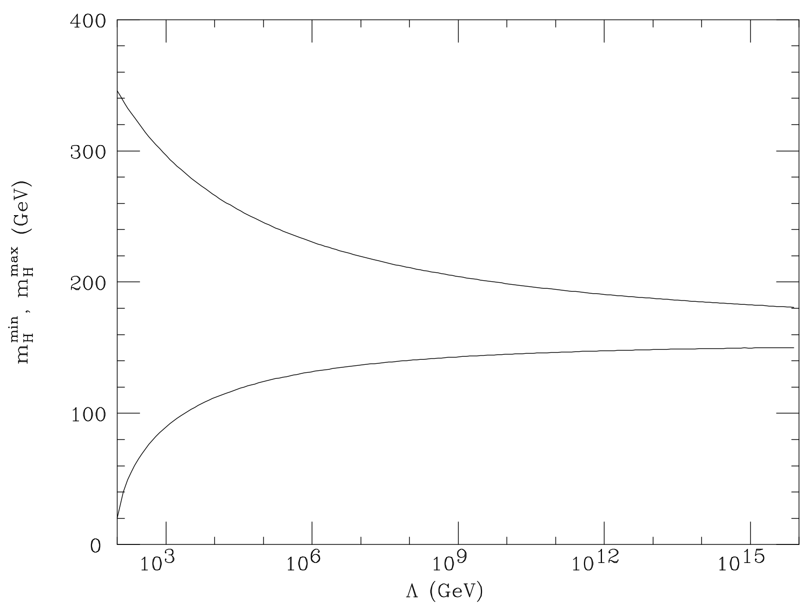

Fig. 3. *Theoretical upper and lower bounds on the Higgs mass.*

As of the Osaka conference of 2000 the experiments could set the following limits: from a fit to all the electroweak observables[1] the most probable value is m(H)=62^{+53}_{-30} $\mathrm{GeV/c^2}$, implying an upper limit at 95% CL of m(H)$\leq$ 170 $\mathrm{GeV/c^2}$ as shown in Figure 4. In a completely independent way the direct search could set a lower limit of 113.3 $\mathrm{GeV/c^2}$ at 95% CL.[3]

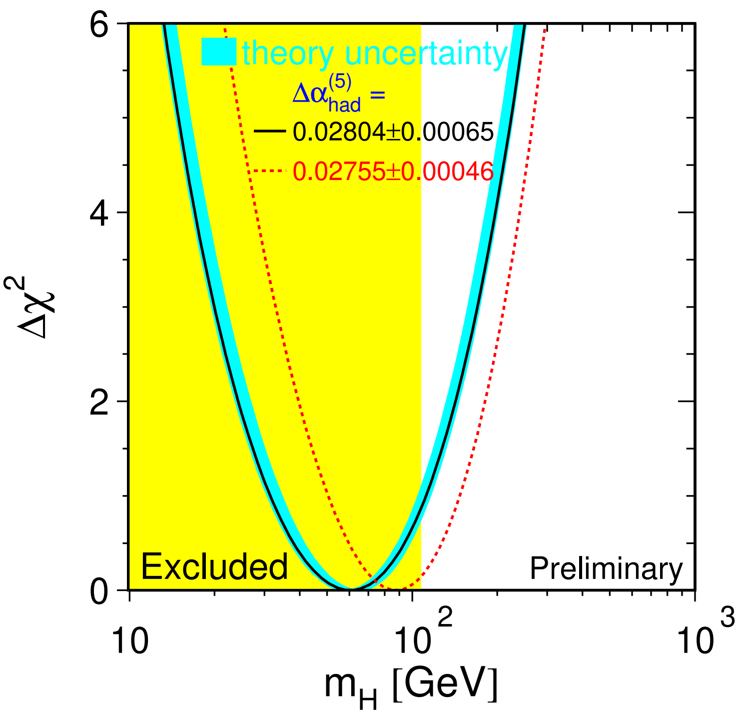

Fig. 4. $\Delta\chi^2 = \chi^2 - \chi^2_{min}$ $m_{\rm H}$*curve. The line is the result of the fit using all data*[1]*; the band represents an estimate of the theoretical error due to missing higher order corrections. The vertical band shows the 95% CL exclusion limit on* $m_{\rm H}$ *from the direct search. The dashed curve is the result obtained using the evaluation of* $\Delta\alpha^5_{\rm had}(m_{\rm Z}{}^2)$ *from Ref. 4.*

2.1 Higgs Production Cross Sections

At LEP the Higgs is expected to be produced mainly via the Higgstrahlung process $\rm e^+e^- \to$ HZ, plus a small contribution from the WW-fusion process (shown in Figure 5). The two diagrams interfere positively. The contribution from the ZZ-fusion process is an order of magnitude smaller than the WW-fusion process and therefore is not considered in the analyses. The Higgstrahlung mechanism dominates for m(H)$\leq \sqrt{s}-$m(Z) (the so-called Higgstrahlung wall) while the WW-fusion mechanism is our only possibility to go beyond. Figure 6 show the various contributions to the cross section as a function of the Higgs mass for a centre of mass energy of 206 GeV.

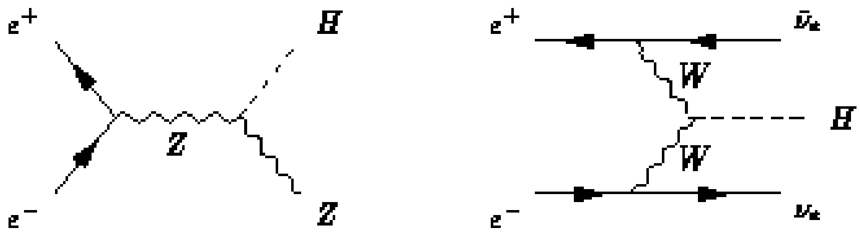

Fig. 5. *The two main diagrams describing the Higgs production at LEP: the Higgsstrahlung process and the WW-fusion process.*

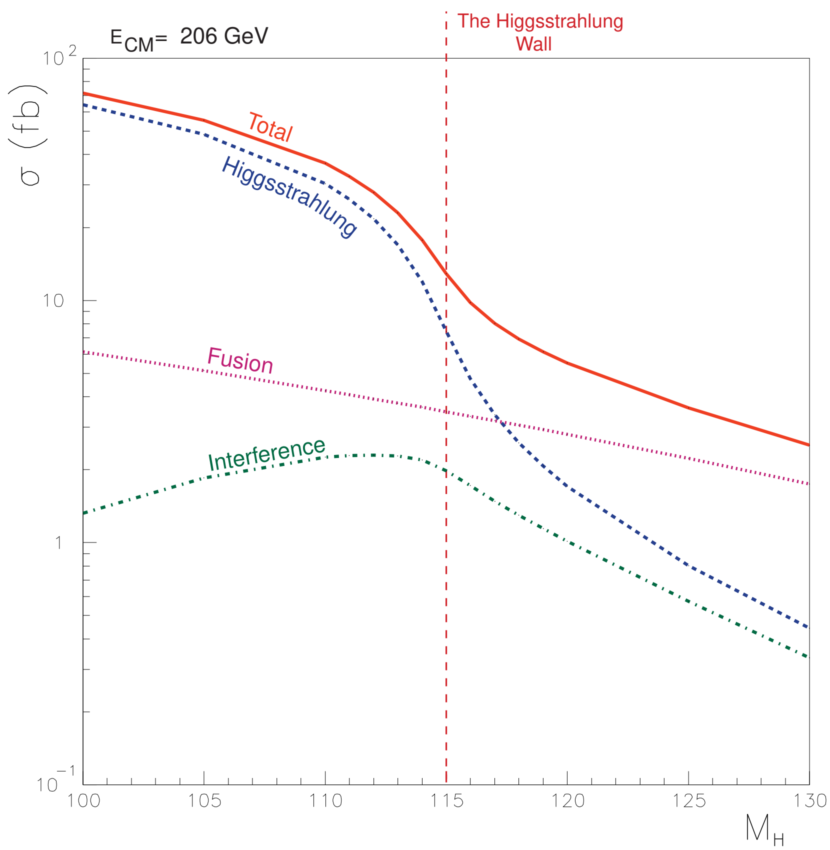

Fig. 6. *The cross section for Higgs production at* $\mathrm{E_{cm}}$*=206 GeV as a function of the Higgs mass for the different production processes.*

2.2 Final State Topologies at LEP

For masses accessible at LEP the Higgs decays predominantly into b quarks (BR(H $\rightarrow \mathrm{b\bar{b}}$) $\sim 85\%$) and $\tau^+\tau^-$pairs (BR(H $\rightarrow \tau^+\tau^-$) $\sim 8\%$). These values are approximately constant for Higgs masses that can be produced at LEP. Thus the Higgs search is typically divided into channels with topologically distinct final states characterised by the decays of the Z as: 4-jets (HZ $\rightarrow \mathrm{b\bar{b}q\bar{q}}$) $\sim 60\%$ of the time, 2-jets and missing energy (HZ $\rightarrow \mathrm{b\bar{b}}\nu\bar{\nu}$) 19% of the time; leptonic (HZ $\rightarrow \mathrm{b\bar{b}e^+e^-}$and $\mathrm{b\bar{b}}\mu^+\mu^-$) and taus (HZ $\rightarrow \mathrm{b\bar{b}}\tau^+\tau^-$and $\tau^+\tau^-\mathrm{b\bar{b}}$) 9% of the time.

The dominant backgrounds are the Standard Model processes with WW, ZZ, $\mathrm{q\bar{q}}(n\gamma)$ and $\mathrm{q\bar{q}}(gluons)$.[5]

2.3 The Fundamental Tools

The identification of a jet coming from a b-quark is the fundamental tool to search for a Higgs boson. The characteristics of hadrons with b-quarks (i.e. an average lifetime of 1.564±0.014 ps and a mass of 4.5 $\mathrm{GeV/c^2}$) imply that b-hadrons produced at LEP will fly for few millimetres and the decay products will have large transverse momentum ($\mathrm{p_T}$) and large impact parameters when compared to mesons from light quarks. These features, combined with other characteristics of the secondary vertices, or the lepton $\mathrm{p_T}$, or the rapidity of the tracks using likelihood techniques or Neural Networks, allowed one to reach very high discrimination, as shown for example in Figure 7 (where for a Higgs efficiency of 60% the WW background is suppressed to the 1% level). In parallel it is essential to have a good agreement between data and simulation, as shown in Figure 8.

In the search for the Higgs boson it is fundamental to reach high accuracy in the measurement of the energy deposited in the detector (especially for final states with neutrinos), and to be able to reconstruct the invariant mass of di-jets with 2-3 GeV precision in order to distinguish the various particles produced.

The experiments[6] use different neural network or likelihood techniques to combine the properties of the events (like b-quark tagging, kinematical or topological informations) into a discriminant variable that allows them to reach a high Higgs signal efficiency and high background rejection. The discriminant variable is then combined with the mass information of the candidates to give each candidate event a weight, expressing its significance with respect to a given Higgs mass hypothesis.

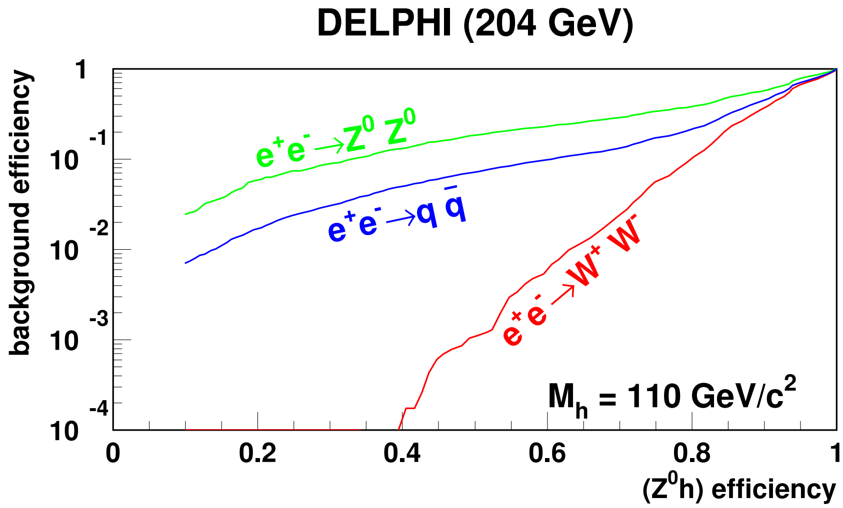

Fig. 7. *The number of background events versus the SM Higgs efficiency (as an example for the DELPHI experiment).*

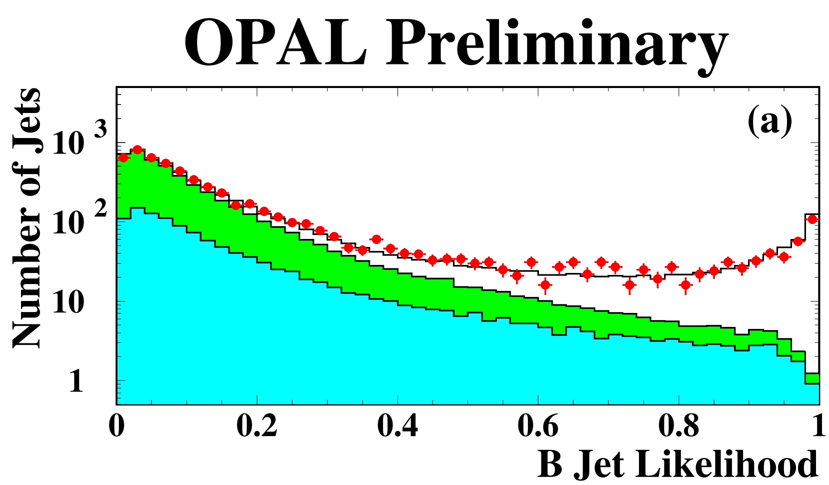

Fig. 8. *Agreement between data and simulation in the b-tagging algorithm output for $Z\gamma$ events (as an example for the OPAL experiment).*

2.4 Problems for each of the topologies

The 4-jet channel: One of the biggest difficulties in this channel is the pairing of the jets. In a genuine 4-jet event there are 3 possible di-jet combinations, while in a 5-jet event there are 10 combinations. Different solutions using more than one criteria are pursued by the different experiments: forcing one of the di-jets to the Z boson; pairing jets with the highest b-tag probability as the ones coming from the Higgs; making all the possible combinations with the WW, ZZ and HZ hypotheses and looking at the minimal χ^2 of the fit; checking the spin of the boson with the jet decay angles. The irreducible background in this channel comes from ZZ and WW production having done the wrong pairing, and from the so-called QCD events, i.e. the $\mathrm{q\bar{q}gg}$ final state. As an example in Figure 9 the 3 possible pairings of a 4-jet b-tagged event from DELPHI at $\mathrm{E_{cm}}$=200 GeV are shown. The "ideogram" plot[7] shows the goodness of the fit for each of the two di-jet masses hypotheses. The dimensions of the circles (standard deviation contours) show that some jet-pairings are more probable than others. In this case the HZ hypothesis (for a Higgs of mass 105 GeV) is more likely than the ZZ hypothesis.

The leptonic channel is the cleanest of the topologies since it is almost background-free. It is the "golden candidate" that every experiment dreams of. Indeed it is possible to fake a high mass candidate in this channel if a photon from initial state radiation or a photon emitted from one of the leptons is associated to one of the jets, artificially increasing the di-jet Higgs mass.

The missing energy channel is probably the most difficult one because of the high background contamination and the poor di-jet mass resolution. In order to increase the mass resolution the missing mass is forced to be that of the Z. By doing so part of the background is also pushed to the kinematic limit: M(jj)=$\mathrm{E_{cm}}$-M(Z). In particular the double radiative return events to the Z (Z$\gamma\gamma$) become the biggest danger, because the cross section is not known with high accuracy. In these events[8] two photons are emitted back to back and the Z is produced at rest. The events are characterised by E($\gamma\gamma$)=$\mathrm{E_{cm}}$-M(Z). If the photons are lost in the beam pipe and the missing mass is forced to be equal to the Z, the visible mass is pushed to the kinematical limit.

2.5 The Results

The results from the four collaborations for the data collected in 2000 are summarised in Table 2. The large spread in the numbers of selected candidates reflects substantial differences in the selection methods and optimisation procedures.

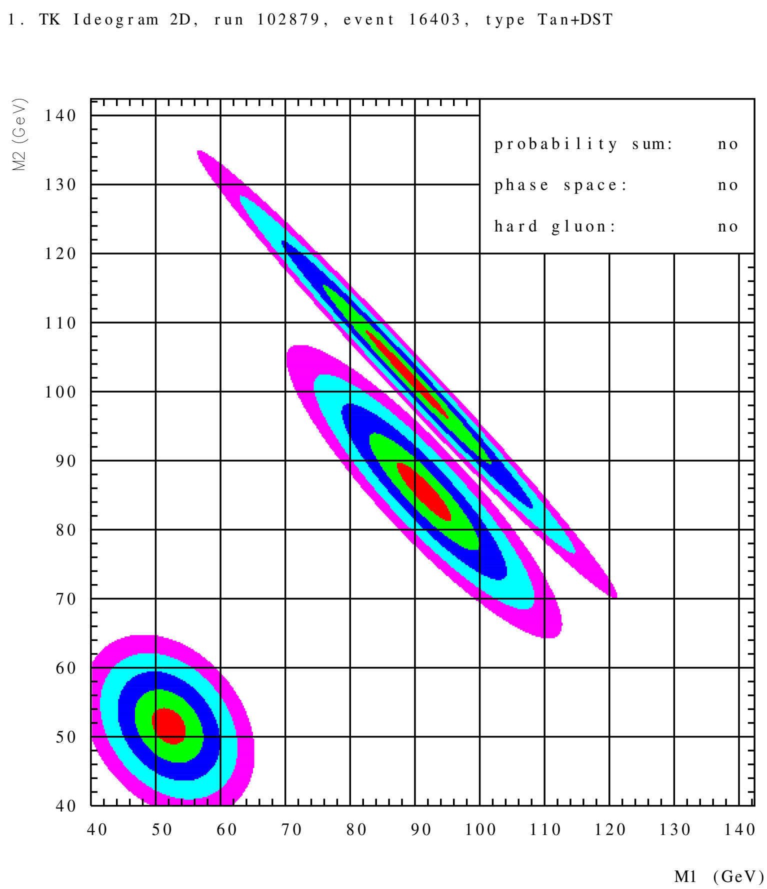

Fig. 9. *The mass of one di-jet versus the mass of the other di-jet for 3 possible pairings of a 4-jet b-tagged event from DELPHI at* $\mathrm{E_{cm}}$*=200 GeV.*

Experiment:	ALEPH	DELPHI	L3	OPAL
Total: Integrated luminosity (pb^{-1}):	94.2	96.1	81.8-84.7	80.0
Backg. predicted / Evts. observed				
Four-jet:	20.2/18	76.4/87	15.0/11	8.9/7
Missing-energy:	17.0/19	42.8/39	5.3/5	13.6/6
Leptonic (e, μ):	12.9/9	9.5/5	1.0/1	3.0/8
Tau channels:	5.9/7	3.2/3	0.69/1	1.3/0
Events in all channels	56.1/53	131.9/134	22.1/18	26.8/21
Limit ($\mathrm{GeV/c^2}$) exp. (median) at 95% CL:	112.0	109.2	108.0	109.5
Limit ($\mathrm{GeV/c^2}$) observed at 95% CL:	110.8	109.0	107.5	109.5

Table 2. *Information on the searches of the LEP experiments for the SM Higgs boson for* $\mathrm{E_{cm}}$*= 200−209 GeV (year 2000 data). In the L3 analysis the event selection depends on the Higgs boson mass hypothesis (here* m_{H}*=110* $\mathrm{GeV/c^2}$*).*

The statistical procedure adopted for the combination of the data, and the precise definition of the confidence levels CL_b, CL_{s+b} and CL_s with which the search results are expressed, are stated in Ref. 3. The main sources of systematic errors affecting the signal and background rate predictions are included, taking into account correlations between search channels, LEP energies and individual experiments. In the procedure used to determine the limits, the treatment of candidate events depends on the values of reconstructed quantities, such as b-tag significances and reconstructed invariant masses. An excess or deficit of candidates may occur in a region of high background and low signal, hence the total count does not indicate whether the actual limit ought to be stronger or weaker than the expectation.

The compatibility of the result with the background hypothesis is given by $1-CL_b$, which is plotted as a function of m_{H} in Figure 10. Values of $1-CL_b$ below 5.7×10^{-7}, indicated by the horizontal full line, corresponding to a 5 standard deviation fluctuation of the background, are considered to be in the discovery region. The dotted line shows the expectation in the presence of a signal of true mass m_{H}; its crossing with the 5σ line at 109.5 $\mathrm{GeV/c^2}$ indicates the range of sensitivity of the presently available data to a discovery. It is not enough just to read off the value of $1-CL_b$ at the value of m_{H} for which $-2\ln(Q)$ has its minimum to claim observation of a signal, because this only gives the probability that the background fluctuated at precisely that mass, while in principle it could have fluctuated anywhere in the mass region considered. This mass region is chosen to include values of m_{H} not strongly excluded by previous searches and for which the present searches have sensitivity. An estimate based on Monte Carlo studies shows that $1-CL_b$ must be multiplied by a factor of four in the present case, corresponding roughly to the width of the mass search region divided by the typical mass resolution.

A 95% confidence level lower limit on the Higgs mass may be set by identifying the mass region where $CL_s < 0.05$, as shown in Figure 11. The median limit expected in the absence of a signal is 113.4 $\mathrm{GeV/c^2}$, and the limit observed by combining the LEP data is 113.3 $\mathrm{GeV/c^2}$. The inclusion of systematic errors, together with their correlations, has decreased the limits by approximately 100 MeV/c^2.

Figure 12 shows the distribution of reconstructed Higgs masses for a subset of the events in Table 2. The corresponding background from SM processes and the signal expected from a SM Higgs boson of 110 $\mathrm{GeV/c^2}$ mass are also shown. The figure has been obtained requiring that the contributions from the four experiments (selecting the most signal-like set of events) be roughly equal. Since all events enter with

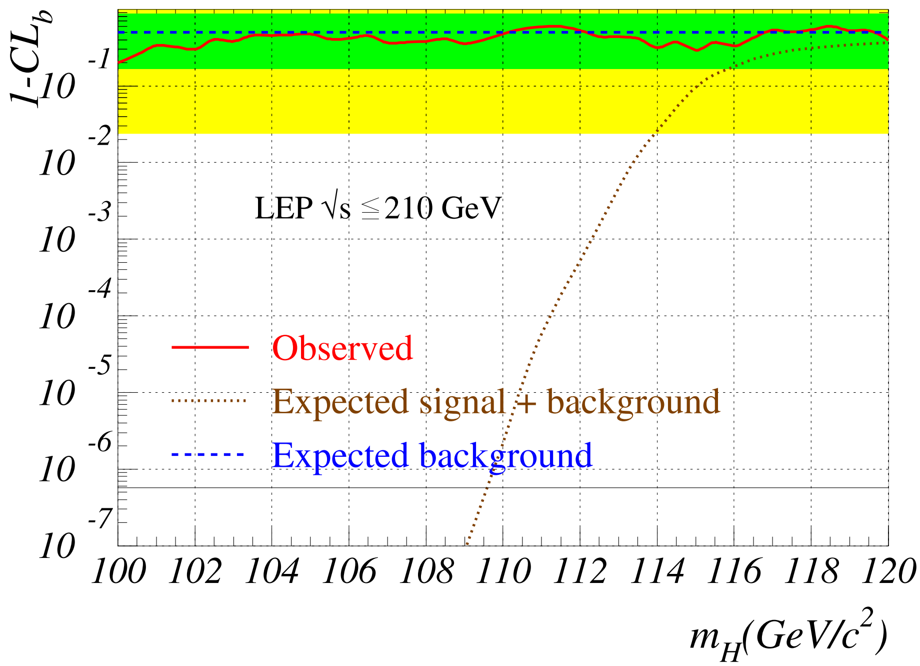

Fig. 10. *The confidence level* $1 - CL_b$ *as a function of* $m_{\rm H}$. *The straight dashed line at 50% and the shaded bands represent the median result and the* $\pm 1\sigma$ *and* $\pm 2\sigma$ *probability bands expected in the absence of a signal. The solid curve is the observed result and the dotted curve shows the median result expected for a signal when tested at the "true" mass. The horizontal line at* 5.7×10^{-7} *indicates the level for a* 5σ *discovery.*

equal weight, such a distribution does not reflect for example differences in mass resolutions, signal sensitivities and background rates, which characterise the various search channels and individual experiments.

3 The Minimal Supersymmetric Standard Model Higgs

There are conceptual problems in the Standard Model that are solved by its supersymmetric extension: the extrapolation of the SM at very high energy, the unification of the couplings, the hierarchy problems, the dark matter.[9]

In the Minimal Supersymmetric extension of the Standard Model (MSSM) the symmetry is "softly" broken in a hidden sector,[9] that communicates with the visible sector via gravity (SUGRA model) or via gauge bosons (GMSB model). The MSSM predictions tend to reproduce the result of the SM with a light Higgs of mass less than 130 $\mathrm{GeV/c^2}$ as shown in Figure 13[5] and Figure 14.[10]

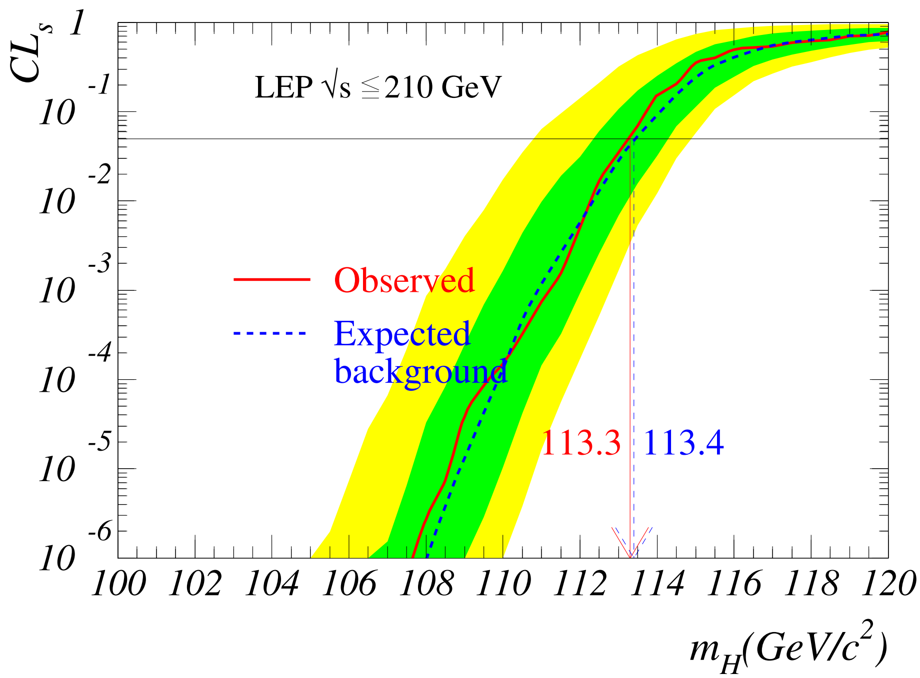

Fig. 11. *The confidence level CL_s for the signal hypothesis versus $m_{\rm H}$. The solid curve is the observed result, the dashed curve the median result expected in the absence of a signal. The shaded areas represent the symmetric 1σ and 2σ probability bands of CL_s in the absence of a signal. The intersections of the curves with the horizontal line at $CL_s = 0.05$ give the mass limits at the 95% confidence level.*

In the MSSM there are two fundamental Higgs field doublets, and the Higgs sector comprises five physical states: two CP-even neutral Higgs bosons, h and H ($m_{\rm h}$<$m_{\rm H}$), one CP-odd neutral Higgs boson, A, and a pair of charged Higgs bosons, $\rm H^+$ and $\rm H^-$. At LEP energies the h and A particles are expected to be produced mainly via the Higgs-stralung process $\rm e^+e^- \rightarrow$ hZ (analogous to the main SM production process) or the pair production process $\rm e^+e^- \rightarrow$ hA. The two processes are complementary: the cross-section of the first is proportional to $\sin^2(\beta-\alpha)$ and that of the second proportional to $\cos^2(\beta-\alpha)$ ($\tan\beta$ is the ratio of the vacuum expectation values of the two Higgs field doublets and α is a mixing angle in the CP-even Higgs sector).

3.1 Results

The combined data of the four LEP experiments are interpreted here within the framework of a 'constrained' MSSM where universal values $M_{\rm SUSY}$ and M_2 are assumed

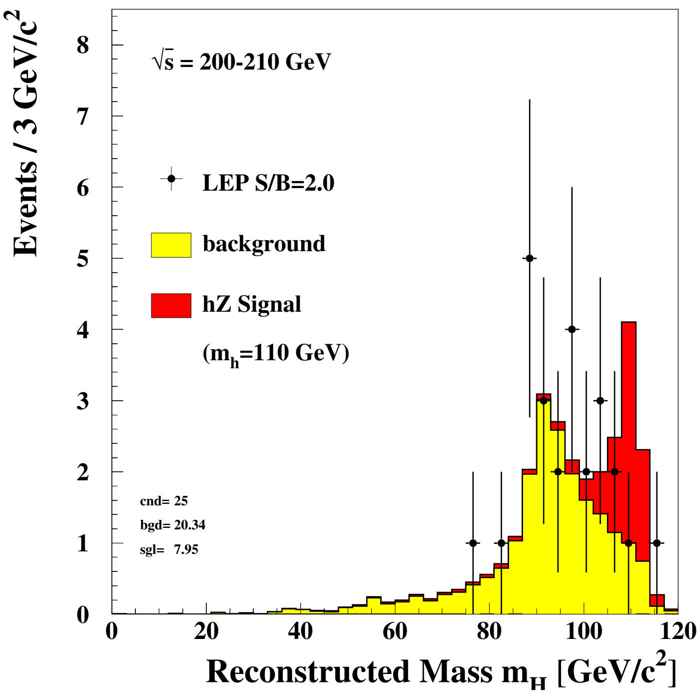

Fig. 12. *LEP-combined distribution of the reconstructed SM Higgs boson mass in searches conducted at* $\sqrt{s}$ *between 200 and 209 GeV. The events satisfy the condition S/B>2, where the S/B cut applies to the region m>105* $\mathrm{GeV/c^2}$ *and for* m_{H}*=110* $\mathrm{GeV/c^2}$*. The figure displays the data (dots with error bars), the predicted SM background (shaded histogram) and the prediction for a Higgs boson of 110* $\mathrm{GeV/c^2}$ *mass (dashed histogram). The number of data events selected for this figure is 25 while 20.34 are expected from SM background processes. A signal at 110* $\mathrm{GeV/c^2}$ *mass would contribute with 7.95 events.*

for the SUSY breaking sfermion and gaugino masses, respectively, at the electroweak scale. Combined search results are given for two new 'benchmark' MSSM parameter scans.[11] The first benchmark corresponds to *no-mixing* in the scalar-top sector; the second to large mixing and other parameters tuned to allow maximal values for m_{h} for each value of $\tan\beta$ (m_{h}*-max* hereafter). In both benchmark scans the top mass, which has an impact on the results via radiative corrections, is fixed to the experimental[12] central value of m_{t}=174.3 $\mathrm{GeV/c^2}$, and to two alternative values where the central value is decreased and increased by the current experimental error of 5.1 $\mathrm{GeV/c^2}$. In each case, the exclusion limits obtained are valid for m_{t} less than or equal to the chosen value.

The individual searches of the four LEP collaborations for the processes $\mathrm{e^+e^-} \rightarrow \mathrm{hZ}$

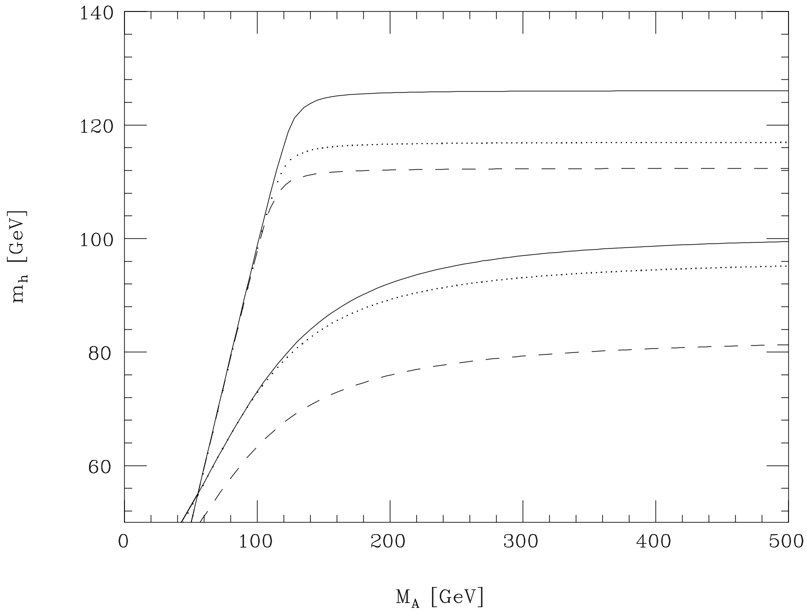

Fig. 13. *Lightest neutral Higgs h in the MSUGRA model as a function of $m_{\rm A}$ for zero mixing (dashed line), for intermediate mixing (dotted line) and for maximal mixing in stop sector (solid line); for two values of tanβ=1.6 (lower set), 15 (upper set).*

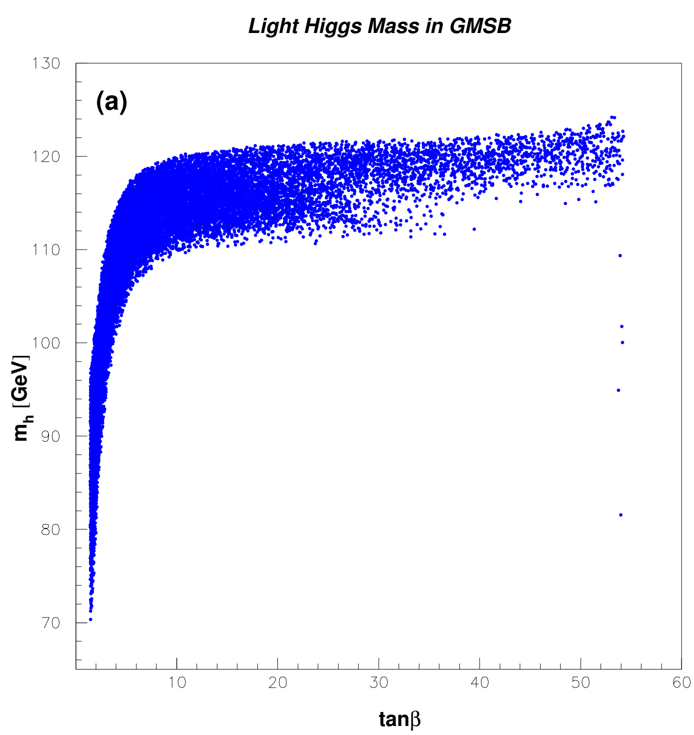

Fig. 14. *Scatter plot for the light scalar Higgs boson as a function of tanβ for the GMSB model.*

and $e^+e^- \to hA$, which include the data taken at $\sqrt{s}$ from 200 to 209 GeV, are described in Ref. 6. For the process $e^+e^- \to hZ$, the searches for the SM Higgs boson are interpreted in the MSSM while taking into account the reduced cross-section due to the factor $\sin^2(\beta - \alpha)$ and the predicted variations of the decay branching ratios of the h boson in the scans. For the process $e^+e^- \to hA$, the most relevant final states are $b\bar{b}b\bar{b}$, $\tau^+\tau^- b\bar{b}$ and $b\bar{b}\tau^+\tau^-$.

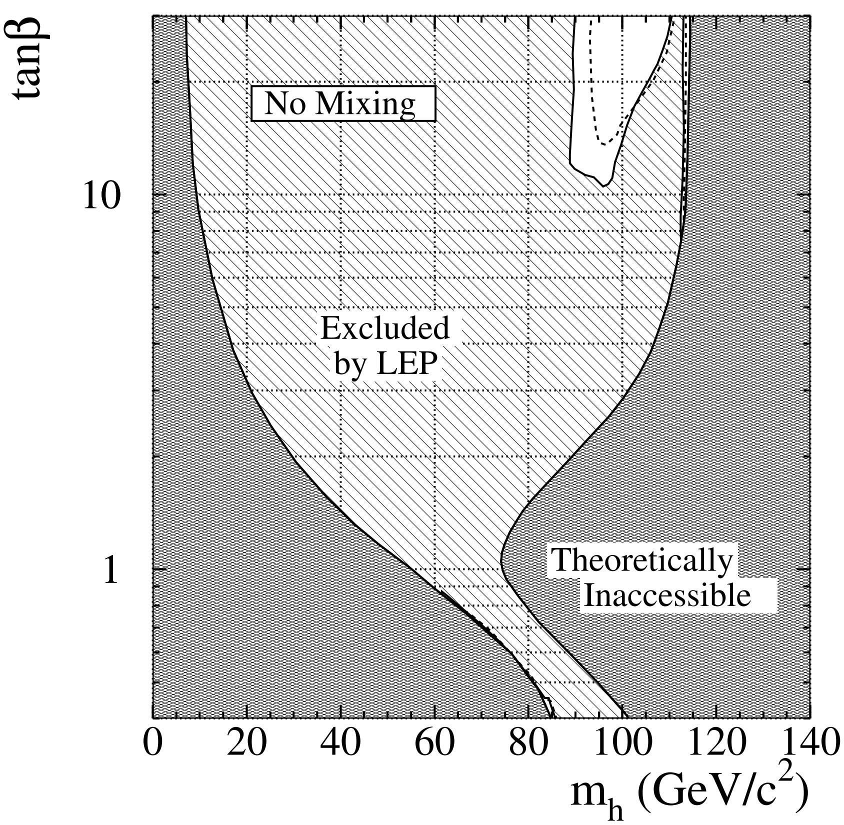

Fig. 15. *The 95% CL bounds on m_h, m_A and $\tan\beta$, for the no-mixing benchmark, from combining the data of the four LEP experiments at 200 to 209 GeV with earlier data taken at lower energies. The full lines represent the actual observation and the dashed lines the median limits expected on the basis of 'background only' Monte Carlo experiments.*

The results are shown in Figures 15 and 16, for the *no-mixing* and m_h-*max* benchmarks. The limits are presented for $\tan\beta$>0.4 and in one parameter projection, (m_h, $\tan\beta$). Boundaries obtained from the data and the ones expected on the basis of background Monte Carlo experiments are shown.

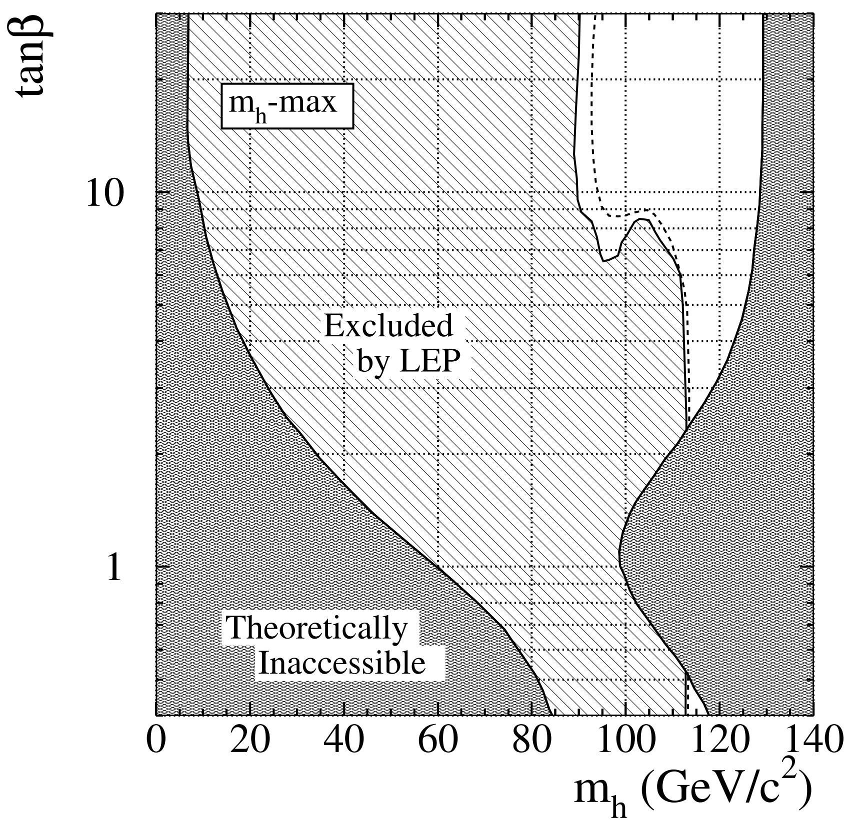

Fig. 16. *The 95% CL bounds on* $m_{\rm h}$, $m_{\rm A}$ *and* $\tan\beta$, *for the* $m_{\rm h}$*-max benchmark, from combining the data of the four LEP experiments at 200 to 209 GeV with earlier data taken at lower energies. The full lines represent the actual observation and the dashed lines the median limits expected on the basis of 'background only' Monte Carlo experiments.*

	no-mixing	$m_{\rm h}$-max
Limits for $m_{\rm h}$ $(\mathrm{GeV/c^2})$		
expected (median) :	92.4	92.2
observed :	90.4	90.5
Limits for $m_{\rm A}$ $(\mathrm{GeV/c^2})$		
expected (median):	92.9	92.8
observed :	90.5	90.5
Exclusion in $\tan\beta$		
expected (median):	0.8-8.6	0.5-2.3
observed :	0.9-7.7	0.5-2.3

Table 3. *Combined 95% CL MSSM limits for* $m_{\rm h}$ *and* $m_{\rm A}$ *(valid for* $\tan\beta > 0.4$*) and excluded ranges in* $\tan\beta$*, for the two benchmark scenarios, and for top masses less than 174.3* $\mathrm{GeV/c^2}$*. The quoted limits were obtained including systematic errors and their correlations.*

The mass limits obtained for the two benchmark scans are presented in Table 3.

4 The Charged Higgs Boson Search

At LEP2 energies charged Higgs bosons are expected to be produced mainly through the process $\mathrm{e^+e^-}\to\mathrm{H^+H^-}$. In the MSSM and at tree-level the $\mathrm{H^\pm}$ is constrained to be heavier than the $\mathrm{W^\pm}$ bosons but loop corrections drive the mass to lower values for some values of the MSSM parameters. Since the sensitivity of current searches is limited to the range below $m_{\rm W}$ due to the background from $\mathrm{e^+e^-}\to$ $\mathrm{W^+W^-}$, a signal for $\mathrm{H^+H^-}$ would indicate either new physics beyond the MSSM or place very stringent constraints on the MSSM parameter values. The present searches for charged Higgs bosons are placed in the general context of 2 Higgs Doublet Models (2HDM) where the mass is not constrained. The searches are carried out under the assumption that the two decays $\mathrm{H^+}\to\mathrm{c\bar{s}}$ and $\mathrm{H^+}\to\tau^+\nu_\tau$ exhaust the $\mathrm{H^+}$ decay width; however, the relative branching ratio is not predicted. Thus, the searches encompass the following $\mathrm{H^+H^-}$ final states: $(\mathrm{c\bar{s}})(\mathrm{\bar{c}s})$, $(\tau^+\nu_\tau)(\tau^-\bar{\nu}_\tau)$ and the mixed modes $(\mathrm{c\bar{s}})(\tau^-\bar{\nu}_\tau)$, $(\mathrm{\bar{c}s})(\tau^+\nu_\tau)$. The combined search results are presented as a function of the branching ratio B($\mathrm{H^+}\to\tau^+\nu_\tau$).

In the search for the $\mathrm{H^\pm}$ c-quark and s-quark tags, plus the polar angles of the jets to identify the spin of the boson, are used to reject the dominant $\mathrm{W^\pm}$ background, while

	Mass limit in $\mathrm{GeV/c^2}$
B($\mathrm{H}^+ \to \tau^+ \nu_\tau$)=0	
Limit expected (median) :	79.7
Limit observed :	80.8,“islands”
B($\mathrm{H}^+ \to \tau^+ \nu_\tau$)=1	
Limit expected (median) :	90.5
Limit observed :	87.7
Any B($\mathrm{H}^+ \to \tau^+ \nu_\tau$)	
Limit expected (median):	78.5
Limit observed :	77.4

Table 4. *The combined 95% CL lower bounds for the mass of the charged Higgs boson, expected and observed, for fixed and arbitrary values of the branching ratio B(*$\mathrm{H}^+ \to \tau^+ \nu_\tau$*).*

shape variables and acoplanarity are used to reject the QCD background.[13]

The expected and observed mass limits are shown in Figure 17. The combined 95% CL bounds are listed in Table 4 for B($\mathrm{H}^+ \to \tau^+ \nu_\tau$)=0, 1, and for arbitrary values of the branching ratio.

5 The Invisible Higgs

The Higgs boson decays into the heaviest kinematically accessible particle. In the MSSM it can decay into invisible super-particles, like the lightest neutralino χ_1^0: $\mathrm{h} \to \chi_1^0\chi_1^0$. If the χ_1^0 is purely photino then this process is suppressed and $\mathrm{h} \to \chi_2^0\chi_1^0$ with $\chi_2^0 \to \chi_1^0$ Z/γ^*. The final state is characterised by the 2 leptons or the two jets from the Z decay and missing energy and momentum carried away by the neutralinos. The analysis is then similar to the search for the SM Higgs, in the $\mathrm{H}\nu\bar{\nu}$ final state, but there is no need for the b-tag. The main backgrounds are $\mathrm{q\bar{q}}(\gamma)$, single W production and WW production for the final state $\mathrm{Z} \to l\bar{l}$. The consistency of the combined data with the background expectation can be seen in Figure 18. There is an extreme minimum of $1-\mathrm{CL}_b$ of 0.018 at 110.2 $\mathrm{GeV/c^2}$. There is also a maximum of 0.986 at 83 $\mathrm{GeV/c^2}$, corresponding to a deficit of candidates. Each of these deviations is a little over two sigma. The observed limit is $m_{\mathrm{H}}>$ 107.6 $\mathrm{GeV/c^2}$ (expected limit is $m_{\mathrm{H}}>$ 109.9 $\mathrm{GeV/c^2}$) for $\mathrm{E_{cm}}$=200-209 GeV, for only 3 experiments combined together.

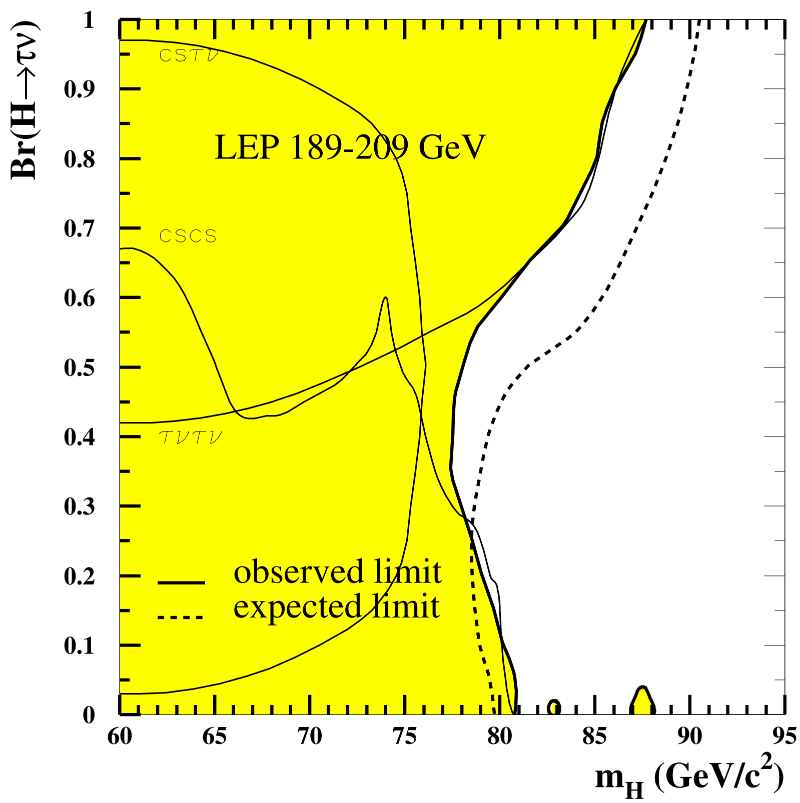

Fig. 17. *The 95% CL bounds on $m_{\mathrm{H}^\pm}$ as a function of the branching ratio $B(\mathrm{H}^+ \to \tau^+ \nu_\tau)$, combining the data collected by the four LEP experiments at energies up to 209 GeV. The median expected exclusion limits are indicated by the dashed line and the observed limits by the heavy full line. The light full lines show the observed limits channel by channel.*

6 Non Fermionic Higgs couplings

Anomalous coupling. In the SM the anomalous coupling $\mathrm{e}^+\mathrm{e}^- \to \mathrm{H}\gamma$ has a very small cross section, but it would be the ideal channel to reach $m_\mathrm{H} \leq \mathrm{E}_{\mathrm{cm}}$. In a more general 2 Higgs Doublet Model (of which the MSSM is a particular case) it can be enhanced. At LEP the following final states are studied: $\mathrm{e}^+\mathrm{e}^- \to \mathrm{H}\gamma \to \gamma\gamma\gamma$, $\mathrm{b}\bar{\mathrm{b}}\gamma$, $\mathrm{e}^+\mathrm{e}^- \to \mathrm{HZ} \to \gamma\gamma\nu\bar{\nu}$, $\mathrm{e}^+\mathrm{e}^- \to \mathrm{HZ}/\gamma^* \to \gamma\gamma\mathrm{q}\bar{\mathrm{q}}$. No signal has been found at LEP in 2000 data.

Fermiophobic decays. In both the SM and in the 2HDM the Higgs can decay into photons via quark or W boson loop. While in the SM the rate is too small to be observed at LEP, in the 2HDM there is a value of the parameter α that can cause

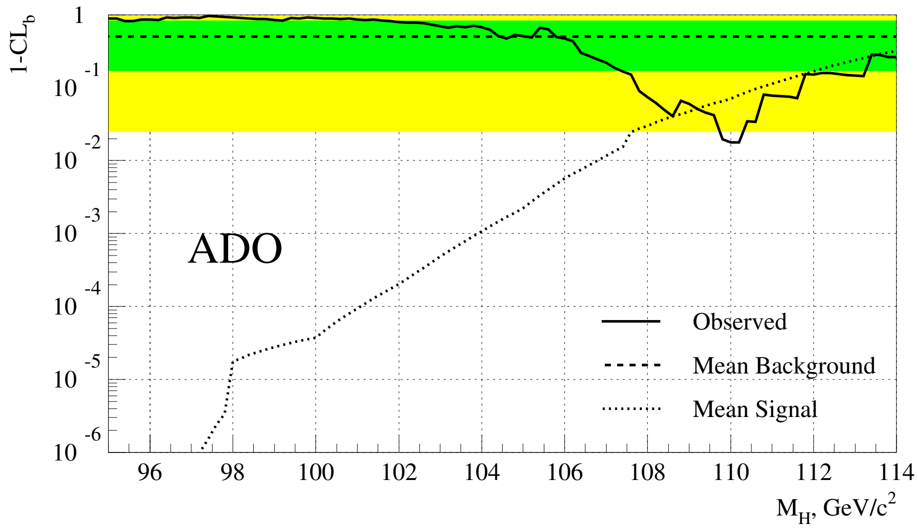

Fig. 18. *The value of $1-CL_b$ for the A,D,O combined data in the $h \rightarrow \chi_1^0\chi_1^0$ search. The step nature of the results comes because ALEPH used a sliding window (in test mass) analysis and reports relevant candidates in the a discretised way. There is a "knee" in the curve of signal expectations; below 98* $\mathrm{GeV/c^2}$ *the ALEPH results from lower energies contribute.*

the h to couple only to bosons. The final state can be very simple, i.e. 2 photons only and missing energy from the process $\mathrm{e^+e^-} \rightarrow \mathrm{hZ} \rightarrow \gamma\gamma\nu\bar{\nu}$, or more complex in the case of associated production of hA: $\mathrm{e^+e^-} \rightarrow \mathrm{hA} \rightarrow \gamma\gamma\mathrm{A} \rightarrow \gamma\gamma\mathrm{b\bar{b}}$, $\mathrm{e^+e^-} \rightarrow \mathrm{hA} \rightarrow \mathrm{AAA} \rightarrow \gamma\gamma\gamma\gamma\nu\bar{\nu}$, $\gamma\gamma\gamma\gamma\mathrm{b\bar{b}}$.[14]

The four LEP experiments combine the results only for events with two energetic and isolated photons. In addition, the Z decay products are either classified, or, in the case of $\mathrm{Z} \rightarrow \nu\bar{\nu}$, acoplanarity in the photons is required. The analysis procedures of the four LEP experiments producing the inputs for the present combination are described in individual documents.[15]

As a benchmark for exclusion of Higgs bosons in fermiophobic models, we consider an h produced in $\mathrm{e^+e^-} \rightarrow \mathrm{hZ}$ with the Standard Model production cross section and with the partial width for $\mathrm{h} \rightarrow \gamma\gamma$ given by the SM,[16] but with the di-fermion partial width set to zero. Figure 19 shows the combined data for the 4 LEP experiments, together with the expected signal of a fermiophobic Higgs of mass 100 $\mathrm{GeV/c^2}$. The 95% confidence level upper limit for BR($\mathrm{h} \rightarrow \gamma\gamma$) incorporating all the combined ADLO data is shown in Figure 20. A lower mass limit for fermiophobic Higgs boson is obtained where the limit curve crosses the $\mathrm{B}_{\gamma\gamma}(m_\mathrm{h})$ curve; for the combined ADLO data this limit is 106.4 $\mathrm{GeV/c^2}$.

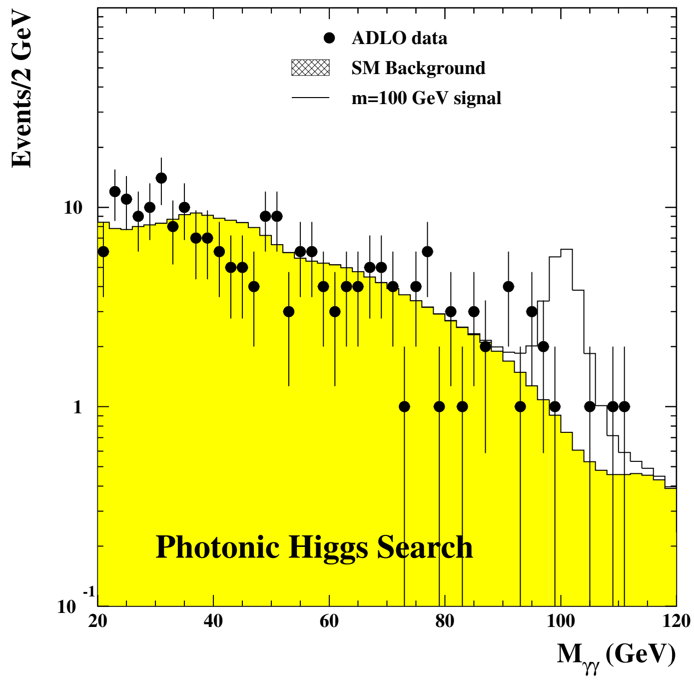

Fig. 19. *Distribution of the di-photon mass in the h $\rightarrow\gamma\gamma$ search. All the search channels are included. The white histogram is the benchmark signal for* $m_{\rm h}$= *100* $\mathrm{GeV/c^2}$.

7 The end of LEP

The year 2000 is scheduled to be the last year of LEP. In the first period of the year the maximum of the luminosity was collected at $\mathrm{E_{cm}}\sim$205 GeV, while in the second part of the year it was at $\mathrm{E_{cm}}\sim$206.7 GeV. About 10 pb^{-1} has been collected at $\mathrm{E_{cm}}\sim$208.1 GeV so far. With increasing energy and luminosity the Higgs reach of LEP increases day by day. At the end of the year 2000 the SM Higgs will be observed if $m_{\rm H}\leq$115 $\mathrm{GeV/c^2}$. At LEP the experiments are still working to see if 1 or 2 $\mathrm{GeV/c^2}$ can be gained in the final Higgs mass reach if the signal over background ratio of the analysis can be further improved optimising the search for a 115 $\mathrm{GeV/c^2}$ mass Higgs and going towards a "background-free" analysis (keeping in mind that 1 event for 0 expected is a discovery!). For example, for a Higgs of 115 $\mathrm{GeV/c^2}$ we expect for all the 4 experiments, integrating over all the channels and over data from 1998 to the end of 2000, a total of 20 events for 100% efficiency. Considering an average efficiency of 30% we need no more than 3 events of background in all LEP! It is also clear that only the 4 experiments together can hope to make it.

If the Higgs is discovered at LEP then future experiments will determine its nature

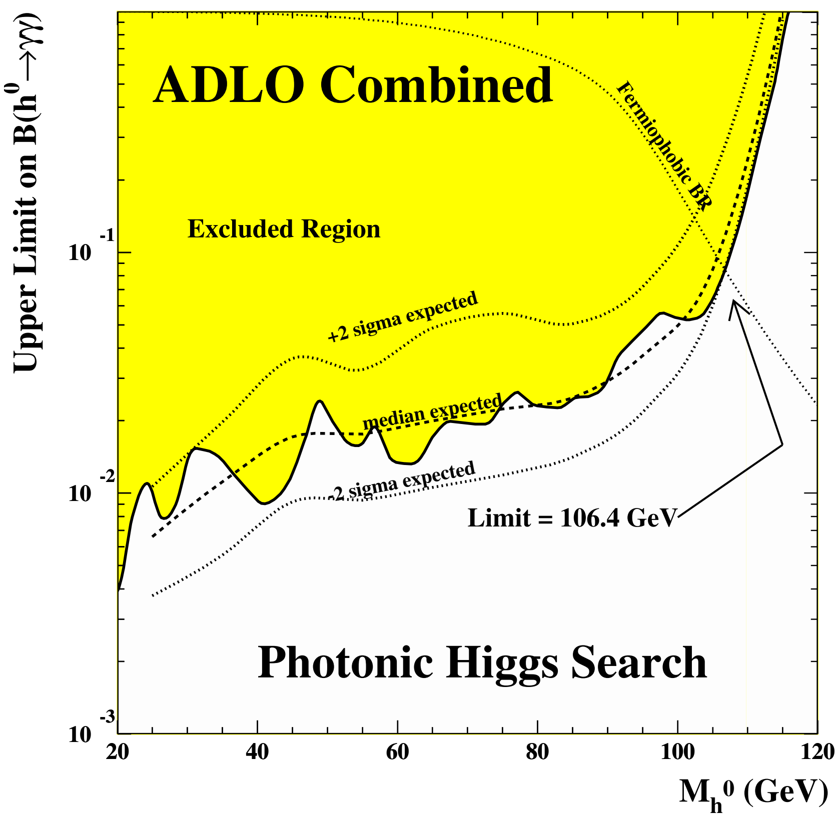

Fig. 20. *98% CL level upper limit on the di-photon branching fraction for a SM Higgs boson production rate. The shaded area is excluded. The dashed line is the predicted benchmark di-photon branching fraction assuming $B(h \rightarrow f\bar{f})=0$. The intersection of the dotted line with the exclusion curve gives a lower limit of 106.4* $\mathrm{GeV/c^2}$ *for a fermiophobic Higgs model. Also shown (dotted lines) are the median expected limit and the 95% CL zone for the expected limit.*

(SM, MSSM...). If it is not discovered at LEP, i.e. its mass is heavier than 115 $\mathrm{GeV/c^2}$, then a very small region is left for the MSUGRA and GMSB scenarios. For a top mass of $\sim$175 $\mathrm{GeV/c^2}$ and for large tan(β) the lightest Higgs h is predicted to be lighter than 125-130 $\mathrm{GeV/c^2}$. This also means that 7 GeV more to LEP would have allowed the machine to cover the entire MSSM plane!

8 After LEP: Tevatron and LHC

The experiments at the Tevatron will soon start to take data again with upgraded detectors. At a $\mathrm{p\bar{p}}$ collider the Higgs is produced mainly via gluon-gluon fusion or together with a W or a Z ($\mathrm{q\bar{q}}\rightarrow$W*(Z*) $\rightarrow$HW(Z)). The first process has a higher cross section, but the second one has a clearer signature. Studies[17] have shown that assuming 10% resolution on M($\mathrm{b\bar{b}}$), and a 30% improvement in the S/B with respect to the actual analyses combining all the channels and the two experiments, they can exclude at 95% CL a Higgs of mass $\leq$114 $\mathrm{GeV/c^2}$ with 2 fb^{-1} of luminosity. With about 30 fb^{-1} they can cover all the masses up to $\sim$180 $\mathrm{GeV/c^2}$, as shown in Figure 21.

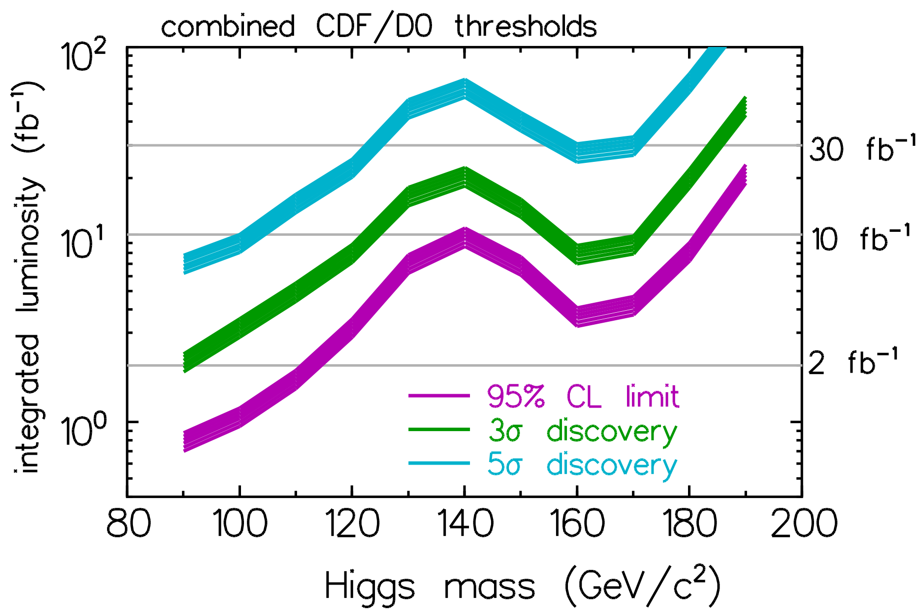

Fig. 21. *Minimum luminosity needed at the Tevatron to exclude (bottom curve), or discover (top curve) a SM Higgs boson at* $\mathrm{E_{cm}}$*= 2 TeV.*

The experiments at the LHC pp collider will start to take data in 2005. integrating 10 fb^{-1} per year for the first 3 years. In Figure 22 the signal significance versus the

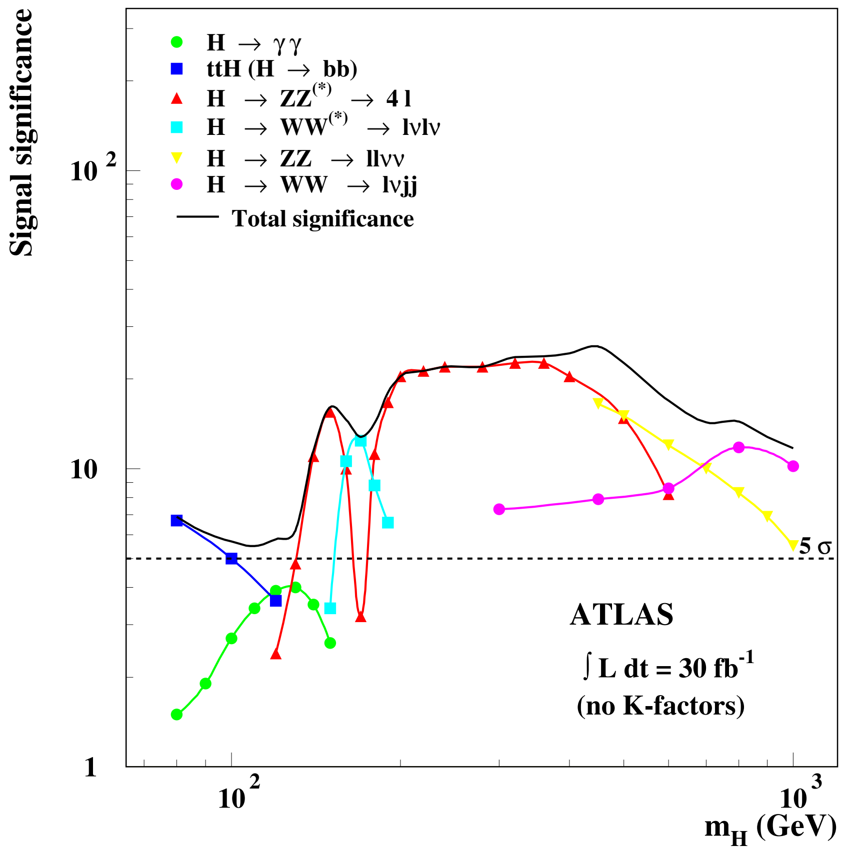

Fig. 22. *Individual channels and combined statistical significance for a discovery in ATLAS as a function of* m_{H} *for a total integrated luminosity of 30 fb*-1

Higgs mass is shown for one of the experiments (ATLAS)[18] for every final state and for their combination after the first 30 fb^{-1}. If the Higgs is discovered before then, LHC will measure its characteristics: the mass with a 0.1-1% accuracy, the coupling and branching ratios with $\sim$20% accuracy, and it will determine its nature (SM or MSSM).

9 The search for supersymmetric particles

In models invoking supersymmetry (SUSY) each elementary particle is accompanied by a supersymmetric partner whose spin differs by half a unit. SUSY models require a minimum of 2 Higgs doublets to generate the masses of the bosons and fermions. The super-partners of the gauge bosons are fermions called gauginos, the ones of the gluons are the gluinos and the ones of the Higgs fields are the Higgsinos. The super-partners of the fermions are the sfermions (f_R and f_L) with zero spin.

If there are 2 Higgs doublets, the fields of the fermionic partners of the $W^{\pm}$ and of the charged Higgs $H^{\pm}$ mix to form two mass eigenstates, the charginos $\chi^{\pm}_{1,2}$. The partners of the photon, of the Z and of the neutral Higgs bosons mix to form four eigenstates, the neutralinos $\chi^0_{1,2,3,4}$, where the χ^0_1 is often assumed to be the lightest SUSY particle (LSP).

Particles and s-particles are characterised by a quantum number: the R-parity (defined as R=$(-1)^{3(B-L)+2S}$). The particles have positive R-parity while s-particles have negative. If R-parity conservation is assumed SUSY particles can only be produced in pairs and the LSP cannot decay.

In the Minimal Supersymmetric Model (MSSM) there are 124 parameters,[9] 2 Higgs doublets and R-parity is conserved. These parameters are reduced to 5 at the GUT scale: $m_{1/2}$ (=M_1=M_2=M_3) the masses of the gauginos, m_0 the masses of the s-fermions, μ the mass coupling strength between the 2 Higgs super-fields, tanβ the ratio of the vacuum expectations of the 2 Higgs fields that couple respectively to up and down quarks, A_t the trilinear stop-Higgs coupling. Most of LEP results are interpreted within this model. If, on top of the above GUT scale constraints, one also requires that the Higgs mass will be universal, $m_H^2 = m_0^2 + \mu^2$, the number of parameters is further constrained, the sign of μ is determined and one ends up with the mSUGRA model with 5 parameters, m_0, $m_{1/2}$, A_t, tanβ and $sign(\mu)$.

In SUSY the breaking of the symmetry occurs in a hidden sector, which then communicates it to the visible sector of the particles via *messengers*. In mSUGRA the messengers are the gravity forces, the scale is broken at $\sqrt{F} = 10^{10}$ GeV and the

Lightest Supersymmetric Particle (LSP) is the neutralino χ_1^0.

In another SUSY scenario, the Gauge Mediated Susy Breaking model (GMSB), the messengers are the gauge forces and the symmetry is broken at a much lower scale $\sqrt{F} = 10^2 - 10^4$ TeV. The LSP is the gravitino.

9.1 The MSSM topologies

If R-parity is conserved the s-particles are produced in pairs and the LSP is stable. This means that at LEP the final state of an event with super-particles will be characterised by 2 acoplanar objects (2 leptons, or 2 jets or 2 photons) and missing energy from the two undetected neutralinos. The topology will also then depend of the difference in mass between the s-particle produced and the LSP $\Delta M = M(\tilde{s}) - M(\chi^0)$.

Recently a particular MSSM case has been explored: the LSP being the gluino $\tilde{\mathrm{g}}$ instead of the neutralino. The gluino hadronises in R hadrons ($\mathrm{R}^{\pm}$, R^0) so there will be no missing energy signature, but instead the presence of R hadrons.[19]

9.2 The search for the Chargino

The charginos are pair produced at LEP either in the s-channel or in the t-channel via the exchange of a sneutrino. The cross section of this process in generally very high, so the chargino is likely to be the first sparticle detected at LEP. In the case where the charginos are gaugino-like ($\mu \gg M_2$) and the sneutrinos are light (small m_0), there is a destructive interference between the two processes which reduces the cross section and thus the search sensitivity. The decrease in sensitivity also occurs when the difference in mass between the chargino and the neutralino is quite small (a few hundred MeV). The decay of the chargino into a neutralino is via a $\mathrm{W}^{(*)}$, so the final state will be characterised by the decays of the 2 $\mathrm{W}^{(*)}$ and the missing energy carried away by the 2 undetectable χ_1^0. About 5-10 pb^{-1} per experiment are sufficient to reach masses close to the kinematic limit in most of the parameter space. In Figure 23 the combined LEP limit on the chargino mass for $\mathrm{E_{cm}}>$ 206.5 GeV is shown as a function of the sneutrino mass (plot on the left), and for the DELPHI experiment as a function of mass difference ($\Delta M = M(\tilde{s}) - M(\chi^0)$) for $\mathrm{E_{cm}}$=205.3 GeV (plot on the right).

At the end of LEP the limit on the chargino mass will be (unless it is found!) $\mathrm{E_{cm}}^{max}/2$ for most of the parameter space.

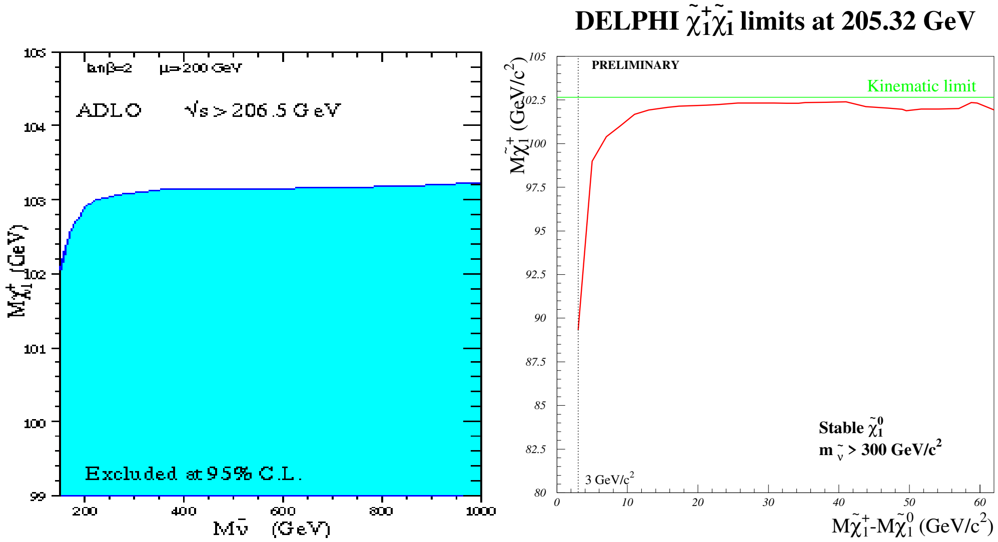

Fig. 23. *Left: The chargino mass limit as a function of the sneutrino mass for the four experiments combined together and for* $\mathrm{E_{cm}}$*>206.5 GeV. Right: The chargino mass limit as a function of the ΔM value under the assumption of a heavy sneutrino. The limit applies to the case of a stable χ_1^0. The straight horizontal line shows the kinematic limit.*

9.3 The search for the stau

It is likely, due to potentially large mixing parameters, that the lightest slepton is the stau. At LEP a pair of $\tilde{\tau}_R$, or of $\tilde{\tau}_L$, is produced via s-channel process. The main decay mode is $\tilde{\tau} \to \tau\chi_1^0$, i.e. a final state characterised by 2 acoplanar τ's and missing energy, for a total of 2 LSP and 4 neutrinos escaping detection. The efficiency is strongly dependent on the visible energy, i.e. on $\Delta M = M(\tilde{s}) - M(\chi^0)$. In the 1998 and 1999 data there was an excess observed by the 4 experiments (as shown in Figure 24), compatible with a M($\tilde{\tau}$)=85 $\mathrm{GeV/c^2}$ and M(χ_1^0)=22 $\mathrm{GeV/c^2}$. The systematic error on this measurement is estimated to be of the order of 4%, for an excess of the order of 20%, where the main background is coming by 80% from the WW final state and 20% from $\gamma\gamma$ pprocesses.

In the 2000 data and with a luminosity of about 85 pb^{-1} per experiment the excess was not confirmed (while for a given $\tilde{\tau}$ and χ_1^0 mass the cross section was supposed to be higher at the higher energies of the 2000 run) and the data agreed perfectly with the expectation from background only (49 events were observed in data while 51.6 were expected for the 4 experiments). Limits are then computed as shown in Figure 25.

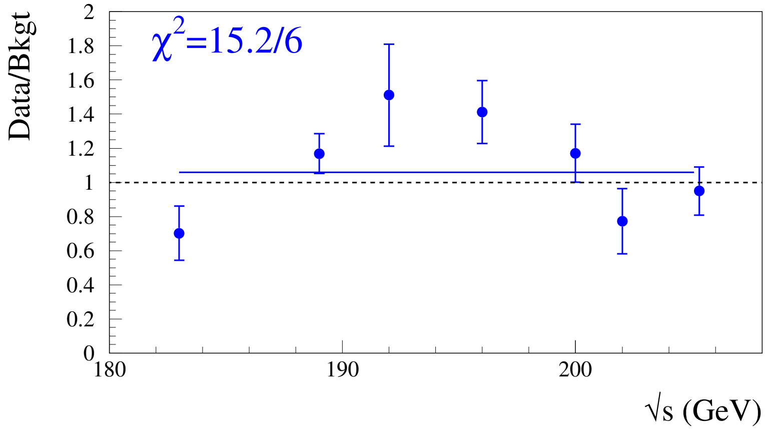

Fig. 24. *The ratio of data over background only simulation in the combined LEP $\tilde{\tau}$ analyses as a function of* $\mathrm{E_{cm}}$. *The full line is the average value.*

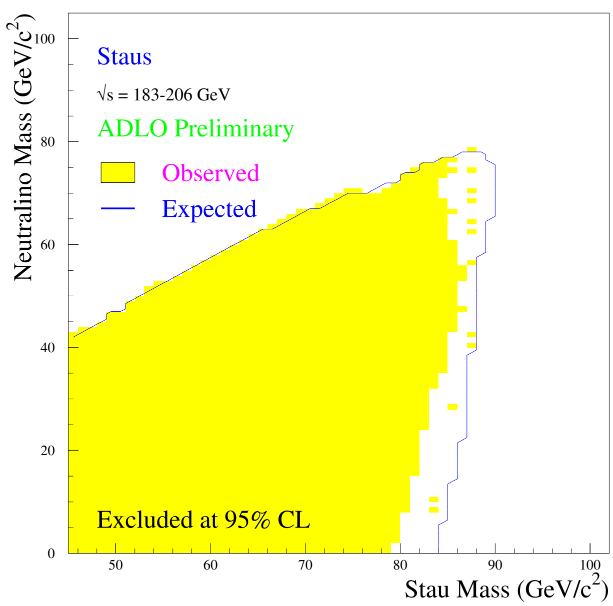

Fig. 25. *Exclusion limit at 90% CL for $\tilde{\tau}$. The line represents the expected limit from the combination of the 4 LEP experiments in the hypothesis of background only. The shaded area is the excluded region obtained from the combination of the 4 LEP experiments.*

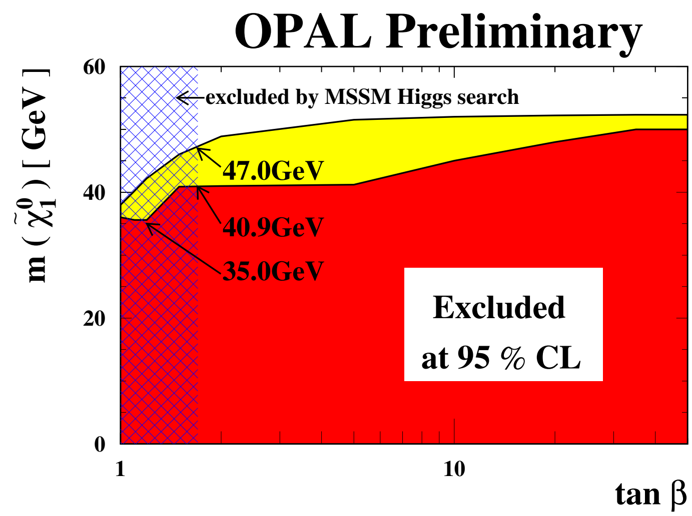

Fig. 26. *The 95% CL mass limit on the lightest neutralino χ_1^0 as a function of tanβ. The exclusion region for $m_0 \geq$ 500 GeV is shown by the lighter area and the exclusion valid for all m_0 values by the darker area. The hatched area shows the region in tanβ excluded by the MSSM Higgs search.*

9.4 Limit on the LSP

The results of the search for the Lightest Supersymmetric Particle will be one of the important milestones of LEP. SUSY models with R-parity conservation predict the existence of cold dark matter (CDM) in the universe, i.e. the relic LSP remaining from the Big Bang. Thus the importance of a discovery or even setting limits on this particle. At LEP no evidence of neutralino production has been seen and limits can be set as a function of the SUSY parameters. Combining the direct search for the neutralino with the searches for charginos and sleptons and by scanning the MSSM parameter space the lower bound for M(LSP) is set to 36-38 $\mathrm{GeV/c^2}$ by each experiment. Limits around 46-48 $\mathrm{GeV/c^2}$ are obtained if constraints on tanβ from MSSM Higgs searches are also used (see section 3.1), as shown in Figure 26 for the OPAL experiment.[20] The four LEP experiments' results on the LSP will be combined at the end of this year.

9.5 The GMSB scenario and the photons only final state

In the GMSB scenario the lightest supersymmetric particle is the gravitino. The phenomenology is then determined by the nature of the next to lightest supersymmetric

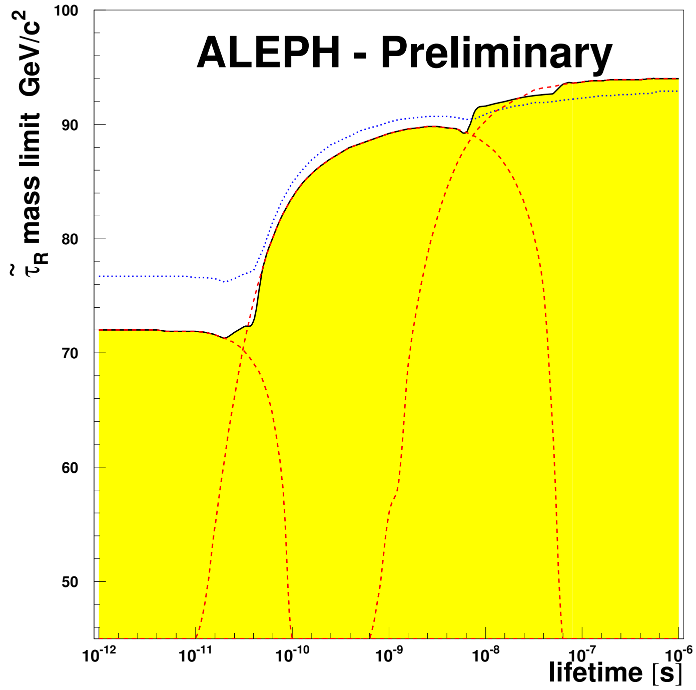

Fig. 27. *Lower bound for the stau NLSP mass in GMSB as a function of its lifetime, for the ALEPH experiment*

particle (NLSP), which could be the χ_1^0 or the $\tilde{\tau}_R$. The final state should thus contain isolated photons or $\tau^\pm$ leptons from the NLSP decays: $\chi_1^0 \to \gamma \tilde{\mathrm{G}}$ or $\tilde{\tau}_R \to \tau^\pm \tilde{\mathrm{G}}$. This is a clear supplementary signature for the search for GMSB processes. The NLSP lifetime is not defined in GMSB. If it is very short ($c\tau \ll L_{det}$) the final state will be characterised by two acoplanar photons or two acoplanar leptons; if $c\tau \approx L_{det}$ there will be non-pointing photons towards the beam spot or "kinks" (i.e. non-pointing tracks); if $c\tau \gg L_{det}$ then it will be an invisible final state in the case of LSP being the χ_1^0 or there will be the presence of heavy stable particles. The current NLSP limits,[21] independent of the lifetime, are m(χ_1^0)> 95 $\mathrm{GeV/c^2}$, m($\tilde{\tau}$)>75 $\mathrm{GeV/c^2}$ (see for example Figure 27 for the ALEPH result). The two photons mass plot for the all-LEP data in Figure 28 shows a good agreement between the data and the SM expectation, and no hint of a new signal.

9.6 R-parity violation

If R-parity is not conserved, then

a) the LSP is not stable any longer and the s-particles decay into SM ones. The clean

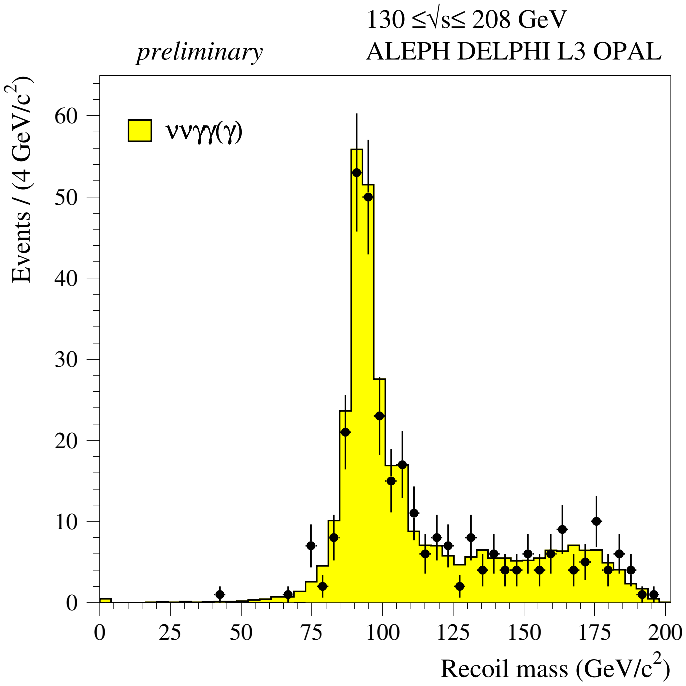

Fig. 28. *The recoil mass for final states with two acoplanar photons only, for the LEP data integrated over the full LEP2 statistics.*

missing energy signature is lost.
b) single s-particles production is possible, and s-particle exchange in the s- or t-channel contributes to SM processes.
R-parity violation predicts 45 new couplings with baryon- and/or lepton-number violation: λ_{ijk}, λ'_{ijk}, λ''_{ijk}. The proton lifetime and low-energy data impose severe constraints on these couplings, but LEP data can test even smaller values.

A LSP sfermion would decay directly into fermions ($\tilde{\rm f} \to {\rm ff'}$). If the LSP is the χ^0_1 then the decay into fermions is indirect: $\tilde{\rm f} \to {\rm f}\chi^0_1 \to {\rm ff'f''}$. The final state is then characterised by a large number of leptons or jets due to the LSP decay. At LEP most of these final states have been studied, but with the assumption that only one of the λ couplings is nonzero at a time. Limits on gauginos in this scenarios are very similar to those obtained in the R-parity conserving case.

R-parity violation also predicts the lepton-number violating s-channel process $\rm e^+e^- \to \tilde{\nu}$. Anomalies in the distributions of $\rm e^+e^- \to \tilde{\nu} \to e^+e^-$, $\mu^+\mu^-$ and $\tau^+\tau^-$ have been searched for at LEP.[22] No signal of new physics has been found in these channels.

R-parity may also be broken spontaneously in the third generation via the bilinear Higgs term $\epsilon L H_u$ in the Lagrangian (generated by a vacuum expectation of the right-handed sneutrino). The resulting massless Majoron J has been searched for by DELPHI[23] in the process $\chi^{\pm}_{1,2} \rightarrow \tau^{\pm}$J, and large domains of m($\chi^{\pm}_{1,2}$) have been excluded.

10 Search for LeptoQuarks

LeptoQuarks (LQ) are coloured objects that carry both lepton L and baryon B quantum numbers and interact directly with SM fermions. There are 18 different LQ, 9 scalar (spin S=0) and 9 vector (S=0). Their decay is LQ $\rightarrow$l$^{\pm}$q, νq. At the Tevatron and at Hera the lower bound on the LQ mass has been set around 250 $\mathrm{GeV/c^2}$ (for S=0) and 340 $\mathrm{GeV/c^2}$ (for S=1). At LEP the first generation of LQ can also be produced. The LQ can be directly produced in pairs (in a s-channel process) if their mass is M(LQ)$<$ $\mathrm{E_{cm}}$/2 or singly (the positron emits a photon that goes into a $\mathrm{q\bar{q}}$ pair, then one of the quarks couples to the electron to form a LQ) reaching M(LQ)$<$ $\mathrm{E_{cm}}$. The indirect production (i.e. $\mathrm{e^+e^-}\rightarrow$LQ $\rightarrow$ql) can instead reach higher masses and, depending on the final state, L3 and ALEPH set limits ranging from 100 to 400 $\mathrm{GeV/c^2}$.

11 Search for single top production

The single production of the top quark by the process $\mathrm{e^+e^-}\rightarrow t\bar{c}$ or $t\bar{u}$ became kinematically possible with LEP2 energies larger than 180 GeV. Flavour Changing Neutral Currents (FCNC) are known to be absent at tree level in the Standard Model (the cross section is very low, $\sim 10^{-9}$ fb), but can naturally appear at the one-loop level due to CKM mixing. Many extended models[24] give rise to detectable FCNC amplitudes already at tree level. The detection of a single top would be a sign of an anomalously large tcZ or $tc\gamma$ coupling (k_Z, k_γ). The searches at LEP have been combined,[25] giving rise to upper bounds in the plane of the couplings (see the upper plot of Figure 29), improving slightly on previous limits from CDF. Alternatively, limits on the BR(t $\rightarrow$cZ+uZ) can be set, as shown in the bottom plot of Figure 29 for LEP and CDF.

12 Technicolor

Technicolor (TC) models provide an alternative way to the Higgs mechanism to give mass to the particles by assuming a new very strong interaction ($\Lambda_{TC} \gg \Lambda_{QCD}$). The

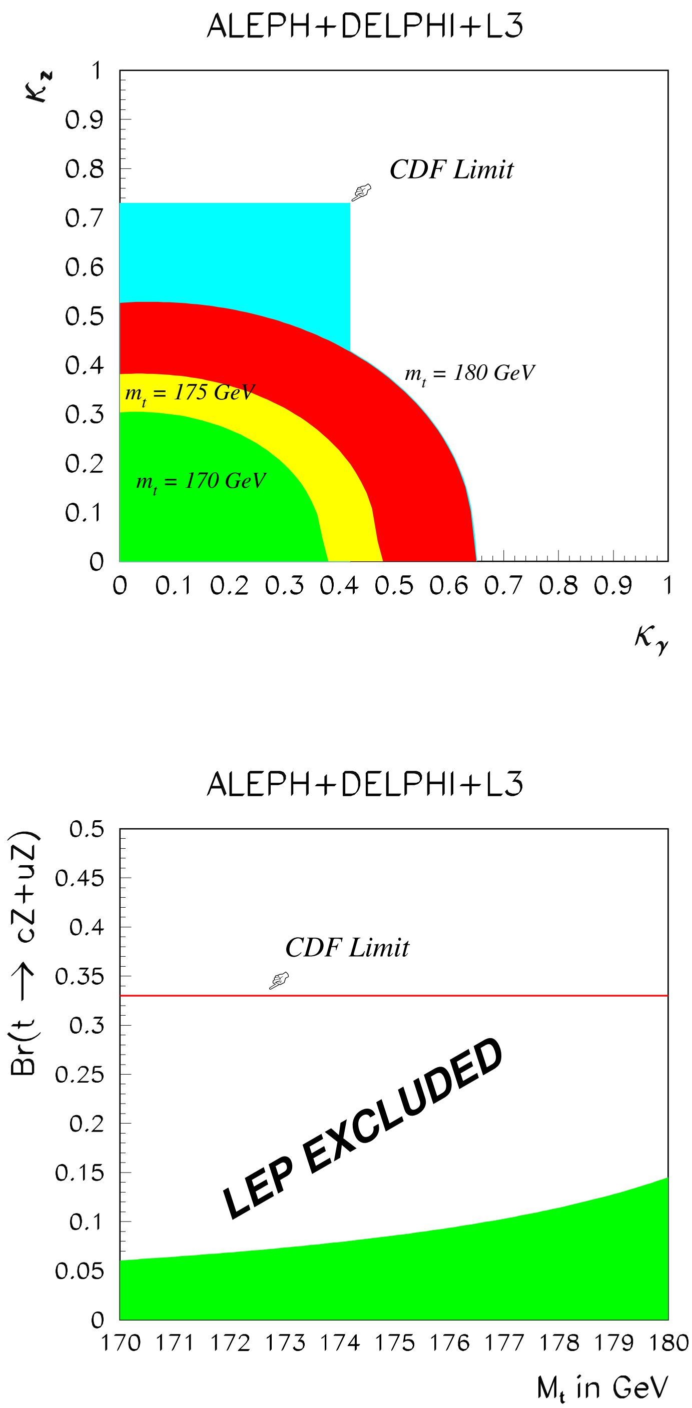

Fig. 29. *Top: Exclusion in the plain of couplings (k_Z, k_γ) for various top quark masses from the LEP combined data and from CDF. Bottom: Excluded values (at 95%CL) for the BR(t $\rightarrow$cZ+uZ) from the LEP combined data and from CDF. The shaded area is the region not excluded.*

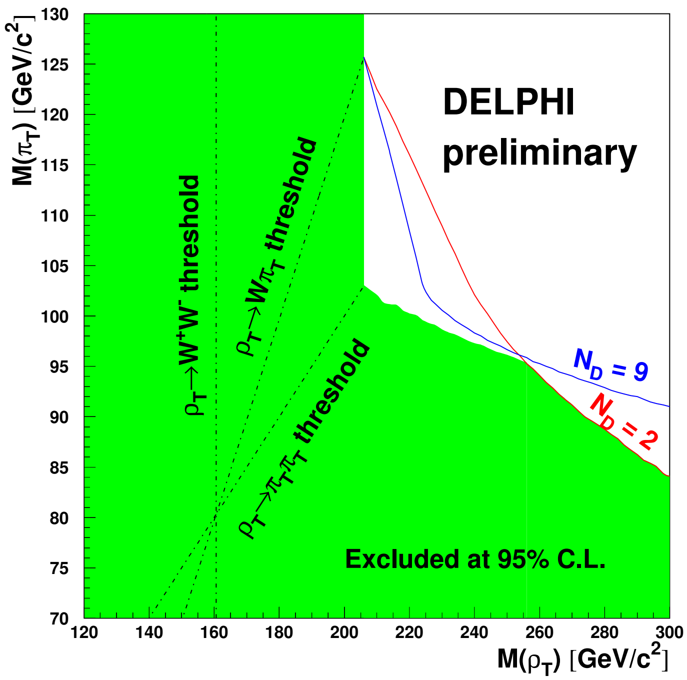

Fig. 30. *The region in the (M_{ρ_T} - M_{π_T}) plane (filled area) excluded at 95% C.L. for any value of W_L - π_T mixing for the DELPHI experiment with 2000 data.*

"standard" TC with a QCD-like running of Λ_{TC} is ruled out by precision measurements, but an extension of this model with a "slower" running (the "walking Technicolor" model) predicts light bound states of TC particles accessible at LEP. The parameters of the model are the mass of the Technipion π_T, the mass of the Technirho ρ_T, the number of doublets (up to 9, while in the original model it was 2) and the mixing between the π_T and the longitudinal component of the W, W$_L$. LEP data has been analysed in the framework of this model by L3 (for E$_{\rm cm}$=189 GeV)[26] and by DELPHI (for E$_{\rm cm}$=189-210 GeV)[27].[28]

For the case in which M(ρ_T) $<$ E$_{\rm cm}$ the following channel can be studied: $e^+e^- \to \rho_T \to$ W$^+$W$^-$, $f\bar{f}$(g), $\pi_T\gamma$. The expected cross section for $\rho_T \to$ WW is $\approx$ 3 pb. The precision on the WW cross section is of the order of 0.5 pb and the measurement is in good agreement with the SM expectation, leaving no room for the ρ_T to be lighter than E$_{\rm cm}$. As well from the direct search in $\mu^+\mu^-\gamma$ or $\pi_T\gamma$ spectra there is no indication of a resonant production. From these measurements a lower bound of M(ρ_T)$<$E$_{\rm cm}$ can be set as shown in Figure 30 for the DELPHI 2000 data.

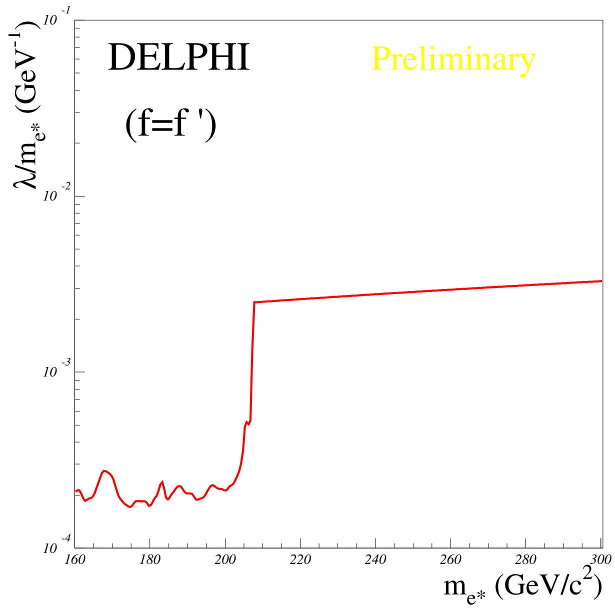

Fig. 31. *Upper bounds on the ratio λ/m_{e^*} combining direct and indirect limits, by DELPHI.*

Independent of the value of M(ρ_T) (i.e. also for M(ρ_T) $>$ E$_{\rm cm}$) the following processes can be studied: $\rm e^+e^-\to\rho_T\to\pi_T\pi_T$, π_TW$_L$ where $\pi_T\to$bc. Since no signal has been found at LEP during the first half of this year (nor in the previous year) a lower bound on the mass of the π_T as a function of the ρ_T mass and the number of doublets can be set as shown in Figure 30.

13 Excited lepton

Excited leptons would be a clear signal for substructure. They can be produce in pairs, or singly in the s- or t-channel, with the subsequent decay l* $\to$l(γ/Z), ν^* $\to\nu$(γ/Z),[28].[6]

The current emphasis is on the production of a single excited lepton with mass close to E$_{\rm cm}$. The new interaction is characterised by a compositness scale Λ, by charged- and neutral-current couplings f and f' which control the rate of the radiative and weak decays (e* $\to$eγ/Z/W, ν^* $\to$eW, e* $\to\nu$W, ν^* $\to\nu\gamma$/Z). Upper bounds for $\lambda/m_{e^*} = f/\Lambda\sqrt{2}$ are obtained, see Figure 31. In the figure direct and indirect limits (from the process $\rm e^+e^-\to\gamma\gamma$ in a t-channel process where an l* is exchanged) have been combined.

A nice candidate for excited lepton production has been observed at LEP by L3 ($\rm e^+e^-\to e\gamma\nu W\to e\gamma\nu\mu\nu$) and DELPHI ($\rm e^+e^-\to\mu\mu^*\to\mu\mu\gamma$). These events are also compatible with being produced by SM processes.

14 Extra dimensions

New models of low scale quantum gravity in extra dimensions predict the gauge and gravitational forces to unify at a mass scale smaller than M_{Planck}.[29] These theories solve the "scale-hierarchy problem" of the SM without introducing SUSY or compositness. The gravitational coupling could become of the same order of the gauge ones already at a weak scale if our 4-dimensional world would be inside a N-dimensional world where only gravitons G can roam. If N=4+δ and the extra dimensions δ have dimension R, then $M^2_{Planck} = R^\delta M^{\delta+2}$.

Models with $\delta = 1$ have already been excluded by test of the gravitational force ($R \sim 10^{13}$ cm) and astronomical observations. $\delta \geq 2$ is tested at LEP either by searching for the graviton G in the reaction $e^+e^- \rightarrow \gamma G$ and $e^+e^- \rightarrow ZG$ or in an indirect way via virtual effects on $e^+e^- \rightarrow f\bar{f}\, \gamma\gamma$, WW and ZZ distributions. Lower bounds on M of 1-1.3 TeV, 0.7-0.8 TeV, $\sim$0.5 TeV are obtained respectively for δ=2, 4 and 6. Thus current results from e^+e^-collisions do not favour low-scale quantum gravity with a scale close to the electroweak scale.

15 Summary and Conclusions

LEP is a unique machine to study new physics and to search for new particles. Many theories and models have been studied by the LEP experiments and strong constraints have been set on their parameters.

With the data taken until summer 2000 the four collaborations exclude a Standard Model Higgs lighter than 113.3 $\mathrm{GeV/c^2}$ at 95% CL. At the end of data taking in 2000 LEP will be able to exclude or observe with a 3σ significance a Higgs with a mass of $\sim$115 $\mathrm{GeV/c^2}$. For the lack of just a few GeV, LEP will not able to cover the MSSM plane entirely, although strong constraints have been put up to now: m_{h}, $m_{\mathrm{A}} \geq$ 90.5 $\mathrm{GeV/c^2}$, tan(β)>2.3 or tan(β)>0.9, $m_{\mathrm{H^\pm}}$>77.4 $\mathrm{GeV/c^2}$.

From the SUSY world there is no evidence of a supersymmetric particle and a lower bound on the chargino mass can be set at 104 $\mathrm{GeV/c^2}$ in most of the MSSM parameter space, and for the LSP mass at 46-48 $\mathrm{GeV/c^2}$ when including the results from the Higgs search.

No other anomaly has been found up to now in the framework of any other model and no deviation from the SM prediction has been observed.

In these days LEP is still running very well and at very high energies (E_{cm}=206.7

GeV and 208.1 GeV) so let's wait for these last exciting days!

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