PHYSICS AT LEP200*

D. Treille

CERN, CH-1211 Geneva 23, Switzerland

(Received April 1, 1999)

This talk summarizes the status of LEP200 physics and the prospective for its last two years.

PACS numbers: 01.52.+r

1. Introduction

After a short reminder of LEP1 achievements, I will turn to LEP2, describing its scenery, presenting the current results, in measurements and searches, and discussing the prospects. Since on several topics LEP2 competes with other present programmes, I will briefly indicate their results and promises as well. Most of the results come from LEP2 exposures up to 183 GeV center-of-mass energy, but whenever possible the preliminary results from 189 GeV available at the time of writing will be given.

2. Overview of LEP1 results

In the first phase of LEP, the four experiments have registered a total number of $\sim$20 million Z^0 under optimal experimental conditions. This has led to a breakthrough of the quantitative tests of the Standard Model (SM).

The Z^0 mass, finally measured to two parts in 10^5, after an epic and most exciting experimental fight, has acquired a prestigious status, by becoming one of the three basic entries of the SM. This was obtained through a clever exploitation of the transverse polarization of the particles in LEP and a close collaboration between the machine and the experiments.

The Z^0 resonance line shape has been determined with an extreme accuracy: one per mille on its width, 1.5 per mille on its "height", namely the

* Presented at the XXVII International Meeting on Fundamental Physics, Sierra Nevada, Granada, Spain, February 1–5, 1999.

production cross-section of the Z^0. An important quantity, derived from the line shape parameters, is the number of light neutrino species:

$$N_\nu = 2.994 \pm 0.011\,.$$

Drawing the legitimate conclusion that they are three, one can deduce the amount of helium expected in primordial nucleo-synthesis: one expects ~24%, in fair agreement with astrophysical data.

The universality of the electroweak couplings of the three lepton species has been demonstrated at the 2.5 per mille level. The muon and tau appear thus more and more as mere replications of the electron.

The flavour content of the Z^0 has been carefully measured: in particular the fraction of beauty–antibeauty in the hadronic final state, R_b, a potential carrier of information on phenomena beyond the SM, has been obtained with an accuracy of 4 per mille, less than one sigma away from its SM expectation (figure 1).

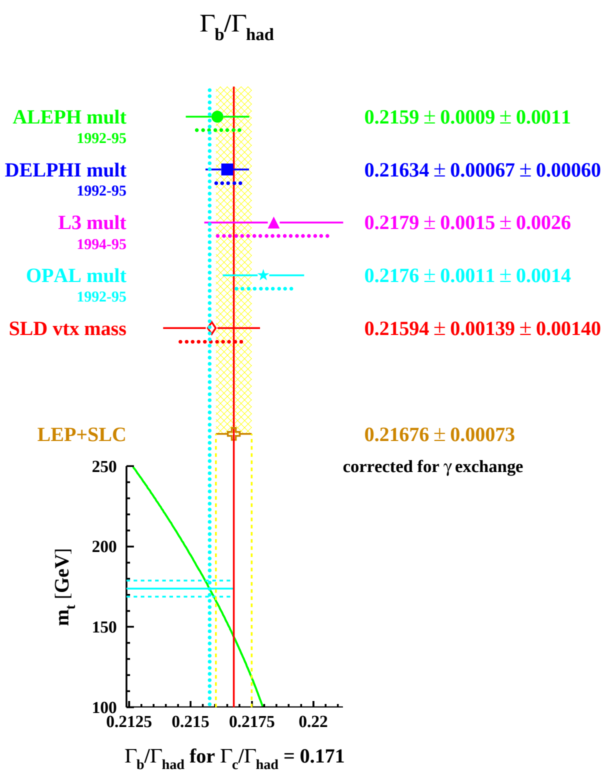

Fig. 1. The R_b measurement at LEP1

From all LEP electroweak measurements, and adding the specific contribution of the SLAC Collider, a value of

$$\sin^2\theta_w = 0.23157 \pm 0.00018$$

has been obtained for the electroweak mixing angle. This result is 25 times more accurate than it was before LEP era, and it definitely excludes some theories, like the simplest grand-unified model, SU(5).

A fit to these results, in the frame of the SM, leads to the indirect measurement of the top quark mass, through its contribution as a virtual particle in loops, since LEP energy is too low to pair-produce it directly:

$$M_t = 161\,^{+12}_{-9}\ \text{GeV}\,.$$

Such a result, indicative of a heavy top, has been available from LEP well before the direct observation of the top quark at the Fermilab Tevatron Collider. The present Tevatron direct mass measurement is:

$$M_t^{\text{direct}} = 174.3 \pm 5.1\ \text{GeV}\,.$$

Using this precise value as an input, one can then focus on the next and last unknown of the SM, the Higgs boson. Unfortunately, the effects of this particle as a virtual state give access only to the logarithm of its mass. Within the SM frame one finds:

$$\log_{10}(M_H[\text{GeV}]) = 1.85^{+0.31}_{-0.39} \pm 0.05$$

or $M_H \leq 230$ GeV at 95 % confidence level. We will come back later on this upper bound.

The set of LEP/SLC accurate electroweak measurements can also be confronted to the expectation of models beyond the SM.

To go beyond the Standard Model, one can take two main avenues. The first one introduces more symmetry and the most achieved version is Supersymmetry (SUSY). The second postulates the existence of new constituents and/or forces, and an example is Technicolor (TC). More generally this option can be considered under the heading of compositeness.

The predictions of SUSY for the electroweak observables are always in fair agreement with those of the SM, as shown in figure 2 [1], which, for each observable, confronts the experimental value (set to zero), the SM expectation and the prediction of three quite different SUSY models. One sees that SUSY and the SM provide fits of similar quality to the EW data. This does not prevent these accurate measurements to start rejecting, under given assumptions, peripheral regions of the SUSY parameter space [1].

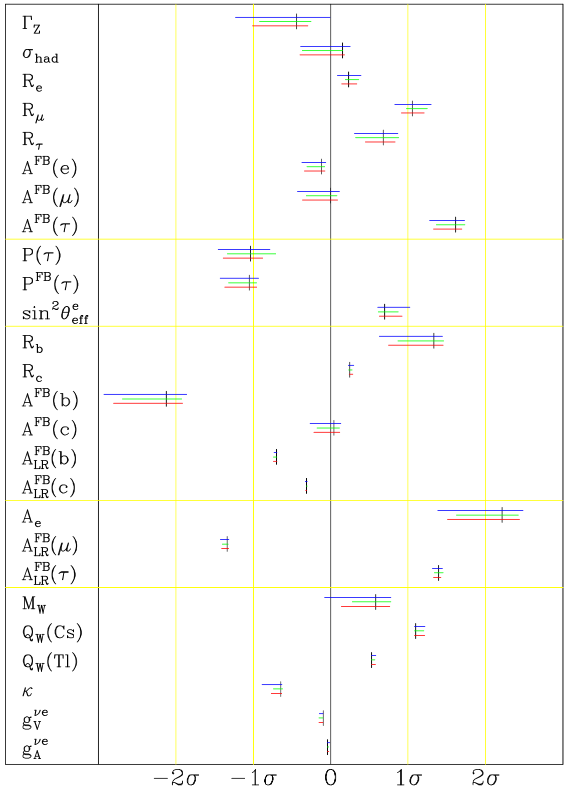

Fig. 2. Pulls of the SM (vertical bars) and three SUSY models (horizontal bars) for various electroweak observables [1].

On the contrary figure 3 [2] recalls that, in the case of TC, there is a basic disagreement between data and predictions. This fact should be kept in mind, and possibly cured, by the proponents of this alternative road.

Another important set of results from LEP1 improved our knowledge of the tau lepton and of heavy flavours of quarks, charm and especially beauty. The LEP1 harvest has indeed provided huge samples of these particles, in all kind of species and in optimal experimental conditions, in particular with a strong Lorentz boost, welcome to exploit their finite lifetimes which are of the order of a picosecond. A key asset in these studies has been the impressive progress made in the field of microvertexing, thanks to the development of elaborate microstrip silicon detectors, providing a spatial accuracy of ~ 10 micrometers. This is also a vital need for searches at LEP200.

All LEP1 results have been obtained with accuracies better, and sometimes much better, than foreseen in the prospective studies made earlier.

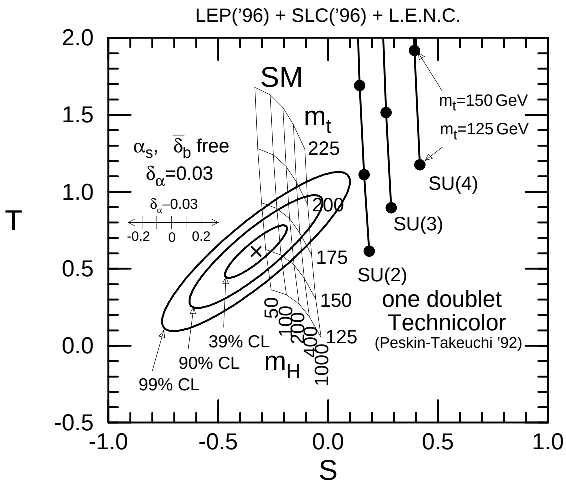

Fig. 3. The SM expectation and the expectation of a one doublet technicolor model, confronted to the data [3].

As we said, the electroweak measurements, interpreted in the frame of the SM, announce a light Higgs boson: $M_H \leq 230$ GeV at 95 % confidence level.

Does that imply the existence of such a boson? Or are there possible loopholes, where something else happening at higher energy mimics the effect of a light boson? It may be so and the correct way is to "go and see": this is being done at existing machines and is the *raison d'etre* of future colliders.

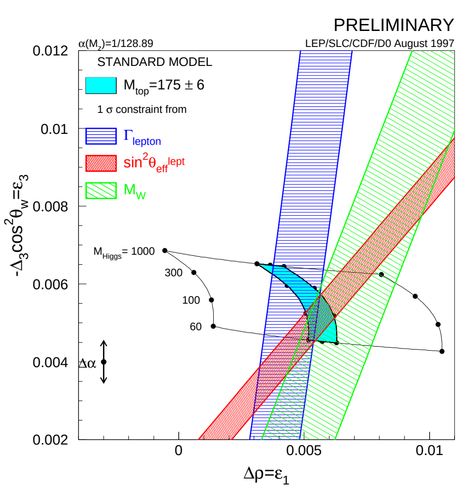

Fig. 4. Contribution of various observables to the determination of ε_1 and ε_3.

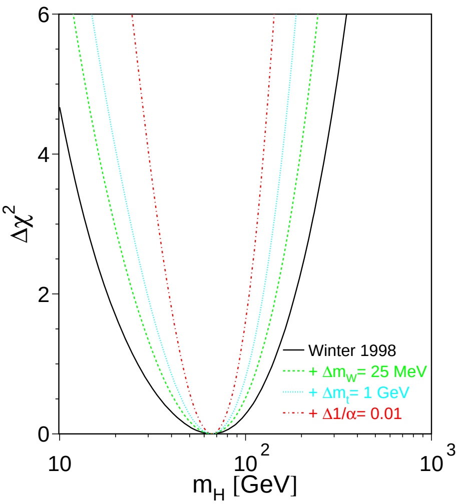

Fig. 5. Foreseable progress in the indirect determination of the Higgs mass bounds [3]

Meanwhile the quest for accuracy in EW measurements should be pursued vigorously. As recalled by figure 4, to pinpoint the Higgs mass in the SM frame, the key ingredients are the top mass and $\sin^2\theta_w$ (therefore $\alpha(M_Z)$ for the latter), while a very accurate measurement of M_W can temporarilly play its role as well. Figure 5 [3] gives an optimistic view of the possible evolution of $\Delta \log M_H$ in the future, which will find its interest once the Higgs boson is found, as a check of the SM or MSSM coherence at loop level, or in the case of no discovery.

3. The LEP2 scenery and its standard measurements

Collisions at higher energies in LEP still provide clear and clean events. However the rates of interesting SM ones has gone down by typically three orders of magnitude, compared to those at the Z^0 resonance. And, at energies not far above this resonance, a new class of events appear, which, in first approximation, are simply parasitic ones: by radiating one or more photons in the initial state, the colliding $e^{\pm}$ may "return" to a reduced effective center-of-mass energy equal to the Z^0 mass. This occurs with a small probability, but, because of the huge cross-section at the resonance, the rate of such "radiative return" events actually dominates all other annihilation ones. Photon radiation is mostly collinear to the $e^{\pm}$ and, in the plane normal to the beam direction, does not carry transverse momentum. There is however some probability that it does so. In principle, the emitted photons are then visible in the detector and it is crucial to detect them with maximum efficiency, in order not to fake missing transverse momentum events besides the unavoidable SM ones; one must therefore ensure the hermeticity of the detector.

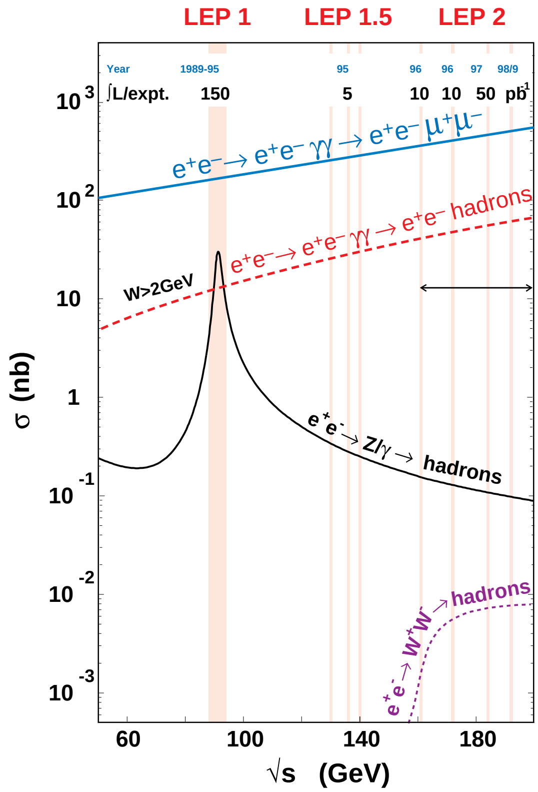

Fig. 6. The LEP scenery

As shown in figures 6 and 7, the most abundant new SM process, besides radiative return to the Z^0 and normal fermion pair production, is the production of pairs of $W^{\pm}$. The first W pair was observed when LEP reached 161 GeV CM energy in 1996 and, since then, the four LEP experiments have collected ~15000 such pairs. The physical interest of this process is considerable. It represents a clean and relatively abundant source of W bosons and allows to accurately measure the W mass. It allows also to perform an accurate check of a still poorly known aspect of the SM: the triple boson couplings. This opportunity stems from the fact that, among the processes leading to W pair production, one finds virtual Z^0 and photon exchange, in which such triple boson couplings obviously intervene.

The Tevatron Collider at Fermilab has also the potential to perform these measurements and the two machines are thus in competition.

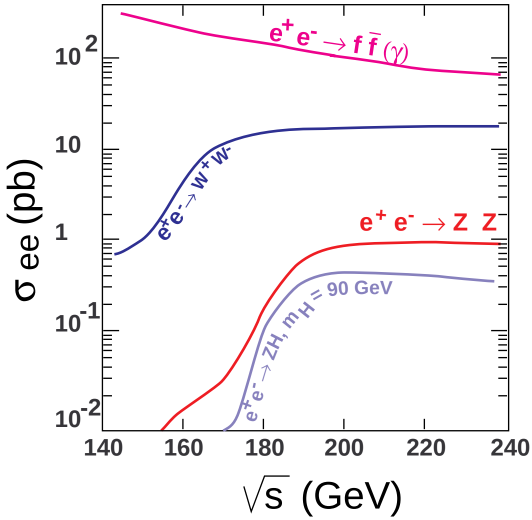

Fig. 7. The cross sections of the main processes at LEP200

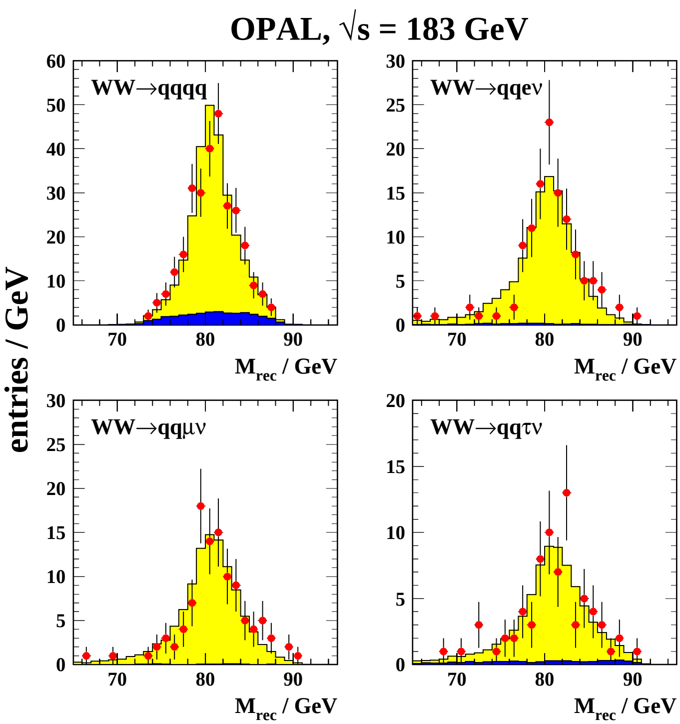

Fig. 8. OPAL mass spectra.

For the M_W measurement, the LEP energy does not matter much, once it is far enough above the threshold of the reaction, and what counts is the total number of events registered, since statistics will be the ultimate limitation.

For gauge coupling measurements, the number of events, as well as the quantity of information one can exploit in each of them, are important, but there is also a rapid growth of sensitivity with energy: typically a gain of a factor two for an increase of 20 GeV CM energy.

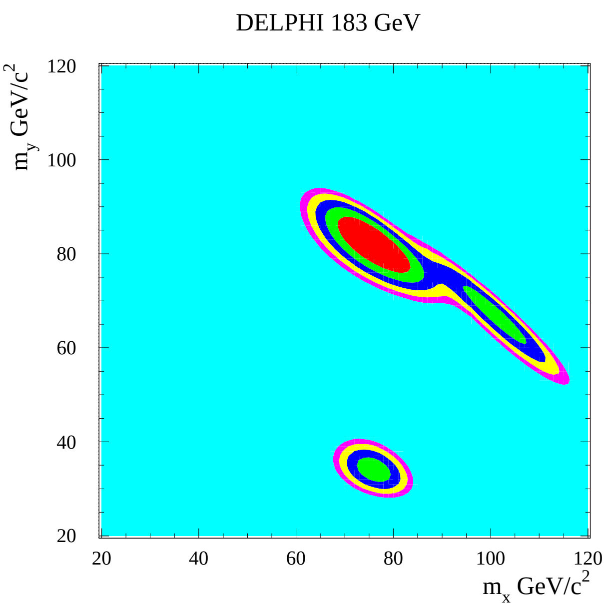

Fig. 9. A two-dimensional ideogram for a 4-jet event

The W mass measurement can be performed at LEP in all hadronic final states, as well as in mixed decays, one hadronic, one leptonic. An example of the relevant mass spectra of reconstructed W's, after appropriate fits and pairings, are shown by figure 8. The reconstructed W mass is shifted relative to the real one, and the problem is to correct for that shift, in particular its part due to initial state radiation, and assess the correct uncertainty. To keep and exploit the full information contained in an multijet event, in order to define the right pairing, the use of ideograms can be convenient (figure 9). Another interesting technique is to mimic W pair events by superposing two Z events, adequately boosted: one thus gets a very similar final state, for which one knows the correct answer.

Presently, the LEP2 accuracy on M_W is ± 65 MeV, statistically dominated, quite similar to the one from hadron colliders (figure 10 and 12).

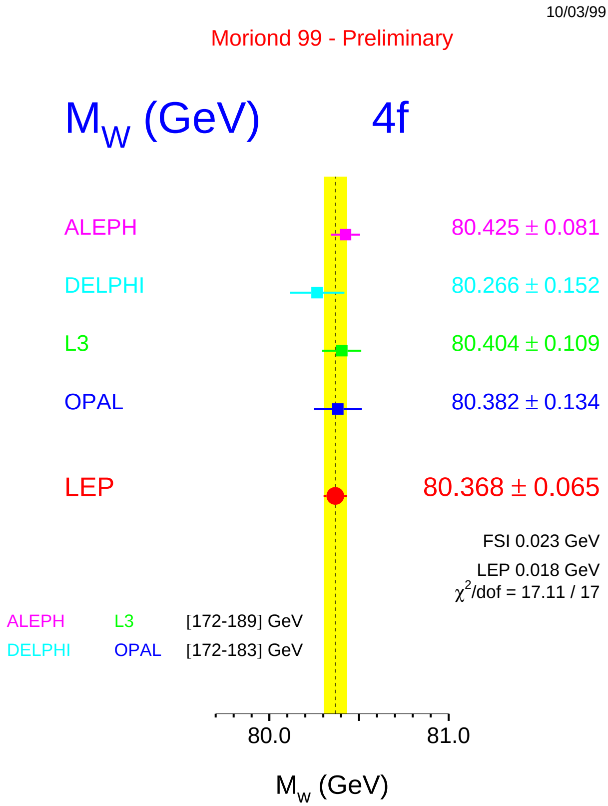

Fig. 10. The LEP W mass measurements

At LEP, it should steadily improve with luminosity and, for the total luminosity foreseen, reach ~30 to 50 MeV, depending on our ability to master the most tricky systematic uncertainties. These appear in the all-hadronic decay mode of the W pairs, which is also the most abundant one. They concern the possible interconnection of the decay products of the two W's and, besides their possible impact on M_W, such effects are quite interesting *per se*. For the time being, there is no indication that Bose–Einstein correlations occur between different W's, although the situation is still far from being settled (figure 11). The possible effect of colour reconnection on the W mass uncertainty is being studied as well within a variety of models.

As for the triple boson couplings, figure 13 gives the present LEP limits. The sensitivity increases with energy, as we said, and with the quantity of information one can extract from the final state. LEP should ultimately set bounds on possible departures from the SM at the few % level. Is this sensitivity sufficient to reveal new physics effects, which are not yet excluded by

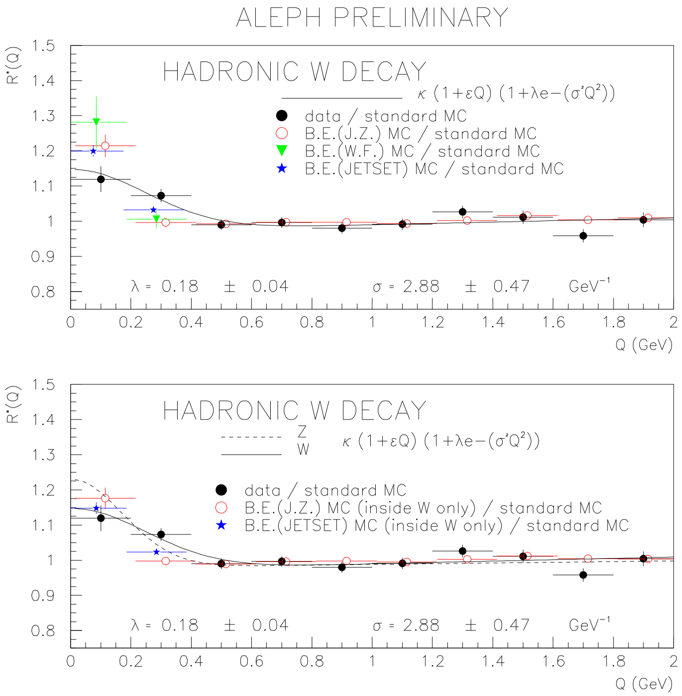

Fig. 11. The Bose–Einstein correlations in Aleph

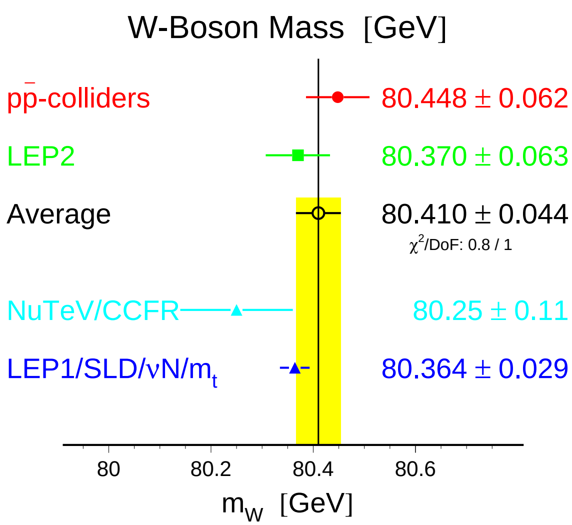

Fig. 12. The World W mass measurement

the very accurate LEP1 results? This has been the subject of hot discussions, with the conclusion that it is still possible, although unlikely.

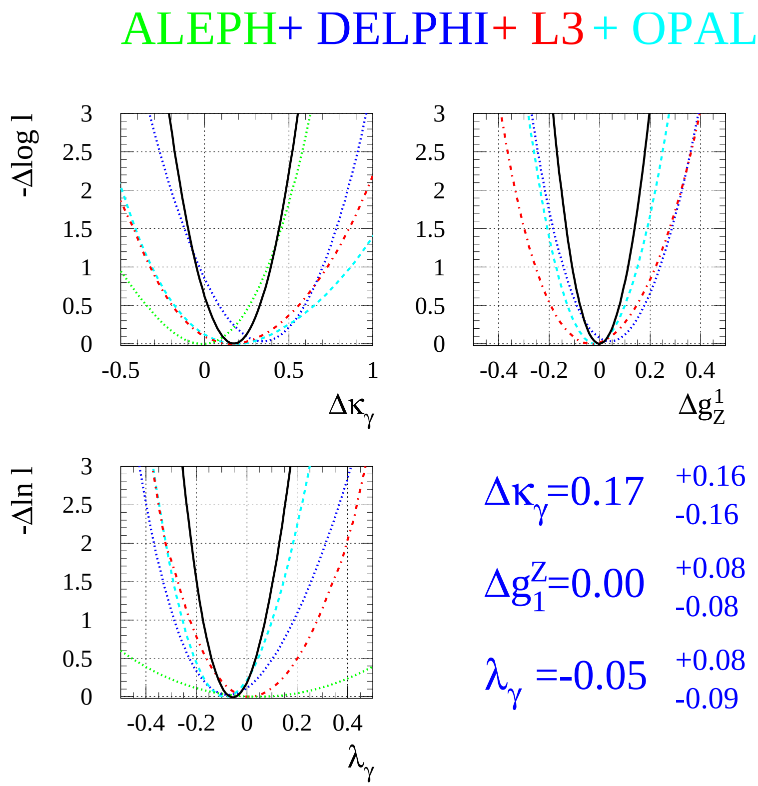

Fig. 13. The LEP limits on triple boson couplings

The Tevatron, presently stopped for major improvements, will resume its data–taking in 2000 with an increased luminosity. As far as one can predict, it should achieve in both sectors a performance quite comparable to LEP, but involving a very different set of systematic errors.

Whatever be the interest of these new electroweak measurements, it is nevertheless clear that, for LEP200, the strong emphasis put on the last few GeV of its energy range finds its real justification when one considers the search potential of this machine for the Higgs sector, and to a lesser extent, for the particles predicted by Supersymmetry (SUSY).

4. The composite way

Keeping in mind the caveat mentioned above, let us explore first the possible signals linked with composite scenarios. They imply the potential existence of at least one among the following effects:

— technicolor particles

— contact interactions

— excited states of the known fermions

— recurrence of vector bosons: W', Z'

— leptoquarks (LQ)

The last two can also appear in fundamental theories with an extended gauge group. Since, besides LEP, HERA and the Tevatron have much to say in these searches, I will confront the results of the three machines.

4.1. Search for technicolor [4]

The CDF experiment has performed a search for TC vector bosons (TVB), ω_T and ρ_T, as predicted by the model of Ref. [5]. The TVB are produced by TVB-dominance. They are supposed to decay respectively into gamma-technipion (TP) and W-technipion or Z-technipion, since multi TP states are kinematically disfavoured. The charged (neutral) TP decays to $b\bar{c}$ ($b\bar{b}$).

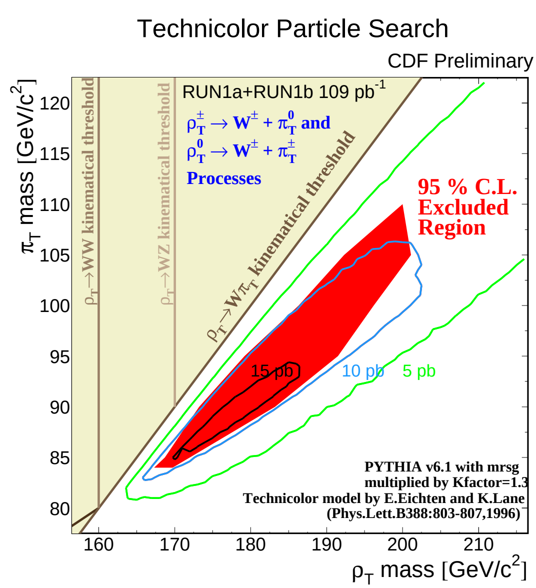

Fig. 14. CDF search for a Technirho

Figure 14 shows that these searches are sensitive to TVB (TP) in the 200 (100) GeV region. The domain where one could expect such particles is however very model dependent and one should consider these first explorations as an appetizer for what more luminosity (at the Tevatron) and more energy (at LHC) will offer. Similarly, on behalf of topcolor models [6], a welcome systematic study of $b\bar{b}$ (and later of $t\bar{t}$) mass spectra is beeing undertaken.

At LEP low scale TC is searched for by analyses exploring similar final states (see charged Higgs searches below), under the assumption that a techni-resonance could be produced in the s-channel.

4.2. Contact interactions [7]

I recall the usual parameterization of the effective contact interaction Lagrangian in terms of coefficients $\eta_{i,j}$, where i, j imply left- or right-handedness, and where $\eta = \pm(g^2/\Lambda^2)$, ratio of a coupling constant and an energy scale squared. The sign indicates a positive or negative interference of the contact amplitude with the SM one. Setting as usual $g^2/4\pi = 1$, one is left with the parameters Λ_+ and Λ_- on which lower limits are set. If one has an idea of the possible origin of the contact terms (for instance a LQ exchange) one can obtain a limit on λ/m where λ is the (Yukawa) coupling implied and m the mass of the exchanged object (LQ).

All three colliders have been performing such measurements. Focusing on quark-lepton compositeness, the Tevatron obtained limits from the study of the Drell–Yan spectrum, HERA did it through neutral currents and LEP through $q\bar{q}$ final states. Let us list the limits in TeV obtained for $\Lambda_\pm$ in the case of two parity-conserving combinations, AA and VV, since Atomic Parity Violation (APV) experiments have ruled out PV combinations up to $\Lambda \sim 10$ TeV:

	CDF	D0	Zeus	H1	A	L3	O
VV+	3.5	4.7	4.9	4.5	4.0	3.9	4.1
VV−	5.2	5.8	4.6	2.5	5.2	5.0	5.7
AA+	3.8	4.6	2.0	2.0	5.6	5.6	6.3
AA−	4.8	5.3	4.0	3.8	3.7	3.5	3.8

One sees that the three machines set quite similar limits. This reflects the fact that their constituent CM energies and luminosities are not too dissimilar.

4.3. Excited fermions [8]

In brief, the Tevatron covers the field of excited quarks up to ∼700–800 GeV. For excited leptons, LEP and HERA compete well, the LEP limits on

λ/m beeing stronger, while HERA has a higher mass reach. This is well illustrated in the case of radiatively decaying excited electrons.

4.4. New vector bosons [9]

Its higher mass reach gives the advantage to the Tevatron; searches are performed there both in the leptonic and di-jet channels, with limits reaching 700 GeV. However the power of indirect searches at LEP, through the mixing with the Z^0, is high. Comparing the limits of CDF and L3 (183 GeV) for various models one finds, in GeV:

Type of Z'	χ	ψ	η	LR	SSM
Limit of L3	365	260	270	375	805
Limit of CDF	595	590	620	630	690

For a Z recurrence with sufficient coupling to the fermions, like a sequential SM Z' (SSM), the LEP limit can be the strongest one. From 189 GeV data, Aleph now sets a limit of 1050 GeV to a SSM boson.

4.5. Leptoquarks [10]

Leptoquarks (LQ) appear in all theories attempting to relate leptons and quarks. They carry the quantum numbers of both objects. Their phenomenology is complex [11]. LQ can be scalars or vectors. The search is restricted to pure chiral couplings of the LQ, given the features of pseudoscalar meson decays: there are 14 species of such chirally-coupled LQ. Those accessible to accelerators are assumed to couple only to one generation (otherwise one would be in trouble with FCNC processes), while much heavier ones (like Pati–Salam LQ) can have non-diagonal couplings. LQ can carry a fermion number 0 (case of $e^-\bar{q}$ as in Hera e^+q collisions) or 2 (case of e^-q).

Limits on LQ have been set by EW measurements ($\Gamma_Z, \ldots$), APV experiments, neutrinoless double beta decay and studies of rare decays. In particular CDF, by putting stringent limits on $B_d^0 \to e\mu$, $B_s^0 \to e\mu$ [12], has pushed the lower mass limit of Pati–Salam LQ up to $\sim$20 TeV.

The production mechanisms of LQ at the three machines are quite contrasted.

At HERA, where LQ are singly produced by e–q interaction, the Yukawa coupling λ of the LQ to e–q is a key parameter, as well as its decay branching ratio β into charged lepton + quark. One can thus expect either limits on the LQ mass versus β for given values of λ (a useful value to consider being a coupling of EM strength, $\lambda_{\rm EM} \sim 0.3$), or limits on the mass as function of λ, in theories which provide the value of β (usually 0.5 or 1) [11]. This is shown in figure 15 from H1. Zeus has reported very similar limits [13].

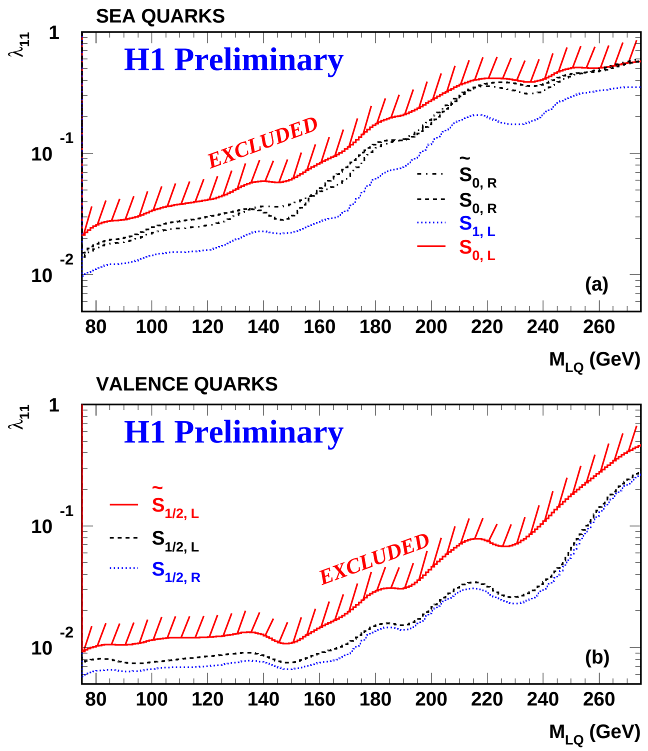

Fig. 15. H1 limits on leptoquarks in the λ-M plane

One sees that HERA sets quite high mass limits, even for small values of λ and β. For β=1 and $\lambda_{\rm EM}$, the limit reaches $\sim$ 275 GeV in the case of LQ involving valence quarks (the variety of LQ with fermion number=0).

At the Tevatron, LQ are pair produced through normal gauge interactions, and λ does not intervene. LQ coupled to each of the three families can be produced and have been searched for. In the case of scalar LQ with β=1, the combined limit of CDF and D0, independent of λ, is 242 GeV. See reference [14] for a complete panorama of the Tevatron LQ searches.

LEP has a mixed situation. LQ can be pair produced (λ is then irrelevant) but with obvious mass reach limitations. They can be singly produced, by fusion of an $e^{\pm}$ with a quark of a photon radiated by the partner e. Limits were presented by the LEP experiments: for LQ with $\lambda_{\rm EM}$, those of Delphi for 189 GeV extend up to $\sim$ 150-180 GeV, for β=1 and depending on their quantum numbers. Finally the process $e^+e^- \to q\bar{q}$ allows to set indirect limits on LQ exchange in the t- or u-channel. As anticipated above, such limits are given for $\lambda/m_{\rm LQ}$ and, provided λ is not too small, they extend up to very high masses (figure 16).

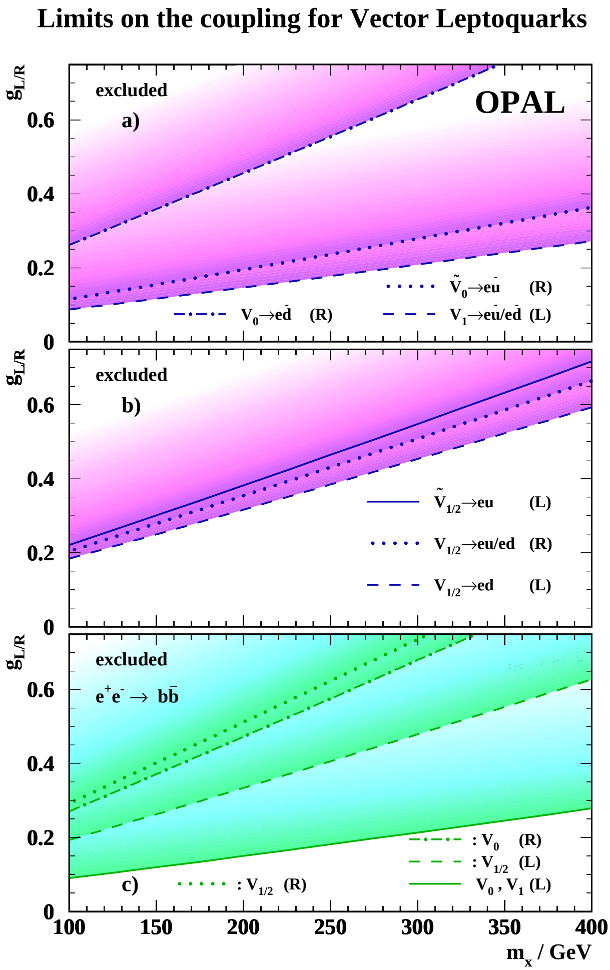

Fig. 16. Opal limits on leptoquarks in the λ–M plane

Actually squarks and leptoquarks behave similarly, with for instance the correspondance between the LQ $\tilde{S}_{1/2}$ and a $\tilde{u}_L$: the results presented here can be interpreted in terms of $\not{R}$ production of squarks as we shall see in 7.4.

5. A tour through SUSY world

SUSY can be minimal (the minimal number of superpartners, only two Higgs doublets, R-parity conserved) or non-minimal (introduction of an additional Higgs singlet, R-parity breaking (RPB), *etc.*). I will consider the latter option in relation with RPB in 7.4.

Minimal SUSY [15] has overall 124 parameters, including the SM ones. Not only are most of the parameter sets physically non-viable, but the situation is phenomenologically untractable and one is led to decrease the number of independent parameters, staying minimal, by assuming a mechanism of soft SUSY breaking (SSB).

SSB can be mediated by gravity, and this leads to minimal Supergravity (mSUGRA), which, beyond the SM parameters, has only 5 new ones: m_0, the common scalar mass at high scale, $m_{1/2}$, the common gaugino mass, A, the common trilinear coupling, μ, the Higgs mixing parameter, and B, the common bilinear coupling. Actually the implementation of EW symmetry breaking allows to trade B and μ against M_Z (known) and $\tan\beta$, up to the sign of μ. These are the mSUGRA parameters and most analyses, including LHC prospective studies, are done within this set.

From there on two attitudes prevail. One is to search for a still reduced set of independent parameters: one can for instance invoke the idea of fixed-point behaviour [16] which amounts to fix $\tan\beta$ once M_t is known. One can also, using GUT and string-inspired considerations, get relations between the remaining parameters (dilaton, no-scale models, light gluino models, ...).

On the contrary one can consider that, with mSUGRA, one has gone too far, without justification, on the way to universality, and be led to relax partly such an assumption, either for scalars (for instance by dissociating the Higgs sector from the sfermion sector) or for gauginos (for instance by giving up the mSUGRA relation between the M_i obtained at the EW scale, where $i = 1, 2, 3$ stands for U(1), $\mathrm{SU(2)_L}$ and $\mathrm{SU(3)_C}$, respectively).

As an alternative to SUGRA one can build SUSY models in which SUSY soft breaking occurs through ordinary gauge interactions [17] instead of gravity. Such models are, at least, as constrained as mSUGRA.

The phenomenologies of both classes are very contrasted: because of the different values of the scale at which SUSY is broken in the hidden sector ($\sqrt{F} \sim 10^{11}$ GeV in SUGRA, $\sim 10^{2-4}$ GeV in GMSB), the gravitino, $\tilde{G}$, has a totally different behaviour in the two scenarios: in mSUGRA its mass ($M_{3/2} = F/(\sqrt{3}M_{\mathrm{Planck}})$) is heavy (of EW mass scale) and $\tilde{G}$ is so weakly coupled that one can forget about it. In GMSB versions, $\tilde{G}$ is extremely light and is certainly the lightest SUSY particle (LSP); although still weakly coupled, it is nevertheless of paramount phenomenological importance, essentially through the decay of the next-to-LSP (NLSP) particle.

This guided tour through SUSY scenarios is needed to understand what is beeing searched for and in which channels (in particular to understand the decoupage of the talks in the parallel sessions of conferences ...). However all these a priori considerations should not compromise the main task of a search program which is to explore, in an unbiased way, all channels accessible with enough purity and sensitivity. Furthermore there exists in SUSY a particle whose properties are precisely predicted and quasi-independent of the exact scenario under consideration, provided one stays in the minimal theory: the lightest scalar Higgs boson.

6. Searches for Higgs bosons

6.1. Higgs phenomenology: a digest

To get a fair idea of the relevance of LEP200 (and of its limitations) for Higgs boson search, one must consider some basic facts of Higgs phenomenology.

In the SM the Higgs mass is not predicted. This reflects our ignorance of the magnitude of the Higgs self-coupling. However reasonable additional constraints allow to reduce the possible domain. If one requires that the Higgs sector should stay perturbative up to a high energy scale, a condition which is mandatory if one wants to deal with a computable theory, one can set an upper limit on the boson mass as a function of that scale. By requiring that the Higgs potential should stay bounded from below, a quite legitimate condition indeed, not to destabilize the vacuum, one can set a lower limit on the mass of the boson, depending on the same scale, and also very strongly on the top mass. If one defines the SM as a theory which should stay valid up to a very high energy scale – this is in a sense a tautological statement, since the SM *sensu stricto* does not contain any new ingredient, neither force nor constituent, until the Planck scale — the Higgs boson should then be found in the 130–180 GeV mass range (figure 17). This will certainly be a privileged region for the LHC, but it is out of reach for LEP200.

On the other hand the scenario offered by supersymmetry (SUSY) is radically different.

The most solid and dramatic prediction of SUSY models concerns the Higgs sector. SUSY, in its minimal version, requires the existence of two Higgs doublets, *i.e.* 8 real quantities; once the three vector bosons have acquired mass, five bosons are left: two scalars, h^0, H^0, whose mixing involves an angle α, a pseudoscalar, A^0, and two charged bosons, $H^\pm$. At tree level, two parameters, for instance M_A and $\tan\beta = v_1/v_2$ (where $v_1 =$ v.e.v. of the doublet giving mass to up-quarks, $v_2 =$ v.e.v. of the doublet giving mass to down quarks and leptons) are enough to describe the Higgs sector. At loop level, and focusing here on h^0, its tree level mass is increased by radiative corrections and reads:

$$M_{h^0}^2 = M_Z^2 \cos^2 2\beta + \Delta M^2 \,.$$

The increment ΔM^2 depends on the 4th power of M_t, hence the importance of its accurate knowledge, and logarithmically on the stop masses $M_{\tilde{t}_1}$ and

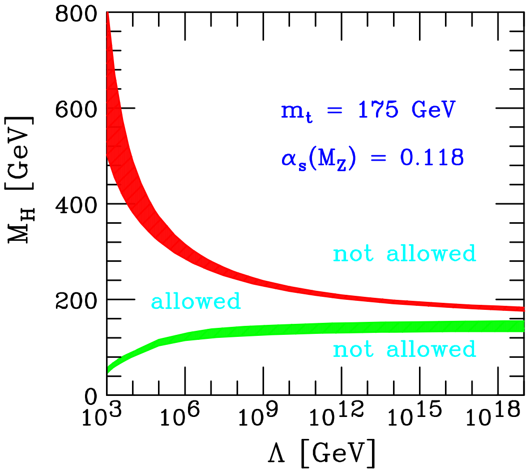

Fig. 17. Higgs standard mass limits, from perturbativity (upper curve) and vacuum stability (lower curve), from [18].

$M_{\tilde{t}_2}$, themselves determined by the mixing parameter in the stop sector $\propto A_t - \mu \cot\beta$ (beware notations which change with authors). It is through this mixing parameter that M_h, and the Higgs sector, ultimately depends on the other parameters of the MSSM.

A fact to keep in mind is the complementarity between the couplings $h^0Z^0Z^0 \propto \sin(\alpha-\beta)$ and $h^0A^0Z^0 \propto \cos(\alpha-\beta)$.

An interesting case is when M_A is large: the h^0 mass is unaffected and stays light, while all other Higgs bosons become mass degenerate with A^0. Furthermore h^0 is SM-like ($\sin(\alpha-\beta)=1$)

How heavy, or light, is h^0?

This is shown in figure 18: M_h has to be lower than ∼125 GeV for any $\tan\beta$ and stop mixing [19]. For small $\tan\beta$, a case which includes the infrared fixed point scenario (IFP) [16], this limit is $\simeq$ 100 GeV. The striking difference between the two models is due to the well-known fact that, while in the SM the Higgs boson self-coupling is unknown, it is perfectly defined in the MSSM in terms of the gauge couplings g and g'.

If one quits the minimal version of SUSY and introduces a Higgs singlet, or even triplets, it is possible to get a somewhat higher mass limit for the lightest boson [20]. One can also, by invoking explicit CP violation, get some decoupling from vector bosons. This may be temporary "graceful" exits, keeping the SUSY frame, in case of non discovery of this boson, and until LHC and NLC bring an answer.

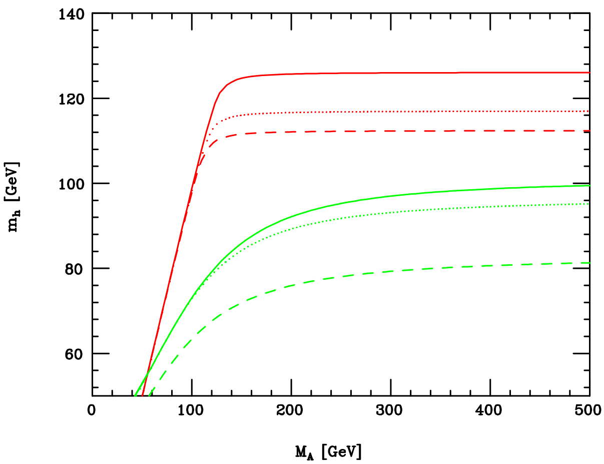

Fig. 18. Mass of the lightest SUSY higgs scalar versus M_A for small $\tan\beta$ (lower curves) and large $\tan\beta$ (upper curves). Within each family the full line is for maximal stop mixing, the dashed one for minimal stop mixing. From [19]. The top mass is at its central value, the SUSY mass at 1 TeV.

6.2. Higgs search at the Tevatron [21]

The Higgs boson at the Tevatron would be produced in association with a vector boson and is searched for in its dominant decay mode, $b\bar{b}$. A simple glance at figure 19 shows that the limits obtained with 100 pb^{-1} are still far above (20 to 100 times) the SM expectation. The future may however be promising, in spite of the severity of the experimental challenge. Figure 20

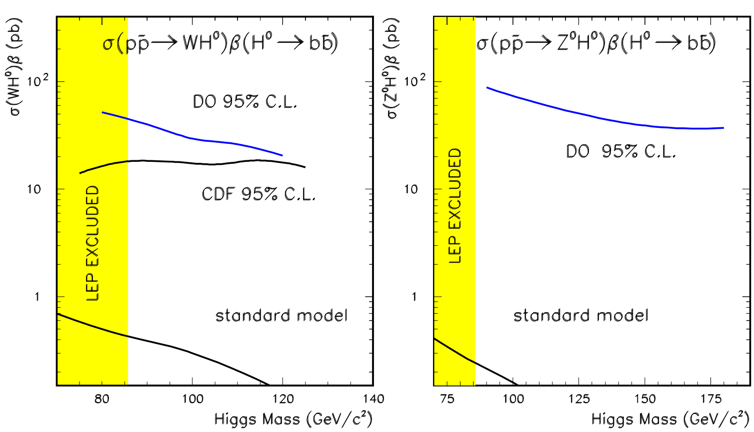

Fig. 19. D0 limit on higgs production compared to the SM expectation.

[22] gives the results of MC simulations and shows that, with 20–25 fb^{-1}, masses up to 120 GeV are potentially accessible. Such a figure of integrated luminosity represents $\sim$ 10 times what is planned for runII (in 2000 onward) and implies that a project like TeV33 becomes a reality.

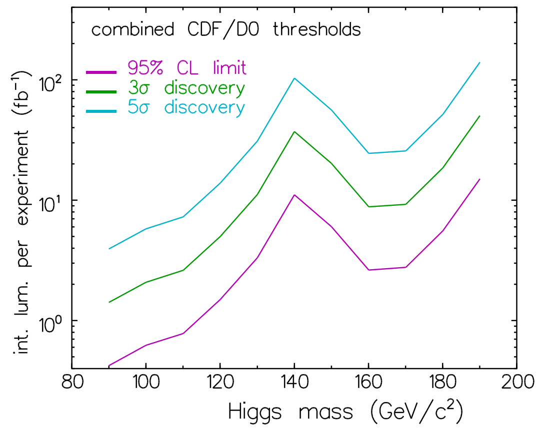

Fig. 20. The luminosity needed at TeV33 to discover a Higgs boson of a given mass [22].

Tevatron experiments, as well as LEP ones, have looked for various "anomalous" Higgses. In particular, following the model of Ref. [23], a Higgs boson coupled only to bosons ("bosophilic") and, for the masses considered, decaying dominantly into gamma-gamma, has been searched for. The limits set, at 95 % CL, are:

$$\text{D0} \ \geq 81.4 \text{ GeV},$$

$$\text{CDF} \ \geq 82 \text{ GeV},$$

$$\text{OPAL} \ \geq 92.6 \text{ GeV}(183 \text{ GeV})$$

while Delphi translates its negative result in terms of limits on anomalous couplings.

A last comment on Higgs searches at Tevatron: a coupling like the one of A^0 to $b\bar{b}$ is proportionnal to $\tan\beta$. The process of $b\bar{b}$ production, with a b radiating a A^0 boson, which leads to a 4-b final state, has therefore a large cross-section and a distinct signature at large $\tan\beta$ [24]. The analysis is under development. More theoretical input is still needed to evaluate properly the expected rates. But there is thus a possibility for the Tevatron to explore a region of the parameter space complementary to the one of LEP.

6.3. Higgs boson searches at LEP [25]

The LEP scenery is well known (figure 6 and 7). LEP2 is working above the Z^0, a huge resonance indeed, so that phenomena of radiative return (simple, double,...) are a plague and require absolutely hermetic detectors, as we explained.

The reaction under study is, for the SM Higgs, the Higgsstrahlung one $e^+e^- \to H^0Z^0$, the H^0 decaying 90 % into $b\bar{b}$. As we said, the SM Higgs, strictly speaking, should be at higher mass. For the MSSM one considers both the $e^+e^- \to h^0Z^0$ process, as before, and the $e^+e^- \to h^0A^0$ associated production, leading to $4b$ and even to $6b$, when $h^0 \to A^0A^0$ decay is permitted. I recall that if M_A is large enough, and the second process is therefore closed, h^0 is SM-like.

The experimental situation at LEP200 is relatively comfortable (figure 7) since the most offending backgrounds are not much larger than the signal. Furthermore W do not decay appreciably into beauty. On the other hand the Z^0Z^0 final state, when one Z^0 goes to $b\bar{b}$ and for $M_h \simeq M_Z$, the situation recently explored, is an irreducible background. Nevertheless the purity is sufficient to allow the exploitation of all decay modes of the associated Z^0: $q\overline{q}, \nu\overline{\nu}, l^+l^-$.

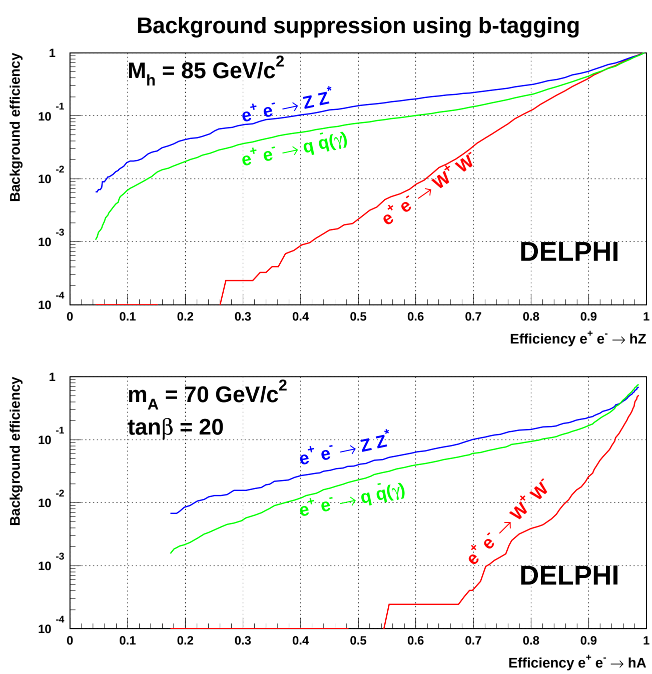

Fig. 21. b-tag rejection of the various backgrounds versus signal efficiency

B-tagging is very useful and very powerful (figure 21): for Delphi, as an example, an efficiency of 60 percent to the h^0Z^0 signal in 4-jets can be kept, while the W-pair background is rejected by a factor ~ 100. Figure 22 gives much physics insight: it shows, in the case of a 4-jet analysis, the evolution when the severity of the cuts increases, decreasing therefore the efficiency, of the number of observed events and of the expected background, total and split into its three components: as expected the Z^0Z^0 background is the most resistant.

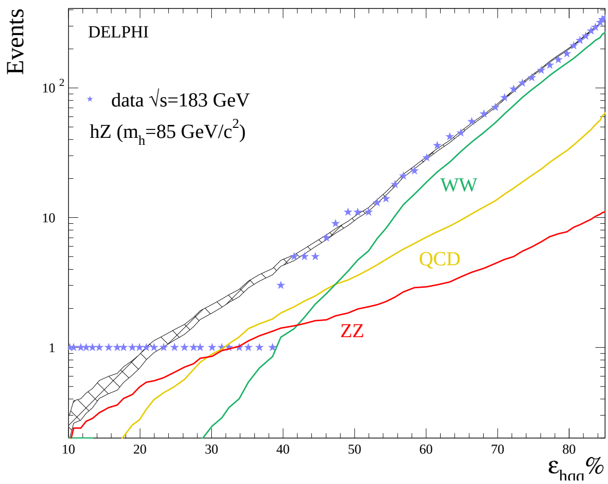

Fig. 22. Events kept versus efficiency, when the cuts get more severe, in a 4-jet analysis. Also shown are the expected backgrounds.

A candidate is shown in figure 23.

The mass limits expected and obtained at 95 % level by each of the LEP experiments from their data up to 183 GeV are, in GeV:

	expected	obtained
ALEPH	85.5	87.9
DELPHI	86.5	85.7
L3	85.0	87.6
OPAL	86.2	88.3

The limits obtained by combining the results of the four experiments (the ADLO Collaboration) with four different statistical methods to estimate the overall CLs are the following, in GeV:

	expected	obtained
Method A	90.0	90.1
Method B	89.9	90.1
Method C	90.4	89.8
Method D	90.5	90.1
Spread	± 0.3	± 0.15

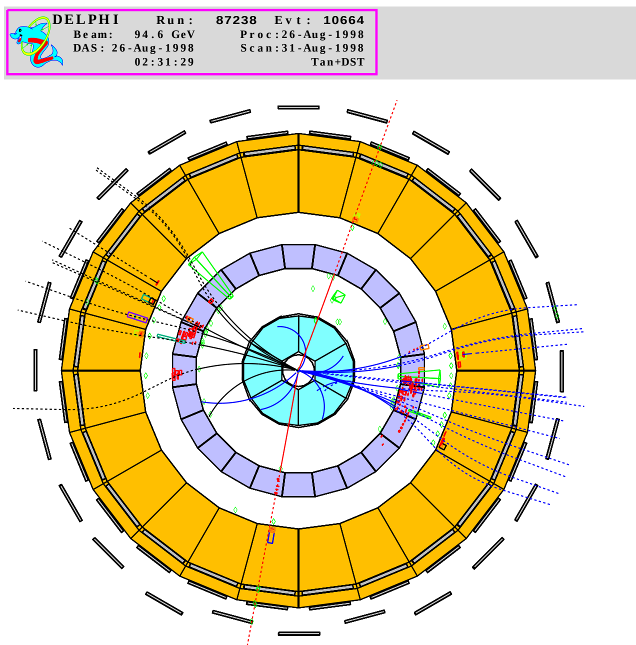

Fig. 23. A registered $Z^0\,Z^0$ event, with a boson decaying into two muons, the other into two quarks. The production of a $\sim$90 GeV Higgs boson would look the same, with two b-quarks. Such a Higgs boson has already been excluded, on a statistical basis.

The results of the different methods, both for expectation and for observation, are in fair agreement. The lowest of the four limits is presently the official exclusion limit of LEP: $M_h \geq 89.8$ GeV at 95 % CL, while 90.4 GeV was expected. Figure 24 shows the summed mass spectrum of the ADLO candidates, in agreement with the expected background and excluding clearly the presence of a 87 GeV Higgs boson. Figure 25 gives the limit on the SM Higgs mass obtained by method C (OPAL's statistical method).

The totality of the data taken at 189 GeV in 1998 has now been processed by each of the four collaborations. Figure 26 gives the Opal mass spectrum

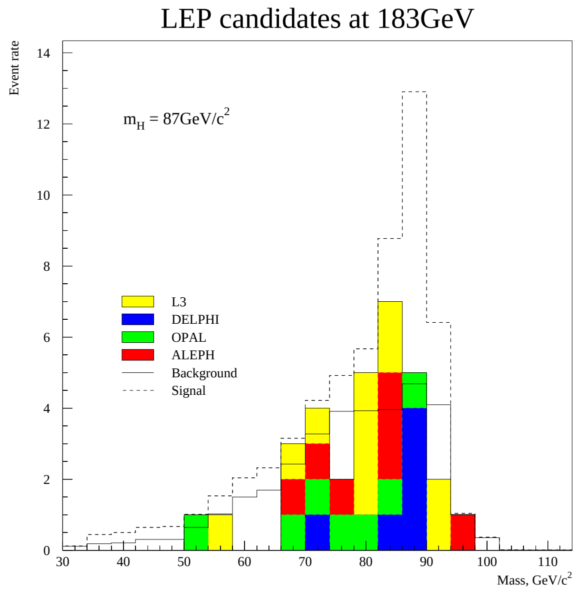

Fig. 24. LEP200 Higgs candidates at 183 GeV CM and the expected signal of a 87 GeV Higgs boson

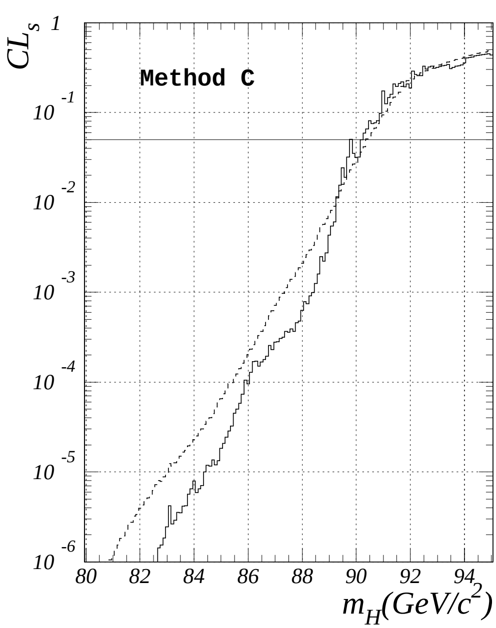

Fig. 25. Limit on the SM Higgs mass of ADLO (OPAL method)

and mass limit. No attempt to combine the results has been done yet. The very preliminary limits of each experiment are in GeV:

	expected	obtained
ALEPH	95.7	90.2
DELPHI	94.8	95.2
L3	94.4	95.2
OPAL	94.9	91.0

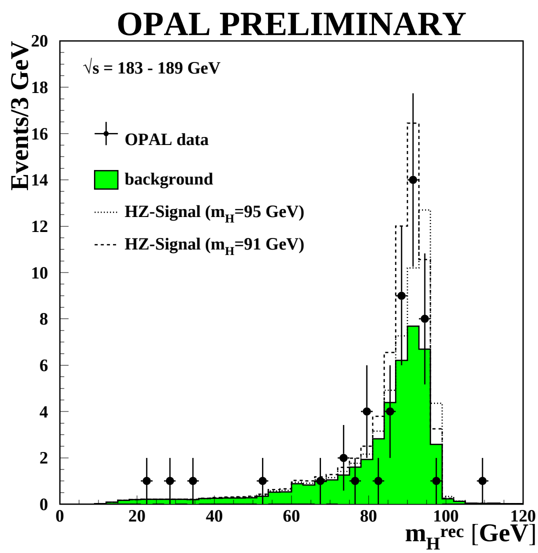

Fig. 26. Preliminary spectrum from OPAL at 189 GeV

6.4. SUSY Higgses at LEP [26]

In the case of SUSY Higgses, one has to combine the results obtained for the two production channels previously described. The analysis has been performed in the frame of two Higgs doublet models [27], as well as in the MSSM scenario. For the latter, results are expressed as exclusion contours in the plane of the two main variables chosen: $\tan\beta$-M_A, or $\tan\beta$-M_h, or M_h-M_A.

The question is then to decide what to do with the other parameters which intervene, at loop level, in the Higgs sector. The usual way, called the "benchmark" scan, is to choose them in order to ensure a given level of stop mixing, with minimal, typical or maximal effect on the exclusion region. The corresponding results of the ADLO collaboration, for their data up to

183 GeV, are shown in figure 27 and 28. The figures show the theoretically excluded regions, for the two extreme cases of mixing, as well as the expected and observed experimental exclusion contours from the combination of the four experiments up to 183 GeV. One sees that, in the case of no mixing, a domain of low values of $\tan\beta$ (between 0.8 and 2.1) is already excluded. For $\tan\beta$=1, one recovers the results of the SM Higgs search. For $\tan\beta \geq 0.8$ LEP excludes M_h below 77 GeV, M_A below 78 GeV.

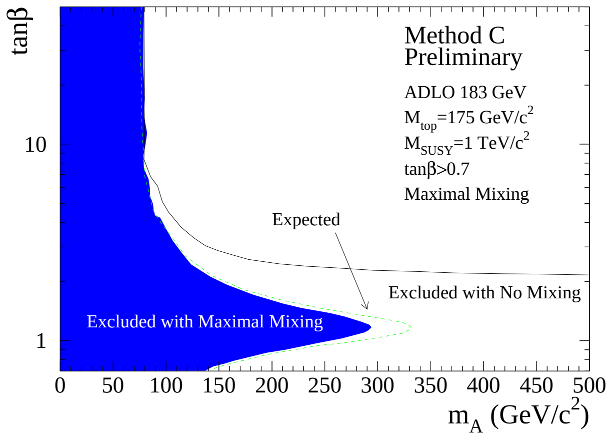

Fig. 27. The benchmark results in the plane $\tan\beta - M_A$

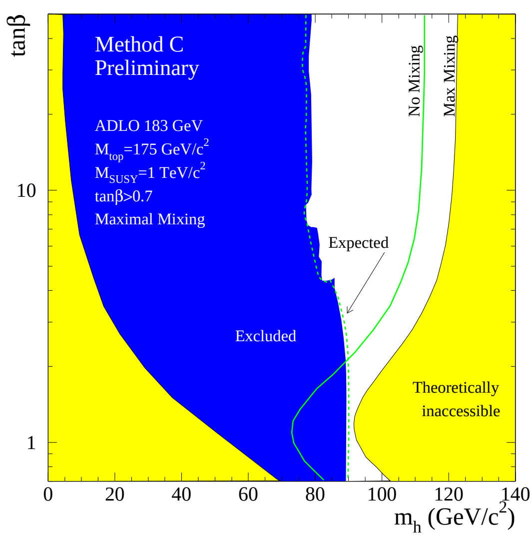

Fig. 28. The benchmark results in the plane $\tan\beta - M_h$

The region below $\tan\beta = 0.8$ is a difficult one. Close to the M_h lower bound, M_A is small, possibly below the $b\bar{b}$ threshold, and the decay $h \to AA$ is open. LEP200 has not fully covered this scenario. One can however get there the help of Tevatron H^+ searches, with the caveat we will mention in 6.6.

From data including the 189 GeV ones, preliminary limits of the individual experiments (figure 29), at 95 % CL, are, in GeV:

	M_h	M_A
ALEPH $\tan\beta \geq 1$	80.8	81.2
DELPHI $\tan\beta \geq 0.5$	83.5	84.5
L3 $\tan\beta \geq 1$	77	78
OPAL $\tan\beta \geq 1$	74.8	76.5

One sees again the fast improvement with CM energy.

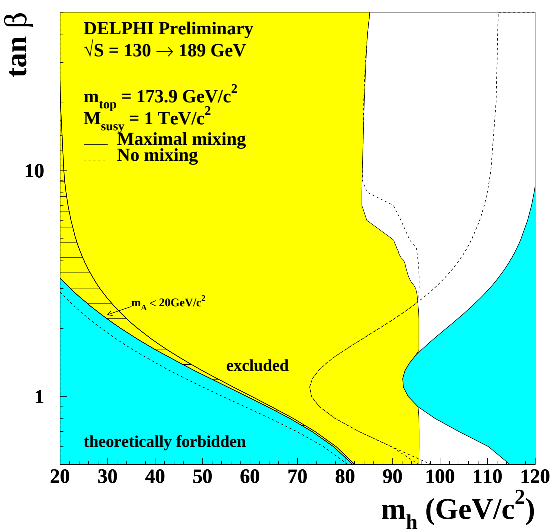

Fig. 29. Delphi MSSM exclusion plot at 189 GeV

One would like, however, to check whether a more general scan of the parameters under consideration can reveal "weak" points, for which the limit on Higgs masses is reduced, and, in such an occurence, to understand the reasons for this weakening. This approach, started by Opal, has been developped by A, D, O. Aleph [28] in particular has performed a thorough scan of the parameter space ($M_A, \tan\beta, m_0, m_{1/2}, \mu, A, \ldots$) with more than 30 million sets. They impose 10 conditions, theoretical and mostly experimental, the most effective ones beeing obviously their negative searches for Higgses at LEP200. They find that 10^{-4} of the sets for low $\tan\beta$, 10^{-3} of them for large $\tan\beta$, lead to a reduced limit. The reasons are understood: generally a small $\sin(\beta-\alpha)$, reducing the Higgsstrahlung cross-section, combined to a large M_A, compromising the associated production. Moreover the diagnostic is that, by implementing a few more legitimate conditions, either theoretical (no charge nor color breaking, ...) or experimental (impact of EW measurements, of rare decays, foreseable increase in luminosity, ...) these pathological cases can be still reduced and possibly eliminated. One can thus say that LEP limits are quite robust.

6.5. Prospective

Figure 30 [29] shows the discovery limits one can expect, as a function of the integrated luminosity per experiment, by combining their results, for several CM energies, from 189 GeV, the present one, to 200 GeV which represents what one can ultimately hope for with the number of RF cavities available and provided their mean accelerating field can be raised from the design value of 6 MV/m to about 6.8 MV/m. With 200 pb^{-1} per experiment at 200 GeV, one can discover a SM-like boson up to 107 GeV, exclude it up to 109 GeV. About 8 percent more CM energy, corresponding to 1.36 times

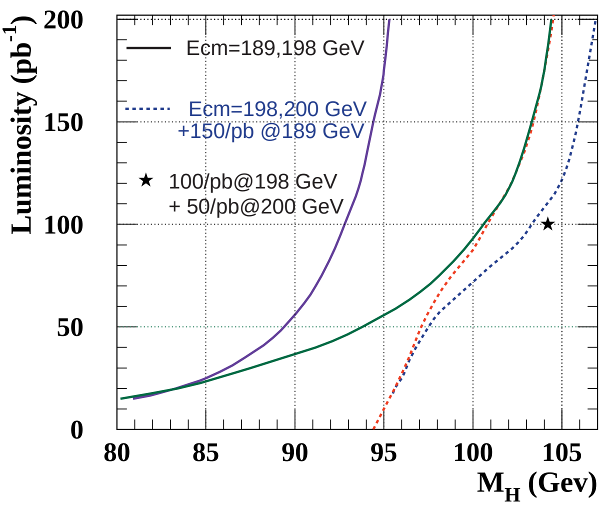

Fig. 30. The prospective for SM Higgs boson discovery at LEP200 [29]

more cavities, would have been needed to exclude a SM like Higgs boson up to ~ 125 GeV.

Should one be despaired by the non observation of a higgs boson below 90 GeV? Probably not. Figure 31 by Barbieri and Strumia [30] shows the level of naturalness, a quantity easy to define but of a somewhat subjective interpretation, in the MSSM scenario as a function of the h^0 mass. This figure seems to indicate that the best is still to come, unfortunately in a region difficult for all machines.

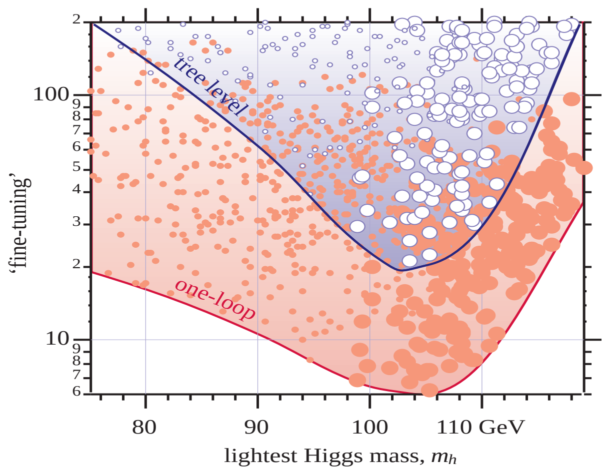

Fig. 31. The required level of fine-tuning as a function of the Higgs mass [30].

6.6. Other Higgs searches at LEP [31]

The h^0 boson could decay invisibly, either to a pair of $\tilde{\chi}_1^0$ LSP neutralinos, or to a pair of majorons, the Goldstone boson associated to a spontaneous breaking of R-parity. This possibility has been investigated by the four LEP experiments. From 183 GeV data, their results on the mass limit of an invisible Higgs boson produced with a SM like cross section are:

	$M_{H_{\rm inv}}$
ALEPH	80 GeV
DELPHI	85 GeV (updated with part of 189 GeV data)
L3	83.6 GeV
OPAL	81 GeV

Delphi has also obtained a mass limit of 82.1 GeV for a boson which decays either invisibly, or visibly into SM like channels, and has interpreted this result in terms of a Majoron model [32].

The preliminary mass limits extracted from 189 GeV data are: 92.8 GeV from Aleph for an invisible Higgs boson and 90.2 GeV from Delphi (figure 32) for a Higgs boson with an arbitrary fraction of invisible decay.

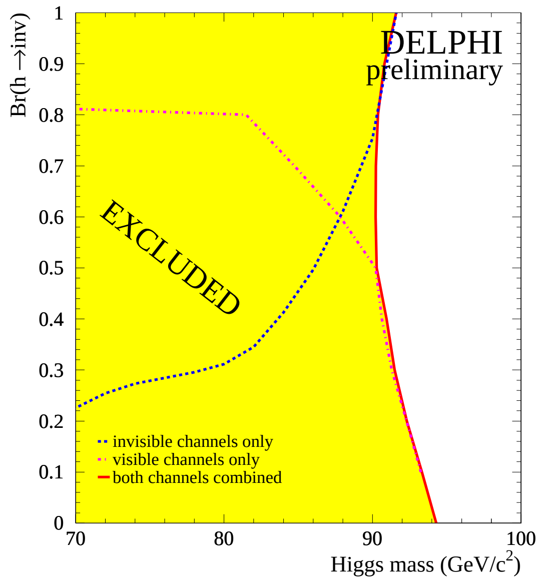

Fig. 32. Delphi invisible Higgs: combined limit at 189 GeV.

Charged Higgs bosons in the MSSM should be heavier than M_W. In a non minimal model with a singlet it is however possible to obtain lighter $H^{\pm}$ [33]. Their pair production has been looked for by the LEP collaborations in the modes $c\bar{s}$ and $\tau\nu$, assumed to saturate its decay. One has therefore three decay channels: all leptonic, all hadronic and mixed, as indicated in figure 33. The mass limits obtained from the 183 GeV data are:

ALEPH	59 GeV
DELPHI	56.6 GeV
L3	57.5 GeV
OPAL	59 GeV

Their combination leads to a limit of 69–70 GeV depending on the method.

From 189 GeV data the preliminary limits are 62.5 GeV from Aleph, 65.1 GeV from Delphi, 67.5 GeV from L3 and 68.7 GeV from Opal (figure 33).

LEP limits will probably never cross nor even reach the value of the W mass. We recall the Tevatron analyses [34] searching for charged Higgses

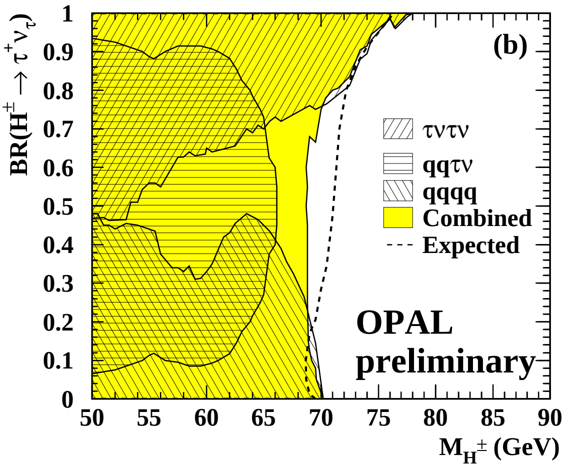

Fig. 33. Limit set by Opal on the charged Higgs mass from 189 GeV data.

in the top decay, when it is supposed to occur, namely at very small and high $\tan\beta$. There is however nothing new in this respect. Furthermore some aspects of these analyses seem to be under question [35].

7. Searches for SUSY particles

7.1. The SUGRA scheme [36]

Once the MSSM parameters are fixed at high scale, renormalization group equations (RGE) allow to follow their evolution, as well as the one of coupling constants and masses, down to the EW scale. In mSUGRA one expects the following characteristics:

a) with the high top mass, EWSB occurs automatically

b) sleptons, whose mass is essentially governed by m_0, may be light, the partner of the right-handed (RH) fermion being the lighter. Electrons machines are ideal to search for them. Figure 34 gives the ADLO limit for the stau, as an example. The ADLO limits are presently: 85 GeV for selectrons, 71 GeV for smuons, 72 GeV for staus, obtained from the combination of 183 GeV data. Here again, because of the accumulation of data at higher energy, they will rapidly be superseeded. For instance, Aleph, from the 189 GeV data, excludes smuons up to 80 GeV(preliminary), for a mass difference larger than 10 GeV.

c) charginos, $\tilde{\chi}^{\pm}_{1,2}$, and neutralinos, $\tilde{\chi}^{0}_{1,2,3,4}$, are the mass eigenstates of 2 by 2 and 4 by 4 mass mixing matrices, respectively. The chargino sector depends on M_2, μ, $\tan\beta$ and the neutralino sector on M_1, M_2, μ, $\tan\beta$, while the gluino mass is given by M_3. The three M_i evolve as the α_i

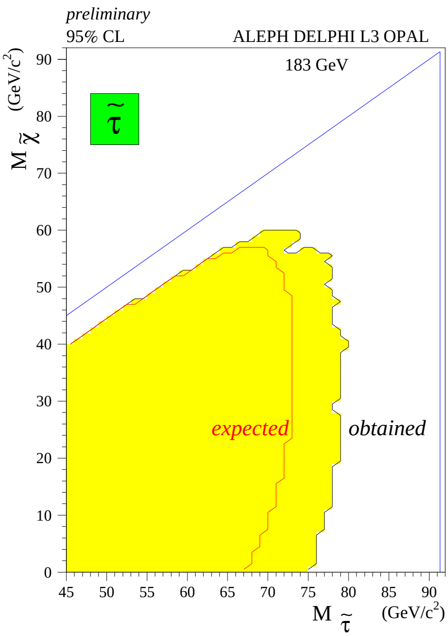

Fig. 34. Combined stau limit from ADLO

coupling constants, and this, in the case of a universal $m_{1/2}$, leads to the relation at the EW scale:

$$M_1/M_2/M_3 \sim 0.4/0.8/2.7$$

and to the mass hierarchy:

$$M_{\chi_1^0}/M_{\chi_2^0}, M_{\chi_1^\pm}/M_{\chi_2^\pm} \sim M_1/M_2/\mid\mu\mid .$$

The lightest neutralino is the LSP, gaugino-like when $\mid\mu\mid\gg M_2$. If, however, the gaugino mass universality is dropped, one may then have any kind of relation between the M_i. For instance a model [37], invented to provide a possible explanation for the CDF event, has M_1 about equal to M_2, a $\tilde{\chi}_1^0$ mostly higgsino, $\tilde{\chi}_2^0$ mostly gaugino, so that the cascade $\tilde{\chi}_2^0 \to \tilde{\chi}_1^0$ + photon dominates.

The nature of the $\tilde{\chi}_1^0$ LSP, as well as the existence of mass degeneracies between charginos and neutralinos, are of great importance for the cold dark matter problem.

Electron machines are well suited to study these particles and to set limits on their masses. These limits, for charginos, depend on their nature, gaugino, higgsino or mixed state, and on the mass difference ΔM between the chargino and the LSP. In general values close to the kinematic limit are reached, and one even goes beyond it when neutralino searches can help. See Ref. [36] for a complete review.

However when the $\tilde{\chi}_1^\pm$ is a gaugino and when m_0 is small and sneutrinos are light, the production amplitudes of γ/Z s-channel exchange and of sneutrino t-channel exchange interfere destructively and decay modes via slepton exchange appear: this leads to a reduced production rate and efficiency and to a lower mass limit.

For neutralinos the reaction:

$$e^+e^- \to \tilde{\chi}_1^0\tilde{\chi}_1^0$$

is of no use in the MSSM since the neutralino is invisible. Generally the production of higher masses neutralinos, like:

$$e^+e^- \to \tilde{\chi}_1^0\tilde{\chi}_2^0$$

and of charginos help setting limits. But in the case of small m_0 just described these limits are weakened. One must then look for help from charged lepton searches. In order to relate the charged slepton to the sneutrino sector one must also assume some degree of universality for m_0.

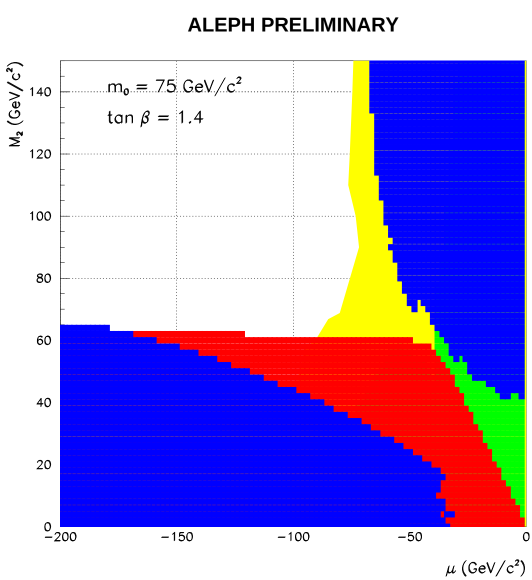

Fig. 35. The contributions of various searches to the exclusion in the $M_2 - \mu$ plane, see Ref. [36].

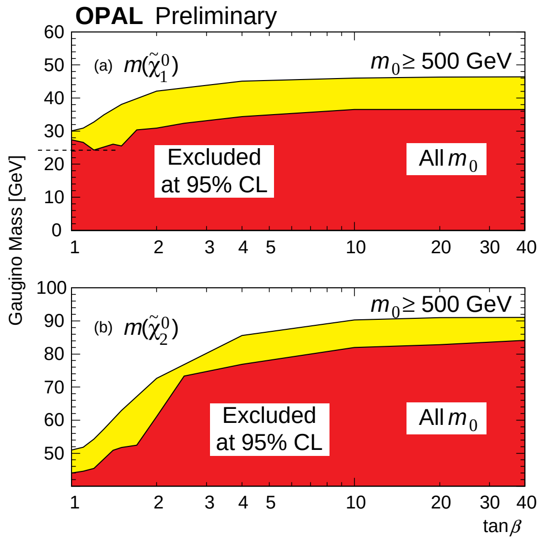

Fig. 36. Lower limit to the neutralino LSP mass, whatever be m_0, from OPAL.

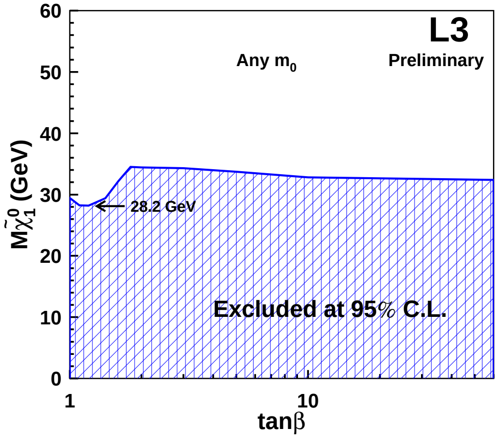

Fig. 37. Lower limit to the neutralino LSP mass, whatever be m_0, from L3

This most difficult situation is illustrated by figure 35, 36 and 37. From 183 GeV data, the lower mass limit (at 95% CL) of the LSP, whatever be m_0, are:

ALEPH	28 GeV(updated with part of 189 GeV data)
DELPHI	23.4 GeV
L3	25.9 GeV
OPAL	24.2 GeV

Preliminary values from 189 GeV data are 32.3 GeV from Aleph, 31.2 GeV from Delphi, 28.2 GeV from L3 and 27.9 GeV from Opal.

In the usual case LEP gives limits on charginos masses which approach the kinematic limit, as illustrated in figure 38, which gives Delphi preliminary results at 189 GeV.

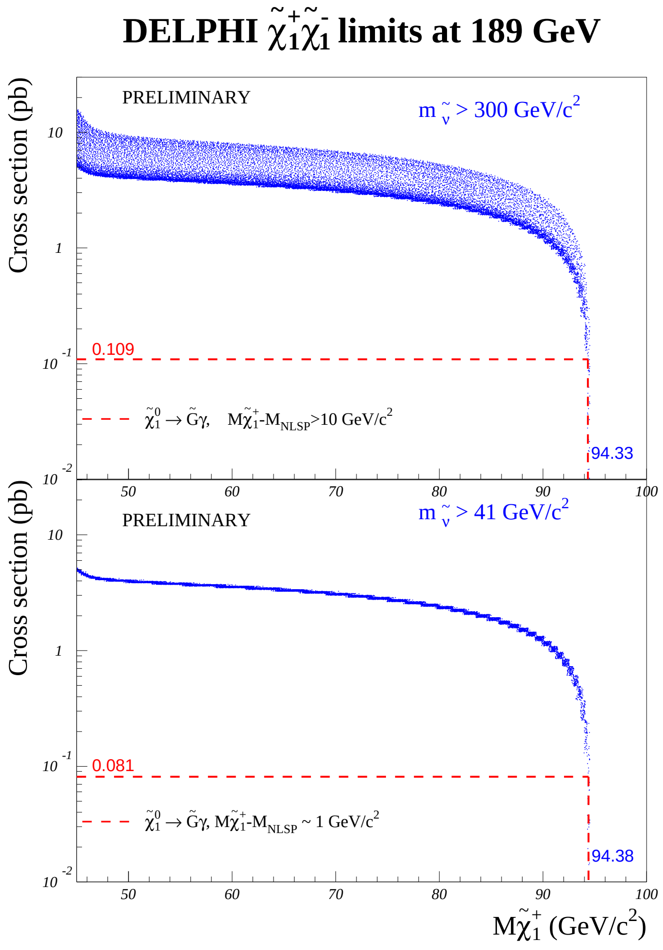

Fig. 38. Limits on charginos at 189 GeV set by Delphi

At the Tevatron searches for charginos and neutralinos proceed via the associated production:

$$p\overline{p} \rightarrow \tilde\chi_2^0\tilde\chi^{\pm} + X$$

with

$$\tilde\chi_2^0 \rightarrow \tilde\chi_1^0 l^+ l^- \quad \text{and} \quad \tilde\chi^+ \rightarrow \tilde\chi_1^0 l^+$$

leading to the very clean trilepton signature, which is an excellent discovery channel. However in case of a negative result, only very model-dependent mass limits can be set [38].

d) the Tevatron is the right machine to search for squarks and gluinos (figure 39). HERA also can, in a limited window of the parameter space, look for squark-gluino associated production [39].

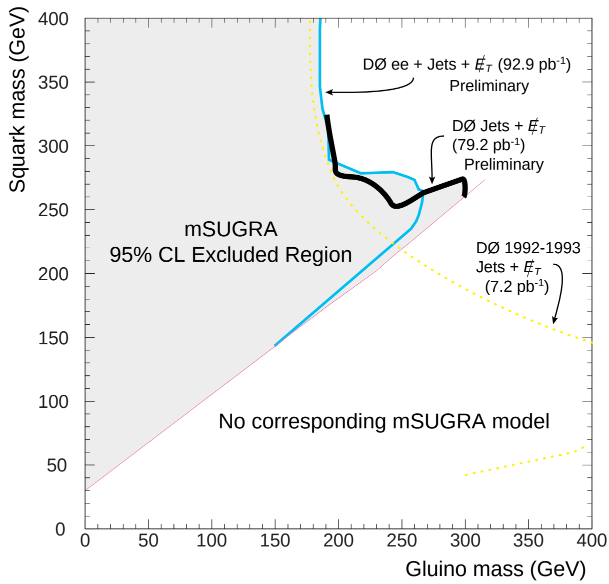

Fig. 39. D0 limit in the plane of squark versus gluino masses

e) in the sfermion sector a special role is played by the spartners of the third family, because of the potential existence of strong mixing effects. The lightest mass eigenstate, for instance of the stop, $\tilde{t}_1$, can be quite light and special searches at LEP and Tevatron were devoted to it. For the mass range under consideration, it is assumed that the decay $\tilde{t}_1 \to c + \tilde{\chi}_1^0$, although occuring at loop level, is dominant: this would however be invalidated if $\tilde{t}_1 \to b + \tilde{\chi}_1^+$ is kinematically accessible, for instance in the high mass region of the Tevatron exploration. The results are given in figures 40 and 41, showing the complementarity of the two machines.

Similarly ADLO has provided limits for the $\tilde{b}$ in the $\tilde{\chi}^0 + b$ mode, reaching 86 GeV in the case of no mixing.

An example of preliminary stop mass limit from 189 GeV data is 87.2 GeV from Opal, in the worst case of coupling.

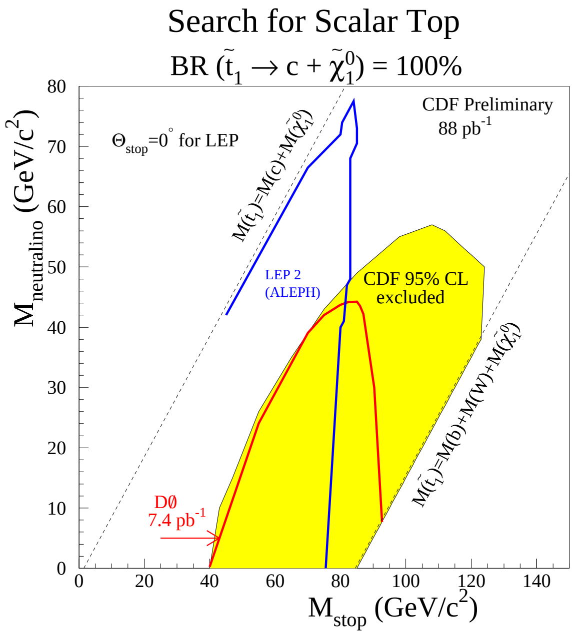

Fig. 40. CDF exclusion contour for the stop, as compared to LEP one

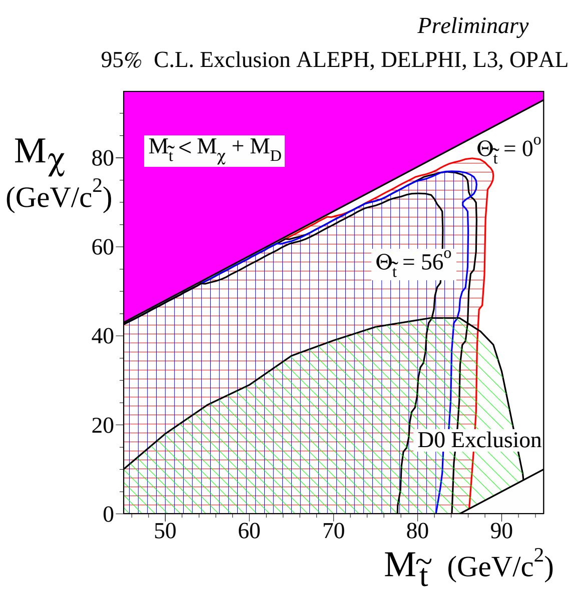

Fig. 41. The combined stop limit from the ADLO combination for data up to 183 GeV CM.

7.2. SUSY searches in the GMSB models

As explained in 5, the LSP of these models is the gravitino, $\tilde{G}$, whose mass may range from 10^{-6} eV to the keV domain.

This fact dominates their phenomenology. Its details depend now on the identity of the next-to LSP (NLSP) particle. The NLSP can be the lightest neutralino [40], decaying into $\gamma + \tilde{G}$: this scenario provides an alternative explanation to the CDF event. The NLSP can also be a slepton, most likely a stau [41]. Very important is the relation between the lifetime of the NLSP and the $\tilde{G}$ mass, or equivalently the scale $\sqrt{F}$ at which SUSY is broken in the hidden sector:

$$L(\text{in cm}) = 1.76\,10^{-3} \times \sqrt{(E^2/m_{\tilde{\tau}}^2) - 1} \times (m_{\tilde{\tau}}/100\text{GeV})^{-5} \times (m_{\tilde{G}}/1\text{eV})^2 .$$

A sufficiently high $\tilde{G}$ mass can lead to a long-lived NLSP, which can then manifest itself as a particle with offset, or decaying within the detector, or even as a heavy semi-stable particle leaving the detector before decaying.

For instance a neutralino NLSP decaying far enough from the vertex can lead to a non-pointing gamma: this has been looked for by Delphi and Aleph, in a systematic study of single and two-photon final states plus missing energy.

For a charged NLSP, slepton or more specifically stau, Aleph and Delphi performed a complete study of all possible manifestations of a long life-

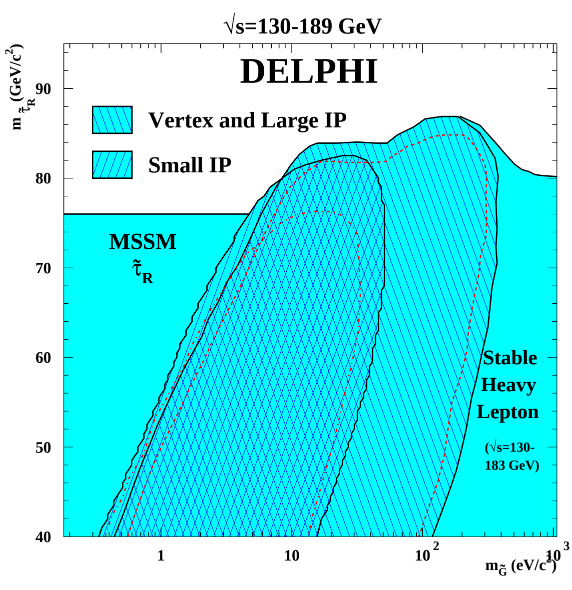

Fig. 42. The exclusion mass limit versus the $\tilde{G}$ mass for a long lived stau.

time, from prompt emission to an heavy stable charged particle, through the search for offsets, kinks, secondary vertices, ... (figure 42). Furthermore a systematic search for heavy stable particles has been performed by the LEP experiments, using dE/dx information (A,D,L3,O) or the RICH information (Delphi).

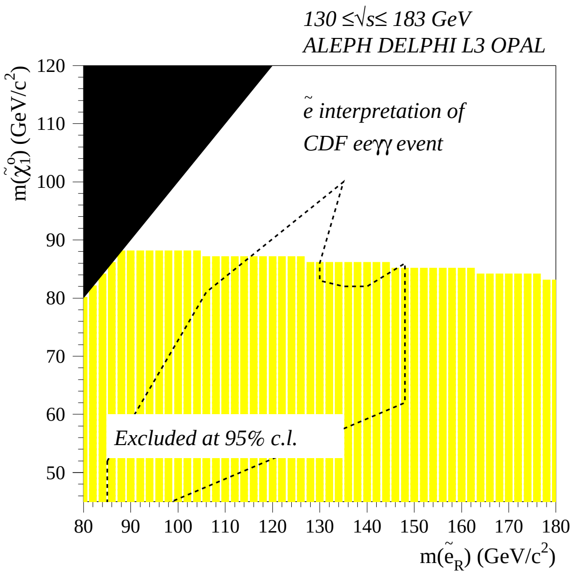

Fig. 43. In the GMSB interpretation of the CDF event (contour), the zone excluded by ADLO.

In the same case, pair production of $\tilde{\chi}_1^0$, now considered as the next-to-NLSP, NNLSP, can lead, through $\tilde{\chi}_1^0 \rightarrow \tau + \tilde{\tau}$, to a 4-tau final state, as explored by Delphi.

Several other searches, like the one for charginos, in the GMSB scenario, are actually greatly facilitated by the request of prompt gammas in the final state and lead to limits even better than in the SUGRA case.

The CDF event ($ee\gamma\gamma+\not{E}_T$) has been a strong incentive to promote the GMSB scenarios. It would then be interpreted as:

$$p\,\overline{p} \rightarrow \tilde{e}\tilde{\tilde{e}} + \mathrm{X}$$

where $\tilde{e} \rightarrow e+\tilde{\chi}_1^0$ and $\tilde{\chi}_1^0 \rightarrow \gamma+\tilde{G}$. Figure 43 shows the relevant region in the $\tilde{e}-\tilde{\chi}_1^0$ mass plane. If it were so, LEP, through neutralino pair production with $\tilde{e}-$exchange in the t$-$channel, should observe $\gamma\gamma+\not{E}$ final states. Figure 44, from ADLO, shows that the LEP gamma-gamma mass spectrum is well explained by standard sources and figure 43 that the domain of the CDF event, in the GMSB scenario, is nearly excluded by this negative result.

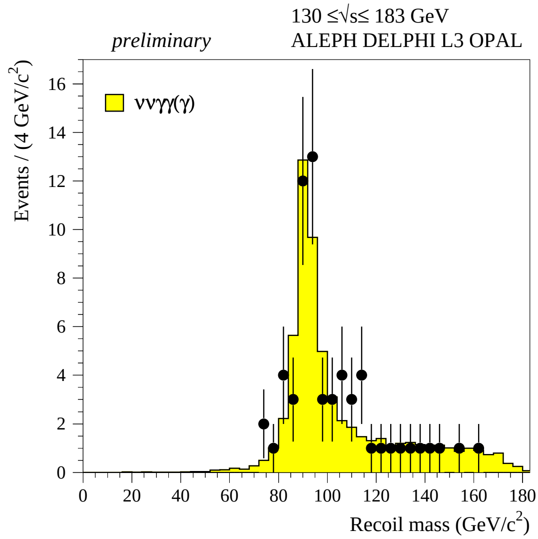

Fig. 44. The ADLO spectrum for the mass recoiling against two acoplanar photons.

7.3. A light gluino? [42]

It is well known that hadron colliders are unable to exclude the existence of a light (few GeV) gluino. Such an object would, at LEP, modify the running of α_s since it would intervene as an extra set of three fermionic degrees of freedom in the RGE. It would also modify the behaviour of the 4-jet final state. Several studies [43] claimed that there is no room in the data for such a light gluino. The relevance of these conclusions was however criticized in reference [42].

The author of [42] foresees that a light gluino will form a bound state with the gluon, the glueballino or $\tilde{R}^0$ hadron, long-lived and visible through its photino+hadron decay, or by its calorimetric interaction. The mass is predicted to be in the 1 to 3 GeV region,with a lifetime ranging between 10^{-5} to 10^{-10} s. Previous direct searches have looked for it, but were considered as still inconclusive, due to an unsufficient kinematical coverage. More recently both KTEV [44], looking at the supposedly dominant $\tilde{R}^0 \to \pi^+\pi^-\tilde{\gamma}$ decay mode, and NA48 [45], considering the decay into η+photino, whose branching ratio is more uncertain, have obtained negative results in a mass versus lifetime domain which now excludes nearly completely the model (figure 45).

However other incarnations of the light gluino scenario have appeared recently [46]. Some authors suggest that one may relate the $\tilde{R}^0$ to very high energy cosmic events. *A suivre* ...

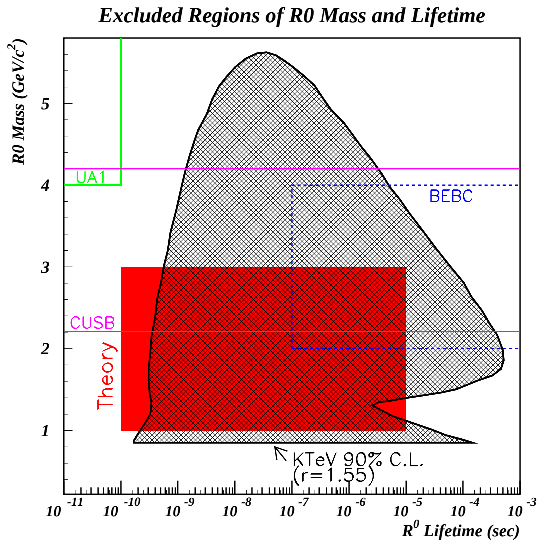

Fig. 45. KTeV exclusion of a light gluino

7.4. R-parity breaking [47]

We leave here the minimal version of SUSY which by definition was R-parity conserving. The possibility of its violation was certainly boosted by the former HERA anomaly; on the other hand there is no good reason to impose *a priori* its conservation.

$\not{R}$ is obtained by adding the Lagrangian:

$$L = \lambda_{ijk} L_i L_j \bar{E}_k + \lambda^{'}_{ijk} L_i Q_j \bar{D}_k + \lambda^{''}_{ijk} \bar{U}_i \bar{D}_j \bar{D}_k + \mu_i L_i H \,.$$

The first three terms bring into the game 45 new Yukawa couplings λ_{ijk}. The indices represent generations, the letters supermultiplets, doublets or singlets of $\mathrm{SU(2)_L}$. Among the trio of particles involved, one is a superpartner, and the choice of helicities clearly matters. $\lambda^{'}$ and $\lambda^{''}$ cannot be both simultaneously present, otherwise the proton would decay too fast. One assumes — but without any good reason either — that one of the couplings dominates all others. Low energy measurements provide upper limits on the λ_{ijk} which can be very strong, for instance on λ_{133} from the ν_e mass, or on $\lambda^{\prime}_{111}$ from neutrinoless double beta decay.

The last term brings in a special phenomenology and may turn out to be the most interesting, especially in relation with the problem of neutrino mass [48]. It has not yet however received the attention it deserves.

The newly introduced couplings allow for a large variety of possibilities. The LSP, say $\tilde{\chi}^0$, is now unstable, for instance decaying into three leptons and it is therefore visible. The various loopholes quoted previously in R-parity conserving scenarios disappear; on the other hand the golden signature of $\not{E}$ has gone as well. A crucial new fact is that sparticles can now be produced singly, for instance a sneutrino as an s-channel resonance in e^+e^- or a squark from e–q collision.

A $\not{R}$ decay is called direct if the sparticle goes directly into ordinary ones, indirect if it cascades to the LSP, by a R-conserving gauge interaction, the LSP decaying then via a $\not{R}$ mode.

In the physics analyses, one makes the assumption that sparticles are decaying quasi promptly: less than 1 cm of $c\tau$, so that particles appear to originate from the main vertex. This sets lower limits on the λ_{ijk} which are however well below the upper limits set by indirect measurements.

The variety of final states to be explored is extreme. Even the first new term in the Lagrangian involves jets, besides leptons, since cascading occurs. Actually most of the final states involving a combination of isolated charged leptons, neutrinos and jets are potentially interesting. R-parity breaking is thus an excellent motivation to push physicists to study all final states which, at a given machine, are accessible with enough purity and sensitivity: exactly what a search program should be ...

I will illustrate the main points with a few examples. Figure 46 gives the lower limit of the neutralino mass, whatever be m_0: as expected this limit is higher and more easily obtained than in the R-parity conserving case.

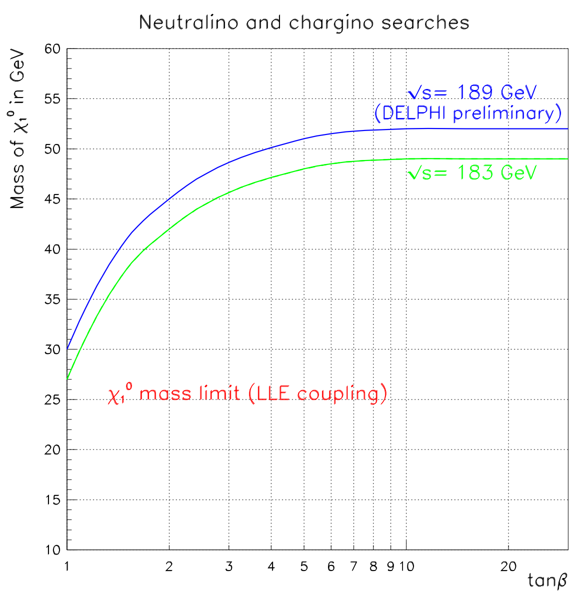

Fig. 46. Delphi mass limit for the lightest neutralino in a $\not{R}$ scenario

Figure 47 shows what one could expect from the s-channel production in e^+e^- of a sneutrino ($\tilde{\nu}_\tau$) decaying into $\mu^+\mu^-$ (couplings λ_{131} and λ_{232}, supposed to be equal) and the corresponding limit set on this coupling by LEP200 which extends beyond the indirect one from the limits on tau anomalous decays.

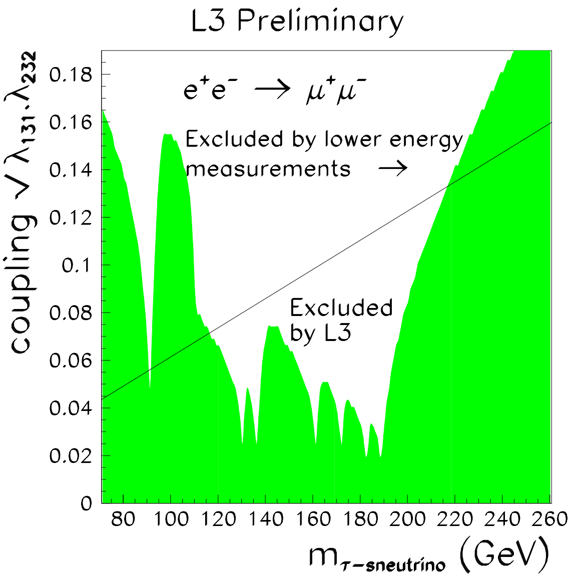

Fig. 47. From the search for s-channel $\tilde{\nu}_\tau$ or $\tilde{\nu}_\mu$ exchange, limits on the relevant coupling versus the sneutrino mass.

Figure 48 involving LQD couplings sets limits on slepton/sneutrinos masses through the study of a 4-jet final state.

HERA and the Tevatron are in the game as well. Hera, as announced, looks for the single production of squarks and sets limits on λ' couplings. For instance those on λ'_{3jk} from $\tilde{u}^j_L$ search are, locally, better than those from rare τ and B decays. The Tevatron sets limits on the mass of stops and squarks, supposed to be normally pair produced and then to have an indirect(through $\tilde{\chi}^0$) $\not{R}$ decay, which would lead to like-sign di-electrons plus jet.

Even if R-parity breaking studies are still in their infancy, the general conclusion, as drawn by G. Ganis in Vancouver, is already quite impressive: it states that for most of the relevant final states, even complicated ones, LEP — and in some cases HERA and the Tevatron — have the required sensitivity and purity to perform a meaningful measurement. The limits set are at least as good as in the normal case. In other terms, LEP results on SUSY will not be invalidated by the eventual occurence of $\not{R}$. Already,

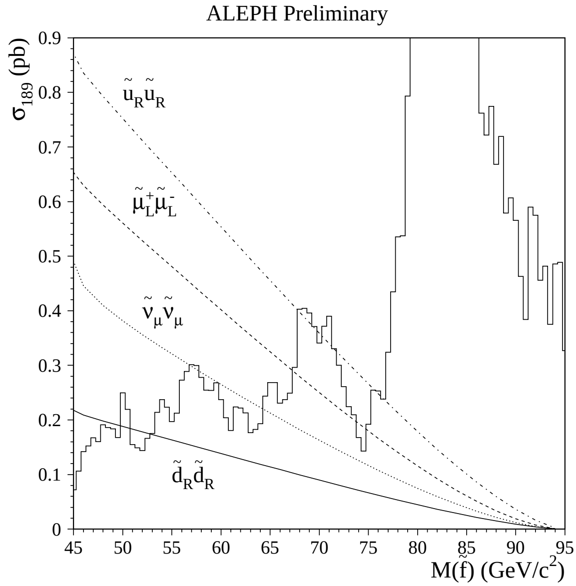

Fig. 48. LQD R parity breaking through 4-jet topologies: limits on slepton/sneutrino masses.

mostly due to the exploitation of possible single sparticle production, some limits on the couplings superseed the low energy ones.

8. New ideas

Among the alternative ideas which appeared recently [52], the possibility to extend space-time by introducing new large extra compact dimensions at the TeV scale (TeV gravity) is particularly attractive, in particular because it predicts a variety of new phenomena and modifications to the SM observables [53].

Gravity becoming strong at the TeV scale, a possibility which is not ruled out since direct tests of the gravity law below ∼1mm do not exist, the graviton starts playing a role in particle physics. Graviton radiation would lead to an excess of single photon events at electron colliders, of monojets at hadron colliders. Delphi, by the non-observation of extra single photons, could thus set an upper limit to the radius of extra-dimensions: in case there are two such dimensions, the limit is 0.4 mm [54]. But the phenomenology of SN1987A supernova may have already ruled out the case of two extra dimensions down to a micron or so.

From the study of fermion-antifermion and two-photon final state at LEP2, Opal was also able to set lower bounds in the range of 0.5 to 0.75 TeV, for the corresponding mass scale [54].

Since, in such models, the hierarchy problems are alleviated, one may be able to do without invoking SUSY. It may also be that the precision electroweak bound on the Higgs boson mass is removed in some range of the energy scale, reopening the possibility that this boson could behave in a non-standard way, or be heavy or even non existing [55]. Here again, *a suivre ...*

9. Conclusions

The number and variety of the searches presented in this review demonstrate the vitality of the field. While LEP2 brings most of the significant limits on new physics, all machines are in the game and have provided results of high quality. Besides the usual channels, whose study is motivated by the SM and familiar theories, a systematic exploration of a large set of final states has been achieved, either to cross-check some hints of possible deviations from the SM, or motivated by new ideas (R-parity breaking, ...). LEP physicists have adopted the very beneficial procedure of combining the results of the four experiments: for some channels the gain is substantial. This combination will be vital to reach the ultimate possibilities of LEP200 for Higgs searches.

Unfortunately there is no solid evidence for new physics up to now. On the other hand, the limits set, especially by LEP, start to be relevant and instructive in a predictive frame like the MSSM. No SM-like Higgs boson is observed up to $\sim$ 90 GeV, officially, and 95 GeV or so in a preliminary way from two individual experiments. MSSM ones are heavier than $\sim$ 80 GeV, and bounds seem to be robust. If this absence persists, scenarios like the Infrared Fixed Point one (or more generally small $\tan\beta$ ones) and possibilities like electroweak baryogenesis [50] will soon be in difficulty.

Under some relatively mild assumptions, LEP has also put a lower limit of $\sim$ 32 GeV on the neutralino LSP, a result which, as interpreted by [51], is close to "seal the fate of Higgsino Dark Matter".

HERA is starting running in e^-p and should accumulate $\sim$ 50pb^{-1} in 98–99, 1 fb^{-1} between 2000 and 2005. The Tevatron should resume data-taking in 2000 and register 2 fb^{-1} or so in Run II, and possibly ten times more if the TeV33 option is realized. LEP200, having accumulated $\sim$ 180 pb^{-1} per experiment last year at 189 GeV, will hopefully get 200 pb^{-1} per year per experiment close to 200 GeV until it closes in 2000.

Existing machines have still a large potential to exploit!

I congratulate the organizers of this meeting for the excellent atmosphere. I thank all those of my colleagues who provided me with information and explanations.

LEP2 physics is described in detail in the LEP2 Yellow Book, CERN 96-01. A large set of interesting reviews are those of the 1998 Vancouver ICHEP Conference, 22-29 july 1998. These give usually the “official” combined LEP2 results up to 183 GeV. The most recent updates available at the time of writing come from presentations at the LEPC (nov.98, march 99) and to Moriond 1999.

REFERENCES

[1] J. Erler, D.M. Pierce, *Nucl. Phys.* **B526**, 53 (1998) and hep-ph/9801238.

[2] K. Hagiwara *et al., Eur. Phys. J.*~~**C2**~~, 95 (1998) and hep-ph/9706331.

[3] C. Paus, private communication.

[4] C. Grosso-Pilcher, in Vancouver proceedings.

[5] E. Eichten *et al., Phys. Lett.* **B405**, 305 (1997) and hep-ph/9704445.

[6] C.T. Hill, *Phys. Lett.* **B345**, 483 (1995); K. Lane, *Phys. Rev.* **D54**, 2204 (1996).

[7] M. Pieri, L. Stanco, in Vancouver proceedings.

[8] R. Teuscher, C. Diaconu, *ibid.*

[9] C. Grosso-Pilcher, *ibid.*

[10] E. Gallo, *ibid.*

[11] W. Buchmuller *et al., Phys. Lett.* **B191**, 442 (1987).

[12] G. Valencia, S. Willenbrock, *Phys. Rev.* **D50**, 6843 (1994).

[13] Zeus Collaboration, paper 754 submitted to Vancouver Conference.

[14] D0 Collaboration, paper 594 submitted to Vancouver Conference.

[15] H.E. Haber, Supersymmetry (Theory), in Particle Data Group,1998 edition.

[16] J.A. Casas *et al., Nucl. Phys.* **B526**, 3 (1998) and hep-ph/9801365.

[17] G.F. Guidice, R. Rattazzi, CERN-TH/97-380.

[18] T. Hambye, K. Riesselmann, DESY-97-152 and hep-ph/9708416.

[19] M. Carena *et al., Phys. Lett.* **B355**, 209 (1995) and hep-ph/9504316.

[20] M. Masip *et al., Phys. Rev.* **D57**, 5340 (1998) and hep-ph/9801437; A. Pilaftsis, C. Wagner, hep-ph/9902371.

[21] J. Valls, in Vancouver proceedings.

[22] J. Womersley, FERMILAB-Conf-98/079 and references thereof J. Conway, in Tevatron Run 2 SUSY/Higgs Workshop, nov. 1998.

[23] J. Valls, K. Desch, in Vancouver proceedings.

[24] C. Balazs *et al.*, FERMILAB-PUB-98/182-T and hep-ph/9807349.

[25] P. McNamara, in Vancouver proceedings.
[26] K. Desch, *ibid.*
[27] see for instance H.E. Haber, SCIPP 97/11 and hep-ph/9707213.
[28] ALEPH 98-039, CONF 98-018.
[29] E. Gross *et al.*, CERN-EP/98-094.
[30] R. Barbieri, A. Strumia, *Phys. Lett.* **B433**, 63 (1998) and hep-ph/9801353.
[31] J. Valls, K. Desch, in Vancouver proceedings.
[32] F. de Campos *et al.*, *Phys. Rev.* **D55**, 1316 (1997).
[33] M. Drees *et al., Phys. Lett.* **B433**, 346 (1998).
[34] see for instance B. Bevensee, in Proc. of the 33rd Rencontres de Moriond, QCD and High Energy Hadronic Interactions.
[35] F.M. Borzumati, A. Djouadi, ZU-TH 5/98,PM-98/1 and hep-ph/9806301.
[36] P.P. Rebecchi, in Vancouver proceedings.
[37] S. Ambrosanio *et al.*, PRD55, 1372 (1997).
[38] M. Carena et al., HEPEX-9802006, hep-ex/9802006.
[39] Z. Zhang, in Vancouver proceedings.
[40] M. Paterno, J. Fay, *ibid.*
[41] G. Wolf, *ibid.*
[42] G.R. Farrar, *Nucl. Phys. Proc. Suppl.* **62**, 485 (1998) and hep-ph/9710227.
[43] see Aleph Collaboration, CERN-PPE/97-002; F. Csikor, Z. Fodor, CERN-TH/96-323.
[44] A. Lath, in Vancouver proceedings.
[45] M.Velasco, *ibid.*
[46] S. Raby, K. Tobe, OHSTPY-HEP-T-98-012 and hep-ph/9807281.
[47] G. Ganis, H. Lee Sawyer, Zhiqing Zhang, in Vancouver proceedings.
[48] R. Hempfling, UCDPHY-96-36, hep-ph/9702412.
[49] M. Diaconu, in Vancouver proceedings.
[50] M. Carena *et al., Nucl. Phys.***B524**, 3 (1998) and hep-ph/9710401; J. Cline, G.D. Moore, McGill 98-11, hep-ph/9806354.
[51] J. Ellis *et al.*, CERN-TH/98-32, hep-ph/9801445.
[52] N. Arkadi-Hamed *et al., Phys. Lett.* **B249**, 263 (1998).
[53] E.A. Mirabelli *et al.*, SLAC-PUB-8002, hep-ph/9811337.
[54] Presentations in LEPC, march 99, by N. Kjaer and D. Glenzinski.
[55] L. Hall, C. Kolda, hep-ph/9904236, LBNL-43085.