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Search for Higgs Bosons in e^+e^- Colliders

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Introduction

In spite of theoretical and experimental outstanding achievements, particle physics has not been able to reach a conclusion on the simple question: from which mechanism does mass originate ? It is a common belief that such a mechanism will be characterized by the observation of at least a scalar particle. Whether this object is elementary (SM or MSSM scenario), composite (technicolor scenario) or too heavy to be observed as a particle (cf. M. Chanowitz'talk at this school) remains uncertain.

In this talk, I will discuss the first scenario and argue that a leptonic collider provides the best tool to study the properties of the Higgs boson(s). In the first chapter, I will recall the theoretical and experimental arguments in favour of this scenario and the predicted properties of the neutral Higgs boson within the SM scheme and its supersymmetric extensions (for a thorough discussion of the theoretical aspects, I refer the reader to the talk given by Z. Kunszt at this school).

In the second part of my talk, I will describe the strategy followed at LEP2 for the neutral Higgs boson searches, discuss the present results and future prospects.

In the third part, I will go through the future lepton colliders under study and give some examples of what could be achieved with such machines.

Theory

The SM scenario

In this scenario one simply assumes that there is a single scalar complex iso-doublet[1] Φ "which does everything":

- It gives masses to $W^{\pm}$ and Z bosons (and leaves the photon massless) through the Higgs mechanism. The masses are given in terms of the vacuum expectation of Φ, v, and of the gauge couplings. 3 components of Φ are "eaten" to create the longitudinal components of $W^{\pm}$ and Z, while the last degree of freedom left is identified to the Higgs boson.

- It generates the fermion masses (with the exception of neutrinos) through the Yukawa couplings. As a consequence, the Higgs boson couples to the fermions proportionally to their masses.

This scenario is clearly minimal in the sense that it implies a common source for all masses. Nature could clearly be less "economical" and use different fields for both purposes. As we shall see in describing the detectability of the Higgs boson through b-tagging, this would have serious consequences on the on-going experimental searches.

The scalar potential of Φ can be written:

$$V(\Phi) = \mu^2|\Phi|^2 + \lambda|\Phi|^4$$

The Higgs mechanism, i.e. V minimal for a non zero expectation value of Φ, requires a negative value for μ^2 (λ is the quartic dimensionless coupling which has to be positive for V to be bounded from below). The dynamical origin of this negative mass is not explicit in the SM.

The mass of the Higgs boson is simply given by $m_H^2=2\lambda v^2$ where v is the vacuum expectation of Φ simply related to the W boson mass. While λ is not explicitly known, it can be severely constrained if one assumes that the SM remains perturbative up to very high energy scales (Planck or unification). Typically one finds that $m_H <200$ GeV. The requirement of vacuum stability imposes a minimum value of about 140 GeV which can be relaxed if new physics appears at an energy scale well below the Planck scale[2].

Loop corrections to the mass term being u.v. divergent would give corrections of the order of the Planck scale. The SM alone assumption is therefore not acceptable (the hierarchy problem). One accordingly assumes that either new physics occurs before the TeV scale, as in technicolor[3] or SUSY, or one avoids the appearance of a light Higgs boson by postulating a strongly interacting sector related to electroweak symmetry breaking (e.g. the so-called BESS model[4]).

Another possibility, recently proposed in [5], is to assume that gravitation becomes a strong force at the TeV scale, therefore providing a natural u.v. cut-off to the theory.

As a final remark, one should emphasize the incompleteness of the theory in the fermion sector. There is a complete arbitrariness in the values given to the Yukawa coupling constants without mentioning the neutrino mass aspects which fall outside the SM framework.

Higgs mass from precision measurement

From previous discussions, it seems that we have no clear theoretical guidance on the existence of a light Higgs. Fortunately there is an indirect source of information relying on the precise measurements performed at LEP, SLC and FNAL. The SM allows to compute loop corrections[6] which can be measured precisely from various independent observations at LEP/SLC:

$$M_Z, \sigma_{f\bar{f}}, \Gamma_{f\bar{f}}, A^f_{FB}, A^e_{LR}, P_\tau, M_W, \sigma_{WW}$$

All quantities, at the tree level, are known in terms of the 3 most precise quantities:

$$M_Z, G_F \text{ and } \alpha.$$

The main correction comes from the running of α up to the Z mass and we will come back to this point shortly. The second main correction comes from loops involving the top quark and depends quadratically on the top mass. It can be computed precisely from the measurement of the top mass coming from FNAL so that one can separate the effect from the Higgs contribution. The loop effect has logarithmic dependence on the Higgs mass and therefore provides a rather imprecise determination of m_H. Nevertheless, with significant improvements on the experimental side (more precise results and internal consistency between the various measurements) and on the theoretical computations (h.o. terms well under control which means that the calculations are meaningful for Higgs masses up to 1 TeV[7]) one can safely give an upper limit on the Higgs mass in the SM[8]:

$$m_H < 280 \text{ GeV at } 95\% \text{ C.L.}$$

The corresponding central value is still rather imprecise:

$$m_H = 84^{+91}_{-51}\text{GeV}$$

The computation of this result relies on $\alpha(M_Z)$ which is known to $\pm 7 10^{-4}$ due to our poor knowledge of the e^+e^- hadronic cross-section. Using τ hadronic decays measurements plus some theoretical inputs,[9] has shown that this error can be reduced to $\pm 3 10^{-4}$. This improvement has the effect of consolidating the upper bound on m_H as shown in figure 1.

In conclusion, one can say that precision measurements put severe restrictions on the mass domain allowed for the Higgs boson within the SM but it is fair to add that this domain can be extended if new physics appears at finite mass scales (see e.g. [10]).

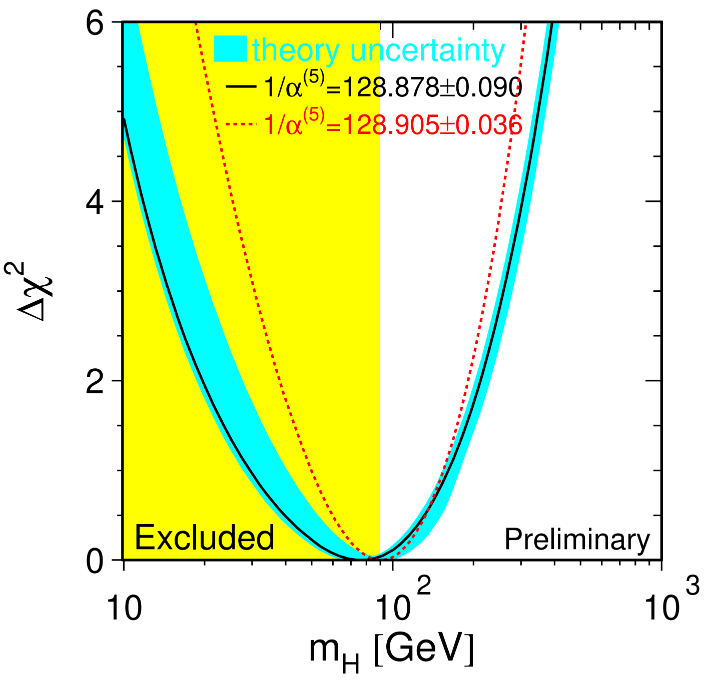

Figure 1: χ^2 distribution obtained from the precision measurements. The dotted curve corresponds to an improved estimate of $\alpha(M_Z)$.

The MSSM scenario

The minimal SUSY extension of the SM offers a viable solution to the hierarchy problem provided that the SUSY partners have masses in the TeV region or below. The theory therefore remains finite up to the Planck or GUT scale. A simple picture of the origin of the EWSB effect emerges: μ^2 starts from a positive value at the GUT scale and, under the influence of the top Yukawa constant, runs to a negative value at the EW scale. The λ coefficient, and therefore the Higgs mass is simply related to the gauge couplings.

The price to pay, in the Higgs sector, is the appearance of two Higgs doublets Φ_u and Φ_d which are required to provide the fermion mass terms. One can simply justify this by saying that a single Higgs boson model is not viable within SUSY since it would have a single fermion SUSY partner which would generate a triangle anomaly.

Five physical particles originate from this scheme: h and H the light and heavy CP even components (which are mixtures of Φ_u and Φ_d components with a free mixing angle called α), a CP odd component A, two charged components $H^{\pm}$. Two vacuum expectations occur which can be parametrized as v$\cos\beta$ and v$\sin\beta$, where β is an unknown angle.

Expected Higgs mass

Within MSSM

Two parameters are sufficient to describe the Higgs sector. For instance one has m_h^2=F(m_A,$\tan\beta$) $\rightarrow m_Z^2\cos^2 2\beta$ when $m_A \gg m_Z$.

Large loop corrections affect this simple scheme and occur mainly through the top/stop sector. One can simply write :

$$m_h^2 = m_Z^2 cos^2 2\beta + 3m_t^4/4\pi^2 v^2 ln(m_{\tilde{t_1}} m_{\tilde{t_2}}/m_t^2) + \tilde{A}_t^2 F(m_{\tilde{t_1}}, m_{\tilde{t_2}}, \tilde{A}_t)$$

where $m_{\tilde{t_1}}$ and $m_{\tilde{t_2}}$ are obtained by diagonalizing the stop mass matrix given by:

$$\begin{pmatrix} m_{\tilde{t_L}}^2 & m_t\tilde{A}_t \\ m_t\tilde{A}_t & m_{\tilde{t_R}}^2 \end{pmatrix}$$

where $\tilde{A}_t$ is called the mixing parameter.

The second term in the expression giving m_h^2 clearly shows the strong influence of the top mass in these loop corrections.

In this framework, the upper bound on the Higgs mass, initially m_Z, can reach up to 125 GeV when $\tan\beta$ is large (i.e. when the 1st term is maximum).

The following question naturally arises: what is the most likely value for m_h ?

The answer can be given with an assumption on the GUT behaviour of the top Yukawa coupling Y_t. If this value is not too small (here I assume $\tan\beta$ <10 such that one can neglect the bottom Yukawa term Y_b), one observes an infrared fixed point(IRFP) behaviour: whatever the value of Y_t at GUT, Y_t converges to the same value at the EW scale.

This gives the following relation: m_t=200$\sin\beta$ GeV, from which one derives $\tan\beta \sim$1.6 and therefore m_h <105 GeV[11]. This upper bound is a safe approximation: it includes, for instance, the uncertainty on the calculation due to the present error on the top mass. There are however objections to this scenario. Firstly, Y_t can be small at GUT without creating any problem to the theory. Secondly, there is an other IRFP solution $\tan\beta \sim m_t/m_b$, where m_b is the bottom quark mass. This solution tends to create several problems among which a large amount of fine-tuning to generate EWSB. This effect can be precisely quantified in the following way: given a parameter m from SUSY, fine-tuning is defined as Δ=(dm_Z^2/m_Z^2)/(dm^2/m^2). Recently [12] have argued that, taking into account one loop corrections, fine-tuning is small for a large range of m_h values. It is minimal for m_h=105 GeV and grows fast above 115 GeV when $\tan\beta$ becomes larger than 10.

Beyond MSSM

Since the prediction of a light Higgs boson seems to be an unavoidable consequence of the SUSY scheme and, as we will argue later, since this prediction can be tested either with LEP or with future machines, one may ask how model dependent is the 125 GeV upper limit obtained within MSSM.

Beyond the MSSM scheme there is the possibility to introduce an iso-singlet S which would have no effect on precision measurements but could help in solving the "μ problem". In the SUSY superpotential one needs a mixing term of the type $\mu\Phi_u\Phi_d$ where μ is a mass parameter of the order of the EW scale which is "put by hand". This arbitrariness can be reduced by replacing the previous term by $\lambda_1 S\Phi_u\Phi_d$, and assuming that S acquires a vacuum expectation which generates μ. This term can modify the quartic coupling by $\Delta\lambda=\lambda_1^2\sin^2 2\beta$

and therefore the resulting Higgs mass. If one requires that the theory remains perturbative up to the GUT scale, one can also set a bound on λ_1 and therefore on m$_h$. This bound increases if one assumes that new physics sets in before GUT. Introducing also an iso-triplet field which can couple to the $\Phi_u \Phi_d$ term, the authors of [13] achieve an upper bound of 205 GeV.

Cosmology

MSSM has the necessary ingredients to produce the right baryon asymmetry in the universe through electroweak baryogenesis. This scenario, not unique, requires a Higgs boson lighter than 100 GeV (see [14] and references therein).

To summarize one has:

- m$_h$ <280 GeV from precision measurement
- m$_h$ <205 GeV from SUSY + new physics before GUT
- m$_h$ <200 GeV from SM with no new physics before GUT
- m$_h$ <125 GeV from MSSM

This bound can still be decreased by requesting limited fine-tuning and/or an IRFP solution (see [15] for a more detailed discussion).

Higgs production in e$^+$e$^-$ colliders

In SM, production occurs through the Higgsstrahlung process where a virtual Z* emits a Higgs boson and becomes real[1]. This process has a cross-section of a few 0.1 pb provided that $\sqrt{s} > m_H + m_Z$. There is a sharp energy threshold for Higgs production in e$^+$e$^-$ colliders and one cannot compensate a lack of energy by increasing luminosity as in a hadron collider.

This statement is however partially true since the fusion mechanism, in which two virtual W (or Z) are radiated by the incoming leptons and "fuse" into an H, has no sharp threshold. It turns out however that this process gives very low cross-sections at LEP2 and only becomes predominant when $\sqrt{s} \gg m_H + m_Z$.

Other mechanisms, which proceed through loops, like Z→Hγ[16] or Z→Hgg [17], give negligible contributions unless enhanced by anomalous couplings [18].

In MSSM, one has $\sigma_{hZ} = \sigma_{SM}\sin^2(\alpha - \beta)$. When this process is extinct due to mixing, a complementary channel, Z→hA, can be used with $\sigma_{hA} = 0.5\sigma_{Z^* \to \nu\bar{\nu}}\cos^2(\alpha - \beta)\Lambda^{3/2}$, where Λ is a phase-space factor. This process is relevant when m$_h$ ∼m$_A$.

In MSSM one can also produce H either through the Higgsstrahlung process ($\cos^2(\alpha - \beta)$ dependence) or into HA ($\sin^2(\alpha - \beta)$ dependence).

Higgs Decays

In SM, H decays predominantly into bottom quarks when m$_H$ < 130 GeV. Above this mass, couplings to W and Z pairs become dominant.

In MSSM this is also true unless h→2A becomes kinematically accessible (and usually dominant). This possibility, disfavoured in usual SUSY schemes which tend to prefer a heavy A, requires very specific searches. When m$_A$ >10GeV, A decays into open beauty and the final state can easily be identified through b-tagging techniques.

A light Higgs boson can decay into gluons (few per cent level) or photons (per mill level) through loops. SUSY contribution, mostly from the top squark sector, can affect significantly these modes which are therefore interesting but not measurable at LEP2. A light "fermiophobic" Higgs boson, i.e. without Yukawa couplings, would only decay into photons through a W loop and therefore be detectable at LEP2.

As pointed out in the introduction, there is no overwhelming reason to believe that light Higgs bosons necessarily decay into bottom quarks. Even assuming a scenario where fermion masses come from Higgs Yukawa coupling, the bottom quark coupling in a two-doublet scheme goes like sinα/cosβ and can therefore vanish (α=0). An alternate scenario, explained in [16], is to assume two-doublets with only one of them coupling to fermions. This scheme, which falls outside of MSSM, is consistent with FCNC constraints and can lead to different decay patterns for h and A.

A Higgs boson may also decay invisibly. In the SUSY scenario it can go into neutralino, gravitino or sneutrino[19]. In models with lepton number violation it could decay into majorons[20]. The Higgsstrahlung process, in which the Z can be used as a tag, gives an excellent tool to identify these modes.

In conclusion, Higgs searches should be open minded and take full advantage of the clean experimental environment offered by lepton colliders.

Searches at LEP2

Machine parameters

In a circular machine with a radius R, synchrotron radiation energy losses grow like γ^4/R^2. Since it is impractical to increase further R, LEP can therefore be seen as the last high energy circular collider. At 100 GeV, electrons loose 3GeV/turn which, for an RF gradient of 6MV/m, requires an accelerating length of about 500 m. With a current of 2x4 mA, one has to provide 24MW to the beam, and therefore draw about 10 times more AC power with warm cavities. This figure justifies the major technological effort invested by CERN in building supraconductive cavities. 272 copper cavities with thin niobium film have been produced by european industries under the supervision of CERN. This represents a major technical challenge: e.g. these cavities correspond to 2000 m^2 of Nb film without any defect at the mm^2 scale.

A center of mass energy of 189 GeV has already been reached in 1998 and the plan is to reach 200 GeV in 1999 by raising the average field value to 7 MV/m. Extra cooling power will also be needed which will require an important upgrade of the cryo-plants during the 1998-1999 shut-down.

The maximum luminosity is now reaching $10^{32} cm^{-2} sec^{-1}$. In practice the relevant figure is the integrated luminosity which, taking into account the efficiency of the machine and the effective life-time of the beams, is roughly equal to the maximum luminosity multiplied by the elapsed time and divided by $\sim 2\pi$. This figure is not unusual with colliders and one should bear this in mind when estimating the physics potential of a given machine. In 1997 about 60 pb^{-1} were collected in each experiment and this figure will increase to about 150 pb^{-1} in 1998.

Taking into account that LEP2 will also run during year 2000, one may reasonably expect that each experiment will accumulate a luminosity of 200 pb^{-1} at a center of mass energy of 200 GeV.

Experimental Tools

Primordial backgrounds (figure 2) are W pair production, QCD four jet final states $q\bar{q}gg$ and ZZ. Assuming that the Higgs boson decays into $b\bar{b}$ allows to eliminate the first component(see figure 3) and suppresses the two others.

The $q\bar{q}$ component is dominated by radiative return to the Z resonance. This type of effect has a definite pattern and can be removed. The 4 jet final states ($q\bar{q}gg$) has a cross-section of a few pb before b-tagging.

If $m_H \sim m_Z$, as is the case in the range of LEP2, ZZ appears as an "incompressible background" since Z bosons decay into $b\bar{b}$ in about 17 % of the cases.

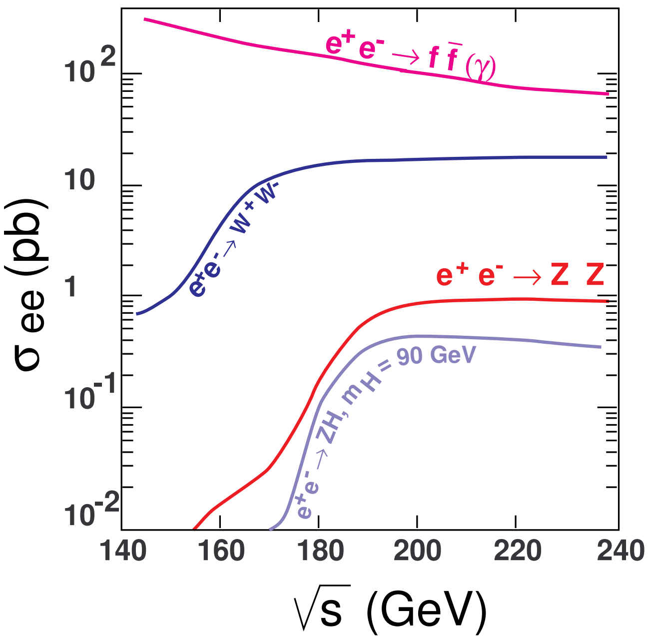

Figure 2: Relevant cross-sections for LEP2.

B-tagging relies on the measurement of several charged tracks not pointing to the main vertex. Charm decays can be well separated since they give a lower multiplicity. The detector resolution effect is directly measured using the sample of non pointing tracks which seem to originate from a particle decaying upstream of the main vertex. One then constructs a probability function which is uniformly distributed between 0 and 1 for light quarks. Bottom decays correspond to a very low probability. More involved methods have been developed which include the definition of secondary vertices, the mass of the particles at these vertices etc...[21]

A tremendous effort went into the tuning of this tagging method[22] with the motivation of measuring R_b, the b fraction of Z hadronic decays at LEP1. In view of LEP2, the Si detectors were improved with some emphasis on the solid angle coverage.

An illustration of the efficiency/rejection of the method is shown in figure 3.

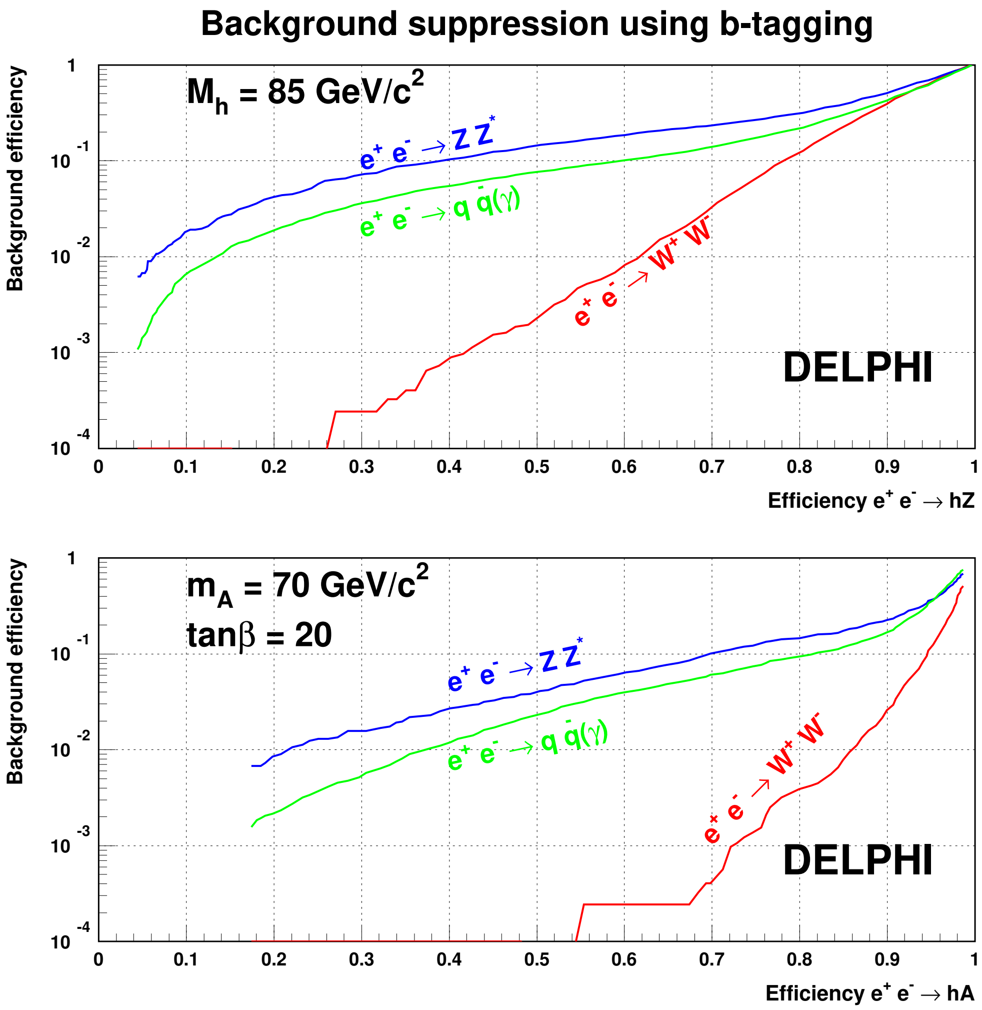

Figure 3: Background suppression versus efficiency: top curves are given for h(85GeV)Z, bottom curves for hA with $m_h \sim m_A \sim$70 GeV.

Results

The various analyses performed in the 4 LEP experiments include b-tagging plus some extra selections, mostly against QCD background (the two gluons emitted in 4 jet events tend to be soft and collinear to the quark jets). One can either build a global probability which integrates all selective variables or train a neural network to separate the Higgs signal from the SM processes. The key element of this procedure is a careful check of data/simulation agreement at the various levels. This requires a good tuning of the SM generators and of the detector response.

An important element of the procedure is an optimal choice of the cut on the selective variable(s), of the combination of the various channels (e.g. corresponding to the different Z decay modes) and, at the final stage, of the 4 experiments. This optimization procedure works automatically on the basis of simulation, avoiding any bias coming from the data.

Typical figures are given in table I.

Table 1: Typical results for LEP2 Higgs searches with 50 pb^{-1}

	Eff%	BR %	ZZ	QCD	WW	Signal
$H\nu\bar{\nu}$	30	20	0.2	0.2	0.1	1.25
$H\ell\ell$	60	7	1			0.7
HJJ	40	70	1.3	1.6	0.8	4

It is worth noticing that the figures quoted in this table are far better (∼twice more efficient in the case of the 4 jet channel) than anticipated during the workshop[23] preparing the LEP2 program.

Data taken in 1997 have been statistically combined through the Higgs Working Group. For the SM the final result is[24]:

$$m_H > \ 89.8 \ GeV \ at \ 95\% \ C.L.$$

No excess is observed in the number and the mass distribution of the candidates. The limit obtained is very close to expectation.

The gain obtained by combining the 4 experiments is +3 GeV with respect to the expected limit from individual experiments. Clearly one may obtain a similar limit on the basis of one "lucky" experiment, that is an experiment for which the background has fluctuated negatively yielding a better mass limit than expected. Although not obviously incorrect, this choice, frequently done, does not seem the safest.

The hA channel has been searched mainly in $b\bar{b}b\bar{b}$ final state for which the analysis is almost background free and has an efficiency above 50%.

Combining hZ and hA searches, one can try to exclude the MSSM scenario in terms of 2 parameters, e.g. m_h and tanβ. Loop corrections introduce additional parameters, like the squark top masses and the mixing parameter $\tilde{A}_t$. Following the recommendation of the LEP2 workshop[23], one usually assumes an average squark mass of 1 TeV and $\tilde{A}_t$ either small, "no mixing case", or such that it maximizes the loop corrections, "large mixing". As can be seen in figure 4 the effect of these hypotheses reflects in the definition of the limits of the domain of parameters allowed by the theory. One can notice that the present result eliminates the low tanβ region in the no mixing case which corresponds to the IRFP solution.

A more correct theoretical treatment[25], involving detailed scans of the SUSY parameters has been performed by the LEP collaborations with the conclusion that results do not change significantly except for very narrow windows of parameters.

Specific searches were carried out for the Higgs decaying invisibly with the conclusion that the mass limit on m_h is above 80 GeV[24]. The "fermiophobic" case, with h decaying into 2 photons, is also well treated [25]. The general two-doublet model, without assuming b decays, has weak limits [25].

One should recall the caveat about the influence of the h→2A scenario. For a given tanβ, the minimal value for m_h corresponds to m_A=0 and therefore to the lowest limit of the allowed m_h domain in figure 4 (e.g. for tanβ=1 and $m_h \sim$ 55 GeV). It seems fair to say that no dedicated effort has been devoted to prove that such a possibility is experimentally excluded. One may however argue that in supergravity and in the gauge mediated SUSY breaking schemes a light A is excluded [26]: m_A >115 GeV.

The limit on m_h is weaker at large tanβ. This effect is due to the hA channel. If one again assumes, as suggested by theory, that A is heavy, then the limit on m_h becomes independent of tanβ.

Prospects for the future

Assuming $\sqrt{s}$=200 GeV and 200 pb^{-1} per experiment, one can expect a discovery reach up to 107 GeV or an exclusion up to 109 GeV for the SM Higgs[27]. The MSSM coverage is shown in figure 5 for the maximal mixing case[28]. One can see that the IFRP scenario is well covered but, given the uncertainty on the top mass which can move the Higgs maximum mass by a few GeV, it is very important to collect more than 100 pb^{-1} per experiment.

Again, if one assumes that m_A is heavy, the limit on m_h will not depend on tanβ. For a complete coverage of MSSM, one would need $m_A > (m_h)_{max}$, a condition not yet reached in [26], but which could be reached by the time LEP2 is at its maximal energy. A full coverage of MSSM within supergravity therefore requires $\sqrt{s} \sim$215 GeV, a value tantalizingly close to the potential of LEP2. It would mean either reaching ∼9 MV/m or increasing by 30% the number of cavities. There are other limitations discussed in [29].

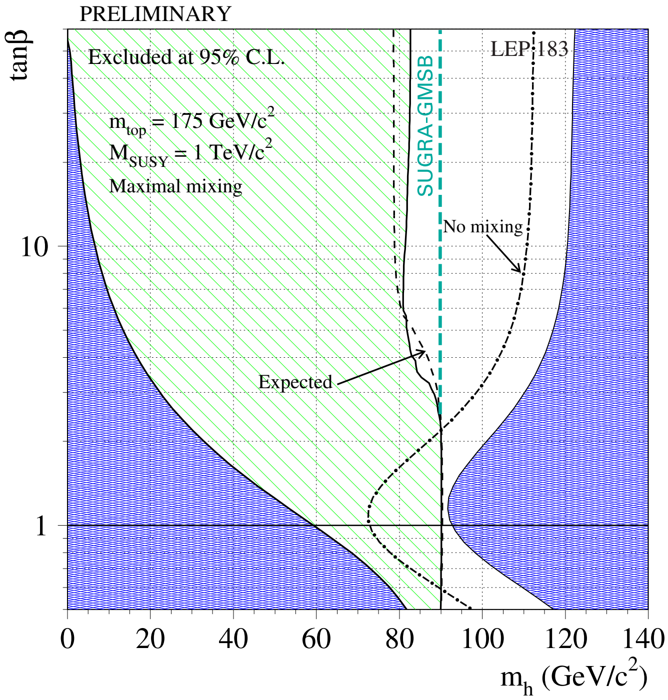

Figure 4: MSSM limits reached by combining the 4 LEP experiments (1997 data only). The dashed line labelled SUGRA-GMSB indicates the limit reached assuming Supergravity or the Gauge Mediated SUSY breaking schemes.

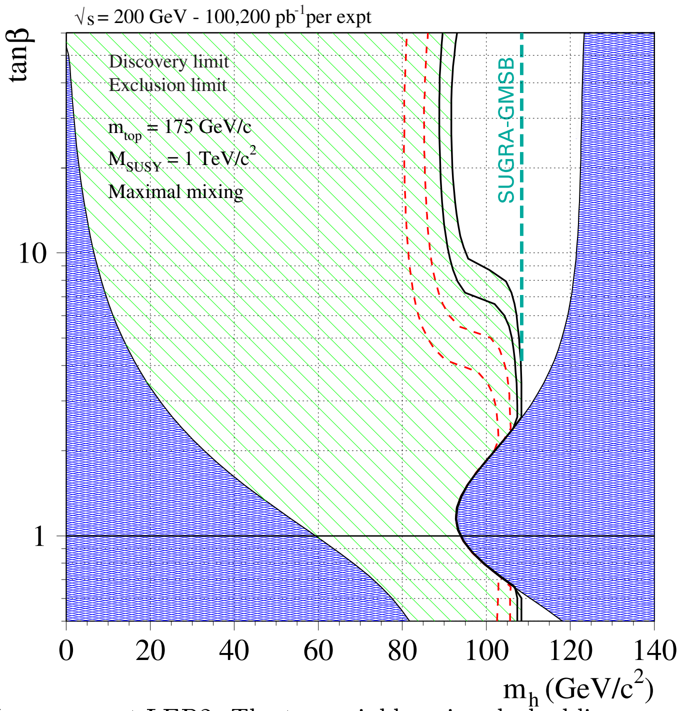

Figure 5: Expected MSSM coverage at LEP2. The two neighbouring dashed lines correspond to discovery limits reachable with 100 pb^{-1} and 200 pb^{-1} per LEP experiment at $\sqrt{s}$=200 GeV. The full lines are the corresponding exclusion limits. The SUGRA-GMSB dashed line is defined as in figure 4.

Future Colliders[30]

SM Higgs search at LHC (cf. presentation of D. Denegri), for masses below 130 GeV, use the decay mode into 2 photons. This channel is not always accessible in MSSM, specially at low m_A, but can be covered indirectly using complementary channels. It is however fair to say that a full study of the Higgs boson properties can only be done at a lepton collider.

Muon colliders[31] are very promising in two respects. They can reach energies well above 1 TeV and therefore cover an energy reach comparable or even beyond LHC. For what concerns the Higgs sector they offer the possibility of single H production with reasonable rate given the Higgs coupling to muons and the excellent energy resolution of these beams. Before a realistic project can be launched, a long and active R&D program is needed to test the various elements of this complex scheme.

Electron linear colliders have entered in an intensive R&D period to demonstrate the feasibility of the various schemes under consideration. One may distinguish 3 approaches:

- The high frequency approach which allows to reach high gradients (>50 MV/m) under study at SLAC and KEK. The limitations for this scheme are the power sources (several 1000 klystrons are needed) and the wakefields, i.e. fields induced by the beam bunches which travel closely to RF walls which can distort the beam. It is fair to say that this type of approach has been progressing very well but seems limited to 1-2 TeV center of mass energy.

- A two beam accelerator, in which an auxiliary low energy beam generates the power and replaces the many klystrons is generally acknowledged as the most promising solution to go beyond 1-2 TeV. CERN has been actively testing this idea and has recently re-designed the auxiliary beam into a more realistic solution. This ambitious scheme, known as CLIC, aims at 100 MV/m gradient and 30GHz frequency. The luminosity goal is $>10^{34} cm^{-2} sec^{-1}$ with a maximum energy of 5 TeV. The limitations of this scheme are the wakefields and a very critical alignment.

- A supra-conductive solution, TESLA, is under active study at DESY. This solution can only work at low frequency, low gradients (<40 MV/m). It therefore has a limited energy, below 1 TeV but can provide very high currents, with very good duty cycle, which could allow to reach luminosities $\sim 10^{34} cm^{-2} sec^{-1}$.

Common to all these schemes is the request for a vertical spot size of a nanometer at the interaction point. The FFTB experiment[32] has been able to reach a beam spot size of ~60 nm, but there is still some way to go (e.g. improvement of the emittances in storage rings now tested at KEK) before one can reliably count on the final figure.

In the parameter list for these projects, one should notice that the energy loss experienced during beam-crossings is at the few % level in such a way that one keeps almost intact the possibility of measuring inclusively (i.e. including the invisible decay modes) the process HZ using the leptonic Z decay, plus energy momentum conservation. This allows to observe a clean and narrow mass peak and deduce the total cross section.

For what concerns light Higgs physics, energy does not seem an issue but luminosity can be of interest, as will be discussed shortly. The main uncertainty, in the MSSM case, is on the H and A bosons masses which could be heavy and therefore require more than 1 TeV center of mass energy for associated production $e^+e^- \to$HA.

Higgs Physics at Future Colliders

With a luminosity x1000 with respect to LEP2, one could produce several 10^4 HZ events, which would provide a clean sample if m_H is sufficiently distinct from m_Z. Precise measurements become possible, including the rare modes into two photons and two gluons. For the latter, this requires a serious improvement of the tagging techniques to separate this state from beauty and charm decays. This challenging goal seems reachable given the superior track extrapolations which can be achieved in a linear collider with reduced beam pipe size (1cm radius instead of 5cm at LEP). First estimates indicate that for Z decays it would be possible to tag charm decays with a purity of ~80% and an efficiency of ~60% [33].

The measurement of the ratio $c\bar{c}/b\bar{b}$, which seems experimentally feasible, can be of great interest to distinguish between SM and MSSM. Provided that $\tan\beta > 2$, one can show that this ratio deviates by more than 20% from the SM if m_A <450 GeV[34]. Unfortunately this ratio also depends on the effective charm mass at the Higgs mass scale, a quantity poorly known given the large QCD corrections. The present uncertainty due to this effect is ~15%[35].

The Higgs total width can be measured with a muon collider to a fraction of an MeV. For an electron collider, one can use an indirect method. $\Gamma_{H\to 2\gamma}$ is measurable in an $\gamma\gamma$ collider[36]. This type of collider has been envisaged and it was shown that, shooting with a laser on an electron beam, one can generate photons which carry 80% of the incident energy. The Higgs total width is deduced from BR(H$\to 2\gamma$) and $\Gamma_{H\to 2\gamma}$.

The Yukawa coupling to fermions is accessible in $t\bar{t}$H final states [1]. The cross-section is at the fb level.

Given the very large luminosity considered for TESLA, one could also test the self coupling H$\to$2H which simply originates from the quartic term of the Higgs Lagrangian (the λ term). The largest contribution comes from the Higgsstrahlung diagram in which a virtual Higgs H^* is emitted and subsequently decays into 2 on-shell Higgs bosons. This process gives a very distinct final state HHZ. Unfortunately the cross section, assuming $m_H \sim 100$ GeV, is 0.3 fb at $\sqrt{s}$=500 GeV[37] and therefore one needs the highest possible luminosity.

The heavy Higgs bosons from MSSM, $H^{\pm}$, H and A, could be pair-produced up to masses of $\sqrt{s}/2$. Single production of H and A is possible at a muon collider with excellent mass resolution, a key feature since H and A tend to be degenerate in mass in MSSM. If a $\gamma\gamma$ collider can be operated, it could also allow single production of H and A and therefore increase the mass range for these bosons up to about 80% of the maximum center of mass energy. This idea deserves detailed investigation, in particular concerning the detectability of these channels.

Final Remarks

After this presentation one may wonder if there could be an escape for a light Higgs discovery in the next 10-15 years ?

This possibility is clearly present at LHC, even in the MSSM scheme. For instance, as recently shown [38], one can concoct a scenario with large mixing in the top squark sector in which there is strong cancellation between stop and top loop contributions in the gluon-gluon fusion mechanism which provides the largest part of the production cross-section at LHC.

Beyond MSSM, there could even be difficult cases for a lepton collider. We have already seen how it was possible to raise the upper bound on the Higgs mass by introducing singlets and triplets. This game has also been played in [39] assuming a large multiplicity of Higgs n-plets, including the possibility of invisible decays. The conclusion was that detectability cannot fail given the well constrained final states and provided that one can reach an integrated luminosity of 500fb^{-1}.

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