

Higgs Search : Present and Future.¹

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Abstract

In this talk I review theoretical bounds on mass of the Higgs scalar in the Standard Model(SM) and then summarise current experimental limits from the LEP experiments. Following this I discuss the search strategies for the SM Higgs at LEP 200 and the TeV energy e^+e^- colliders which are under discussion. This will be followed by a summary of the Higgs search potential of the pp supercolliders such as SSC/LHC. I then close with a brief discussion of a 'Dark Higgs' whose dominant decay modes are into invisible channels.

1)Introduction

In spite of the spectacular confirmation of various predictions and features of the Standard Model (SM), including effects of radiative corrections, at LEP [1] the discovery of the as yet missing top quark and Higgs boson is essential for the complete vindication of the theoretical formulation of the SM. Hence Higgs search has formed (and will continue to form) an important part of the physics programme at the current(future) accelerators. Since the presence of Higgs in the SM is intimately related to the question of giving masses to the fermions and the gauge bosons, even the failure to find a Higgs boson may shed light on the mass generation and symmetry breaking mechanism. Various extensions of the SM almost always enlarge the Higgs sector, but almost always there is one scalar in these theories which mimics, more or less, the couplings of a SM Higgs.

In this talk I will concentrate mainly on the SM Higgs. I will first briefly review, in section (2), the theoretical 'bounds' on the Higgs mass m_H followed in section (3) by a summary of information about the branching fractions of Higgs in SM into various relevant channels. Then in the next section I will state current bounds on m_H from LEP data and discuss search strategies/discovery limits at future e^+e^- colliders: LEP 200 and the TeV energy (≤ 0.5 TeV) e^+e^- colliders under planning currently. This will be followed in section (5) by a discussion of the search possibilities offered by future colliders like SSC/LHC for the Higgs, with an emphasis on the $\gamma\gamma$ signal in the intermediate Higgs mass range: $m_Z < m_H < 2m_W$, the four lepton signal for the heavier Higgs as well as use of forward

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jet tagging to isolate $qq \rightarrow qqH \rightarrow qqWW$ contributions to the WW signal for Higgs. This technique can prove useful in the investigations of a strongly interacting vector boson sector should one exist; a clear non-standard feature. Following this in section (6) I will discuss yet another non-SM feature; *viz.* the possibility of a ‘Dark Higgs’ where the dominant decay mode of the lightest scalar is into invisible channels. This can affect current LEP limits on m_H . Then I will end with some conclusions.

2) SM Higgs: Theoretical mass bounds

As is well known in SM couplings of Higgs to matter and gauge fields are completely predicted [2] but as far as the mass is concerned there exist only bounds. What is definitely known is that Higgs can not be too heavy or perturbative theory breaks down [3]. For $m_H \geq O(1\text{TeV})$ the perturbative $VV \rightarrow VV$ scattering amplitude for $V = Z/W$ violates unitarity [4]. More serious is the fact that the electroweak theory is not asymptotically free in the Higgs sector. Thus the self coupling λ blows up in renormalisation group improved perturbation theory. The energy scale at which λ blows up is called the Landau pole. In addition the self coupling λ increases with m_H^2 . Hence the position of the Landau pole itself depends on m_H . Demanding that SM with an elementary Higgs scalar should make sense upto an energy scale Λ , i.e., the Landau pole should lie beyond Λ , then gives an upper bound on SM [5]. Fig. 1, taken from [6], shows the bound obtained from such

Figure 1: Bounds on m_H and m_t from Landau pole and vacuum stability [6].

an analysis, for different values of Λ . As we can see for a light Higgs $m_H \leq 180 - 200$, GeV the perturbative regime is valid upto $\Lambda \simeq m_{GUT}$ or m_{Pl} . As m_H increases this region of validity decreases till finally for $m_H \simeq 1$ TeV the theory is valid only upto $\Lambda \simeq 1$ TeV.

This limit on m_H can be understood in a simplified manner [3] as follows. The renormalisation group equation for the quartic coupling λ , in the limit of neglecting the gauge and

Yukawa couplings, becomes:

$$\frac{d\lambda(t)}{dt} = \frac{3}{4\pi^2}\lambda^2(t) \quad (2.1)$$

where $t = \ln(\Lambda/v)$, where v is the vacuum expectation value and Λ the scale where λ is evaluated. Of course this equation can be solved only when some normalisation condition for λ at scale v is provided. This is chosen to be

$$\lambda \equiv \lambda(v) = \sqrt{2}G_F m_H^2 \quad (2.2)$$

$$v = (2\sqrt{2}G_F)^{1/2}. \quad (2.3)$$

The coefficient of $3/4\pi^2$ in eq. (2.1) is the lowest order expression for the β – function which is obtained from the one–loop corrections to the quartic coupling in the $\lambda(\phi^\dagger\phi)^2$ theory. Solving eq. (2.1) we get

$$\lambda(t) = \frac{1}{1 - 3\lambda t/(4\pi^2)}. \quad (2.4)$$

Then the Landau pole is avoided upto a scale Λ provided,

$$\frac{3}{4\pi^2}\lambda t = \frac{3}{4\pi^2}\sqrt{2}G_F m_H^2 \ln(\Lambda/v) < 1 \quad (2.5)$$

This gives,

$$m_H \leq \frac{893\text{GeV}}{\sqrt{\ln(\Lambda/v)}} \quad (2.6)$$

or $m_H < 144, 165, 675$ GeV for $\Lambda = 10^{19}, 10^{15}, 10^3$, respectively. The bounds shown in fig. 1 are of course obtained from the full renormalisation group analysis as the Yukawa couplings, particularly the top Yukawa coupling, are non–negligible.

The obvious question is of course validity of a perturbative analysis of the β functions near the Landau pole. However, recent lattice calculations [7] confirm this bound and conclude that

$$m_H < (8 - 10)m_W \simeq 600 - 800\text{GeV}. \quad (2.7)$$

Thus, if the SM is to be internally consistent, an upper bound ~ 1 TeV exists on the mass of Higgs–scalar. Hence a search strategy for SM–Higgs should cover the mass range upto 1 TeV.

There is yet another consideration which leads to bounds on m_H viz., considerations of vacuum stability [3, 8, 9, 10]. This essentially demands that (i) the one loop corrected scalar potential $V(\phi)$ has a minimum at $\phi = v$ so as to have spontaneous symmetry breakdown and further (ii) $V(\phi) \rightarrow \infty$ as $|\phi| \rightarrow \infty$ so that the Hamiltonian is bounded from below. At the tree level the scalar potential is,

$$V(\phi) = -\mu^2|\phi|^2 + \frac{\mu^2}{2v^2}|\phi|^4. \quad (2.8)$$

Quantum corrections, at one loop level [11] give us,

$$V(\phi) = -\mu^2|\phi|^2 + \frac{\mu^2}{2v^2}|\phi|^4 + \gamma|\phi|^4 \left[\ln \frac{|\phi|^4}{v^2} - \frac{1}{2} \right] \quad (2.9)$$

where

$$\gamma = \frac{3 \sum_{\text{vectors}} m_v^4 + \sum_{\text{scalars}} m_s^4 - 4 \sum_{\text{fermions}} m_f^4}{64\pi^2 v^4} \quad (2.10)$$

The first condition mentioned above would give a lower limit on m_H if the fermions are light so that their contribution to γ in eq. 2.10 can be neglected; *e.g.* if $m_t < 80$ GeV, the requirement (i) above gives $m_H > 7$ GeV [9, 10]. However in view of the current bounds on the top mass [12] this limit is by now void. The second requirement really means that γ in eq. 2.10 should not become too negative. This means that m_H should increase with m_t [8]. Again at large $|\phi|$ again the one loop results of eq. 2.9 can not be valid. The large logarithms have to be resummed and then a bound on m_H has to be obtained. The bound so obtained in ref. [6] is the one shown in fig. 1.

The above bounds strictly apply only to SM, *i.e.* a simple scalar sector with a single Higgs doublet. In case of a more complicated Higgs sector these bounds refer to some average mass. This clearly means that the lower bounds on m_H given in fig. 1 can be avoided, but not the upper bounds. Hence if the SM is correct we expect to find either a Higgs below 1 TeV or some evidence for new physics beyond the SM or occurrence of the onset of new perturbative regime. So in principle, a comprehensive discussion of search strategies for Higgs at current and future colliders should include the latter two possibilities as well. Out of the possible extensions of the SM, supersymmetry [13] is perhaps the most attractive as well as predictive one. These theories have an extended scalar sector. Search strategies for a supersymmetric Higgs will be discussed separately at the symposium [14]. The possibility of strongly interacting Higgs sector [15] will not be, however, covered in much detail here.

3) Production modes and decays of the Higgs

As said earlier, as a result of Higgs mechanism for spontaneous symmetry breakdown Higgs couplings to fermions and gauge bosons are completely fixed [2] and are proportional to their masses. Hence, for a given m_H , the largest branching ratio is into the heaviest fermion–antifermion pair or the heavy gauge boson pair. In view of the above, the CDF limit on m_t [12] and LEP limits on m_H [16], the dominant decay modes for Higgs are

1. $H \rightarrow b\bar{b}$ for $m_H < m_Z$,
2. $H \rightarrow b\bar{b}, H \rightarrow ZZ^*, H \rightarrow WW^*$ for Higgs in the intermediate mass range $m_Z < m_H < 2m_W$,
3. $H \rightarrow VV$ for $m_H > 2m_V$.

Calculations of the total width and branching ratios of the SM Higgs were done from scratch in ref. [17] by Kunszt and Stirling. Fig. 2 shows the decay branching ratios into fermion and gluon pairs (fig. 2(a)) and into a pair of electroweak gauge bosons (fig. 2(b)) for the mass range $m_H < 2m_Z$ as well as for the dominant channels for $m_H > 2m_Z$ (fig. 2(c)) with $m_t = 90$ GeV. These branching ratios are not very sensitive to the top mass apart from the position of the $t\bar{t}$ threshold.

Figure 2: Decay branching ratios for SM Higgs for $m_H < 2m_Z$ (a,b) and $m_H > 2m_Z$ (c) for $m_t = 90$ GeV[18].

In the case of a very light Higgs boson, which has already been ruled out by LEP, the following points should be kept in mind:

1. For $m_H < 2m_\mu$, an ultra light Higgs boson can decay even outside the detector or $c\tau_H \simeq$ at least a few cm.
2. For $2m_\pi < m_H < 2m_c$ the calculations of the different branching ratios have some theoretical uncertainties.
3. For $m_H > 2m_b$ of course $H \rightarrow b\bar{b}$ is the dominant mode, but BR ($H \rightarrow \tau^+\tau^-$) is $\simeq 8\%$. The last can be seen from fig. 2(a).

In the case of the heavier Higgs boson for which the decay branching ratios have been presented in figs. 2(a,b), the dominant decay mode of Higgs into a $b\bar{b}$ pair suffers from enormous QCD backgrounds and hence the rare decay mode $H \rightarrow \gamma\gamma$ plays an important role in the search strategies of such a Higgs, particularly at a Hadron collider, by providing a much cleaner final state. The rare decays like $H \rightarrow \gamma\gamma$ and $H \rightarrow gg$ take place via loops and the loop contribution will be dominated by gauge boson and heavy fermions. Hence these rare decay modes are also good pointers to new physics. The effect of the running of the b quark mass, has been included in the calculations [18] and it reduces the partial width for the $H \rightarrow b\bar{b}$ considerably and hence increases the branching ratios into channels like $H \rightarrow \gamma\gamma$, $H \rightarrow gg$ and $H \rightarrow \tau^+\tau^-$.

For the intermediate mass Higgs, the channels involving at least one real vector boson open up and begin to dominate the decay branching width. In fig. 2(b) the dip in the branching ratio in the ZZ^* channel, around $2m_W$, corresponds to the threshold for the WW channel. Fig. 2(c) shows the dominant branching ratios for $m_H > 2m_Z$. One can see from there complete domination of H decays by gauge boson and $t\bar{t}$ channels.

Fig. 3 shows the variation of the total Higgs decay width Γ_H^{tot} with m_H for two different values of m_t . Again we see that the dependence of Γ_H^{tot} on m_t is marginal. The width rises sharply once the VV(V=W/Z) channel opens up. For the superheavy Higgs ($m_H >$

Figure 3: Total width Γ_H^{tot} as a function of m_H . The solid(dashed) line corresponds to $m_t = 90(100)$ GeV[18].

700 – 800 GeV) the total width becomes comparable to the Higgs mass itself. The calculations of [18] of the Higgs decay width and branching ratios have been updated to include the effects of the electroweak and QCD radiative corrections [19]. None of these change the trends discussed above and amount to a few % in most cases.

Just as the dominant decay modes of Higgs are into the heaviest fermion pair accessible for a given Higgs mass m_H or into a gauge boson pair, the dominant Higgs production mode at a given collider are also controlled by same large couplings. Over most of the Higgs mass range of interest and the current or planned e^+e^- collider centre of mass energies, Higgs production is dominantly through the large HVV coupling and possible processes are shown in fig. 4. Over most of the mass range of the Higgs, for $m_t \simeq 100$

Figure 4: Different production modes for a Higgs at an e^+e^- collider.

GeV, the production at Hadron colliders takes place via gg fusion. Different possible modes of single Higgs production at a Hadron collider are depicted in fig. 5.

From above discussions it is clear that the efficacy of the Higgs search will be decided by the ability to reject against $b\bar{b}$ backgrounds or to use the rare decay modes for a Higgs lighter than $2m_V$ and by the ability of isolating VV signal due to Higgs production in the case of heavier Higgses. In the latter case one would like to be able to distinguish between the VV pairs coming from Higgs production from gluon fusion(at a Hadron collider) and its subsequent decays from those due to Higgs production via VV fusion shown in fig. 5. Furthermore, a discrimination of the VV production due to a strongly interacting Higgs sector from the above signal, is also desirable. The details of the expected cross-

Figure 5: Different production modes for a Higgs at a hadron collider.

sections for the signal and the backgrounds at different colliders will be discussed in the next sections. First I will discuss current limits on the SM Higgs from LEP, followed by a discussion of search strategies of the Higgs at the supercolliders [20]: at a TeV energy e^+e^- collider [21, 22] as well as at the pp supercolliders [17, 23].

4) Search for the SM Higgs at e^+e^- colliders

4a) Higgs search at LEP 100

e^+e^- colliders are ideally suited for Higgs search due to the clean environment they offer and the precise knowledge of the initial energy. Both these are a considerable advantage over the hadron colliders, in view of the discussion of section 2. One of the production modes for Higgs at an e^+e^- collider is the Bjorken process [24] shown in fig. 4. This is the dominant production mode at low m_H ($m_H < 70$ GeV), at the Z pole, which is the energy at which LEP-100 has so far collected data. Before the LEP collider went into action a variety of different processes and experiments had provided limits on m_H ². However, almost all these limits suffered to some extent from theoretical uncertainties such as long distance effects in the production of Higgs or in the calculation of $H \rightarrow \mu^+\mu^-$ branching ratio when $m_H < \text{few GeV}$. Hence the limits obtained by LEP, which are almost free of these uncertainties, are crucially important.

The production process at LEP-100 [24] is,

$$\begin{aligned} e^+e^- &\rightarrow Z \rightarrow Z^*H \\ &\rightarrow f\bar{f}H. \end{aligned} \tag{4.1}$$

This will give rise to different final states due to different decays of the Z^* and H . The off shell Z^* decays into a $q\bar{q}$ pair in about 70% of the cases, into a $\nu\bar{\nu}$ pair in about 20% cases and into a l^+l^- pair remaining $\simeq 10\%$ of the times. In the final case of course a sum over all the three lepton types ($l = e, \mu, \tau$) is implied. However, normally only the final states involving e/μ are useful. The dominant final states of Higgs decays will of course depend on Higgs mass m_H .

The initial suggestion by Bjorken [24] was to look for Z^* decaying into a l^+l^- (with $l = \mu$) final state, regardless of the H decay and study the distribution in the invariant mass

²For a good summary of these mass limits, see *e.g.* ref. [25].

$m_{\mu^-\mu^+}$. The production of Higgs via the process of eq. 4.1 is then signalled by a peak in this distribution. Fig. 6 taken from Ref. [26], shows BR ($Z \rightarrow H\mu^+\mu^-$) (left axis) and

Figure 6: BR ($Z \rightarrow H\mu^+\mu^-$) (left axis) and total number of hadronic Z decays which would correspond to $3 H f \bar{f}$ ($f = \nu/e/\mu$) events at the Z pole (right axis) as a function of m_H [26].

total number of hadronic Z decays which would correspond to $3 H f \bar{f}$ ($f = \nu/e/\mu$) events at the Z pole (right axis) as a function of m_H . From this figure, one can see how only with 25,000 hadronic Z decays per experiment, the nonobservation of a signal in the 1989 LEP data [27] could rule out Higgs upto $m_H \simeq 25$ GeV. The very steep dependence of the BR ($Z \rightarrow H\mu^+\mu^-$) on m_H however, makes it clear that further improvements on the limit on m_H , with increasing number of Z events are slower.

In the search for the light Higgs boson the four LEP groups (for a good summary see, *e.g.*, Ref. [16]), used not only the final state resulting from $Z^* \rightarrow \mu^+\mu^-$ but also those from $Z^* \rightarrow e^+e^-$ and $Z^* \rightarrow \nu\bar{\nu}$ decays. They also used the specific topologies resulting from different Higgs decays, as allowed in the SM, depending on the value of m_H . For an ultra light Higgs boson ($m_H < 2$ GeV) the search is complicated, in spite of the large production rate, due to the large variety of possible signals and theoretical uncertainties in the Higgs decay branching ratios. These somewhat model dependent analyses [16] excluded a light SM Higgs. OPAL has further excluded a light Higgs upto a mass of 11 GeV, even in a decay mode independent search [28].

For a heavier Higgs boson ($>$ a few GeV), the process of eq. 4.1 gives rise to following final states in decreasing order of abundance (for $m_H > 2 m_b$):

- (i) ($Z^* \rightarrow hadrons$)($H \rightarrow hadrons$)
- (ii) ($Z^* \rightarrow \nu\bar{\nu}$) ($H \rightarrow hadrons$)
- (iii) ($Z^* \rightarrow \tau^+\tau^-$) ($H \rightarrow hadrons$) + ($Z^* \rightarrow hadrons$) ($H \rightarrow \tau^+\tau^-$)
- (iv) ($Z^* \rightarrow e^+e^-/\mu^+\mu^-$) ($H \rightarrow hadrons$)
- (v) ($H \rightarrow \tau^+\tau^-$) [($Z^* \rightarrow \nu\bar{\nu}$), ($Z^* \rightarrow l^+l^-$)]

The relative abundances of these various final states, *e.g.* for $m_H = 55$ GeV, are 64%, 18%, 9%, 6% and 3% respectively. However, due to the large QCD backgrounds, the first channel is quite ineffective. The second channel is the most useful as it gives rise to an acoplanar pair of hadronic jets which can be easily discriminated against the Z decay background. The high efficacy of this channel at LEP 100 is due to the absence of $t\bar{t}$ production at this energy. The final states involving taus are less clear and hence have lower search efficiency. Therefore the final state in (iv) with somewhat lower rates but cleaner signature serves better. This final state, however, suffers from an irreducible background from $e^+e^- \rightarrow q\bar{q} l^+l^-$, where the $q\bar{q}$ (l^+l^-) comes from a photon radiated off a final state lepton (a final state quark). The bounds on Higgs mass given by the different LEP groups are given in Table 1 [26].

Table 1: Lower bounds on the SM Higgs mass from the four LEP experiments, from ref. [26]

	ALEPH	DELPHI	L3	OPAL
$m_H(\text{GeV})$	56.3	47	52	52.6

Since the total number of hadronic Z events collected by all the four groups by now is $\simeq 2453 K$ [26], we see from fig. 6 that for all the four groups combined together one would expect $\simeq 3.50 Hf\bar{f}$ ($f = \nu, e, \mu$) events. This means that a combined 95 % confidence level limit from all the four groups currently is $m_H > 60$ GeV. This indicates that no LEP group individually will be able to do better than this limit. Further progress must come from the higher energy e^+e^- colliders *viz.* LEP 200, the next linear collider (NLC) and the pp supercolliders.

4b) Higgs search at LEP 200

LEP 200 will not run at a fixed energy and is expected to have $175 < \sqrt{s} < 190$ GeV. The production process is similar to that of eq. 4.1 but the role of the real and the virtual Z's have got interchanged. The process is

$$e^+e^- \rightarrow Z^* \rightarrow Z + H \quad (4.2)$$

and is shown in fig. 4. This process has appreciable cross-sections for $m_H < (\sqrt{s} - m_Z)$. Figure 7 taken from [29] shows the expected cross-section for Higgs production for different values of m_H for $175 < \sqrt{s} < 190$ GeV. Again various final states possible due to different decays of the Z and H are the same as discussed in sec. (4a). The search strategy now uses the fact that the final state contains a real Z. However, the search has to proceed differently than at LEP 100 due to the rise with increasing energy in the cross-sections of various t-channel processes which should be contrasted with the $1/s$ behaviour of the cross-section of the process of eq. 4.2. There exist different t-channel processes such as $e^+e^- \rightarrow ZZ, e^+e^- \rightarrow W^+W^-, e^+e^- \rightarrow Z\nu\bar{\nu}, e^+e^- \rightarrow Ze^+e^-, e^+e^- \rightarrow e\nu W$ which lead to final states similar to those one will look here for. Fig. 7 shows expected cross-sections for these various background processes as well. It can be clearly seen from the figure that the signal lies well below various background processes.

Figure 7: Higgs production cross-section via the bremsstrahlung process along with different background processes and their cross-sections for $\sqrt{s} = 175$ and 190 GeV [29].

The most difficult region in m_H is the case where Higgs is degenerate with Z *i.e.* $m_H \simeq m_Z$. In this case the process

$$e^+e^- \rightarrow ZZ \tag{4.3}$$

constitutes an extremely serious background as the signal to background ratio is about 5 and the final states extremely similar.

For values of m_H considered here, $H \rightarrow b\bar{b}$ is the dominant decay mode whereas for Z the $b\bar{b}$ branching ratio is only $\sim 14\%$. So concentrating on the $b\bar{b}$ final states and using μ vertex detectors to tag the ‘b-quark’ one can handle the background. (It should be perhaps mentioned here that the ‘b-tagging’ is useful not only in this degenerate Higgs case but for the full heavy m_H range.) Further the angular distribution of the fermions can be used [30, 31] to discriminate ZH signal from ZZ one. The conclusion of both the references was that at $\sqrt{s} = 190$ GeV an integrated luminosity ($\int \mathcal{L}dt = 5fb^{-1}$) will be needed to get a decent signal to background ratio. A recent analysis of ref. [29] takes into account realistic detector simulation and concludes that using all the channels of the different Z/H decays *viz.* $H\nu\bar{\nu}$, Hl^+l^- , $\tau^+\tau^-$, $q\bar{q}$ and $4q$ jets, one could search right upto $m_H = m_Z$, with a similar integrated luminosity.

Fig. 8 shows the minimum integrated luminosity required for a Higgs discovery at a fixed \sqrt{s} as a function of m_H . Discovery here is being defined as a combined signal at

Figure 8: Minimum integrated luminosity, $\int \mathcal{L} dt$, required for Higgs boson discovery for $\sqrt{s} = 175$ [190] GeV is shown in fig. (a) [(b)][29].

the level of 5 events in all the different channels and five standard deviations above the expected background. Essentially it shows that at the lower energy of $\sqrt{s} = 175$ GeV the maximum sensitivity to m_H ($\simeq 80$ GeV) is already reached at an integrated luminosity of 150 pb^{-1} . If one should however increase the energy to 240 GeV, the cross-section for the process of eq. 4.2 falls off but even then range of m_H accessible in the process grows. As stated earlier at a given \sqrt{s} the above process has a reach upto $\sqrt{s} - m_Z$. At $\sqrt{s} = 240$ GeV, this limit will be reached with an integrated luminosity of 300 pb^{-1} .

4c) Higgs search at the higher energy e^+e^- colliders:

At higher energy e^+e^- collider Higgs production can also take place via the WW/ZZ fusion [32] processes shown in fig. 4 which are given by,

$$e^+e^- \rightarrow \nu\bar{\nu}WW \rightarrow \nu\bar{\nu}H \quad (4.4)$$

$$e^+e^- \rightarrow e^+e^-ZZ \rightarrow e^+e^-H. \quad (4.5)$$

The cross-section of the fusion process begins to grow in importance over the bremsstrahlung process of the 4.2, due to the $\ln(s/m_H^2)$ dependence of the former as opposed to the $1/s$ dependence of the latter. This is clearly seen in the figure. The figure also shows that for the values of m_H and \sqrt{s} under consideration ($m_H > 60$ GeV, $\sqrt{s} < 500$ GeV), the WW fusion contribution is comparable to the beamstrahlung one whereas the ZZ fusion gives a contribution which is about ten times smaller. By now the electroweak radiative corrections to the cross-sections have been calculated [34]. The QED corrections are indeed large and come dominantly from the photon radiation from the initial e^+/e^- , whereas the weak corrections are only at the level of a few % ($-7\% < \Delta < 4\%$). On the whole, the radiative corrections are well under control and well understood.

The real advantage of the high energy linear e^+e^- colliders is to be able to explore the intermediate mass range for the Higgs in great detail. As is clear from fig. 2 (c), for the relevant m_H values the dominant decays are into the $V^*V^*/VV^*/VV$ where V is W/Z boson. As the discussions in the last sections show, LEP 200 would certainly probe region upto $m_H < m_Z$. The region $m_H \simeq m_Z$ requires special attention. For the case of a Higgs degenerate with the Z, the characteristic nature of the missing mass spectrum of the signal $e^+e^- \rightarrow ZX$, X=H can be used effectively to separate the signal from

Figure 9: Higgs production cross-section, in fb, in e^+e^- collisions for the bremsstrahlung and the fusion processes for $\sqrt{s} = 500$ GeV, as a function of m_H [33].

the ZZ background [35]. The use of $b\bar{b}$ final state and flavour tagging using vertex detectors to identify the b's, also helps reduce the background from ZZ production. For $100 < m_H < 140$ GeV, the worst background is single Z production but can again be handled by flavour tagging. For $140 < m_H < 160$ GeV, the dominant background is from

$$e^+e^- \rightarrow ZWW^* \rightarrow ZW(W^* \rightarrow q\bar{q}'), \quad (4.6)$$

which is again manageable as it is suppressed by electroweak couplings. Beyond $m_H = 160$ GeV the channel containing three real vector bosons in the final state open up. Now for a realistic estimate of the discovery potential one has to look at the variety of background processes which can give rise to similar final states, containing two or more real vector bosons. A detailed analysis of these backgrounds has been performed [36, 37]. In these cases the invariant mass distribution for the VV pair can be used to remove the background. The conclusion of these studies is that a Higgs boson upto 0.35 TeV can be observed at an e^+e^- collider with $\sqrt{s} = 500$ GeV, with 10 fb^{-1} luminosity.

One more aim of these e^+e^- colliders will be to use their cleaner environment (modulo the potential problems that may be caused by the hadronic backgrounds [38] induced by the beamstrahlung [39] photons) to make detailed studies of the properties of the Higgs, once it is found. Independent of Higgs decay, the monoenergetic nature of the recoiling Z boson produced in the reaction of eq. 4.2 can be used to determine m_H once a Higgs signal is seen. In this case the accuracy of Higgs mass determination is limited by smearing of the incident electron beam energy caused by the phenomenon of beamstrahlung [39]. A study of the angular distribution of Higgs produced in the bremsstrahlung process of eq. 4.2 can yield information about the spin of the Higgs. Radiative corrections to the angular distributions are also well under control [34]. The strength of the HVV coupling can be determined from the production cross-sections. As far the $Hf\bar{f}$ couplings are concerned, only their relative strength w.r.t the HVV couplings can be extracted from the decay branching ratio measurements. A determination of the $Ht\bar{t}$ coupling is possible by studying the production of a light Higgs via bremsstrahlung off t(\bar{t})quark [40] or a light Higgs decay to a $t\bar{t}$ pairs [41] as shown in fig.4 *viz.*,

$$e^+e^- \rightarrow t\bar{t}H \quad (4.7)$$

$$e^+e^- \rightarrow t\bar{t}Z. \quad (4.8)$$

But these processes are useful only in a limited range of Higgs mass.

From the above discussion we can conclude that, e^+e^- colliders with $\sqrt{s} > 300$ GeV are ideally suited for the discovery as well as a detailed study of the properties of a SM Higgs in the intermediate mass range and above.

5) Higgs search at Hadron colliders:

5a) Higgs search for $m_H > 0.6 - 0.8$ TeV

Eventhough, the high energy e^+e^- colliders are the ideal place to look for an intermedaite mass Higgs and construction of such linear e^+e^- colliders does seem possible, they still lie in somewhat distant future [21, 22]. One of the major goals of the pp supercolliders like the LHC/SSC that are being planned is the hunt for Higgs. The expected cross-sections for different Higgs production processes of fig.5, at the LHC pp collider($\sqrt{s} = 16$ TeV) are shown in fig. 10. The uncertainties in these cross-sections are much higher than the

Figure 10: Expected cross-sections for the Higgs production at the LHC for different production processes of fig. 5[18].

corresponding predictions at an e^+e^- collider and they come from uncertainties in the knowledge of the structure functions as well as the size of the higher order corrections. For the gg fusion mechanism, which dominates the production upto $m_H \simeq 0.8$ TeV, the QCD corrections [42] increase the cross-section by as much as 80% for both the LHC and SSC energies. This is shown in fig. 11 taken from [43]. The figure clearly shows that the QCD corrections are much higher than the structure function uncertainties.

This increase is a welcome news as can be seen from the fig. 12 taken from [44]. The Higgs search does indeed need good search strategies to boost the signal above all the other, much more abundant, processes. The strategy of course depends crucially on Higgs mass. The information on different branching ratios of the Higgs, shown in fig. 2, can be translated into different effective search channels for it as shown in fig. 13, taken from [44]. We see from this figure that for the mass range $m_Z < m_H < 2m_Z$, the best

Figure 11: Higher order QCD corrections to the $gg \rightarrow H$ production, taken from [43].

Figure 12: Cross-sections for different relevant processes at hadronic colliders from the current $p\bar{p}$ colliders to supercolliders [44].

signal is obtained by using the rare decay mode $H \rightarrow \gamma\gamma$ [45]. The dominant decay mode $H \rightarrow b\bar{b}$ suffers from the enormous QCD backgrounds shown in fig. 12.

The rates for the process $pp \rightarrow HX \rightarrow \gamma\gamma X$ are indeed very small, but the signal is observable over the QCD continuum diphoton background [46] in the $m_{\gamma\gamma}$ distribution. However, this demands a very good $m_{\gamma\gamma}$ resolution (to better than 1%). A major source of another reducible background to the signal is hadron misidentification and hence very good π/γ separation is needed to achieve the rejection factors $\sim 10^8$ that are required. The expected number of the signal events and the intrinsic QCD diphoton background are shown in Table 2. The numbers in Table 2 are for $m_H = 80 - 150$ GeV and $\int \mathcal{L} dt \simeq 10^5 pb^{-1}$. From this one can conclude that the $\gamma\gamma$ channel can make the discovery of Higgs in the intermediate mass range at a hadronic collider a possibility.

Table 2: The expected number of the $pp \rightarrow HX \rightarrow \gamma\gamma X$ signal events and the intrinsic bakground at LHC [18].

Figure 13: Signatures for Higgs at LHC [44].

$m_H(\text{GeV})$	$\Delta m(\text{GeV})$	Signal	Background	S/\sqrt{B}
80	1.0	570	11800	5.2
100	1.5	1180	13700	10.1
150	2.0	830	5600	11.1

However, a word of caution has to be added here. In the above studies the QCD induced diphoton production has been calculated using only the Born level box diagrams for the $q\bar{q}(gg) \rightarrow \gamma\gamma$. Recent results from CDF [47] show that the box contribution underestimates their measured $\gamma\gamma$ cross-sections by about a factor 5 and even the inclusion of the higher order correction still gives a discrepancy of a factor ~ 3 between theory and experiment. Of course, CDF has had to use very loose cuts in order to retain a measurable signal and possibility of a contamination of the signal by misidentified jets can not be ruled out. In the SSC/LHC environment much stricter cuts will be allowed which can be used to avoid such contamination. This disagreement also underscores the importance of a good knowledge of the structure functions for these predictions. In view of the crucial role played by this channel in the Higgs search, this issue needs to be studied further more carefully.

Another possibility [48] for the intermediate mass Higgs is to look for associate production of the W and H followed by the decay of Higgs in two photons :

$$pp \rightarrow WHX \rightarrow (W \rightarrow l\nu)(H \rightarrow \gamma\gamma)X \quad (5.1)$$

Again the rates are very small but the background from $pp \rightarrow W\gamma\gamma$ is even smaller. The numbers given in Table 3 show that such a study seems feasible. Again the numbers are for an integrated luminosity of $10^5 pb^{-1}$ for LHC. The WHX signal can also be augmented by $t\bar{t}HX$ channel where the H decays into the $\gamma\gamma$ channel [49]. The two channels together do provide a possibility for the intermediate mass Higgs detection [44].

Table 3: The expected number of events for the signal ($pp \rightarrow HW \rightarrow (H \rightarrow \gamma\gamma)(W \rightarrow l\nu)$) and background expected at LHC [18])

$m_H(\text{GeV})$	Signal	Background		
		irreducible	reducible	total
75	17	6	1	7
100	22	3	1	4
130	18	2	< 1	3

Figure 14: Higgs signal corresponding to $m_H = 600$ and 800 GeV, expected at the LHC for an integrated luminosity of 10^5 pb^{-1} , taken from ref. [44]. The solid line shows the expected background.

For $m_H > m_Z$, the best signal is via the process [50],

$$pp \rightarrow HX \rightarrow ZZX \rightarrow l^+l^-l^+l^-X \quad (5.2)$$

Fig. 14 shows the expected signal in this channel for $m_H = 600$ and 800 GeV, along with the expected background. Thus we see that it is possible to devise cuts to get a significant signal, above the background, in the four lepton channel upto $m_H = 800$ GeV. From fig. 3 it can be seen that $m_H \sim \Gamma_H$, and the concept of Higgs as a fundamental particle does not make much sense. This value is also at the upper end of the limits on Higgs mass implied by the theoretical arguments mentioned in Section 2. Thus we see that the pp colliders will be able to look for a standard model Higgs over the whole practical Higgs mass range, beyond the one that is accessible to LEP 200. The pp collider SSC has a discovery potential similar to that of the LHC only the luminosity required would be a factor 10 smaller due to the higher energy of the SSC [51].

5b) Heavy Higgs ($m_H > 0.6 - 0.8 \text{ TeV}$)

For a heavy Higgs, even for large values of the top mass VV production mechanism of for Higgs given by,

$$qq \rightarrow qqVV \rightarrow qqH \rightarrow qqVV \quad (5.3)$$

dominates over the gluon fusion mechanism

$$gg \rightarrow H \rightarrow VV. \quad (5.4)$$

If $m_t = 100(150)$ GeV the former begins to dominate if $m_H > 0.6(0.8)$ TeV. For such large values of m_H , the possibility of strongly interacting Higgs sector can not be ruled out. This means that VV scattering could produce the same final states as due to Higgs production and decay. Eventhough, the Higgs sector does not become strongly interacting, it would be still necessary to separate the two production processes of the Higgs given in eqs. 5.3 and 5.4. The suggestion to use the high energy, ‘forward’ jets to ‘tag’ the VV fusion events was put forward [52] quite some back. Recently this was analysed for the WW decay mode of H at the LHC workshop [53] and then in more detail for both qqWW and qqZZ final states [54]. The basic idea here is that the forward jets in the process of eq. 5.3 have high energy, high rapidity and $p_T \sim O(m_W)$. The backgrounds are due to the QCD processes (i) $q\bar{q}(gg) \rightarrow t\bar{t}, q\bar{q}(gg) \rightarrow t\bar{t}g$, (ii) $q\bar{q} \rightarrow W^+W^-g$ and of course (iii) the WW scattering. All these are about three to four orders of magintude higher than the signal. However judicious choice of cuts on the rapidities and p_T of the jets gives about 25% efficiency for the $qq \rightarrow qqWW$ channel and roughly 70% efficiency for the $qq \rightarrow qqZZ$. The feasibility of such tagging is very important from the point of vies of analysing the strongly interacting W/Z^s , should they exist.

6) Dark Higgs.

So far we discussed only the SM Higgs search where the dominant decay modes were always into the heaviest fermion–antifermion pair or gauge boson pair. In some extensions of the SM there exists a light scalar but its dominant decay modes are ‘invisible’. Here we are talking about a heavy Higgs ($>$ a few GeV) which is ‘invisible’. Some examples are

1. Certain parameter space in Supersymmetric theories where the dominant decay modes of the lightest Higgs are into neutralinos [55].
2. Majoran models [56] with spontaneously broken lepton number which have Higgs decaying dominantly into a Majoran pair
3. Models where the lightest scalar decays into a pair of Goldstone bosons [57].

Griest and Haber had studied the implications of this for Higgs search at LEP, in the first case. Recently Djouadi[58] and collaborators analysed this issue in view of the LEP constraints on the SUSY parameter space. Their conclusion is that the parameter space which corresponds to a light, ‘invisible’ Higgs, will have other light sparticles *i.e.*, neutralinos and charginos, which should have been seen at LEP-100 or should be seen at LEP 200. The issue of the ‘invisible’ Higgs in the Majoran models was taken up recently [59, 60]. This work demonstrated that it is possible to construct models with a global symmetry such that Higgs will have invisible decays without causing the Z to have large invisible width. A similar analysis in the context of models with spontaneously broken R–parity was also done [61]. Now the signal due to the bremsstrahlung process 4.2 at LEP-100 would be

$$e^+e^- \rightarrow Z^* \rightarrow f\bar{f} + \text{missingenergy}. \quad (6.1)$$

The (theoretical) analyses of [59, 61] show that indeed the LEP mass limits on m_H can be affected by this and the issue should be examined carefully.

If such an invisible Higgs is in the intermediate mass range then it will lead to very characteristic missing energy signatures at the hadron colliders [62] via the process

$$pp \rightarrow ZHX; pp \rightarrow WHX. \quad (6.2)$$

A preliminary analysis of the viability of this signal against the background from the processes

$$pp \rightarrow ZZX; pp \rightarrow WZX \quad (6.3)$$

followed by the decay of Z into $\nu\bar{\nu}$ has been done in first of [62]. It seems indeed possible to separate the signal due to processes of eq. 6.2 from the background. Hence the phenomenology of such an invisible Higgs for different mass ranges and different colliders is an interesting topic for future investigations.

7) Conclusions

Our discussion can be summarised as follows:

- If we demand that the Standard Model be consistent upto an energy scale $\Lambda \sim 1$ TeV a Higgs scalar must exist with $m_H < 600 - 800$ GeV or we should find some evidence for new physics beyond the SM or new perturbative regime at an energy scale ~ 1 TeV.
- LEP 100 has ruled out a SM Higgs with $m_H < 60$ GeV. Further improvements on this limit can now come only from LEP 200.
- Future e^+e^- colliders with $\sqrt{s} = 500$ GeV should be able to look for the SM Higgs upto $m_H \sim 350$ GeV and can in principle afford a detailed determination of its properties to confirm that it is indeed the SM Higgs, should one be found.
- Since the e^+e^- colliders still lie somewhat in the distant future the real Higgs discovery machines are perhaps the pp supercolliders LHC/SSC. These should be able to look for the SM Higgs over the entire range of interest (upto $m_H = 800$ GeV) with an integrated luminosity of $10^5 pb^{-1}$ ($10^4 pb^{-1}$) at the LHC(SSC).
- The $H \rightarrow \gamma\gamma$ decay mode plays a crucial role in making the detection of the SM Higgs over the entire mass range possible. QCD computation of the diphoton production seems to underestimate the current CDF data and this issue needs to be studied carefully before drawing conclusions about the observability of the SM Higgs in the $\gamma\gamma$ channel.
- There exist models where the dominant decay mode of the lightest scalar is into invisible channels and which can affect the current LEP bounds. Phenomenology of such models needs to be investigated.

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