THE SEARCH FOR THE STANDARD MODEL HIGGS BOSON

AT PRESENT AND FUTURE COLLIDERS

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ABSTRACT

I briefly review the Higgs sector in the Standard Model. After summarizing the properties of the Higgs boson, I will discuss the prospects for discovering this particle at the present colliders LEP2 and Tevatron and at the next generation colliders LHC and a high–energy $e^+e^-$ linear collider. The possibilities of studying the properties of the Higgs particle will be then summarized.

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1. The Standard Higgs Boson

1.1 Introduction

The search for Higgs particles is one of the main missions of present and future high–energy colliders. The observation of this particle is of utmost importance for the present understanding of the interactions of the fundamental particles. Indeed, in order to accommodate the well–established electromagnetic and weak interaction phenomena, the existence of at least one isodoublet scalar field to generate fermion and weak gauge bosons masses is required. The Standard Model (SM) makes use of one isodoublet field: three Goldstone bosons among the four degrees of freedom are absorbed to build up the longitudinal components of the massive $W^\pm, Z$ gauge bosons; one degree of freedom is left over corresponding to a physical scalar particle, the Higgs boson [1]. Despite of its numerous successes in explaining the present data, the Standard Model will not be completely tested before this particle has been experimentally observed and its fundamental properties studied.

In the Standard Model, the mass of the Higgs particle is a free parameter. The only available information is the upper limit $M_H > \sim 77$ GeV established at LEP2 [2], although the high–precision electroweak data from LEP and SLC seem to indicate that its mass is smaller than a few hundred GeV [3]. However, interesting theoretical constraints can be derived from assumptions on the energy range within which the model is valid before perturbation theory breaks down and new phenomena would emerge:

- If the Higgs mass were larger than $\sim 1$ TeV, the $W$ and $Z$ bosons would interact strongly with each other to ensure unitarity in their scattering at high energies.
- The quartic Higgs self–coupling, which at the scale $M_H$ is fixed by $M_H$ itself, grows logarithmically with the energy scale. If $M_H$ is small, the energy cut–off $\Lambda$ at which the coupling grows beyond any bound and new phenomena should occur, is large; conversely, if $M_H$ is large, $\Lambda$ is small. The condition $M_H \lesssim \Lambda$ sets an upper limit on the Higgs mass in the SM; lattice analyses lead to an estimate of about 630 GeV for this limit. Furthermore, top quark loops tend to drive the coupling to negative values for which the vacuum is no more stable. Therefore, requiring the SM to be extended to the GUT scale, $\Lambda_{\text{GUT}} \sim 10^{15}$ GeV, and including the effect of top quark loops on the running coupling, the Higgs boson mass should roughly lie in the range between 100 and 200 GeV; see the account given in Ref. [4].

The search for the Higgs particle will be the major goal of the next generation of colliders. In the following, after summarizing the properties of the Higgs boson, I will briefly discuss the discovery potential of the present colliders LEP2 [4] and Tevatron [5] as well as the pp collider LHC [6, 7] with a c.m. energy of $\sim 14$ TeV and a future $e^+e^-$ linear collider [8, 9] with a c.m. energy in the range of 300 to 500 GeV. A more detailed discussion and a complete set of references can be found in Refs. [4–7].
1.2 Decay Modes

In the SM, the profile of the Higgs particle is uniquely determined once $M_H$ is fixed. The decay width, the branching ratios and the production cross sections are given by the strength of the Yukawa couplings to fermions and gauge bosons, the scale of which is set by the masses of these particles. To discuss the Higgs decay modes, it is convenient to divide the Higgs mass into two ranges: the “low mass” range $M_H < \sim 130$ GeV and the “high mass” range $M_H \gtrsim 130$ GeV.

In the “low mass” range, the Higgs boson decays into a large variety of channels. The main decay mode is by far the decay into $b\bar{b}$ pairs with a branching ratio of $\sim 90\%$ followed by the decays into $c\bar{c}$ and $\tau^+\tau^-$ pairs with a branching ratio of $\sim 5\%$. Also of significance, the top–loop mediated Higgs decay into gluons, which for $M_H$ around 120 GeV occurs at the level of $\sim 5\%$. The top and $W$–loop mediated $\gamma\gamma$ and $Z\gamma$ decay modes are very rare the branching ratios being of $O(10^{-3})$; however these decays lead to clear signals and are interesting being sensitive to new heavy particles.

In the “high mass” range, the Higgs bosons decay into $WW$ and $ZZ$ pairs, with one of the gauge bosons being virtual below the threshold. Above the $ZZ$ threshold, the Higgs boson decays almost exclusively into these channels with a branching ratio of $2/3$ for $WW$ and $1/3$ for $ZZ$. The opening of the $t\bar{t}$ channel does not alter significantly this pattern, since for large Higgs masses, the $t\bar{t}$ decay width rises only linearly with $M_H$ while the decay widths to $W$ and $Z$ bosons grow with $M_H^3$.

In the low mass range, the Higgs boson is very narrow $\Gamma_H < 10$ MeV, but the width becomes rapidly wider for masses larger than 130 GeV, reaching 1 GeV at the $ZZ$ threshold; the Higgs decay width cannot be measured directly in the mass range below 250 GeV. For large masses, $M_H \gtrsim 500$ GeV, the Higgs boson becomes obese: its decay width becomes comparable to its mass.

2. Higgs searches at Present Colliders

2.1 Searches at LEP

The most comprehensive search of Higgs bosons done so far was undertaken by the LEP experiments. In the SM, the main production process is the so-called Bjorken or bremsstrahlung process, where the $Z$ resonance emits a Higgs boson, turns virtual and decays into two massless fermions

$$Z \rightarrow Z^*H \rightarrow Hf\bar{f}$$

Although the virtuality of the $Z$ boson is penalizing since the cross section is suppressed by a power of the electroweak coupling, the large number of $Z$ bosons collected at LEP1 allows to have a sizeable rate for not too heavy Higgs bosons. From the negative search of such events, a lower bound of $M_H \gtrsim 65$ GeV has been set. Note
Figure 1: Total decay width $\Gamma(H)$ in GeV and the main branching ratios $BR(H)$ of the SM Higgs decay channels.
that even almost massless Higgs bosons have been ruled out using this process: indeed, even in this case, the Higgs particle will carry momentum and will alter the kinematics of the visible final $Z^* \to f \bar{f}$ state.

At LEP2 \cite{4}, with a center of mass energy above the $2M_W$ threshold, the SM Higgs boson will be searched for using the previous process with the difference that now the final $Z$ boson is on-shell. Although the production rates are much smaller than on the $Z$ resonance, the process is at lowest order in the electroweak coupling and gives a decent cross section. The Higgs bosons will mainly decay into $b\bar{b}$ final states, requiring efficient means to tag the $b$–quark jets. The backgrounds are rather small, except for the process $e^+e^- \to ZZ \to b\bar{b}Z$ for Higgs masses close to $M_Z$. Depending on the final energy which will be reached at LEP2, $\sqrt{s} = 175$ or $192$ GeV, Higgs masses close to 80 and 90 GeV, respectively, can be probed with an integrated luminosity of $\int \mathcal{L} = 150$ pb$^{-1}$. The current Higgs mass bound from these searches is $M_H \gtrsim 77$ GeV \cite{2}.

2.2 Searches at the Tevatron

Currently, the Fermilab Tevatron collider \cite{5} is operating at a c.m. energy $\sqrt{s} = 1.8$ TeV with a luminosity $\mathcal{L} \sim 10^{31}$ cm$^{-2}$s$^{-1}$. With the main injector, which is expected to begin operation in a few years, the luminosity will be increase to $\mathcal{L} \sim 2 \times 10^{32}$ cm$^{-2}$s$^{-1}$ and the c.m. energy to $\sqrt{s} = 2$ TeV. An increase of the luminosity to the level of $\mathcal{L} \sim 10^{33}$ cm$^{-2}$s$^{-1}$ [the so–called TEV33 option] is also currently discussed.

The most promising production mechanism of the SM Higgs boson at the Tevatron collider is the $WH$ process \cite{13}, with the Higgs boson decaying into $b\bar{b}$ [or $\tau^+\tau^-$] pairs

$$qq \to WH \to Wb\bar{b}$$

For Higgs masses $M_H \sim 100$ GeV, the cross section is of the order of a few tens of a picobarn. The related production process $q\bar{q} \to ZH \to Zb\bar{b}$ [which is the equivalent of the Bjorken process in pp collisions] has a smaller cross section, a result of the small neutral current couplings compared to charged current couplings.

The main irreducible backgrounds will consist of $Wb\bar{b}$ and $WZ \to Wb\bar{b}$ for $M_H \sim M_Z$, as well as $t\bar{t}$ production for $M_H \gtrsim 100$ GeV. These backgrounds have cross sections which are of the same order as the signal cross section; an important issue will be the $b\bar{b}$ invariant mass resolution which needs to be measured with a very good accuracy. The Higgs search at the Tevatron with a luminosity of $\sim 2$ fb$^{-1}$ will probably be limited to $M_H \lesssim M_Z$, a mass region which will be already covered at LEP2. To probe Higgs masses larger than $M_Z$, a higher luminosity will be required, and the TEV33 option will be mandatory. A rather detailed analysis for TEV33 with an integrated luminosity of $\int \mathcal{L} \sim 30$ fb$^{-1}$, concluded that Higgs masses up to $M_H \sim 120$ GeV could possibly be reached. The processes $WH, ZH$ with $H \to \tau^+\tau^-$ and $W, Z \to 2$ jets will not significantly change this picture.
3. Higgs Searches at Future Colliders

3.1 Production at LHC

The main production mechanisms of neutral Higgs bosons at hadron colliders are the following processes:

- (a) gluon–gluon fusion: \( gg \rightarrow H \)
- (b) \( W W/ZZ \) fusion: \( VV \rightarrow H \)
- (c) association with \( W/Z \): \( q\bar{q} \rightarrow V + H \)
- (d) association with \( t\bar{t} \): \( gg, q\bar{q} \rightarrow t\bar{t} + H \)

In the interesting mass range, \( 100 \lesssim M_H \lesssim 250 \text{ GeV} \), the dominant production process of the SM Higgs boson is the gluon–gluon fusion mechanism \([14]\) [it is the case of the entire Higgs mass range] for which the cross section is of order a few tens of \( \text{pb} \). It is followed by the \( W W/ZZ \) fusion processes \([15]\) [especially for large \( M_H \)] with a cross section of a few \( \text{pb} \); the cross sections of the associated production with \( W/Z \) \([13]\) or \( t\bar{t} \) \([16]\) are an order of magnitude smaller. Note that for a luminosity of \( \mathcal{L} = 10^{33}(10^{34}) \text{ cm}^{-2}\text{s}^{-1} \), \( \sigma = 1 \text{ pb} \) would correspond to \( 10^4(10^5) \text{ events per year} \).

![Figure 2: Production cross sections of the Higgs boson at LHC; from Ref. [17].](image-url)
Besides the errors due to the relatively poor knowledge of the gluon distribution at small $x$, the lowest order cross sections are affected by large uncertainties due to higher order corrections. Including the next to leading QCD corrections, the total cross sections can be defined properly: the scale at which one defines the strong coupling constant is fixed and the [generally non-negligible] corrections are taken into account. The “K-factors” for $WH/ZH$ production [which can be inferred from the Drell–Yan $W/Z$ production] and the $VV$ fusion mechanisms are small, increasing the total cross sections by $\sim 20$ and $10\%$ respectively [18]; the QCD corrections to the associated $t\bar{t}H$ production are still not known. The [two-loop] QCD corrections to the main mechanism, $gg \rightarrow H$, have been computed [19] and found to be rather large since they increase the cross sections by a factor $\approx 1.8$ at LHC [there is, however, an uncertainty of $\sim 20\%$ due to the arbitrariness of the choice of the renormalization and factorization scales and also of the parton densities].

The signals which are best suited to identify the produced Higgs particles at the LHC have been studied in great detail in Ref. [6]. I briefly summarize here the main conclusions of these studies.

For Higgs bosons in the “high mass” region, $M_H \gtrsim 130$ GeV, the signal consists of the so-called “gold-plated” events $H \rightarrow ZZ^{(*)} \rightarrow 4l^{\pm}$ with $l = e, \mu$. The backgrounds [mostly $pp \rightarrow ZZ^{(*)}, Z\gamma^{*}$ for the irreducible background and $t\bar{t} \rightarrow WWb\bar{b}$ and $Zb\bar{b}$ for the reducible one] are relatively small. One can probe Higgs masses up to $\mathcal{O}(700$ GeV) with a luminosity $\int L = 100$ fb\(^{-1}\) at LHC. The $H \rightarrow WW^{(*)}$ decay channel is more difficult to use because of the large background from $t\bar{t}$ pair production; the $H \rightarrow t\bar{t}$ signal is swamped by the irreducible background from $gg \rightarrow t\bar{t}$. For $M_H \gtrsim 700$ GeV [where the Higgs boson total decay width becomes very large], the search strategies become more complicated; see Ref. [8].

For the “low mass” range, the situation is more complicated. The branching ratio for $H \rightarrow ZZ^{*}$ becomes too small and due to the huge QCD jet background, the dominant mode $H \rightarrow b\bar{b}$ is practically useless; one has then to rely on the rare $\gamma\gamma$ decay mode with a branching ratio of $\mathcal{O}(10^{-3})$. At LHC with a luminosity of $\int L = 100$ fb\(^{-1}\), the cross section times the branching ratio leads to $\mathcal{O}(10^{3})$ events but one has to fight against formidable backgrounds. Jets faking photons need a rejection factor larger than $10^{8}$ to be reduced to the level of the physical background $q\bar{q}, gg \rightarrow \gamma\gamma$ which is still very large. However, if very good geometric resolution and stringent isolation criteria, combined with excellent electromagnetic energy resolution to detect the narrow $\gamma\gamma$ peak of the Higgs boson are available [one also needs a high luminosity $L \simeq 10^{34}$ cm\(^{-2}\)s\(^{-1}\)], this channel, although very difficult, is feasible: for $\int L = 100$ fb\(^{-1}\), ATLAS claims a sensitivity for $110 \lesssim M_H \lesssim 140$ GeV and requires five times more luminosity to reach down masses $M_H \sim 80$ GeV; CMS [which benefits from a good electromagnetic calorimeter] claims a coverage $85 \lesssim M_H \lesssim 150$ GeV for $100$ fb\(^{-1}\). The low end of the mass range is the most challenging due to the small branching ratio and the larger backgrounds.
Complementary production channels would be the \( pp \rightarrow WH, t\bar{t}H \rightarrow \gamma\gamma l\nu \) processes for which the backgrounds are much smaller since one requires an additional lepton. However the signal cross sections are very small too making these processes also difficult. The processes \( pp \rightarrow WH \) and \( t\bar{t}H \) with \( H \rightarrow b\bar{b} \) seem also promising provided that very good micro–vertexing to tag the \( b \)--quarks can be achieved \cite{20}. Another complementary detection channel in the intermediate mass range is \( H \rightarrow WW^* \) \cite{21} which has a larger branching ratio than \( H \rightarrow ZZ^* \); the correlations among the final particles would help to extract the signal from the \( WW \) background.

3.2 Production at \( e^+e^- \) Colliders

At \( e^+e^- \) linear colliders operating in the 500 GeV energy range the main production mechanisms for SM Higgs particles are \cite{8}

\[
\begin{align*}
(a) & \quad \text{bremsstrahlung process} \quad e^+e^- \rightarrow (Z) \rightarrow Z + H \\
(b) & \quad \text{WW fusion process} \quad e^+e^- \rightarrow \bar{\nu} \nu \,(WW) \rightarrow \bar{\nu} \nu + H \\
(c) & \quad \text{ZZ fusion process} \quad e^+e^- \rightarrow e^+e^-\,(ZZ) \rightarrow e^+e^- + H \\
(d) & \quad \text{radiation off tops} \quad e^+e^- \rightarrow (\gamma, Z) \rightarrow t\bar{t} + H 
\end{align*}
\]

The Higgs–strahlung \cite{11} cross section scales as \( 1/s \) and therefore dominates at low energies while the WW fusion mechanism \cite{15, 22} has a cross section which rises like \( \log(s/M_H^2) \) and dominates at high energies. At \( \sqrt{s} \sim 500 \text{ GeV} \), the two processes have approximately the same cross sections for the interesting range \( 100 \text{ GeV} \lesssim M_H \lesssim 200 \text{ GeV} \). With an integrated luminosity \( \int L \sim 50 \text{ fb}^{-1} \), approximately 2000 events per year can be collected in each channel; a sample which is more than enough to discover the Higgs boson and to study it in detail. The ZZ fusion mechanism \( (c) \) and the associated production with top quarks \( (d) \) \cite{23} have much smaller cross sections. But these processes will be very useful when it comes to study the Higgs properties as will be discussed later.

In the Higgs-strahlung process, the recoiling \( Z \) boson [which can be tagged through its clean \( \mu^+\mu^- \) decay] is mono-energetic and the Higgs mass can be derived from the energy of the \( Z \) if the initial \( e^+ \) and \( e^- \) beam energies are sharp [beamstrahlung, which smears out the c.m. energy should thus be suppressed as strongly as possible, and this is already the case for machine designs such as TESLA]. Therefore, it will be easy to separate the signal from the backgrounds. For low Higgs masses, \( M_H \lesssim 130 \text{ GeV} \), the main background will be \( e^+e^- \rightarrow ZZ \). The cross section is large, but it can be reduced by cutting out the forward and backward directions [the process is mediated by \( t--\text{channel} \) \( e \) exchange] and by selecting \( b\bar{b} \) final states by means of \( \mu \)--vertex detectors [while the Higgs decays almost exclusively into \( b\bar{b} \) in this mass range, \( \text{BR}(Z \rightarrow b\bar{b}) \) is small, \( \sim 15\% \)]. The background from single \( Z \) production, \( e^+e^- \rightarrow Zq\bar{q} \), is small and can be further reduced by flavor tagging. In the mass range where the decay \( H \rightarrow WW^* \) is dominant, the main background is triple gauge
boson production and is suppressed by two powers of the electroweak coupling.

The $WW$ fusion mechanism offers a complementary production channel. For small $M_H$, the main backgrounds are single $W$ production, $e^+e^- \rightarrow e^\pm W^\mp \nu$ [$W \rightarrow q\bar{q}$ and the $e^\pm$ escape detection] and $WW$ fusion into a $Z$ boson, $e^+e^- \rightarrow \nu\bar{\nu}Z$, which have cross sections 60 and 3 times larger than the signal, respectively. Cuts on the rapidity spread, the energy and momentum distribution of the two jets in the final state [as well as flavor tagging for small $M_H$] will suppress these background events.

Additional processes are provided by the loop induced associated production of the Higgs boson with a photon [24] and double Higgs production [25]. The cross sections are very small and large luminosities will be required for these processes.

It has been shown in detailed simulations [8], that just a few fb$^{-1}$ of integrated luminosity are needed to obtain a 5$\sigma$ signal for a Higgs boson with a mass $M_H \lesssim 140$ GeV at a 500 GeV collider [in fact, in this case, it is better to go to lower energies where the cross section is larger], even if it decays invisibly [as it could happen in SUSY models for instance]. Higgs bosons with masses up to $M_H \sim 350$ GeV can be discovered at the 5$\sigma$ level, in both the strahlung and fusion processes at an energy of 500 GeV and with a luminosity of 50 fb$^{-1}$. For even higher masses, one needs to increase the c.m. energy of the collider, and as a rule of thumb, Higgs masses up to $\sim 70\%$ of the total energy of the collider can be probed. This means than a $\sim 1$ TeV collider will be needed to probe the entire Higgs mass range in the SM.
4. Study of Higgs properties

Once the Higgs boson is found it will be of great importance to explore all its fundamental properties. This can be done at great details especially in the clean environment of $e^+e^-$ linear colliders: the Higgs mass, the spin and parity quantum numbers and the couplings to fermions and gauge bosons can measured. In the following we will summarise these features in the case of the SM Higgs boson.

4.1 Studies at $e^+e^-$ Colliders

In the Higgs–strahlung process with the $Z$ decaying into visible particles, the mass resolution achieved with kinematical constraints is close to 5 GeV, and a precision of about $\pm 200$ MeV can be obtained on the Higgs mass with $\int \mathcal{L} = 10 \text{ fb}^{-1}$ if the effects of beamstrahlung are small [26]. For masses below 250 GeV, the Higgs boson is extremely narrow and its width cannot be resolved experimentally; only for higher masses [or at $\mu^+\mu^-$ colliders, see [27] e.g.] $\Gamma_H$ can be measured directly.

The angular distribution of the $Z/H$ in the Higgs–strahlung process is sensitive to the spin–zero of the Higgs particle: at high–energies the $Z$ is longitudinally polarized and the distribution follows the $\sim \sin^2 \theta$ law which unambiguously characterizes the production of a $J^P = 0^+$ particle. The spin–parity quantum numbers of the Higgs bosons can also be checked experimentally by looking at correlations in the production $e^+e^- \to ZZ/WW$ bosons, as well as in the more difficult channel $H \to \tau^+\tau^-$ [29] for $M_H \lesssim 140$ GeV. An unambiguous test of the CP nature of the Higgs bosons can be made in the process $e^+e^- \to t\bar{t}H$ [30] or at laser photon colliders in the loop induced process $\gamma\gamma \to H$ [31].

The masses of the fermions are generated through the Higgs mechanism and the Higgs couplings to these particles are proportional to their masses. This fundamental prediction has to be verified experimentally. The Higgs couplings to $ZZ/WW$ bosons can be directly determined by measuring the production cross sections in the bremsstrahlung and the fusion processes. In the $e^+e^- \to H\mu^+\mu^-$ process, the total cross section can be measured with a precision of less than 10% with $50 \text{ fb}^{-1}$ [26].

The Higgs couplings to light fermions are harder to measure, except if $M_H \lesssim 140$ GeV. The Higgs branching ratios to $b\bar{b}$, $\tau^+\tau^-$ and $c\bar{c} + gg$ can be measured with a precision of $\sim 5, 10$ and $40\%$ respectively for $M_H \sim 110 \text{ GeV}$ [12]. For $M_H \sim 140$ GeV, $\text{BR}(H \to WW^*)$ becomes sizeable and can be experimentally determined; in this case the absolute magnitude of the $b$ coupling can be derived since the $HWW$ coupling is fixed by the production cross section. The Higgs coupling to top quarks, which is the largest coupling in the SM is directly accessible in the process $e^+e^- \to t\bar{t}H$ [3]. For $M_H \lesssim 130$ GeV, $\lambda_t$ can be measured with a precision of about $10$ to $20\%$ at $\sqrt{s} \sim 500 \text{ GeV}$ with $\int \mathcal{L} \sim 50 \text{ fb}^{-1}$. For $M_H \gtrsim 350$ GeV, the $Ht\bar{t}$ coupling can be derived by measuring the $H \to t\bar{t}$ branching ratio at higher energies [34].
Finally, the measurement of the trilinear Higgs self-coupling, which is the first non-trivial test of the Higgs potential, is accessible in the double Higgs production processes $e^+e^- \to ZHH$ and $e^+e^- \to \nu\bar{\nu}HH$ [35]. However, the cross sections are rather small and very high luminosities [and very high energies in the second process] are needed.

4.2 Studies at the LHC

In the “low mass” range, the Higgs boson will appear as a very narrow bump in the $\gamma\gamma$ invariant mass spectrum. The ATLAS and CMS collaborations [6] claim a $\gamma\gamma$ invariant mass resolution of approximately 1 GeV; so the Higgs boson mass will be measured with a good accuracy if it is detected via its two-photon decay mode.

For masses above 250 GeV, the Higgs boson width will be greater than the experimental $4l^\pm$ resolution and can therefore be measured directly. This allows the determination of the $HW$ and $HZZ$ couplings [assuming that are related by SU(2) custodial symmetry] since the $H \to t\bar{t}$ branching ratio is rather small. Since the $4l^\pm$ rate is proportional to $\sigma(gg \to H) \times \text{BR} (H \to ZZ)$, one could then determine $\Gamma(H \to gg)$ which allows to extract the $Ht\bar{t}$ coupling [since the $Hgg$ couplings is dominantly mediated by the top quark loop contribution]. Some ratios of couplings could also be determined by considering the processes $gg \to H, qq \to WH$ and $gg \to ttH$ with the subsequent decays $H \to \gamma\gamma$ or $b\bar{b}$.

5. Summary

At the hadron collider LHC, the Standard Model Higgs boson can, in principle, be discovered up to masses of $\mathcal{O}(1 \text{ TeV})$. While the region $M_H > 130$ GeV can be easily probed through the $H \to 4l^\pm$ channel, the $M_H \lesssim 130$ GeV region is difficult to explore and a dedicated detector as well as a high–luminosity is required to isolate the $H \to \gamma\gamma$ decay.

$e^+e^-$ linear colliders with energies in the range of $\sim 500$ GeV are ideal instruments to search for Higgs particles in the mass range below $\sim 250$ GeV. The search for the Standard Model Higgs particle can be carried out in several channels and the clean environment of the colliders allows to investigate thoroughly its properties. Once the Higgs bosons are found, the clean environment of $e^+e^-$ colliders allows to study at great details the fundamental properties of these particles. In this respect, even if Higgs particles are found at LHC, high energy $e^+e^-$ colliders will provide an important information which make them complementary to hadron machines.

References
[1] For a review on the Higgs sector see J.F. Gunion, H.E. Haber, G.L. Kane and S. Dawson, “The Higgs Hunter’s Guide”, Addison–Wesley, Reading 1990.

[2] P. Janot, talk given at the International Europhysics Conference on High Energy Physics, 19-26 August 1997, Jerusalem.

[3] For a review see, W. Hollik, Talk given at 28th International Conference on High-energy Physics (ICHEP 96), Warsaw, Poland, 25-31 Jul 1996; hep-ph/9610457.

[4] M. Carena and P.M. Zerwas, Report of the Higgs working group in ”Physics at LEP2”, CERN Yellow Report 96–01.

[5] Report of the Tev2000 study group on ”Future Electroweak Physics at the Tevatron”, D. Amidei and R. Brock, eds. (1995).

[6] ATLAS Collaboration, Technical Proposal, Report CERN–LHCC 94–43; CMS Collaboration, Technical Proposal, Report CERN–LHCC 94–38.

[7] Froidevaux, Z. Kunszt and J. Stirling [conv.] et al., in Proceedings of the Large Hadron Collider Workshop, Aachen 1990, Report CERN 90–10, Vol. II; See also the Rapporteurs talks by G. Altarelli and D. Denegri in the same proceedings.

[8] Report ”Conceptual Design of a 500 GeV e+e− Collider”, DESY 1997–048, R. Brinkman et al. (eds); S. Kuhlman et al., NLC ZDR Design Group and the NLC Physics Working Group, SLAC–R–0485.

[9] Proceedings of the Workshops “e+e− Collisions at 500 GeV: the Physics Potential”, DESY Reports 92–123A–D, P. Zerwas ed.

[10] For an update of the Higgs decay modes see A. Djouadi, M. Spira and P.M. Zerwas, Z. Phys. C70 (1995) 435.

[11] J. Ellis, M. K. Gaillard and D.V. Nanopoulos, Nucl. Phys. B106 (1976) 292; B.W. Lee, C. Quigg and H.B. Thacker, Phys. Rev. D16 (1977) 1519; J.D. Bjorken, Proceedings of Summer Institute on Particle Physics, SLAC Report 198 (1976); B.L. Ioffe and V.A. Khoze, Sov. J. Part. Nucl. 9 (1978) 50.

[12] Particle Data Group, Phys. Rev. D54 1 (1996).

[13] S.L. Glashow, D.V. Nanopoulos and A. Yildiz, Phys. Rev. D18 (1978) 1724; Z. Kunszt, Z. Trocsanyi and W.J. Stirling, Phys. Lett. B271 (1991) 247.

[14] H. Georgi et al., Phys. Rev. Lett. 40 (1978) 692.
[15] G. Altarelli, B. Mele and F. Pitoli, Nucl. Phys. B287 (1987) 205; 
R.N. Cahn and S. Dawson, Phys. Lett. 136B (1984) 196.

[16] Z. Kunszt, Nucl. Phys. B247 (1984) 339; 
J.F. Gunion, Phys. Lett. B253 (1991) 269; 
W. Marciano and F. Paige, Phys. Rev. Lett. 66 (1991) 2433.

[17] M. Spira, hep-ph/9705337.

[18] T. Han and S. Willenbrock, Phys. Lett. B273 (1991) 167; 
T. Han, G. Valencia and S. Willenbrock, Phys. Rev. Lett. 69 (1992) 3274.

[19] A. Djouadi, M. Spira and P.M. Zerwas, Phys. Lett. B264 (1991) 440; 
S. Dawson, Nucl. Phys. B359 (1991) 283; 
M. Spira et al., Nucl. Phys. B453 (1995) 17.

[20] J. Dai, J.F. Gunion and R. Vega, Phys. Rev. Lett. 71 (1993) 2699; 
D. Froidevaux and E. Richter-Was, Z. Phys. C67 (1995) 213.

[21] M. Dittmar and H. Dreiner, Phys. Rev. D55 (1997) 167.

[22] D.R.T. Jones and S.T. Petcov, Phys. Lett. 84B (1979) 440; 
K. Hikasa, Phys. Lett. 164B (1985) 341; 
W. Kilian, M. Kramer and P.M. Zerwas, Phys. Lett. B373 (1996) 135.

[23] A. Djouadi, J. Kalinowski and P. M. Zerwas, Z. Phys. C54 (1992) 255.

[24] A. Barroso, J. Pulido, J. C. Romao, Nucl. Phys. B267 (1985) 509; 
A. Abbasabadi, D. Bowser-Chao, D. A. Dicus and W. A. Repko, Phys. Rev. D52 
(1995) 3919; 
A. Djouadi, V. Driesen, W. Hollik and J. Rosiek, Nucl. Phys. B491 (1997) 68.

[25] K.J.F. Gaemers and F. Hoogeveen, Z. Phys. C26 (1984) 249; 
A. Djouadi, V. Driesen and C. Jünger, Phys. Rev. D54 (1996) 759.

[26] P. Janot, Talk given at the Workshop on Physics and Experiments with Linear 
Colliders, Hawaii, 1993.

[27] V. Barger, M. S. Berger, J.F. Gunion and T. Han, Phys. Rept. 286 (1997) 1.

[28] V. Barger, K. Cheung, A. Djouadi, B. A. Kniehl and P. Zerwas, Phys. Rev. D49 
(1994) 79; 
K. Hagiwara and M. L. Stong Z. Phys. C62 (1994) 99.

[29] M. Krämer, J. Kühn, M. L. Stong and P. M. Zerwas, Z. Phys. C64 (1994) 21.

[30] J.F. Gunion, B. Grzadkowski and X.G. He, Phys. Rev. Lett. 77 (1996) 5172.
[31] B. Grzadkowski and J. F. Gunion, Phys. Lett. B294 (1992) 361.

[32] M. Hildreth, T. L. Barklow and D. L. Burke, Phys. Rev. D49 (1994) 3441.

[33] Proceedings of the Workshops “$e^+e^-$ Collisions at 500 GeV: The Physics Potential”, DESY Reports 92–123A (August 1992) and 93–123C (September 1993), P. Zerwas, ed.

[34] K. Hagiwara, H. Murayama and I. Watanabe, Nucl. Phys. B367 (1991) 257.

[35] G. Gounaris, D. Schildknecht and F. Renard, Phys. Lett. B83 (1979) 191 and (E) 89B (1980) 437;
   V. Barger and T. Han, Mod. Phys. Lett. A5 (1990) 667;
   A. Djouadi, H. E. Haber and P. M. Zerwas, Phys. Lett. B375 (1996) 203;
   V. Ilyin, A. Pukhov, Y. Kurihara, Y. Shimitzu and T. Kaneko, Phys. Rev. D54 (1996) 6717;
   F. Boudjema and E. Chopin, Z. Phys. C73 (1996) 85.