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HIGGS PHENOMENOLOGY: A SHORT REVIEW

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ABSTRACT

I briefly review the Higgs sector in the Standard Model and in its minimal supersymmetric extension. After summarizing the properties of the Higgs bosons, I will discuss the prospects for discovering these particles 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 bosons will be then summarized.

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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 accomodate 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 $M_H \gtrsim 65$ GeV established at LEP1 [2], although the high–precision electroweak data from LEP and SLC seem to indicate that its mass is smaller than a few hundred GeV [2]. 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 ~ 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 Λ at which the coupling grows beyond any bound and new phenomena should occur, is large; conversely, if M_H is large, Λ 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, $\Lambda_{\rm GUT} \sim 10^{15}$ 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 Ref. [3] for a recent discussion.

However, there are two problems that one has to face when trying to extend the SM to $\Lambda_{\rm GUT}$. The first one is the so–called hierarchy or naturalness problem: the Higgs boson tends to acquire a mass of the order of these large scales [the radiative corrections to M_H are quadratically divergent]; the second problem is that the simplest GUTs predict a value for $\sin^2\theta_W$ that is incompatible with the measured value $\sin^2\theta_W \simeq 0.23$. Low energy supersymmetry solves these two problems at once: supersymmetric particle loops cancel exactly the quadratic divergences and contribute to the running of the gauge coupling constants, correcting the small discrepancy to the observed value of $\sin^2\theta_W$; see Ref. [3] for a recent review.

The minimal supersymmetric extension of the Standard Model (MSSM) requires the existence of two isodoublets of Higgs fields, to cancel anomalies and to give mass separately to up and down–type fermions [1]. Three neutral, h/H(CP=+), A(CP=–) and a pair of charged scalar particles, $H^{\pm}$, are introduced by this extension of the Higgs sector. Besides the four masses, two additional parameters define the properties of these particles: a mixing angle α in the neutral CP–even sector and the ratio of the two vacuum expectation values tgβ, which from GUT restrictions is assumed in the range $1 \lesssim \mathrm{tg}\beta \lesssim m_t/m_b$ with the lower and upper ranges favored by Yukawa coupling unification.

Supersymmetry leads to several relations among these parameters and only two of them are in fact independent. These relations impose a strong hierarchical structure on the mass spectrum, $M_h < M_Z, M_A < M_H$ and $M_W < M_{H^\pm}$, which however is broken by radiative corrections if the top quark mass is large [4]. For instance, the upper bound on the mass of the lightest Higgs boson h is shifted from the tree level value M_Z to ~ 130 GeV. The masses of the heavy neutral and charged Higgs particles can be expected, with a high probability, in the range of the electroweak symmetry breaking scale.

Some of these features are not specific to the minimal extension and are expected to be realized also in more general SUSY models. For instance, a light Higgs boson with a mass below $\mathcal{O}(200$ GeV) is quite generally predicted by SUSY theories [5].

The search for these Higgs particles will be the major goal of the next generation of colliders. In the following, after summarizing the properties of the Higgs bosons, I will briefly discuss the discovery potential of the present colliders LEP2 [6] and Tevatron [7] as well as the pp collider LHC [8–10] with a c.m. energy of ~ 14 TeV and a future e^+e^- linear collider [11–13] with a c.m. energy in the range of 300 to 500 GeV. The case of future muon colliders is discussed in Ref. [13]. More detailed discussions and a complete set of references can be found in Refs. [6–14].

2. Couplings and Decay Modes

2.1 Standard Higgs boson

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 [1, 14], it is convenient to divide the Higgs mass into two ranges: the "low mass" range $M_H \lesssim 130$ 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 $\mathcal{O}(10^{-3})$; 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.

2.2 MSSM Higgs bosons

In the MSSM, one usually chooses the basic parameters to be the mass of the pseudoscalar Higgs boson M_A and tgβ. Once these two parameters are specified, all other masses and the angle α can be derived at the tree–level. These relations are however affected by radiative corrections, the leading part of which grows as m_t^4 and logarithmically with the common squark mass. Subleading corrections will introduce the soft–SUSY breaking trilinear coupling $A_{t,b}$ and Higgs–higgsino mass parameter μ.

The couplings of the various neutral Higgs bosons [collectively denoted by Φ] to fermions and gauge bosons will in general strongly depend on the angles α and β; normalized to the SM Higgs couplings, they are given by

Φ	$g_{\Phi\bar{u}u}$	$g_{\Phi\bar{d}d}$	$g_{\Phi VV}$
h	$\cos\alpha/\sin\beta$	$-\sin\alpha/\cos\beta$	$\sin(\beta-\alpha)$
H	$\sin\alpha/\sin\beta$	$\cos\alpha/\cos\beta$	$\cos(\beta-\alpha)$
A	$1/\mathrm{tg}\beta$	$\mathrm{tg}\beta$	0

The pseudoscalar has no tree level couplings to gauge bosons, and its couplings to down (up) type fermions are (inversely) proportional to tgβ. It is also the case for the couplings of the charged Higgs particle to fermions which are a mixture of scalar and pseudoscalar currents and depend only on tgβ. For the CP–even Higgs bosons, the couplings to down (up) type fermions are enhanced (suppressed) compared to the SM Higgs couplings [tg$\beta \gtrsim 1$]. If the pseudoscalar mass is large, the h boson reaches its upper limit [which depends on the value of tgβ] and its couplings to fermions and gauge bosons are SM like; the CP–even and charged Higgs bosons H and $H^\pm$ will be degenerate with A. In this decoupling limit, it is very difficult to distinguish the

Higgs sector of the MSSM from the one of the SM.

Since its mass is smaller than $\sim$ 130 GeV, the lightest Higgs boson will decay mainly into fermion pairs, mostly $b\bar{b}$ and $\tau^+\tau^-$ pairs since the couplings of these particles are enhanced for tg$\beta > 1$; the decays into $c\bar{c}$ as well as the gg decay are in general strongly suppressed especially for large values of tgβ. In the decoupling limit, the h branching ratios become SM–like and for masses close to 130 GeV, the $h \to WW^*$ becomes of some relevance. The two–photon decay mode of the h is suppressed in general compared to the SM.

The decay pattern of the heavier MSSM Higgs bosons [1, 14] depend strongly on the value of tgβ. For large tgβ values, the pattern is quite simple: the neutral Higgs boson H and A will mainly decay into $b\bar{b}$ and $\tau^+\tau^-$ pairs with branching ratios close to 90% and 10% respectively, and the charged Higgs boson will decay into $\tau\nu_\tau$ or tb pairs, depending on whether it is lighter or heavier than the top quark.

For small values of tgβ the situation is simple only above the $2m_t$ $[m_t + m_b]$ threshold for neutral [charged] Higgs bosons: the decay channels $H, A \to t\bar{t}$ and $H^+ \to t\bar{b}$ are then dominating. Below the top threshold, the H boson mainly decays into two light Higgs bosons $H \to hh$, while the pseudoscalar decays into the lightest Higgs boson h and a Z boson. The decays into $b\bar{b}$ and *a fortiori* the decays into the lighter fermions are rare in general; for $b\bar{b}$ they are important only for small A, H masses when the channel $A \to Zh$ is closed or the trilinear Hhh coupling is small. The decays into WW/ZZ pairs are suppressed for H and due to CP invariance are absent in the case of A. For the charged Higgs boson, the decays $H^\pm \to hW^\pm$ [and if A is light, the decays $H^\pm \to AW^\pm$] are also of significance below the tb threshold.

The branching ratios of the $\gamma\gamma$ and $Z\gamma$ decays are smaller than in the SM; this is due to the fact that the $b\bar{b}$ decays are enhanced for tg$\beta \gtrsim 1$ and the dominant W–loop contribution is suppressed (absent) in the case of the CP–even (odd) Higgs bosons.

Other possible channels are the decays into SUSY particles. Indeed the Higgs decays into charginos and neutralinos could be very important since some of these particles are expected to have masses of $\mathcal{O}(M_Z)$. For small values of tgβ and below the $t\bar{t}$ threshold, these decays become in fact dominant. The decays into squarks, and in particular top squarks can also be very important for small tgβ since the Higgs couplings to top squark is very strong [proportional to m_t^2]; in fact, when they are kinematically allowed, these channels are the dominant ones. Decays of the Higgs bosons into sleptons when kinematically allowed are marginal.

Adding up the various decay modes, the width of all five Higgs bosons are relatively narrow compared to the SM case: for small masses they are below a few GeV, while for masses $\sim$ 1 TeV they can reach values of order a few ten GeV if tgβ is extremely large. This has to be contrasted with the SM where the width becomes comparable to its masses in the TeV range: in the MSSM, the decay into massive gauge boson pairs is either absent or strongly suppressed and the widths increase only linearly with the Higgs masses.

3. Higgs searches at Present colliders

3.1 Searches at LEP

The most comprehensive search of Higgs bosons done so far was undertaken by the LEP experiments [2]. 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

$$(a) \qquad Z \to Z^* H \to H f \bar{f}$$

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 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.

The LEP collaborations have also searched for the MSSM lightest CP–even Higgs boson h and for a light pseudoscalar particle A. The h boson can be produced in the Bjorken process as in the case of the SM Higgs, but here the cross section is suppressed by the hZZ coupling squared $\sin^2(\beta - \alpha)$. The h boson can also be produced in association with the pseudoscalar Higgs boson A

$$(b) \qquad Z \to hA$$

The cross section is suppressed by a factor $\cos^2(\beta - \alpha)$ and therefore this process is complementary to the bremsstrahlung process. For A masses below $M_A \lesssim M_Z/2$, the sum of the cross sections of the two production channels is always large; a bound of $M_h \sim M_A \gtrsim 45$ GeV has been set on the two particles.

At LEP2 [6], with a center of mass energy above the $2M_W$ threshold, the SM Higgs boson will be searched for using the same process (a) with the difference that now the final Z boson is on–shell. The process is thus at lowest order in the electroweak coupling and gives a decent cross section, although we are no more on the Z resonance. 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} [6].

Similarly to the LEP1 case, the MSSM Higgs bosons can be searched for in the bremsstrahlung and the associated production processes $e^+e^- \to hZ$ and $e^+e^- \to Ah$ with the Z boson being on–shell for the first channel. The h and A bosons will mainly decay into $b\bar{b}$ final states. Again the background events are rather small, and using the complementarity of the two processes, the range $M_h \lesssim 80$ or 90 GeV can be probed with a luminosity $\int \mathcal{L} \sim 150$ pb^{-1} at c.m. energies $\sqrt{s} = 175$ or 192 respectively [6]. This means that the entire range for the h mass, $M_h \lesssim 80$ GeV, for small values of tg$\beta \lesssim 1.5$ [which are favored by the requirement of b–τ Yukawa coupling unification] can be probed at LEP2. If the Higgs boson has a mass in the range $90 \lesssim M_h \lesssim 130$ GeV [for larger tgβ values], its production will have to await for the next generation of colliders.

3.2 Searches at the Tevatron

Currently, the Fermilab Tevatron collider 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 $\mathcal{L} \sim 2.10^{32}$ 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 [7].

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

$$(c) \qquad qq \to WH \to Wb\bar{b}$$

For Higgs masses $M_H \sim 100$ GeV, the cross section is of the order of a few tenths 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 ~ 2 fb^{-1} will probably be limited to $M_H \lesssim M_Z$ [7], 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 [7]. The processes WH, ZH with $H \to \tau^+\tau^-$ and $W, Z \to 2$ jets will not significantly change this picture.

In the MSSM, the only useful production mechanism will also be the Wh strahlung process with $h \to b\bar{b}$, since the associated production mechanism $q\bar{q} \to Ah$ would have a too small cross section as in the case of the $q\bar{q} \to Zh$ process. However, the Wh production cross section will be suppressed by a factor $\sin^2(\beta - \alpha)$ compared to the SM Higgs boson case, except if the h mass is maximal for a given value of tgβ for which $\sin^2(\beta - \alpha) = 1$. In this case, h is almost SM like and the discovery reach of the Tevatron will be the same as previously discussed.

4. Production at LHC

4.1 SM Higgs Boson

The main production mechanisms of neutral Higgs bosons at hadron colliders are the following processes [8, 9]

$$\begin{array}{clrcl} (a) & \text{gluon}-\text{gluon fusion} & gg & \rightarrow & H \\ (b) & WW/ZZ \text{ fusion} & VV & \rightarrow & H \\ (c) & \text{association with } W/Z & q\bar{q} & \rightarrow & V+H \\ (d) & \text{association with } \bar{t}t & gg, q\bar{q} & \rightarrow & t\bar{t}+H \end{array}$$

In the interesting mass range, $100 \lesssim M_H \lesssim 200$ GeV, the dominant production process of the SM Higgs boson is the gluon–gluon fusion mechanism [in fact, it is the case of the entire Higgs mass range] for which the cross section is of order a few tens of pb. It is followed by the WW/ZZ fusion processes [especially for large M_H] with a cross section of a few pb; the cross sections of the associated production with W/Z or $t\bar{t}$ are an order of magnitude smaller. Note that for a luminosity of $\mathcal{L} = 10^{33}(10^{34})$ cm^{-2}s^{-1}, $\sigma = 1$ pb would correspond to $10^4(10^5)$ events per year.

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; 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 [15] and found to be rather large since they increase the cross sections by a factor $\simeq 1.8$ 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 Refs. [8,9]. 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 $\int \mathcal{L} = 100$ 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 $H \to ZZ^*$ becomes too small and due to the huge QCD jet background, the dominant mode $H \to b\bar{b}$ 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 $\int \mathcal{L} = 100$ 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 $q\bar{q}, gg \to \gamma\gamma$ 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 $\mathcal{L} \simeq 10^{34}$ cm^{-2}s^{-1}], this channel, although very difficult, is feasible: for $\int \mathcal{L} = 100$ fb^{-1}, ATLAS claims a sensitivity for 110 GeV $\lesssim M_H \lesssim$ 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 GeV $\lesssim M_H \lesssim$ 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 $pp \to WH, t\bar{t}H \to \gamma\gamma l\nu$ 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 $pp \to WH$ and $t\bar{t}H$ with $H \to b\bar{b}$ seem also promising provided that very good micro–vertexing to tag the b–quarks can be achieved.

4.2 MSSM Higgs Bosons

In the MSSM, the situation is more difficult than in the SM. The production mechanisms of the neutral SUSY Higgs bosons are practically the same as those of the SM Higgs; one only has to take the b quark [whose couplings are strongly enhanced for large tgβ values] contributions into account in the $gg \to$ Higgs process [and also the extra contributions from squarks loops, which however decouple for high squark masses] and for tg$\beta \gg 1$, the $q\bar{q} \to b\bar{b} + A/H$ processes become the dominant production mechanisms for the H and A bosons. The cross sections are the same as in the case of the SM, modulo mixing angle suppression/enhancement factors.

The various signals for the SUSY Higgs bosons can be summarized as follows:

i) Since the lightest Higgs boson mass is always smaller than $\sim$ 130 GeV, the ZZ signal cannot be used. Furthermore, the $hWW(hb\bar{b})$ coupling is suppressed (enhanced) leading to a smaller $\gamma\gamma$ branching ratio than in the SM [additional contributions from chargino and sfermion loops can also alter the decay width] making the search more difficult. If M_h is close to its maximum value, h has SM like couplings and the situation is similar to the SM case with $M_H \sim$ 80–130 GeV.

ii) Since A has no tree–level couplings to gauge bosons and since the couplings of the heavy CP–even H are strongly suppressed, the gold–plated ZZ signal is lost [for H it survives only for small tgβ values, provided that $M_H < 2m_t$]. In addition, the $A, H \to \gamma\gamma$ signals cannot be used since the branching ratios are suppressed. One has then to rely on the $A, H \to \tau^+\tau^-$ channels for large tgβ values; this mode, which is hopeless for the SM Higgs, seems to be feasible in this case. For small tgβ and below the $t\bar{t}$ threshold, the cascade decays $H \to hh \to b\bar{b}b\bar{b}$ and $A \to hZ \to Zb\bar{b}$ have large branching ratios and can be employed if efficient b–tagging is available at LHC. The decays $H/A \to t\bar{t}$ are challenging to detect.

iii) Charged Higgs particles, if lighter than the top quark, can be accessible in top decays $t \to H^+b$. This results in a surplus of τ lepton final states [the main decay mode is $H^- \to \tau\nu_\tau$] over μ, e final states, an apparent breaking of τ *vs.* e, μ universality. At LHC, $H^\pm$ masses up to $\sim$ 140 GeV can be probed for $m_t \sim 175$ GeV. Additional improvements in some areas of the parameter space can be made by considering the process $gg \to tbH^\pm \to t\bar{t}b\bar{b}$ with efficient b–tagging.

iv) All the previous discussion assumes of course that the decays into supersymmetric particles are kinematically inaccessible. This seems to be very unlikely, since at least the decays of the heavy Higgs particles H, A and $H^\pm$ into charginos and neutralinos should be possible. If this scenario is realised, the discovery of these Higgs particles will be even more challenging. If the lightest neutralinos are lighter than $M_h/2$, then the discovery of the lightest Higgs [and also of the heavier ones] will be practically impossible at LHC.

Thus, the search for SUSY Higgs bosons is more difficult than the search for the SM Higgs, especially if the decays into SUSY particles are possible. If SUSY decays are kinematically not allowed, detailed analyses of the ATLAS and CMS collaborations concluded that at least one Higgs boson will be discovered in the entire MSSM parameter space, after a few years of running with a luminosity of $10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$.

5. Production at $\mathrm{e}^+\mathrm{e}^-$ Colliders

5.1 SM Higgs boson

At e^+e^- linear colliders operating in the 500 GeV energy range the main production mechanisms for SM Higgs particles are [11, 12]

$$\begin{array}{llll} (a) & \text{bremsstrahlung process} & e^+e^- & \to (Z) \to Z + H \\ (b) & WW \text{ fusion process} & e^+e^- & \to \bar{\nu}\ \nu\ (WW) \to \bar{\nu}\ \nu\ + H \\ (c) & ZZ \text{ fusion process} & e^+e^- & \to e^+e^-(ZZ) \to e^+e^- + H \\ (d) & \text{radiation off tops} & e^+e^- & \to (\gamma, Z) \to t\bar{t} + H \end{array}$$

The Higgs–strahlung cross section scales as $1/s$ and therefore dominates at low energies while the WW fusion mechanism has a cross section which rises like $\log(s/M_H^2)$ and dominates at high energies. At $\sqrt{s} \sim 500$ GeV, the two processes have approximately the same cross sections for the interesting range 100 GeV $\lesssim M_H \lesssim$ 200

GeV. With an in integrated luminosity $\int \mathcal{L} \sim 50$ 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) 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, $M_H \lesssim 130$ GeV, the main background will be $e^+e^- \to ZZ$. The cross section is large, but it can be reduced by cutting out the forward and backward directions [the process is mediated by t–channel e exchange] and by selecting $b\bar{b}$ final states by means of μ–vertex detectors [while the Higgs decays almost exclusively into $b\bar{b}$ in this mass range, BR($Z \to b\bar{b}$) is small, $\sim 15\%$]. The background from single Z production, $e^+e^- \to Zq\bar{q}$, is small and can be further reduced by flavor tagging. In the mass range where the decay $H \to WW^*$ 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, $e^+e^- \to e^\pm W^\mp \nu$ [$W \to q\bar{q}$ and the $e^\pm$ escape detection] and WW fusion into a Z boson, $e^+e^- \to \nu\bar{\nu}Z$, 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.

It has been shown in detailed simulations, that just a few fb^{-1} of integrated luminosity are needed to obtain a 5σ 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 5σ 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 ~ 1 TeV collider will be needed to probe the entire Higgs mass range in the SM.

5.2 MSSM Higgs bosons

An even stronger case for e^+e^- colliders in the 300–500 GeV energy range is made by the MSSM. In e^+e^- collisions, besides the usual bremsstrahlung and fusion processes for h and H production, the neutral Higgs particles can also be produced pairwise:

$e^+e^- \to A + h/H$. The cross sections for the bremsstrahlung and the pair production as well as the cross sections for the production of h and H are mutually complementary, coming either with a coefficient $\sin^2(\beta-\alpha)$ or $\cos^2(\beta-\alpha)$. The cross section for hZ production is large for large values of M_h, being of $\mathcal{O}(50$ fb); by contrast, the cross section for HZ is large for light h [implying small M_H]. In major parts of the parameter space, the signals consist of a Z boson and a $b\bar{b}$ or a $\tau^+\tau^-$ pair, which is easy to separate from the main background, $e^+e^- \to ZZ$ [for $M_h \simeq M_Z$, efficient b detection is needed]. For the associated production, the situation is opposite: the cross section for Ah is large for light h whereas AH production is preferred in the complementary region. The signals consists mostly of four b quarks in the final state, requiring efficient $b\bar{b}$ quark tagging; mass constraints help to eliminate the QCD jets and ZZ backgrounds. The CP–even Higgs particles can also be searched for in the WW and ZZ fusion mechanisms.

In e^+e^- collisions, charged Higgs bosons can be produced pairwise, $e^+e^- \to H^+H^-$ through γ, Z exchange. The cross section depends only on the charged Higgs mass; it is large up to $M_{H^\pm} \sim 230$ GeV. Charged Higgs bosons can also be created in laser–photon collisions, $\gamma\gamma \to H^+H^-$ but due to the reduced energy, only smaller masses than previously can be probed. The cross section, however, is enhanced in the low mass range. Finally, charged Higgs bosons can be produced in top decays as discussed above in the case of proton colliders. In the range $1 < \mathrm{tg}\beta < m_t/m_b$, the $t \to H^+b$ branching ratio varies between $\sim 2\%$ and 20% and since the cross section for $t\bar{t}$ production is $\mathcal{O}(0.5$ pb) at $\sqrt{s} = 500$ GeV, this corresponds to 200 and 2000 charged Higgs bosons at a luminosity $\int \mathcal{L} = 10$ fb^{-1}.

The preceding discussion on the MSSM Higgs sector in e^+e^- linear colliders can be summarized in the following points [11, 12]:

i) The Higgs boson h can be detected in the entire range of the MSSM parameter space, either through the bremsstrahlung process or through pair production. In fact, this conclusion holds true even at a c.m. energy of 300 GeV.

ii) There is a substantial area of the $(M_h, \mathrm{tg}\beta)$ parameter space where *all* SUSY Higgs bosons can be discovered at a 500 GeV collider. This is possible if the H, A and $H^\pm$ masses are less than ~ 230 GeV. For large Higgs masses, one simply has to increase the c.m. energy.

iii) Even if SUSY Higgs decays are allowed to occur, the Higgs particles can be easily detected in e^+e^- collisions. Using the missing mass technique, the CP–even h and H bosons can be detected in the bremsstrahlung process even if they decay invisibly. The pseudoscalar and the charged Higgs bosons can also be detected by looking at mixtures of SUSY and standard decays which occur at observable rates.

vi) In some parts of the MSSM parameter space, the lightest Higgs h can be detected, but it cannot be distinguished from the SM Higgs boson. In this case, Higgs production in $\gamma\gamma$ fusion [which receives extra contributions from SUSY particle loops] can be helpful.

6. 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 summarize these features in the case of the SM Higgs boson; some of this discussion can be of course extended to the case of the lightest MSSM Higgs particle.

6.1 Studies at e^+e^- Colliders [11, 12]

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 ± 200 MeV can be obtained on the Higgs mass with $\int \mathcal{L} = 10$ fb^{-1} if the effects of beamstrahlung are small. 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 [13] e.g.] Γ_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 $e^+e^- \to HZ \to$ 4–fermions or decay $H \to WW^* \to$ 4–fermion processes, as well as in the more difficult channel $H \to \tau^+\tau^-$ for $M_H \lesssim 140$ GeV. An unambiguous test of the CP nature of the Higgs bosons can be made in the process $e^+e^- \to tt\bar{H}$ or at laser photon colliders in the loop induced process $\gamma\gamma \to H$.

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 fb^{-1}.

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 $M_H \sim 110$ GeV. For $M_H \sim 140$ GeV, 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 $e^+e^- \to t\bar{t}H$. For $M_H \lesssim 130$ GeV, λ_t can be measured with a precision of about 10 to 20% at $\sqrt{s} \sim 500$ GeV with $\int \mathcal{L} \sim 50$ 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.

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 $e^+e^- \to \nu\bar{\nu}HH$. However, the cross sections are rather small and very high luminosities [and very high energies in the second process] are needed.

6.2 Studies at the LHC [9]

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 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 HWW 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 $\sigma(gg \to H)\times$ BR$(H \to ZZ)$, one could then determine $\Gamma(H \to gg)$ which allows to extract the $Ht\bar{t}$ coupling [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 $gg \to t\bar{t}H$ with the subsequent decays $H \to \gamma\gamma$ or $b\bar{b}$.

7. Summary

At the hadron collider LHC, the Standard Model Higgs boson can, in principle, be discovered up to masses of $\mathcal{O}(1$ TeV). While the region $M_H \gtrsim 130$ 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. SUSY Higgs bosons are more difficult to search for, especially if decays into SUSY particles are kinematically allowed. In this case, it is possible that no Higgs particle will be found in some areas of the MSSM parameter space.

e^+e^- linear colliders with energies in the range of ~ 500 GeV are ideal instruments to search for Higgs particles in the mass range below ~ 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. In the MSSM, at least the lightest neutral Higgs particle must be discovered and the heavy neutral and charged Higgs particles can be observed if their masses are smaller than the beam energy. 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.

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