

Phenomenology of SM and SUSY Higgs bosons at the LHC

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I briefly review the physics of the Higgs sector in the Standard Model (SM) and its supersymmetric extension, in particular the MSSM, and discuss the prospects for discovering the Higgs particles at the Large Hadron Collider. Some emphasis will be put on the theoretical developments which occurred in the last few years.

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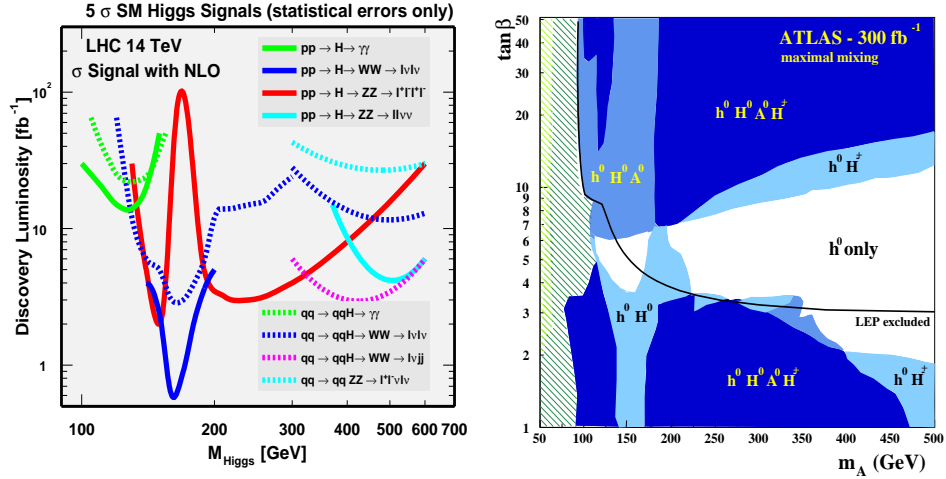
1 A brief introduction

The search for the Higgs particles [1], the remnants of the mechanism introduced forty years ago to achieve the breaking of the electroweak symmetry, is the primary mission of the LHC. Detailed theoretical and experimental studies performed in the last few years, have shown that the single neutral Higgs boson that is predicted in the SM [2] can be detected at the LHC [3, 4, 5] over its entire mass range, $114.4 \text{ GeV} \leq M_H \lesssim 1 \text{ TeV}$, in many redundant channels; see Fig. 1 (left). [It could also be discovered at the upgraded Tevatron, if it is relatively light and if enough integrated luminosity is collected; see Ref. [6] for instance.] In the context of the Minimal Supersymmetric Standard Model (MSSM), where the Higgs sector is extended to contain two CP-even neutral Higgs bosons h and H , a pseudoscalar A boson and a pair of charged scalar particles H^\pm [2], it has been shown that the lighter h boson cannot escape detection at the LHC and that in large areas of the parameter space more than one Higgs particle can be found; Fig. 1 (right).

However, discovering the Higgs boson is not the entire story and another goal, that is just as important, is to probe the electroweak symmetry breaking mechanism in all its facets. Once Higgs bosons are found, the next step would therefore be to explore all their fundamental properties. To achieve this goal in great detail, one needs to measure all possible cross sections and decay branching ratios of the Higgs bosons to derive their masses, their total decay widths, their couplings to the other particles and their self-couplings, their spin-parity quantum numbers, etc... This needs very precise theoretical predictions and more involved and combined theoretical and experimental studies. In particular, all possible production and decay channels of the Higgs particles, not only the dominant and widely studied ones allowing for clear discovery, should be investigated.

In this talk, I will summarize some studies that were performed recently in the SM and MSSM Higgs sectors; a few remarks will be made for non-minimal SUSY extensions. After a résumé of the present constraints, I discuss the new developments in the calculation of the Higgs spectrum, the decay and production rates and possible measurements of the Higgs properties at the LHC.

Fig. 1. The integrated luminosity needed for the discovery of the SM Higgs boson at the LHC in various production and decay channels (left) and the number of Higgs particles that can be detected in the MSSM $[\tan \beta, M_A]$ parameter space (right); from Refs. [7].



2 The profile of the Higgs bosons

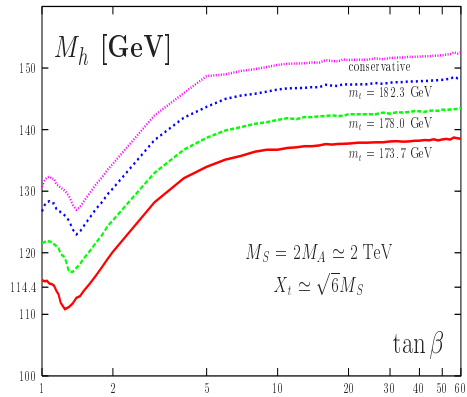
In the SM, the profile of the Higgs boson is uniquely determined once M_H is fixed: the decay width and branching ratios, as well as the production cross sections, are given by the strength of the couplings to fermions and gauge bosons, which is set by the masses of these particles. There are two experimental constraints on this free parameter: *i*) from the negative searches for Higgs bosons at LEP2 in the Higgs–strahlung process $e^+e^- \rightarrow HZ$ with c.m. energies up to $\sqrt{s} = 209$ GeV, the limit $M_H \geq 114.4$ GeV is established at the 95% CL [8] and *ii*) from the high precision measurement of electroweak observables at LEP, SLC and the Tevatron and with the latest Tevatron value of the top quark mass, $m_t = 178 \pm 4.3$ GeV [9], one obtains a preferred Higgs boson mass of $M_H = 114^{+69}_{-45}$ GeV from a global fit of all data, leading to the 95% CL upper limit of $M_H < 260$ GeV [10].

However, theoretical constraints can also be derived from assumptions on the energy range within which the SM is valid before perturbation theory breaks down and New Physics should appear. If $M_H \gtrsim 1$ TeV, the longitudinal W and Z bosons would interact strongly; to ensure unitarity in their scattering at high energies, one needs $M_H \lesssim 710$ GeV at tree-level. In addition, the quartic Higgs self-coupling, which at the weak scale is fixed by M_H , grows logarithmically with energy and a cut-off Λ should be imposed before it becomes infinite. The condition $M_H \lesssim \Lambda$ sets an upper limit at $M_H \sim 630$ GeV, that is confirmed with simulations on the lattice which take into account the strong interactions near the limit. Furthermore, top quark loops tend to drive the coupling to negative values, for which the vacuum becomes unstable. Requiring the SM to be extended to the GUT scale, $\Lambda \sim 10^{16}$ GeV, the Higgs mass should lie in the range $130 \text{ GeV} \lesssim M_H \lesssim 180 \text{ GeV}$. For a review of these issues, see Ref. [11] for instance.

In the MSSM, two doublets of Higgs fields are needed to break the electroweak symmetry, leading to two CP–even neutral h, H bosons, a pseudoscalar A boson and a pair of charged scalar particles, H^\pm [2]. Besides the four masses, two additional parameters define the properties of the particles: a mixing angle α in the neutral CP–even sector, and the ratio of the two vacuum expectation values, $\tan\beta$. Because of Supersymmetry constraints, only two of them, e.g. M_A and $\tan\beta$, are in fact independent at tree–level. While the lightest Higgs mass is bounded by $M_h \leq M_Z$, the masses of the A, H and H^\pm states are expected to be below $\mathcal{O}(1 \text{ TeV})$. However, mainly because of the heaviness of the top quark, radiative corrections are very important: the leading part grows as the fourth power of m_t and logarithmically with the common top squark mass M_S ; the stop trilinear coupling A_t also plays an important role and maximizes the correction for the value $A_t \sim \sqrt{6}M_S$ [12].

Recently, new calculations of the two–loop radiative corrections have been performed. Besides the already known $\mathcal{O}(\alpha_t\alpha_s)$ correction [12], the contributions at $\mathcal{O}(\alpha_t^2)$, $\mathcal{O}(\alpha_s\alpha_b)$ and $\mathcal{O}(\alpha_b^2)$ have been derived [13]. [The small $\mathcal{O}(\alpha_t^2)$ corrections have been also evaluated [14], which completes the two–loop corrections to the Higgs masses due to the strong and third–generation Yukawa couplings.] These corrections are sizable, increasing the predicted value for M_h [for given $\tan\beta$ and M_A inputs] by several GeV. Also recently, these radiative corrections have been implemented [14] in three codes for the determination of the MSSM particle spectrum, which appeared in the last few years: **SuSpect**, **Softsusy** and **Spheno** [15].

Fig. 2: The lighter Higgs boson mass M_h in the MSSM as a function of $\tan\beta$ as obtained from a full scan of the parameter space for the top mass values $m_t = 173.7, 178.0$ and 182.3 GeV . The thick dotted line on the top is for the conservative case, where $m_t = 182.3 \text{ GeV}$ is used and a theoretical error [due to the renormalization scale variation and scheme dependence, and to the approximation of zero–momentum transfer in the two–loop contributions] is added linearly; from Ref. [14].

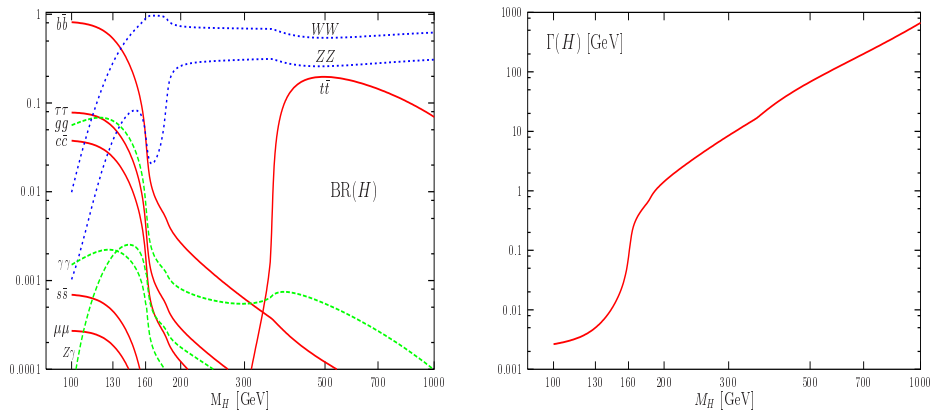


These radiative correction shift the upper bound of the lighter h boson in the MSSM from the tree–level value, $M_h = M_Z$ by several ten GeV. A full scan of the MSSM parameter space performed in Ref. [14] shows that the most conservative upper bound, when $m_t = 182.3 \text{ GeV}$ is used and an estimated theoretical error of 4 GeV is added linearly, is $M_h^{\max} \simeq 150 \text{ GeV}$; Fig. 2. Furthermore, if one takes into account the absolute limits $M_h \sim M_A \gtrsim 92 \text{ GeV}$ from the negative searches at LEP2 [16], as well as the constraint $M_h \gtrsim 114 \text{ GeV}$ when the h boson has SM–like couplings, one can in principle constrain $\tan\beta$. However, as can be seen in Fig. 2, no lower bound can be set in the conservative case mentioned above, provided that $\tan\beta$ is larger than unity which is the case in SUSY extensions of the SM.

The production and the decays of the MSSM Higgs bosons depend strongly on their couplings to gauge bosons and fermions. The pseudoscalar has no tree level couplings to gauge bosons, and its couplings to down (up)-type fermions are (inversely) proportional to $\tan\beta$. 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 $\tan\beta$. For the CP-even Higgs bosons, the couplings to down-(up)-type fermions are enhanced (suppressed) with respect to the SM Higgs couplings for $\tan\beta > 1$. They share the SM Higgs couplings to vector bosons since they are suppressed by $\sin(\beta - \alpha)$ and $\cos(\beta - \alpha)$ factors, respectively for h and H . If the pseudoscalar mass is large, the h boson mass reaches its upper limit [which depends on the value of $\tan\beta$] and the angle α reaches the value $\alpha = \beta - \frac{1}{2}\pi$. The h couplings to fermions and gauge bosons are then SM-like, while the heavier CP-even H and charged H^\pm bosons become degenerate in mass with A . In this decoupling limit, it is very difficult to distinguish the SM and MSSM Higgs sectors.

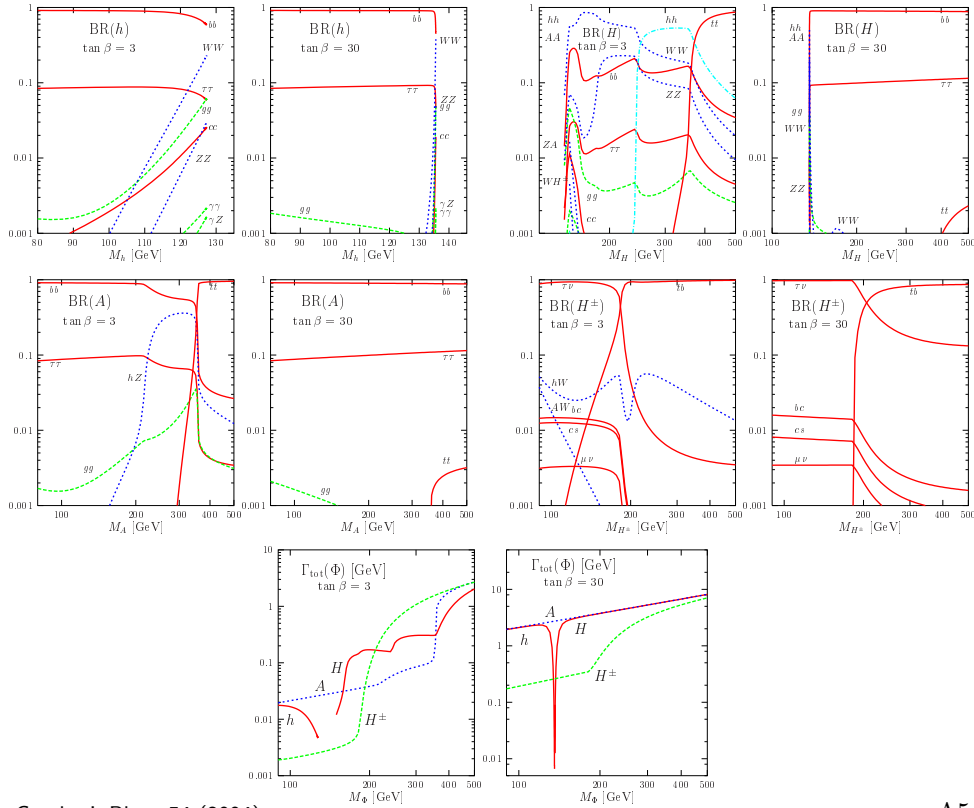
Let us now discuss the Higgs decay modes and branching ratios (BR) [17] and start with the SM case. In the “low-mass” range, $M_H \lesssim 130$ GeV, the Higgs boson decays into a large variety of channels. The main mode is by far the decay into $b\bar{b}$ with BR $\sim 90\%$ followed by the decays into $c\bar{c}$ and $\tau^+\tau^-$ with BRs $\sim 5\%$. Also of significance is the top-loop mediated decay into gluons, which occurs at the level of $\sim 5\%$. The top and W -loop mediated $\gamma\gamma$ and $Z\gamma$ decay modes, which lead to clear signals, are very rare with BRs of $\mathcal{O}(10^{-3})$. In the “high-mass” range, $M_H \gtrsim 130$ GeV, the Higgs bosons decay into WW and ZZ pairs, one of the gauge bosons being possibly virtual below the thresholds. Above the ZZ threshold, the BRs are 2/3 for WW and 1/3 for ZZ decays, and the opening of the $t\bar{t}$ channel for higher M_H does not alter this pattern significantly. In the low-mass range, the Higgs is very narrow, with $\Gamma_H < 10$ MeV, but this width becomes wider rapidly, reaching 1 GeV at the ZZ threshold. For very large masses, the Higgs becomes obese, since $\Gamma_H \sim M_H$, and can hardly be considered as a resonance. The BRs and total decay widths are summarized in Fig. 3, which is obtained from a recently updated version of the code HDECAY [18] and where the new value $m_t = 178$ GeV is used as input.

Fig. 3. The decay branching ratios (left) and the total decay width (right) of the SM Higgs boson as a function of its mass, as obtained with an updated version of HDECAY [18].



In the MSSM, the lightest h boson will decay mainly into fermion pairs since $M_h \lesssim 140$ GeV; Fig. 4. This is, in general, also the dominant decay mode of the A and H bosons, since for $\tan\beta \gg 1$, they decay into $b\bar{b}$ and $\tau^+\tau^-$ pairs with BRs of the order of $\sim 90\%$ and 10% , respectively. For large masses, the top decay channels $H, A \rightarrow t\bar{t}$ open up, yet they are suppressed for large $\tan\beta$. The H boson can decay into gauge bosons or h boson pairs, and the A particle into hZ final states; however, these decays are strongly suppressed for $\tan\beta \gtrsim 5$. The H^\pm particles decay into fermions pairs: mainly $t\bar{b}$ and $\tau\nu_\tau$ final states for H^\pm masses, respectively, above and below the $t\bar{b}$ threshold. If allowed kinematically, they can also decay into hW final states for $\tan\beta \lesssim 5$. Adding up the various decays, the widths of all five Higgses remain rather narrow; Fig. 4. Other possible decay channels for the heavy H, A and H^\pm states, are decays into light charginos and neutralinos, which could be important if not dominant [19, 20]; decays of the h boson into the lightest neutralinos (LSP) can also be important, exceeding 50% in some parts of the parameter space and altering the searches at hadron colliders. Light SUSY particles can also affect the BRs of the loop-induced modes in a sizable way [21].

Fig. 4. The decay branching ratios and total widths of the MSSM Higgs bosons as functions of their masses for $\tan\beta = 3$ and 30 as obtained with an update of HDECAY; $m_t = 178$ GeV and the maximal mixing scenario $X_t = \sqrt{6}M_S$ with $M_S = 2$ TeV are assumed.



3 SM Higgs production and detection at the LHC

There are essentially four mechanisms for the single production of the SM Higgs boson at hadron colliders [22]; some Feynman diagrams are shown in Fig. 5. The total cross sections, obtained with the programs of Ref. [23], are displayed in Fig. 6 for the LHC with $\sqrt{s} = 14$ TeV as a function of the Higgs mass; the top quark mass is set to $m_t = 178$ GeV and the MRST parton distributions functions have been adopted. The NLO, and eventually NNLO, corrections have been implemented as will be summarized later. In the following, we discuss the main features of each production channel and highlight the new theoretical developments which occurred in the evaluation of the cross sections and detection signals at the LHC.

Fig. 5. The production mechanisms for SM Higgs bosons at hadron colliders.

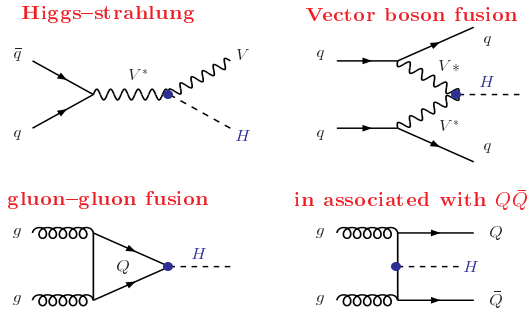
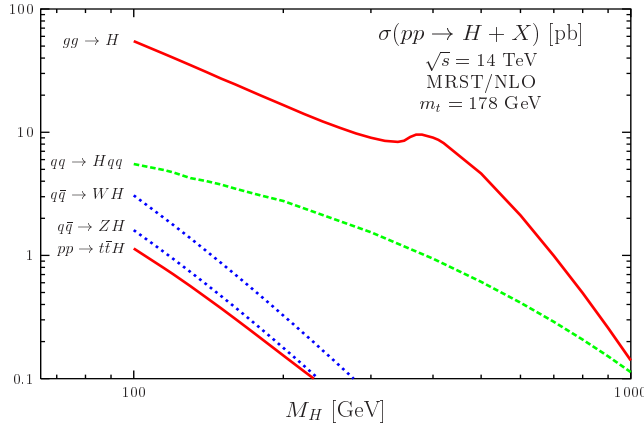


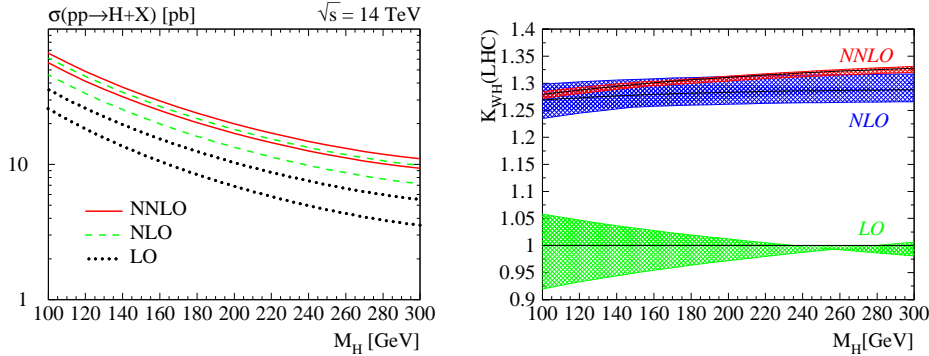
Fig. 6. The production cross sections for the SM Higgs boson at the LHC.



a) $gg \rightarrow H$: which is by far the dominant production process at the LHC, up to masses $M_H \approx 1$ TeV. The most promising detection channels are [24] $H \rightarrow \gamma\gamma$ for $M_H \lesssim 130$ GeV and slightly above this mass value, $H \rightarrow ZZ^* \rightarrow 4\ell^\pm$ and $H \rightarrow WW^{(*)} \rightarrow \ell\ell\nu\nu$ with $\ell = e, \mu$ for masses below, respectively, $2M_W$ and $2M_Z$. For higher Higgs masses, $M_H \gtrsim 2M_Z$, it is the golden mode $H \rightarrow ZZ \rightarrow 4\ell^\pm$, which from $M_H \gtrsim 500$ GeV can be complemented by $H \rightarrow ZZ \rightarrow \nu\bar{\nu}\ell^+\ell^-$ and $H \rightarrow WW \rightarrow \nu\bar{\nu}jj$ to increase the statistics; see Ref. [3].

The next-to-leading order (NLO) QCD corrections have been calculated in both the limit where the internal top quark has been integrated out [25], an approximation which should be valid in the Higgs mass range $M_H \lesssim 300$ GeV, and in the case where the full quark mass dependence has been taken into account [26]. The corrections lead to an increase of the cross sections by a factor of ~ 1.7 . Recently, the “tour de force” of deriving the three-loop corrections has been performed in the infinite top-quark mass limit; these NNLO corrections lead to the increase of the rate by an additional 30% [27]. This results in a nice convergence of the perturbative series and a strong reduction of the scale uncertainty, which is the measure of unknown higher order effects; see Fig. 7 (left). The resummation of the soft and collinear corrections, performed at next-to-next-to-leading logarithm accuracy, leads to another increase of the rate by $\sim 5\%$ and a decrease of the scale uncertainty [28]. The QCD corrections to the differential distributions, and in particular to the Higgs transverse momentum and rapidity distributions, have also been recently calculated at NLO [with a resummation for the former] and shown to be rather large [29]. The dominant components of the electroweak corrections, some of which have been derived very recently, are comparatively very small [30].

Fig. 7. Left: SM Higgs boson production cross sections in the gg fusion process at the LHC as a function of M_H at the three different orders with the upper (lower) curves are for the choice of the renormalization and factorization scales $\mu = \frac{1}{2}M_H$ ($2M_H$); from Harlander and Kilgore in Ref. [27]. Right: K -factors for $pp \rightarrow HW$ at the LHC as a function of M_H at LO, NLO and NNLO with the bands represent the spread of the cross section when the scales are varied in the range $\frac{1}{3}M_{HV} \leq \mu_R(\mu_F) \leq 3M_{HV}$; from Brein et al. Ref. [33].



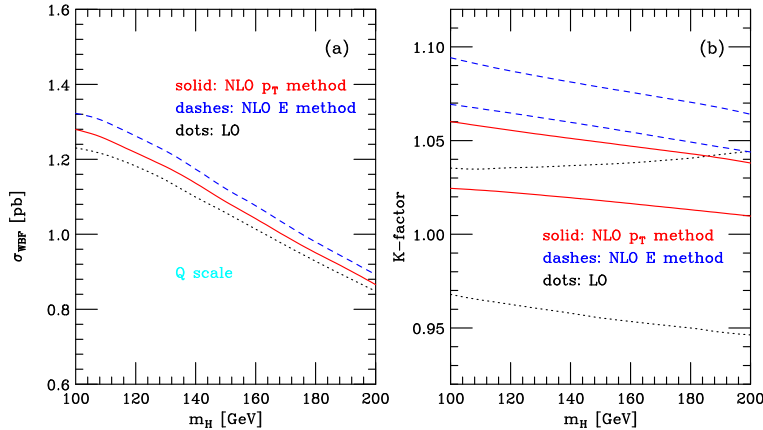
b) $q\bar{q} \rightarrow HV$: The associated production with gauge bosons, with $H \rightarrow b\bar{b}$ and possibly $H \rightarrow WW^* \rightarrow \ell^+\nu jj$, is the most relevant mechanism at the Tevatron [6], since the dominant gg mechanism has too large a QCD background. At the LHC, this process plays only a marginal role; however, the channels $HW \rightarrow \ell\nu\gamma\gamma$ and eventually $\ell\nu b\bar{b}$ could be useful for the measurement of Higgs couplings.

The QCD corrections, which at NLO [31, 32], can be inferred from Drell–Yan production, have been calculated recently at NNLO [33]; they are of about 30% in toto (Fig. 7). The $\mathcal{O}(\alpha)$ electroweak corrections have been also derived recently [34] and decrease the rate by 5 to 10%. The remaining scale dependence is very small, making this process the theoretically cleanest of all Higgs production processes.

c) The WW/ZZ fusion mechanism has the second largest cross section at the LHC. The QCD corrections, which can be obtained in the structure–function approach, are at the level of 10% and thus small [35, 32]. The corrections including cuts, and in particular corrections to the p_T and η distributions, have also been calculated recently and implemented into a parton–level Monte–Carlo program [36]. With the specific cuts to the process, the output for the production cross section is shown in Fig. 8 for a Higgs in the mass range 100–200 GeV.

For several reasons, the interest in this process has grown in recent years: it has a large enough cross section [a few picobarns for $M_H \lesssim 250$ GeV] and one can use cuts, forward–jet tagging, mini–jet veto for low luminosity as well as triggering on the central Higgs decay products] [37], which render the backgrounds comparable to the signal, therefore allowing precision measurements. In the past, it has been shown that the decay $H \rightarrow \tau^+\tau^-$ and possibly $H \rightarrow \gamma\gamma, ZZ^*$ can be detected and could allow for coupling measurements [4, 38]. In the last years, parton–level analyzes have shown that various other channels can be possibly detected [39]: $H \rightarrow WW^*$ for $M_H \sim 125\text{--}180$ GeV, $H \rightarrow \mu^+\mu^-$ [for second–generation coupling measurements], $H \rightarrow b\bar{b}$ [for the $b\bar{b}H$ Yukawa coupling] and $H \rightarrow$ invisible. Recent experimental simulations [40] have assessed more firmly the potential of this channel.

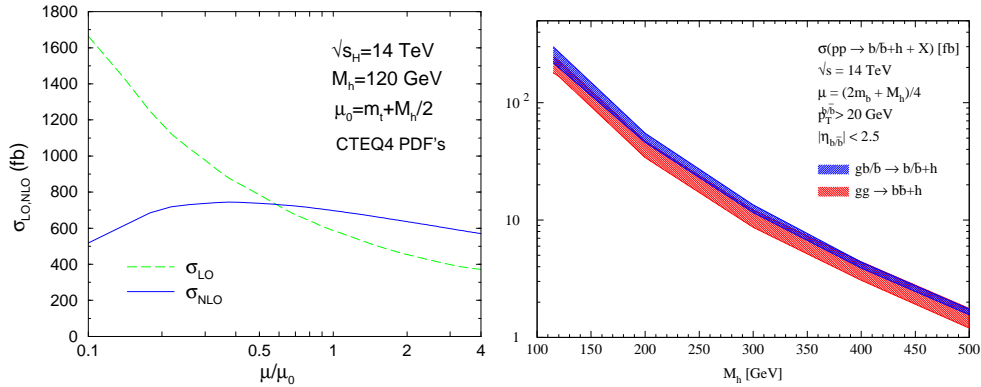
Fig. 8. The $pp \rightarrow Hqq$ cross section after cuts as a function of M_H at LO (dotted line) and NLO with the tagging jets defined in the P_T and E_T methods (left) and the scale variation of the LO and NLO cross sections as a function of M_H (right); from Ref. [36].



d) Finally, Higgs boson production in association with top quarks, with $H \rightarrow \gamma\gamma$ or $b\bar{b}$, can be observed at the LHC and would allow for the direct measurement of the top Yukawa coupling. The cross section is rather involved at tree–level since it is a three–body process, and the calculation of the NLO corrections was a real challenge, since one had to deal with one–loop corrections involving pentagonal diagrams and real corrections involving four particles in the final state. This challenge was taken up by two groups [of US ladies and DESY gentlemen], and this calculation was completed two years ago [42]. The K –factors turned out to be rather small, $K \sim 1.2$ at the LHC [and ~ 0.8 at the Tevatron, an example that K –factors can also be

less than unity]. However, the scale dependence is drastically reduced from a factor two at LO to the level of 10–20% at NLO; see Fig. 9 (left). Note that the NLO corrections to the $q\bar{q}/gg \rightarrow b\bar{b}H$ process, which is more relevant in the MSSM, have been also recently completed [43]: compared with the NLO rate for the $bg \rightarrow bH$ process where the initial b -quark is treated as a parton [44], the calculations agree now within the scale uncertainties [45] as shown in Fig. 9 (right).

Fig. 9. Left: The production cross sections in the $t\bar{t}H$ process as a function of the renormalization/factorization scale μ ; from Dawson et al. in Ref. [42]. Right: the total cross sections for $pp \rightarrow b\bar{b}H + X$ as a function of M_H with one high- p_T b jet identified in the final state and the scales varied by a factor of two around $\mu = \frac{1}{4}M_H$ from [45].



Note that the PDF uncertainties have also been recently estimated for the four production processes using the new scheme provided by the CTEQ and MRST collaborations, as well as by Alekhin [46]. At the LHC, the uncertainties range from 5% to 15% depending on the considered process and the Higgs mass [47].

Let us now turn to the measurements that can be performed at the LHC.

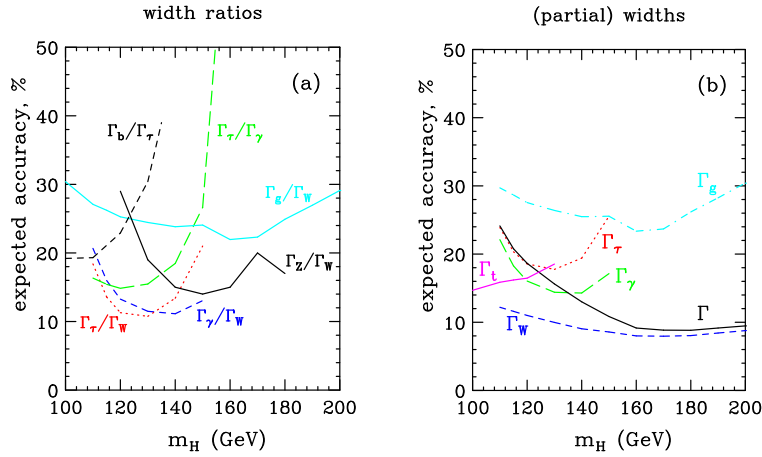
- The Higgs mass can be measured with a very good accuracy [3, 7]. For $M_H \lesssim 400$ GeV, where Γ_H is not too large, a precision of $\Delta M_H/M_H \sim 0.1\%$ can be achieved in $H \rightarrow ZZ^{(*)} \rightarrow 4\ell^\pm$. In the “low-mass” range, a slight improvement can be obtained by considering $H \rightarrow \gamma\gamma$. For $M_H \gtrsim 400$ GeV, the precision deteriorates because of the smaller rates but it is still at the level of 1% up to $M_H \sim 800$ GeV if theoretical errors, such as width effects, are not taken into account.

- Using the same process, $H \rightarrow ZZ^{(*)} \rightarrow 4\ell^\pm$, the total Higgs width can be measured for $M_H \gtrsim 200$ GeV, when it is large enough [3, 7]. While the precision is very poor near this mass value [a factor of two], it improves to reach the level of $\sim 5\%$ around $M_H \sim 400$ GeV. Here also, theoretical errors are not included.

- The Higgs boson spin can be measured by looking at angular correlations between the fermions in the final states in $H \rightarrow VV \rightarrow 4f$ [48], but the cross sections are rather small and the environment too difficult; only the measurement of the decay planes of the two Z bosons decaying into four leptons seems promising. In vector boson fusion, the azimuthal distribution of the two tagging jets is different for

CP-even and CP-odd particles and might be used for discrimination [49]. However, if the Higgs boson were a mixture of CP-even and CP-odd states, only the former component would couple to the gauge bosons. A more decisive test of the CP numbers should be performed in processes where the Higgs boson couples to fermions, such as in $pp \rightarrow t\bar{t}H$ with $H \rightarrow b\bar{b}$ as proposed in Ref. [50], but this seems too difficult and no experimental analysis has been attempted yet. A possibility might be provided by double diffractive Higgs production with large rapidity gaps between the Higgs and the protons in which only scalar Higgs production is selected [51].

Fig. 10. Relative accuracy expected at the LHC with a luminosity of 200 fb^{-1} for various ratios of Higgs boson partial widths (left) and the indirect determination of partial and total widths (right) with some theoretical assumptions; from Ref. [41].



- The direct measurement of the Higgs couplings to gauge bosons and fermions is possible, but with a rather poor accuracy as a result of the limited statistics, the large backgrounds, and the theoretical uncertainties from the limited precision on the parton densities and the higher-order radiative corrections. To reduce some uncertainties, it is more interesting to measure ratios of cross sections where the normalizations cancel out. One can then make, in some cases, a measurement of ratios of BRs at the level of 10% and with some theoretical assumptions, determine the partial and total widths [38, 40, 41]. An example of determination of cross sections times branching fractions in various channels at the LHC is shown in Fig. 10. [Note that experimental analyzes accounting for the backgrounds and for the detector efficiencies, as well as further theoretical studies for the signal and backgrounds, need to be performed to confirm these values.]

- Finally, the trilinear Higgs self-coupling λ_{HHH} is too difficult to measure at the LHC because of the smallness of the cross sections [52] for $gg \rightarrow HH$ [and a fortiori the ones for the other channels $VV \rightarrow HH$ and $q\bar{q} \rightarrow HHV$] and the very large backgrounds. A parton level analysis has been recently performed in the channel $gg \rightarrow HH \rightarrow (W^+W^-)(W^+W^-) \rightarrow (jj\nu)(jj\nu)$ and $(jj\nu)(\ell\nu)$, including all the relevant backgrounds and only at the SLHC with 6 ab^{-1} luminosity that one can hope to determine this coupling but with a limited accuracy [53].

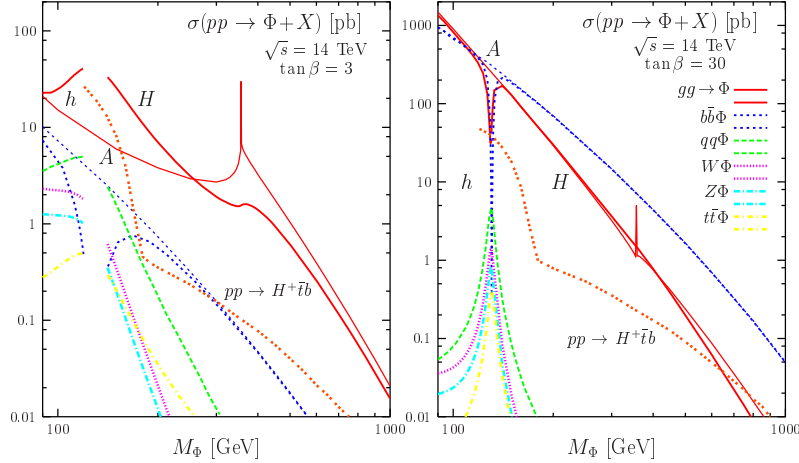
4 The MSSM Higgs bosons

In the MSSM, the production processes for the h, H bosons are practically the same as for the SM Higgs. However, for large $\tan\beta$ values, one has to take the b quark, whose couplings are strongly enhanced, into account: its loop contributions in the $gg \rightarrow \Phi$ fusion process [and also the extra contributions from squarks loops, which however decouple for high squark masses; the SUSY NLO QCD corrections are also available [54] and are moderate] and associated production with $b\bar{b}$ pairs, $gg \rightarrow b\bar{b} + \Phi$ [for which the QCD corrections are available in both the gg and $gb \rightarrow b\Phi, b\bar{b} \rightarrow \Phi$ pictures [43, 44, 45] depending on how many b -quarks are to be tagged, and which are equivalent if the renormalization and factorization scales are chosen to be small, $\mu \sim \frac{1}{4}M_\Phi$]. The cross sections for the associated production with $t\bar{t}$ pairs and W/Z bosons as well as the WW/ZZ fusion processes, are suppressed for at least one of the particles as a result of the coupling reduction. Because of CP invariance, the A boson can be produced only in the gg fusion and in association with heavy quarks. However, the one-loop induced processes [55, 56] $gg \rightarrow AZ, gg \rightarrow Ag$ [which hold for CP-even Higgses] and associated production with other Higgs particles, $pp \rightarrow A + h/H/H^+$ [57] are possible but the rates are much smaller in general.

The cross sections for the dominant production mechanisms are shown in Fig. 11 as a function of the Higgs masses for $\tan\beta = 3$ and 30 for the same set of input parameters as Fig. 4. The NLO QCD corrections are included, except for the $pp \rightarrow \Phi Q\bar{Q}$ processes where, however, the scales have been chosen as to approach the NLO results; the top mass is fixed to $m_t = 178$ GeV and the MRST NLO PDFs have been adopted. As can be seen, at high $\tan\beta$, the largest cross sections are by far those of the $gg \rightarrow \Phi_A/A$ and $q\bar{q}/gg \rightarrow b\bar{b} + \Phi_A/A$ processes, where $\Phi_A = H(h)$ in the (anti-)decoupling regimes $M_A > (<)M_h^{\max}$: the other processes involving these two Higgs bosons have cross sections that are several orders of magnitude smaller. The production cross sections for the other CP-even Higgs boson, that is $\Phi_H = h(H)$ in the (anti-)decoupling regime when $M_{\Phi_H} \simeq M_h^{\max}$, are similar to those of the SM Higgs boson with the same mass and are substantial in all the channels which have been displayed. For small values of $\tan\beta$, the gg fusion and $b\bar{b}$ -Higgs cross sections are not strongly enhanced as before and all production channels [except for $b\bar{b}$ -Higgs which is only slightly enhanced] have cross sections that are smaller than in the SM Higgs case, except for h in the decoupling regime.

For the charged Higgs boson, the dominant channel is the production from top quark decays, $t \rightarrow H^\pm b$, for masses not too close to $M_{H^\pm} = m_t - m_b$. For higher masses [58], the fusion process $gg \rightarrow H^\pm tb$ supplemented by $gb \rightarrow H^\pm t$ [the two processes have to be properly combined and the K -factor for the gb process has been derived recently [59] and is moderate $K \sim 1.2$ – 1.5 if the cross section is evaluated at scales $\mu \sim \frac{1}{2}(m_t + M_{H^\pm})$] are the ones to be considered. In Fig. 11, shown are the $q\bar{q}/gg \rightarrow \bar{H}^\pm tb$ process which include the possibility of on-shell top quarks and hence, $pp \rightarrow t\bar{t}$ with $t \rightarrow H^\pm b$. Additional sources [60] of H^\pm states for masses below $M_{H^\pm} \approx 250$ GeV are provided by pair and associated production with neutral Higgs bosons in $q\bar{q}$ annihilation as well as pair and associated $H^\pm W^\mp$ production in gg and/or $b\bar{b}$ fusion but the cross sections are not as large in general.

Fig. 11. The cross section for the neutral and charged MSSM Higgs production in the main channels at the LHC as a function of their respective masses for $\tan\beta = 3$ and 30.



The principal detection signals of the neutral Higgs bosons at the LHC, in the various regimes of the MSSM, are as follows [3, 4, 5, 61, 62, 63]:

In the decoupling regime, i.e. when $M_h \simeq M_h^{\max}$, the lighter h boson is SM-like and has a mass smaller than ≈ 140 GeV. It can be detected in the $h \rightarrow \gamma\gamma$ decays [possibly supplemented with a lepton in associated Wh and $t\bar{t}h$ production], and eventually in $h \rightarrow ZZ^*, WW^*$ decays in the upper mass range, and if the vector boson fusion processes are used, also in the decays $h \rightarrow \tau^+\tau^-$ and eventually $h \rightarrow WW^*$ in the higher mass range $M_h \gtrsim 130$ GeV; see Fig. 12. For relatively large values of $\tan\beta$ ($\tan\beta \gtrsim 10$), the heavier CP-even H boson which has enhanced couplings to down-type fermions, as well as the pseudoscalar Higgs particle, can be observed in the process $pp \rightarrow b\bar{b} + H/A$ where at least one b -jet is tagged and with the Higgs boson decaying into $\tau^+\tau^-$, and eventually, $\mu^+\mu^-$ pairs in the low mass range. With a luminosity of 100 fb^{-1} [and in some cases lower] a large part of the $\tan\beta$ - M_A space can be covered; Fig. 12.

In the antidecoupling regime, i.e. when $M_A < M_h^{\max}$ and at high $\tan\beta$ ($\gtrsim 10$), it is the heavier H boson which will be SM-like and can be detected as above, while the h boson will behave like the pseudoscalar Higgs particle and can be observed in $pp \rightarrow b\bar{b} + h$ with $h \rightarrow \tau^+\tau^-, \mu^+\mu^-$ provided its mass is not too close to M_Z not to be swamped by the background for Z production. The part of the $\tan\beta$ - M_A space which can be covered is also shown in the left-hand side of Fig. 12.

In the intermediate coupling regime, that is for not too large M_A values and moderate $\tan\beta \lesssim 5$, the interesting decays $H \rightarrow hh$, $A \rightarrow hZ$ and even $H/A \rightarrow t\bar{t}$ [as well as the decays $H^\pm \rightarrow Wh$] still have sizable branching fractions and can be searched for; Fig. 13 (left). In particular, the $gg \rightarrow H \rightarrow hh \rightarrow b\bar{b}\gamma\gamma$ process [the $4b$ channel is more difficult] is observable for $\tan\beta \lesssim 3$ and $M_A \lesssim 300$ GeV, and would allow to measure the trilinear Hhh coupling. These regions of parameter space have to be reconsidered in the light of the new Tevatron value for the top quark mass and the recent analyzes which have re-opened the small $\tan\beta$ window.

Fig. 12. The areas in the $(M_A, \tan \beta)$ parameter space where the lighter (left) and heavier (right) MSSM neutral Higgs bosons can be discovered at the LHC with an integrated luminosity of 30 fb^{-1} in the standard production channels; from [62].

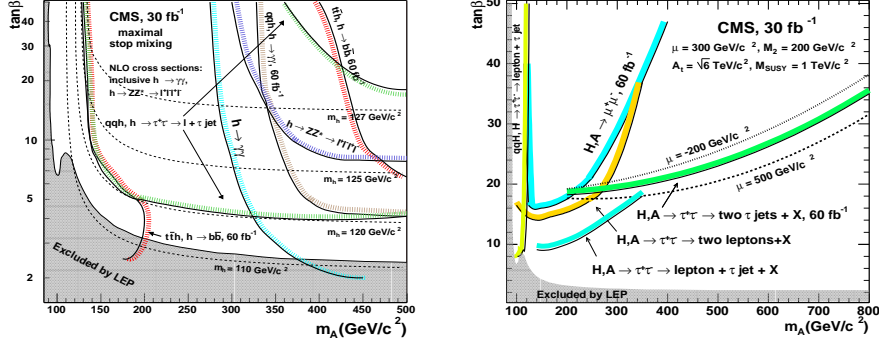
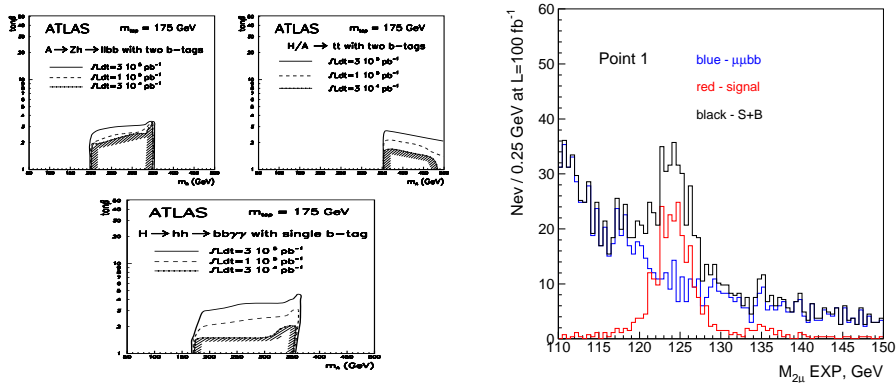


Fig. 13. Left: the regions in the M_A - $\tan \beta$ parameter space where the channel $gg \rightarrow H \rightarrow hh \rightarrow b\bar{b}\gamma\gamma$, $gg \rightarrow A \rightarrow hZ \rightarrow b\bar{b}\ell^+\ell^-$ and $gg \rightarrow H/A \rightarrow t\bar{t} \rightarrow \ell\nu jj b\bar{b}$ can be detected at the LHC; from Ref. [61]. Right: the $\mu^+\mu^-$ pair invariant mass distributions for the three Higgs signal peaks with $M_A = 125 \text{ GeV}$ and $\tan \beta = 30$ [leading to $M_h \sim 124 \text{ GeV}$ and $M_H \sim 134 \text{ GeV}$] and backgrounds after detector resolution smearing; from Ref. [63].



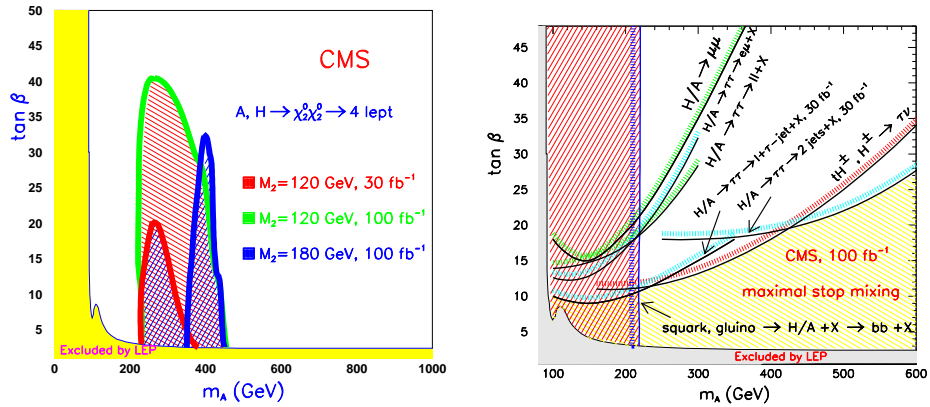
In the intense-coupling regime, that is for $M_A \sim M_h^{\max}$ and $\tan \beta \gg 1$, the three neutral Higgs bosons $\Phi = h, H, A$ have comparable masses and couple strongly to isospin $-\frac{1}{2}$ fermions leading to dominant decays into $b\bar{b}$ and $\tau\tau$ and large total decay widths [63, 64]. The three Higgs bosons can only be produced in the channels $gg \rightarrow \Phi$ and $gg/q\bar{q} \rightarrow b\bar{b} + \Phi$ with $\Phi \rightarrow b\bar{b}, \tau^+\tau^-$ as the interesting $\gamma\gamma, ZZ^*$ and WW^* decays of the CP-even Higgses are suppressed. Because of background and resolution problems, it is very difficult to resolve between the three particles. A solution advocated in [63] (see also [65]), would be the search in the channel $gg/q\bar{q} \rightarrow b\bar{b} + \Phi$ with the subsequent decay $\Phi \rightarrow \mu^+\mu^-$ which has a small BR, $\sim 3 \times 10^{-4}$, but for which the better muon resolution, $\sim 1\%$, would allow to disentangle between at least two Higgs particles. [The backgrounds are much larger for the $gg \rightarrow \Phi \rightarrow \mu^+\mu^-$ signal]. The simultaneous discovery of the three Higgs particles is very difficult and in many cases impossible, as exemplified in Fig. 13 (right) where one observes only one single peak corresponding to h and A production.

Finally, as mentioned previously, light H^\pm particles with masses below $M_{H^\pm} \sim m_t$ can be observed in the decays $t \rightarrow H^+ b$ with $H^- \rightarrow \tau \nu_\tau$, and heavier ones can be probed for large enough $\tan \beta$, by considering the properly combined $gb \rightarrow tH^-$ and $gg \rightarrow t\bar{b}H^-$ processes using the decay $H^- \rightarrow \tau \nu_\tau$ and taking advantage of the τ polarization to suppress the backgrounds, and eventually the decay $H^- \rightarrow \bar{t}b$ [66] which however, seems more problematic than thought as recently pointed out [67]. See Ref. [68] for more detailed discussions on H^\pm production.

The whole discussion made previously assumes that Higgs decays into SUSY particles are kinematically inaccessible. This seems to be unlikely since at least some charginos and neutralinos should be not too heavy [69] and in this SUSY regime, $\Phi \rightarrow \chi\chi$ decays are possible [19]. Preliminary analyzes show that decays $H/A \rightarrow \chi_2^0 \chi_2^0 \rightarrow 4\ell^\pm X$ and $H^\pm \rightarrow \chi_2^0 \chi_1^\pm \rightarrow 3\ell^\pm X$ can be detected in some cases; see the l.h.s of Fig. 14. It is also possible that the lighter h decays invisibly into the lightest neutralinos [or sneutrinos]; if this scenario is realized, the discovery of these Higgs particles will be challenging but possible [5]. Light SUSY particles can also alter the loop-induced production and decay rates. For instance, light top squarks can couple strongly to the h boson, leading to a possibly drastic suppression of the product $\sigma(gg \rightarrow h) \times \text{BR}(h \rightarrow \gamma\gamma)$ compared to the SM [21]. In this case, associated $\tilde{t}_1 \tilde{t}_1 h$ production might be accessible with reasonable rates [70].

MSSM Higgs boson detection from the cascade decays of strongly interacting sparticles, which have large production rates at the LHC, is also possible. In particular, the lighter h boson and the heavier A, H and H^\pm particles with $M_\Phi \lesssim 200$ GeV, can be produced from the decays of squarks and gluinos into the heavier charginos/neutralinos, which then decay into the lighter ones and Higgs bosons. This can occur either in “little cascades”, $\chi_2^0, \chi_1^\pm \rightarrow \chi_1^0 + \Phi$, or in “big cascades” $\chi_{3,4}^0, \chi_2^\pm \rightarrow \chi_{1,2}^0, \chi_1^\pm + \Phi$. Recent studies [71, 72] show that these processes can be complementary to the direct production ones in some areas of the MSSM parameter space [in particular one can probe the region $M_A \sim 150$ GeV and $\tan \beta \sim 5$, where only the h boson can be observed in standard searches]; see Fig. 14 (right).

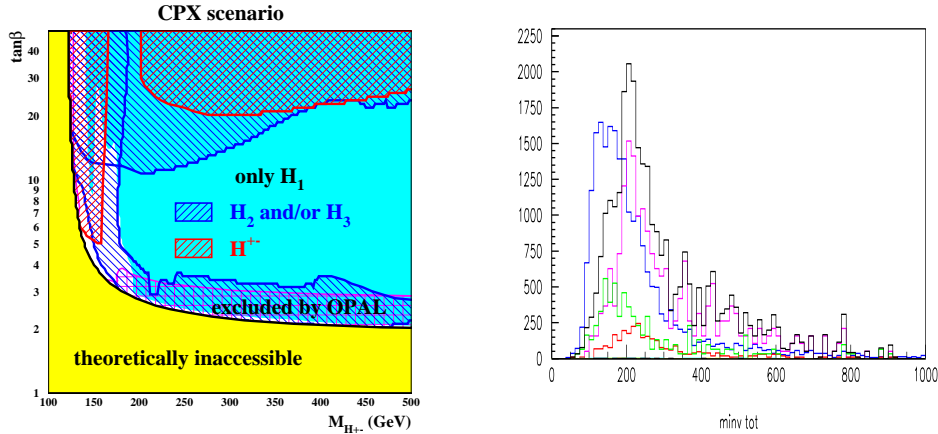
Fig. 14. Areas in the $(M_A, \tan \beta)$ parameter space where the MSSM Higgs bosons can be discovered at the LHC with 100 fb^{-1} data in the $A/H \rightarrow \chi_2^0 \chi_2^0 \rightarrow 4\ell^\pm + X$ decays (left) and in cascades of SUSY particles (right) for a given set of the MSSM parameters.



Finally, there is the extended regime in which some basic assumptions of the MSSM are relaxed. In the presence of CP-violation in the SUSY sector, the new phases will enter the MSSM Higgs sector through the large radiative corrections. The masses and the couplings of the neutral and charged Higgs particles will be altered [in particular, the three neutral Higgs bosons will not have definite CP quantum numbers and will mix with each other] and their production cross sections and decay branching ratios will be affected; for a review, see e.g. Ref. [73]. The impact of CP-violation on the LEP2 bounds on the Higgs masses has been recently evaluated [74] and the discovery potential of the LHC has been studied [75] for several benchmarks [73]. An ATLAS simulation with 300 fb^{-1} data has shown that the lighter neutral Higgs boson can escape observation in a small region of the parameter space with low M_A and $\tan\beta$ values, while the heavier H, A and H^\pm bosons can be accessed in smaller areas than in the usual MSSM; Fig. 15 (left).

Another extension of the MSSM which started to be studied intensively is the NMSSM where a singlet superfield is introduced, leading to an additional CP-even and CP-odd Higgs particles [76]. The upper bound on the mass of the lighter CP-even Higgs particle of the model exceed that of the MSSM h boson and the negative searches at LEP2 lead to looser constraints on the masses. A new code, NMHDECAY [77], which determines the Higgs spectrum in the model has appeared recently. Several new decay channels take place which complicate the searches at the LHC [78]. For instance, the lighter CP-even h_1 boson could decay into two pseudoscalar a_1 bosons which have masses of order of a few ten GeV, that are not excluded at LEP2. If such a scenario occurs, it would be extremely difficult to access to these particles at the LHC as shown in an ATLAS analysis summarized in Fig. 15 (right), which compares the signal cross sections in the fusion process $pp \rightarrow h_1 qq$ with the various backgrounds [79]. More detailed studies are thus needed in this context.

Fig. 15. Left: the overall discovery potential for Higgs bosons in ATLAS in a CP-violating scenario after collecting 300 fb^{-1} of data, with the white region indicating the area where no Higgs boson can be found; from [75]. Right: the signal and backgrounds as a function of the invariant mass $M_{bb\tau\tau}$ in GeV for the production of a Higgs boson in the NMSSM in the reaction $pp \rightarrow qq + h_1$ with $h_1 \rightarrow a_1 a_1 \rightarrow b\bar{b}\tau^+\tau^-$; the signal $\times 500$ (blue), $t\bar{t}$ (purple), $\gamma^* \rightarrow e^+e^-$, $\mu\mu$ (green), $Z \rightarrow \tau^+\tau^-$ (red) and total background (black); from [79].



5 Conclusions and outlook

The last few years have witnessed a large activity in the determination of the profile of the Higgs particles in the SM and its SUSY extensions, and in their production and detection modes at the LHC and other colliders. Major theoretical advance has been made and in particular, the determination of the production cross sections and the decay rates has reached a rather high level of accuracy; even some NNLO QCD and some electroweak corrections are now available. Major advance on the knowledge of the most important backgrounds has also been made [80].

Many theoretical and experimental analyzes have been performed in the context of the SM and MSSM and it has been shown that at least one Higgs particle cannot escape detection at the LHC. While this fact should give us some confidence that a breakthrough in the field will certainly occur at the LHC, this is clearly not the end of the story and we need to perform many very important studies and investigate other aspects, to be ready when the machine starts operating. Without being exhaustive, I simply list below examples of points which need further efforts.

- We should make sure that the SM Higgs boson is observed in as many channels as possible and in the MSSM, that the maximal number of Higgs particles is detected. In other words, we should work harder to extend the reach of all the searches which have been performed up to now, and to complete them with new ones. In the case of the MSSM for instance, we should make much smaller the areas of parameter space in which only the lighter Higgs boson is observable and in which several Higgs particles cannot be resolved experimentally.

- We should move to a more ambitious program and think more about the next major step after discovery: how to determine experimentally the complete profile of the Higgs particles and to unravel the mechanism of electroweak symmetry breaking. Measuring the masses, the total widths, the couplings to fermions and gauge bosons and the self-coupling as precisely as possible and determining the spin and parity quantum numbers of the observed Higgs bosons, should be a priority.

- We should move from the orthodox MSSM [or the $\tan\beta$ - M_A parameter space ...] which has been the benchmark, besides the SM Higgs sector, that was mostly studied up to now, and consider other more complicated or richer SM extensions. The SUSY regime in which some superparticles are light enough to affect the phenomenology of the Higgs bosons, either through direct decays and production or indirectly through loop contributions, must be scrutinized in more details. Extensions of the MSSM in which some basic assumptions, such as the absence of new sources of CP-violation and/or minimal gauge group or particle content, are relaxed should be considered more seriously. Models such as the NMSSM for instance, which leads to a more challenging phenomenology, should be investigated in detail.

A number of analyzes on these issues has already been made in the recent years, but they need to be extended, completed and systematized. For this purpose, a joint theoretical and experimental effort will be vital and will be required more than it used to be in the past, as the phenomenology to be studied is richer. It is at this price that we will make a maximal scientific benefit from the data to be delivered at the LHC, and to make the experiment a very successful scientific enterprise.

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