SM and MSSM Higgs at the LHC

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In the standard model (SM) there is one single neutral Higgs boson, a weak isospin doublet. Three of the components of the two complex fields are absorbed by the $W^\pm$ and Z^0 leaving one field

$$H = \begin{pmatrix} 0 \\ \frac{f}{\sqrt{2}} \end{pmatrix}, \tag{1}$$

where f is the "vacuum expectation value" of the field. The masses are (g is the weak SU(2) coupling constant [1])

$$M_W = \frac{gf}{2}, \quad M_Z = \frac{gf}{2\cos\theta_w}, \quad M_H = \sqrt{2\lambda}\, f. \tag{2}$$

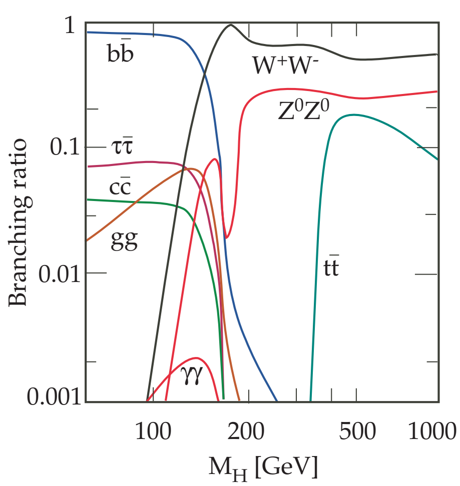

Figure 1: Higgs branching ratios as a function of Higgs mass.

The constants f and g are known but not λ, hence the mass of the Higgs is not predicted in the SM, but can be calculated from the top mass and radiative corrections: M_H <186 GeV (95% CL) [2]. The Higgs coupling to a pair of fermions $F\bar{F}$

$$g_f = \sqrt{2}\frac{m_F}{f} \tag{3}$$

is proportional to the fermion mass m_F, therefore the decay to heavy quarks and leptons is favored. Figure 1 shows the Higgs decay branching ratios as a function of Higgs mass. A light Higgs (M_H <130 GeV), decays mainly to $b\bar{b}$, a heavy Higgs mainly to four leptons via WW or Z^0Z^0. For a heavy Higgs the most sensitive channels at CMS are therefore $WW \to \ell^+\ell^-$ + missing energy or $Z^0Z^0 \to \ell^+\ell^-$. For a light Higgs the $gg \to b\bar{b}$ background dominates the $H \to b\bar{b}$ signal in an inclusive search (see table 1). The width of the Higgs is rather small below 130 GeV (< 10 MeV) but rises rapidly to 1 GeV at 200 GeV as the $2W$ and $2Z^0$ channels open up, to reach 100 GeV at 500 GeV.

Channel	Rate/year
H (M_H = 120 GeV)	4×10^6
H, (M_H = 800 GeV)	5×10^4
$t\bar{t}$	10^8
$b\bar{b}$	5×10^{13}

Table 1: Production rates at the full luminosity of 10^{34} cm^{-2}s^{-1}

For CMS the most sensitive discovery channel is $H \to \gamma\gamma$ (which has a much smaller decay branching ratio, see fig. 1) thanks to its crystal γ-calorimeter. Unless the Higgs is heavy, a significant (5σ) signal will be observed in the $\gamma\gamma$ invariant mass distribution with about 20 fb^{-1} which corresponds to 2 years of operation at a reduced initial luminosity of 10^{33}cm^{-2}s^{-1}.

At LEP the main production channel would have been $e^+e^- \to Z^0 \to HZ^0$, at FNAL $q\bar{q} \to (W, Z^0) \to (W, Z^0)H$. The main production channels for the SM Higgs at LHC are shown in fig. 2, together with their production cross section at 14 TeV. The main contribution is from the heavy quark loop. Compare the cross section of the order of 1 pb with the total cross section of about 100 mb!

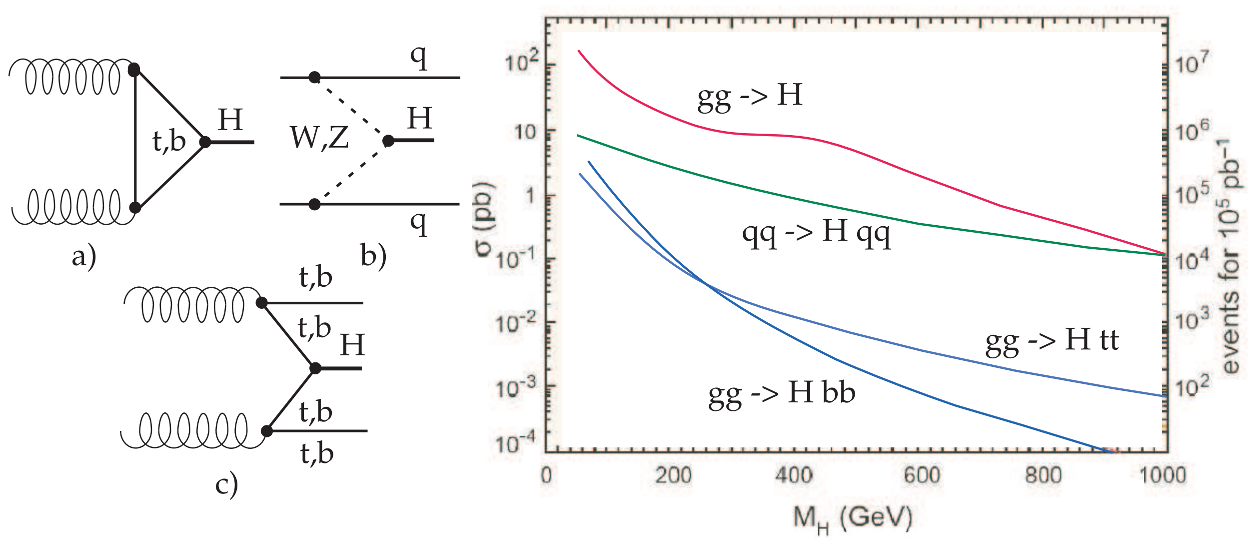

Figure 2: Left: the main contributions to the SM Higgs production at the LHC (in decreasing importance). Right: corresponding cross sections at 14 TeV.

Loop corrections in the SM drive the Higgs mass to infinity. Furthermore, the three running coupling constants which describe the weak, e.m. and strong interactions do not intersect at the grand unification energy ($\sim 10^{16}$ GeV).The minimal supersymmetric standard model (MSSM)[3] is the most popular extension of the SM which provides a solution to both issues and also correctly predicts the Weinberg angle when embedded in a GUT scenario. In addition to the SUSY particles the MSSM requires 2 Higgsdoublets corresponding to 8 - 3 = 5 spin zero fields, the neutral h, H, A and the charged H^+ and H^-. In general CP invariance is assumed in the Higgs sector: the h and H are CP = +1 and the A CP = -1 eigenstates[1]. Two parameters are required to fix the masses of the five Higgs bosons. They are usually chosen as the M_A and tanβ, where tanβ is the ratio f_2/f_1 (see eqn.(1)) of the vacuum expectation values of the doublets. Figure 3 shows a prediction for the masses. The lightest Higgs (h) lies below 130 GeV. The MSSM Higgs have been searched for at LEP and FNAL. Typical lower limits are 91 GeV for the h/H, 93 GeV for the A, and 80 GeV for the $H^{\pm}$. Also, large value of tan$\beta \geq 5$ are favored (fig. 4).

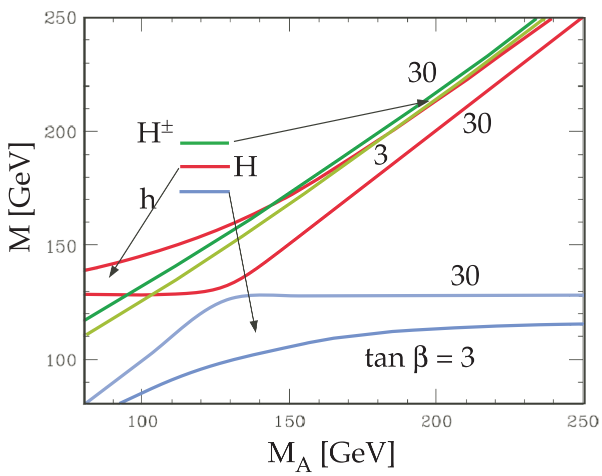

Figure 3: Prediction of the MSSM Higgs masses as a function M_A and tanβ (from ref. [4]).

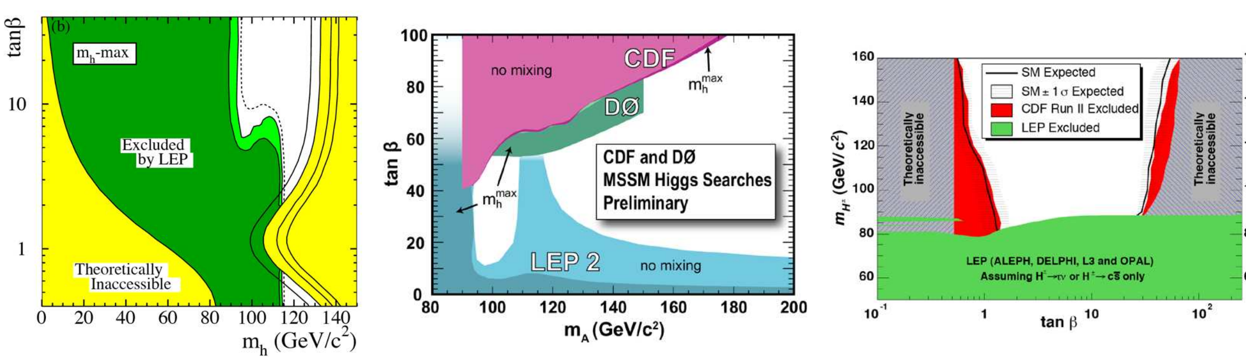

Figure 4: Exclusion plots for the h, A and $H^{\pm}$ (from [5]).

At pp colliders the h, H, A should be produced dominantly by two gluons through the b and t loops (fig. 2a) supplemented by SUSY contributions from $\tilde{b}$ and $\tilde{t}$ loops, this as long as tanβ is not too large. Higgs radiation off the t-quark plays a role for light Higgs only. Higgs radiation off the W and

[1] There are SUSY models which incorporate CP violation in which the three neutral Higgs $H_{1,2,3}$ are not CP eigenstates. In these models the mass of the lightest (H_1), which decays mainly to $b\bar{b}$, can be arbitrarily small. These models provide an attractive explanation for the baryon - antibaryon asymmetry in the universe.

Z^0 is not important at the LHC. The process depicted in fig. 2a is important for a h or a light H near 120 - 130 GeV. For large tanβ the main Higgs production mechanism is radiation off b quarks (fig. 5). The $H^{\pm}$ are mainly produced associated with a $t\bar{b}$, or $b\bar{t}$ pair or are pair produced, see e.g. fig. 6.

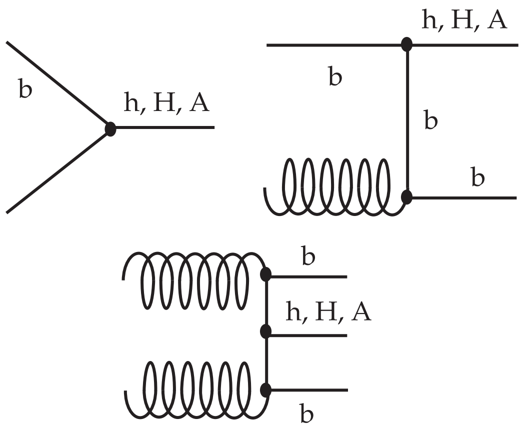

Figure 5: Higgsstrahlung from the b - quark becomes important for large tanβ.

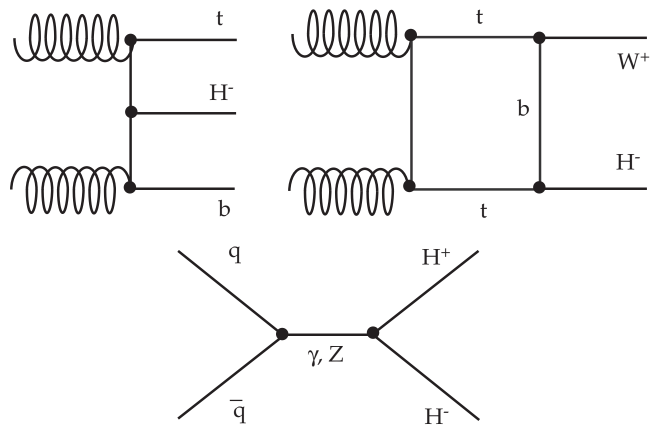

Figure 6: Examples of graphs for charged Higgs production and H^+H^- pair - production.

Higgs	tanβ = 3	tanβ = 30	
h	$b\bar{b}$ ($\sim$ 0.9)		
	$\tau^+\tau^-$ ($\sim$ 0.1)		
H	hh, W^+W^-	$b\bar{b}$	for m_H below $\sim$ 400 GeV
	$t\bar{t}$	$b\bar{b}$	for m_H above $\sim$ 400 GeV
A	$b\bar{b}$		for m_A below $\sim$ 400 GeV
	$t\bar{t}$	$b\bar{b}$	for m_A above $\sim$ 400 GeV
$H^{\pm}$	$\tau\nu$		for $m_{H^{\pm}}$ below $\sim$ 200 GeV
	$t\bar{b}$		for $m_{H^{\pm}}$ above $\sim$ 200 GeV

Table 2: Dominant decay branching ratios of the MSSM Higgs bosons (from ref. [6]).

Let us now examine the decay branching ratios given in table 2.The h always decays dominantly into $b\bar{b}$, the H dominantly into $b\bar{b}$ pairs for large tanβ. For small tanβ the dominant modes are hh and $t\bar{t}$, which also lead to b-quarks. A also decays to $b\bar{b}$ except for small tanβ and above $t\bar{t}$ threshold. A charged Higgs below 200 GeV decays mainly into τ and missing energy, a heavy one into $t\bar{b}$. Hence the detection of B mesons is of crucial importance in Higgs physics.

Several benchmark channels for Higgs searches have been studied in CMS [6]. As mentioned earlier, at low masses the likely discovery channel for the SM Higgs is $H \to \gamma\gamma$, for heavy Higgs $H \to 2\mu^+2\mu^-$. For large values of tanβ the likely signal for MSSM Higgs is associated production $b\bar{b}(h/H/A \to \tau^+\tau^-)$, as the gg production graph becomes dominant (fig. 5). Here one would search for 2 b-jets and 2 τ-jets or $e + \tau$-jet, $\mu + \tau$-jets, $e\mu$, or $\mu^+\mu^-$. Obviously b-tagging is important. The channel $b\bar{b}(h/H/A \to b\bar{b})$ is also possible, but difficult due to the QCD background. With 30 fb^{-1}

one would obtain a 6 σ significance in the $\tau^+\tau^-$ mass spectrum with a signal over background ratio of about one. This is fairlz independent of Higgs mass between 130 and 500 GeV.

An interesting channel is associated production $t\bar{t}(h/H/A \to b\bar{b})$ which leads to 4 b jets and 2 W, hence 8 quark jets or 6 quark jets and one lepton with missing energy. Preliminary studies show that with 60 fb^{-1} one could reach a 2σ signal at 115 GeV. The signal over background ratio isf 9%. The significance decreases with Higgs mass, hence this channel is attractive for light Higgs and high luminosity operation.

Charged Higgs $H^\pm$ can be searched for in t-decays for $M_H < m_t$, e.g with the channel $gg \to t\bar{t} \to H^\pm W^\mp b\bar{b}$ (where the $W^\mp$ stems from t-decay), or $gg \to tbH^\pm$ for $M_H > m_t$, see fig. 6. A light $H^\pm$ decays into $\tau\nu$, a heavy one into $t\bar{b}$.

The Higgs triplet model postulates the existence of seven Higgs bosons. These are the five previous states plus two doubly charged Higgs H^{++} and H^{--}. The latter are pair-produced by the Drell-Yan mechanism with a photon or a Z^0. They decay into two like-charge leptons. The scenario of doubly charged Higgs is particularly attractive to introduce spontaneous symmetry breaking in models involving right-handed doublets, as it naturally leads to finite neutrino masses[2]. The sensitivity for doubly charged Higgs with masses between 100 and 650 GeV has been studied in ref. [7]. With an integrated luminosity of 10 fb^{-1} one would observe a 5σ signal in the $\mu^\pm\mu^\pm$ mass spectrum.

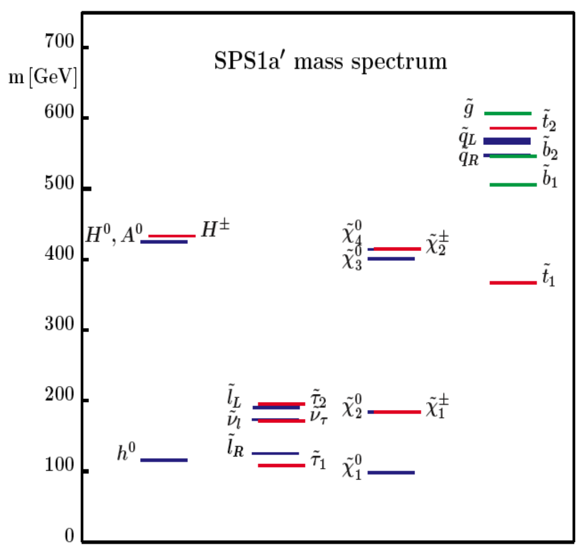

Figure 7: Mass spectrum for SUSY and Higgs at the mSUGRA reference point SPS 1a′ (from ref. [8]).

Another possibility is to search for Higgsbosons in the decay of supersymmetric particles. In the MSSM - mSUGRA model five parameters are needed to describe the SUSY spectrum: m_0 (common scalar mass), $m_{1/2}$ (common gaugino mass), A_0, tan β and signμ). The two neutral (spin 1/2) higgsinos mix with the two (spin 1/2) neutral gauginos ($\tilde{W}_3^0$ and $\tilde{B}$) to produce the (spin 1/2) neutralinos $\tilde{\chi}^0_{1,2,3,4}$. Since R-parity conservation is assumed (i.e. SUSY particles are always produced in pairs), the lightest SUSY, the neutralino called $\tilde{\chi}^0_1$, is stable. This is the dark matter candidate. Since dark matter was produced at high temperatures in the very early universe, the $\tilde{\chi}^0_1$ is heavy. Also, dark

[2] A spin 0 Higgs couples to a left-handed fermion and a left-handed antifermion. Since there are no left-handed antineutrinos, neutrinos cannot acquire mass in the standard model.

matter has survived until today, hence $\tilde{\chi}_1^0$ must be interacting only weakly with matter. Its signature in the CMS detector would therefore be a large missing energy.

The two charged higgsinos mix with the two charged winos ($\tilde{W}^{\pm}$) to produce the four charginos $\tilde{\chi}_{1,2}^{\pm}$. Figure 7 shows the SUSY mass spectrum in the so-called SPS 1a' reference point of mSUGRA which is consistent will all observations from collider data and cosmology. One finds that the $\tilde{\chi}_{1,2}^0$, $\tilde{\chi}_1^{\pm}$, the light squarks and the sleptons lie around 200 GeV, the other states (gluino, stop, sbottom, etc.) above 400 GeV[3].

At the SPS 1a$'$ reference point the gluino $\tilde{g}$ decays to an squark and a quark, $\tilde{g} \rightarrow \tilde{q}$q. The main decay chain of the $\tilde{q}$ is as follows:

$$\tilde{q} \rightarrow \tilde{\chi}_2^0 q, \tilde{\chi}_2^0 \rightarrow \tilde{\chi}_1^0 h, h \rightarrow b\bar{b}, \tag{4}$$

since the h is light and decays mainly to $b\bar{b}$. The overall branching ratio of this chain is 21%![4]. The signature will be 2 b-jets, missing energy ($>$ 200 GeV) and multiple jets from the quark q and the associated decay of the antigluino/antisquark. The main background stems from $t\bar{t}$ production, W and Z^0 + jets and $\tilde{b}$ decays to b-quarks. A preliminary simulation has been performed [9] which requires at least 4 jets, 2 tagged b-jets and missing energy above 200 GeV. Figure 8 shows the $b\bar{b}$ invariant mass distribution for an integrated luminosity of 10 fb^{-1} and fig. 9 the mass region covered in the m_0 - $m_{1/2}$ plot (5σ limit). Clearly the signal in fig. 8 could be observed rather early at LHC.

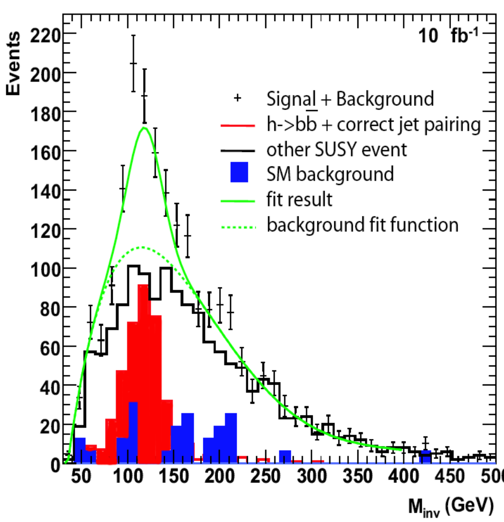

Figure 8: Invariant mass distribution of 2b-jets after 10 fb^{-}1. The Higgs signal is the red (dark) area(from ref. [9]).

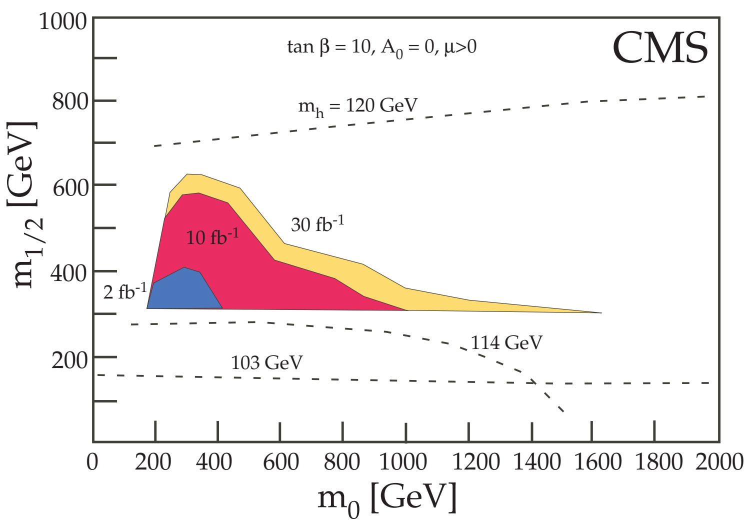

Figure 9: MSSM Higgs boson discovery reach for various integrated luminosities (from ref. [9]).

[3]There are two stops, two staus and two sbottoms. This is because there is a SUSY partner for each left-handed and right-handed quark or lepton, which mix as their spin is zero. There are two SUSY squarks and sleptons for each flavor. However, the mass splittings between the SUSY partners of the light quarks and leptons are small.

[4]The $\tilde{\chi}_2^0$ decays mainly into $\ell\tilde{\ell}$ if kinematically allowed.

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