Higgs Physics at LHC

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Abstract

Expectations for SM and MSSM Higgs boson production at LHC are presented. The recent investigations on the weak boson fusion channels and the Higgs searches in the invisible final states are discussed. Results on the precision measurements are also shown.

1 Introduction

The LHC collider is expected to give the final answer to the question of the Higgs boson existence and to measure its properties with good precision. The first pp collisions are expected in 2007. Two large detectors, CMS and ATLAS with the main goal to find the Higgs boson, are presently under construction. The experimental reaches of these two detectors are expected to be similar although different and complementary design concepts and technologies are used in many detector elements [1, 2].

LEP has recently been closed without solid evidence for the Higgs boson. The measurements yield as lower bounds 114.1 GeV for the Standard Model (SM) Higgs and 91.0 and 91.9 GeV for the light (h) and the pseudoscalar (A) Higgs bosons of the MSSM Model [3]. The excluded $\tan\beta$ regions are 0.5$<\tan\beta<$ 2.4 for the maximal m_h scenario and 0.7$<\tan\beta<$ 10.5 for the no mixing scenario [3]. The indirect searches, performing fits to all existing electroweak data, indicate a light SM Higgs boson with the most probable mass m_H = 88 GeV+53 GeV-21 GeV and a 95% CL upper limit of 196 GeV [4].

The CMS [5-10] and ATLAS [11] collaborations have established the expected discovery ranges for the most important production and decay channels of the SM and MSSM Higgs bosons. The $H \rightarrow ZZ, ZZ^* \rightarrow 4\ell^{\pm}$ provides an excellent signature for the SM Higgs boson over a large mass range from $m_H \sim$ 130 GeV to $m_H \sim$ 500 GeV. The low Higgs mass range, $m_H \lesssim$ 120 GeV, is the most difficult one at LHC. The $H \rightarrow \gamma\gamma$ and $H \rightarrow b\bar{b}$ decay modes are feasible in this mass range, but may require several years of running with the initial low luminosities. Therefore other channels like the experimentally demanding weak boson fusion channels with Higgs boson decaying to $H \rightarrow \gamma\gamma$, $H \rightarrow \tau\tau$, and $H \rightarrow WW^*$ have been studied intensively.

For the light MSSM Higgs boson practically the whole expected parameter space will be explored with an integrated luminosity of $30 fb^{-1}$ using the $h \rightarrow \gamma\gamma$ and $h \rightarrow b\bar{b}$ decay modes. The high $\tan\beta$ values are strongly favoured in the searches of the heavy MSSM Higgs bosons thanks to the enhanced Higgs boson couplings to the down type fermions. The discovery of the heavy neutral Higgs bosons is possible with several final states with the $\mu\mu$ and $\tau\tau$ and possibly $b\bar{b}$ decay channels using b-tagging in the $b\bar{b}H_{SUSY}$ associated production processes. The charged Higgs boson, produced in $tH^{\pm}$ final states, can be searched in the $H^{\pm} \rightarrow \tau\nu$ and $H^{\pm} \rightarrow tb$ decay channels with $H^{\pm} \rightarrow \tau\nu$ providing the largest reach and a clean signature. Due to the suppression of the Higgs coupling to weak bosons the medium and low $\tan\beta$ range is difficult. Although part of this space can be covered with SUSY particle decay modes, as will be shown later, some parameter space areas may remain at LHC where only by the light Higgs boson can be found.

In some extensions of SM or in some regions of MSSM parameter space or other possible scenarios the Higgs boson can decay predominantly to particles like gravitinos, neutralinos or gravitons leading to invisible final states. It has been shown recently that these decay channels cannot escape detection at LHC when searched in the weak boson fusion channels, provided the forward jets identifying the events can be measured [12].

The studies on the precision measurements have started and indicate a good precision for Higgs boson mass, couplings and the width. As these measurements are highly detector dependent full simulation studies are in progress for the final estimates.

2 Simulation methods

PYTHIA [13] is most frequently used to generate the events. Polarized τ decays are incorporated using the TAUOLA package [14]. Programs with exact matrix element calculations like HDECAY [15] are often used to normalize the cross sections and branching ratios, or are directly interfaced to the PYTHIA event generator like CompHEP [16]. Detector simulations are performed in general with the fast simulation packages [17]. However, the detector dependent issues like trigger simulations, resolutions of the narrow mass states, missing transverse energy resolution, b - and τ-tagging and jet resolution are studied with full GEANT-based detector simulation packages. The results are either used directly or parametrized for the fast simulation studies. Systematic errors are presently estimated only in some cases. Most of the following results are based on a simple cut analysis; more sophisticated analysis, like neural network, will be applicable to real data resulting in still better sensitivities.

3 Standard Model Higgs boson

The production of the SM Higgs boson is predominantly by gluon-gluon fusion $gg \rightarrow H$ over the entire mass range. The associated processes $q\bar{q}' \rightarrow HW$, $q\bar{q} \rightarrow HZ$, $gg, q\bar{q} \rightarrow t\bar{t}H$ and $gg, q\bar{q} \rightarrow b\bar{b}H$ have cross sections lower by a factor of $\sim$ 100 but in a number of cases provide better signal to background ratios. The cross section for the weak boson fusion channel $qq \rightarrow qqH$ is $\sim$10% of the $gg \rightarrow H$ cross section for $m_H \lesssim$ 200 GeV and becomes comparable to that for very heavy Higgs boson. The QCD corrections are expected to be large for $gg \rightarrow H$ with a k-factor of 1.5 - 1.8, while they are small (k-factor $\lesssim$ 1.2) for the associated production

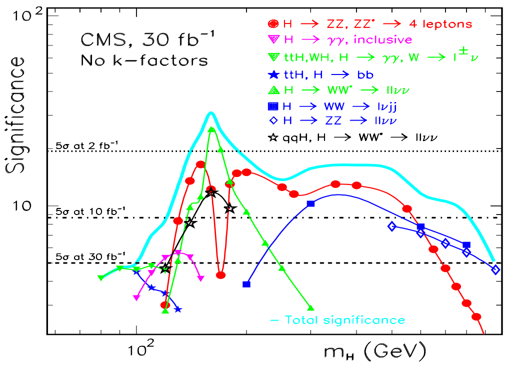

Figure 1: Expected statistical significance for the SM Higgs boson in the CMS detector for 30 fb^{-1} as a function of m_H.

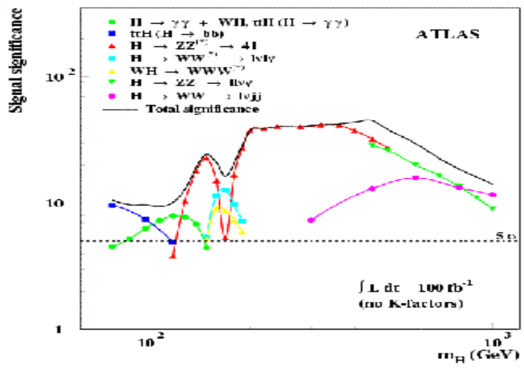

Figure 2: Expected statistical significance for the SM Higgs boson in the ATLAS detector for 100 fb^{-1} as a function of m_H.

processes [18]. In the following, the lowest order cross sections are used in general due to the difficulty of generating in many cases the background processes with higher order corrections.

The branching ratio to $b\bar{b}$ dominates in the low mass range $m_H \lesssim$ 150 GeV but the $H \to \tau\tau$ decay rate is also sizable $\sim$ 8%. The branching ratio for the $H \to \gamma\gamma$ decay mode is only $\sim 2 \times 10^{-3}$, but due to the clean signature it is one of the major Higgs boson discovery channels at LHC. Beyond the corresponding mass thresholds the decays to weak boson pairs strongly dominate and provide several useful final states for the SM Higgs boson searches.

Figure 1 shows the expected statistical significance for the SM Higgs boson in the CMS detectors for 30 fb^{-1} as a function of m_H. Figure 2 shows the same in the ATLAS detector for 100 fb^{-1} [11]. The intermediate mass range from $\sim$ 130 GeV to $\sim$ 500 GeV is covered with $H \to \gamma\gamma$ and with several final states from weak boson pair production with real or virtual W and Z bosons: $H \to ZZ^*/ZZ \to 4\ell^{\pm}$, $H \to WW^*/WW \to \ell^+\ell^-\nu\nu$, $H \to WW \to lepton + jets$ and $H \to ZZ \to 2\ leptons + jets$. While the $4\ lepton$ and $H \to \gamma\gamma$ channels provide an excellent Higgs mass measurement, the mass resolution is modest for the channels involving jets and E_t^{miss} and only the transverse Higgs boson mass can be reconstructed for the $H \to WW \to \ell^+\ell^-\nu\nu$ channel [8].

3.1 $H \to \gamma\gamma$

An excellent electromagnetic calorimeter resolution is mandatory for the inclusive $H \to \gamma\gamma$ channel due to the large prompt $\gamma\gamma$ background with a signal to background ratio (S/B) close to 0.1. The search of $H \to \gamma\gamma$ in the associated production channels, $t\bar{t}H$ and WH, is less sensitive to the $\gamma\gamma$ mass resolution as in this case the backgrounds can be effectively reduced by the lepton or jet requirement giving $S/B \sim 1$. Higgs mass resolution better than 1% is expected with the CMS $PbWO4$ crystal calorimetry in the mass range 100 GeV $< m_H <$ 150 GeV, including the recovery of the photons converted in the tracker material [19]. Figure 3 shows the reconstructed Higgs mass superimposed on the total background for m_H = 120 GeV with 100 fb^{-1} [6]. Statistical significance better than 5σ is expected for 120 GeV $< m_H <$ 140 GeV in the inclusive $H \rightarrow \gamma\gamma$ channel already with 30 fb^{-1} in the CMS detector as is shown in Fig. 1. Figure 2 shows the the significance for the combined inclusive and exclusive channels with 100 fb^{-1} in the ATLAS detector [11].

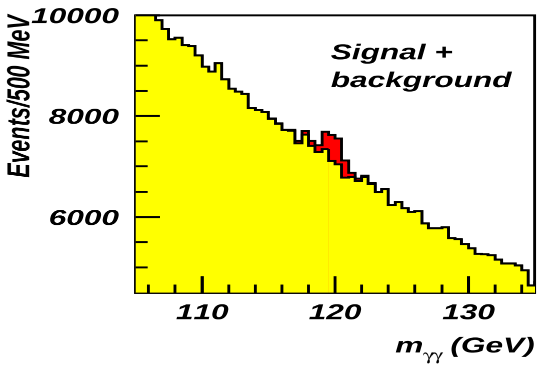

Figure 3: Signal superimposed on the total background for $H \rightarrow \gamma\gamma$ with m_H = 120 GeV for 100 fb^{-1} in the CMS detector.

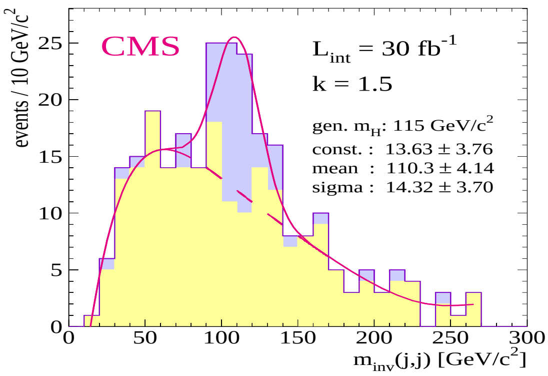

Figure 4: Signal superimposed on the total background for $t\bar{t}H \rightarrow l^{\pm}\nu q\bar{q}b\bar{b}b\bar{b}$ with m_H = 115 GeV for 30 fb^{-1} in the CMS detector.

3.2 $H \rightarrow b\bar{b}$

The large $H \rightarrow b\bar{b}$ branching ratio for $m_H \lesssim$ 130 GeV can be exploited only in the associated production channels WH and $t\bar{t}H$. To extract the Higgs signal in the more promising $t\bar{t}H \rightarrow l^{\pm}\nu q\bar{q}b\bar{b}b\bar{b}$ channel requires tagging of up to 4 b-jets in the presence of a large hadronic activity, reconstruction of the Higgs mass from two b-jets and the reconstruction of the associated leptonic and hadronic top. The channel is one of the most demanding for b-tagging at LHC. Large efforts has been made in the collaborations to optimize the b-tagging capabilities including dedicated vertexing detectors in addition of the precise tracking devices [20]. Full simulation studies with realistic track reconstruction using impact parameter measurements and track counting methods indicate that good efficiencies, $\sim$ 60%, are expected for the b-jets with $E_t \gtrsim$ 50 GeV - with a mistagging probability $\leq$1%. The b-tagging, however, is highly process dependent with $t\bar{t}H \rightarrow l^{\pm}\nu q\bar{q}b\bar{b}b\bar{b}$ being one of the most hostile environments. The CMS analysis for $t\bar{t}H \rightarrow l^{\pm}\nu q\bar{q}b\bar{b}b\bar{b}$ [7] is based on a more sophisticated likelihood method while the simpler cut method is used in the ATLAS analysis [11]. The main backgrounds from $t\bar{t}b\bar{b}$, $t\bar{t}jj$ and $t\bar{t}Z$ are generated in the CMS analysis with the CompHep-PYTHIA package [16] which includes the calculation of the matrix elements with higher order corrections while PYTHIA is used for the ATLAS study. Figure 4 shows the reconstructed invariant mass for the SM Higgs boson in the $t\bar{t}H$ channel superimposed on the total background for m_H = 115 GeV with 30 fb^{-1} in the CMS detector. The expected discovery ranges are shown in Figs. 1 and 2 for 30 fb^{-1} in the CMS detector and for 100 fb^{-1} in the ATLAS detector, respectively.

3.3 Higgs boson searches in the weak boson fusion $qq \to qqH$

The weak boson fusion channels $qq \to qqH$ are the most promising ones for the searches of the heavy Higgs boson, $m_H \gtrsim$ 500 GeV, and may provide a signal for the medium mass Higgs boson as well [9]. Several phenomenological studies [21] published in recent years propose these channels as potential discovery channels for the Higgs boson in the difficult mass range near to the LEP limit. The dynamics of the process leads to energetic jets in the forward and backward directions, and the absence of colour exchange in the hard process leads to small jet activity in the central region. Thus detecting these forward jets and imposing a veto on the jet activity in the rapidity range between the forward jets leads to a large reduction against the backgrounds from $t\bar{t}$, single W and Z production and the QCD jet events. Electro-weak production of weak boson pairs shares the same dynamics with the signal and is therefore irreducible against these methods, but the background levels are initially lower. The $H \to \tau\tau$, $H \to \gamma\gamma$ and $H \to WW^*$ decay channels have been investigated [12, 22, 23]. The $qq \to qqH$, $H \to WW^*$ channels in particularly interesting as it contains the HWW coupling at production and decay. The two-lepton plus E_t^{miss} final state from $H \to WW^* \to \ell\nu\ell\nu$ is promising and provides a discovery for $m_H \geq 120$ GeV as is shown in Fig. 1. The spin correlations, leading to small opening angles between the two leptons, are used to suppress the backgrounds where the kinematics favours the back-to-back configurations. Thanks to the spin correlations a Jacobian type structure is visible in the Higgs boson transverse mass reconstructed from the lepton pair and E_t^{miss}. The m_T distribution superimposed on the total background for m_H = 160 GeV in the ATLAS detector is shown in Fig.5 [12]. The Higgs boson invariant mass can be reconstructed for the $H \to \tau\tau$ channels with $lepton + jet$ and $2 - lepton$ final states using the collinearity approximation for the neutrinos from τ decay. The signal rate is small due to the small $H \to \tau\tau$ branching ratio and statistical significancies less than 4 are expected from the $lepton + jet$ and $2 - lepton$ final states.

3.4 Precision measurements for the SM Higgs boson

Figure 6 shows expected precision for the measurement of the SM Higgs boson mass for $300 fb^{-1}$ combining the CMS and ATLAS results [11]. The $H \to \gamma\gamma$ and $H \to ZZ/ZZ^* \to 4\ell^{\pm}$ channels provide a precision better than 0.1% for $100 \lesssim m_H \lesssim 500$ GeV. The main source of systematic error is the energy scale for lepton and photon measurement estimated to be known within 0.1%. The same channels are expected to provide the best measurement for the Higgs boson production rates with the precision of $\sim$ 10% for $100 \lesssim m_H \lesssim 600$ GeV. The main systematic errors on rates are due to the luminosity measurement (5-10%), and due to the uncertainty from background substraction ($\sim$ 10%).

Direct measurement of the SM Higgs boson width is possible only for $m_H > 200$ GeV where the natural width exceeds the experimental mass resolution of $\sim$ 1 GeV. Precision better than 1% is expected from $H \to ZZ \to 4\ell^{\pm}$ for $m_H > 250$ GeV with a systematic error of 1.5% dominated by the radiative decays. For $m_H < 200$ GeV the width can be measured using an indirect method with a precision of 10-20% as is shown in ref. [24]. The weak boson fusion channels, especially the $H \to WW^*$ decay providing the normalization of the HWW coupling are used, assuming the fraction of unknown decay modes (including $c\bar{c}$) $< 10\%$.

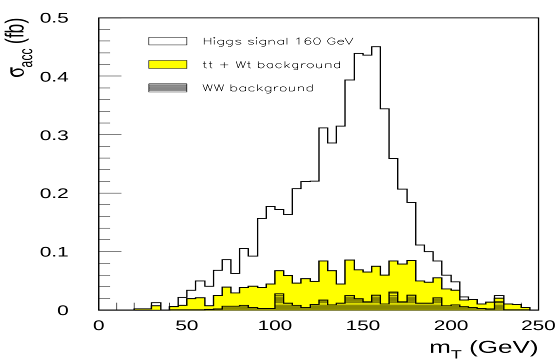

Figure 5: Signal superimposed on the total background (fb) for $qq \to qqH, H \to WW^* \to \ell\nu\ell\nu$ with m_H=160 GeV in the ATLAS detector.

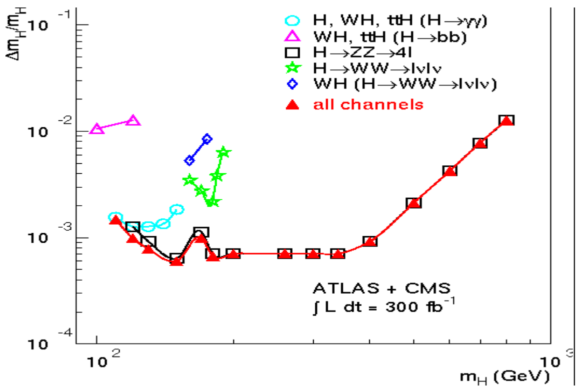

Figure 6: Expected precision for the SM Higgs boson mass measurement for $300 fb^{-1}$ in CMS and ATLAS detector.

The large variety of Higgs production and decay channels at LHC allow to measure the coupling ratios where the rate uncertainties largely cancel. For instance, the ratio of Higgs coupling to weak bosons, Γ_W/Γ_Z can be measured in the direct production using $\sigma \times BR(H \to WW^*)/\sigma \times BR(H \to ZZ^*)$= $\Gamma_g\Gamma_W/\Gamma_g\Gamma_Z$=$\Gamma_W/\Gamma_Z$ or can be measured using the fact that $H \to \gamma\gamma$ is mediated with a W loop using $\sigma \times BR(H \to \gamma\gamma)/\sigma \times BR(H \to ZZ^*)$= $\Gamma_g\Gamma_\gamma/\Gamma_g\Gamma_Z$=$\Gamma_W/\Gamma_Z$. Precision of better than 20% is expected for these measurements with 300 fb^{-1}. Similar measurements are possible for the ratios of weak boson to fermion couplings with the expected precisions varying from 10 to 80% [11].

4 MSSM Higgs bosons

The production of the heavy neutral MSSM Higgs bosons is predominantly through $gg \to H_{SUSY}$ and $gg \to b\bar{b}H_{SUSY}$. As the Higgs coupling to b-quarks (and to τ's) is enhanced at high $\tan\beta$ ($g_{Hb\bar{b}}, g_{H\tau\tau} \sim \cos\beta^{-1}$) the associated production dominates and is about 90% of the total rate for $\tan\beta \gtrsim$ 10 and $m_H \gtrsim$ 300 GeV. The gluon fusion is mediated by quark loops and can then be affected by stop mixing. Due to the dominance of the associated production and because only the CP-even Higgs can be affected, expectations for the heavy SUSY Higgs are not sensitive to the loop effects.

At high $\tan\beta$ the decay to $b\bar{b}$ strongly dominates. However this mode has not yet been shown as viable for the heavy Higgs bosons. The branching ratio to $\tau\tau$ is about 10% and that to $\mu\mu$ about 3×10^{-4}. The branching ratios for the heavy SUSY Higgs bosons are not sensitive to the amount of stop mixing. For lower $\tan\beta$ and large Higgs boson masses the $A, H \to \chi^0\chi^0$ and $A, H \to \chi^+\chi^-$ decay modes can significantly suppress the decays to SM particles. The thresholds for these decay modes are functions of the SUSY parameters like the Higgsino mass

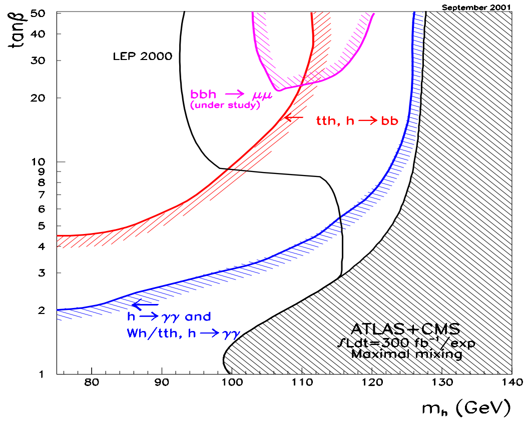

Figure 7: Expected 5σ-discovery range for the light MSSM Higgs boson with maximal stop mixing in the ATLAS detector for 600 fb^{-1}.

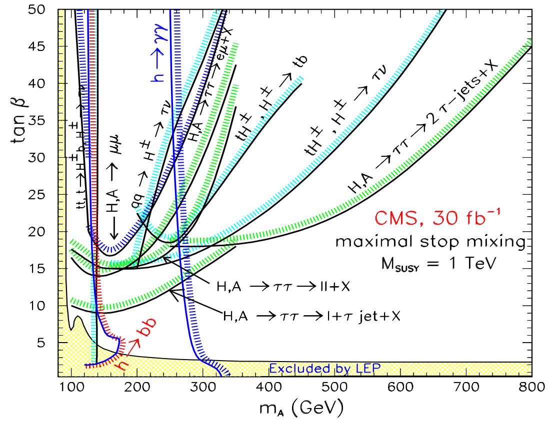

Figure 8: Expected 5σ-discovery range for the MSSM Higgs bosons with maximal stop mixing in the CMS detector for 30 fb^{-1}.

parameter μ and therefore the $\tan\beta$ range 10 - 30 for $m_A \gtrsim$ 300 GeV, expected to be within the experimental reach, is sensitive to the SUSY parameters.

4.1 Light MSSM Higgs boson

Figure 7 shows the expected discovery reaches for the light MSSM Higgs boson in the $h \to b\bar{b}$ and $h \to \gamma\gamma$ decays as a function of m_h and $\tan\beta$ in the ATLAS detector for the ultimate luminosities 600 fb^{-1} assuming maximal stop mixing. The inclusive and the associated production are combined for the $H \to \gamma\gamma$ channel. The parameter space outside the light Higgs reach at LHC around $m_h \sim m_A \sim$ 100 GeV at high $\tan\beta$ may be partly covered by the $gg \to b\bar{b}h$, $h \to \mu\mu$ channel as is shown in the figure. The discovery reaches in the CMS detector for $h \to b\bar{b}$ and $h \to \gamma\gamma$ are shown in Fig. 8 as a function of m_A and $\tan\beta$ for 30 fb^{-1} assuming maximal stop mixing. The rate for $gg \to h \to \gamma\gamma$ is calculated with the HDECAY program [15] using the next-to-leading order cross sections. Thus the CMS result is a conservative NLO limit as only the gluon-gluon fusion production process is included.

The rate for $gg \to h \to \gamma\gamma$ could be significantly reduced in the case of large stop mixing if the stop becomes light, $m_{\tilde{t}_1} \lesssim$ 200 GeV due to the destructive interferences between the top and stop loops in $gg \to h$ [25]. The $h \to \gamma\gamma$ partial width is enhanced by these loop effects but this positive contribution is smaller than the negative for $gg \to h$ and the net effect is a reduction of the overall $gg \to h \to \gamma\gamma$ rate which could lead to no discovery with inclusive $gg \to h \to \gamma\gamma$ channel for $m_{\tilde{t}_1} \lesssim$ 200 GeV [26].

4.2 Searches for the heavy neutral MSSM Higgs bosons

The branching ratio for $A, H \to \mu\mu$ is small, $\sim 3\times10^{-4}$, but the excellent Higgs mass resolution better than 2% for $A, H \to \mu\mu$ in the CMS detector [27] makes the channel nevertheless very

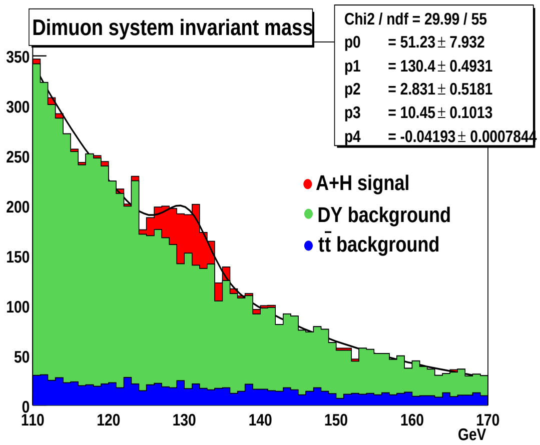

Figure 9: Signal superimposed on the total background for $gg \to b\bar{b}H/A \to \mu^+\mu^-b\bar{b}$ with m_H=130 GeV in the CMS detector for 20 fb^{-1}.

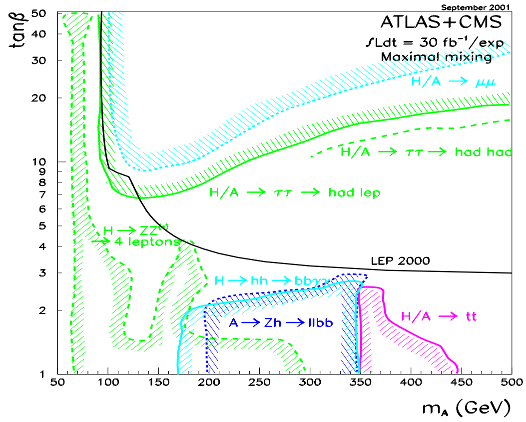

Figure 10: Expected 5σ-discovery range for the heavy neutral MSSM Higgs bosons with maximal stop mixing in the ATLAS detector assuming the statistics of ATLAS+CMS for 30 fb^{-1}.

interesting. Figure 9 shows the signal superimposed on the total background for m_A = 130 GeV and $\tan\beta$ = 30 with 20 fb^{-1} in the CMS detector from full simulation and event reconstruction [28]. The dominant background from $Z, \gamma^* \to \mu\mu$ is suppressed with b-tagging. As the event rate is small and the associated b-jets are soft with distributions peaking around $E_t^{jet} \sim 20$ GeV the b-tagging is performed reconstructing the secondary vertecies from B-hadron decays. This method allows a very efficient veto on central jets to suppress the $t\bar{t}$ background. The 5σ-discovery reach for $A, H \to \mu\mu$ in the m_A, $\tan\beta$ - plane is shown in Fig. 8 for 30fb^{-1} including the discovery reaches for the main discovery channels for the MSSM higgs bosons. The corresponding discovery reaches in the ATLAS detector are shown in Fig. 10 for 60fb^{-1}.

The final states of $2\ leptons$ [29], $lepton + \tau\ jet$ [30] and $2\ \tau\ jets$ [31] have been studied for $A, H \to \tau\tau$. Efficient τ-jet identification has been developed based on the low multiplicity, narrowness and isolation of the τ-jet in $H \to \tau\tau$. This identification has been shown to provide a rejection factor of $\gtrsim$ 1000 per QCD jet, needed to suppress the initially very large QCD background. The key element in the QCD jet rejection is the isolation, thus the tracker capability to reconstruct soft tracks with high efficiency. A further rejection against the QCD background can be obtained exploiting the τ lifetime using the impact parameter measurement for the hard tracks from τ or the secondary vertex reconstruction for the 3-prong τ decays. For the $2-lepton$ final states the τ-tagging allows to double the signal statistics by including all $\ell^+\ell^-$ and not only $e + \mu$ final states; this can extend the discovery range towards larger masses.

The Higgs boson mass can be reconstructed in the $H \to \tau\tau$ channels from the visible τ momenta (leptons of τ-jets) and E_t^{miss} using the collinearity approximation for the neutrinos from τ decays. The mass resolution depends on the $\Delta\phi$-angle between the visible τ momenta as $1/sin(\Delta\phi)$ and is sensitive to the E_t^{miss} measurement. The CMS full simulation studies indicate a mass resolution of 14.5% for the $2\ \tau\ jet$ final state for m_A = 200 GeV with a loose cut in the $\Delta\phi$-angle, $\Delta\phi < 175^0$ [32]. The efficiency of the mass reconstruction method is low, $\sim$ 37%, but improves significantly, by a factor of $\sim$ 2, when a b-jet is required.

The signal superimposed on the total background for the $e + \mu$ final states with m_A= 200 GeV and $\tan\beta$=20 for $30 fb^{-1}$ is shown in Fig. 11, and that for the 2τ-jet final state with m_A= 500 GeV and $\tan\beta$=20 is shown in Fig. 12. The $Z, \gamma^* \rightarrow \tau\tau$ background is suppressed with b-tagging using the impact parameter method. The efficiency (including jet E_t threshold) for tagging one b-jet in the signal events is $\sim$ 20% when the mistagging rate in the $Z + jets$ events is kept under 1% level. The $t\bar{t}$ background with real τ's in the final state is irreducible by the above methods, but can be reduced with a veto on a second jet. The expected discovery reaches for the $2\ lepton$, $lepton + \tau\ jet$ and $2\ \tau\ jet$ [30] final states in the CMS detector are shown in Fig. 8 for 30 fb^{-1} assuming maximal stop mixing. The expected discovery ranges in the ATLAS detector for $lepton + \tau\ jet$ and $2\ \tau\ jet$ final states are shown in Fig. 10 for 60 fb^{-1}. Investigations for $gg \rightarrow b\bar{b}H_{SUSY}$, $H_{SUSY} \rightarrow b\bar{b}$ are in progress.

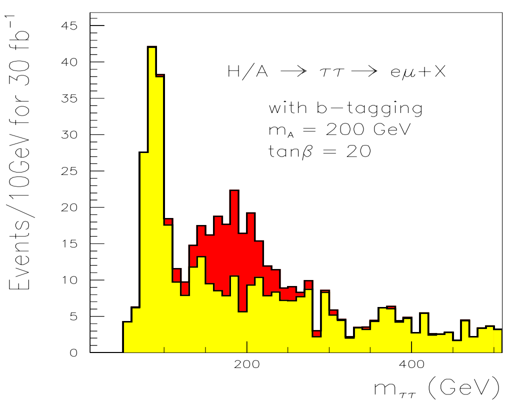

Figure 11: Signal superimposed on the total background for $gg \rightarrow H/A \rightarrow \tau\tau \rightarrow e + \mu + X$ with m_A=200 GeV and $\tan\beta$=20 in the CMS detector for 30 fb^{-1}.

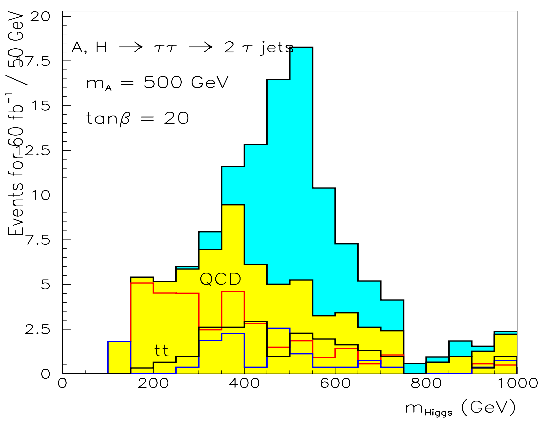

Figure 12: Signal superimposed on the total background for $gg \rightarrow H/A \rightarrow \tau\tau \rightarrow 2\tau - jets + X$ with m_A=500 GeV and $\tan\beta$=20 in the CMS detector for 30 fb^{-1}.

Precision of the Higgs boson mass measurement is estimated to be 0.1 - 1.5% for $A, H \rightarrow \mu\mu$ and 1 - 10% for $A, H \rightarrow \tau\tau$ at high $\tan\beta$ values. For the $\tan\beta$ measurement from the event rates a precision of 5 - 12% is expected from $A, H \rightarrow \tau\tau$ and $A, H \rightarrow \mu\mu$ assuming 10% systematic error dominated by luminosity measurement. The theoretical error on the cross sections, not included in these estimates, is expected to be the dominant one for the $\tan\beta$ measurement. For large enough p_t^b the cross section for $gg \rightarrow b\bar{b}H_{SUSY}$ can be calculated with much higher precision than the $gg \rightarrow H_{SUSY}$ cross section [18]. Therefore extracting the pure $gg \rightarrow b\bar{b}H_{SUSY}$ component using double b-tagging the theoretical errors can be significantly reduced. However, ultimate luminosities may be needed due to low double b-tagging efficiencies. The good mass resolution for $A, H \rightarrow \mu\mu$ gives the possibility for direct Higgs boson width measurement which in turn may give information on $\tan\beta$ as the natural width for the accessible $\tan\beta$ values varies from GeV to $\sim$ 10 GeV range.

4.3 Charged Higgs at LHC

Discovery of a charged Higgs at LHC would be a clear signature for physics beyond SM. The $H^{\pm}$ coupling to fermions has components proportional to $cot^2\beta$ and $tan^2\beta$ leading to a sensitivity at low and at high $\tan\beta$. Below the top mass $H^{\pm}$ decays to $\tau\nu$ with an almost 100% branching ratio. For $m_{H^+} \gtrsim$ 200 GeV the $H^{\pm} \to tb$ decay dominates and BR($H^{\pm} \to \tau\nu$) approaches a 10% level for $m_{H^+} \gtrsim$ 400 GeV.

If the charged Higgs is light, $m_{H^+} < m_{top}$, the production is through the the $t\bar{t}$ events followed by $t \to H^{\pm}b$. Using the $H^{\pm} \to \tau\nu$ decay mode the expected discovery range for 30 fb^{-1} is for $m_A \lesssim$ 160 GeV almost independent of $\tan\beta$ and is shown in Figs. 14 and 8. The heavy charged Higgs is mainly produced in association with the top quark through the processes $gb \to tH^{\pm}$ and $gg \to tbH^{\pm}$. The total cross section is a sum of the $2 \to 2$ and $2 \to 3$ processes with substraction of the common terms [33]. The experimental simulations have been done with PYTHIA using the $2 \to 2$ process only. The cross section for $m_{H^+} \gtrsim$ 300 GeV is in good agreement with the theoretical cross section while for $m_{H^+} <$ 300 GeV PYTHIA overestimates the rate by a factor of 2. Other production processes like $gg \to H^+H^-$and $gg \to W^{\pm}H^{\mp}$ have much smaller cross sections [34] or lead to the final states difficult to isolate from the backgrounds like the s-channel production $q\overline{q}' \to H^{\pm}$ [35].

For the $H^{\pm} \to \tau\nu$ channel the signal can be strongly enhanced against the background from $t\bar{t}$, Wtb, $W \to \tau\nu$ exploiting the τ polarization [36]. Due to spin correlations, the single pion from a one-prong τ decay is harder when the τ originates from an $H^{\pm}$ than from a W. Requiring 80% of the visible τ-jet energy to be carried by a single charged pion, the $t\bar{t}$ background can be reduced by a factor of $\sim$ 300 while keeping the signal efficiencies at a 20% level [37].

In purely hadronic final states in $gb \to tH^{\pm}$, $H^{\pm} \to \tau\nu$ with hadronic top decay the transverse mass reconstructed from the τ jet and the E_t^{miss} vector has a Jacobian peak structure with an endpoint at m_W for the backgrounds. This leads to an almost background-free situation as can be seen from Fig. 13 showing the reconstructed transverse mass for $m_{H^{\pm}}$ = 400 GeV (m_A = 400 GeV) and $\tan\beta$ = 40 superimposed on the total background for 30fb^{-1}. The low-mass background can be further reduced applying a lower limit on the $\Delta\phi$ angle between the τ-jet and E_t^{miss} vector ($\Delta\phi > 30^0$ in Fig. 13). The discovery reaches in the CMS and ATLAS detectors are shown in Figs. 8 and 14 for 30 fb^{-1} and 60 fb^{-1}, respectively.

The $H^{\pm} \to tb$ decay channel in the $gb \to tH^{\pm}$ production has been studied requiring one isolated lepton from the decay of one of the top quarks [38, 11]. To extract the Higgs signature in these multi-jet events requires tagging of three b-jets, reconstruction of the leptonic and hadronic top quark and the Higgs mass reconstruction from a top quark and one b-jet. After selection cuts and b-tagging, the background is concentrated in the signal area requiring precise knowledge of the background distributions. The discovery ranges at high and low $\tan\beta$ can be seen in Fig. 14 in the ATLAS detector and at high $\tan\beta$ in the CMS detector in Fig. 8.

The s-channel production of $H^{\pm}$ in $q\overline{q}' \rightarrow H^{\pm} \rightarrow \tau\nu$ has been investigated using the hadronic τ decay and exploiting the τ polarization [35], but the reduction of the large $q\overline{q}' \rightarrow W \rightarrow \tau\nu$ background is difficult for this channel. The expected discovery reach is shown in Fig. 8 in the CMS detector for 30 fb^{-1}. In MSSM the $H^{\pm} \rightarrow Wh$, $h \rightarrow b\overline{b}$ has been found to be viable only at low $\tan\beta$ ($\lesssim$ 2) but could be a promising discovery channel in NMSSM where the low $\tan\beta$ values survive the LEP bounds.

A precision of 1-2% is expected for the charged Higgs mass measurement in the expected $\tan\beta$ range. Due to the $\sigma \sim tan^2\beta$ behaviour of the cross section the statistical error of the $\tan\beta$ measurement is half of that for the rate measurement. Precision better than $\sim$ 7 % is expected for $\tan\beta >$ 20 at $m_{H^{\pm}}$=250 GeV.

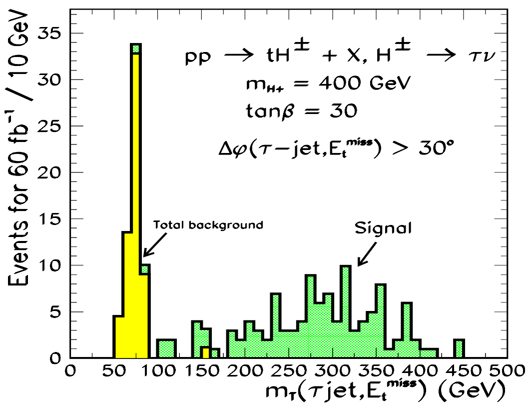

Figure 13: Signal superimposed on the total background for $gg \rightarrow tH^{\pm}$, $H^{\pm} \rightarrow \tau\nu$, $\tau \rightarrow hadrons + \nu$ for m_A=400 GeV and $\tan\beta$=30 in the CMS detector for 30 fb^{-1}.

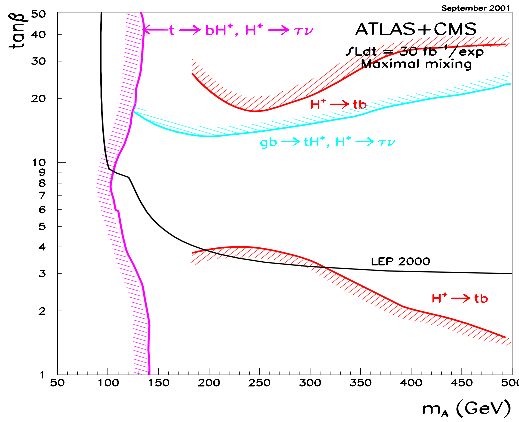

Figure 14: Expected 5σ-discovery ranges for the charged Higgs boson in the ATLAS detector for 60 fb^{-1}.

4.4 Heavy MSSM Higgs searches with sparticle decay modes

As shown above, the heavy MSSM Higgses are expected to be found at high $\tan\beta$ with several decay modes, discovery ranges extending down to $\tan\beta \sim 10$ in the low mass range $m_A \lesssim$ 200 GeV. For the $\tan\beta$ values between these boundaries and the LEPII limit, where no SM decay channel looks viable, the decays to sparticles may be used as the Higgs boson branching ratios to neutralino and chargino pairs can be sizable, up to $\sim$20%. The channel $A, H \rightarrow \chi_2^0\chi_2^0 \rightarrow 4\ell^{\pm} + X$ has been found to be the most favourable one for the neutral Higgs bosons, provided neutralinos and sleptons are light enough so that the $\chi_2^0(\rightarrow \tilde{\ell}\ell) \rightarrow \chi_1^0\ell^+\ell^-$ branching ratio is significant. The expected m_A-$\tan\beta$ reach for the $\chi_2^0\chi_2^0$ channel is shown in Fig. 15 for 30 fb^{-1} and 100 fb^{-1} with the following MSSM parameters: M_1 = 60 GeV, M_2 = 120 GeV, μ = -500 GeV, $M_{\tilde{q},\tilde{g}}$ = 1000 GeV, $M_{\tilde{\ell}}$ = 250 GeV and A_t = 0 [39]. The discovery ranges for the Higgs decays to SM particles in Figs. 8 and 10 are not affected by this parameter choice with light sleptons. For M_2 = 180 GeV the reach is reduced due to the neutralino pair mass threshold moving to higher m_A values.

The decay channel $H^{\pm} \to \chi^0_{2,3}\chi^{\pm}_{1,2} \to 3\ell + X$ could extend the $H^{\pm}$ discovery to the medium $\tan\beta$ range. However the branching ratio is large only for a limited range in the parameter space: for light sleptons and for small $|\mu|$ values near to the LEP limit [40]. Investigations have started to exploit the Higgs production in the SUSY cascades expected to be large.

5 Searches for invisible Higgs boson

The Higgs boson can decay to stable neutral weakly interacting particles like to the lightest neutralinos in MSSM. Investigations have started on how to trigger and to identify these events at LHC [12]. The studies have been done for the weak boson fusion channel where the forward jets, large E_t^{miss} and low jet activity in the central area are used to identify the events. CMS trigger for these events is based on jets up to $|\eta|$ = 5 combined with E_t^{miss} at the first trigger level, while the topological cuts like $\Delta\eta$ between the two tagging jets can be used at higher levels to reduce the events to an acceptable rate. In addition to the backgrounds where E_t^{miss} originates from weak boson decays (electroweak or QCD production) there is a large potential background from QCD jet events with E_t^{miss} from measurement errors or from heavy flavour decays. The dynamics of the $qq \to qqH$ process favours the configurations where the forward jets scatter against the E_t^{miss} from the invisible particles while for the backgrounds the forward jets tend to be in a back-to-back configuration with E_t^{miss} following one of the jets. This feature can be exploited to reduce the backgrounds applying an upper cut in the $\Delta\phi_{jj}$ angle. The background levels can be finally obtained from data using leptons measured with high precision from weak boson decays in Zjj, $Z \to \ell\ell$ and Wjj, $W \to \ell\nu$. Figure 16 shows the 95% CL sensitivity to $H \to invisible$ signal for 10 fb^{-1} in CMS and ATLAS detector assuming that the background can be determined with an accuracy of 3% [12]. The difference between the CMS and ATLAS results is mainly due to the central jet veto method. For the CMS result the survival probability is taken from analytical calculations while in the ATLAS study it comes from PYTHIA generation of soft jets and further reconstruction of these jets in the calorimeter with fast detector simulation. Further studies are clearly needed to understand better the central jet veto and forward jet tagging in these processes. In MSSM no sensitivity is possible for the heavy scalar due to the suppression of the $qq \to qqH$ cross section by $\cos^2(\alpha - \beta)$ while Standard Model like production and sensitivity in major part of the parameter space is expected for the light MSSM Higgs boson.

6 Conclusions

Expectations for the searches of the SM and MSSM Higgs bosons at LHC in the most important production and decay channels are discussed. For the SM Higgs boson the discovery is guaranteed in the whole expected mass range 100 GeV $\lesssim m_H \sim$ 1 TeV with at least two decay channels in the CMS and ATLAS detectors already with 30 fb^{-1}. The range $m_H \lesssim$ 120 GeV is the most difficult one at LHC. In addition to the $H \to \gamma\gamma$ and $H \to b\bar{b}$ the weak boson fusion channels with $H \to \gamma\gamma$, $H \to \tau\tau$ and $H \to WW^*$ decays have been investigated in this mass mass range and are promising.

For the MSSM Higgs bosons almost the full m_A, $\tan\beta$ - parameter space can be explored with the $h \to \gamma\gamma$ and $h \to b\bar{b}$ decay modes already with 30 fb^{-1}. The heavy neutral MSSM Higges

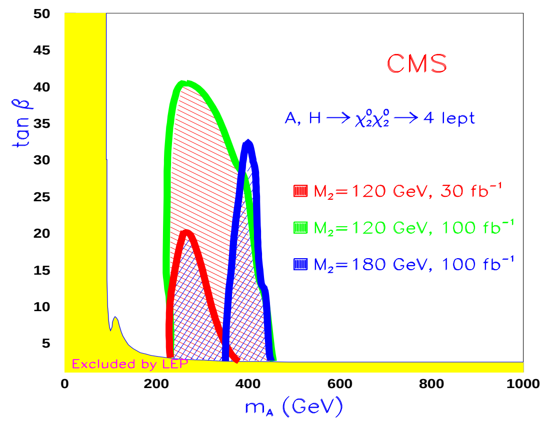

Figure 15: Expected 5σ-discovery ranges for $A, H \rightarrow \chi_2^0 \chi_2^0 \rightarrow 4\ell^\pm + X$ for 30 fb^{-1} and 100 fb^{-1} and for M_2=120 and 180 GeV in the CMS detector.

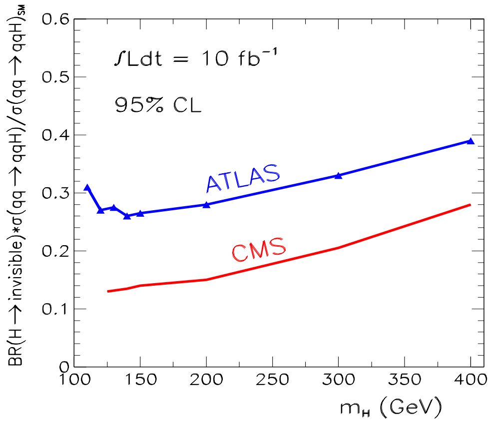

Figure 16: 95% CL sensitivity to $H \rightarrow invisible$ signal for 10 fb^{-1} in the CMS and ATLAS detectors.

are expected to be discovered for $\tan\beta \gtrsim$ 10 with the $H, A \rightarrow \mu\mu$ and $H, A \rightarrow \tau\tau$ decays with the reaches extending up to $m_A \sim$ 800 GeV with the 2 τ jet final states. For the search of the charged Higgs, the $gb \rightarrow tH^\pm$, $H^\pm \rightarrow \tau\nu$ channel with fully hadronic final states is found to be the most favourable one with a discovery reach for $\tan\beta \gtrsim$ 20 around $m_{H^\pm} \sim$ 400 GeV. The intermediate and low $\tan\beta$ range is difficult for the search of the heavy MSSM Higgs bosons. If the sleptons and neutralinos are light enough part of this parameter space is covered with the SUSY particle decay modes. Studies are in progress for the Higgs boson searches in the SUSY cascades.

Higgs boson mass is expected to be measured with a $\sim$ 0.1% precision in $H \rightarrow \gamma\gamma$ and $H \rightarrow ZZ^* \rightarrow 4\ell^\pm$. Detailed studies for the precision measurements have started and indicate good precision also for the Higgs width, production rates, couplings and for $\tan\beta$.

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