

# MSSM Higgs searches with tau lepton final states in CMS

S. Gennai<sup>a</sup>

<sup>a</sup>Scuola Normale Superiore and Istituto Nazionale di Fisica Nucleare Pisa, Italy.

The present understanding of large mass MSSM Higgs sector is reviewed. The most profitable channels:  $A/H \rightarrow \tau\tau$  and  $H^\pm \rightarrow \tau\nu$  are considered; a glimpse of the trigger chain studied for events with tau lepton final states is presented. The MSSM Higgs discovery reach of the general-purpose experiment CMS is summarised.

## 1. Introduction

The Standard Model [1] of strong and electroweak interactions is in excellent agreement with the experimental measurements. However, the core of the theory, the electroweak symmetry breaking manifesting itself in the heavy vector bosons  $W$  and  $Z$  and the massless photon, is the least known sector of the model. The Higgs mechanism [2] provides a mathematical explanation to this phenomenon, and one of the main tasks of the LHC collider will be the quest of the Higgs particle experimental evidence, or any observable of some other symmetry breaking mechanism. Without the Higgs boson the Standard Model is neither consistent nor complete, since the masses of the gauge bosons and fermions are generated through the interaction with the Higgs field.

The only unknown parameter in the SM Higgs sector is the mass of the Higgs boson. This is not predicted by the theory, but indirect constraints for the possible mass range can be deduced from theoretical arguments [3]. Furthermore, the electroweak precision measurements, where the Higgs mass enters in the radiative corrections, can be used to predict the most likely value of the Higgs mass consistent with all the experimental data used in the fit. Such fits favour a rather light Higgs boson,  $m_H < 196$  GeV with 95% confidence level [4]. Direct searches at LEP exclude the SM Higgs boson below  $m_H = 114.1$  GeV at 95% confidence level [5]. The SM Higgs would be the first fundamental scalar particle. However, when the bare mass of this scalar particle is com-

puted in the perturbation theory, it turns out that the mass diverges quadratically. Technically, this problem could be solved by renormalization, resulting in a counter-term balancing the quadratic divergence in each order of the perturbative calculations, but such fine-tuning cannot be considered natural or elegant. This unpleasant feature of the SM is one of the main motivations to search for a theory without such a drawback as supersymmetric theories [6]. In this report, the Higgs sector of one of these supersymmetric theories is reviewed. The production mechanism at the LHC are briefly discussed as well as the possible decay modes. The discovery potential of the general-purpose detector CMS [7] is summarised without going into details of the detector performance.

### 1.1. The MSSM Higgs sector

In supersymmetric theories, for each SM particle a supersymmetric partner is introduced. These particles have the same quantum numbers as the particles but their spin differs by one half. The introduction of the supersymmetric partners cancels the quadratic divergence in the Higgs boson mass, thus solving the fine-tuning problem, provided the masses of the supersymmetric partners are not beyond 1 TeV scale. In this report, we concentrate on the Minimal Supersymmetric extension [8] of the Standard Model, which is minimal in the sense that a minimum number, i.e. two, of Higgs doublets is introduced. This results in five observable Higgs particles in the MSSM: two neutral CP-even scalars, a light  $h$  and a heavy  $H$ , a CP-odd  $A$ , and charged  $H^+$  and  $H^-$ . In the MSSM, at tree level, the Higgs sector is de-

fined by two parameters which can be chosen to be the mass of the CP-odd A,  $m_A$  and  $\tan\beta$ , the ratio of the vacuum expectation values of the two Higgs doublets. There are other parameters which affect the Higgs sector through radiative corrections, such as the top quark mass, the mass scales of the SUSY particles and the mixing between the left and right handed components of the stop squark. The two parameters,  $m_A$  and  $\tan\beta$ , define the masses of other Higgs particles [9]. The light h reaches its maximal mass already at moderate  $m_A$  values. Above  $m_A \sim 200$  GeV the heavy Higgses (H, A and  $H^+$ ) are almost degenerate in mass. The LEP experiments have excluded a light h below 91 GeV, an A below 91.9 GeV and a charged Higgs below 78.6 GeV [10]. For maximal stop mixing the range  $0.5 < \tan\beta < 2.4$  has been excluded, and for minimal mixing  $0.7 < \tan\beta < 10.5$  [10].

In this report we concentrate on large mass A/H and  $H^+$ , decaying in tau lepton which are the most promising channels investigated till now.

## 2. Higgs bosons production and decay at LHC

In this section, Higgs production and decay at the LHC are reviewed. The cross-sections have been computed with the Higgs production programs HIGLU, VV2H, V2HV and HQQ [11] based on the calculations in [12] and the branching ratios have been computed with HDECAY [13].

In the MSSM, the SM Higgs couplings are modified as a function of the  $m_A$  and  $\tan\beta$  at tree level. The resulting cross-sections are shown for  $\tan\beta = 30$  in figure 1 for h,H and A. For comparison, the dominant SM Higgs production process through the gluon-gluon fusion, is shown in the plots. It can be concluded that the total rate is enhanced, respect to SM value, at high  $\tan\beta$  and  $m_A < 400$  GeV. The vector boson fusion is suppressed, for h and H especially at high  $\tan\beta$ , and altogether for A which does not couple to vector bosons at tree level. Higgs production in association with a  $b\bar{b}$  pair is strongly enhanced and it becomes the dominant production mechanism at high  $\tan\beta$ . The Higgs decay pattern can be

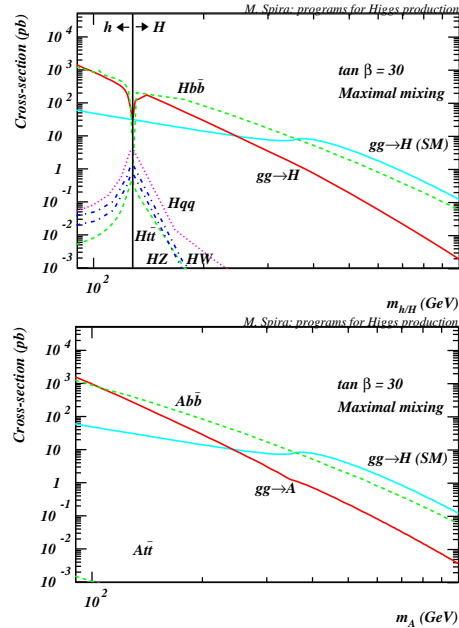


Figure 1. The upper plots is the Higgs production cross-section of the light h and heavy H as a function of their masses. The lower one is Pseudo-scalar Higgs production cross-section as a function of  $m_A$ .

extremely complicated as shown in figure 2 for h and H. For the light h, the branching ratios reach their SM value when  $m_h$  reaches its maximum value. It is worth noting that even if this area is just a narrow line when plotted as a function of  $m_h$ , it covers most of the  $m_A - \tan\beta$  parameter plane. The decay into a  $b\bar{b}$  pair is dominant for the light h with  $m_h < m_h^{max}$  and for the heavy H at high  $\tan\beta$ . The same figure shows the branching ratios for A. The  $b\bar{b}$  decay is dominant and the  $\tau\tau$  decay much more significant than in the SM where the opening of the vector boson channels suppresses the fermion decays. As illustrated in the plot, the decays to SUSY particle may be important if their masses are light enough. The charged Higgs can be produced in the top quark decay if its mass is lighter than the top

quark mass. If it is heavier, it is produced in other processes alone, or in association with a top quark or a tb quark pair, see figure 3 where also the branching ratios of  $H^+$  decays are shown. The decay to a tb quark pair is dominant where kinematically possible. Below top quark mass, the  $\tau\nu$  decay is dominant. The SUSY parameters chosen for the plot allow the decay to a chargino neutralino pair in the high mass range. From

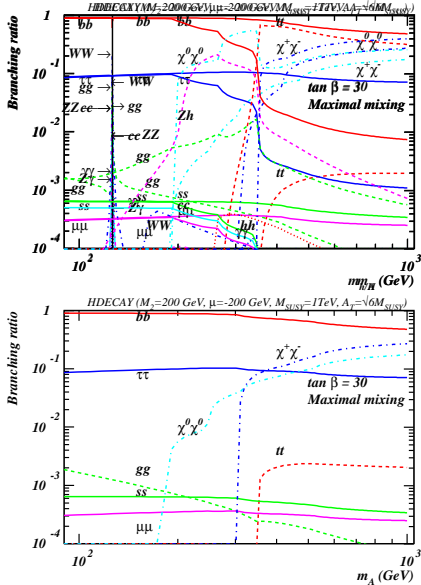


Figure 2. The upper plots is the Higgs branching ratios of the light h and heavy H as a function of their masses. The lower one is for the pseudo-scalar Higgs A as a function of  $m_A$ .

the values of the branching ratios it can be seen that the channels with b quarks in the final states are favoured. However from more detailed studies it turned out that the channel with  $\tau$  final states have bigger discovery potential, thanks to the cleaner signal and lower background.

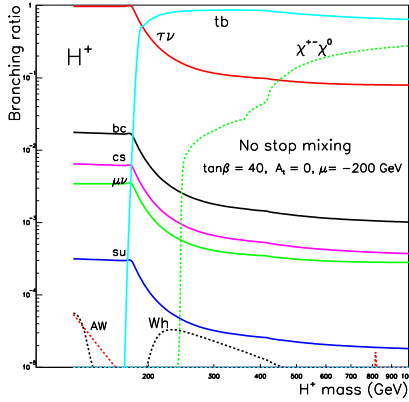
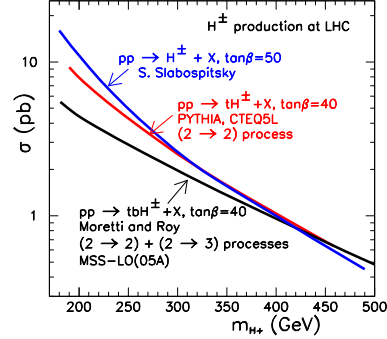


Figure 3. The upper plot is the charged Higgs production cross section as a function of  $m_{H^+}$ . The lower one is the charged Higgs branching ratios as a function of  $m_{H^+}$ .

### 3. Higgs searches

One of the aim of LHC is to cover the entire  $m_A - \tan\beta$  plane in order to discover or exclude the existence of the MSSM Higgs sector. Among the several MSSM decay modes two channels containing tau lepton final states are of great importance  $H/A \rightarrow \tau\tau$  and  $H^+ \rightarrow \tau\nu$ , which have been studied in detailed. These channels will be shortly discussed in the following. There are several other channels to study different regions of the parameter space, such as heavy H or A decaying in light h, muonic decay of H or A and tb

pair decay of the charged Higgs. Furthermore, if the SUSY mass scale allows the decay into SUSY particles the  $H/A \rightarrow \chi_2^0 \chi_2^0$  could be visible. However  $H/A \rightarrow \tau\tau$  decay [14] is the most promising channel in the search for the neutral heavy Higgses, and it is particularly significant at high  $\tan\beta$ . Experimentally, the  $\tau$  decays are very interesting, they require an interplay of different detector elements measuring missing  $E_T$  due to the escaping neutrinos, leptons from the leptonic  $\tau$  decay, jets from the hadronic  $\tau$  decays. Furthermore some b-tagging could be required in order to suppress the background when b-quarks are produced in association with the Higgs. Indeed the best significance for this channel is obtained with the Higgs production in association with a  $b\bar{b}$  pair. Three final states have been considered:  $\tau\tau \rightarrow ll + \nu's$ ,  $\tau\tau \rightarrow \tau_{jet}l + \nu's$  and  $\tau\tau \rightarrow \tau_{jet}\tau_{jet} + \nu's$ . The event with two  $\tau_{jet}$  can be triggered with a specific  $\tau$  trigger [15], while the other can be triggered with combined electron and muon trigger as described in the next section. The main backgrounds for this channel are represented by:

- $Z, \gamma^* \rightarrow \tau\tau$
- $t\bar{t}$
- $W, Z + \text{jets}$
- QCD jets

The QCD background, the one with the biggest cross section, is effectively suppressed by the isolation criteria and the missing  $E_T$  cut. Isolation criteria applied at a high level trigger on the total hadronic  $\tau$  decays can reduce QCD contamination by a factor of 1000 when applied to both jets. Furthermore, the leptonic  $\tau$  decays can be identified with  $\tau$  tagging using an impact parameter cut. Assuming the neutrinos collinear to the  $\tau_{jet}$  directions is possible to reconstruct the invariant mass of the final state. The reconstructed mass in the  $H/A \rightarrow \tau\tau \rightarrow 2\tau_{jet}$  channel is shown in figure 4 [16], for a Higgs mass of 500 GeV (the main background is superimposed). As shown in the plot the signal can be clearly extracted from background with a fit to the reconstructed mass.

The same figure [16] shows the mass resolu-

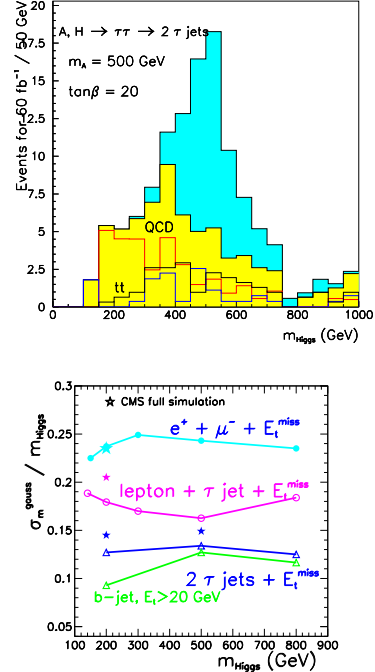


Figure 4. The upper plot is the reconstructed mass in the  $H/A \rightarrow \tau\tau \rightarrow 2\tau_{jet}$  channel, for a Higgs mass of 500 GeV (the main background is superimposed). The lower one is the mass resolution for the several studied channels.

tion for the different considered channels. The best resolution is obtained with the two  $\tau_{jet}$  final state when using also b-tagging. The parameter space coverage for the heavy Higgs H and A is shown in figure 5 [16]. The  $\tau$  decay channels cover the high  $\tan\beta$  part of the parameter space. The discovery range for these channels extend down to  $\tan\beta \sim 15$  at  $m_A = 300$  GeV and down to  $\tan\beta \sim 20$  at  $m_A = 500$  GeV. The middle  $\tan\beta$  values are not covered by these channels, other possibilities involving SUSY sparticle decays are under study [17]. The charged Higgs can be observed in the  $t\bar{t}$  events if  $m_{H^\pm} < m_{top}$  or in the decay into  $\tau\nu$  when  $m_{H^\pm} > m_{top}$  and  $H^\pm$  is produced in association with a top quark. In this re-

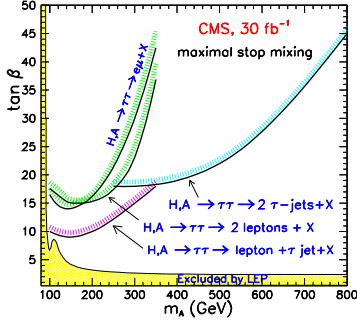


Figure 5. Expected 5 sigma discovery region in the  $m_A - \tan\beta$  plane for the heavy Higgs H and A with the  $\tau\tau$  final state for  $30 \text{ fb}^{-1}$ .

port we will focus on the  $m_{H^\pm} > m_{top}$  considering the  $\tau\nu$  final state, while only total hadronic top quark decay will be considered. Figure 6 shows the reconstructed transverse mass for  $m_{H^\pm} = 400 \text{ GeV}$  with expected background for  $30 \text{ fb}^{-1}$  [18]. To obtain a clear separation between the signal and the background the  $\tau$  polarisation properties has been exploited. The polarisation of a  $\tau$  depend on the spin of the mother particle. The hadronic decay products of  $\tau$  originating from the Higgs, in particular in  $\tau \rightarrow \pi\nu$ , are expected to be boosted into the  $\tau$  direction. Furthermore, the W and the top mass are reconstructed, and the b-jet from the top quark decay is tagged. More over a selection on missing  $E_T$  is applied also in this case. Figure 7 summarises the expected 5  $\sigma$  discovery reach for  $30 \text{ fb}^{-1}$  for maximal stop mixing [19]. A significant signal is expected for  $\tan\beta > 15$  between  $180 \text{ GeV} \leq m_A \leq$ . The sensitivity for  $m_A > 400 \text{ GeV}$  is for  $\tan\beta > 25$  Almost all the parameter plane can be covered with the exception of a small area at low  $m_A$  and low  $\tan\beta$ .

#### 4. Triggering $\tau$ final states

In order to permit the study of channels with  $\tau$  final states a dedicated trigger system has been studied. This trigger system is designed to be

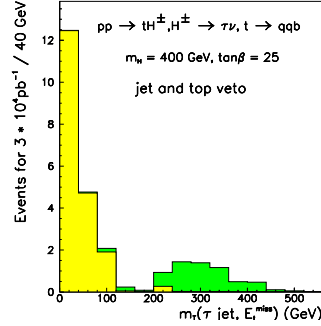


Figure 6. Transverse mass reconstruction from  $\tau_{jet}$  and missing  $E_T$  for  $pp \rightarrow tH^\pm, H^\pm \rightarrow \tau\nu$  for a  $m_{H^\pm} = 400 \text{ GeV}$  and  $\tan\beta = 30$ . The total background is superimposed with a veto for a second top and a central jet in the event.

used in the selection of isolated  $\tau$  leptons such as those expected in the MSSM Higgs decays  $A/H \rightarrow \tau\tau$  and  $H^\pm \rightarrow \tau\nu$ . These include events with a lepton plus a  $\tau_{jet}$ , two  $\tau_{jet}$  and single  $\tau_{jet}$  final states. The identification of  $\tau_{jet}$  at trigger level is based on the isolation criteria made with the reconstructed tracks. Calorimeter triggers will provide a region to search for an isolated groups of tracks, well matched to the jet axis given by the calorimeter. Two different approaches can be used: one reconstructs tracks using only the inner part of the tracking detector [20], the other uses tracking made with also the outer part of the tracking detector [15]. For the  $H/A \rightarrow \tau\tau$  with hadronic  $\tau$  decays both of them can be used, the first is fastest while the second has bigger efficiency on signal events. As already mentioned isolation criteria can reduce QCD contamination by a factor of 1000 when applied to both jets. For the  $H^\pm \rightarrow \tau\nu$  channel and the other channels with one  $\tau$  decaying leptonically only the second selection can be used because it is the only one that can achieve the desired background rejection. These algorithms have satisfactory efficiency on signal events within the timing specification required by a trigger apparatus.

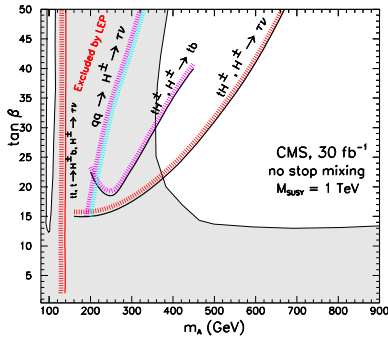


Figure 7. Expected 5 sigma discovery region in the  $m_A - \tan \beta$  plane for the  $H^+ \rightarrow \tau\tau$  and  $H^+ \rightarrow tb$  for  $30 \text{ fb}^{-1}$  for maximal stop mixing.

## 5. Conclusions

In the MSSM, the almost the entire Higgs sector parameter space can be covered with  $30 \text{ fb}^{-1}$  by the LHC experiments. In many areas, several Higgs bosons and decay modes will be available. The parameter choice for the MSSM physics studies is unavoidably restricted. The aim is to study a representative set of parameters, and the detector performance and analysis lessons learned from the MSSM studies will serve to explore any non-MSSM scenario. In conclusion, as elusive as it is now, the Higgs sector will be well known, or well constrained, in seven years from now.

## 6. Acknowledgements

This report relies on the enormous amount of work done by my CMS colleagues. I thank especially Daniel Denegri, Sasha Nikitenko, Ritva Kinnunen, K. Lassilla-Perini and Giuseppe Bagliesi for useful advice and for providing the illustration.

## REFERENCES

1. S. Glashow: Nucl. Phys.22 (1961) 579  
S. Weinberg: Phys. Rev. Lett. 19 (1967) 1264  
A. Salam in Elementary Particle Theory, ed. by N. Svartholm, Aspenasgarden (1968) 367
2. P. Higgs: Phys. Lett. 12 (1964) 132; Phys. Rev. Lett. 113 (1964) 508; Phys. Rev. 1145 (1966) 145  
F. Englert and R. Brout: Phys. Rev. Lett. 13 (1964) 321  
G. S. Guralnik, C. R. Hagen and T. W. Kibble: Phys. Rev. Lett. 13 (1964) 585
3. T. Hambye and K. Riesselmann, Phys. Rev. D 55 (1997) 7255
4. D. Charlton: BHAM-HEP/01-02 presented in EPS-HEP Budapest, Summer 2001
5. The LEP working group for Higgs boson searches: CERN-EP/2001-055
6. P. Fayet and S. Ferrara: Phys. Rep. 32 (1977) 249  
H. P. Nilles: Phys. Rep. 110 (1984) 1  
H. Haber and G. Kane: Phys. Rep. 117 (1985) 75  
S. Martin: hep-ph/9709356 (1997)
7. CMS Technical Proposal CERN/LHCC/94-38
8. H. P. Nilles: Phys. Rep. 110 (1984) 1  
S. Dawson: hep-ph/9712464 (1997)
9. M. Carena, J. S. Conway, H. E. Haber, J. D. Hobbs: hep-ph/0010338
10. The LEP working group for Higgs boson searches: LHWG Note 2001-04
11. These programs are available from Michael Spira's website  
<http://www.desy.de/spira/proglist.html>  
M. Spira: hep-ph/9510347
12. M. Spira: Fortsch. Phys. 46 (1998) 203
13. A. Djouadi, J. Kalinowski, M. Spira: Comput. Phys. Commun. 108 (1998) 56
14. R. Kinnunen and D. Denegri: CMS Note 1999/037
15. G. Bagliesi, S. Dutta, S. Gennai, G. Sguazzoni, CMS IN2001/045  
G. Bagliesi, S. Gennai, G. Sguazzoni, CMS IN2001/047  
G. Bagliesi, S. Gennai, G. Sguazzoni: CMS Note 2002/018
16. R. Kinnunen talk at SUSY02, DESY Hamburg
17. R. Kinnunen private communication
18. R. Kinnunen: CMS Note 2000/045
19. R. Kinnunen et al.: CMS Note 2001/032

20. S. Eno, S. Dasu, R. Kinnunen, A. Nikitenko  
and W. Smith: CMS Note 2000/055  
D. Kotlinski, A. Nikitenko, R. Kinnunen:  
CMS Note 2001/017