

## Search for the MSSM Higgs boson with the CMS detector at LHC.

---

**Federica Primavera on behalf of the CMS Collaboration<sup>\*†</sup>**

*Univerisity of Bologna and INFN, Bologna, Italy*

*E-mail: [federica.primavera@cern.ch](mailto:federica.primavera@cern.ch)*

In the Minimal Supersymmetric extension of the Standard Model (MSSM), the Higgs sector contains two Higgs boson doublets, including, after electroweak symmetry breaking, the CP-odd neutral scalar  $A^0$ , the two charged scalars  $H^\pm$ , and the two CP-even neutral scalars  $h$  and  $H^0$ . The results in the search for neutral and charged Higgs bosons with the CMS detector at LHC are presented, based on the data samples collected at  $\sqrt{s} = 7$  and 8 TeV. The neutral Higgs boson is searched in the  $b\bar{b}$ ,  $\tau\tau$  and  $\mu\mu$  final states, whereas the charged Higgs state is searched in top quark decays with at least one  $\tau$  in the final state.

*LHC on the March - IHEP-LHC,*

*20-22 November 2012*

*Institute for High Energy Physics, Protvino, Moscow region, Russia*

---

<sup>\*</sup>Speaker.

<sup>†</sup>Presented at the LHC on the March 2012 Conference.

## 1. Introduction

The electroweak symmetry breaking mechanism of the Standard Model (SM) predicts the existence of a neutral scalar boson, the Higgs particle. While a boson consistent so far with its expected properties has been recently observed at a mass of about 125 GeV/c<sup>2</sup> [1, 2], its exact properties and the detailed structure of the Higgs sector still need further investigation.

However, the SM Higgs boson suffers from quadratically divergent self-energy corrections at high energy. Numerous extensions to the SM have been proposed to address these divergencies.

In the model of supersymmetry (SUSY), a symmetry between fundamental bosons and fermions, a cancelation of these divergencies occurs. In the MSSM the Higgs sector contains two Higgs boson doublets [3, 4]. One doublet couples to the up-type and one to the down-type fermions. After electroweak symmetry breaking, five Higgs bosons remain: the CP-odd neutral scalar  $A^0$ , the two charged scalars  $H^\pm$  and the two CP-even neutral scalars  $h$  and  $H^0$ . The model is described by a large number of parameters, but, by constraining a lot of them in the most conservative way, it can be described in terms of just two free parameters:  $m_{A^0}$ , the mass of the neutral scalar  $A^0$ , and  $\tan\beta$ , the ratio between the vacuum expectation values of the two doublets. For this scenario, the most conservative  $m_h^{max}$ , the masses of the other four Higgs bosons can be expressed as:

$$m_{H^\pm} = (m_W^2 + m_{A^0}^2)^{1/2} \quad (1.1)$$

$$m_{h^0} = \left\{ \frac{1}{2} \{ m_{A^0}^2 + m_{Z^0}^2 - [(m_{A^0}^2 + m_{Z^0}^2)^2 - 4m_{A^0}^2 m_{Z^0}^2 \cos^2 2\beta]^{1/2} \} \right\}^{1/2} \quad (1.2)$$

$$m_{H^0} = \left\{ \frac{1}{2} \{ m_{A^0}^2 + m_{Z^0}^2 + [(m_{A^0}^2 + m_{Z^0}^2)^2 - 4m_{A^0}^2 m_{Z^0}^2 \cos^2 2\beta]^{1/2} \} \right\}^{1/2} \quad (1.3)$$

where  $m_W$  and  $m_Z$  are the masses of the  $W^\pm$  and  $Z^0$  bosons.

In this lecture the results concerning both searches for charged and neutral MSSM Higgs bosons in the  $m_h^{max}$  scenario are presented: the charged Higgs has been studied in the low mass hypothesis, in the dominant  $\tau\nu$  decay channel; the neutral Higgs have been studied in the  $b\bar{b}$ ,  $\tau^+\tau^-$  and  $\mu^+\mu^-$  channels.

## 2. Search for charged Higgs

The searches for charged Higgs performed at CMS [?] concern just a light mass hypothesis [5]. The assumption that the charged Higgs mass is smaller than the difference between the masses of the top and the bottom quarks is applied. If  $m_{H^\pm} < m_t - m_b$ , the Higgs can be produced in the top quark decays  $t \rightarrow H + b$ . For values of  $\tan\beta > 5$ , the charged Higgs boson preferentially decays to a  $\tau$  lepton and a neutrino, therefore, deriving the experimental limits, we assume that the branching fraction  $B(H^\pm \rightarrow \tau^\pm \nu_\tau)$  is equal to 1.

The dominant top quarks production process at LHC is  $pp \rightarrow tt + X$  via gluon fusion. The possible decays of the top pairs are  $tt \rightarrow H^\pm W^\mp b\bar{b}$  and  $tt \rightarrow H^\pm H^\mp b\bar{b}$ , where each charged Higgs boson decays into a  $\tau$  lepton and a neutrino. Depending on the  $\tau$  decay, three not-overlapped final states are searched for, all requiring missing transverse energy and multiple jets coming from the hadronization of b-quarks: fully hadronic, semi-leptonic and leptonic channel. After a first

common pre-selection, each final state is independently studied: more specific selection cuts are applied, systematic errors and limits are calculated, and finally the results are combined between them.

Depending on the final states, we have different background sources. Several processes affect all the three categories like SM decays of top pairs; multi-jets events with large  $E_T^{miss}$ , where the jets are misidentified as  $\tau_h$  or  $b$ -jets; and  $W$  + jet events. Processes as Drell-Yan affect only the semi-leptonic and the leptonic channels. Therefore a different background estimation is performed for each category: for the hadronic and semi-leptonic channels both data and simulation are used, while for the leptonic channel only the simulation is exploited. The results are obtained for an amount of

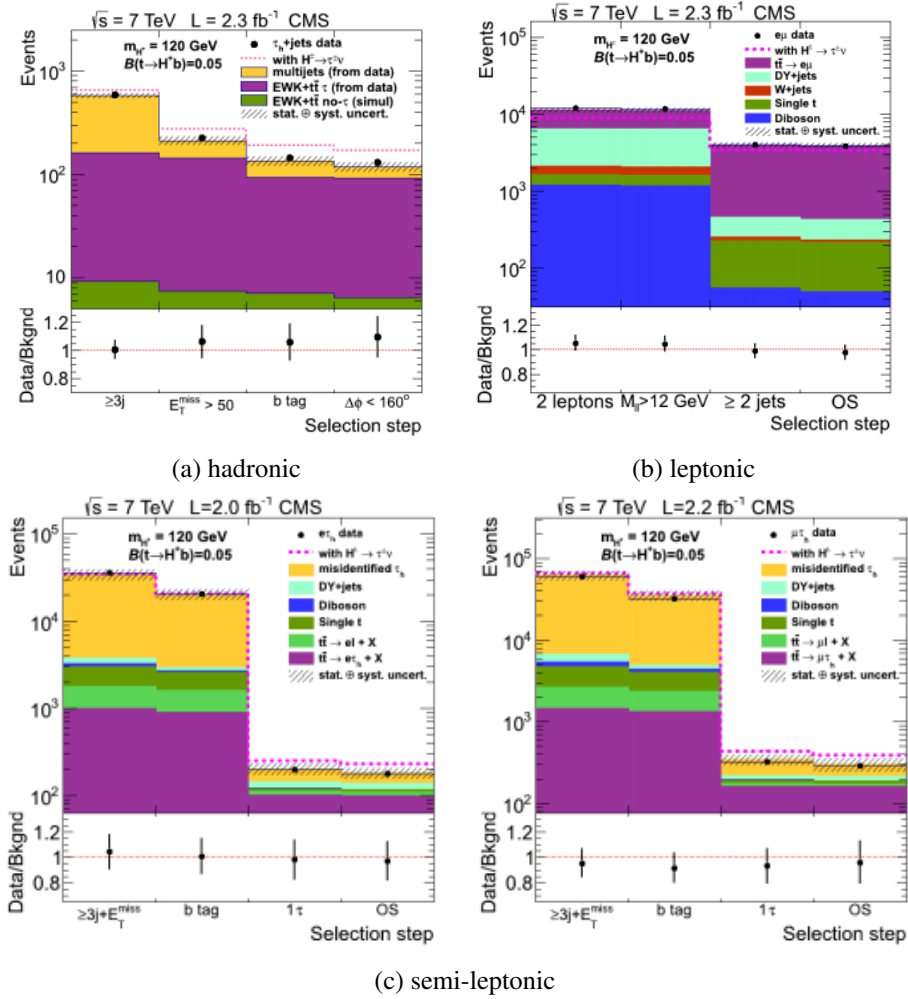


Figure 1: The event yields after each selection step for the  $\tau_h$ +jets (1a),  $e\mu$  (1b),  $e\tau_h$  (1c-left) and  $\mu\tau_h$  (1c-right) analyses. The backgrounds are estimated from simulation and normalized to the SM prediction. The expected event yield is shown as a dashed line for  $m_{H^+} = 120$  GeV and under the assumption that  $B(t \rightarrow H^+ b) = 0.05$ . The bottom panel shows the ratios of data over background with the total uncertainties. OS indicates the requirement to have opposite electric charges for a  $\tau_h$  and a  $e$  or  $\mu$ . Statistical and systematic uncertainties are added in quadrature.

data recorded by CMS in pp collision at  $\sqrt{s} = 7$  TeV, that correspond to an integrated luminosity

ranging from 1.99 to  $2.27 fb^{-1}$ , depending on the final state. Figure 1 shows the event yields of each category: the signal is expected as an excess of events, with respect to the SM prediction, in the hadronic (fig. 1a) and semi-leptonic (fig. 1c) channel, and as a deficit of events in the leptonic (fig. 1b) final state. Since no deviation is observed, upper limit on the branching fraction  $B(t \rightarrow H + b)$  and the exclusion region in the  $(m_{H^+} - \tan\beta)$  plane (fig. 2) are set by combining all the three analysis.

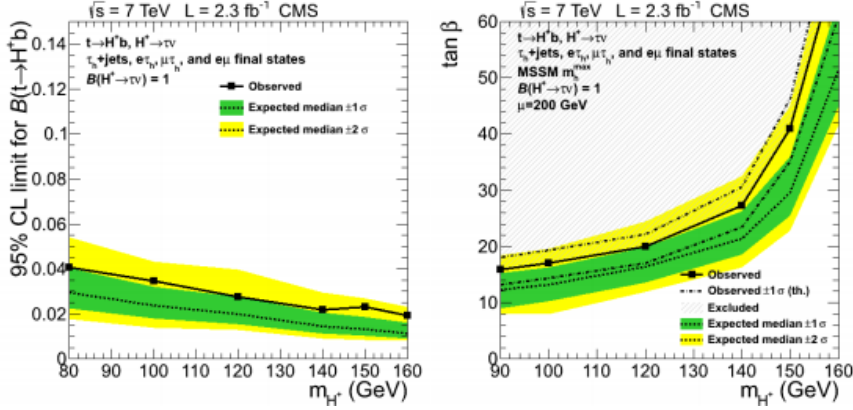


Figure 2: The exclusion limits for the MSSM cross-section production (left) and its projection in the  $(m_{H^+} - \tan\beta)$  plane (right).

### 3. Search for neutral Higgs

The MSSM neutral Higgs production  $pp \rightarrow \Phi^0 + X$  at the LHC is dominated by two processes:  $b\bar{b}$ -associated production, where  $\Phi^0$  is produced together with a  $b\bar{b}$  pair, and the gluon-gluon (gg) fusion process. For relatively large values of  $\tan\beta$ , the Higgs couplings to u-type particles are suppressed while the couplings to d-type particles are enhanced by a factor  $\tan\beta$ , relative to the SM. Therefore, in the MSSM, the combined cross section of Higgs boson production in association with b quarks is enhanced by a factor  $2 \tan^2 \beta$ .

For the same reason the Higgs decay into b quarks has a very high branching fraction (90%), even at large values of the Higgs mass, with the disadvantage to be difficult to separate from the very large QCD background. Despite their low branching ratios, the  $\Phi^0 \rightarrow \tau^+ \tau^-$  and the  $\Phi^0 \rightarrow \mu^+ \mu^-$  decay channels provide higher sensitivity than  $\Phi^0 \rightarrow b\bar{b}$ . While the first process has a branching ratio larger by a factor  $(m_\tau/m_\mu)^2$  and provides better sensitivity in terms of limits calculation, the  $\Phi^0 \rightarrow \mu^+ \mu^-$  has a cleaner experimental signature, due to the full reconstruction of the final state. The analyses performed so far at CMS concern these three final states.

In case of  $b\bar{b}$  final state, in order to discriminate the signal, only the associated production is taken into account. There are two analyses for this channel: one using a full hadronic trigger based on a high  $p_T$  threshold for jets and on-line b-tagging; the other exploiting dedicated triggers based on the detection of moderately high transverse momentum  $p_T$ , non-isolated muons and two

jets with on-line b-tagging. The use of a muon- and jet-triggered dataset allows to tag the semi-muonic decay of one of the b-quarks, and also to tolerate lower energy thresholds on jets in the trigger, improving the overall sensitivity, especially in the low mass region. The main background arises from the heavy flavor multi-jet QCD. Both the analyses adopt a data-driven approach for the background estimation.

The first analysis [6], done on  $4.0 \text{ fb}^{-1}$  of data taken in pp collision at  $\sqrt{s} = 7 \text{ TeV}$ , reconstructs the invariant mass of the two b-tagged leading jets, for events containing at least three leading jets that are also coming from b-quark.

Even the second analysis [7], done on  $4.8 \text{ fb}^{-1}$  of data taken in same condition of the previous one, reconstructs the invariant mass of the two b-tagged leading jets, but for events with three b-tagged leading jets of which one of them contains the not isolated muon selected by the trigger. There is no evidence of signal in data, and the upper limit is set on the  $\sigma(pp \rightarrow b\Phi) \times B(\Phi \rightarrow b\bar{b})$ ,

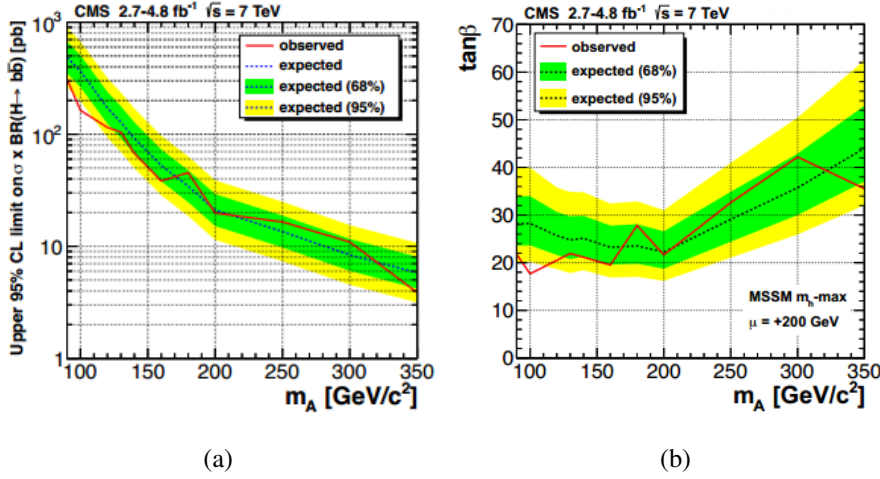


Figure 3: Combined upper limit on  $\sigma(pp \rightarrow b\Phi) \times B(\Phi \rightarrow b\bar{b})$  (3a), and its projection in the  $(m_{A^0}, \tan\beta)$  plane (3b), where the region above the red line is excluded.

and also projected in the  $(m_{A^0}, \tan\beta)$  plane, by combining the two analyses (fig. 3).

The searches for neutral Higgs in leptonic decays, are instead sensitive to both production mechanisms,  $b\bar{b}$ -associated and gluon-gluon fusion production, that dominates at low  $\tan\beta$  values.

The search for  $\Phi^0 \rightarrow \tau^+ \tau^-$  is done on data collected during 2011 and 2012, that correspond to an integrated luminosity of  $4.9 \text{ fb}^{-1}$  in pp collision at 7 TeV and  $17 \text{ fb}^{-1}$  at 8 TeV [8]. Four different  $\tau^+ \tau^-$  final states are studied where one or two taus decay leptonically  $e\tau_h, \mu\tau_h, e\mu, \mu\mu$ , where  $\tau_h$  denotes a hadronic decay of  $\tau$ .

In all the cases two high  $p_T$ -isolated leptons,  $E_T^{\text{miss}}$  in a compatible direction with visible  $\tau$ -decay, and two high  $p_T$  jets are required. In order to maximize the sensitivity, the selected events are split in two categories: one with at least one jet coming from b-quark (associated production) and the other with the rest of events (gluon fusion). After all the cuts the main backgrounds come from Drell-Yan processes, QCD multijets where one jet is misidentified as an isolated electron or

muon, and  $W$ +jets events where one jet is misidentified as a  $\tau_h$ . All these contribution are estimated from data, while other less relevant processes are evaluated on simulation.

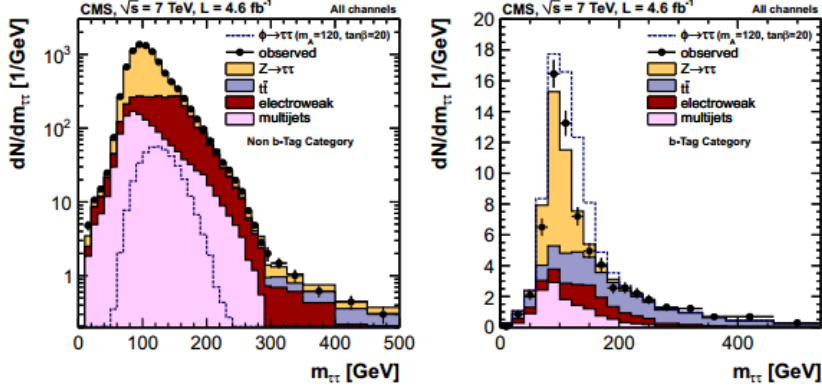


Figure 4: The  $\tau^+\tau^-$  invariant mass distributions for the sum of the four final states: no-b-tag category on the left and b-tag category on the right. Signal distribution with  $m_{A^0} = 120 \text{ GeV}/c^2$  and  $\tan\beta = 20$  is superimposed.

The  $\tau$ -pair mass is reconstructed using a maximum likelihood technique. The algorithm computes the  $\tau$ -pair mass that is most compatible with the observed momenta of visible  $\tau$  decay products and the missing transverse energy reconstructed in the event. The algorithm gives a  $\tau$ -pair mass distribution (fig. 4) consistent with the true value and a width of 15-20%.

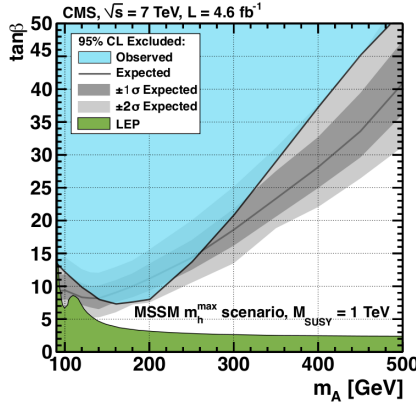


Figure 5: Exclusion limit at 95% CL in the  $m_{A^0}$ - $\tan\beta$  parameter space for the MSSM  $m_h^{\max}$  scenario. The exclusion limits from the LEP experiments are also shown.

No excess is observed in the  $\tau$ -pair invariant-mass spectrum. Exclusion limits (fig. 5) in the MSSM parameter space have been obtained for the  $m_h^{\max}$  scenario.

The signal for  $\Phi^0 \rightarrow \mu^+\mu^-$  is characterized by the presence of two oppositely charged muon tracks with high  $p_T$ , isolated from the other particles and jets in the event. Such events also have

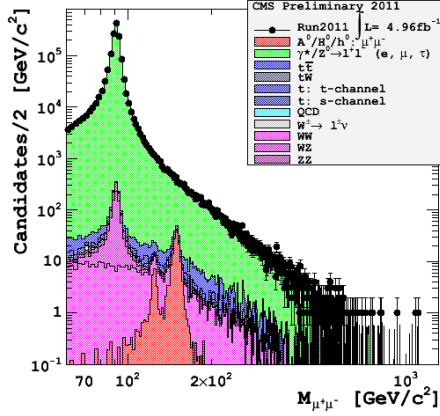


Figure 6: The  $\mu^+\mu^-$  invariant mass distribution for the sum of three categories. The expected di-muon invariant mass distribution for signal with  $m_{A^0} = 150 \text{ GeV}/c^2$  and  $\tan\beta = 30$  is superimposed.

a rather small missing transverse energy  $E_T^{miss}$ . In order to have the best significance the events are divided in three non-overlapping categories: events with at least one jet tagged as a  $b$ -jet candidate, events without  $b$ -jet but with an additional third muon, and all other events that do not belong to previous categories.

The analysis [9] is performed on  $4.96 \text{ fb}^{-1}$  collected in  $pp$  collision at  $\sqrt{s} = 7 \text{ TeV}$ . As can be seen from figure 6 the main remaining sources of background, after the overall selection, are the Drell-Yan events, in particular the  $b\bar{b}-Z^0$  process is an irreducible background for  $b\bar{b}$ -associated production, and the decays from  $t\bar{t}$ . The background is estimated by fitting the data and Monte Carlo simulation is used only to compute the expected signal efficiency. No evidence of the MSSM  $m_h^{max}$  scenario Higgs boson production is found within the sensitivity of each category. Upper

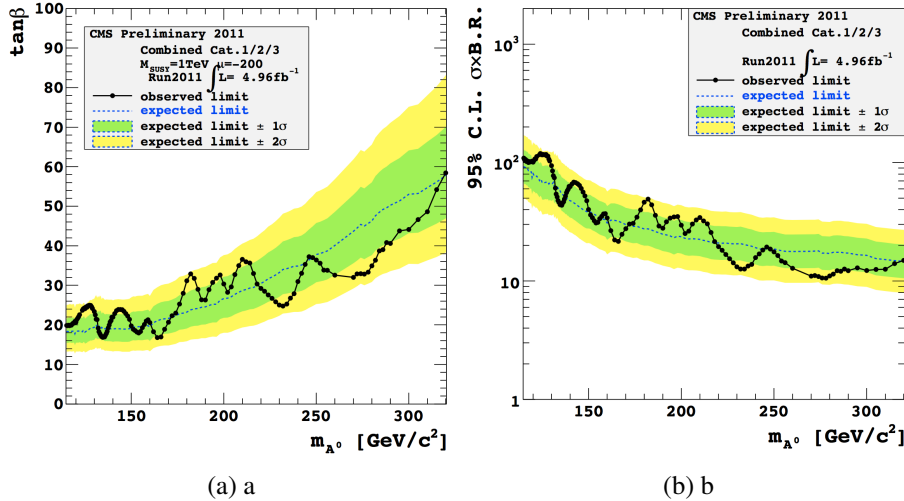


Figure 7: The combined exclusion limit in the  $(m_{A^0}, \tan\beta)$  plane (7a), and for the MSSM production cross-section times the B.R. at 95% CL (7b). The excluded regions are above the curves.

limits are calculated in the  $(m_{A^0}, \tan\beta)$  plane, excluding, for each  $m_{A^0}$  point, all the values above



the first one that excludes the signal at 95% CL. Using this limit on the ratio  $\sigma_{MSSM}/\sigma_{SM}$  and the knowledge of the MSSM cross section, also the limit on the  $\sigma_{MSSM} \times B.R.$  is obtained (fig. 7).

#### 4. Conclusions

In this letter MSSM Higgs boson searches are presented, for both the charged and neutral higgs physical states. The results are obtained with the full statistic collected at CMS during the 2011 at 7 TeV, except for the  $\Phi^0 \rightarrow \tau^+ \tau^-$  that exploits also a part of 2012 data at 8 TeV.

No signal was observed, providing 95% CL exclusion limits for cross section times B.R. of each process, and their projection in the MSSM ( $m_H, \tan\beta$ ) parameter space, where  $m_H$  denotes a generic charged or neutral Higgs boson. These limits are expected to improve with the overall statistics of the 2012.

#### References

- [1] CMS Collaboration: The CMS experiment at the CERN LHC, JINST 3:S08004 (2008).
- [2] CMS Collaboration: Observation of a new boson at mass of 125 GeV with CMS experiment at LHC, Phys. Lett. B 716 (2012) 30-61.
- [3] Atlas Collaboration: Observation of a new particle in the search for the Standard Model Higgs boson with the ATLAS detector at LHC, Phys. Lett. B 716 (2012) 1-29.
- [4] Aitchison, Ian J.R.: Supersymmetry and the MSSM: An Elementary introduction, hep-ph/0505105.
- [5] Martin, Stephen P.: A Supersymmetry primer, hep-ph/9709356.
- [6] CMS Collaboration: Search for a light charged Higgs boson in top quark decays in pp collisions at  $\sqrt{s} = 7$  TeV, JHEP 1207 (2012) 143.
- [7] CMS Collaboration: Search for a Higgs boson produced in association with b quarks and decaying into a b-quark pair, CMS PAS HIG-12-026.
- [8] CMS Collaboration: Search for SuperSymmetric Higgs boson states decaying into bb and produced in association with b-quarks in events collected by semi-leptonic triggers in pp collisions at  $\sqrt{s} = 7$  TeV, CMS PAS HIG-12-027.
- [9] CMS Collaboration: Search for MSSM Neutral Higgs Bosons Decaying to Tau Pairs in pp Collisions, CMS PAS HIG-12-050.
- [10] CMS Collaboration: Search for Neutral MSSM Higgs Bosons in the  $\mu^+ \mu^-$  final state with the CMS experiment in pp Collisions at  $\sqrt{s} = 7$  TeV, CMS PAS HIG-12-011.