

# Beyond the discovery: Higgs results from CMS

Rainer Mankel<sup>1,a</sup>, on behalf of the CMS collaboration

<sup>1</sup>Deutsches Elektronen-Synchrotron (DESY), Notkestr. 85, D-22607 Hamburg, Germany

**Abstract.** The observation of a Higgs boson at a mass near 125 GeV in the year 2012 has been a milestone for elementary particle physics. Since this fundamental discovery, the CMS collaboration has scrutinized the complete LHC Run I dataset in depth, and studied the properties of the observed state in full detail. This includes investigations of more elusive production and decay modes, as well as searches for first indications of an extended Higgs sector, which would represent very likely a promising gateway to new physics. This article summarizes recent Higgs results from the CMS experiment.

## 1 Introduction

The observation of a Higgs boson at a mass of about 125 GeV, in the following referred to as H(125), by the ATLAS and CMS experiments [1–3] has been a fundamental step forward for particle physics. Since this discovery, further Higgs research focuses on two essential questions. The first concerns the detailed properties of the new state, and whether they are precisely in accord with the expectations of the Standard Model (SM). The second question is whether there are additional Higgs bosons. Both kinds of studies have the potential to reveal physics beyond the SM. A huge number of new results have been obtained by the CMS collaboration, and selected highlights are discussed in this article.

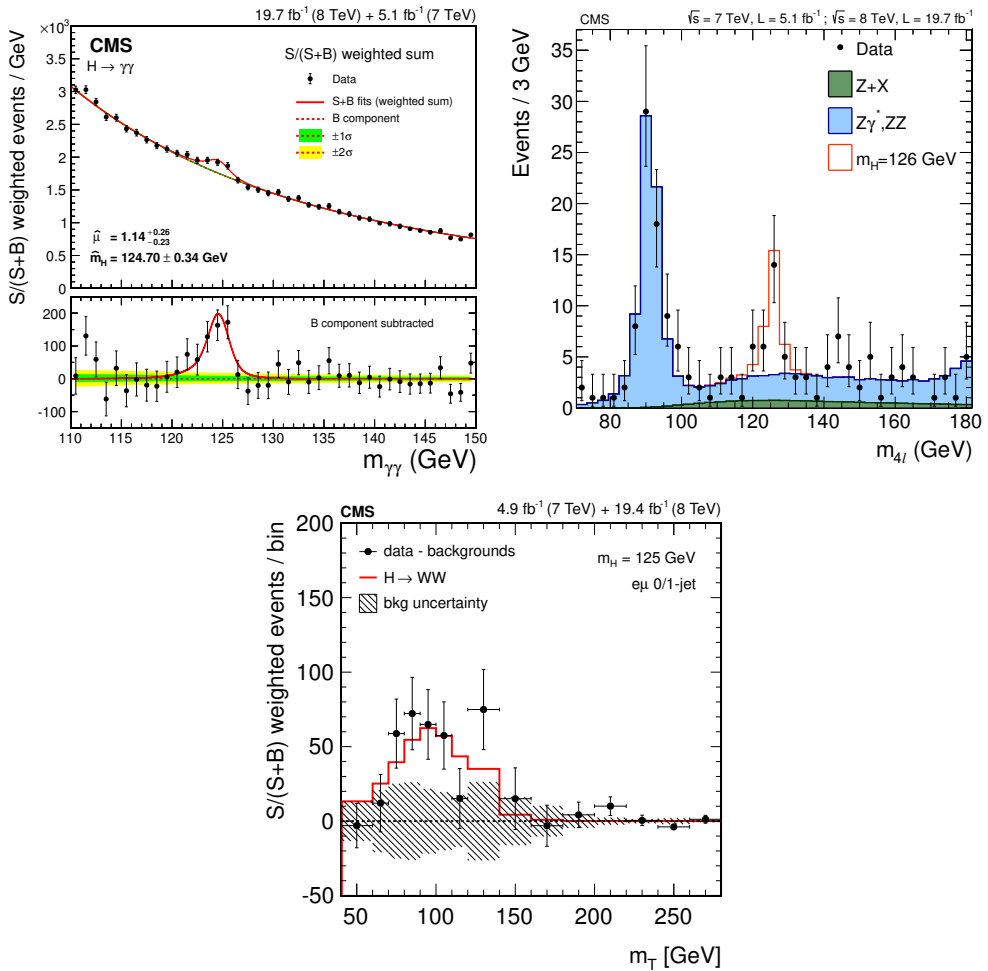
## 2 Properties of the H(125) state

### 2.1 Bosonic decay channels

At the level of the Run I legacy results, the existence of the Higgs boson state at 125 GeV is firmly established in the di-boson decay channels,  $H \rightarrow \gamma\gamma$  [4],  $H \rightarrow ZZ^* \rightarrow 4\ell$  [5] and  $H \rightarrow WW$  [6]. The corresponding signals are shown in Fig. 1. A recent combination of ATLAS and CMS measurements in the  $\gamma\gamma$  and  $4\ell$  channels [7, 8] has determined the mass to be  $m_H = 125.09 \pm 0.24$  GeV. The spin-parity analysis favors the  $J^P = 0^+$  hypothesis, although the possibility of a mixed state with a small pseudoscalar component is not excluded yet. More detailed results concerning Higgs couplings are presented in Section 2.6.

---

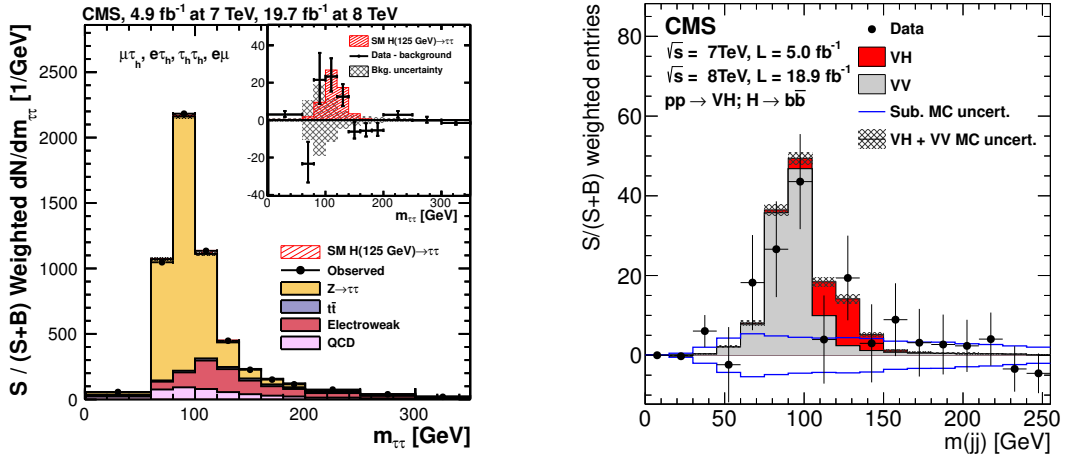
<sup>a</sup>e-mail: Rainer.Mankel@desy.de



**Figure 1.** Higgs signals observed by CMS in the di-boson decay channels:  $H \rightarrow \gamma\gamma$  (top left),  $H \rightarrow ZZ^* \rightarrow 4l$  (top right) and  $H \rightarrow WW$  (bottom) [4–6].

## 2.2 Evidence for $H \rightarrow \tau\tau$

Higgs decays into fermionic channels are far more elusive, but their study is essential to establish the nature of the Higgs boson. The leptonic mode with the highest expected branching fraction is the  $H \rightarrow \tau\tau$  channel. The spectrum of the reconstructed mass of  $\tau$  pairs from the combined Run I data of the CMS experiment is shown in Fig. 2 (left) [9] for the most sensitive channels. While the distribution is generally in very good agreement with the expected backgrounds, an enhancement is observed which is compatible with a SM Higgs boson at a mass of 125 GeV. The excess corresponds to an observed significance of  $3.2 \sigma$  (with  $3.7 \sigma$  expected), and is thus already a strong indication of the Higgs boson coupling to the  $\tau$  lepton as expected by the SM theory.

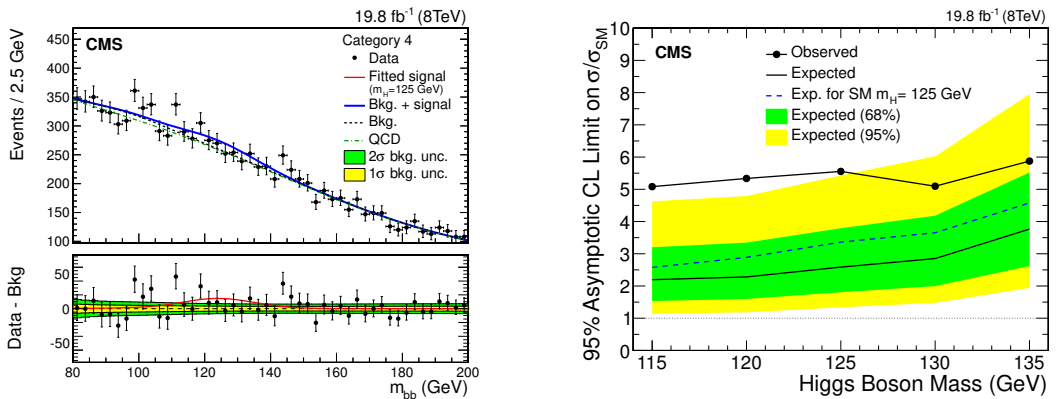


**Figure 2.** Left: Observed and predicted  $m_{\tau\tau}$  distributions for the  $\mu\tau_h$ ,  $e\tau_h$ ,  $\tau_h\tau_h$  and  $e\mu$  channels [9]. The inset shows the difference between the observed data and expected background distributions, together with the signal distribution for a SM Higgs boson at  $m_H = 125$  GeV. Right: Weighted b-tagged dijet invariant mass distribution, combined for all channels in the  $H \rightarrow b\bar{b}$  analysis [10]. All backgrounds, except dibosons, have been subtracted. The line histograms for signal and for VV backgrounds are also shown superimposed.

### 2.3 Search for $H \rightarrow b\bar{b}$

According to the SM, the decay  $H \rightarrow b\bar{b}$  has the largest branching fraction, but this channel has also very difficult background conditions, which make an inclusive observation impossible with the current dataset. The situation is much more favorable for the production in association with a vector boson, which can be either a W or Z boson and is commonly referred to as “V”. This leads to an improved signature with easier triggering and an improved signal-to-background ratio. The invariant mass spectrum of the pair of b-jets from this analysis [10], after background subtraction, is shown in Fig. 2 (right). A clear peak at the Z mass is visible, which is attributed to vector boson pair production, serving as a “standard candle”. The invariant mass of the b-jet pair is combined with other variables discriminating between signal and background to enhance the sensitivity of the search. The multivariate analysis reveals an excess with a significance of about two standard deviations above the SM background expectation. Since the publication of [10], the modeling of the signal cross section has been improved by including the  $gg \rightarrow ZH$  process [11]. The measured relative signal strength for the  $H \rightarrow b\bar{b}$  channel, including also the contribution from production in association with top quark pairs [14] (see Section 2.4) is  $\sigma/\sigma_{SM} = 0.84 \pm 0.44$ , in good agreement with the SM. The corresponding observed significance is  $2.0 \sigma$  (with  $2.6 \sigma$  expected) [11]. The measurement [10] has been combined with the  $H \rightarrow \tau\tau$  measurement shown in Section 2.2, resulting in a joint evidence of  $3.8 \sigma$  for fermionic Higgs decays [12].

Very recently, the  $H \rightarrow b\bar{b}$  production strength has also been analyzed in a topology expected for vector boson fusion (VBF) [13]. In this process, quarks from the initial protons emit vector bosons (W or Z), which then fuse to form the Higgs boson. No QCD color is exchanged. This leads to a very clean final state characterized by the decay products of the Higgs boson and two hadronic jets with large difference in rapidity and large invariant mass. This first search for the SM Higgs boson in a purely hadronic final state makes strong use of categorization with boosted decision trees (BDT),



**Figure 3.** Left: Fit of the invariant mass of the two b-jet candidates for the Higgs boson signal ( $m_H = 125$  GeV) in the VBF event categories of highest signal enrichment [13]. Data are shown by the points. The solid line is the sum of the post-fit background and signal shapes, the dashed line is the background component, and the dashed-dotted line is the QCD component alone. The bottom panel shows the background-subtracted distribution, overlaid with the fitted signal, and with the  $1\sigma$  and  $2\sigma$  background uncertainty bands. Right: Expected and observed 95% confidence level limits on the signal cross section in units of the SM expected cross section, as a function of the Higgs boson mass, including all event categories. The limits expected in the presence of a SM Higgs boson with a mass of 125 GeV are indicated by the dashed curve.

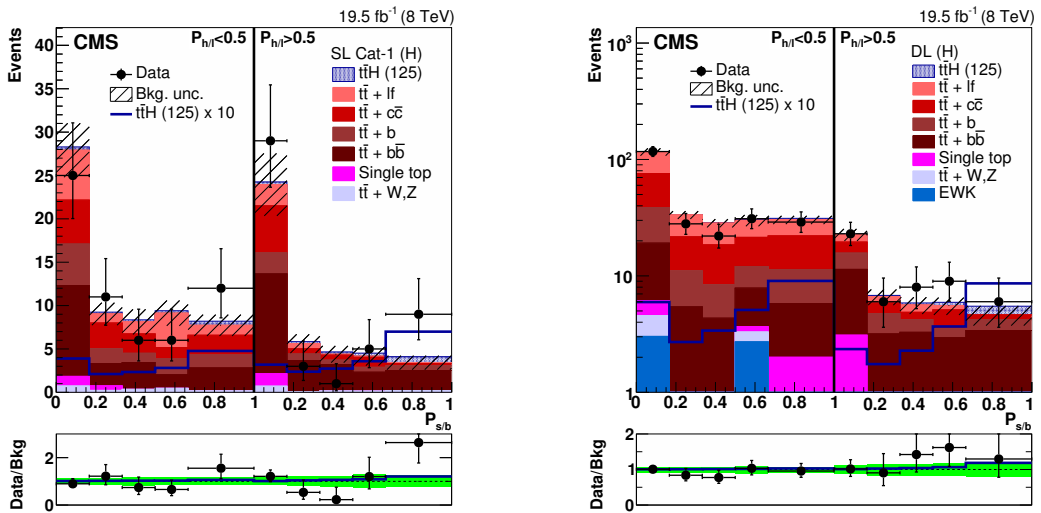
which is validated with  $Z(\rightarrow b\bar{b}) + \text{jets}$  production. The invariant mass spectrum in the most signal enriched category is shown in Fig. 3 (left); a fit indicates some enhancement near 125 GeV. A signal significance of  $2.2\sigma$  is observed, while  $0.8\sigma$  is expected. The upper limit for the cross section in Fig. 3 (right) shows a corresponding excess.

The VBF result has been combined with the BDT-based searches for  $H \rightarrow b\bar{b}$  in the VH and ttH (see Section 2.4) production modes [13]. The resulting combined signal strength is  $\sigma/\sigma_{\text{SM}} = 1.03 \pm 0.44$ , and the observed signal significance is  $2.6\sigma$  (with  $2.7\sigma$  expected). In conclusion, the Run I measurements show a convincing hint for the H(125) boson coupling to b quarks in accord with the SM.

## 2.4 Higgs production in association with top quarks

In the SM, the Higgs boson is expected to have a particularly large Yukawa coupling to the top quark. Indirectly, this coupling is accessible via fermion loops which occur in the gluon fusion production process and the Higgs decay to photon pairs. For an unambiguous measurement, it is important to probe the top-Higgs coupling directly. This is possible through the measurement of Higgs production in association with top quark pairs. In an earlier CMS publication, the analysis combined many different topologies and decay channels, and used a BDT discriminant to enhance the signal-to-background ratio [14].

A more recent CMS analysis [15] is based on matrix elements (ME) of the signal process and the most relevant background process,  $pp \rightarrow t\bar{t}b + X$ . This analysis is currently restricted to the  $H \rightarrow b\bar{b}$  decay channel. To each event, corresponding probability density values are assigned according to signal or background hypothesis, and the ratio,  $P_{s/b}$ , is used as a discriminant in a likelihood fit to extract the signal. This leads to an optimized separation of signal and background.

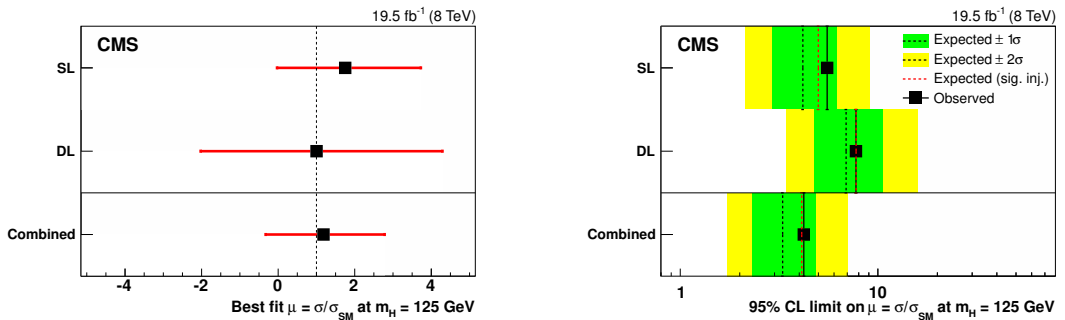


**Figure 4.** Distributions of the  $P_{s/b}$  discriminant in the two  $P_{h/l}$  bins of the  $t\bar{t}H$  ME analysis in the  $H \rightarrow b\bar{b}$  channel, for selected high-purity (H) categories of the single-lepton (left) and double-lepton (right) selections for data, together with the estimated background contributions. The bottom panel of each plot shows the ratio between the observed and the overall background yields. The solid blue line indicates the ratio between the signal-plus-background and the background-only distributions, enhanced by a factor of 10. The shaded and solid green bands correspond to the  $\pm 1 \sigma$  uncertainty in the background prediction after the fit.

The signal is searched for in a binned distribution of two parameters, the discriminant  $P_{s/b}$  and a second discriminant  $P_{h/l}$  which distinguishes between the heavy- and the light-flavor components of the  $t\bar{t}$ +jets background. Figure 4 shows the distribution of the data of selected high-purity categories in the single-lepton (left) and double-lepton (right) samples. The data are consistent with the background estimation; there is no evidence for a  $t\bar{t}H$  signal. The results of the best fit are shown in Fig. 5 (left). The combined result corresponds to a signal strength of  $\sigma/\sigma_{SM} = 1.2^{+1.6}_{-1.5}$ , which is consistent with the SM. Upper limits at 95% confidence level (CL) are shown in Fig. 5 (right). In combination, the observed limit on  $\sigma/\sigma_{SM}$  is 4.2. The expected limit is 4.1 with the expected  $t\bar{t}H$  signal injected, and 3.3 without. Given the fact that only the  $H \rightarrow b\bar{b}$  decay channel is used, the ME method is found to be competitive with the BDT-based analysis.

## 2.5 Differential Higgs production cross sections

Differential cross sections are a direct test of perturbative QCD calculations in the Higgs sector. Recently, the CMS collaboration has measured such cross sections using the di-photon decay channel [16]. For example, the transverse momentum distributions of the di-photon system and the leading accompanying jet are sensitive to higher order QCD effects, while the distribution of the rapidity of the di-photon system is sensitive to the proton PDF and the production mechanism in general. All three are shown in Fig. 6, and found to be in agreement with the QCD predictions within uncertainties. In particular, there is no hint yet of extra contributions from new production processes.



**Figure 5.** Left: Best-fit value of the signal strength modifier  $\mu$  with its  $\pm 1 \sigma$  CL interval obtained from the individual channels and from their combination in the  $t\bar{t}H$  ME analysis. Right: Observed 95% CL upper limits on  $\mu$  are compared to the median expected limits under the background-only and the signal-plus-background hypotheses. The former are shown together with their  $\pm 1 \sigma$  and  $\pm 2 \sigma$  CL intervals. Results are shown separately for the individual channels and for their combination.

## 2.6 Higgs couplings

The measurements in the various production processes and decay channels are combined to extract information about the coupling of the Higgs boson to fundamental fermions and gauge bosons of the SM [11]. For one of the many studies, coupling modifiers for fermions and vector bosons have been introduced and profiled. The constraints from the different decay channels, expressed as 68% CL confidence regions, are shown in Fig. 7 (top left). The combined likelihood shows a clear maximum near the point  $\kappa_V = \kappa_f = 1$ , which corresponds to the SM expectation.

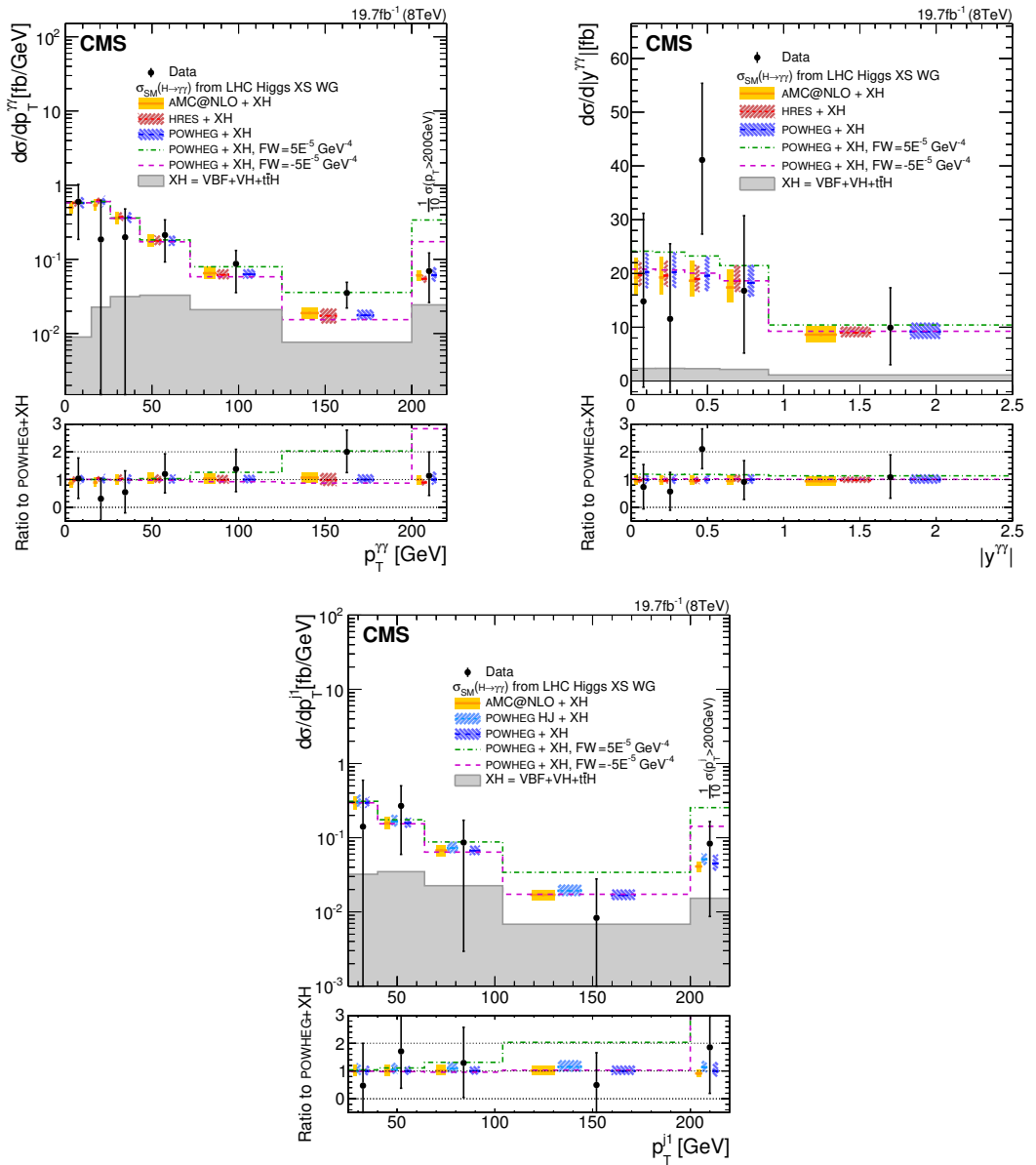
The mass dependence of the couplings can be regarded as an essential “fingerprint” of a Higgs boson. The SM predicts that the Yukawa couplings to fermions have a linear mass dependence, while the couplings to weak bosons are proportional to the square of the boson mass. For these reasons, a “reduced” weak boson coupling is computed, such that all couplings can be compared in one plot in Fig. 7 (top right). The results agree well with the linear mass dependence expected from the SM.

The same data can also be used to profile the branching ratio of the Higgs boson into invisible particles. Such a scan is shown in Fig. 7 (bottom). Also the results of the direct searches into invisible Higgs decays are included. An observed upper limit of 0.49 at 95% CL is inferred.

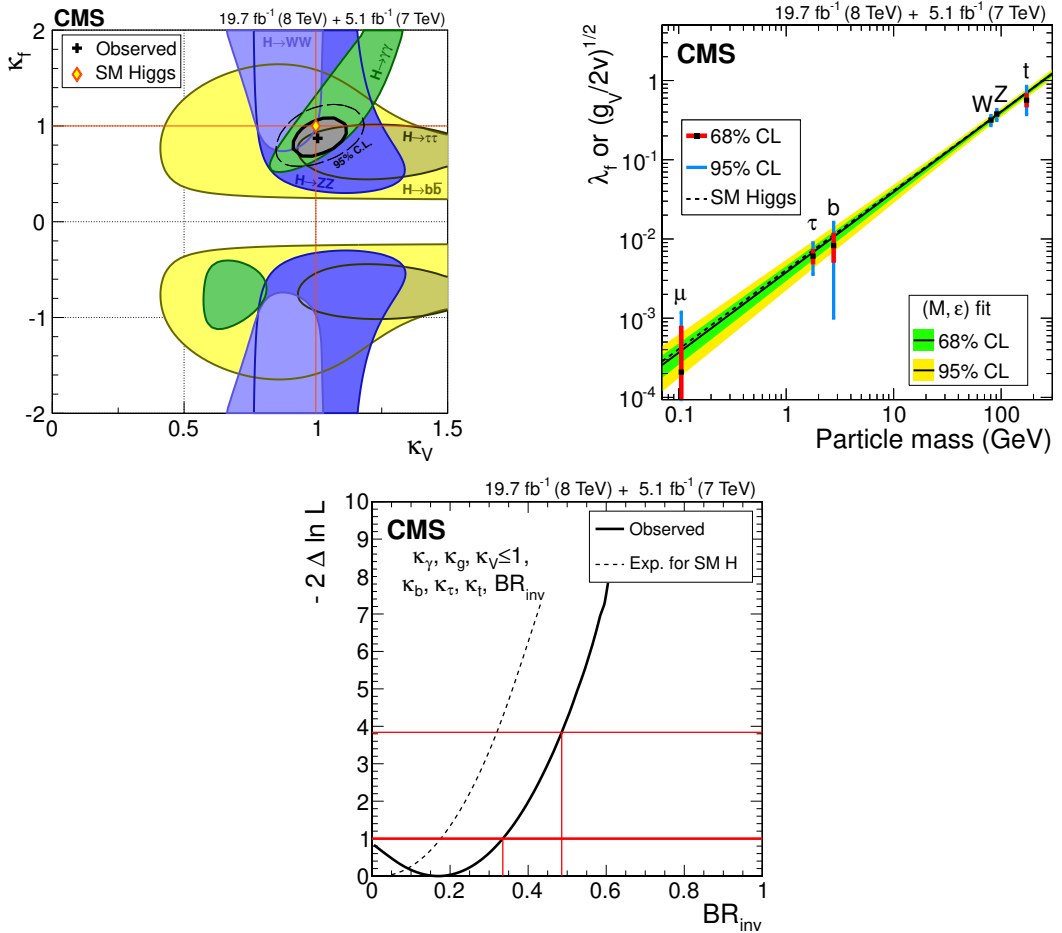
At the current level of measurement precision, the observed Higgs boson couples to fundamental fermions and gauge bosons as expected in the SM. On the other hand, there is still plenty of room for non-standard invisible decays. It is an important question whether the  $H(125)$  is indeed the SM Higgs boson, or just one member of an extended Higgs sector, which happens to be SM-like. Direct searches for additional Higgs bosons are essential to clarify this question, and will be discussed in the following section.

## 3 Higgs bosons beyond the Standard Model

Supersymmetry is a theory which naturally features extended Higgs sectors. In the minimal (MSSM) and next-to-minimal (NMSSM) supersymmetric extensions of the SM, three or five neutral Higgs bosons are predicted, respectively, as displayed in Table 1. One of these bosons must be SM-like and coincide with the observed boson at 125 GeV. In the MSSM, the  $H(125)$  state would correspond most likely to the  $h$  boson, since other assignments are already strongly disfavored by the current



**Figure 6.** The  $H \rightarrow \gamma\gamma$  differential cross section for inclusive events as a function of  $p_T^{\gamma\gamma}$  (top left),  $|y^{\gamma\gamma}|$  (top right) and  $p_T^{j1}$  (bottom) [16]. All the SM contributions are normalized to their cross section from the LHC Higgs Cross Section Working Group [17]. Theoretical uncertainties in the renormalization and factorization scales, PDF, and branching fraction are added in quadrature. The error bars on data points reflect both statistical and systematic uncertainties. The last bin of the  $p_T^{\gamma\gamma}$  distribution sums the events above 200 GeV. For each graph, the bottom panel shows the ratio of data to theoretical predictions from the POWHEG generator.



**Figure 7.** Top left: The 68% CL confidence regions for individual channels (coloured swaths) and for the overall combination (thick curve) for the coupling modifiers  $\kappa_V$  and  $\kappa_f$ . The cross indicates the global best-fit values. Top right: Reduced coupling constants of the Higgs boson to various fermions and bosons as a function of the particle mass. The dashed line corresponds to the SM expectation. Bottom: Result of a likelihood scan versus  $BR_{BSM} = \Gamma_{BSM}/\Gamma_{tot}$ . The solid curve represents the observation in data, and the dashed curve indicates the expected median result in the presence of the SM Higgs boson. The data from the searches for invisible Higgs decays are also taken into account [11].

measurements. In the NMSSM, several assignments are possible, including  $H(125) \equiv h_2$ , and Higgs bosons with masses below 125 GeV are thus feasible.

### 3.1 Search for MSSM Higgs bosons in the $b\bar{b}$ channel

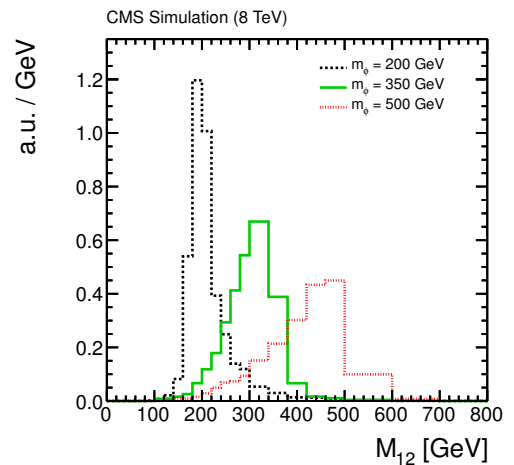
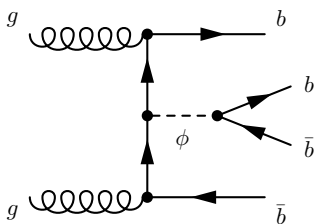
With a SM-like  $h$  boson at 125 GeV, the  $H$  and  $A$  bosons are searched for at higher masses; they are expected to be degenerate, and their coupling to  $b$  quarks is enhanced by the MSSM parameter  $\tan\beta$ .



**Table 1.** Higgs sectors in the minimal (MSSM) and next-to-minimal (NMSSM) supersymmetric extensions of the SM.

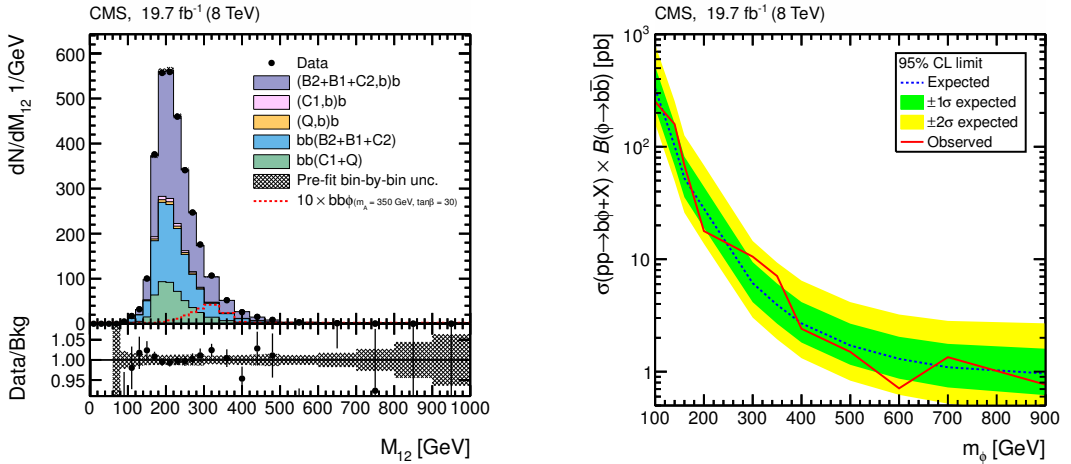
Model	Structure	CP-even	CP-odd	Charged
MSSM	2 doublets	$h, H$	$A$	$H^\pm$
NMSSM	2 doublets + 1 singlet	$h_1, h_2, h_3$	$a_1, a_2$	$h^\pm$

For large  $\tan\beta$  values, even at large masses the by far dominant decay mode should be the decay into b-quark pairs. The main challenge of this decay channel is the huge background rate from QCD multijet production. It is most promising to search for production in association with additional b quarks, as depicted in Fig. 8 (left), which is enhanced by a factor of  $2 \tan^2\beta$ , including the degeneracy effect, and also leads to a better signal-to-background relation. A dedicated hadronic trigger is mandatory for this analysis.

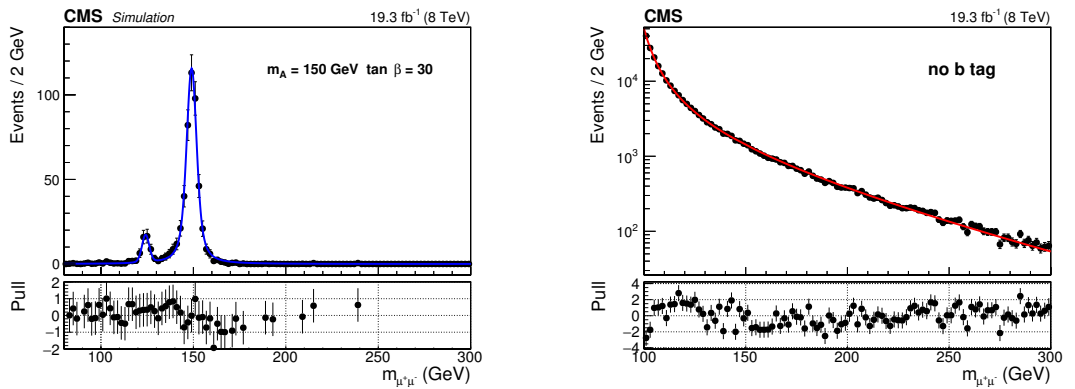


**Figure 8.** Left: Feynman diagram of one of the processes contributing to the MSSM  $H \rightarrow b\bar{b}$  production in association with additional b quarks. Right: Distributions of the dijet invariant mass for expected signals, for Higgs boson masses of 200, 350 and 500 GeV. The vertical scale is shown in arbitrary units [18].

This CMS analysis [18] is unique at the LHC. The selection requires the three leading jets to be b-tagged, and a signal is expected to emerge as a peak in the invariant mass distribution of the two leading jets, as shown according to simulation in Fig. 8 (right). The dijet invariant mass spectrum from the triple-b-tag data sample is shown in Fig. 9 (left). The background is modeled with a set of templates reflecting the different flavor combinations, which are derived from the double-b-tag data sample, and fitted to the data. This background model is found to describe the data well, and there is no indication of a signal. The addition of signal templates to the fit does not result in significant signal strength at any of the probed Higgs masses. Upper limits on cross section time branching ratio are derived and shown in Fig. 9 (right), they agree well with the expected limits. A detailed MSSM model interpretation will be presented in Section 3.3.



**Figure 9.** Left: Distribution of the dijet mass in the triple-b-tag sample in the search for MSSM Higgs bosons in the  $bb$  channel, together with the corresponding distributions of the fitted background templates. The hatched area shows the total bin-by-bin background uncertainty of the templates prior to the fit. For illustration, the signal contribution expected in the  $m_h^{\max}$  benchmark scenario of the MSSM with  $m_A = 350$  GeV,  $\tan\beta = 30$ , and  $\mu = +200$  GeV is overlaid, scaled by a factor 10 for better readability. In addition, the ratio of data to the background estimate is shown at the bottom. Right: Expected and observed upper limits at 95% CL on  $\sigma(pp \rightarrow b\phi + X)BR(\phi \rightarrow b\bar{b})$ , where  $\phi$  denotes a generic neutral Higgs-like state [18].

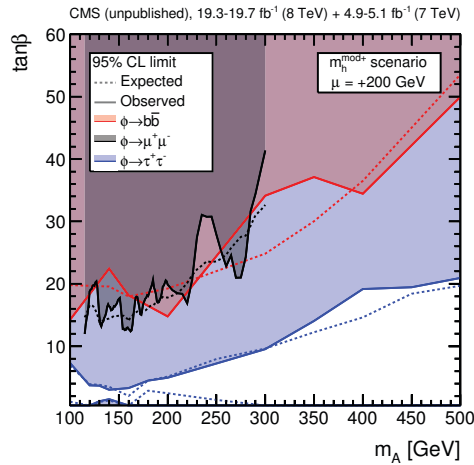


**Figure 10.** Invariant mass distribution of the expected signal for  $m_A = 150$  GeV and  $\tan\beta = 30$  (left) for the MSSM Higgs boson search in the di-muon channel, and an example of the fit to the data at  $\sqrt{s} = 8$  TeV including the same signal assumption (right). The distribution represents the expected number of events for an integrated luminosity of  $19.3 \text{ fb}^{-1}$ . For each plot the pull of the fit as a function of the dimuon invariant mass is shown [19].

### 3.2 Search for MSSM Higgs bosons in the di-muon final state

While the branching ratio of MSSM Higgs bosons into muon pairs is expected to be small, this is compensated by the excellent mass resolution. The dominant background component originates from Drell-Yan production, and leads to a smooth background shape. The recent CMS analysis [19] distinguishes between two categories, named “b tag” and “no b tag”, depending on whether the Higgs candidate is accompanied by an additional b-tagged jet or not. The signal model containing all three neutral MSSM Higgs bosons is shown for one set of parameters in Fig. 10 (left). The left of the two peaks corresponds to a h boson with SM-like properties at a mass of 125 GeV, while the right peak is the combined signal of the H and A bosons, whose cross sections are greatly enhanced due the MSSM parameter choice of  $\tan\beta = 30$ . The analysis proceeds with parametric signal and background models. The fit of these models to the observed di-muon mass spectrum in data is shown in Fig. 10 (right); there is no indication of an excess.

### 3.3 Interpretation within the MSSM

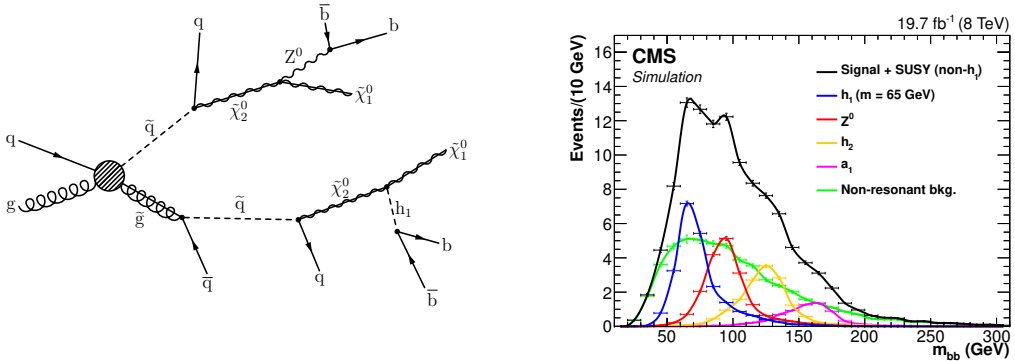


**Figure 11.** Comparison of the expected and observed upper limits at 95% CL for the MSSM parameter  $\tan\beta$  versus  $m_A$  in the  $m_h^{\text{mod}+}$  benchmark scenario [18] obtained in different final states:  $\phi \rightarrow b\bar{b}$  [18],  $\phi \rightarrow \mu\mu$  [19], and  $\phi \rightarrow \tau\tau$  [22]. The shaded areas mark the excluded regions.

The results from the neutral Higgs boson searches are interpreted in the  $m_h^{\text{mod}+}$  benchmark scenario [20] of the MSSM. The published CMS results in the  $\phi \rightarrow \tau\tau$  channel [21] have recently been updated with an improved identification of semihadronic  $\tau$  decays [22]. The results are illustrated in the MSSM parameter space for all three decay modes in Fig. 11. The most stringent MSSM limits are achieved in the  $\tau\tau$  channel, while the  $b\bar{b}$  and  $\mu\mu$  channels are at comparable levels. At large values of  $m_A$ , a relatively wide range for  $\tan\beta$  is still open according to the measurements, as can also be seen in Ref. [22].

### 3.4 Light NMSSM Higgs boson search

While the possibility of light Higgs bosons with SM-like couplings in the mass region below 100 GeV has already been largely excluded by measurements at LEP [23], such bosons are nevertheless feasible



**Figure 12.** Left: Feynman diagram of squark-gluino production with subsequent cascade decays via neutralinos into  $h_1$ . Right: Signal + non- $h_1$  SUSY prediction of the modified NMSSM P4 scenario with  $m_{h_1} = 65$  GeV and normalized to the integrated luminosity of  $19.7 \text{ fb}^{-1}$  [25].

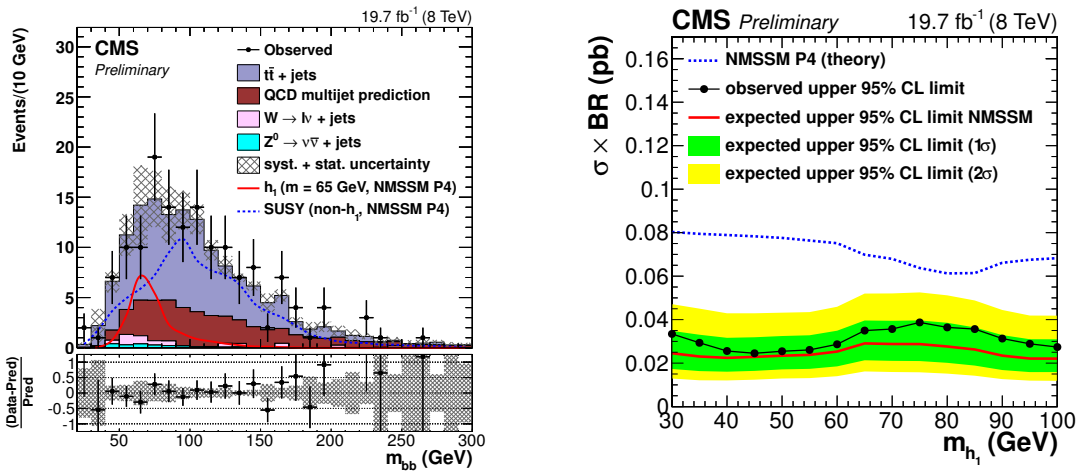
in NMSSM scenarios. In a slightly modified version of the P4 scenario [24], the  $h_2$  state is assumed to be the H(125) boson. The lighter  $h_1$  is assumed to have a very large singlet component, due to which it would be strongly suppressed in the standard Higgs production channels, and thus have escaped detection so far. However, it would be copiously produced in SUSY cascades, as illustrated in Fig. 12 (left). Its observation would thus imply a simultaneous discovery of supersymmetry and an extended Higgs sector.

This option has been explored for the first time at the LHC by the CMS experiment [25]. Besides the  $h_1$ , other bosons, namely  $Z$ ,  $h_2$  and  $a_1$  should appear in the SUSY cascade as well, resulting in a complex signal mass spectrum as shown in Fig. 12 (right). The analysis searches for events with two energetic jets originating from squarks in the cascade, two b jets which might come from the Higgs decay, and large hadronic activity and missing energy. The resulting invariant b-jet pair mass spectrum measured in data is shown in Fig. 13 (left). The distribution shows no excess beyond the estimated SM backgrounds, and there is no indication for a signal. The resulting upper limit on cross section times branching ratio is shown in Fig. 13 (right). The modified NMSSM P4 scenario is excluded over the whole mass range from 30–100 GeV at  $M_{\text{SUSY}} = M_{\tilde{g}} = 1 \text{ TeV}$ .

## 4 Summary

Beyond the H(125) discovery, a wealth of new CMS Higgs results have been obtained, which can be regarded as the legacy results of CMS from the LHC Run I. The properties of the observed H(125) state have already been determined to a remarkable precision. The methodology has been enhanced in many places, which is expected to fully bear fruit with the Run II data. At the current level of measurement accuracy, the properties of this state are found to be in agreement with those expected in the SM.

The quest for New Physics as it would be indicated by additional Higgs states has equally progressed. Stringent limits for the MSSM parameters have been obtained in three direct search channels, and as a result the region of low  $m_A$  is already strongly constrained, while at large values of  $m_A$ , large values of  $\tan\beta$  are still possible. There is still a widely open parameter space for the Higgs sector in the NMSSM model.



**Figure 13.** Left: Background-only fit result of the invariant mass of the selected b-tagged jets, where the SM background contributions are stacked, in the light NMSSM Higgs boson search. The theoretical  $h_1$  and non- $h_1$  contributions are overlaid to illustrate the sensitivity of the analysis to the modified NMSSM P4 scenario expectation. Right: Upper limits for the NMSSM cross section times the branching ratio into b-quarks [25].

The Run II of the LHC at higher CM energy and large luminosity will provide a hugely extended capability for studying the properties of the H(125) boson, and searching for extensions of the Higgs sector.

## References

- [1] ATLAS Collaboration, “Observation of a new particle in the search for the Standard Model Higgs boson with the ATLAS detector at the LHC”, *Phys. Lett. B* **716** (2012) 1.
- [2] CMS Collaboration, “Observation of a new boson at a mass of 125 GeV with the CMS experiment at the LHC”, *Phys. Lett. B* **716** (2012) 30.
- [3] CMS Collaboration, “Observation of a new boson with mass near 125 GeV in pp collisions at  $\sqrt{s} = 7$  and 8 TeV”, *JHEP* **06** (2013) 081.
- [4] CMS Collaboration, “Observation of the diphoton decay of the Higgs boson and measurement of its properties”, *Eur. Phys. J. C* **74** (2014) 3076.
- [5] CMS Collaboration, “Measurement of the properties of a Higgs boson in the four-lepton final state”, *Phys. Rev. D* **89** (2014) 092007.
- [6] CMS Collaboration, “Measurement of Higgs boson production and properties in the WW decay channel with leptonic final states”, *JHEP* **01** (2014) 096.
- [7] P. Vanlaer, “ATLAS+CMS combined H boson mass measurement, search for offshell decays and for high mass scalars”, *these proceedings*.
- [8] ATLAS and CMS Collaborations, “Combined Measurement of the Higgs Boson Mass in pp Collisions at  $\sqrt{s} = 7$  and 8 TeV with the ATLAS and CMS Experiments,” *Phys. Rev. Lett.* **114** (2015) 191803.
- [9] CMS Collaboration, “Evidence for the 125 GeV Higgs boson decaying to a pair of  $\tau$  leptons,” *JHEP* **05** (2014) 104 .

- [10] CMS Collaboration, “Search for the standard model Higgs boson produced in association with a W or a Z boson and decaying to bottom quarks”, *Phys. Rev. D* **89** (2014) 012003.
- [11] CMS Collaboration, “Precise determination of the mass of the Higgs boson and tests of compatibility of its couplings with the standard model predictions using proton collisions at 7 and 8 TeV”, *Eur.Phys.J. C* **75** (2015) 212.
- [12] CMS Collaboration, “Evidence for the direct decay of the 125 GeV Higgs boson to fermions”, *Nature Phys.* **10** (2014) 557.
- [13] CMS Collaboration, “Search for the standard model Higgs boson produced through vector boson fusion and decaying to bb”, *Phys. Rev. D* **92** (2015) 032008.
- [14] CMS Collaboration, “Search for the associated production of the Higgs boson with a top-quark pair”, *JHEP* **09** (2014) 087.
- [15] CMS Collaboration, “Search for a standard model Higgs boson produced in association with a top-quark pair and decaying to bottom quarks using a matrix element method”, *Eur.Phys.J. C* **75** (2015) 251.
- [16] CMS Collaboration, “Measurement of differential cross sections for Higgs boson production in the diphoton decay channel in pp collisions at  $\sqrt{s} = 8$  TeV”, arXiv:1508.07819 (2015), submitted to *Eur.Phys.J. C*.
- [17] LHC Higgs Cross Section Working Group, “Handbook of LHC Higgs cross sections: 3. Higgs Properties”, CERN Report CERN-2013-004 (2013), arXiv:1307.1347.
- [18] CMS Collaboration, “Search for neutral MSSM Higgs bosons decaying into a pair of bottom quarks”, *JHEP* **11** (2015) 071.
- [19] CMS Collaboration, “Search for neutral MSSM Higgs bosons decaying to  $\mu^+\mu^-$  in pp collisions at  $\sqrt{s} = 7$  and 8 TeV”, *Phys.Lett.B* **752** (2016) 221.
- [20] M. Carena et al., “MSSM Higgs boson searches at the LHC: benchmark scenarios after the discovery of a Higgs-like particle”, *Eur.Phys.J. C* **73** (2013) 2552.
- [21] CMS Collaboration, “Search for neutral MSSM Higgs bosons decaying to a pair of tau leptons in pp collisions”, *JHEP* **10** (2014) 160.
- [22] CMS Collaboration, “Search for additional neutral Higgs bosons decaying to a pair of tau leptons in pp collisions at  $\sqrt{s} = 7$  and 8 TeV”, CMS-PAS-HIG-14-029 (2015).
- [23] ALEPH, DELPHI, L3 and OPAL Collaborations, LEP Working Group for Higgs Boson Searches Collaboration, “Search for neutral MSSM Higgs bosons at LEP”, *Eur. Phys. J. C* **47** (2006) 547.
- [24] O. Stål, G. Weiglein, “Light NMSSM Higgs bosons in SUSY cascade decays at the LHC”, *JHEP* **01** (2012) 071.
- [25] CMS Collaboration, “Search for a light NMSSM Higgs boson produced in supersymmetric cascades and decaying into a b-quark pair”, CMS-PAS-HIG-14-030 (2015).