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Higgs boson parameters and decays into fermions

Michal Bluj on behalf of the ATLAS and CMS collaborations.

Abstract

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HIGGS BOSON PARAMETERS AND DECAYS INTO FERMIONS

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In 2012 the discovery of a new boson with a mass of about 125 GeV and properties in agreement with those expected for the Higgs boson in the standard model was announced. In this note we review the results of searches for the fermionic decays the Higgs boson and the study of its properties performed with the proton-proton collision data recorded by the ATLAS and CMS detectors at the LHC in 2011 and 2012, corresponding to an integrated luminosity of approximately 5 fb^{-1} and approximately 20 fb^{-1} per experiment at $\sqrt{s} = 7$ TeV and $\sqrt{s} = 8$ TeV, respectively. Decay rates to fermions and extracted couplings are consistent with the expectation of the standard model. In addition, we present a search for lepton flavour violating decays of the Higgs boson which can occur in several extensions of the standard model, and a search for neutral Higgs bosons decaying to tau pairs performed in the context of the minimal supersymmetric extension of the standard model (MSSM).

1 Introduction

After the discovery of a new standard-model-like Higgs boson announced by the ATLAS and CMS collaborations in July 2012 [1,2] it became essential to establish the nature of this new boson, i.e. observe its decay modes, measure its couplings to standard model particles, etc. This goal is achieved by a set exclusive analyses sensitive to different production processes and decay modes of the Higgs boson which are then combined to extract its properties in the most precise way. In this report we focus on searches for the fermionic decays the Higgs boson, $\mathrm{H} \to \tau\tau$, $\mathrm{H} \to \mathrm{b\bar{b}}$, $\mathrm{H} \to \mu\mu$. Those studies were performed with the proton-proton collision data recorded by the ATLAS [3] and CMS [4] detectors at the LHC in 2011 and 2012, corresponding to an integrated luminosity per experiment of approximately 5 fb^{-1} at $\sqrt{s} = 7$ TeV and approximately 20 fb^{-1} at $\sqrt{s} = 8$ TeV. In addition we decided to report here two interesting examples of searches for phenomena predicted by extensions of the standard model: a search for lepton flavour violating decays of the Higgs boson, and a search for neutral Higgs bosons decaying to tau pairs performed in the context of the minimal supersymmetric extension of the standard model (MSSM).

2 Search for fermionic decays of the Higgs boson

Two fermionic decay modes of the standard model Higgs boson which the experiments at the LHC are already sensitive to are $\mathrm{H} \to \mathrm{b\bar{b}}$ and $\mathrm{H} \to \tau\tau$. Both are characterized by a relatively high branching fraction, respectively about 58% and 6.3% at $\mathrm{m_H}$=125 GeV for $\mathrm{H} \to \mathrm{b\bar{b}}$ and $\mathrm{H} \to \tau\tau$, allow to reconstruct the Higgs boson mass with resolution of 10–20% and suffer from large background. Therefore, a special strategy is employed in searches for those decay modes.

The $\mathrm{H} \to \mathrm{b\bar{b}}$ search explores the VH associated production mode, where $\mathrm{V} = \mathrm{W}, \mathrm{Z}$ is a vector boson. In the search it is imposed a requirement of a significant boost of the vector boson, $p_{\mathrm{T}}(\mathrm{V})$, which substantially reduces background. The final observables used to discriminate between signal and background is based on boosted decision tree classifiers (BDTs) trained separately in all categories defined by decay modes of a vector boson and $p_{\mathrm{T}}(\mathrm{V})$. The invariant mass the Higgs candidate, $\mathrm{m_{jj}}$, defined by a pair of b-tagged jets is among the most discriminant variables used to build the BDT classifiers for all categories. A distribution of $\mathrm{m_{jj}}$, combined for all categories, weighted by the signal purity, $\mathrm{S/(S+B)}$, reconstructed by the CMS detector is shown in Fig. 1 (left).

The ATLAS Collaboration reports a deviation from the background-only hypothesis corresponding to a significance of 1.4 standard deviations, σ, while 2.6σ is expected for $\mathrm{m_H}$=125 GeV[5], Fig. 1 (middle). The ratio of the measured signal yield to the standard model expectation, a signal strength, is $\mu = 0.52 \pm 0.32(\mathrm{stat.}) \pm 0.24(\mathrm{syst.})$.

The corresponding analysis performed by the CMS sees an excess of events over expected background with a significance of 2.1σ (2.1σ expected), Fig. 1 (right), giving the signal strength $\mu = 1.0 \pm 0.5$[6].

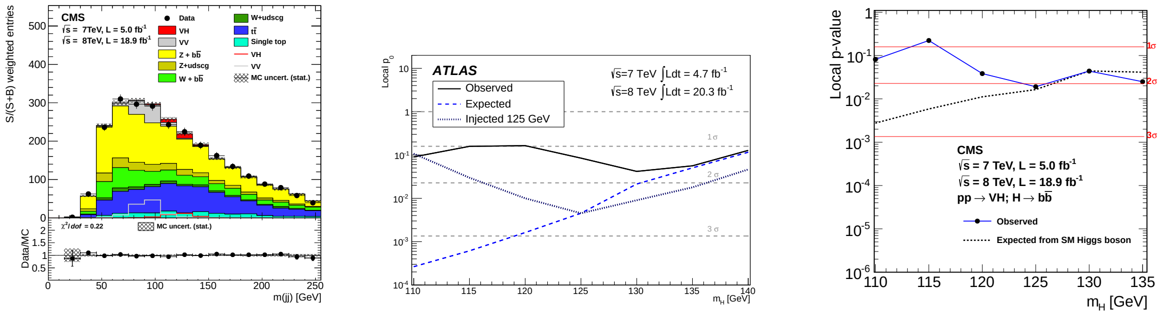

Figure 1 – Distribution of the $\mathrm{b\bar{b}}$ mass in CMS (left); The expected (dashed line) and observed (solid line) significance of the $\mathrm{VH(b\bar{b})}$ signal in ATLAS (middle) and CMS (right).

The searches for the $\mathrm{H} \to \tau\tau$ channel is based on an event classification to enhance the impact of events produced in the VBF and VH processes, but also in the gluon fusion process with additional jets, which increases the signal-to-background ratio. In the $\mathrm{H} \to \tau\tau$ analyses both experiments use an estimate of a full $\tau\tau$ invariant mass, $\mathrm{m}_{\tau\tau}$, calculated using a likelihood based method taking as input the kinematics of the visible decay products and $E_{\mathrm{T}}^{\mathrm{miss}}$. It gives better separation between H and Z than the mass of the visible $\tau\tau$ system.

The ATLAS experiment defines two categories, the VBF category characterized by the presence of two jets with a large separation in pseudorapidity and the boosted category which contains events where the reconstructed Higgs boson candidate has a large transverse momentum. In order to exploit correlations between final state observables a set of discriminants based on BDT classifiers, one for each category and each tau pair decay channel, is used to extract the final results. Among the BDT input variables with the highest signal-background discrimination power are an estimate of a full $\tau\tau$ invariant mass, distance between visible products of two tau leptons and separation in pseudorapidity between two jets[7]. Expected and observed number of events in bins of $\log_{10}(S/B)$, where S/B is the signal-to-background ratio, for each BDT output bin in all categories and channels is shown in Fig. 2 (left).

The CMS experiment implements different strategy with the signal extracted from the distribution of the invariant mass of the $\tau\tau$-lepton pair in a high number of categories. The categories are defined by the jet multiplicity including the VBF category with two jets with a large separation in pseudorapidity, transverse momentum of the Higgs candidate, and transverse momentum of τ visible products[8]. A distribution of $\mathrm{m}_{\tau\tau}$, combined for all categories, weighted by the signal purity, $\mathrm{S/(S+B)}$, reconstructed by the CMS detector is shown in Fig. 2 (right).

The significance of an excess of events over the expected background in the ATLAS analysis amounts to 4.5σ (3.4σ expected) which provides evidence for the direct coupling of the Higgs

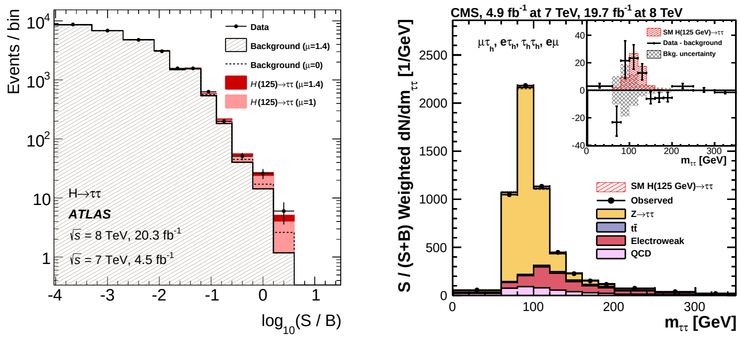

Figure 2 – Event yields seen by the ATLAS experiment as a function of $\log_{10}(S/B)$, where S (signal yield) and B (background yield) are taken from each BDT output bin for all categories and channels (left); Distribution of the $\tau\tau$-lepton pair mass, $m_{\tau\tau}$, combined across decay channels and categories in the CMS search (right).

boson to tau leptons, Fig. 3 (left). The measured signal strength is μ=1.43$^{+0.43}_{-0.37}$.

Also the CMS experiment observes an excess of events above background only hypothesis which allows to report evidence of the H $\rightarrow \tau\tau$ decay with a significance of 3.2σ (3.7σ expected), Fig. 3 (right), and a signal strength μ=0.78 $\pm$ 0.27.

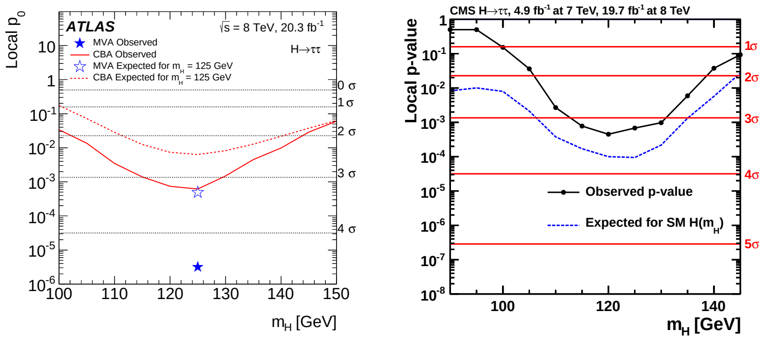

Figure 3 – Observed (solid line) and expected (dashed line) significance of the $H \rightarrow \tau\tau$ decay as a function of the SM Higgs boson mass hypothesis in ATLAS (left) and CMS (right).

The H $\rightarrow \mu\mu$ decay channel with an expected branching fraction of 2.2×10^{-4} at m_H=125 GeV completes the list of fermionic decay modes of the standard model Higgs boson accessible at the LHC. This channel provides an unique way to probe the coupling of the Higgs boson to the second generation of fermions.

The H $\rightarrow \mu\mu$ channel is characterized by a very clean final state and it is sought as a peak in the dimuon mass spectrum, on top of a smoothly falling background dominated by contributions from Drell-Yan, $t\bar{t}$, and vector boson pair production processes, Fig. 4 (left). The sensitivity of the search is enhanced by an event categorization based on a jet multiplicity, with the VBF category defined by the presence of two jets with a large separation in pseudorapidity, a transverse momentum of a $\mu\mu$ pair and pseudorapidity of a muon which dimuon mass resolution is related to.

Despite a small expected signal event yield limiting sensitivity in this channel with current data, first analyses were launched by the ATLAS [9] and CMS [10] collaborations. In a result limits at 95% CL on the signal strength in this channel were set $\mu < 7.0$ ($\mu < 7.2$ expected) and $\mu < 7.4$ ($\mu < 6.5$ expected) for m_H=125 GeV in ATLAS and CMS, Fig. 4 (middle, right), respectively.

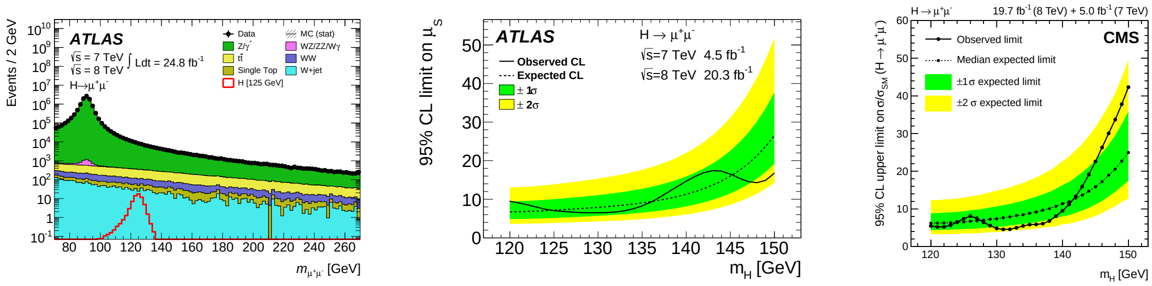

Figure 4 – The distribution of the dimuon invariant mass at ATLAS (right); Observed (solid) and expected (dashed) 95% CL upper limits on the $\mathrm{H} \rightarrow \mu\mu$ signal strength as a function of $\mathrm{m_H}$ in ATLAS (middle) and CMS (right).

3 Combination: production and decay rates and couplings

Assuming that the width of the Higgs boson can neglected, i.e. the zero-width approximation [a], the rate in any combination of production and decay modes of the Higgs boson can be related to the production cross section, and the partial and total widths in the following way:

$$\sigma_{\mathrm{ii}} \times \mathcal{B}(\mathrm{H} \rightarrow \mathrm{ff}) = \frac{\sigma_{\mathrm{ii}} \times \Gamma_{\mathrm{ff}}}{\Gamma_{\mathrm{tot}}},$$

where ii represents the production mechanism, Γ_{ff} is the partial width into the final state ff and Γ_{tot} is the total width of the Higgs boson. It allows to parametrise measured signal strengths in terms of coupling strength scaling factors $\kappa_{\mathrm{i}}=\mathrm{g_i}/g_{\mathrm{SM}}$, e.g. for the ZH $\rightarrow \mathrm{b\bar{b}}$ process one can write

$$\mu_{\mathrm{ZH}\rightarrow\mathrm{b\bar{b}}} = [\sigma_{\mathrm{ZH}} \times \mathcal{B}(\mathrm{H} \rightarrow \mathrm{b\bar{b}})]_{\mathrm{obs.}}/[\sigma_{\mathrm{ZH}} \times \mathcal{B}(\mathrm{H} \rightarrow \mathrm{b\bar{b}})]_{\mathrm{SM}} = (\kappa_{\mathrm{Z}}^2 \times \kappa_{\mathrm{b}}^2)/\kappa_{\mathrm{H}}^2.$$

By construction all parameters μ, κ, and $\lambda_{\mathrm{xy}} = \kappa_{\mathrm{x}}/\kappa_{\mathrm{y}}$ are equal 1 for the SM Higgs boson. The parameters can be constrained by a simultaneous analysis of the data selected in all exclusive channels accounting for statistical and systematic uncertainties and their correlations. However, as the size of the current dataset is too small to quantify all these parameters, some relation between them is assumed defining specific benchmark models [11].

The ATLAS and CMS collaborations performed common combined measurements in this interpretation model [12]. Production and decay signal strengths obtained with the combined analysis are shown in Fig. 5, all in agreement with the standard model expectations. The significances for the observation of the different production processes and decay channels involving direct Higgs-to-fermion couplings are reported in table 1. The combined significance of the $\mathrm{H} \rightarrow \tau\tau$ decay is above 5σ, and 4.4σ for the ttH production process while only 2.0σ is expected which corresponds to an observed excess of 2.3σ with respect to the standard model prediction.

Table 1: Significances for the observation of Higgs boson production processes and decay channels involving a direct Higgs-to-fermion coupling for the combination of ATLAS and CMS

Production process	Measured significance (σ)	Expected significance (σ)
ttH	4.4	2.0
Decay channel		
$\mathrm{H} \rightarrow \tau\tau$	5.5	5.0
$\mathrm{H} \rightarrow \mathrm{b\bar{b}}$	2.6	3.7

Results of the combined coupling measurement are summarised in Fig. 6 and are in all cases consistent with expectations for the standard model Higgs boson. For instance, Fig. 6 (right)

[a] The standard model predicts the total width of about 4 MeV for the Higgs boson with mass $\mathrm{m_H}$=125 GeV

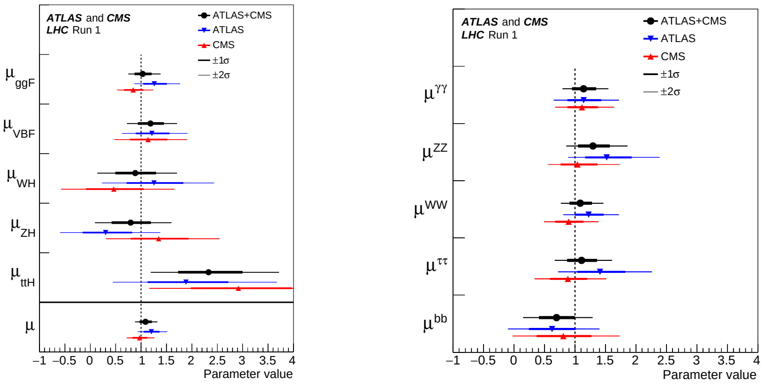

Figure 5 – Combined production (left) and decay (right) signal strengths.

shows the linear scaling as a function of the particle masses of coupling parameters defined as $\kappa_{\mathrm{F}} \cdot \mathrm{m_F}/\mathrm{v}$ for a fermion with mass $\mathrm{m_F}$ and $\sqrt{\kappa_{\mathrm{V}}} \cdot \mathrm{m_V}/\mathrm{v}$ for a weak vector boson with mass $\mathrm{m_V}$, where v=246 GeV is the vacuum expectation value of the Higgs field.

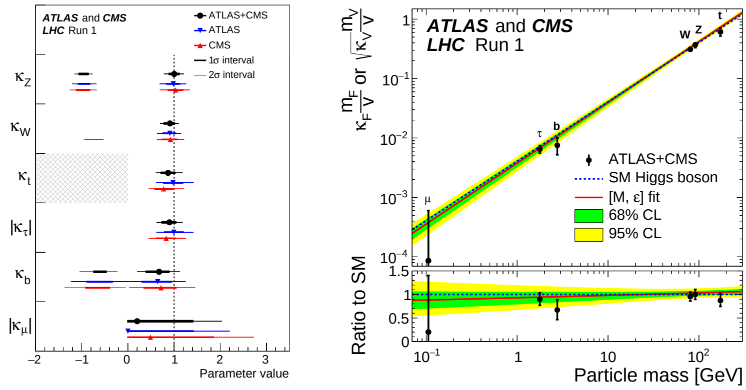

Figure 6 – Measured values of coupling strength scaling factors κ (left) and coupling parameters defined as $\kappa_{\mathrm{F}} \cdot \mathrm{m_F}/\mathrm{v}$ for the fermions, and as $\sqrt{\kappa_{\mathrm{V}}} \cdot \mathrm{m_V}/\mathrm{v}$ for the weak vector bosons, where v=246 GeV is the vacuum expectation value of the Higgs field (right).

4 Lepton flavour violating Higgs boson decays

Lepton flavour violating (LFV) decays of the Higgs boson can occur naturally in in several extensions of the standard model, e.g. models with more than one Higgs doublet. The presence of LFV couplings would allow $\mu \to \mathrm{e}$, $\tau \to \mathrm{e}$ and $\tau \to \mu$ transitions through a virtual Higgs boson. The experimental limits on these can be translated into constraints on the branching fractions $\mathcal{B}(\mathrm{H} \to \mathrm{e}\mu) < \mathcal{O}(10^{-8})$, $\mathcal{B}(\mathrm{H} \to \mathrm{e}\tau) < \mathcal{O}(10^{-1})$ and $\mathcal{B}(\mathrm{H} \to \mu\tau) < \mathcal{O}(10^{-1})$ [13].

Both ATLAS and CMS collaboration have performed direct searches for the LFV $\mathrm{H} \to \mathrm{e}\tau$ and $\mathrm{H} \to \mu\tau$ decays with 20 fb^{-1} of 8 TeV data collected in 2012 [14,15,16,17]. The searches have been performed in several event categories improving sensitivity, with the signal extracted with an estimator of the full invariant mass of the $\ell\tau$ ($\ell = \mathrm{e}, \mu$) pair. Table 2 presents a summary of results for the expected and observed 95% CL upper limits and the best-fit values for the branching fractions.

There is no indication of a signal in the search for the LFV $\mathrm{H} \to \mathrm{e}\tau$ decay. A small 1σ excess over the predicted background is observed by the ATLAS Collaboration in the search for the LFV $\mathrm{H} \to \mu\tau$ decay, while the CMS Collaboration reports an excess of 2.4σ. These correspond to the best fit value for the branching fraction $\mathcal{B}(\mathrm{H} \to \mu\tau)$ of $0.53^{+0.51}_{-0.51}$% and $0.84^{+0.39}_{-0.37}$% in ATLAS

Table 2: Results of the search for the LFV $H \to e\tau$, $H \to \mu\tau$ and $H \to e\mu$ decays.

Channel	Experiment	Expected limit (%)	Observed limit (%)	Best-fit $\mathcal{B}$ (%)
$H \to e\tau$	ATLAS	$< 1.21^{+0.49}_{-0.34}$	< 1.04	$-0.34^{+0.64}_{-0.66}$
	CMS	$< 0.75^{+0.32}_{-0.22}$	< 0.69	–
$H \to \mu\tau$	ATLAS	$< 1.01^{+0.40}_{-0.29}$	< 1.43	$0.53^{+0.51}_{-0.51}$
	CMS (8 TeV)	$< 0.75 \pm 0.38$	< 1.51	$0.84^{+0.39}_{-0.37}$
	CMS (13 TeV)	$< 1.62 \pm 0.58$	< 1.20	$-0.76^{+0.81}_{-0.84}$
$H \to e\mu$	CMS	$< 0.048 \pm 0.14$	< 0.035	–

and CMS, respectively. The CMS Collaboration repeated the $H \to \mu\tau$ search with 2.3 fb^{-1} of 13 TeV data collected in 2015 [18]. No excess is observed with 2015 data, but due to limited size of the dataset the search is not sensitive enough to exclude the 8 TeV result (details in table 2).

Finally, the CMS Collaboration have performed a search for the LFV $H \to e\mu$ decay [17]. There is not signal observed; observed and expected exclusion limits on $\mathcal{B}(H \to e\mu)$ are given in table 2.

5 Neutral Higgs bosons decaying to tau pairs in the context of the MSSM

The minimal supersymmetric extension of the standard model (MSSM) contains two Higgs doublets which lead to five physical Higgs bosons after electroweak symmetry breaking, two charged Higgs bosons $H^{\pm}$ and three neutrals: the light and heavy CP-even (scalar) Higgs bosons h and H, and the CP-odd (pseudoscalar) Higgs boson A (for simplicity the neutral Higgs bosons are collectively denoted as Φ further in this section). At tree level, the Higgs sector of the MSSM is described by two free parameters, conventionally chosen to be the mass of the pseudoscalar boson, m_A, and the ratio of vacuum expectation values of the two Higgs doublets, $\tan\beta$.

The main neutral MSSM Higgs boson production mechanisms are the gluon fusion process dominating for small and moderate values of $\tan\beta$ and b-quark associated production dominating for high values of $\tan\beta$ thanks to the enhanced Higgs bosons couplings to down-type fermions. The enhancement of Higgs bosons couplings to down-type fermions results also in increased branching fraction to tau leptons. This together with relatively clean experimental signature motivate the search for the $\Phi \to \tau\tau$ decays in the context of the MSSM.

The MSSM searches for the $\Phi \to \tau\tau$ decay performed by the ATLAS and CMS collaborations follow the same general strategy: events with a reconstructed tau lepton pair are split into two categories based on the presence or absence of a b-tagged jet to increase the sensitivity of the search. Then, the signal is extracted with a fit to the tau pair mass distribution.

The ATLAS collaboration reported results of searches with 20 fb^{-1} of data at $\sqrt{s}$ =8 TeV [19] and 3.2 fb^{-1} of data at $\sqrt{s}$ =13 TeV [20]. Despite the limited size of the latter dataset, the sensitivity of the search is improved for $m_A > 200$ GeV thanks to the increase of the pp collision energy. Results obtained by the CMS Collaboration base on 5 fb^{-1} and 20 fb^{-1} of data respectively at $\sqrt{s}$ =7 TeV and $\sqrt{s}$ =8 TeV [21,22].

No evidence of the $\Phi \to \tau\tau$ process has been found. In a result limits at 95% CL on the signal rate were set, which are then translated on exclusions limits at the m_A-$\tan\beta$ plane for a set of MSSM benchmark models, Fig 7.

6 Summary

Searches for fermionic decays of the standard model Higgs boson and measurements of its properties were reviewed. All performed tests favour the standard model Higgs boson hypothesis,

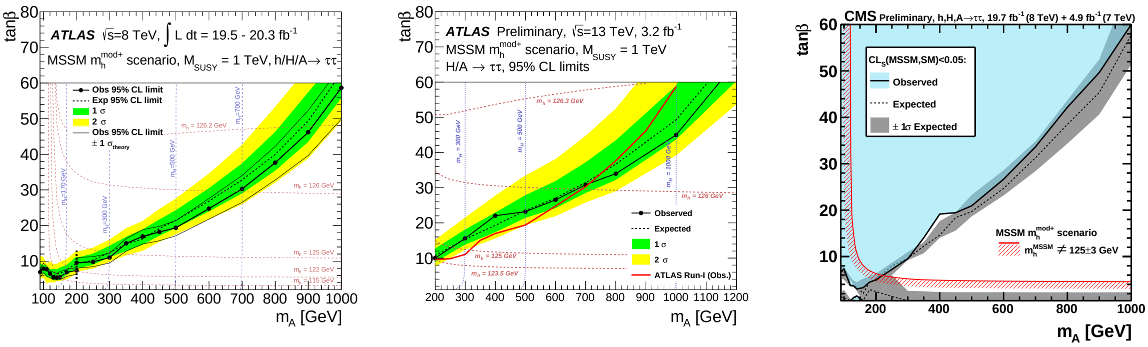

Figure 7 – Expected (dashed line) and observed (solid line) 95% CL upper limits on $\tan\beta$ as a function of $\mathrm{m_A}$ for the $\mathrm{m_h}^{mod+}$ scenario of the MSSM in ATLAS with 8 TeV data (left), in ATLAS with 13 TeV data (middle) and in CMS with 7 and 8 TeV data (right).

with production and decay rates consistent with expectation of the standard model. In particular, the $\mathrm{H} \to \tau\tau$ decay mode is observed with significance above 3σ by both the ATLAS and CMS experiments separately and above 5σ when the two results are combined.

In addition, two searches for fermionic decays of Higgs bosons predicted by beyond standard model scenarios were discussed: the search for the LFV $\mathrm{H} \to \mathrm{e}\tau, \mu\tau, \mathrm{e}\mu$ decays and the search for neutral Higgs bosons decaying to tau pairs in the context of the MSSM. Both searches give negative results which allow to constrain probed models.

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