PROCEEDINGS OF SCIENCE

Search for a Higgs boson decaying to a pair of 125 GeV Higgs bosons (*hh*) or for a Higgs boson decaying to *Zh*, with τ- leptons in the final state

Ram Krishna Dewanjee*
Tata Insitute Of Fundamental Research, Homi Bhabha Road, Colaba, Mumbai- 400005.
E-mail: ram.krishna.dewanjee@cern.ch
On behalf of CMS collaboration

A search for heavy Higgs boson (H) decaying into a pair of lighter (Standard Model like) 125 GeV Higgs bosons (h) or a Higgs boson (A) decaying into a Z boson and an h boson is presented. This search is performed on a dataset corresponding to an integrated luminosity of 19.7 fb^{-1} of pp collision data collected by CMS in 2012 at $\sqrt{s} = 8$ TeV. A final state consisting of two τ-leptons and two b-jets is used to search for the $H \rightarrow hh$ mode while a final state consisting of two τ-leptons and two additional light leptons (electrons/muons), the latter compatible with the decay products of a Z boson, is used to search for the $A \rightarrow Zh$ mode. This search is performed in the context of two benchmark scenarios: one of the minimal supersymmetric extension to the standard model and other of a two Higgs Doublet Model. No excess is found and upper limits at 95 % confidence level are set on the production cross-section in the mass range 220 GeV to 350 GeV for the Higgs boson A and 260 GeV to 350 GeV for the Higgs boson H.

The European Physical Society Conference on High Energy Physics
22–29 July 2015
Vienna, Austria

*Speaker.

PoS(EPS-HEP2015)122

1. Introduction

With the recent discovery of the Standard Model higgs boson (h) of mass around 125 GeV by the CMS [1] and the ATLAS [2] collaborations at the LHC at CERN, there have been attempts to interpret this newly discovered resonance in the context of beyond Standard Model physics scenarios. The Two Higgs Doublet Model (2HDM) is one of the simplest extensions of the Higgs sector. It predicts 5 physical higgs bosons: a heavy CP even scalar (H), a light CP even scalar (h), a pseudo scalar (A) and two charged higgs bosons ($H^{\pm}$). The Minimal SuperSymmetric Standard Model (MSSM) is a particular case of 2HDM and at the tree level its Higgs sector is completely specified by 2 parameters: pseudo scalar mass (m_A) and $\tan\beta$[1]. For high M_{SUSY} [2] (> 1TeV) and low $\tan\beta$, the decay modes $H \to hh$ (H being the heavy CP even scalar boson) and $A \to Zh$ (A being the pseudoscalar boson) have significant branching fractions in the mass range 260(220) GeV to 350 GeV where the lower bound is motivated by the kinematic thresholds for the daughters *hh(Zh)* to be produced onshell and the upper bound is due to the opening of the $t\bar{t}$ decay of the heavy Higgs bosons that becomes the dominant one when allowed.

2. CMS Detector

CMS is a general purpose particle detector[3] consisting of a superconducting solenoid (6 m internal diameter), providing a magnetic field of 3.8 Tesla. Within the solenoid volume are a silicon pixel and strip tracker, a lead tungstate crystal electromagnetic calorimeter, and a brass/scintillator hadron calorimeter, each composed of a barrel and two endcap sections. Muons are measured in gas-ionization detectors embedded in the steel flux-return yoke outside the solenoid. Extensive forward calorimetry complements the coverage of the barrel and endcap detectors. Event selection is done in 2 stages (called triggers): Level-1 (40 MHz to 100 kHz) and High Level Trigger (HLT) (100 kHz to O(100) Hz). While Level-1 is predominantly hardware oriented, HLT is software based and is implemented in a farm of about 10000 commercial processor cores.

3. Event and Object reconstruction

CMS uses Particle Flow (PF) algorithm [5] for global event reconstruction using full granularity of all the subdetectors. This algorithm reconstructs isolated leptons (muons) from the event followed by charged hadrons, electrons, photons and neutral hadrons (which are all clustered into jets using the anti-kT algorithm [6]). τ-leptons decay either leptonically (into light leptons[3] along with 2 neutrinoes) or hadronically (into a narrow jet of charged hadrons, 1 neutrino and/or neutral pions). Consequently, τ-leptons need to be identified from their decay products. While leptonic τ decay identification is similar to prompt leptons[4], hadronic τ decay identification uses a dedicated algorithm. The hadronic τ-lepton identification efficiency at CMS is 60% and the probability of a quark/light lepton to fake a τ-lepton remains within 0.1% to 1%[7].

[1] Ratio b/w the Vacuum expectation values of the 2 higgs Doublets that give mass to up and down type fermions in MSSM

[2] Breaking scale of SuperSymmetry

[3] e/μ

[4] Leptons coming directly from hard interaction vertex e.g $W \to l\nu / Z \to ll$, where l = e/μ.

To identify jets coming from b-quarks, a likelihood based algorithm is used which combines secondary vertex and track based lifetime information to compute a score that is proportional to the probability that the jet is produced by a b-quark. The CMS b-quark tagging algorithm has an efficiency of 70%. Light jets ($u/d/s$ quarks) can fake b-quark signature approximately 1% of times [8].

4. Analysis strategy and event categorization

In the $A \to Zh \to l\bar{l}\tau\bar{\tau}$ analysis, first of all a $Z \to l\bar{l}$ candidate is identified by requiring the prescence of a pair of oppositely charged electrons/muons of p_T[5] > 20 GeV(10 GeV) for the leading (subleading) lepton in the pseudorapidity range 2.5 for the electrons and 2.4 for the muons respectively. The lepton pair must also be isolated (relative isolation < 0.3), satisfy track quality cuts and must have invariant mass in the range 60 GeV-120 GeV. On top of this, a $h \to \tau\bar{\tau}$ candidate is demanded in the 4 distinct di-τ channels: $\mu\tau_h$, $e\tau_h$, $\tau_h\tau_h$ and $e\mu$ [6]. Finally a channel dependent selection, optimized to maximize the expected significance is applied to the scalar p_T sum of the τ candidates to reduce backgrounds.

In the case of the $H \to hh \to b\bar{b}\tau\bar{\tau}$ analysis, due to the presence of 2 b-quarks along with 2 τ-leptons in the final state, at least 2 jets of $p_T > 20$ GeV in the pseudorapidity range of 2.4 is required. 4 categories are then defined depending on b-tagged jet multiplicity:

1. **2jet0Tag**: None of the 2 leading jets in the event are b-tagged (least sensitive category).

2. **2jet1Tag**: The leading jet is b-tagged.

3. **2jet2Tag**: Both the leading jets are b-tagged (most sensitive category).

Besides, the di-tau invariant mass ($m_{\tau\bar{\tau}}$) is computed by a likelihood based algorithm which uses the constraint imposed by the missing transverse energy to give the best possible estimate of the true $m_{\tau\bar{\tau}}$. Additionally, mass window cuts: 90 GeV < $m_{\tau\bar{\tau}}$ < 150 GeV and 70 GeV < $m_{b\bar{b}}$ < 150 GeV are applied to the h→ $\tau\bar{\tau}$ and h→$b\bar{b}$ candidates and a kinematic fit is performed where the energies of the jets and the τ-leptons are varied within their resolutions imposing the constraint: $m_{b\bar{b}} = m_{\tau\bar{\tau}} = 125$ GeV to have better shape discrimination of signal over backgrounds. This search was performed in 3 distinct di-τ channels: $\mu\tau_h$, $e\tau_h$ and $\tau_h\tau_h$.

5. Backgrounds

The Main backgrounds for the $A \to Zh \to l\bar{l}\tau\bar{\tau}$ analysis are:

1. ***ZZ* di-boson production**: This is the dominant irreducible background and is estimated from NNLO simulation.

2. **Reducible backgrounds**: These are mainly due to Z+jets and WZ+jets. The yield is estimated using fake rate method and the shape from same sign sideband region of the 2 τ-leptons.

[5] transverse momentum

[6] here e/μ and τ_h denote leptonic and hadronic tau decays respectively

PoS(EPS-HEP2015)122

3. **Rare backgrounds**: These are due to processes like: $Z \to Zh \to l\bar{l}\tau\bar{\tau}$, $Z \to Zh \to ZW^+W^- \to l\bar{l}\tau\bar{\tau}$, Tri-boson (*WWZ/WZZ/ZZZ*) production and $t\bar{t}Z$ (where $Z \to l\bar{l}$ and $t/\bar{t} \to e/\mu/\tau$) and are estimated from simulation.

Similarly, major backgrounds for the $H \to hh \to b\bar{b}\tau\bar{\tau}$ analysis are:

1. **Drell-Yan+jets/**$Z \to \tau\bar{\tau}$: This is the dominant irreducible background in $\mu\tau_h$, $e\tau_h$ and $e\mu$ final states and is estimated in shape from $Z \to \mu\mu$ events in data from which the muons are removed and replaced by τ-leptons from simulation (Embedding).

2. **Drell-Yan+jets/**$Z \to \mu\bar{\mu}/e\bar{e}$: This background primarily arises from e$\to \tau_h$ and $\mu \to \tau_h$ fakes and is estimated (for $\mu\tau_h$ and $e\tau_h$ channels) from simulation with a correction applied according to the e$\to \tau_h$ fake rate measured in data using tag and probe.

3. **QCD Multijets**: This is the dominant background in the $\tau_h\tau_h$ channel and is estimated using a data driven method from control regions defined by di-τ charge and isolation.

4. $t\bar{t}$**+jets**: This is estimated in shape from simulation and in yield from a sideband region in data which is rich in $t\bar{t}$ events.

5. **Electroweak background**: This comprises 2 backgrounds viz. W+jets and di-boson production. The former is an important background in $\mu\tau_h$ and $e\tau_h$ final states and is caused by a jet faking a τ_h. It is modelled in shape from simulation and in normalization from a high m_T[7]region ($m_T > 70$ GeV) in data which is rich in W+jets events. The latter is estimated from simulation normalised to NLO cross sections at 8 TeV.

6. Results

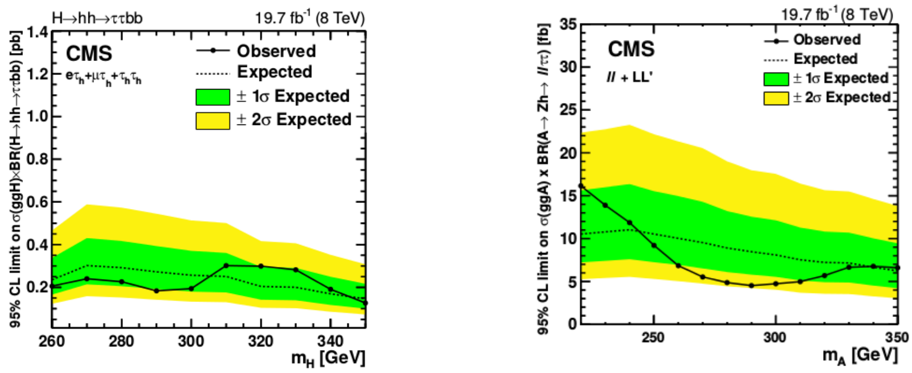
In the absence of signal, exclusion limits are set on the "cross section $\times$ branching ratio" for the signal processes. Results of the searches are interpreted in 2 different ways using a PLR (profile likelihood ratio) [8] based test statistic. These are:

1. **Model independent limits**: In this case, a narrow signal peak is searched on top of a falling background across channels and event categories. In case of absence of signal, 95% confidence level exclusion limits are obtained on the "cross section $\times$ branching ratio" for the signal process. The dependence of the signal cross section on $\tan\beta$ is ignored here (hence model independent). These are shown in **Fig. 1**.

[7]Transverse mass: $\sqrt{2p_T^{\mu}E_T(1-\cos\phi)}$, where p^{μ} = Muon p_T, E_T = missing transverse energy and ϕ is the angle b/w them.

[8]Profile likelihood ratio: $q_\mu = -2\ln\frac{L(N_{obs}|\mu.s+b,\hat{\theta}_\mu)}{L(N_{obs}|\hat{\mu}.s+b,\hat{\theta})}$, with $0 \leq \hat{\mu} \leq \mu$. Here N_{obs} is the number of observed events, b and s are expected background and signal events, μ is the signal strength modifier and θ are the nuisance parameters (systematic uncertainties). $\hat{\theta}_\mu$ maximizes q_μ for a given μ while $\hat{\mu}$ and $\hat{\theta}$ maximize it globally. $L(N|\theta)$ is the likelihood of parameter(s) θ given the outcome N.

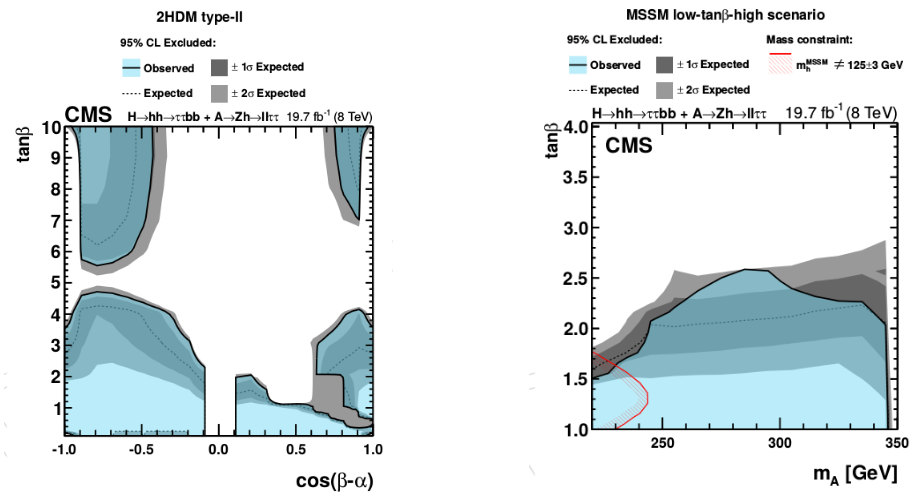
PoS(EPS-HEP2015)122



(a) (b)

Figure 1: Model independent upper limits at 95% CL on $\sigma \times B$ at 8 TeV center-of-mass energy as a function of Higgs boson mass for $H \to hh \to b\bar{b}\tau\bar{\tau}$ (a) and $A \to Zh \to l\bar{l}\tau\bar{\tau}$ (b).

2. **Model dependent limits**: Here, test of compatibility of the data to a signal due to heavy neutral higgs boson (*H/A*) decay is performed against SM background only hypothesis. 95% confidence level limits are computed in those regions of 2-dimensional phenomenological parameter space ("$\tan\beta - m_A$" plane for MSSM and "$\tan\beta - \cos(\beta - \alpha)$" plane in a generic type-II 2HDM model[9]) where $H \to hh \to b\bar{b}\tau\bar{\tau}$ and $A \to Zh \to l\bar{l}\tau\bar{\tau}$ channels are significant. These are shown in **Fig. 2**. It should be noted that for the case of 2HDM, in the alignment/decoupling regime (when $\cos(\beta - \alpha) << 1$ where α is the mixing angle between two neutral scalar fields), the lightest Higgs becomes exactly Standard Model like and the $H \to hh$ and $A \to Zh$ couplings vanish[4] (**Fig. 2(a)**). In the MSSM however, they do not vanish due to large radiative corrections and in the decoupling regime, for large mass of H, the $H \to t\bar{t}$ channel opens up and dominates.



(a) (b)

Figure 2: Model dependent limits at 95% CL in the 2-dimensional parameter space of type-II 2HDM (a) and MSSM (b).

7. Conclusions

A search for Neutral Heavy Higgs bosons (*A/H*) in the $H \to hh \to b\bar{b}\tau\bar{\tau}$ and $A \to Zh \to l\bar{l}\tau\bar{\tau}$ channels using Run-1 luminosity at $\sqrt{s} = 8$ TeV was performed. No evidence of signal is observed and exclusion limits have been set on the cross section $\times$ branching ratio of the signal processes in both model dependent and model independent ways.

References

[1] 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, doi:10.1016/j.physletb.2012.08.021.*

[2] 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. B716 (2012) 1-29, doi:10.1016/j.physletb.2012.08.020.*

[3] CMS collaboration, *The CMS experiment at the CERN LHC, 2008 JINST 3 S08004.*

[4] D. Asner et al., ILC Higgs White Paper, arXiv:1310.0763.

[5] CMS Collaboration, *Particle-Flow Event Reconstruction in CMS and Performance for jets, Taus, and Missing ET, CMS PAS PFT-09-001 (2009).*

[6] The anti-kt jet clustering algorithm, *http://arxiv.org/abs/0802.1189*

[7] CMS Collaboration, *Performance of tau-lepton reconstruction and identification in CMS, JINST 7 (2012) P01001, doi:10.1088/1748-0221/7/01/P01001, arXiv:1109.6034.*

[8] CMS collaboration, *Identification of b-quark jets with the CMS experiment, 2013 JINST 8 P04013 [arXiv:1211.4462].*

[9] A. Djouadi et al., The post-Higgs MSSM scenario: Habemus MSSM?, arXiv:1307.5205v1.

[10] MSSM H->hh/A->Zh in tau channels, CMS CADI HIG-14-034

PoS(EPS-HEP2015)122