Higgs Boson in Lepton Decay Modes at the CMS Experiment

Somnath Choudhury[1] for the CMS collaboration
[1]DESY - Hamburg, Germany

DOI: http://dx.doi.org/10.3204/DESY-PROC-2014-04/120

The results on the standard model Higgs boson in lepton decay channels with tau pair and muon pair final states using 25 fb^{-1} of pp collision data at 7 and 8 TeV center-of-mass energies collected by the CMS detector at the LHC has been summarized. A direct evidence of the Higgs-lepton coupling is established with the tau pair decay mode. Searches for Higgs bosons decaying to leptons in scenarios beyond the standard model such as supersymmetry within the minimal extension of the model has also been reported.

1 Introduction

The ATLAS and CMS collaborations in July 2012 came out with the observation of a Higgs boson [1, 2] using proton-proton collision data from the LHC at CERN corresponding to integrated luminosities of around 5 fb^{-1} at 7 TeV and 5 fb^{-1} at 8 TeV center-of-mass energies. The LHC has completed its first run with the detectors having recorded about 95% of delivered collision data, among which about 90% were certified and used to obtain the results reported here. The final analysis is based on integrated luminosity of 20 fb^{-1} at 8 TeV in addition to the 5 fb^{-1} at 7 TeV collected by the CMS detector [3]. The observation of a Higgs boson around mass of 125 GeV in the high resolution boson decay channels motivates the search in major fermion decay modes as decays of the Higgs boson to tau pairs and bottom quark pairs have significantly large branching fraction in this mass regime. The 125 GeV Higgs boson opens an interesting avenue for its decays to fermions as this would provide an effective handle for the measurement of the Higgs coupling to fermions. The Higgs boson suffers from quadratically divergent self-energy corrections at high energies. Numerous extensions to the standard model (SM) have been proposed to address these divergences one of which is supersymmetry, a symmetry between fundamental bosons and fermions, which results in cancellation of the divergences. The Minimal Supersymmetric extension of the standard model (MSSM), outlays the introduction of 2 Higgs doublets leading to 5 physical Higgs bosons after electroweak symmetry breaking, where, h and H are the CP-even scalar bosons, A is the CP-odd pseudoscalar boson and H^+ and H^- are the charged bosons. If the discovered Higgs boson is the low mass Higgs within MSSM, then the search for its heavy partners gains a lot of interest in tau pair decay which has a branching fraction around 10% enhanced at all masses.

The CMS detector plays a crucial role in robustly identifying individual particles in the collision events. The detector subsystems employed for the analysis are the pixel detector and the silicon tracker forming the innermost component of the detector followed by the electromagnetic calorimeter of lead tungstate crystals and hadronic calorimeter of brass / scintillator

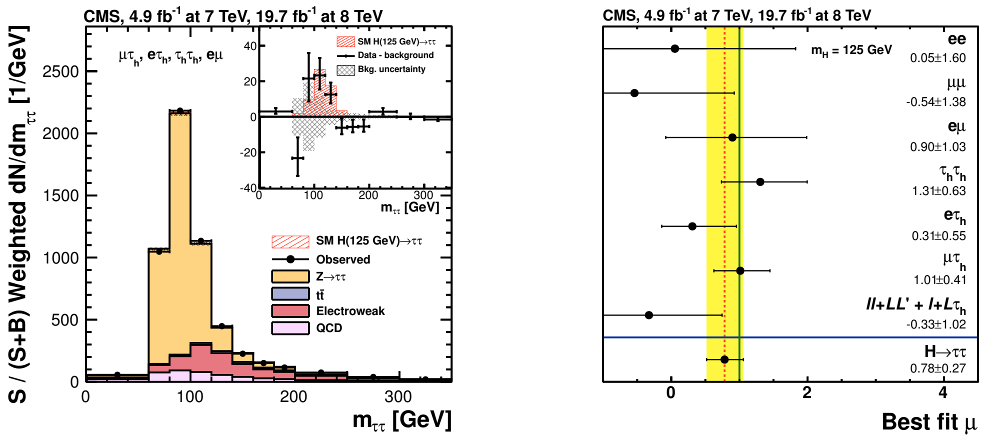

Figure 1: The di-tau invariant mass distribution combining all categories (on left) and the signal strength with respect to SM expectation in different di-tau decay channels and result of the combination (on right).

samplers which is enveloped by the 3.8 T superconducting solenoid. Outside the solenoid are the muon chambers which are gas ionization detectors in steel return yoke composed of cathode strip chambers, resistive plates and drift tubes. For the physics object reconstruction in a collision event, CMS uniquely employs a particle flow technique which provides event description in the form of mutually exclusive particles identifying all stable particles produced in the event by combining the capabilities of each sub-detector with the most precise measurement of the energy and direction for each particle and then individual measurements from each sub-detector are combined by a geometrical linking alogorithm providing particle identification on blocks of these linked elements. The experiment had to establish methods to cope with a high number of multiple collisions per beam crossing (pileup), which occurs at high luminosity. The average number of pileup events is about 9 and 21 interactions in the years 2011 and 2012 respectively. The successful mitigation of pileup was demonstrated and an almost uniform response of the missing transverse energy resolution as a function of the number of primary vertices in the event is achieved. The SM Higgs boson analysis utilises the major Higgs boson production mechanisms in pp collisions in order of decreasing cross-sections namely gluon fusion, vector boson fusion (VBF) and associated production with vector bosons (VH). The MSSM Higgs bosons search utilises the production in gluon fusion and in association with bottom quarks or in bottom quark fusion.

2 Higgs to Taus

The SM H$\to\tau\tau$ search [4] is performed using all possible decays in fully leptonic, semi-leptonic and fully hadronic states using the final-state signatures eμ, $\mu\mu$, ee, eτ_h, $\mu\tau_h$ and $\tau_h\tau_h$, where electrons and muons arise from leptonic τ-decays and τ_h denotes hadronic tau lepton decays. To enhance the sensitivity of the search, each of these categories is further divided into three exclusive sub-categories according to the nature of the associated jets in the event. The gluon-

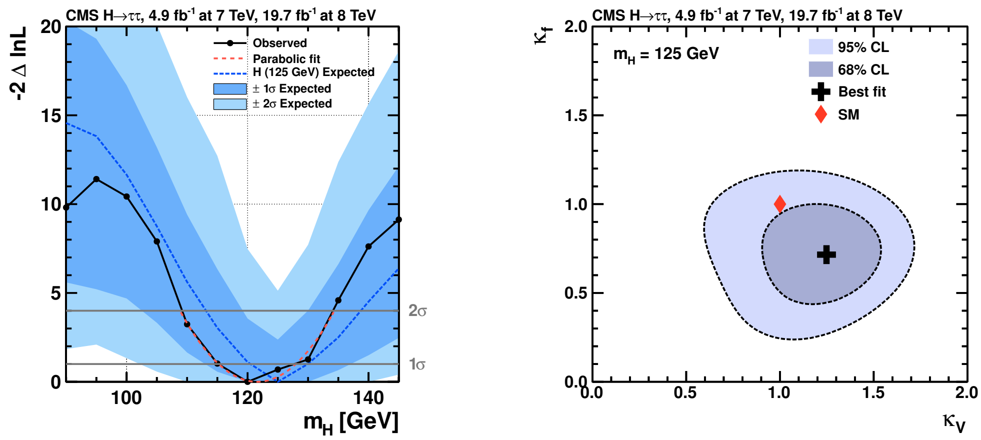

Figure 2: The measured mass from log-likelihood scan in the di-tau channel (on left) and the 2-D scan of couplings to vector bosons and fermions scaled to the SM expectation (on right).

fusion production mechanism has the largest production cross section. However, in the mass region of interest, background from Drell–Yan production of tau pairs overwhelms the expected Higgs boson signal. This search therefore relies strongly upon the signature of Higgs bosons produced via vector boson fusion (VBF) or in association with a high transverse momentum (p_T) jet recoiling against the tau pair. In the former case, the distinct topology of two jets with a large rapidity separation greatly reduces the background. In the latter, requiring a high-p_T jet both suppresses background, and improves the resolution of the tau-pair invariant mass. The search has been categorized into 0-jet, 1-jet and 2-jet VBF categories to extract the signal which are further split on the basis of hadronic tau p_T and di-tau p_T for 0 and 1 jet categories or di-tau p_T, di-jet invariant mass and di-jet pseudorapidity separation for 2-jet category. The 0-jet category constrains the background normalization, identification efficiencies and energy scales, the 1-jet category improves the resolution of Higgs boson mass and the VBF category has high signal over background ratio. The analysis is also performed in the VH category with lepton tagging from vector bosons along with the tau lepton pair.

To distinguish the Higgs boson signal from the background, the tau-pair mass is reconstructed using a maximum likelihood technique. The algorithm estimates the original momentum components of the two taus by maximizing a likelihood with respect to free parameters corresponding to the missing neutrino momenta, subject to kinematic constraints. Other terms in the likelihood take into account the tau-decay phase space and the probability density in the tau transverse momentum, parametrized as a function of the tau-pair mass. This algorithm yields a tau-pair mass with a mean consistent with the true value, and distribution with a nearly Gaussian shape. The relative $m_{\tau\tau}$ mass resolution estimated from simulation is 10–20% depending on the di-tau decay channel and category. The likelihood based mass reconstruction allows for a better separation between simulated 125 GeV Higgs signal and Z$\rightarrow \tau\tau$ background than the visible mass alone, yielding an improvement in the final expected significance of 40%.

In each of these categories, a search is performed for an excess of events in the reconstructed di-tau invariant mass distribution. The largest source of irreducible background is Z$\rightarrow \tau\tau$ which is estimated using an observed sample of Z$\rightarrow \mu\mu$ events, where the reconstructed muons are

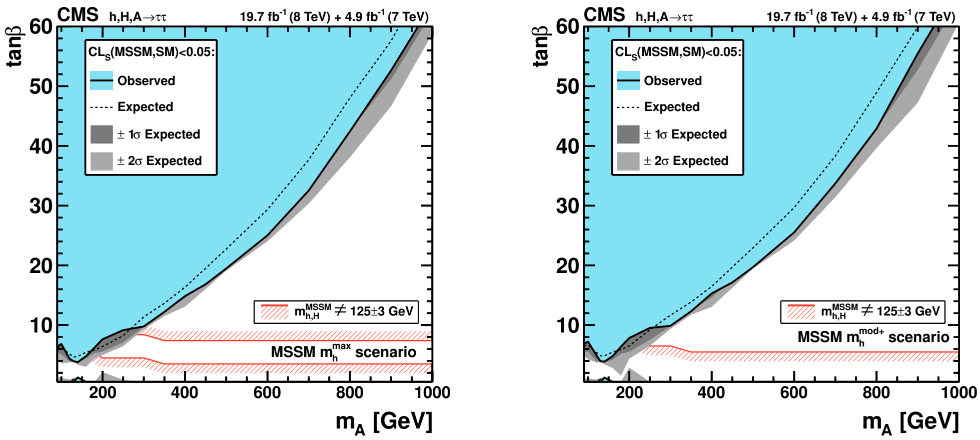

Figure 3: Region in the parameter space of tanβ versus m_A excluded at 95% CL in the context of the MSSM maximal mixing scenario (on left) and a modified mixing $m_h{}^{mod+}$ benchmark scenario (on right). The expected one- and two- standard deviation ranges and the mean expected 95% CL upper limits are shown together with the observed excluded region.

replaced by the reconstructed particles from simulated tau decays, a procedure called "embedding". The normalization for this process is determined from the measurement of the CMS measured cross section. The reducible backgrounds (W + jets, multijet production, Z + jets) are also evaluated from control samples in data. The QCD multijet background is evaluated using the ratio of opposite-sign (OS) to same-sign (SS) di-tau events and relaxed lepton isolation after an estimate of the W + jets background using the high transverse mass ($m_T{}^{\ell E_T^{miss}}$) side-band W boson enriched region and extrapolating it to the signal region. The Z + jets background is evaluated from fake rate and OS/SS ratio with the shape from simulation. The top pair produced events and diboson contribution are estimated using simulation.

Combining all event categories, a broad excess of events is observed in the tau pair invariant mass distribution as seen in Figure 1 over a range of the Higgs boson mass consistent with the 125 GeV scalar boson observed in the high resolution boson decay channels. The observed (expected) significance of the excess at Higgs boson mass of 125 GeV is 3.2σ (3.7σ). The best-fit value of the signal strength is μ=0.78$\pm$0.27, obtained in the global fit combining all channels included in this analysis where the H$\to$WW process has been added as a background for the observed process. This result provides the first direct indication of the Higgs boson coupling to leptons. The mass of the Higgs boson measured in this channel is 122$\pm$7 GeV from a parabolic fit of the log-likelihood scan of the observed mass points in data shown in Figure 2. The measured couplings of the Higgs boson to vector bosons and fermions scaled with respect to SM, shows consistency within around one standard deviations from SM predictions where the H$\to$WW process has been added as a signal for this measurement.

A Higgs-like state at 125 GeV is rather large for the light MSSM Higgs boson which can be achieved by maximizing the radiative corrections to Higgs mass at 1-loop level. The tau-pair decays of the neutral Higgs bosons in the MSSM, having a branching fraction of roughly 10%, serve as the best experimental signature for this search. The $b\bar{b}$ mode, though it has a much larger branching fraction, suffers from an overwhelming background from multi-jet production.

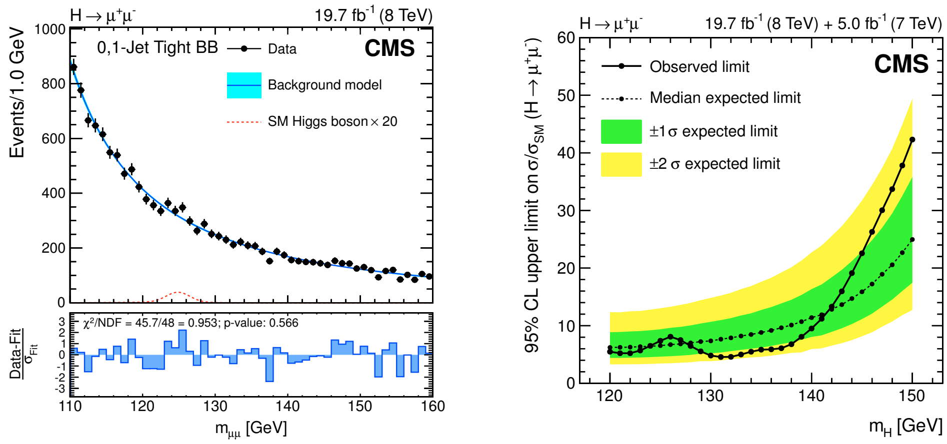

Figure 4: The di-muon invariant mass distribution combining all categories (on left) and 95% CL upper limits on cross section times the branching ratio normalized to the SM expectation as a function of Higgs boson mass (on right).

The MSSM Higgs bosons search [5] is performed using the di-tau final-state signatures eμ, $\mu\mu$, eτ_h, $\mu\tau_h$ and $\tau_h\tau_h$. The τ_h decay modes considered for the analysis are a single charged hadron, a charged hadron with neutral pion via the $\rho(770)$ resonance and three charged hadrons via the a_1 resonance. The data sample has been divided on the b-jet multiplicity into b-tag and non b-tag categories to enhance the sensitivity to bbΦ coupling:

• b-Tag category: At most one jet with p_T>30 GeV and at least one b-tagged jet with p_T>20 GeV.

• Non b-Tag category: At most one jet with p_T>30 GeV and no b-tagged jet with p_T> 20 GeV.

The di-tau invariant mass spectrum shows no evidence for a Higgs boson signal and hence 95% confidence level (CL) upper bound on the Higgs boson production cross-section times the branching fraction to tau pairs have been set using the mass shape of the tau pair mass spectrum and uncertainties from theory (parton distribution function and renormalization / factorization), normalization (luminosity and efficiency) and shape (energy scale). These limits are further interpreted in the MSSM parameter space on the m_A-tanβ plane as shown in Figure 3 in the maximal mixing scenario of the stop-top sector with a soft SUSY breaking mass of 1 TeV as the stop mass scale as well as a modified m_h mixing benchmark scenario [6]. It excludes all previously unexplored regions reaching as low as tanβ = 3.9 for mass of the pseudoscalar Higgs boson m_A=140 GeV.

3 Higgs to Muons

One of the properties of the Higgs boson that has to be checked is the couplings to first and second generation leptons. Indeed, the SM Higgs decays to fermions should not be universal. A search for H→ $\mu\mu$ [7] is performed with at total luminosity of the 7 and 8 TeV dataset from Run-1 LHC. In the SM, the decay H→ $\mu\mu$ presents a vary small branching ratio of 2.2x10^{-4} at m_H = 125 GeV. However, the search takes advantage of the clean signature in the detector and the excellent di-muon invariant mass resolution. The gluon fusion and VBF production modes are utilized by the jet multiplicity of events in the final state. In addition, events are split into categories according to the p_T of the di-muon system, the properties of jets in the 2-jet category, and according to the detector regions (barrel, endcap, overlap regions) in which the two muons are reconstructed. The latter make use of the different experimental resolutions of the reconstructed di-muon mass for muons from different detector regions. The signal is extracted by means of a fit to the di-muon invariant mass distribution using signal and background shapes. The combined di-muon mass distribution is shown in Figure 4, weighted for the ratio of the signal and signal-plus-background distributions in the dfferent event categories. The background distribution is estimated using an analytic fit function, and, amongst others, systematic uncertainties are estimated by modifying the used fit function. Upper limits on the cross section times H$\rightarrow \mu\mu$ branching ratio have been derived and the observed (expected) limit is found to be 7.4 (5.1) times the SM prediction. The observed significance at 125 GeV is 1.1σ and no significant excess of events is expected in this channel at the Run-1 LHC luminosity.

4 Conclusion

A broad excess of events is observed for the SM Higgs boson search in the tau pair decay mode consistent with the 125 GeV Higgs boson signal from high resolution boson decay modes ($\gamma\gamma$ and $ZZ^\star\rightarrow 4\ell$) providing the first direct indication of the Higgs boson coupling to leptons. Combining tau pair and bottom quark pair decay modes, the significance for Higgs boson decay to fermions at 125 GeV is more than 3σ showing the first direct evidence of Higgs-fermion coupling [8] at the LHC. The mass of the Higgs boson measured in the di-tau channel is 122$\pm$7 GeV from a parabolic fit of the likelihood scan of the Higgs mass. The results on the SM Higgs boson in di-tau and di-muon decays reveal lepton non-universality. The search for MSSM Higgs bosons in tau pair decay has set stringent bounds in the m_A-tanβ plane with different MSSM benchmark scenarios tested and reaching as low as tanβ=3.9 at m_A=140 GeV at a modified mixing scenario consistent with the observed Higgs boson at 125 GeV. In the Run-2 LHC, the measurement of properties of the Higgs-like state in tau decay would continue looking for deviations from SM as well as searches for Higgs bosons beyond the SM in lepton decays.

References

[1] The ATLAS Collaboration, Phys. Lett. **B 716** 1 (2012).

[2] The CMS Collaboration, Phys. Lett. **B 716** 30 (2012).

[3] The CMS Collaboration, JINST **3** S08004 (2008).

[4] The CMS Collaboration, JHEP **05** 104 (2014) and all references therein.

[5] The CMS Collaboration, arXiv: 1408.3316 [hep-ex] and all references therein.

[6] M. Carena et. al., Eur.Phys.J. **C73** 2552 (2013).

[7] The CMS Collaboration, CMS-PAS-HIG-13-007 and all references therein.

[8] The CMS Collaboration, Nat. Phys. **10**, 557 (2014) and all references therein.