PROCEEDINGS OF SCIENCE

Search for low-mass Higgs bosons at CMS experiment at LHC

Abdollah Mohammadi* **for the CMS collaboration**
Kansas State University
E-mail: abdollah.mohammadi@cern.ch

Two searches are performed for light Higgs bosons, one for production of the light pseudoscalar Higgs boson in association with a $b\bar{b}$ pair and decaying to a pair of τ leptons, and the other for the pair production of new light bosons, each decaying into a pair of muons. The results are based on pp collision data at a centre-of-mass energy of 8 TeV collected by the CMS experiment at the LHC and corresponding to an integrated luminosity up to 20.7 fb^{-1}. No excess of events is observed on top of the standard model background expectation and upper limits are set on the production cross section of the new boson times branching fraction to the lepton pairs.

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*Speaker.

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1. Introduction

The discovery of a new boson with a mass close to 125GeV [1, 2], consistent with the standard model (SM) Higgs boson, is a major triumph of the SM. Although this discovery reveals an important question in particle physics, which is the origin of the mass, SM cannot address several crucial issues such as the hierarchy problem, the origin of the matter-antimatter asymmetry and the nature of dark matter. Theories predicting new physics beyond the SM have been proposed to address these open questions. Many of them predict the existence of more than one Higgs boson.

Two-Higgs-doublet models (2HDM) are the most generic extension of the SM. Starting with the two doublet fields Φ_1 and Φ_2 and assuming an absence of CP violation in the Higgs sector, after $SU(2)_L$ symmetry breaking five physical states are left: two CP-even (h and H), one CP-odd (A), and two charged ($H^\pm$) bosons. In the exact Z_2 symmetry limit, the Higgs sector of a 2HDM can be described by six parameters: four Higgs boson masses (m_h, m_H, m_A, and $m_{H^\pm}$), the ratio of the vacuum expectation values of the two doublets ($\tan\beta \equiv v_2/v_1$) and the mixing angle α of the two neutral CP-even Higgs states. It has been shown that in some regions of the parameter space of different types of the 2HDMs, light pseudoscalar Higgs boson with large cross section, between 10 and 100 pb, might exist, even after imposing all the constraints from LEP, Tevatron, and LHC data [3]. The cross section depends on whether the coupling of the SM-like Higgs boson to down-type fermions is SM-like or negative ("wrong-sign" Yukawa coupling). The first analysis presented in this report shows a search for a low-mass pseudoscalar Higgs boson produced in association with a $b\bar{b}$ pair and decaying to a pair of τ leptons.The τ leptons are reconstructed via their muon, electron and hadronic decays. The invariant mass distributions of the τ pairs in all three channels are used to set limits on the cross section times branching fraction of such pseudoscalar bosons with masses between 25 and 80 GeV [4].

In the NMSSM which is the extension of the minimal supersymmetric standard model (MSSM), i.e. by adding a singlet field to the two Higgs doublets, seven physical Higgs bosons are predicted: three CP-even neutral Higgs bosons $h_{1,2,3}$, two CP-odd neutral Higgs bosons $a_{1,2}$ and a pair of charged Higgs bosons $H^\pm$. The h_1 and h_2 can decay to a pair of pseudoscalar a_1 bosons, where either the h_1 or h_2 can be the SM-like Higgs boson. The a_1 boson can be light and couple weakly to SM particles with a coupling to fermions proportional to the fermion mass. Therefore it can have a substantial branching fraction $\mathscr{B}(a_1 \to \mu^+\mu^-)$ if its mass is within the range $2m_\mu < m_{a_1} < 2m_\tau$. The second analysis reported here, shows a search for the pair production of the light pseudoscalar Higgs boson into two dimuon pairs [5]

2. CMS detector and event reconstruction

The central feature of the CMS apparatus is a superconducting solenoid of 6 m internal diameter, providing a magnetic field of 3.8 T. Within the superconducting solenoid volume are a silicon pixel and strip tracker, a lead tungstate crystal electromagnetic calorimeter (ECAL), and a brass and scintillator hadron calorimeter (HCAL), each composed of a barrel and two endcap sections. Muons are detected in gas-ionization detectors embedded in the steel flux-return yoke outside the solenoid. Extensive forward calorimetry complements the coverage provided by the barrel and endcap detectors. A detailed description of the CMS detector, together with a definition of the coordinate system used and the relevant kinematic variables, can be found in Ref. [6].

The event reconstruction follows the particle-flow (PF) algorithm, which aims at exploiting all the information from all subdetectors to identify individual particles, such as charged hadrons, neutral hadrons, muons, electrons, or photons. Complex objects, such as taus, jets and missing transverse energy, are reconstructed from these individual particles.

Muon reconstruction starts from matching the silicon tracker tracks to standalone-muon tracks (tracks from muon spectrometer). A global muon track is fitted combining hits from the tracker tracks and standalone-muon tracks. Several quality requirements are applied on muon track and muon impact parameter to distinguish real prompt muons from spurious muons or muons coming from cosmic rays. Additionally, muons are required to pass isolation criteria to separate the prompt muons from those coming within a jet, usually from the semi-leptonic decay of heavy quarks.

Electron reconstruction starts from ECAL superclusters, which are groups of one or more associated clusters of energy deposit in the ECAL. Superclusters are matched to track seeds in the inner tracker layers and electron tracks are built from those. Electron identification is based on a multivariate technique Boosted Decision Tree (BDT) to discriminate real electrons from jets being misidentified as electrons. Similar to muons, isolation criterion is used to select the real prompt electrons from the ones within a jet.

The Hadron Plus Strips (HPS) algorithm is used to reconstruct the hadronic decays of taus. It starts from a jet and searches for tau lepton decay candidates produced by any of the hadronic decay modes of the tau lepton. Taus decay hadronically either directly to one charged hadron or indirectly via intermediate ρ and a1 mesons to one charged hadron plus one to two neutral pions and three charged hadrons and always accompanied by a neutrino. In most tau decays to charged hadrons, some neutral pions are produced and decay instantly to a pair of photons. The HPS algorithm takes into account the possible conversion of photons into e^+e^- pairs in material in front of the ECAL, and their corresponding bremsstrahlung in the magnetic field that consequent broadening of the distribution of the shower.Taus are required to satisfy the isolation criteria and not to be matched to electrons and muons to reduce electron and muon mis-identification rates, respectively.

PF jets are reconstructed using the anti-kt algorithm with a cone size of 0.5. Several corrections are applied to the jet energy to reduce the pileup (multiple interaction per bunch crossing) effect. Jets originating from a b-quark (b-jets) are identified with the Combined Secondary Vertex (CSV) algorithm, which is based on a likelihood technique and exploits all known parameters to distinguish b-jets from jets not originating from b-quarks such as impact parameter significance, presence of a secondary vertex and jet kinematics.

Finally, missing transverse energy, $\vec{E}_T^{miss}$, is defined as the negative of the vector sum of the transverse momenta of all final state particles reconstructed in the detector.

3. Light pseudoscalar Higgs boson decaying to a pair of τ leptons

A search is performed for a low-mass pseudoscalar Higgs boson produced in association with a $b\bar{b}$ pair and decaying to a pair of τ leptons. Associated production of the A boson with a $b\bar{b}$ pair has the advantage of the higher signal over background ratio compared to the gluon-gluon fusion production. The analysis is done in three di-τ final state $\mu\tau_h$, $e\tau_h$, and $e\mu$. Events are selected based on the requirement on presence of a muon(electron) of 20(24) GeV for $\mu\tau_h(e\tau_h)$ channels. Leptons are required to pass identification and isolation criteria. In both channels, τ leptons must have p_T greater than 20 GeV and are required to be isolated. Leptons and τ_h candidates are required to be separated by $\Delta R = \sqrt{\Delta\eta^2 + \Delta\phi^2} > 0.5$. In $e\mu$ channel, events are required to have either a muon with $p_T >$ 18 GeV and an electron with p_T 10 GeV, or a muon with $p_T >$ 10 GeV and an electron with $p_T >$ 20 GeV. Leptons are required to pass identification and isolation criteria. Events having additional identified and isolated leptons are vetoed in all channels. Further requirements on lepton transverse mass in $\mu\tau_h$ and $e\tau_h$ channels, and dilepton transverse mass and P_ζ as defined in [4] in $e\mu$ channel, are imposed to suppress W+jets and $t\bar{t}$ backgrounds. In addition to the above selections, events in all channels are also required to have at least one b-tagged jet with $p_T >$ 20 GeV.

Several types of background are present in these channels. The main background including multijet QCD and W+jets events have been estimated from data from some control regions for $\mu\tau_h$ and $e\tau_h$ channels and from lepton misidentification rate method in $e\mu$ channel. The other main background in all three channels is $Z/\gamma^* \to \tau\tau$ which is modelled using "embedded" technique. In this technique, $Z \to \mu\mu$ events are selected in data and the reconstructed muons are replaced by simulated tau leptons that are subsequently decayed.The $t\bar{t}$ background is estimated from simulation and normalised to the most precise measurement of the $t\bar{t}$ cross section. Single top quark, diboson (WW, WZ, ZZ), and SM Higgs backgrounds represent a small fraction of the total background, and are taken from simulations and normalised to the next-to-leading order cross sections

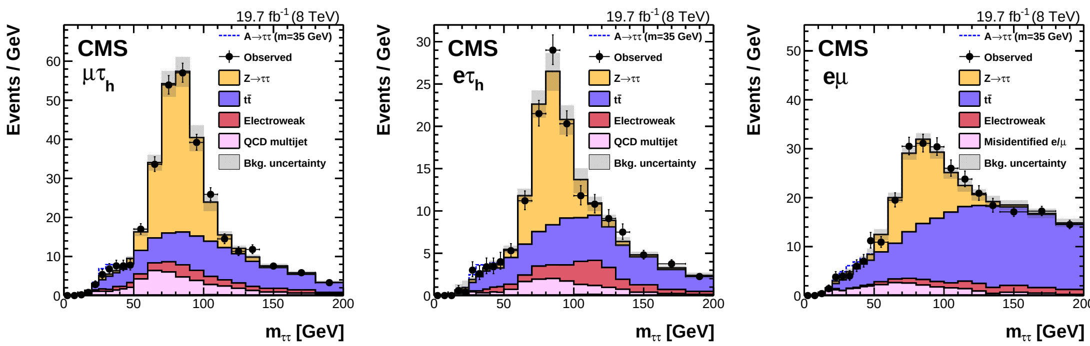

Figure 1: Observed and predicted $m_{\tau\tau}$ distributions in the $\mu\tau_h$ (left), $e\tau_h$ (middle), and $e\mu$ (right) channels. A signal for a mass of $m_A = 35$ GeV is shown for a cross section of 40 pb.

The mass distributions for the three channels are shown in Fig. 1. No significant excess of events of data is observed on top of the SM backgrounds. A binned maximum likelihood fit has been applied simultaneously to all three distributions. The upper limits from the combination of all final states are presented in Fig. 2. They range from 7 to 39 pb for A boson masses between 25 and 80 GeV. In addition, superimposed in Fig. 2 are several typical production cross sections for the pseudoscalar Higgs boson produced in association with a pair of b quarks in Type II 2HDM, for m_A less than half of the 125 GeV Higgs boson (h), and for $\mathscr{B}(h \to AA) < 0.3$ [3]. The points are obtained from a series of scans in the 2HDM parameter space. Points with small $\tan\beta$ represent the models with SM-like Yukawa coupling and points with $\tan\beta > 5$ represent the models with 'wrong sign" Yukawa coupling. While the combined results of the current analysis are not sensitive to the SM-like Yukawa coupling, they exclude the “wrong sign" Yukawa coupling for almost the entire mass range.

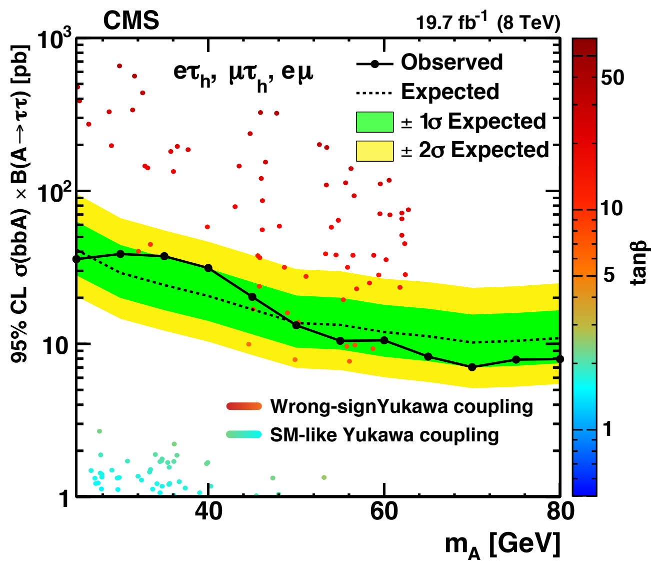

Figure 2: Expected cross sections for Type II 2HDM, superimposed on the expected and observed combined limits from this search. Cyan and green points, indicating small values of $\tan\beta$ as shown in the colour scale and correspond to models with SM-like Yukawa coupling, while red and orange points, with large $\tan\beta$ correspond to the models with “wrong sign" Yukawa coupling.

4. Pair production of light bosons decaying into muons

A search for the pair production of new light bosons, each decaying into a pair of muons is done. Events are selected by requiring at least four muon candidates with $p_T > 8$ GeV where at least on of the muons should has $p_T > 17$ GeV. Each two muons are grouped into a pair of muons provided that have opposite electric charge and consistent with arising from the same vertex. Each dimuon pair is required to be isolated from other event activity. The invariant mass $m_{1\mu\mu}$ refers to the dimuon containing a muon with $p_T > 17$ GeV.

The SM background for this search is dominated by $b\bar{b}$ production. The leading part of the $b\bar{b}$ contribution is due to b quark decays that result in a pair of muons, via either the semileptonic decays of both the b quark and the resulting c quark, or via resonances, i.e. ω, ρ, ϕ, J/ψ. A smaller contribution comes from events with one genuine dimuon candidate and a second dimuon candidate containing one muon from a semileptonic b quark decay and a charged hadron misidentified as another muon. Using data control samples, the $b\bar{b}$ background is modeled as a two-dimensional template $B_{b\bar{b}}(m_{1\mu\mu}, m_{2\mu\mu})$ in the plane of the invariant masses of the two dimuons. The data events that satisfy all analysis selections but fail the $m_{1\mu\mu} \simeq m_{2\mu\mu}$ requirement are used to aquire the $B_{b\bar{b}}(m_{1\mu\mu}, m_{2\mu\mu})$ normalization.

Direct J/ψ pair production is the other source of background and is estimated from data by requiring at least four muons with p_T> 3.5 GeV which form dimuon pairs and their invariant mass to be consistent with that of the J/ψ particle (between 2.8 and 3.3 GeV). No requirement on isolation is applied on the muon pairs. Following these requirements the data sample consists of events containing prompt and nonprompt J/ψ. To subtract the nonprompt component, the control sample is divided to four non-overlapping regions where in each region the muons pairs either pass or fail the isolation requirement. The number of events in which both dimuons satisfy the requirement is extrapolated from the regions in which at least one of the dimuons fails isolation. The contribution from other SM processes (low mass Drell–Yan production and pp $\rightarrow Z\gamma^* \rightarrow 4\mu$) is small and estimated from simulation.

After the full selection is applied to the data sample, one event is observed in the diagonal signal region which is consistent with 2.2 ± 0.7 expected background contribution, as shown in Fig. 3.

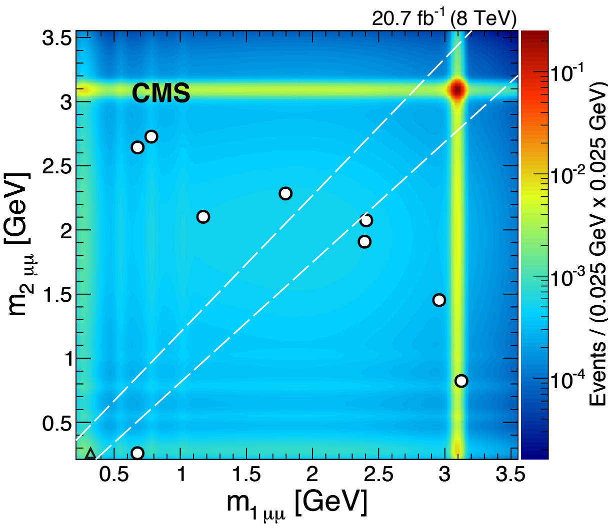

Figure 3: Distribution of the invariant masses $m_{1\mu\mu}$ vs. $m_{2\mu\mu}$ for the isolated dimuon events. Nine data events, shown as white circles in the non-diogonal mass region and one data event, shown as a black triangle, in diagonal signal region are observed.

Results of this analysis have been interpreted in the context of 2 models, NMSSM and dark SUSY. In the case of NMSSM benchmark scenario, the production cross section times branching fractions for h_1 and h_2 can be different and depend on the selected parameters. In this model it is typical than one of the h boson has a cross section close to that of SM with small branching fraction to a pair of pseudoscalar a bosons while the other has a suprresed cross section and large branching fraction to a pair of pseudoscalar a bosons, due to the its large singlet fraction. Left plot in Fig. 4 shows the 95% CL upper limits for the NMSSM scenarios on $\sigma(\mathrm{pp} \rightarrow \mathrm{h}_{1/2} \rightarrow 2\mathrm{a}_1)\mathscr{B}^2(\mathrm{a}_1 \rightarrow 2\mu)$ as a function of m_{h_1} in the range $86 < m_{\mathrm{h}_1} < 125$ GeV and of m_{h_2} for $m_{\mathrm{h}_2} > 125$ GeV for different values of the m_{a_1}: 0.25 GeV (dashed curve), 2 GeV (dash-dotted curve), and 3.55 GeV (dotted curve).The limits are also compared to the predicted rate (solid curve) obtained using a simplified scenario with $\sigma(\mathrm{pp} \rightarrow \mathrm{h}_i \rightarrow 2a_1) = 0.008\,\sigma_{\mathrm{SM}}$, which yields predictions for the rates of dimuon pair events comparable to the obtained experimental limits, and $\mathscr{B}(\mathrm{a}_1 \to 2\mu) = 7.7\%$. In the case of the dark SUSY scenario, limit is set on the production cross section times branching fractions of the Higgs boson decay to a pair of dark photons in the $(\mathrm{m}_{\gamma\,D}, \varepsilon)$ plane, where ε is the kinetic mixing parameter. Dark photon life time is directly relative to its mass and ε via $\tau_{\gamma_\mathrm{D}}(\varepsilon, \mathrm{m}_{\gamma_\mathrm{D}}) = \varepsilon^{-2} f(\mathrm{m}_{\gamma_\mathrm{D}})$, where $f(\mathrm{m}_{\gamma_\mathrm{D}})$ is a function that depends only on the mass of the dark photon. Right plot in Fig. 4 shows 95% CL upper limits (black solid curves) from this search on $\sigma(\mathrm{pp} \to \mathrm{h} \to 2\gamma_\mathrm{D} + X)\mathscr{B}(\mathrm{h} \to 2\gamma_\mathrm{D} + X)$ in the plane of two of the parameters (ε and $\mathrm{m}_{\gamma_\mathrm{D}}$) for the dark SUSY scenarios, along with constraints from other experiments showing the 90% CL exclusion contours. The colored contours represent different values of $\mathscr{B}(\mathrm{h} \to 2\gamma_\mathrm{D} + X)$ in the range 0.1–40%

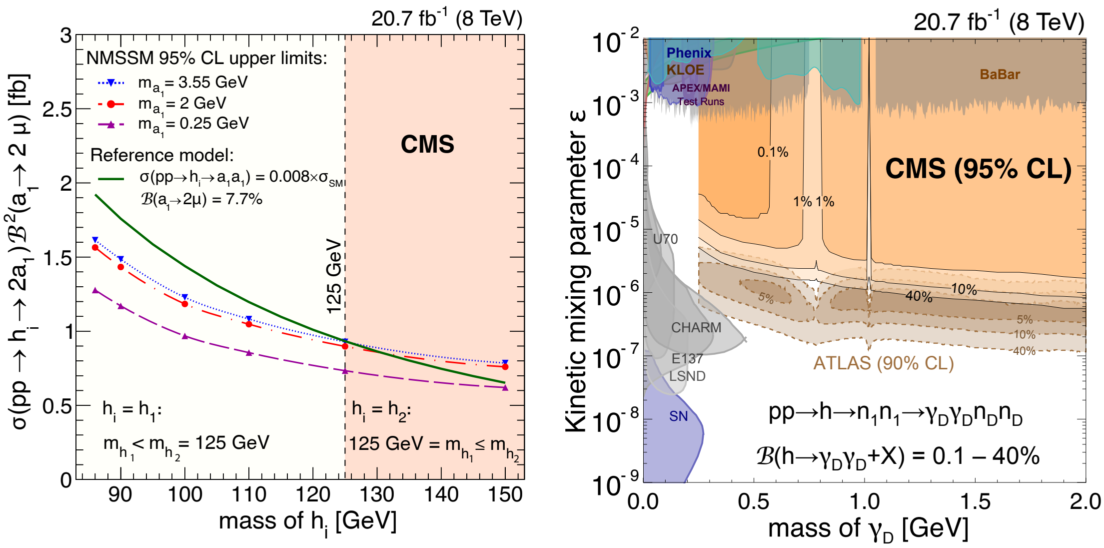

Figure 4: Interpretation of the results for the search on the $\sigma(\mathrm{pp} \to \mathrm{h}_{1/2} \to 2\mathrm{a}_1)\mathscr{B}^2(\mathrm{a}_1 \to 2\mu)$ in NMSSM benchmark scenario (left) and interpretation of results from the search on $\sigma(\mathrm{pp} \to \mathrm{h} \to 2\gamma_\mathrm{D} + X)\mathscr{B}(\mathrm{h} \to 2\gamma_\mathrm{D} + X)$ in dark SUSY scenario (right).

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