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SEARCH FOR THE STANDARD MODEL HIGGS BOSON WITH THE CMS DETECTOR AT THE LHC*

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In this paper, we present searches for the Standard Model Higgs boson performed by the CMS experiment using data recorded during proton–proton collisions at centre-of-mass energy of 7 and 8 TeV. Analyses performed in WW, ZZ, $b\bar{b}$, $\tau\tau$ and $\gamma\gamma$ channels are discussed. The combination of the above searches is presented.

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1. Introduction

The Standard Model (SM) of particle physics is a theory describing precisely three out of four known elementary interactions: electromagnetic, weak and strong. Tests of the Standard Model performed during past 30 years show no deviations from its predictions. Despite its perfect agreement with the experimental data, the Standard Model theory leaves a number of questions open:

Unification of interactions — in 1979 Salam [1], Glashow [2] and Weinberg [3] found a method to describe the electromagnetic and the weak interactions as a manifestation of a single interaction, called the electroweak interaction. The strong interactions in the Standard Model are described by quantum chromodynamics which is not related to the electroweak interaction. It is still a subject of theoretical studies whether a theory consistent with Nature that unifies electroweak and strong interactions can be developed.

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Neutrino masses — in 1998 the Super-Kamiokande Collaboration announced the first experimental evidence of a non-zero neutrino mass [5]. Prior to this date, neutrinos were assumed to be massless particles in the Standard Model. Current limits on the neutrino masses indicate that the heaviest neutrino mass is at least six orders of magnitude smaller than the electron mass. It is unclear what mechanism leads to such a big difference in the mass scales.

Matter over antimatter dominance — the astronomical observations show that the Universe is made mainly of matter, while antimatter exists only in trace amounts. The mechanisms present in the Standard Model are not strong enough to account for the observed matter to antimatter ratio.

Matter energy balance — several astronomical observations indicate that the observable matter constitutes only 4.6% [6] of matter and energy in the Universe, while the rest consists of the hypothetical Dark Matter[1] and Dark Energy. There are no candidate particles present in the Standard Model that could form the Dark Matter.

The above questions led to a common conviction among physicists that the Standard Model is not a final theory, and that new phenomena should manifest at interaction energies higher than those already tested by LEP and Tevatron experiments. This belief was one of the main reasons for building the Large Hadron Collider (LHC) and the experiments exploiting its power. One of the most important questions for the LHC experiments to answer was regarding the nature of the electroweak symmetry breaking. In the Standard Model, the Higgs mechanism is used in order to give the weak interaction carriers their mass, while keeping the photon massless [4]. Prior to the LHC era the Higgs mechanism, while most likely, was not fully proven experimentally.

During years 2010–2012 the LHC machine was running mostly in proton–proton mode. It collided two opposite beams at the centre-of-mass energy of 7 TeV (2010 and 2011 runs) and 8 TeV (2012 run). The products of collisions in the LHC were recorded, among others, by two general purpose experiments: ATLAS (A Toroidal LHC Apparatus) and CMS (Compact Muon Solenoid).

In this paper, we present searches for the Standard Model Higgs boson performed by the CMS Collaboration using data recorded at 7 TeV and 8 TeV, and corresponding to an integrated luminosity of up to 5 fb^{-1} and 12fb^{-1}, respectively. A detailed description of the CMS experiment can be found in [7].

[1] Dark Matter particles interact very weakly and, therefore, are hard to be detected directly.

2. Higgs boson searches

2.1. Search in ZZ decay mode

A search for the SM Higgs boson in the ZZ decay mode was performed using 5.1 fb^{-1} of data recorded at $\sqrt{s} = 7$ TeV, and using 12.2 fb^{-1} of data recorded at $\sqrt{s} = 8$ TeV [8]. In this analysis, events consistent with a ZZ hypothesis are selected. Two pairs of opposite-sign and the same-flavour isolated lepton candidates (e^+e^-, $\mu^+\mu^-$, $\tau^+\tau^-$) are required to be present in the selected events. Event topologies with four tau leptons are not used in this search. The measured and predicted distributions of the invariant mass of the four leptons are shown in Fig. 1.

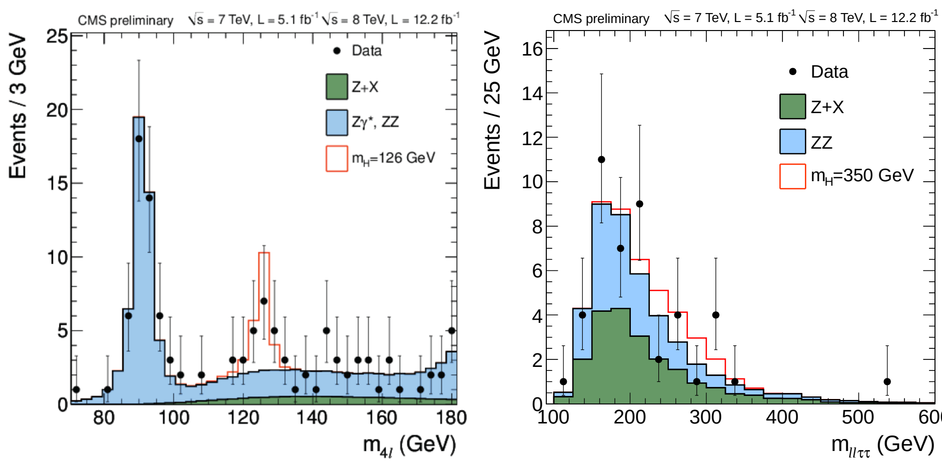

Fig. 1. Measured (points) and predicted (stacked histograms) distributions of the four lepton invariant mass for the sum of the $4e$, 4μ, $2\mu 2e$ final states (left) and for the sum of the $2\mu 2\tau$, $2e2\tau$ final states (right).

In order to enhance sensitivity of the search, a matrix element likelihood analysis (MELA) is performed. A signal to background kinematic discriminant $K_{\rm D} = P_{\rm sig}/(P_{\rm sig}+P_{\rm bkg})$ is built, which depends on the invariant masses and angles of the four selected lepton candidates in a given event [9, 10]. The measured distributions of the $K_{\rm D}$ discriminant as a function of the four lepton invariant mass are shown in Fig. 2 (points) along with predicted distributions corresponding to a 126 GeV SM Higgs boson signal (contours, left) and the SM background events (contours, right).

The expected and observed 95% C.L. limits on the SM Higgs production through the ZZ decay channel with respect to the SM expectation are shown in Fig. 3 (left). The SM Higgs boson masses in the range of 113–116 GeV and 129–720 GeV are excluded at 95% C.L. The significance of the local excess relative to the background expectation (represented by the local p-values) for

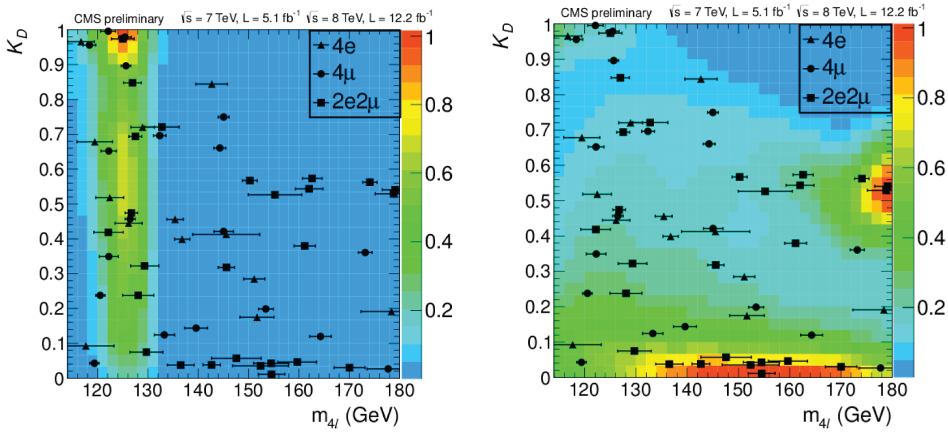

Fig. 2. Measured (points) and expected (colour contours) distributions of the K_{D} discriminant *versus* the four lepton invariant mass. The contours correspond to the expected distribution for the SM Higgs boson of 126 GeV (left) and to the expected distribution for the background events (right).

all Higgs boson masses considered in the analysis is shown in Fig. 3 (right). For the analyzed amount of data, a new particle with the mass of about 125 GeV is observed in the ZZ decay channel with the local significance of 4.5 standard deviations over the expected background.

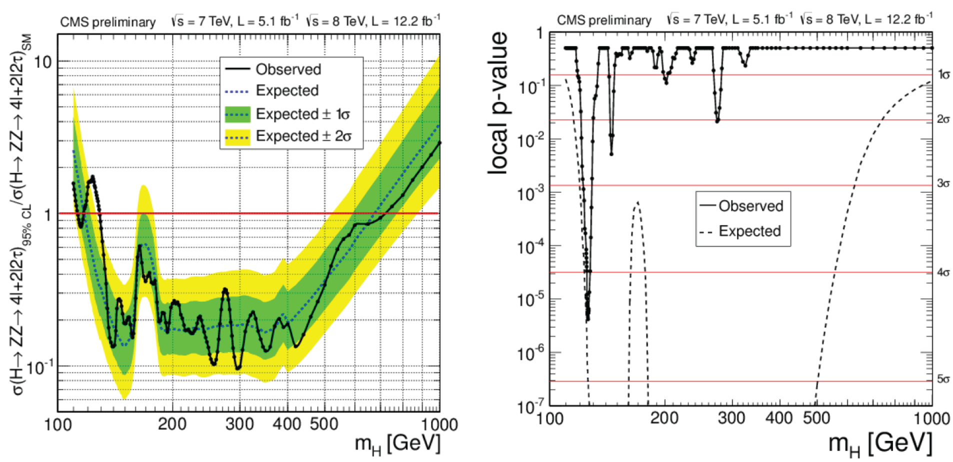

Fig. 3. Left plot: expected and observed 95% C.L. limits on the SM Higgs production in the ZZ decay mode obtained with respect to the SM expectation. The dark grey/green (light grey/yellow) band represents the expected one (two) standard deviation range. Right plot: observed local p-values as a function of the Higgs boson mass.

2.2. Search in WW decay mode

A search for the SM Higgs boson decaying to leptons via the W^+W^- state was performed using 12.1 fb^{-1} of data recorded at $\sqrt{s} = 8$ TeV [11]. The search is performed by requiring a presence of two isolated and oppositely charged lepton candidates (electrons or muons) with high transverse momenta. Since neutrinos are produced in leptonic W boson decays, events are also required to have large missing transverse energy.

In order to enhance sensitivity, the analysis is performed in 3 mutually exclusive categories depending on the number of high energetic jets (*i.e.* with $E_{\rm T} > 30$ GeV and $|\eta| < 4.7$) present in the event. The three categories studied are: 0-jet, 1-jet and 2-jets. The 2-jets category also includes events with 3 or more jets fulfilling the $E_{\rm T}$ and η selection criteria. To further enhance sensitivity of the search for events in the 0-jet and 1-jet categories with $e\mu$ pair in the final state, a two-dimensional analysis in $m_{\ell\ell}$–$m_{\rm T}$ plane is performed, where $m_{\ell\ell}$ denotes the dilepton invariant mass and $m_{\rm T}$ — the transverse mass of the dilepton and missing $E_{\rm T}$ system. The expected two-dimensional distributions are shown in Fig. 4 for the background (left) and 125 GeV Standard Model Higgs boson (right) for the 0-jets category.

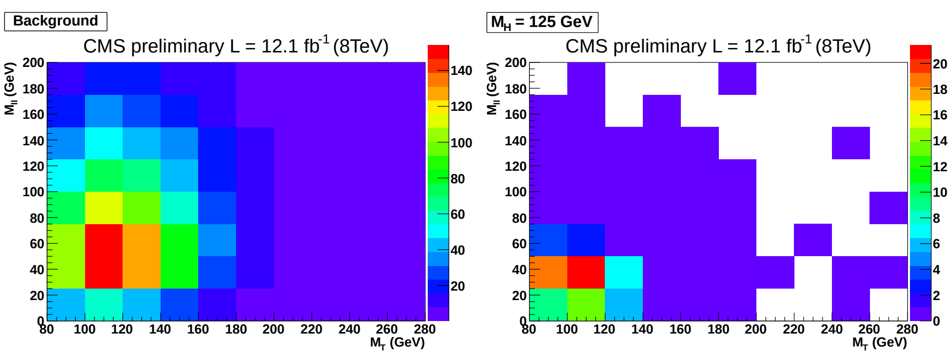

Fig. 4. Expected $m_{\ell\ell}$–$m_{\rm T}$ distributions for background (left) and 125 GeV Standard Model Higgs boson (right) for the 0-jets category.

Results corresponding to $\sqrt{s} = 8$ TeV were combined with results of the previous analysis performed at $\sqrt{s} = 7$ TeV using 4.9 fb^{-1} of data [12]. The combined result excludes the SM Higgs boson with the mass in 128–600 GeV range at 95% C.L. (Fig. 5, left). The observed and expected significance for the 125 GeV SM Higgs boson in this search channel are 3.1 and 4.1 standard deviations respectively (Fig. 5, right).

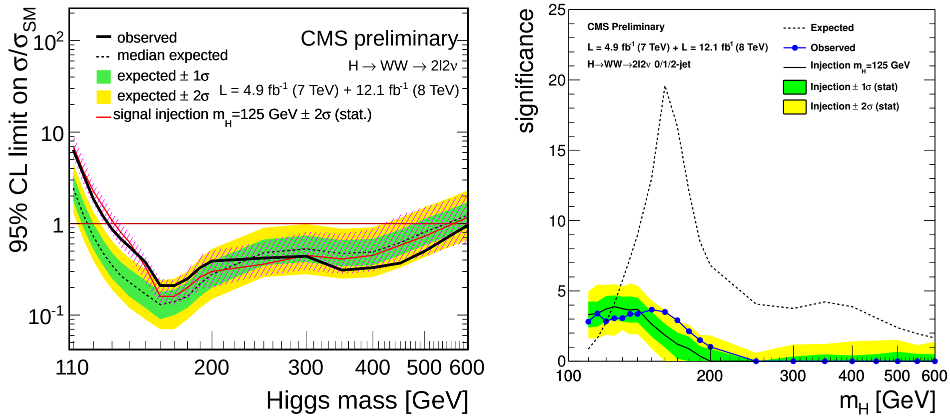

Fig. 5. Expected and observed 95% C.L. limits on the SM Higgs production in the WW decay mode obtained with respect to the SM expectation (left), and the expected and observed significances (right) as a function of the Higgs boson mass.

2.3. Search in $\tau\tau$ decay mode

A search for the SM Higgs boson decaying to τ pairs was performed using 12.1 fb^{-1} of data recorded at $\sqrt{s} = 8$ TeV, and 4.9 fb^{-1} of data recorded at $\sqrt{s} = 7$ TeV [14]. Five topologies of the final states were studied: $\mu\tau_h$, $e\tau_h$, $e\mu$, $\tau_h\tau_h$ and $\mu\mu$. The hadronic decays of tau leptons (denoted as τ_h) are reconstructed using the Hadron Plus Strips algorithm [15, 16]. The selected candidates (e, μ or τ_h) are required to have high transverse momenta and to be isolated.

Similarly to the SM Higgs boson search performed in the W^+W^- channel, events are categorised according to the number of jets with high transverse energy present in the event. Due to the low number of the expected signal events the 0-jet category is used only to constrain background normalizations, reconstruction efficiencies and energy scales.

For each topology of the final state, the analysis is performed using reconstructed mass of the di-tau candidate, $m_{\tau\tau}$. The $m_{\tau\tau}$ mass is calculated, with the SVFit algorithm [14], using visible momenta of the τ decay products and the missing transverse energy, in order to account for the energy carried out by neutrinos involved in the τ decays. Comparison of the basic mass reconstruction method (*i.e.* using only visible momenta of the τ decay products) and the full mass reconstruction is shown in Fig. 6. The SVFit algorithm provides better signal and background separation and, as a result, improves sensitivity of the analysis.

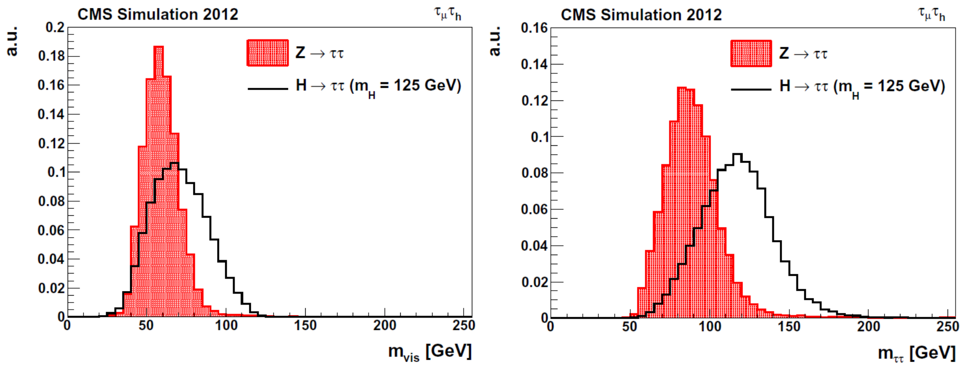

Fig. 6. Distribution of the visible mass $m_{\rm vis}$ (left) and the reconstructed mass $m_{\tau\tau}$ (right) of the di-tau system for the main irreducible background due to $Z \to \tau\tau$ process and for the 125 GeV SM Higgs boson.

The expected and observed 95% C.L. limits on the SM Higgs production in the $\tau\tau$ channels obtained with respect to the SM expectation are shown in Fig. 7. For the 125 GeV SM Higgs boson, the expected and observed 95% confidence level limits are 1.00 and 1.63 respectively. The observed mild excess of events corresponds to a local significance of 1.5 standard deviations for the 125 GeV Higgs boson mass (2.45 standard deviations expected). For the same mass, the measured signal strength, $\sigma/\sigma_{\rm SM}$, (*i.e.* the ratio of measured and expected SM Higgs boson event yields) in this channel is 0.7 ± 0.5.

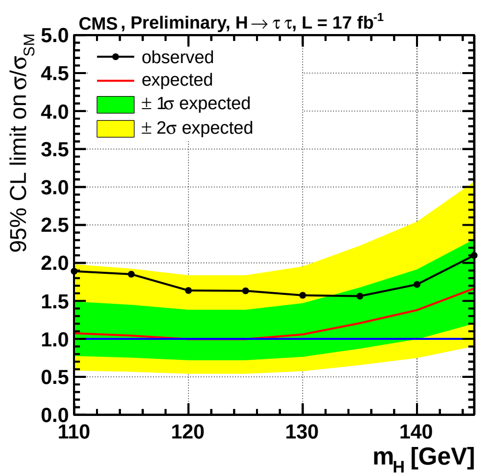

Fig. 7. Expected and observed 95% C.L. limits on the SM Higgs production in the $\tau\tau$ channels obtained with respect to the SM expectation.

2.4. Search in $b\bar{b}$ decay mode

A search for the SM Higgs boson decaying to $b\bar{b}$ quark pairs was performed using 12.1 fb^{-1} of data recorded at $\sqrt{s} = 8$ TeV, and 5.0 fb^{-1} of data recorded at $\sqrt{s} = 7$ TeV [13]. Since the signature of the final state consists of two jets, the SM Higgs boson production in association with W or Z boson is exploited in order to improve the ratio of signal to background events. The $W(\mu\nu)H$, $W(e\nu)H$, $Z(\mu\mu)H$, $Z(ee)H$ and $Z(\nu\nu)H$ final states are used in this search, forming five mutually exclusive event categories. In the $W(\mu\nu)H$ and $W(e\nu)H$ categories, the events are required to have: a single isolated muon or electron candidate of high transverse momentum, and a large missing transverse energy. For $Z(\mu\mu)H$ and $Z(ee)H$ categories, the presence of a pair of isolated muons or electrons of opposite charge is required with the invariant mass between 75 and 105 GeV. The $Z(\nu\nu)H$ mode is selected by requiring a large missing transverse energy to be present in the event.

The SM Higgs boson decay to $b\bar{b}$ is selected by requiring two b-tagged jets with high transverse momenta. In the last stage of the analysis, every event passing all selection criteria is assigned a final discriminant value, which is calculated using a Boosted Decision Tree (BDT) algorithm trained on the simulated Monte Carlo (MC) samples.

The expected and observed 95% C.L. limits on the SM Higgs production in association with W or Z bosons in the $b\bar{b}$ channel with respect to the SM expectation are shown in Fig. 8. For the 125 GeV Higgs boson, the observed limit is 2.5 while the expected one is 1.2. The observed excess of events corresponds to a local significance of 2.2 standard deviations for 125 GeV Higgs boson mass. For this mass value, the measured signal strength $\sigma/\sigma_{\mathrm{SM}}$ in this channel is $1.3^{+0.7}_{-0.6}$.

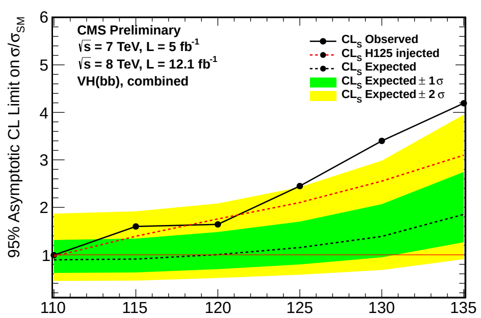

Fig. 8. Expected and observed 95% C.L. limits on the SM Higgs production in association with W or Z bosons in the $b\bar{b}$ decay mode with respect to the SM expectation.

2.5. Search in $\gamma\gamma$ final state

A search for the SM Higgs boson decaying to two photons is performed using 5.1 fb^{-1} of data recorded at $\sqrt{s} = 7$ TeV, and 5.3 fb^{-1} of data recorded at $\sqrt{s} = 8$ TeV [17]. Despite very low branching ratio, this channel is very sensitive to the Higgs boson signal. Two isolated photons in the final state provide very clean topology. Thanks to an excellent photon energy resolution in the CMS detector a relatively narrow peak in the di-photon invariant mass distribution is expected.

The events are split into two mutually exclusive categories: one with two forward jets consistent with the topology of the Vector Boson Fusion (VBF) production mode, and the non-VBF one (*i.e.* all the remaining events). The latter category is further divided into subcategories using a BDT classifier trained to distinguish events with: good di-photon mass resolution, signal-like kinematics and good quality of reconstructed photons. The classifier is independent of the di-photon invariant mass.

The di-photon invariant mass distribution (*i.e.* the sum of distributions weighted by the ratio of signal to signal plus background in each event category) is shown in Fig. 9. An excess of events is visible in the mass spectrum at about 125 GeV. The observed local p-values as a function of the Higgs boson mass are shown in Fig. 10. For a Higgs boson mass of 125 GeV, the observed excess of events over the SM expected background corresponds to a local significance of 4.1 standard deviations.

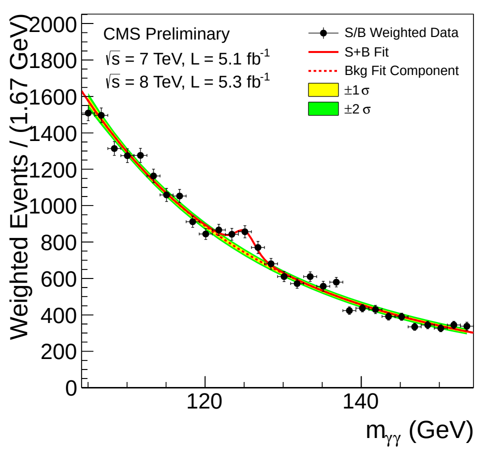

Fig. 9. The di-photon invariant mass distribution (sum of the distributions weighted by the ratio of signal to signal plus background in each event class).

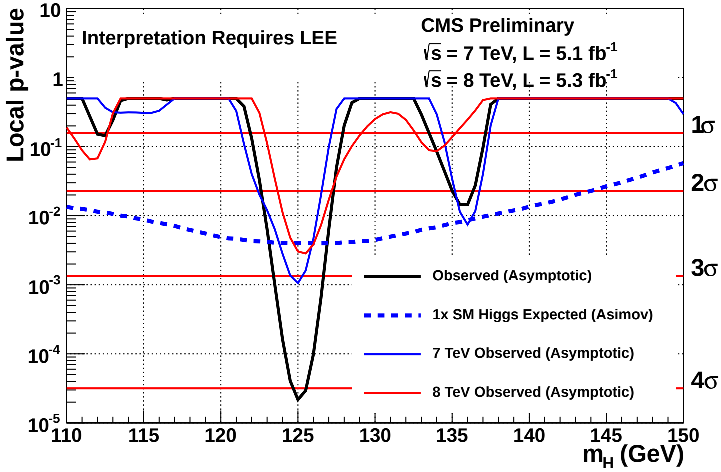

Fig. 10. Observed local p-values in the $\gamma\gamma$ channel as a function of the Higgs boson mass.

3. Combination of the searches

The results from the five search channels presented above (ZZ, WW, $\tau\tau$, $b\bar{b}$ and $\gamma\gamma$) were combined in order to determine properties of the new particle [18]. The statistical and systematic uncertainties, and their correlations among channels were properly accounted for. The new boson with a mass near 125 GeV is observed with a significance of 6.9 sigma (Fig. 11).

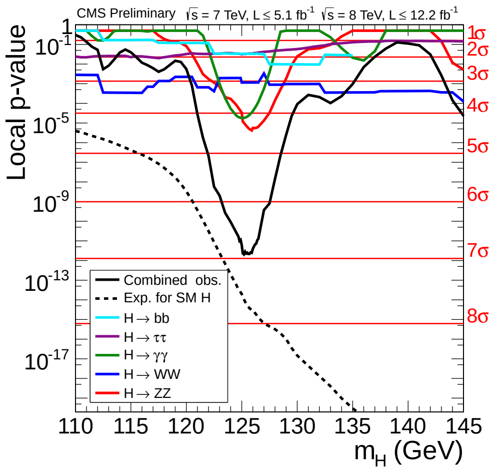

Fig. 11. The observed local p-value for all decay modes used and the overall combination as a function of the SM Higgs boson mass.

Analyses performed in the ZZ and $\gamma\gamma$ decay modes are characterized by a very good mass resolution. In those sub-channels alone the observed excess is 4.4 and 4.0 standard deviations respectively. In order to determine the mass of a new particle in a model independent way, the mass measurement is performed without constraining the Higgs boson event yields to the SM expectations. The 68% confidence level contours in a two-dimensional plane of the mass, m_X, and the signal strength modifier, $\sigma/\sigma_{\rm SM}$, are shown in Fig. 12. The resulting mass of the new particle is $125.8 \pm 0.4\,({\rm stat}) \pm 0.4\,({\rm sys})$ GeV.

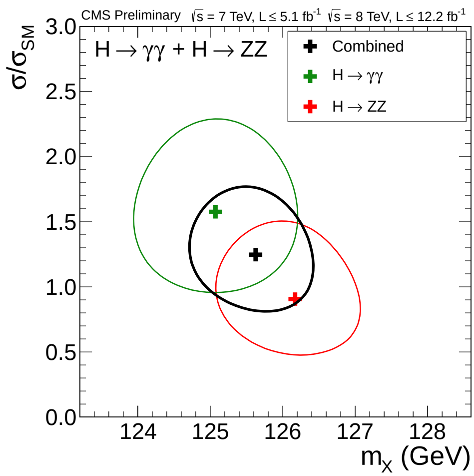

Fig. 12. 68% confidence level contours in a two-dimensional plane of the mass (m_X) and the signal strength modifier ($\sigma/\sigma_{\rm SM}$).

4. Summary

Searches for the Standard Model Higgs boson performed by the CMS experiment using data corresponding to proton–proton collisions at centre-of-mass energy of 7 and 8 TeV are presented. Searches were performed in: WW, ZZ, $b\bar{b}$, $\tau\tau$ and $\gamma\gamma$ decay channels, and the results were combined. A new particle is observed with 6.9 standard deviations excess over the Standard Model expected background. The new particle mass is determined to be: $125.8 \pm 0.4\,({\rm stat}) \pm 0.4\,({\rm sys})$ GeV.

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