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2013 J. Phys.: Conf. Ser. 455 012027

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Search for the Standard Model Higgs in $H \rightarrow ZZ \rightarrow 4l$ channel with the CMS experiment

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Abstract. Results of the experimental search for the Standard Model Higgs in the $H \rightarrow ZZ \rightarrow 4l$ (with $l=e,\mu$) decay channel at collision energies of 7 and 8 TeV at the LHC are presented. The analysis uses pp collision data recorded by the CMS detector at the LHC, corresponding to integrated luminosities of 5.05 fb^{-1} at collision energy of 7 TeV and 12.2 fb^{-1} at 8 TeV. A complete description of the $H \rightarrow ZZ \rightarrow 4l$ analysis is provided by inspecting the most important aspects such as the lepton identification and isolation, the kinematics, the selection steps and the background control from data. The existence of the Higgs boson would be statistically revealed by the presence of a resonance peak in the four-lepton invariant mass distribution. The search covers the overall Higgs boson mass hypotheses in the range $110 < m_H < 1000\text{ GeV}/c^2$ and a statistical interpretation of the results in that range is provided. The existence of the Standard Model Higgs boson has been excluded in a wide region of mass at 95% of confidence level, while a 4.5σ excess has been observed around a mass of $126\text{ GeV}/c^2$. A measurement of the mass of the new boson discovered gives $126.2 \pm 0.6(\text{stat}) \pm 0.2(\text{syst})\text{ GeV}/c^2$. The hypothesis 0^+ of the standard model for the spin $J=0$ and parity $P=+1$ quantum numbers is found to be consistent with the observation.

1. Introduction

The Higgs boson is a scalar particle predicted by the Standard Model (SM) of electroweak interactions [1, 2, 3], responsible for the mechanism of spontaneous symmetry breaking [4, 5, 6, 8, 7, 9] that allow fermions and gauge bosons to acquire mass. The mass of the boson is not predicted by the theory and needs to be established experimentally.

The search for the Standard Model (SM) Higgs boson is one of the major goals of the LHC physics program. In July 2012, the CMS and ATLAS experiments announced the discovery of a new boson at a mass around $125\text{ GeV}/c^2$, with properties compatible with the SM Higgs boson [10, 11]. By using 2011 data at 7 TeV, CMS excluded the SM Higgs boson in the mass range $127\text{--}600\text{ GeV}/c^2$ at 95% confidence level (CL) [12] while ATLAS excluded the ranges $111.4\text{--}116.6\text{ GeV}/c^2$, $119.4\text{--}122.1\text{ GeV}/c^2$, and $129.2\text{--}541\text{ GeV}/c^2$ at 95% CL [13, 14].

The production of the SM Higgs boson at the LHC proceeds through several mechanisms. The dominant production mechanism is gluon-gluon fusion with a cross section between 0.1 and 50 pb depending on the SM Higgs mass, after including the most recent next-to-next-to-leading-order and next-to-next-leading-log calculations of the cross sections [15]. Other production mechanisms including associated production with the weak vector bosons, the weak vector



boson fusion processes and the associated production with heavy top or bottom quarks are less favoured.

In the high mass range the most important decay channels of the SM Higgs particle are $H \rightarrow WW^{(*)}$ and $H \rightarrow ZZ^{(*)}$ which give a clear signature of multi-leptons in the final state. At low and intermediate the values of the Higgs mass the decay to $b\bar{b}$ and $\tau\tau$ fermions are favoured but the high background and the experimental resolution for the searches in those channels make them much less powerful than the $H \rightarrow ZZ$ decay which has a clean experimental signature and the possibility to reconstruct the mass; the the $H \rightarrow \gamma\gamma$ channel suffers from a low branching ratio and is quite sensitive to the background modeling. The product of the cross section times the branching fraction ranges from a few to about 10 fb for the $H \rightarrow ZZ \rightarrow 4l$ final state.

2. CMS detector and physics object reconstruction

The CMS detector [16] consists of a superconducting solenoid providing a uniform magnetic field of 3.8 T in the core, equipped with silicon pixel and strip tracking systems ($|\eta| < 2.5$) surrounded by a lead tungstate crystal electromagnetic calorimeter (ECAL) and a brass-scintillator hadronic calorimeter (HCAL) covering $|\eta| < 3.0$. The steel return yoke outside the solenoid is instrumented with gas ionization detectors used to trigger and identify muons up to $|\eta| < 2.4$.

The reconstruction and the identification of individual particles in the collision event relies on the the Particle Flow algorithm [17, 18] that uses the information from all CMS sub-detectors to provide a list of mutually exclusive categories: charged hadrons, neutral hadrons, photons, muons, and electrons.

Muons are reconstructed within the geometrical acceptance $|\eta| < 2.4$ and with transverse momentum $p_T > 5 \text{ GeV}/c$ by using information from both the inner tracker and the muon spectrometer [19]. Minimal requirements on the track components in the muon system and on the compatibility with energy deposits in the calorimeters are applied for the Particle Flow identification.

Electrons are reconstructed within the geometrical acceptance of the detector ($|\eta| < 2.5$) and with $p_T > 7 \text{ GeV}/c$ by combining the information from clusters of energy deposits in the ECAL and the trajectory in the inner tracker [20]. The criteria for the electron identification are based on a multivariate technique that combines observables sensitive to the amount of bremsstrahlung along the electron trajectory, the geometrical and momentum matching between the electron trajectory and associated clusters, as well as shower-shape observables.

The isolation of individual e or μ leptons is measured relative to their transverse momentum, by summing over the transverse momenta of the charged hadrons originating from the primary vertex, the neutral hadron and the photon candidates provided by the Particle Flow algorithm. The electrons or muons are considered isolated if the isolation variable is smaller than 0.4, that corresponds to a loose requirement, aimed to preserve the signal efficiency.

The impact parameter of the track associated to the lepton with respect to the primary vertex normalized to the related uncertainty, hereafter referred as the significance of the impact parameter, SIP , is used to select prompt leptons coming from the primary vertex. Only leptons with $|SIP| < 4$ and passing the identification and isolation criteria mentioned above are considered ‘good’ leptons for the $H \rightarrow ZZ \rightarrow 4l$ analysis.

The tag-and-probe method [21] is used to measure the muon/electron reconstruction, identification and isolation efficiency from data and compare with expectation from simulation. The method relies upon $Z \rightarrow \mu^+\mu^-/e^+e^-$ decays to provide an unbiased and high purity muon/electron sample from which the efficiency of a particular selection step or cut can be measured by using the Z mass constraint.

3. Event selection

Data collected by the CMS experiment for which all sub-detectors performed properly have been used for this analysis. The data were officially-validated by the CMS collaboration for trigger selection and event reconstruction in 2011 and 2012.

A full set of Monte Carlo (MC) simulated samples are produced using several generators according to the given production process and decay: POWHEG [22], PYTHIA 6.4 [23], Madgraph 5 [24]. The full CMS detector simulation and reconstruction chain is used at a later stage after the event production. The cross sections for all the background processes are re-weighted to next-to-leading-order (NLO) calculations.

Collision events are selected first by the trigger system that requires the presence of a pair of electrons or a pair of muons, or a triplet of electrons, with threshold on the p_T of leptons and additional selection according to the instantaneous luminosity of the LHC, varied over the range $10^{29} - 10^{33} \text{ cm}^{-2} \text{ s}^{-1}$ during 2011 and 2012 periods. The trigger efficiency within the acceptance of this analysis is greater than 98% for a Higgs boson signal with $m_H > 120 \text{ GeV}/c^2$.

The event selection is designed to reconstruct two pairs with opposite-sign and same-flavor "good" leptons, preserving the signal efficiency, especially in low Higgs mass region, while rejecting the background from SM processes, mostly $ZZ/Z\gamma^*$ events and $Zb\bar{b}/t\bar{t}$ events including non-prompt leptons from the secondary vertex of the b-hadrons decay. The background sources related to the probability of a jet to be mis-identified as a "good" lepton ("fake" leptons) are referred as "instrumental" background and include Z +light jets and WZ +light jets events with at least two or one "fake" leptons, respectively.

Between all the pairs of opposite-sign and same-flavor "good" leptons the one with an invariant mass closest to the nominal Z mass is chosen (Z_1) and retained if it satisfies the condition $40 < m_{Z_1} < 120 \text{ GeV}/c^2$. A second pair of opposite-sign and same-flavor "good" leptons (Z_2) is built with the remaining leptons and chosen if it satisfies the condition: $12 < m_{Z_2} < 120 \text{ GeV}/c^2$. In case of ambiguities for the choice of the Z_2 the one built with the leptons of higher p_T is kept. In order to ensure that the events passing the selection have leptons on the high-efficiency plateau for the trigger, at least one lepton of the Z_1 or the Z_2 candidates is required to have $p_T > 20 \text{ GeV}/c$ and another one to have $p_T > 10 \text{ GeV}/c$.

Any opposite-charge pair of leptons chosen among the four selected leptons (irrespective of flavour) has to satisfy the requirement $m_{ll'} > 4 \text{ GeV}/c^2$ in order to further reject events with leptons originating from hadron decays in jet fragmentation or from the decay of low-mass hadronic resonances.

The phase space for the search of the SM Higgs boson is defined by restricting the mass range to $m_{4l} > 100 \text{ GeV}/c^2$.

The kinematics of the Higgs or exotic boson decay to ZZ final state can be further described by five angles in its centre-of-mass frame $\vec{\Omega} = (\theta^*, \Phi_1, \theta_1, \theta_2, \Phi)$, defined in Ref. [25], and the invariant masses of the lepton pairs, m_{Z_1} and m_{Z_2} . The distribution of those observables is related to the spin/parity quantum numbers of the decaying resonance. By using a matrix element likelihood analysis (MELA) a kinematic discriminant (K_D) built with that set of observables can be defined for each value of m_{4l} , based on the probability ratio of the signal and background hypotheses, $K_D = \mathcal{P}_{\text{sig}}/(\mathcal{P}_{\text{sig}} + \mathcal{P}_{\text{bkg}})$, as described in Refs. [25, 26]. The use of the K_D provides additional discrimination between the signal and the background (especially the ZZ).

A complete description of the $H \rightarrow ZZ \rightarrow 4l$ analysis with additional details can be found in Ref.[27].

4. Background control

The ZZ background is evaluated from the Monte Carlo simulation; the shape of the four-lepton mass distribution is taken from the simulated samples while the event yield is normalized to the cross section for ZZ production at NLO calculated with MCFM [28, 29, 30], including the

contribution from $q\bar{q}$ annihilation, as well as that from the gluon fusion and the luminosity of the data sample.

To estimate the reducible background ($Zb\bar{b}$, $t\bar{t}$) and the "instrumental" (Z + light jets, WZ + jets) background, a $Z+X$ background control region is defined. The event rates measured in the background control region are then extrapolated to the signal region.

Two approaches are used to define the background control region both starting from events with a well reconstructed Z_1 and relaxing the isolation and identification criteria for two additional reconstructed lepton objects. For the first method the additional pair of leptons is required to have the same charge (to avoid signal contamination) and same flavour ($e^\pm e^\pm, \mu^\pm \mu^\pm$), a reconstructed invariant mass $m_{Z_2} > 12 \text{ GeV}/c^2$ and $m_{4l} > 100 \text{ GeV}/c^2$. The second method relies on the control region with two opposite-sign leptons failing the isolation and identification criteria.

The expected number of $Z+X$ background events in the signal region is obtained by taking into account the lepton mis-identification probability for each of the two additional leptons; that probability is measured with a sample $Z+l$, with at least one reconstructed lepton object. The lepton misidentification probability computed as the probability for a reconstructed lepton to pass identification and isolation requirements is compared with the one derived from MC simulation and found compatible.

Since both methods provide comparable background counts in the signal region within uncertainties, an envelope of these is used as the final estimate in Table 1.

5. Systematic uncertainties

Systematic uncertainties on the theoretical calculation of the SM Higgs boson cross section (17–20%) and branching fraction (2%) are described in Ref. [15].

The uncertainties on the evaluation of the ZZ background come from the QCD and PDF scales and are computed for each final state following standard prescriptions; they amount to 8% on average.

The uncertainty on the integrated luminosity amounts to 2.2% at 7 TeV, 4.4% at 8 TeV [31] and enters in the normalization of the ZZ background and of the signal.

An uncertainty of approximately 50% comes from the limited statistical precision in the reducible and "instrumental" background control regions as well as from the difference in background composition between the control regions and the sample on which the lepton misidentification probability is derived.

Systematic uncertainties on the selection efficiency coming from trigger (1.5%), and combined lepton reconstruction, identification and isolation efficiencies (varying from 1.2% to 3.8% in the 4μ channel and from 5.5% to 11% in $4e$ channel, depending on the considered mass) are evaluated from data.

6. Final results and statistical interpretation

The reconstructed four-lepton invariant mass distributions are shown in Figure 1 in the full mass range (left) and in the low mass region (right), using 2011 data at 7 TeV and 2012 data at 8 TeV. Data distributions are compared with the expectation from SM background processes. The measured distribution at higher mass is dominated by the irreducible ZZ background while at low mass the contribution of the $Z+X$ estimated from data is visible. A clear peak around $m_{4l} = 126 \text{ GeV}/c^2$ is seen, confirming the previous observation of the a new boson. The peak at around $m_{4l} = 91 \text{ GeV}/c^2$ corresponds to the $Z \rightarrow 4l$ standard candle, as predicted by the SM.

Table 1 reports the number of candidates observed in data, the estimated background and the expected number of signal events for several SM Higgs boson mass hypotheses, in the full mass measurement range, $100 < m_{4l} < 1000 \text{ GeV}/c^2$. The observed event rates for the various channels are compatible with SM background expectation.

Table 1. The number of event candidates observed, compared to the mean expected background and signal rates for each final state in the range $100 < m_{4l} < 1000 \text{ GeV}/c^2$, with 2011 and 2012 data.

Channel	$4e$	4μ	$2e2\mu$
ZZ background	53.0 ± 6.3	82.7 ± 8.9	131.1 ± 14.3
Z + X	$7.6^{+6.9}_{-5.2}$	$2.9^{+2.2}_{-1.6}$	$10.1^{+9.9}_{-6.5}$
All background expected	$60.7^{+9.3}_{-8.2}$	$85.6^{+9.2}_{-9.1}$	$141.3^{+17.3}_{-15.7}$
$m_H = 125 \text{ GeV}/c^2$	2.4 ± 0.4	4.6 ± 0.5	6.0 ± 0.7
$m_H = 126 \text{ GeV}/c^2$	2.7 ± 0.4	5.1 ± 0.6	6.6 ± 0.8
$m_H = 200 \text{ GeV}/c^2$	15.5 ± 1.9	23.1 ± 2.6	38.5 ± 4.3
$m_H = 350 \text{ GeV}/c^2$	9.5 ± 1.2	13.6 ± 1.5	23.2 ± 2.7
$m_H = 500 \text{ GeV}/c^2$	3.3 ± 0.4	4.7 ± 0.6	8.1 ± 0.9
$m_H = 800 \text{ GeV}/c^2$	0.5 ± 0.1	0.6 ± 0.1	1.1 ± 0.1
Observed	59	95	162

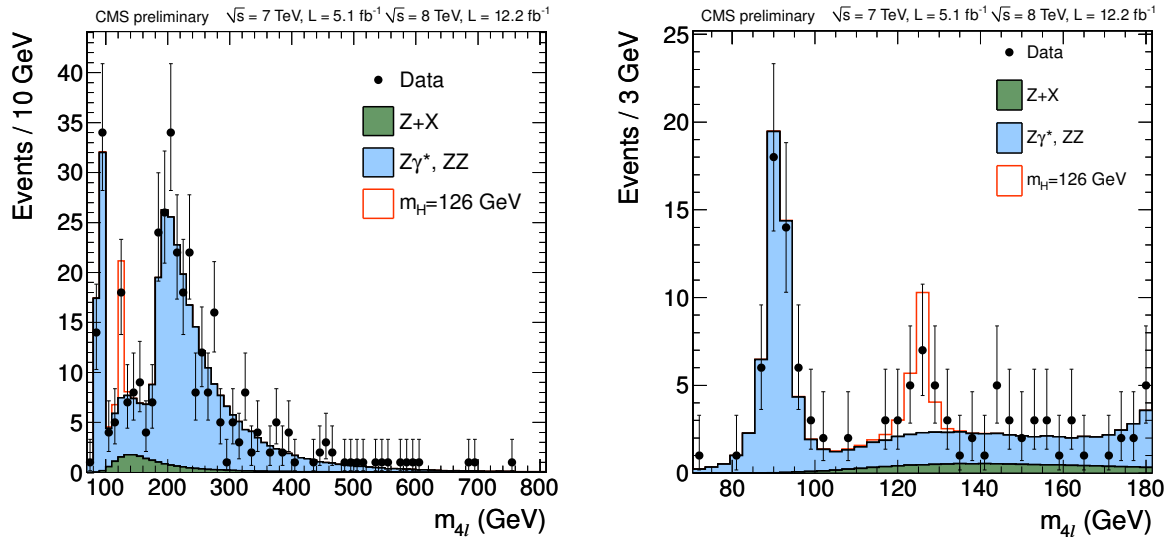


Figure 1. Distribution of the four-lepton reconstructed mass in the full mass range (left) and low mass region (right) for the sum of the $4e$, 4μ and $2e2\mu$ channels. Points represent the data, shaded histograms represent the background and unshaded histogram the signal expectations. The expected distributions are presented as stacked histograms. The measurements are presented for the sum of the data collected at $\sqrt{s} = 7 \text{ TeV}$ and $\sqrt{s} = 8 \text{ TeV}$.

The distributions of the K_D as a function of the four-lepton reconstructed mass m_{4l} for the selected events in data and compared to signal and background expectation are shown in Figure 2; values of K_D close to 1 mean a better compatibility with the hypothesis of the SM Higgs signal.

A statistical approach for testing hypotheses is used to derive both the exclusion limits at 95% CL on the ratio of the production cross section for the SM Higgs boson to the SM expectation and the significance for the discovery of a new particle. The modified frequentist construction CL_s [32, 33] is used; details and current implementation can be found in Ref. [34]. For each mass

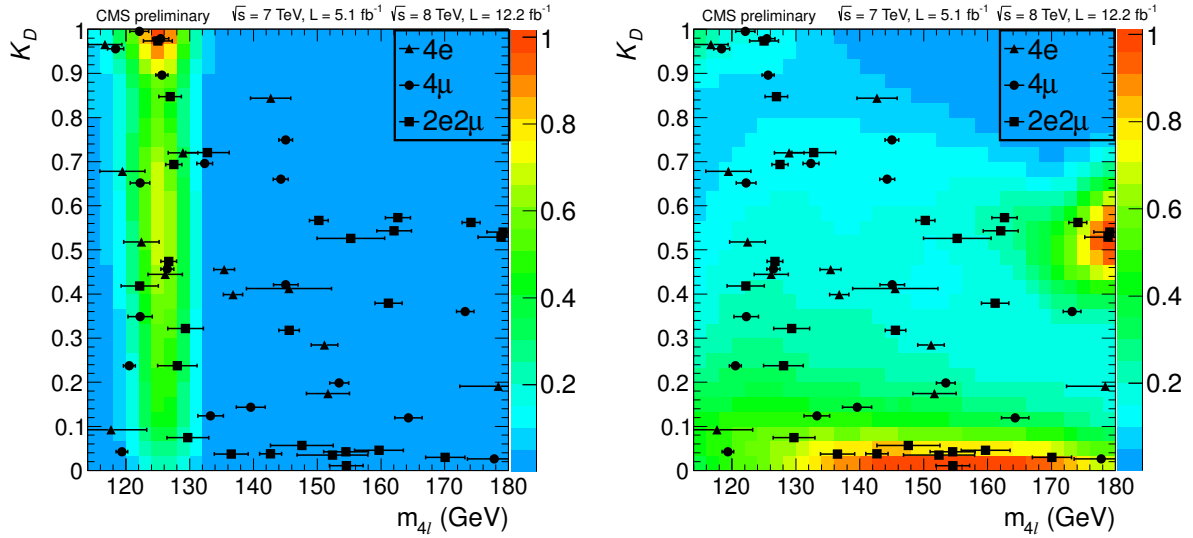


Figure 2. Distribution of the K_D versus the four-lepton reconstructed mass m_{4l} in the low-mass regions for the signal at $m_H = 126 \text{ GeV}/c^2$ (left) and for the background (right). The contours represent the expected relative density of signal (left) or background events (right). The points show data with measured invariant mass uncertainties.

hypothesis, a simultaneous likelihood fit of the two-dimensional (m_{4l}, K_D) distributions is performed, separately for the three channels and the two data taking periods at 7 and 8 TeV. All systematic uncertainties are included in the likelihood with log-normal distributions.

The upper limit at 95% CL on the ratio of the production cross section for the SM Higgs boson to the SM expectation is shown in Figure 3 (top left) and a zoom at low mass is shown at bottom left. The SM Higgs boson is excluded by the four-lepton channels at 95% CL in the ranges 113–116 GeV/c^2 and 129–720 GeV/c^2 .

The local p -values, representing the probability that the background can fluctuate to give an excess of events equal to or larger than the observed number of events, are shown for the full and the low mass range as a function of SM Higgs mass hypothesis in Figure 3 (right). The minimum p -value is reached at mass around $m_{4l} = 125.9 \text{ GeV}/c^2$ and corresponds to a local significance of 4.5σ .

7. Mass and spin/parity measurements

A simultaneous likelihood fit using for each event the three-dimensional distribution (m_{4l}, er_{4l}, K_D) of the four-lepton invariant mass, the associated per-event mass error (er_{4l}), and the kinematic discriminant, is performed to get the mass measurement of the new boson. Per-event errors on the four-lepton invariant mass are calculated from the individual lepton momentum errors by using the full error matrix, as obtained from the muon track fit, in case of muons and by using the estimated momentum error, as obtained from the combination of the ECAL and tracker measurements, in case of electrons. Figure 4 (left) shows the two-dimensional confidence level regions for the ratio of the production cross section for the SM Higgs boson to the SM expectation as a function of the Higgs mass hypothesis. The result of the fit gives $m_H = 126.2 \pm 0.6$ (stat) ± 0.2 (syst) GeV/c^2 .

The spin and quantum numbers of the new boson are studied following the MELA methodology, replacing the signal-to-background probability ratio with the probability ratio for two different signal hypotheses as the new discriminant. The pure pseudo-scalar state $J^P = 0^-$

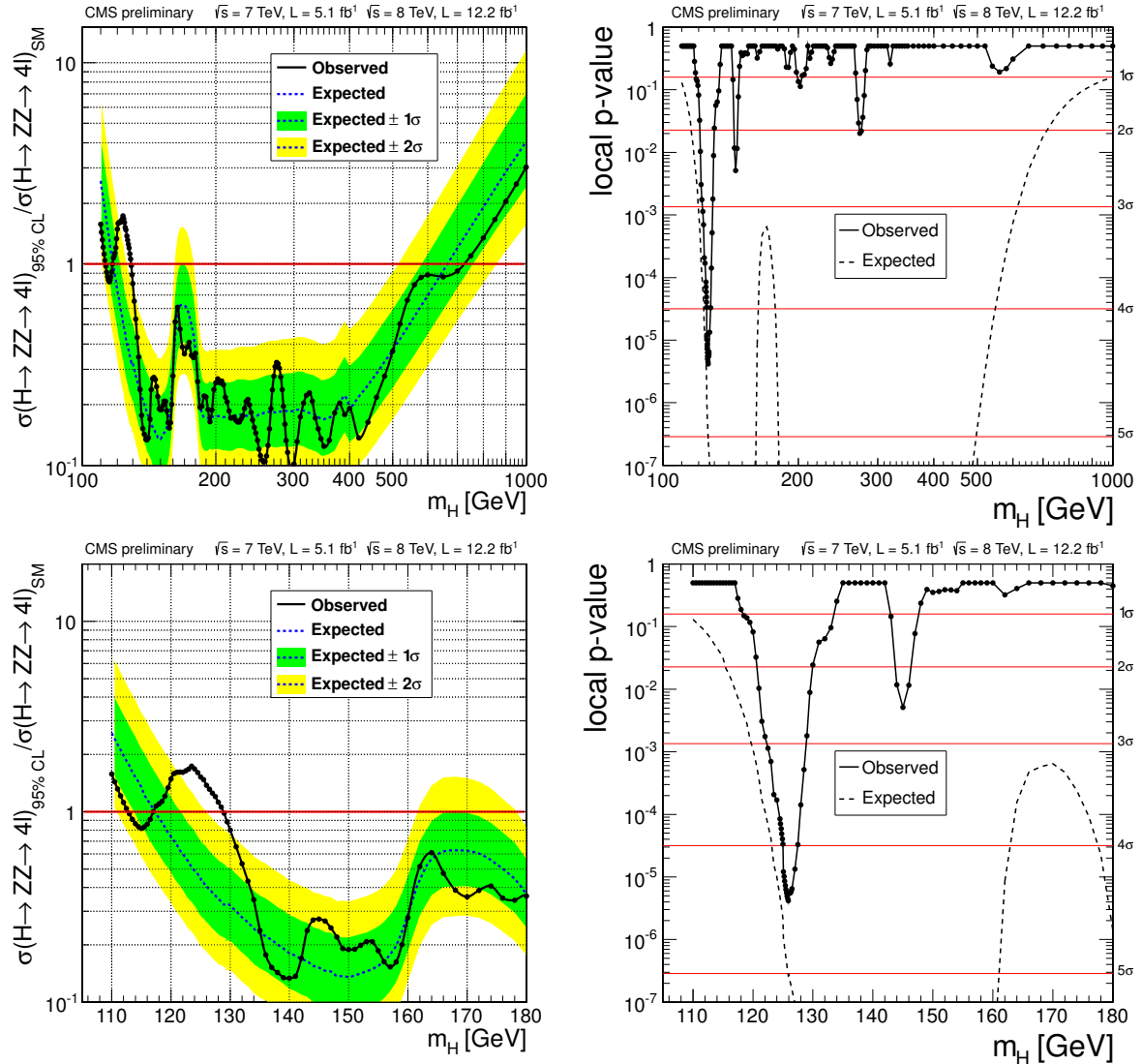


Figure 3. Observed and expected 95% CL upper limit (left) on the ratio of the production cross section to the SM expectation in the full mass range (top) and the low-mass region (bottom). The 68% and 95% ranges of expectation for the background-only model are also shown with green and yellow bands, respectively. Local p -values (right) represent the significance of the local excess with respect to the standard model background expectation as a function of the Higgs boson mass in the full and low mass range.

is considered here as an alternative hypothesis. The same statistical approach previously introduced is used and the likelihoods involved, \mathcal{L} , are calculated with the signal rates allowed to float independently for each signal type. The distributions of $q = -2\ln(\mathcal{L}_{0-}/\mathcal{L}_{0+})$ obtained with simulated events for both a 0^- resonance and the SM 0^+ Higgs boson with $m_H = 126 \text{ GeV}/c^2$ are shown in Figure 4 (right). The observed value of q , indicated by an arrow in the previous figure, is consistent with expectation within 2.4σ if assuming $J^P = 0^-$ and within 0.5σ if assuming $J^P = 0^+$.

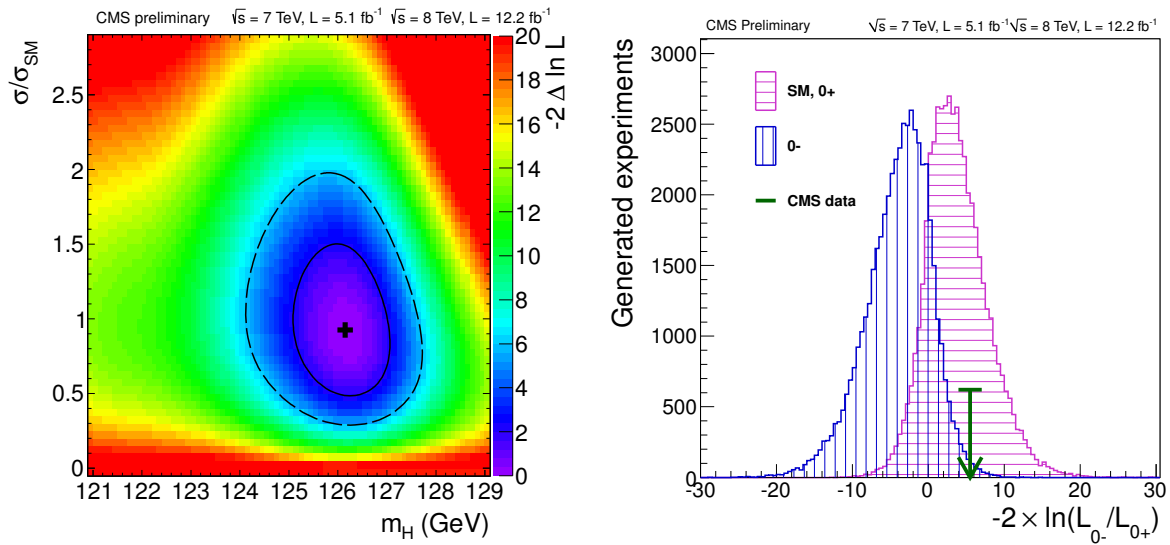


Figure 4. (Left) Distribution of $-2\ln\mathcal{L}$ as a function mass m_H and ratio of the production cross section for the SM Higgs boson to the SM expectation. The central point shows the minimum value of $-2\ln\mathcal{L}$, the solid and dashed contours show 68% and 95% CL contours in two dimensions. (Right) Distribution of $q = -2\ln(\mathcal{L}_{0-}/\mathcal{L}_{0+})$ for two signal types (0^+ horizontally hatched histogram, 0^- vertically hatched histogram) for $m_H = 126$ GeV shown with a large number of generated experiments. The arrow indicates the observed value.

8. Conclusions

A search for the SM Higgs boson has been performed in the four-lepton decay modes by using 2011 data at $\sqrt{s} = 7$ TeV and 2012 data at $\sqrt{s} = 8$ TeV. The SM Higgs boson is excluded at 95% CL in the mass ranges 113–116 and 129–720 GeV/ c^2 . The recently discovered new boson is observed with a local significance of 4.5σ and its mass is measured to be 126.2 ± 0.6 (stat) ± 0.2 (syst) GeV/ c^2 . The hypothesis 0^+ of the standard model for the spin $J = 0$ and parity $P = +1$ quantum numbers is found to be consistent with the observation.

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