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Nuclear Physics B Proceedings Supplement 00 (2012) 1–7
Nuclear Physics B Proceedings Supplement

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Abstract

We present the results of the standard model Higgs boson search in proton-proton collisions at 7 and 8 TeV center of mass energy collected by the Compact Muon Solenoid experiment at Large Hadron Collider. Data correspond to integrated luminosity of about 5 fb^{-1} at 7 TeV and another 5 fb^{-1} at 8 TeV. Five decay modes of Higgs boson are analysed: $\gamma\gamma$, ZZ, WW, $\tau^+\tau^-$, and $b\bar{b}$. The observed excess has a significance of 5.0 σ standard deviations at the mass of about 125 GeV, while the expected significance of the standard model Higgs boson at this mass is 5.8 σ. Analysis of $\gamma\gamma$ and ZZ decay channels, that offer the best mass resolution, yield the measurement of the new particle's mass to be 125.3 ± 0.4(stat.) ± 0.5(syst.) GeV.

Keywords: CMS, physics, Higgs

1. Introduction

Within the standard model (SM), particles acquire mass through interaction with the Higgs field [1, 2, 3, 4, 5, 6, 7, 8, 9]. The precision electroweak measurements imply that the mass of Higgs boson m_H is below 152 GeV at 95% confidence level (CL) [10]. For a few decades scientists have been searching for this elusive particle : direct searches performed by LEP collider ruled out Higgs boson with m_H<114.4 GeV at 95% CL [11], while Tevatron results exclude mass range 162-166 GeV at 95% CL [12] and observe an excess of events, recently reported in [13, 14, 15], in the range 120-135 GeV. One of the major goals of LHC is to discover or exclude the Higgs boson. The results from the last year's direct searches at CMS excluded Higgs boson in mass range from 127 to 600 GeV at 95% CL, using data of total integrated luminosity of 5 fb^{-1} with a center of mass energy 7 TeV [16]. ATLAS experiment, using the same amount of data, perfomed same search and excluded Higgs boson at 95% CL in the range of 111.4 – 116.6, 119.4 – 122.1, and 129.2 – 541 GeV. Both experiments observed a slight excess of events near 125 GeV [17]. In 2012 the center of mass energy of proton-proton collisions was increased to 8 TeV, and significanly enhanced the sensitivity to Higgs boson search. The results presented below are a summary of searches performed on combined data, taken in 2011 and 2012. These include searches for Higgs boson in five decay modes: $\gamma\gamma$, ZZ, WW, $\tau^+\tau^-$, and $b\bar{b}$. The combined results indicate an excess of events of events above the expected background near 125 GeV. Excess has a local significance of 5.0 standard deviations (σ). This compares well with the expected significance for SM Higgs boson of 5.8 σ. The excess is most prominent in two final states: $H \rightarrow \gamma\gamma$ with a significance of 4.1 σ and $H \rightarrow ZZ$ with a significance of 3.2 σ. Observed new particle must be a boson with spin different from one, as it decays into a pair of photons. As most sensitivity comes from di-photon and ZZ modes, only searches for Higgs boson in these two decay modes will be described in details below, while the study of the other three decay modes are described briefly.

2. Search for $H \rightarrow \gamma\gamma$

An excellent energy resolution of photons at CMS makes the Higgs boson search to di-photon final state the most promising channels at low mass [18]. Nevertheless, the search is complicated by a small branching fraction and very large background, dominated by multijet processes, where jets are misidentified as photons.

Thus, the photon resolution is crucial in this study, so we employ boosted decision tree (BDT) [19, 20] algorithms to improve the photon energy scale using Monte Carlo (MC) simulation and cross check the procedure with $Z \to ee$ and $Z \to \mu\mu\gamma$ data events. As the resolution of photon energy depends on pseudorapidity, we split events into four non-overlapping event classes based on the photon pseudorapidity and the shape of the energy deposition of the photon candidates. Further improvement is achieved by categorizing events using a multivariant analysis technique (MVA) [21]. We use event-by-event mass resolution, photon identification discriminant, di-photon kinematic variables, and vertex identification probability in the BDT that results in a significant improvement in sensitivity. The further sensitivity is obtained by separately optimizing vector boson fusion (VBF) production process. Overall, compared to previous studies [21, 22, 23, 24, 25], we achieve an improvement on the combined exclusion sensitivity of approximately 10% in cross section by utilizing BDT, MVA, and above mentioned categorization.

We illustrate in Fig. 1 an invariant mass of di-photon candidates weighed on the event-by-event basis by $S/(S+B)$ [26] of the event's category. Here, S and B are the number of signal and background events obtained from simultaneous signal plus background best-fit on $\gamma\gamma$ invariant mass distribution to all categories. In the same figure we also show the unweighted distribution. In both cases we see an obvious excess in data with respect to smoothly falling background from multijet events. Here, the background shape is estimated by a polynomial fit to the di-photon mass spectrum in sidebands of the diphoton mass distribution in each of the categories. The background-only hypothesis indicate the expected 95% CL upper limits on the signal strength σ/σ_{SM} to be 0.75 near 125 GeV. The results are crosschecked with an independend sideband background model featuring the same observed limit.

The local p-value is defined as the probability of a background to fluctutate into the observed excess. This quantitiy, as a function of the mass of the Higgs boson for 7 and 8 TeV data and their combination, is shown in Fig. 2. The minimum local p-value in data occurs at $m_H \sim 125$ GeV and has a significance of 4.1 σ, while the expected significance is 2.8 σ. A production cross section times the relevant branching fractions, relative to the SM expectation is referred to as the signal strength and denoted as σ/σ_{SM}. The signal strength of best-fit obtained from a SM Higgs boson with mass 125 GeV hypothesis is $\sigma/\sigma_{SM} = 1.6 \pm 0.4$.

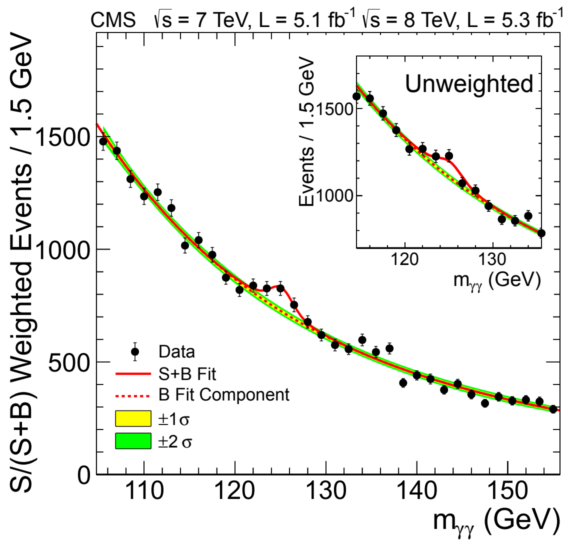

Figure 1: The di-photon invariant mass distribution with each event weighted by the $S/(S+B)$ value of its category. The lines represent the fitted background and signal, and the inset shows the central part of the unweighted invariant mass distribution.

3. Search for $H \to ZZ$

In The $H \to ZZ$ decay mode, signal has four well-isolated leptons in the final state - making this channel to stand out by having a very distinct signature that allows significantly suppressing most background processes. The later consist mainly of irreducible SM ZZ production and instrumental $Z+b\bar{b}$, $t\bar{t}$ production, where a final state contains two true leptons and two b jets that produce lepton candidates from B-meson decays. Additionally, small background comes from Z+jet and WZ+jet production, where jets are misidentified as leptons. However, background processes do not affect the sensitivity to Higgs boson signal as backgrounds result in a smooth four-lepton candidates invariant mass distribution, whereas the Higgs boson signal would result in a narrow peak. Thus, to increase the sensitivity to the Higgs boson production, we focus on optimizing the signal selection efficiency. This is achieved by lowering the thresholds on the transverse momentum p_T of the lepton candidates identified by very efficient MVA algorithms. We also treat analyses of $4e$, 4μ, and $2e2\mu$ final states separately, as these have different background rates and invariant mass resolutions. To further improve the sensitivity to the Higgs boson signal, an algorithm to recover the final state radiation photons is designed and used in this analysis.

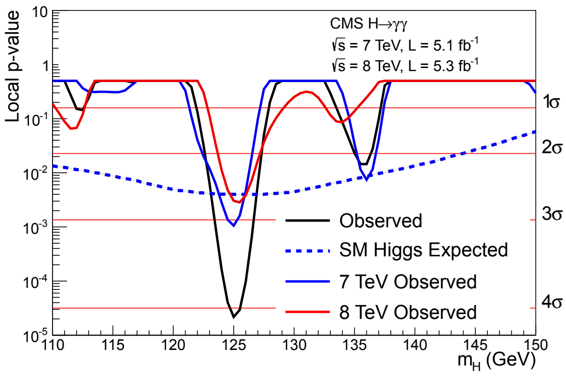

Figure 2: The local p-value as a function of m_H in the $\gamma\gamma$ decay mode for the combined 7 and 8 TeV data sets. The additional lines show the values for the two data sets taken individually. The dashed line shows the expected local p-value for the combined data sets, should a SM Higgs boson exist with mass m_H.

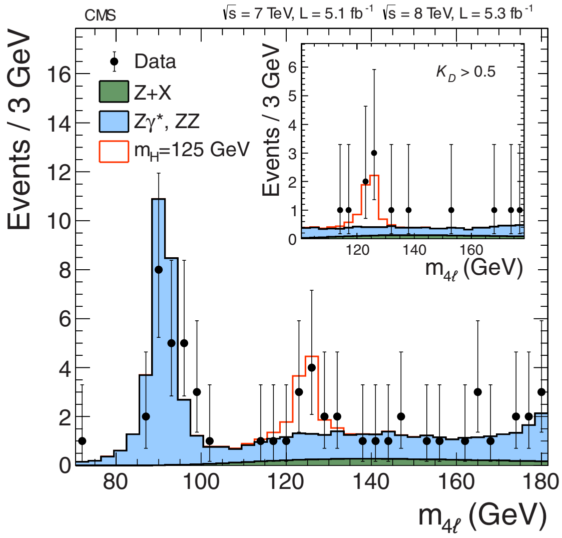

Figure 3: Distribution of the four-lepton invariant mass for the $ZZ \to 4l$ analysis. The points represent data, the filled histograms represent the background, and the open histogram shows the signal expectation for a Higgs boson of mass $m_H = 125$ GeV, added to the background expectation. The inset shows the $m_{4\ell}$ distribution after selection of events with $K_D > 0.5$, as described in the text.

The four lepton invariant mass distribution is shown in Fig. 3, where an excess is seen at 125 GeV.

A kinematic discriminant (K_D), exploiting the decay kinematics expected for the signal events, is used to provide a significant discriminating power between signal and background. The four lepton system is fully described by five angles and the di-lepton invariant masses (one for each Z boson) [27, 28, 29], thus a probability ratio of the signal and background hypothesis is constructed, $K_D = \mathcal{P}_{sig}/(\mathcal{P}_{sig} + \mathcal{P}_{bkg})$, as described in Ref. [30]. We perform six simultaneous two-dimensional (in $m_{4\ell}$ and K_D space) maximum-likelihood fits (two data sets and three decay modes) for each value of m_H.

We show local probability as a function of the mass of the Higgs boson for 7 and 8 TeV data and their combination in Fig. 4. The minimum local p-value in data occurs at $m_H = 125.6$ GeV and has a significance of 3.2 σ, while the expected significance is 3.8 σ. The best-fit signal strength for a SM Higgs boson mass hypothesis at the same mass point is $\sigma/\sigma_{SM} = 0.7^{+0.4}_{-0.3}$.

4. Search for Higgs boson in WW, $\tau\tau$ and $b\bar{b}$ channels

These three channels have less sensitivity to Higgs boson production with the current data samples, and therefore, we only provide a short summary of searches in these channels.

In $H \to WW$ channel, the 95% CL expected and observed limits for the combination of the 7 and 8 TeV analyses are shown in Fig. 5. A broad excess is observed across the mass range. Given the modest mass resolution in this channel, this excess is consistent with a SM Higgs boson with a mass around 125 GeV. This is illustrated by the dotted curve in Fig. 5 showing the median expected limit under the hypothesis of the presence of a SM Higgs boson with mass 125 GeV. The expected significance for a SM Higgs boson with mass 125 GeV is 2.4 σ and the observed significance is 1.6 σ.

In $H \to \tau\tau$ decay mode, the expected and observed 95% CL limits on the signal strength for the combination of all categories are shown in Fig. 6. The expected and observed limits are 1.3 and 1.1 times the SM Higgs boson cross section at mass 125 GeV, respectively. The expected significance for a SM Higgs boson with mass 125 GeV is 1.4 σ, and the observed value is zero σ.

In $H \to b\bar{b}$ channel, combined results for expected and observed 95% CL limits obtained from the 7 and 8 TeV data sets are displayed in Fig. 7. The expected and observed limits are 1.6 and 2.1 times the SM Higgs boson cross section at mass 125 GeV. The expected significance for a SM Higgs boson of mass 125 GeV corresponds to 1.9 σ, while the observed one corresponds to 0.7 σ.

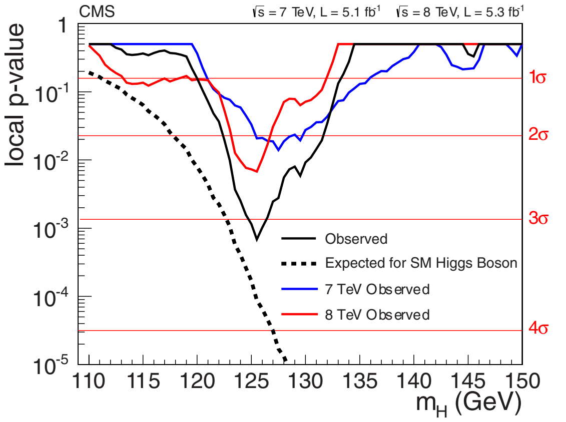

Figure 4: The observed local p-value for the ZZ decay mode as a function of the SM Higgs boson mass. The dashed line shows the expected local p-values for a SM Higgs boson with a mass m_H.

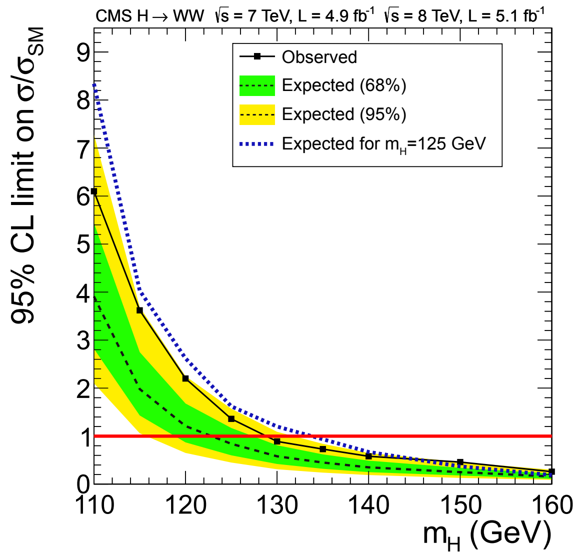

Figure 5: The 95% CL limit on $\sigma/\sigma_{\rm SM}$ for a Higgs boson decaying, via a W boson pair, to two leptons and two neutrinos, for the combined 7 and 8 TeV data sets. The symbol $\sigma/\sigma_{\rm SM}$ denotes the production cross section times the relevant branching fractions, relative to the SM expectation. The background-only expectations are represented by their median (dashed line) and by the 68% and 95% CL bands. The dotted curve shows the median expected limit for a SM Higgs boson with m_H = 125 GeV.

5. Combined results

The results from each individual channel analysed are combined using the modified frequentist criterion $\mathrm{CL_s}$ [31, 32]. In combination, we assume the relative branching fractions predicted by the SM and take into account all statistical and systematic uncertainties, as well as the theoretical uncertainties. The $\mathrm{CL_s}$ is shown in Fig. 8 as a function of the Higgs boson mass hypothesis. The observed values are shown by the solid points. The dashed line indicates the median of the expected results for the background-only hypothesis and shaded regions reflect the ranges in which the $\mathrm{CL_s}$ values lie in 68% and 95% CL with the background-only hypothesis. The probabilities of background-only hypothesis to fluctuate into observationfor at the 68% (95%) CL are 16% (2.5%) each. The thick horizontal lines indicate $\mathrm{CL_s}$ values of 0.05, 0.01, and 0.001. The mass regions where the observed $\mathrm{CL_s}$ values are below these lines are excluded with the corresponding $(1 - \mathrm{CL_s})$ confidence levels, resulting in new exclusion range of Higgs boson with $110 < m_H < 121.5$ GeV at 95% CL. A significant excess is observed in mass range $121.5 < m_H < 128$ GeV and the SM Higgs boson cannot be excluded at 95% CL.

In Fig. 9 we show a scan of the local p-value for each decay modes and combined p-value. Overall combination has significance of 5.0 σ for m_H = 125.5 GeV. The largest contribution comes from $\gamma\gamma$ and ZZ channels, as they both are high mass resolution decay modes. The excess indicates the observation of a new particles with mass near 125 GeV. A new particle must be a boson with spin other than one, as it decays into two photons [33, 34].

The mass of the observed particle is determined using the ZZ and $\gamma\gamma$ decay modes, the later one is split in untagged and di-jet tagged categories. The precision of this measurement is dominated by ZZ channel. A fit on invariant mass is performed. In order to decrease the model dependence the fit allows the signal strength to float. The combined best-fit mass is $m_X = 125.3 \pm 0.4$ (stat.) $\pm$ 0.5 (syst.) GeV. In Fig. 10 we display the two-dimensional 68% CL regions of the signal strength σ/σ_{SM} and m_X. The results from all three channels are compatible within uncertainties.

The scan of signal strength for combined results as a function of SM Higgs boson is provided in Fig. 11. The band corresponds to the $\pm1\sigma$ fluctuation. The results indicate that the observed particle is compatible with the SM Higgs boson with mass of 125 GeV within ±1 σ. The results illustrated in Fig. 12 indicate that the results in all analyzed channels are compatible with each other.

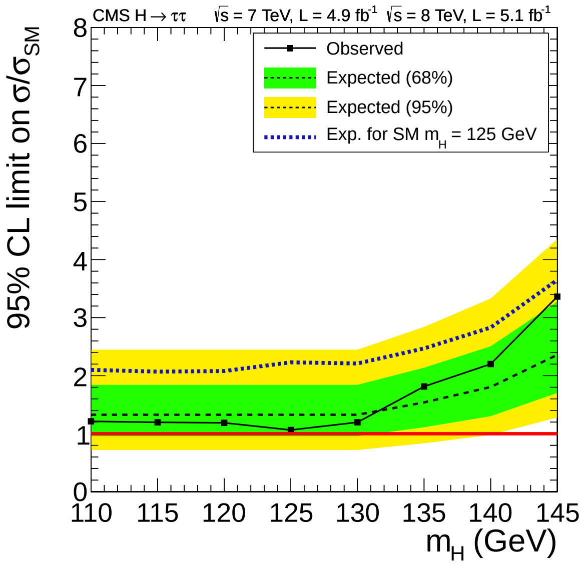

Figure 6: The 95% CL limit on the signal strength $\sigma/\sigma_{\rm SM}$ for a Higgs boson decaying to τ pairs, for the combined 7 and 8 TeV data sets. The symbol $\sigma/\sigma_{\rm SM}$ denotes the production cross section times the relevant branching fractions, relative to the SM expectation. The background-only expectations are represented by their median (dashed line) and by the 68% and 95% CL bands. The dotted curve shows the median expected limit fo r a SM Higgs boson with $m_H = 125$ GeV.

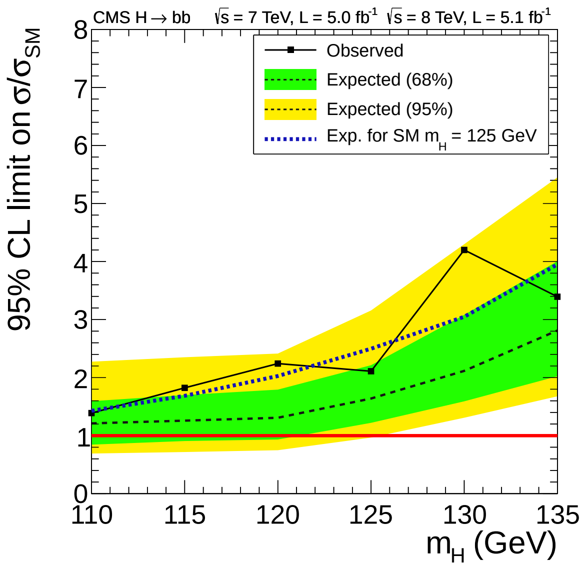

Figure 7: The 95% CL limit on the signal strength $\sigma/\sigma_{\rm SM}$ for a Higgs boson decaying to two b quarks, for the combined 7 and 8 TeV data sets. The symbol $\sigma/\sigma_{\rm SM}$ denotes the production cross section times the relevant branching fractions, relative to the SM expectation. The background-only expectations are represented by their median (dashed line) and by the 68% and 95% CL bands. The dotted curve shows the median expected limit for a SM Higgs boson with $m_H = 125$ GeV.

6. Conclusions

The results of the SM Higgs boson search in CMS experiment are presented using the proton proton collisions data at 7 TeV (5 fb^{-1}) and 8 TeV (5 fb^{-1}). Five decay modes of Higgs boson are analysed - $\gamma\gamma$, ZZ, WW, $\tau^+\tau^-$, and $b\bar{b}$. We observe a new particle with the invariant mass of about 125 GeV with local significance of 5 σ. This agrees well with the SM Higgs boson expected significance of 5.8 σ. The excess is most prominent in $\gamma\gamma$ and ZZ decay modes, as these two have the best mass measurement resolution, compared to other channels. A fit to these two channels results in a mass measurement of a new particle to be 125.3 ± 0.4 (stat.) ± 0.5 (syst.) GeV. Two photon decay indicated that observed particles is a boson with spin different from one. The presented results show that new particles if fully consistent within uncertainties with the SM Higgs boson particle.

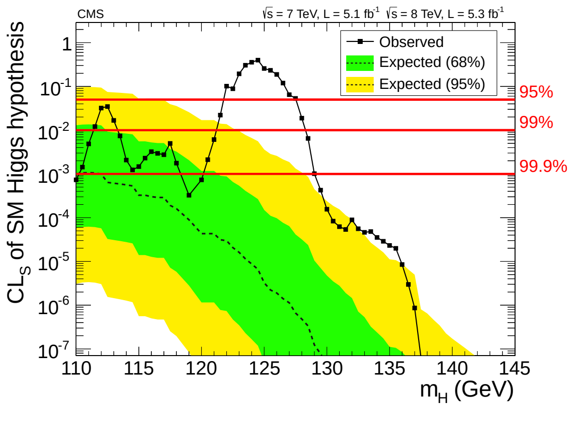

Figure 8: The $\mathrm{CL_s}$ values for the SM Higgs boson hypothesis as a function of the Higgs boson mass in the range 110-145 GeV. The background-only expectations are represented by their median (dashed line) and by the 68% and 95% CL bands.

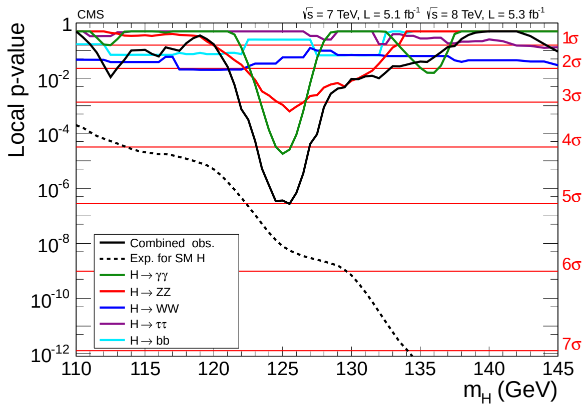

Figure 9: The observed local p-value for the five decay modes and the overall combination as a function of the SM Higgs boson mass. The dashed line shows the expected local p-values for a SM Higgs boson with a mass m_H.

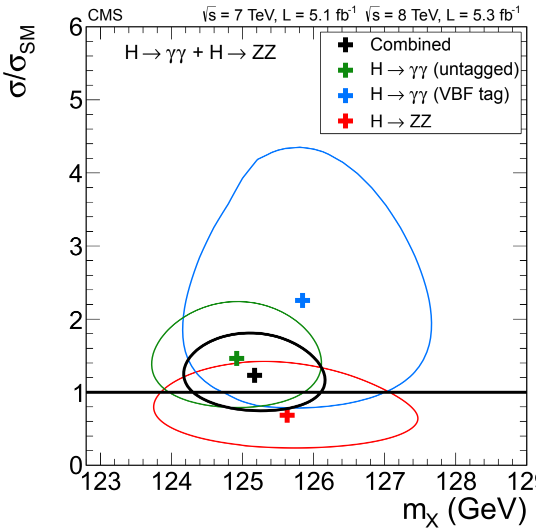

Figure 10: The 68% CL contours for the signal strength σ/σ_{SM} versus the boson mass m_X for the untagged $\gamma\gamma$, $\gamma\gamma$ with VBF-like dijet, 4ℓ, and their combination. The symbol σ/σ_{SM} denotes the production cross section times the relevant branching fractions, relative to the SM expectation. In this combination, the relative signal strengths for the three decay modes are constrained by the expectations for the SM Higgs boson.

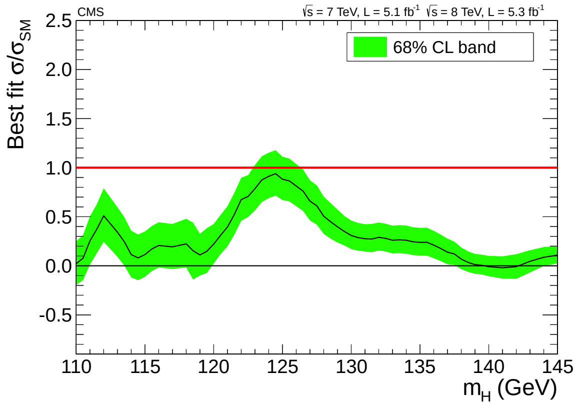

Figure 11: The observed best-fit signal strength $\sigma/\sigma_{\rm SM}$ as a function of the SM Higgs boson mass in the range 110-145 GeV for the combined 7 and 8 TeV data sets. The symbol $\sigma/\sigma_{\rm SM}$ denotes the production cross section times the relevant branching fractions, relative to the SM expectation. The band corresponds to the ± 1 standard deviation uncertainty in $\sigma/\sigma_{\rm SM}$.

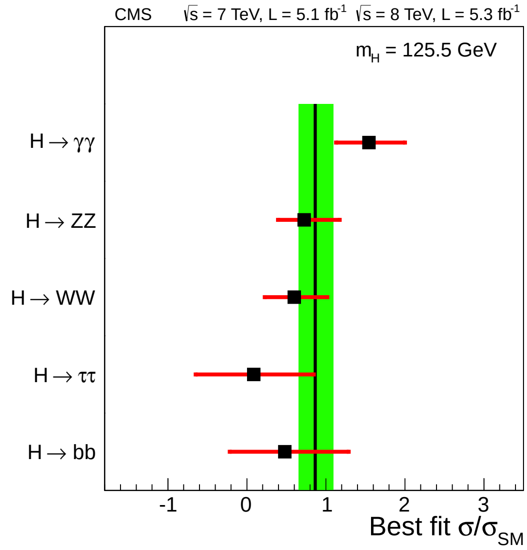

Figure 12: Values of σ/σ_{SM} for the combination (solid vertical line) and for individual decay modes (points). The vertical band shows the overall σ/σ_{SM} value 0.87 ± 0.23. The symbol $\sigma/\sigma_{\rm SM}$ denotes the production cross section times the relevant branching fractions, relative to the SM expectation. The horizontal bars indicate the ± 1 standard deviation uncertainties in the σ/σ_{SM} values for individual modes; they include both statistical and systematic uncertainties.

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