Searches for Standard Model Higgs boson at CMS

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A search for the Standard Model Higgs boson has been performed by the CMS Collaboration, with the full dataset delivered by the LHC during the 2011, in a wide spectrum of channels. The statistical combination of the results allows to exclude a wide region of its mass at 95% confidence level: 127.5 – 600 GeV/c^2. A modest excess at about 125 GeV/c^2 is observed, with a significance of 1.6 σ in the range 110 – 150 GeV/c^2. More data are needed to ascertain the origin of the observed excess.

Standard Model (SM) Higgs boson (H) searches are of primary importance in the analysis of the first data delivered by the LHC, since they can lead to the understanding of the electroweak symmetry breaking mechanism, which gives elementary particles their mass [1, 2, 3, 4].

The CMS experiment [5], one of the two multi-purpose detectors installed at the LHC pp collider at CERN, features a 3.8 T magnetic field parallel to the beam axis, generated by a super-conducting solenoid of 6 m diameter and 13 m length, which hosts the central tracking and calorimetry detectors of the experiment. The former is composed by ten layers of silicon pixels or strips, while the latter is subdivided into a fine-grained scintillating crystals homogeneous detector to detect electromagnetic showers, and a segmented brass-plastic scintillators calorimeter, measuring hadronic showers. Outside the solenoid, and placed in the iron return yoke of the magnetic field, gas detectors measure the passage of muons produced in the interactions.

Events produced by the beam collisions are triggered by means of a two-layers system: the first one reduces the rate by three orders of magnitude by means of dedicated electronics; the second one, running on a farm of commercial PCs, selects the events after a fast reconstruction and event analysis, and by gaining other three orders of magnitude brings the rate at the level of few hundreds events per second.

During the offline analysis and the last phase of the triggering, physics objects produced by the collisions are reconstructed in the detector from the measurement of each single particle flowing in the CMS volume, with a particle flow approach [6].

The CMS experiment collected about 5 fb^{-1} of data, that have been analyzed to search for the Higgs boson in its decay into several final states, which cover a wide range of the expected Higgs boson mass: in case it does not exist, the corresponding expected exclusion range with the available statistics is 114.5 – 543 GeV/c^2 at 95% confidence level. Such a large coverage is obtained thanks to the statistical combination of the results obtained in each of the sub-channels studied, where a modified CL$_S$ technique is applied to extract limits [7].

At low mass, above the 114.4 GeV/c^2 limit set by LEP [8], the most sensitive channel is $\mathrm{H} \to \gamma\gamma$ [9, 10], which despite the low expected rate is very well identified using the characteristic signature of two isolated photons resonating in a narrow peak, thanks to the excellent energy resolution of the electromagnetic calorimeter. The two decay products are selected vetoing charged activity in their neighborhood, from the shape of their energy deposit and with p_T cuts relative to their invariant mass. The vertex they originate from is chosen, among the various interactions that happen during a LHC bunch crossing, by looking at tracks in the event. The collected events are divided into five different categories, four of which are chosen as a function of photon reconstruction resolution, goodness of identification and kinematics of the di-photon system. The last one exploits the vector boson fusion (VBF) signature, where the Higgs boson is produced together with two energetic jets well separated in pseudorapidity. The continuum background to the Higgs signal, mainly due to QCD di-photon or photon+jet production, is modeled using a polynomial fit to the observed di-photon mass spectrum. As the expected sensitivity of the analysis does not allow to exclude the SM Higgs, the observed exclusion range at 95% confidence level depends on the statistical fluctuations of data with respect to the predictions, and translates into several disjoint intervals: 110.0 – 111.0, 117.5 – 120.5, 128.5 – 132.0, 139.0 – 140.0, 146.0 – 147.0 GeV/c^2 (see Figure 1). Among the non-excluded sections, around the value of 125 GeV the probability that the background fluctuation produces a signal (the p-value) corresponds to a local discovery significance of 2.8 σ.

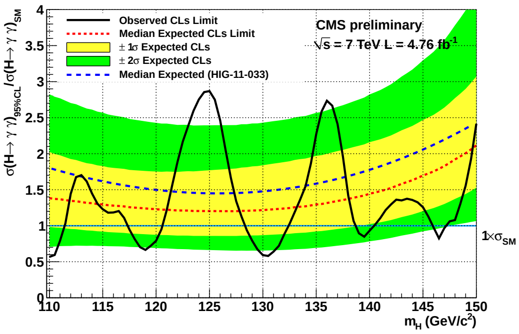

Figure 1: The exclusion limit obtained with the H $\rightarrow \gamma\gamma$ search.

Another resonance searched in the low Higgs mass range is the decay into two τ leptons, in the fully- and semi-leptonic τ final states [11]. Events are selected with a p_T selection on the τ candidates and the major background due to Z boson production is measured by selecting Z bosons decaying into muons and substituting the muons for simulated τs. Also in this case, events are subdivided into categories, depending on the number of observed jets: no jets, one boosted jet ($p_T > 150$ GeV) and two jets in the VBF topology. The most sensitive channel is the VBF one. The $\tau\tau$ channel alone is not able and exclude the SM higgs boson, but it contributes to final exclusion in combination with the other analyses.

Also the Higgs decay into two b quarks has been exploited [12], selecting the two b candidates by tagging tracks with large impact parameter in the jets detected in each event. The huge QCD di-jet background is reduced by searching for the associated production of a Higgs boson with a W or Z boson, the decay products of which have to be present in the event (electrons, muons or neutrinos as unbalanced energy in the transverse plane with respect to the beam direction). In addition, the vector boson is required to be boosted. As for the $\tau\tau$ channel, results obtained from this study do not put an exclusion limit to the SM Higgs boson, but contribute to the global CMS limit.

As its mass increases, the Higgs boson primarily decays into a pair of vector bosons. Similarly to the $\gamma\gamma$ case, the final state with two Z bosons decaying leptonically [13] shows a very clean signature, characterized by four isolated leptons with appropriate flavour and charge combinations, so that one of the two pairs can be required not to be on-shell. Also in this case, the invariant mass resolution of the Higgs resonance is very good. The main background to fight is the electro-weak production of Z boson pairs, which is estimated from simulation. The low background level of this channel makes it a powerful probe to test a very wide mass range, resulting in an observed exclusion at 95% confidence level in the following intervals: 134 –158, 180 – 305 and 340 – 465 GeV/c^2. The inaccessible window between 158 and 180 GeV/c^2 is due to the decrease in cross section for this channel, because of the competition with the decay into WW, while the other inaccessible window is determined by a statistical fluctuation of data with respect to the expectations. The largest excess is observed at 119.5 GeV/c^2, that corresponds to a local significance of 2.5 σ.

The H $\to$ WW $\to \ell\nu\ell\nu$ analysis [14] complements the ZZ one along the Higgs mass spectrum. The final state is characterized by the presence of two oppositely charged, isolated leptons and missing energy due to neutrinos escaping CMS. The main backgrounds are due to the electroweak production of WW pairs and top pairs, as well as Z production with jets. Besides this, QCD dijet and W + jets production can contaminate the signal region, because of misidentification of jets as leptons: the huge cross section of the backgrounds balances the small misidentification probability. Dedicated treatment of the missing energy reconstruction is necessary to suppress the Z + jets background. The analysis is performed separately in the no-jets case, one jet case and two jets case with VBF topology. While profiting of the highest cross-section over a wide mass range, this study suffers from the presence of the two neutrinos in the final state, that prevents the invariant mass reconstruction of the Higgs resonance. Therefore, the resolution in the exclusion limit is much worse with respect to the ZZ or $\gamma\gamma$ cases, and all the backgrounds have been carefully measured in signal-free regions in data, as no invariant mass fit can be performed to identify the signal. The Higgs mass range excluded at 95% confidence level by this study is 129 – 270 GeV/c^2.

The most powerful exclusion at higher Higgs masses is provided by the H $\to$ ZZ $\to 2\ell 2\nu$ [15]. The final state of this analysis is identified as a same-flavour, opposite-charge high-p_T leptons pair consistent with the Z boson mass, and large missing energy due to neutrinos. The WW and ZZ backgrounds that contaminate the signal region are estimated from control regions with opposite-flavour lepton pairs, while the Z + jets one, which depends on the missing energy reconstruction in the detector, is modeled by kinematically reweighting a γ + jets sample. The resulting excluded 95% confidence level range is 270 – 440 GeV/c^2. Also the H $\to$ WW $\to \ell\nu\ell\nu$, the H $\to$ ZZ $\to 4\ell$ and the H $\to$ ZZ $\to 2\ell 2q$ [16] play an important role in the high mass regime. In particular, the latter searches for a pair of opposite charge same flavour leptons, together with two jets resonating at the Z mass, and the Z+jets background is evaulated from sidebands in the m_{jj} spectrum.

The results of all the CMS Higgs analyses [17, 18] have been combined with the frequentist LHC-type CL$_S$ with profiled likelihood test-statistics and log-normal treatment of nuisance parameters. The obtained exclusion limits are, for 95% confidence level, 127.5 – 600 GeV/c^2, and for 99% confidence level 129 – 525 GeV/c^2, as shown in Figure 2 on the left.

The observed limit on the high mass side is larger than expected, because of a down-fluctuation of data, while the lower limit is higher than expected because of excess in data at low mass. The smallest p-value observed is situated at 125 GeV/c^2 and corresponds to a global significance of 0.8 σ when considering the full investigated range for the look-elsewhere effect

(110 – 600 GeV/c^2), while it becomes 1.6 σ in a narrower range (100 – 150 GeV/c^2). To check the compatibility of this deviation with the SM, a global fit is performed on the results of all the analyses with signal-plus-background hypothesis, where the free parameter is a multiplicative factor to the signal cross section (the signal strength). The result of the fit is shown in Figure 2 on the right, as a function of the Higgs mass. when looking at the 125 GeV/c^2 point, the fit has been also performed in single channels and the maximum of the signal strengths compared. All the final states are compatible with the SM hypothesis.

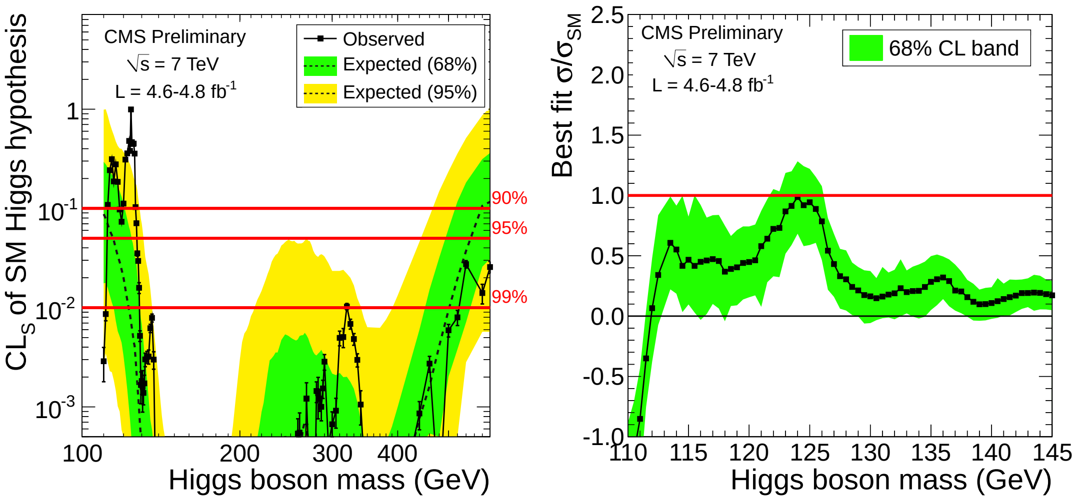

Figure 2: The confidence level of exclusion for the SM Higgs as a function of its mass (left), and the best fit of the signal strength, in the low region of the investigated invariant mass spectrum (right).

In conclusion, the full dataset acquired by CMS during 2011 has been studied searching for the SM Higgs boson, with a broad range of Higgs decay channels. The global combination of the analyses outcomes excludes the Higgs boson at 95% confidence level in the 127.5 – 600 GeV/c^2 mass range. A modest excess at about 125 GeV/c^2 is observed, with a local significance 2.8 σ, and a global one of 0.8 σ (1.6 σ) in the full search range (in 100 – 150 GeV/c^2 range). More data are required to ascertain the origin of the observed excess.

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