PROCEEDINGS OF SCIENCE

Study of Higgs Production in Bosonic Decay Channels at CMS

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ATLAS and CMS have recently reported the observation of a new bosonic state near a mass of 125 GeV, compatible with the Standard Model Higgs boson. In this article we report on the most recent results of the searches in the bosonic decay channels with the full 7 and 8 TeV datasets recorded by the CMS detector. Emphasis is given to the channels W^+W^-, ZZ and $\gamma\gamma$ which are the most sensitive ones in this mass region.

XXI International Workshop on Deep-Inelastic Scattering and Related Subjects -DIS2013,
22-26 April 2013
Marseilles, France

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PoS(DIS 2013)094

1. Introduction

The Higgs mechanism was proposed nearly 50 years ago [1–4] to allow gauge bosons to acquire mass while keeping gauge field theories renormalizable. The ATLAS [5] and CMS [6] collaborations have recently discovered a new boson at a mass of about 125 GeV which is a good candidate for the Standard Model Higgs Boson. While the Higgs mechanism is also used to make the fermion mass terms gauge invariant, this article focuses on recent results of the analyses searching for decays of the Higgs boson into pairs of W, Z bosons or photons using the full 7 and 8 TeV datasets recorded with the CMS detector [7]. The expected branching ratios at $m_{\mathrm{H}} = 125$ GeV are 21.5% / 2.64% / 0.228% for the WW* / ZZ* / $\gamma\gamma$ decay modes respectively [8].

Table 1 gives an overview of searches for bosonic decay modes performed by the CMS collaboration which are not discussed in more detail here. None of these searches found a significant excess above the expected background.

Decay Mode	Search mass range [GeV]	Int. Lumi. [fb^{-1}]		Reference
		7 TeV	8 TeV	
$\mathrm{H} \to \mathrm{ZZ} \to 2\ell 2\nu$	200 - 1000	5.0	19.6	[9]
$\mathrm{H} \to \mathrm{ZZ} \to 2\ell 2j$	130 - 600	4.6	-	[10]
$\mathrm{H} \to \mathrm{W^+W^-} \to \ell\nu jj$	170 - 600	5	12	[11]
$\mathrm{H} \to \mathrm{W^+W^-} \to \ell\nu jj$	600 - 1000	-	19.3	[12]
$\mathrm{H} \to \mathrm{Z}\gamma$	120 - 150	5.0	19.6	[13]
$\mathrm{WH} \to \mathrm{WWW} \to 3\ell 3\nu$	110 - 200	4.9	19.5	[14]

Table 1: List of searches for bosonic decay modes of the Standard Model Higgs boson performed within CMS. While the Zγ mode covers the mass range around 125 GeV, its sensitivity is at least six times above the expected Standard Model Higgs production rate. The WH $\to$ WWW search has a sensitivity three times above the Standard Model Higgs rate at 125 GeV.

2. WW fully leptonic channel

This channel, when both of the W decay into leptons, is characterized by a relatively high branching ratio but poor mass resolution. The selection requires two isolated, oppositely charged, high transverse momentum electrons or muons and large missing transverse momentum [15]. The analysis rejects events with more than two identified jets.

One of the main backgrounds comes from non-resonant production of W pairs. A key variable to discriminate the signal from this background is the angle between the two leptons in the plane transverse to the beam direction. This angle is expected to be smaller on average for the signal than for the background because the leptons (antileptons) are preferably produced parallel (anti-parallel) to the direction of flight of the W^- (W^+) boson due to the polarization of the W bosons originating from a spin 0 particle decay.

The analysis distinguishes events where both leptons have same flavour (e^+e^- and $\mu^+\mu^-$) or different flavour ($e^\pm\mu^\mp$). For the same flavour class, a final set of cuts on the two lepton transverse momenta, the dilepton mass, the azimuthal angle between the leptons and the transverse mass are used before confidence levels are calculated based on the number of observed events. For the different flavour class, the two dimensional distributions of transverse mass versus the dilepton mass are used to quantify the outcome of the search.

At 125.7 GeV, CMS observes a 3.9σ excess in the data over the background, corresponding to a signal cross section of 0.68 ± 0.20 times the Standard Model Higgs prediction.

3. Diphoton channel

Despite its small branching ratio (below 1%) it is possible to reach a signal to background ratio close to one at reasonable signal efficiency. In addition, unlike with the WW fully leptonic channel, the Higgs candidate mass can be fully reconstructed.

The main backgrounds are non-resonant production of photon pairs and single photons produced in association with a jet which is misidentified as a photon (e.g. when a π^0 with high transverse energy carries a large fraction of the jet's energy).

At a given efficiency, the required integrated luminosity for a 5σ discovery is inversely proportional to the *square* of the diphoton mass resolution. The latter is determined by the single photon energy resolution and the resolution of the angle between the two photons. To achieve the best possible photon energy resolution, in addition to relying on in-situ detector calibration, a boosted regression tree has been trained to estimate a correction factor to the standard reconstructed photon energy based on additional information such as the location of the electromagnetic cluster in the detector, shower shape variables, ratio of hadronic to electromagnetic energy, the number of reconstructed primary vertices and the median energy density in the event [16]. The resolution of the angle between the two photons is mainly determined by the resolution of the reconstruction of the position of the hard interaction vertex. A boosted decision tree (BDT), using variables based on the transverse momenta of the diphoton system and the tracks in the event, is used to select the interaction vertex among the reconstructed primary vertices.

For the selection and ranking diphoton events, the main analysis relies on a BDT (based on kinematic variables, the estimated diphoton resolution and the output of the photon identification BDT for the two photons) and groups the selected events into four categories depending on the BDT response.

A cut based control analysis groups events into four categories based on whether both photons are observed in the barrel or not and based on the fraction of energy in the most energetic 3x3 crystal region (which is expected to be lower for converted photons).

In addition to the inclusive categories mentioned so far, the analyses also put events with two back to back forward jets (to enrich the vector boson fusion production mechanism) and events with electrons, muons or significant missing transverse energy (to enrich the WH and ZH production mechanisms) into separate categories.

In all cases, the background is determined from a fit of a polynomial to the data. The p-value (probability for the background to generate a signal like fluctuation like the data observed) as function of the Higgs mass hypothesis is shown in Figure 1. The observed significance at 125.7 GeV is 3.2σ and the ratio of the observed to the expected Higgs signal cross section is 0.77 ± 0.27.

Recently, a dedicated search for production of Higgs bosons (decaying into two photons) in association with a pair of top quarks was made public [17]. This analysis uses the full 8 TeV dataset

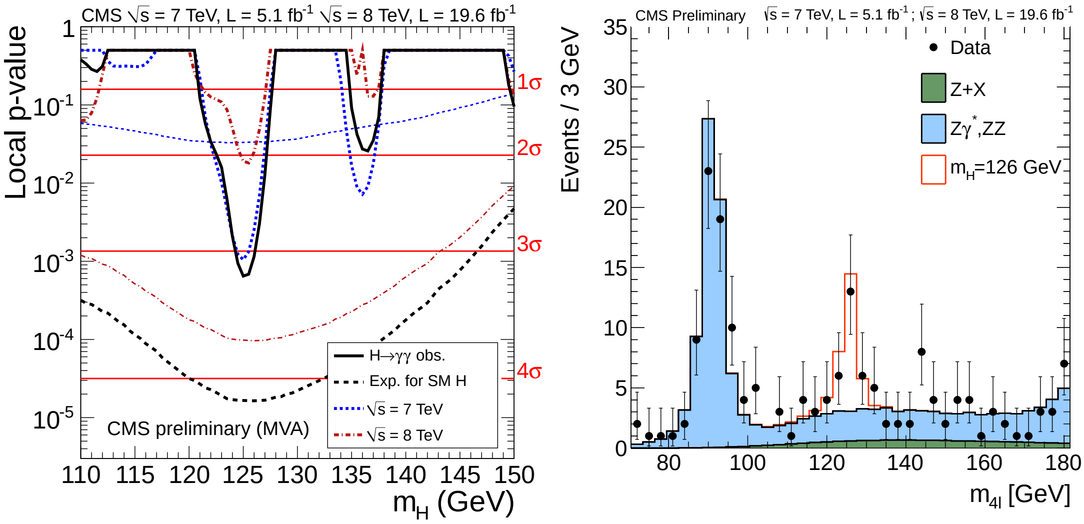

Figure 1: P-values for the $\gamma\gamma$ decay mode as function of the Higgs mass hypothesis (left) and four lepton mass distribution in the ZZ fully leptonic channel (right).

and sets an upper limit on the cross section times branching ratio at 5.4 times the Standard Model prediction, in agreement with the expected sensitivity.

4. ZZ to four charged leptons channel

This channel is often referred to as the 'golden channel'. Despite having a relatively low branching ratio, the full kinematics of the Higgs decay can be reconstructed (as in the case of the $\gamma\gamma$ channel) but in addition the angles of the leptons from the Z decays contain further information on the spin state of the Higgs candidate.

The selection requires four isolated, prompt, high transverse momentum leptons out of which one pair can be reconstructed τ candidates [18]. The analysis separates events with at most one selected jet and at least two selected jets into separate categories. The latter is designed to enrich the sample in Higgs events produced via vector boson fusion.

The mass distribution at the level of the final selection is shown in Figure 1. The peak around 125 GeV is clearly visible. The peak at the Z mass, originating from decays of single Z bosons into *four* charged leptons, constitutes a confirmation of the sensitivity of the analysis and has been measured in [19].

The significance in terms of fluctuations of the background to the observed data and the signal strengths are extracted from a likelihood function in three variables: the reconstructed mass, a discriminant built from signal and background matrix elements (based on decay angles), and the transverse momentum of the Higgs candidate divided by the four-lepton mass (≤ 1 jet category) or a linear discriminant in the dijet mass and the difference in pseudorapidity of the two leading jets in the case of at least two jets.

The fitted signal strength is 0.92 ± 0.28 times the predicted Standard Model Higgs value and the significance of the excess with respect to the background only hypothesis is 6.7σ.

Channel	Expected significance	Observed significance	σ/σ_{SM}
WW	5.3	3.9	0.68 ± 0.20
$\gamma\gamma$	3.9	3.2	0.77 ± 0.27
ZZ	7.1	6.7	0.92 ± 0.28

Table 2: Expected and observed significances and measured cross section ratio (with respect to the Standard Model prediction) at $m_H = 125.7\,\text{GeV}$ for the bosonic search channels sensitive at this mass.

5. Conclusions and outlook

We reported on decays of the new state near 125 GeV into pairs of bosons. The WW $\to \ell\nu\ell\nu$, ZZ $\to \ell\ell\ell\ell$ and $\gamma\gamma$ channels all show excesses above the background which are consistent with the Standard Model Higgs boson with a mass of about 125 GeV. Table 2 summarizes the observed signal strengths in the relevant bosonic channels at the mass measured by CMS (125.7 GeV) [20].

After the current long shutdown, LHC is expected to resume proton collisions at a centre-of-mass energy of 13-14 TeV which will raise cross sections for gluon induced processes (such as the dominant production mechanism for Higgs Bosons) more than those for quark induced processes (most of the backgrounds). With enough integrated luminosity, this will allow to establish 5σ significances in individual channels and to more precisely determine spin and couplings of the new boson.

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