

# Search for Standard Model Higgs boson using the $H \rightarrow ZZ \rightarrow 2l2\nu$ channel in pp collisions at CMS

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**Abstract.** A search for the Standard Model (SM) Higgs boson in pp collisions at the LHC at a center-of-mass energy of 7 TeV is presented. The results are based on a data sample corresponding to an integrated luminosity of  $1.6 \text{ fb}^{-1}$  recorded by the CMS experiment. The search is conducted in the decay channel  $H \rightarrow ZZ \rightarrow 2l2\nu$ . No excess is observed in the transverse mass distributions. Limits are set on the production of the Higgs boson in the context of the Standard Model and in the presence of a sequential fourth family of fermions with high masses.

## 1 Introduction

The search for the SM Higgs boson and its discovery are central to the goals of the experiments at the LHC. The primary production mechanism of the Higgs at the LHC is gluon fusion with the small contribution from vector boson fusion. This note presents search for SM Higgs boson in the  $H \rightarrow ZZ \rightarrow 2l2\nu$  channel which is sensitive to Higgs searches in the high mass range ( $250 - 600 \text{ GeV}/c^2$ ). The branching fraction of this decay channel is about six times higher than that of golden channel  $H \rightarrow ZZ \rightarrow l^+l^-l^+l^-$ . This may lead to better sensitivity to SM Higgs boson production at higher masses, where background can be effectively suppressed kinematically.

## 2 Event Selection

Since, this analysis is carried out for Higgs mass above  $250 \text{ GeV}/c^2$  so  $H \rightarrow ZZ \rightarrow 2l2\nu$  event is characterized by the presence of a boosted Z boson decaying to  $e^+e^-$  or  $\mu^+\mu^-$  and large missing transverse energy (MET) arising from the decay of the other Z boson into neutrinos. Muons are measured with the silicon tracker and the muon system [3]. Further identification criteria based on the number of hits in the tracker and muon system, the fit quality of the muon track and its consistency with the primary vertex, are imposed on the muon candidates to reduce fakes. Electrons are detected in the ECAL as energy clusters and as tracks in the tracker [4]. These reconstructed electrons are further required to pass certain identification criteria based on the ECAL shower shape, track-ECAL cluster matching and consistency with the primary vertex. They are measured in pseudorapidity range  $|\eta| < 2.4$  for muons and  $|\eta| < 2.5$  for electrons, though for electrons the transition range between the barrel and endcap,  $1.44 < |\eta| < 1.57$ , is excluded. Events are selected such that there are two well-identified, isolated, opposite charge leptons of the same flavor with  $p_T > 20 \text{ GeV}/c$  that form an invariant mass consistent with

Z mass. With this selection the principal backgrounds in this analysis are:

- **Z+jets:** with fake missing transverse energy due to jet mismeasurement and detector effects.
- **Non-Resonant**(i.e., events without a Z resonance): top decays, fully leptonic  $WW$  decays,  $W$ +jets with a fake lepton.
- **Irreducible:** electroweak  $ZZ$  pair production and fully leptonic decays of  $WZ$  pairs.

The other selection variables which are used in this analysis are as follows-

- **B-tagging and soft-muon veto:** Since top quark events contain b-jets, this background can be suppressed by vetoing events with at least one b-tagged jet. B jets are tagged using "Track Counting High Efficiency" (TCHE) algorithm [5] which uses displaced track in a jet to compute a b-tagging discriminator. In addition to the b-jet veto, a soft muon veto is applied to further suppress top events in which b-quarks decay leptonically [6].
- **Third lepton veto:** In order to suppress the  $WZ$  background in which the both  $W, Z$  decay leptonically, events are required to have exactly two leptons in the event with  $p_T > 10 \text{ GeV}/c$ .
- **MET:** Particle flow MET [7] is used in the analysis. The hard cut on MET mainly suppresses Drell-Yan background which has very less real missing energy.
- $\Delta\phi(\text{MET}, \text{jet})$ : To suppress backgrounds with MET coming from jet mis-measurements, events in which the MET is aligned with a jet are removed using a cut on  $\Delta\phi(\text{MET}, \text{jet})$  variable.
- **Transverse mass of Higgs ( $M_T$ ):** Signal events have a narrower  $M_T$  distribution. A two-sided cut is applied on the  $M_T$  variable to further separate signal with respect to the background.

The details of the cut values are in Table 1. MET,  $\Delta\phi(\text{MET}, \text{jet})$ ,  $M_T$  cuts are Higgs mass dependent Table 2. The cuts for these variables have been optimized with GARCON [8].

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**Table 1.** Event selection cuts.

Cut	Cut Value
Lepton $p_T$	$p_T > 20\text{GeV}/c$
Z mass window	$ m_{ll} - 91.1876  \leq 15\text{GeV}/c^2$
Z $p_T$	$Z_{p_T} > 25\text{GeV}/c$
b-tag veto	TCHE discriminator $< 2$
$\Delta\phi(\text{MET}, \text{jet})$	see Table 2
MET	see Table 2
$M_T$	see Table 2

**Table 2.** Higgs mass-dependent  $\Delta\phi(\text{MET}, \text{jet})$ , MET (GeV), and  $M_T$  (GeV/ $c^2$ ) cuts optimized using GARCON.

$M_H(\text{GeV}/c^2)$	$\Delta\phi(\text{MET}, \text{jet})$	MET	$M_T$
250	$> 0.62$	$> 69$	$> 216$ AND $< 272$
300	$> 0.28$	$> 83$	$> 242$ AND $< 320$
350	$> 0.14$	$> 97$	$> 267$ AND $< 386$
400	$> -$	$> 112$	$> 292$ AND $< 471$
450	$> -$	$> 126$	$> 315$ AND $< 540$
500	$> -$	$> 141$	$> 336$ AND $< 600$
550	$> -$	$> 155$	$> 357$ AND $< 660$
600	$> -$	$> 170$	$> 377$ AND $< 720$

### 3 Background Estimation

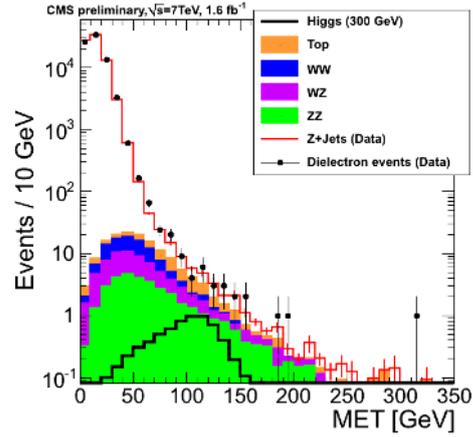
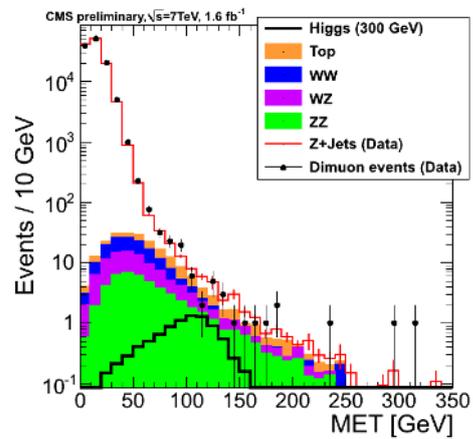
ZZ/WZ backgrounds are modeled using simulation, while the remaining backgrounds (Z+jets and all non-resonant ones) are estimated using the data-driven methods described below.

#### 3.1 Z+jets Estimation

Photon+jets ( $\gamma$ +jets) events are used to estimate the Z+jets events in data because both processes have same MET response from detector and  $\gamma$ +jets have higher cross section than that of Z+jets. Re-weighting of  $\gamma$ +jets data is done event-by-event, so that the  $p_T$  spectrum of photon agrees with the observed dilepton  $p_T$  spectrum. An additional reweighting is done to match the jet multiplicity between  $\gamma$ +jets and dilepton events in the 0 and 1 jet bins (jets with  $p_T > 30$  GeV/ $c$  are considered). Then, a mass sampled from a fit to the observed Z mass spectrum is assigned to each photon. The yield of  $\gamma$ +jets events is normalized to the observed yield of dilepton events. The transverse mass  $M_T$  is computed and the full analysis selection is applied to the weighted  $\gamma$ +jets events. This procedure produces an accurate model of the MET distribution in Z+jets as can be seen in Fig1 and Fig2.

#### 3.2 Top/WW/W+jets Estimation

To estimate the non-resonant background using data, events with final state comprising of  $e^+\mu^-/e^-\mu^+$  pairs and passing the full analysis selection are used. The non-resonant background in the  $e^+e^-/\mu^-\mu^+$  final states is estimated by

**Fig. 1.** MET spectrum of di-electron events and re-weighted single photon events in  $1.6\text{fb}^{-1}$ .**Fig. 2.** MET spectrum of di-muon events and re-weighted single photon events in  $1.6\text{fb}^{-1}$ .

applying a scale factor ( $\alpha$ ) to these events:

$$N_{\mu\mu} = \alpha_{\mu} \times N_{e\mu}, N_{ee} = \alpha_e \times N_{e\mu} \quad (1)$$

This scale factor  $\alpha$  is computed from the sidebands (SB) to the Z peak ( $40\text{GeV}/c^2 < m_H < 70\text{GeV}/c^2$  and  $110\text{GeV}/c^2 < m_H < 200\text{GeV}/c^2$ ) using the following relations:

$$\alpha_{\mu} = \frac{N_{\mu\mu}^{SB}}{N_{e\mu}^{SB}}, \alpha_e = \frac{N_{ee}^{SB}}{N_{e\mu}^{SB}} \quad (2)$$

where  $N_{ee}^{SB}$ ,  $N_{\mu\mu}^{SB}$  and  $N_{e\mu}^{SB}$  are events in the sidebands in the  $e^+e^-$ ,  $\mu^+\mu^-$  and  $e^+\mu^-/e^-\mu^+$  final states respectively, passing all the analysis requirements that are independent of the Higgs mass (with the exception of anti-btag) and  $\text{MET} > 70$  GeV. This method cannot distinguish between the non-resonant background and  $H \rightarrow WW \rightarrow 2l2\nu$  events, which are very small. Table3 and Table4 list the predicted yields for the non-resonant backgrounds with integrated luminosity of  $1.6\text{fb}^{-1}$ . Statistical uncertainties on these estimates are also quoted.

## 4 Systematics and Results

The systematic uncertainties are summarized in Table5. No evidence of SM Higgs boson production is found in

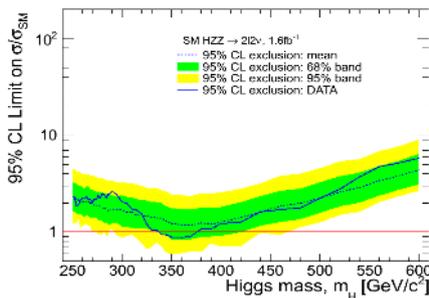
**Table 3.** Electron Channel: yields from  $1.6fb^{-1}$  data for non-resonant backgrounds.

$m_H$	Predicted Yields	MC Prediction
250	$12 \pm 2 \pm 2$	$12 \pm 1$
300	$4.0 \pm 0.7 \pm 1.3$	$4.5 \pm 0.5$
350	$1.8 \pm 0.3 \pm 0.9$	$1.1 \pm 0.2$
400	$0.44 \pm 0.07 \pm 0.44$	$0.51 \pm 0.14$
500	0	$0.21 \pm 0.10$
600	0	0

**Table 4.** Muon Channel: yields from  $1.6fb^{-1}$  data for non-resonant backgrounds.

$m_H$	Predicted Yields	MC Prediction
250	$16 \pm 2 \pm 3$	$15 \pm 1$
300	$5.3 \pm 0.6 \pm 1.8$	$6.2 \pm 0.5$
350	$2.3 \pm 0.3 \pm 1.2$	$1.8 \pm 0.3$
400	$0.58 \pm 0.07 \pm 0.58$	$0.49 \pm 0.13$
500	0	$0.059 \pm 0.043$
600	0	0

$H \rightarrow ZZ \rightarrow 2l2\nu$  channel with integrated luminosity of  $1.6fb^{-1}$ . The 95% mean expected and observed C.L. upper limits on the cross section,  $\sigma \times BR(H \rightarrow ZZ \rightarrow 2l2\nu)$ , for masses in the range 250-600  $GeV/c^2$  has been measured. Results are obtained using a CLs approach with a flat prior for the cross-section. The ratio R of the  $\sigma_{upperlimit}$  to the  $\sigma_{SM}$  at 95% CL is shown in Fig.3.  $\sigma_{upperlimit}$  as a function of the Higgs mass  $m_H$  at 95% CL has also been measured and is shown in Fig.4. With  $1.6fb^{-1}$ , the SM Higgs with masses in the range 340-375  $GeV/c^2$  can be excluded at 95% CL.

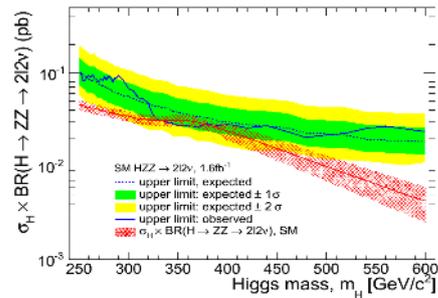
**Fig. 3.** 95% CL limit of the ratio of expected/observed cross section  $\times$  BR over Standard Model for  $1.6fb^{-1}$  of data.

## References

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**Table 5.** Systematic uncertainties on the final event yields for both electron and muon final states.

Uncertainty	value,%
Luminosity	4.5
pdf, gluon-gluon initial state	6-11
pdf, quark-quark initial state	3.3-7.6
QCD scale,(ggH)	7.6-11
QCD scale,(VBF)	0.2-2
QCD scale,(ggZZ)	20
QCD scale,(qqVV)	5.8-8.5
Anti b-tagging	1-1.2
Lepton ID+Isolation	2
Lepton Momentum Scale	5(for 2e), 2(for 2 $\mu$ )
Jet energy scale	1-1.5
PU effects	1-3
Trigger	1(for 2e), 2(for 2 $\mu$ )
non-resonant backgrounds	7%( $\alpha$ )
Z+jets estimation from data	19-57%

**Fig. 4.** Upper limit of the expected/measured cross section  $\times$  BR over Standard Model for  $1.6fb^{-1}$  of data.

## CMS Physics Analysis Summary CMS-PAS-HIG-11-016(2011)

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