PROCEEDINGS OF SCIENCE

# Search for the SM Higgs Boson in the $H \rightarrow ZZ^*$ in 4 leptons at CMS

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A prospective analysis for the search of the Standard Model Higgs boson in the decay channel $H \rightarrow ZZ^* \rightarrow 4$ leptons ($4e$, $4\mu$ or $2e2\mu$) is presented with the CMS experiment at the LHC. The analysis relies on a full simulation of the detector response. The $H$ to $ZZ^*$ channel offers a discovery reach with a significance exceeding 5 standard deviations already for LHC integrated luminosities of 10 fb$^{-1}$ in a wide range of possible Higgs boson mass, from about 130 to 500 GeV/c$^2$. An analysis is presented for a Higgs search at an integrated luminosity of 30 fb$^{-1}$ and also new strategies are introduced for the control of backgrounds and early searches at very low luminosities of $\mathscr{O}(1\text{ fb}^{-1})$.

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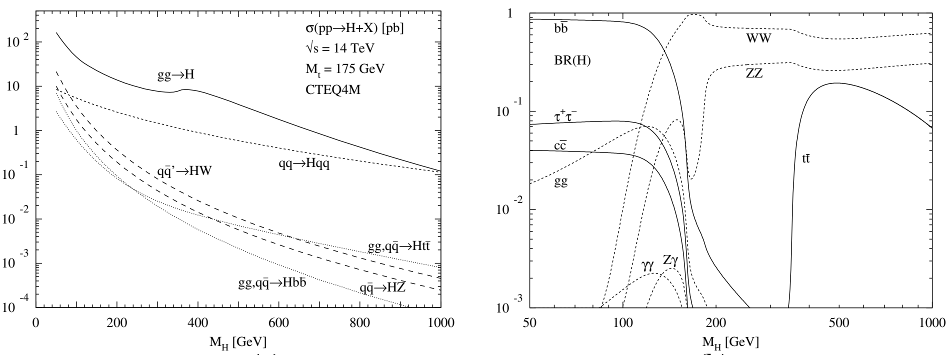
## 1. Introduction

One of the main goals of the CMS experiment at the Large Hadron Collider is the search for the Higgs boson, the only missing element of the Standard Model (SM). Its mass is a free parameter of the theory, but direct searches at LEP-II have set a lower bound at 114.4 GeV/c$^2$ and precision measurements from LEP and the Tevatron suggest light Higgs scenarios, with m$_H$ < 185 GeV at 95% CL. A mass value of 170 GeV/c$^2$ has been recently excluded at the Tevatron. However, the allowed Higgs mass range extends up to $\sim$ 1 TeV and will be entirely explored at the LHC.
The $H \rightarrow ZZ^{(*)} \rightarrow 4\ell$ ($\ell = \mu, e$) process is called the "golden channel" for a SM Higgs discovery at the LHC: the four high energy leptons in the final state and the relatively low backgrounds provide a very clear signature and allow precise measurements of the Higgs mass and cross section. The main background processes are $t\bar{t} \rightarrow 4\ell + X$, $Zb\bar{b} \rightarrow 4\ell + X$ and the irreducible $ZZ \rightarrow 4\ell$ ($Z$ stands for $Z$, $Z^*$ and $\gamma^*$).
In this paper, a complete analysis (see [1] [2] [3]) for an integrated luminosity of 30 fb$^{-1}$ at the nominal LHC centre of mass energy of 14 TeV is outlined. The trigger settings correspond to the LHC low luminosity ($2 \times 10^{33}$ cm$^{-2}$s$^{-1}$) scenario and no pile-up events are included. Another study has been performed for an integrated luminosity of 1 fb$^{-1}$ and in the LHC start-up scenario ($10^{32}$ cm$^{-2}$s$^{-1}$ instantaneous luminosity, 14 TeV energy), in order to investigate the discovery potential and the control of systematics with very low statistics. This analysis is here just introduced, highlighting the improvements and different strategies with respect to the former one. Both analyses were performed using the full CMS detector simulation and reconstruction software.

## 2. The Higgs boson production and decay

As shown in Fig. 1-a, the main Higgs production mode at the LHC is the gluon-gluon fusion. The vector boson fusion (VBF) accounts for $\sim$ 20% and reaches the gluon fusion at $\sim$ 1 TeV/c$^2$. For masses above 140 GeV/c$^2$, the Higgs decays mainly in weak bosons (Fig. 1-b). The $H \rightarrow WW$ mode has the highest branching ratio ($\sim$ 3 times higher than $H \rightarrow ZZ$), but its leptonic decays bear two neutrinos, thus forbidding mass reconstruction.

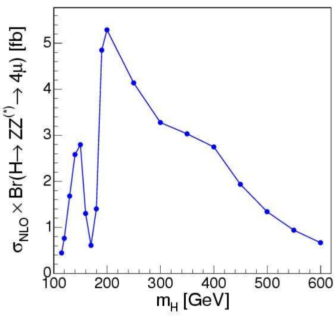



(a) (b)

**Figure 1:** (a) Higgs production cross sections as a function of its mass. (b) Higgs decay branching ratios as a function of its mass.

## 3. Signal and background simulation

Dedicated signal and background samples were produced using different Monte Carlo generators: PYTHIA [4], and CompHEP [5] for $Zb\bar{b}$. The Higgs was generated via $gg$-fusion and VBF at leading order (LO) for masses from 115 to 600 GeV/c$^2$. Next-to-leading order (NLO) contributions were introduced *a posteriori* by normalising the cross sections with appropriate *k-factors* [6]. Other corrections were applied to the $H \to 4e/4\mu$ cross sections to account for identical lepton permutations not included in PYTHIA.
The $ZZ$ background was simulated at LO via $qq \to ZZ$ process, then normalised to NLO with a mass dependent $k$-factor. A further 20% enhancement was introduced to take into account the $gg \to ZZ$ mode. $t\bar{t}$ and $Zb\bar{b}$ were instead brought to NLO using constant $k$-factors. In Fig. 2 the cross sections for signal and backgrounds are summarised.




(a)

| | $\sigma$ [pb] | $\sigma \cdot BR \cdot \varepsilon$ [fb] | | |
|---|---|---|---|---|
| | | $4\mu$ | $4e$ | $2\mu 2e$ |
| $ZZ$ | 29 | 89 | 20 | 37 |
| $Zb\bar{b}$ | 276 (555 $2e2\mu$) | 290 | 120 | 390 |
| $t\bar{t}$ | 840 | 233 | 194 | 743 |

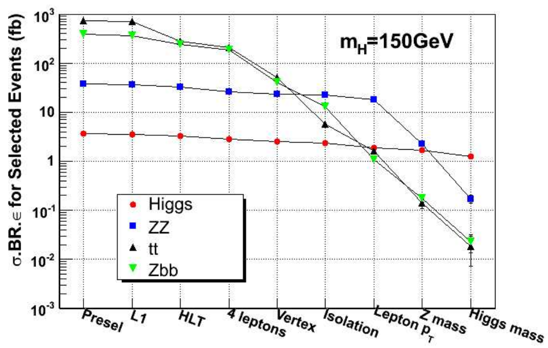
(b)

**Figure 2:** (a) NLO cross sections for Higgs production and decay in 4 muons for different masses. (b) Production cross sections for the three main background processes. The last column includes the decay branching ratios and some generator-level selection efficiencies.

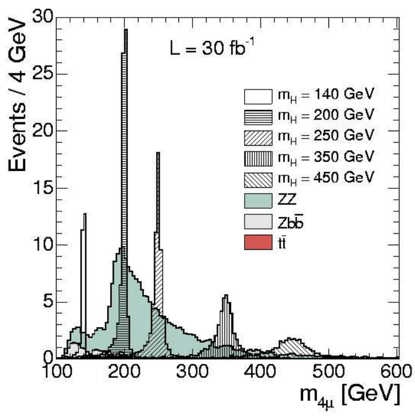
## 4. Analysis and results

Three independent analyses have been performed for the three channels, but with common tools. They are all cut-based and mass dependent (i.e. depending on a Higgs mass hypothesis) and use a counting experiment approach. Strategies for the estimation of systematics and control of backgrounds from data have also been developed.
The *trigger selection* of signal events is ensured by the presence of at least one or two high $p_T$ leptons in the final state. Different High Level Trigger (HLT) sequences are combined with a logical OR, in order to maximise the selection efficiency: single and double muon triggers for $4\mu$, single and double electron for $4e$, double muon and double electron for $2\mu 2e$.
After the HLT, a *pre-selection* is applied to reduce the contribution from "fake leptons": the presence of at least $4\mu$, $4e$ or $2\mu 2e$ with right charges is required and some cuts are applied on lepton $p$ or $p_T$, lepton isolation and lepton pair invariant masses.
Requirements on lepton *isolation* and *impact parameter* (IP) allow then to strongly suppress the $t\bar{t}$ and $Zb\bar{b}$ backgrounds, characterised by two non-isolated and non-primary leptons coming from the $b$-jets. The isolation is evaluated by looking at the particles contained in a cone built around the

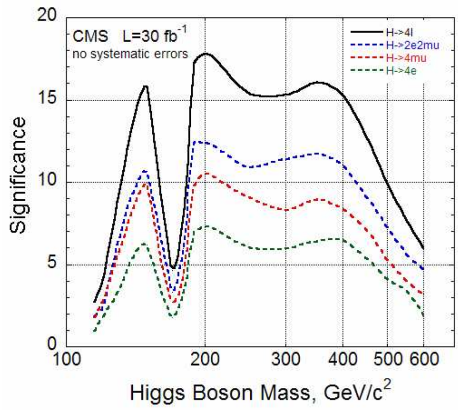
lepton track. Three different isolation variables are here used, based on the information from the Inner Tracker ($p_T$ of tracks), the Electromagnetic Calorimeter or the Hadronic Calorimeter (energy deposits). Two separate cuts are also applied to the *longitudinal* and *transverse* IP's, respectively projections of the IP on the beam axis or orthogonal to it. More precisely, the IP *significance* is used, i.e. IP/$\sigma_{\rm IP}$, to take into account the finite detector resolution.
The final selection relies on *kinematical cuts*. Thresholds on the $p_T$ of leptons (and in particular of the two lowest $p_T$ leptons) serve again to suppress $t\bar{t}$ and $Zb\bar{b}$, and so does the cut on the invariant mass of lepton pairs, which are expected to come from $Z$ bosons. A further cut on the invariant mass of the four selected leptons, instead, is used to reduce all the backgrounds, including the "irreducible" $ZZ$, not resonating at the Higgs mass. This last cut is obviously mass dependent. Fig. 3 summarises the results of the whole selection.



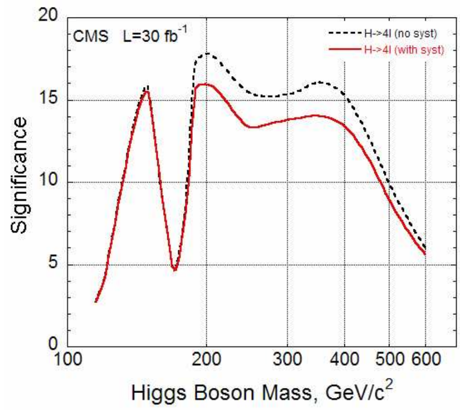

(a)




(b)




(c)




(d)

**Figure 3:** (a) Expected cross sections for the $2\mu 2e$ channel after each analysis cut. (b) $4\mu$ invariant mass after all analysis cuts for different Higgs mass hypothesis. (c) Expected significances for the three separate channels and their combination at 30 fb$^{-1}$. (d) Expected significance for the combination of the three channels without (black, dashed) and with (red, continuous) the inclusion of the estimated systematic errors.

## 5. Requirements for 1 fb$^{-1}$ analysis

At 1 fb$^{-1}$, very few Higgs events are expected, so a different strategy is needed, in order to keep the highest possible selection efficiency. Moreover, a common analysis for the three channels allows an immediate cross-check of any possible result. In this new analysis, besides the cited $t\bar{t}$, $Zb\bar{b}$ and $ZZ$, the very large QCD background is also taken into account: events with $n$ jets, Z/W$^{\pm}+n$ jets, $t\bar{t}+n$ jets and $\gamma+n$ jets are the main sources.
The trigger selection for all the channels is now performed via a global OR of single/double electron/muon triggers. Further reduction of the event rate is obtained via a *skimming* step, requiring at least three leptons of any flavour and charge within the detector acceptance. This reduces the volume of data for analysis to a manageable level. The signal selection efficiency for the HLT and skimming is above 90% (98% for $4\mu$).
The pre-selection step is still applied to reduce the amount of fake leptons and bring the QCD multijets and Z/W+jets contributions at a level comparable to the three main backgrounds.
To further reject the reducible backgrounds, a single isolation variable is now used, which is a combination of the three separate variables previously described. Also the transverse and longitudinal IP's are here replaced by a single three-dimensional IP, exploiting the CMS Pixel detector which provides a good resolution also in the longitudinal direction.
The estimation of systematics and the control of backgrounds (mainly $ZZ$ and $Zb\bar{b}$) are particularly stressed in this analysis at very low statistics.

## 6. Conclusions

Strategies for the search of the SM Higgs boson in the decay mode $H \to ZZ^{(*)} \to 4\ell$ with the CMS detector were described for an integrated luminosity of 30 fb$^{-1}$ and for Higgs masses from 115 and 600 GeV/c$^2$. It was shown that the discovery limit of $5\sigma$ is achievable in almost all the allowed mass range with such statistics, even when systematic errors are included in the analysis. New strategies for early searches with very low statistics were also outlined.

## References

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