

# Discovery Potential for the SM Higgs Boson in the Inclusive Search Channels

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**Abstract.** This paper gives an overview of the potential to discover a Standard Model Higgs Boson in the inclusive search channels at the ATLAS and CMS experiments at the LHC. The most important decay modes,  $H \rightarrow \gamma\gamma$ ,  $H \rightarrow WW \rightarrow l\nu\nu$  and  $H \rightarrow ZZ \rightarrow 4l$  are described and a summary of recently published analyses using realistic detector simulations is presented.

**PACS.** 14.80.Bn Standard-model Higgs bosons

## 1 Introduction

The allowed decay modes of the Higgs Boson are predicted within the Standard Model and depend only on its mass  $m_H$ . Direct searches conducted at LEP have given a lower limit of  $m_H > 114.4 \text{ GeV}/c^2$  at the 95% confidence limit [1]. In the low mass region,  $m_H < 150 \text{ GeV}/c^2$  the small width of the Higgs Boson  $\Gamma_H < 1 \text{ GeV}/c^2$  can be utilized to find a narrow peak in the  $H \rightarrow \gamma\gamma$  and  $H \rightarrow ZZ^* \rightarrow 4l$  channels, because the invariant mass resolution due to the measurement is larger than the intrinsic width. For Higgs masses around the WW Boson resonance at  $160 \text{ GeV}/c^2$ , the  $H \rightarrow WW \rightarrow l\nu\nu$  decay is the preferred search channel because the branching ratio  $\text{BR}(H \rightarrow WW)$  is almost one, but it is not possible to reconstruct a mass peak because of the two neutrinos. For masses above the WW resonance, the  $H \rightarrow ZZ$  channel is again the most promising search channel.

In the exclusive searches for the Higgs Boson, characteristic properties of the event topology of the particular production and decay modes are exploited for event selection. For example, in the exclusive search for Higgs production through Vector Boson Fusion, the typical feature are forward jets that are used to identify the event. Similarly, in the search for associated Higgs production,  $t\bar{t}H$ , the signatures of the two top quarks are used for this purpose. In contrast, the inclusive searches do not separate between the various production topologies. The latter are described in more detail in the following sections.

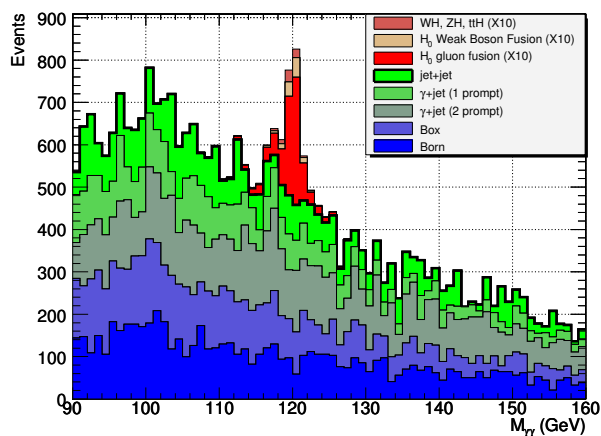
In case of CMS, the analysis results presented in the following are based upon publications in the context of the ‘‘Physics Technical Design Reports’’ [2,3] (PTDR) published in the year 2006. All analyses apply realistic detector simulations based on GEANT4, including Level-1 and High-Level Trigger simulations. Where available, Next-to-Leading Order (NLO) calculations have been used and systematic errors due

to theory and detector effects have been taken into account. In the case of ATLAS, the PTDR has been published in 1999 when NLO calculations and full detector simulations have not been available for the channels discussed here [4]. The ATLAS collaboration is currently updating the Higgs analyses according to the most recent simulations and theoretical calculations. Some updates on the  $H \rightarrow \gamma\gamma$  channel are available, but the results on the  $H \rightarrow ZZ$  and  $H \rightarrow WW$  are not official yet and cannot be presented in this paper.

## 2 The Channel $H \rightarrow \gamma\gamma$

The decay into two photons is a rare decay mode with a branching ratio of 0.2% at  $m_H = 120 \text{ GeV}/c^2$  [5]. The total NLO cross section times branching ratio, including all production modes is  $\sigma \times \text{B.R.} = 99.3 \text{ fb}$  for  $m_H = 115 \text{ GeV}/c^2$  and drops to 41.5 fb for  $m_H = 150 \text{ GeV}/c^2$  [6, 7]. Background processes are separated into reducible and irreducible backgrounds. Irreducible backgrounds have two real high  $E_t$  photons produced via born and box diagrams with a cross section of about 80 pb each. Reducible backgrounds arise from  $\gamma$  plus jet or multi-jet events in which one or two jets are misidentified as photons. The photon identification is very clean at the ATLAS and CMS detectors. The electromagnetic calorimeter at ATLAS has a presampler that reduces the fake rate to a level that is not reached by CMS. For example, a jet rejection factor between 4000 and 10000 can be reached at 80% photon selection efficiency at ATLAS, depending on the transverse momentum [8]. This is achieved by isolation criteria exploiting the fact that misidentified jets are accompanied by particles measured in the tracker, electromagnetic and hadronic calorimeters. Therefore, reducible backgrounds can be suppressed sufficiently.

Both in ATLAS and CMS the standard cut-based analyses are supplemented by more powerful separa-



**Fig. 1.** Distribution of the invariant mass  $m_{\gamma\gamma}$  for signal (red, brown) with  $m_H = 120 \text{ GeV}/c^2$  and background (blue, green) in case of CMS and the neural network analysis. Events are normalized to an integrated luminosity of  $7.7 \text{ fb}^{-1}$  and the signal is scaled by a factor of 10 for better visibility. [7, 3]

tion tools using neural networks and likelihood methods. In case of CMS, the cut-based analysis introduces quality categories based on the electromagnetic shower shape and pseudo-rapidity. In a more optimized analysis, a neural network is trained with kinematic observables in addition to the isolation. These observables are chosen to be independent of the Higgs Boson mass. The training of the network is done on the sidebands of the distribution of the invariant mass. This method can be used for the determination of background rates directly on data since the narrow peak in the invariant mass distribution sits on an almost linear background as illustrated in Figure 1. Systematic errors have a moderate impact on the discovery potential, mostly because the background can be measured from data. This means that the error resides in the uncertainty of the fit as well as statistics and the fitting functions. It has been evaluated to be of the order of 1%. The error on the signal is estimated to be about 20%. About 15% are contributed to the theoretical error and the rest to instrumental effects like luminosity, trigger and tracker material. The error on the signal affects primarily the determination of exclusion limits since this has to rely on theoretical predictions.

The results in terms of observability are similar for ATLAS and CMS, even though slightly different methods (neural networks and likelihoods) and observables have been used. For the cut based analyses, the discovery significance is expected to be  $6\sigma$  for  $m_H = 120 \text{ GeV}/c^2$  and for the optimized analyses  $10\sigma$  for an integrated luminosity of  $L = 30 \text{ fb}^{-1}$ . Details on these analyses can be found in [7, 3, 8, 9].

### 3 The Channel $H \rightarrow WW \rightarrow ll\nu\nu$

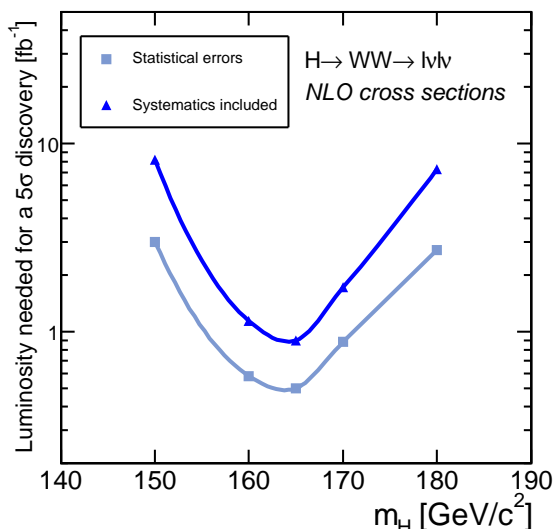
For intermediate masses  $2m_W < m_H < 2m_Z$  the  $H \rightarrow WW \rightarrow ll\nu\nu$  channel is expected to be the main discovery channel at LHC. In this mass range, the  $H \rightarrow WW$  branching ratio is almost one. However, no mass peak can be reconstructed because of the two neutrinos. The normalization of the background is therefore more difficult. The total NLO signal cross section, including gluon fusion and vector boson production is largest at  $m_H = 160 \text{ GeV}/c^2$  with  $\sigma_{NLO} \times \text{B.R.}(e, \mu, \tau) = 2.34 \text{ pb}$  [10]. Backgrounds to this channel arise from continuum di-vector-boson production ( $WW, ZZ, WZ$ ) with a cross section of  $\sigma_{NLO} \times \text{B.R.}(e, \mu, \tau) = 15 \text{ pb}$ . Further backgrounds are  $t\bar{t}$  and single top production in association with a W Boson  $tWb$  with  $\sigma_{NLO} \times \text{B.R.}(e, \mu, \tau) = 86.2 \text{ pb}$  and  $3.4 \text{ pb}$ , respectively. For CMS, a special technique of re-weighting the  $p_t$  spectra of the Higgs Boson from PYTHIA to the MC@NLO [11, 12] prediction has been developed and applied in this analysis [13]. This method of introducing  $p_t$  dependent k-factors has also been used for the WW background.

The event selection exploits properties of the event topologies in order to reject background. For example, the spin correlation between the W Bosons of the Higgs decay provides a handle to select signal events based on the angle between the two leptons. Furthermore, the cuts on missing energy, the invariant mass of leptons, the transverse momenta and isolation criteria have been optimized in order to maximize the discovery significance. In addition, a central jet veto is applied which rejects the  $t\bar{t}$  background by roughly a factor of 30 and signal events only by a factor of about two [10].

Since this analysis is basically a counting experiment, the normalization of the background is the largest source of systematic errors. The  $t\bar{t}$  can be estimated by replacing the jet veto with a double b-tag while keeping all other cuts identical. The expected uncertainty is 16%. The WZ background can be determined by requiring a third lepton which gives an uncertainty of 20%. For the measurement of the WW background rates, a normalization region in  $\phi_{ll}$  and  $m_{ll}$  can be defined, again keeping all other cuts identical. This results in an expected uncertainty of 17%. For the WW background produced by gluon fusion and for the single top background, it is difficult to define a normalization region and one has to rely on the theoretical prediction which leads to an uncertainty of 30%. All these numbers refer to an integrated luminosity of  $5 \text{ fb}^{-1}$ . The resulting effect on the discovery potential in terms of required luminosity for a  $5\sigma$  discovery is shown in Figure 2.

The analysis of this channel is currently being revisited in CMS, in particular to get better control of the systematics due to missing transverse energy and jets. Furthermore, an attempt is made to increase the sensitivity towards lower  $m_H$  by e.g. applying multivariate analysis techniques [14].

The analysis strategy adopted by ATLAS is similar to the CMS analysis, but it uses a transverse mass in addition which is defined as  $m_T = \sqrt{2p_t^l E_t^{\text{miss}}(1 - \cos \Delta\phi)}$ ,

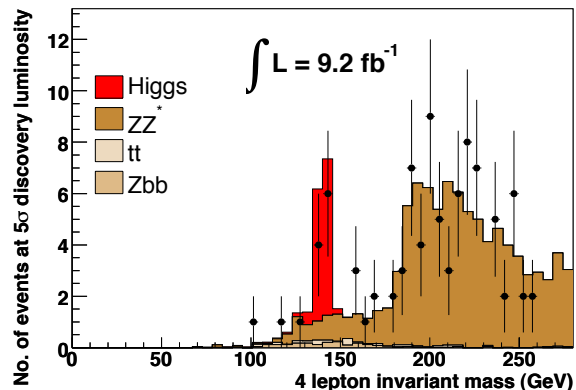


**Fig. 2.** Required luminosity for a  $5\sigma$  discovery in the  $H \rightarrow WW \rightarrow ll\nu\nu$  channel at CMS. [10]

where  $\Delta\phi$  is the azimuthal angle between the di-lepton system and the missing transverse energy. This transverse mass is correlated to the invariant mass of the Higgs Boson and can therefore be used to define a mass window in order to further reject background events. In this case a result reaching a significance of  $\sigma = 10$  for  $m_H = 160 \text{ GeV}/c^2$  including a systematic error of 5% is obtained for an integrated luminosity of  $30 \text{ fb}^{-1}$  [4].

#### 4 The Channel $H \rightarrow ZZ \rightarrow 4l$

This channel has a very clean signature due to the presence of four leptons. It is very promising in the mass range  $130 \text{ GeV}/c^2 < m_H < 500 \text{ GeV}/c^2$  except for  $2m_W < m_H < 2m_Z$ . The analysis designs for the different final states ( $4e$ ,  $2e2\mu$  and  $4\mu$ ) are very similar, except for the lepton identification. In the following, the  $2e2\mu$  final state will be described in more detail. The NLO signal cross section times branching ratio has two maxima, one at  $m_H = 150 \text{ GeV}/c^2$  of  $\sigma_{NLO} \times \text{B.R.}(2e2\mu) = 13 \text{ fb}$ , and another one at  $m_H = 200 \text{ GeV}/c^2$  of  $\sigma_{NLO} \times \text{B.R.}(2e2\mu) = 24 \text{ fb}$  [15]. This behaviour is mostly dominated by the branching ratio since the cross section itself is continuously falling from  $30 \text{ pb}$  for  $m_H = 150 \text{ GeV}/c^2$  to  $5 \text{ pb}$  for  $m_H = 500 \text{ GeV}/c^2$ . Backgrounds to this channel are  $t\bar{t}$  events with leptonic W Boson decays and leptons in b-jets which have a cross section of  $\sigma_{NLO} \times \text{B.R.}(2e2\mu) = 743 \text{ fb}$ . Further backgrounds are  $Zbb$  with  $\sigma_{NLO} \times \text{B.R.}(2e2\mu) = 390 \text{ fb}$  and  $ZZ^*/\gamma^*$  events with  $\sigma_{NLO} \times \text{B.R.}(2e2\mu) = 37 \text{ fb}$ . For the  $ZZ^*/\gamma^*$  background, a re-weighting procedure has been implemented, which introduces  $m_{4l}$ -dependent k-factors in order to account for contributions from all NLO diagrams and from NNLO gluon fusion  $gg \rightarrow ZZ^*/\gamma^*$  [15].

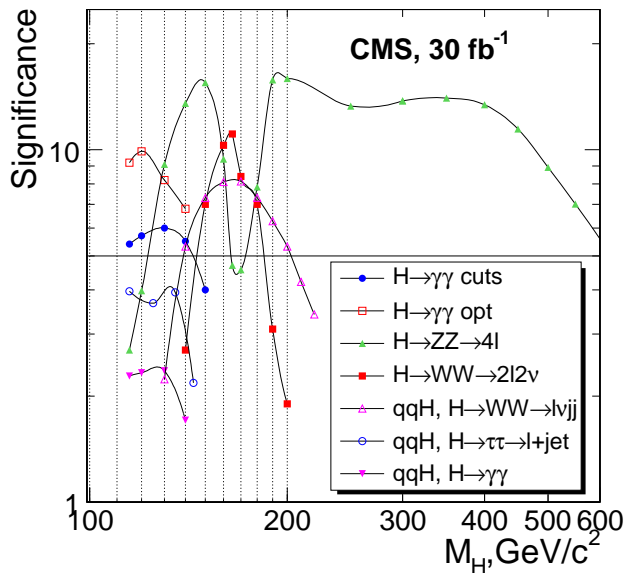


**Fig. 3.** Number of expected events for signal and background for an integrated luminosity corresponding to a discovery significance of  $5\sigma$  for a Higgs Boson mass of  $m_H = 140 \text{ GeV}/c^2$ . As an illustration, a toy Monte Carlo distribution based on the histograms is superimposed to simulate real CMS data. [15]

The analysis strategies at CMS and ATLAS are again similar. Both apply several tools to reduce the background. Lepton isolation reduces contributions from leptons in jets. Cuts on the impact parameter of leptons reduce b-jets. In addition, leptons are required to come from the same primary vertex. For lower Higgs Boson masses, one of the Z Bosons is on-shell, for higher masses with  $m_H > 2m_Z$ , both Z Bosons are on-shell. Mass windows around the Z resonance help to reduce  $t\bar{t}$  and  $Zbb$  backgrounds. By applying these cuts, the  $t\bar{t}$  and  $Zbb$  backgrounds can be suppressed by a factor of more than 1900 after online selection, while the signal (with  $m_H = 120 \text{ GeV}/c^2$ ) and  $ZZ^*/\gamma^*$  background are only reduced by a factor of about two. As an illustration, Figure 3 shows the distribution of the invariant mass of four leptons after offline selection.

The systematic uncertainties in this channel are defined by the uncertainty of the determination of the background rates from data using sidebands in the mass distribution. The analysis shows that this is possible with a precision of less than 10% for Higgs Boson masses below  $200 \text{ GeV}/c^2$ . For higher masses the uncertainty increases up to 30% for  $m_H = 400 \text{ GeV}/c^2$ , because the background is not flat anymore as visible in Figure 3.

An important alternative to the determination of the background rates from sidebands is to measure the  $Z \rightarrow 2l$  process as control sample and scale it down by a theoretical factor  $\sigma_{ZZ}/\sigma_Z$ . This reduces the PDF and QCD scale uncertainties as well as luminosity uncertainties [3]. The impact of the systematic error on the discovery significance has found to be small (at the percent level), especially in the low mass range below  $200 \text{ GeV}/c^2$ .



**Fig. 4.** Signal significance (in units of  $\sigma$ ) as a function of the Higgs Boson mass for an integrated luminosity of  $30 \text{ fb}^{-1}$  at CMS.

## 5 Summary and Conclusion

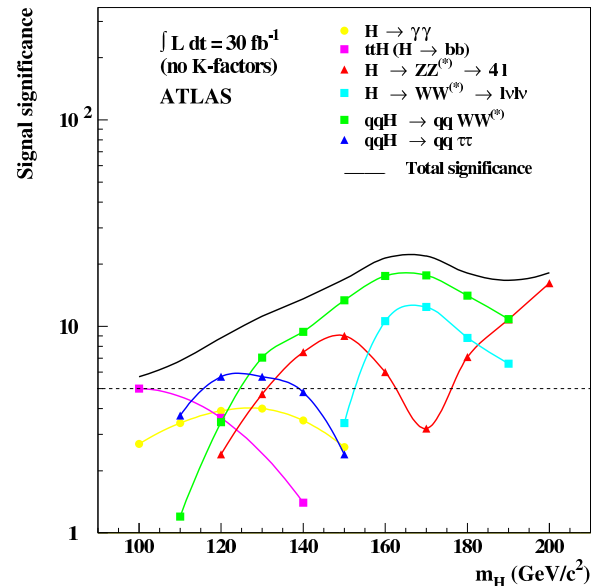
The three analyses discussed in this paper are complementary in the sense that they are sensitive to distinct Higgs Boson mass ranges. For lower masses up to  $150 \text{ GeV}/c^2$  the  $H \rightarrow \gamma\gamma$  channel provides a good discovery potential. For intermediate masses around  $160 \text{ GeV}/c^2$  the  $H \rightarrow WW \rightarrow 2l2\nu$  channel is promising. The  $H \rightarrow ZZ \rightarrow 4l$  channel is interesting for higher masses, but it also fills a gap at around  $140 \text{ GeV}/c^2$  where the  $H \rightarrow WW$  branching ratio is not yet high enough, and the  $H \rightarrow \gamma\gamma$  sensitivity starts to decrease. By combining all these analyses the full mass range is covered. This is shown in Figures 4 and 5. From these figures one can conclude that a Standard Model Higgs Boson is very unlikely to escape the LHC.

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**Fig. 5.** Signal significance (in units of  $\sigma$ ) as a function of the Higgs Boson mass for an integrated luminosity of  $30 \text{ fb}^{-1}$  at ATLAS. For many channels the agreement with the CMS results improves if k-factors are introduced.

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