INCLUSIVE HIGGS BOSON SEARCHES IN FOUR-LEPTON FINAL STATES AT THE LHC

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The inclusive search for the Standard Model Higgs boson in four-lepton final states with the ATLAS and CMS detectors at the LHC pp collider is presented. The discussion focusses on the $H \to ZZ^{(*)} \to 4l + X$ decay mode for a Higgs boson in the mass range $120 \lesssim M_H \lesssim 600$ GeV/c^2. A prospective analysis is presented for the discovery potential based on a detailled simulation of the detector response in the experimental conditions of the first years of LHC running at low luminosity. An overview of the expected sensitivity in the measurement of the Higgs boson properties is also given.

1 Introduction

The Standard Model (SM) of electroweak interactions contains one Higgs boson whose mass, M_H, is a free parameter of the model. The inclusive single production reaction $p + p \to H + X$ followed by the decay $H \to ZZ^{(*)} \to l^+l^-l'^+l'^-$ (in short $H \to 4l$) is the cleanest ("golden") decay mode for the discovery of the SM Higgs boson at the LHC and can provide a sensitivity over a wide range of masses M_H from 120 to 600 GeV/c^2. There are three different final states which depend on the flavour of the Z-boson decay leptons: $H \to 4e$, $H \to 4\mu$ and $H \to 2e2\mu$. Thanks to the relatively small background contamination, the $H \to 4l$ also allows a precise measurement of the Higgs boson properties (mass, width, spin, couplings, etc...).

The report summarizes the expected potential of ATLAS and CMS in SM Higgs boson searches in the $H \to 4l$ channel. For more details on the analyses described here, the reader is directed to the ATLAS [1] and CMS [2] Physics Technical Design Reports.

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2 Higgs boson signal and backgrounds

At LHC energies, there are two dominant SM Higgs boson production processes: gluon-gluon, $gg \to H$, and weak boson fusion $qq \to qqH$. In the mass range $M_H \lesssim 135$ GeV$/c^2$, the SM Higgs boson decays mainly into $b\bar{b}$ (BR $\approx$ 85%) and $\tau^+\tau^-$ (BR $\approx$ 8%) pairs but the search in the $H \to \gamma\gamma$ decay mode is priviledged despite its small branching ratio (BR $\approx$ 0.2%) because of its clean experimental signature. For $M_H \gtrsim 135$ GeV$/c^2$, the decay into $H \to W^+W^-$ is dominant. The branching ratio for the $H \to ZZ^{(*)}$ decay is sizable for $M_H \geq 115$ GeV$/c^2$.

The $H \to ZZ^{(*)} \to 4l$ signal event topology is characterized by two pairs of oppositely charged and isolated same-flavour leptons coming from the same vertex with a di-lepton invariant mass compatible with the Z-boson mass. The Higgs boson signal manifests itself as a narrow mass peak in the reconstructed four-lepton invariant mass spectrum. There are three main background sources to the $H \to 4l$ signal. The reducible $Zb\bar{b}$ and $t\bar{t}$ background processes differ from the signal by the presence of two non-isolated leptons inside b-jets with displaced vertices. The irreducible $ZZ^{(*)}$ background has kinematical properties which are very similar to that of the signal except for the four-lepton invariant mass which shows a broad spectrum.

3 Event selection

All selections are optimised to have the highest significance for discovery with emphasis on a realistic strategy for the control of experimental errors and background systematics.

The on-line preselection consists of a logical OR of basic single and double electron or muon triggers. The off-line preselection starts with the search for events with at least four lepton candidates within the fiducial volume. The aim is to reduce as much as possible the contamination of background sources involving "fake" leptons from QCD jets while preserving as much as possible the signal detection efficiency. The $Zb\bar{b}$ and $t\bar{t}$ backgrounds have at least one non-isolated lepton-pair with often detectable displaced vertices in contrast to the signal and $ZZ^{(*)}$ background. Therefore, the most descriminating preselection variables against these backgrounds come from vertex constraints and isolation criteria relying on the measurement of primary tracks in the tracker and/or the energy flow in the calorimeters.

The kinematical selection consists of cuts on the lepton transverse momenta and the reconstructed di-lepton invariant mass spectra. The first cut exploits the fact that b-decay leptons from the $Zb\bar{b}$ and $t\bar{t}$ backgrounds have on average a softer p_T spectrum than leptons from the Higgs boson signal or $ZZ^{(*)}$ background. The second requirement is powerful against all backgrounds.

The number of signal and background events is determined by a simple window sliding in the reconstructed four-lepton invariant mass spectrum. After the full selection, the reducible backgrounds are suppressed well below the level of the $ZZ^{(*)}$ contamination which remains the dominant and sole remaining background. The typical rejection factors vary from 2×10^3 to 10^4 for $t\bar{t}$, from 500 to 10^5 for $Zb\bar{b}$ and from 20 to 4 for $ZZ^{(*)}$, depending on the M_H-hypothesis, for a signal selection efficiency of 25-55 %.

4 Systematics

The systematics on the signal significance are related to the knowledge of the $ZZ^{(*)}$ background rate in the signal region and the uncertainty on this knowledge. Two approaches have been followed to estimate the background directly from the data: a normalisation to single Z, $Z \to 2l$, data and a normalisation to sidebands. Both approaches lead to a reduced sensitivity to theoretical and experimental uncertainties as well as a full cancellation of the luminosity uncertainty. The theoretical uncertainty is of the order of 2 to 8% for the normalisation to $Z \to 2l$ and 0.5

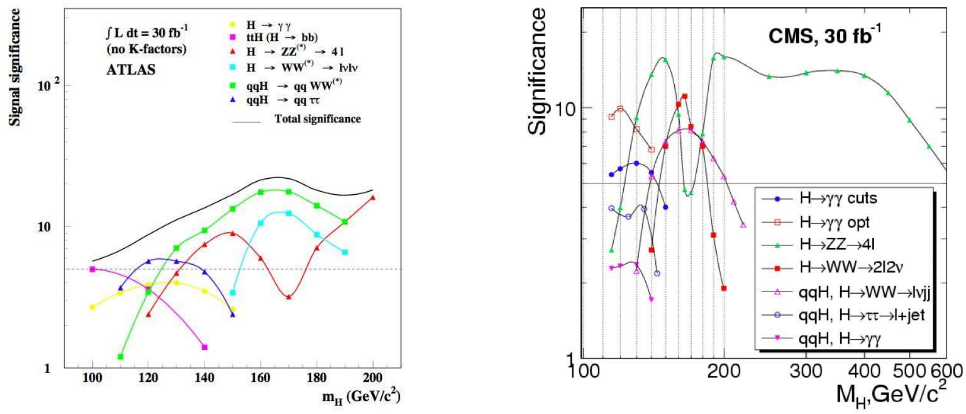

Figure 1: The expected statistical significance for the Standard Model Higgs boson signal as function of its mass for an integrated luminosity of 30 fb^{-1} for the ATLAS (Left) and CMS (Right) experiments.

to 4% for the normalisation to sidebands. The low statistics of $ZZ^{(*)}$ events could be a limiting factor for the sidebands method.

The overal strategy for controling the detector systematics is to estimate the efficiency and the precision of the energy and momentum measurements from experimental data. Single Z and single W processes have huge cross section at the LHC, and are expected to lead to a significant reduction of the reconstruction uncertainties already after few fb^{-1}.

5 Discovery reach

Figure 1 shows the expected statistical significance for the SM Higgs boson signal as function of its mass for an integrated luminosity of 30 fb^{-1}. A 5σ-discovery is possible over a wide range of masses in the $H \to 4l$ channel: $130 < M_H < 160$ GeV/c^2 and $2m_Z < M_H < 550$ GeV/c^2. The drop in sensitivity around $M_H \approx 180$ GeV/c^2 will be filled by the complementary channel $H \to WW^{(*)} \to 2l2\nu$ where less than 1 fb^{-1} is needed for 5σ-discovery. For $M_H < 130$ GeV/c^2, the highest discovery potential is obtained in the $H \to \gamma\gamma$ decay mode.

6 Measurement of the Higgs boson properties

The Higgs boson mass and width are obtained from a fit to the four-lepton invariant mass spectrum. For an integrated luminosity of 30 fb^{-1}, the expected statistical precision of the mass measurement is better than 1% over a wide range of masses (Figure 2 Left). The Higgs boson width measurement is only possible for Higgs boson masses beyond 200 GeV/c^2 when the Higgs boson natural width starts to dominate the experimental resolution. The expected precision on the width is smaller than 30%.

The Higgs boson couplings to fermions and gauge bosons can be extracted from rate measurements in the different Higgs boson production and decay channels. Relative precision on the squared Higgs boson couplings, assuming 300 fb^{-1} of data collected by both the ATLAS and the CMS experiments, varies between 10% and 40% depending on the coupling, except for the Yukawa coupling to the b-quark which suffers from large uncertainties related to b-tagging and background normalisation [4].

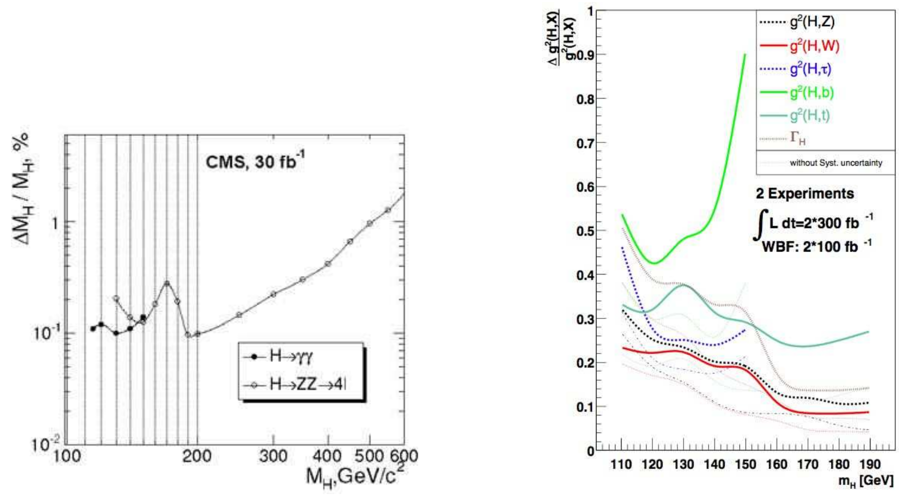

Figure 2: Left: The expected statistical precision of the Higgs boson mass measurement in CMS for an integrated luminosity of 30 fb^{-1}. Right: The relative precision on the Higgs boson couplings assuming 300 fb^{-1} of data collected by both the ATLAS and the CMS experiments.

The $H \to 4l$ channel is particularly suitable to measure the Higgs boson spin and CP state because its small background contamination and the fact that the event kinematics can be completely reconstructed with good precision. The angular correlations between the Z-boson decay products are used to extract the spin and CP state of the resonance. A study based on ATLAS fast simulation shows that with 100 fb^{-1} a pseudo-scalar Higgs boson can be ruled out if $M_H > 200$ GeV$/c^2$ and an axial vector and vector Higgs boson can be excluded if $M_H > 230$ GeV$/c^2$ [5]. A recent analysis by the CMS experiment considers also CP-violating spin-0 Higgs boson states via the introduction of a CP-mixing parameter and determines the minimal enhancement or suppression in cross section needed in order to exclude the SM pseudo-scalar Higgs boson. It is shown that the distinction between a scalar and a pseudo-scalar Higgs boson is already possible with 60 fb^{-1} integrated luminosity [6].

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