34th International Conference on High Energy Physics, Philadelphia, 2008

Standard Model Higgs Searches at the LHC

R. Gonçalo

Royal Holloway, University of London

On behalf of the ATLAS and CMS collaborations

The study of the mechanism behind electroweak symmetry breaking is one of the main goals of the Large Hadron Collider and of its general-purpose experiments, ATLAS and CMS. This paper reviews some of the ongoing studies by these collaborations and, when possible, highlights the differences between equivalent channels in both experiments.

1. Introduction

The Higgs mechanism [1] is central to the Standard Model of particle physics (SM). The existence of the Higgs field maintains the theory weakly interacting up to high energy scales and prevents some processes from violating unitarity. In the process of spontaneous breaking of electroweak symmetry, the weak bosons $W^{\pm}$ and Z^0, as well as leptons and quarks, acquire mass through interactions with the Higgs field. In the SM, the simplest form of the Higgs mechanism is assumed, which predicts the existence of a single scalar particle, the Higgs boson and a single free parameter, its mass (m_H). The discovery of this particle would provide experimental evidence for the Higgs mechanism. The discovery and study of the mechanism of electroweak symmetry breaking is one of the main goals of the ATLAS [2] and CMS [3] experiments, operating at the Large Hadron Collider (LHC). Many models of physics beyond the SM predict a more complex Higgs sector, covered elsewhere [4].

Direct searches for the Higgs boson produced in association with a Z^0 were performed in the Large Electron Positron collider (LEP). These resulted in the exclusion of the Higgs boson in the mass range up to 114.4 GeV at 95% confidence level [5]. On the other hand, precision fits [6] of electroweak observables, including data from the LEP and Tevatron colliders, provide an indirect estimate of the Higgs boson mass, assuming the SM scenario. The latest fit results give $m_H = 84^{+34}_{-26}\,\mathrm{GeV/c^2}$, or the one-sided 95% confidence-level limit $m_H < 154\,\mathrm{GeV}$. Including the LEP direct search results, this limit increases to $185\,\mathrm{GeV/c^2}$. Recent combined results from the Tevatron experiments have, for the first time, excluded the hypothesis of a Higgs boson mass around 170 GeV [7] at 95% confidence level. Although the expected sensitivity of Tevatron experiments is not enough to make a 5σ discovery of the SM Higgs boson [8], it is enough to exclude it out up to $m_H \sim 200\,\mathrm{GeV/c^2}$ at 95% confidence level, or to make a 3σ observation.

ATL-PHYS-PROC-2008-060
21 November 2008

2. Higgs boson searches in ATLAS and CMS

The Higgs boson production at the LHC is dominated by the gluon-gluon fusion process, described at leading order through a heavy-quark loop. The next-to-leading order cross section for this process is $37.6\,pb$, for $m_H = 120\,\mathrm{GeV/c^2}$. The Higgs boson can also be produced by Vector Boson Fusion (VBF) with a cross section of $4.25\,pb$, or by associated production with a $W^{\pm}$, a Z^0, or a $t\bar{t}$ quark pair, with $3.19\,pb$ for the three processes and $m_H = 120\,\mathrm{GeV/c^2}$ (cross sections calculated at next-to-leading order using parton density function sets CTEQ6M and CTEQ6L1 [9]).

The Higgs boson branching ratio is strongly dependent on its mass. At $m_H \lesssim 135\,\mathrm{GeV/c^2}$, the main decay mode is to a $b\bar{b}$ pair ($BR = 81\%$), followed by the decay to a $\tau^+\tau^-$ pair ($BR \sim 8\%$). For a small but important interval of m_H, the Higgs boson decays to a pair of photons with a small branching ratio. At higher masses, the decay to a pair of (possibly off-shell) $W^{\pm}$ or Z^0 bosons becomes dominant.

The most abundant signal topologies, containing $b\bar{b}$ pairs are unfortunately hard to separate from the large QCD background. The following gives a summary of the discovery channels being investigated at the LHC. In all cases, full detector simulation was used, which included realistic descriptions of the material budget and detector geometry. The trigger response was also realistically simulated, and systematic uncertainties were estimated. Next-to-leading order cross sections were used whenever available, and used to normalise simulated event samples.

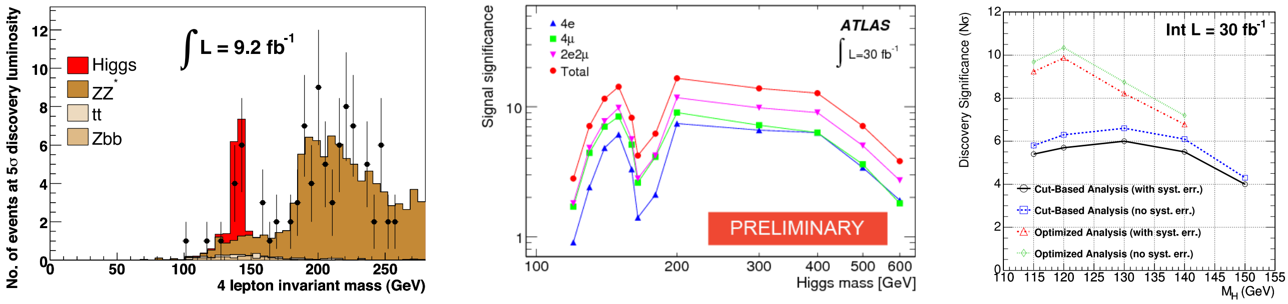

Figure 1: Left: ATLAS sensitivity in the $H \to 4l$ channel for $30\,fb^{-1}$ [9] (background estimation systematic uncertainties are included); centre: four-lepton invariant mass distribution in the $H \to ZZ^{(*)} \to 2e2\mu$ channel in CMS [10]; right: CMS sensitivity in $H \to \gamma\gamma$ channel for $30\,fb^{-1}$ [10].

2.1. Higgs boson decay to four leptons: $H \to ZZ^{(*)} \to 4l$ ($4e$, 4μ or $2e2\mu$)

This channel provides excellent sensitivity for a wide range of m_H above 130 GeV/c^2, except for the interval between $2m_W$ and $2m_Z$, where the Higgs boson branching ratio is dominated by $H \to W^+W^-$. The main background is $pp \to ZZ^{(*)} \to 4l^{\pm}$. Other backgrounds, such as $Zb\bar{b}$, ZW, $t\bar{t}$, and $Z + X$ are effectively suppressed by the analysis event selection. Both CMS and ATLAS rely on selecting events which contain pairs of electrons or muons with opposite charge. At least one Z^0 is expected to be on mass shell, and the two-lepton invariant mass is used to reject fake and misidentified leptons. A clear four-lepton mass peak above a flat background is expected in this channel (see figure 1, left), thus allowing a good background estimation from the peak sidebands. Two factors are especially significant for analyses of this channel: the lepton reconstruction efficiency and the invariant-mass resolution. Both experiments show similar experimental sensitivities in this channel, with the total signal significance for each experiment expected to be in excess of 10 for an integrated luminosity of $30\,fb^{-1}$ (see figure 1, centre).

2.2. Higgs boson decay to two photons: $H \to \gamma\gamma$

In spite of the low Higgs boson branching ratio to two photons (around 0.2% for $m_H = 120$ GeV/c^2), this channel shows very good sensitivity in a range of m_H between the LEP limit and $m_H \sim 140$ GeV/c^2. The main irreducible background is the direct $\gamma\gamma$ production. Signal appears as a sharp peak over a smoothly falling di-photon invariant mass distribution. Reducible instrumental backgrounds such as $\gamma + jet$ and multijet production, where one or more particles are misidentified as photons, are important due to the large QCD cross sections. Both experiments need to take photon conversions into account, since $\sim 60\%$ of Higgs events contain at least one converted photon.

Both collaborations classify the selected events into several categories, according to the event kinematics or topology. In this way, the event selection can be optimized, in order to maximize the background discrimination without degrading the efficiency for selecting signal events. In ATLAS, a significance of about 3.5σ is expected for $10\,fb^{-1}$, assuming $m_H = 120$ GeV/c^2. With an optimized analysis employing a neural network, CMS expects up to 10σ after collecting $30\,fb^{-1}$ and a 5σ after accumulating $8\,fb^{-1}$ (see figure 1, right). Analyses are also being developed to target the associated production channels ZH, WH and $t\bar{t}H$.

2.3. Higgs boson decay to a tau pair: $H \to \tau^+\tau^-$

This channel currently provides one of the best sensitivities at low m_H. Analyses rely on the topology of VBF events to provide additional rejection against SM backgrounds. In this process, the Higgs boson is radiated by $W^{\pm}$ or Z^0 bosons exchanged between the interacting partons. Due to the lack of colour flow between the two interacting partons, the characteristic event topology consists of two relatively forward jets with a rapidity gap in between, containing little hadronic activity. Both ATLAS and CMS investigate this channel for all final states, in which at

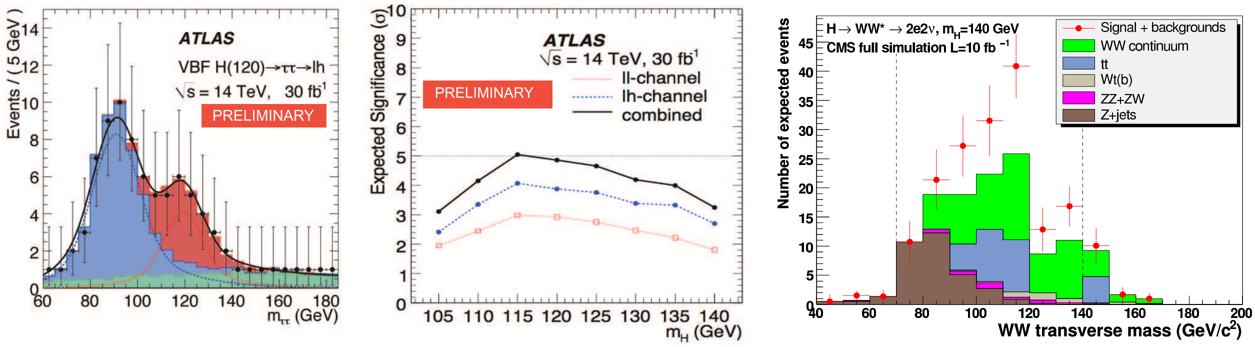

Figure 2: Left: $\tau^+\tau^-$ invariant mass distribution in the $H \to \tau^+\tau^-$ channel in ATLAS with one τ decaying hadronically and $m_H = 120\,\mathrm{GeV/c^2}$ [9]; centre: expected sensitivity for the $H \to \tau^+\tau^-$ channel in ATLAS (systematic uncertainties due to the background estimation are included) [10]; right: transverse mass in the $H \to W^+W^- \to l\nu l\nu$ in the CMS analysis [10].

least one tau decays to an electron or muon plus neutrinos. The final state where both taus decay hadronically was also investigated by ATLAS and proved to be feasible, but there is as yet no detailed sensitivity estimates. The dominant background in all cases is $Z + jets$ with the Z boson decaying to $\tau^+\tau^-$. Both collaborations have developed data-driven methods to estimate these backgrounds. Other backgrounds are $W + N$ jets, $t\bar{t}$, and di-jet events.

The $\tau^+\tau^-$ invariant mass reconstruction requires an approximation, in which the $\tau^\pm$ is assumed to be collinear with the visible lepton (in $\tau \to e$ or $\tau \to \mu$ decays). The resulting Higgs mass resolution can be observed in figure 2 (left). The expected sensitivity for this channel, currently reaches up to 5σ for $30\,fb^{-1}$.

2.4. Higgs boson decay to a W boson pair: $H \to W^+W^- \to l\nu l\nu$ ($l = e^\pm$ or $\mu^\pm$)

The Higgs boson decay to a W^+W^- pair provides the most sensitive search channel in the mass range $2m_W < m_H < 2m_Z$, where this decay mode has a branching ratio above 95%. Analyses have concentrated on final states containing electrons or muons from the $W^\pm$ decay. Contrary to the remaining channels, though, the presence of high transverse momentum neutrinos makes it unfeasible to obtain a Higgs mass peak. The transverse mass [10] can still be calculated and used in the event selection (see figure 2, right). Analyses in this channel then need to rely on a very good knowledge of the background shape and normalisation.

The dominant backgrounds come from events containing a W-boson pair, most importantly W^+W^- and $t\bar{t}$ production. The $H \to W^+W^-$ decay creates a correlation between the W spins in the Higgs reference frame which translates into an angular correlation between the leptons emitted in the W-bosons decay. This is exploited to suppress the W^+W^- background. The $t\bar{t}$ background can be effectively suppressed by a veto on central jets (jets with a small pseudorapidity value). Separate analyses are performed for the cases where there are no high transverse momentum jets present in the event and where there are two additional jets, directed at the gluon fusion and the VBF production modes, respectively. For a Higgs boson mass close $160\,\mathrm{GeV/c^2}$ a sensitivity in excess of 10σ is expected for each experiment for $30\,fb^{-1}$ of integrated luminosity. Additional channels being explored are the VBF $H \to W^+W^- \to l\nu + 2jets$ and the associated production channels $W^\pm H$ and $t\bar{t}H$.

3. Summary and Outlook

The expected sensitivity of ATLAS and CMS to a SM Higgs boson was evaluated by both collaborations. Analyses in both experiments show similar sensitivity in most channels. The sensitivity for SM Higgs discovery in the various channels is illustrated by figure 3 for the CMS case. An integrated luminosity of less than $10\,fb^{-1}$ should be enough to make a 5σ discovery in the mass range above the LEP limit. Preliminary ATLAS studies indicate that an integrated

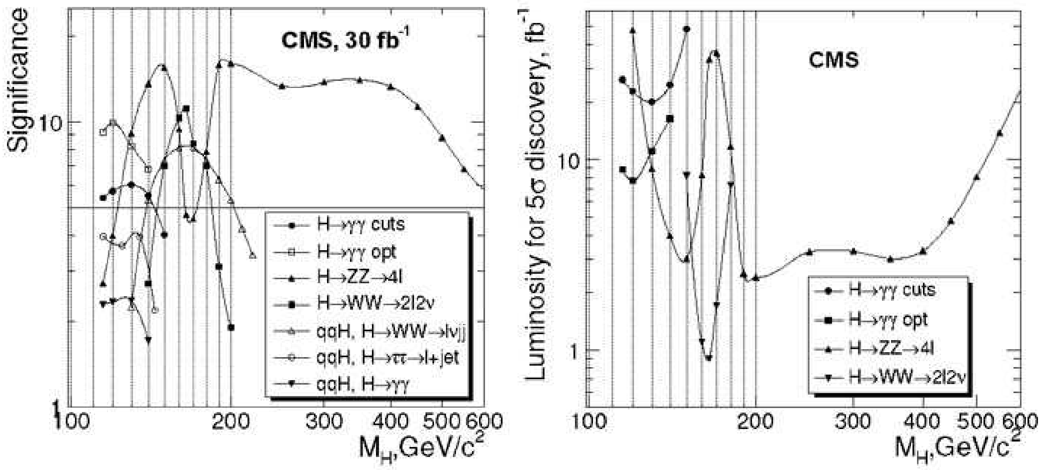

Figure 3: SM Higgs discovery potential for CMS assuming an integrated luminosty of 30 fb^{-1} (left) and integrated luminosity needed for a 5σ Higgs discovery, versus Higgs boson mass [10]).

luminosity of 2 fb^{-1} would be enough to exclude the Higgs boson in the range $121\mathrm{GeV/c^2} \lesssim \mathrm{m_H} \lesssim 460\mathrm{GeV/c^2}$ at 95% confidence level. Other analyses, not described here, may contribute to further enhancements of the sensitivity.

Acknowledgments

The author would like to express his thanks to ATLAS and CMS colleagues. Special thanks to Chiara Mariotti, Yves Sirois, Louis Fayard, Aleandro Nisati, Ketevi Assamagan, Eilam Gross, and Glen Cowan, and to many other colleagues who have kindly contributed with work and material for this paper.

References

1 P.W. Higgs, *Phys.Lett.*, **12** 132 (1964); P.W. Higgs, *Phys.Rev.Lett.*, **13** 508 (1964); P.W. Higgs, *Phys.Rev.*, **145** 1156 (1966); F.Englert and R.Brout, *Phys.Rev.Lett.* **13** 321 (1964); G.S.Guralnik, C.R.Hagen and T.W.B.Kibble, *Phys.Rev.Lett.* **13** 585 (1964).

2 The ATLAS Collaboration, G. Aad et al., *The ATLAS Experiment at the CERN Large Hadron Collider*, *JINST* (2008) 3 S08003; M. Bosman, *ATLAS Detector Status and Physics Startup Plans*, these proceedings.

3 The CMS Collaboration, G.L.Bayatian et al., *CMS Technical Design Report, vol.I - Detector Performance & Software*, CERN/LHCC 2006-001, February 2006; The CMS Collaboration, S. Chatrchyan et al., *The CMS experiment at the CERN LHC*, JINST (2008) 3 S08004.

4 S.Lowette, *Beyond the Standard Model Higgs at LHC*, these proceedings.

5 The LEP Higgs Working Group, *Search for the Standard Model Higgs Boson at LEP*, Phys.Lett. **B565** 61 (2003); CERN-EP/2003-11.

6 P. Renton, *"Standard Model Electroweak fits"*, these proceedings; The LEP Electroweak Working Group website *http://lepewwg.web.cern.ch/LEPEWWG/.*

7 M. Herndon, *"Searches for the Higgs Boson"*, these proceedings.

8 S.Söldner-Rembold, *Standard Model Higgs Searches*, [arXiv:hep-ex/0803.1451v2].

9 ATLAS Collaboration, *Expected Performance of the ATLAS Experiment, Detector, Trigger and Physics*, CERN-OPEN-2008-020, Geneva, 2008, to appear.

10 The CMS Collaboration, G.L.Bayatian et al., *CMS Technical Design Report, vol.II - Physics Performance*, *J.Phys.* **G** (2007) 995, CERN/LHCC 2006-021, June 2006.