Higgs search prospects at the LHC

Rebeca Gonzalez Suarez[a]*

[a]Instituto de Física de Cantabria
Santander, Spain

An overview on the different Higgs searches to be performed in the LHC is presented. Projections are made to estimate the potential of ATLAS and CMS to a possible discovery or exclusion of the Higgs boson during the first run at a centre of mass energy of 7 TeV, with a recorded integrated luminosity of around 1 fb^{-1}, expected by the end of 2011.

1. Current Status of the Higgs Searches

At the end of the Large Electron Positron (LEP) collider era, a solid exclusion was reached by combining the results of all the Higgs search channels performed by the four experiments, establishing a lower limit on m_H of 114.4 GeV/c^2 at more than 95% confidence level [1].

More recently, the direct Higgs searches performed in the CDF and D0 experiments at the Tevatron accelerator have reached better sensitivity, making possible the exclusion of a SM Higgs boson with a mass between 158 and 175 GeV/c^2 [2].

2. Higgs production and decay modes at the LHC

The LHC started functioning again at the end of 2009, and is continuously collecting luminosity at a centre of mass energy of 7 TeV since March 30th 2010. The projected luminosity deliver before the shut-down to go to higher energies is 100 pb^{-1} by November 2010 and 1 fb^{-1} by the end of 2011.

The main production modes for the Standard Model (SM) Higgs at 7 TeV at the LHC, presented in figure 1 are: gluon-gluon fusion gg, dominant in all the mass range; Vector-Boson fusion (VBF) qqH, increasingly important for

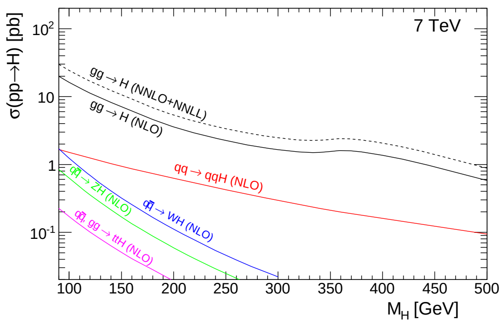

Figure 1. Production cross sections of the SM Higgs boson in proton-proton collisions as function of m_H for a centre of mass energy of 7.

high masses, that leads to a characteristic signature in the final state with two forward jets; and associated production, with W and Z bosons or top quarks WH ZH ttH, that is relevant in the low mass region and allows for easy triggering.

Concerning the decay modes, presented in figure 2, for low masses ($m_H < 2m_Z$), $H \rightarrow b\bar{b}$ decay has the highest branching ratio, although this channel is experimentally challenging due to the huge QCD background present. Another important decay mode for low masses is $H \rightarrow \tau\tau$, accessible through VBF, where the Higgs mass is reconstructed via a collinear approximation; and $H \rightarrow \gamma\gamma$, in which the Higgs mass peak can be

*Office: 13 3-022 Mailbox: F21700, CERN, Switzerland

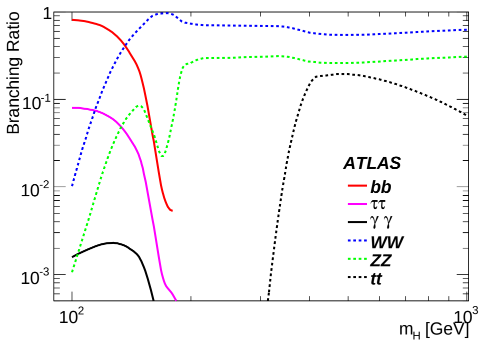

Figure 2. The branching ratios for the Standard Model Higgs decay modes at the LHC as functions of m_H.

reconstructed with a good resolution. For high masses ($m_H > 2m_Z$), the $H \to t\bar{t}$ can be studied, however, it presents difficulties in the selection due to the small signal-to-noise ratio.

The $H \to WW^*$ and $H \to ZZ^*$ decay channels are powerful in the whole mass range. The Higgs decay into two W bosons gives the earliest sensitivity and it is the dominant decay mode for a wide mass range. Higgs to ZZ^* has a very clean experimental signature with four leptons where a narrow mass peak is reconstructed above a smoothly varying background.

2.1. LHC and Tevatron scenarios

The Higgs searches in ATLAS [3] and CMS [4] at the first run of the LHC will go in parallel with the last era of the Tevatron experiments, CDF and DO. By the end of 2011, the Tevatron is expected to have 10 fb^{-1} at a centre of mass energy of 2 TeV compared with the 1 fb^{-1} at 7 TeV of the LHC.

Higher Higgs cross-sections are expected in the LHC, more than a factor 10 for gg processes. And a better signal-to-background ratio is expected, as the rise in cross section is less pronounced for qq-induced processes, that produce the main backgrounds. Additionally, ATLAS and CMS detectors have been designed and optimized for Higgs searches over the full mass range $120 < m_H < 900\ GeV/c^2$.

2.2. Prospective Higgs Searches in ATLAS and CMS

Both experiments utilize a wide range of Higgs decay channels and have public results available at different $\sqrt{s}$. For 7 TeV, projections are made from results obtained using Monte Carlo samples at different centre of mass energies, 14 and 10 TeV [5,6].

These projections are not new analyses done with 7 TeV Monte Carlo samples and new detector simulation and reconstruction software, they are done starting from public results at 14 and 10 TeV (made assuming $\int L \sim 1 - 30 fb^{-1}$).

The signal and background event counts are re-scaled by the ratio of 7 TeV to 14 TeV cross-sections and then normalized to 1 fb^{-1}. No corrections for higher acceptance at smaller $\sqrt{s}$ or for improvements in the reconstruction are applied.

3. SM Higgs search channels at the LHC

The main Higgs search channels relevant for the current running conditions of the LHC will be presented in the following.

3.1. Higgs to WW^*

The $H \to WW^* \to l^+\nu_l l'^- \bar{\nu_{l'}}$ decay channel is considered the discovery channel for a SM Higgs boson in a wide mass range at the LHC. The Higgs to WW^* branching ratio is close to 1 in the $2m_W < m_H < 2m_Z$ mass range, and the leptonic decay of the W bosons gives a clear experimental signature characterized by two high P_T leptons with opposite charge and a small transverse opening angle.

Missing transverse energy is expected, due to the undetected neutrinos. No central jet activity characterizes the $gg \to H$ processes while two high rapidity jets are expected in the VBF processes (smaller cross-section).

The backgrounds to consider in the analysis will be all sources of real or fake multi-lepton final states and missing E_T, like the irreducible continuum WW production (also other di-boson processes such as WZ and ZZ), $t\bar{t}$ processes (also other top backgrounds like tW), Drell-yan and W+jets, amongst others.

The final states studied in ATLAS and CMS are ee, $\mu\mu$ and $e\mu$. As no mass peak can be reconstructed, the best knowledge of backgrounds is mandatory. This is achieved by using control regions and the use of data-driven methods. The systematic uncertainties are carefully addressed and both experiments have developed a complementary multivariate approach.

ATLAS applies three different event selections as a function of the jet content of the event: $H+0j$, $H+1j$ and $H+2j$. Also, ATLAS analyses make use of the transverse mass. CMS proposes a sequential cut-based analysis independently optimized for the three considered final states in the 0-jet bin (H+0j) plus an independent VBF analysis. In the multivariate analysis all the final states are considered together.

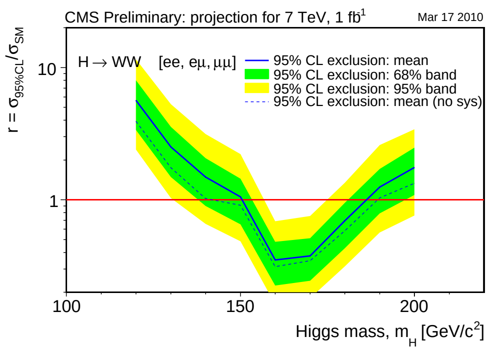

Figure 3. Projected exclusion limits for a search for $H \to WW^* \to 2l2\nu$ with the CMS experiment.

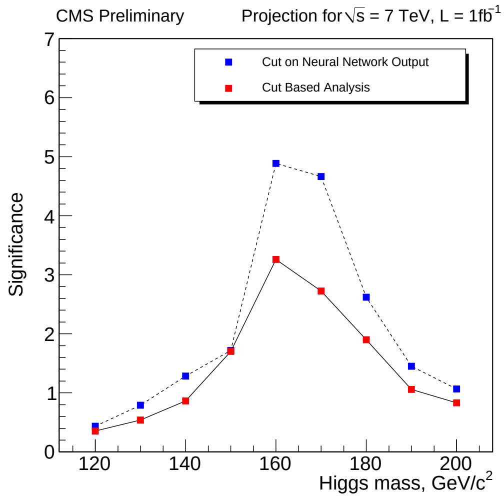

Figure 4. Significance of a projected excess of events in a search for $H \to WW^* \to 2l2\nu$ with the CMS experiment.

For an integrated luminosity of 1 fb^{-1} at 7 TeV, as shown in figures 3 and 5, exclusion would be possible at 95%CL in this channel from around 140 to 180 GeV/c^2, and discovery level sensitivity ($\sim 5\sigma$) would be achieved for masses around 165 GeV/c^2 as presented in figure 4.

3.2. Higgs to ZZ^*

The $H \to ZZ^* \to l^+l^-l'^-l'^+$ decay channel is known as the golden Higgs decay, as it has the cleanest experimental signature for discovery with a narrow four-lepton invariant mass peak on top of a smooth background. It is powerful in a wide high mass range, however, it can be a challenge for Higgs masses between 120 and 150 GeV/c^2, where one of the Z bosons is off-shell.

The main backgrounds are the irreducible ZZ^* and $Zb\bar{b}$, $t\bar{t}$, ZW and $Z+X$, which can be almost completely eliminated.

In the analysis, two pairs of same flavor, opposite-sign leptons ($4e$, 4μ, $2e2\mu$), are selected and the Higgs mass is reconstructed. The lepton isolation

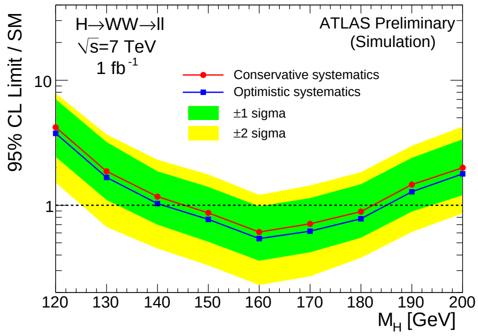

Figure 5. Projected exclusion limits for a search for $H \to WW^* \to 2l2\nu$ with the ATLAS experiment.

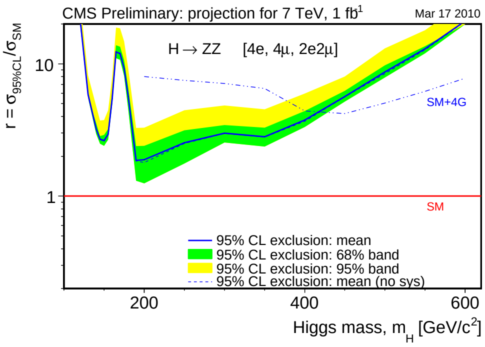

Figure 6. Projected exclusion limits for a search for $H \to ZZ^* \to 4l$ with the CMS experiment. The SM with a 4th generation is also represented with a dashed blue line.

and the cuts on the impact parameter are key to reduce background. The background rates are estimated by extrapolation to sidebands.

With an integrated luminosity of 1 fb^{-1} at 7 TeV, as shown in figure 6 for CMS, the SM Higgs boson cannot be excluded anywhere in the entire mass range.

However, the Higgs boson with a mass $m_H < 400$ GeV/c^2 would be excluded, if a fourth generation of quarks exists [7], as an extra doublet of quarks would make the ggH production rate ~ 9 times larger, regardless of how massive the the two extra 4th generation quarks might be.

3.3. Higgs to $\gamma\gamma$

In the low mass range, $110 < m_H < 140$ GeV/c^2, $H \to \gamma\gamma$ is a promising channel. Two high energy isolated photons in the final state allow for a mass peak reconstruction, but due to the small branching ratio, it is considered a high Luminosity analysis.

The backgrounds are the irreducible $\gamma\gamma$ and $\gamma\gamma + jets$, and $\gamma + jets$, $jets$ and Drell-Yan. The background is assessed from data sidebands.

In ATLAS, $H \to \gamma\gamma$ and $H \to \gamma\gamma + jets$ are studied, and the analysis is based in an unbinned maximum-likelihood fit, while in CMS, a cut-based analysis and an event-by-event kinematical likelihood ratio are proposed.

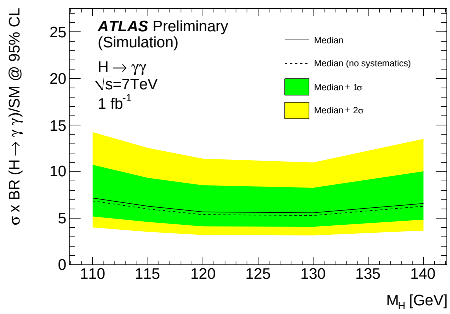

Figure 7. Projected exclusion limits for a search for $H \to \gamma\gamma$ with the ATLAS experiment.

For an integrated luminosity of 1 fb^{-1} at 7 TeV, as shown in figure 7 for ATLAS, the SM Higgs boson cannot be excluded anywhere in the entire mass range.

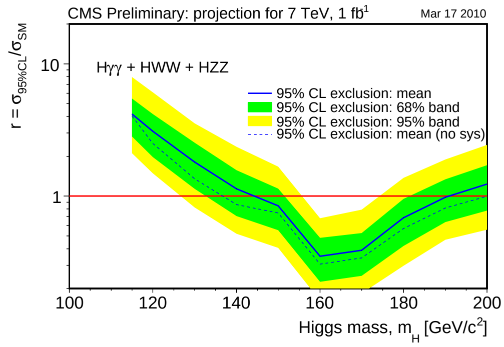

Figure 8. Projected exclusion limits for a SM Higgs by combining results of the $H \rightarrow WW^* \rightarrow 2l2\nu$, $H \rightarrow ZZ^* \rightarrow 4l$, and $H \rightarrow \gamma\gamma$ with the CMS experiment.

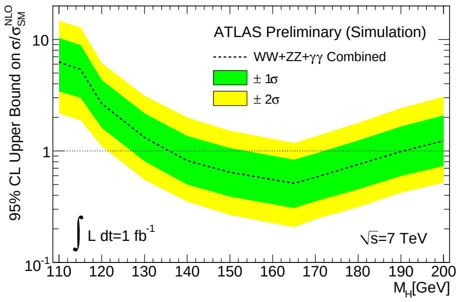

Figure 9. Projected exclusion limits for a SM Higgs by combining results of the $H \rightarrow WW^* \rightarrow 2l2\nu$, $H \rightarrow ZZ^* \rightarrow 4l$, and $H \rightarrow \gamma\gamma$ with the ATLAS experiment.

Figure 8 shows the projected exclusion limits for a SM Higgs by combining results of the $H \rightarrow WW^* \rightarrow 2l2\nu$, $H \rightarrow ZZ^* \rightarrow 4l$, and $H \rightarrow \gamma\gamma$. The expected exclusion mass range is $145 < m_H < 190\ GeV/c^2$. Projection is obtained by combing results provided by CMS and similar results are obtained in ATLAS as can be seen in figure 9.

Figure 10 shows the projected exclusion limits assuming twice the amount of data of CMS. This plot is intended to indicate what ATLAS + CMS combined sensitivity might be at 1 fb^{-1}. The expected exclusion mass range for the SM Higgs is $140 < m_H < 200\ GeV/c^2$.

The Higgs boson with a mass $m_H < 500\ GeV/c^2$ would be excluded, if a fourth generation of heavy quarks exists.

4. MSSM Higgs search channels at the LHC

The main channel for Minimal Supersymmetric Standard Model (MSSM) Higgs searches in the first period of running of the LHC will be heavy neutral MSSM Higgs produced via b quark association with subsequent decay to τ, $bb\Phi$, $\Phi \rightarrow \tau\tau$.

The main backgrounds are $Z + bb/cc/jets$ and $t\bar{t}$. Final states with isolated pairs of $\tau_{had}\tau_\mu$, $\tau_{had}\tau_e$ and $\tau_e\tau_\mu$ are selected. Missing E_T is also required in as well as one b-tagged jet and extra jets are vetoed.

The analysis is performed by counting events in the $\tau\tau$ invariant mass window, reconstructed by collinear approximation, where the τ decay products are assumed to be in the same direction as the τ.

Figure 11 shows the projected discovery and exclusion contours in the MSSM (m_A, $tan\beta$)-plane for a search for a neutral MSSM Higgs bosons in the $pp \rightarrow bb\Phi \rightarrow bb\tau\tau$ channel with the CMS experiment. At $m_A \sim 90\ GeV/c^2$, the discovery can be possible for $tan\beta > 20$ and the exclusion limit is expected to reach down to $tan\beta \sim 15$.

5. Conclusions

The performance of ATLAS and CMS in collision data has been very good since the start of the data taking and the reconstruction of the main physics objects used in the Higgs analyses

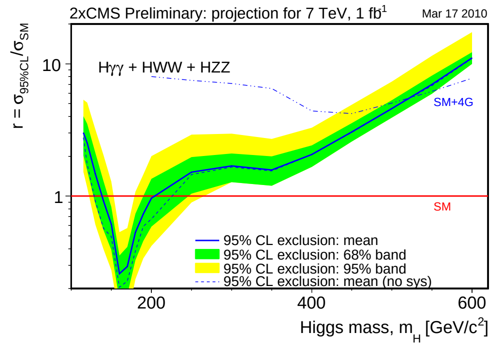

Figure 10. Projected exclusion limits for a SM Higgs by combining results of the $H \to WW^* \to 2l2\nu$, $H \to ZZ^* \to 4l$, and $H \to \gamma\gamma$ assuming twice amount of data.

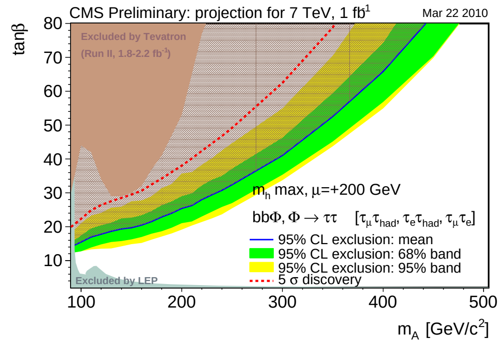

Figure 11. Projected discovery and exclusion contours in the MSSM (m_A, $tan\beta$)-plane for a search for neutral MSSM Higgs bosons in the $pp \to bb\Phi \to bb\tau\tau$ channel with the CMS experiment.

is performing well. It is already possible to start exploring Standard Model processes, namely W and Z.

At 7 TeV, with enough luminosity (1 fb^{-1}), the LHC experiments will begin to explore a sizable range of Higgs mass, reaching SM Higgs discovery sensitivity for masses between 160 and 170 GeV/c^2, and exclusion between 140 and 200 GeV/c^2, while low mass SM Higgs searches will require higher centre of mass energy and integrated luminosity.

For MSSM Neutral Higgs, the discovery range at $\sqrt{s} = 7$ TeV for small m_A would be $tan\beta \sim 20$, and exclusion be possible down to $tan\beta \sim 15$.

REFERENCES

1. Barate, R. et al, Search for the standard model Higgs boson at LEP, Phys. Lett. B565 (2003) 61-75.
2. The TEVNPH Working Group, Combined CDF and D0 Upper Limits on Standard Model Higgs-Boson Production with up to 6.7 fb^{-1} of Data, FERMILAB-CONF-10-257-E, 2010.
3. The ATLAS Collaboration, Expected Performance of the ATLAS Experiment - Detector, Trigger and Physics, http://cdsweb.cern.ch/record/1125884, CERN-OPEN-2008-020, 2009.
4. The CMS Collaboration, CMS physics: Technical design report, http://cdsweb.cern.ch/record/922757, CERN-LHCC-2006-001, 2006.
5. The CMS Collaboration, The CMS physics reach for searches at 7 TeV, http://cdsweb.cern.ch/record/1264099, CMS NOTE 2010/008, 2010.
6. The ATLAS Collaboration, ATLAS Sensitivity Prospects for Higgs Boson Production at the LHC Running at 7 TeV, http://cdsweb.cern.ch/record/1278455, ATL-PHYS-PUB-2010-009, 2010.
7. N. Becerici et al, The Fourth Standard Model Family and the Competition in Standard Model Higgs Boson Search at Tevatron and LHC, http://arxiv.org/abs/0908.2653, Eur.Phys.J.C66:119-126, 2010.