SM Higgs boson searches in the early ATLAS data

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Abstract

ATLAS exclusion and discovery potentials of Standard Model Higgs boson searches at the LHC at 14 TeV, 10 TeV and 7 TeV center-of-mass energy are reviewed. For a LHC center-of-mass energy of 7 TeV and integrated luminosity of 1 fb$^{-1}$, contributions from the important decay channels $H \to WW^{(*)} \to ℓνℓν$, $H \to ZZ^{(*)} \to ℓℓℓℓ$ and $H \to γγ$ are considered, based on recent full Monte Carlo simulations at 14 and 10 TeV and the cross-section rescaling for the 7 TeV center-of-mass energy. First measurements of backgrounds to Standard Model Higgs boson search are also presented.
1 Introduction

The primary objective of the Large Hadron Collider (LHC) is to study the origin of electroweak symmetry breaking. Within the Standard Model (SM), the Higgs mechanism \[1\][2][3] is invoked to explain this breaking, but the predicted SM Higgs boson still remains undiscovered. The direct search at the $e^+e^-$ collider LEP has led to the lower limit on its mass of 114.4 GeV at 95% confidence level (C.L.) \[4\]. In addition, high precision electroweak data constrain the Higgs boson mass via their sensitivity to loop corrections. The corresponding upper limit is $m_H \leq 185$ GeV at 95% C.L., provided that the result of the direct search at LEP is also used in the determination of this limit \[5\]. Combined analysis of the Tevatron data from CDF and D0, based on the integrated luminosity up to 6.7 fb$^{-1}$ at 1.8 TeV, yields a 95% C.L. exclusion of a Higgs boson with mass between 158 GeV $\leq m_H \leq 175$ GeV \[6\].

The ATLAS experiment \[7\] at the LHC is designed to search for the Higgs boson over a wide mass range. Since the end of March 2010, LHC was running at a total energy of 7 TeV for pp-collisions and by the end of the year reached the integrated luminosity of less than 50 pb$^{-1}$. In this report, the ATLAS sensitivity to discover or exclude the SM Higgs boson and recent developments to enhance this sensitivity are summarized. In addition, the results of first measurements of backgrounds to SM Higgs boson production are presented.

2 SM Higgs search channels

2.1 SM Higgs production and decays at the LHC

The dominant production mechanism for a SM Higgs boson production is gluon fusion ($gg \rightarrow H$). At 14 TeV, it has a cross-section at NLO of 20–40 pb \[8\] in the Higgs boson mass range between 114 and 185 GeV\[1\]. The vector-boson fusion (VBF) process ($qq \rightarrow qqH$) has a factor of eight smaller NLO cross-section than the $gg \rightarrow H$ mode but has a characteristic signature: the Higgs boson is accompanied by two energetic, mainly forward-going, jets.

The SM Higgs boson is predicted to have many decay channels with branching ratios strongly dependent on its mass. The evaluation of the search sensitivity of various channels should take into account the cross-sections of the relevant backgrounds. At low Higgs boson mass the dominant decay mode is through $b\bar{b}$. However, due to the enormous QCD backgrounds this channel is not optimal for the SM Higgs discovery. The $H \rightarrow WW^{(*)} \rightarrow \ell\nu\ell\nu$ final state is the main search channel in a wide $m_H$ range below 200 GeV, due to a large branching ratio. For the $H \rightarrow ZZ^{(*)} \rightarrow \ell\ell\ell\ell$ mode, the resulting decay probability is small but the signal is easy to trigger on and allows for a full and precise reconstruction of the Higgs mass. The $\gamma\gamma$ final state has a small branching fraction but a very clean signature. ATLAS and CMS Collaborations have performed extensive GEANT-based Monte Carlo (MC) \[9\] studies with full simulation and reconstruction at 14 TeV \[10\],[11] to explore the feasibility of observing different Higgs decay channels. It was concluded that with an integrated LHC luminosity of 2 fb$^{-1}$ ATLAS alone is able to discover the SM Higgs boson in the mass range between 143 and 179 GeV. ATLAS Collaboration also estimated $H \rightarrow WW^{(*)} \rightarrow \ell\nu\ell\nu$ exclusion potential at 10 TeV and 200 pb$^{-1}$ \[12\]. When it became clear that the LHC will work at 7 TeV during a prolonged period of time, the related study was performed for this energy \[8\], by re-scaling the expectations from detailed analyses at 10 or 14 TeV and using re-weighted cross-section ratios or parton distribution functions\[2\]. Similar cross section rescaling is performed also for other Higgs decay channels \[8\].

\[1\] Although the NNLO corrections increase the cross-section by a factor of $\approx 1.5$, ATLAS used conservative (NLO) approach in the sensitivity studies.

\[2\] Note, that the signal and background cross-sections at 7 TeV are roughly four times smaller than at 14 TeV.
2.2 $H \rightarrow WW^{(*)} \rightarrow ℓνℓν$

At low integrated luminosity, the decay channel $H \rightarrow WW^{(*)}$ provides the best sensitivity for the SM Higgs boson search in ATLAS. However, unlike with the $H \rightarrow ZZ^{(*)} \rightarrow 4ℓ$ and $H \rightarrow γγ$ channels, a full mass reconstruction is impossible in this channel, therefore an accurate background estimate is very important. The main background is $q\bar{q},gg \rightarrow WW^{(*)}$-production giving two oppositely charged leptons in the final state. Additional smaller background contributions are $t\bar{t}$ and $Wt$. These processes can be suppressed, in particular, by exploiting the spin correlation between the two final state leptons, and applying an upper cut on the lepton pair invariant-mass. Another important background comes from $W \rightarrow ℓν + jets$, with one of the jets misidentified as a lepton. Data-driven methods have been developed to estimate this background. Fig. 1(left) shows the exclusion reach as a function of the Higgs boson mass $m_H$ for different integrated luminosity scenarios at 7 TeV. With 1 fb$^{-1}$, ATLAS expects to exclude a region $140 \text{ GeV} \leq m_H \leq 185 \text{ GeV}$ at 95% C.L., see Fig. 1(right). A $5σ$-discovery for the SM Higgs boson with $m_H$ around 160 GeV is expected in the $H \rightarrow WW^{(*)} \rightarrow ℓνℓν$ mode alone with the integrated LHC luminosity of $≈5 \text{ fb}^{-1}$.

2.3 $H \rightarrow ZZ^{(*)} \rightarrow 4ℓ$

The “golden” channels ($4µ,2e2µ$ and $4e$ final states of $ZZ^{(*)}$ decays) are expected to have a good discovery potential in a wide mass range (except $m_H \leq 130 \text{ GeV}$ and $m_H \approx 2m_W$). The irreducible background is a non-resonant $ZZ^{(*)}$-continuum. For a low mass region with $m_H \leq 180 \text{ GeV}$, there are additional reducible backgrounds mainly from $Zb\bar{b}$, $t\bar{t}$, $WZ$ and $Z + jet$ processes. They can be suppressed by using the impact parameter and lepton isolation requirements. Simulations of the signal and the background processes made at the NLO level show that at 7 TeV energy and 1 fb$^{-1}$ integrated luminosity a 95% C.L. exclusion is not expected.

2.4 $H \rightarrow γγ$

Despite of a small (0.2%) branching ratio in the Higgs mass region from 120–140 GeV, $H \rightarrow γγ$ remains a promising channel due to a very clean signal signature is very clean. Irreducible backgrounds originate from the continuum, $q\bar{q},gg \rightarrow γγ$. Reducible backgrounds are mostly due to γ-jet and jet-jet events with one or more jets misidentified as photons. The high-granularity electromagnetic calorimeter of ATLAS is capable of determining the photon direction with a great precision and has an excellent energy and angular resolution. It permits the suppression of the reducible backgrounds well below the γγ-continuum. Like in the case of $H \rightarrow ZZ^{(*)} \rightarrow 4ℓ$, with 7 TeV and 1 fb$^{-1}$ one cannot exclude at 95% C.L. the SM Higgs boson with the $H \rightarrow γγ$ channel alone.

2.5 Summary of the SM Higgs exclusion potential

Figure 1(right) shows a combined exclusion reach of the inclusive Higgs boson search with the decay modes $H \rightarrow WW^{(*)} \rightarrow ℓνℓν$, $H \rightarrow ZZ^{(*)} \rightarrow 4ℓ$ and $H \rightarrow γγ$ in ATLAS. In this plot, conservative systematic errors for $H \rightarrow WW^{(*)} \rightarrow ℓνℓν$ mode, conservative NLO calculation of the signal cross-sections and 10% uncertainty on the LHC integrated luminosity are assumed. With 7 TeV LHC energy and 1 fb$^{-1}$ of integrated luminosity it would be possible to exclude the region $135 \text{ GeV} \leq m_H \leq 188 \text{ GeV}$ at 95% C.L. The exclusion limits could be improved by adding channels such as VBF $H \rightarrow ττ$ and $VH \rightarrow b\bar{b}$ at low $m_H$, as well as $H \rightarrow ZZ^{(*)} \rightarrow ℓνℓν$ and $H \rightarrow ZZ^{(*)} \rightarrow ℓνb\bar{b}$ decays at high $m_H$ values. Furthermore, using NNLO signal cross-sections, instead of NLO, will make the exclusion region

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3To estimate a background contribution in a signal region, one selects the background-dominated control region and uses the MC prediction to extrapolate this background contribution into the signal region.
significantly wider. Finally, one could benefit from possible LHC running at 8 or 9 TeV in 2011, instead of 7 TeV. The results based on all these improvements are summarized in a recent Ref. [13]. With 2 fb$^{-1}$, 8 TeV and the analysis improvements, the 95% C.L. exclusion range will span from 114 to over 500 GeV.

3 First ATLAS measurements of backgrounds to the SM Higgs searches

Based on 310 nb$^{-1}$ data at 7 TeV, ATLAS observed $W + jet$ background to the $H \rightarrow WW^{(*)} \rightarrow ℓνℓν$ search [14] and made data-driven estimation of the dijet and $W + jet$ backgrounds for the $H \rightarrow ττ \rightarrow ℓh$ search [15].

3.1 Observation of the $W + jet$ background to the $H \rightarrow WW^{(*)} \rightarrow ℓνℓν$ search

Nine events with large missing transverse momentum and two lepton candidates, one of which passes the tighter and the other one the looser identification criteria [7], were observed. This is consistent with the MC expectation. It therefore validates our MC based sensitivity studies. This data sample is dominated by $W + jet$ events and will be used as a control region to estimate the $W + jet$ background contribution from the signal-like region defined for the Higgs boson search, as demonstrated in Ref. [12]. In addition to a pure MC estimate, the contamination from the QCD background in this control region is also estimated by means of data-driven methods. The estimation of the $W + jet$ contribution to the Higgs boson search requires the knowledge of the rate of fake lepton events in which a loosely identified lepton candidate is also identified using tighter identification criteria. Fake lepton rates down to the lepton transverse momenta of 10 GeV are obtained from dijet and $γ + jet$ data samples and agree well with the MC predictions. They are shown in Fig. 2 separately for electrons and muons.

3.2 Data-driven background estimation for the $H \rightarrow ττ \rightarrow ℓh$ search

To estimate the background in this channel, events with an electron or a muon having, in addition, a hadronically decaying tau lepton of the opposite charge and a large missing transverse energy, were selected. Candidate events with $E_{T}^{miss} ≥ 20$ GeV were found in both electron and muon channels – 12 and 17 events, respectively. This is consistent with the total of $25±9$ events expected from a data-driven background estimation based on the control regions with low missing transverse energy and with the same sign charge of the lepton and hadronically decaying tau lepton.. The observed shape of the visible mass distribution also agrees with the estimation. With an additional requirement of a large transverse mass, 3 and 7 candidate events remain in the electron and muon channels, respectively. They are expected to come mainly from the $W + jet$ and $Z + jet$ processes, representing backgrounds for the $H \rightarrow ττ \rightarrow ℓh$ search. This study provides a starting point for future Higgs boson searches in di-tau channels and the corresponding data-driven background estimation.

4 Conclusion

The ATLAS simulations show that at 7 TeV and with the integrated LHC luminosity of 1 fb$^{-1}$ the SM Higgs boson can be excluded at 95% C.L. in the range $135$ GeV ≤ $m_H$ ≤ $188$ GeV, by combining $H \rightarrow WW^{(*)} \rightarrow ℓνℓν$, $H \rightarrow ZZ^{(*)} \rightarrow ℓℓℓℓ$ and $H \rightarrow γγ$ channels and using conservative assumptions. Should 2 fb$^{-1}$ and 8 TeV be available, one can cover the exclusion range from 114 to over 500 GeV by adding extra decay channels and improving the analysis. First measurements of backgrounds to the SM Higgs boson production have been performed. They will be extended as more data become available.
Figure 1: Left: expected 95% C.L. upper limits on the SM Higgs boson production rate normalized to
the SM prediction, for different integrated luminosity scenarios at 7 TeV, for the $H \rightarrow WW^{(*)} \rightarrow \ell\ell\nu\nu$ channel alone. Right: the expected upper bound on the Higgs boson production cross-section after collecting 1 fb$^{-1}$ of integrated luminosity at 7 TeV in ATLAS. $H \rightarrow WW^{(*)} \rightarrow \ell\ell\nu\nu$, $H \rightarrow ZZ^{(*)} \rightarrow \ell\ell\ell\ell$ and $H \rightarrow \gamma\gamma$ decay channels are combined. The coloured area represent the 1$\sigma$ and 2$\sigma$ error bands.

Figure 2: Fake lepton rates as function of lepton $p_T$. The fake rate measured from dijet data is compared with the MC prediction. Left: electrons. Right: muons.

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