Higgs Discovery Potential with the ATLAS Detector at the LHC

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Abstract. In this paper we report on a summary of the most recent strategies developed to discover the Higgs boson with the ATLAS detector at the LHC. We cover both the Standard Model Higgs framework as well as its minimal supersymmetric extension. We review the main observable channels together with the experimental aspects more relevant for their observation.

1. Introduction
One of the primary objectives of the ATLAS experiment at the LHC is the search and eventual discovery of the Higgs boson. Within the Standard Model (SM), the Higgs mechanism is thought to explain the origin of electroweak symmetry breaking and predicts the existence of a single scalar particle, the Higgs boson, with its mass, \( m_H \), as a free parameter.

In the Minimal Supersymmetric Extension of the Standard Model (MSSM) the Higgs sector is extended to two complex Higgs doublets of scalar fields which, under the assumption of \( \mathcal{CP} \) conservation, lead to five physical Higgs states, three neutral (two \( \mathcal{CP} \)-even states, \( h \) and \( H \), and one \( \mathcal{CP} \)-odd state, the pseudoscalar \( A \)) and two charged \( (H^\pm) \). Only the \( \mathcal{CP} \)-even bosons couple to weak gauge bosons. At tree level, the Higgs properties are determined by only two real parameters, usually chosen to be the mass of the pseudoscalar, \( m_A \), and the ratio of the vacuum expectation value of the two Higgs doublets, \( \tan \beta \). Loop corrections, mainly from the \( t/\bar{t} \) sector, modify the tree level formulas for masses and mixing patterns in the Higgs sector through dependences in additional parameters. Representative benchmark scenarios have been introduced, where only \( \tan \beta \) and \( m_A \) are varied, while the rest of parameters are fixed [1].

In this paper, we summarize the most recent results regarding the prospects to observe one of these particles in the ATLAS detector [2]. ATLAS is a general purpose experiment optimized for the detection of a wide span of physics signatures in 14 TeV pp collisions. We emphasize the sensitivities and expected signal significances for different individual and combined production modes.

The present strongest experimental bounds on the Higgs boson mass come from direct searches at LEP, and exclude a Higgs mass \( m_H < 114.4 \text{ GeV} \) at the 95% CL [3]. An indirect measurement of the Higgs boson mass from precision fits of electroweak observables, including data from LEP and Tevatron colliders, and assuming the SM scenario, results in a one-sided 95% CL upper limit of \( m_H < 154 \text{ GeV} \). This limit increases to 185 GeV when including the LEP direct search results [4].

All results shown in this paper represent an overview from a long and extensive project within the collaboration to estimate the sensitivity and quantify the significances with a realistic
knowledge of the detector performance and theoretical uncertainties on background and signal cross-sections [5].

2. Standard Model Higgs Boson

The dominant production mechanism for SM Higgses at the LHC energy of 14 TeV is gluon-gluon fusion via heavy top quark loops (gg → H), which contributes with a cross-section of ∼ 20–60 pb in the mass range between 114 – 185 GeV. The Vector Boson Fusion (VBF) process (qq → qqH) has a factor eight smaller cross-section. However, in this case, the Higgs boson is accompanied by two energetic jets going mainly in the forward directions and with a large pseudorapidity gap in-between, which, as we shall see, leads to interesting topologies. Other processes like associated production with weak vector bosons (qg → W/ZH) and associated production with top quark pairs (gg, qg → tH) have smaller cross-sections. Figure 1 summarizes these theoretical results for the different Higgs SM production mechanisms as given in [6].

The expected SM Higgs decay channel and branching ratios as a function of mass are shown in figure 2. At low Higgs masses the dominant decay mode is through b̅b pairs. This channel is, however, quite difficult to isolate experimentally due to the huge QCD background. The γγ decay is loop-induced and thus, rare. However, with an excellent diphoton invariant mass resolution and γ/j separation, this mode may become one of the best discovery channels at these low energies. The ττ decay mode offers a modest Higgs mass resolution and thus, inclusive analysis are weak. This channel offers, however, a sizeable rate, and should be visible with a good purity via VBF when the Higgs is produced in association with jets. For larger Higgs masses, one should consider the WW* and ZZ* channels which give rise to different final state signatures.

2.1. Search for H → γγ

The H → γγ channel represents one of the best discovery channels for the low mass region between the LEP limit and m_H ~ 140 GeV, in spite of the low Higgs boson branching ratio to two photons (around 0.2% for m_H ~ 120 GeV, as shown in figure 2, with a production cross-section of ~ 50 fb). The final state consists of two high p_T identified photons (p_T > 25 GeV) with an invariant mass compatible with the Higgs boson mass.
The main irreducible background is the continuum direct diphoton production $gg \rightarrow \gamma\gamma$. Thus, an excellent energy and angular resolution are needed in order to observe a mass peak above these QCD $\gamma\gamma$ backgrounds. Reducible backgrounds are mostly due to $\gamma j$ and $jj$ events, where at least one jet is misidentified as a real photon. These are also important backgrounds due to the large QCD cross-sections. In order to reject them, a powerful photon identification and jet rejection capability are also required. This last requires optimized isolation cuts and $\pi^0$ rejection. As in the mass range covered by this analysis the Higgs width is negligible, $\sim \mathcal{O}$(MeV), the mass resolution is dominated by experimental effects, basically photon energy and position. The photon energy is optimized with careful calibrations, while the position contribution to the mass resolution is reduced by an accurate measurement of the photon direction. An example of invariant mass distribution of diphoton events is shown in figure 3 for a $m_H = 120$ GeV. A relative mass resolution $\sigma_m/m \sim 1.2\%$ is obtained, degrading by a few percent with pileup. Note that the background shape in this channel allows for a direct estimation of the background from data from a sideband fit with respect to the signal peak.

Figure 4 shows the significance results for an inclusive analysis where at least two photons with a $p_T$ above 40 and 25 GeV are required, and from a combined analysis of several exclusive channels. The significances are estimated from both the statistical ratio $S/\sqrt{B}$ and from an unblinded extended multivariate maximum likelihood fit.

2.2. Search for $t\bar{t}H$, $H \rightarrow b\bar{b}$

The observation of the SM Higgs boson through $H \rightarrow b\bar{b}$ decays through gluon fusion and VBF is hopeless due to the enormous backgrounds from jet production in QCD production. Nevertheless, the observation might still be possible through associated production with top quark pairs in the process $gg, q\bar{q} \rightarrow t\bar{t}H$. The final states in this channel are complex and the analysis selects semileptonic decays of the W’s, i.e., $t\bar{t}H \rightarrow \ell\nu qq\bar{b}b\bar{b}$, where the high $p_T$ charged lepton is used to trigger the signal. This channel has the advantage that the Higgs mass may be fully reconstructed and offers, thus, the opportunity to suppress backgrounds, which consist mainly of non resonant QCD and electroweak $t\bar{t}b\bar{b}$ production (irreducible) and
2.3. Search for $H \rightarrow \tau \tau$ in VBF Events

Higgs production via VBF events has recently been proved to be an important channel for the Higgs. In VBF, Higgs bosons are radiated off by $W^\pm$ or $Z^0$ bosons exchanged between the interacting particles. This process provides a characteristic event topology of two relatively forward jets with a rapidity gap in between containing little hadronic activity, mainly due to the lack of colour flow between the initial interacting particles. Three different final states of $\tau$ decays are considered, $\ell\ell$, $\ell h$ and $hh$. For all cases, the Higgs mass may be reconstructed, despite the presence of neutrinos, if the collinear approximation is applied for the $\tau$ decays. Within this approximation the $\tau$ is assumed to be collinear with the visible lepton (for $\tau \rightarrow e, \mu$ decays). The mass resolution obtained this way is $\sim 10\%$, and it is dominated mainly by the resolution on $E_T^{miss}$. This is shown in figure 7 for $\tau \tau \rightarrow \ell h$ decays and for a Higgs mass of 120 GeV.
Figure 7. Example fit to a signal plus background data sample model for VBF $H \to \tau\tau$ decays in the $\ell h$ channel, with $m_H = 120$ GeV and for $30$ fb$^{-1}$.

Figure 8. Expected signal significances as a function of mass as obtained from a fit to the $m_{\tau\tau}$ spectrum for VBF $H \to \tau\tau$ decays and for $30$ fb$^{-1}$.

Figure 9. Reconstructed 4-lepton mass, $m_{4\ell}$, for signal and individual main SM background processes (ZZ is, though, the dominant contribution) for a Higgs mass of $m_H = 150$ GeV. Data is normalized to a total integrated luminosity of $30$ fb$^{-1}$.

Figure 10. Signal significance as a function of Higgs mass for all combined decay modes for the $H \to 4\ell$ channel. Results are shown for both the profile likelihood ratio as well as the Poisson statistics significance analysis for a total luminosity of $30$ fb$^{-1}$.

The main source of SM backgrounds for this process are both QCD and electroweak $Z +$ jets production (with $Z \to \tau\tau$) and $t\bar{t}$ ($\to WbWb$) events. Other background sources for this channel include $W +$ jets, single top production, etc. Data-driven methods have also particularly developed in this channel to estimate these types of backgrounds.

Figure 8 shows the expected significance results for the individual and combined $\ell\ell$ and $\ell h$ channels with $30$ fb$^{-1}$ luminosity as a function of mass. All results are obtained from a profile likelihood fit to the mass spectrum and include background uncertainties.
2.4. Search for $H \rightarrow ZZ^* \rightarrow 4\ell$

Final state signatures with four leptons from ZZ* decays (4$\mu$, 2e2$\mu$ and 4e) represent “golden” channels, expected to account for discovery modes in a wide mass range, between 120 to 600 GeV. These signatures are also considered as benchmark channels for detector performance. At low masses, below $\sim 130$ GeV and for $m_H \sim 2m_W$, we expect a dip in significance due to a low $p_T$ lepton spectrum (one of the Z bosons is off-shell) and the opening of the $H \rightarrow WW$ channel, respectively. The main source of background is the irreducible ZZ*/$\gamma^*$ → 4$\ell$ continuum, while other reducible backgrounds are Zb$\bar{b}$, ZW and $t\bar{t}$. The first one is rejected through lepton isolation and impact parameter significance cuts. As with the $\gamma\gamma$, this channel allows for a background shape and normalization to be inferred directly from data through the fit of the sidebands of the clear four-lepton mass peak above a flat background.

The signal mass peak is fully reconstructed in this channel, with resolutions between 1.5–2%, depending on the Higgs mass. Figure 9 shows an example of the 4$\ell$ mass reconstruction for signal and background processes in the case of a $m_H = 150$ GeV Higgs normalized to a luminosity of 30 fb$^{-1}$. Figure 10 shows the signal significance as a function of Higgs mass as obtained from both the ratio $S/\sqrt{B}$ in a Poisson counting experiment (no systematic errors on signal and background included) and from a profile likelihood ratio fit. All results are shown for 30 fb$^{-1}$.

2.5. Search for $H \rightarrow WW^*$

The $H \rightarrow WW^*$ decay mode represents the main search channel in the Higgs mass range $2m_W \leq m_H \leq 2m_Z$ due to the large $H \rightarrow WW$ branching ratio above 95%. But this mode performs also well at lower masses (down to $m_H \sim 130$ GeV) and at high $m_H$. Two different final states are considered in this channel, $\ell\ell\nu\nu$ and $t\bar{t}q\bar{q}$. Note that unlike the $H \rightarrow ZZ^* \rightarrow 4\ell$ and $H \rightarrow \gamma\gamma$ channels, full mass reconstruction is not possible with this channel due to the presence of high $p_T$ neutrinos. Nevertheless, the Higgs transverse mass can still be calculated and used in the event selection. An accurate background estimation is, thus, critical for this channel. The dominant background is $q\bar{q}, gg \rightarrow WW^*$ production for the $H(\rightarrow WW)+0$ jets mode in gluon fusion events, which may be suppressed by exploiting the spin correlation between the two final state leptons from the Higgs boson scalar decay. For the $H(\rightarrow WW)+2$ jets channel...
3. MSSM Higgs Boson

The ATLAS discovery potential for MSSM Higgs bosons has been performed from the SM results as well as from dedicated MSSM analysis. For neutral Higgs bosons, the following channels have all been included (in the following, $\phi$ stands for a neutral Higgs boson mass eigenstate): VBF ($qq\rightarrow qq\phi$) with $\phi \rightarrow \tau \tau$, $WW$, $\gamma \gamma$, top-associated production with $\phi \rightarrow bb$, $b$-associated production with $\phi \rightarrow \mu \mu$, $\tau \tau$, gluon fusion with $\phi \rightarrow \gamma \gamma$, $\phi \rightarrow ZZ \rightarrow 4\ell$ and $\phi \rightarrow WW \rightarrow \ell \nu \ell \nu$, gauge-boson-associated production with $\phi \rightarrow \gamma \gamma/bb/WW \rightarrow \ell \nu \ell \nu$, $H/A \rightarrow t\bar{t}$, $H \rightarrow hh \rightarrow \ell \ell bb$ and $A \rightarrow Zh \rightarrow \ell \ell bb$. For charged Higgs bosons $gb \rightarrow tH^{\pm}$, $H^{\pm} \rightarrow \tau \nu$ and $tt \rightarrow tH^{\pm}b$, $H^{\pm} \rightarrow \tau \nu$ contribute. A summary of the discovery potential in several $CP$ conserving MSSM scenarios has been previously shown in [7] for 30 fb$^{-1}$ and 300 fb$^{-1}$, and it is shown in figures 13 and 14, respectively, for the $m_{h}^{\text{max}}$ scenario. In the following we report only on more recently analysis for the Higgs decay modes $\phi \rightarrow \tau \tau$, $\mu \mu$ produced either through gluon fusion (which dominates for low $\tan \beta$) or in association with b quarks. This last case is an example Higgs boson coupling to down-type fermions, which in the MSSM might be enhanced by a factor $\tan^2 \beta$, so channels which have limited sensitivity in the SM become most important here.

3.1. Search for $h/H/A \rightarrow \mu \mu, \tau \tau$

The experimental signature for the $\mu \mu$ channel is two isolated muons of opposite charge and no $E_{T}^{\text{miss}}$. The main backgrounds include Z boson production ($Z \rightarrow \mu \mu$) and $t\bar{t}$ pairs. The former
Figure 15. $5\sigma$ discovery contour in the $\tan\beta - m_A$ plane for the MSSM $\mu\mu$ channel, for the combination of tagged and b-vetoed analysis and for an integrated luminosity of 10 fb$^{-1}$ and 30 fb$^{-1}$. The dashed (dotted) lines indicate results with (without) systematic uncertainties. The bands show the theoretical uncertainty. All results correspond to the $m^\text{max}_h$ scenario.

Figure 16. $5\sigma$ discovery contour in the $\tan\beta - m_A$ plane for the MSSM $\tau\tau$ channel and for 30 fb$^{-1}$. The grey lines indicate the theoretical uncertainty on the signal, the solid line shows the contour with experimental systematics only and the dashed line includes an additional theoretical uncertainty on the $t\bar{t}$ cross-section of 10%.

may be suppressed by requiring the presence of at least one b-quark jet in the event, while the later is mainly reduced with $E_T^{miss}$ cuts. The main backgrounds in the b-tagged sample arise from $Z + b$ jets, mistagged $Z+$ jets and the dominant $t\bar{t}$ production. On the other hand, the irreducible $Z+$ jets background is dominant in the b-vetoed analysis. Figure 15 shows the significance results, in a $5\sigma$ discovery $\tan\beta - m_A$ plane, from a maximum likelihood fit to the dimuon invariant mass distribution.

The results reported here regarding the $\tau\tau$ channel correspond to $h/H/A \rightarrow \tau^+\tau^- \rightarrow 2\ell + 4\nu$ signatures, i.e., we require two oppositely charged leptons and $E_T^{miss}$ from the neutrinos. The Higgs boson mass can be fully reconstructed with the collinear approximation, which leads to a resolution about one order of magnitude larger than the intrinsic width and dependent on $m_A$. Relevant backgrounds for this channel are $Z \rightarrow \tau\tau+jets$, $Z\rightarrow\ell\ell+jets$, $W\rightarrow\ell\nu+jets$ and $t\bar{t}$ production, where the relative contributions depend on the mass. Figure 16 shows the $\tau\tau$ →dilepton discovery potential on the $\tan\beta - m_A$ plane and for an integrated luminosity of 30 fb$^{-1}$.

4. Higgs Properties

The measurements related to the properties of an hypothetical discovered Higgs particle at the LHC include its mass, width, coupling to fermions and gauge bosons, spin and CP quantum numbers. The study of these measurements would give insights into the origin of the electroweak symmetry-breaking mechanism and should allow, in some cases, for a distinction between a SM and an eventual MSSM Higgs mass spectrum. As an example, figure 17 shows results of the expected Higgs mass and width resolutions as a function of mass for an integrated luminosity of 300 fb$^{-1}$ as originally given in [8]. We expect mass precisions of $\sim 0.1\%$ between 100 – 400 GeV and width precisions of $\sim 10\%$ for masses above $\sim 250$ GeV. For Higgs boson masses below 200 GeV, the observed width of the Higgs resonance peak is dominated by detector resolution and a direct width measurement is not possible. Higgs boson couplings and widths are expected to be measurable under wild theoretical assumptions, with typical precisions of a few 10% for masses
Figure 17. Expected precision on the Higgs mass, width and cross-section times branching ratios as a function of mass for a total integrated luminosity of 300 fb$^{-1}$.

Figure 18. Expected SM Higgs discovery significance for various individual channels and combined together for an integrated luminosity of 10 fb$^{-1}$ for the lower mass range (left) and for masses up to 600 GeV (right).

below 200 GeV. Non-standard combinations of spin and CP quantum numbers are expected to result in significant deviations from SM expectations for Higgs masses above 200 GeV [9]. In particular, the VBF channel offers good prospects for CP studies of the Higgs boson as well as the structure of its couplings [10], also in the mass range below 200 GeV.

5. Summary
The discovery potential of a SM and a MSSM Higgs boson has been extensively studied within the ATLAS experiment. This paper shows an overall summary of the results for some of the most important channels and experimental signatures. Figure 18 shows a combined 5σ discovery reach, which may already be achieved in the mass range between 130 and 450 GeV with just 10 fb$^{-1}$ of integrated luminosity, provided that detector performance and background systematics will be well under control.
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