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Higgs Physics with ATLAS

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The discovery potential of the ATLAS experiment at the CERN Large Hadron Collider (LHC) also includes the Higgs boson. Several channels important for the discovery or exclusion of the Standard Model (SM) and the Minimal Supersymmetric Standard Model Higgs boson(s) are reviewed. Measurements of the properties of a Higgs-like particle are also briefly discussed.

1. Introduction

The ATLAS experiment [1] at the LHC is designed for precise measurements and fundamental discoveries in proton-proton collisions at the center-of-mass energy up to 14 TeV [2]. One of the key issues is to understand the mechanism by which particles acquire their mass. This feature may be explained by the concept of the electro-weak symmetry breaking via Higgs mechanism, which results in the existence of the not-yet-discovered particle in the SM, called Higgs boson. There are several theoretical frameworks extending the SM, for example the minimal supersymmetric (MSSM) extension predicts the existence of five Higgs bosons.

Searches for the SM Higgs boson were performed in previous experiments at LEP and they continue at Tevatron. Direct searches at LEP resulted in the lower mass limit $m_{\mathrm{H}} > 114.4$ GeV [3], recently published Tevatron results exclude the mass region $160 < m_{\mathrm{H}} < 170$ GeV at 95 % CL [4]. Precision electro-weak measurements at LEP predict the upper mass limit of 157 GeV (186 GeV if the lower experimental bound is also considered in the fits) [5]. Experimental limits also exist for the MSSM Higgs bosons, see e.g. Ref. [6].

This paper reviews several channels for the discovery or exclusion of the SM Higgs boson, the searches within the MSSM are also briefly mentioned. Last part is devoted to measurements of the properties of a Higgs-like particle if it has been discovered. These measurements would finally confirm the nature of such new particle.

All studies presented here were performed assuming the LHC center-of-mass energy $\sqrt{s} = 14$ TeV [6] and no pile-up. When pile-up is considered, it corresponds to the luminosity $\mathcal{L} = 10^{33}$ cm^{-2}s^{-1}. Nevertheless, the LHC running scenario starts with only $\sqrt{s} = 7$ TeV, probably not exceeding 10 TeV in 2009/2010.

2. SM Higgs Boson Searches

Since the Higgs boson mass is not predicted by theory, the ATLAS searches must cover a broad Higgs mass range from the LEP limit up to about 1 TeV.[1]

In the pp collisions at LHC, the Higgs boson can be born in several processes. The dominant contribution comes from the gluon fusion (GF), followed by the vector boson fusion (VBF) that however exhibits a unique signature of two forward jets with no central colour activity resulting in the so-called rapidity gap. Other mechanisms like the production associated with W, Z or $\mathrm{t\bar{t}}$ pair show much lower cross-section as displayed in Fig. 1.

The Higgs decay modes suitable for searches have to account for the strong mass-dependence of the Higgs branching ratios (BR), see Fig. 1. For the low mass range ($m_{\mathrm{H}} \leq 130 \div 150\,\mathrm{GeV}$) the considered channels are $\mathrm{H} \rightarrow \mathrm{b\bar{b}}$, $\mathrm{H} \rightarrow \gamma\gamma$, $\mathrm{H} \rightarrow \tau\tau$, whereas for the higher masses the decay modes to vector boson pairs (W, Z) will be exploited.

The important decay modes are reviewed in the following Sections. The complete list as well as details of the individual analyses can be found in Ref. [6].

2.1. $\mathrm{H} \rightarrow \gamma + \gamma$

Two isolated photons provide a clean event signature, but the cross-section is extremely small (see Fig. 1) since the decay proceeds via W and t-loop. Two issues deserve special attention:

- At least one photon converts in about 60 % cases before entering the calorimeter (see Fig. 2). Efficient recovery requires the detailed knowledge of the material upstream of the EM calorimeter.
- Huge irreducible and reducible background (γ+jet or di-jet events, where photons come from leading π^0 decays) can be suppressed by requiring 1 or 2 additional high-p_{T} jets in the event, since the gluon radiation patterns in GF and VBF processes significantly differ from those in background events.

2.2. $\mathrm{H} \rightarrow \tau + \tau$

This decay mode represents the second highest BR for low m_{H}. Since τ-leptons further decay either to leptons or hadrons, there are at least 2 neutrinos in the final state. The invariant mass is reconstructed using the collinear approximation, where it is assumed that neutrinos are emitted in the direction of original τ-leptons that are strongly boosted.

Dominant background comes from $\mathrm{Z}(\tau\tau)$+jets, $\mathrm{W}(\ell\nu)$+jets and $\mathrm{t\bar{t}}$+jets. The reasonable event selection can only be performed by exploiting the VBF signature. Further selection criteria involve missing transverse energy $E_{\mathrm{T}}^{\mathrm{miss}}$, central jet veto and b-jet veto in the forward direction.[2]

The Higgs search in this channel requires detailed understanding of the whole detector, in particular the $E_{\mathrm{T}}^{\mathrm{miss}}$ measurement. Data driven method for estimating the $\mathrm{Z}(\tau\tau)$+jets background have been developed. Shape is obtained from MC by substituting real data μ with MC τ, the absolute normalisation will be obtained

[1] The perturbative unitarity considerations lead to $m_{\mathrm{H}} \lesssim 1$ TeV.

[2] The latter cut suppresses the $\mathrm{t\bar{t}}$+jets background.

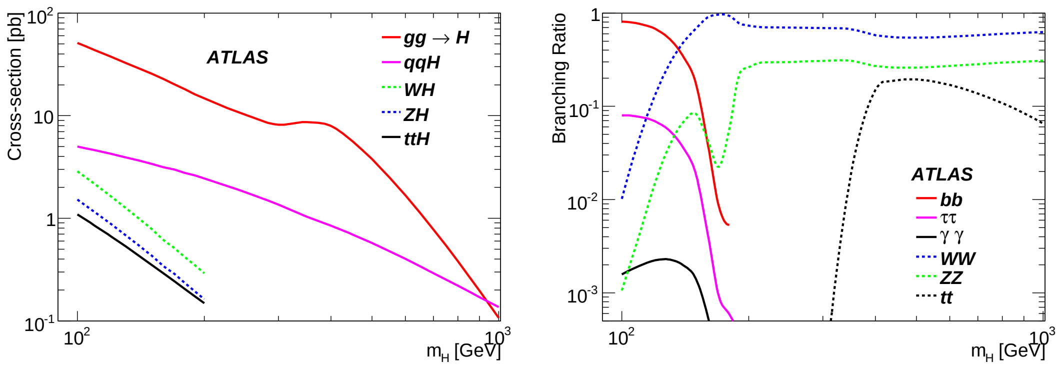

Figure 1. The SM Higgs boson production cross-section for the most important mechanisms (left) and the Higgs branching ratios for the decay modes considered for the Higgs boson search in ATLAS experiment (right) as a function of m_{H} [6].

from the $\mathrm{Z} \rightarrow \tau\tau$ peak measurement. The latter process will also be used for τ-trigger commissioning and cross-section measurements.

So far the results are available only for the $\ell\ell$-mode (both τ's decay only to leptons) and the ℓh-mode (one τ decays to hadrons). The hh-mode is still under investigations [6].

2.3. $\mathrm{H} \rightarrow \mathrm{Z} + \mathrm{Z}^{(*)} \rightarrow 4\ell$

Studies of this so-called gold-plated channel exploit a very clean signature of 4 charged leptons (electrons or muons) in the final state. The event selection criteria are based on two pairs of opposite charged leptons of the same flavour, sufficiently isolated from other activities in the inner detector and calorimeters. In addition, at least one pair must satisfy the m_{Z} invariant mass constraint (on-shell Z) and a cut is imposed on the impact parameter significance to further suppress the reducible background from $\mathrm{Zb\bar{b}}$ and $\mathrm{t\bar{t}}$ (leptons from heavy quark decays come from displaced vertices). The irreducible background comes from the ZZ continuum.

An example of the reconstructed invariant mass spectrum is shown in Fig. 3. The above mentioned cuts efficiently remove the reducible background over the full Higgs mass range studied. The pile-up and cavern background lower the total efficiency by about 10 % [6].

2.4. $\mathrm{H} \rightarrow \mathrm{W} + \mathrm{W}^{(*)} \rightarrow 2\ell + 2\nu$

The Higgs decay to a pair of W-bosons is the most powerful channel for searching the SM Higgs boson over the wide range of its mass (see Section 2.5). Since there are two neutrinos in the final state, the invariant mass reconstruction cannot be performed[3] and the transverse mass m_{T} is

[3]The collinear approximation cannot be applied as W bosons are not highly boosted because their mass is of the same order as m_{H}.

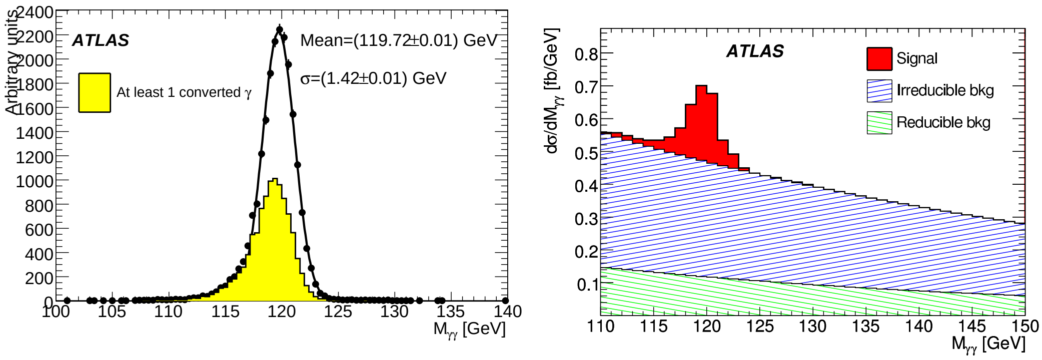

Figure 2. Left: the invariant mass peak from the $\mathrm{H} \to \gamma\gamma$ signal with displayed contribution from converted photons. Right: the expected signal on top of background for H+2 jets (luminosity 10 fb^{-1}, $m_{\mathrm{H}} = 120$ GeV). This channel provides better signal/background ratio (S/B) than H+1 jet and H+no jet channels, while the significance $S/\sqrt{B}$ remains approximately the same [6].

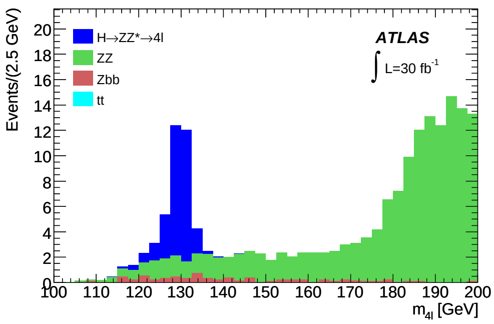

Figure 3. The reconstructed invariant mass $m_{4\ell}$ of four leptons in the decay $\mathrm{H} \to \mathrm{ZZ}^{(*)} \to 4\ell$ ($m_{\mathrm{H}} = 130$ GeV) superimposed on top of the corresponding background [6].

used instead:

$$m_{\mathrm{T}}^2 \equiv \left(E_{\mathrm{T}}^{\ell\ell} + E_{\mathrm{T}}^{\mathrm{miss}}\right)^2 - \left(\vec{p}_{\mathrm{T}}^{\,\ell\ell} + \vec{p}_{\mathrm{T}}^{\,\mathrm{miss}}\right)^2 \quad (1)$$

Events are selected by requiring two isolated high-p_{T} leptons and $E_{\mathrm{T}}^{\mathrm{miss}} >$ 30 GeV; central jet veto and b-jet veto are applied to remove the main background from W+jet and $\mathrm{t\bar{t}}$. The angular correlation between the two charged leptons is also used to further suppress the irreducible background from QCD WW production as shown in Fig. 4.

The searches are performed in two statistically independent event sets: H+0 jet (GF) and H+2 jets (VBF). The analysis is finalised for $e\nu\mu\nu$ final state only, studies of $e\nu e\nu$ and $\mu\nu\mu\nu$ are still ongoing.

2.5. Combined discovery and exclusion

The SM Higgs boson discovery and exclusion limits are combined from four in-

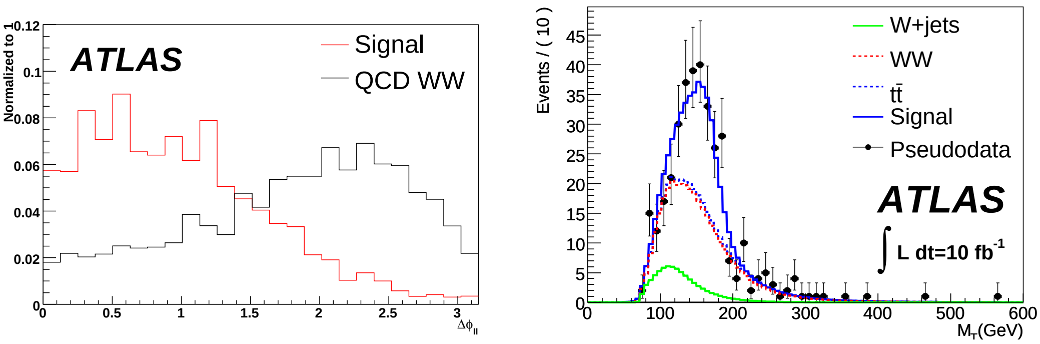

Figure 4. Left: the opening angle $\Delta\phi_{\ell\ell}$ between the two charged leptons for signal and WW background. Right: the transverse mass distribution for signal and background in the $\mathrm{H}+0$ jet channel [6].

vestigated channels (Sections 2.1 − 2.4) using frequentist statistical methods, the systematic uncertainties are incorporated with the profile likelihood ratio [6]. The results are shown in Fig. 5.

With 10 fb^{-1} of acquired data, ATLAS is expected to discover the Higgs boson in the mass range $125 < m_{\mathrm{H}} \lesssim 450$ GeV. This range should still broaden once further developments in $\mathrm{H} \to \gamma\gamma$ and additional final states (associated production modes for low m_{H} and other decay modes in $\mathrm{H} \to \mathrm{WW}$ and $\mathrm{H} \to \mathrm{ZZ}$ for high m_{H}) will be added. The discovery significance is calculated at a fixed m_{H}. However, when testing a large range of Higgs mass values, the probability of fluctuation leading to an apparent signal for some mass increases (so-called "look-elsewhere effect"). These corrections that effectively slightly lower the significance are not considered here yet, although they were already studied for some individual channels [6]. Of course the Higgs boson discovery must be confirmed by measurements of its properties, see Section 4.

The Higgs boson exclusion is possible already with 2 fb^{-1} in the range $115 < m_{\mathrm{H}} < 460$ GeV. Like that, ATLAS can basically close the gap set by the LEP limit and latest Tevatron results (see Section 1) and extend the explored region further to higher m_{H}.

3. MSSM Higgs boson(s) searches

The MSSM predicts the existence of 3 neutral (CP-even h/H, CP-odd A) and two charged ($\mathrm{H}^{\pm}$) Higgs bosons. Several MSSM scenarios have been explored, nevertheless only the m_{h}-max[4] results are reported here. At the tree-level, the Higgs sector is essentially described in terms of

[4]The lightest Higgs boson mass is constraint at the tree-level $m_{\mathrm{h}} < m_{\mathrm{Z}}$. Loop corrections, sensitive in particular to the mixing in stop sector, can enhance the mass up to $m_{\mathrm{h}} \approx 135$ GeV.

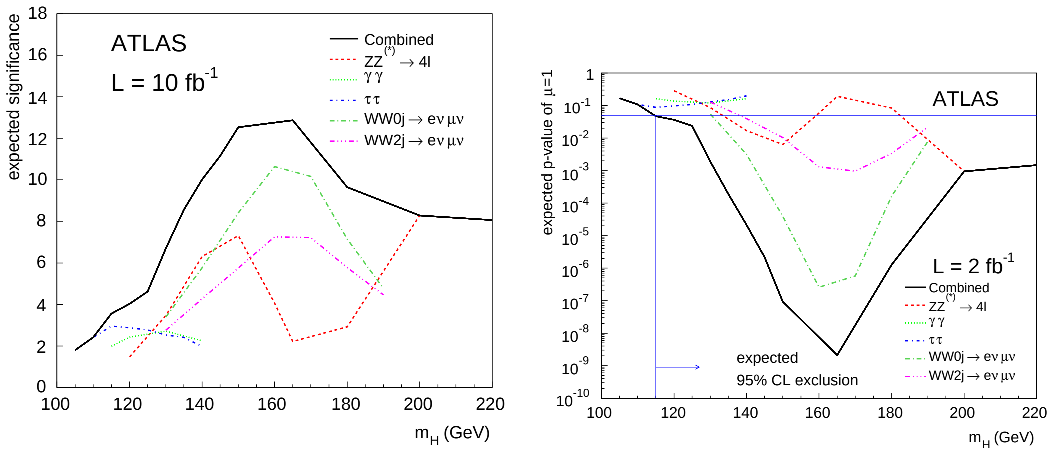

Figure 5. The expected discovery significance (left) and exclusion limits (right) for the SM Higgs boson. Displayed are contribution from individual decay modes as well as the combined results after 10 fb^{-1} (discovery) or 2 fb^{-1} (exclusion) data are acquired [6].

two parameters $\tan\beta$ (ratio of the vacuum expectation values of the two Higgs doublets) and m_{A}.

Searches for h/H/A were investigated in the decay modes to $\tau\tau$, $\mu\mu$ and in the SUSY cascades [6]. The strategies in the $\tau\tau$ channel are very similar to that of SM Higgs (see Section 2.2), except that instead of two forward jets (VBF) at least 1 b-tagged jet is required in this final state (associated b-quark production).

The $\mu\mu$ channel is significantly suppressed with respect to $\tau\tau$ mode due to different fermion masses, on the other hand it provides a clean signature and allows for the full m_{H} reconstruction. Two independent samples with 0 b-jet and $\geq$ 1 b-jet have been considered, the combined discovery contour is shown in Fig. 6 for two different integrated luminosities.

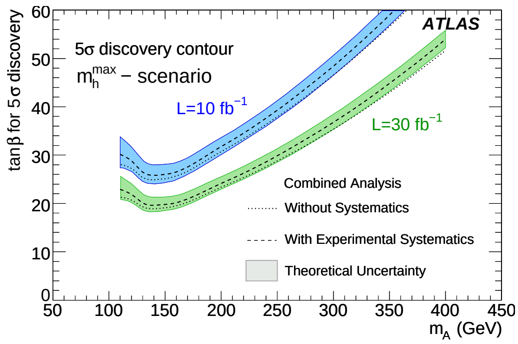

Figure 6. The 5σ discovery contour for the h/H/A $\rightarrow \mu\mu$ channel in the $\tan\beta, m_{\mathrm{A}}$ parametric plane [6].

The sensitivity is comparable to that of h/H/A $\rightarrow \tau\tau \rightarrow 2\ell + 4\nu$ channel.

The searches for charged Higgs bosons include the following final states: $\tau\nu$, tb

($m_{\mathrm{H}^{\pm}} > m_{\mathrm{t}}$) and cs ($m_{\mathrm{H}^{\pm}} < m_{\mathrm{t}}$), the latter still being studied [6].

4. Higgs boson properties

Once a Higgs-like particle is discovered and its mass is measured, the focus turns on its fundamental properties like spin, CP, and couplings. Provided only one Higgs-like particle is observed, the above mentioned properties also disentangle between SM and MSSM Higgs bosons.

4.1. Spin and CP

The spin of the Higgs-like boson can be determined in various discovery channels. The observation of the decay $\mathrm{H} \to \gamma\gamma$ immediately rules out $S(\mathrm{H}) = 1$, the spin zero is assumed in the selection criteria of the $\mathrm{H} \to \mathrm{WW}$ searches (Section 2.4).

The spin and CP could be simultaneously determined in the gold-plated channel described in Section 2.3). Provided $m_{\mathrm{H}} > 2m_{\mathrm{Z}}$, the distributions of the angle φ between the two Z^0 decay planes and the polar angle θ of the emitted leptons in the Z^0 rest frame are sensitive to the Z^0-polarisation:

$$F(\varphi) = 1 + \alpha \cos\varphi + \beta \cos 2\varphi \qquad (2)$$

$$G(\theta) = T(1 + \cos^2\theta) + L \sin\theta \qquad (3)$$

Here T, L stand for transverse and longitudinal Z-boson polarisation respectively and α, β are free parameters. The expected results with 100 fb^{-1} of accumulated data are shown in Fig. 7. The ratio $R \equiv (L - T)/(L + T)$ provides good separation for $m_{\mathrm{H}} > 230$ GeV, the use of α, β parameters improves the sensitivity for $m_{\mathrm{H}} \approx 200$ GeV. The discrimination power can still be enhanced by measuring sign $(\cos\theta)$ [7].

If the Higgs boson mass is below the ZZ threshold, the spin can still be determined from the invariant mass distribution of the two leptons from the off-shell Z in the decay $\mathrm{H} \to \mathrm{ZZ}^* \to 4\ell$ as demonstrated in Ref. [8].

4.2. Couplings

The direct measurement of the Higgs boson couplings is not feasible since some decay modes are either not detectable (like decays to light fermions) or very difficult to observe.[5] Measurements of the rates $\sigma \times \mathrm{BR}$ of individual channels is foreseen instead, nevertheless the relative uncertainties range between 10 % and 100 % depending on the channel [10] even with 30 fb^{-1} of accumulated data.

Combining all observable Higgs production and decay modes, the widths $\Gamma_{\mathrm{Z}}, \Gamma_{\gamma}, \Gamma_{\tau}, \Gamma_{\mathrm{b}}$ are evaluated relative to Γ_{W} that is determined most precisely. The absolute couplings can then be fitted with few more theoretical assumptions — e.g. fixing $\Gamma_{\mathrm{b}}/\Gamma_{\tau}$ to its SM value since it is very poorly measured or requiring $\Gamma_{\mathrm{W,Z}} \leq \Gamma^{\mathrm{SM}}_{\mathrm{W,Z}}$ — and including a free parameter $\Gamma_{\mathrm{invisible}}$ for undetectable decays [11].

[5] An example is $\mathrm{H} \to \mathrm{b\bar{b}}$, originally supposed to be measured in the associated production channel $\mathrm{t\bar{t}H}$. It turns out to be very difficult now, however new analyses show that measurements are feasible in the HW and HZ associated production modes where both bosons are produced at high transverse momenta [9].

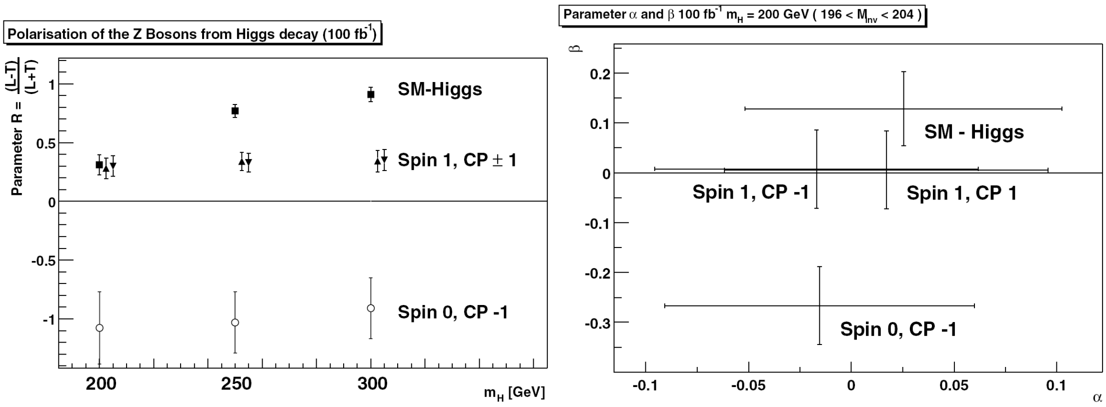

Figure 7. The ATLAS sensitivity to spin and CP of a Higgs-like particle in the $H \to ZZ \to 4\ell$ channel with 100 fb^{-1} of acquired data [7]. The ratio R as a function of m_H (left) and parameters α, β (right) for various Higgs boson's spin and CP combinations.

4.3. SM vs MSSM Higgs boson

In the whole MSSM Higgs sector parameter space at least one Higgs boson should be discovered. Observation of more than one Higgs boson allows to distinguish between the SM and MSSM directly. However, there is large area of intermediate $\tan\beta$ where only the light Higgs boson (h) can be discovered. The discrimination between SM and MSSM can be performed using the ratio R of the BR measured in the VBF production mode: $R \equiv \mathrm{BR}(h \to \tau\tau)/\mathrm{BR}(h \to WW)$.

The sensitivity to distinguish between the two mentioned models is shown in Fig. 8 in terms of $\Delta \equiv (R(\mathrm{MSSM}) - R(\mathrm{SM}))/\sigma(R)$, where $\sigma(R)$ denotes the expected error on the measured ratio R [12].

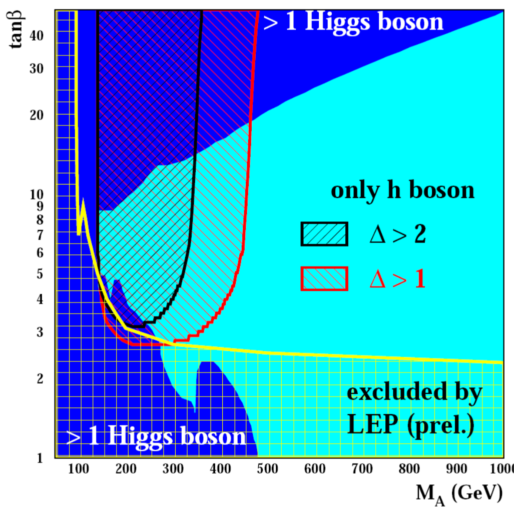

Figure 8. The ATLAS discrimination power between SM and MSSM Higgs boson in the m_h-max scenario after collecting 300 fb^{-1}. Only the statistical uncertainties are considered, m_h is assumed to be known with high precision [12].

5. Conclusions

The ATLAS potential to discover the SM and/or MSSM Higgs boson(s) has been explored in several channels. For an integrated luminosity of 2 fb^{-1}, the SM Higgs boson 5σ discovery is expected for $143 < m_{\rm H} < 179$ GeV while the absence of the signal leads to its exclusion in the range $115 < m_{\rm H} < 460$ GeV at 95 % CL. The presented studies concentrate on the lower Higgs mass region, future developments and inclusion of other channels will lead to greater sensitivity.

The discovery of the Higgs boson and its mass determination must be confirmed by determining its properties. Spin and CP measurements were investigated in several channels. The measurement of the Higgs couplings requires large integrated luminosity and can also eventually distinguish between the SM and MSSM nature of the observed Higgs boson.

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