Investigation of the Discovery Potential for Higgs Bosons of the Minimal Supersymmetric Extension of the Standard Model (MSSM) with ATLAS

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ABSTRACT

The discovery potential of the ATLAS experiment at the LHC for Higgs bosons of the MSSM is discussed. Several CP conserving and one CP violating benchmark scenario are investigated.

1. The Higgs sector of the MSSM and Benchmark Scenarios

The Higgs sector of the MSSM contains two Higgs doublets leading to five physical Higgs bosons: three neutral and two charged ones. At Born level the phenomenology of the Higgs sector is determined by two parameters which can be chosen as \( \tan \beta \), the ratio of the vacuum expectation values of the Higgs doublets, and one physical Higgs boson mass. The lightest neutral Higgs is bounded by the mass of the Z boson and the Higgs sector is CP conserving at Born level. However, the Higgs sector receives large radiative corrections which e.g. shift the mass of the lightest Higgs boson up to about 133 GeV \[1\] for a top quark mass of 175 GeV and a SUSY mass scale of 1 TeV. The masses and couplings depend on additional SUSY parameters appearing at the level of radiative corrections: \( M_0 \), \( M_2 \), \( \mu \), \( A \) and \( M_{\text{gluino}} \). In the CP conserving scenarios (CPC) all parameters are real and the neutral mass eigenstates are equal to the CP eigenstates: two CP even, \( h, H \) ordered by mass, and one CP odd, \( A \). Only the CP even bosons couple to weak gauge bosons. In the CP violating scenarios (CPV) the complex phases related to \( A \) and \( M_{\text{gluino}} \) are additional parameters. Non vanishing phases mix the CP eigenstates to the mass eigenstates \( H_1, H_2 \) and \( H_3 \), ordered by mass, to which no well defined CP property can be assigned. All neutral mass eigenstates may couple to weak gauge bosons and among each other in these scenarios.

The interpretation of ATLAS Higgs searches is performed in the four CPC benchmark scenarios, \( m_h \text{-} \text{max} \) scenario, nomixing scenario, gluophobic scenario, small \( \alpha \) scenario, as suggested in \[2\] and in one CPV benchmark scenario, called CPX scenario, as suggested in \[3\]. The five parameters entering at loop level are fixed in the individual benchmark scenarios and a scan is performed over \( \tan \beta \) between 1 and 50 and the mass of the CP odd Higgs boson \( M_A \) in the CPC scenarios (the mass of the charged Higgs boson mass \( M_{H^\pm} \) in the CPV scenario) between 50 and 1000 GeV. The phenomenology and parameter sets are explained in great detail in \[2\] for the CPC case and in \[3\] for the CPV case.

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\( a \) is the common sfermion mass at the electroweak scale, \( M_2 \) is the SU(2) gaugino mass parameter at the electroweak scale and \( M_1 \), the U(1) gaugino mass parameter, is derived from \( M_2 \) using the GUT relation \( M_1 = M_2 (5 \sin^2 \theta_W / 3 \cos^2 \theta_W) \), where \( \theta_W \) is the weak mixing angle, \( \mu \) denotes the supersymmetric Higgs mass parameter, \( A \) is the common trilinear Higgs-squark coupling and \( M_{\text{gluino}} \) denotes the gluino mass.
The $m_{h_{\text{max}}}$ scenario yields the largest values for $M_h$ up to 133 GeV. The nonmixing scenario is similar to the $m_{h_{\text{max}}}$ scenario, but with vanishing mixing in the stop sector yielding the smallest values for $M_H$ below 116 GeV. In the gluophobic scenario the effective coupling of $h$ to gluons is strongly suppressed for a large area of the $\tan\beta$ and $M_A$ plane. Therefore the production cross section for gluon gluon fusion is strongly suppressed. Values of $M_h$ up to 119 GeV are obtained. In the small $\alpha$ scenario the branching ratio into $b\bar{b}$ and $\tau^+\tau^-$ is suppressed for large $\tan\beta$ and not too large values of $M_A$. Values of $M_h$ up to 123 GeV are obtained. In the CPX scenario, the parameters are chosen in order to maximize the CP violating effects in the Higgs sector.

2. Technicalities

The masses of the Higgs bosons, their coupling strength and branching ratios for all five benchmark scenarios are calculated with FeynHiggs (Version 2.1) \cite{1}. Leading order cross sections have been used for all production processes. For the production of neutral Higgs bosons via gluon gluon fusion (GGF), weak vector boson fusion (VBF), associated production with weak gauge bosons ($W_H$)\cite{5} and heavy quarks ($ttH$ and $bbH$) the SM like cross sections have been calculated using the programs from reference \[5\] and then applying the appropriate correction factors to obtain the MSSM cross section values. The production cross section of charged Higgs bosons via $g\rightarrow tH^\pm$ has been calculated following \[6\]. The cross section for $t\bar{t}\rightarrow b\bar{b}WH^\pm$ has been obtained with PYTHIA \[7\]. A top quark mass of 175 GeV \[d\] has been used in all calculations.

The signal efficiencies and number of expected background events are taken from published ATLAS fast MC studies\[7\]. The key performance figures for e.g. lepton identification and isolation, b-tagging, $\tau$ identification, trigger efficiencies and mass resolutions have been obtained from studies using a full simulation of the ATLAS detector. The effect of almost mass degeneracy of Higgs bosons leading to a signal overlap and the effect of a larger total decay width of a Higgs boson when compared to its SM value have been taken into account when determining the number of expected signal events.

Discovery here means that the probability of a background fluctuation to the number of expected signal+background events is less than $2.85 \times 10^{-7}$ using Poissionian statistics.

\[1\] For the CPX scenario the results will be cross checked with the calculations from CPSUPERH \[4\] in the near future.

\[2\] $H$ here and in the following denotes a general neutral Higgs mass eigenstate. Only its CP even component couples to W and Z boson.

\[3\] The mass of the $h$ depends linearly on $m_t$, which current central value is 180 GeV. Generally a heavier Higgs boson is easier to discover at the LHC. The discovery potential of the individual channels might change slightly, but the general conclusions should be robust against an increase of $m_t$.

\[4\] The following channels have been considered: for neutral Higgs bosons: VBF with $H \rightarrow \tau\tau, WW$ and $\gamma\gamma$ \[8\], $ttH$ with $H \rightarrow bb$ \[9\], $H \rightarrow \mu\mu$ \[10\] and $H \rightarrow \tau\tau$ \[11\] from GGF and $bbH$, $H \rightarrow \gamma\gamma$ from GGF, $W, H$ and $ttH$, $H \rightarrow ZZ \rightarrow 4\ell$ and $H \rightarrow WW \rightarrow \ell\ell\nu\nu$ from GGF, $W, H$ with $H \rightarrow bb$ and $H \rightarrow WW \rightarrow \ell\nu\ell\nu$, $H/A$ with $H/A \rightarrow tt$, $H \rightarrow hh \rightarrow \gamma\gamma bb$ and $A \rightarrow Zh \rightarrow \ell\ell bb$ all from \[12\]. For the discovery of charged Higgs bosons: $gb \rightarrow tH^\pm$ with $H \rightarrow \tau\nu$ \[13\] and in the decay of top quarks $pp \rightarrow tt$ with $t \rightarrow bH^\pm$ and $H \rightarrow tb, \tau\nu$ \[14\]. The VBF channels, $H \rightarrow \tau\tau$ decays and charged Higgs bosons production from t quark decays have only been studied for luminosity running of the LHC and results are only shown for an integrated luminosity of 30 fb$^{-1}$. 


More details of the updated interpretation can be found in [15]. The LEP exclusion contours shown are taken from [16] and [17].

3. Discovery Potential in the CPC benchmark scenarios

The discovery potential for the light CP even Higgs boson $h$ in the four CPC benchmark scenarios after collecting an integrated luminosity of 30 (300) fb$^{-1}$ are shown in figure 1 (2). The VBF channel with $h \to \tau\tau$ dominates the discovery potential at low luminosity running and covers most of the parameter space left over from the LEP exclusions. The differences between the $m_h$—max, no mixing and gluophobic scenario is mainly due to the fact that in the same point of the parameter space the mass of the $h$ is different, giving rise to increased or decreased sensitivity of the channels under consideration. In the small $\alpha$ scenario the effect of suppressed branching ratios into $\tau$ leptons is visible for $\tan\beta > 20$ and approximately $200 \text{ GeV} < M_A < 300 \text{ GeV}$. This hole in the discovery region is nicely complemented by $h$ decays to gauge bosons from VBF or GGF. For high luminosity running also the channels $h \to \gamma\gamma$ and $h \to ZZ \to 4 \text{ leptons}$ and $tth$ with $h \to bb$ contribute significantly. For all benchmark scenarios in a large part of the MSSM parameter space discovery is possible via several channels, which should allow a determination of parameters of the Higgs sector.

Figure 1: Discovery potential for the light CP-even Higgs boson in the CPC benchmark scenarios after collecting 30 fb$^{-1}$. The cross hatched area is excluded by LEP at 95% CL.
Figure 2: Discovery potential for the light CP-even Higgs boson in the CPC benchmark scenarios after collecting 300 fb$^{-1}$. The cross hatched area is excluded by LEP at 95% CL.

phenomenology of the heavy Higgs boson sector is small especially for larger values of $M_A$, hence only the $m_h$-max scenario is discussed below. The discovery potential for the heavy neutral Higgs bosons $H$ and $A$ in the not yet by LEP excluded area is given by associated production with $b$ quarks and the decay into a pair of myons and tau leptons. Charged Higgs bosons can be observed from top quark decays for $M_{H^+} < 170$ GeV and from gluon bottom fusion for $M_{H^+} > 180$ GeV. The overall discovery potential after collecting 300 fb$^{-1}$ is shown in figure 3 (left). In the whole model parameter space at least one Higgs boson can be discovered and for a significant part of parameter space more than one Higgs boson can be observed allowing to distinguish between the Higgs sector of the SM and its MSSM extension via direct observation. However a large area at intermediate $\tan\beta$ is left where only the light Higgs boson $h$ can be discovered. The observation of the light Higgs boson $h$ in various search channels might allow a discrimination via the measurement of e.g. ratio of branching ratios in the same production mode, which is advantageous as several systematic uncertainties are cancelled. A first estimate for the sensitivity of such a discrimination between SM and MSSM has been performed using the ratio $R$ of the branching ratios measured in the VBF production mode: $R = BR(h \rightarrow \tau\tau)/BR(h \rightarrow WW)$. The red (black) area in figure 3 (right) indicates this sensitivity for which $\Delta$, defined as $\Delta = (R_{MSSM} - R_{SM})/\sigma_{exp.}$ is larger than
Here $\sigma_{\text{exp.}}$ denotes the expected error on the ratio $R$ in this particular point of MSSM parameter space. Only statistical uncertainties have been taken into account and it has been assumed that $M_h$ is measured with high precision. Similar results have been obtained in [18].

![Figure 3: Left: overall discovery potential for Higgs bosons in the $m_{h_{\text{max}}}$ scenario after collecting 300 fb$^{-1}$. The cross hatched area is excluded by LEP at 95% CL. Right: sensitivity for discrimination between SM and MSSM from the measurement of $\Delta$ (see text) in the $m_{h_{\text{max}}}$ scenario.](image)

1. Discovery Potential in the CPX benchmark scenario

The discovery potential for the lightest neutral Higgs boson $H_1$ in the CPX scenario after collecting an integrated luminosity of 300 fb$^{-1}$ is shown in figure 4 (left). The coverage is similar to the CPC scenarios, but the LEP exclusion is weaker and even low Higgs boson masses $M_{H_1}$ between 0 and 60 GeV are not excluded yet [17]. The overall discovery potential for Higgs bosons in the CPX scenario after collecting an integrated luminosity of 300 fb$^{-1}$ is shown in figure 4 (right). A region at low $M_{H_1}$ and small $\tan\beta$ remains where no discovery is possible with the channels and mass ranges investigated so far within the ATLAS collaboration. In this area the mass of $H_1$ ($H_2$, $H_3$) is in the range < 70 GeV (105 to 120 GeV, 140 to 180 GeV).

5. Conclusions

An updated evaluation of the discovery potential of ATLAS Higgs searches based on most recent calculations for masses and branching ratios in four CPC benchmark scenarios and the CP violating CPX scenario has been discussed. A good discovery potential for the whole MSSM parameter space in the four CPC benchmark scenarios is expected. The light Higgs boson can be discovered in multiple search channels, allowing maybe an indirect discrimination whether the SM or MSSM is realised in nature. In the CPX scenario an area at low $M_{H_1}$ and small $\tan\beta$ remains which is not covered by today’s ATLAS MC studies which are limited to Higgs boson masses above 70 GeV. Further MC studies are needed to show whether this area can be covered at the LHC.

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Figure 4: Left: discovery potential for the lightest Higgs boson in the CPX scenario after collecting 300 $\text{fb}^{-1}$. The cross hatched area is excluded by LEP at 95% CL. Right: overall discovery potential for Higgs bosons in the CPX scenario after collecting 300 $\text{fb}^{-1}$.

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