

Beyond the Standard Model Higgs searches at the LHC

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The Run I at the LHC marks the birth of the "Higgs physics", a path which will be followed at its full extent in the future runs of the LHC. Indeed there are two complementary paths to be followed to new physics in the Higgs sector: precision measurements of the Higgs properties (couplings, mass, spin and parity), where new physics can manifest as deviation from the Standard Model, or direct search for processes not foreseen in the Standard Model (Higgs decays not foreseen in the Standard Model, additional scalars which would indicate an extended Higgs sector). The current status of these studies at the LHC is presented, focussing in particular on the direct searches for rare or invisible Higgs decays or for an extended Higgs sector. The results are based on the analysis of the proton-proton collisions at 7 and 8 TeV center-of-mass energy at the LHC by the ATLAS and CMS collaborations.

1 Introduction

The discovery of a Higgs boson by the ATLAS and CMS collaborations with a mass around 125 GeV^{1, 2} represents a historical milestone in the understanding of the electro-weak (EW) symmetry breaking mechanism. The hierarchy problem, concerning the naturalness of the Higgs boson mass, the nature of dark matter, and other open questions that the Standard Model (SM) is not able to answer, motivate the possible existence of additional new particles or interactions which could be revealed in the data accumulated by the ATLAS and CMS collaboration during the Run I at the LHC.

LHC data allows to study with increasing precision the Higgs boson couplings to fermions and bosons, and to look for rare or forbidden decays of the discovered Higgs boson. Discrepancy will unveil physics beyond the Standard Model (BSM) and can potentially give new directions to look for new particles. Several BSM theories have been proposed in the last 20-30 years, which are still to be ruled out by the current experimental constraints. Focussing on the Higgs sector, it is still possible that the discovered Higgs boson could be part of an extended Higgs sector, with additional charged or neutral (CP-even or odd) Higgs bosons, or that the Higgs boson is not an elementary particle, representing instead a pseudo-Goldstone boson of a new strong interaction at energies beyond the TeV scale (little or composite Higgs). In these BSM scenarios, the couplings of the Higgs boson are expected to show discrepancies with respect to the SM ones; however the current precision on the measurement of the Higgs scalar couplings³ (20-30%) still leave ample space for new physics. It is possible to interpret the experimental measurements of the Higgs couplings and its CP properties in the context of BSM scenarios, understanding which is the parameter phase space being excluded by the current experimental precision. Several studies have been performed, either using specific BSM models (MSSM, MCHM, ...) or more generally using an effective lagrangian approach. An example is given in ⁴, where limits are set within the parameter space of several BSM theories: composite Higgs, Two Higgs Doublet Models (2HDM), additional EW singlet, a simplified Minimal Super-Symmetric Standard Model

(MSSM); another example is given in this recent paper⁵, which contain also several references to previous works. More important, with more statistics, such as it will be achieved during Run 2 at the LHC and beyond, the precision of these measurements will improve, moving the Higgs physics into the "precision" era. It will be possible not only to look for scalar deviations of the couplings, but also for kinematic discrepancies as allowed by measuring differential cross-sections for the different Higgs production modes.

This way to look for new physics in the Higgs sector can be complemented by a direct approach which searches directly new processes not foreseen in the SM. Focussing on the Higgs sector, additional neutral or charged Higgs bosons, at lower or higher masses than the discovered Higgs boson, still represent a viable opportunity; they are foreseen by several extensions of the SM. As we will see, there is also a large window of opportunity to search for decays of the Higgs boson which are not expected in the SM, which would also represent a direct sign of new physics.

In the rest, we will focus on the current status of the direct searches for BSM physics in the Higgs sector.

2 Rare Higgs decays searches

The observed value of the Higgs mass, 125 GeV, allows to explore several final states for the Higgs boson decays, already with the statistics provided by the LHC Run I data. Intriguingly, as reported in⁶ the product of branching ratios of the SM Higgs boson in all decay channels available below the top-antitop threshold is maximum at $m_H = 125$ GeV. As discussed before, no significant discrepancy with the SM expected rates in the different Higgs decay channels explored so far has been reported. In addition, using all the Higgs measured rates in different sub-channels, it is possible to place a limit on undetected or invisible Higgs decays^{7, 8}, constraining effectively the Higgs total width. This indirect constraint is $BR(H \rightarrow \text{invisible}/\text{undetected}) < \approx 30\%$ at 95% CL, still allowing ample space to look for BSM Higgs decays.

Searches have been performed for decays with very small expected branching ratios in the SM, $H \rightarrow \mu^+ \mu^-$, $H \rightarrow Z(\rightarrow l^+ l^-) \gamma$, but the current sensitivity is not able to probe yet the SM expected rate of events. Only cross-section limits have been placed^{9, 10, 11, 12}. In these channels, you will need the full statistics of next runs at the LHC to start reaching the SM sensitivity.

An excess of events (2.4σ) is reported in the search performed by the CMS collaboration of the lepton flavour violating decay $H \rightarrow \mu\tau$ ¹³. This search probes directly non-diagonal term of the Yukawa matrix, $|Y_{\mu\tau}|^2 + |Y_{\tau\mu}|^2$, with a sensitivity about 1 order of magnitude higher than looking at exotic τ decays ($\tau \rightarrow 3\mu, \tau \rightarrow \mu\gamma$). An upper limit $BR(H \rightarrow \mu\tau) < 1.57\%$ at 95% CL is placed. The corresponding analysis from ATLAS is not yet public.

Recently the first search for $H \rightarrow J/\Psi \gamma$ (and also $H \rightarrow \Upsilon \gamma$) and has been made public by the ATLAS collaboration. The search aims at revealing anomalous Higgs couplings to the charm quark (or to the bottom); at the moment, it is able to put a limit on the rate of the process $H \rightarrow J/\Psi \gamma$ at about 540 times the SM expected rate at 95% CL, excluding universality in the quark sector, assuming the gluon-fusion production to be driven mostly by the coupling of the Higgs to the top quark. Even at the HL-LHC, however, it will be very difficult that this search will be sensitive to the event rate expected in the SM for this process.

2.1 Invisible Higgs decays searches

An appealing possibility is represented by the the Higgs boson decay into stable or long-lived neutral particles, escaping direct detection, as it is motivated by some BSM theories. This type of decays are currently probed in associate Higgs production with a Z boson or vector boson fusion (VBF); these searches are exploiting the detectable objects in the final state (a lepton pair compatible with the Z mass hypothesis, a pair of forward high pt jets,...) as taggers for the Higgs production. Some attempts are also being made in exploiting boosted gluon fusion events,

signalled by the presence of an unbalanced event with an high pt jet, or associate production with top quarks. ATLAS has released 2 new results in time for this conference^{14, 15}, improving the sensitivity of the previous searches. In particular, a limit on invisible Higgs decays BR is placed at 29% with 95% CL for a 125 GeV Higgs by the VBF+H(\rightarrow invisible) search, which represent the most sensitive single search performed to date. It is also possible to interpret these results as searches for dark matter (DM)¹⁷, recasting the BR upper limit into a DM-nucleon scattering cross section upper limit. These interpretations are performed in the "Higgs-portal to DM"¹⁸ scenario, where an effective lagrangian operator couples directly the Higgs field to the DM field; it is possible to assume different nature for the DM candidate (scalar, fermion, vector). Within these assumptions, these results provide competitive cross-section upper limits for low-mass dark matter candidates (indeed assuming an Higgs decay into a pair of DM candidates, only DM candidate masses below half of the mass of the Higgs could be probed).

In addition to completely invisible Higgs decays, the possibility of having one or more additional photons in the final state (quasi-invisible Higgs decays) is considered too. Apart for being experimentally interesting, these searches are motivated, just to give an example, by R-parity conserving super-symmetric scenarios, where Higgs decays into neutralino(NLSP)+LSP, and then the neutralino decays into a photon+LSP (for NLSP masses below half of the Higgs mass, Higgs decays into a NLSP pair is allowed). One or more photons are present in the final state, in addition to transverse missing energy due to the undetected LSP particles. CMS¹⁹ has performed this analysis inclusively, exploiting a low transverse momentum photon trigger, while ATLAS²⁰ has exploited the VBF production mode. The cross-section limits which are placed by these analysis, are interpreted in a simplified model approach, showing a sensitivity to $BR(H \rightarrow NLSP + LSP)$ as good as 10%, depending on the NLSP mass, and assuming for the mass of the LSP 1 GeV.

3 Extended Higgs sector searches

A non minimal Higgs sector is required by several BSM theories, most notably the Minimal Supersymmetric Standard Model (MSSM).

The Higgs sector of the MSSM is part of a class of models termed "Two-Higgs-Doublet Models" (2HDM)²¹, where two Higgs doublets mix to generate EWSB and fermion masses. Four types of 2HDM models can be derived satisfying flavour changing neutral current constraints, classifying them according to their couplings to fermions and bosons. 2HDMs predict the existence of five Higgs bosons: two neutral CP-even bosons h and H , one neutral CP-odd boson A , and two charged bosons H^\pm .

The Next to Minimal Super-Symmetric Standard Model (NMSSM) extends the MSSM by an additional gauge singlet field under a new $U(1)_{PQ}$ symmetry in the Higgs sector of the super-potential²². This allows to naturally generate the mass parameter μ term of the MSSM Higgs super potential at the EW scale. With respect to the MSSM, the Higgs sector consists of an additional CP-even boson and an additional CP-odd boson. In the NMSSM it is still possible to have bosons lighter than the discovered Higgs boson, so decays of the Higgs boson into light (pseudo)scalars ($h \rightarrow 2a_1$) represent still an interesting possibility to be looked at. Depending on the a_1 mass, preferential decays in a pair of μ, τ or b are exploited to search for these light scalars.

Other simpler SM extensions can be foreseen too, for example an additional EW singlet. This class of models can also provide a possible dark matter candidate²³. Mixing of the EW singlet with the Higgs field, leads to modifications of the Higgs couplings, which get reduced by a scale factor, and generate a neutral heavy mass CP-even Higgs boson.

Most of the searches for additional Higgs bosons presented here are performed in a model independent way: interpretation is given in terms of cross-section upper limits for the process which is being probed. No significant attempt is made so far by the ATLAS and CMS collabo-

ration to combine searches in different final states into a single exclusion plots. Some attempts can be found in literature, see for example²⁴.

3.1 2HDM, MSSM and Heavy Higgs searches

For large $\tan\beta$ the branching ratio of the heavy neutral MSSM Higgs bosons to tau leptons is enhanced, making the search for $A/H \rightarrow \tau\tau$ particularly attractive. ATLAS and CMS have published results^{25, 26} based on the full Run I statistics, excluding a large region of heavy scalar masses: $\tan\beta$ upper limit increases as the neutral heavy Higgs boson hypothesis (almost independently by the MSSM scenario being considered for the exclusion). Model independent upper limits are also given for the gluon-fusion and the b-associated heavy Higgs production.

Charged Higgs bosons searches are particularly sensitive when considering masses of the charged Higgs below the top mass, ($m_{H^\pm} < m_t$), where the decay of the top $t \rightarrow bH^\pm$ can be searched for in the abundant $t\bar{t}$ events. The decay $H^\pm \rightarrow \tau\nu$ decay is the preferential decay in the MSSM already from small $\tan\beta$ values. The most updated results for the $H^\pm \rightarrow \tau\nu$ searches reported by ATLAS and CMS^{27, 28} are able to exclude $m_{H^\pm} < 160$ GeV independently of the $\tan\beta$ assumption. Other searches for $H^\pm \rightarrow cs$ are performed in the low mass region, while for the high mass region $H^\pm \rightarrow tb$ is considered too.

The most difficult region to be covered in the MSSM search is the in the medium (≈ 5) to low $\tan\beta$ region for $m_A > 200$ GeV. This region can be covered by the searches for $A \rightarrow ZH$ and $H \rightarrow hh$. Recent results are reported by ATLAS²⁹ and CMS³⁰ for $A \rightarrow ZH$, which are able to put some constraints in this region.

Heavy scalars are also searched in the WW and ZZ final states. For 2HDM models these searches are sensitive in the medium (≈ 5) to low $\tan\beta$ region for $m_H > 150$ GeV, but are also motivated by other simpler extensions of the SM, like for example an additional EWK singlet. A narrower state than the SM Higgs hypothesis for the same mass value is expected. The most updated results on these searches by the CMS collaboration are reported in detail in these proceedings³¹.

For the region $m_A > 2m_{top}$ at intermediate $\tan\beta$ the most sensitive analysis is assumed to be the search in the di-top final state. It is possible to re-interpret the current searches done by ATLAS and CMS for di-top resonances in this context, but more dedicated searches are expected to be performed during Run 2.

Searches for neutral heavy scalars are finally performed in the di-photon and $Z\gamma$ final states too^{32, 33, 34}. Cross-section upper limits are established.

3.2 Low mass scalar searches

The most updated results are reported by the ATLAS collaboration in the search for $h \rightarrow 2a_1 \rightarrow 2\mu 2\tau$ final state³⁵. This search is able to exclude $\text{BR}(h \rightarrow 2a)$ below 10% for mass m_a below 10 GeV and above $2m_\tau$. 4μ final state is also explored³⁶, while combinations like 4τ and $2\mu 2b$ will be reported in the future.

Associated production of the light pseudo scalar with b is also considered, and will be reported in the future as well.

4 Summary and prospects

The current status of the searches for BSM physics in the Higgs sector is reported. The results are based on the full statistics of the LHC Run I data, some additional analyses are being performed by both collaborations and will be reported in the future. No evidence for BSM physics has been reported so far, but significantly improved precision and sensitivity is expected to be achieved in the future LHC Run II analyses.

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