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Beyond-the-Standard Model Higgs Physics using the ATLAS Experiment

Marco Vanadia[*]
on behalf of the ATLAS Collaboration
Sapienza University of Rome and INFN
E-mail: marco.vanadia@cern.ch

The discovery of a Higgs boson with a mass of about 125 GeV has prompted the question of whether or not this particle is part of a larger and more complex Higgs sector than that envisioned in the Standard Model. In this report, the latest Run 1 results from the ATLAS Experiment on Beyond-the-Standard Model Higgs searches are outlined. Searches for additional Higgs bosons are presented and interpreted in well motivated Beyond-the-Standard Model Higgs frameworks, including the two-Higgs-doublet Models and the Minimal and Next to Minimal Supersymmetric Standard Model.

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[*]Speaker.

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1. Introduction

The ATLAS and CMS collaborations announced in 2012 the discovery of a new particle with a mass of approximately 125 GeV [1, 2]. Further measurements performed in the following years on the production and decays mechanisms of this particle, and on its mass, CP and spin properties showed that this new particle is compatible with the scalar Higgs boson predicted by the Standard Model (SM) [3, 4, 5, 6]. In the following this particle is assumed to be the SM Higgs boson. This discovery represented a crucial confirmation of the SM as a self-consistent theory of massive elementary particles. Several questions are left open by the SM in its current formulation: among others, the need of an extremely precise tuning of higher-order loop corrections and the lack of an explanation for the observation of dark matter in the Universe are fundamental questions a complete theory is expected to address.
Many beyond SM (BSM) models have been developed, in order to overcome the known limitations of the SM. Several of these models introduce a modified Higgs Sector, including new fields (and therefore new particles), or provide new interpretations of the Higgs boson, e.g. as a composite particle or as a possible portal to a hidden sector of particle physics. Experimental tests of these models have been performed with indirect measurements exploiting LHC Run-1 data [4, 6, 7], by studying the couplings of the SM Higgs boson, which are modified when BSM physics is introduced in the Higgs sector. No significant deviations from SM predictions have been observed in data. However, uncertainties on the measured couplings are sizeable, and no better than 25-30% in any channel. Furthermore, a 95% CL limit on the branching ratio for the possible decay of the SM Higgs boson to non-SM particles has been determined to be ≈30%. Thus, current indirect measurements leave ample room for BSM physics in the Higgs sector. In this report I will review most recent direct searches performed in this contexts with the ATLAS experiment at the LHC.

2. Searches for additional Higgs bosons

Two-Higgs doublets models (2HDMs) introduce a second doublet of fields in the Higgs sector, predicting the existence of five distinct Higgs boson particles: two neutral CP-even bosons h and H, and a neutral CP-odd A and two charged $H^{\pm}$ bosons. Assuming no CP-violation and no tree-level flavour changing neutral currents, 2HDMs are determined by 7 free parameters: 4 masses, one soft symmetry breaking parameter, the ratio of the vacuum expectation values of the two doublets $\tan\beta = v_2/v_1$, and the mixing angle between h and H, α. Often $\cos(\beta-\alpha)$ is used as a parameter of study for these models. Depending on the structure of the couplings of the Higgs bosons to up-type quarks, down-type quarks and leptons, 2HDMs are classified in 4 types. This class of models is an important benchmark for experimental searches of new physics in the Higgs sector. Type-II models are an approximation for Supersymmetry (SUSY) with a high mass scale, with a MSSM-like Higgs sector (where MSSM is the Minimal Supersymmetric SM). In the interpretation of experimental results, often the Higgs-like resonance discovered at 125 GeV is identified as the lower mass CP-even boson, h.
Reference [8] reports a search for MSSM neutral Higgs bosons in the $\tau\tau$ decay channel, which is of particular interest for the high $\tan\beta$ region. The search has been performed exploiting both leptonic and hadronic decays of the τ. The experimental challenge is the presence of at least two neutrinos

in the final state, which doesn't allow for a complete kinematics reconstruction of the events. A technique based on a statistical reconstruction of the most probable kinematics configuration based on the measurements of the transverse missing momentum (E_T^{miss}) and of the 4-momenta of all visible objects is exploited in the $\ell\ell$ and ℓh channels, and used to reconstruct the mass of the candidate heavy Higgs boson and distinguish it from the non-resonant background. In the hh channels, which has a background dominated by multi-jet QCD events, best discrimination between signal and background is obtained by exploiting the total transverse mass of the $\tau\tau$ system. The distributions of these variables are used to derive exclusion limits and constraints on the MSSM parameters space for different benchmark scenarios of the MSSM, as shown for example for the m_h^{max} scenario in Figure 1. These results show that the high $\tan\beta$ region of the MSSM is significantly constrained by Run-1 data for m_A of the order of hundreds of GeV. The high $\tan\beta$ region for $m_A \approx$1 TeV will be of extreme interest in the next moths at the LHC, as it can be explored with early Run-2 searches, thanks to the increase in center-of-mass energy from 8 to 13 TeV.
Reference [9] reports a search for a pseudoscalar Higgs boson in its $A \to Zh$ decay, which is most sensitive in the low-intermediate mass region, i.e. for m_A of the order of few hundreds of GeV. This analysis is performed exploiting the $h \to b\bar{b}$ decays, where b-jets are identified with a multivariate tagging algorithm, with the Z boson decaying into two charged leptons or two neutrinos. Furthermore, the $h \to \tau\tau$ decay channel is also exploited, with the Z boson decaying into two electrons or muons. In the latter case, a similar reconstruction technique as that described above for the $h/H/A \to \tau\tau$ search is adopted. The distributions of the reconstructed mass for the selected events obtained in data are in good agreement with the background-only hypothesis, and are used to constrain the parameter space of 2HDMs, as shown in Figure 1. There is a good complementarity of $h/H/A \to \tau\tau$ and $A \to Zh$ results for type-II 2HDMs for m_A values of few hundreds of GeV, as they are able to exclude the high $\tan\beta$ and the low $\tan\beta$ regions respectively. When taking into account also constraints obtained with indirect measurements [7], type-II 2HDMs appear to be very significantly constrained for $m_A \approx 300$ GeV.

Charged Higgs boson production at the LHC is predicted by several models. For instance, the MSSM comprises production mechanisms for a $H^\pm$ associated with b and t quarks. Reference [10] reports a search for MSSM $H^\pm$ decaying into $H^\pm \to \tau^\pm\nu$, which is the dominant decay for $m_{H^\pm} \lesssim$200 GeV, with $H^\pm \to tb$ decays becoming dominant above that value. The analysis is performed in two mass regions, 80< $m_{H^\pm} < 160$ GeV and $m_{H^\pm} > 180$ GeV. The measurement exploits the hadronic decays of the τ. Events with a reconstructed τ_{had}, with a high transverse missing momentum E_T^{miss}, no electron or muon and at least four jets (three jets) in the low (high) mass region, are selected. One of the jets is required to be identified as a $b-$jet by a dedicated tagging algorithm. The transverse mass of the event is then used as a discriminating variable to draw limits on $H^\pm$ production for several benchmark scenarios of MSSM. The $m_{H^\pm} < 160$ GeV region of the $m_{H^\pm}$ vs $\tan\beta$ is almost entirely excluded by this measurement, while only a small part of the parameter space is excluded in the high mass region.
Charged Higgs bosons are predicted also by Higgs Triplet Models (HTMs), where a triplet of fields is added in the Higgs sector to the SM doublet. In these models $H^\pm$ can directly couple with $W^\pm$ and Z boson, while this is not possible at tree-level in 2HDMS. The $H^\pm$ can therefore be produced via vector boson fusion (VBF) in HTMs. A search for $H^\pm$ produced via VBF and decaying in the

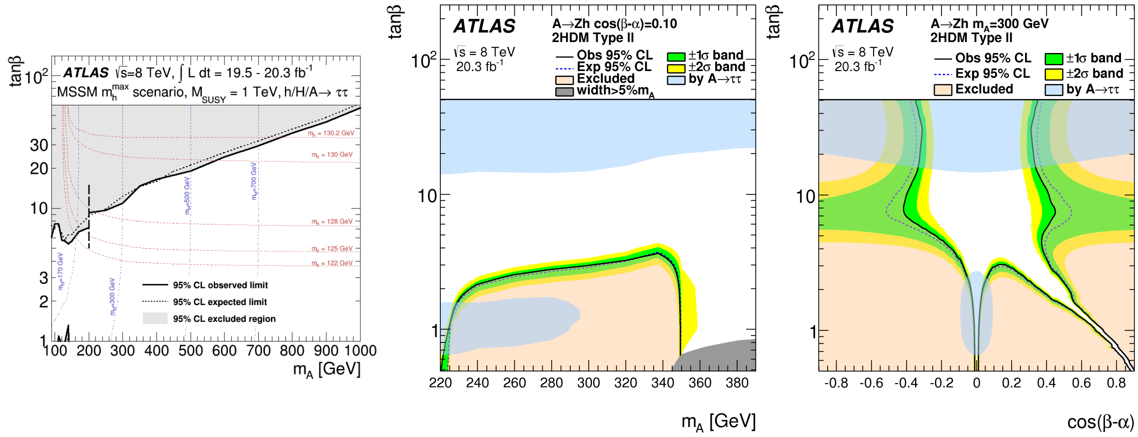

Figure 1: (Left) 95% CL upper limits on $\tan\beta$ as a function of m_A for the m_h^{max} benchmark scenarios of the MSSM obtained by the $h/H/A \to \tau\tau$ search. (Center) interpretation of the $A \to Zh$ and $h/H/A \to \tau\tau$ cross-section limits in the context of the parameters space of 2HDMs, with exclusion regions shown in the $\tan\beta$ vs m_A plane for type-II 2HDMs [9]. (Right) exclusion limits obtained in the $\tan\beta$ vs $\cos(\beta-\alpha)$ plane for type-II 2HDMs obtained with the $h/H/A \to \tau\tau$ and $A \to Zh$ searches.

$H^\pm \to W^\pm Z$ channel is presented in Reference [11]. Leptonic decays of the Z and hadronic decays of the W are exploited, and events are required to have the standard signature of VBF production, i.e. two forward jets (which must not be identified as b-jets) in opposite hemispheres of the detector. The invariant mass of the $\ell\ell qq'$ system measured in data is in agreement with the background-only hypothesis within uncertainties, and used to set limits on $\sigma(VBF \to H^\pm) \times BR(H^\pm \to W^\pm Z)$.

3. Searches for double Higgs events

The production of SM Higgs bosons in pairs is an important testing field for the SM and for BSM theories, which allows for directly probing the structure of the Higgs potential. The SM production cross section σ_{hh} is very small in proton-proton collisions, of the order of few tens of femtobarns at $\sqrt{s}$ =13-14 TeV, and will be studied in the long-term at the LHC. Several BSM models predict an enhancement of hh production. For example 2HDMs, theories comprising particles in a hidden sector with a coupling to h_{SM}, and specific gravitons models predict an enhancement with a resonant structure of σ_{hh}. On the other hand, models with a composite h, or comprising coloured scalars or a fourth generation of fermions, and other models, predict a non-resonant enhancement of σ_{hh} with respect to the SM. Searches for hh production with a $h \to b\bar{b}$ and a $h \to \gamma\gamma$ decay and with two $h \to b\bar{b}$ decays performed in LHC Run-1 data have been published by the ATLAS collaboration respectively in References [12] and [13]. For the $b\bar{b}\gamma\gamma$ search, events with a di-photon system, with an invariant mass compatible with that of the h, and two jets identified as $b-$jets by a multivariate tagging algorithm, with an invariant mass compatible with m_h as well, are selected. The mass of the di-photon system is used as a discriminating variable for the search of non-resonant production, with a fit of the sum of background continuum, of the SM hh production and of the possible BSM contributions to the data. The search for resonant enhancement is performed with a counting experiment, by cutting on the total invariant mass of the $b\bar{b}\gamma\gamma$ system as a function of the mass of the resonance considered. Both the resonant and non-resonant searches set limits on double Higgs production, which are weaker than the ones expected by SM predictions due to excesses in data with respect to predictions, with a 2.1 (2.4) σ significance for the resonant (non-resonant) production. While these excesses are still compatible with the background-only hypothesis, these searches will be of high interest for the second run of the LHC.

The search for double h production in the $b\bar{b}b\bar{b}$ decay channel described in [13] is also aimed both at resonant and non-resonant hh production. The search for resonant enhancement is performed in two categories of mass of the resonance, m_X. For 500< m_X <1100 GeV events with a *resolved* topology, i.e. with four jets reconstructed with a standard jet reconstruction algorithm and identified as b-jets by a multivariate tagging algorithm, are exploited. Above that value of the mass, the h are so boosted that standard jet reconstruction algorithms cannot resolve the two jets produced in the $h \to b\bar{b}$ decay. Candidates for the m_X >1100 GeV category are therefore identified requiring exactly two jets reconstructed with an algorithm with a larger cone size in the calorimeters (*boosted* topology). Each one of these jets must contain two separate track-jets, i.e. jets reconstructed only using tracks of the ATLAS inner tracker, and the track-jets must be identified as b-jets by a tagging algorithm. This technique significantly improves the sensitivity of this search for high values of m_X. The resonant search is performed exploiting the total invariant mass of the selected jets both in the resolved and boosted topologies, while the non-resonant search is performed with a counting experiment in the resolved topology. In both cases the exclusion limits obtained by the analysis are in good agreement with SM expectations, and the results are used to produce constraints for 2HDMs and for an excited graviton model.

4. Invisible decays of the Higgs boson

Decays of the SM Higgs boson or of additional Higgs bosons to particles non detectable by detectors at colliders are predicted by many BSM models. As discussed in the introduction, the indirect limit obtained in LHC Run-1 data is $BR(H \to INV) \lesssim$30%. Direct searches for $H \to INV$ have been performed by the ATLAS collaboration in different channels. Reference [14] reports a search for ZH events with $Z \to \ell\ell$ ($\ell = e, \mu$) and $H \to INV$ decays. Events with a missing transverse momentum $E_{\mathrm{T}}^{\mathrm{miss}}$ >90 GeV and a di-lepton system with an invariant mass compatible with m_Z are selected. Furthermore, as the Z boson momentum is expected to balance that of the H, a cut is applied on the separation between the transverse momentum of the di-lepton system and the direction of $E_{\mathrm{T}}^{\mathrm{miss}}$. Limits are set for $\sigma_{ZH} \times BR(H \to INV)$ for H candidates with a mass between 110 and 400 GeV using $E_{\mathrm{T}}^{\mathrm{miss}}$ as a discriminating variable, with a 95% CL limit on $BR(h_{SM} \to INV)$ <75%, in agreement with expectations. Limits are reported in the Reference also for the DM-nucleon cross-section in the Higgs-portal scenario.

Reference [15] reports a measurement performed for VH production, with $V \to hadrons$ and $H \to INV$ decays. Events with $E_{\mathrm{T}}^{\mathrm{miss}}$ >120 GeV and two or three jets, with a di-jet invariant mass compatible with that of a W or Z boson, are selected. The $E_{\mathrm{T}}^{\mathrm{miss}}$ and the di-jet system are also required to be well-separated in the azimuthal plane, due to the expected balance between the V and the H momenta. Limits are set for H candidates with a mass between 115 and 300 GeV, with a 95% CL limit for a SM h set to $BR(h_{SM} \to INV)$ <78%, compatible with the expectations.

A search for a Higgs boson produced via VBF and decaying to invisible particles is reported in Reference [16]. The typical VBF signature is exploited, with two jets produced with a very big gap in rapidity between them. This selection, combined with a requirement of a high $E_{\mathrm{T}}^{\mathrm{miss}}$ (greater than 150 GeV) in the event, allows for a extremely efficient rejection of background events, with remaining contributions mostly from V+jets events. A 95% CL limit for a SM h is measured as $BR(h_{SM} \to INV)$ <29%, in agreement with expected exclusion in the hypothesis of no signal. This result is extremely interesting as it reaches the same region of exclusion of the indirect limit, allowing for an important confirmation obtained with a direct search.

5. Other recent results for new physics in the Higgs sector

The ATLAS collaboration recently published a search for a decay of a Higgs boson H into two light pseudoscalar Higgs bosons a [17], which are predicted by the Next-to-Minimal Supersymmetric Standard Model (NMSSM). Experimental signatures of $H \to aa$ significantly depends on the mass of these new particles m_a, and this search targets the $m_a > m_\tau$ region. For this reason, one of the a candidates in the event is required to decay via $a \to \tau\tau$. Reconstructing events with 4 τ is experimentally challenging, thus the $a \to \mu\mu$ decay is exploited for the second a candidate. That results in a reduction of a factor 100 in the production rate, but the better signal-to-background ratio and the much higher trigger efficiency results in an overall higher sensitivity of the search. The reconstructed invariant mass of the $\mu\mu$ system is used as a discriminating variable. Limits are set on the $h \to aa$ BR as a function of m_a for $H = h_{SM}$, and as a function of m_H for Higgs candidates with a mass between 100 and 500 GeV for m_a =5 GeV.

Reference [18] presents a search for $H \to ZZ_d$ and $H \to Z_dZ_d$ decays, where Z_d is a light gauge boson mediator of a $U(1)_d$ gauge symmetry in a dark sector. Events with four leptons (e or μ) are exploited in the analysis. The $H \to ZZ_d$ search is performed requiring a di-lepton pair of same flavour, opposite charge and with an invariant mass compatible with m_Z. A search for resonances is then performed in the invariant mass of the remaining di-lepton pair. For the $H \to Z_dZ_d$ channel events with two di-lepton pairs, with an invariant mass non-compatible with that of Z, J/Ψ and Υ, and which have similar invariant masses (within few GeVs), are selected. No significant excesses are found in both channels, and limits are set on $H \to ZZ_d$ and $H \to Z_dZ_d$ BRs.
Reference [19] reports a search for decays of the h_{SM} into neutralinos and/or gravitinos, with one or more photons produced in the subsequent decays. These decays are predicted by several SUSY models, gauge-mediated supersymmetry breaking (GMSB) models and the NMSSM among the others. Events with a h produced via VBF, at least one γ and $E_{\mathrm{T}}^{\mathrm{miss}} > 50$ GeV are selected and used for a counting experiment. No significant excess is found in data and limits are obtained on the BR of h decays into neutralinos and/or gravitinos for different mass hypothesis for these particles.

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