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Beyond-the-Standard-Model Higgs physics using the ATLAS experiment

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Summary. — The ATLAS and CMS experiments at the Large Hadron Collider discovered a new particle, with a mass of 125 GeV and properties compatible with that predicted for the Higgs boson by the Standard Model. Understanding if this particle is part of a larger and more complex Higgs sector is one of the major challenges for particle physics experiments. In this report, an overview on latest results obtained on LHC Run-1 data by the ATLAS experiment on Beyond-the-Standard-Model Higgs searches is presented. Searches for new physics in the Higgs sector are presented and interpreted in well-motivated theoretical frameworks, including the two-Higgs-doublet Models and the Minimal and Next-to-Minimal Supersymmetric Standard Model.

1. – Introduction

In 2012 the discovery of a new particle with a mass of approximately 125 GeV was announced by the ATLAS and CMS experiments at the Large Hadron Collider [1, 2]. The measurements performed in the following years allowed for a determination of the properties of this new particle, which were found to be compatible with that of the Standard Model (SM) Higgs boson [3-6]. In the following this particle is assumed to be the SM Higgs boson. This groundbreaking discovery represents a crucial confirmation of the description of elementary particle physics envisioned in the SM. However, this description is known to be incomplete: for example, there is no acceptable Dark Matter candidate included in the SM. Many beyond SM (BSM) models have been developed, to overcome the limitations of the SM. Several of these models include a Higgs sector modified with respect to that of the SM, adding new fields (*i.e.* new particles), or with new interpretations of the SM Higgs boson, *e.g.* as a composite particle, or as a portal to new or hidden sectors of particle physics. Experimental tests of BSM models have been performed with LHC Run-1 data by means of indirect measurements on the couplings of the SM Higgs boson [4, 6, 7]. No significant deviations from SM predictions have been observed. Uncertainties on the couplings are however sizeable, no better than 25–30%

in any channel. A 95% confidence level (CL) limit on the branching ratio (BR) for the decay of the SM Higgs boson to non-SM particles has been measured to be $\approx$ 30%. Indirect measurements leave therefore ample room for new physics in the Higgs sector. In this report I'm presenting an overview on most recent direct searches performed in this context with the ATLAS experiment.

2. – Searches for additional Higgs bosons

In Two-Higgs doublets models (2HDMs) a second doublet of fields is added in the Higgs sector, which therefore comprises five bosons: two neutral CP-even h and H, one neutral CP-odd A, and two charged $H^{\pm}$ particles. The Higgs-like resonance discovered at 125 GeV is often identified in 2HDMs as the lower mass CP-even boson, h. With minimal assumptions (*i.e.* no CP violation and no tree-level flavour-changing neutral currents), 2HDMs are fully 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. $\cos(\beta - \alpha)$ is often used as a study parameter for 2HDMs. 2HDMs are classified in four types, depending on the structure of the couplings of the two Higgs field doublets with up-type quarks, down-type quarks and leptons. This class of models is an important benchmark for experimental searches of BSM physics in the Higgs sector, and type-II 2HDMs are an approximation for Supersymmetry (SUSY) with a high mass scale.

The ATLAS collaboration recently published several results of searches for additional Higgs bosons in the 2HDMs context. Reference [8] reports a search for MSSM neutral Higgs bosons in the $\tau\tau$ decay channel, particularly relevant for the high-$\tan\beta$ region of the 2HDMs parameters space. Both leptonic and hadronic τ decays are considered in this analysis. The experimental challenge is the presence of at least two neutrinos in the final state: a complete kinematic reconstruction is therefore not feasible. A technique based on statistical reconstruction of the kinematic configuration is exploited in the $\ell\ell$ and ℓh channels, which uses the transverse missing momentum ($E_{\mathrm{T}}^{\mathrm{miss}}$) and the 4-momenta of all objects reconstructed in the detector to reconstruct the most probable value of the mass of the heavy Higgs candidate. This quantity is then used as a discriminating variable against the non-resonant background. In the hh channel, where the most relevant background is due to multi-jet QCD events, best discrimination between signal and background is obtained by exploiting the total transverse mass of the $\tau\tau$ system. Exclusion limits are derived from the distributions of the discriminating variables for several benchmark scenarios of the MSSM. Figure 1 shows the results for the m_h^{max} scenario. The experimental 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 $\tan\beta$, $m_A \approx 1\,\mathrm{TeV}$ region will be of extreme interest in the next months at the LHC, as it can be explored with early Run-2 searches, thanks to the increase of the centre-of-mass energy from 8 to 13 TeV.

In ref. [9] a search for a pseudoscalar Higgs boson decaying via $A \to Zh$ is reported. This decay channel is most sensitive for low-intermediate values of m_A, *i.e.* for m_A of the order of few hundreds of GeV. The analysis is performed by 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. 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 A candidate in

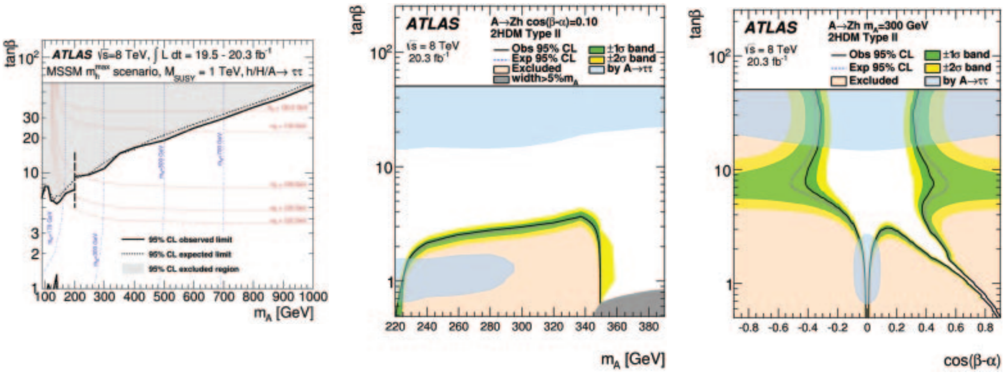

Fig. 1. – Left: 95% CL upper limits on $\tan\beta$ as a function of m_A for the m_h^{max} benchmark scenarios of the MSSM obtained by the $h/H/A \to \tau\tau$ search. Centre: interpretation of the $A \to Zh$ and $h/H/A \to \tau\tau$ cross-section limits in the context of the parameters space of 2HDMs, with exclusion regions shown in the $\tan\beta$ *vs.* m_A plane for type-II 2HDMs. 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.

data are found to be in good agreement with the background-only hypothesis. Resulting constraints for the parameters space of type-II 2HDMs are shown in fig. 1. $h/H/A \to \tau\tau$ and $A \to Zh$ results for type-II 2HDMs for m_A values of few hundreds of GeV show a good complementarity, as they are able to exclude the high $\tan\beta$ and the low $\tan\beta$ regions respectively. Considering also constraints obtained with indirect measurements [7], type-II 2HDMs appear to be very significantly constrained for $m_A \approx 300\,\text{GeV}$ by LHC Run-1 data.

Charged Higgs boson production at the LHC is predicted by several models. For example, the MSSM comprises production mechanisms for a $H^\pm$ associated with b and t quarks. A search for MSSM $H^\pm$ decaying into $H^\pm \to \tau^\pm\nu$, which is the dominant decay for $m_{H^\pm} \lesssim 200\,\text{GeV}$, is reported in ref. [10]. Two mass regions, $80 < m_{H^\pm} < 160\,\text{GeV}$ and $m_{H^\pm} > 180\,\text{GeV}$, are explored in this measurement, which exploits the hadronic decays of the τ. Events with a reconstructed τ_{had}, with a high transverse missing momentum $E_{\mathrm{T}}^{\mathrm{miss}}$, no electrons or muons 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. Limits on $H^\pm$ production for several benchmark scenarios of MSSM are drawn from the distribution of the reconstructed transverse mass for selected events. The $m_{H^\pm} < 160\,\text{GeV}$ region of the $m_{H^\pm}$ *vs.* $\tan\beta$ space is almost entirely excluded by this measurement, while only a small part of the parameter space is excluded in the high mass region. The ATLAS collaboration recently released also a search for charged Higgs bosons produced via vector boson fusion and decaying via $W^\pm Z$ [11]. This production/decay channel is forbidden at tree level in 2HDMs, but allowed, for example, by Higgs Triplet Models (HTMs), where a triplet of fields is added in the Higgs sector to the SM doublet. Exclusion limits are derived for $\sigma(VBF \to H^\pm) \times BR(H^\pm \to W^\pm Z)$.

3. – Searches for production of Higgs pairs

The production of SM Higgs bosons in pairs allows for directly probing the structure of the Higgs potential. Since the production cross section is small in the SM, of the order of few tens of fb for pp collisions at $\sqrt{s} = 13$–$14\,\text{TeV}$, this study is only feasible in the very long term at the LHC in the SM context. Several BSM models predict an enhancement of hh production, either in a resonant (*e.g.* 2HDMs) or non-resonant (*e.g.* composite Higgs) way, which is therefore interesting for searches also in Run-1 data. Reference [12] reports a search for hh production in the $b\bar{b}\gamma\gamma$ channel. 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. For the non-resonant search, the mass of the di-photon system is used as a discriminating variable, and the contributions of the background continuum, of the SM hh production and of the possible BSM physics are fitted from data. For the resonant search a counting experiment is performed, with a cut 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 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.

A search for double h production in the $b\bar{b}b\bar{b}$ decay channel is presented in ref. [13]. The search for resonant enhancement is performed in two categories of mass of the resonance, m_X. For $500 < m_X < 1100\,\text{GeV}$ 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, is exploited. Above that value of the mass, the h boost does not allow for a resolved reconstruction of jets produced in the $h \to b\bar{b}$ decay. Candidates for the $m_X > 1100\,\text{GeV}$ category are therefore identified by 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. The track-jets must be identified as b-jets by a tagging algorithm. The resonant search is performed by exploiting the total invariant mass of the selected jets both in the resolved and boosted topologies. 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

Several BSM models predict decays of the SM Higgs boson or of additional Higgs bosons to particle non detectable by detectors at colliders. The indirect limit obtained in LHC Run-1 data for such decays is $BR(H \to INV) \lesssim 30\%$ [4, 6]. Several channels have been explored by the ATLAS collaboration for direct searches for $H \to INV$ decays. 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 $E_{\mathrm{T}}^{\mathrm{miss}} > 90\,\text{GeV}$ and a di-lepton system with an invariant mass compatible with m_Z are selected. An additional cut is applied on the angular separation between the transverse momentum of the di-lepton system and the direction of $E_{\mathrm{T}}^{\mathrm{miss}}$, as the Z boson momentum is expected to balance that of the H. $E_{\mathrm{T}}^{\mathrm{miss}}$ is used as a discriminating variable and limits are set on $\sigma_{ZH} \times BR(H \to INV)$ for H candidates with a mass between 110 and 400 GeV. The 95% CL limit on $BR(h_{SM} \to INV) < 75\%$ is in agreement with expectations. Limits are reported in the ref. [14] also for the DM-nucleon cross-section in the Higgs-portal scenario.

Reference [15] presents a search for VH production with $V \to hadrons$ and $H \to INV$ decays. Events with $E_{\mathrm{T}}^{\mathrm{miss}} > 120\,\mathrm{GeV}$ and two or three jets, with a di-jet invariant mass compatible with that of a W or Z boson, are selected. Due to the expected balance between the V and the H momenta, the $E_{\mathrm{T}}^{\mathrm{miss}}$ and the di-jet system are also required to be well-separated in the azimuthal plane. 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.

Reference [16] presents a search for Higgs bosons produced via VBF and decaying to invisible particle. The typical VBF signature is exploited, with two jets produced with a very big gap in rapidity between them. This selection is combined with a requirement of a high $E_{\mathrm{T}}^{\mathrm{miss}}$ (greater than 150 GeV) in the event, allowing for an efficient rejection of background events, with remaining contributions mostly due to V+jets events. The 95% CL limit for a SM h is measured to be $BR(h_{SM} \to INV) < 28\%$, in agreement with expected exclusion in the hypothesis of no signal. This result is of extreme interest, as it reaches the same region of exclusion of the indirect limit.

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

Reference [17] reports a search for the decay of Higgs bosons H into two light pseudoscalar Higgs bosons a, which are included in the Next-to-Minimal Supersymmetric Standard Model (NMSSM). The experimental signatures of $H \to aa$ depends on the mass of these new particles m_a; this search is aimed at the $m_a > m_\tau$ region. One of the a candidates in the event is required to decay via $a \to \tau\tau$. Reconstructing events with four τ is experimentally challenging, thus a $a \to \mu\mu$ decay is required for the second a candidate. The production rate is reduced due to the lower $a \to \mu\mu$ BR, by a $O(100)$ factor, but the better signal-to-background ratio and the much higher trigger efficiency result in an overall better sensitivity of the search. The reconstructed invariant mass of the $\mu\mu$ system is used as a discriminating variable to set limits 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 $m_a = 5\,\mathrm{GeV}$.

A search for $H \to ZZ_d$ and $H \to Z_dZ_d$ decays is presented in ref. [18], where Z_d is a light gauge boson mediator of a $U(1)_d$ gauge symmetry in a dark sector. The analysis exploits events with four leptons (e or μ). The $H \to ZZ_d$ search requires a di-lepton pair of same flavour, opposite charge and with an invariant mass compatible with m_Z. A search for resonances in then performed on 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.

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