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Beyond the Standard Model Higgs searches at high mass

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Summary. — Extensions of electroweak Higgs sector received a great attention by both experimentalist and phenomenologist after the discovery of the Higgs boson announced by both ATLAS and CMS Collaborations. This work presents two models, namely the additional singlet model and the two-Higgs-doublet model, discussing the model parameters that are crucial in experimental analyses. Higgs boson searches at high mass, made by the ATLAS Collaboration using *pp* collisions data recorded during Run I of LHC, are also shown.

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1. – Introduction

The discovery of the Higgs boson at the Large Hadron Collider at CERN, announced by both ATLAS and CMS Collaborations [1,2], is actually a milestone of theoretical and experimental particle physics. The discovered particle has been analyzed to evaluate its properties showing that the Higgs boson is a $J^P = 0^+$ particle with a mass of about 125 GeV [3]. Nevertheless, theory does not exclude the existence of additional singlets or duplets of Higgs scalar fields and these hypotheses are considered in many extensions of the Standard Model. With a view to the forthcoming LHC upgrade, exploration of extended theories Beyond the Standard Model (BSM) will be crucial for the next physics analyses.

2. – Theoretical models

In the Standard Model (SM) the scalar sector is defined in the simplest possible way by assuming the existence of just one $\mathbb{SU}(2)$ doublet. The crucial theoretical aspect about scalar sector is the ρ parameter that was experimentally demonstrated to be very close to one. Since both $\mathbb{SU}(2)$ singlets with $Y = 0$ and $\mathbb{SU}(2)$ doublets with $Y = \pm 1$ give $\rho = 1$, the simplest way to extend Higgs sector is to add a real singlet or a complex doublet of scalar fields.

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2.1. *Additional electroweak singlet.* – In addition to the doublet Higgs field of the SM a real electroweak (EW) singlet of $\mathbb{SU}(2)$ is assumed. Spontaneous symmetry breaking leads to mixing between the two states, resulting in two CP-even Higgs bosons assumed to be non-degenerate. The two Higgs bosons, h (the lighter) and H (the heavier), couple to fermions and vector bosons as the SM Higgs boson but with strengths reduced by a scale factor, denoted as k (k') for h (H), and constrained by unitarity to be $k^2+(k')^2 = 1$.

In this model, the lighter Higgs boson h is assumed to have identical production and decay modes to the SM Higgs boson, but with decay rates σ_h and total decay width Γ_h reduced by a factor k^2. Since the heavier Higgs boson H can decay in new modes, *e.g.* $H \to hh$, if they are kinematically accessible, its decay rates σ_H and total decay widths Γ_H are defined, with respect to those of the SM Higgs boson with equal mass and in terms of branching ratio of all new decay modes BR_{new}, as

$$\sigma_H = (k')^2 \times \sigma_{H,\text{SM}} \quad \text{and} \quad \Gamma_H = \frac{(k')^2}{1 - BR_{\text{new}}} \times \Gamma_{H,\text{SM}}. \tag{1}$$

2.2. *Two-Higgs-Doublet Model (2HDM).* – In the two-Higgs-Doublet model (2HDM) the Higgs sector is extended by an additional doublet of $\mathbb{SU}(2)$ and it predicts the existence of five physical bosons: two neutral CP-even bosons (h, H), one neutral CP-odd boson (A) and two charged bosons ($H^{\pm}$). Furthermore, this model can be described by six parameters: four Higgs boson masses (m_h, m_H, m_A and $m_{H^{\pm}}$), the ratio between the vacuum expectation values of the two fields $\tan\beta = v_1/v_2$, with $v_1^2 + v_2^2 = v^2 \approx (246\,\text{GeV})^2$, and the mixing angle of the two neutral CP-even states (α). The couplings of the two neutral CP-even Higgs bosons to vector bosons relative to their SM values are constrained from gauge invariance to be

$$g_{hVV}^{\text{2HDM}}/g_{hVV}^{\text{SM}} = \sin(\beta - \alpha) \quad \text{and} \quad g_{HVV}^{\text{2HDM}}/g_{HVV}^{\text{SM}} = \cos(\beta - \alpha). \tag{2}$$

Depending on assumptions made about Higgs doublets coupling to fermions and vector bosons, it is possible to define four different types of 2HDM as described in [4].

3. – Experimental analyses

The ATLAS experiment at the LHC has determined the coupling of the Higgs boson to other particles, as well as its mass, and it has exploited a wide mass range in many production and decay channels by using both $4.8\,\text{fb}^{-1}$ at $\sqrt{s} = 7\,\text{TeV}$ and $20.3\,\text{fb}^{-1}$ at $\sqrt{s} = 8\,\text{TeV}$ of pp collision data.

In the case of the additional EW singlet model, using the signal strength of the light Higgs boson, $\mu_h = k^2$, as measured combining all studied channels [5], it is possible to extract an upper limit on the coupling of the heavy Higgs boson, $(k')^2$. The maximum signal strength for contamination of a heavy Higgs boson into the light Higgs boson signal observed (expected) at 95% CL is $k' < 0.12$ (0.29). The approach for 2HDMs is quite different since the rescaling of production and decay rates is a function of the light Higgs boson couplings to vector bosons, fermions and leptons, which in turn are functions of α and β; thus, analyses usually scan the $[\cos(\beta - \alpha), \tan(\beta)]$ plane. Results [5] show that data are consistent with the SM limit at $\cos(\beta - \alpha) = 0$ within $\sim$ 1–2 σ in each of the four models considered.

The $H \rightarrow ZZ \rightarrow 4l$ decay channel [6] is sensitive across a wide range of mass values m_H and it is characterized by a high signal to background ratio S/B and a very sharp invariant mass resolution; nevertheless, this channel is affected by statistical limitations due to small branching ratio. The Higgs mass range has been scanned up to 1 TeV and, through this, it is possible to extract constraints on heavier Higgs boson cross sections and, consequently, its couplings. Indeed, results show that 95% CL limit on $(\sigma_H \times BR)/(\sigma_H \times BR)_{\mathrm{SM}}$ at Higgs boson mass $m_H = 500\,\mathrm{GeV}$ is ~ 0.3 (~ 1.5) for gluon-gluon fusion (vector boson fusion plus associated production) channel.

Also the $H \rightarrow ZZ \rightarrow llqq$ decay channel [7] is sensitive to a wide range of mass values m_H and, furthermore, it is favored with respect to the 4l channel by the higher branching ratios; nevertheless, this channel is affected by a very huge irreducible background mostly constituted by Z boson produced in association with one or more jets and top quarks productions. In this case, the 95% CL limit on $(\sigma_H \times BR)/(\sigma_H \times BR)_{\mathrm{SM}}$ at Higgs boson mass $m_H = 500\,\mathrm{GeV}$ is ~ 2.5 for gluon-gluon fusion and vector boson fusion production channels extracted by using only $4.7\,\mathrm{fb}^{-1}$ of integrated luminosity collected at $\sqrt{s} = 7\,\mathrm{TeV}$.

The $H \rightarrow WW \rightarrow l\nu l\nu$ decay channel [8] is characterized by the missing transverse energy, E_T^{miss}, due to the neutrinos produced in the W boson leptonic decays and the crucial variable used to study the Higgs boson production is the W bosons transverse mass m_T. Thus, the major background to this channel is constituted by top quarks and diboson productions. The Higgs boson mass range m_H has been scanned up to 1 TeV and results show that 95% CL limit on $(\sigma_H \times BR)/(\sigma_H \times BR)_{\mathrm{SM}}$ at Higgs boson mass $m_H = 500\,\mathrm{GeV}$ is ~ 0.7 for gluon-gluon fusion production channel.

4. – Conclusions

Beyond the Standard Model extensions of the Higgs sector has been discussed, namely the additional electroweak singlet model and the two-Higgs-Doublet-Model (2HDM), presenting the most important parameters for searches of heavier Higgs bosons. The experimental analyses of the ATLAS Collaboration, done by using *pp* collisions data recorded at the LHC at a center-of-mass energy of $\sqrt{s} = 7$ and $8\,\mathrm{TeV}$, have been also shown confirming the feasibility of BSM Higgs searches at high mass values that will be crucial in the study of the Higgs sector during the planned Run II of the LHC.

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