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Higgs boson and vacuum stability in models with extended scalar sector

Abstract

In this dissertation Two-Higgs-Doublet Models (2HDMs) with a $\mathbb{Z}_2$-symmetric scalar potential are studied from different perspectives. Two kinds of models, which differ by the choice of the vacuum state, are analysed. One of them is the so-called 2HDM (mixed) which breaks the symmetry of the potential by non-zero vacuum expectation values (VEVs) of the neutral components of the two scalar doublets. The other one, the exactly $\mathbb{Z}_2$-symmetric Inert Doublet Model (IDM) with only one non-vanishing VEV, is of central interest to this work. It contains a SM-like Higgs boson and a candidate for the dark matter (DM) particle.

The first part of this thesis is devoted to the analysis of the allowed parameter space of the studied 2HDMs. The models are subject to a number of constrains, such as: positivity of the potential, stability of the vacuum state, perturbative unitarity, electroweak precision tests and the LEP bounds. We also take into account the fact that the scalar discovered at the LHC is a SM-like Higgs boson with mass around 125 GeV. We present the allowed regions in the parameter space for the parameters of the potential and the physical masses. For the 2HDM (mixed), within a scenario where the lightest CP-even scalar plays a role of the SM-like Higgs particle, we find a strong bound on the parameter $\tan\beta$, which is independent of the type of Yukawa interactions. In the IDM we derive an upper bound on the mass parameter of the potential which is based on the condition for the stability of the vacuum and excludes a phenomenologically interesting part of the parameter space.

In the second part of the present dissertation, constraints on the properties of the new scalars of the IDM, based on the experimental results for the Higgs particle, are analysed. First of all, we study the Higgs diphoton decay. We show, that the additional scalars (in particular the charged scalar and the DM candidate) can affect the observed signal strength of this decay. From this fact, we infer strong upper and lower limits on the masses of these particles. Next, the decay of the Higgs to a Z boson and a photon is analysed. We demonstrate that the correlation between the diphoton and $Z\gamma$ signal strength is positive, which gives a possible experimental probe of the IDM. Furthermore, we study the invisible and total decay widths of the Higgs boson and infer constraints on the DM particle and its coupling to the Higgs particle. In the following, the Higgs results are combined with the DM data. We derive constraints and exclusions for different possible DM scenarios, proving the idea of combining different sources of results very fruitful. Interestingly, the results of this combination, when translated to the parameters probed by the direct detection experiments, give constraints which are comparable or even stronger than the results of the dedicated searches.

In the final part of the present dissertation, the issue of vacuum stability is studied, in particular, the influence of the additional scalars on this problem. Two distinct approaches are adopted. First, the additional scalars of the IDM are assumed to be heavy, and thus they contribute to the effective potential only through loop corrections. We demonstrate that the heavy inert scalars can change the structure of the effective potential, introducing a new minimum which is deeper than the SM one and this way they can destabilise the vacuum state. In addition, the regions where destabilisation of the vacuum may occur are confronted with theoretical and experimental constraints, and we prove that the IDM, in the valid part of the parameter space, is free from the threat of vacuum instability. The other approach to the issue of vacuum stability adopted in this thesis admits all of the scalar fields in the effective potential, and thus allows the study of the coexistence of different minima. We show that the inert minimum can coexist with an inert-like one at one-loop level in a vaster region of the parameter space than at tree level. Moreover, we demonstrate that the loop corrections may invert the ordering of the minima, i.e. a tree-level global minimum may, in certain cases, become a local one at one-loop level. This shows the importance of beyond-tree-level analysis of the issue of vacuum stability.