Chapter 24

The physics of a heavy gauge boson in a Stueckelberg extension of the two-Higgs-doublet model

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Abstract

String theory constructions using D-brane physics offer a framework where ingredients like extra abelian factors in the gauge group, more than one Higgs doublet and a generalized Green-Schwarz mechanism appear at the same time. Motivated by works towards the direction of obtaining the Standard Model in orientifold constructions, we study in the present work a Stueckelberg extension of the two-Higgs-doublet model. The distinctive features of our model are i) a sharp decay width for the heavy gauge boson, and ii) a charged Higgs boson having two main decay channels at tree level with equal branching ratios.

24.1. Introduction

The Standard Model of Particle Physics (SM) (for a review see e.g. [1]) has been extremely successful in describing all low energy phenomena, being in excellent agreement with a vast amount of experimental data. The only missing part of the SM today is the Higgs boson that gives masses to fermions and to $W^{\pm}$ and Z bosons. The Stueckelberg mechanism [2] gives mass to abelian vector bosons without breaking gauge invariance on the Lagrangian, and thus provides an alternative to the Higgs mechanism. Most of the well motivated extensions of the SM, which have been developed to address its open issues, involve an extra $U(1)$ in the gauge group. A new heavy gauge boson, Z', is predicted which would have profound implications for particle physics and cosmology. Another famous minimal extension of the SM consists in the addition of one scalar doublet to the theory [3]. This idea has been particularly successful for its simplicity and the rich phenomenology that generates, being able to introduce new dynamical possibilities, like different sources of CP violation or dark matter candidates, helps to solve some of the SM problems. In the most general version of the two-Higgs-doublet model (2HDM), the fermionic couplings of the neutral scalars are not diagonal in flavour, which generates dangerous flavour-changing neutral current (FCNC) phenomena.

Since these are tightly constrained by the experimental data, it is necessary to implement ad-hoc dynamical restrictions to guarantee their absence at the required level. Many attempts have been made in order to embed the SM in open string theory, with some success [4]. They consider the SM particles as open string states attached on different stacks of D-branes. N coincident D-branes typically generate a unitary group $U(N) \sim SU(N) \times U(1)$. Therefore, every stack of branes supplies the model with an extra abelian factor in the gauge group. Such $U(1)$ fields have generically four-dimensional anomalies [5,6]. These anomalies are cancelled via the Green-Schwarz mechanism [7,8,9,10] where a scalar axionic field is responsible for the anomaly cancellation. This mechanism gives a mass to the anomalous $U(1)$ fields and breaks the associated gauge symmetry. This class of models is characterized by i) the existence of two Higgs doublets necessary to give masses to all fermions, and ii) the massive gauge bosons acquire their mass from two sources, namely the usual Higgs mechanism, as well as the stringy mechanism related to the generalized Green-Schwarz mechanism, which is very similar to the Stueckelberg mechanism. In the light of these developments, it becomes clear that it is natural to study the 2HDM with additional $U(1)$s and the Stueckelberg mechanism together with the Higgs mechanism. In the present work we wish to study the phenomenology of a simple four-dimensional, non-GUT, non-supersymmetric model with an additional Higgs doublet, and just one extra $U(1)$ factor in the gauge group for simplicity.

24.2. Z' searches

The gauge group of the model is the SM gauge group times an extra abelian factor $U(1)_X$, with a coupling constant g_X and a gauge boson C_μ associated with it. We have three generations of quarks and leptons with the usual quantum numbers under the SM gauge group, and they are assumed to be neutral under the extra $U(1)$. This is a simple choice that ensures that there are no anomalies in the model. We consider the presence of two Higgs doublets, H_1 and H_2, with the same quantum numbers under the SM gauge group, the only difference being is that H_1 is assumed to be neutral under $U(1)_X$, while H_2 is charged under the additional abelian factor with charge $Y_X = \pm 1$. Finally, the Stueckelberg contribution is [11]

$$\mathcal{L}_{\rm St} = -\frac{1}{4} C_{\mu\nu} C^{\mu\nu} - \frac{1}{2} (\partial_\mu \sigma + M_1 C_\mu + M_2 B_\mu)^2 \ , \tag{24.1}$$

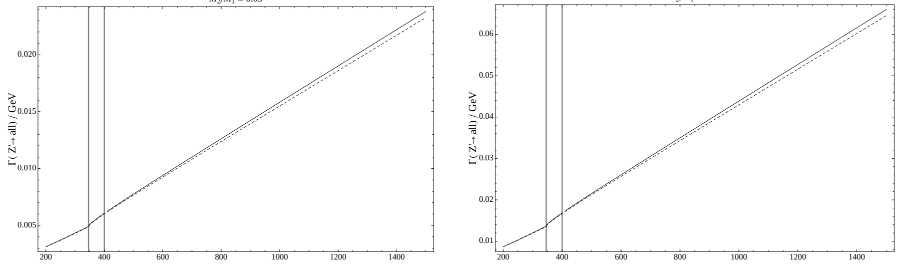
where C_μ is the gauge boson associated with the $U(1)_X$, $C_{\mu\nu}$ is the corresponding field strength, σ is the scalar axionic field which is assumed to couple both to B_μ and C_μ, and M_1 and M_2 are two mass scales which serve as two extra parameters of the model. The details regarding the Higgs potential, the electroweak symmetry breaking as well as the new interaction vertices can be found in [12].

The LHC is designed to collide protons with a center-of-mass energy 14 TeV. Since the center-of-mass energy of proton-proton collisions at LHC is 14 TeV, the particle cascades coming from the collisions might contain Z' if its mass is of the order of 1 TeV. Therefore a heavy gauge boson can be discovered at LHC, and in fact new gauge bosons are perhaps the next best motivated new physics, after the Higgs and supersymmetric particles, to be searched for at future experiments. The mass, total decay width as well as branching ratios for various decay modes are some of the properties of Z' that should be accurately measurable, and could be used to distinquish between various models at colliders. Thus, in this section we discuss the phenomenology of the model as far as the physics of the new gauge boson is concerned.

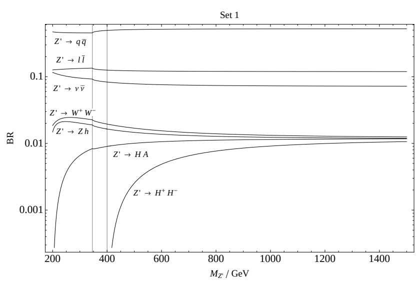
Our results are summarized in the figures below. We have fixed the Higgs boson masses (Set 1 and Set 2 as can be seen in the table below), as well as the coupling constant g_X considering two cases, one in which the coupling is small, $g_X = 0.001$, and one in which the coupling is comparable to the SM couplings, $g_X = 0.1$. Then the only free parameter left is the heavy gauge boson mass. Therefore, in the figures shown below the independent variable is the mass of Z'. First we focus on the case where $g_X = 0.001$. Figures 1 and 2 show the total decay width of Z' (in GeV) as a function of its mass for Set 1, with M_2/M_1 = 0.03 and 0.05, respectively. In the rest of the figures the impact of changing the value for the ratio M_2/M_1 is negligible, so it is fixed at 0.03. Figures 3 and 4 show all branching ratios as a function of $M_{Z'}$ (for Set 1 and Set 2 respectively). All the decay channels into quarks have been considered together as a single quark channel. However, we have checked that Z' decay into quarks is dominated by the up quark contributions. The straight vertical lines correspond to the thresholds, one for the top quark (~ 346 GeV), one for the neutral Higgs bosons (600 GeV for Set 2 only) and one for the charged Higgs bosons (400 GeV for Set 1 and 1000 GeV for Set 2). We remind the reader that in the SM, the branching ratio of the Z boson to electrons or muons or tau leptons is 0.034 for each of them, to all neutrino species (invisible channel) is 0.2, and to hadrons is 0.7. In the model with one Higgs doublet there are no decay channels to inert Higgs bosons, and for a large enough $M_{Z'}$, where the branching ratios of Z' to the inert Higgs bosons become significant, the decay widths in the two models tend to differ. However, the difference is small since the dominant contribution to the decay width is from Z' to fermions, which scales as $M_{Z'} g_Y^2 (M_2/M_1)^2$. Furthermore, in the model with one Higgs doublet only, there is just the SM neutral Higgs boson, while in the model with two Higgs doublets there are both neutral and charged Higgs bosons.

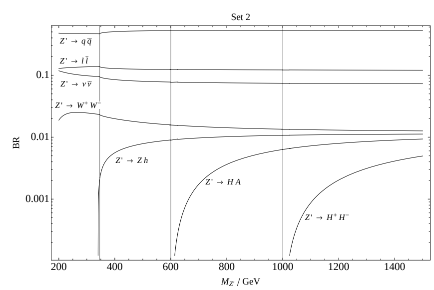
	Set 1	Set 2
$M_{H^\pm}$ (GeV)	200	500
$M_{H,A}$ (GeV)	100	300
M_h (GeV)	100	250

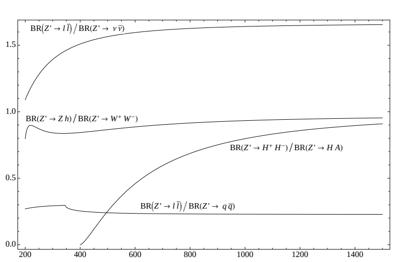
Table 24.1
The two sets of Higgs boson masses used in the analysis.

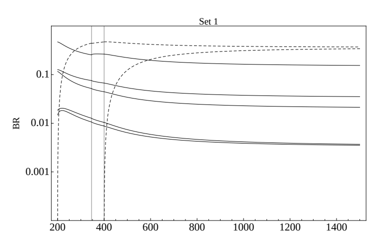


Clearly, if a charged Higgs boson is seen at colliders, this would be a direct evidence of physics beyond the SM. Without Yukawa couplings the charged Higgs bosons cannot directly decay into fermions, and therefore









the dominant decay channels of the charged Higgs bosons are just two, $H^{\pm} \to W^{\pm}\, H$ and $H^{\pm} \to W^{\pm}\, A$. Taking into account that H and A are degenerate in mass, the model discussed here predicts that there are two main decay channels for $H^{\pm}$ with the two branching ratios being equal to $1/2$. A detailed discussion of the Higgs phenomenology is postponed to a future work. We can also mention here in passing that if the decay channel $h \to ZZ$ is kinematically allowed, the SM Higgs boson can be easily found through the so-called four-lepton golden Higgs channel, $h \to ZZ \to l^+l^-l^+l^-$. As in the case with one Higgs doublet, the total decay width is much smaller than in other models [13,14], and therefore a heavy gauge boson is expected to show up at colliders as a sharp resonance. Finally, in Figure 5 we show ratios of decay widths of two channels as a function of $M_{Z'}$, and in particular we have chosen to show the following ratios: Leptons to hadrons, leptons to neutrinos, charged Higgs to neutral Higgs, and $W^\pm$ bosons to SM Higgs and Z boson. Recall that in the SM the ratio of leptons to neutrinos is 0.17, and the ratio of leptons to hadrons is 0.05.

Finally, notice that in Figures 1 and 2, although they look very similar, the scale is different. When the ratio M_2/M_1 is increased from 0.03 to 0.05, the total decay width also increases by a factor ~ 3, because the couplings of the new gauge boson are now larger. We have also checked that the plot with larger mass ratio showing the branching fractions cannot be distinguished from the one with smaller mass ratio.

We now consider the case where $g_X = 0.1$ for Set 1 and $M_2/M_1 = 0.03$. Most of the decay modes remain the same, apart from the ones into the inert Higgs bosons, for which the coupling now is larger, leading to larger partial decay widths. Figure 6 shows the effect on the branching ratios. The curves corresponding to the decays into the inert Higgs bosons preserve their shape, but now they are above the rest. The sign of Y_X has been taken to be positive. If we change the sign of Y_X we obtain a similar plot where the branching ratios for the inert Higgs bosons are slightly larger.

24.3. Conclusion

A model with an extra $U(1)$ and a second Higgs doublet has been investigated. It is assumed that the fermions and the SM Higgs are neutral under the extra $U(1)$, while the dark Higgs is charged. Thus, Yukawa couplings for the additional Higgs are not allowed, and the FCNC problem is avoided. From this point of view the model is similar to the inert 2HDM, although the gauge symmetry is more restrictive than the $\mathcal{Z}_2$ discrete symmetry. The massive gauge bosons obtain their masses from two separate mechanisms, namely from the usual Higgs mechanism, as well as from the Stueckelberg mechanism. The interplay between the heavy gauge boson and the extended Higgs sector makes the phenomenology of this model very rich. We have computed the total decay width and all the branching ratios of Z' as a function of its mass for two different sets of the Higgs bosons masses. We find that two distinct features of the model are a) a sharp decay width for the heavy gauge boson, characteristic of the Stueckelberg mechanism like in the corresponding model with just one Higgs doublet, and b) a pair of charged Higgs bosons with no Yukawa couplings decaying dominantly into a $W^\pm$ boson and a neutral Higgs boson H or A, with the two branching ratios being equal to $1/2$ each.

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