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Theoretical constraints on masses of heavy particles in Left-Right symmetric models

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Left-Right symmetric models with general $g_L \neq g_R$ gauge couplings which include bidoublet and triplet scalar multiplets are studied. Possible scalar mass spectra are outlined by imposing Tree-Unitarity, and Vacuum Stability criteria and also using the bounds on neutral scalar masses $M_{H_{FCNC}}$ which assure the absence of Flavour Changing Neutral Currents (FCNC). We are focusing on mass spectra relevant for the LHC analysis, i.e., the scalar masses are around TeV scale. As all non-standard heavy particle masses are related to the vacuum expectation value (VEV) of the right-handed triplet (v_R), the combined effects of relevant Higgs potential parameters and $M_{H_{FCNC}}$ regulate the lower limits of heavy gauge boson masses. The complete set of Renormalization Group Evolutions for all couplings are provided at the 1-loop level, including the mixing effects in the Yukawa sector. Most of the scalar couplings suffer from the Landau poles at the intermediate scale $Q \sim 10^{6.5}$ GeV, which in general coincides with violation of the Tree-Unitarity bounds.

1. Introduction

After the 2012 discovery of the spin-zero boson at the LHC [1,2] we are even more convinced that the theoretical concept of the mass generation within the gauge theory is correct. The discovered particle fits well within the predictions of the Standard Model (SM) of electroweak interactions. In the SM the mass of the Higgs boson is a free parameter. This, along with (very) weak interaction of the Higgs boson were the main reasons why it took decades to fix its mass experimentally, happened to be at the 125 GeV level [1,2]. In the meantime many theoretical concepts connected with both the scalar sector of SM and perturbation techniques have been developed and understood. It has been noted that the SM Higgs boson's mass can be bounded from both ends using quantum field theoretical (QFT) techniques [3–7]. These concepts are basic and general, and can be useful also nowadays when, after the LHC discovery, we would like to know much more. For instance, what is the actual representation of the scalar multiplets and what is the shape of the scalar potential of the fundamental theory in particle physics? A priori, the SM theory is not the end of the story, for many reasons.

One of the main theoretical constraints on the SM Higgs boson mass comes from the simple fact that its mass depends on the strength of the Higgs quartic coupling, so the mass should not exceed an upper limit above which the theory is strongly coupled and in turn the perturbative QFT is invalid. In other words, to have a consistent weakly coupled theory involving the Higgs boson, its mass must be smaller than that upper limit. This constraint of weak interactions at high energies is called the unitarity limit. In the context of SM, the upper limit of the SM Higgs boson mass must be within $\mathcal{O}(G_F^{-1/2})$ as deduced long time ago [3–7]. This limit had been computed more precisely in [6,7] as $\sqrt{8\pi\sqrt{2}/3G_F^{-1/2}} \simeq \mathcal{O}$ (TeV).

This is very important to understand the weakly coupled limit of all beyond Standard Model (BSM) theories which are considered, and which are tested in present or future accelerators, notably at the LHC. The problem has been already worked out within some popular and basic models involving two Higgs doublet models (THDM) [8–14] or models involving triplet scalar multiplets [15,16]. Unitarity constraints have been considered in [17] in the context of the Minimal Left-Right Symmetric model (MLRSM) which contains an enriched Higgs sector: a bidoublet and two

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triplets scalar fields [18–20]. Some basic remarks on unitarity in the scalar sector of MLRSM can be also found in the seminal work [21]. In a recent paper [22] perturbativity and mass scales of Left-Right Higgs bosons are also discussed.

In the present study we derive Tree-Unitarity (TU) constraints in MLRSM which are written in form of individual and (or) linear combinations of the quartic couplings. Thus these bounds are easily translated in terms of the physical scalar masses. We have also combined the Vacuum Stability (VS) criteria (for recent work on this subject in a general context, see [23]) and TU constraints with Flavour Changing Neutral Currents (FCNC) bounds which give an additional limit on the mass of the right-handed charged gauge boson. In addition, in the present work we have come up with a complete set of renormalization group equations (RGEs) and perform the necessary RGEs of quartic couplings.

Interestingly, the concept of Left-Right (LR) symmetry has been revived recently at the LHC in the context of dilepton [24–28], diboson [29,30] and diphoton [31–39] excesses, which might be connected with heavy particles of LR models. It is then useful to understand possible contributions to such signals coming from the scalar sector of the theory in future studies (some first results can be found in [40]) using bounds on the scalar sector of the theory. In the context of MLRSM we started such analysis in [41], taking into account interplay of the collider signals with low energy precision data. In that paper we treated Higgs boson masses practically as free parameters, not taking into account many possible theoretical constraints. Nonetheless, there we showed that correlations between the Higgs bosons and gauge bosons as well as the radiative muon decay at 1-loop level impose strong constraints on high energy LHC signals. To understand the realistic scalar spectrum of the theory, dedicated analyses have been further performed in [42–45]. In these papers the constraints from FCNC, VS along with the LHC exclusions were considered. It has been found among others that not all four charged Higgs bosons of the theory can be simultaneously light (below 1 TeV). Taking into account this limitation, we have found several benchmark points [43,44] which are within reach of the LHC future runs. For other studies of the Higgs sector of the theory, see e.g. [46–65,45].

Here, we incorporate TU constraints and further extend the analysis. We also take care of the constraints and potentially problematic structures due to Landau poles which arise from the concept of RGEs [66]. RGEs in MLRSM have been considered at the one-loop level, originally in [67]. Here, we have performed independent RG analysis after correcting some misprints in the published article, see Sec. 5 of the present work for details. In addition, we provide a complete set of 1-loop RGEs, including all couplings of the theory. It is important for two reasons: (i) to prepare a well-tested background for higher-loops analysis, and (ii) the earlier results [67] have been used repeatedly in recent studies [68,69,17] and it is better to avoid proliferation of misprints in the future.

In the SM, as the EWSB scale is determined from the observed gauge boson masses, the upper limit on the SM Higgs boson can be fixed. Similarly, if in a near future the right-handed gauge boson masses are fixed from observation then the absolute upper mass bounds of the scalars can be provided. Thus, as of now, the bounds depend on the $SU(2)_R$ breaking scale v_R. In this paper upper limits on the heaviest mass of these Higgs bosons compatible with the TU bounds are computed as functions of v_R.

2. Model: Left-Right symmetry

The model is based on the $SU(2)_L \otimes SU(2)_R \otimes U(1)_{B-L}$ Left-Right gauge symmetry (LR) [18–20]. The spontaneous symmetry breaking occurs in two steps: $SU(2)_R \otimes U(1)_{B-L} \to U(1)_Y$, and $SU(2)_L \otimes U(1)_Y \to U(1)_{em}$. To achieve this symmetry breaking we choose a traditional spectrum of Higgs sector multiplets with a bidoublet and two triplets [20,21]

$$\phi = \begin{pmatrix} \phi_1^0 & \phi_1^+ \\ \phi_2^- & \phi_2^0 \end{pmatrix} \equiv [2,2,0], \tag{1}$$

$$\Delta_{L(R)} = \begin{pmatrix} \delta^+_{L(R)}/\sqrt{2} & \delta^{++}_{L(R)} \\ \delta^0_{L(R)} & -\delta^+_{L(R)}/\sqrt{2} \end{pmatrix} \equiv [3(1),1(3),2], \tag{2}$$

where the quantum numbers in square brackets are given for $SU(2)_L$, $SU(2)_R$ and $U(1)_{B-L}$ groups, respectively.

The vacuum expectation values (VEVs) of the scalar fields can be recast in the following form:

$$\langle\phi\rangle = \begin{pmatrix} \kappa_1/\sqrt{2} & 0 \\ 0 & \kappa_2/\sqrt{2} \end{pmatrix}, \quad \langle\Delta_{L,R}\rangle = \begin{pmatrix} 0 & 0 \\ v_{L,R}/\sqrt{2} & 0 \end{pmatrix}. \tag{3}$$

VEVs of the right-handed triplet (Δ_R) and the bi-doublet (ϕ), propel the respective symmetry breaking: $SU(2)_R \otimes U(1)_{B-L} \to U(1)_Y$, and $SU(2)_L \otimes U(1)_Y \to U(1)_{em}$. As $v_L \ll \kappa_{1,2} \ll v_R$, we take safely $v_L = 0$.

We set the coefficients of the quartic couplings that are linear in $\Delta_{L,R}$ to be zero [70]. We also assume that the right-handed symmetry breaking scale, v_R, is much larger than the electroweak scale, $\kappa_+ \equiv \sqrt{\kappa_1^2+\kappa_2^2}$. Thus the terms proportional to κ_+ will be neglected comparing to the terms proportional to v_R. This assumption is phenomenologically viable and supported also by the exclusion limits given by the LHC. In addition $\kappa_1 \gg \kappa_2 \simeq 0$ [70]. These relations simplify correlations among the unphysical and physical Higgs fields which are related to each other by Eq. (74) in [71].

3. Unitarity bounds

The quartic part of the scalar potential can be written in terms of the physical fields as follows:

$$V(H^0_{0,1,2,3}; A^0_{1,2}; H^\pm_{1,2}; H^{\pm\pm}_{1,2}) = \sum_{m=1,..,72} \Lambda_m H_i H_j H_k H_L,$$

where $H_i, H_j, H_k, H_l \in (H^0_{0,1,2,3}; A^0_{1,2}; H^\pm_{1,2}; H^{\pm\pm}_{1,2})$. To understand the unitarity constraints one needs to look at the following scattering processes [8]:

$$H_i + H_j \to H_p + H_q, \tag{4}$$

where $H_{i,j,p,q}$ are the physical Higgs fields. These scatterings can happen in two ways at the tree level through: (i) Contact terms, i.e., four point scalar couplings which are outcome of the scalar quartic potential, and (ii) Higgs–Higgs–Gauge boson couplings. We know that the Higgs–Higgs–Gauge boson couplings contain derivatives owing to their Lorentz structure, thus when they are connected with the gauge boson exchange diagrams the maximum divergences which can appear through these diagrams are logarithmic. Considering theories up to the Planck scale, we do not need to worry about the logarithmic unitarity violations [8].

One can estimate the strength of these scalar four-point contact interactions in two ways. First, consider the process in terms of the unphysical scalar fields and reconstruct all the elements in terms of the physical neutral and charged scalars. In this case a vertex factor will be a polynomial function of the couplings which can be thought of as a rotated quartic coupling basis. As the model under consideration contains many scalar field components, it would be difficult to pin down the unitarity bounds in terms of the couplings and translate them to the masses of the scalar fields. There is an alternative option which we have adopted in this paper. Instead of rotating the quartic couplings we have sorted out all possible