Exotic Higgs decays in a neutrino mass model with discrete S_3 symmetry

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Abstract
Exotic Higgs decays can arise in lepton flavor models with horizontal symmetries. We investigate the scalar sector of a neutrino mass model using an S_3 family symmetry as an example. The model's symmetry leads to an enlarged scalar sector with features that might be used to test the model experimentally, such as scalar particles with masses below 1 TeV and manifestly non-zero matrix elements for lepton flavor violating decays. We compare different decay channels of the scalars as well as leptonic processes that violate lepton flavor, in order to compare model predictions with experimental bounds.

1 Model review

Lepton flavor models can lead to an enriched phenomenology in the scalar sector. As a prototypical example we study the S_3 family symmetry proposed in [1]. It has the attractive property of being able to explain the close-to-maximal mixing in the atmospheric neutrino sector and at the same time to accommodate the observed CKM angles. It is minimal in the sense that S_3 is the smallest non-abelian discrete symmetry group.

In order to generate the required masses of the matter particles as well as their mixings, three scalar electroweak doublets are introduced. The masses of the neutrinos are produced using electroweak triplets and a type II see-saw mechanism while the close-to-maximal $\mu\tau$ mixing originates from the charged lepton sector. The model's symmetry structure leads to off-diagonal entries in the mass matrices which, after diagonalizing and spontaneous symmetry breaking, also leads to flavor violating couplings through Yukawa interactions with the physical scalars.

The mixings that also lead to lepton flavor violating couplings are induced by the following assignment of the particles into S_3 multiplets:

$$\begin{aligned} &(L_2, L_3) \propto \mathbf{2} && L_1, \ell_1^c, \ell_2^c \propto \mathbf{1} && \ell_3^c \propto \mathbf{1'} \\ &(Q_2, Q_3) \propto \mathbf{2} && Q_1, u_1^c, u_2^c, d_1^c, d_2^c \propto \mathbf{1} && u_3^c, d_3^c \propto \mathbf{1'} \\ &(\phi_2, \phi_3) \propto \mathbf{2} && \phi_1 \propto \mathbf{1}, && \end{aligned}$$

where the L_i are electroweak lepton doublets, the ℓ_i^c are right-handed singlets and the ϕ_i are scalar fields and electroweak doublets. The quark sector is represented by the quark doublets Q_i and the right-handed up or down type singlets u_i^c, d_i^c, in exact analogy to the leptons. The allowed mass terms to appear in the Lagrangian follow from the basic multiplication rules of the group:

$$\mathbf{2} \times \mathbf{2} = \mathbf{1} + \mathbf{1'} + \mathbf{2} \qquad\qquad \mathbf{1'} \times \mathbf{1'} = \mathbf{1}$$

2 The scalar sector

We consider only the three neutral scalars h_a, h_b and h_c that emerge after symmetry breaking. To determine the mass spectrum of the scalars, the mass matrix of the physical scalars is diagonalized after symmetry breaking. The model contains three vacuum expectation values v_i for the scalar fields ϕ_i, out

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of which the VEVs $v_1 = v_2 = v$ are enforced to be equal by the S_3 symmetry. Imposing certain restrictions on the vacuum expectation values (the squared sum of the VEVs v_3 and v has to be equal to the squared Standard Model Higgs VEV and a ratio of $v_3/v \approx 10$ is favored by [1] in order to accommodate the Cabibbo angle and θ^q_{13}, the mixing angle of the first and third generation quarks in the CKM matrix) and masses leads to the mass eigenvalues.

To obtain a set of allowed data points and corresponding scalar masses we have scattered randomly over the parameter space of the scalar potential restricted by the condition that the mass eigenvalues must be larger than zero and real-valued. While a slight hierarchy in the masses is possible, all data points found this way point to masses in the sub $450\,\mathrm{GeV}$ range.

After diagonalizing the lepton mass matrix and the quark mass matrices, the couplings to the physical scalars can be determined. It can be shown that there are two basic patterns of possible couplings that emerge:

- The scalars h_b and h_c couple diagonally to the charged leptons as well as to the quarks. Additionally, they have an off-diagonal coupling to the 1-2 sector, i.e. to $e\mu$, uc and ds. These scalars can be expected to behave similar to the Standard Model Higgs particle.
- h_a does not have any diagonal couplings. It only couples off-diagonally to the 1-3 and 2-3 sectors, i.e. to $e\tau$, $\mu\tau$, ut, ct, db and sb.

The strength of the off-diagonal coupling in the 1-2 sector for h_b and h_c is determined by the Yukawa coupling which is not fixed by the masses. It is assumed to take the largest allowed value compatible with generating the known particle masses in the following results. All branching ratios for off-diagonal decays are thus understood as upper bounds.

3 Predictions

Scalar decay processes which differ from Standard Model Higgs decay channels are the main predictions being potentially testable by experiment.

- The branching ratios for decays of h_b and h_c into vector bosons and fermions can be found in Figs. 2 and 3. Only lowest order calculations are used to plot the branching ratios [2–4]. The results are very similar to the behavior of the Standard Model Higgs with some key differences:
  - There are off-diagonal channels, but their branching ratios are very small.
  - The couplings to the fermions are not directly proportional to the fermion masses. This is obvious from the very large branching ratio ($\approx 10^{-3}$–10^{-4}) for the decay into uu pairs.
- The scalar h_a only decays off-diagonally into quarks and leptons. As can be seen in Fig. 1, in the region of light masses (< $200\,\mathrm{GeV}$), h_a decays dominantly into sb or ct pairs, with a small mass region in which WW decays dominate. For heavier masses (> $400\,\mathrm{GeV}$) the particle mainly decays into ct. The branching ratio is even larger than the one for the decay into vector bosons. A very clear signature in all mass regions, even in the WW dominated one, is the second strongest decay into sb with a branching ratio larger than 0.01. To avoid large lepton flavor violating effects, the mass of h_a would have to be much larger or the corresponding coupling constants would have to be arbitrarily small. This is not easily explainable in this framework and would require some modifications to the minimal model.
- Lepton flavor violating decays such as $\mu \to e\gamma$ and $\mu \to eee$ are suppressed in this model. Using the results from [5] for the loop process, the branching ratios are many orders of magnitude below the current bounds for both processes.

4 Acknowledgements

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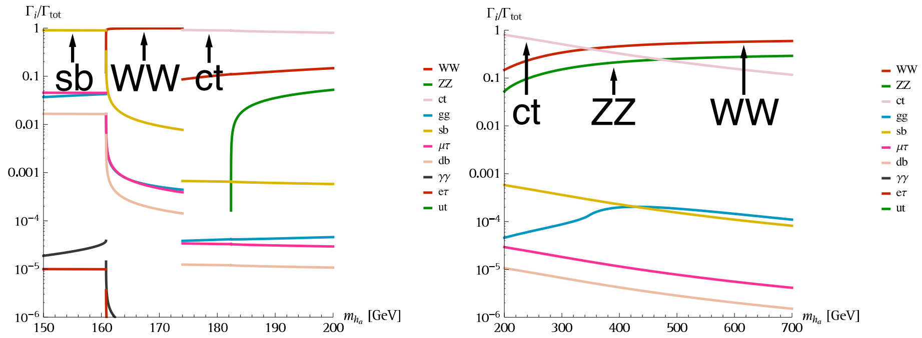

Fig. 1: Branching ratios for the decay of h_a.

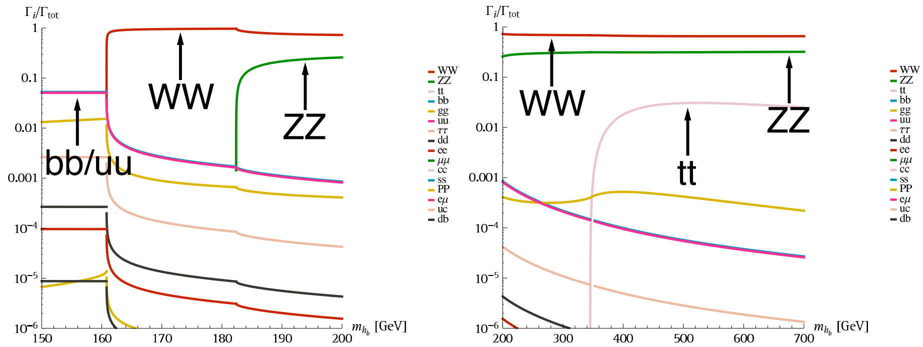

Fig. 2: Branching ratios for the decay of h_b.

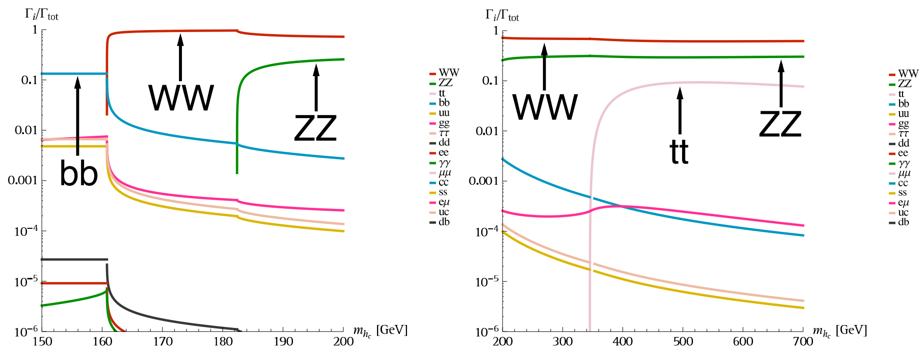

Fig. 3: Branching ratios for the decay of h_c.