Snowmass2021 - Letter of Interest

Flavorful Two Higgs Doublet Models at Future Colliders

Thematic Areas: (check all that apply □/■)

□ (EF1) EW Physics: Higgs Boson properties and couplingse
■ (EF2) EW Physics: Higgs Boson as a Portal to New Physics
□ (EF3) EW Physics: Heavy flavor and top quark physics
□ (EF4) EW Precision Physics and constraining new physics
□ (EF5) QCD and strong interactions: Precision QCD
□ (EF6) QCD and strong interactions: Hadronic structure and forward QCD
□ (EF7) QCD and strong interactions: Heavy Ions
□ (EF8) BSM: Model specific explorations
□ (EF9) BSM: More general explorations
□ (EF10) BSM: Dark Matter at colliders

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It has been well-established that the 125 GeV Higgs boson (h) observed at the LHC [1, 2] shows good agreement with Standard Model (SM) predictions, and that the origin of mass for the weak gauge bosons, the top quark, the bottom quark, and the tau lepton is the vacuum expectation value (VEV) of the 125 GeV Higgs Boson. Recently, ATLAS and CMS have observed the rare decay $h \to \mu\mu$ at the 2σ [3] and 3σ [4] level, respectively. However, little is known about the origin of the masses of the remaining first and second generation fermions: from an experimental point of view it is unknown if the 125 GeV Higgs boson gives mass to all SM fermions. In addition, the masses of SM fermions and the CKM quark mixing matrix exhibit a hierarchical structure that is no a priori explained by the SM.

One approach to address this issue is to assume that there is an additional source of electroweak symmetry breaking that couples exclusively to the first and second generations, as proposed in [5]. The simplest realization of this scenario is a two Higgs doublet model (2HDM) in which on Higgs doublet (identified as the 125 GeV Higgs boson) couples to mainly to the third generation fermions, while the second HIggs doublet couples mainly to the first and second generations. The observed pattern of fermion masses and the CKM matrix can then be obtained by asserting a suitable Yukawa textures, leading to the "flavorful" 2HDM (F2HDM).

This collider signatures of this setup differ significantly from well-studied 2HDMs, such at Type I and Type II 2HDMs [6]. In particular, in the F2HDM we find that the 125 GeV Higgs modified couplings to first and second generation fermions that can be enhanced compared to the third generation, which are close to their SM values. In addition, flavor violating couplings of the 125 GeV Higgs are present and can be probed in rare top decays $t \to hq$ ($q = u, c$), which can be enhanced in F2HDMs by many orders of magnitude compared to their SM values [7].

The heavy neutral Higgs bosons have couplings to first and second generations that are enhanced by $\tan\beta$ while their couplings to third generations are suppressed. In addition, the Yukawa textures lead to flavor violating decays of the heavy Higgs bosons. Generically we find that the decays $H \to c\bar{c}$ and $H \to ct$ that are comparable in size to $H \to t\bar{t}$, and that the decays into $\mu^+\mu^-$, $\tau^+\tau^-$, and $\tau\mu$ can be of the same order. A similar behavior is observed in the decay modes of the charged Higgs $H^\pm$, which are dominated by flavor violating decay in cb and ts. Furthermore, the rate for $H^\pm \to \mu\nu_\mu$ can be larger than the decay to $\tau\nu_\tau$, a hierarchy that is very distinct from standard 2HDMs.

Because of the non-standard decays of the heavy neutral and charged Higgs bosons, the standard searches for heavy Higgs bosons are not the most sensitive probes of the model. In particular, low mass di-muon searches place the most stringent constraints on the model rather than di-tau searches, but these only constrain heavy Higgs bosons below $\sim$ 400 GeV. There is still a lot of parameter space open for current and future experiments to probe this model, in flavor violating signatures such as $pp \to H \to \tau\mu$, $pp \to H \to tc$, $pp \to H^\pm \to cs$ and $pp \to H^\pm \to cb$, or final states with same sign tops $pp \to tH \to ttc$ or $pp \to tH^\pm \to tts$.

Given the unique signatures of our model, we propose to study the prospects for flavorful 2HDMs at future colliders such as HL/HE-LHC and the FCC. As as first step, we will consider future projections on the 125 GeV couplings to SM fermions and place constraints on the allowed parameter space of the $\cos(\beta - \alpha)$ vs. $\tan\beta$ plane. We will then see how our model is constrained by future projections using traditional search channels with third generation fermions, making comparisons with standard 2HDMs. We expect that the reach of these kinds of searches will not be very strong and we will investigate signatures of our model that have the best chance at probing the available parameter space. Recommendations for experimental studies based on these signatures will be provided.

References

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