Chapter 213
Probing Wrong-Sign *hbb* Couplings in $h \to \Upsilon\gamma$

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213.1 Motivation

Couplings of the 125 GeV scalar discovered at the LHC should be probed in detail to compare it with the SM Higgs. One interesting possibility is the "wrong-sign" solution, where the hbb coupling has a sign opposite to that of the SM. Among variants of two Higgs doublet model (2HDM) with a softly broken Z_2 symmentry [1, 2], type II and Flipped can have a "wrong sign" solution. These models have BSM scalars $H^\pm$, A, H, apart from a scalar h, which can be identified to be the 125 GeV scalar of LHC.

A hbb sign change does not alter the SM Higgs total decay width, dominated by $h \to b\bar{b}$ rate. To probe wrong-sign effects indirectly through interference effects, one-loop contribution to $gg \to h$ and $h \to \gamma\gamma$ can be probed. For these cases there are uneven competition between bottom and top loops and top and W boson loops respectively. So even with wrong sign the values will be close to the SM, and only a very precise LHC measurement of order 5% in $pp \to h \to \gamma\gamma$ will distinguish the normal sign from the wrong-sign solutions. In contrast, the rare decay $h \to \Upsilon\gamma$ consists of two diagrams with almost the same magnitude, suppressing the rate in the SM due to an accidental precise cancellation between them [3]. Reversal of the

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hbb sign will destroy the precise cancellation and this makes $h \to \Upsilon\gamma$ decay the best channel to probe the wrong-sign solutions. In this proceeding, we show impact of $h \to \Upsilon\gamma$ channel in probing wrong-sign solution, following our work, [4].

213.2 Theoretical Framework

The direct and indirect diagrams for $h \to \Upsilon\gamma$ decay are given in Fig. 2 of [4]. The direct diagram arises from the direct $hb\bar{b}$ coupling. The indirect diagram arises from the effective $h\gamma\gamma$ coupling with a virtual photon giving an Υ. With a CP-conserving 2HDM scalar potential with a softly broken Z_2 and the field parametrization used in [1, 2], the gauge and Yukawa couplings of the lightest 125 GeV scalar (h) are given as,

$$\begin{aligned} \mathcal{L}_{hVV} &= \sin(\beta-\alpha)h\left[\tfrac{m_Z^2}{v}Z^{\mu}Z_{\mu} + 2\,\tfrac{m_W^2}{v}W^{+\mu}W^{-}_{\mu}\right], \\ -\mathcal{L}_{Yuk} &= \tfrac{m_t}{v}k_U h\bar{t}t + \tfrac{m_b}{v}k_D h\bar{b}b + \tfrac{m_\tau}{v}k_\tau h\tau^+\tau^-. \end{aligned} \tag{213.1}$$

Here $k_U = \frac{\cos\alpha}{\sin\beta}$, $k_D = -\frac{\sin\alpha}{\cos\beta}$ and $k_\tau = k_D$ (Type II), $k_\tau = k_U$ (Flipped). The SM (alignment) limit corresponds to $\sin(\beta-\alpha) = 1$ which translates to $k_U = k_D = k_\tau = 1$. The wrong sign limit is defined as $\sin(\beta+\alpha) = 1$ which gives $k_U = 1, k_D = -1$. Only type II and Flipped 2HDMs are experimentally consistent with this wrong sign possibility [5–7]. Fig. 1 of [4] shows the parameter space allowing the wrong sign solution.

213.3 Results

In Fig. 213.1 results are presented where the red/dark-grey points pass all theoretical constraints. The blue/black (green/light-grey) points pass those and also μ_{VV} ($V \equiv W, Z$), $\mu_{\gamma\gamma}$, and $\mu_{\tau\tau}$ at 20% (10%). With only the theoretical constraints, a very large range of k_D gets allowed but it does not improve BR($h \to \Upsilon\gamma$) much, as it also increases the total width with k_D. After adding experimental constraints, only right-sign ($k_D \sim 1$) and wrong-sign ($k_D \sim -1$) regions get allowed. This is mostly due to μ_{VV} being very close to the SM values. In contrast to the $k_D = 1$ case, constructive interference in the wrong sign case makes BR($h \to \Upsilon\gamma$) larger by two orders of magnitude.

The possible experimental reach at 13 TeV LHC is presented in Fig. 213.1 (right), where we find a $\sigma \times BR$ value around 0.06 fb. For total integrated luminosity around 100 fb^{-1}, a measurement is becoming possible. A high-Luminosity LHC, will allow for either the detection or complete ruling out of the wrong-sign solution.

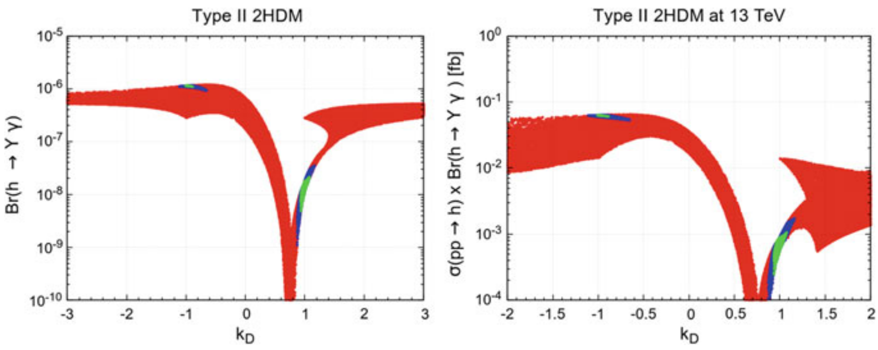

Fig. 213.1 BR($h \to \Upsilon\gamma$) (left), $\sigma \times$ BR($h \to \Upsilon\gamma$) at 13 TeV LHC (right), as a function of k_D

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