Can the Hbb coupling be equal in magnitude to its Standard Model value but opposite in sign?

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Outline

I. Higgs physics after discovery
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   - Toward the Standard Model (SM)-like Higgs boson

II. Model framework—a constrained 2HDM
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   - Higgs-fermion Yukawa interactions
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III. Wrong-sign Yukawa couplings
   - Why wrong sign Hbb (but not Htt) couplings are possible
   - Constraining this scenario with future LHC and ILC Higgs data
   - Implications for the MSSM Higgs sector

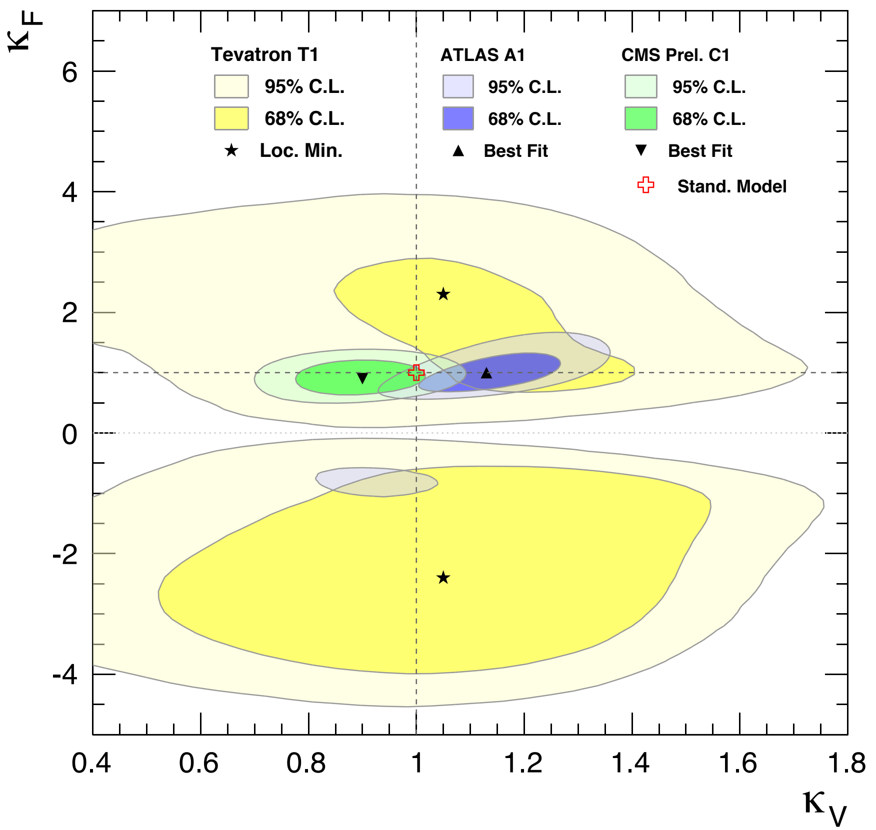
IV. Conclusions

References

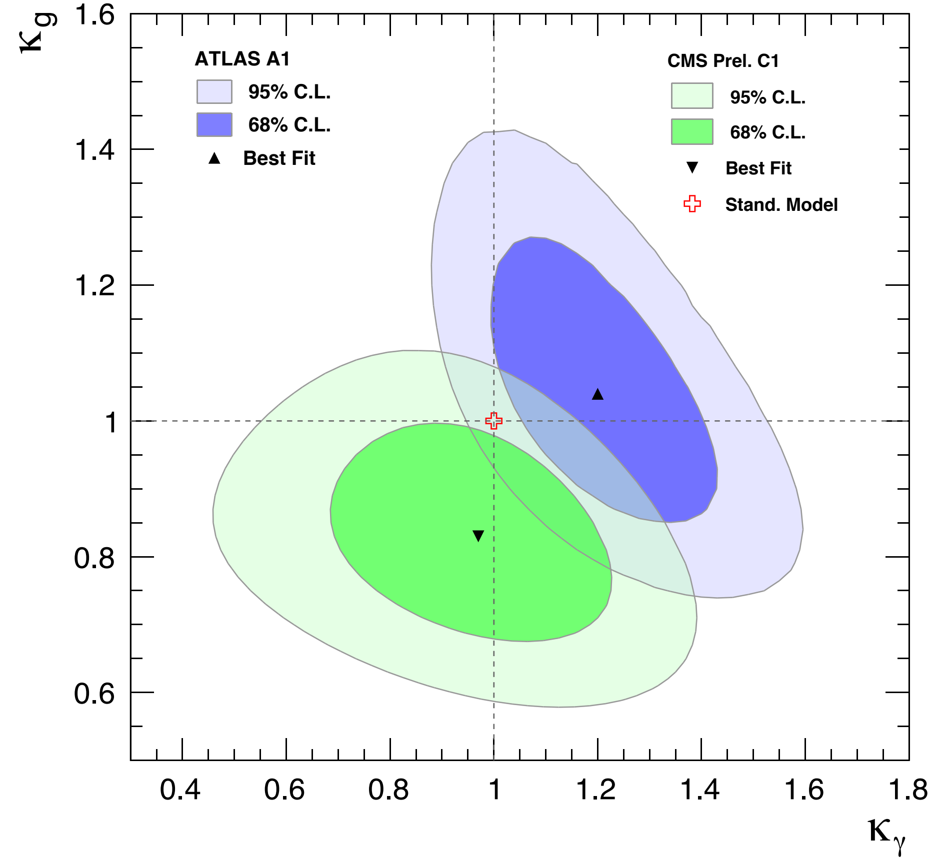
1. P.M. Ferreira, J.F. Gunion, H.E. Haber and R. Santos, Probing wrong-sign Yukawa couplings at the LHC and a future linear collider, Phys. Rev. D89 (2014) 115003, arXiv:1403.4736 [hep-ph].

2. H.E. Haber, The Higgs data and the Decoupling Limit, arXiv:1401.0152 [hep-ph], in the Proceedings of the Toyama International Workshop on Higgs as a Probe of New Physics 2013, 13-16 February 2013, Toyama, Japan.

The Higgs data set (taken from the 2013 PDG Higgs review) is consistent with a SM-like Higgs boson.



Likelihood contours of the global fit in the (κ_F, κ_V) plane for the Higgs data from ATLAS, CMS, D0 and CDF.



Likelihood contours of the global fit in the $(\kappa_g, \kappa_\gamma)$ plane for the Higgs data from ATLAS and CMS.

The 2HDM with a softly-broken $\mathbb{Z}_2$ symmetry

$$\mathcal{V} = m_{11}^2\Phi_1^\dagger\Phi_1 + m_{22}^2\Phi_2^\dagger\Phi_2 - \left(m_{12}^2\Phi_1^\dagger\Phi_2 + \text{h.c.}\right) + \tfrac{1}{2}\lambda_1\left(\Phi_1^\dagger\Phi_1\right)^2 + \tfrac{1}{2}\lambda_2\left(\Phi_2^\dagger\Phi_2\right)^2$$
$$+\lambda_3\Phi_1^\dagger\Phi_1\Phi_2^\dagger\Phi_2 + \lambda_4\Phi_1^\dagger\Phi_2\Phi_2^\dagger\Phi_1 + \left[\tfrac{1}{2}\lambda_5\left(\Phi_1^\dagger\Phi_2\right)^2 + \text{h.c.}\right],$$

such that $\langle\Phi_a^0\rangle = v_a/\sqrt{2}$ (for $a = 1, 2$), and $v^2 \equiv v_1^2 + v_2^2 = (246\ \text{GeV})^2$. For simplicity, assume m_{12}^2, λ_5 are real and the vacuum is CP conserving. We define Higgs basis fields, $H_1 \equiv (v_1\Phi_1 + v_2\Phi_2)/v$ and $H_2 \equiv (v_1\Phi_2 - v_2\Phi_1)/v$, so that $\langle H_1^0\rangle = v/\sqrt{2}$ and $\langle H_2^0\rangle = 0$.

$$\mathcal{V} \ni \ldots + \tfrac{1}{2}Z_1(H_1^\dagger H_1)^2 + \ldots + \left[Z_6(H_1^\dagger H_1)H_1^\dagger H_2 + \text{h.c.}\right] + \ldots,$$

where $\tan\beta \equiv v_2/v_1$, $c_\beta \equiv \cos\beta$, $s_\beta \equiv \sin\beta$, etc., and

$$Z_1 \equiv \lambda_1 c_\beta^4 + \lambda_2 s_\beta^4 + 2(\lambda_3 + \lambda_4 + \lambda_5)s_\beta^2 c_\beta^2,$$
$$Z_6 \equiv -s_\beta c_\beta\left[\lambda_1 c_\beta^2 - \lambda_2 s_\beta^2 - (\lambda_3 + \lambda_4 + \lambda_5)c_{2\beta}\right].$$

Higgs fermion Yukawa couplings in the 2HDM

The m_{12}^2 term of the Higgs potential softly breaks the discrete symmetry $\Phi_1 \to +\Phi_1\,, \Phi_2 \to -\Phi_2$. This discrete symmetry can be extended to the Higgs-fermion Yukawa interactions in a number of different ways.

		Φ_1	Φ_2	U_R	D_R	E_R	U_L, D_L, N_L, E_L
Type I		$+$	$-$	$-$	$-$	$-$	$+$
Type II	(MSSM like)	$+$	$-$	$-$	$+$	$+$	$+$
Type X	(lepton specific)	$+$	$-$	$-$	$-$	$+$	$+$
Type Y	(flipped)	$+$	$-$	$-$	$+$	$-$	$+$

Four possible $\mathbb{Z}_2$ charge assignments that forbid tree-level Higgs-mediated FCNC effects.

The main benefit of these models is that flavor changing neutral currents mediated by tree-level neutral Higgs exchange are automatically absent.

Decoupling and alignment limits of the 2HDM

In the $\{\Phi_1\,,\,\Phi_2\}$ basis, we diagonalize the neutral Higgs squared-mass matrix. The scalar mass eigenstates are: CP-even scalars: h and H (with Higgs mixing angle α and $m_h < m_H$), a CP-odd scalar A, and a charged Higgs pair $H^\pm$.

Conventionally, $0 \leq \beta \leq \frac{1}{2}\pi$ and $0 \leq \beta - \alpha \leq \pi$. Assume that $h \simeq h_{\rm SM}$. Since

$$\frac{g_{hVV}}{g_{h_{\rm SM}VV}} = s_{\beta-\alpha}\,, \quad \text{where } V = W^\pm \text{ or } Z\,,$$

it follows that h is SM-like in the limit of $c_{\beta-\alpha} \to 0$. In light of:

$$c^2_{\beta-\alpha} = \frac{Z_1 v^2 - m_h^2}{m_H^2 - m_h^2}\,, \qquad s_{\beta-\alpha}c_{\beta-\alpha} = -\frac{Z_6 v^2}{m_H^2 - m_h^2}\,,$$

- **decoupling limit:** $m_H \gg m_h \implies m_H \sim m_A \sim m_{H^\pm} \gg v$
- **alignment limit:** $|Z_6| \ll 1$. Then, H, A, $H^\pm$ need not be heavy (and $m_h^2 \simeq Z_1 v^2$)

In the decoupling and alignment limits, all tree-level couplings of h approach their SM values. Consider the Type-II Yukawa coupling to up-type ($U = t, \ldots$) and down-type ($D = b, \tau, \ldots$) fermions, relative to their SM values:

$$h\overline{D}D: \qquad -\frac{\sin\alpha}{\cos\beta} = s_{\beta-\alpha} - c_{\beta-\alpha}\tan\beta\,,$$

$$h\overline{U}U: \qquad \frac{\cos\alpha}{\sin\beta} = s_{\beta-\alpha} + c_{\beta-\alpha}\cot\beta\,.$$

delayed decoupling: if $|c_{\beta-\alpha}| \ll 1$ but $c_{\beta-\alpha}\tan\beta \sim \mathcal{O}(1)$, then it is possible to see deviations of the $h\overline{D}D$ coupling from its SM value while all other h couplings to SM particles show no deviations.

Finally, the hhh and $hhhh$ couplings also approach their SM values in the decoupling or alignment limits. For example,

$$\begin{aligned} g_{hhh} &= -3v\big[Z_1 s^3_{\beta-\alpha} + 3Z_6 c_{\beta-\alpha} s^2_{\beta-\alpha} + \mathcal{O}(c^2_{\beta-\alpha})\big]\,, \\ &= g^{\rm SM}_{hhh}\big[1 + 3(Z_6/Z_1)c_{\beta-\alpha} + \mathcal{O}(c^2_{\beta-\alpha})\big]\,. \end{aligned}$$

Deviations from SM-like Higgs behavior at loop level

The $H^\pm$ loop contribution to $h \to \gamma\gamma$ depends on the hH^+H^- coupling and $m_{H^\pm}$. In the softly-broken $\mathbb{Z}_2$–symmetric 2HDM,

$$g_{hH^+H^-} = \frac{1}{v}\Big[\big(2m_A^2 - 2m_{H^\pm}^2 - m_h^2 - \lambda_5 v^2\big)s_{\beta-\alpha} \\ + \big(m_A^2 - m_h^2 + \lambda_5 v^2\big)(\cot\beta - \tan\beta)c_{\beta-\alpha}\Big] .$$

Since $m_A^2 - m_{H^\pm}^2 = \frac{1}{2}v^2(\lambda_4 - \lambda_5)$, and $m_A^2 c_{\beta-\alpha} \sim \mathcal{O}(v^2)$ in the decoupling limit, we see that $g_{hH^+H^-} \sim \mathcal{O}(v)$ as expected. But, there exists a regime where $\lambda_4 - \lambda_5$ is large (but with λ_4 and λ_5 still within their unitarity bounds) such that $g_{hH^+H^-} \sim \mathcal{O}(m_{H^\pm}^2/v)$. In this case, the $H^\pm$ loop contribution to the $h \to \gamma\gamma$ decay amplitude is approximately constant.

This is analogous to the non-decoupling contribution of the top-quark in a regime where $m_t > m_h$ but the Higgs–top Yukawa coupling lies below its unitarity bound.

Wrong-sign Yukawa couplings

Recall that in the softly-broken $\mathbb{Z}_2$–symmetric 2HDM with Type-II Higgs-fermion Yukawa couplings, we had

$$h\overline{D}D: \qquad -\frac{\sin\alpha}{\cos\beta} = s_{\beta-\alpha} - c_{\beta-\alpha}\tan\beta\,,$$
$$h\overline{U}U: \qquad \frac{\cos\alpha}{\sin\beta} = s_{\beta-\alpha} + c_{\beta-\alpha}\cot\beta\,.$$

We noted the phenomenon of delayed decoupling where $c_{\beta-\alpha}\tan\beta \sim \mathcal{O}(1)$. Suppose nature were devious and chose (in a convention where $0 \leq \beta-\alpha \leq \pi$)

$$s_{\beta-\alpha} - c_{\beta-\alpha}\tan\beta = -1+\epsilon\,,$$

allowing for a small error ϵ (the precision of the experimental measurement). For $\epsilon = 0$, the tree-level partial widths of $h \to b\bar{b}$ and $h \to \tau^+\tau^-$ would be the same as in the SM. Could we experimentally distinguish the case of the wrong-sign $h\overline{D}D$ coupling from the SM Higgs boson?

Note that the wrong-sign $h\overline{D}D$ Yukawa coupling arises when

$$\tan\beta = \frac{1 + s_{\beta-\alpha} - \epsilon}{c_{\beta-\alpha}} \gg 1\,,$$

under the assumption that the hVV coupling is SM-like [i.e., $|c_{\beta-\alpha}| \ll 1$]. It is convenient to rewrite:

$$\begin{aligned} h\overline{D}D: \qquad & -\frac{\sin\alpha}{\cos\beta} = -s_{\beta+\alpha} + c_{\beta+\alpha}\tan\beta\,, \\ h\overline{U}U: \qquad & \frac{\cos\alpha}{\sin\beta} = \quad s_{\beta+\alpha} + c_{\beta+\alpha}\cot\beta\,. \end{aligned}$$

Thus, the wrong-sign $h\overline{D}D$ Yukawa coupling actually corresponds to $s_{\beta+\alpha} = 1$. Indeed, one can check that (without approximation),

$$s_{\beta+\alpha} - s_{\beta-\alpha} = 2(1-\epsilon)\cos^2\beta\,,$$

which shows that the regime of the wrong-sign $h\overline{D}D$ Yukawa is consistent with a SM-like h for $\tan\beta \gg 1$.

Likewise, the wrong sign $h\overline{U}U$ coupling corresponds to $s_{\beta+\alpha} = -1$. Defining,

$$s_{\beta-\alpha} + c_{\beta-\alpha} \cot\beta = -1 + \epsilon' \,,$$

which yields

$$\cot\beta = \frac{-s_{\beta-\alpha} - 1 + \epsilon'}{c_{\beta-\alpha}} \gg 1 \,,$$

again under the assumption that the hVV coupling is SM-like. However, this case requires large $\cot\beta$, which would lead to non-perturbative behavior in the couplings of H, A and $H^{\pm}$ to top-quarks at scales far below the Planck scale.

Consequently, it is theoretically (and phenomenologically) desirable to assume that $(m_t/v)\cot\beta \lesssim 1$ and $(m_b/v)\tan\beta \lesssim 1$ in which case,

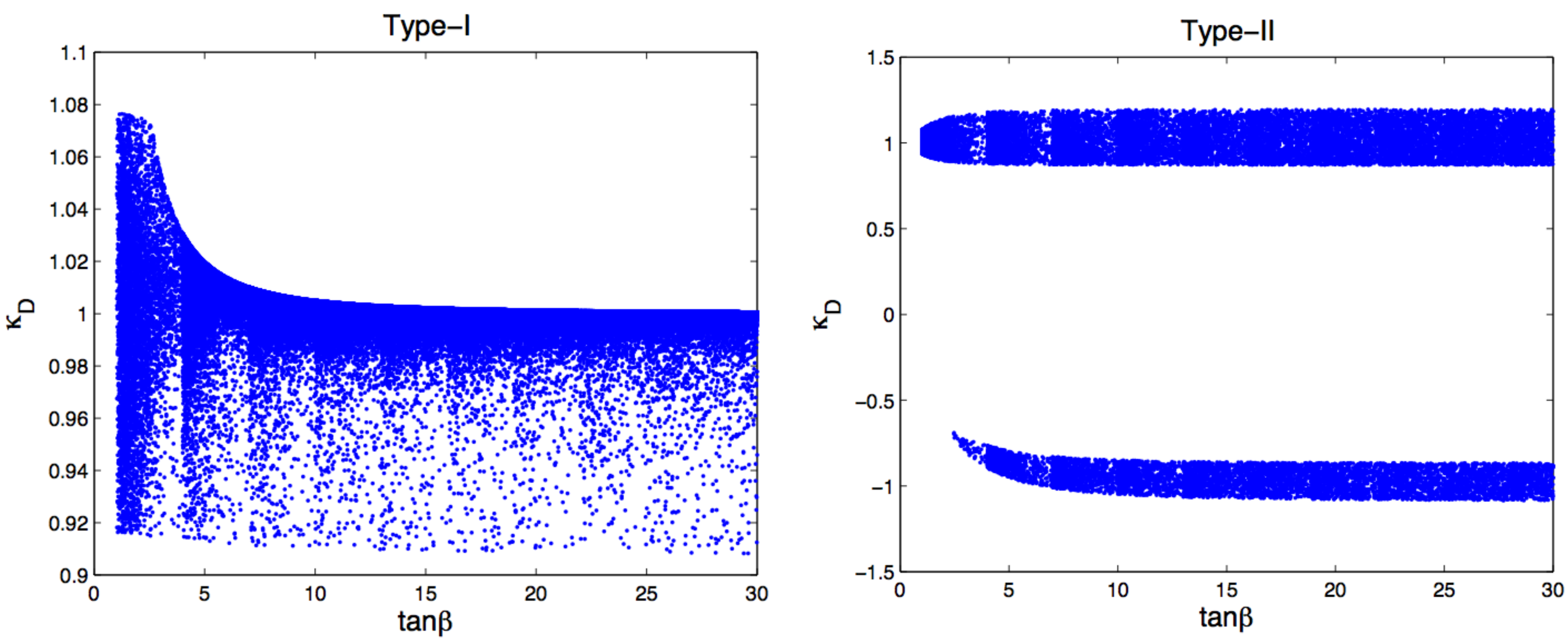
$$1 \lesssim \tan\beta \lesssim 50 \,.$$

Thus, the wrong-sign $h\overline{U}U$ coupling is not viable in a Type-II 2HDM. In the Type-I 2HDM, the couplings of h to both $\overline{U}U$ and $\overline{D}D$ are given by the Type-II $h\overline{U}U$ coupling. That is, neither a wrong sign $h\overline{U}U$ nor $h\overline{D}D$ coupling is viable in a Type-I 2HDM.

We have scanned the 2HDM parameter space, imposing theoretical constraints, direct LHC experimental constraints, and indirect constraints (from precision electroweak fits, B physics observables, and R_b). The latter requires that $m_{H^\pm} \gtrsim 340$ GeV in the Type-II 2HDM.

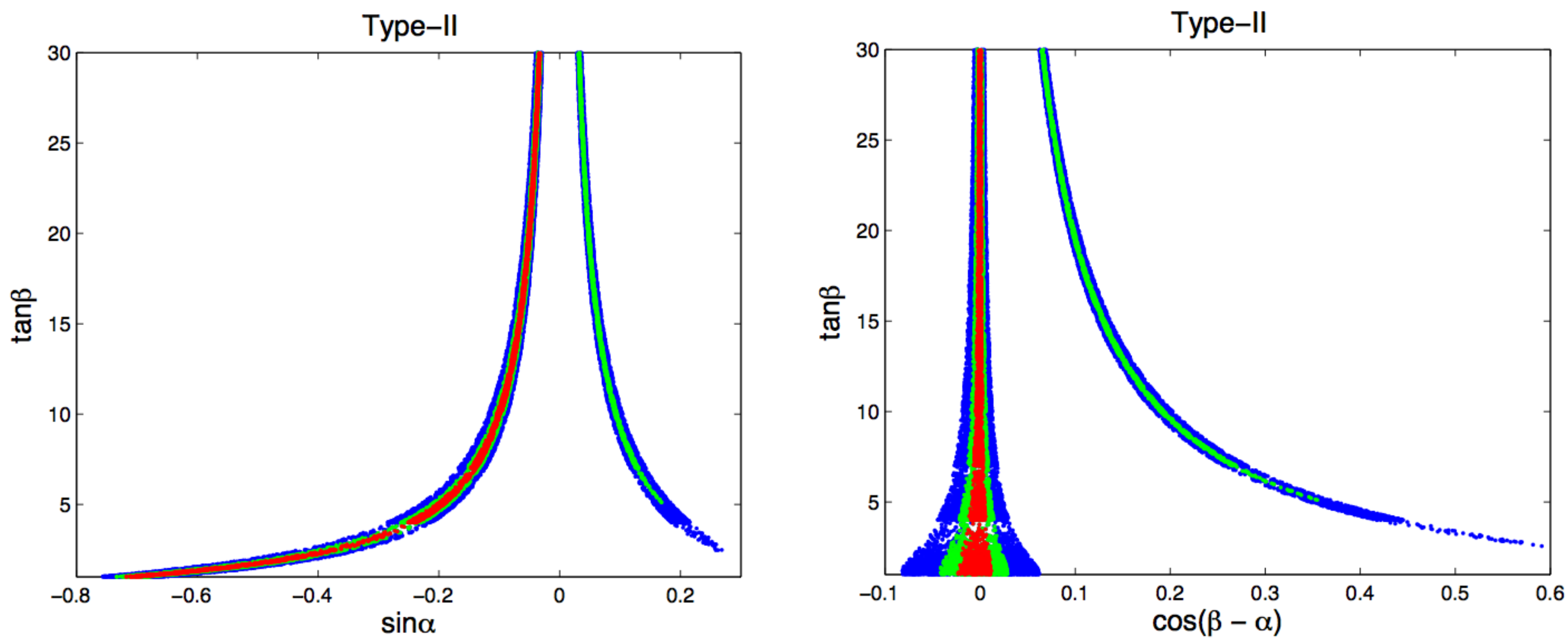
Given a final state f resulting from Higgs decay, we define

$$\mu_f^h(\mathrm{LHC}) = \frac{\sigma^{\mathrm{2HDM}}(pp \to h)\, BR^{\mathrm{2HDM}}(h \to f)}{\sigma^{\mathrm{SM}}(pp \to h_{\mathrm{SM}})\, BR(h_{\mathrm{SM}} \to f)}\,.$$

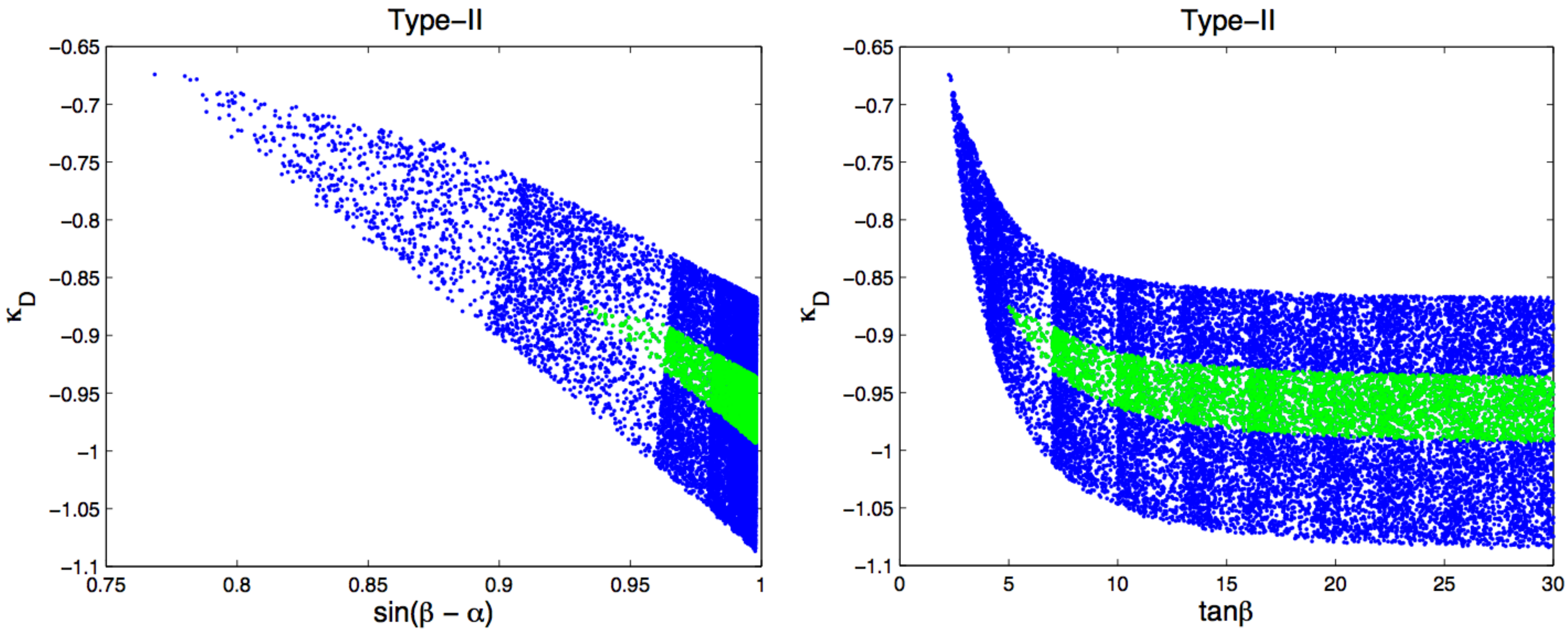


Ratio of the $h\overline{D}D$ coupling [κ_D] in the 2HDM relative to the SM vs. $\tan\beta$. All $\mu_f^h(\mathrm{LHC})$ are within 20% of the SM value.

Our baseline will be to require that the $\mu^h_f(\mathrm{LHC})$ for final states $f = WW$, ZZ, $b\bar{b}$, $\gamma\gamma$ and $\tau^+\tau^-$ are each consistent with unity within 20% (blue), roughly the precision of the current data. We then examine the consequences of taking all the $\mu^h_f(\mathrm{LHC})$ be within 10% (green) or 5% (red) of the SM prediction.



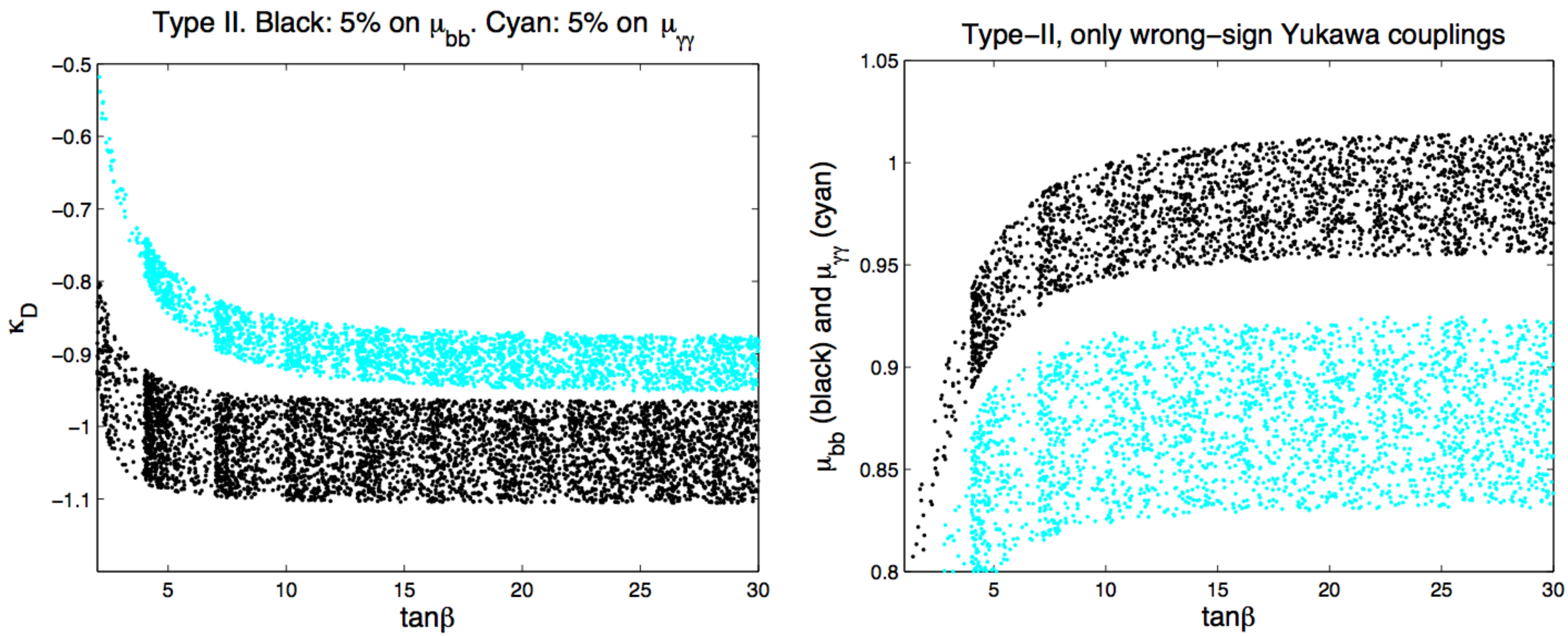
Points in the left branch correspond to $s_{\beta-\alpha} \sim 1$ and $\kappa_D > 0$. Points in the right branch correspond to $s_{\beta+\alpha} \sim 1$ and $\kappa_D < 0$. The absence of a red region in the latter indicates that a precision in the Higgs data at the 5% level is sufficient to rule out the wrong-sign $h\overline{D}D$ Yukawa regime.



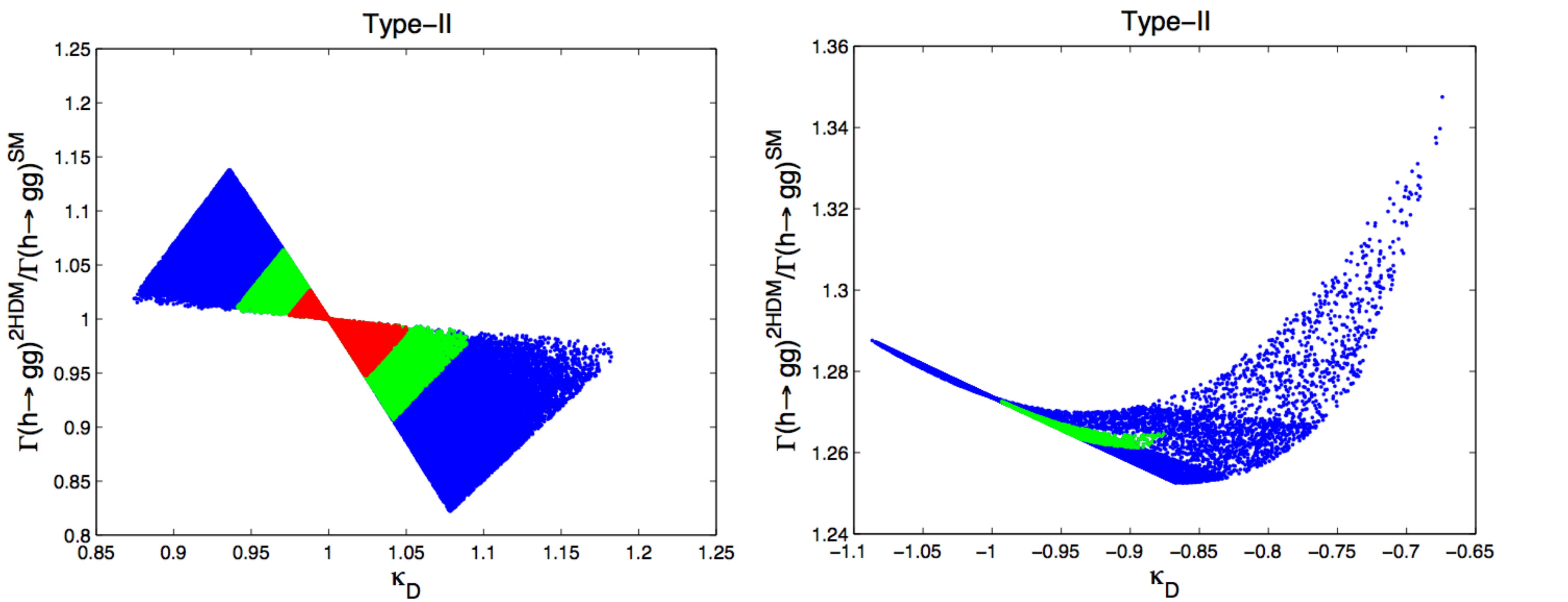
The Yukawa coupling ratio $\kappa_D = h_D^{2HDM}/h_D^{SM}$ with all $\mu_f^h(\mathrm{LHC})$ within 20% (blue) and 10% (green) of their SM values. If one demands consistency at the 5% level, no points survive.

As the Higgs data requires h to be more SM-like (and $s_{\beta-\alpha}$ is pushed closer to 1), the value of $\tan\beta$ required to achieve the wrong-sign $h\overline{D}D$ coupling becomes larger and larger, and $|\kappa_D|$ is forced to be closer to 1.

The main effects of the wrong-sign $h\overline{D}D$ coupling is to modify the hgg and $h\gamma\gamma$ loop amplitudes due to the interference of the b-quark loop with the t-quark loop (and the W loop in $h \to \gamma\gamma$). In addition, a non-decoupling $H^\pm$ contribution can reduce the partial width of $h \to \gamma\gamma$ by as much as 10%.

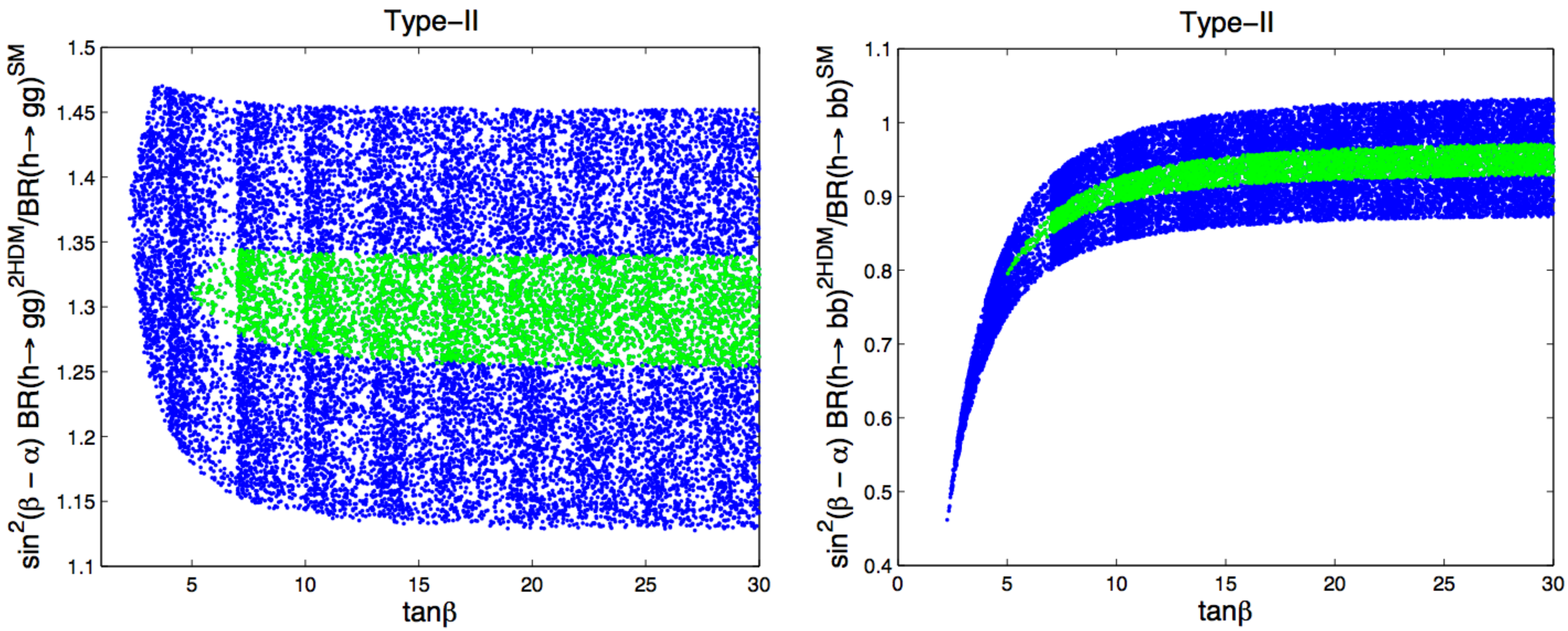


For points where $\mu^h_{WW,ZZ,bb}(\mathrm{LHC})$ are within 5% of the SM value of 1, $\mu^h_{\gamma\gamma}(\mathrm{LHC})$ is always more than 7–8% below unity, implying that 5% accuracy for this channel would exclude the $\kappa_D < 0$ branch. Thus, it is the suppression of the $\gamma\gamma$ final state that is key to ruling out $\kappa_D < 0$ at the LHC.



$\Gamma(h \to gg)^{2HDM}/\Gamma(h_{\rm SM} \to gg)$ as a function of $\kappa_D = h_D^{2HDM}/h_D^{SM}$ with all $\mu_f^h(\rm LHC)$ within 20% (blue), 10% (green) and 5% (red) of their SM values. Left panel: $\sin\alpha < 0$. Right panel: $\sin\alpha > 0$.

Remarkably, despite the large deviation in the $h \to gg$ partial width in the wrong-sign $h\overline{D}D$ coupling regime, the impact on $\sigma(gg \to h)$ is significantly less due to NLO and NNLO effects. Indeed, M. Spria finds $\sigma(gg \to h)_{\rm NNLO}/\sigma(gg \to h_{\rm SM})_{\rm NNLO} \simeq 1.06$ while the ratio of partial widths, $\Gamma(h \to gg)/\Gamma(h_{\rm SM} \to gg)$ does not suffer any significant change going from leading order to NNLO.



All $\mu_f^h(\mathrm{LHC})$ are taken within 20% of the SM values for the blue points and 10% for the green points, with $\kappa_D < 0$.

The ILC can probe $\mathrm{BR}(h \to gg)$ more easily and directly using the process $e^+e^- \to Zh \to Zgg$. The left panel shows the quantity

$$\mu_{gg}^h(\mathrm{ILC}) = \frac{\sigma(e^+e^- \to Zh)\,\mathrm{BR}(h \to gg)}{\sigma^{\mathrm{SM}}(e^+e^- \to Zh)\,\mathrm{BR}(h_{\mathrm{SM}} \to gg)}$$

The right panel shows the analogous quantity $\mu_{bb}^h(\mathrm{ILC})$. The expected precision of ILC Higgs couplings would exclude all gg points and all bb green points above.

Wrong-sign $h\overline{D}D$ coupling and the MSSM Higgs sector

In the MSSM, $Z_6 = -\frac{1}{4}(g^2 + g'^{\,2})\sin 2\beta\cos 2\beta$. Hence at tree-level in the decoupling limit,

$$c_{\beta-\alpha}\tan\beta \simeq \frac{2m_Z^2\sin^2\beta\cos 2\beta}{m_A^2} \ll 1\,,$$

for *all* values of $\tan\beta$. In particular, for $\tan\beta \gg 1$, one can never have $c_{\beta-\alpha}\tan\beta \sim \mathcal{O}(1)$ in the decoupling regime. Thus one cannot achieve the wrong-sign $h\overline{D}D$ Yukawa coupling in the region of the tree-level MSSM Higgs sector parameter space where the hVV coupling is SM-like.

Including radiative corrections (which are required to be significant in order to explain the observed Higgs mass of 126 GeV), we find that at large $\tan\beta$, the loop corrections to $c_{\beta-\alpha}$ can dominate over its tree-level value. It was just barely possible to achieve a wrong sign $h\overline{D}D$ coupling for somewhat extreme parameter choices. However, the ATLAS and CMS bounds in the m_A–$\tan\beta$ plane obtained in SUSY-Higgs searches seem to rule out this possibility.

Conclusions

- The initial Higgs data suggest that the Higgs boson is SM-like.
- Taking the Type-II 2HDM in the decoupling/alignment limit as a framework for new Higgs physics beyond the SM, the phenomenon of *delayed decoupling* permits a significant deviation of the $h\overline{D}D$ coupling from the SM even if all other observed Higgs couplings are SM-like.
- Indeed, it is even possible that the magnitude of the $h\overline{D}D$ coupling is close to its SM value but its sign is negative relative to the hVV coupling.
- The wrong-sign $h\overline{D}D$ coupling cannot be ruled out with present data. In future Higgs studies at the LHC, it is possible to rule out the wrong-sign couplings with Higgs precision measurements at the 5% level.
- At the ILC, the wrong-sign $h\overline{D}D$ coupling can be excluded using precision Higgs couplings to gg and/or bb (assuming in the latter case a 10% precision in the LHC Higgs couplings).