Decoupling and Alignment in Light of the Higgs Data

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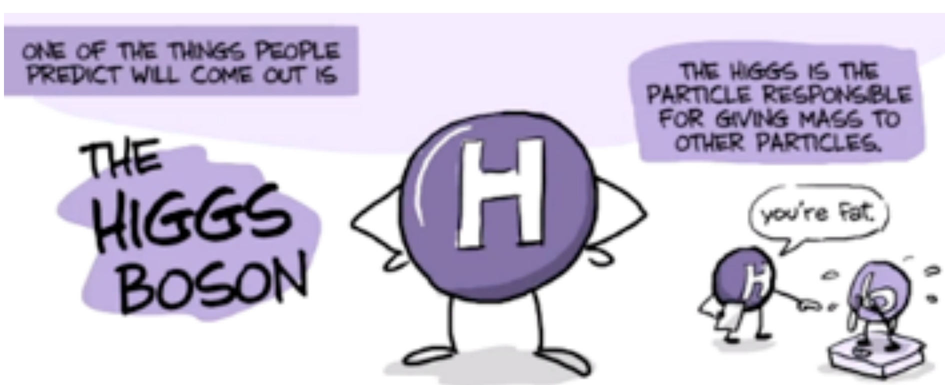
Pi Day, 2014
Bay Area Particle Physics Seminar
San Francisco State Univ.



Outline

I. Introduction

- Snapshot of the LHC Higgs data
- Suggestions of a SM-like Higgs boson

II. Decoupling and alignment limits of the 2HDM

- Tree-level considerations
- Loop corrections

III. Application to the MSSM Higgs sector

- Is the alignment limit allowed by the data?

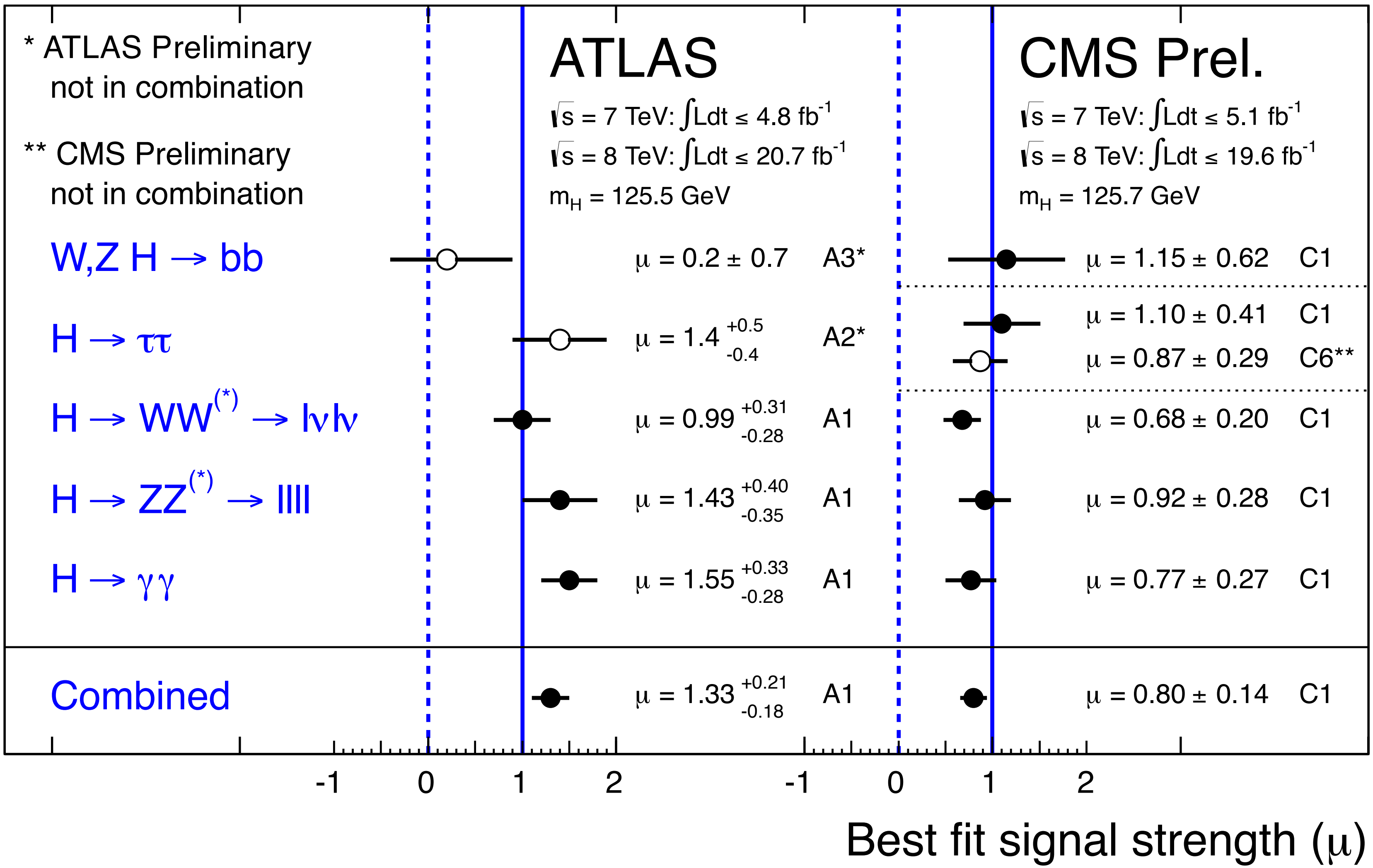
IV. The wrong-sign Yukawa coupling regime

- Can this be ruled out at the LHC?

The Higgs boson discovered on the 4th of July 2012

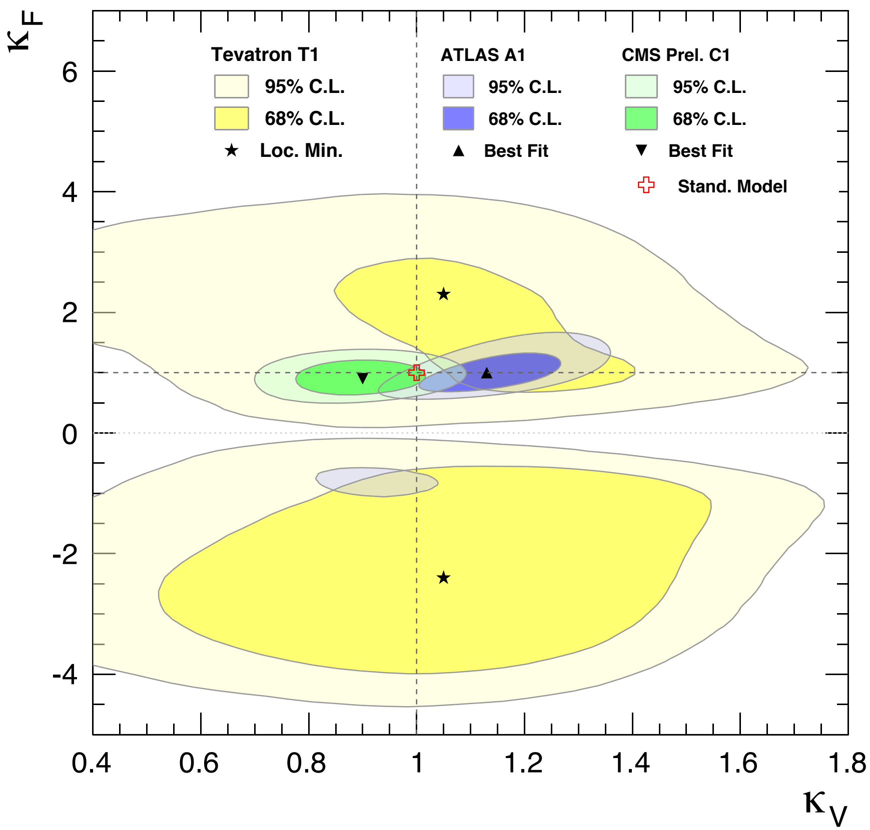
- Is it the Higgs boson of the Standard Model?
- Is it the first scalar state of an enlarged Higgs sector?
- Is it a premonition for new physics beyond the Standard Model at the TeV scale?

Let’s look at a snapshop of the current LHC Higgs data.

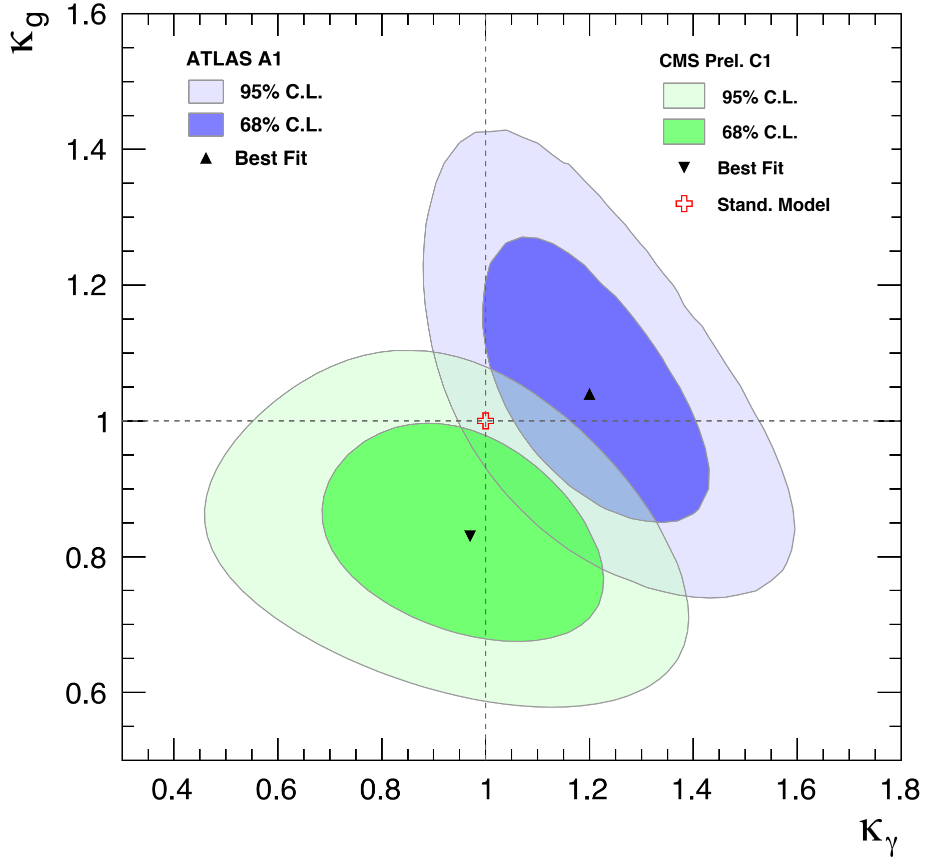


The signal strengths μ measured by the ATLAS and CMS experiments in the five principal channels and their combination. It should be noted that the ATLAS combination only includes the bosonic $\gamma\gamma$, ZZ and WW channels. [Taken from the 2013 PDG Higgs review.]

Even with the limited Higgs data set, it is fair to say that this is a Standard Model—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 (κ_g,κ_γ) plane for the Higgs data from ATLAS and CMS.

Any theory that introduces new physics beyond the Standard Model (SM) must contain a SM-like Higgs boson. This constrains all future model building.

In this talk I will exhibit how this constraint impacts the two-Higgs doublet Model (2HDM), which will be a stand-in for a general extended Higgs sector or a supersymmetric extension of the SM, which requires at least two Higgs doublet fields.

The 2HDM with a SM-like Higgs boson

Typically, none of the scalar states of the 2HDM will resemble a SM-Higgs boson. However, a SM-like Higgs boson ($h_{\rm SM}$) can arise in two different ways:

- **The decoupling limit** (Haber and Nir 1990, Gunion and Haber 2003)

All but one of the scalar states (h) are very heavy ($M \gg m_h$). Integrating out the heavy states below the mass scale M yields an effective one-Higgs-doublet theory—i.e. the Standard Model, and $h \simeq h_{\rm SM}$.

- **The alignment limit** (Craig, Galloway and Thomas 2013, Haber 2013)

In the Higgs basis $\{H_1\,,\,H_2\}$, the vev $v = 246$ GeV resides completely in the neutral component of one of the Higgs doublets, H_1. In the limit where the mixing between H_1 and H_2 in the mass matrix goes to zero, one of the neutral mass eigenstates aligns with ${\rm Re}(H_1^0 - v)$. This state h is nearly indistinguishable from the SM Higgs boson.

Example: 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 $v^2 \equiv v_1^2 + v_2^2 = (246~\text{GeV})^2$. 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 Higgs basis of the CP-conserving softly-broken $\mathbb{Z}_2$–symmetric 2HDM

Assume m_{12}^2, λ_5 real and a CP-conserving vacuum. Define Higgs basis fields,

$$H_1 = \begin{pmatrix} H_1^+ \\ H_1^0 \end{pmatrix} \equiv \frac{v_1\Phi_1 + v_2\Phi_2}{v}\,, \qquad H_2 = \begin{pmatrix} H_2^+ \\ H_2^0 \end{pmatrix} \equiv \frac{-v_2\Phi_1 + v_1\Phi_2}{v}\,,$$

so that $\langle H_1^0\rangle = v/\sqrt{2}$ and $\langle H_2^0\rangle = 0$. The Higgs basis is uniquely defined up to $H_2 \to -H_2$. In the Higgs basis, the scalar potential is given by:

$$\begin{aligned}\mathcal{V} = {} & Y_1 H_1^\dagger H_1 + Y_2 H_2^\dagger H_2 + [Y_3 H_1^\dagger H_2 + \text{h.c.}] \\ & + \tfrac{1}{2}Z_1(H_1^\dagger H_1)^2 + \tfrac{1}{2}Z_2(H_2^\dagger H_2)^2 + Z_3(H_1^\dagger H_1)(H_2^\dagger H_2) + Z_4(H_1^\dagger H_2)(H_2^\dagger H_1) \\ & + \left\{\tfrac{1}{2}Z_5(H_1^\dagger H_2)^2 + \big[Z_6(H_1^\dagger H_1) + Z_7(H_2^\dagger H_2)\big] H_1^\dagger H_2 + \text{h.c.}\right\}\,.\end{aligned}$$

Scalar potential minimum conditions are:

$$Y_1 = -\tfrac{1}{2}Z_1 v^2\,, \qquad Y_3 = -\tfrac{1}{2}Z_6 v^2\,,$$

leaving Y_2 as the only free squared-mass parameter of the model.

We define $\tan\beta = v_2/v_1$, $c_\beta \equiv \cos\beta$, $s_\beta \equiv \sin\beta$, etc.

$$Z_1 \equiv \lambda_1 c_\beta^4 + \lambda_2 s_\beta^4 + 2(\lambda_3 + \lambda_4 + \lambda_5) s_\beta^2 c_\beta^2 \,,$$

$$Z_2 \equiv \lambda_1 s_\beta^4 + \lambda_2 c_\beta^4 + 2(\lambda_3 + \lambda_4 + \lambda_5) s_\beta^2 c_\beta^2 \,,$$

$$Z_i \equiv (\lambda_1 + \lambda_2 - 2\lambda_3 - 2\lambda_4 - 2\lambda_5) s_\beta^2 c_\beta^2 + \lambda_i \,, \qquad \text{for } i = 3, 4, 5 \,,$$

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

$$Z_7 \equiv -s_\beta c_\beta \left[\lambda_1 s_\beta^2 - \lambda_2 c_\beta^2 + (\lambda_3 + \lambda_4 + \lambda_5) c_{2\beta}\right] \,.$$

Mass eigenstates: CP-even scalars: h and H (with Higgs mixing angle α), CP-odd scalars: A, charged Higgs pair: $H^\pm$. Some useful relations:

$$Z_1 v^2 = m_h^2 s_{\beta-\alpha}^2 + m_H^2 c_{\beta-\alpha}^2 \,,$$

$$Z_3 v^2 = 2(m_{H^\pm}^2 - Y_2) \,,$$

$$Z_4 v^2 = m_h^2 c_{\beta-\alpha}^2 + m_H^2 s_{\beta-\alpha}^2 + m_A^2 - 2m_{H^\pm}^2$$

$$Z_5 v^2 = m_h^2 c_{\beta-\alpha}^2 + m_H^2 s_{\beta-\alpha}^2 - m_A^2$$

$$Z_6 v^2 = -(m_H^2 - m_h^2) s_{\beta-\alpha} c_{\beta-\alpha} \,.$$

Decoupling and alignment limits of the 2HDM

Adopt a convention where $0 \leq \beta \leq \frac{1}{2}\pi$ and $0 \leq \beta - \alpha \leq \pi$. 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:

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

where $Z_1/(4\pi)$, $Z_6/(4\pi) \lesssim 1$ (tree-level unitarity limit), we see that

- **decoupling limit:** $m_H \gg m_h$ (i.e., $Y_2 \gg v$) $\Longrightarrow m_H \sim m_A \sim m_{H^\pm} \gg v$
- **alignment limit:** $|Z_6| \ll 1$. Then, H, A, $H^\pm$ need not be heavy (and $m_h^2 \simeq Z_1 v^2$)

Since

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

it follows that H is SM-like in the limit of $s_{\beta-\alpha} \to 0$. This is not compatible with the decoupling limit, but is an allowed possibility in the alignment limit. This case is not completely ruled out by Higgs data. But, henceforth, we focus on the case of $|c_{\beta-\alpha}| \ll 1$, in which case $h \simeq h_{\rm SM}$.

In the decoupling or alignment limits, all tree-level couplings of h approach their SM values. Consider the Type-II Yukawa coupling to up-type and down-type 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, in the softly broken $\mathbb{Z}_2$–symmetric 2HDM,

$$g_{hhh} = \frac{-3v}{s_\beta^2 c_\beta^2}\left[s_\beta c_\beta (c_\beta c_\alpha^3 - s_\beta s_\alpha^3) m_h^2 - c_{\beta-\alpha}^2 c_{\beta+\alpha} m_{12}^2\right],$$

and it is easy to check that for $s_{\beta-\alpha} = 1$, we have $c_\alpha = s_\beta$ and $s_\alpha = -c_\beta$. Hence, in the decoupling and alignment limits,

$$g_{hhh} \to g_{hhh}^{\rm SM} = -3vm_h^2\,.$$

In a more general (CP-conserving) 2HDM,

$$\begin{aligned} g_{hhh} &= -3v\big[Z_1 s_{\beta-\alpha}^3 + 3Z_6 c_{\beta-\alpha} s_{\beta-\alpha}^2 + (Z_3+Z_4+Z_5) s_{\beta-\alpha} c_{\beta-\alpha}^2 + Z_7 c_{\beta-\alpha}^3\big]\,, \\ &= g_{hhh}^{\rm SM}\big[1 + 3(Z_6/Z_1) c_{\beta-\alpha} + \mathcal{O}(c_{\beta-\alpha}^2)\big]\,. \end{aligned}$$

Since $c_{\beta-\alpha} \simeq -Z_6 v^2/(m_H^2 - m_h^2)$, we see that the approach to the alignment limit is *faster* than to the decoupling limit (and similarly for the $hhhh$ coupling).

The decoupling and alignment limits beyond tree level

- **decoupling limit:** The corrections to the exchange of H, A, and $H^{\pm}$ is suppressed by terms of $\mathcal{O}(v^2/M^2)$, where $M \sim m_H \sim m_A \sim m_{H^{\pm}}$, relative to the SM radiative corrections.

- **alignment limit:** Since the masses of H, A, and $H^{\pm}$ need not be heavy, loops mediated by these particles can compete with the SM radiative corrections.

Thus, we have found two instances where the decoupling and alignment limits can be distinguished in principle. Of course, the primary technique for distinguishing between these two limiting cases is to discover the some of the non-minimal Higgs states (H, A, and $H^{\pm}$), whose masses may not be significantly larger than m_h.

example: the $H^\pm$ loop contribution to $h \to \gamma\gamma$

In a general CP-conserving 2HDM, $g_{hH^+H^-} = -v\big[Z_3 s_{\beta-\alpha} + Z_7 c_{\beta-\alpha}\big] \sim \mathcal{O}(v)$. Specializing to 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 $m_A^2 - m_{H^\pm}^2 = \frac{1}{2}v^2(\lambda_5 - \lambda_4)$, and $m_A^2 c_{\beta-\alpha} \sim \mathcal{O}(v^2)$ in the decoupling limit, we see that the above expression is consistent with $g_{hH^+H^-} \sim \mathcal{O}(v)$. But, there exists a regime where Z_3 and Z_7 are approaching 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.

The alignment limit of the MSSM Higgs sector

The Higgs sector of the SM is a softly-broken Z_2–symmetric 2HDM with additional relations imposed by SUSY on the quartic Higgs potential parameters. In terms of the Z_i, we have:

$$Z_1 = Z_2 = \tfrac{1}{4}(g^2 + g'^2)\cos^2 2\beta\,, \qquad Z_3 = Z_5 + \tfrac{1}{4}(g^2 - g'^2)\,, \qquad Z_4 = Z_5 - \tfrac{1}{2}g^2\,,$$

$$Z_5 = \tfrac{1}{4}(g^2 + g'^2)\sin^2 2\beta\,, \qquad Z_7 = -Z_6 = \tfrac{1}{4}(g^2 + g'^2)\sin 2\beta\cos 2\beta\,,$$

There is no phenomenologically relevant alignment limit at tree-level since $Z_6 v^2 = \frac{1}{2}m_Z^2 \sin 4\beta$ is not that much smaller than m_h^2 for sensible values of $\tan\beta$. But at one-loop order, each of the Z_i receive radiative corrections, ΔZ_i. Non-decoupling contributions exist (with $\tan\beta$–enhancements), since below $M_{\rm SUSY}$ the low-energy effective theory is a general 2HDM. Is it possible to have

$$\tfrac{1}{4}(g^2 + g'^2)\sin 2\beta\cos 2\beta + \Delta Z_6 \simeq 0\,,$$

for a suitably chosen $\tan\beta$?

The following approximate expressions were obtained by M. Carena, I. Low, N.R. Shah and C.E.M. Wagner, arXiv:1310.2248,

$$\tan\beta \simeq \frac{m_h^2 + m_Z^2 - v^2(\Delta L_{11} + \Delta\tilde{L}_{12})}{v^2 \Delta L_{12}},$$

where

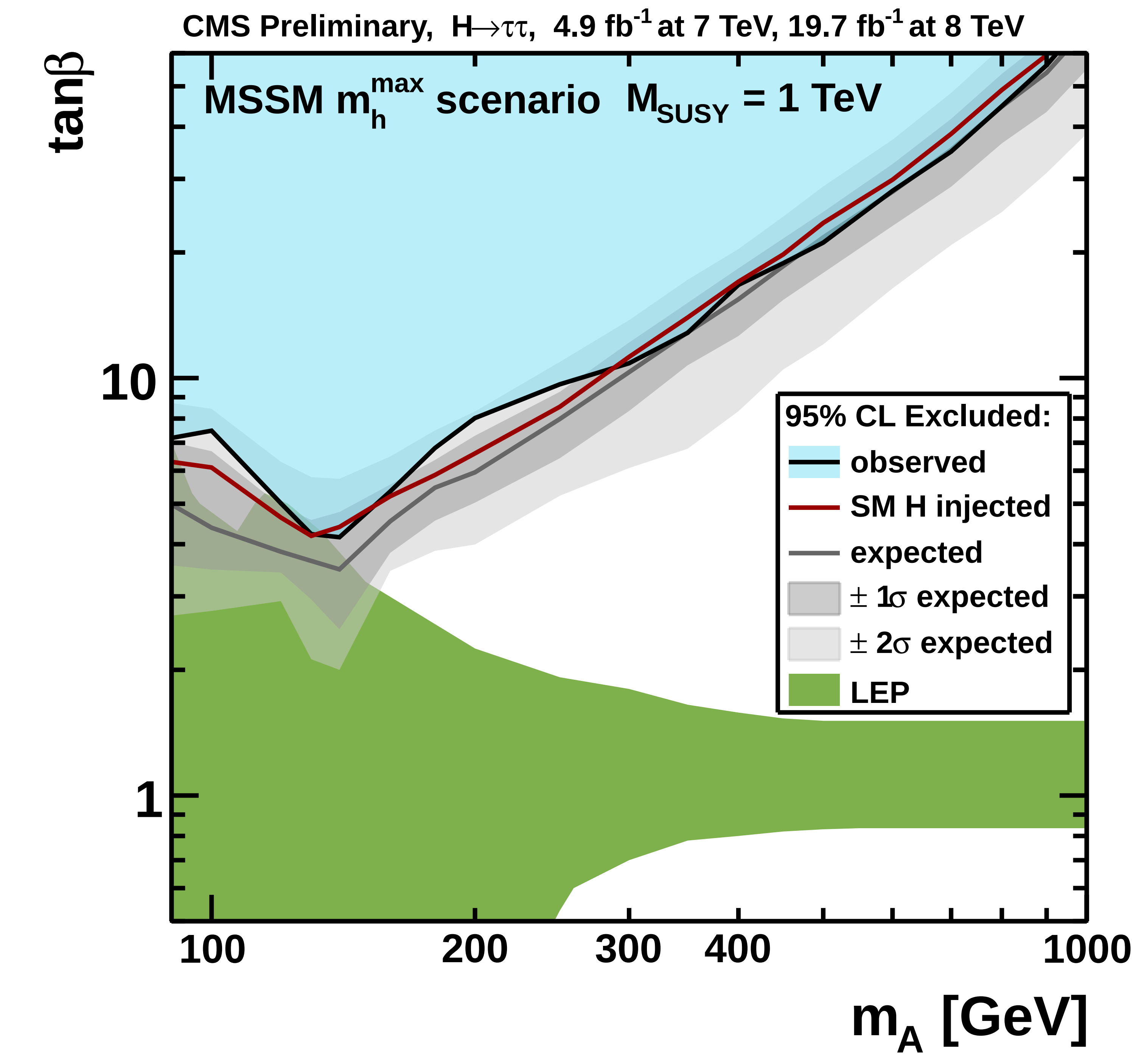
$$\Delta L_{12} \simeq \frac{1}{32\pi^2}\left[h_t^4 \frac{\mu A_t}{M_{\rm SUSY}^2}\left(\frac{A_t^2}{M_{\rm SUSY}^2} - 6\right) + h_b^4 \frac{\mu^3 A_b}{M_{\rm SUSY}^4}\right],$$

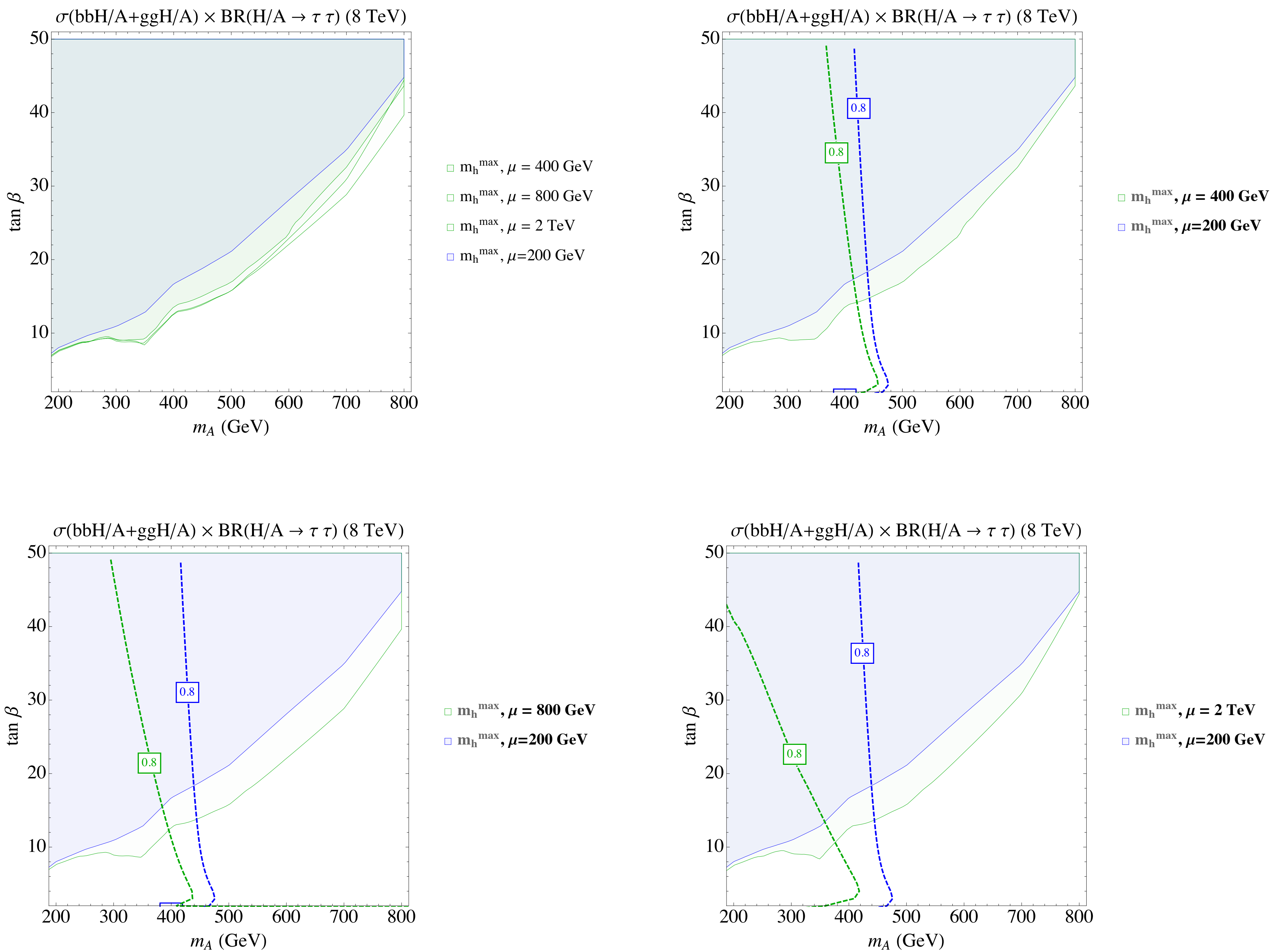
$$\Delta\tilde{L}_{12} + \Delta L_{11} \simeq \frac{3\ \mu^2}{16\pi^2 M_{\rm SUSY}^2}\left[h_t^4\left(1 - \frac{A_t^2}{2M_{\rm SUSY}^2}\right) + h_b^4\left(1 - \frac{A_b^2}{2M_{\rm SUSY}^2}\right)\right],$$

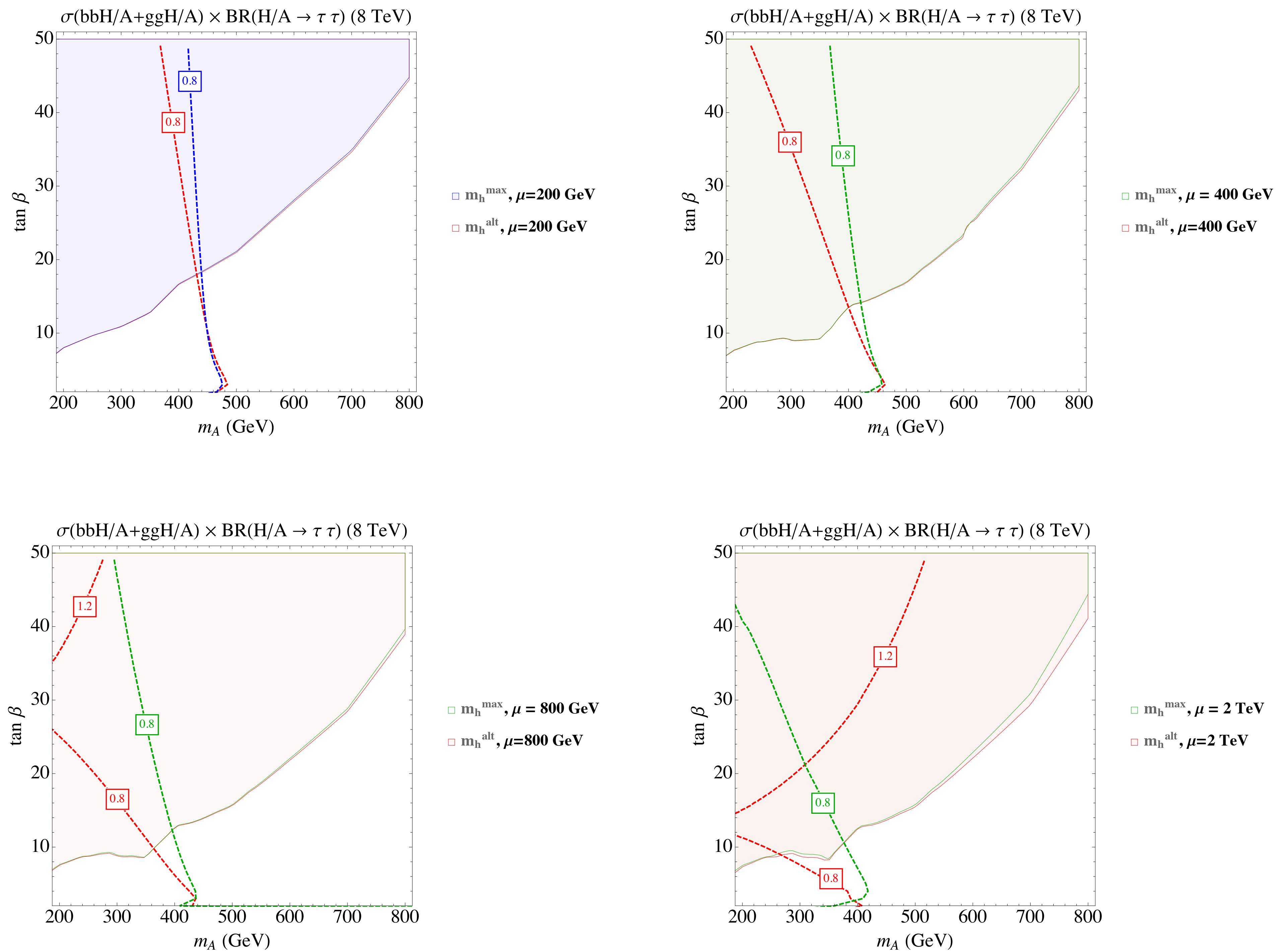
and the τ contributions have been omitted.

Can the MSSM alignment region be ruled out by LHC Higgs data?

Using recent data from the CMS collaboration, and working in collaboration with M. Carena, I. Low, N.R. Shah and C.E.M. Wagner, we have examined various MSSM Higgs scenarios and checked whether they survive the CMS limits.


CMS Preliminary, H→ττ, 4.9 fb-1 at 7 TeV, 19.7 fb-1 at 8 TeV
MSSM mhmax scenario MSUSY = 1 TeV
tanβ
10
1
100
200
300
400
1000
mA [GeV]
95% CL Excluded:
observed
SM H injected
expected
± 1σ expected
± 2σ expected
LEP


σ(bbH/A+ggH/A) × BR(H/A → τ τ) (8 TeV)
tan β
m_A (GeV)
m_h^{max}, μ = 400 GeV
m_h^{max}, μ = 800 GeV
m_h^{max}, μ = 2 TeV
m_h^{max}, μ=200 GeV
σ(bbH/A+ggH/A) × BR(H/A → τ τ) (8 TeV)
tan β
m_A (GeV)
0.8
0.8
m_h^{max}, μ = 400 GeV
m_h^{max}, μ=200 GeV
σ(bbH/A+ggH/A) × BR(H/A → τ τ) (8 TeV)
tan β
m_A (GeV)
0.8
0.8
m_h^{max}, μ = 800 GeV
m_h^{max}, μ=200 GeV
σ(bbH/A+ggH/A) × BR(H/A → τ τ) (8 TeV)
tan β
m_A (GeV)
0.8
0.8
m_h^{max}, μ = 2 TeV
m_h^{max}, μ=200 GeV



σ(bbH/A+ggH/A) × BR(H/A → τ τ) (8 TeV)
tan β
m_A (GeV)
0.8
0.8
m_h^max, μ=200 GeV
m_h^alt, μ=200 GeV
σ(bbH/A+ggH/A) × BR(H/A → τ τ) (8 TeV)
tan β
m_A (GeV)
0.8
0.8
m_h^max, μ = 400 GeV
m_h^alt, μ=400 GeV
σ(bbH/A+ggH/A) × BR(H/A → τ τ) (8 TeV)
tan β
m_A (GeV)
1.2
0.8
0.8
m_h^max, μ = 800 GeV
m_h^alt, μ=800 GeV
σ(bbH/A+ggH/A) × BR(H/A → τ τ) (8 TeV)
tan β
m_A (GeV)
1.2
0.8
0.8
m_h^max, μ = 2 TeV
m_h^alt, μ=2 TeV

Wrong-sign Yukawa couplings

Returning to the (non-SUSY) 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 (recall that $0 \leq \beta-\alpha \leq \pi$)

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

where we allow for a small error ϵ (the precision of the experimental measurement). For $\epsilon=0$, the 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. 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

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

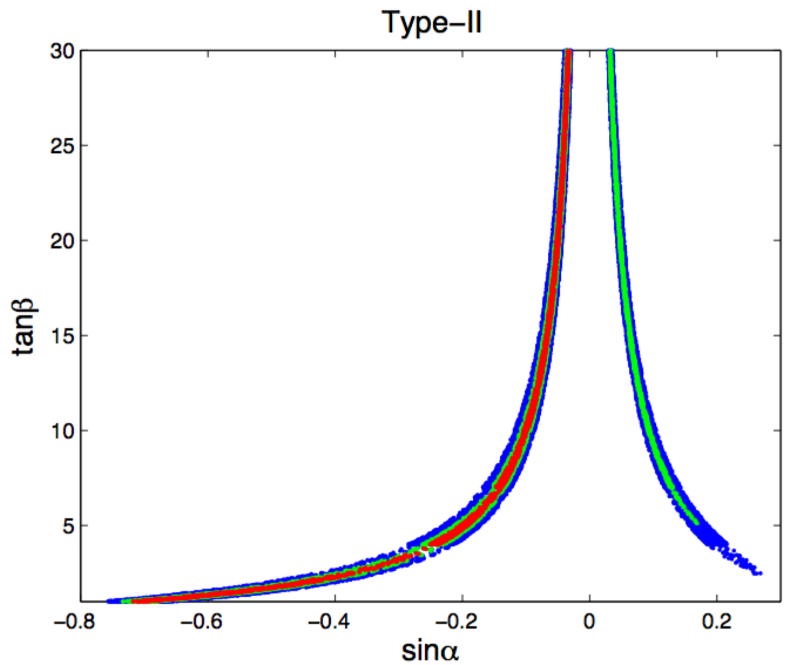
which shows that the regime of the wrong-sign $h\overline{D}D$ Yukawa is consistent with a SM-like h for $\tan\beta \gg 1$.

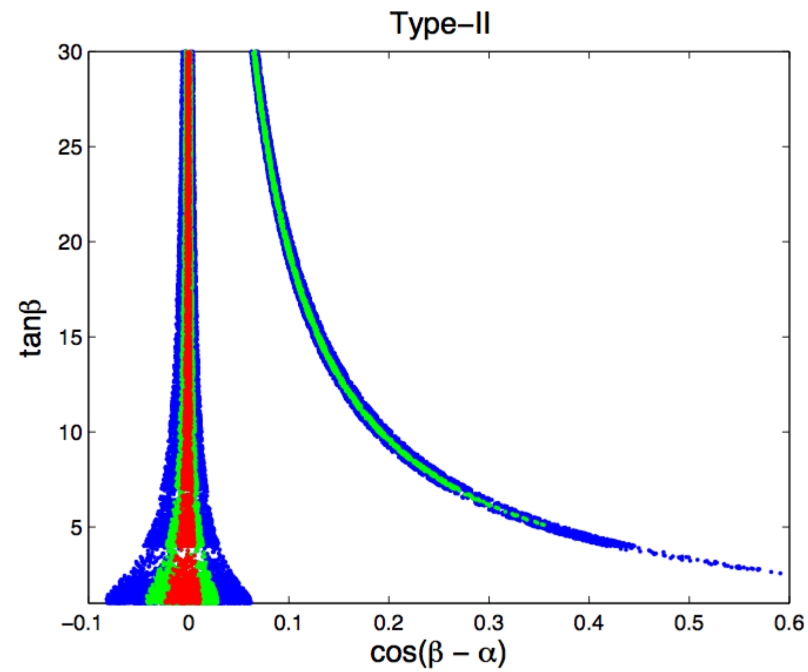
In collaboration with P. Ferreira, J.F. Gunion and R. Santos, we have scanned the 2HDM parameter space, imposing theoretical constraints, direct LHC experimental constraints, and indirect constraints (from precision electroweak fits, B physics observables, and R_b). The latter requires that $m_{H^\pm} \gtrsim 340$ GeV in the Type-II 2HDM.

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

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

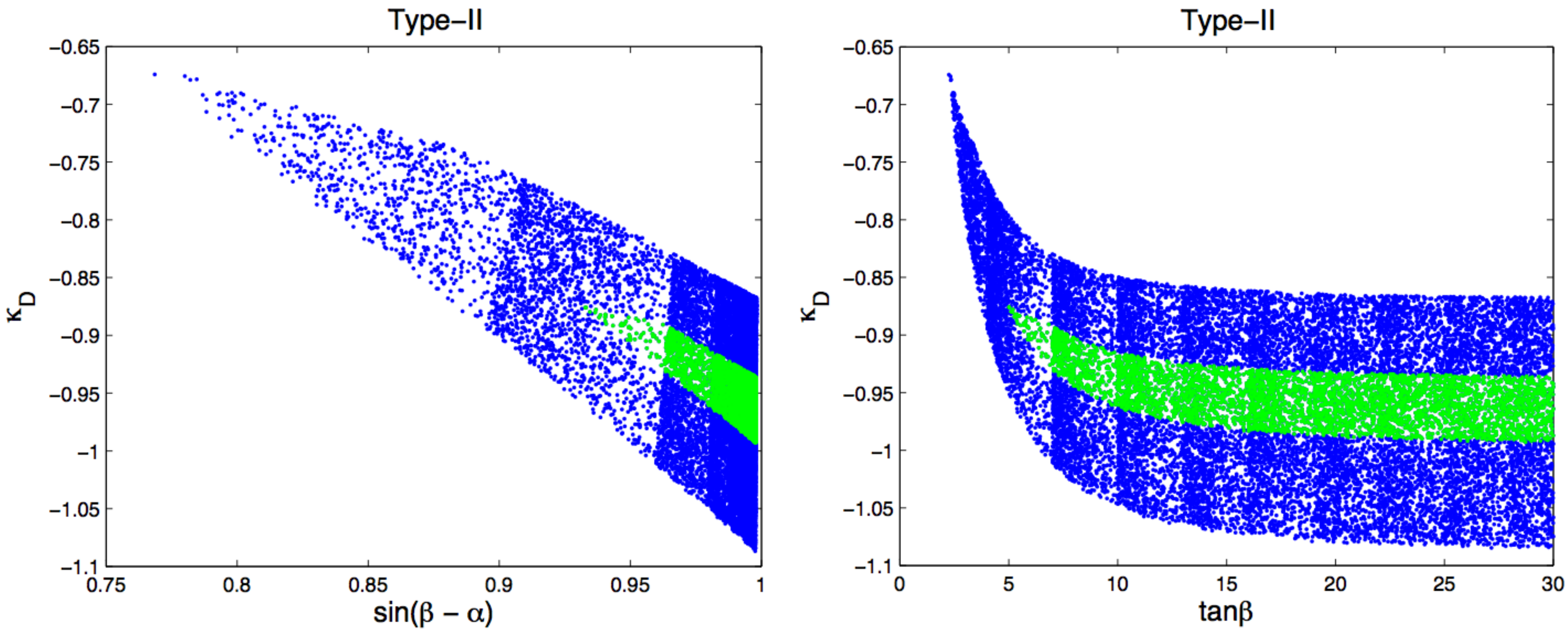
Our baseline will be to require that the $\mu_f^h(\mathrm{LHC})$ for final states $f = WW$, ZZ, $b\bar{b}$, $\gamma\gamma$ and $\tau^+\tau^-$ are each consistent with unity within 20% (blue), which is a rough approximation to the precision of current data. We will then examine the consequences of requiring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





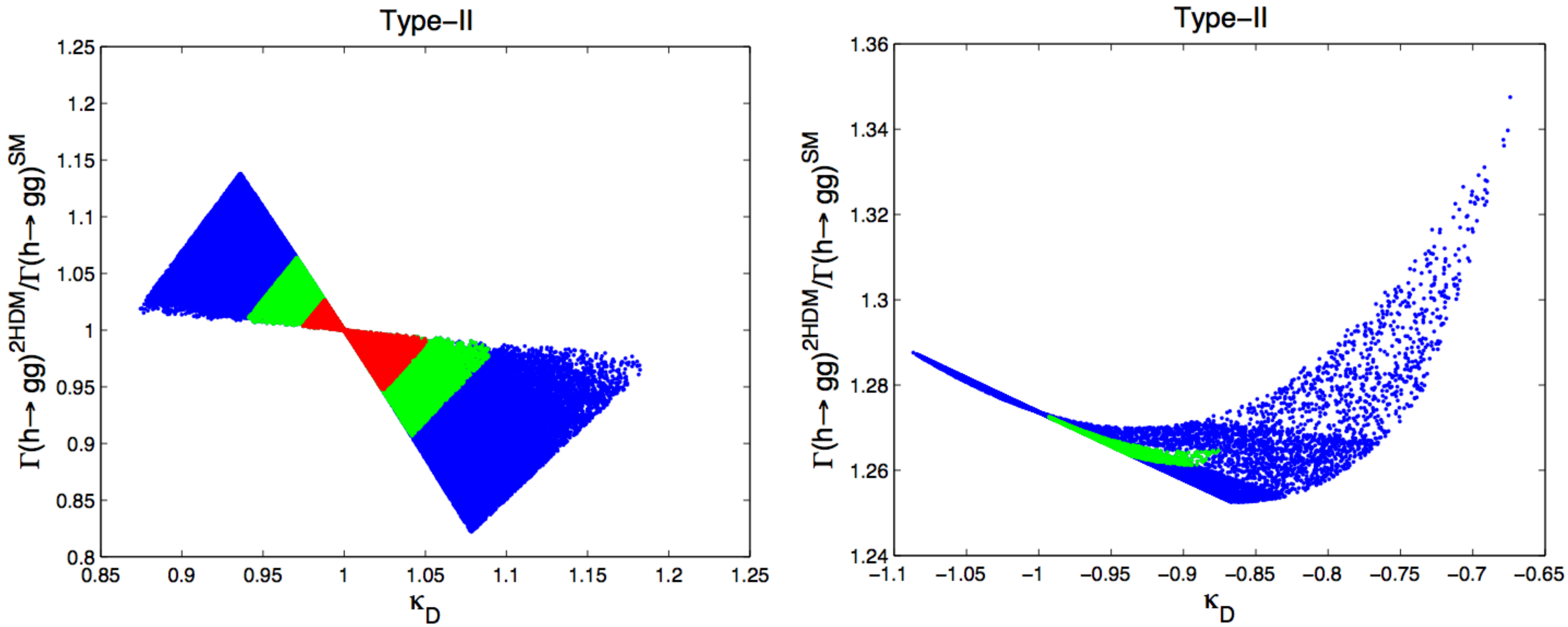
The main effects of the wrong-sign $h\overline{D}D$ coupling is to modify the hgg and $h\gamma\gamma$ loop amplitudes due to the interference of the b-quark loop with the t-quark loop (and the W loop in the case of $h \to \gamma\gamma$). In addition, the possibility of a contributing non-decoupling charged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

The absence of a red region for $\sin\alpha > 0$ (the wrong-sign $h\overline{D}D$ Yukawa regime) demonstrates that a precision in the Higgs data at the 5% level is sufficient to rule out this possibility.



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.



$\Gamma(h \to gg)^{2HDM}/\Gamma(h_{\rm SM} \to gg)$ 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.