Higgs Physics at Hadron Colliders (II)

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Outlook

The future

Pushing for new analysis (CP at the LHC)

- scalar vs. pseudoscalar components: $\tau\tau h$ and tth
- the bonus of an improved tth analysis
- decay of a scalar into two scalars of different masses

Corrections to Higgs decays

the example of the CP-conserving 2HDM

The past

Extended Scalars (Yellow Report 4)

CP-violation at the LHC

CP - what have ATLAS and CMS measured so far?

Correlations in the momentum distributions of leptons produced in the decays

$$h \to ZZ^* \to (\bar{l}_1 l_1)\ (\bar{l}_2 l_2)$$

$$h \to WW^* \to (l_1 n_1)\ (l_2 n_2)$$

S.Y. Choi, D.J. Miller, M.M. Muhlleitner and P.M. Zerwas, Phys. Lett. B 553, 61 (2003).

C. P. Buszello, I. Fleck, P. Marquard, J. J. van der Bij, Eur. Phys. J. C32, 209 (2004)

The results obtained from these studies can be applied to specific classes of models.

$$\mathcal{L}_{HZZ} \sim \kappa \frac{m_Z^2}{v} H Z^\mu Z_\mu + \frac{\alpha}{v} H Z^\mu \Box Z_\mu + \frac{\beta}{v} H Z^{\mu\nu} Z_{\mu\nu} + \frac{\gamma}{v} H Z^{\mu\nu} \tilde{Z}_{\mu\nu}$$

CP, the Higgs and the LHC

$$\mathcal{L}_{HZZ} \sim \kappa \frac{m_Z^2}{v} H Z^\mu Z_\mu + \frac{\alpha}{v} H Z^\mu \Box Z_\mu + \frac{\beta}{v} H Z^{\mu\nu} Z_{\mu\nu} + \frac{\gamma}{v} H Z^{\mu\nu} \tilde{Z}_{\mu\nu}$$

Obtained 95% CL intervals on the *allowed* couplings of alternative, not SM-like, spin-zero states with respect to those of the SM scalar state.

		α/κ	β/κ	γ/κ
$H \to ZZ \to 4l$	ATLAS	not tested	$[-2.5, 0.75]$	$[-0.95, 2.9]$
	CMS	$[-1.2, 1.5]$	$[-\infty, 0.69]$ $[1.9, 2.3]$	$[-2.2, 2.1]$
$H \to WW \to 2l2\nu$	ATLAS	not tested	$[-0.4, 0.85]$ $[1, 2.2]$	$[-5, 6]$
	CMS	$[-\infty, +\infty]$	$[-\infty, 0.71]$ $[1.2, +\infty]$	$[-\infty, +\infty]$
combined, assuming that ratios of "couplings" are the same for ZZ and WW	ATLAS	not tested	$[-0.63, 0.73]$	$[-0.83, 2.2]$
	CMS	$[-1.7, 1.6]$	$[-0.76, 0.58]$	$[-1.6, 1.5]$

α/κ, β/κ, γ/κ < 1-2

If CP(H)=1, hzz(WW) coupling is constant relative to the SM one,

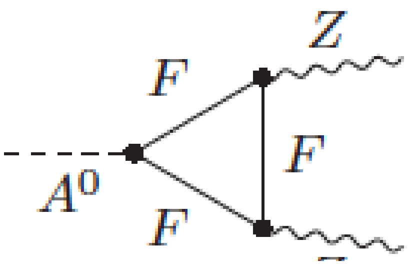
reverse not true!

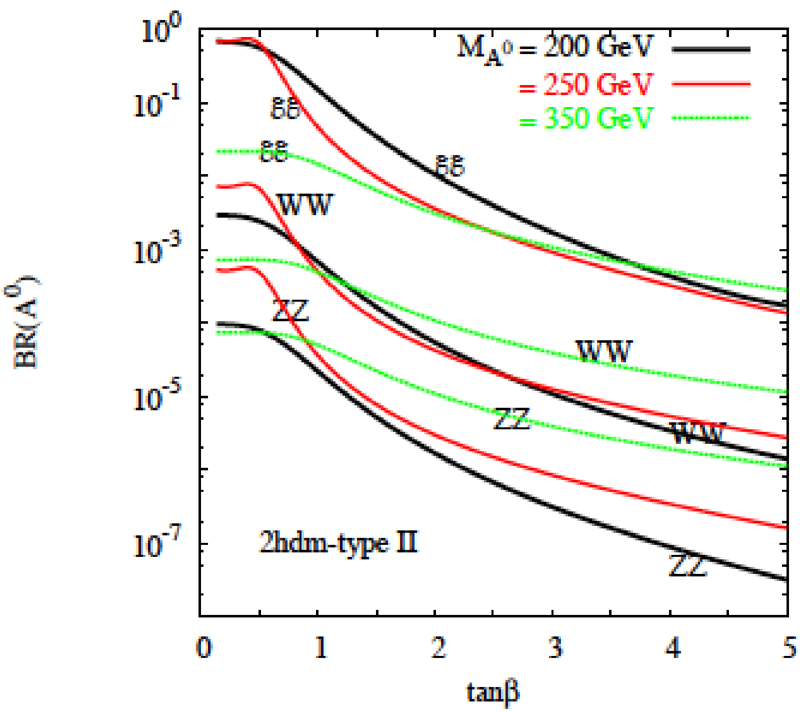
$$g_{C2HDM}^{hVV} = \cos(\alpha_2)\cos(\beta - \alpha_1)\, g_{SM}^{hVV}$$

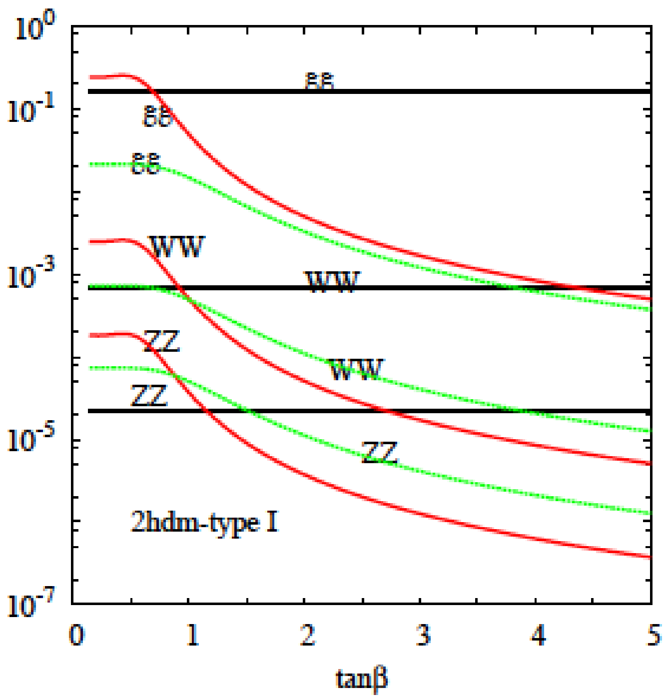
In models with only one SM-like Higgs boson, radiative corrections can generate different HVV terms. This is also possible in extensions of the scalar sector like for instance in the 2HDM. ATLAS and CMS results have shown that if these corrections exist they are small.

For each particular model one should check

$$A \to ZZ\ (W^+W^-)$$







Arhrib, Benbrik, Field (2006).

The C2HDM as a counterexample

In the complex 2HDM the three neutral scalars have indefinite CP.

The interaction of each scalar with the Z bosons comes exactly from the same kinetic term as the SM one

$$g^{hVV}_{C2HDM} = \cos(\alpha_2)\cos(\beta - \alpha_1)\, g^{hVV}_{SM}$$

Therefore the analysis of the correlations in momenta in

$$h \to ZZ^* \to (\bar{l}_1 l_1)\ (\bar{l}_2 l_2)$$

$$h \to WW^* \to (l_1 \nu_1)\ (l_2 \nu_2)$$

will not allow to draw any conclusion on the scalar's CP.

Again, they show however that any radiate contribution to CP-violating terms in hZZ(WW) is small.

The C2HDM as a counterexample

Using again the C2HDM as a benchmark, if all neutral scalars have indefinite CP it is likely that we get the first hints in the study of the process

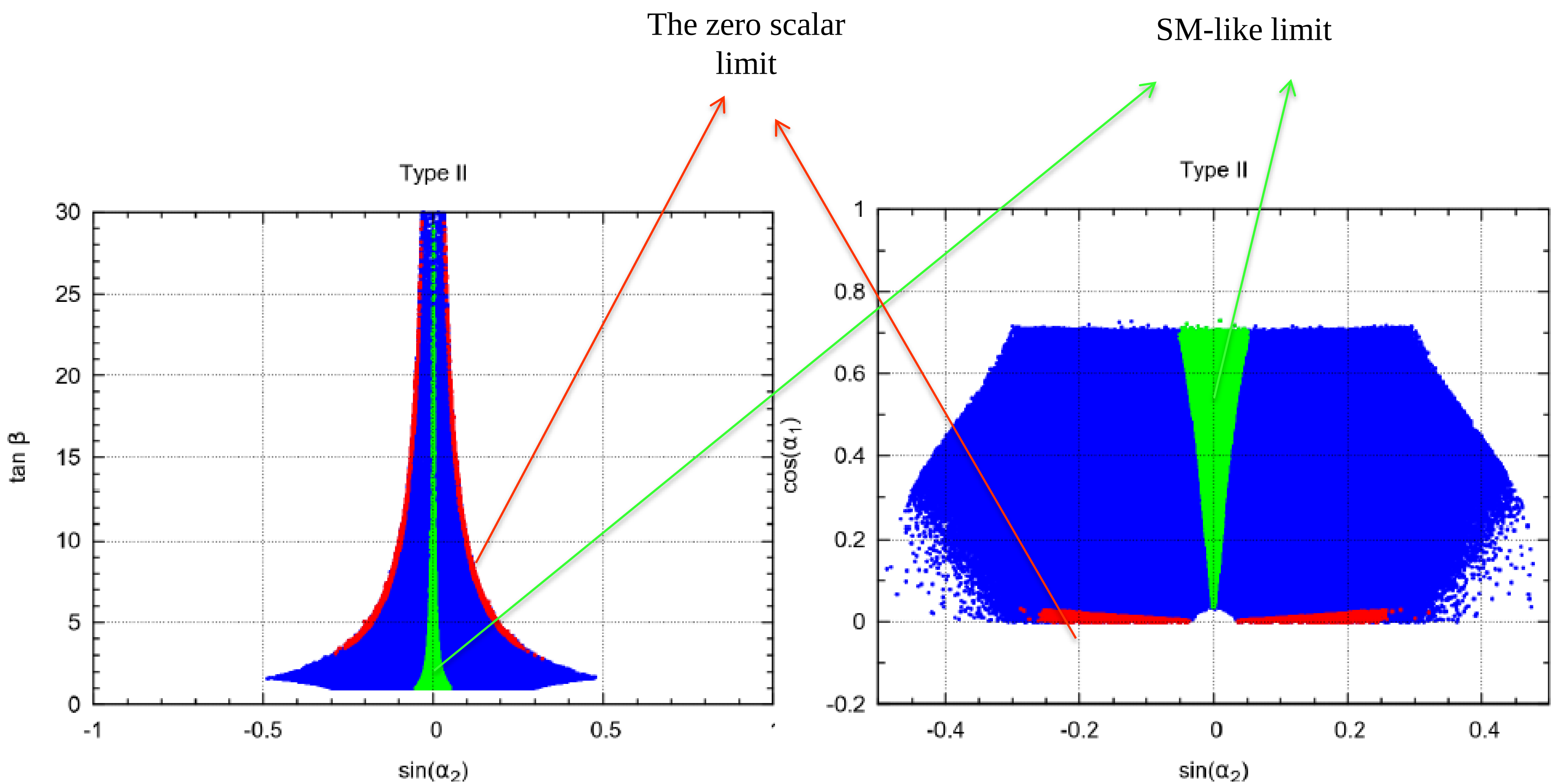
$$pp \rightarrow h \rightarrow \tau^+ \tau^-$$

And later (in luminosity) possibly also using

$$pp \rightarrow h(\rightarrow b\bar{b})t\bar{t}$$

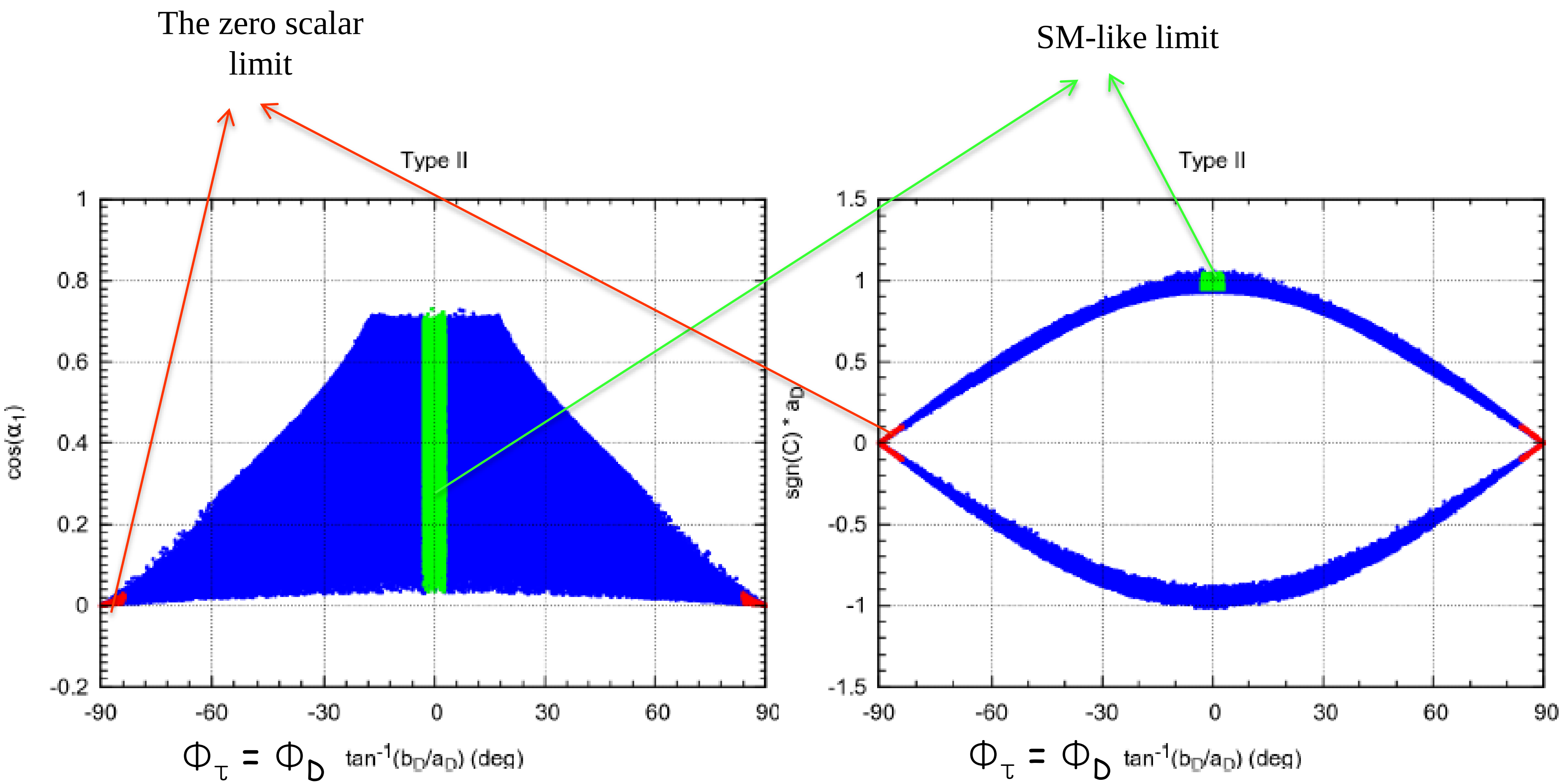
Direct probing of Yukawa couplings – C2HDM as a benchmark model

Direct probing at the LHC



Left: $\tan\beta$ as a function of $\sin\alpha_2$ for Type II, 13 TeV, with all rates at 10% (blue); $|a_D| < 0.1$ $||b_D|-1| < 0.1$ (green); $|b_D| < 0.05$ $||a_D|-1| < 0.05$ (red).
Right: same with $\tan\beta$ replaced by $\cos\alpha_1$

Direct probing at the LHC



$\Phi_\tau = \Phi_D$ $\Phi_\tau = \Phi_D$

Left: $\cos\alpha_1$ as a function of Φ_D for Type II, 13 TeV, with all rates at 10% (blue); $|a_D| < 0.1$ $||b_D|-1| < 0.1$ (green); $|b_D| < 0.05$ $||a_D|-1| < 0.05$ (red).

Right: same with $\tan\beta$ replaced by $\mathrm{sgn}(C)\, a_D$.

Direct probing at the LHC

- For the C2HDM we need three independent measurements

$$\tan f_i = \frac{b_i}{a_i}; \qquad i = U, D, L$$

- Just one measurement for type I (U = D = L), two for the other three types.
At the moment there are studies for tth and $\tau\tau$h.

- If $\Phi_t \neq \Phi_\tau$ type I and F (Y) are excluded.

- To probe model F (Y) we need the bbh vertex.

Direct probing at the LHC (ττh)

$$pp \to h \to \tau^+\tau^-$$

Berge, Bernreuther, Ziethe 2008
Berge, Bernreuther, Niepelt, Spiesberger, 2011
Berge, Bernreuther, Kirchner 2014

- A measurement of the angle

$$\tan\phi_\tau = \frac{b_L}{a_L}$$

can be performed with the accuracies

$$\begin{cases} \Delta\phi_\tau = 40^\circ & 150\ \mathrm{fb}^{-1} \\ \Delta\phi_\tau = 25^\circ & 500\ \mathrm{fb}^{-1} \end{cases}$$

Numbers from:
Berge, Bernreuther, Kirchner, EPJC74, (2014) 11, 3164.

$$\tan\phi_\tau = -\frac{s_\beta}{c_1}\tan\alpha_2 \quad \Rightarrow \quad \tan\alpha_2 = -\frac{c_1}{s_\beta}\tan\phi_\tau$$

- It is not a direct measurement of the CP-violating angle α_2.

Direct probing at the LHC (tth)

$$pp \rightarrow jjh$$

Hankele, Klamke, Zeppenfeld 2006

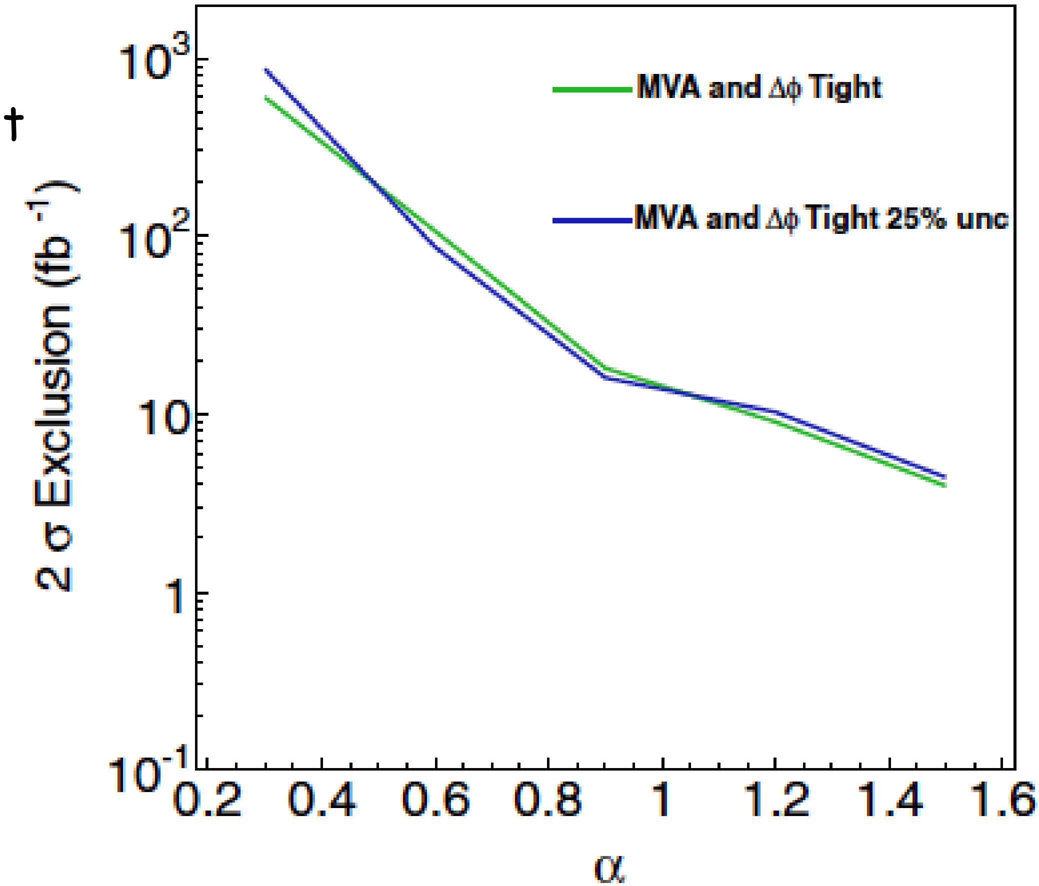
Corresponds to the C2HDM in the limit

$$\cos(b - a_1) = 0; \ \tan b = 1$$

In this case

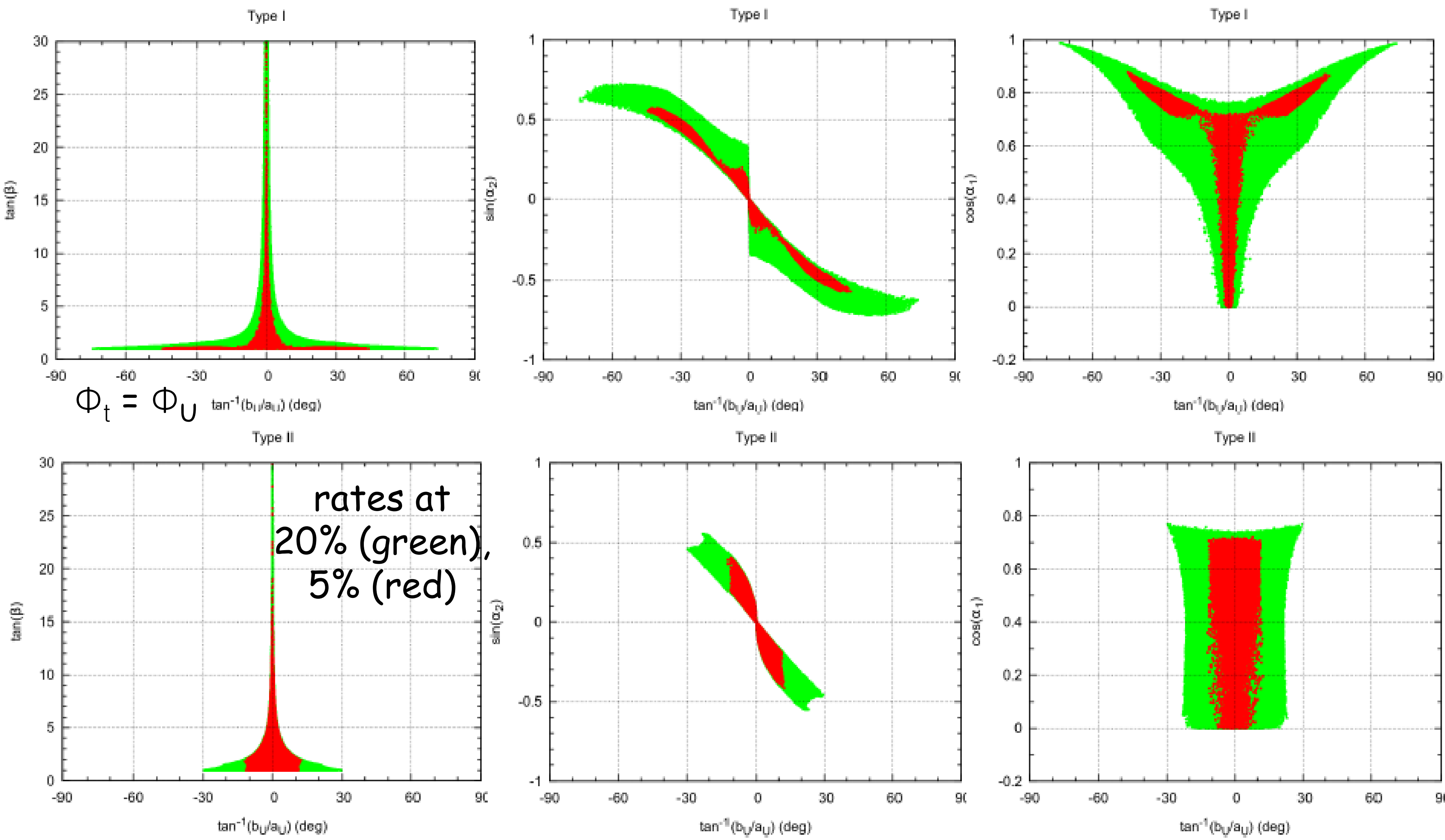
$$f_t = a_2$$

$$\begin{cases} f_t < 40^{o} & 50\ \text{fb}^{-1} \\ f_t < 25^{o} & 300\ \text{fb}^{-1} \end{cases}$$



Plot from: Dolan, Harris, Jankowiak, Spannowsky, PRD90, 073008 (2014).

Limits on Φ_t based on the rates only

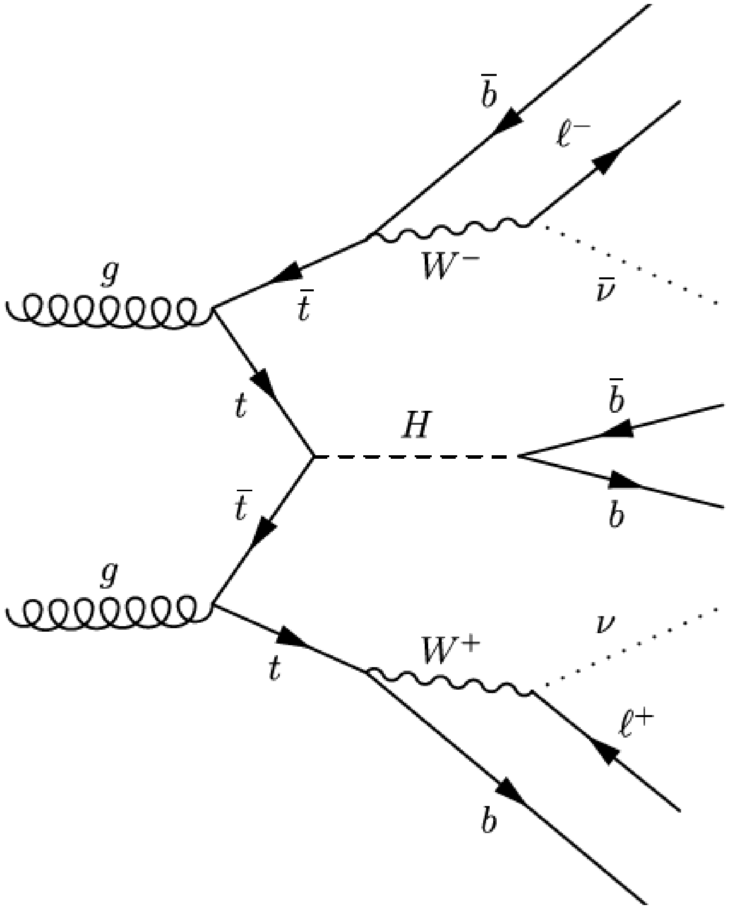


Competitive for Type I but not for Type II

Direct probing at the LHC (tth)

$$pp \to h(\to b\bar{b})t\bar{t}$$

Gunion, He 1996
Boudjema, Godbole, Guadagnoli, Mohan 2015 Amor dos Santos *eal* 2015



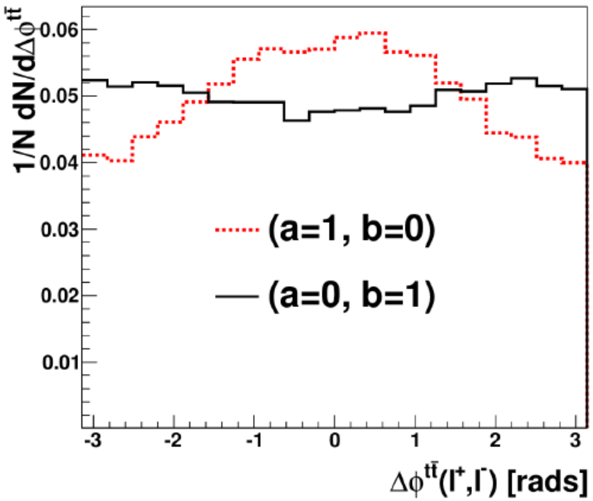
$$\mathcal{L}_{Hf\bar{f}} = -\frac{y_f}{\sqrt{2}}\bar{\psi}_f(a_f + ib_f\gamma_5)\psi_f h$$

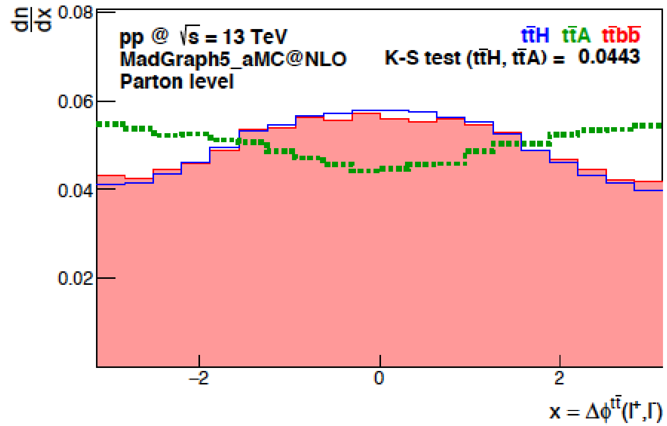
Signal: tt fully leptonic and H -> bb

Background: most relevant is the irreducible tt background

Review of tth

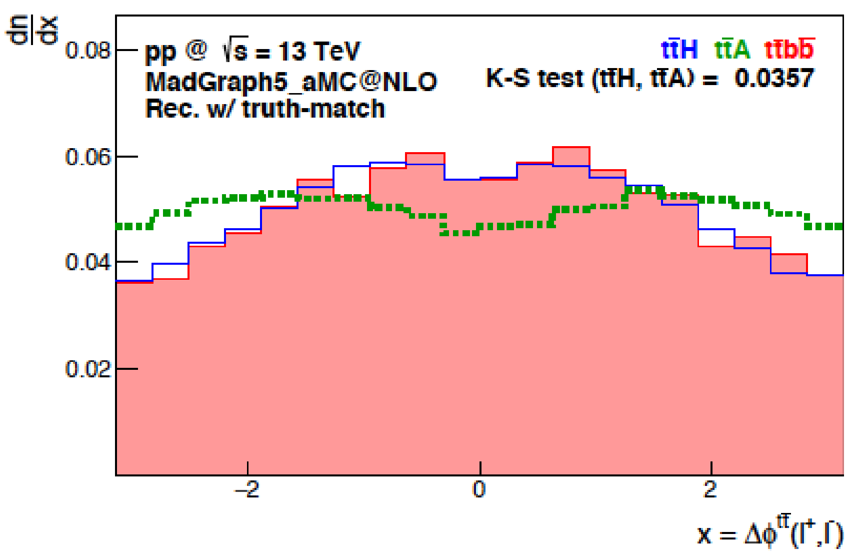
$$\mathcal{L}_{Hf\bar{f}} = -\frac{y_f}{\sqrt{2}}\bar{\psi}_f(a_f + i b_f \gamma_5)\psi_f h$$

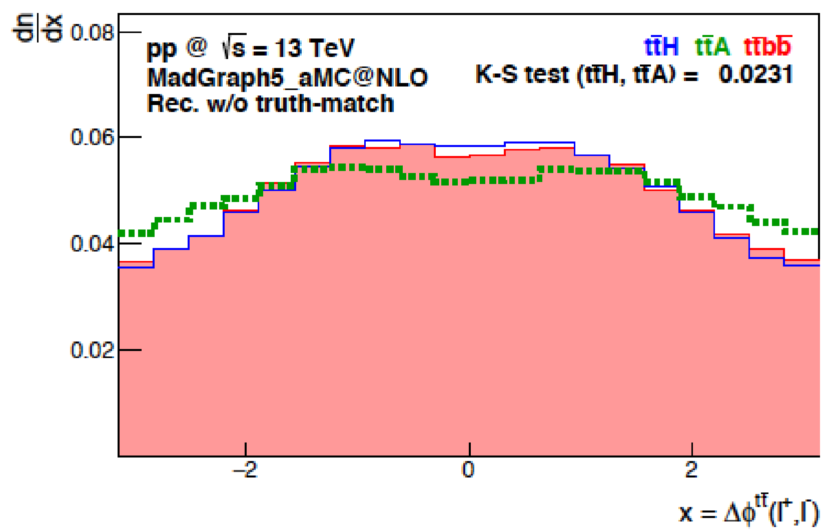




Boudjema, Godbole, Guadagnoli, Mohan 2015

Azimuthal difference between l$^+$ in the t rest frame and l$^-$ in the tbar rest frame



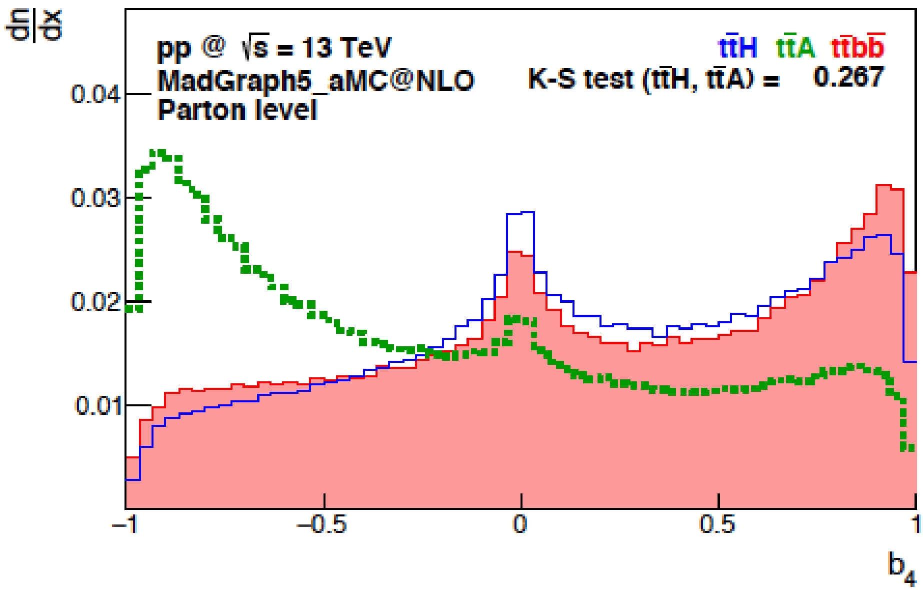


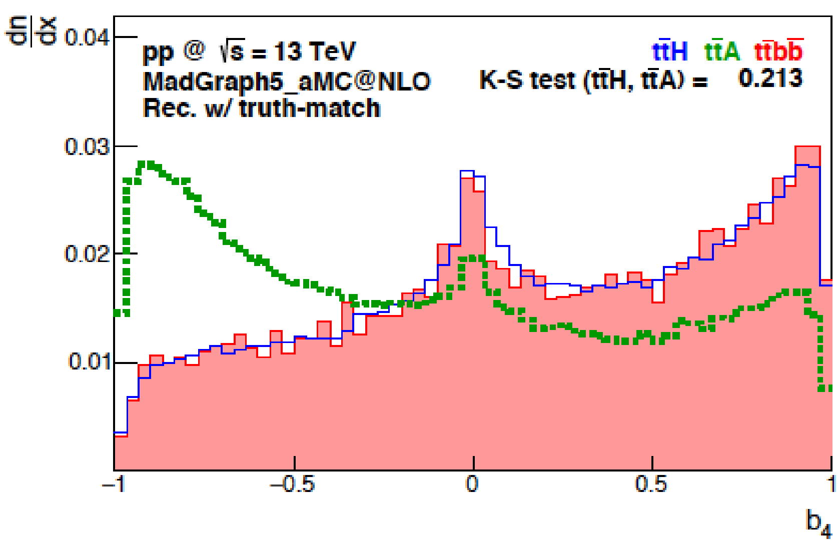
Review of tth

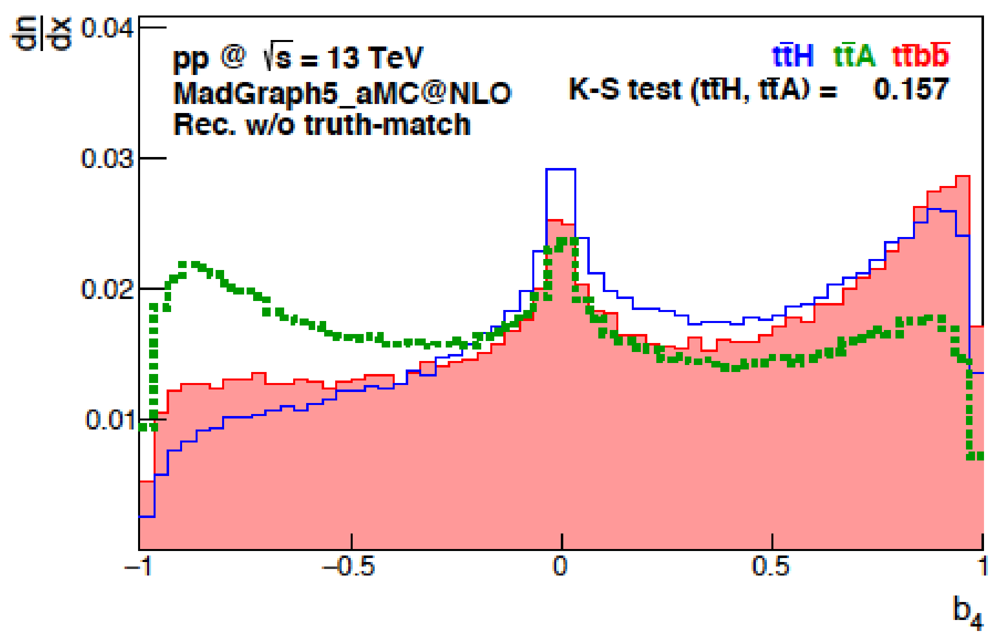
$$\mathcal{L}_{Hf\bar{f}} = -\frac{y_f}{\sqrt{2}}\bar{\psi}_f(a_f + ib_f\gamma_5)\psi_f h$$

Gunion, He 1996

$$b_4 = \frac{p_t^z p_{\bar{t}}^z}{p_t p_{\bar{t}}}$$







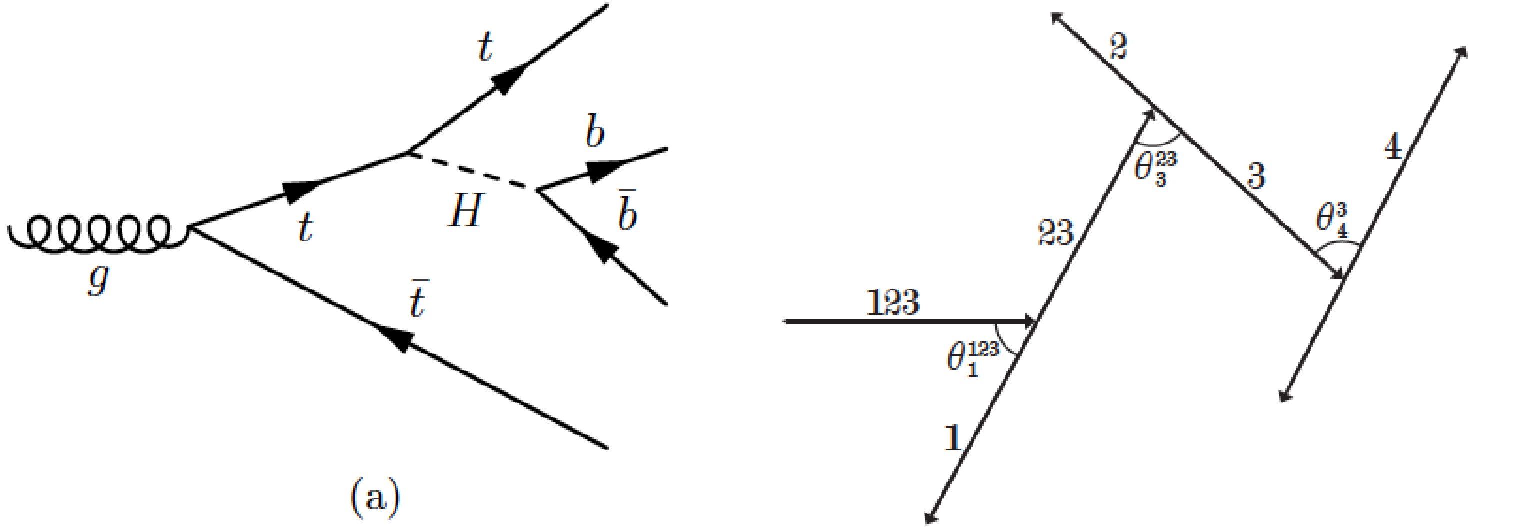


Figure 32: **Left:** $t\bar{t}H$ production through an s-channel gluon, which splits into a $\bar{t}$ and a t. In its turn, the t radiates a Higgs boson, which decays into $b\bar{b}$. **Right:** General decay chain with particles labeled 1, 2, 3 and 4.

Define the angles

q_1^{123} : system 123 in lab frame and 1 in frame 123

q_3^{23} : system 23 in frame 123 and 3 in frame 23

q_4^{3} : 3 in frame 23 and 4 in frame 3

1, 2 and 3 are any permutation of t $\bar{\text{t}}$ or H

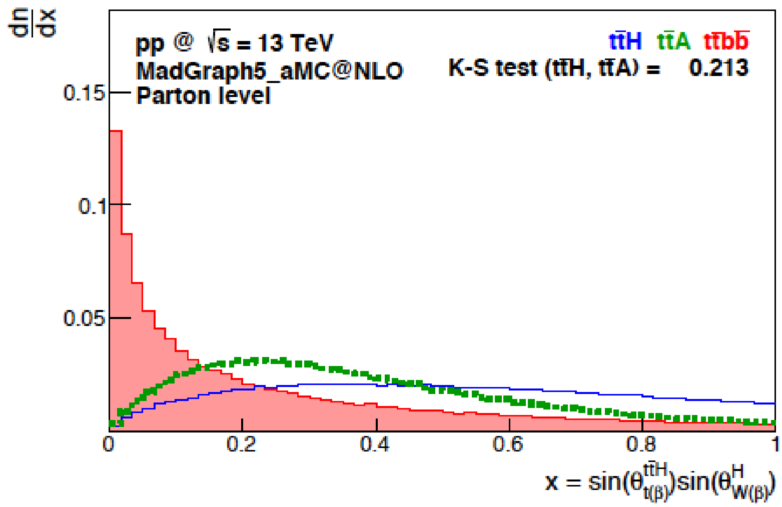
4 is a particle decaying from t $\bar{\text{t}}$ or H

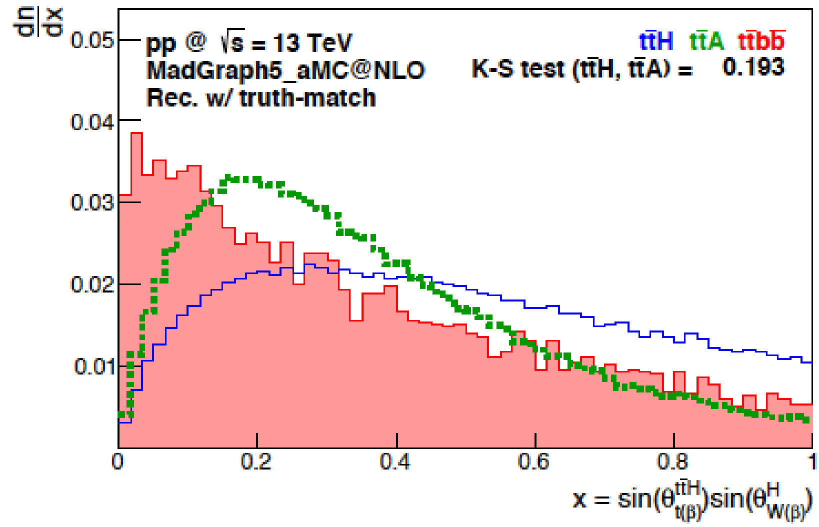
Build functions of the angles

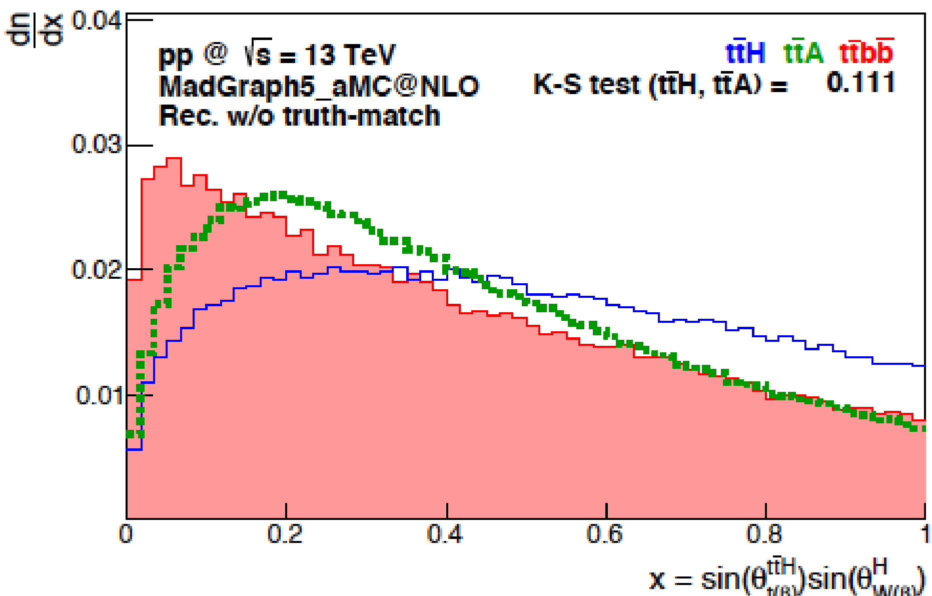
Review of tth

$$\mathcal{L}_{Hf\bar{f}} = -\frac{y_f}{\sqrt{2}}\bar{\psi}_f(a_f + ib_f\gamma_5)\psi_f h$$

Amor dos Santos *ea l* 2015



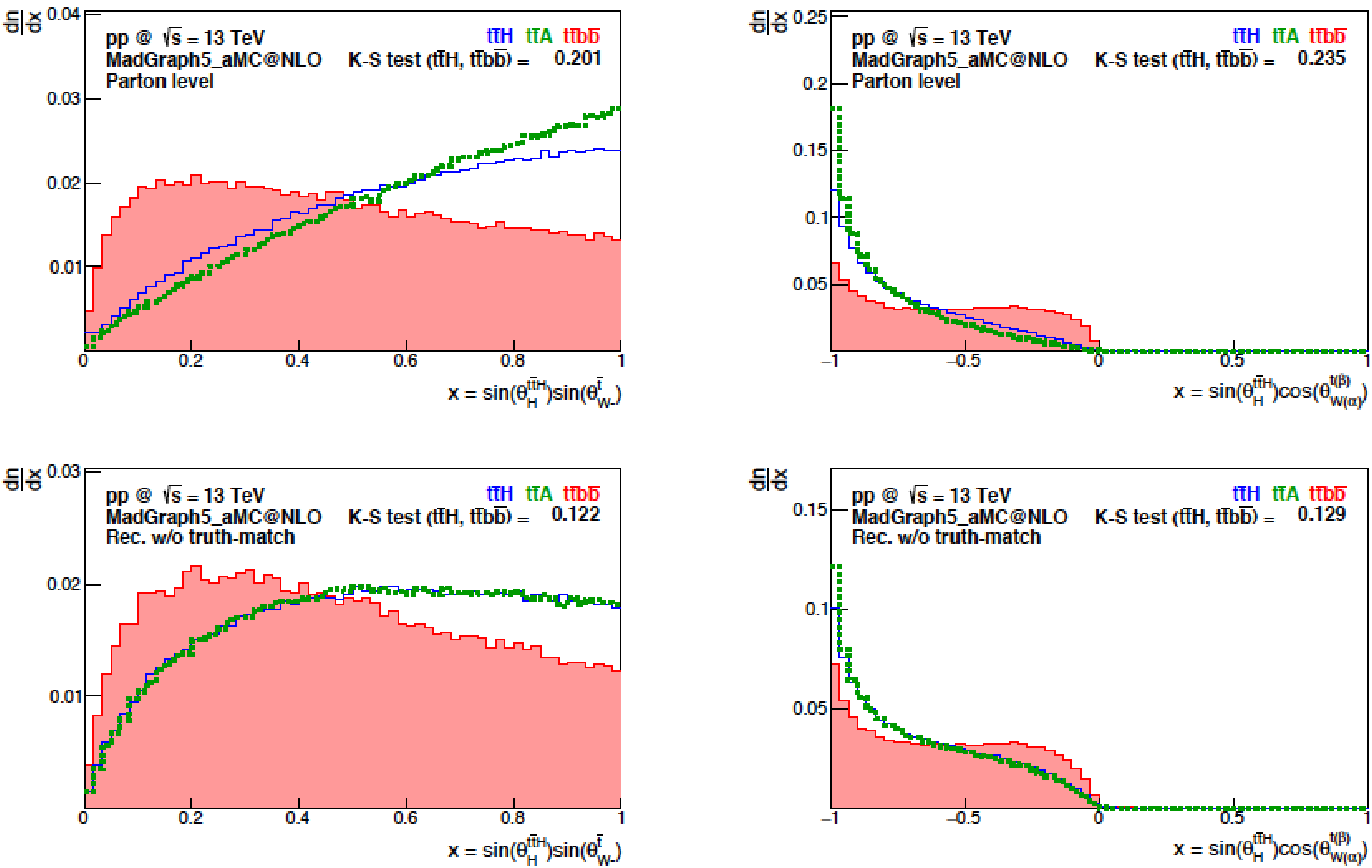




Combinatorial background plays a very important role.

Some variables are also good discriminants between ttΦ and ttbb

Amor dos Santos *ea l* 2015



More results to appear soon.

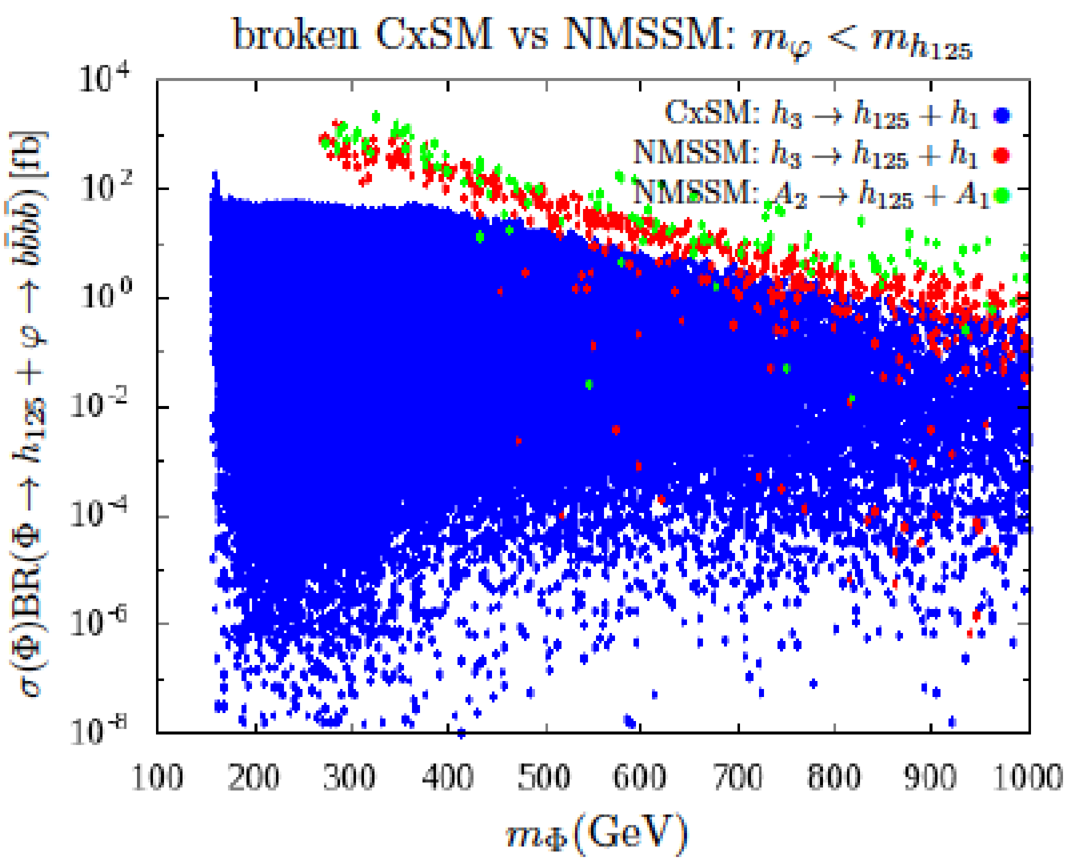
Scalar decaying to two scalars of different masses

The decay $H_i \to H_j H_k \quad j \neq k$

To distinguish between models

Singlet Extensions of the Standard Model at LHC Run 2: Benchmarks and Comparison with the NMSSM

R. Costa, M. Mühlleitner, M.O.P. Sampaio, R. Santos; JHEP 1606 (2016) 034.



A comparison between the NMSSM and the broken Complex Singlet extension of the SM for final states with two scalars with different masses.

The models can be distinguished in some regions of the parameter space.

The decay $H_i \to H_j H_k \quad j \neq k$

Hint for CP violation? Combinations of three decays

$h_1 \to ZZ \quad \Leftarrow \quad \mathrm{CP}(h_1) = 1$	$h_3 \to h_2 h_1 \quad \Rightarrow \quad \mathrm{CP}(h_3) = \mathrm{CP}(h_2)\,\mathrm{CP}(h_1) = \mathrm{CP}(h_2)$

Already observed

Decay	CP eigenstates	Model
$h_3 \to h_2 Z \quad \mathrm{CP}(h_3) = -\,\mathrm{CP}(h_2)$	None	C2HDM, other CPV extensions
$h_{2(3)} \to h_1 Z \quad \mathrm{CP}(h_{2(3)}) = -1$	2 CP-odd; None	C2HDM, NMSSM,3HDM...
$h_2 \to ZZ \quad \mathrm{CP}(h_2) = 1$	3 CP-even; None	C2HDM, cxSM, NMSSM,3HDM...

C2HDM - D. Fontes, J.C. Romão, R. Santos, J.P. Silva; PRD92 (2015) 5, 055014.

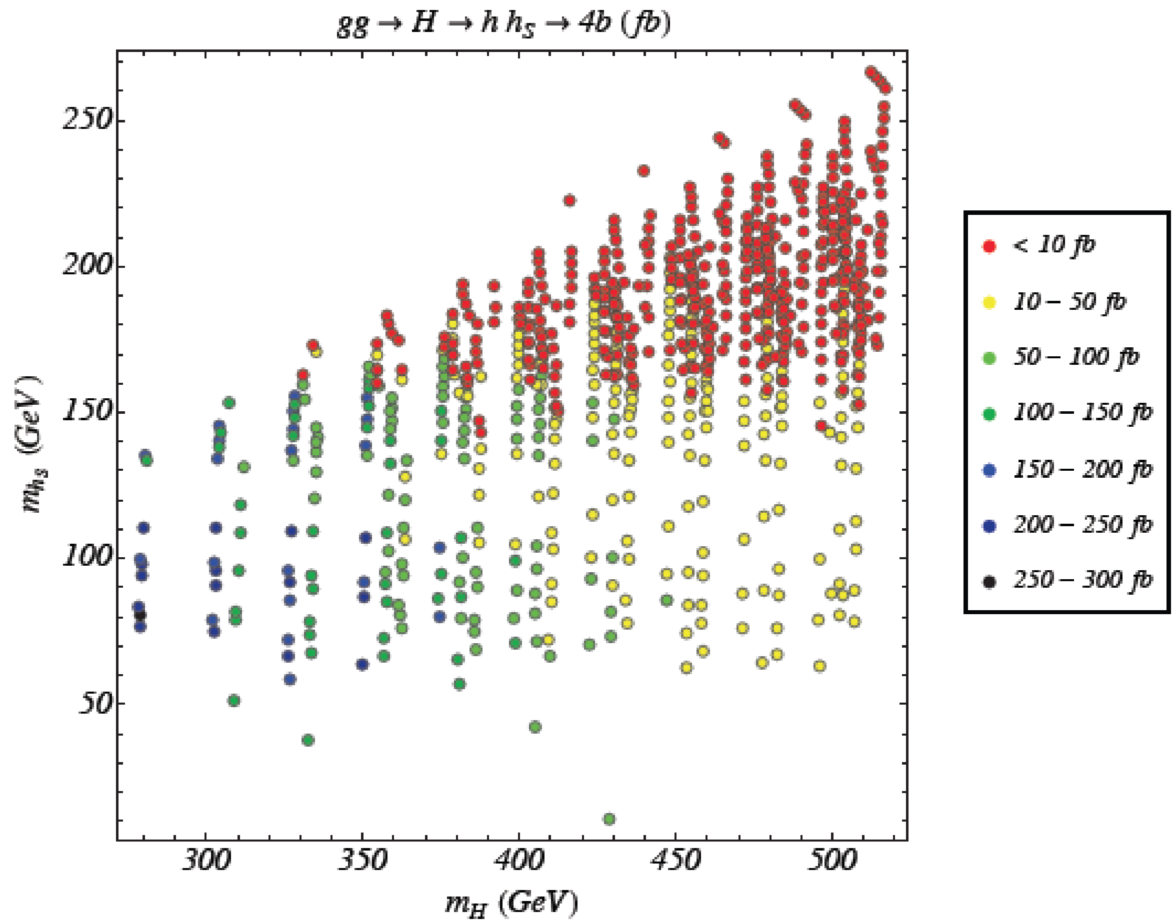
NMSSM - S.F. King, M. Mühlleitner, R. Nevzorov, K. Walz; NPB901 (2015) 526-555.

The decay $H_i \to H_j H_k \quad j \neq k$

Large rates in the aligned NMSSM

Alignment limit of the NMSSM Higgs sector

M. Carena, H.E. Haber, I. Low, N.R. Shah, C.E. M. Wagner; PRD93 (2016) 3, 035013.



In the alignment limit of the NMSSM Higgs decays to two other scalars with the same mass are supressed.

Radiative corrections to BSM models

A new renormalization procedure for the 2HDM that is <u>gauge independent</u>, <u>process independent</u> and <u>stable</u>

Krause, Lorenz, Muhlleitner, RS, Ziesche (2016)
Krause, Muhlleitner, RS, Ziesche (to appear)

Barroso, RS (1997)

Kanemura, Okada, Senaha, Yuan, Yamada, Lopez-Val Sola, Pilaftsis, Freitas, Stöckinger
Boudjema, Baro, Denner, Jenniches, Lang, Sturm, ···

Process dependent – On-shell plus two particular processes to renormalize the angles and/or soft breaking parameter

Process independent – On-shell plus conditions for the angles based on the mixing matrix properties plus MS for the soft breaking parameter

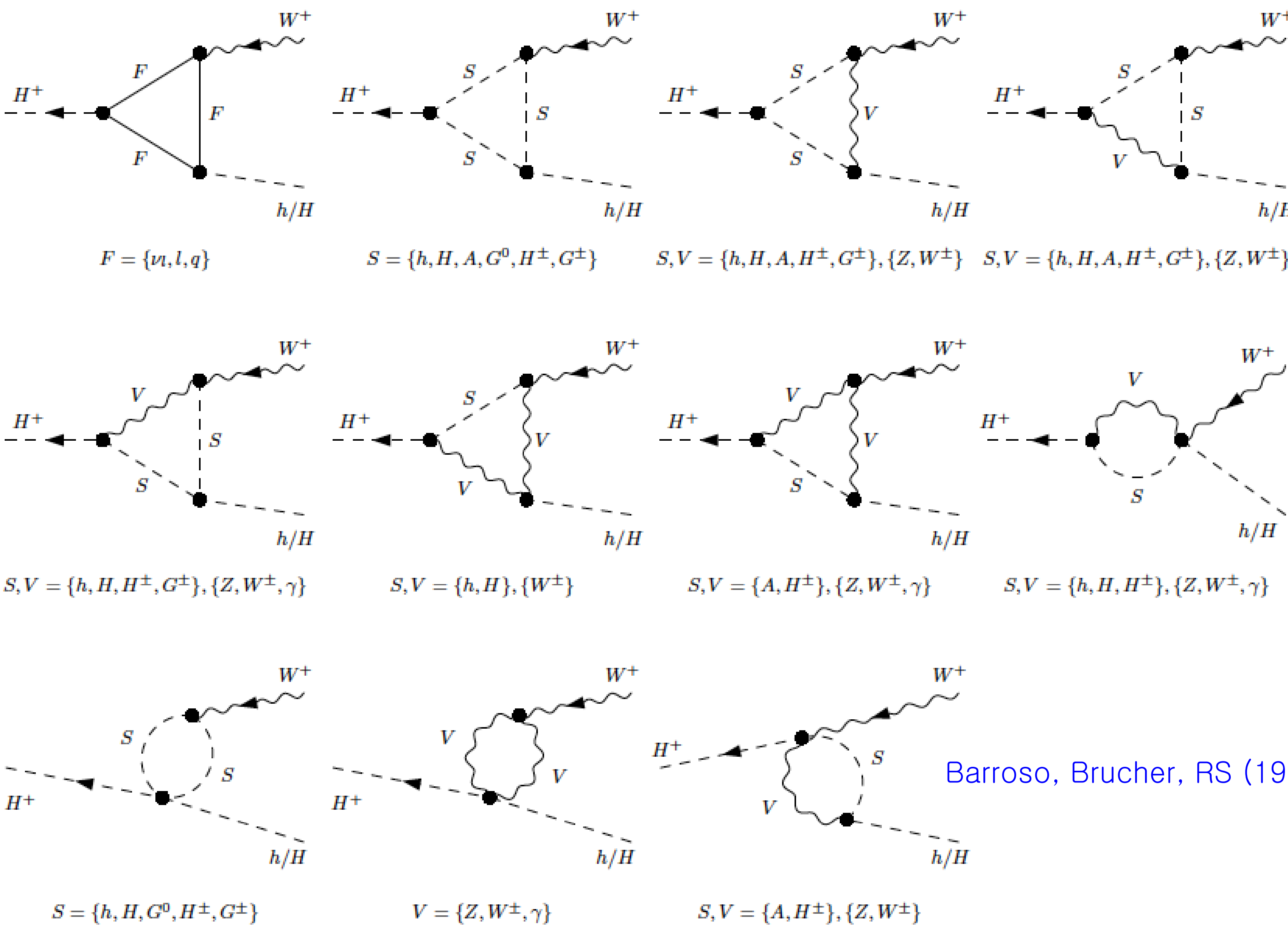
$$\delta O_{ij} = \frac{1}{4}(\delta Z_{il} - \delta Z_{li})O_{lj}$$

Pilaftsis (1997)

Kanemura, Okada, Senaha, Yuan (2004)

<u>Input parameters:</u> $m_h,\ m_H,\ m_A,\ m_{H^\pm},\ T_1,\ T_2,\ \alpha,\ \tan\beta,\ m_{12}^2,\ M_W^2,\ M_Z^2,\ e,\ m_f$

For historical reasons we have started with the corrections to a charged Higgs decaying to a neutral Higgs and a W boson.



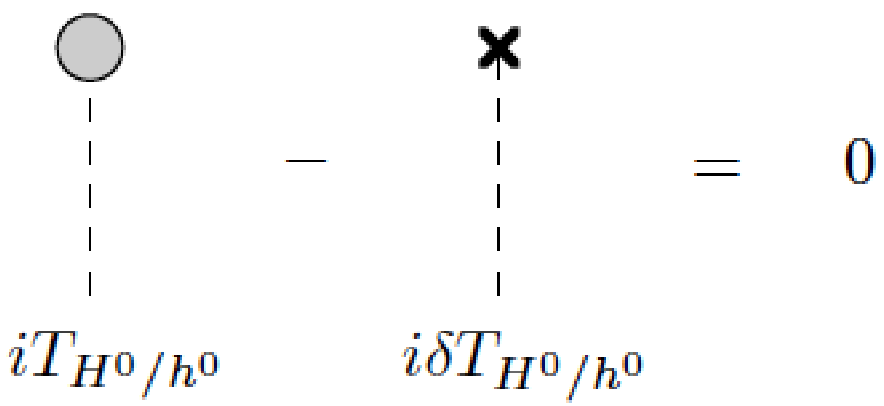
Barroso, Brucher, RS (1997)

Quantities are redefined according to

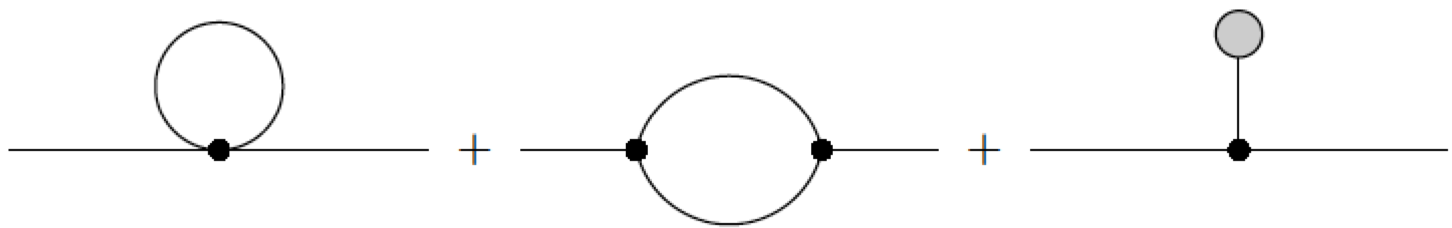
$$\rho_{i,0} = \rho_i + \delta\rho_i$$ for the parameters.

$$\phi_{j,0} = \sqrt{Z_{\phi_j}}\phi_j \approx \left(1 + \frac{\delta Z_{\phi_j}}{2}\right)\phi_j$$ for the fields.

Renormalization condition for the tadpoles



The difference in what we call "the tadpole scheme" is the inclusion of the tadpole graph in the calculation of the self-energies

$i\Sigma^{\text{tad}}(p^2) :=$ 

$$\delta Z_{\phi_1\phi_1} = -\text{Re}\left[\frac{\partial \Sigma^{\text{tad}}_{\phi_1\phi_1}(p^2)}{\partial p^2}\right]_{p^2=m^2_{\phi_1}} ,$$

$$\delta Z_{\phi_1\phi_2} = \frac{2}{m^2_{\phi_1} - m^2_{\phi_2}}\text{Re}\left[\Sigma^{\text{tad}}_{\phi_1\phi_2}(m^2_{\phi_2})\right] ,$$

$$\delta Z_{\phi_2\phi_1} = \frac{2}{m^2_{\phi_2} - m^2_{\phi_1}}\text{Re}\left[\Sigma^{\text{tad}}_{\phi_1\phi_2}(m^2_{\phi_1})\right] ,$$

$$\delta Z_{\phi_2\phi_2} = -\text{Re}\left[\frac{\partial \Sigma^{\text{tad}}_{\phi_2\phi_2}(p^2)}{\partial p^2}\right]_{p^2=m^2_{\phi_2}} ,$$

$$\delta m^2_{\phi_1} = \text{Re}\left[\Sigma^{\text{tad}}_{\phi_1\phi_1}(m^2_{\phi_1})\right] ,$$

$$\delta m^2_{\phi_2} = \text{Re}\left[\Sigma^{\text{tad}}_{\phi_2\phi_2}(m^2_{\phi_2})\right] .$$

on-shell renormalization conditions for a generic Lagrangian with two scalars with the same quantum numbers

Proposed for the SM by

J. Fleischer and F. Jegerlehner (1981).

In this appendix we consider the problems related to the shift (2.4) of the Higgs field. The quantities considered in this appendix are the bare ones if not indicated otherwise. If the shift parameter v has the correct value, the physical Higgs field satisfies the gauge-invariant condition

(A1)

when the trivial tadpole

$$t = v m_0^2 = v(\lambda v^2 - \mu^2) \tag{A2}$$

and the Higgs-boson mass

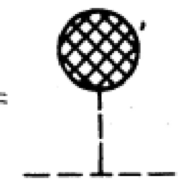
$$m_H^2 = 3\lambda v^2 - \mu^2 \tag{A3}$$

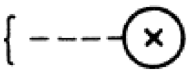
are given the ground-state values

$$m_0^2 = 0 \text{ and } m_H^2 = 2\lambda v^2 . \tag{A4}$$

The proper value of v, however, is not known *a priori* and it must be determined order by order in the perturbation expansion. We denote by v_0 and v the proper values of v to the nth and the $(n+1)$th order, respectively. Thus we write

$$v = v_0 + \delta v_t . \tag{A5}$$

$-i\Delta m_H^2 = -i6\lambda v_0 \delta v_t =$ 

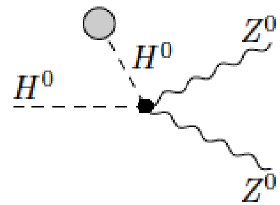
$\delta v_t =$  $= \frac{i}{-m_{Ho}^2}$ $\{$  $\}$

$$= \frac{\delta t}{m_{Ho}^2} \tag{A13}$$

J. Fleischer and F. Jegerlehner (1981).

The other difference relative to the usual on-shell scheme is to include diagrams with tadpoles whenever there is a vacuum expectation value in the vertex

$$
\begin{aligned}
i g_{H^0 Z^0 Z^0} &\to i g_{H^0 Z^0 Z^0} + \frac{i g^2}{2 c_W^2} \left(c_\alpha \delta v_1 + s_\alpha \delta v_2 \right) \\
&= i g_{H^0 Z^0 Z^0} + \frac{i g^2}{2 c_W^2} \left[\left(c_\alpha^2 + s_\alpha^2 \right) \frac{\delta T_{H^0}}{m_{H^0}^2} + \left(s_\alpha c_\alpha - s_\alpha c_\alpha \right) \frac{\delta T_{h^0}}{m_{h^0}^2} \right] \\
&= i g_{H^0 Z^0 Z^0} + \frac{i g^2}{2 c_W^2} \frac{-i}{m_{H^0}^2} i \delta T_{H^0} \\
&= i g_{H^0 Z^0 Z^0} + \left(\quad \right)_{\text{trunc}} .
\end{aligned}
$$



Self-energies: The self-energies appearing in the definitions of the wave function renormalization constants and counterterms are changed such that they contain additional tadpole contributions: $\Sigma(p^2) \to \Sigma^{\text{tad}}(p^2)$.

Tadpole counterterms: The tadpole counterterms $\delta T_{\phi_i \phi_j}$ $(i, j = 1, 2)$ in the scalar sector vanish: $\delta T_{\phi_i \phi_j} \to 0$.

Vertex corrections: The virtual vertex corrections change to contain additional tadpole contributions if the resulting coupling exists within the 2HDM.

Results for the alternative tadpole scheme

$$\mathcal{M}_{H^\pm \to W^\pm h}\Big|^{\text{standard}}_{\text{ct, } \xi, \delta c_{\beta-\alpha} \text{ only}} = \frac{g \Lambda_5 c_{\beta-\alpha} s^2_{\beta-\alpha} \, p_1 \cdot \epsilon^*(p_3)}{32\pi^2 (m_H^2 - m_h^2)} \left[2M_W^2 (1-\xi_W)\alpha_W + M_Z^2 (1-\xi_Z)\alpha_Z \right] .$$

$$\mathcal{M}_{H^\pm \to W^\pm h}\Big|^{\text{tad}}_{\text{NLO}, \, \xi, \, \delta c_{\beta-\alpha}=0} = 0 \, .$$

The virtue of the alternative tadpole scheme is to lead to gauge independent amplitudes when the angular countertems are set to zero.

Now we just need a gauge independent way to define the angle and soft breaking counterterms. But the wave function renormalization constants are gauge dependednt. So what to do?

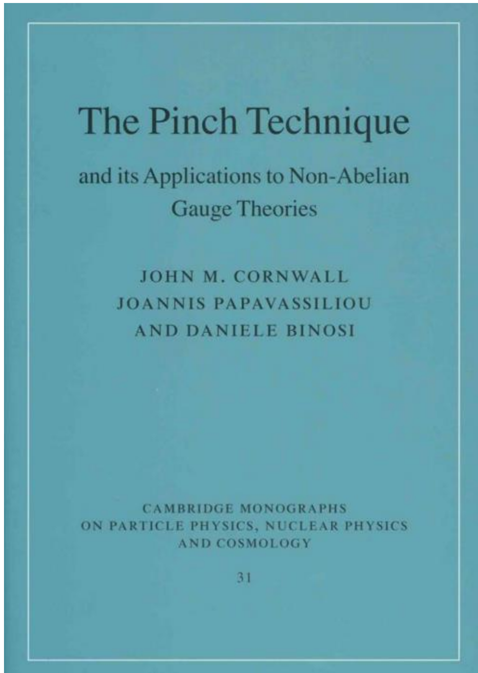
Since the angle counterterms are defined with the help of wave function renormalization constants if these are gauge independent the angle counterterms will also be gauge independent. There is however an unambigous way to remove the gauge dependent part of the self-energies

$$\Sigma^{\text{pinch}}_{\phi_1\phi_2}(p^2) = \left[\Sigma^{\text{tad}}_{\phi_1\phi_2}(p^2)\right]_{\xi=1} + \Sigma^{\text{add}}_{\phi_1\phi_2}(p^2)$$

$$\Sigma^{\text{add}}_{H^0h^0}(p^2) = \frac{g^2 s_{\beta-\alpha} c_{\beta-\alpha}}{32\pi^2 c_W^2}\left(p^2 - \frac{m^2_{H^0}+m^2_{h^0}}{2}\right)\Big\{\left[B_0(p^2;m_Z^2,m_{A^0}^2) - B_0(p^2;m_Z^2,m_Z^2)\right] + 2c_W^2\left[B_0(p^2;m_W^2,m_{H^\pm}^2) - B_0(p^2;m_W^2,m_W^2)\right]\Big\},$$

$$\Sigma^{\text{add}}_{G^0A^0}(p^2) = \frac{g^2 s_{\beta-\alpha} c_{\beta-\alpha}}{32\pi^2 c_W^2}\left(p^2 - \frac{m^2_{A^0}}{2}\right)\left[B_0(p^2;m_Z^2,m_{H^0}^2) - B_0(p^2;m_Z^2,m_{h^0}^2)\right],$$

$$\Sigma^{\text{add}}_{G^\pm H^\pm}(p^2) = \frac{g^2 s_{\beta-\alpha} c_{\beta-\alpha}}{16\pi^2}\left(p^2 - \frac{m^2_{H^\pm}}{2}\right)\left[B_0(p^2;m_W^2,m_{H^0}^2) - B_0(p^2;m_W^2,m_{h^0}^2)\right]$$



Scale – masses of the scalars – OS pinched

Scale – $p_*^2 = \dfrac{m^2_{\phi_1} + m^2_{\phi_2}}{2}$ **p_* pinched**

Alternative tadpole scheme, OS-pinched

$$\delta\alpha = \frac{\mathrm{Re}\Big[\left[\Sigma^{\mathrm{tad}}_{H^0h^0}(m^2_{H^0}) + \Sigma^{\mathrm{tad}}_{H^0h^0}(m^2_{h^0})\right]_{\xi=1} + \Sigma^{\mathrm{add}}_{H^0h^0}(m^2_{H^0}) + \Sigma^{\mathrm{add}}_{H^0h^0}(m^2_{h^0})\Big]}{2\left(m^2_{H^0} - m^2_{h^0}\right)} \,,$$

$$\delta\beta^{(1)} = -\frac{\mathrm{Re}\Big[\left[\Sigma^{\mathrm{tad}}_{G^0A^0}(m^2_{A^0}) + \Sigma^{\mathrm{tad}}_{G^0A^0}(0)\right]_{\xi=1} + \Sigma^{\mathrm{add}}_{G^0A^0}(m^2_{A^0}) + \Sigma^{\mathrm{add}}_{G^0A^0}(0)\Big]}{2m^2_{A^0}} \,,$$

$$\delta\beta^{(2)} = -\frac{\mathrm{Re}\Big[\left[\Sigma^{\mathrm{tad}}_{G^\pm H^\pm}(m^2_{H^\pm}) + \Sigma^{\mathrm{tad}}_{G^\pm H^\pm}(0)\right]_{\xi=1} + \Sigma^{\mathrm{add}}_{G^\pm H^\pm}(m^2_{H^\pm}) + \Sigma^{\mathrm{add}}_{G^\pm H^\pm}(0)\Big]}{2m^2_{H^\pm}} .$$

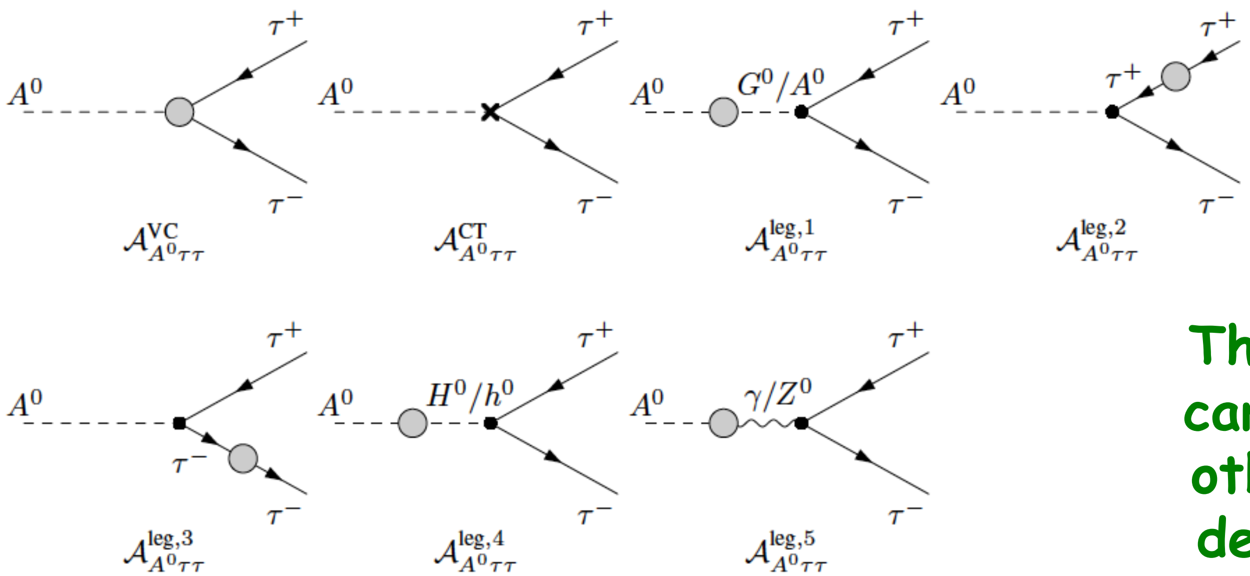
Alternative tadpole scheme, p_*-pinched

$$\delta\alpha = \frac{1}{m^2_{H^0} - m^2_{h^0}} \mathrm{Re}\left[\Sigma^{\mathrm{tad}}_{H^0h^0}\left(\frac{m^2_{H^0} + m^2_{h^0}}{2}\right)\right]_{\xi=1} \,,$$

$$\delta\beta^{(1)} = -\frac{1}{m^2_{A^0}} \mathrm{Re}\left[\Sigma^{\mathrm{tad}}_{G^0A^0}\left(\frac{m^2_{A^0}}{2}\right)\right]_{\xi=1} \,,$$

$$\delta\beta^{(2)} = -\frac{1}{m^2_{H^\pm}} \mathrm{Re}\left[\Sigma^{\mathrm{tad}}_{G^\pm H^\pm}\left(\frac{m^2_{H^\pm}}{2}\right)\right]_{\xi=1} .$$

Process dependent renormalization



This process takes care of β. And the other process is H decaying into taus (not shown). That takes care of α.

$$\Gamma^{\rm LO}_{A^0\tau\tau} \stackrel{!}{=} \Gamma^{\rm NLO,weak}_{A^0\tau\tau}$$

$$\delta\beta = \frac{-Y_3}{1+Y_3^2}\left[\mathcal{F}^{\rm VC}_{A^0\tau\tau} + \frac{\delta g}{g} + \frac{\delta m_\tau}{m_\tau} - \frac{\delta m_W^2}{2m_W^2} + \frac{\delta Z_{A^0A^0}}{2} - \frac{1}{Y_3}\frac{\delta Z_{G^0A^0}}{2} + \frac{\delta Z^{\rm L}_{\tau\tau}}{2} + \frac{\delta Z^{\rm R}_{\tau\tau}}{2}\right],$$

$$\delta\alpha = \frac{-Y_2}{Y_1}\left[\mathcal{F}^{\rm VC}_{H^0\tau\tau} + \frac{\delta g}{g} + \frac{\delta m_\tau}{m_\tau} - \frac{\delta m_W^2}{2m_W^2} + Y_3\delta\beta + \frac{\delta Z_{H^0H^0}}{2} + \frac{Y_1}{Y_2}\frac{\delta Z_{h^0H^0}}{2} + \frac{\delta Z^{\rm L}_{\tau\tau}}{2} + \frac{\delta Z^{\rm R}_{\tau\tau}}{2}\right]$$

Process dependent renormalization

$$\delta\alpha^{\rm sta} = \delta\alpha^{\rm sta}\Big|_{\xi=1} - (1-\xi_W)\frac{\Lambda_5 m_W^2 c_{\beta-\alpha} s_{\beta-\alpha}}{16\pi^2(m_{H^0}^2 - m_{h^0}^2)}\alpha_W - (1-\xi_Z)\frac{\Lambda_5 m_Z^2 c_{\beta-\alpha} s_{\beta-\alpha}}{32\pi^2(m_{H^0}^2 - m_{h^0}^2)}\alpha_Z$$

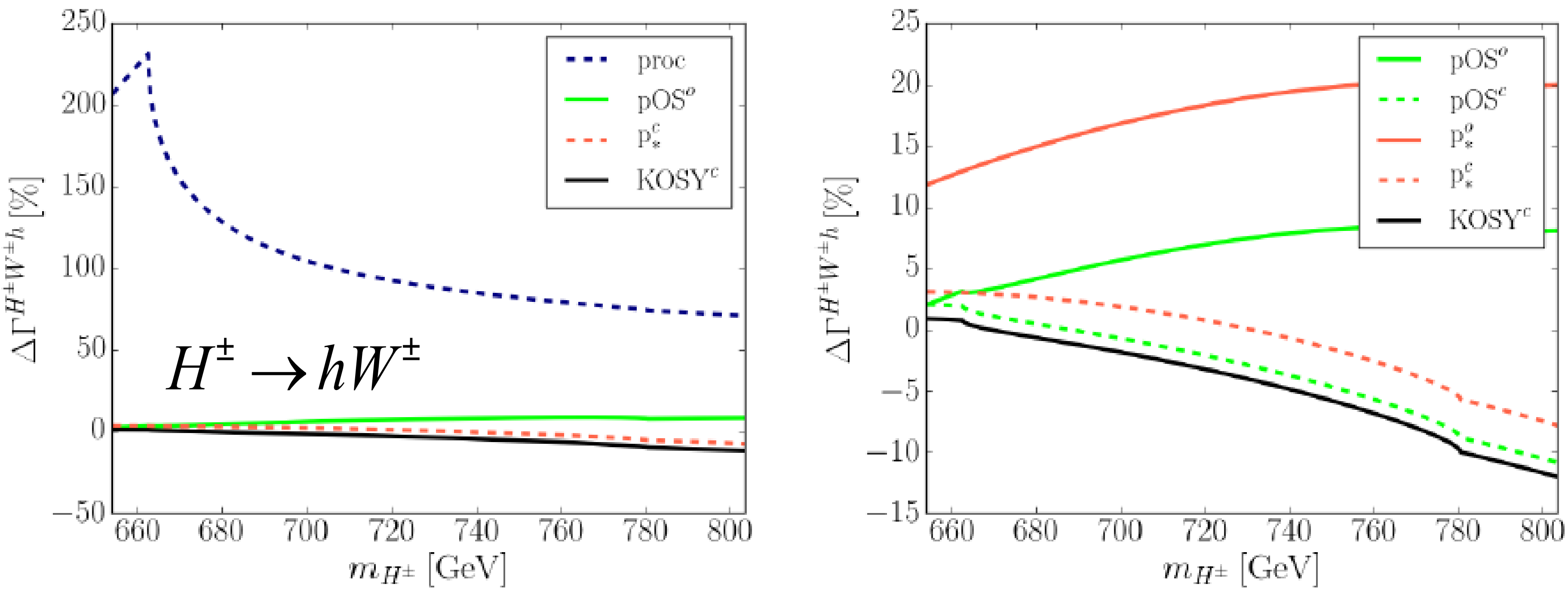
$$\delta\alpha^{\rm alt} = \delta\alpha^{\rm alt}\Big|_{\xi=1}$$

For the two angles the conclusion is that by using the alternative tadople scheme the counterterms for bothe α and β become gauge independent making it much easier to control the overall gauge

Moreover by analysing the amplitudes it is clear that only the 3 schemes proposed here lead to gauge independent amplitudes: process-dependent, p*-pinched and O-Spinched

Results

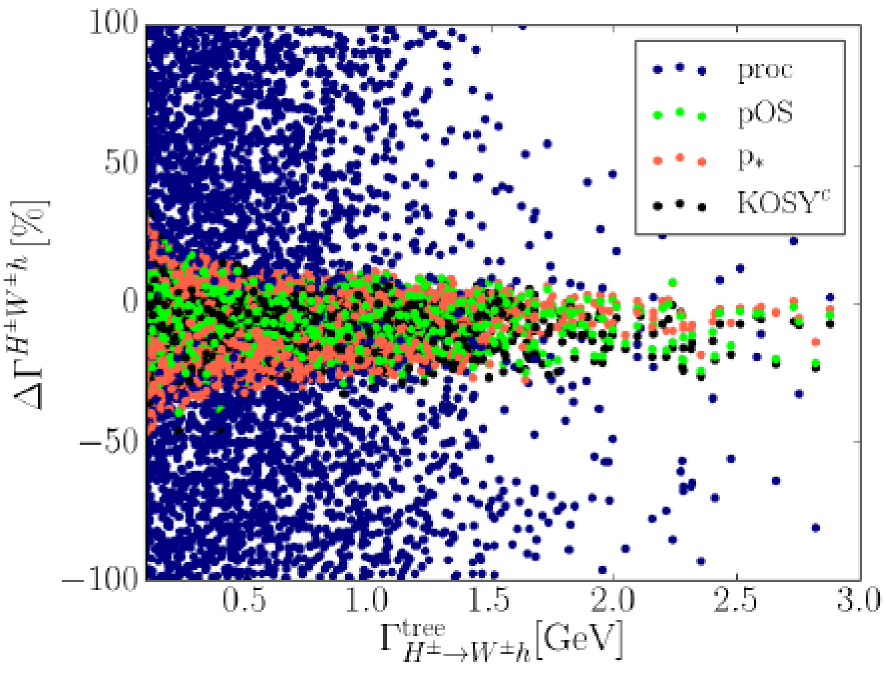
$$\Delta\Gamma \equiv \frac{\Gamma^{\rm NLO} - \Gamma^{\rm LO}}{\Gamma^{\rm LO}}$$

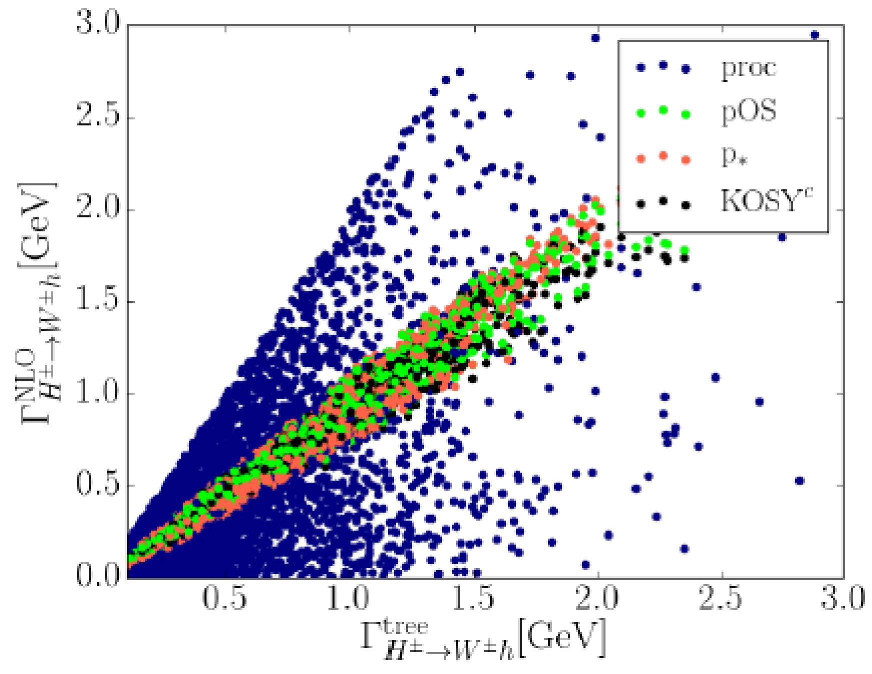


Scen2: $m_{H\pm} = (654...804)$ GeV, $m_H = 742.84$ GeV, $m_A = 700.13$ GeV,
$\tan\beta = 1.46$, $\alpha = -0.57$, $m_{12}^2 = 2.076 \cdot 10^5$ GeV^2

Set of parameters consistent with main theoretical and experimental constraints.

Results

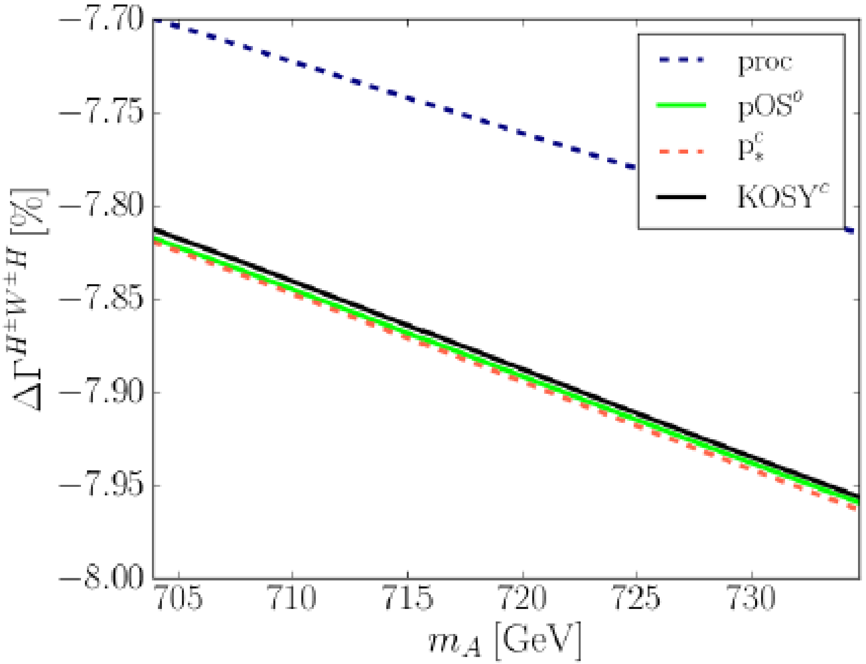


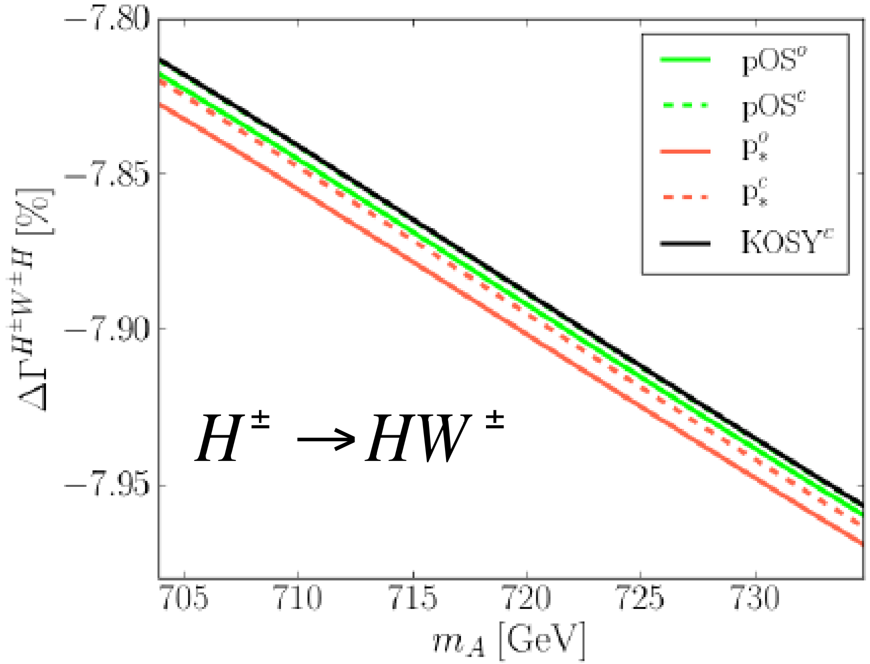


$$H^\pm \to hW^\pm$$

Values blow up for very small tree-level width due to different behaviour with cos(b-a). In the right plot it is clear that NLO behaviour is good relative to the LO one.

Results



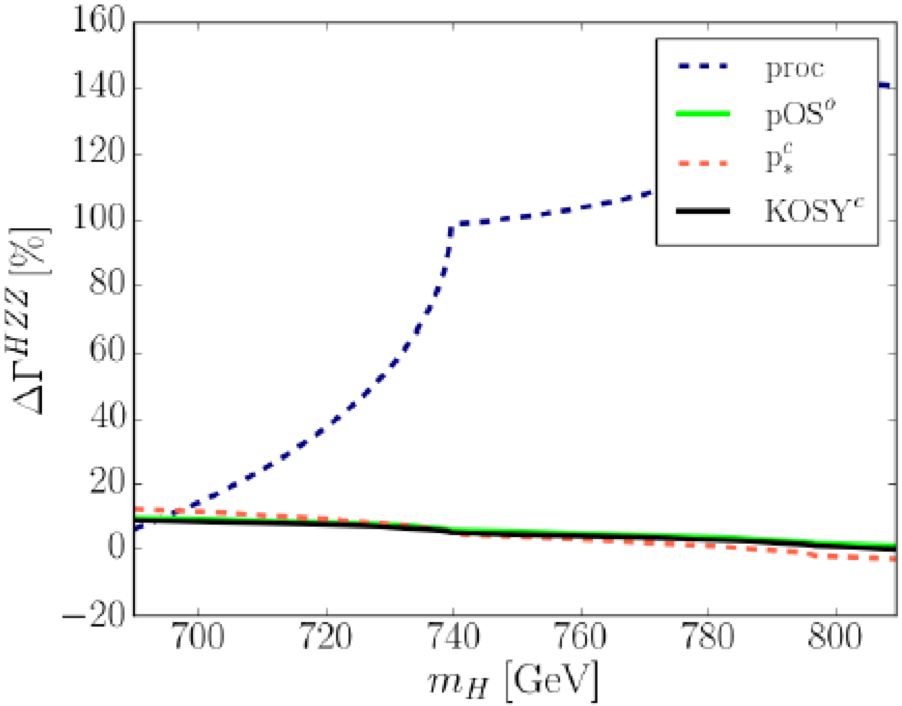


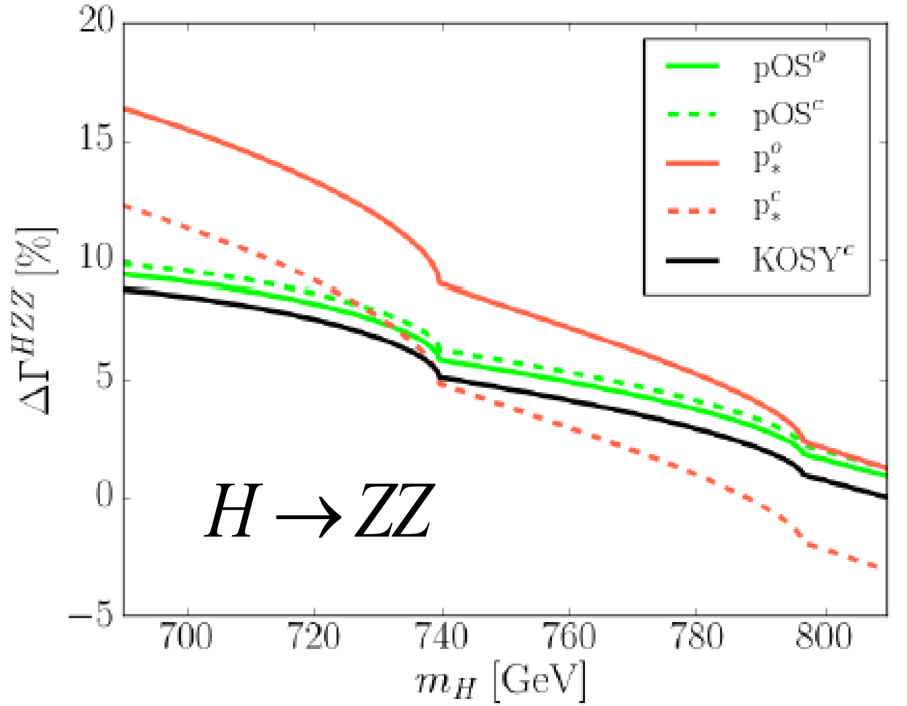
<u>*Scen3:*</u> $m_{H^\pm} = 745.54$ GeV, $m_H = 594.55$ GeV, $m_A = (704...735)$ GeV, $\tan\beta = 1.944$, $\alpha = -0.458$, $m_{12}^2 = 1.941 \cdot 10^5$ GeV^2.

$$\Delta\Gamma \equiv \frac{\Gamma^{\rm NLO} - \Gamma^{\rm LO}}{\Gamma^{\rm LO}}$$

Set of parameters consistent with main theoretical and experimental constraints.

Results

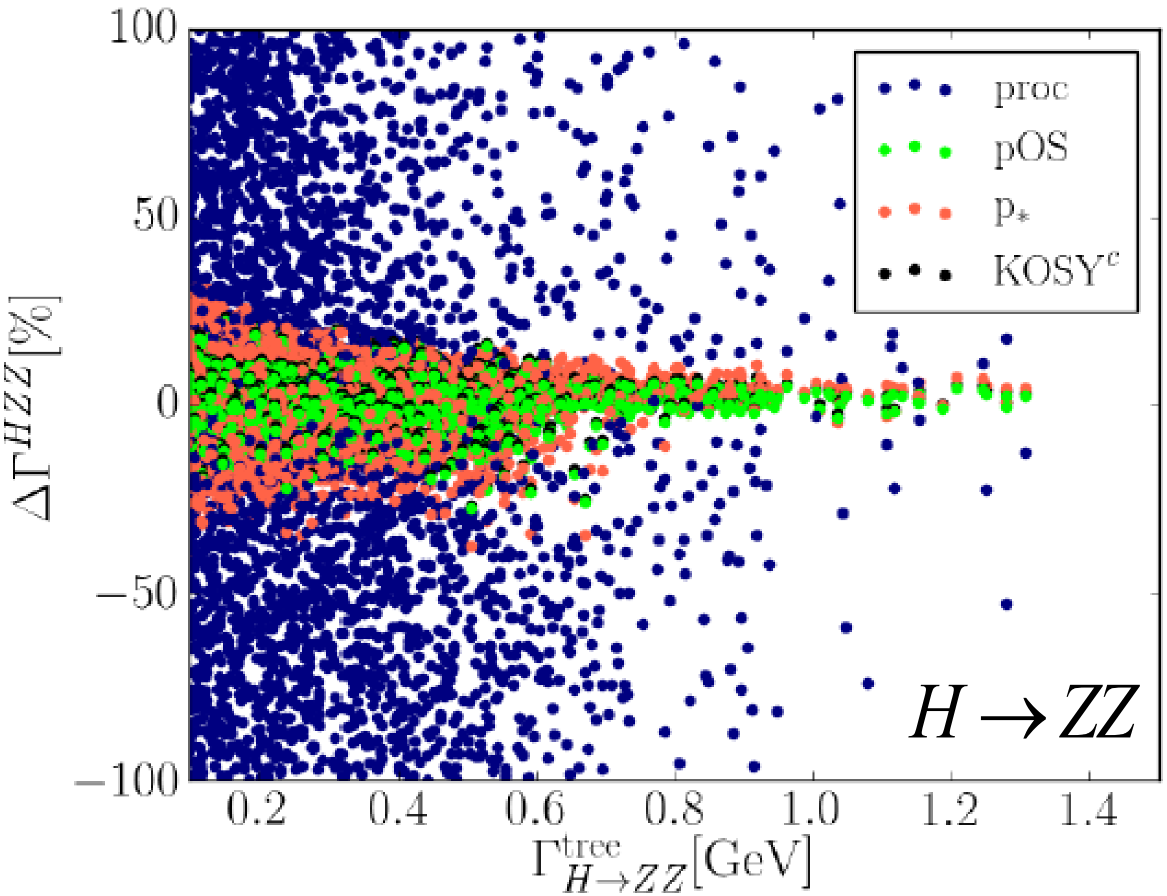




kinks are due to the following thresholds

Kink	Kinematic point	Origin
1	$m_H(739.55 \text{ GeV}) = m_{H^\pm}(659.16 \text{ GeV}) + M_W$	$\delta Z_{HH}, \delta Z_{hH}$
2	$m_H(796.63 \text{ GeV}) = m_A(705.44 \text{ GeV}) + M_Z$	$\delta Z_{HH}, \delta Z_{hH}$

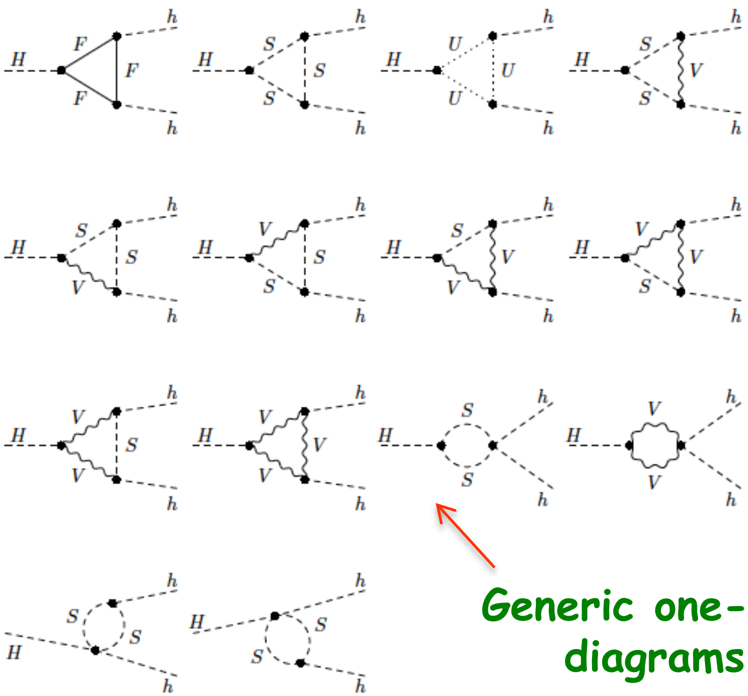
Results



Using scans make clear that the renormalization schemes are stable at least for the parameter points allowed after Run 1.

Conclusion: among these schemes the OS tadpole-pinched scheme turns out to be more stable when changing the renormalization scheme than the p_* scheme for our investigated scenarios. It is clear that the process dependent scheme is the more unstable of all and should be discarded.

Renormalization of the soft breaking term



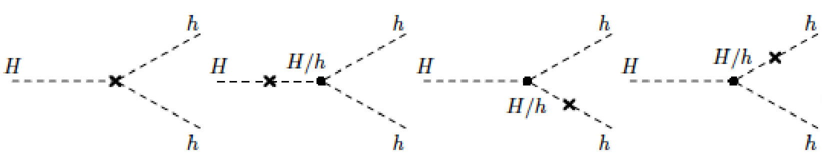
Generic one-loop diagrams

$$\Gamma^{\rm NLO}(H \to hh) = \Gamma^{\rm LO}\left[1 + \Delta^{\rm virt}_{Hhh} + \Delta^{\rm ct}_{Hhh}\right]$$

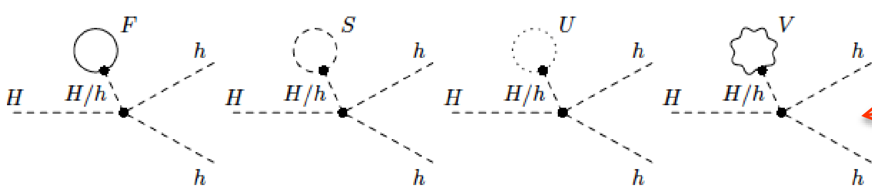
$$\Delta^{\rm ct} = \frac{2\mathcal{M}^{\rm CT}_{Hhh}}{g \cdot g_{Hhh}}$$

$$\mathcal{M}^{\rm CT}_{Hhh} = g\left[g_{hhh}\frac{\delta Z_{hH}}{2} + g_{Hhh}\left(\delta Z_{hh} + \frac{\delta Z_{HH}}{2}\right) + g_{HHh}\delta Z_{Hh} + \frac{1}{g}\delta(g \cdot g_{Hhh})\right]$$

$$\begin{aligned}
\delta(g \cdot g_{Hhh}) \;=\; & g\Big\{ g_{Hhh}\left(\frac{\delta g}{g} - \frac{\delta M_W}{M_W}\right) \\
& + \left(\frac{-c_{\beta-\alpha}}{M_W s_{2\beta}}\right)\left[\frac{s_{2\alpha}}{2}(2\delta m_h^2 + \delta m_H^2) - \left(\frac{3s_{2\alpha} - s_{2\beta}}{s_{2\beta}}\right)\delta m_{12}^2\right] \\
& + \left[g_{Hhh}\left(-t_{\beta-\alpha} - \frac{2}{t_{2\beta}}\right) - \frac{m_{12}^2}{M_W}\left(\frac{c_{\beta-\alpha}}{s_{2\beta}^2}\right)\frac{6s_{2\alpha}}{t_{2\beta}}\right]\delta\beta \\
& + \left[g_{Hhh}(t_{\beta-\alpha} + 6c_{2\alpha}) + \frac{2m_h^2 + m_H^2}{2M_W}\frac{c_{\beta-\alpha}}{3s_{2\alpha} - s_{2\beta}}\right]\delta\alpha\Big\}\,.
\end{aligned}$$



Counterterm diagrams



Extra tadpole diagrams

Renormalization of the soft breaking term

Modified Minimal Subtraction Scheme: In the modified minimal substraction ($\overline{\text{MS}}$) scheme[5] the counterterm δm_{12}^2 is chosen such that it cancels all residual terms of the amplitude, which are proportional to

$$\Delta = \frac{1}{\epsilon} - \gamma_E + \ln(4\pi) \, ,$$

where γ_E denotes the Euler-Mascheroni constant. These terms obviously contain the remaining UV divergences given as poles in ϵ plus additional finite constants that appear universally in all loop integrals [45]. The renormalization of δm_{12}^2 in this scheme is hence given by

$$\delta m_{12}^2 = \delta m_{12}^2(\Delta)|_{\overline{\text{MS}}} \, ,$$

where the right-hand side of the equation symbolicly denotes all terms proportional to Δ that are necessary to cancel the Δ dependence of the remainder of the amplitude.

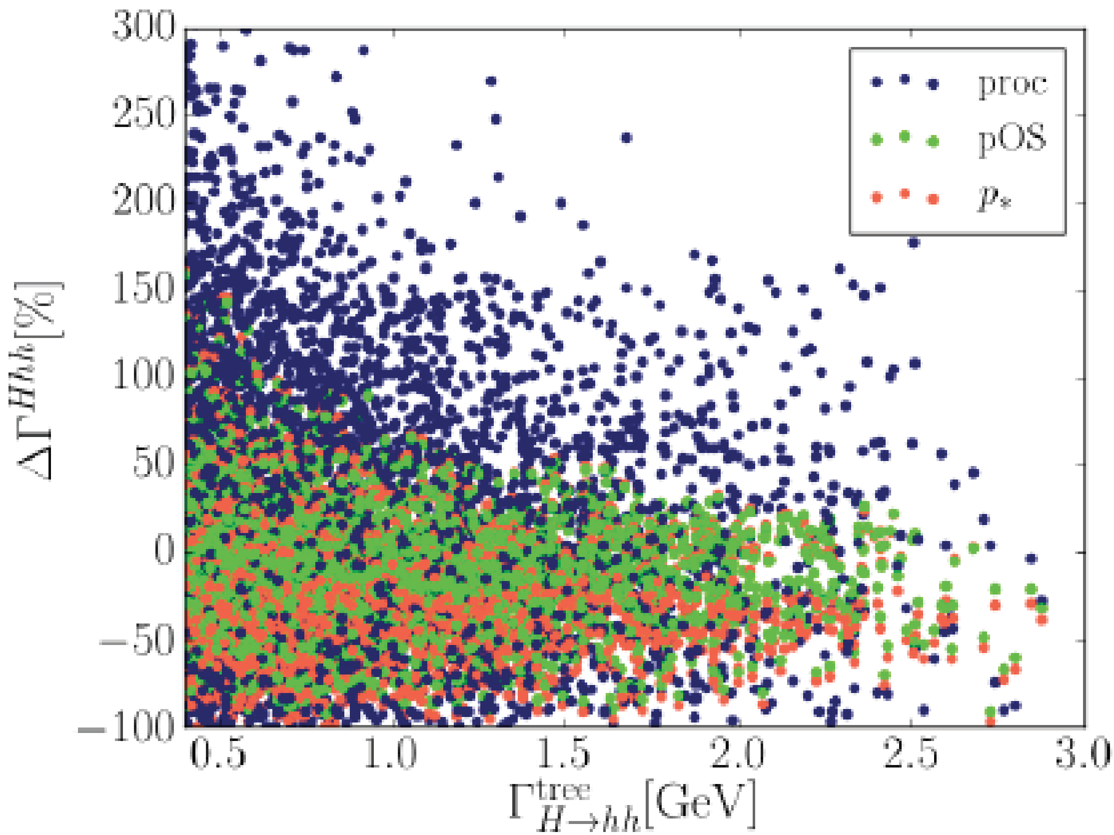
Applying the alternative tadpole scheme instead leads to the cancellation of the UV-divergent gauge-dependent parts within the residual amplitude, *i.e.*

$$\text{\underline{\textit{Alternative tadpole scheme:}}} \qquad \mathcal{M}_{H\to hh}|^{\text{tad}}_{\text{NLO},\delta\xi,\delta p=0} = 0 \, .$$

The angular counterterms in turn can then be defined gauge-independently. The unambiguous gauge-independent definition of the angular counterterms is achieved through the pinched scheme or the definition via a physical process. The counterterm for m_{12}^2 is gauge-independent irrespective of the tadpole scheme and can be renormalized in the $\overline{\text{MS}}$ or the process-dependent scheme.

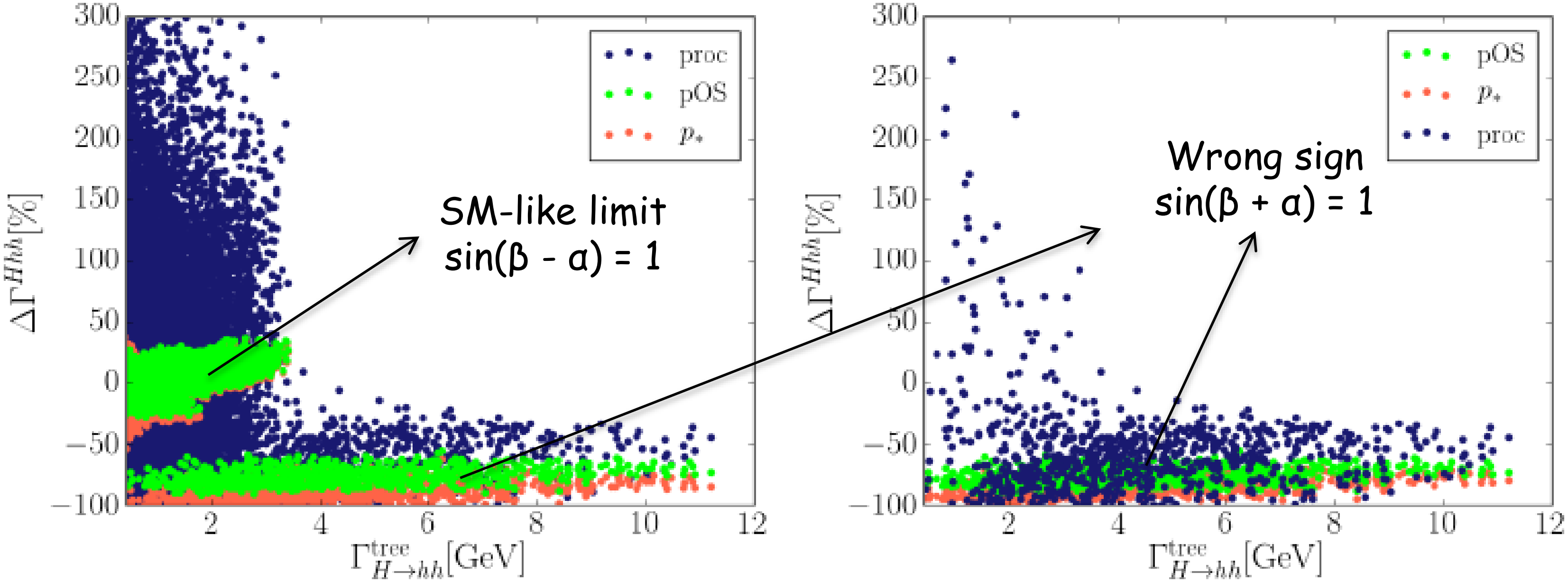
Results

m_{12}^2 has been $\overline{\rm MS}$ renormalized with $\mu_R = 2m_h$.



Scatter plot for the relative NLO corrections to H-> hh for all points passing main experimental and theoretical constraints, as a function of the LO width.

Results



Scatter plot same data, but with following restrictions:

(i) The parameter sets are chosen such that the decay $H \to hh$ is kinematically possible,

$$\textit{Condition (i):} \quad M_H \overset{!}{\geq} 2M_h \,.$$

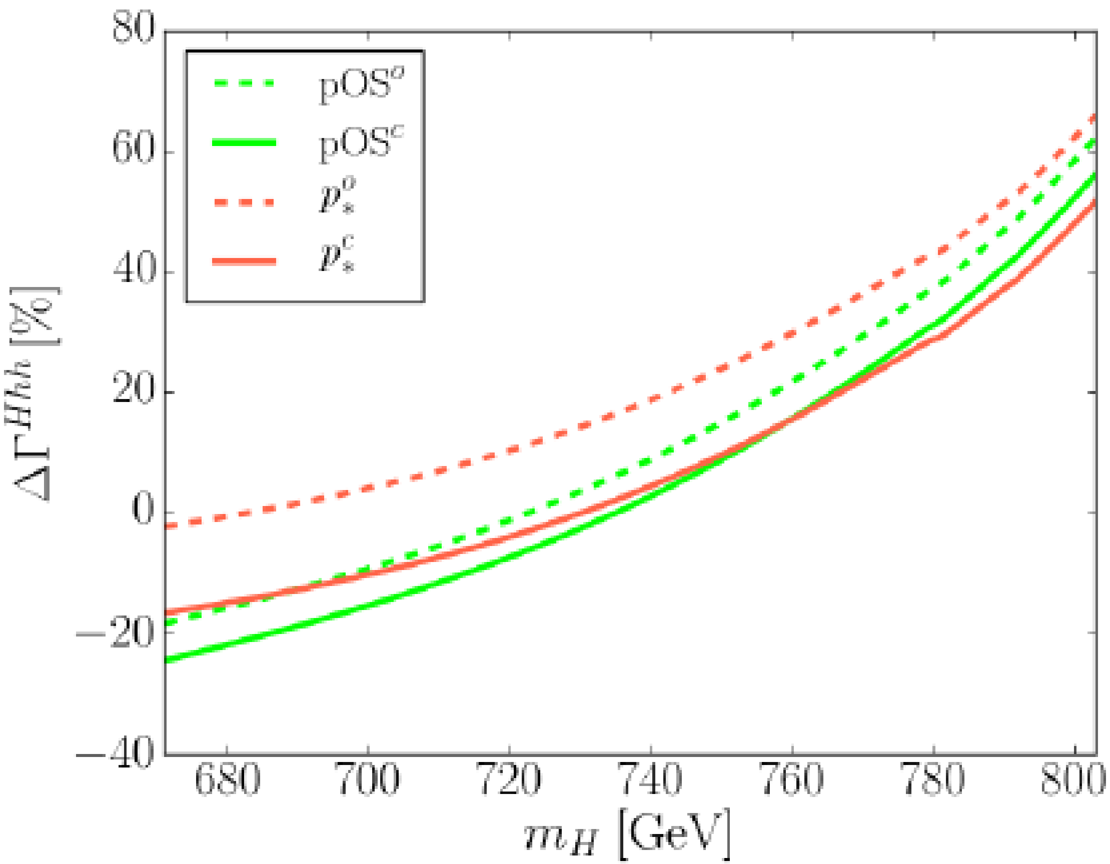
(ii) The parameter sets are chosen such that the decay $H \to hh$ is kinematically possible. Additionally, we require the heavy Higgs boson masses to maximally deviate by $\pm 5\%$ from M, with $M^2 \equiv m_{12}^2/(s_\beta c_\beta)$. We hence have

$$\textit{Condition (ii):} \quad M_H \overset{!}{\geq} 2M_h \quad \text{and}$$

$$m_{\phi_{\rm heavy}} \overset{!}{=} M \pm 5\% \,, \quad \text{with } m_{\phi_{\rm heavy}} \in \{m_H, m_A, m_{H^\pm}\} \,.$$

In these scenarios the non-SM Higgs bosons are approximately mass degenerate and of the order of the $\mathbb{Z}_2$ breaking scale.

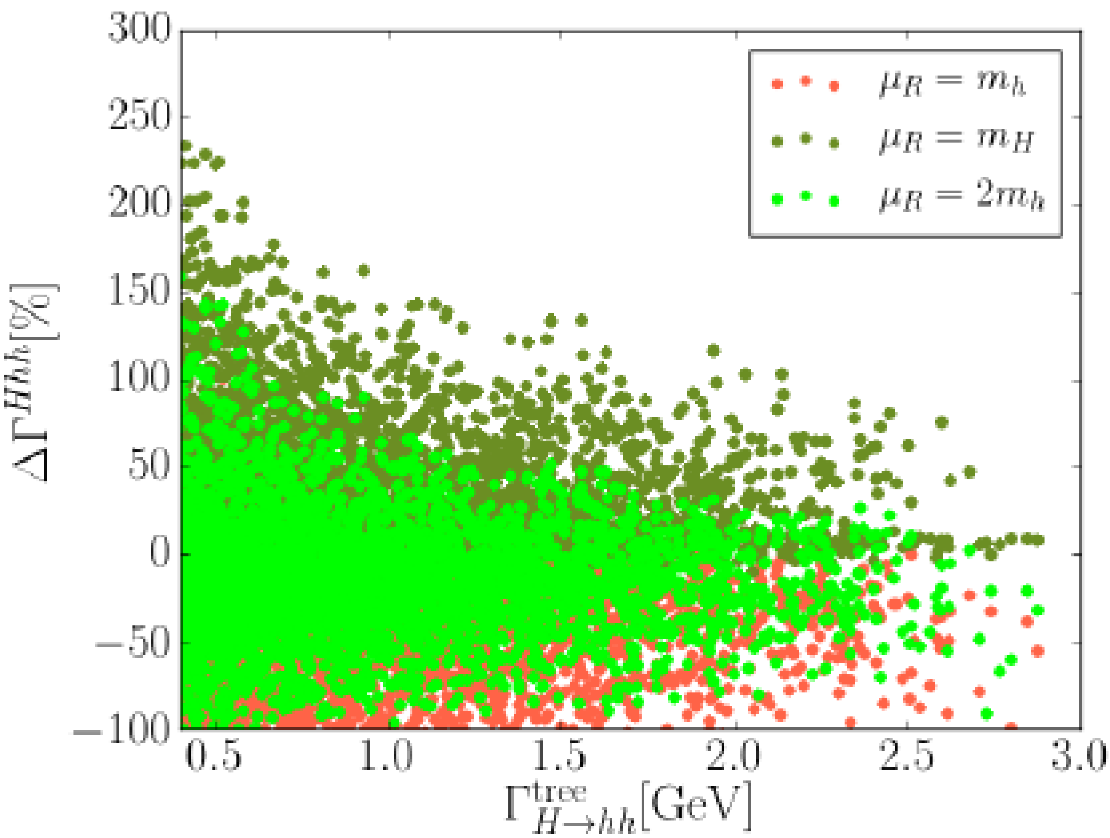
Results



Relative NLO corrections to H-> hh in the tadpole pinched scheme with parameters defined by Scen1.

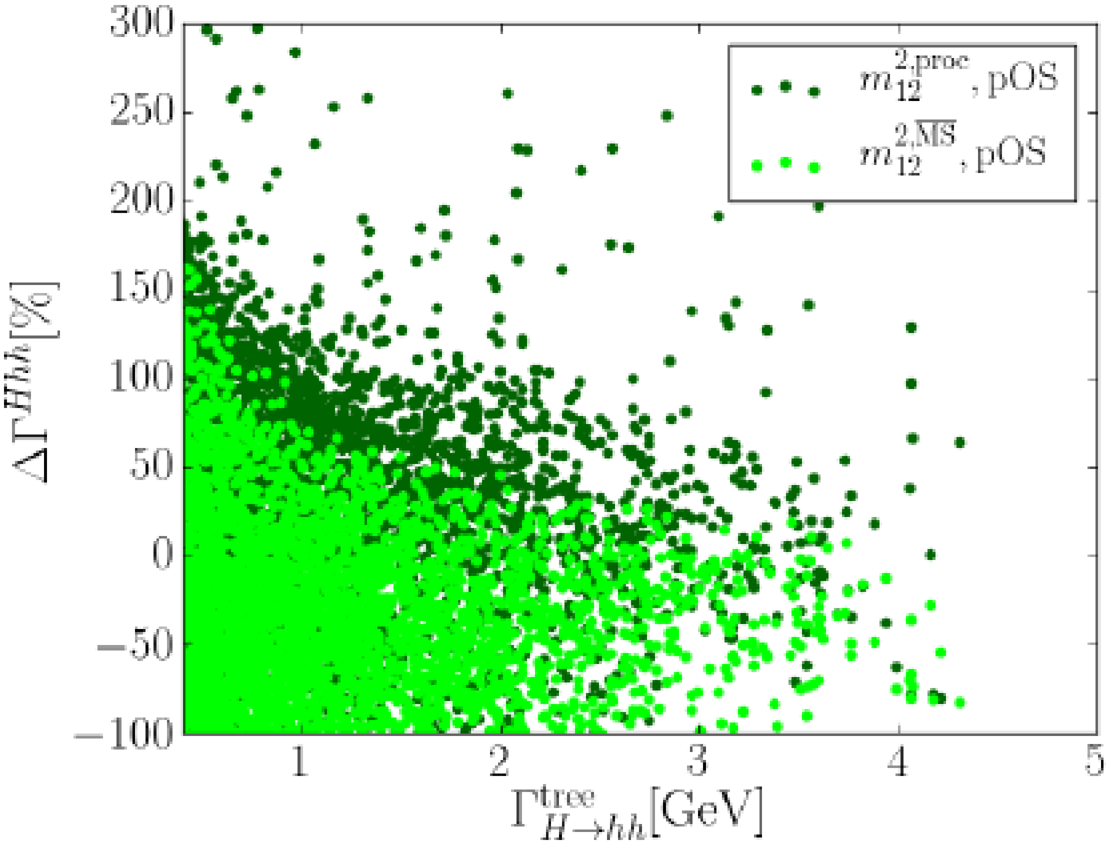
<u>*Scen1:*</u> $m_H = (671.05...803.12)$ GeV , $m_A = 700.13$ GeV , $m_{H^\pm} = 700.35$ GeV ,
$\tan\beta = 1.45851$, $\alpha = -0.570376$, $m_{12}^2 = 2.0761 \cdot 10^5$ GeV^2

Results



Scatter plot for the relative NLO corrections to H->hh (same data set) as a function of the LO width for three different scales. Angles are pOS tadpole pinched renormalized and soft breaking parameter is Msbar renormalized.

Results



Comparison between minimal subtraction and process dependent for the soft breaking term.

Real Singlet model

Kanemura, Kikuchi, Yagyu (2015)

Kanemura, Kikuchi, Yagyu (2016)

$$V(\Phi, S) = (m_\Phi^2 + \mu_{\Phi S}\, v_S' + \lambda_{\Phi S} v_S'^2)|\Phi|^2 + \lambda|\Phi|^4$$
$$+ (\mu_{\Phi S} + 2\lambda_{\Phi S} v_S')|\Phi|^2 S + \lambda_{\Phi S}|\Phi|^2 S^2 + (t_S + 2m_S^2 v_S' + 3\mu_S v_S'^2 + 4\lambda_S v_S'^3)S$$
$$+ (m_S^2 + 3\mu_S v_S' + 6\lambda_S v_S'^2)S^2 + (\mu_S + 4\lambda_S v_S')S^3 + \lambda_S S^4.$$

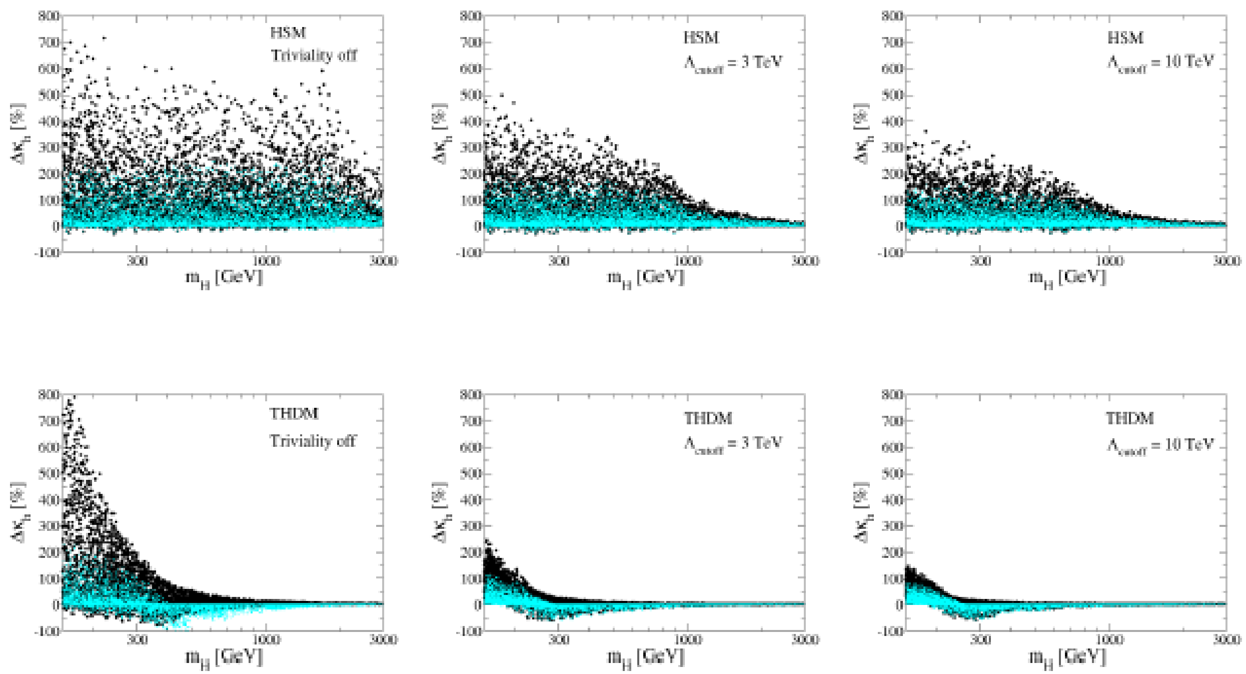
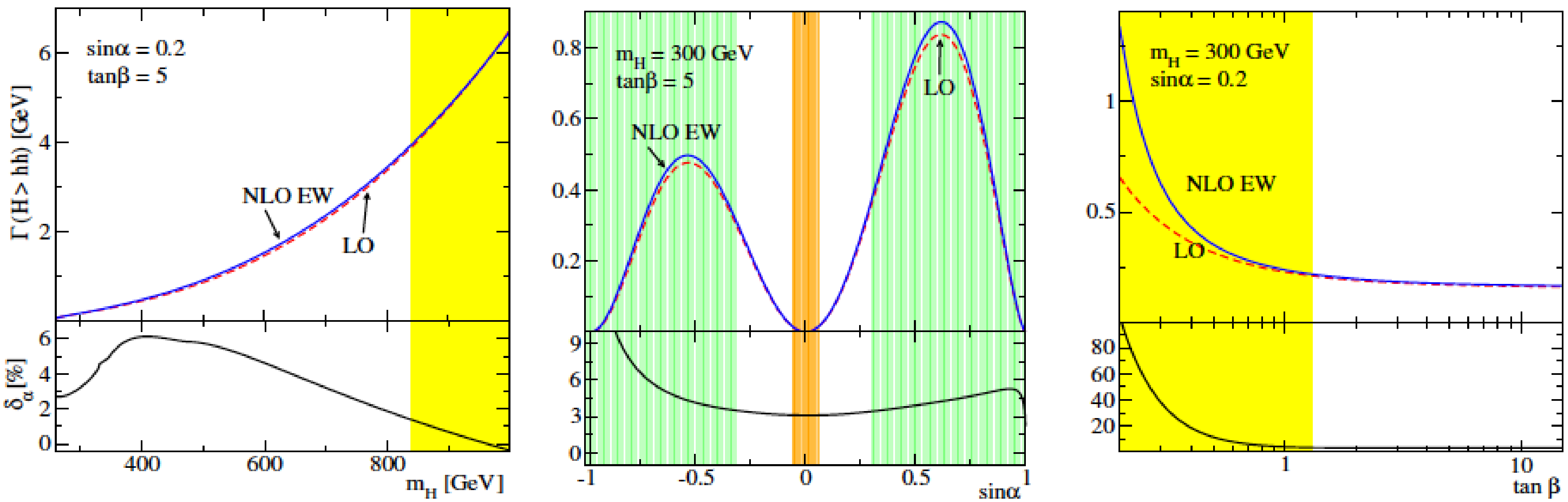


FIG. 4: Scatter plot on the m_H-$\Delta\kappa_h$ plane in the HSM (upper panels) and the Type-I THDM with $\tan\beta = 1$ (lower panels). Each black (light blue) dot is the prediction allowed by theoretical constraints at the one-loop (tree) level. In the left panels, we do not impose the triviality bound, and impose the vacuum stability bound without the scale dependence. In the center and right panel, we impose all the theoretical constraints using $\Lambda_{\rm cutoff} = 3$ and 10 TeV, respectively.

Real Singlet model

Bojarski, Chalons, Lopez-Val, Robens (2016)



$$H \rightarrow hh$$

NLO Corrections shown to be only a few percent

Benchmark Fever in the Scalar Sector

https://twiki.cern.ch/twiki/bin/view/LHCPhysics/LHCHXSWG

https://twiki.cern.ch/twiki/bin/view/LHCPhysics/LHCHXSWGHiggsMailingList

BP1: CP-conserving 2HDM with softly-broken Z2-symmetry. [*Howard Haber, Oscar Stål*]
https://twiki.cern.ch/twiki/pub/LHCPhysics/LHCHXSWG3Benchmarks2HDM/HH_OS_2HDM_Benchmarks.pdf

BP2: **:** CP-conserving 2HDM with softly-broken Z2-symmetry. [*Felix Kling, Shufang Su*]
https://twiki.cern.ch/twiki/pub/LHCPhysics/LHCHXSWG3Benchmarks2HDM/Exotic_Benchmarks.pdf

BP3: **:** CP-conserving 2HDM with softly-broken Z2-symmetry.[*Glauber Dorsch, Stephan Huber, Ken Mimasu, Jose Miguel No*]
https://twiki.cern.ch/twiki/pub/LHCPhysics/LHCHXSWG3Benchmarks2HDM/2HDM_Cosmic_Benchmarks.pdf

BP4: **:** CP-conserving 2HDM with softly-broken Z2-symmetry. [*Robin Aggleton, Daniele Barducci, Alexandre Nikitenko, Stefano Moretti, Claire Shepherd-Themistocleous*]
https://twiki.cern.ch/twiki/pub/LHCPhysics/LHCHXSWG3Benchmarks2HDM/2HDM_WG-final.pdf

BP5: Inert 2HDM. [Agnieszka Ilnicka, Maria Krawczyk, Tania Robens]
https://twiki.cern.ch/twiki/pub/LHCPhysics/LHCHXSWG3Benchmarks2HDM/IDM_benchmarks.pdf

BP6: Fermiophobic 2HDM. [David Lopez-Val]
https://twiki.cern.ch/twiki/pub/LHCPhysics/LHCHXSWG3Benchmarks2HDM/fermiophobic.pdf

BP7 Georgi-Machacek model benchmark *[H. Logan]*
https://twiki.cern.ch/twiki/pub/LHCPhysics/LHCHXSWG3BenchmarksNon2HDM/h5plane-benchmark.pdf

BP8 Complex 2HDM benchmarks *[D. Fontes, J.C. Romao, R. Santos and J.P. Silva]*
https://twiki.cern.ch/twiki/pub/LHCPhysics/LHCHXSWG3BenchmarksNon2HDM/benchmark-C2HDM.pdf

BP9 Flavour-changing 2HDM benchmarks *[F.J. Botella, G.C. Branco, M. Nebot and M. Rebelo]*
https://twiki.cern.ch/twiki/pub/LHCPhysics/LHCHXSWG3BenchmarksNon2HDM/benchmark-FCNC2HDM.pdf

BP10 Real and complex singlet benchmarks *[R. Costa, M. Muhlleitner, M.O.P. Sampaio and R. Santos]*
https://twiki.cern.ch/twiki/pub/LHCPhysics/LHCHXSWG3BenchmarksNon2HDM/BenchmarksCxSM_and_RxSM.pdf

BP11 Singlet benchmarks *[T. Robens and T.Stefaniak]*
https://twiki.cern.ch/twiki/pub/LHCPhysics/LHCHXSWG3BenchmarksNon2HDM/benchmarks_robens_stefaniak.pdf

1st call - CP-conserving 2HDM

Meeting 23 June 2015

BP1: *Howard Haber, Oscar Stål*
Phenomenological benchmarks for the CP-conserving 2HDM with softly-broken Z_2-symmetry.
https://twiki.cern.ch/twiki/pub/LHCPhysics/LHCHXSWG3Benchmarks2HDM/HH_OS_2HDM_Benchmarks.pdf

BP2: *Felix Kling, Shufang Su*
Benchmark points for exotic Higgs decays.
https://twiki.cern.ch/twiki/pub/LHCPhysics/LHCHXSWG3Benchmarks2HDM/Exotic_Benchmarks.pdf

BP3: *Glauber Dorsch, Stephan Huber, Ken Mimasu, Jose Miguel No*
We attach our 2HDM benchmarks for LHC searches, based on our recent work 1405.5537, together with some discussion on their salient features and motivation.
https://twiki.cern.ch/twiki/pub/LHCPhysics/LHCHXSWG3Benchmarks2HDM/2HDM_Cosmic_Benchmarks.pdf

BP4: *Robin Aggleton, Daniele Barducci, Alexandre Nikitenko, Stefano Moretti, Claire Shepherd-Themistocleous*
Here in attach a brief note explaining the benchmark scenarios we chose (.pdf and .tex), together with a file with the definition of the benchmarks in terms of 2HDM parameter. We are still working on other benchmark scenarios mentioned in a previous mail (higgs-to-2-Higgs topologies) and we will provide them shortly.
https://twiki.cern.ch/twiki/pub/LHCPhysics/LHCHXSWG3Benchmarks2HDM/2HDM_WG-final.pdf

BP5: *Agnieszka Ilnicka, Maria Krawczyk, Tania Robens*
Please find attached a short writeup containing benchmarks for the IDM. This note should be seen as a preview of a full publication which should then be used as a reference.
https://twiki.cern.ch/twiki/pub/LHCPhysics/LHCHXSWG3Benchmarks2HDM/IDM_benchmarks.pdf

BP6: *David Lopez-Val*
Following your call for 2HDM benchmark suggestions, I'd like to contribute with one of the scenarios we devised for our Higgs pair study [arXiv:1407.0281]. Please find attached all the details, hopefully complying with the indications given in your email.
https://twiki.cern.ch/twiki/pub/LHCPhysics/LHCHXSWG3Benchmarks2HDM/fermiophobic.pdf

The softly broken Z_2 symmetric 2HDM has no tree-level FCNCs. We further assume a CP-conserving potential

$$V(\Phi_1, \Phi_2) = m_1^2 \Phi_1^\dagger \Phi_1 + m_2^2 \Phi_2^\dagger \Phi_2 - \left(m_{12}^2 \Phi_1^\dagger \Phi_2 + \text{h.c.}\right) + \frac{\lambda_1}{2}\left(\Phi_1^\dagger \Phi_1\right)^2 + \frac{\lambda_2}{2}\left(\Phi_2^\dagger \Phi_2\right)^2$$
$$+ \lambda_3\left(\Phi_1^\dagger \Phi_1\right)\left(\Phi_2^\dagger \Phi_2\right) + \lambda_4\left(\Phi_1^\dagger \Phi_2\right)\left(\Phi_2^\dagger \Phi_1\right) + \frac{\lambda_5}{2}\left[\left(\Phi_1^\dagger \Phi_2\right)^2 + \text{h.c.}\right]$$

- m^2_{12} and λ_5 real and the vacuum configuration is (CP-conserving)

$$\langle \Phi_1 \rangle = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ v_1 \end{pmatrix} \qquad \langle \Phi_2 \rangle = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ v_2 \end{pmatrix}$$

and the common convention for the ratio of the vacuum expectation values is

$$\tan\beta = \frac{v_2}{v_1} \qquad \text{with} \qquad 0 \le \beta \le \frac{\pi}{2}$$

The model has three neutral states and two charged states:

- **Two CP-even states h and H with $m_h < m_H$.**
- **One CP-odd state A.**
- **Two charged states $H^{\pm}$.**

The matrix that diagonalises the CP-even states mass matrix

$$\begin{pmatrix} h_1 \\ h_2 \end{pmatrix} = \begin{pmatrix} \cos\alpha & -\sin\alpha \\ \sin\alpha & \cos\alpha \end{pmatrix} \begin{pmatrix} H \\ h \end{pmatrix}$$

and the common convention for the range of α is

$$-\frac{\pi}{2} \le \alpha \le \frac{\pi}{2}$$

Higgs couplings to gauge bosons

$$g_{2HDM}^{hVV} = \sin(\beta - \alpha)\, g_{SM}^{hVV} \qquad V = W, Z$$

$$g_{2HDM}^{HVV} = \cos(\beta - \alpha)\, g_{SM}^{hVV} \qquad V = W, Z$$

Yukawa couplings

Φ_2 always couples to up-type quarks

Type I	Φ_2 to leptons and to down-type quarks
Type II	Φ_1 to leptons and to down-type quarks
Type F=X=III	Φ_2 to leptons Φ_1 to down-type quarks
Type LS=Y=IV	Φ_1 to leptons Φ_2 to down-type quarks

	Type I	Type II	Lepton Specific	Flipped
Up	$\frac{c_\alpha}{s_\beta}$	$\frac{c_\alpha}{s_\beta}$	$\frac{c_\alpha}{s_\beta}$	$\frac{c_\alpha}{s_\beta}$
Down	$\frac{c_\alpha}{s_\beta}$	$-\frac{s_\alpha}{c_\beta}$	$\frac{c_\alpha}{s_\beta}$	$-\frac{s_\alpha}{c_\beta}$
Leptons	$\frac{c_\alpha}{s_\beta}$	$-\frac{s_\alpha}{c_\beta}$	$-\frac{s_\alpha}{c_\beta}$	$\frac{c_\alpha}{s_\beta}$

Lightest Higgs couplings

$$M^2 = \frac{m_{12}^2}{\sin\beta\cos\beta}$$

$$\kappa_i = \frac{g_{2HDM}}{g_{SM}}$$

at tree-level

$$\kappa_i^2 = \frac{\Gamma^{2HDM}(h \to i)}{\Gamma^{SM}(h \to i)}$$

- **Alignment limit (aka SM-like limit)**

$$\sin(\beta-\alpha)=1 \;\Rightarrow\; \kappa_F = 1;\;\; \kappa_V = 1$$

- **Decoupling limit**

$$\sin(\beta-\alpha)=1 \;\Rightarrow\; m_\Phi^2 = M^2 + \sum_i \lambda_i v^2 + O\left(\frac{v^4}{M^2}\right) \quad (\text{with } \Phi = H, A, H^\pm)$$

Setting $M^2 >> \lambda_i v^2$

Gunion, Haber (2003).
Kanemura, Okada, Senaha, Yuan (2004).
Ginzburg, Krawczyk (2005).

all heavy scalars masses are determined by M and independent of the λ

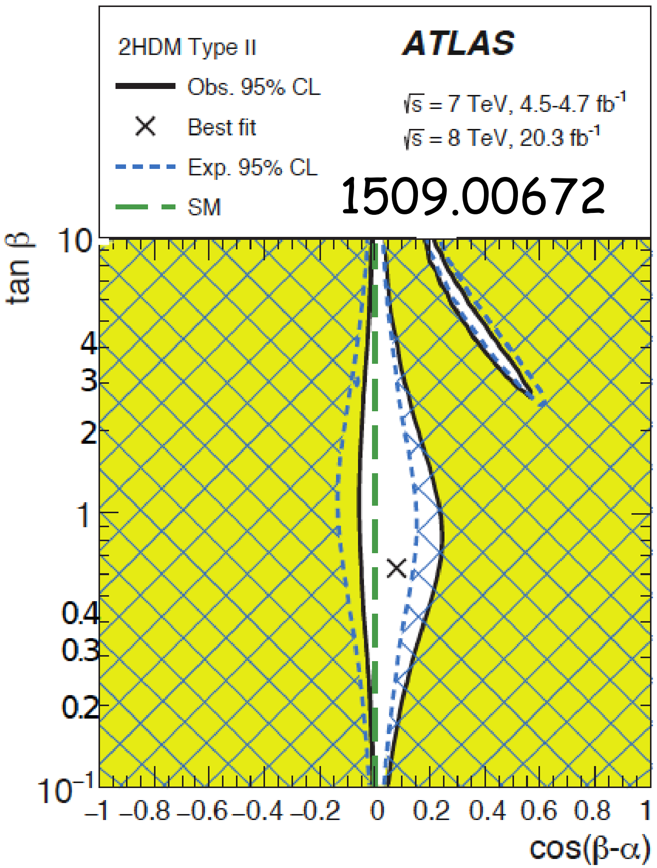
$$M^2 \approx m_H^2 \approx m_A^2 \approx m_{H^\pm}^2 >> \lambda_i v^2$$

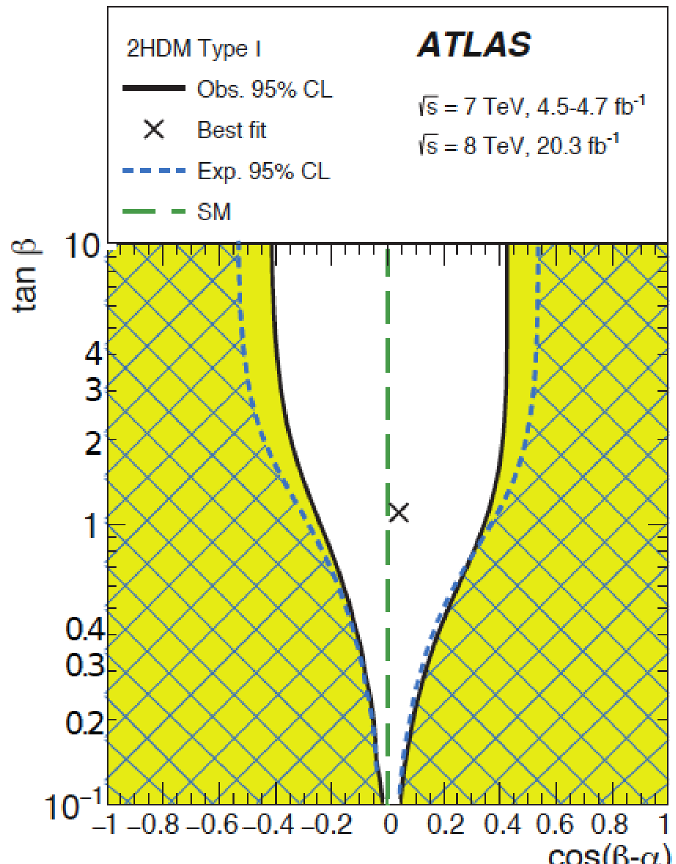
- **Wrong-sign limit (type II and F)**

Ferreira, Gunion, Haber, RS (2014).
Ferreira, Guedes, Sampaio, RS (2014).

$$\sin(\beta+\alpha)=1 \Rightarrow \kappa_D=-1 \quad (\kappa_U=1)$$

$$\sin(\beta-\alpha)=\frac{\tan^2\beta-1}{\tan^2\beta+1} \Rightarrow \kappa_V \geq 0 \text{ if } \tan\beta \geq 1 \qquad \kappa_D\kappa_V<0$$





- **Type I**

$$\sin(\beta+\alpha)=1 \Rightarrow$$

$$\kappa_U=\kappa_D=\kappa_L=1$$

still

$$\sin(\beta-\alpha)=\frac{\tan^2\beta-1}{\tan^2\beta+1}$$

Overview - Classification of Benchmark Points

Overall feature	Signature	Benchmark Points
I. Exotic decay of Higgses		
Neutral Higgs to neutral Higgs + Z		
H->AZ	bbll, tautaull	BP1_D, BP2_2, BP2_3, BP2_4
A->HZ	bbll, tautaull, WWZ, ZZZ	BP2_1, BP2_8, BP3_A1, BP3_A2, BP3_B1, BP3_B2
A->hZ	bbll, tautaull, gagall, WWll, ZZll	BP1_B, BP2_9, BP2_10
	comment	The heavy CP-even Higgs H being the 125 GeV SM-like Higgs or non-alignment
h->ZA	Zmumu, Ztautau, Zbb	BP4_ABCD
	comment	SM Higgs decay

The benchmarks are discussed in detail in

https://twiki.cern.ch/twiki/bin/view/LHCPhysics/LHCHXSWG3Benchmarks2HDM

Neutral Higgs to neutral Higgs + neutral Higgs		
H->AA	bbbb, 4tau, bbtautau, bbgaga	BP2_3, BP2_3, BP2_5
H->hh	bbbb, bbtautau, bbWW, bbZZ, bbgaga	BP1_A, BP2_9
	comment	The heavy CP-even Higgs H being the 125 GeV SM-like Higgs or non-alignment
Neutral Higgs to Hpm Wmp		
H->Hpm Wmp	tblnu	BP1_D, BP2_6, BP2_8
A->Hpm Wmp	tblnu, taunulnu	BP1_D, BP2_6, BP2_7, BP3_A2, BP3_B2
Neutral Higgs to H+H-		
H->H+H-	ttbb	BP2_8
Hpm to neutral Higgs + Wpm, Hpm produced with tbHpm channel		
Hpm->AW	bbbbWW, tautaubbWW	BP1_D, BP2_2, BP2_3, BP2_4, BP2_5
Hpm->HW	bbbbWW, tautaubbWW	BP2_1
Hpm->hW	bbbbWW, tautaubbWW,bbZZWW, bbWWWW, bbgagaWW	BP2_9, BP2_10
	comment	The heavy CP-even Higgs H being the 125 GeV SM-like Higgs
Long cascade		
Hpm->AW->HZW	bbWZ, tautauWZ	BP1_E
A->Hpm Wmp ->WWH	bbWW, tautauWW	BP1_E
	comment	Small branching fraction, <5%

The benchmarks are discussed in detail in

https://twiki.cern.ch/twiki/bin/view/LHCPhysics/LHCHXSWG3Benchmarks2HDM

Which planes to choose?

Scalar to two gauge bosons

$$H \to W^+W^-(ZZ) \qquad \text{plane: } (m_H,\ \cos(b-a))$$

Scalar to one scalar and one gauge boson (m_h = 125 GeV)

$$H \to AZ;\ A \to HZ \qquad \text{plane: } (m_H,\ m_A);\ (m_{H(A)},\ \cos(b-a))$$

Baryogenesis $\quad m_A - m_H \gg v$ and light m_H large Br(A → HZ)

$$A \to hZ \qquad \text{plane: } (m_A,\ \cos(b-a))$$

Which planes to choose?

SM-like Higgs decay to one scalar and one gauge boson (m_h = 125 GeV)

$$h \to (A \to \mu^+\mu^- / \tau^+\tau^- / b\bar{b})\, Z \ \text{ plane: } (m_A,\ \tan\beta);\ (m_A,\ \cos(\beta-\alpha))$$

light m_A = 6 to 70 GeV

Scalar to two scalar decays (m_h = 125 GeV)

$$H \to hh;\ H \to AA \qquad \text{plane: } (m_H,\ \tan\beta \text{ or } \cos(\beta-\alpha));(m_H,\ m_A)$$

$$\mathrm{h} \to AA \qquad \text{plane: } (m_A,\ \tan\beta \text{ or } \cos(\beta-\alpha))$$

Which planes to choose?

Long Cascade

$$pp \to A \to H^{\pm}W^{\square} \to HW^{\pm}W^{\square} \to (H \to)W^{\pm}W^{\square}$$

$$\text{plane: } (m_A,\ m_H);\ (m_A,\ \cos(b - a));\ (m_A,\ \tan b)$$

Scenarios vs. Benchmarks?

The wrong sign scenario

Scenario F (Flipped Yukawa)								
	m_h (GeV)	m_H (GeV)	$c_{\beta-\alpha}$	Z_4	Z_5	Z_7	$\tan\beta$	Type
F2	125	$150\ldots600$	$\sin 2\beta$	-2	-2	0	$5\ldots50$	II

As in Scenario A, we take $m_h < m_H < m_A = m_{H^\pm}$. However, we fix $c_{\beta-\alpha} = s_{2\beta}$ so that

$$\frac{g_{hbb}}{g_{hbb}^{\rm SM}} = s_{\beta-\alpha} - c_{\beta-\alpha}\tan\beta = -1.$$

The Inert 2HDM

$$V(\Phi_1, \Phi_2) /.\, m_{12}^2 \to 0 \qquad \langle \Phi_1 \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v \end{pmatrix}, \quad \langle \Phi_2 \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ 0 \end{pmatrix} \qquad \begin{cases} \Phi_1 \to \Phi_S \\ \Phi_2 \to \Phi_D \end{cases}$$

The first doublet contains the SM-like Higgs boson h, and the second doublet contains four dark (inert) scalars H, A and $H^{\pm}$.

H is taken to be the lightest scalar (stable).

Free parameters (Inert)

Parameter	2HDM (Z_2 basis)	Inert (Z_2 basis)
Masses	$m_h, m_H, m_A, m_{H\pm}$	$m_h, m_H, m_A, m_{H\pm}$
Angles	$\tan\beta, (\beta-\alpha)$	
Other	${m_{12}}^2$	λ_2, λ_{345}

A fermiophobic limit of the 2HDM

- Type I 2HDM with sinα=0
- h is the SM-like Higgs boson with a mass of 125 GeV
- H is the fermiophobic scalar
- Since we are close to alignment

$$\cos(\beta - \alpha) \approx 0 \quad \Rightarrow \quad \frac{1}{\sqrt{1+\tan^2 \beta}} << 1 \quad \Rightarrow \quad \tan\beta >> 1$$

- Relevant variables in the analysis are

  - **tanβ – departure from alignment**
  - **m_H – mass of fermiophobic scalar**
  - **ΔM – heavy scalars mass splitting** $\qquad \Delta M = m_H - m_A (= m_{H^\pm})$

II. Decay of Higgses to WW, ZZ, gaga, bb, tautau		
Fermiophobic heavy H, produced via H+H-, HA, H+A, H+H		
H+->HW, A->HZ	H->WW,ZZ, multigauge boson final states	BP6
	comment	Small production cross section, difficult to search, a rather light, yet very elusive, non-SM scalar.
Non-alignment/H being the SM-like 125 GeV Higgs/mA~mh~125/flipped Yukawa/MSSM-like		
H/h to SM final states	usual SM-like Higgs search channel, higher mass	BP1_A, BP1_B, BP1_C, BP1_F, BP1_G
III. The lightest neutral Higgs being MET		
H in the Inert Doublet Model, produced via H+H-, HA, H+A, H+H		
H+->HW (or AW), A->HZ	W/Z/WW/WZ+MET final states	BP5
	comment	Small production cross section for some benchmarks [masses > 300 GeV], H is dark matter candidate [mass> 50 GeV], unique signal of MET. W,Z decays as in SM.. SM gauge couplings and kinematics determine production cross sections and decays

The benchmarks are discussed in detail in

https://twiki.cern.ch/twiki/bin/view/LHCPhysics/LHCHXSWG3Benchmarks2HDM

Which planes to choose?

Inert

$$pp \to AH \to ZHH \to Z + \mathrm{MET} \qquad \text{plane: } (m_A,\ m_H)$$

$$pp \to H^{\pm}H^{\mp} \to W^{\pm}W^{\mp}HH \to W^{\pm}W^{\mp}MET \quad \text{plane: } (m_{H^{\pm}},\ m_H)$$

cross sections reach 350 fb (first) and 90 fb (second) at 13 TeV with BRs close to 100%

Fermiophobic

$$pp \to AH \to AVV$$

most promising but still with very small cross section (< 2fb)

2^{nd} call – non CP-conserving 2HDM, singlet, triplet

Meeting 10 September 2015

BP7 Georgi-Machacek model benchmark *[H. Logan]*
https://twiki.cern.ch/twiki/pub/LHCPhysics/LHCHXSWG3BenchmarksNon2HDM/h5plane-benchmark.pdf

BP8 Complex 2HDM benchmarks *[D. Fontes, J.C. Romao, R. Santos and J.P. Silva]*
https://twiki.cern.ch/twiki/pub/LHCPhysics/LHCHXSWG3BenchmarksNon2HDM/benchmark-C2HDM.pdf

BP9 Flavour-changing 2HDM benchmarks *[F.J. Botella, G.C. Branco, M. Nebot and M. Rebelo]*
https://twiki.cern.ch/twiki/pub/LHCPhysics/LHCHXSWG3BenchmarksNon2HDM/benchmark-FCNC2HDM.pdf

BP10 Real and complex singlet benchmarks *[R. Costa, M. Muhlleitner, M.O.P. Sampaio and R. Santos]*
https://twiki.cern.ch/twiki/pub/LHCPhysics/LHCHXSWG3BenchmarksNon2HDM/BenchmarksCxSM_and_RxSM.pdf

BP11 Singlet benchmarks *[T. Robens and T.Stefaniak]*
https://twiki.cern.ch/twiki/pub/LHCPhysics/LHCHXSWG3BenchmarksNon2HDM/benchmarks_robens_stefaniak.pdf

BP8 CP-violating 2HDM (C2HDM)

The softly broken Z_2 symmetric CP-violating potential

$$V(\Phi_1, \Phi_2) = m_1^2 \Phi_1^\dagger \Phi_1 + m_2^2 \Phi_2^\dagger \Phi_2 - \left(m_{12}^2 \Phi_1^\dagger \Phi_2 + \text{h.c.}\right) + \frac{\lambda_1}{2}\left(\Phi_1^\dagger \Phi_1\right)^2 + \frac{\lambda_2}{2}\left(\Phi_2^\dagger \Phi_2\right)^2$$
$$+ \lambda_3 \left(\Phi_1^\dagger \Phi_1\right)\left(\Phi_2^\dagger \Phi_2\right) + \lambda_4 \left(\Phi_1^\dagger \Phi_2\right)\left(\Phi_2^\dagger \Phi_1\right) + \frac{\lambda_5}{2}\left[\left(\Phi_1^\dagger \Phi_2\right)^2 + \text{h.c.}\right]$$

- m^2_{12} and λ_5 complex

Free parameters

Parameter	2HDM (Z_2 basis)	C2HDM (Z_2 basis)
Masses	m_h, m_H, m_A, $m_{H\pm}$	m_1, m_2, $m_{H\pm}$
Angles	$\tan\beta$, $(\beta-\alpha)$	$\tan\beta$, α_1, α_2, α_3
Other	$m_{12}{}^2$	$\mathrm{Re}(m_{12}{}^2)$

Lightest Higgs couplings

$$\alpha_1 = \alpha + \pi/2$$

to gauge bosons

$$g^{hVV}_{2HDM} = \sin(\beta - \alpha)\, g^{hVV}_{SM} \qquad V = W, Z$$

CP-conserving

$$g^{hVV}_{C2HDM} = C\, g^{hVV}_{SM} = (c_\beta R_{11} + s_\beta R_{12})\, g^{hVV}_{SM} = \cos(\alpha_2)\cos(\beta - \alpha_1)\, g^{hVV}_{SM}$$

CP-violating

$$g^{hVV}_{C2HDM} = \cos(\alpha_2)\, g^{hVV}_{2HDM}$$

$$C \equiv c_\beta R_{11} + s_\beta R_{12}$$

$$R = \begin{pmatrix} c_1 c_2 & s_1 c_2 & s_2 \\ -(c_1 s_2 s_3 + s_1 c_3) & c_1 c_3 - s_1 s_2 s_3 & c_2 s_3 \\ -c_1 s_2 c_3 + s_1 s_3 & -(c_1 s_3 + s_1 s_2 c_3) & c_2 s_3 \end{pmatrix}$$

$|s_2| = 0 \Rightarrow h_1$ is a pure scalar,

$|s_2| = 1 \Rightarrow h_1$ is a pure pseudoscalar

Lightest Higgs couplings

Yukawa couplings

$$Y_{C2HDM} \equiv c_2 Y_{2HDM} \pm i\gamma_5 s_2 \begin{cases} t_\beta \\ 1/t_\beta \end{cases}$$

$$R = \begin{pmatrix} c_1 c_2 & s_1 c_2 & s_2 \\ -(c_1 s_2 s_3 + s_1 c_3) & c_1 c_3 - s_1 s_2 s_3 & c_2 s_3 \\ -c_1 s_2 c_3 + s_1 s_3 & -(c_1 s_3 + s_1 s_2 c_3) & c_2 s_3 \end{pmatrix}$$

CP-conserving

	Type I	Type II	Lepton Specific	Flipped
Up	$\frac{c_\alpha}{s_\beta}$	$\frac{c_\alpha}{s_\beta}$	$\frac{c_\alpha}{s_\beta}$	$\frac{c_\alpha}{s_\beta}$
Down	$\frac{c_\alpha}{s_\beta}$	$-\frac{s_\alpha}{c_\beta}$	$\frac{c_\alpha}{s_\beta}$	$-\frac{s_\alpha}{c_\beta}$
Leptons	$\frac{c_\alpha}{s_\beta}$	$\frac{c_\alpha}{s_\beta}$	$-\frac{s_\alpha}{c_\beta}$	$\frac{c_\alpha}{s_\beta}$

$$\alpha_1 = \alpha + \pi/2$$

CP-violating

	Type I	Type II	Lepton Specific	Flipped
Up	$\frac{R_{12}}{s_\beta} - ic_\beta \frac{R_{13}}{s_\beta}\gamma_5$	$\frac{R_{12}}{s_\beta} - ic_\beta \frac{R_{13}}{s_\beta}\gamma_5$	$\frac{R_{12}}{s_\beta} - ic_\beta \frac{R_{13}}{s_\beta}\gamma_5$	$\frac{R_{12}}{s_\beta} - ic_\beta \frac{R_{13}}{s_\beta}\gamma_5$
Down	$\frac{R_{12}}{s_\beta} + ic_\beta \frac{R_{13}}{s_\beta}\gamma_5$	$\frac{R_{11}}{c_\beta} - is_\beta \frac{R_{13}}{c_\beta}\gamma_5$	$\frac{R_{12}}{s_\beta} + ic_\beta \frac{R_{13}}{s_\beta}\gamma_5$	$\frac{R_{11}}{c_\beta} - is_\beta \frac{R_{13}}{c_\beta}\gamma_5$
Leptons	$\frac{R_{12}}{s_\beta} + ic_\beta \frac{R_{13}}{s_\beta}\gamma_5$	$\frac{R_{11}}{c_\beta} - is_\beta \frac{R_{13}}{c_\beta}\gamma_5$	$\frac{R_{11}}{c_\beta} - is_\beta \frac{R_{13}}{c_\beta}\gamma_5$	$\frac{R_{12}}{s_\beta} + ic_\beta \frac{R_{13}}{s_\beta}\gamma_5$

Classes of CP-violating processes

Classes	C_1	C_2	C_3	C_4	C_5
Decays	$h_3 \to h_2 Z$ $h_2 \to h_1 Z$ $h_3 \to h_1 Z$	$h_2 \to h_1 Z$ $h_1 \to ZZ$ $h_2 \to ZZ$	$h_3 \to h_1 Z$ $h_1 \to ZZ$ $h_3 \to ZZ$	$h_3 \to h_2 Z$ $h_2 \to ZZ$ $h_3 \to ZZ$	$h_3 \to ZZ$ $h_2 \to ZZ$ $h_1 \to ZZ$

In 2HDMs

Classes	C_6	C_7
Decays	$h_3 \to h_2 h_1$ $h_3 \to h_2 Z$ $h_1 \to ZZ$	$h_{2,3} \to h_1 h_1$ $h_{2,3} \to h_1 Z$ $h_1 \to ZZ$

Classes involving scalar to two scalars decays

Fontes, Romão, RS, Silva (2015).

CP-violating class C2 (and C3 and C4)

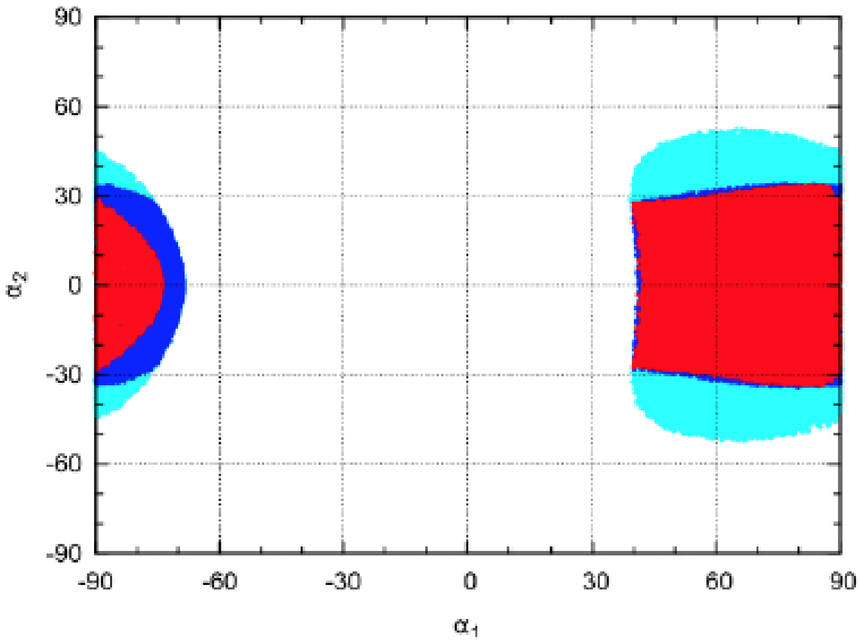
$h_2 \to h_3 \quad h_1 \to h_2$

$$h_1 \to ZZ \quad \Rightarrow \quad \mathrm{CP}(h_1) = 1$$

$$h_2 \to ZZ \quad \Rightarrow \quad \mathrm{CP}(h_2) = 1$$

$$h_2 \to h_1 Z \quad \Rightarrow \quad \mathrm{CP}(h_1) \neq \mathrm{CP}(h_2)$$

Observing the three decays constitutes a "model independent" sign of CP-violation.



$$c = \frac{BR(h_2 \to ZZ)}{BR(h_2 \to h_1 Z)}$$

The benchmark plane is (m_2, χ)

α_2 is already constrained by the first decay. The constraints from the other two decays could be combined in a $(m_2, \sin\alpha_2)$ plane.

CP-violating class C1

$$h_3 \to h_1 Z \quad \Rightarrow \quad \mathrm{CP}(h_3) = -\,\mathrm{CP}(h_1)$$

$$h_2 \to h_1 Z \quad \Rightarrow \quad \mathrm{CP}(h_2) = -\,\mathrm{CP}(h_1)$$

$$h_3 \to h_2 Z \quad \Rightarrow \quad \mathrm{CP}(h_2) \neq \mathrm{CP}(h_3)$$

Observing the three decays constitutes a "model independent" sign of CP-violation.

$$c = \frac{BR(h_3 \to h_1 Z)}{BR(h_3 \to h_1 ZZ)}$$

- The benchmark plane is (m_2, m_3) with χ as a parameter.
- Another benchmark plane is (m_2, χ) with m_3 as a parameter.

TABLE II. Benchmark points for Type II: $P1$, $P2$ and $P3$, and for the flipped model: $P4$, for LHC at $\sqrt{s} = 13$ TeV. All Z bosons decay leptonically which corresponds to a factor of 0.06732 for each Z decay.

	$P1$	$P2$	$P3$	$P4$
α_1	1.12569	1.04842	−1.33589	1.41610
α_2	0.49091	−0.00825	−0.00129	0.24037
α_3	−1.56775	0.00674	0.63749	−0.81993
β	0.92913	1.00182	1.27669	1.29413
$\tan\beta$	1.33845	1.56366	3.30155	3.52171
m_1 (GeV)	125.00	125.00	125.00	125.00
m_2 (GeV)	127.32	273.15	282.53	231.74
m_3 (GeV)	252.63	421.64	287.80	360.59
$m_{H^\pm}$ (GeV)	481.25	452.50	604.89	527.67
$\mathrm{Re}(m_{12}^2)$ (GeV)^2	−0.5625E + 02	0.1183E + 05	0.1590E + 05	0.2156E + 05
b_{D_1}	−0.63099	0.01291	0.00426	−0.83837
b_{L_1}	−0.63099	0.01291	0.00426	0.06760
$C_1[1]\sigma_3 \times \mathrm{BR}(h_3 \to h_2 Z \to b\bar{b}l\bar{l})$	114.528	61.529	0.000	27.484
$C_1[2]\sigma_2 \times \mathrm{BR}(h_2 \to h_1 Z \to b\bar{b}l\bar{l})$	0.000	0.615	7.401	18.462
$C_1[3]\sigma_3 \times \mathrm{BR}(h_3 \to h_1 Z \to b\bar{b}l\bar{l})$	26.656	1.100	24.519	1.787
$C_2[1]\sigma_2 \times \mathrm{BR}(h_2 \to h_1 Z \to b\bar{b}l\bar{l})$	0.000	0.615	7.401	18.462
$C_2[2]\sigma_1 \times \mathrm{BR}(h_1 \to ZZ \to l\bar{l}l\bar{l})$	5.495	5.792	5.592	4.802
$C_2[3]\sigma_2 \times \mathrm{BR}(h_2 \to ZZ \to l\bar{l}l\bar{l})$	1.386	2.598	1.802	1.220
$C_3[1]\sigma_3 \times \mathrm{BR}(h_3 \to h_1 Z \to b\bar{b}l\bar{l})$	26.656	1.100	24.519	1.787
$C_3[2]\sigma_1 \times \mathrm{BR}(h_1 \to ZZ \to l\bar{l}l\bar{l})$	5.495	5.792	5.592	4.802
$C_3[3]\sigma_3 \times \mathrm{BR}(h_3 \to ZZ \to l\bar{l}l\bar{l})$	1.011	0.003	1.733	1.058
$C_4[1]\sigma_3 \times \mathrm{BR}(h_3 \to h_2 Z \to b\bar{b}l\bar{l})$	114.528	61.529	0.000	27.484
$C_4[2]\sigma_2 \times \mathrm{BR}(h_2 \to ZZ \to l\bar{l}l\bar{l})$	1.386	2.598	1.802	1.220
$C_4[3]\sigma_3 \times \mathrm{BR}(h_3 \to ZZ \to l\bar{l}l\bar{l})$	1.011	0.003	1.733	1.058
$C_5[1]\sigma_3 \times \mathrm{BR}(h_3 \to ZZ \to l\bar{l}l\bar{l})$	1.011	0.003	1.733	1.058
$C_5[2]\sigma_2 \times \mathrm{BR}(h_2 \to ZZ \to l\bar{l}l\bar{l})$	1.386	2.598	1.802	1.220
$C_5[3]\sigma_1 \times \mathrm{BR}(h_1 \to ZZ \to l\bar{l}l\bar{l})$	5.495	5.792	5.592	4.802

The points were also chosen so that they would probe more than one class simultaneously. $P1$ probes classes C_3, C_4 and C_5; $P2$ probes C_1 and C_2; $P3$ probes C_2, C_3 and C_5 while the point for the flipped model probes all classes. Furthermore, points $P1$ and $P4$ were also chosen to show that large pseudoscalar components are not only still allowed, as previously discussed in [10], but they can also easily be probed at the next LHC run.

All in fb

Other combinations not possible in the CP-conserving 2HDM

$$h_1 \to ZZ \quad \Leftarrow \quad \mathrm{CP}(h_1) = 1$$

Observed

$$h_3 \to h_2 h_1 \quad \Rightarrow \quad \mathrm{CP}(h_3) = \mathrm{CP}(h_2)\ \mathrm{CP}(h_1) = \mathrm{CP}(h_2)$$

Decay	CP eigenstates	Model
$h_3 \to h_2 Z \quad \mathrm{CP}(h_3) = -\mathrm{CP}(h_2)$	None	C2HDM, ...
$h_{2(3)} \to h_1 Z \quad \mathrm{CP}(h_{2(3)}) = -1$	2 CP-odd	C2HDM, ...
$h_2 \to ZZ \quad \mathrm{CP}(h_2) = 1$	3 CP-even	C2HDM, cxSM, ...

TABLE VIII. Predictions for $\sigma \times \text{BR}$ at $\sqrt{s} = 13$ TeV for the benchmark points *P5* (Type I) and *P6* (lepton specific).

	P5	*P6*
$\sigma(h_1)$ 13 TeV	55.144 [pb]	53.455 [pb]
$\sigma(h_1)\text{BR}(h_1 \to W^*W^*)$	10.657 [pb]	11.069 [pb]
$\sigma(h_1)\text{BR}(h_1 \to Z^*Z^*)$	1.093 [pb]	1.136 [pb]
$\sigma(h_1)\text{BR}(h_1 \to bb)$	33.118 [pb]	32.152 [pb]
$\sigma(h_1)\text{BR}(h_1 \to \tau\tau)$	3.825 [pb]	2.845 [pb]
$\sigma(h_1)\text{BR}(h_1 \to \gamma\gamma)$	119.794 [fb]	122.579 [fb]
$\sigma_2 \equiv \sigma(h_2)$ 13 TeV	1.620 [pb]	4.920 [pb]
$\sigma_2 \times \text{BR}(h_2 \to WW)$	1.032 [pb]	0.542 [pb]
$\sigma_2 \times \text{BR}(h_2 \to ZZ)$	0.427 [pb]	0.232 [pb]
$\sigma_2 \times \text{BR}(h_2 \to bb)$	0.012 [pb]	0.097 [pb]
$\sigma_2 \times \text{BR}(h_2 \to \tau\tau)$	0.001 [pb]	0.109 [pb]
$\sigma_2 \times \text{BR}(h_2 \to \gamma\gamma)$	0.123 [fb]	0.344 [fb]
$\sigma_2 \times \text{BR}(h_2 \to h_1 Z)$	0.140 [pb]	0.075 [pb]
$\sigma_2 \times \text{BR}(h_2 \to h_1 Z \to bbZ)$	0.084 [pb]	0.045 [pb]
$\sigma_2 \times \text{BR}(h_2 \to h_1 Z \to \tau\tau Z)$	9.683 [fb]	3.982 [fb]
$\sigma_2 \times \text{BR}(h_2 \to h_1 h_1)$	0.000 [fb]	3772.577 [fb]
$\sigma_2 \times \text{BR}(h_2 \to h_1 h_1 \to bbbb)$	0.000 [fb]	1364.787 [fb]
$\sigma_2 \times \text{BR}(h_2 \to h_1 h_1 \to bb\tau\tau)$	0.000 [fb]	241.505 [fb]
$\sigma_2 \times \text{BR}(h_2 \to h_1 h_1 \to \tau\tau\tau\tau)$	0.000 [fb]	10.684 [fb]
$\sigma_3 \equiv \sigma(h_3)$ 13 TeV	9.442 [pb]	10.525 [pb]
$\sigma_3 \times \text{BR}(h_3 \to WW)$	0.638 [pb]	0.945 [pb]
$\sigma_3 \times \text{BR}(h_3 \to ZZ)$	0.293 [pb]	0.406 [pb]
$\sigma_3 \times \text{BR}(h_3 \to bb)$	0.004 [pb]	0.422 [pb]
$\sigma_3 \times \text{BR}(h_3 \to \tau\tau)$	0.432 [fb]	407.337 [fb]
$\sigma_3 \times \text{BR}(h_3 \to \gamma\gamma)$	0.140 [fb]	2.410 [fb]
$\sigma_3 \times \text{BR}(h_3 \to h_1 Z)$	0.383 [pb]	0.691 [pb]
$\sigma_3 \times \text{BR}(h_3 \to h_1 Z \to bbZ)$	0.230 [pb]	0.416 [pb]
$\sigma_3 \times \text{BR}(h_3 \to h_1 Z \to \tau\tau Z)$	26.554 [fb]	36.779 [fb]
$\sigma_3 \times \text{BR}(h_3 \to h_2 Z)$	2.495 [pb]	0.000 [pb]
$\sigma_3 \times \text{BR}(h_3 \to h_2 Z \to bbZ)$	0.019 [pb]	0.000 [pb]
$\sigma_3 \times \text{BR}(h_3 \to h_2 Z \to \tau\tau Z)$	2.188 [fb]	0.000 [fb]
$\sigma_3 \times \text{BR}(h_3 \to h_1 h_1)$	433.402 [fb]	6893.255 [fb]
$\sigma_3 \times \text{BR}(h_3 \to h_1 h_1 \to bbbb)$	156.329 [fb]	2493.740 [fb]
$\sigma_3 \times \text{BR}(h_3 \to h_1 h_1 \to bb\tau\tau)$	36.111 [fb]	441.277 [fb]
$\sigma_3 \times \text{BR}(h_3 \to h_1 h_1 \to \tau\tau\tau\tau)$	2.085 [fb]	19.521 [fb]
$\sigma_3 \times \text{BR}(h_3 \to h_2 h_1)$	0.000 [fb]	0.000 [fb]
$\sigma_3 \times \text{BR}(h_3 \to h_2 h_1 \to bbbb)$	0.000 [fb]	0.000 [fb]
$\sigma_3 \times \text{BR}(h_3 \to h_2 h_1 \to bb\tau\tau)$	0.000 [fb]	0.000 [fb]
$\sigma_3 \times \text{BR}(h_3 \to h_2 h_1 \to \tau\tau\tau\tau)$	0.000 [fb]	0.000 [fb]

Class C7

$$h_1 \to ZZ \quad \Rightarrow \quad \text{CP}(h_1) = 1$$

$$h_3 \to h_1 Z \quad \Rightarrow \quad \text{CP}(h_3) = -\ \text{CP}(h_1) = -1$$

$$h_3 \to h_1 h_1 \quad \Rightarrow \quad \text{CP}(h_3) = 1$$

Class C6

	$P1$
$\sigma(h_1)$ 13 TeV	61.600 [pb]
$\sigma(h_1)\text{BR}(h_1 \to W^*W^*)$	11.819 [pb]
$\sigma(h_1)\text{BR}(h_1 \to Z^*Z^*)$	1.212 [pb]
$\sigma(h_1)\text{BR}(h_1 \to bb)$	34.383 [pb]
$\sigma(h_1)\text{BR}(h_1 \to \tau\tau)$	3.969 [pb]
$\sigma(h_1)\text{BR}(h_1 \to \gamma\gamma)$	129.973 [fb]
$\sigma_2 \equiv \sigma(h_2)$ 13 TeV	56.583 [pb]
$\sigma_2 \times \text{BR}(h_2 \to WW)$	2.814 [pb]
$\sigma_2 \times \text{BR}(h_2 \to ZZ)$	0.306 [pb]
$\sigma_2 \times \text{BR}(h_2 \to bb)$	42.534 [pb]
$\sigma_2 \times \text{BR}(h_2 \to \tau\tau)$	4.911 [pb]
$\sigma_2 \times \text{BR}(h_2 \to \gamma\gamma)$	35.041 [fb]
$\sigma_2 \times \text{BR}(h_2 \to h_1 Z)$	0.000 [pb]
$\sigma_2 \times \text{BR}(h_2 \to h_1 Z \to bbZ)$	0.000 [pb]
$\sigma_2 \times \text{BR}(h_2 \to h_1 Z \to \tau\tau Z)$	0.000 [fb]
$\sigma_2 \times \text{BR}(h_2 \to h_1 h_1)$	0.000 [fb]
$\sigma_2 \times \text{BR}(h_2 \to h_1 h_1 \to bbbb)$	0.000 [fb]
$\sigma_2 \times \text{BR}(h_2 \to h_1 h_1 \to bb\tau\tau)$	0.000 [fb]
$\sigma_2 \times \text{BR}(h_2 \to h_1 h_1 \to \tau\tau\tau\tau)$	0.000 [fb]
$\sigma_3 \equiv \sigma(h_3)$ 13 TeV	4.043 [pb]
$\sigma_3 \times \text{BR}(h_3 \to WW)$	0.526 [pb]
$\sigma_3 \times \text{BR}(h_3 \to ZZ)$	0.223 [pb]
$\sigma_3 \times \text{BR}(h_3 \to bb)$	0.047 [pb]
$\sigma_3 \times \text{BR}(h_3 \to \tau\tau)$	5.558 [fb]
$\sigma_3 \times \text{BR}(h_3 \to \gamma\gamma)$	0.059 [fb]
$\sigma_3 \times \text{BR}(h_3 \to h_1 Z)$	0.709 [pb]
$\sigma_3 \times \text{BR}(h_3 \to h_1 Z \to bbZ)$	0.396 [pb]
$\sigma_3 \times \text{BR}(h_3 \to h_1 Z \to \tau\tau Z)$	45.708 [fb]
$\sigma_3 \times \text{BR}(h_3 \to h_2 Z)$	2.263 [pb]
$\sigma_3 \times \text{BR}(h_3 \to h_2 Z \to bbZ)$	1.701 [pb]
$\sigma_3 \times \text{BR}(h_3 \to h_2 Z \to \tau\tau Z)$	196.416 [fb]
$\sigma_3 \times \text{BR}(h_3 \to h_1 h_1)$	0.090 [fb]
$\sigma_3 \times \text{BR}(h_3 \to h_1 h_1 \to bbbb)$	0.028 [fb]
$\sigma_3 \times \text{BR}(h_3 \to h_1 h_1 \to bb\tau\tau)$	0.007 [fb]
$\sigma_3 \times \text{BR}(h_3 \to h_1 h_1 \to \tau\tau\tau\tau)$	0.000 [fb]
$\sigma_3 \times \text{BR}(h_3 \to h_2 h_1)$	263.916 [fb]
$\sigma_3 \times \text{BR}(h_3 \to h_2 h_1 \to bbbb)$	110.732 [fb]
$\sigma_3 \times \text{BR}(h_3 \to h_2 h_1 \to bb\tau\tau)$	25.567 [fb]
$\sigma_3 \times \text{BR}(h_3 \to h_2 h_1 \to \tau\tau\tau\tau)$	1.476 [fb]

$$h_1 \to ZZ \quad \Rightarrow \quad \text{CP}(h_1) = 1$$

$$h_3 \to h_2 Z \quad \Rightarrow \quad \text{CP}(h_3) = -\,\text{CP}(h_2)$$

$$h_3 \to h_2 h_1 \quad \Rightarrow \quad \text{CP}(h_3) = \text{CP}(h_2)$$

BP9 BGL models?

Branco, Grimus, Lavoura (1996)

The Yukawa Lagrangian of BGL models is

$$\mathcal{L}_Y = - \overline{Q_L^0} \left[\Gamma_1 \Phi_1 + \Gamma_2 \Phi_2\right] d_R^0 - \overline{Q_L^0} \left[\Delta_1 \tilde{\Phi}_1 + \Delta_2 \tilde{\Phi}_2\right] u_R^0 - \overline{L_L^0} \left[\Pi_1 \Phi_1 + \Pi_2 \Phi_2\right] l_R^0 - \overline{L_L^0} \left[\Sigma_1 \tilde{\Phi}_1 + \Sigma_2 \tilde{\Phi}_2\right] \nu_R^0 + \mathrm{h.c.},$$

Invariance under

$$Q_{Lj}^0 \mapsto \exp(i\tau)\, Q_{Lj}^0 , \qquad u_{Rj}^0 \mapsto \exp(i2\tau)\, u_{Rj}^0 , \qquad \Phi_2 \mapsto \exp(i\tau)\, \Phi_2$$

leads to <u>Higgs FCNC in the down sector</u>. Invariance under

$$Q_{Lj}^0 \mapsto \exp(i\tau)\, Q_{Lj}^0 , \qquad d_{Rj}^0 \mapsto \exp(i2\tau)\, d_{Rj}^0 , \quad \Phi_2 \mapsto \exp(-i\tau)\, \Phi_2$$

leads to <u>Higgs FCNC in the up sector</u>. The <u>**potential**</u> is

$$V = \mu_1 \Phi_1^\dagger \Phi_1 + \mu_2 \Phi_2^\dagger \Phi_2 - m_{12} \left(\Phi_1^\dagger \Phi_2 + \Phi_2^\dagger \Phi_1\right) + 2\lambda_3 \left(\Phi_1^\dagger \Phi_1\right)\left(\Phi_2^\dagger \Phi_2\right) + 2\lambda_4 \left(\Phi_1^\dagger \Phi_2\right)\left(\Phi_2^\dagger \Phi_1\right) + \lambda_1 \left(\Phi_1^\dagger \Phi_1\right)^2 + \lambda_2 \left(\Phi_2^\dagger \Phi_2\right)^2 ,$$

If Higgs FCNC is in the up sector the couplings are

$$Y^U_{qt}(d_\rho) = -V_{q\rho} V^*_{t\rho} \frac{m_t}{v} c_{\beta\alpha}(t_\beta + t_\beta^{-1}) , \quad q = u, c .$$

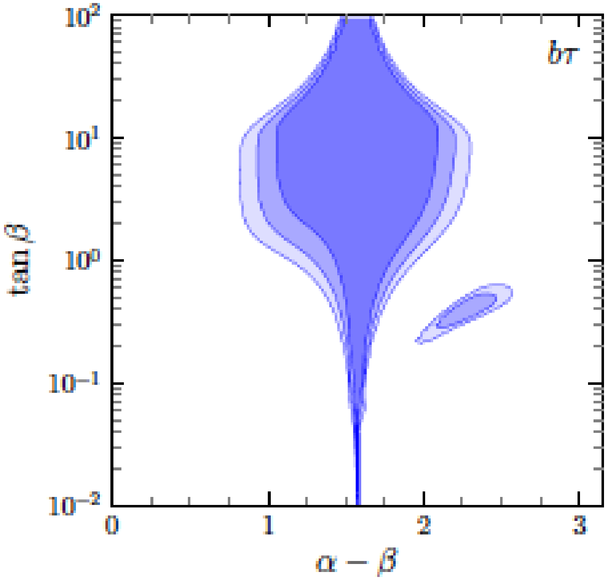
which leads to the top quark decay widths

$$\Gamma_{(d_\rho)}(t \to hq) = \frac{m_t^3}{32\pi v^2} \left(1 - \frac{m_h^2}{m_t^2}\right)^2 |V_{q\rho}|^2 |V_{t\rho}|^2 c^2_{\beta\alpha} (t_\beta + t_\beta^{-1})^2$$

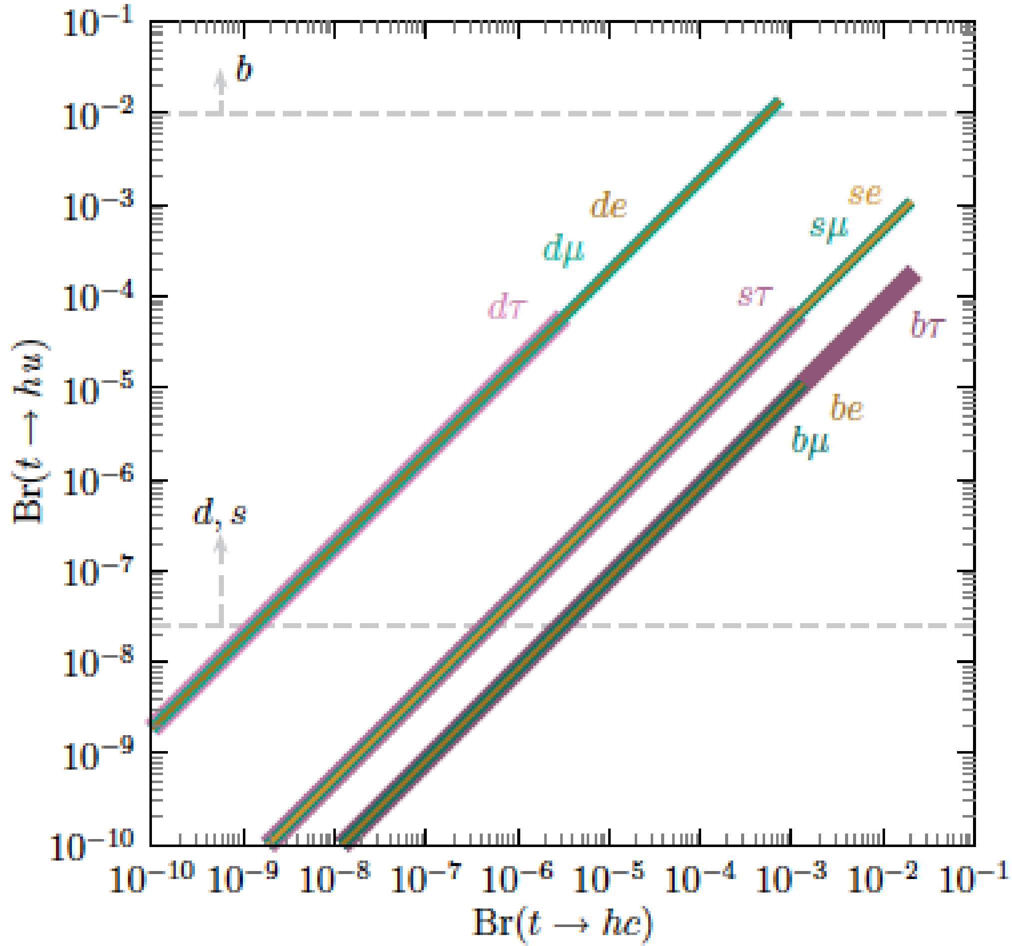
with angles alpha and beta defined in the usual way.

"So we fix our benchmark scenarios by trying to maximise these new effects but in agreement with other low energy flavour constraints. Also we choose those scenarios where important signals can show up at LHC, although in some cases some of the observables could be more relevant for a future linear collider."

Example: the (b,τ) model near decoupling



(d) Model $b\,\tau$



MODEL	$\lvert c_{\beta\alpha}\rvert$	$\tan\beta$	$m_H \sim m_A \sim m_{H^\pm}$	m_h	Interesting Channels
(b,τ)	≤ 0.17	$25 - 100$	≥ 600	125	$t \to hq, h \to b\bar{b}, \tau\bar{\tau}$

Botella, ranco, Nebot, Rebelo (2015)

BP10 and BP11 Scalar singlet

CxSM – dark matter AND new visible scalars

SM plus $\mathbb{S} = (S + iA)/\sqrt{2}$, with residual $\mathbb{Z}_2$ symmetry $A \to -A$ after $\cancel{U(1)}$ symmetry by soft terms (in parenthesis)

$$V = \frac{m^2}{2} H^\dagger H + \frac{\lambda}{4}(H^\dagger H)^2 + \frac{\delta_2}{2} H^\dagger H |\mathbb{S}|^2 + \frac{b_2}{2}|\mathbb{S}|^2 + \frac{d_2}{4}|\mathbb{S}|^4 + \left(\frac{b_1}{4}\mathbb{S}^2 + a_1 \mathbb{S} + c.c.\right)$$

- $\mathbb{Z}_2$ phase ($v_S \neq 0, v_A = 0$): 2 scalars mix + 1 dark

$$\begin{pmatrix} h_1 \\ h_2 \\ A \end{pmatrix} = \begin{pmatrix} \kappa_1 & -\sin\alpha & 0 \\ \kappa_2 & \cos\alpha & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} h \\ S \\ A \end{pmatrix}$$

- $\cancel{\mathbb{Z}_2}$ phase ($v_S \neq 0, v_A \neq 0$): 3 scalars mix

$$\begin{pmatrix} h_1 \\ h_2 \\ h_3 \end{pmatrix} = \begin{pmatrix} \kappa_1 & R_{1S} & R_{1A} \\ \kappa_2 & R_{2S} & R_{2A} \\ \kappa_3 & R_{3S} & R_{3A} \end{pmatrix} \begin{pmatrix} h \\ S \\ A \end{pmatrix}$$

- Many OBSs related to SM up to κ_a factors (Ex. $\frac{\sigma_a}{\sigma_{SM}} \propto \kappa_a^2$)

RxSM – dark matter OR new visible scalar

SM plus S, with $\mathbb{Z}_2$ symmetry $S \to -S$

$$V = \frac{m^2}{2} H^\dagger H + \frac{\lambda}{4}(H^\dagger H)^2 + \frac{\lambda_{HS}}{2} H^\dagger H S^2 + \frac{m_S^2}{2} S^2 + \frac{\lambda_S}{4!} S^4$$

- $\mathbb{Z}_2$ phase ($v_S \neq 0$): 2 scalars mix

$$\begin{pmatrix} h_1 \\ h_2 \end{pmatrix} = \begin{pmatrix} \cos\alpha & -\sin\alpha \\ \sin\alpha & \cos\alpha \end{pmatrix} \begin{pmatrix} h \\ s \end{pmatrix}$$

- $\mathbb{Z}_2$ phase ($v_S = 0$): 1 Higgs + 1 dark

$$\begin{pmatrix} h_1 \\ S \end{pmatrix} = \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix} \begin{pmatrix} h \\ s \end{pmatrix}$$

- We ignore dark phase!

Suggested Benchmarks – CxSM Dark

	CxSM.D1	CxSM.D2	CxSM.D3
⋆ m_1 (GeV)	125.4	125.4	49.116
⋆ m_2 (GeV)	456.57	339.77	125.4
⋆ m_A (GeV)	52.98	77.022	65.054
⋆ α	−0.39506	−0.50029	1.4617
$\Omega_A h^2$	0.115	0.116	0.115
μ_{h_1}	0.852	0.77	0.0118
$\sigma_1 \equiv \sigma(gg \to h_1)$ 13 TeV	26.9 [pb]	24.3 [pb]	2.14 [pb]
$\sigma_1 \times \mathrm{BR}(h_1 \to WW)$	4.59 [pb]	4.84 [pb]	0.0346 [fb]
$\sigma_1 \times \mathrm{BR}(h_1 \to ZZ)$	577 [fb]	609 [fb]	0.011 [fb]
$\sigma_1 \times \mathrm{BR}(h_1 \to bb)$	14.1 [pb]	14.9 [pb]	1.87 [pb]
$\sigma_1 \times \mathrm{BR}(h_1 \to \tau\tau)$	1.35 [pb]	1.43 [pb]	148 [fb]
$\sigma_1 \times \mathrm{BR}(h_1 \to \gamma\gamma)$	49.7 [fb]	52.5 [fb]	0.608 [fb]
$\sigma_1 \times \mathrm{BR}(h_1 \to AA)$	3.84 [pb]	0	0
μ_{h_2}	0.0977	0.135	0.743
$\sigma_2 \equiv \sigma(gg \to h_2)$ 13 TeV	698 [fb]	1.6 [pb]	31.2 [pb]
$\sigma_2 \times \mathrm{BR}(h_2 \to WW)$	251 [fb]	642 [fb]	4.67 [pb]
$\sigma_2 \times \mathrm{BR}(h_2 \to ZZ)$	119 [fb]	292 [fb]	587 [fb]
$\sigma_2 \times \mathrm{BR}(h_2 \to bb)$	0.0764 [fb]	0.432 [fb]	14.3 [pb]
$\sigma_2 \times \mathrm{BR}(h_2 \to \tau\tau)$	$<$ 0.01 [fb]	0.0501 [fb]	1.38 [pb]
$\sigma_2 \times \mathrm{BR}(h_2 \to \gamma\gamma)$	$<$ 0.01 [fb]	$<$ 0.01 [fb]	50.6 [fb]
$\sigma_2 \times \mathrm{BR}(h_2 \to h_1 h_1)$	155 [fb]	429 [fb]	7.74 [pb]
$\sigma_2 \times \mathrm{BR}(h_2 \to h_1 h_1 \to bbbb)$	42.7 [fb]	160 [fb]	5.89 [pb]
$\sigma_2 \times \mathrm{BR}(h_2 \to h_1 h_1 \to bb\tau\tau)$	8.19 [fb]	30.8 [fb]	932 [fb]
$\sigma_2 \times \mathrm{BR}(h_2 \to h_1 h_1 \to bbWW)$	27.8 [fb]	105 [fb]	0.218 [fb]
$\sigma_2 \times \mathrm{BR}(h_2 \to h_1 h_1 \to bb\gamma\gamma)$	0.302 [fb]	1.13 [fb]	3.83 [fb]
$\sigma_2 \times \mathrm{BR}(h_2 \to h_1 h_1 \to \tau\tau\tau\tau)$	0.393 [fb]	1.48 [fb]	36.9 [fb]
$\sigma_2 \times \mathrm{BR}(h_2 \to AA)$	0.0822 [pb]	0.233 [pb]	0
$\mu_{\mathrm{stability}}$ (GeV)	10^{12}	10^{14}	10^{8}

Suggested Benchmarks – CxSM Broken

	CxSM.B1	CxSM.B2	CxSM.B3	CxSM.B4	CxSM.B5
⋆ m_1 (GeV)	125.4	125.4	57.34	98.12	41.61
m_2 (GeV)	258.9	230.8	125.4	125.4	69.51
⋆ m_3 (GeV)	462.4	271.3	345.5	255.2	125.4
⋆ α_1	-0.04867	0.03148	-1.071	-0.7888	-1.169
⋆ α_2	0.4739	-0.5707	1.126	0.7717	1.24
⋆ α_3	-0.4763	-0.3888	-0.005447	-0.1945	1.044
μ_{h_1}	0.79	0.707	0.0426	0.255	0.0161
$\sigma_1 \equiv \sigma(gg \to h_1)$ 13 TeV	24.9 [pb]	22.3 [pb]	5.67 [pb]	12.5 [pb]	4.19 [pb]
$\sigma_1 \times \mathrm{BR}(h_1 \to WW)$	4.97 [pb]	4.45 [pb]	0.262 [fb]	87.4 [fb]	0.0226 [fb]
$\sigma_1 \times \mathrm{BR}(h_1 \to ZZ)$	625 [fb]	560 [fb]	0.0807 [fb]	10 [fb]	$<$ 0.01 [fb]
$\sigma_1 \times \mathrm{BR}(h_1 \to bb)$	15.2 [pb]	13.6 [pb]	4.91 [pb]	10.2 [pb]	3.67 [pb]
$\sigma_1 \times \mathrm{BR}(h_1 \to \tau\tau)$	1.46 [pb]	1.31 [pb]	401 [fb]	936 [fb]	281 [fb]
$\sigma_1 \times \mathrm{BR}(h_1 \to \gamma\gamma)$	53.8 [fb]	48.2 [fb]	2.26 [fb]	17.4 [fb]	0.831 [fb]
μ_{h_2}	0.0636	0.0547	0.768	0.626	0.0205
$\sigma_2 \equiv \sigma(gg \to h_2)$ 13 TeV	559 [fb]	577 [fb]	24.4 [pb]	19.7 [pb]	1.88 [pb]
$\sigma_2 \times \mathrm{BR}(h_2 \to WW)$	390 [fb]	408 [fb]	4.87 [pb]	3.95 [pb]	0.342 [fb]
$\sigma_2 \times \mathrm{BR}(h_2 \to ZZ)$	167 [fb]	167 [fb]	613 [fb]	497 [fb]	0.0998 [fb]
$\sigma_2 \times \mathrm{BR}(h_2 \to bb)$	0.601 [fb]	0.928 [fb]	14.8 [pb]	12.1 [pb]	1.61 [pb]
$\sigma_2 \times \mathrm{BR}(h_2 \to \tau\tau)$	0.0663 [fb]	0.1 [fb]	1.42 [pb]	1.16 [pb]	137 [fb]
$\sigma_2 \times \mathrm{BR}(h_2 \to \gamma\gamma)$	0.0122 [fb]	0.0186 [fb]	52.4 [fb]	42.7 [fb]	1.15 [fb]
$\sigma_2 \times \mathrm{BR}(h_2 \to h_1 h_1)$	0.0467 [fb]	0	195 [fb]	0	0
$\sigma_2 \times \mathrm{BR}(h_2 \to h_1 h_1 \to bbbb)$	0.0175 [fb]	0	146 [fb]	0	0
$\sigma_2 \times \mathrm{BR}(h_2 \to h_1 h_1 \to bb\tau\tau)$	$<$ 0.01 [fb]	0	23.9 [fb]	0	0
$\sigma_2 \times \mathrm{BR}(h_2 \to h_1 h_1 \to bbWW)$	0.0114 [fb]	0	0.0156 [fb]	0	0
$\sigma_2 \times \mathrm{BR}(h_2 \to h_1 h_1 \to bb\gamma\gamma)$	$<$ 0.01 [fb]	0	0.134 [fb]	0	0
$\sigma_2 \times \mathrm{BR}(h_2 \to h_1 h_1 \to \tau\tau\tau\tau)$	$<$ 0.01 [fb]	0	0.976 [fb]	0	0

Suggested Benchmarks – CxSM Broken

	CxSM.B1	CxSM.B2	CxSM.B3	CxSM.B4	CxSM.B5
$\star$ m_1 (GeV)	125.4	125.4	57.34	98.12	41.61
m_2 (GeV)	258.9	230.8	125.4	125.4	69.51
$\star$ m_3 (GeV)	462.4	271.3	345.5	255.2	125.4
μ_{h_3}	0.0774	0.0868	0.111	0.0273	0.777
$\sigma_3 \equiv \sigma(gg \to h_3)$ 13 TeV	659 [fb]	1.95 [pb]	1.31 [pb]	1.07 [pb]	30.4 [pb]
$\sigma_3 \times \mathrm{BR}(h_3 \to WW)$	189 [fb]	496 [fb]	537 [fb]	172 [fb]	4.89 [pb]
$\sigma_3 \times \mathrm{BR}(h_3 \to ZZ)$	89.7 [fb]	215 [fb]	245 [fb]	73.2 [fb]	615 [fb]
$\sigma_3 \times \mathrm{BR}(h_3 \to bb)$	0.0558 [fb]	0.656 [fb]	0.345 [fb]	0.277 [fb]	15 [pb]
$\sigma_3 \times \mathrm{BR}(h_3 \to \tau\tau)$	$<$ 0.01 [fb]	0.073 [fb]	0.0401 [fb]	0.0305 [fb]	1.44 [pb]
$\sigma_3 \times \mathrm{BR}(h_3 \to \gamma\gamma)$	$<$ 0.01 [fb]	0.0133 [fb]	$<$ 0.01 [fb]	$<$ 0.01 [fb]	53 [fb]
$\sigma_3 \times \mathrm{BR}(h_3 \to h_1 h_1)$	3.75 [fb]	1.24 [pb]	280 [fb]	415 [fb]	5.47 [pb]
$\sigma_3 \times \mathrm{BR}(h_3 \to h_1 h_1 \to bbbb)$	1.4 [fb]	464 [fb]	210 [fb]	279 [fb]	4.2 [pb]
$\sigma_3 \times \mathrm{BR}(h_3 \to h_1 h_1 \to bb\tau\tau)$	0.269 [fb]	89 [fb]	34.4 [fb]	51 [fb]	643 [fb]
$\sigma_3 \times \mathrm{BR}(h_3 \to h_1 h_1 \to bbWW)$	0.915 [fb]	302 [fb]	0.0224 [fb]	4.76 [fb]	0.0518 [fb]
$\sigma_3 \times \mathrm{BR}(h_3 \to h_1 h_1 \to bb\gamma\gamma)$	$<$ 0.01 [fb]	3.28 [fb]	0.193 [fb]	0.948 [fb]	1.9 [fb]
$\sigma_3 \times \mathrm{BR}(h_3 \to h_1 h_1 \to \tau\tau\tau\tau)$	0.0129 [fb]	4.27 [fb]	1.41 [fb]	2.33 [fb]	24.6 [fb]
$\sigma_3 \times \mathrm{BR}(h_3 \to h_1 h_2)$	307 [fb]	0	83.5 [fb]	408 [fb]	401 [fb]
$\sigma_3 \times \mathrm{BR}(h_3 \to h_1 h_2 \to bbbb)$	0.202 [fb]	0	43.8 [fb]	204 [fb]	301 [fb]
$\sigma_3 \times \mathrm{BR}(h_3 \to h_1 h_2 \to bb\tau\tau)$	0.0417 [fb]	0	7.78 [fb]	38.3 [fb]	48.7 [fb]
$\sigma_3 \times \mathrm{BR}(h_3 \to h_1 h_2 \to bbWW)$	131 [fb]	0	14.4 [fb]	68.7 [fb]	0.0657 [fb]
$\sigma_3 \times \mathrm{BR}(h_3 \to h_1 h_2 \to bb\gamma\gamma)$	$<$ 0.01 [fb]	0	0.175 [fb]	1.07 [fb]	0.284 [fb]
$\sigma_3 \times \mathrm{BR}(h_3 \to h_1 h_2 \to \tau\tau\tau\tau)$	$<$ 0.01 [fb]	0	0.344 [fb]	1.79 [fb]	1.96 [fb]
$\sigma_3 \times \mathrm{BR}(h_3 \to h_2 h_2)$	0	0	151 [fb]	0.318 [fb]	0
$\sigma_3 \times \mathrm{BR}(h_3 \to h_2 h_2 \to bbbb)$	0	0	55.5 [fb]	0.119 [fb]	0
$\sigma_3 \times \mathrm{BR}(h_3 \to h_2 h_2 \to bb\tau\tau)$	0	0	10.6 [fb]	0.0228 [fb]	0
$\sigma_3 \times \mathrm{BR}(h_3 \to h_2 h_2 \to bbWW)$	0	0	36.6 [fb]	0.0776 [fb]	0
$\sigma_3 \times \mathrm{BR}(h_3 \to h_2 h_2 \to bb\gamma\gamma)$	0	0	0.393 [fb]	$<$ 0.01 [fb]	0
$\sigma_3 \times \mathrm{BR}(h_3 \to h_2 h_2 \to \tau\tau\tau\tau)$	0	0	0.511 [fb]	$<$ 0.01 [fb]	0
$\mu_{\mathrm{RGE\ stability}}$ (GeV)	10^4	10^5	10^{16}	10^9	10^7

Suggested Benchmarks – RxSM Broken

	RxSM.B1	RxSM.B2	RxSM.B3	RxSM.B4
⋆ m_1 (GeV)	125.4	125.4	36.283	117.19
⋆ m_2 (GeV)	279.65	176.3	125.4	125.4
⋆ α	−0.54065	−0.46964	1.4272	−0.97629
μ_{h_1}	0.735	0.795	0.0205	0.314
$\sigma_1 \equiv \sigma(gg \to h_1)$ 13 TeV	23.2 [pb]	25.1 [pb]	7.26 [pb]	11.2 [pb]
$\sigma_1 \times \mathrm{BR}(h_1 \to WW)$	4.62 [pb]	5 [pb]	0.0162 [fb]	1.07 [pb]
$\sigma_1 \times \mathrm{BR}(h_1 \to ZZ)$	581 [fb]	629 [fb]	$<$ 0.01 [fb]	115 [fb]
$\sigma_1 \times \mathrm{BR}(h_1 \to bb)$	14.2 [pb]	15.3 [pb]	6.38 [pb]	8 [pb]
$\sigma_1 \times \mathrm{BR}(h_1 \to \tau\tau)$	1.36 [pb]	1.47 [pb]	475 [fb]	758 [fb]
$\sigma_1 \times \mathrm{BR}(h_1 \to \gamma\gamma)$	50.1 [fb]	54.2 [fb]	1.08 [fb]	22.7 [fb]
μ_{h_2}	0.148	0.205	0.66	0.686
$\sigma_2 \equiv \sigma(gg \to h_2)$ 13 TeV	2.09 [pb]	3.48 [pb]	30.9 [pb]	21.6 [pb]
$\sigma_2 \times \mathrm{BR}(h_2 \to WW)$	810 [fb]	3.31 [pb]	4.15 [pb]	4.32 [pb]
$\sigma_2 \times \mathrm{BR}(h_2 \to ZZ)$	354 [fb]	130 [fb]	522 [fb]	543 [fb]
$\sigma_2 \times \mathrm{BR}(h_2 \to bb)$	0.972 [fb]	24.6 [fb]	12.7 [pb]	13.2 [pb]
$\sigma_2 \times \mathrm{BR}(h_2 \to \tau\tau)$	0.109 [fb]	2.52 [fb]	1.22 [pb]	1.27 [pb]
$\sigma_2 \times \mathrm{BR}(h_2 \to \gamma\gamma)$	0.0196 [fb]	0.429 [fb]	45 [fb]	46.8 [fb]
$\sigma_2 \times \mathrm{BR}(h_2 \to h_1 h_1)$	920 [fb]	0	10.1 [pb]	0
$\sigma_2 \times \mathrm{BR}(h_2 \to h_1 h_1 \to bbbb)$	344 [fb]	0	7.79 [pb]	0
$\sigma_2 \times \mathrm{BR}(h_2 \to h_1 h_1 \to bb\tau\tau)$	66.1 [fb]	0	1.16 [pb]	0
$\sigma_2 \times \mathrm{BR}(h_2 \to h_1 h_1 \to bbWW)$	225 [fb]	0	0.0395 [fb]	0
$\sigma_2 \times \mathrm{BR}(h_2 \to h_1 h_1 \to bb\gamma\gamma)$	2.43 [fb]	0	2.63 [fb]	0
$\sigma_2 \times \mathrm{BR}(h_2 \to h_1 h_1 \to \tau\tau\tau\tau)$	3.17 [fb]	0	43.2 [fb]	0

Tools (2HDM)

Benchmark points were obtained with the tools

Higlu – Higgs production at NNLO — Spira (1995)

SuShi – Higgs production at NNLO — Harlander, Liebler, Mantler, (2013).

sHDECAY – Higgs decays — Djouadi, Kalinowski, Spira (1997) + Costa, Sampaio, RS, Mühlleitner (2015).

ScannerS – Phenomenological constraints; interfaced with — Coimbra, Sampaio, RS, (2013).

HiggsBounds – Limits from Higgs searches at LEP, Tevatron and LHC

HiggsSignals – Signal rates at the Tevatron and LHC

Bechtle, Brein, Heinemeyer, Stål, Stefaniak, Weiglein, Williams (2010−2015)

The end