The cruel and uneventful life of the Extended Higgs sectors

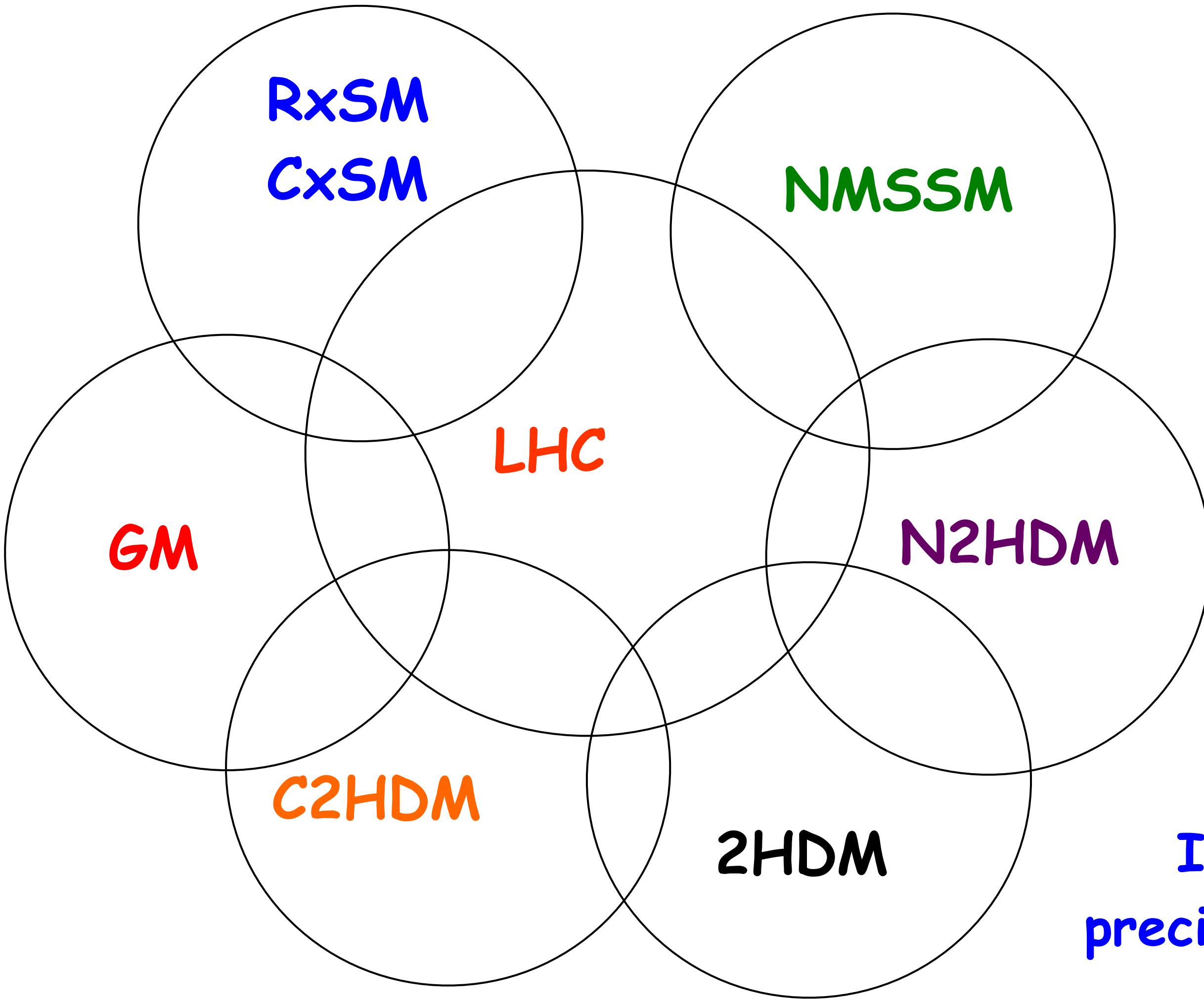
R. Santos

ISEL & CFTC-UL

The future of particle physics: a quest for guiding principles

2 October 2018

BSM-EHS - What are they good for?



Motivate searches

New scalar?

Discovered Higgs very SM-like

Information from precision measurements?

Uneventful

My Life as a Boson

Peter Higgs

School of Physics and Astronomy, University of Edinburgh, James Clerk Maxwell Building, King's Buildings Mayfield Road Edinburgh EH9 3JZ, Scotland

What once was so colourful

Potential

$$V = m_{11}^2 |\Phi_1|^2 + m_{22}^2 |\Phi_2|^2 - m_{12}^2 (\Phi_1^\dagger \Phi_2 + h.c.) + \frac{m_S^2}{2} \Phi_S^2$$
$$+ \frac{\lambda_1}{2} (\Phi_1^\dagger \Phi_1)^2 + \frac{\lambda_2}{2} (\Phi_2^\dagger \Phi_2)^2 + \lambda_3 (\Phi_1^\dagger \Phi_1)(\Phi_2^\dagger \Phi_2) + \lambda_4 (\Phi_1^\dagger \Phi_2)(\Phi_2^\dagger \Phi_1)$$
$$+ \frac{\lambda_5}{2} \left[(\Phi_1^\dagger \Phi_2) + h.c. \right] + \frac{\lambda_6}{4} \Phi_S^4 + \frac{\lambda_7}{2} (\Phi_1^\dagger \Phi_1) \Phi_S^2 + \frac{\lambda_8}{2} (\Phi_2^\dagger \Phi_2) \Phi_S^2$$

with fields

$$\Phi_1 = \begin{pmatrix} \phi_1^+ \\ \frac{1}{\sqrt{2}}(v_1 + \rho_1 + i\eta_1) \end{pmatrix} \quad \Phi_2 = \begin{pmatrix} \phi_2^+ \\ \frac{1}{\sqrt{2}}(v_2 + \rho_2 + i\eta_2) \end{pmatrix} \quad \Phi_S = v_S + \rho_S$$

magenta + blue $\Longrightarrow$ RxSM (also CxSM)

magenta + black $\Longrightarrow$ 2HDM (also C2HDM)

magenta + black + blue + red $\Longrightarrow$ N2HDM

- There is a 125 GeV Higgs (other scalars can be lighter and heavier).
- From the 2HDM on, tan $\beta = v_2/v_1$. Also charged Higgs are present.
- Models (except singlet extensions) can be CP-violating.
- They all have ρ=1 at tree-level.
- You get a few more scalars (CP-odd or CP-even or with no definite CP)
- In case all neutral scalars mix there will be three mixing angles
- They can have dark matter candidates (or not)

Searching (almost) everywhere!

$S_i \rightarrow S_j V$ $\quad H \rightarrow AZ\,(A \rightarrow HZ), h_2 \rightarrow h_1 Z$ **2HDM, C2HDM…**

- **H → AZ, A → ZH and A → Zh$_{125}$, ATLAS and CMS**

$S_i \rightarrow S_j S_k$ $\quad H_i \rightarrow H_j H_j (A_j A_j)$ **R(C)xSM, 2HDM, NMSSM, C2HDM, C-NMSSM, 3HDM…**

- **h$_{125}$ → AA and H → h$_{125}$ h$_{125}$, ATLAS and CMS** **but still no** $H_i \rightarrow h_{125} H_k (j \neq k)$

$S_i \rightarrow f_i \bar{f}_j$ $\quad H_i/A_i \rightarrow b\bar{b}, t\bar{t}, \tau^+\tau^-, \mu^+\mu^-$ $\quad h_{125} \rightarrow \tau\mu, e\mu, e\tau$

Still, the CP-nature of the Higgs not probed (but it is not CP-odd). Attempts in tth (production) and ττh (decay) starting (many theory papers).

For the 2HDM

$$S_i \to VV$$

γγ, ~~ZZ~~, ~~WW~~, ττ, bb, tt

- γγ: small Br
- ZZ, WW: absent or suppressed
- ττ, bb: small Br or large BG
- tt: difficult @ LHC

$$h_1 \to ZZ(+)h_2 \to ZZ(+)h_2 \to h_1 Z$$

Combinations of three decays

$$h_1 \to ZZ \;\Leftarrow\; CP(h_1) = 1$$

$$h_3 \to h_2 h_1 \;\Rightarrow\; CP(h_3) = CP(h_2)$$

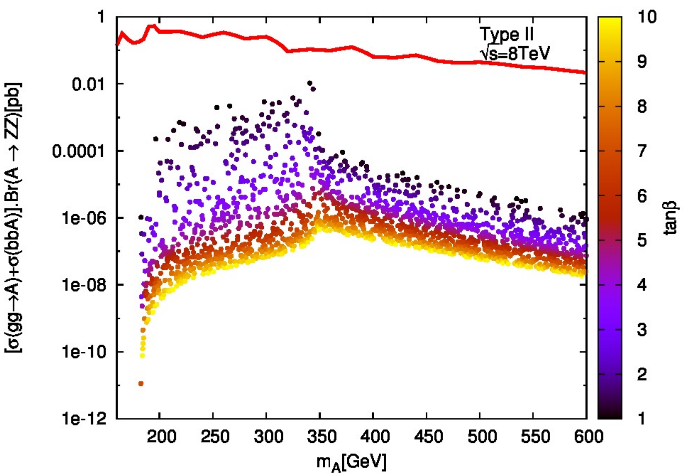
Decay	CP eigenstates	Model
$h_3 \to h_2 Z \quad CP(h_3) = -CP(h_2)$	None	C2HDM, other CPV extensions
$h_{2(3)} \to h_1 Z \quad CP(h_{2(3)}) = -1$	2 CP-odd; None	C2HDM, NMSSM,3HDM...
$h_2 \to ZZ \quad CP(h_2) = 1$	3 CP-even; None	C2HDM, cxSM, NMSSM,3HDM...

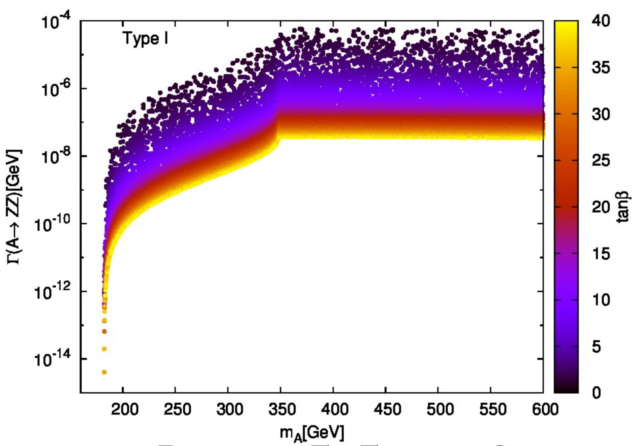
C2HDM – Fontes, Romão, RS, Silva, PRD92 (2015) 5, 055014

CNMSSM – King, Mühlleitner, Nevzorov, Walz; NPB901 (2015) 526-555

Beware of loop induced decays

$A \to VV$ **Is allowed, and if the CP-even decay is suppressed, they could be of the same order.**





Parameters: $\sin(\beta - \alpha) = 1$, $m_h = 125$ GeV, $m_{H^+} = m_H = 600$ GeV. A will decay mainly to fermions.

$\Gamma(A \to ZZ)$ as a function of m_A (Type I) for $\tan\beta$ between 1 and 40.

Below the tt threshold, where $\sigma(pp \to A)BR(A \to ZZ)$ is largest, the width is below 10^{-5} GeV while $\Gamma(H \to ZZ)$ is zero at tree-level ($\sin(\beta - \alpha) = 1$).

At one loop $\Gamma(H \to ZZ)$ can be of the order 10^{-5} to 10^{-4}. So $BR(A \to ZZ)$ and the $BR(H \to ZZ)$ will be of the same order of magnitude.

Even if $BR(H \to ZZ)$ can be slightly larger, also the production cross section of a pseudoscalar is larger than that of a scalar in gluon fusion.

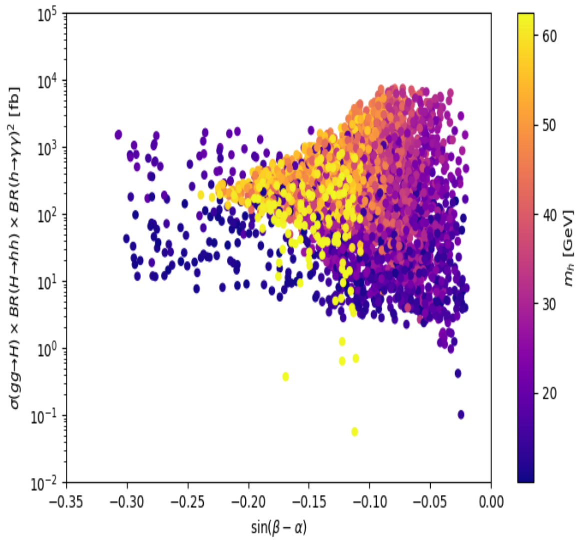
A 100 TeV collider will finally probe $A \to ZZ$ at the level of zero tree-level $H \to ZZ$ (and very model dependent - dependent on higher order corrections).

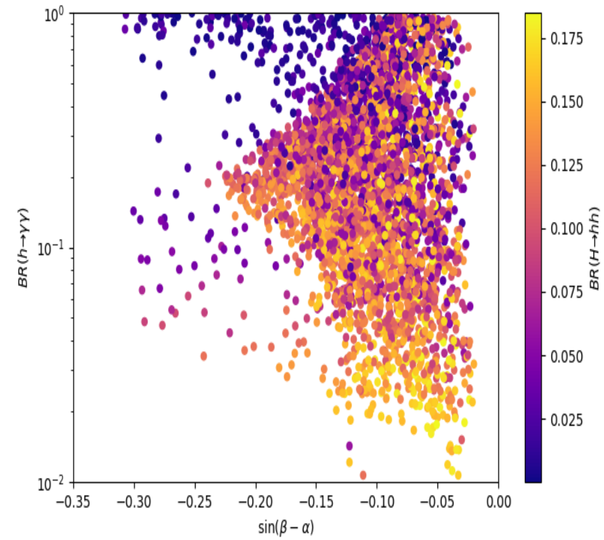
Arhrib, Benbrik, El Falaki, Sampaio, RS, 1809.04805.

Bernreuther, Gonzalez, Wiebusch, EPJC69, 31 (2010).

Other more exotic final states: fermiophobic Higgs

$h_{125} \rightarrow hh \rightarrow 4\gamma$ In the 2HDM and also in any extension beyond the 2HDM

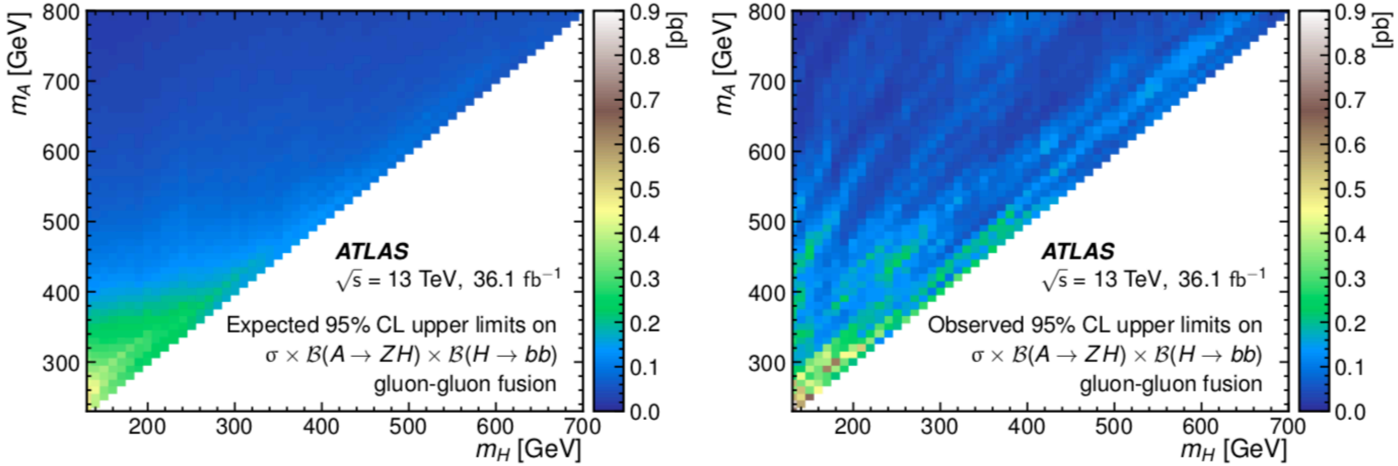




Multi-photon production in the Type-I 2HDM - This paper presents a study of a possible contribution to a Higgs boson signal in the hh → γγγγ channel due to H → hh decays, in the framework of the CP-conserving 2-Higgs Doublet Model Type-I, where the heavier of the two CP-even Higgs bosons, H, is the SM-like Higgs state observed with a mass of 125 GeV at the LHC. Then, after validating our numerical framework against public experimental analyses carried out at the LHC, we proceed to assess its scope in constraining and/or extracting the gg → H → hh → γγγγ signal in presence of a sophisticated Monte Carlo (MC) simulation. We find that, over a substantial region of the 2HDM-I parameter space presently un-accessible, the LHC will be able to establish such a potential signature in the next 2–3 years.

Arhrib, Benbrik, Moretti, Rouchad, Yan, Zhang, JHEP 1807 (2018) 007.

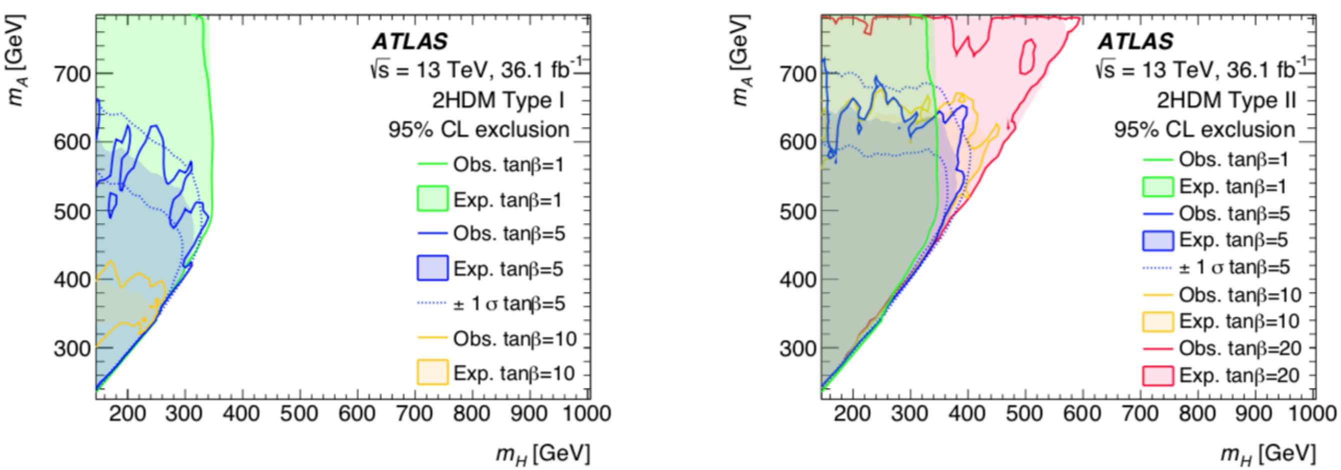
Searches - the physics of limits



Upper bounds at 95% CL on the production cross-section times the branching ratio Br(A → ZH)×Br(H → bb) in pb for gluon–gluon fusion. Left: expected; right: observed.

2HDM (CP-conserving and no tree-level FCNC)

ATLAS 1804.01126v1



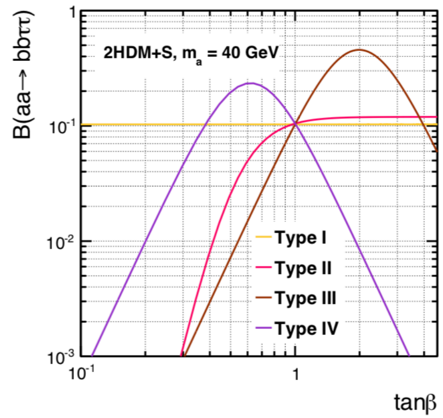
Observed and expected 95% CL exclusion regions in the (m_A,m_H) plane for various tan β values for Type I (left), and Type II (right).

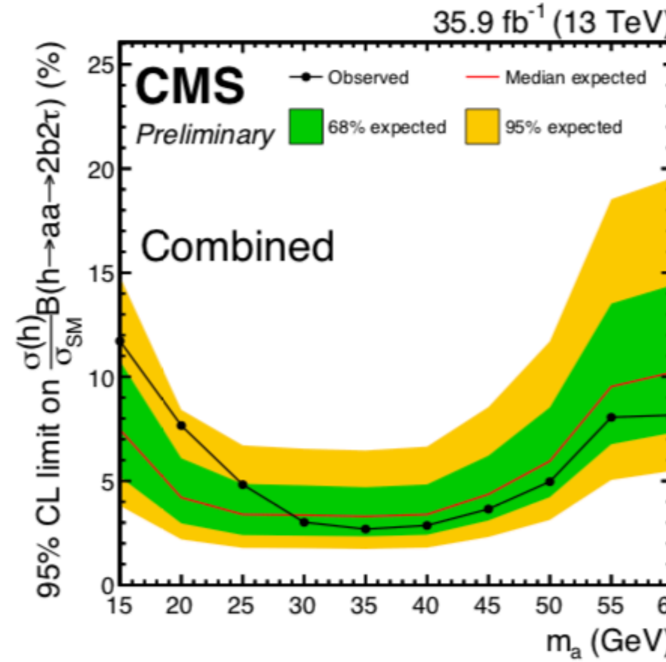
Assumptions: aligment, lightest Higgs 125 GeV, $m_{H+} = m_A$, U(1) symmetry (fixes m_{12}^2).

Searches - the physics of limits

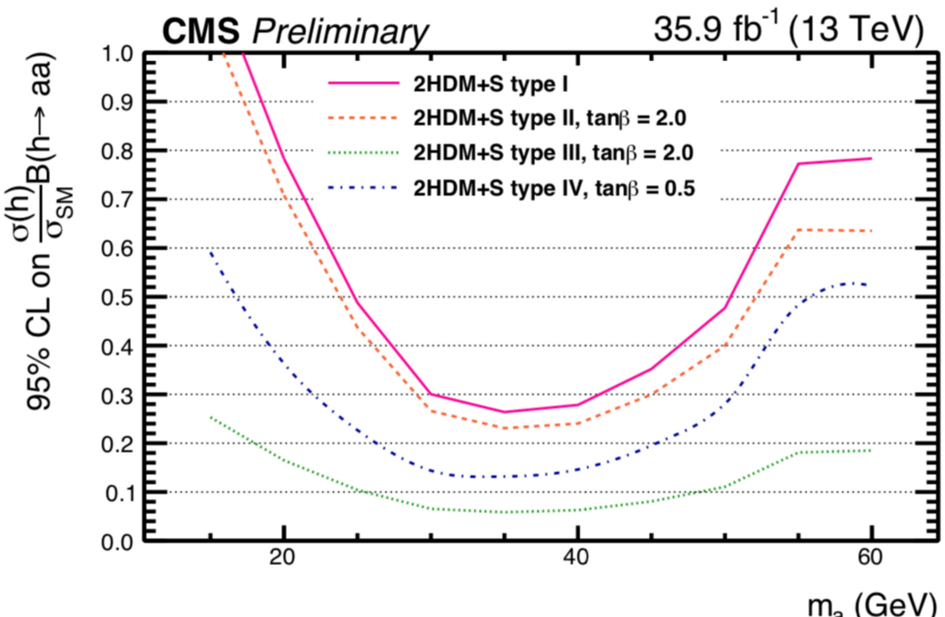
CMS PAS HIG-17-024

BRs for the 4 different versions of the model.





N2HDM (CP-conserving)



Exclusion for the different versions for 2 values of tanβ.

Expected and observed 95% CL limits on σ(h)B(h → aa → 2τ2b) in %. Combined eμ, eτ and μτ channels. The inner (green) band and the outer (yellow) band indicate the regions containing 68 and 95%, respectively, of the distribution of limits expected under the background-only hypothesis.

ATLAS, (γγjj final state),1803.11145

Lightest Higgs coupling modifiers (to gauge bosons)

h_{125} couplings measurements

For many extensions coupling modifiers are similar

$$g^{hVV}_{2HDM} = \sin(\beta - \alpha) g^{hVV}_{SM}$$

CP-violating 2HDM

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

"Pseudoscalar" component (doublet)

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

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

$$g^{hVV}_{N2HDM} = \cos\alpha_2 \, g^{hVV}_{2HDM}$$

Singlet component

$(a+ib)$

SM + Real singlet

$$g^{hVV}_{RxSM} = \cos\alpha_1 \, g^{hVV}_{SM}$$

SM + Complex singlet

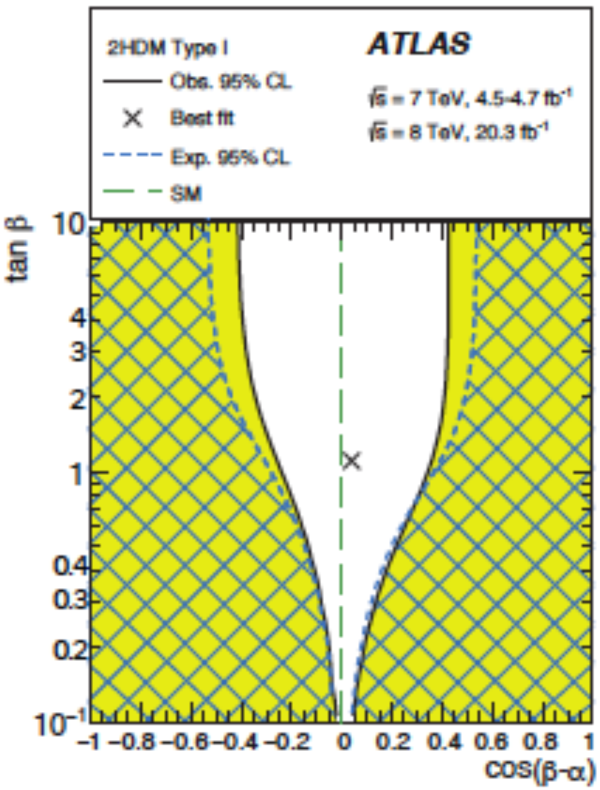
$$g^{hVV}_{CxSM} = \cos\alpha_1 \cos\alpha_2 \, g^{hVV}_{SM}$$

Real component — Imaginary component

h_{125} couplings measurements

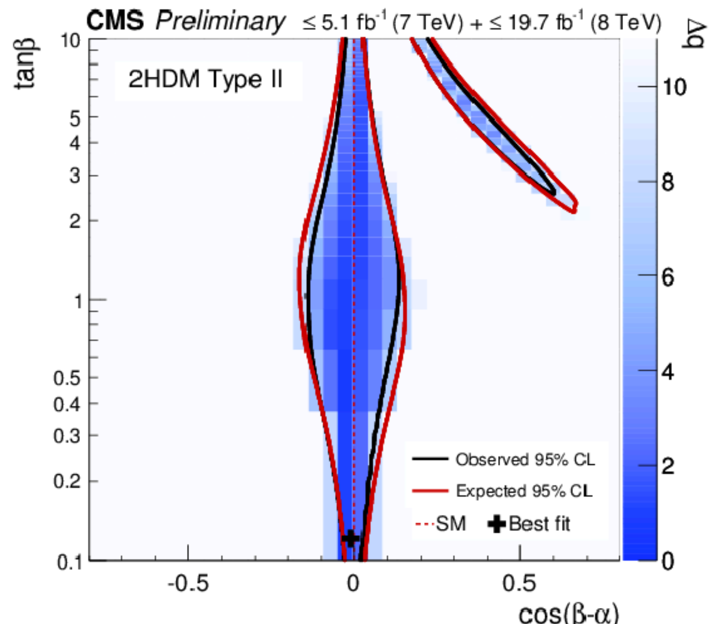
Models need couplings modifiers - simple in many extensions of the scalar sector

The 2HDM (CP-conserving and no tree-level FCNC)



(a) Type I

ATLAS 1509.00672

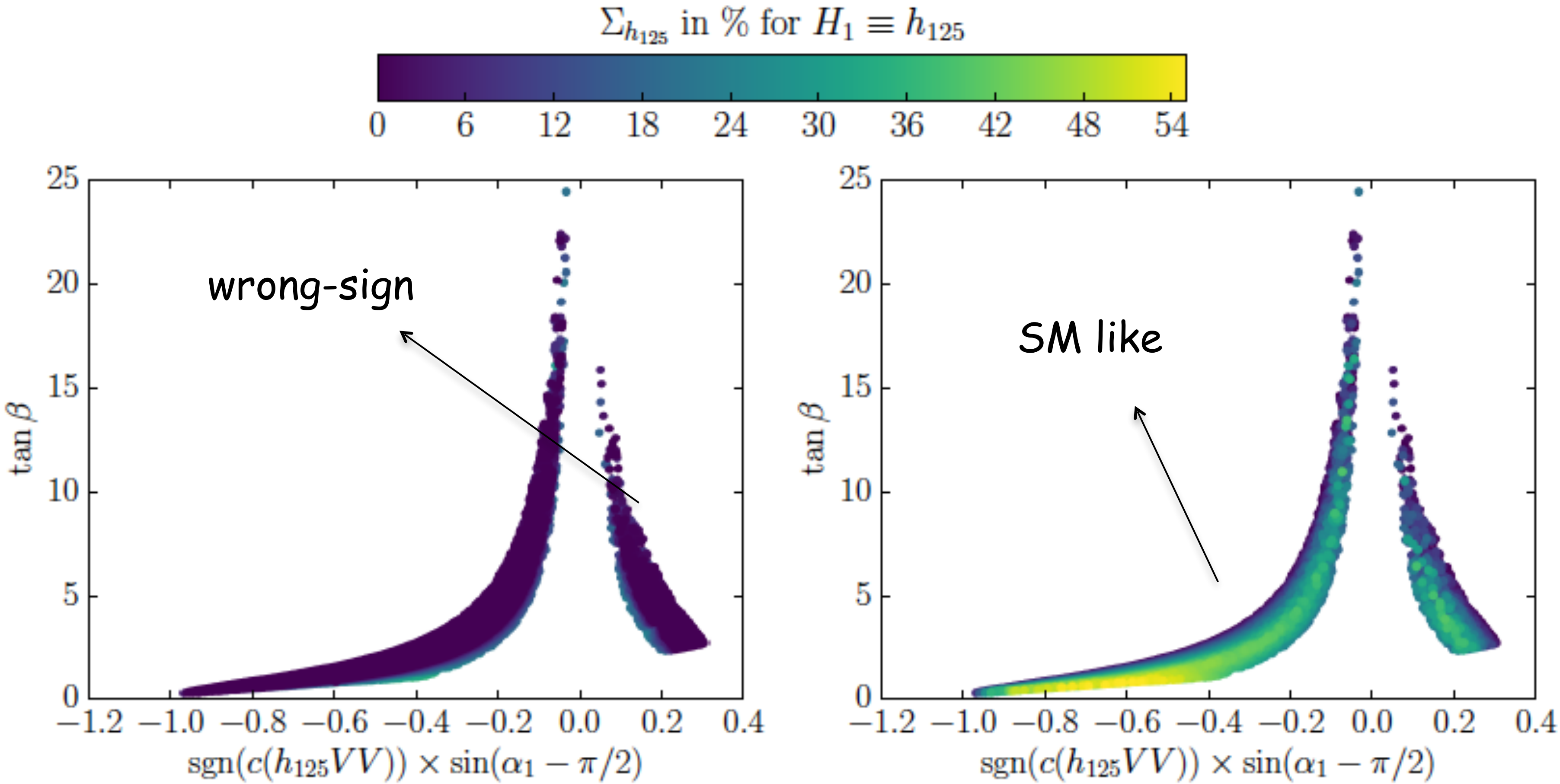


CMS-PAS-HIG-16-007

ATLAS and CMS allowed regions in type I and type II for the CP-conserving 2HDM. The central region is the SM-like limit (or alignment) where the Higgs couplings to the other SM particles are just the SM ones. The extra leg on the right has the wrong sign in the b/tau couplings relative to SM ones.

h_{125} couplings measurements

$\Sigma_i^{\mathrm{N2HDM}} = (R_{i3})^2$ singlet admixture of H_i (measure the singlet weight of H_i)



SM-like and wrong-sign limit in the N2HDM type II – the interesting fact is that in the alignment limit the singlet admixture can go up to 54 %.

Muhlleitner, Sampaio, RS, Wittbrodt, JHEP 1703 (2017) 094

Cruel faith for the EHS?

ABRAMOWICZ EAL, 1307.5288.
CLICDP, SICKING, NPPP, 273-275, 801 (2016)

Parameter	Relative precision [76,77]		
	350 GeV 500 fb^{-1}	+1.4 TeV +1.5 ab^{-1}	+3.0 TeV +2.0 ab^{-1}
κ_{HZZ}	0.43%	0.31%	0.23%
κ_{HWW}	1.5%	0.15%	0.11%
κ_{Hbb}	1.7%	0.33%	0.21%
κ_{Hcc}	3.1%	1.1%	0.75%
κ_{Htt}	–	4.0%	4.0%
$\kappa_{H\tau\tau}$	3.4%	1.3%	<1.3%
$\kappa_{H\mu\mu}$	–	14%	5.5%
κ_{Hgg}	3.6%	0.76%	0.54%
$\kappa_{H\gamma\gamma}$	–	5.6%	< 5.6%

Predicted precision for CLIC

$$\Sigma_i^{CxSM} = R_{i2}^2 + R_{i3}^2$$

$$\Sigma_i^{N2HDM} = R_{i3}^2$$

$$\Psi_i^{C2HDM} = R_{i3}^2$$

Non-doublet pieces of the SM-like Higgs. CxSM - sum of the real and complex component of the singlet. N2HDM - singlet component. C2HDM - pseudoscalar component.

Unitarity $\Rightarrow \kappa_{ZZ,WW}^2 + \Psi_i(\Sigma_1) \le 1$

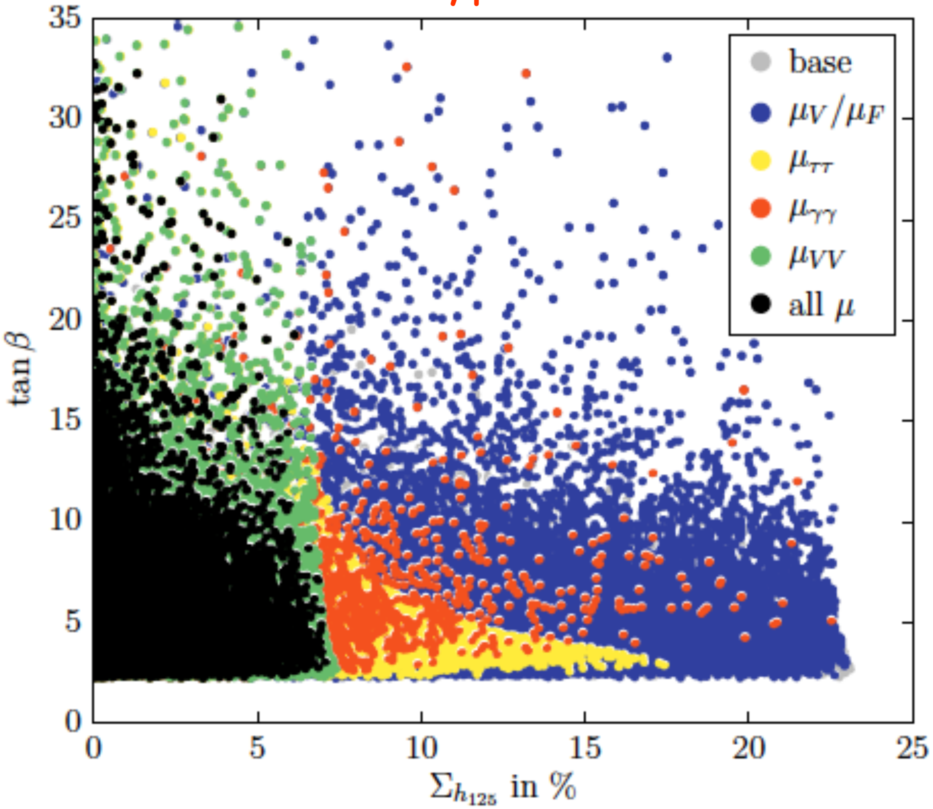
If no new physics is discovered and the measured values are in agreement with the SM predictions the singlet and pseudoscalar components will be below the % level.

Beware of radiative corrections.

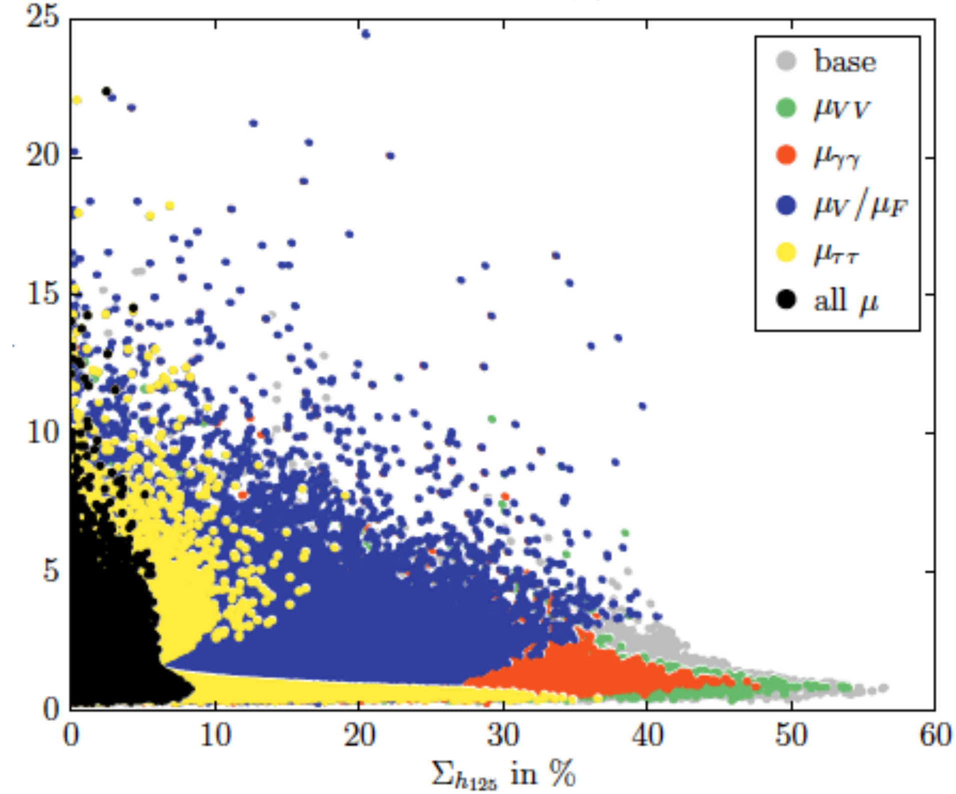
AZEVEDO, FERREIRA, MUHLLEITNER, RS, WITTBRODT, 1808.00755

Singlet admixture

N2HDM type I



N2HDM type II



Muhlleitner, Sampaio, RS, Wittbrodt, JHEP 1703 (2017) 094

tanβ as a function of the singlet admixture for type I N2HDM (left) and type II N2HDM (right) – in grey all points with constraints; the remaining colours denote μ values measured within 5 % of the SM. In black all μ's. Singlet admixture slightly below 10 % almost independently of tanβ.

The plot shows how far we can go in the measurement of the singlet component of the Higgs.

But what kind of people are we after all?

The right to party!

Desperate? -There is still so much to explore!

$$V = m_{11}^2|\Phi_1|^2 + m_{22}^2|\Phi_2|^2 - m_{12}^2(\Phi_1^\dagger\Phi_2 + h.c.) + (A\Phi_1^\dagger\Phi_2\Phi_S + h.c.)$$
$$+\frac{\lambda_1}{2}(\Phi_1^\dagger\Phi_1)^2 + \frac{\lambda_2}{2}(\Phi_2^\dagger\Phi_2)^2 + \lambda_3(\Phi_1^\dagger\Phi_1)(\Phi_2^\dagger\Phi_2) + \lambda_4(\Phi_1^\dagger\Phi_2)(\Phi_2^\dagger\Phi_1)$$
$$+\frac{\lambda_5}{2}\left[(\Phi_1^\dagger\Phi_2) + h.c.\right] + \frac{m_S^2}{2}\Phi_S^2 + \frac{\lambda_6}{4}\Phi_S^4 + +\frac{\lambda_7}{2}(\Phi_1^\dagger\Phi_1)\Phi_S^2 + \frac{\lambda_8}{2}(\Phi_2^\dagger\Phi_2)\Phi_S^2$$

with fields

$$\Phi_1 = \begin{pmatrix} \phi_1^+ \\ \frac{1}{\sqrt{2}}(v_1 + \rho_1 + i\eta_1) \end{pmatrix} \qquad \Phi_2 = \begin{pmatrix} \phi_2^+ \\ \frac{1}{\sqrt{2}}(v_2 + \rho_2 + i\eta_2) \end{pmatrix} \qquad \Phi_S = v_S + \rho_S$$

$\Longrightarrow v_S = 0$ **scalar dark matter**

$\Longrightarrow \mathcal{L} = -iy_\chi \Phi_S \bar{\chi}\gamma_5\chi$ **fermionic dark matter**

Bauer, Haisch, Kahlhoefer, JHEP 1705 (2017) 138

But even stranger things can happen

Two doublets + one singlet and one exact Z_2 symmetry

$$\Phi_1 \to \Phi_1, \qquad \Phi_2 \to -\Phi_2, \qquad \Phi_S \to -\Phi_S$$

with the most general renormalizable potential

$$V = m_{11}^2 |\Phi_1|^2 + m_{22}^2 |\Phi_2|^2 + (A\Phi_1^\dagger \Phi_2 \Phi_S + h.c.)$$
$$+\frac{\lambda_1}{2}(\Phi_1^\dagger\Phi_1)^2 + \frac{\lambda_2}{2}(\Phi_2^\dagger\Phi_2)^2 + \lambda_3(\Phi_1^\dagger\Phi_1)(\Phi_2^\dagger\Phi_2) + \lambda_4(\Phi_1^\dagger\Phi_2)(\Phi_2^\dagger\Phi_1)$$
$$+\frac{\lambda_5}{2}\left[(\Phi_1^\dagger\Phi_2) + h.c.\right] + \frac{m_S^2}{2}\Phi_S^2 + \frac{\lambda_6}{4}\Phi_S^4 + +\frac{\lambda_7}{2}(\Phi_1^\dagger\Phi_1)\Phi_S^2 + \frac{\lambda_8}{2}(\Phi_2^\dagger\Phi_2)\Phi_S^2$$

and the vacuum preserves the symmetry

$$\Phi_1 = \begin{pmatrix} G^+ \\ \frac{1}{\sqrt{2}}(v + h + iG_0) \end{pmatrix} \qquad \Phi_2 = \begin{pmatrix} H^+ \\ \frac{1}{\sqrt{2}}(\rho + i\eta) \end{pmatrix} \qquad \Phi_S = \rho_S$$

The potential is invariant under the CP-symmetry

$$\Phi_1^{CP}(t,\vec{r}) = \Phi_1^*(t,-\vec{r}), \qquad \Phi_2^{CP}(t,\vec{r}) = \Phi_2^*(t,-\vec{r}), \qquad \Phi_S^{CP}(t,\vec{r}) = \Phi_S(t,-\vec{r})$$

except for the term $(A\Phi_1^\dagger\Phi_2\Phi_S + h.c.)$ for complex A

Azevedo, Ferreira, Muhlleitner, Patel, RS, Wittbrodt

Dark CP-violating sector

The Z_2 symmetry is exact - all particles are dark except the SM-like Higgs. The couplings of the SM-like Higgs to all fermions and massive gauge bosons are exactly the SM ones.

The model is Type I - only the first doublet couples to all fermions

The neutral mass eigenstates are h_1, h_2, h_3

$$\begin{pmatrix} h_1 \\ h_2 \\ h_3 \end{pmatrix} = R \begin{pmatrix} \rho \\ \eta \\ \rho_S \end{pmatrix} \qquad R = \begin{pmatrix} c_1 c_2 & s_1 c_2 & s_2 \\ -(c_1 s_2 s_3 + s_1 c_3) & c_1 c_3 - s_1 s_2 s_3 & c_2 s_3 \\ -c_1 s_2 c_3 + s_1 s_3 & -(c_1 s_3 + s_1 s_2 c_3) & c_2 c_3 \end{pmatrix}$$

But now how do we see signs of CP-violation?

Missing energy signals are similar to some extent for all dark matter models. They need to be combined with a clear sign of CP-violation.

$$q\bar{q}(e^+e^-) \to Z^* \to h_1 h_2 \to h_1 h_1 Z$$

Mono-Z and mono-Higgs events.

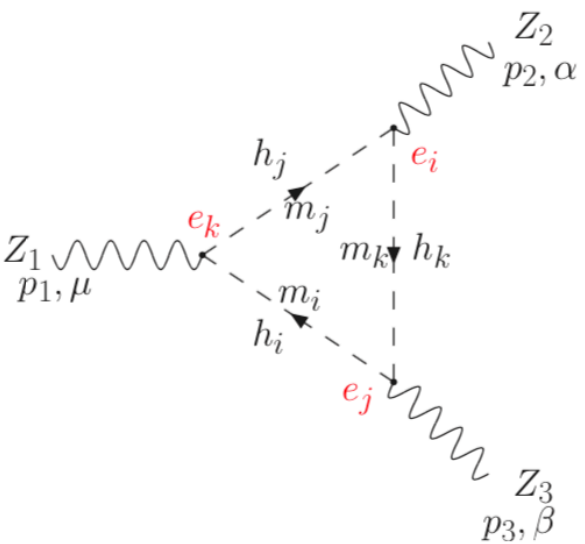
$$q\bar{q}(e^+e^-) \to Z^* \to h_1 h_2 \to h_1 h_1 h_{125}$$

With one Z off-shell the most general ZZZ vertex has a CP-odd term of the form

$$i\Gamma_{\mu\alpha\beta} = -e\frac{p_1^2 - m_Z^2}{m_Z^2} f_4^Z (g_{\mu\alpha}p_{2,\beta} + g_{\mu\beta}p_{3,\alpha}) + \ldots$$

that comes from an effective operator (dim-6)

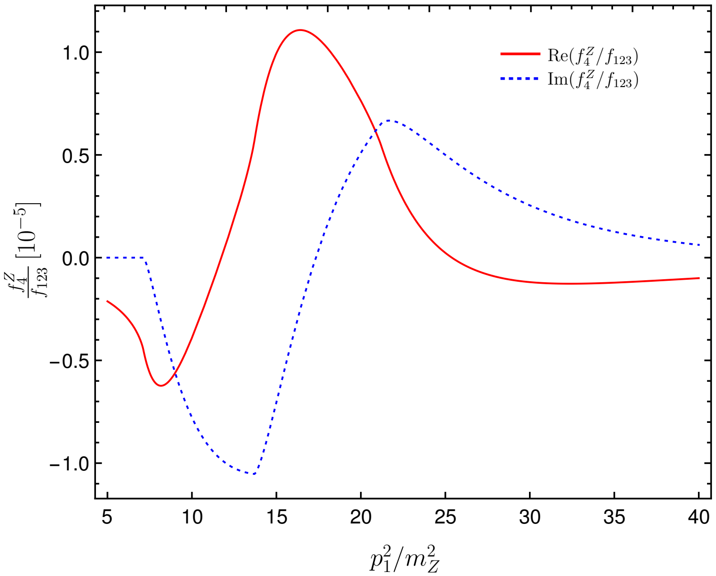
$$\frac{\tilde{k}_{ZZ}}{m_Z^2}\partial_\mu Z_\nu \partial^\mu Z^\rho \partial_\rho Z^\nu$$



in our model it has the simple expression

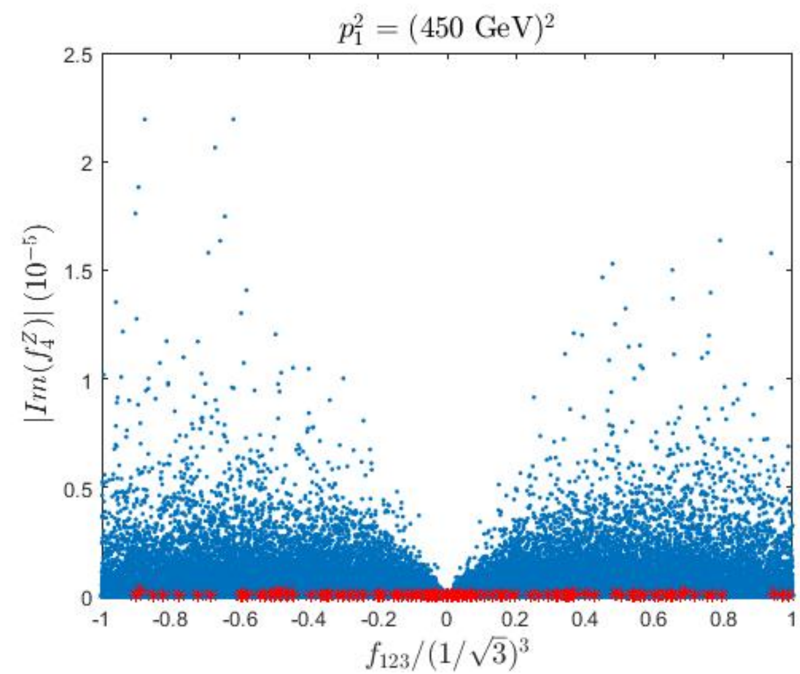
$$f_4^Z(p_1^2) = -\frac{2\alpha}{\pi s_{2\theta_W}^3}\frac{m_Z^2}{p_1^2 - m_Z^2} f_{123} \sum_{i,j,k} \epsilon_{ijk}\, C_{001}(p_1^2, m_Z^2, m_Z^2, m_i^2, m_j^2, m_k^2)$$

$$f_{123} = R_{13}R_{23}R_{33}$$



The form factor f_4 normalised to f_{123} for m_1=80.5 GeV, m_2=162.9 GeV and m_3=256.9 GeV as a function of the squared off-shell Z-boson 4-momentum, normalised to m_Z^2.

Scatter plot for the imaginary part of f_4 as a function of f_{123} normalised to its maximum value. Red points are the ones for which all dark scalars mass are below 200 GeV.



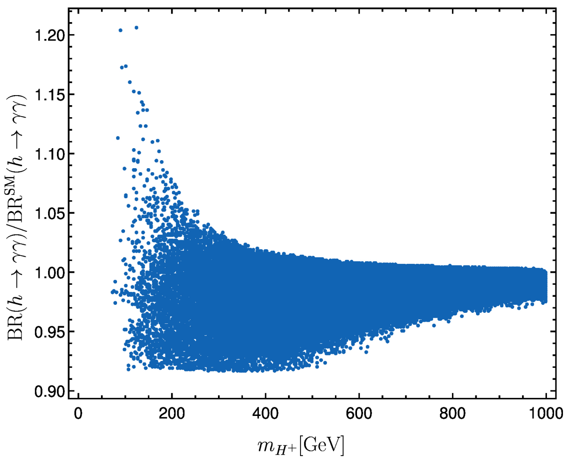
But the bounds we have from present measurements by ATLAS and CMS, we are still two orders of magnitude away from what is needed.

$$\frac{\tilde{k}_{ZZ}}{m_Z^2}\partial_\mu Z_\nu \partial^\mu Z^\rho \partial_\rho Z^\nu$$

Also, the measured quantity is a constant unlike f4.

CMS COLLABORATION, EPJC78 (2018) 165. $-1.2\times 10^{-3} < f_4^Z < 1.0\times 10^{-3}$

ATLAS COLLABORATION, PRD97 (2018) 032005. $-1.5\times 10^{-3} < f_4^Z < 1.5\times 10^{-3}$



Finally: there are also charged particles that that can only decay to to another Z_2-odd particle. They also contribute to the decay of the SM-like Higgs into photons. But again no deviation was found so far.

Stranger things can happen II

What if the discovered 125 GeV reveals different CP behaviour in two decay channels?

The SM-like Higgs coupling to ZZ(WW) relative to the corresponding SM coupling is

$$\kappa^{h_{125}WW}_{C2HDM} = c_2 \sin(\beta - \alpha)$$

and c_2 cannot be far from 1. But α_2 is the CP-violating angle and therefore it should be small. However, the CP-odd component has an extra tanβ factor for down quarks and leptons, but not for the up quarks

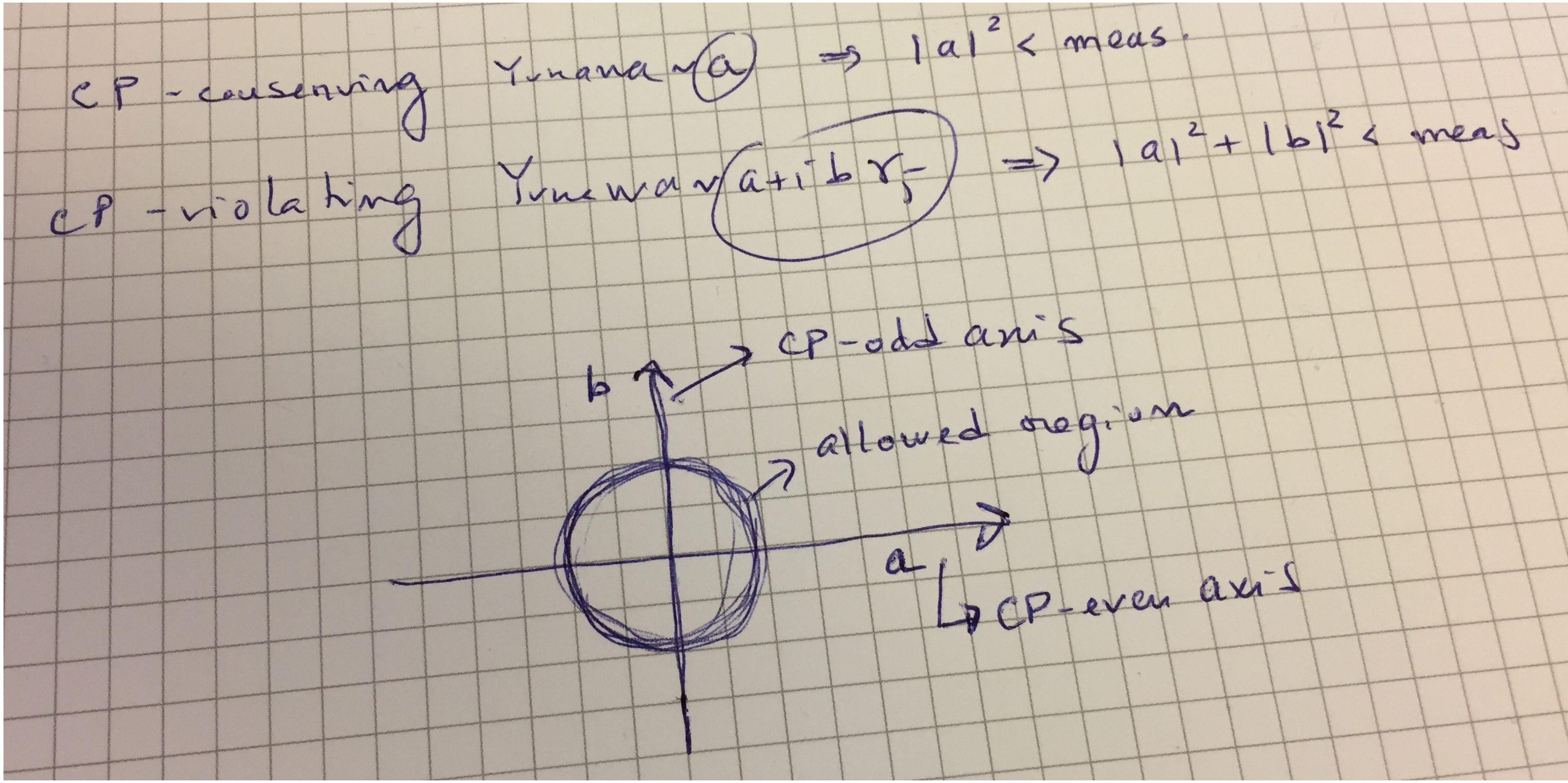
$$Y^{TypeII}_{C2HDM} = c_2 Y^{TypeII}_{2HDM} - i\gamma_5 s_2 t_\beta$$ bottom, tau

$$Y^{TypeII}_{C2HDM} = c_2 Y^{TypeII}_{2HDM} - i\gamma_5 \frac{s_2}{t_\beta}$$ top

Thus, the SM-like Higgs couplings to the tops could be mainly CP-even while couplings to the bottoms and taus could be mainly CP-odd.

Fontes, Muhlleitner, Romão, RS, Silva, Wittbrodt, JHEP 1802 (2018) 073.

In the CP-odd vs. CP-even plane, the bounds on the Yukawa couplings look like rings.



Softly broken Z_2 symmetric 2HDM Higgs potential

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

and CP is not spontaneously broken

$$<\Phi_1> = \begin{pmatrix} 0 \\ \frac{v_1}{\sqrt{2}} \end{pmatrix} \qquad <\Phi_2> = \begin{pmatrix} 0 \\ \frac{v_2}{\sqrt{2}} \end{pmatrix}$$

- m^2_{12} and λ_5 real **2HDM**
- m^2_{12} and λ_5 complex **C2HDM**

Type I $\kappa_U^I = \kappa_D^I = \kappa_L^I = \frac{\cos\alpha}{\sin\beta}$

Type II $\kappa_U^{II} = \frac{\cos\alpha}{\sin\beta}$ $\kappa_D^{II} = \kappa_L^{II} = -\frac{\sin\alpha}{\cos\beta}$

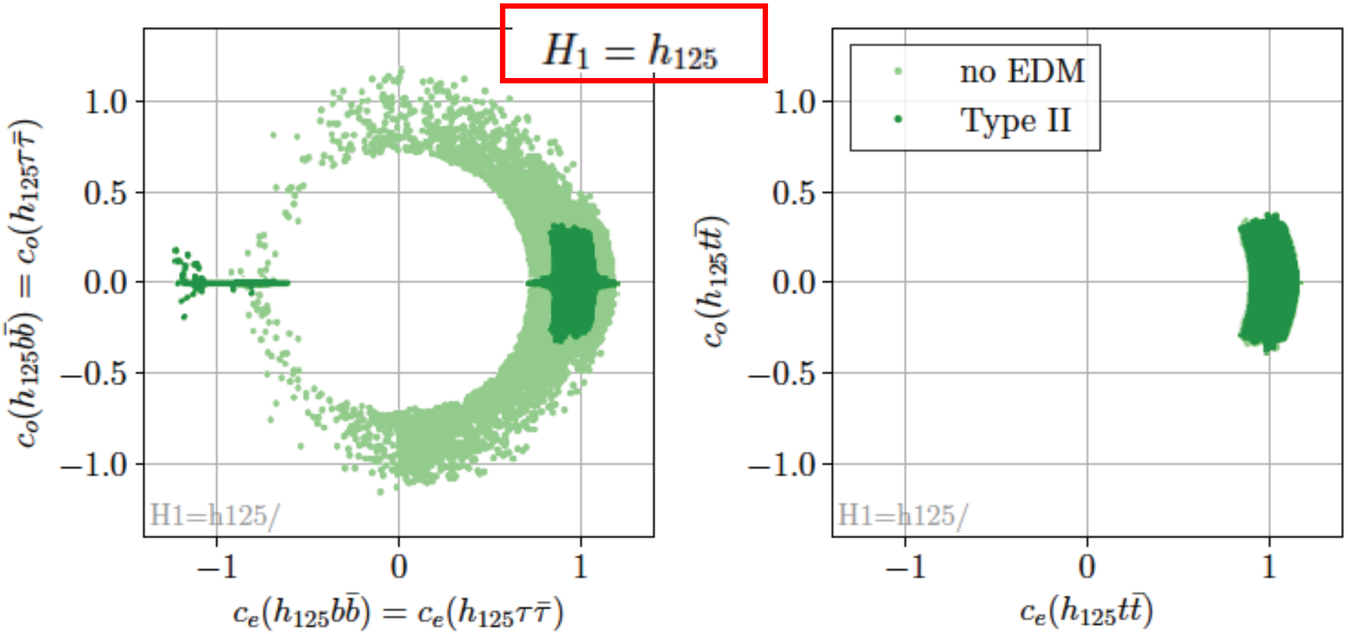
Type F $\kappa_U^F = \kappa_L^F = \frac{\cos\alpha}{\sin\beta}$ $\kappa_D^F = -\frac{\sin\alpha}{\cos\beta}$

$$Y_{C2HDM} \equiv c_2 Y_{2HDM} \pm i\gamma_5 s_2 \begin{cases} t_\beta \\ 1/t_\beta \end{cases} = Y_{N2HDM} \pm i\gamma_5 s_2 \begin{cases} t_\beta \\ 1/t_\beta \end{cases}$$

Type LS $\kappa_U^{LS} = \kappa_D^{LS} = \frac{\cos\alpha}{\sin\beta}$ $\kappa_L^{LS} = -\frac{\sin\alpha}{\cos\beta}$

III = I' = Y = Flipped = 4… **IV = II' = X = Lepton Specific= 3…**

The allowed parameter space in type II C2HDM



$$c_o(h_{125}tt) = \frac{\sin(\alpha_2)}{\tan(\beta)}$$

$$c_o(h_{125}bb(\tau\tau)) = \sin(\alpha_2)\tan(\beta)$$

$$\tan(\beta) \geq 1$$

Bounds are stronger for the up-quarks couplings. They come from μ_{VV} and the bound on $\tan\beta$. In type I all couplings are very constrained.

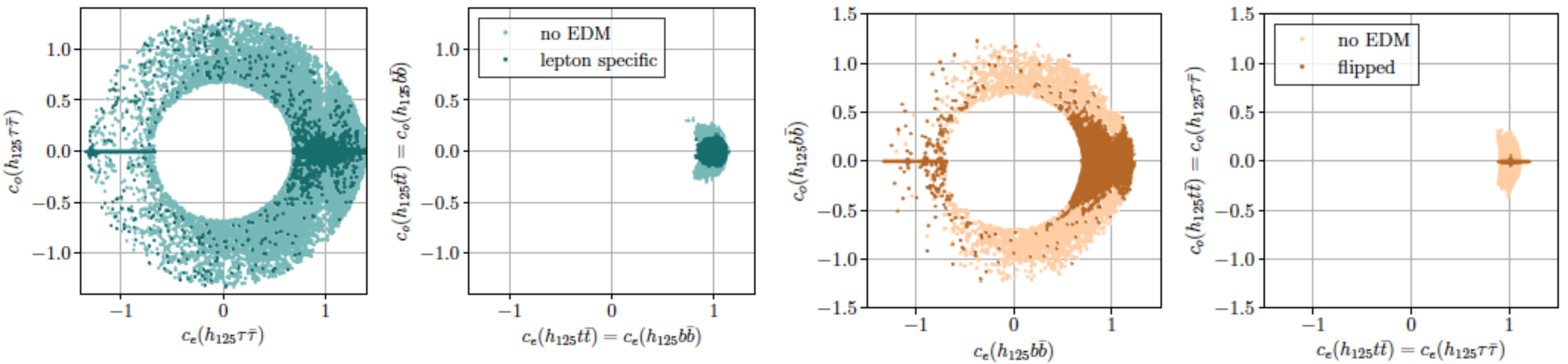
$$a_D = a_L \approx 0 \quad \Rightarrow \quad b_D = b_L \approx 1$$

and the remaining h_1 couplings to up-type quarks and gauge bosons are

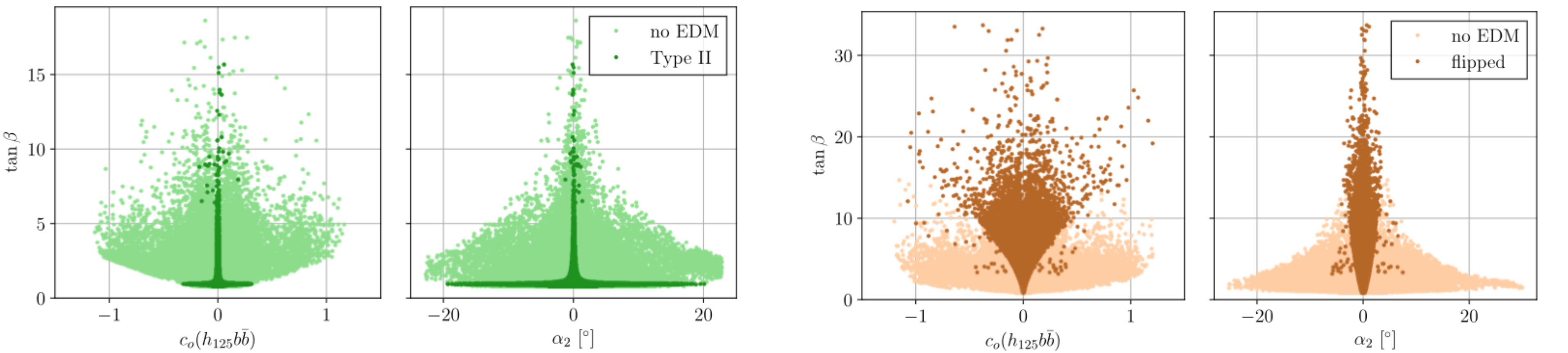
$$\begin{cases} a_U^2 = (1 - s_2^4) = (1 - 1/t_\beta^4) \\ b_U^2 = s_2^4 = 1/t_\beta^4 \end{cases} \qquad \left(\frac{g^{hVV}_{C2HDM}}{g^{hVV}_{SM}}\right)^2 = C^2 = \frac{t_\beta^2 - 1}{t_\beta^2 + 1} = \frac{1 - s_2^2}{1 + s_2^2}$$

EDMs constraints completely kill large pseudoscalar components in Type II.

Not true in Flipped and Lepton Specific.



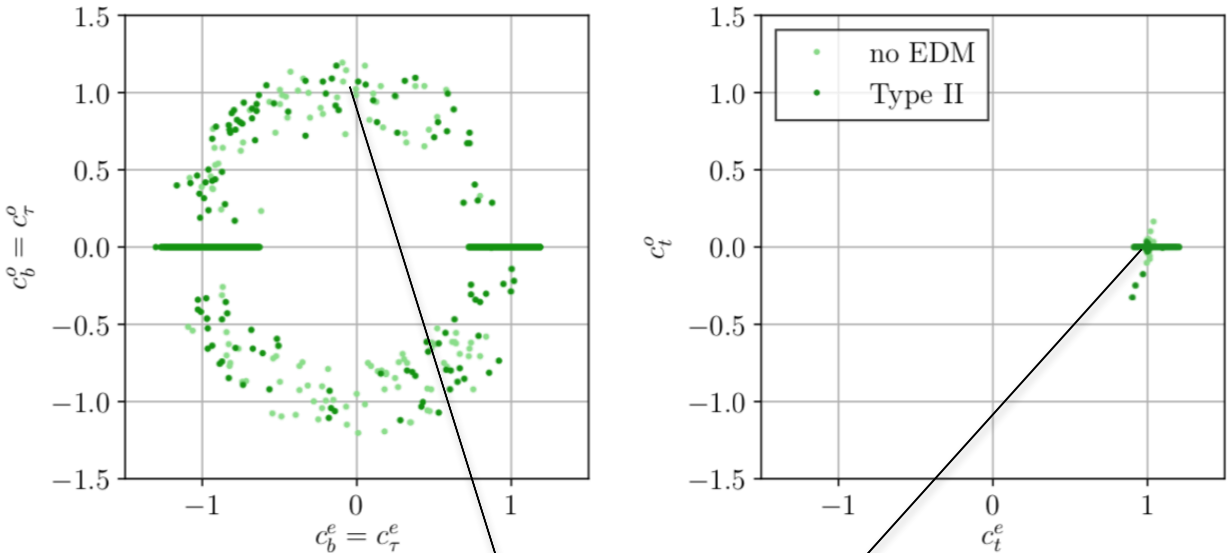
CP-odd coupling proportional to $\sin\alpha_2 \tan\beta$



EDMs act differently in the different Yukawa versions of the model.

Cancellations between diagrams occur.

And this brings a very interesting CP-violation scenario



$$Y_{C2HDM} \equiv a_F + i\gamma_5 b_F$$

$$b_U \approx 0 \quad \text{and} \quad a_D \approx 0$$

A Type II model where H_2 is the SM-like Higgs.

Find two particles of the same mass one decaying to tops as CP-even

$$h_1 = H \to t\bar{t}$$

and the other decaying to taus as CP-odd

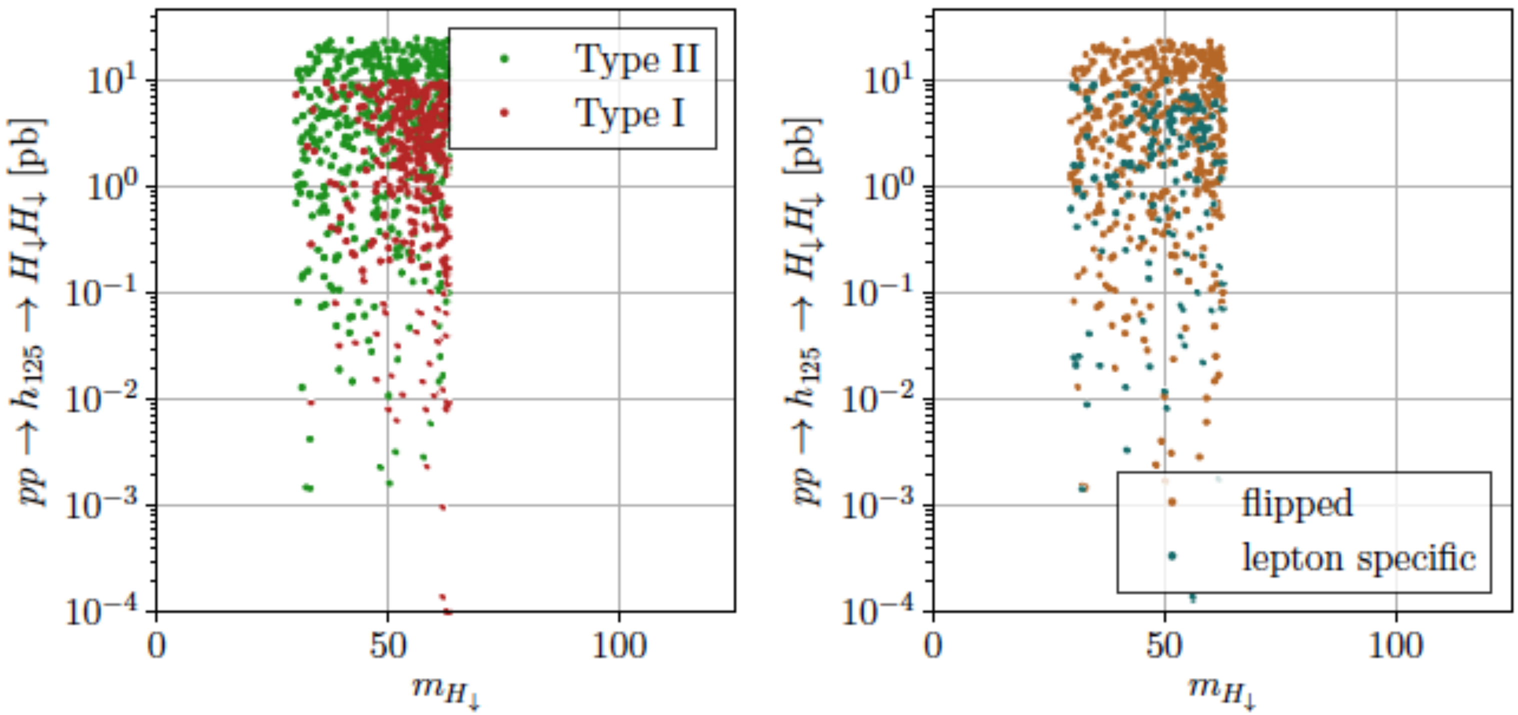
$$h_1 = A \to \tau^+\tau^-$$

Probing one Yukawa coupling is not enough!

Type II	BP2m	BP2c	BP2w
m_{H_1}	94.187	83.37	84.883
m_{H_2}	125.09	125.09	125.09
$m_{H^\pm}$	586.27	591.56	612.87
$\mathrm{Re}(m_{12}^2)$	24017	7658	46784
α_1	-0.1468	-0.14658	-0.089676
α_2	-0.75242	-0.35712	-1.0694
α_3	-0.2022	-0.10965	-0.21042
$\tan\beta$	7.1503	6.5517	6.88
m_{H_3}	592.81	604.05	649.7
$c_b^e = c_\tau^e$	0.0543	0.7113	-0.6594
$c_b^o = c_\tau^o$	1.0483	0.6717	0.6907
μ_V/μ_F	0.899	0.959	0.837
μ_{VV}	0.976	1.056	1.122
$\mu_{\gamma\gamma}$	0.852	0.935	0.959
$\mu_{\tau\tau}$	1.108	1.013	1.084
μ_{bb}	1.101	1.012	1.069

But more: there is still plenty of parameter space to cover!

Decays of h_{125} (h_3 or h_2) to $H_\downarrow H_\downarrow$ for all types in the C2HDM

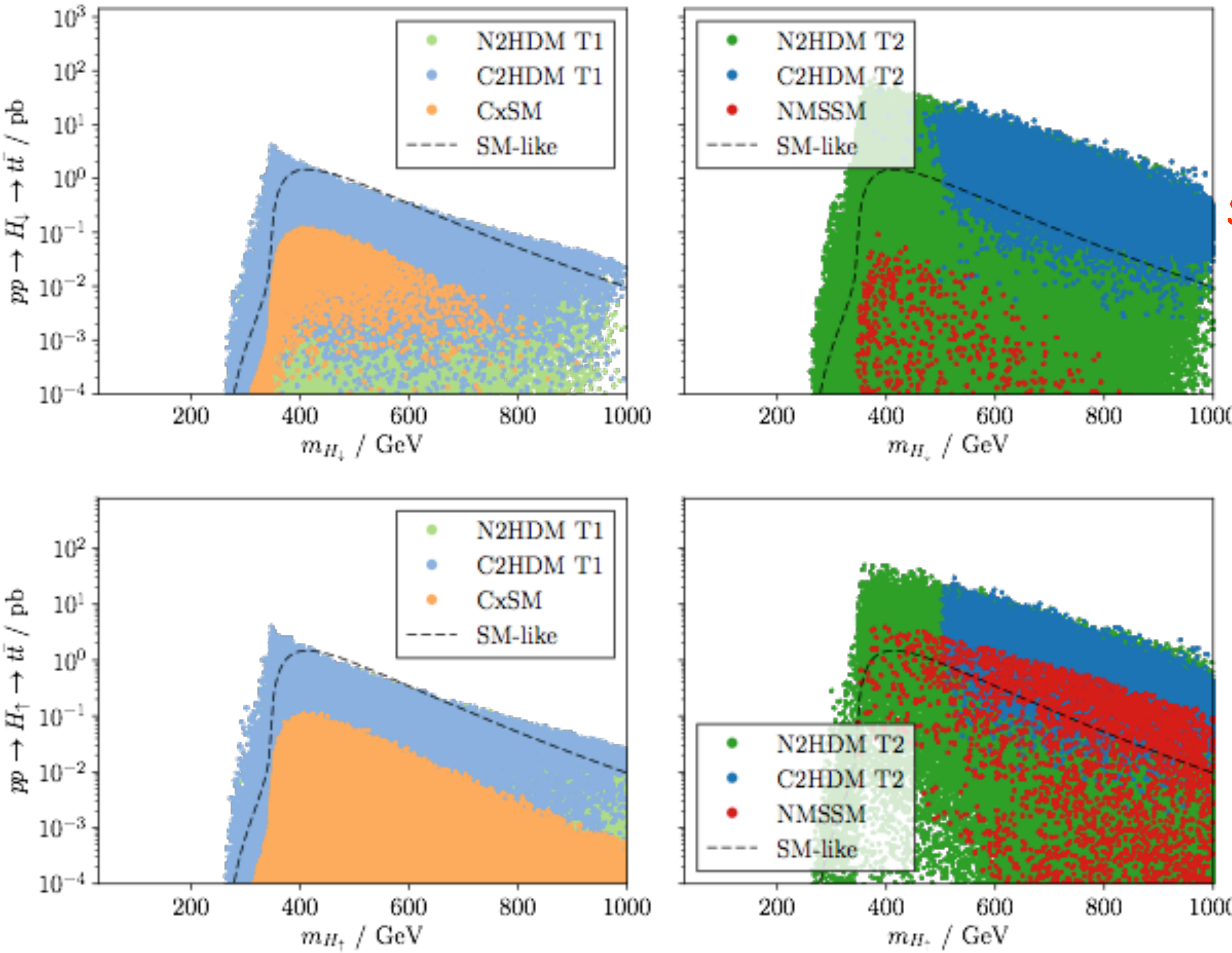


Left - Signal rates for the production of h_{125} decaying to $H_\downarrow H_\downarrow$ for 13 TeV as a function of m_H for Types I and II

Right – Same for Flipped and Lepton Specific

We are able to distinguish different types of the same model - maximal rates range from 10 to 30 pb

Non-125 to tt



Signal rates for the production of H↓ (upper) and H↑ (lower) for 13 TeV as a function of m_H.

Dashed line is the "SM".

Muhlleitner, Sampaio, RS, Wittbrodt, JHEP 1708 (2017) 132

Conclusions

"Ode to Intimations of Immortality"

Though nothing can bring back the hour
Of splendour in the grass, of glory in the flower;
We will grieve not, rather find
Strength in what remains behind;
In the primal sympathy
Which having been must ever be;
In the soothing thoughts that spring
Out of human suffering;
In the faith that looks through death,
In years that bring the philosophic mind.

Or as the poem is known in the HEP community - "Phenomenologists stop whining and just move on as the LHC is still running."

Wordsworth, (1807)

Working Group 3: Sub-group – Neutral Extended Scalars

1. **Motivate searches at the LHC** – Look for new scalars (new signatures?) in simple extensions of the scalar sector – benchmark models for searches.

2. **Precision** - H_{125} couplings measurements (sure-fire investment)

a) How efficiently can the parameter space of these simple extensions be constrained through measurements of the Higgs properties?
b) How SM-like is the SM-like Higgs?
c) What are higher order EW corrections (of extended models) good for?

3. **Distinguishing models** - Can the LHC Higgs phenomenology and in particular signal rates and coupling measurements be used to distinguish models with extended Higgs sectors? Needs new physics but it can also be a guide for signature motivated searches.

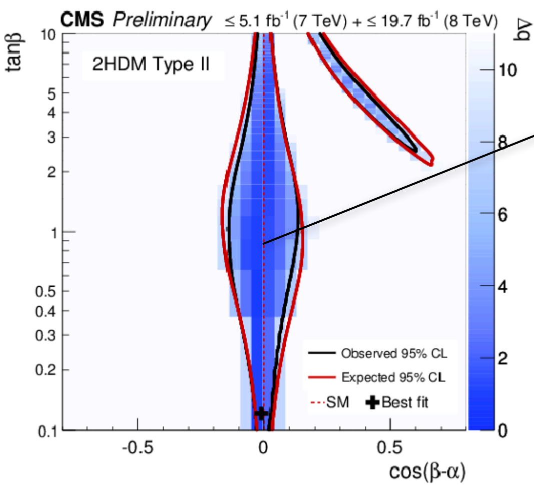
Yellow Report 4: benchmarks proposed in many different extensions, for the LHC Run 2

arXiv:1610.07922v1

Back to The alignment limit in the 2HDM

$$\begin{pmatrix} \\ V_1 \end{pmatrix} \quad \begin{pmatrix} \\ V_2 \end{pmatrix}$$

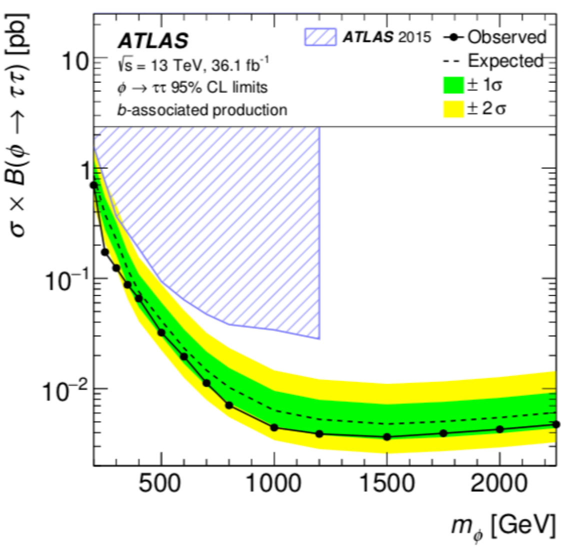
What about tanβ? All couplings of h125 with the other SM particles are SM-like (even hhh).



EVEN IF IN THE END WE WILL HAVE A LINE ONLY, THE MIXING BETWEEN VEVS CAN ONLY BE SEEN WITH NEW PHYSICS.

TWO EXAMPLES:

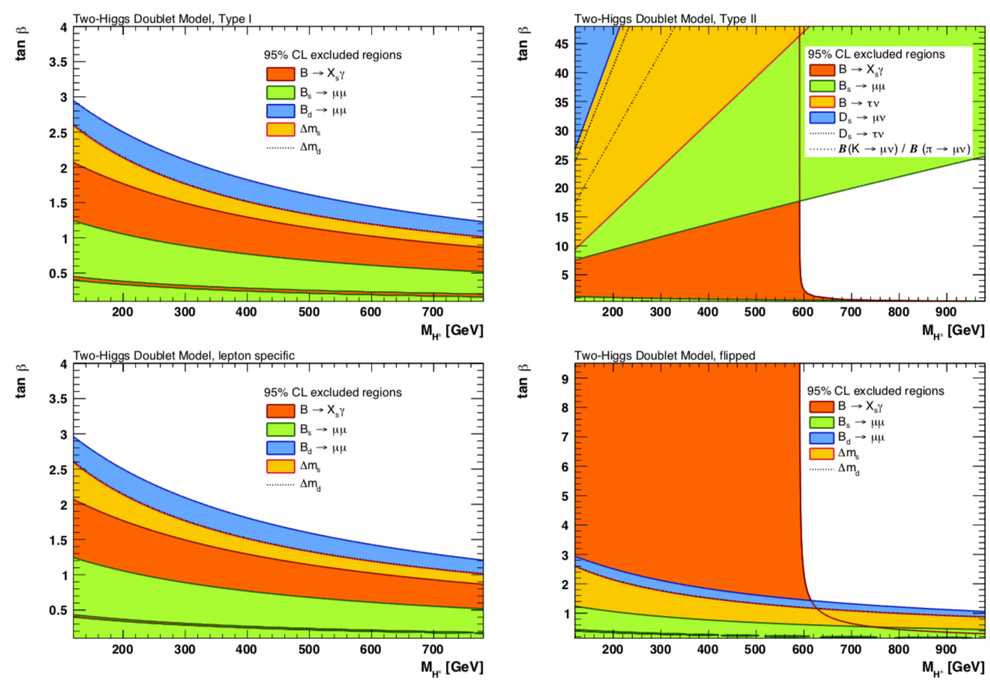
HALLER, HOECKER, KOGLER, PEIFFER, STELZER 1803.01853



(b) $\phi \to \tau\tau$ (b-associated production).

From the LHC: limit on the pseudoscalar mass, tanβ plane.

ATLAS, JHEP01(2018)055

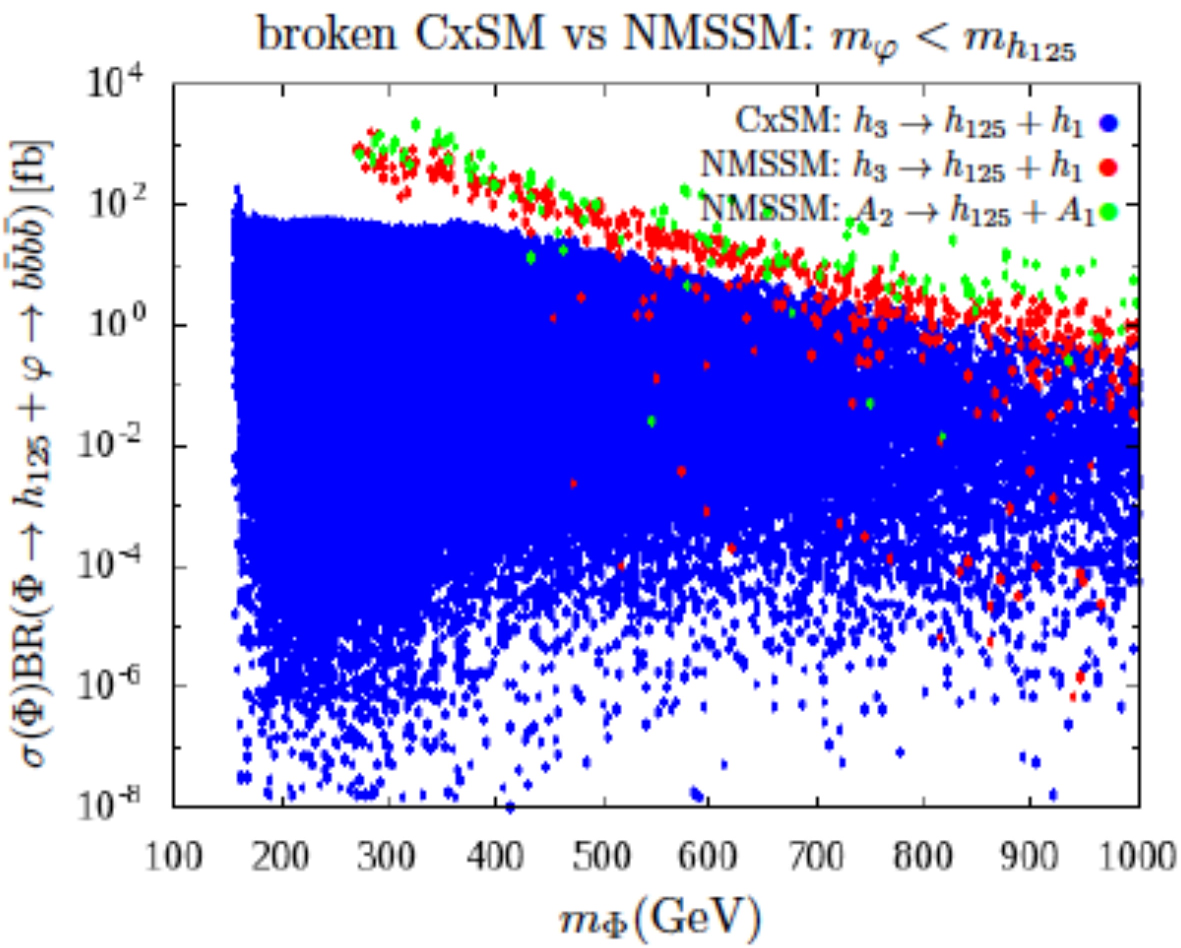


From B-physics: Charged Higgs loops – constraint in the charged Higgs mass, tanβ plane

3. Distinguishing models

The decay

$$H_i \to H_j H_k \qquad j \neq k$$



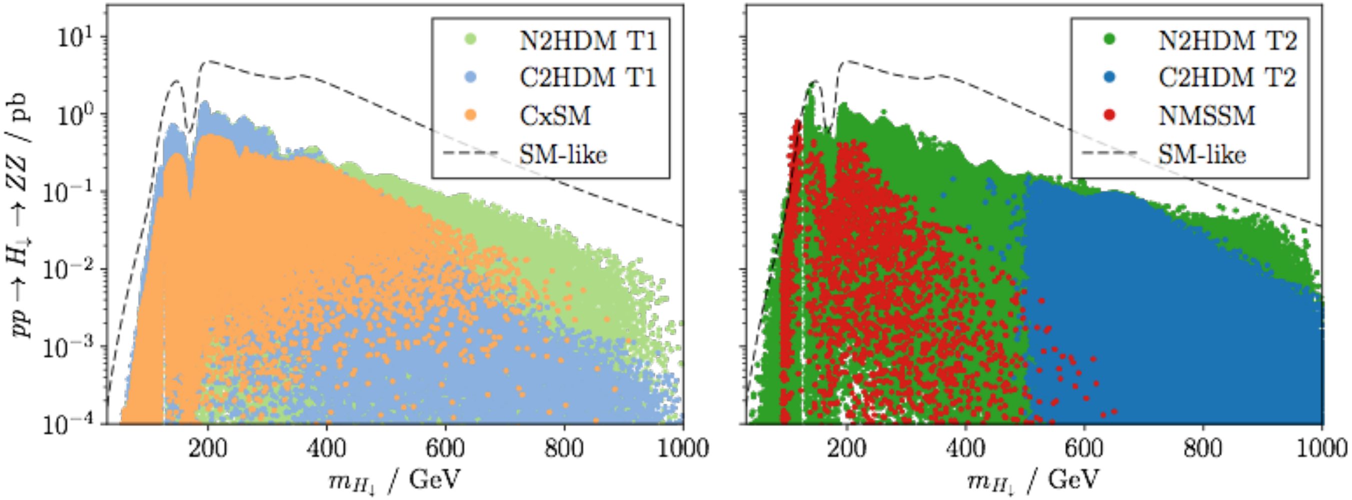
$\Phi \to h_{125} + \varphi$ found to be distinctive

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

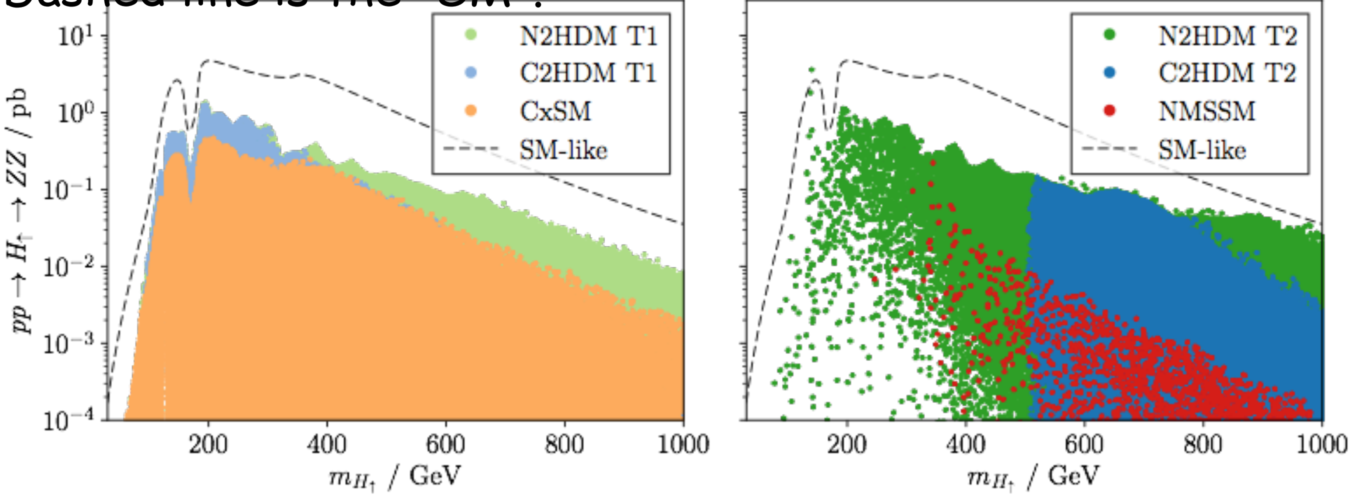
The models can be distinguished in some regions of the parameter space.

Costa, Mühlleitner, Sampaio, RS JHEP(2016) 034

Non-125 CP-even to ZZ in different models



Dashed line is the "SM".



Muhlleitner, Sampaio, RS, Wittbrodt, JHEP 1708 (2017) 132

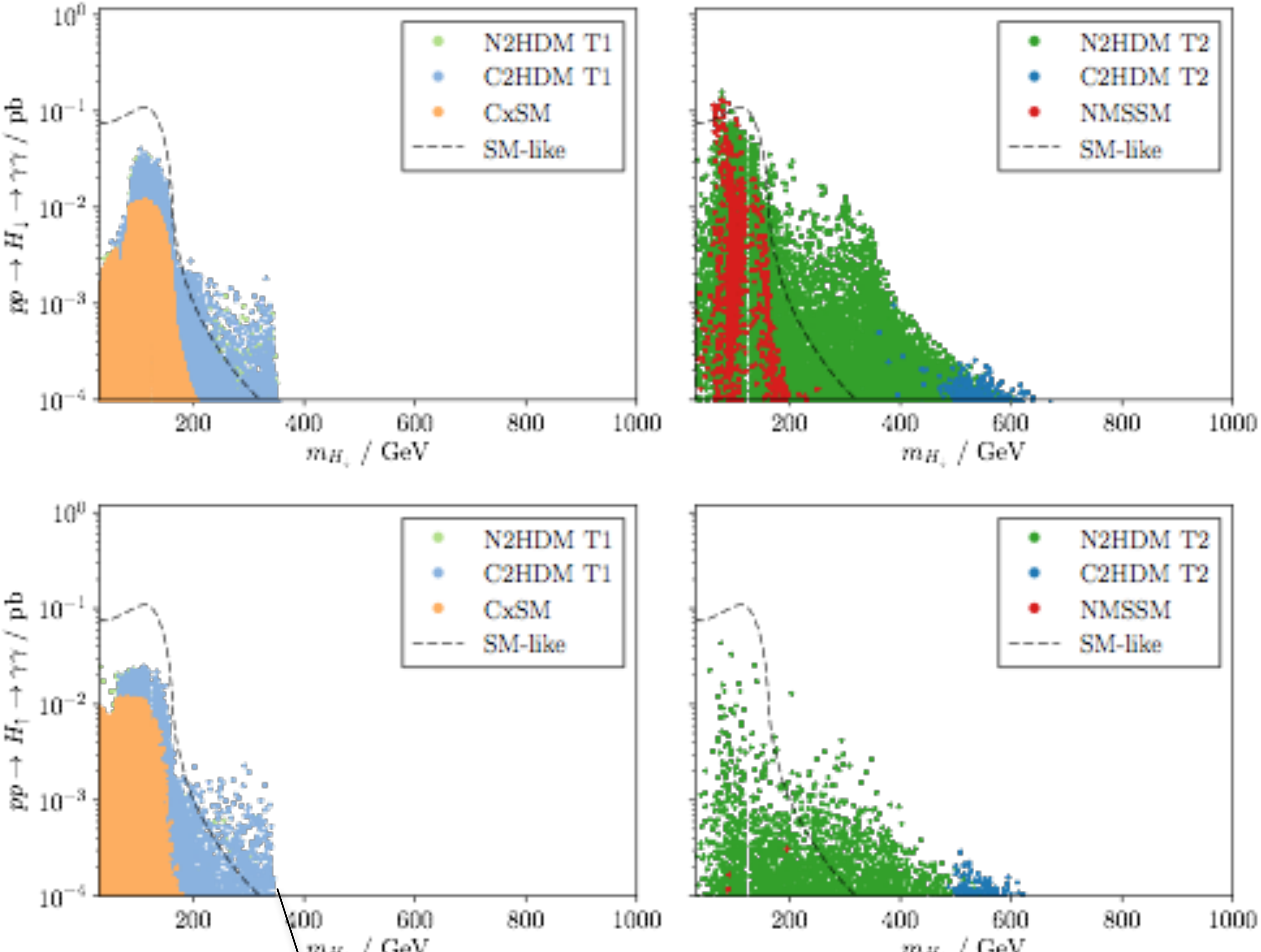
Signal rates for the production of H↓ (upper) and H↑ (lower) for 13 TeV as a function of m_H.

h_{125} takes most of the hVV coupling. Yukawa couplings can be different and lead to enhancements relative to the SM.

Discovery more likely via Higgs to Higgs decays for the heavier ones.

Rates are larger for N2HDM and C2HDM and more in type II because the Yukawa couplings can vary independently.

Non-125 to γγ



Muhlleitner, Sampaio, RS, Wittbrodt, JHEP 1708 (2017) 132

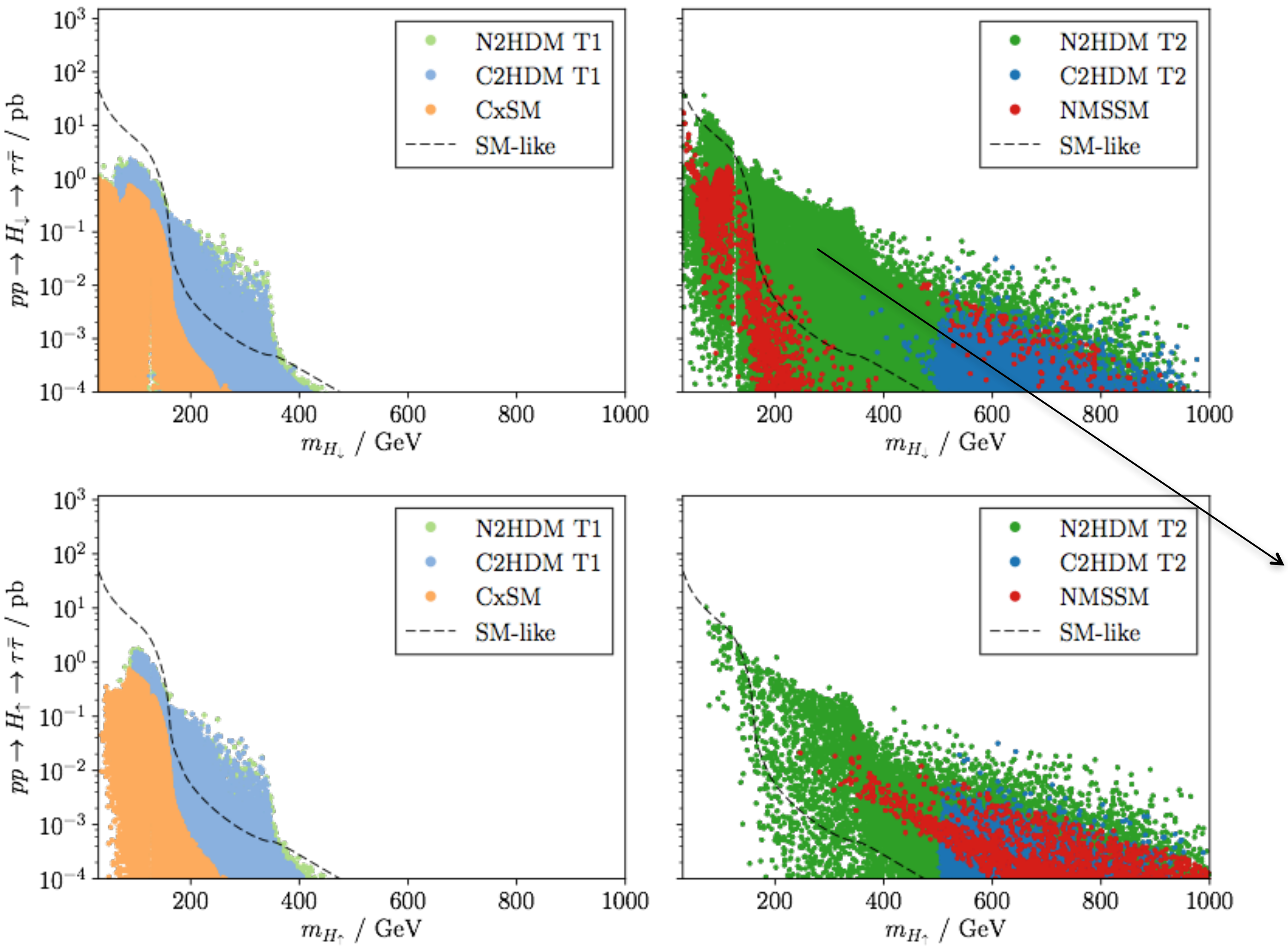
Signal rates for the production of H↓ (upper) and H↑ (lower) for 13 TeV as a function of m_H.

Dashed line is the "SM".

h to tt threshold

Rates can be quite large in the N2HDM and C2HDM. Again more freedom in the couplings.

Non-125 to ττ



Signal rates for the production of H ↓ (upper) and H ↑ (lower) for 13 TeV as a function of m_H.

Dashed line is the "SM".

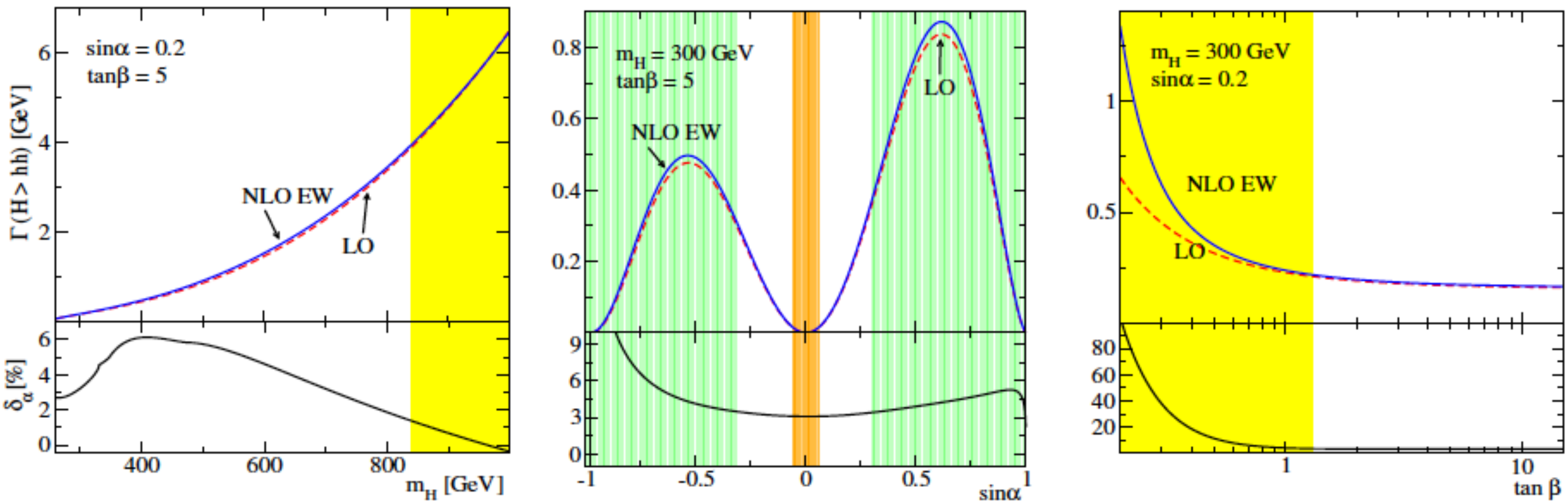
Region where only the N2hDM II survives.

Muhlleitner, Sampaio, RS, Wittbrodt, JHEP 1708 (2017) 132

2.c) What are radiative corrections good for?

Once upon a time we thought we would find more scalars and the radiative corrections would have to be ready. But...

Real Singlet model

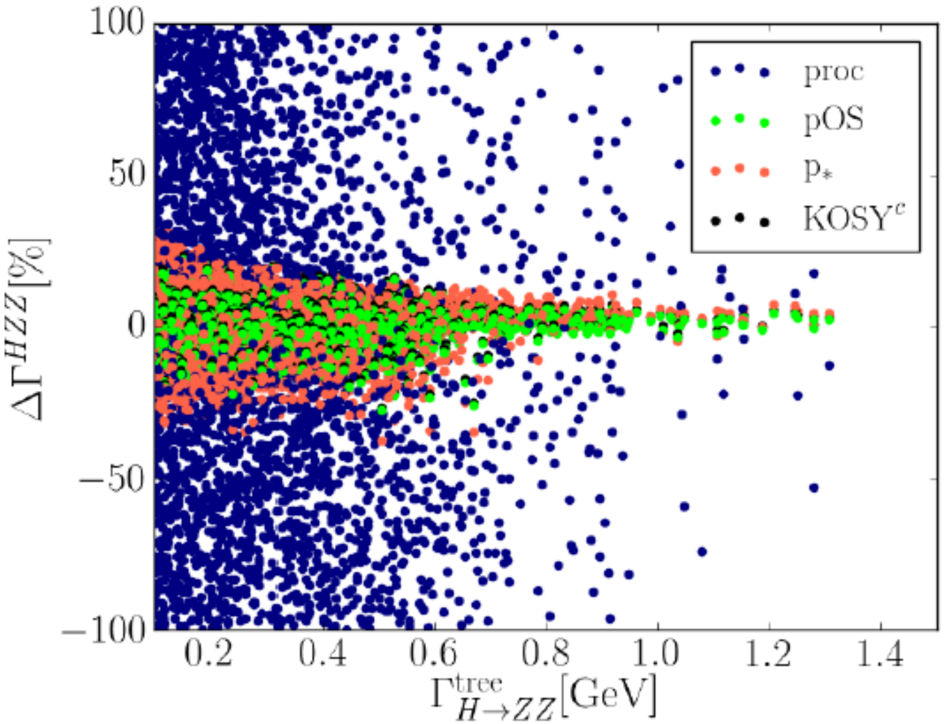


$H \rightarrow hh$

NLO Corrections shown to be only a few percent

Bojarski, Chalons, Lopez-Val, Robens, JHEP1602 (2016) 142

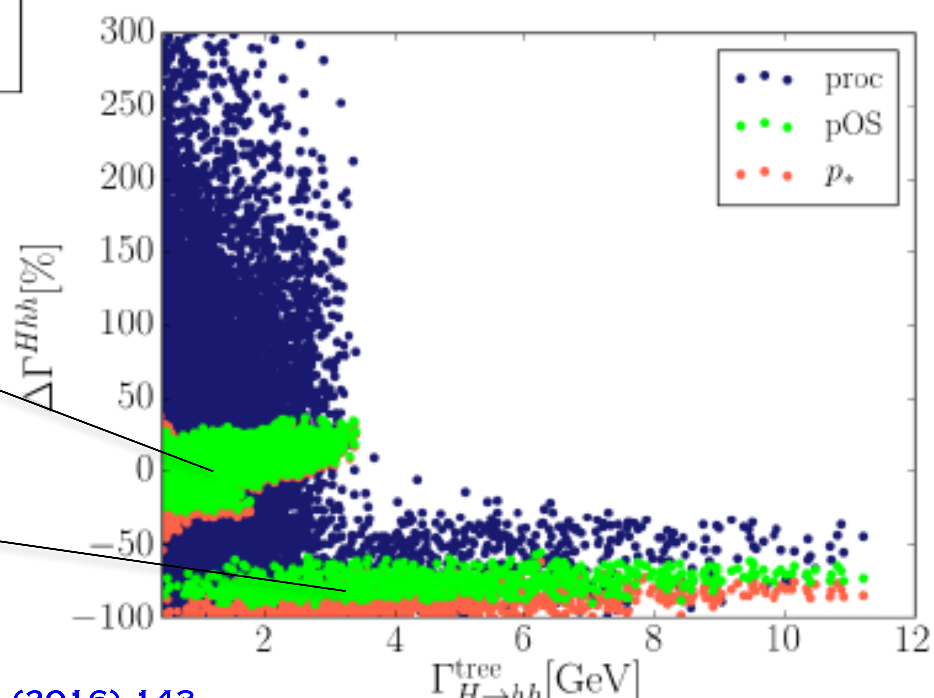
Real 2HDM



Several renormalization schemes are compared. Only process dependent is not stable. Corrections are under control for reasonably large widths. Small widths mean large relative corrections as expected.

SM-like limit
sin(β - α) = 1

Wrong sign
sin(β + α) = 1



Krause, Lorenz, Muhlleitner, RS, Ziesche, JHEP1609 (2016) 143