(The cruel and uneventful life of the) Extended Higgs sectors at the LHC

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ISEL & CFTC-UL

Higgs Couplings 2018 - Tokyo

27 November 2018

Extended Scalars

1. **Direct detection of new physics** - Motivate searches at the LHC in simple extensions of the scalar sector – benchmark models for searches.

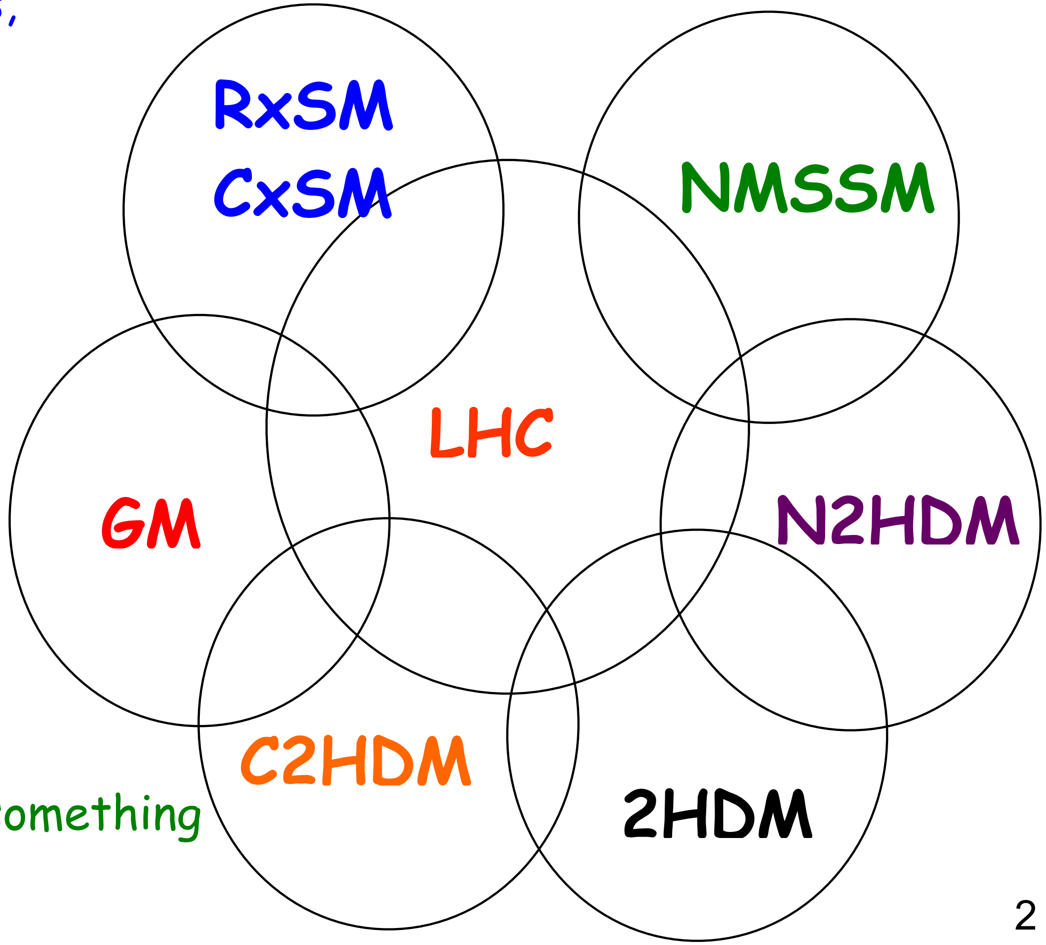
2. **Indirect detection of new physics** (via measurements of the 125 GeV Higgs couplings)

a) Mixing effects with other Higgs bosons, e.g. singlet, doublet, CP admixtures.

b) How efficiently can the parameter space of these simple extensions be constrained through measurements of Higgs properties? Focus on CP.

c) What are higher order EW corrections (of extended models) good for?

3. **Distinguishing models** - Need to find something first!



WG3: Benchmark Discussion

Wednesday 24 Oct 2018, 17:00 → 20:00 Europe/Zurich

304-1-007 (CERN)

Videoconference Rooms WG3__Benchmark_Discussion Join 304-1-007

17:00 → 17:05 **Introduction** 5m

Speaker: Rui Santos (ISEL and CFTC-UL)

17:05 → 17:15 **Benchmark Points for Type-I 2HDMs with a light h** 10m

Speaker: William Klemm

HXSWG_1018_Klem...

17:15 → 17:25 **Benchmark Point with low-mass CP-odd Higgs A with strong couplings to leptons and top quarks** 10m

Speaker: Dominik Stoeckinger

2018OctoberBMPoi... Paul's master thesis

17:25 → 17:35 **Charged Higgs boson benchmarks from top quark polarization** 10m

Speaker: Adil Jueid

LHCHXSWG_AdilJu...

17:35 → 17:45 **IDM benchmarks for the LHC at 13 and 27 TeV** 10m

Speaker: Tania Robens

idm_robens.pdf

17:45 → 17:55 **Updated constraints for the Real Higgs Singlet Extension of the Standard Model** 10m

Speaker: Tania Robens

singlet_robens.pdf

17:55 → 18:05 **Interference effects in H± production at the LHC** 10m

Speaker: Duarte Azevedo

main_v5.pdf

18:05 → 18:15 **A benchmark for LHC searches for H5±±, H5±, and H05 in the Georgi-Machacek model including masses below 200 GeV** 10m

Speaker: Ben Keeshan

BenKeeshanHXSW...

18:15 → 18:25 **Benchmark scenarios in the C2HDM** 10m

Speaker: Jonas Wittbrodt

benchmarks.pdf

Many models with common features

	CxSM (RxSM)	2HDM	C2HDM	N2HDM
Model	SM+Singlet	SM+Doublet	SM+Doublet	2HDM+Singlet
Scalars	$h_{1,2,(3)}$ (CP even)	$H, h, A, H^\pm$	$H_{1,2,3}$ (no CP), $H^\pm$	$h_{1,2,3}$ (CP-even), A, $H^\pm$
Motivation	DM, Baryogenesis	+ $H^\pm$	+ CP violation	+ ...

Similar neutral Higgs sector but different underlying symmetries

- There is a 125 GeV Higgs (other scalars can be lighter and/or 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 $\rho=1$ 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)

- **The $\mathcal{N}$MSSM:** 3 CP-even $H_{1,2,3}$, 2 CP-odd $A_{1,2}$, charged $H^\pm$
- Comparison of the NMSSM, CxSM, N2HDM, C2HDM

Many models with common features

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 $\Longrightarrow$ SM

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

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

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

Note that the particle spectrum may depend on the symmetries imposed on the model, and whether they are spontaneously broken or not.

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

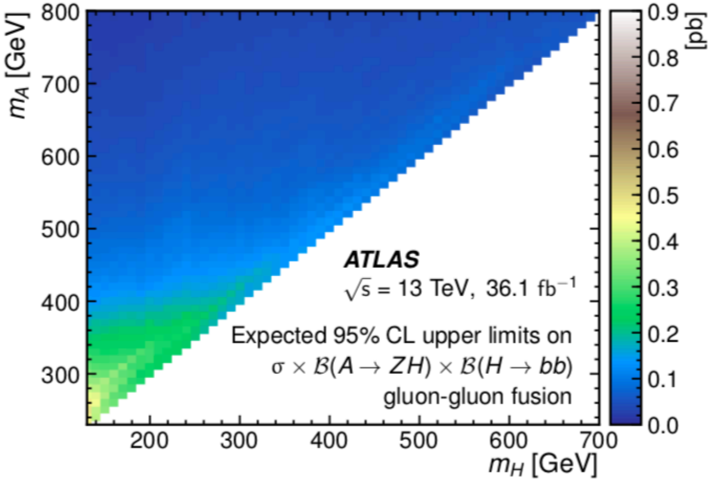
Type F $\kappa_U^F = \kappa_L^F = \frac{\cos\alpha}{\sin\beta}$ $\kappa_D^F = -\frac{\sin\alpha}{\cos\beta}$

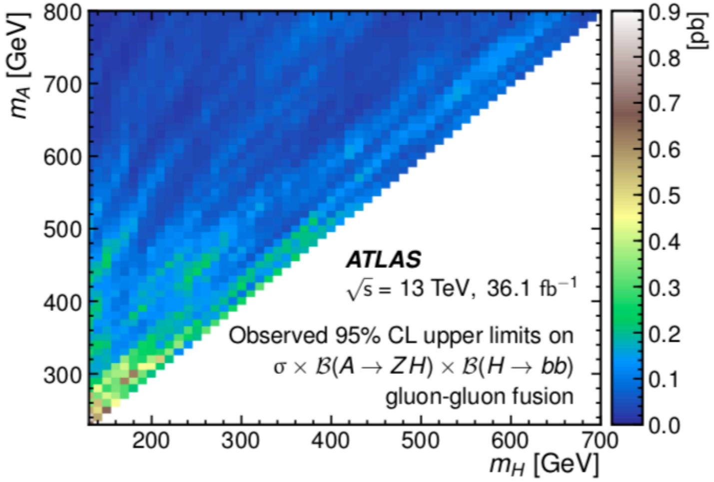
$$Y_{C2HDM} \equiv c_2 Y_{2HDM} \pm i\gamma_5 s_2 \begin{cases} t_\beta \\ 1/t_\beta \end{cases} = Y_{N2HDM} \pm i\gamma_5 s_2 \begin{cases} t_\beta \\ 1/t_\beta \end{cases}$$

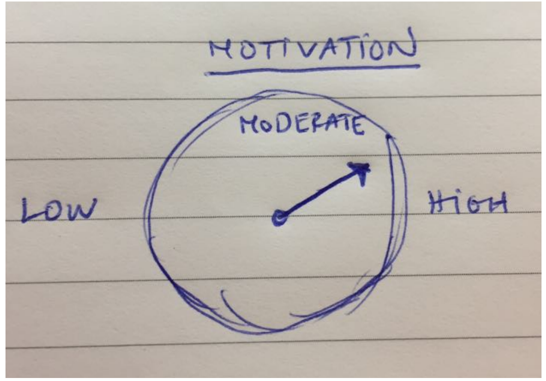
Type LS $\kappa_U^{LS} = \kappa_D^{LS} = \frac{\cos\alpha}{\sin\beta}$ $\kappa_L^{LS} = -\frac{\sin\alpha}{\cos\beta}$

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

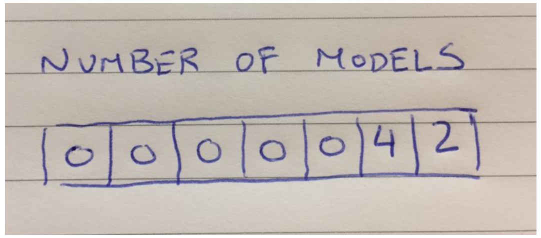
Searches - the results can easily be used <u>for most models</u>



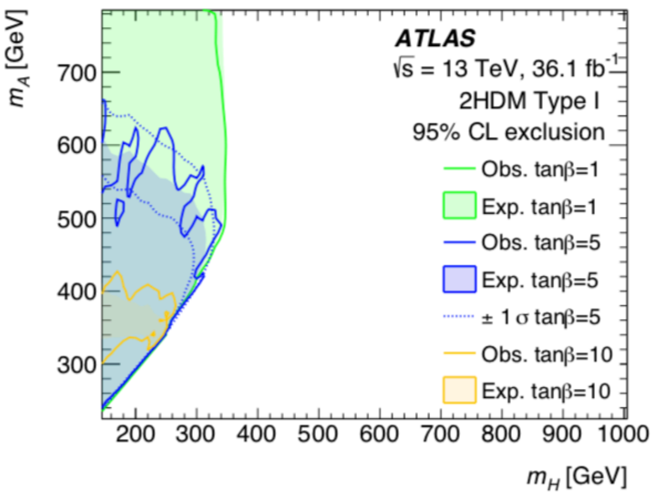


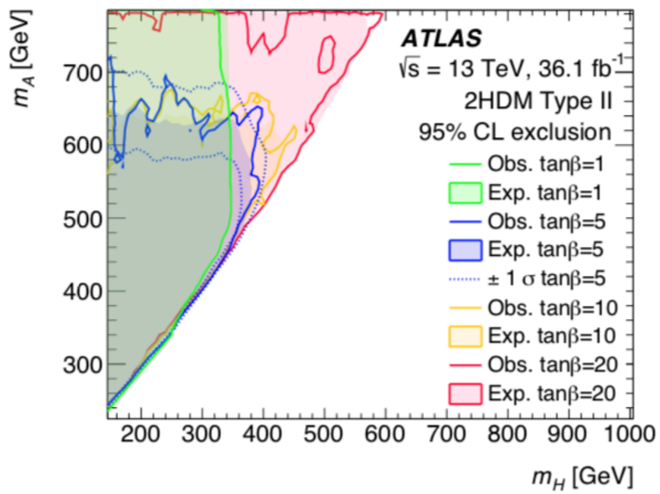


Upper bounds at 95% CL on the production cross-section times the branching ratio Br($A \to ZH$)×Br($H \to bb$) in pb for gluon–gluon fusion. Left: expected; right: observed.



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





ATLAS 1804.01126v1

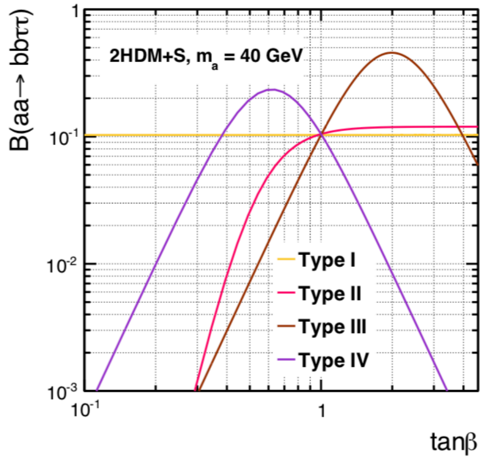
Observed and expected 95% CL exclusion regions in the (m_A,m_H) plane for various tan β values for Type I (left), and Type II (right).

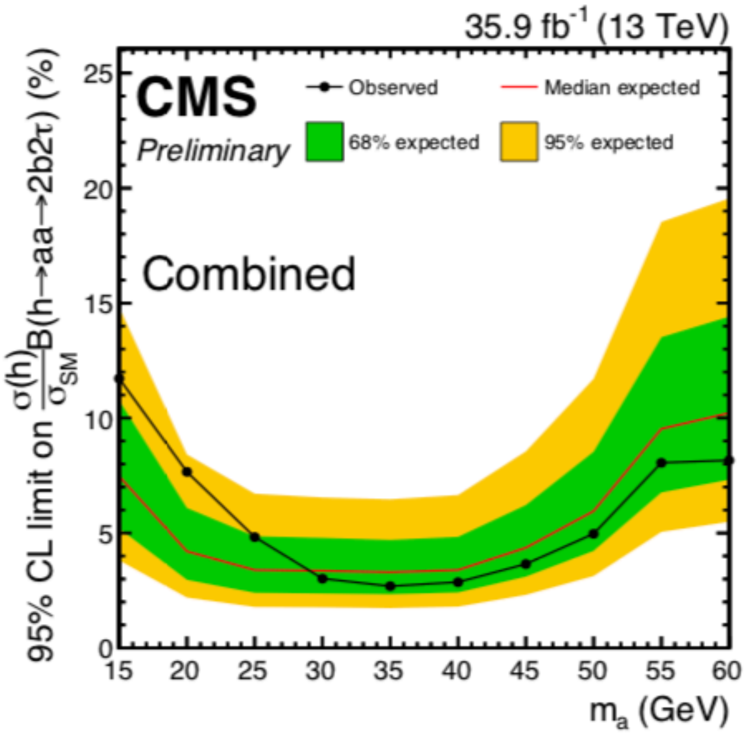
Assumptions: alignment, lightest Higgs 125 GeV, $m_{H+} = m_A$, U(1) symmetry (fixes m_{12}^2).

Searches - the results can easily be used for all the models

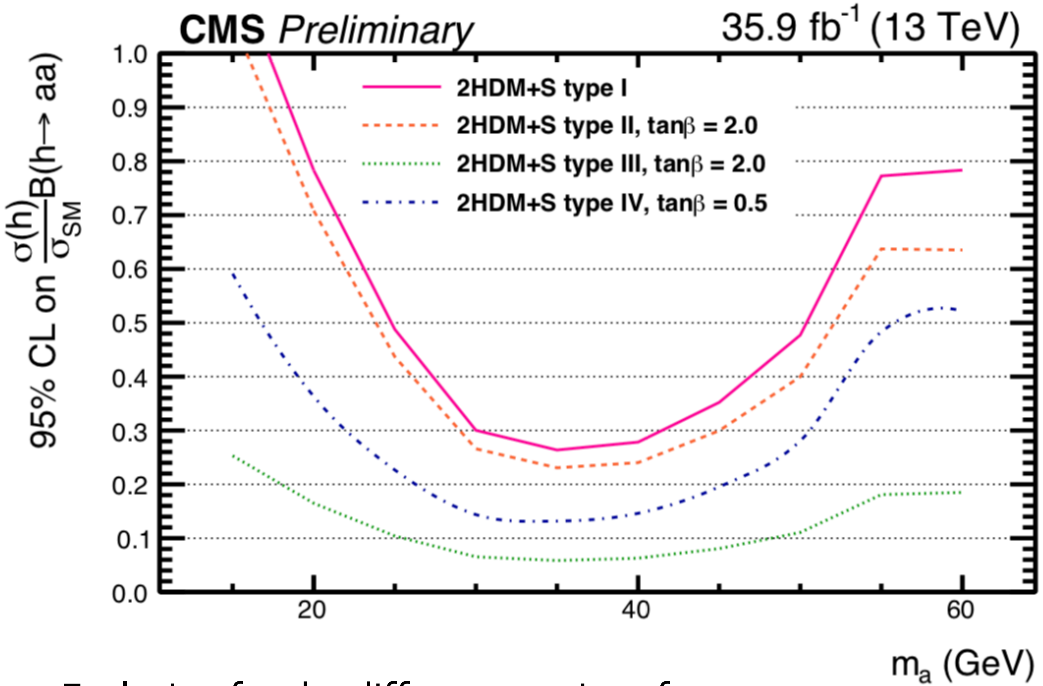
CMS PAS HIG-17-024

BRs for the 4 different versions of the model.





N2HDM (CP-conserving)



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.

Exclusion for the different versions for 2 values of tanβ.

ATLAS, (γγjj final state),1803.11145

Lightest Higgs coupling modifiers (to gauge bosons)

h_{125} couplings measurements

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

CP-VIOLATING 2HDM

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

"PSEUDOSCALAR" COMPONENT (DOUBLET)

$$|s_2| = 0 \;\Rightarrow\; h_1 \text{ is a pure scalar,}$$
$$|s_2| = 1 \;\Rightarrow\; h_1 \text{ is a pure pseudoscalar}$$

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

SINGLET COMPONENT

$(a+ib)$

SM + REAL SINGLET

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

SM + COMPLEX SINGLET

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

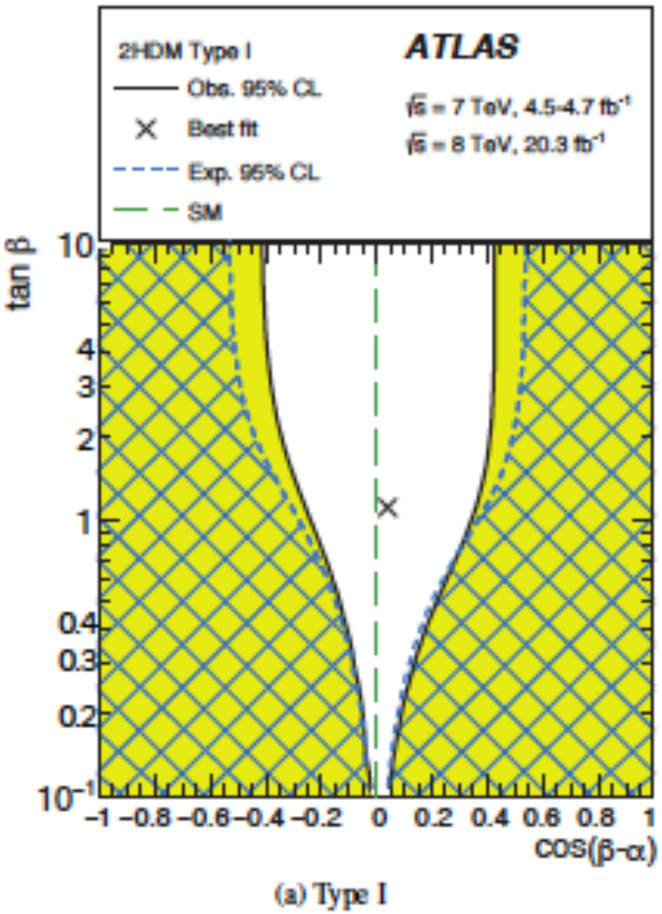
REAL COMPONENT

IMAGINARY COMPONENT

h_{125} couplings measurements

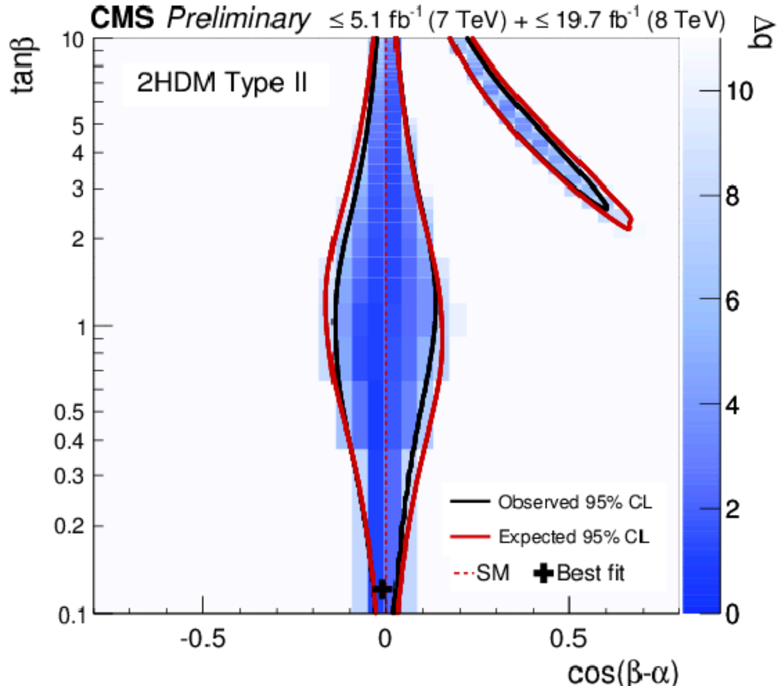
Models need couplings modifiers - simple in many extensions of the scalar sector

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



(a) Type I

ATLAS 1509.00672



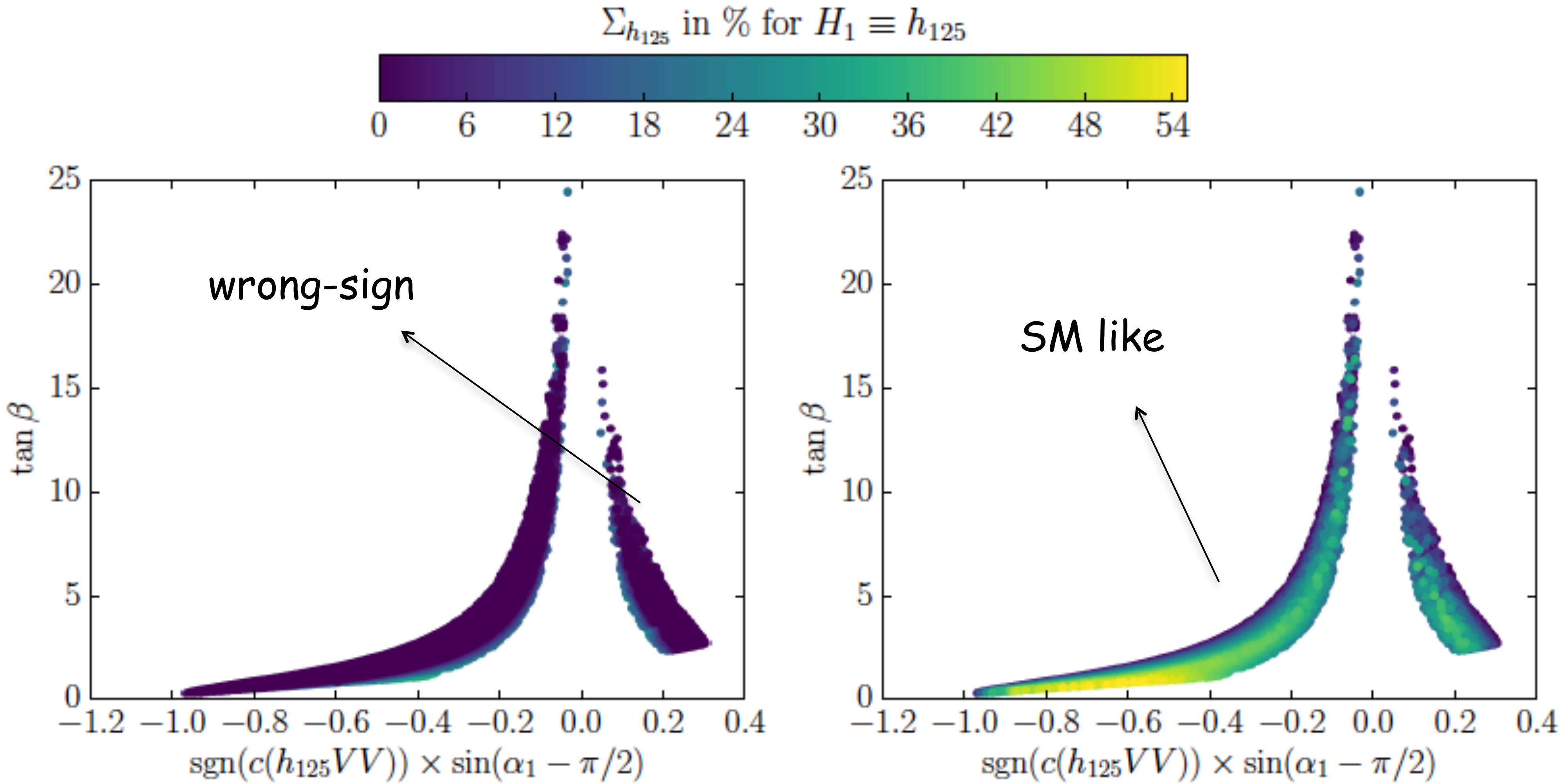
CMS-PAS-HIG-16-007

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 regions in the N2HDM type II – the interesting fact is that in the alignment region the singlet admixture can go up to 54 %.

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

Will they all look the same one day?

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

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

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

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

The deviations can be written in terms of the rotation matrix from gauge to mass eigenstates.

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

Azevedo, Ferreira, Muhlleitner, RS, Wittbrodt, 1808.00755

Will they all look the same one day?

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

All models become very similar and hard to distinguish.

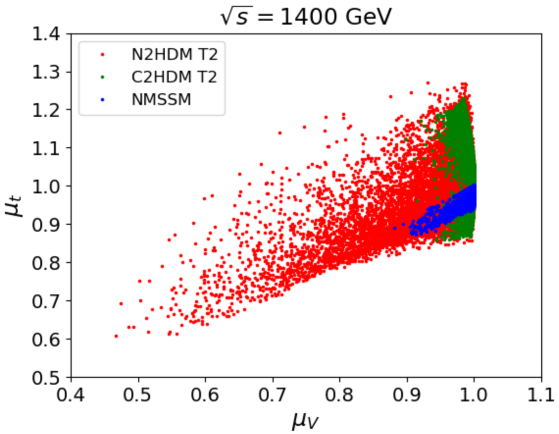
LHC today

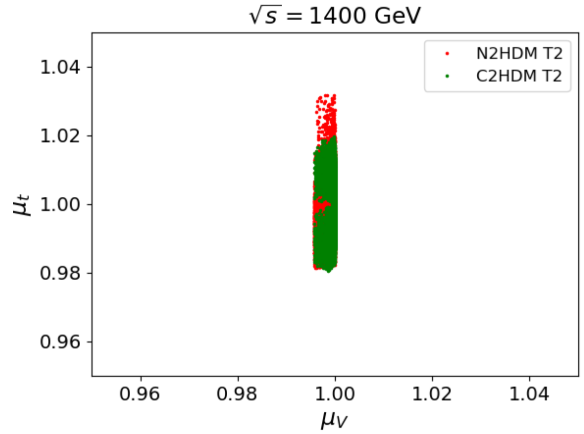
Model	CxSM	C2HDM II	C2HDM I	N2HDM II	N2HDM I	NMSSM
$(\Sigma \text{ or } \Psi)_{\text{allowed}}$	11%	10%	20%	55%	25%	41%

CLIC@350GeV (500/fb)

$$\Psi_i(\Sigma_1) \leq 0.85\,\% \text{ from } \kappa_{ZZ}$$

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.





Azevedo, Ferreira, Muhlleitner, RS, Wittbrodt, 1808.00755

Beware of radiative corrections.

CP-violation at the LHC

Softly broken Z_2 symmetric 2HDM Higgs potential

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and CP is not spontaneously broken

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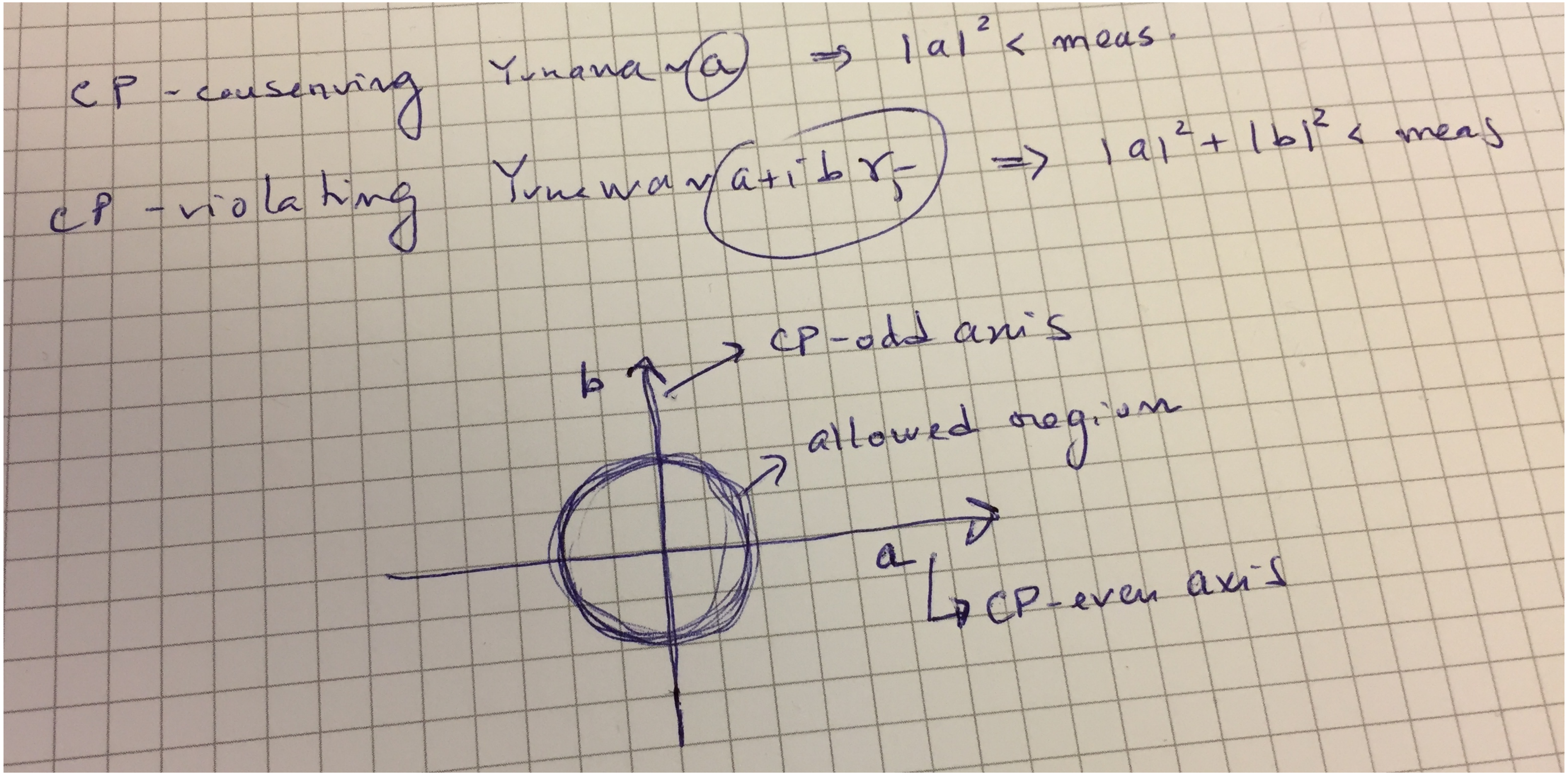
Type F $\kappa_U^F = \kappa_L^F = \frac{\cos\alpha}{\sin\beta}$ $\quad \kappa_D^F = -\frac{\sin\alpha}{\cos\beta}$

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

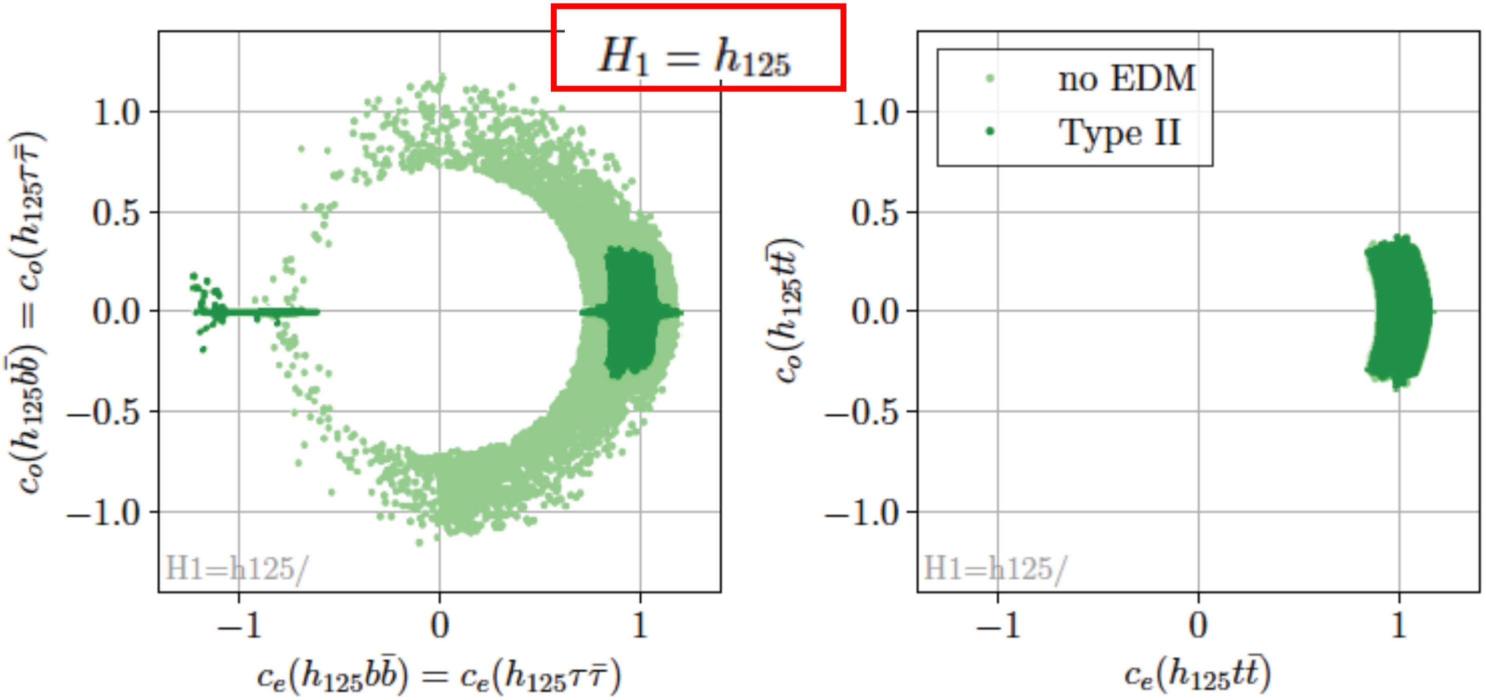
Type LS $\kappa_U^{LS} = \kappa_D^{LS} = \frac{\cos\alpha}{\sin\beta}$ $\quad \kappa_L^{LS} = -\frac{\sin\alpha}{\cos\beta}$

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

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



The allowed parameter space in type II C2HDM



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

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

$$\tan\beta \geq 1$$

Right - Bounds are stronger for the up-quarks couplings. They come from μ_{VV} and the bound on tanβ.

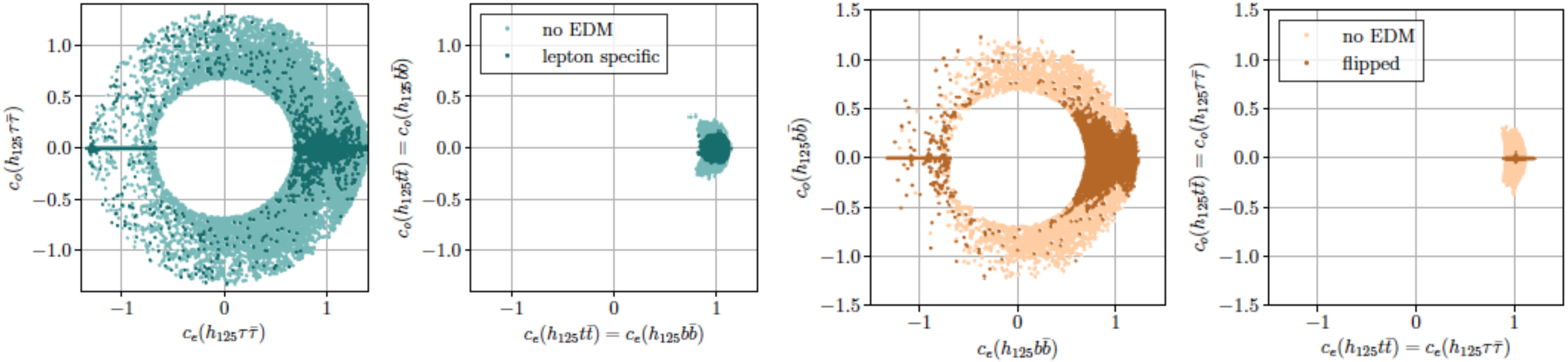
Left - Bounds are weaker and therefore EDMs play a major role.

In type I all couplings are very constrained.

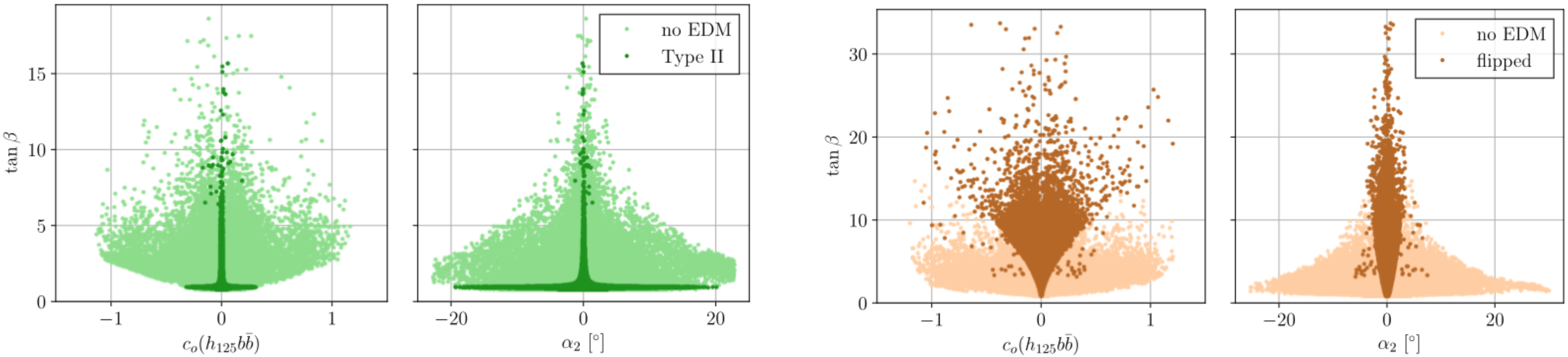
Fontes, Muhlleitner, Romão, RS, Silva, Wittbrodt, JHEP 1802 (2018) 073.

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.

What if the 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

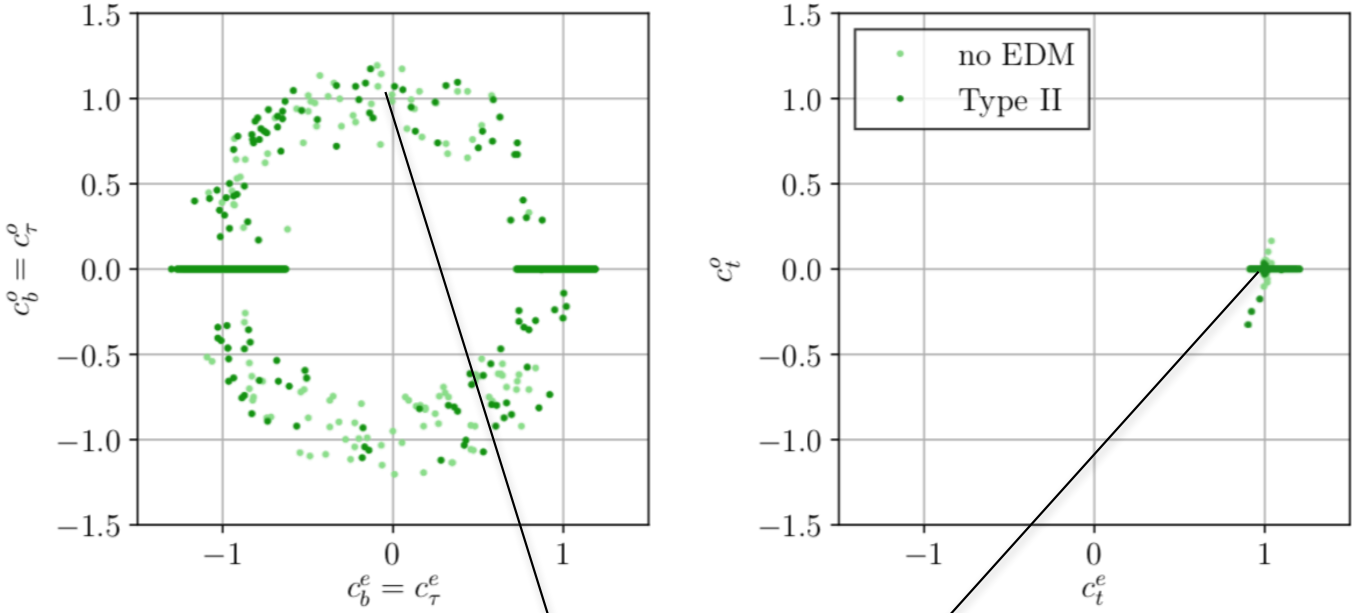
$$Y^{TypeII}_{C2HDM} = c_2 Y^{TypeII}_{2HDM} - i\gamma_5 s_2 t_\beta \qquad \text{bottom, tau}$$

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

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.

And this brings a very interesting CP-violation scenario



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

$$b_U \approx 0; \;\; a_D \approx 0$$

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

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

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

$$h_2 = H \rightarrow t\bar{t}$$

and the other decaying to taus as CP-odd

$$h_2 = A \rightarrow \tau^+\tau^-$$

Probing one Yukawa coupling is not enough!

Direct probing at the LHC (ττh)

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

BERGE, BERNREUTHER, ZIETHE PRL 100 (2008) 171605
BERGE, BERNREUTHER, NIEPELT, SPIESBERGER, PRD84 (2011) 116003

- A measurement of the angle

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

can be performed with the accuracies

$$\Delta\Phi_\tau = 15^o \Leftarrow 150\,\mathrm{fb}^{-1}$$

$$\Delta\Phi_\tau = 9^o \Leftarrow 500\,\mathrm{fb}^{-1}$$

NUMBERS FROM: BERGE, BERNREUTHER, KIRCHNER PRD92 (2015) 096012

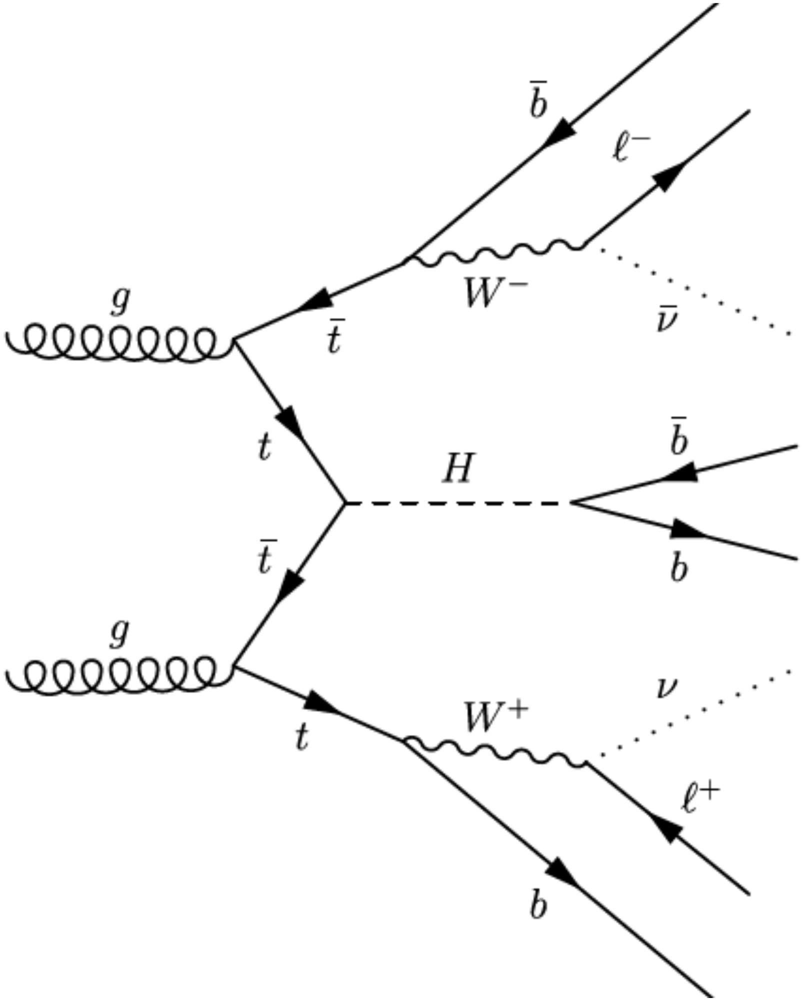
$$\tan\Phi_\tau = -\frac{\sin\beta}{\cos\alpha_1}\tan\alpha_2 \;\Rightarrow\; \tan\alpha_2 = -\frac{\cos\alpha_1}{\sin\beta}\tan\Phi_\tau$$

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

Direct probing at the LHC (tth)

$$pp \to h\bar{t}t$$

GUNION, HE, PRL77 (1996) 5172
BOUDJEMA, GODBOLE, GUADAGNOLI, MOHAN, PRD92 (2015) 015019
AMOR DOS SANTOS EAL PRD96 (2017) 013004



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

Signal: tt fully leptonic and H -> bb

Background: most relevant is the irreducible tt background

CP violation - direct

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

Combinations of three decays

Many other combinations

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

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

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

But what if the three scalars are invisible?

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, JHEP 1811 (2018) 091

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.

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

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

Mono-Z and mono-Higgs events.

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

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

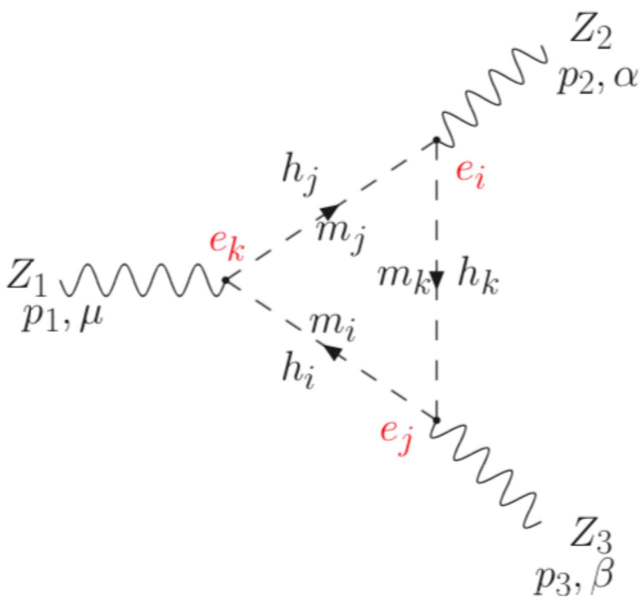
Gaemers, Gounaris, ZPC1 (1979) 259

Hagiwara, Peccei, Zeppenfeld, Hikasa, NPB282 (1987) 253

Grzadkowski, Ogreid, Osland, JHEP 05 (2016) 025

that comes from an effective operator (dim-6)

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

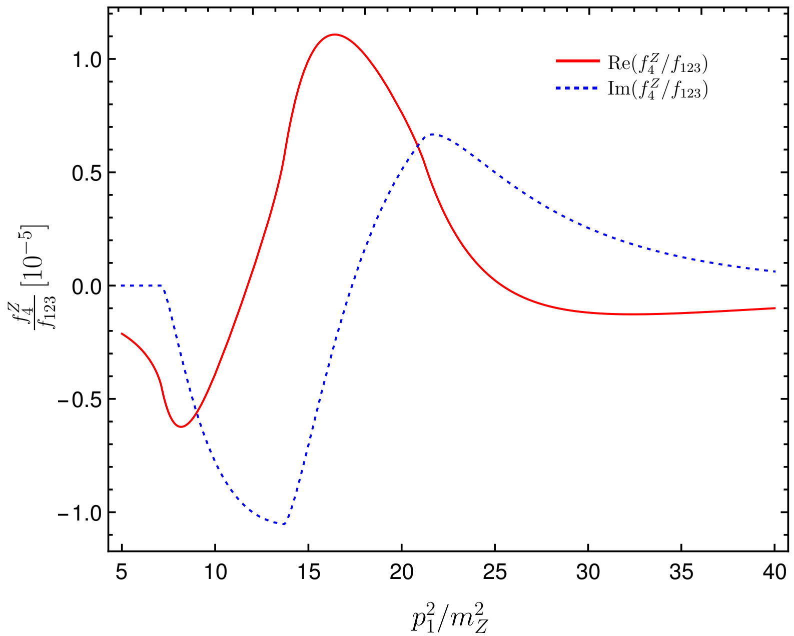


in our model it has the simple expression

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

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

Combining $h_1 h_2 Z$; $h_1 h_3 Z$ and $h_2 h_3 Z$

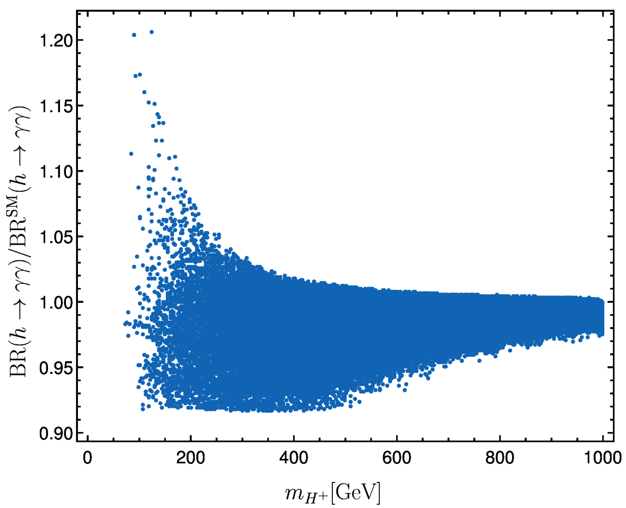


The form factor f_4 normalised to f_{123} for m_1=80.5 GeV, m_2=162.9 GeV and m_3=256.9 GeV as a function of the squared off-shell Z-boson 4-momentum, normalised to m_Z^2.

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

CMS COLLABORATION, EPJC78 (2018) 165. $-1.2\times10^{-3} < f_4^Z < 1.0\times10^{-3}$

ATLAS COLLABORATION, PRD97 (2018) 032005. $-1.5\times10^{-3} < f_4^Z < 1.5\times10^{-3}$



How far can we go in constraining f_4?

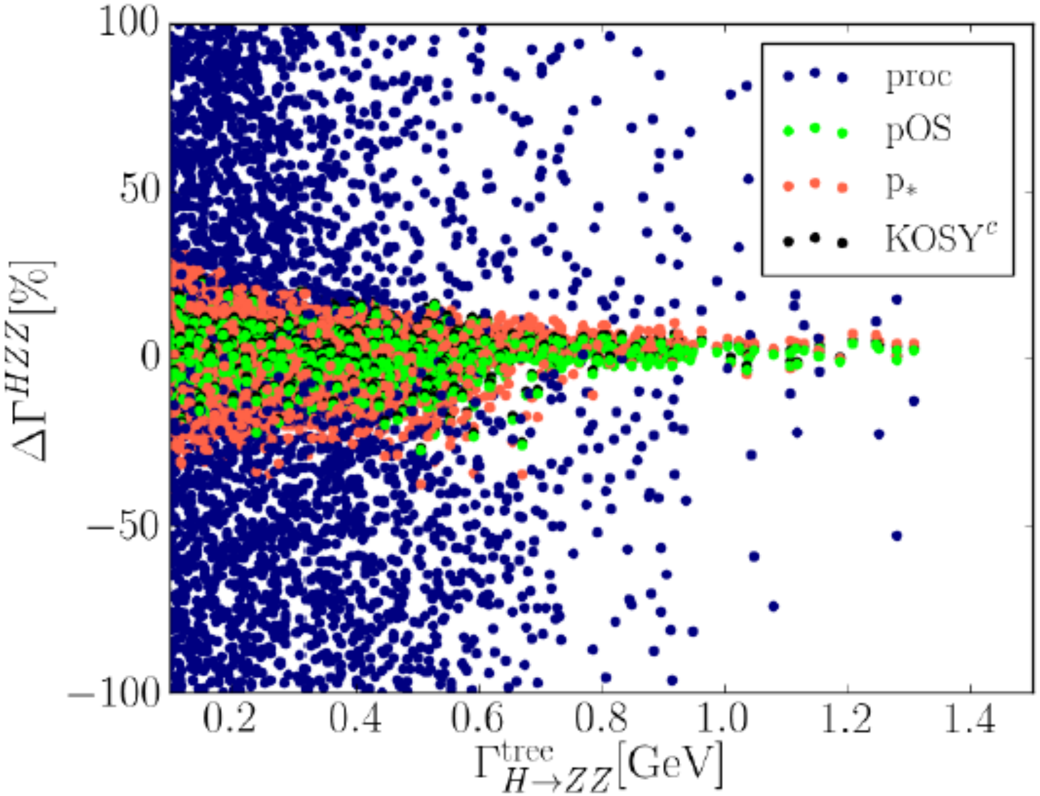
Finally: there are also charged particles that that can only decay to to another Z_2-odd particle. They also contribute to the decay of the SM-like Higgs into photons. But again no deviation was found so far.

Radiative corrections?

Probably later for
the 125 GeV.

Maybe one day for
the others.

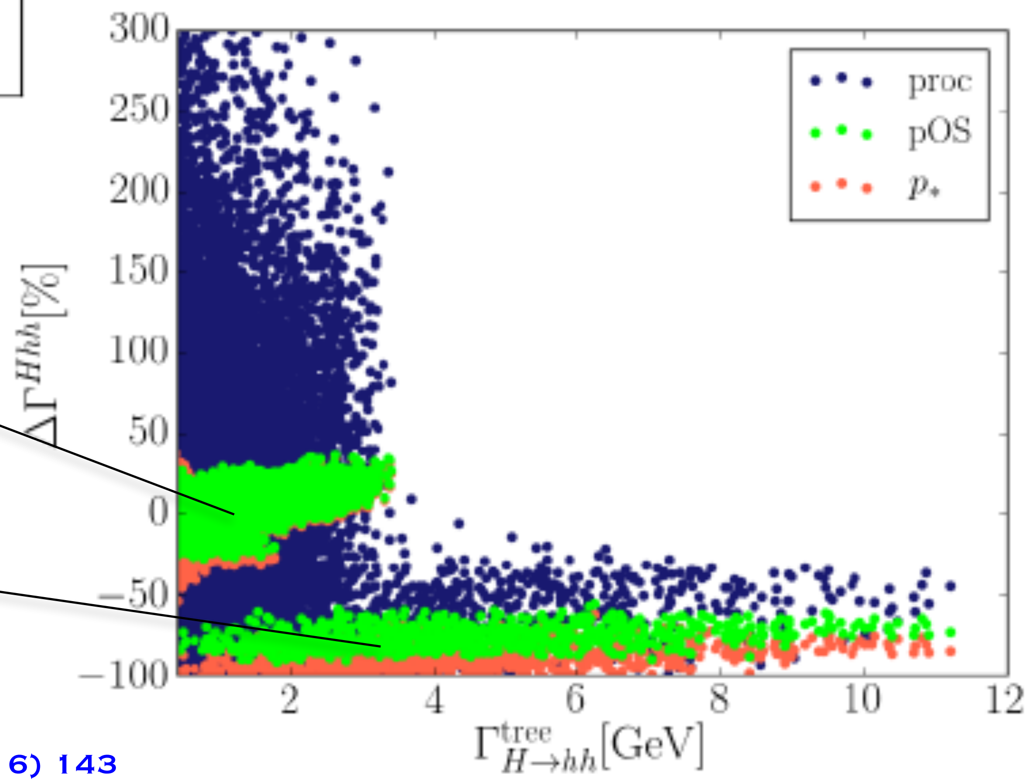
Real 2HDM



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.

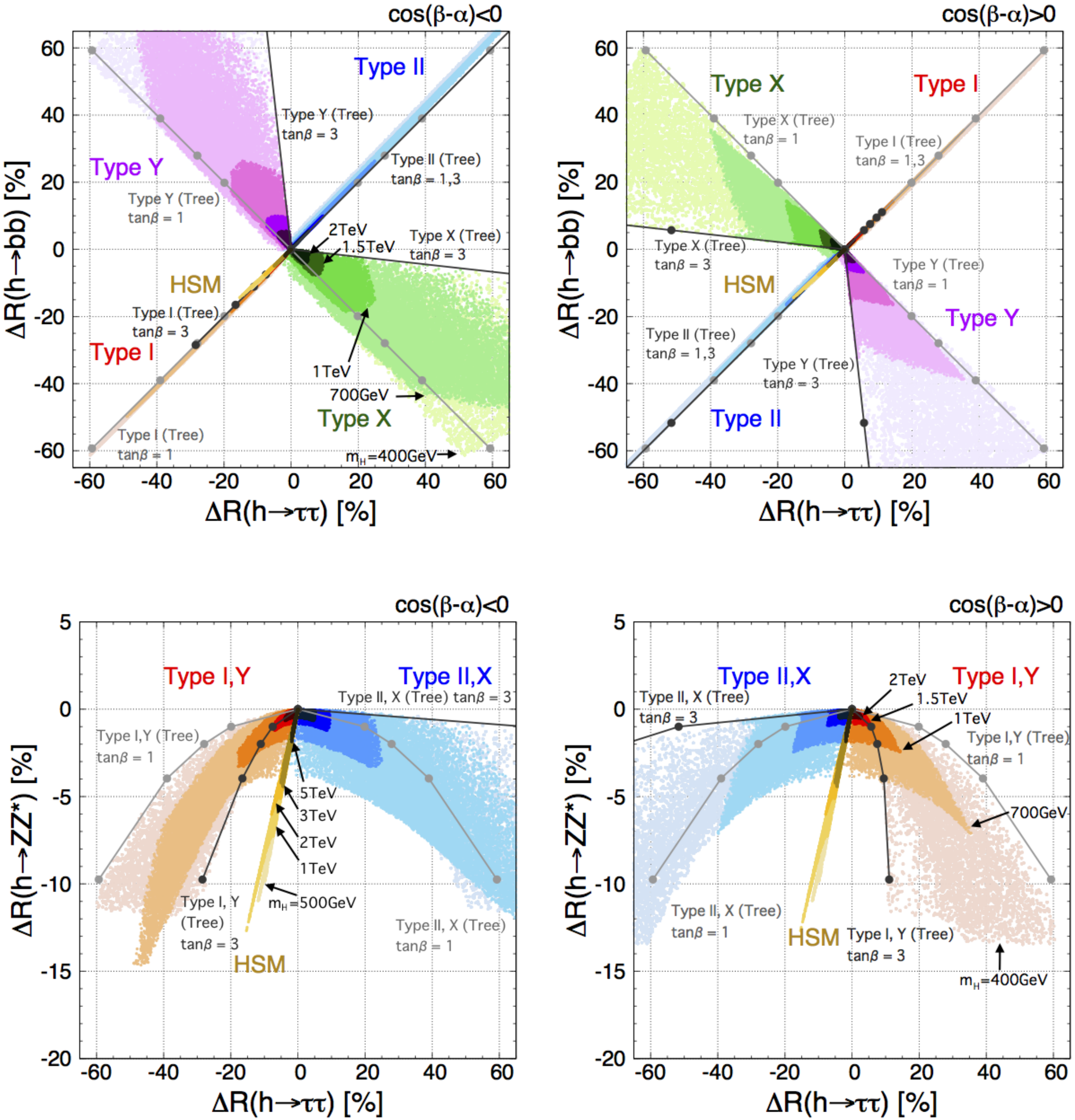
SM-like limit
$\sin(\beta - \alpha) = 1$

Wrong sign
$\sin(\beta + \alpha) = 1$



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

Real 2HDM



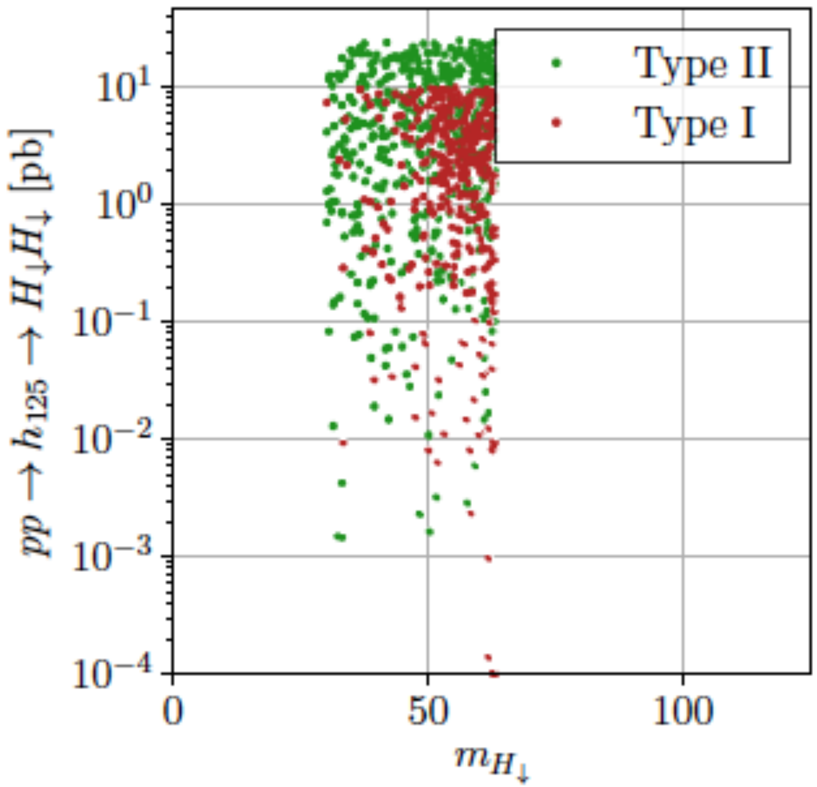
Radiative corrections in the four Yukawa types 2HDM (CP-conserving). Combining several channels could help to distinguish the models.

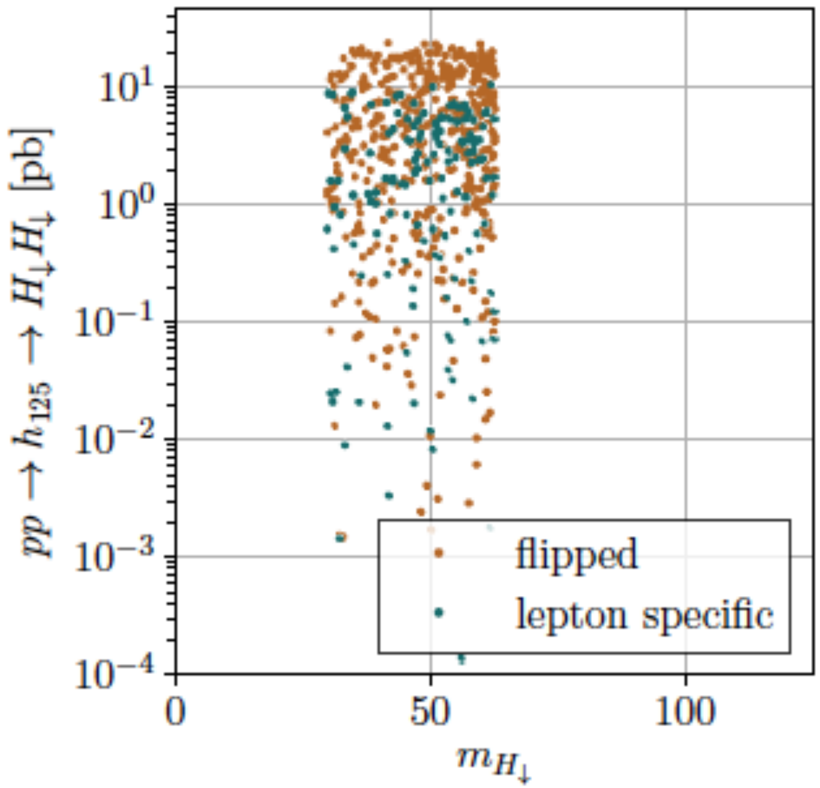
Kanemura, Kikuchi, Yagyu, Mawatari, Sakurai, PLB783 (2018) 140

Comparing models at tree-level

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



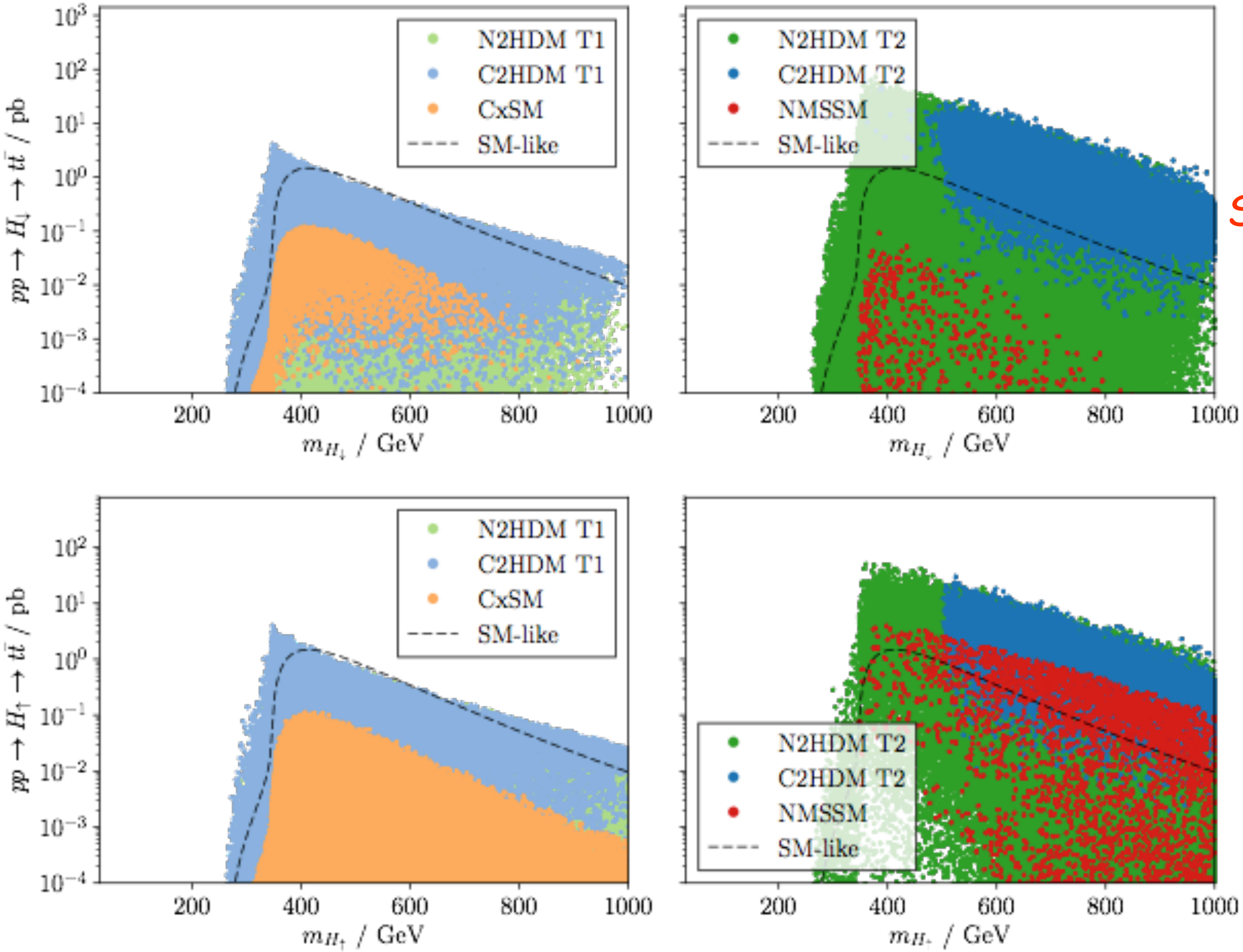


Left - Signal rates for the production of h_{125} decaying to $H_\downarrow H_\downarrow$ for 13 TeV as a function of m_H for Types I and II

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



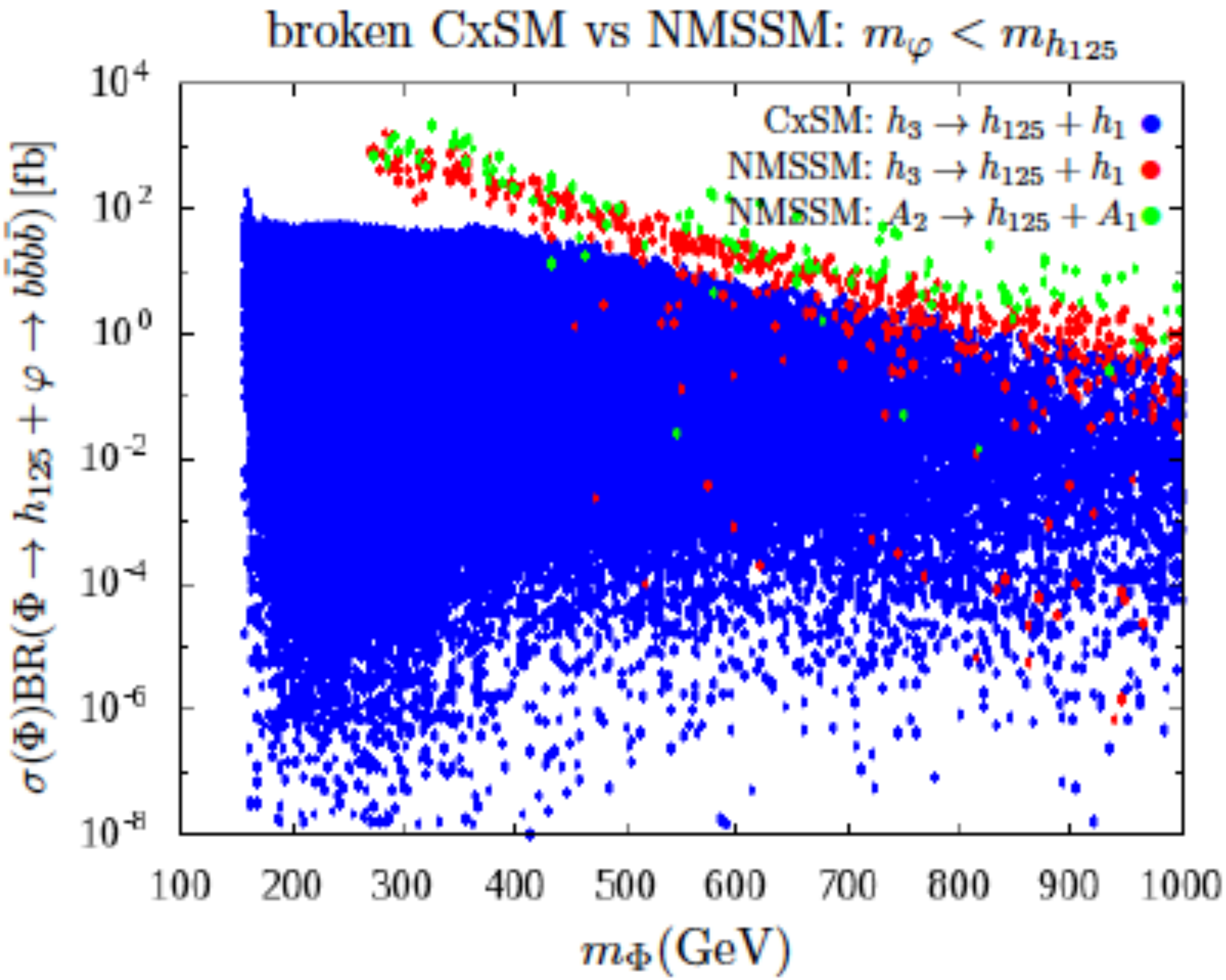
Signal rates for the production of $H_\downarrow$ (upper) and $H_\uparrow$ (lower) for 13 TeV as a function of m_H.

Dashed line is the "SM".

MUHLLEITNER, SAMPAIO, RS, WITTBRODT, JHEP 1708 (2017) 132

The decay

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



$\Phi \rightarrow h_{125} + \varphi$ 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

Summary

We found a scalar

We have to keep looking for more

We have to keep measuring the Higgs couplings

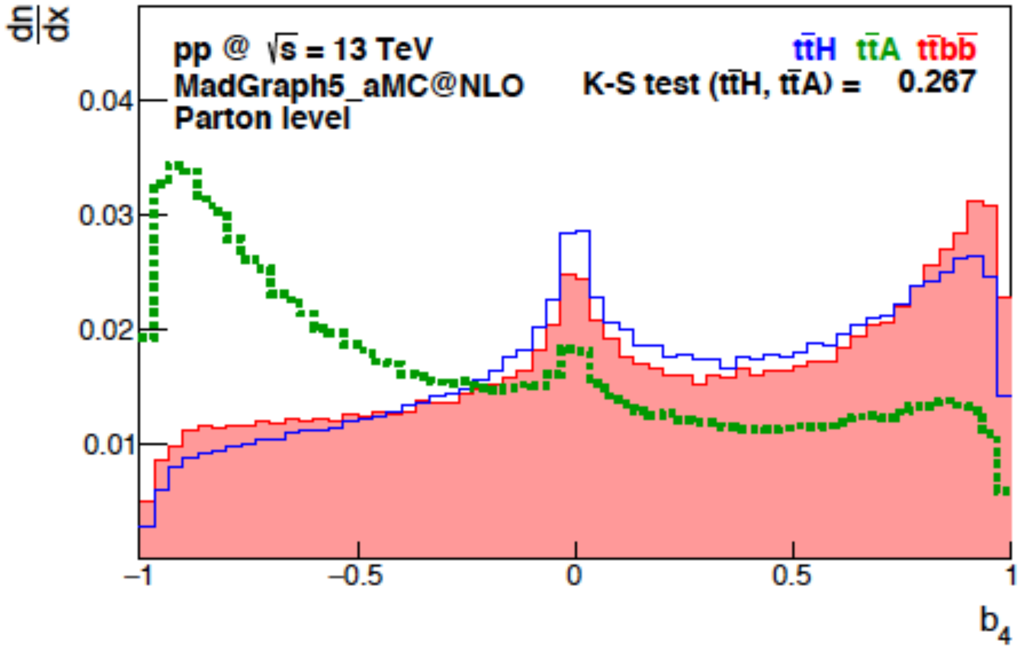
We have to look for direct CP-violation

"Ode to Intimations of Immortality"

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

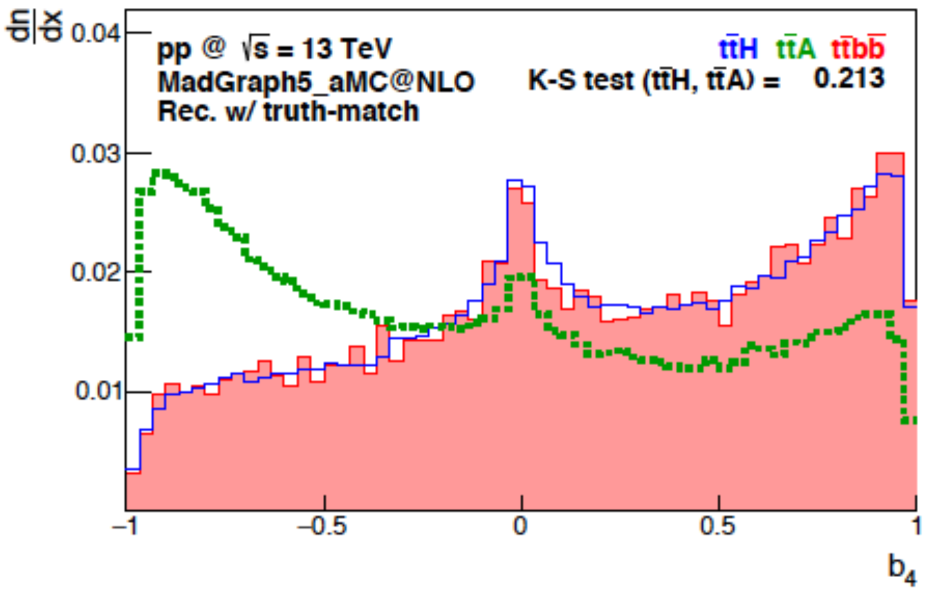
Wordsworth, (1807)

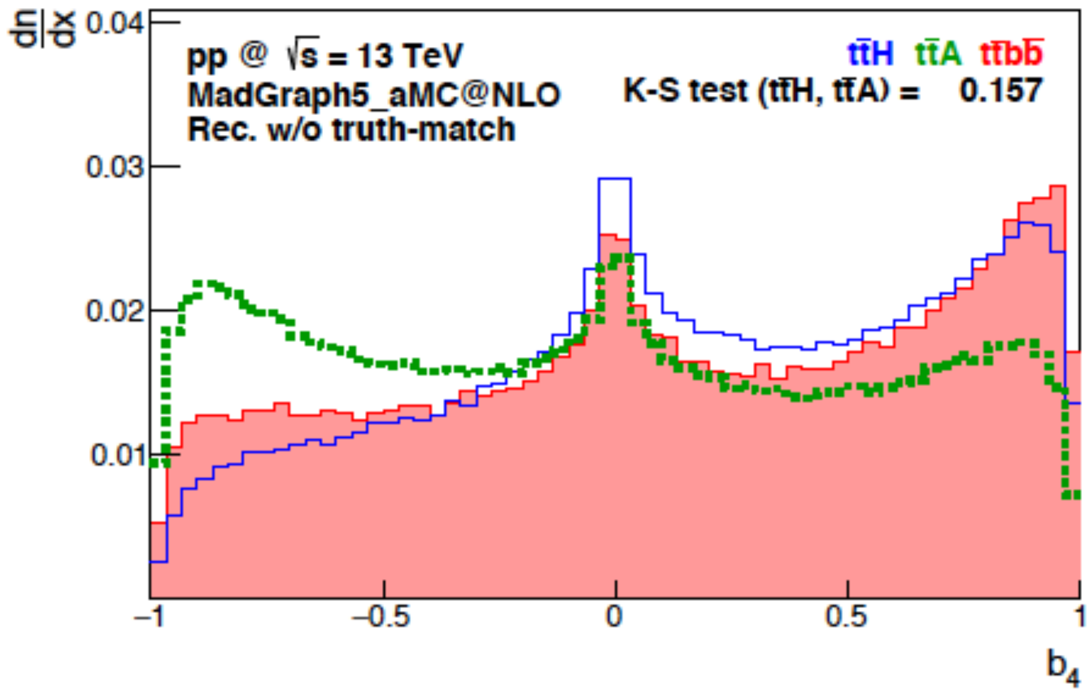
$$\mathcal{L}_{Hf\bar{f}} = -\frac{y_f}{\sqrt{2}}\bar{\psi}_f(a_f + ib_f\gamma_5)\psi_f h$$



Gunion, He, PRL77 (1996) 5172
Amor dos Santos eal PRD96 (2017) 013004

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

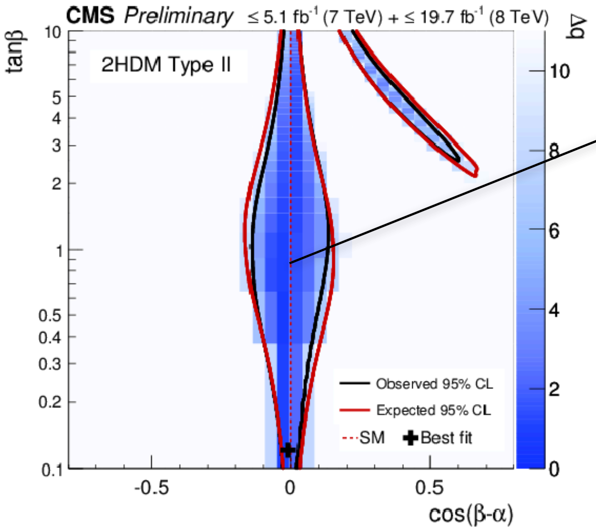




The alignment limit in the 2HDM

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

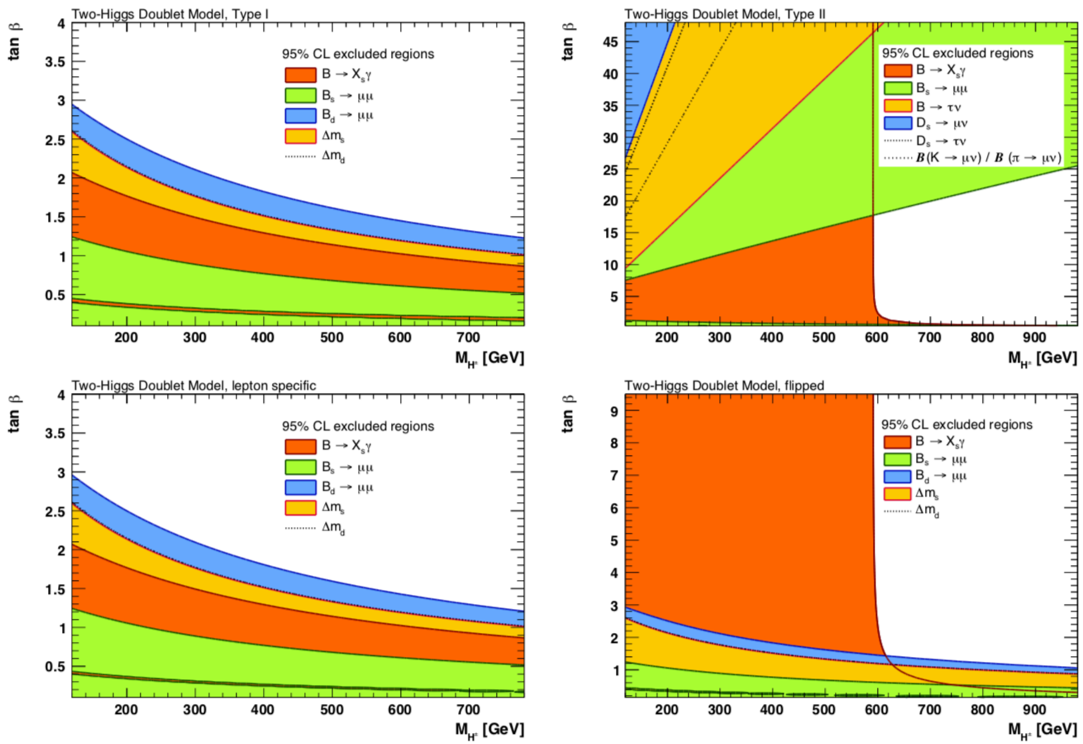
$$\begin{pmatrix} \\ V_1 \end{pmatrix} \begin{pmatrix} \\ V_2 \end{pmatrix}$$



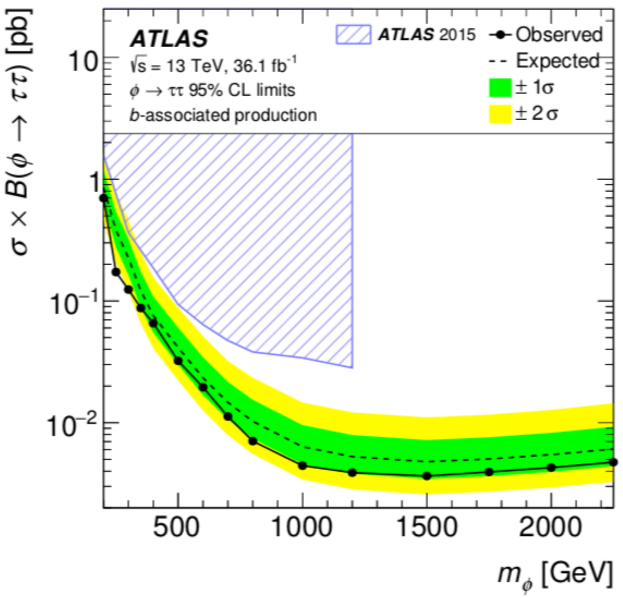
EVEN IF IN THE END WE WILL HAVE A LINE ONLY, THE MIXING BETWEEN VEVS CAN ONLY BE SEEN WITH NEW PHYSICS.

TWO EXAMPLES:

HALLER, HOECKER, KOGLER, PEIFFER, STELZER 1803.01853



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

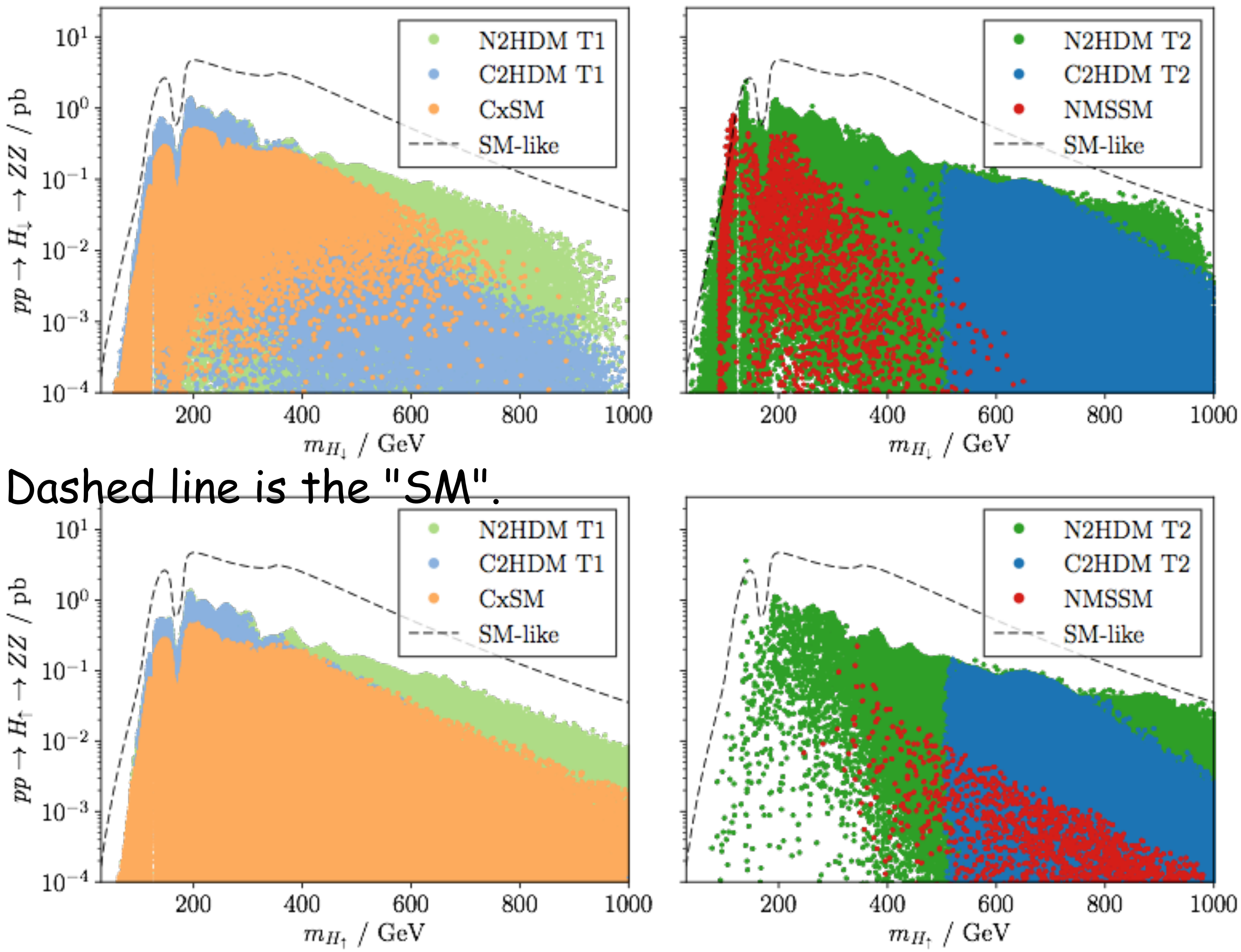


(b) $\phi \to \tau\tau$ (b-associated production).

ATLAS, JHEP01(2018)055

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

Non-125 CP-even to ZZ in different models



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

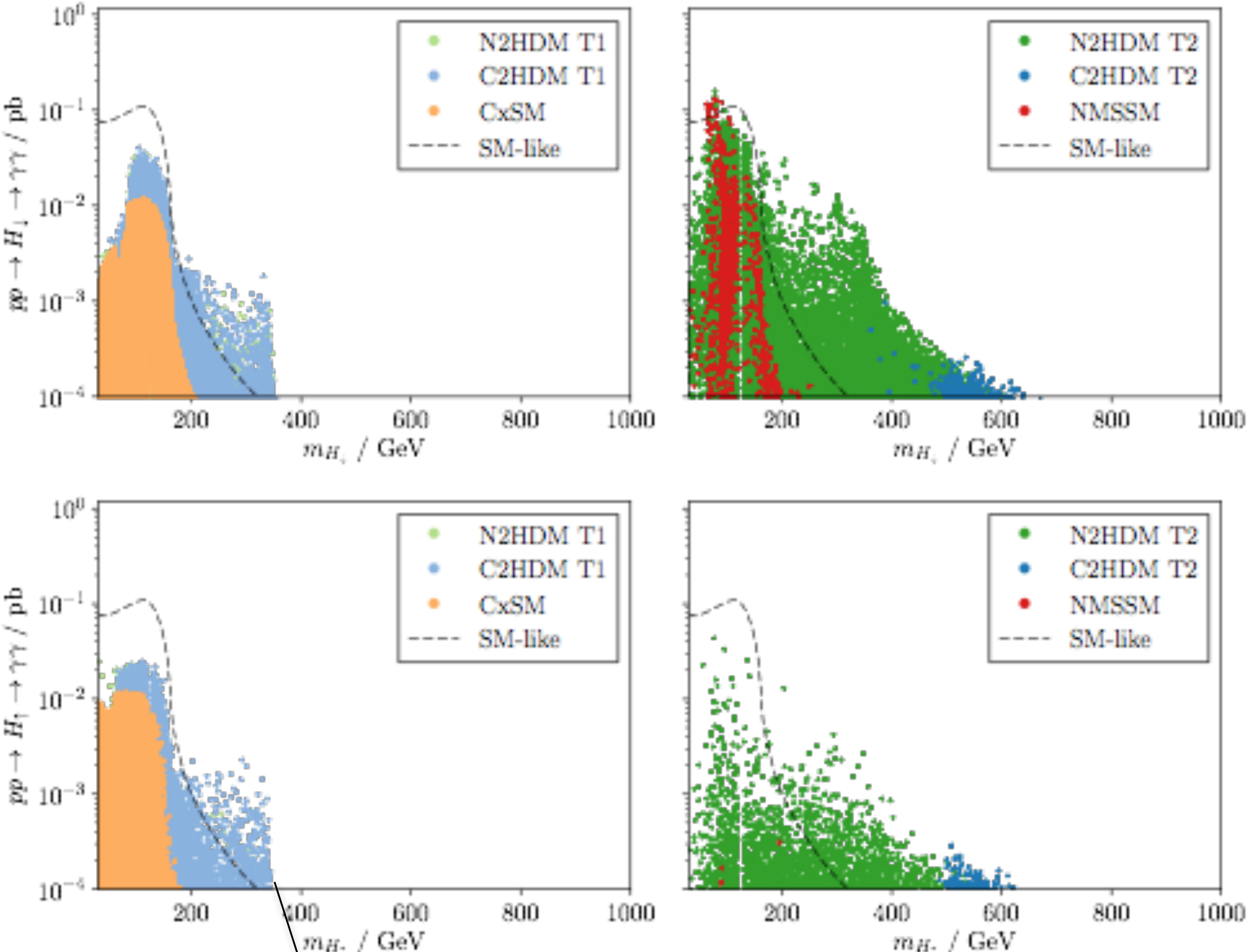
Signal rates for the production of H ↓ (upper) and H ↑ (lower) for 13 TeV as a function of m_H.

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

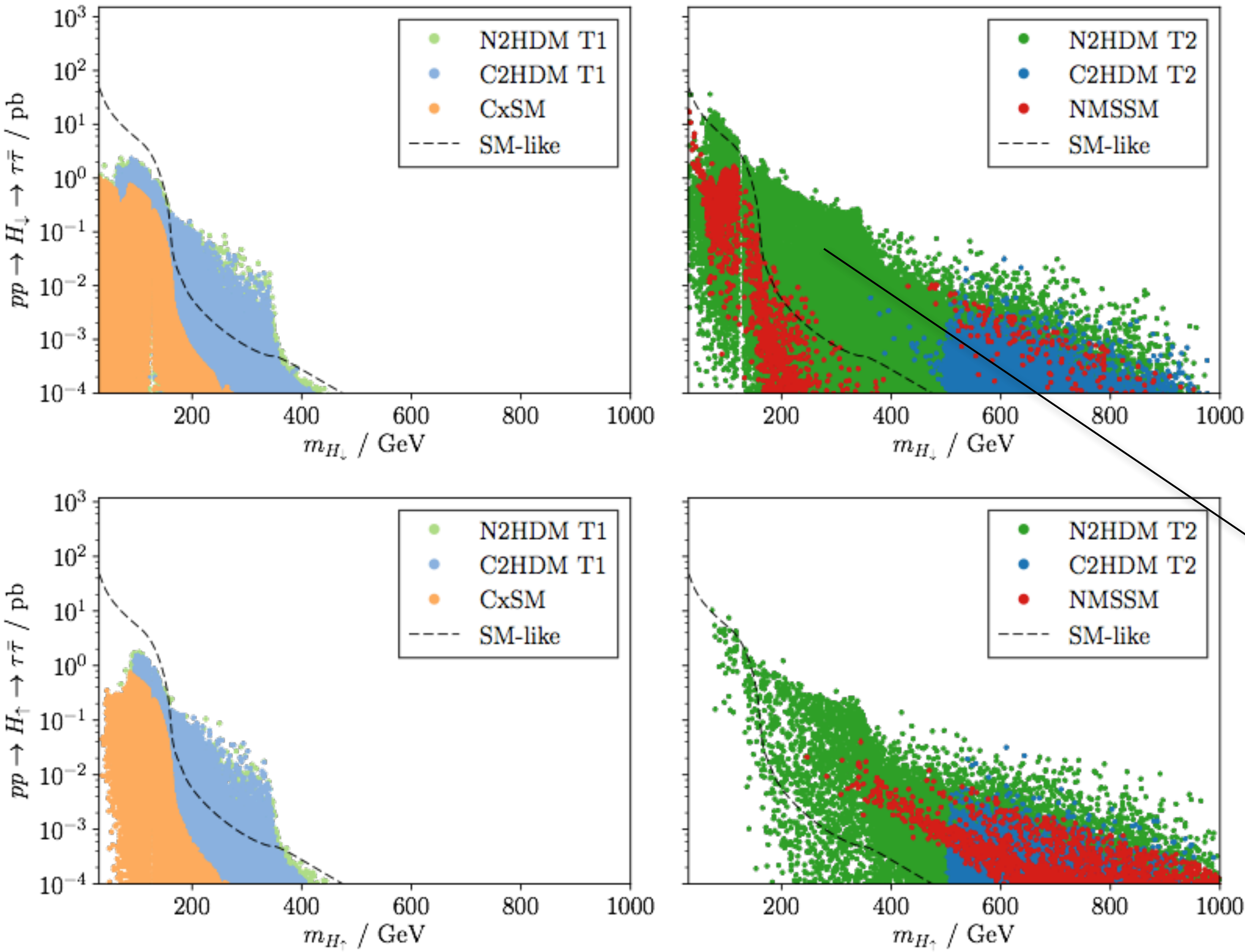
Signal rates for the production of H↓ (upper) and H↑ (lower) for 13 TeV as a function of m_H.

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

CP - what have ATLAS and CMS measured so far?

Correlations in the momentum distributions of leptons produced in the decays

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

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

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!

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

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.

Direct probing at the LHC

- For the C2HDM we need three independent measurements

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

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

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

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

Searching (almost) everywhere!

$S_i \to S_j V$ $\qquad H \to AZ\,(A \to HZ), h_2 \to h_1 Z$ **2HDM, C2HDM...**

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

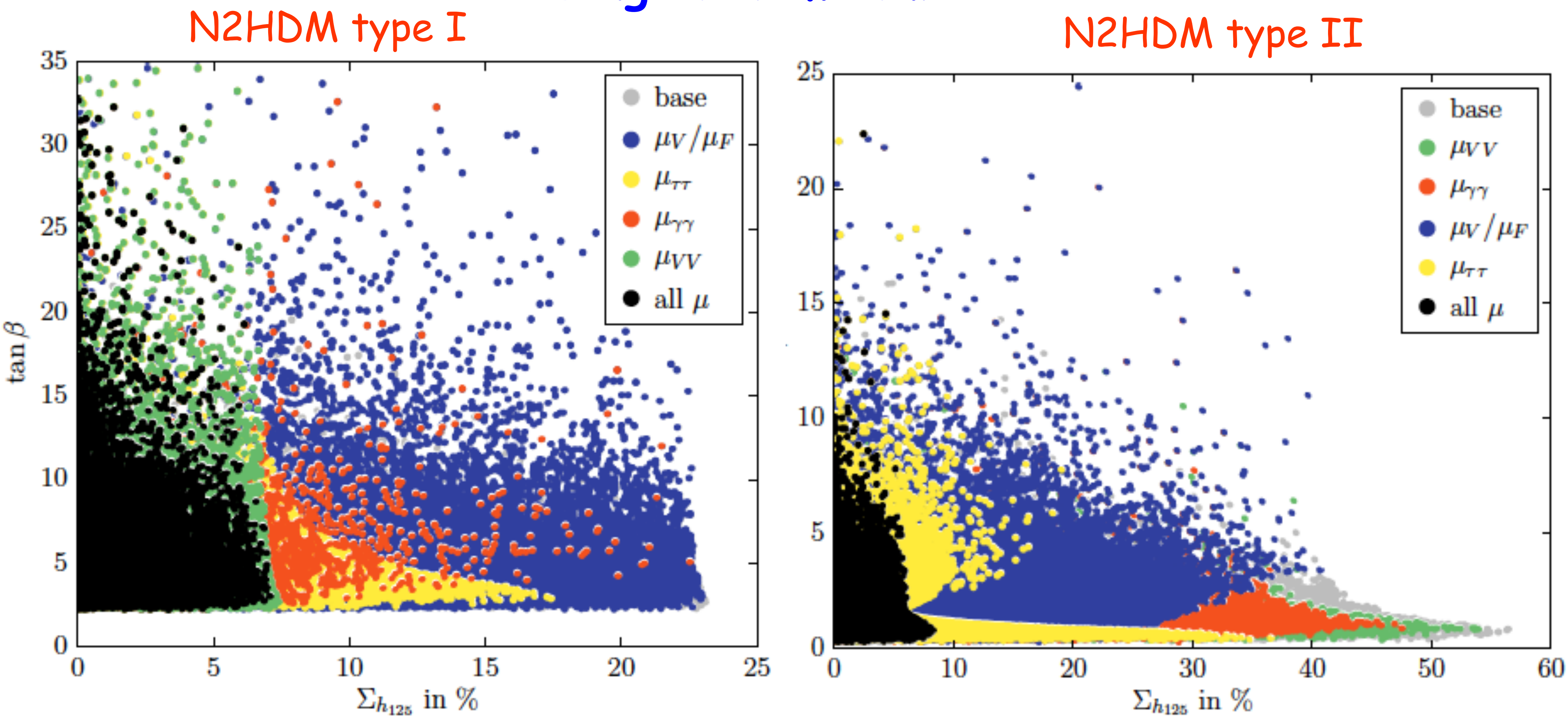
$S_i \to S_j S_k$ $\qquad H_i \to H_j H_j (A_j A_j)$ **R(C)xSM, 2HDM, NMSSM, C2HDM, C-NMSSM, 3HDM...**

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

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

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).

Singlet admixture



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.

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

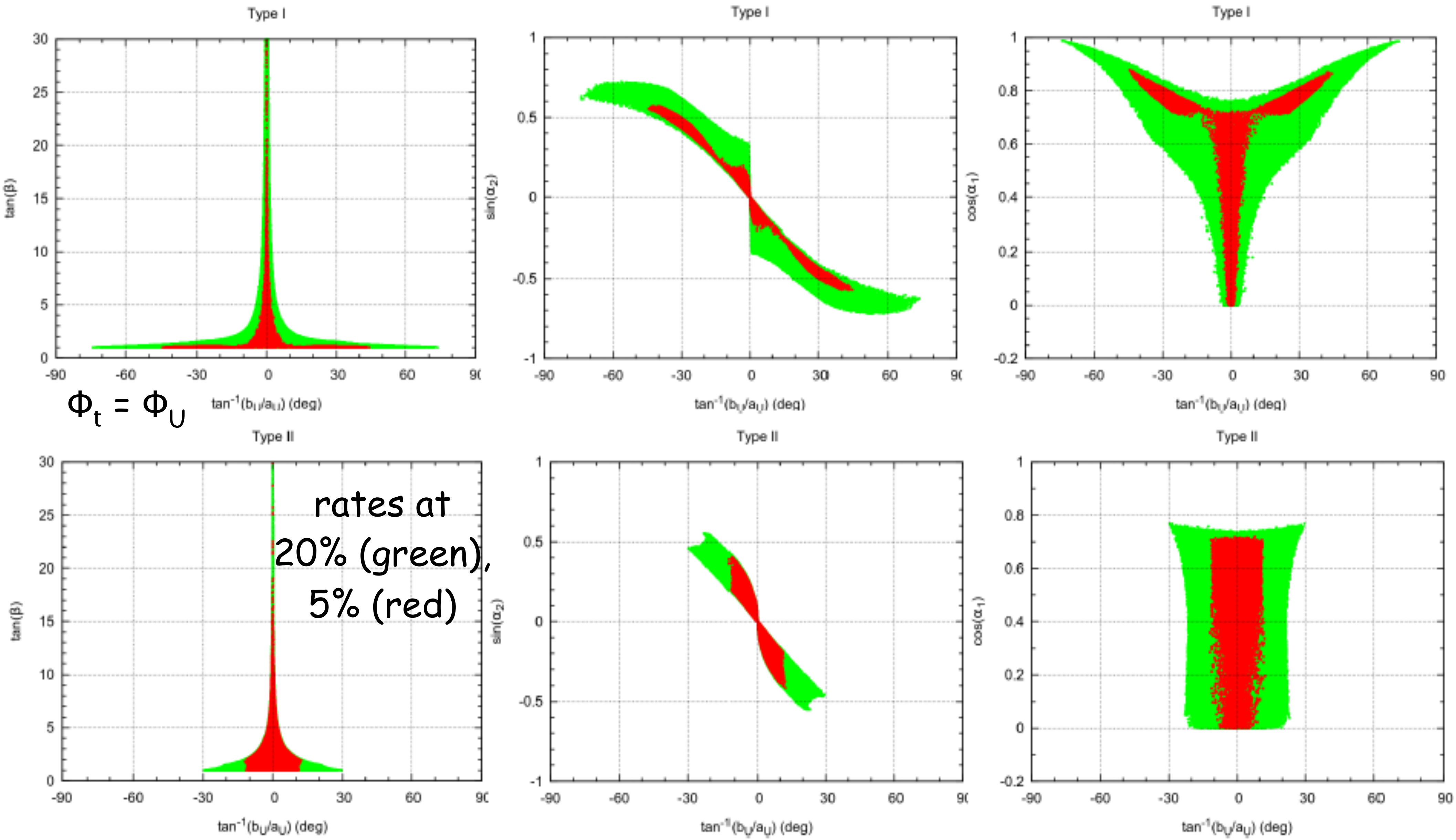
BP8 Complex 2HDM benchmarks *[D. Fontes, J.C. Romao, R. Santos and J.P. Silva]*
https://twiki.cern.ch/twiki/pub/LHCPhysics/LHCHXSWG3BenchmarksNon2HDM/benchmark-C2HDM.pdf

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

Limits on Φ_t based on the rates only



Competitive for Type I but not for Type II