

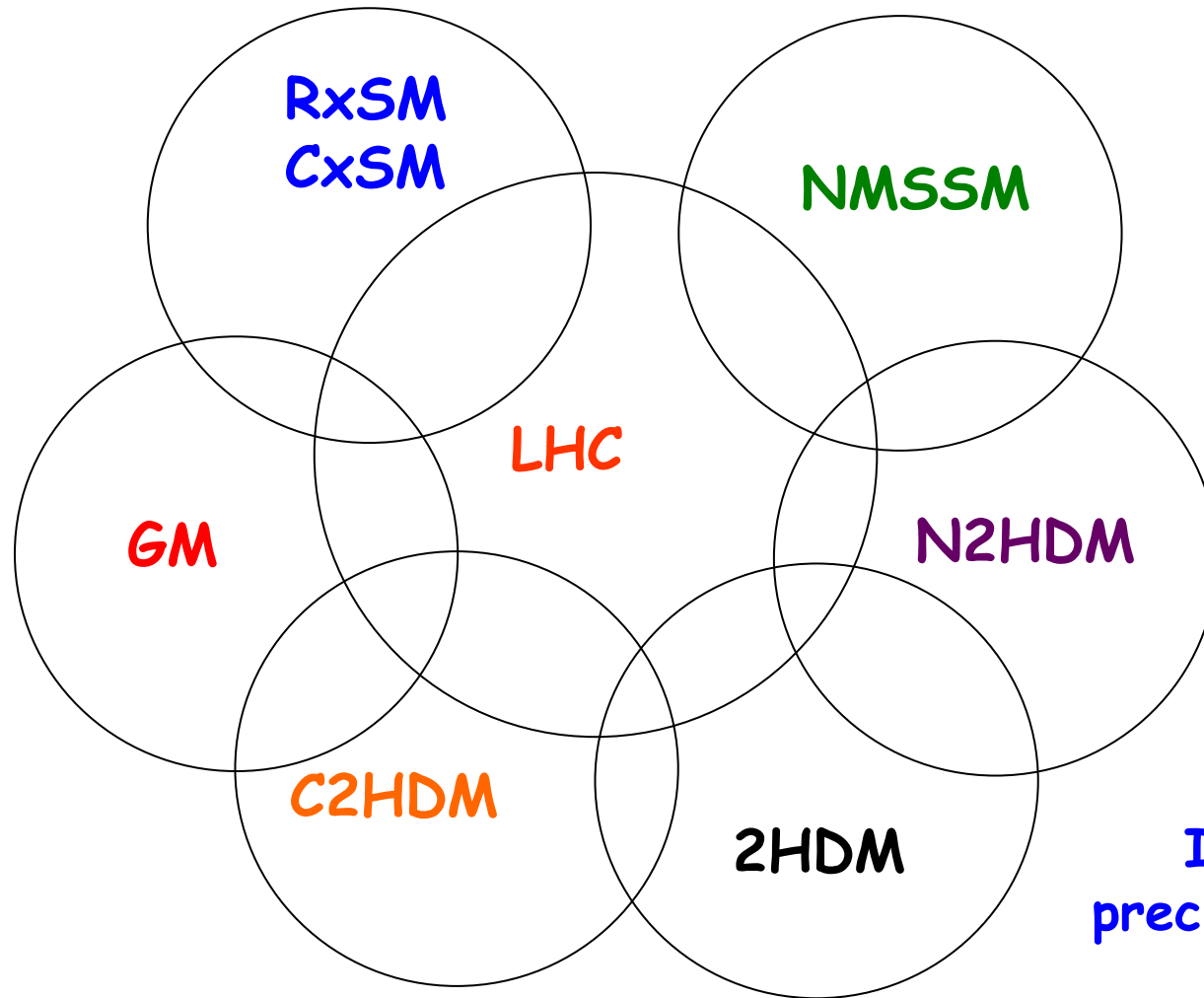
# Extended Higgs sector beyond the MSSM and the LHC

R. Santos  
ISEL & CFTC-UL

ALPS2018 - Third Alpine LHC Physics Summit

17 April 2018

# BSM-EHS – What are they good for?



Motivate searches



New scalar?

Discovered Higgs  
very SM-like



Information from  
precision measurements?

## 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

# 1. Motivate searches - Benchmark models used by ATLAS and CMS

- Real Singlet Extension of the SM (one extra real singlet) - **RxSM**  $\left( \begin{array}{c} \\ v \end{array} \right) \left( v_S \right)$   
**Scalar sector** - 2 CP-even neutral scalars (broken phase)  
SM+complex singlet - **CxSM**
- Two-Higgs Doublet Model (Real - one extra doublet) - **2HDM**  $\rightarrow$  Complex 2HDM - **C2HDM**  
**Scalar sector** - 2 CP-even and 1 CP-odd neutral scalars plus 2 charged scalars
- Next-to-Minimal 2HDM (Real - one extra doublet) - **N2HDM**  
**Scalar sector** - 3 CP-even and 1 CP-odd neutral scalars plus 2 charged scalars

Very minimal versions, CP-conserving and no FCNC (discrete symmetries). Both 2HDM and N2HDM come in 4 types.

- ... and others like Georgi-Machacek model (two extra  $SU(2)_L$  triplet scalars) - **GM**  
**Scalar sector** - 3 CP-even, 4 charged scalars and 2 doubly charged scalars

## Softly broken $Z_2$ symmetric Higgs potential

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

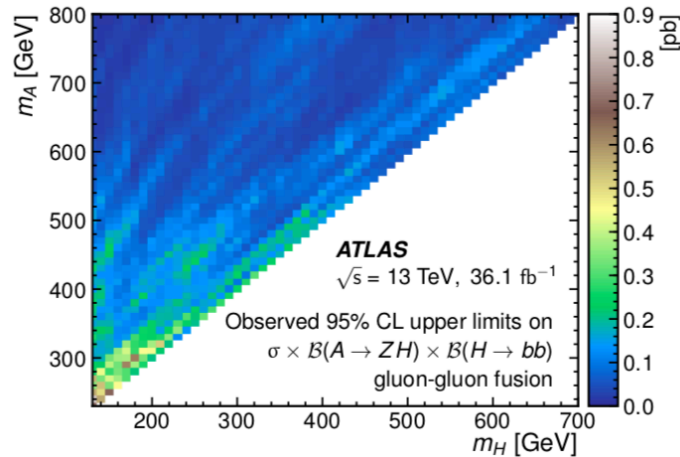
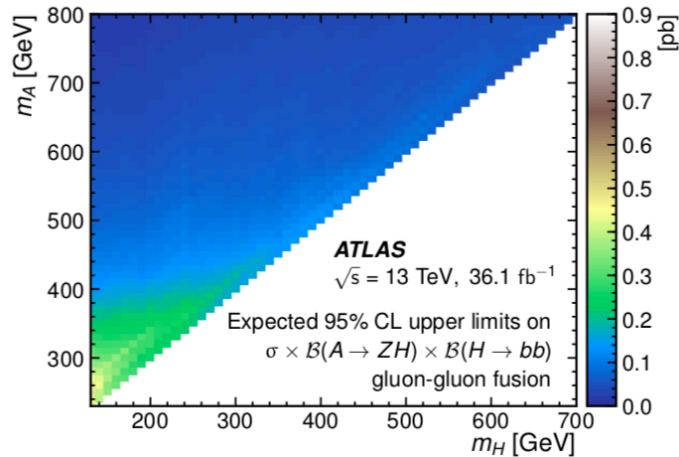
and CP is not spontaneously broken

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

- $m_{12}^2$  and  $\lambda_5$  real      potential is CP-conserving (2HDM)
- $m_{12}^2$  and  $\lambda_5$  complex      potential is explicitly CP-violating (C2HDM)

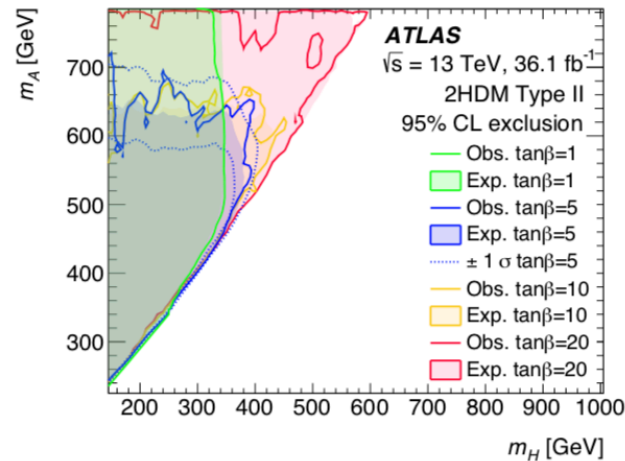
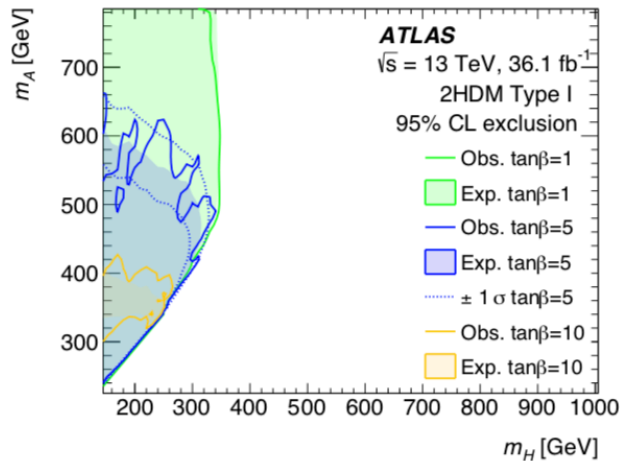
**Inert 2HDM**       $V(\Phi_1, \Phi_2) / . m_{12}^2 \rightarrow 0$        $\langle \Phi_1 \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v \end{pmatrix}; \quad \langle \Phi_2 \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ 0 \end{pmatrix}$       5

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



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

ATLAS 1804.01126v1



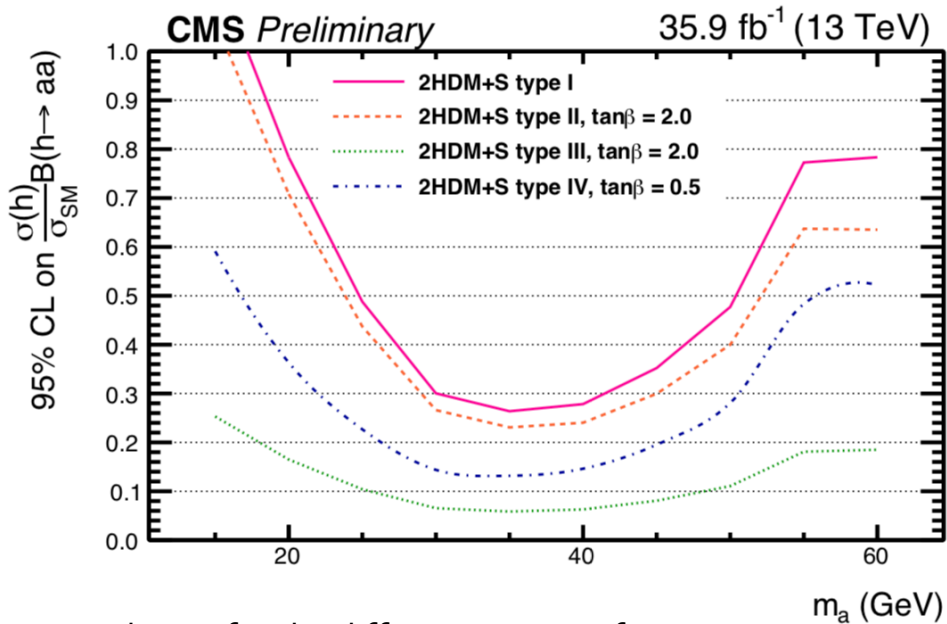
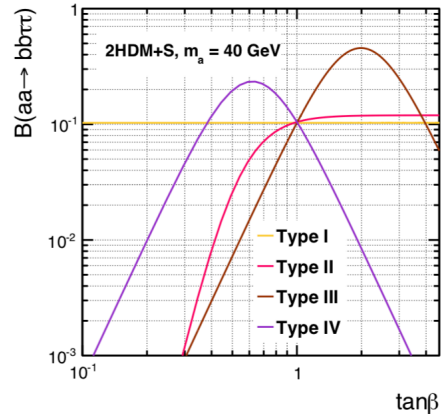
Observed and expected 95% CL exclusion regions in the  $(m_A, m_H)$  plane for various  $\tan\beta$  values for Type I (left), and Type II (right).

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

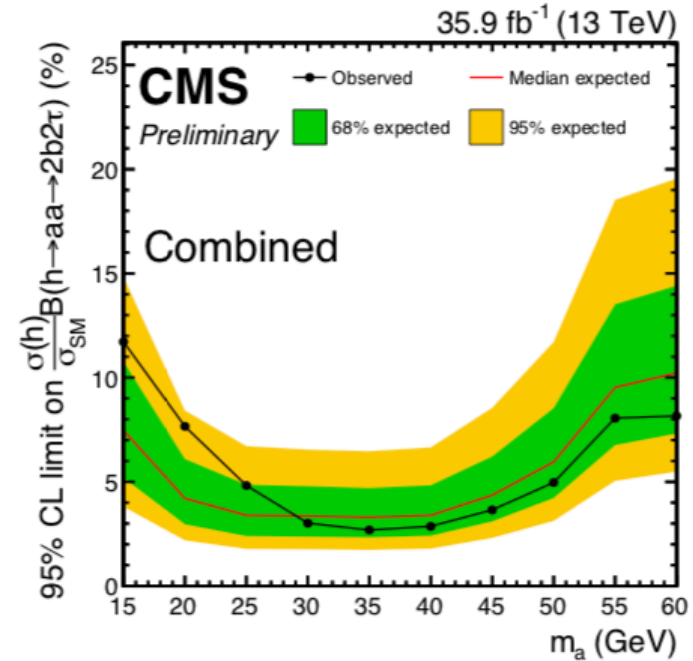
# The N<sub>2</sub>HDM (CP-conserving and no tree-level FCNC)

CMS PAS HIG-17-024

BRs for the 4 different versions of the model.



Exclusion for the different versions for 2 values of  $\tan\beta$ .

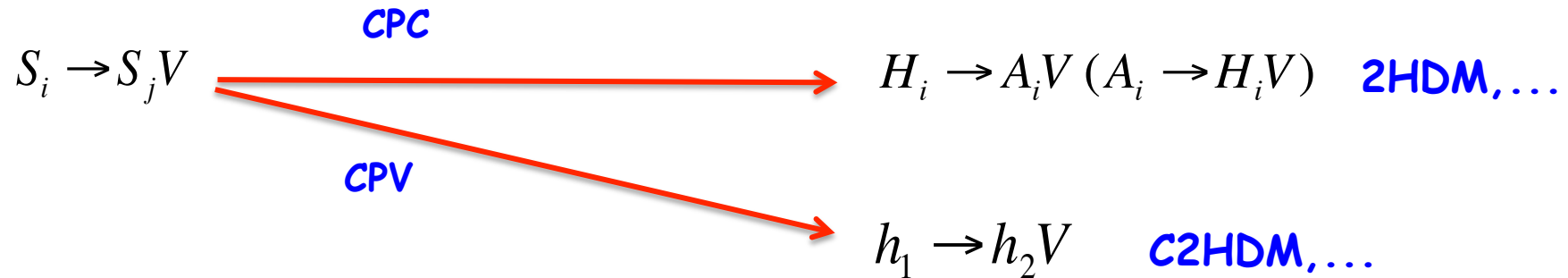


Expected and observed 95% CL limits on  $\sigma(h)B(h \rightarrow aa \rightarrow 2\tau 2b)$  in %. Combined  $e\mu$ ,  $e\tau$  and  $\mu\tau$  channels. The inner (green) band and the outer (yellow) band indicate the regions containing 68 and 95%, respectively, of the distribution of limits expected under the background-only hypothesis.

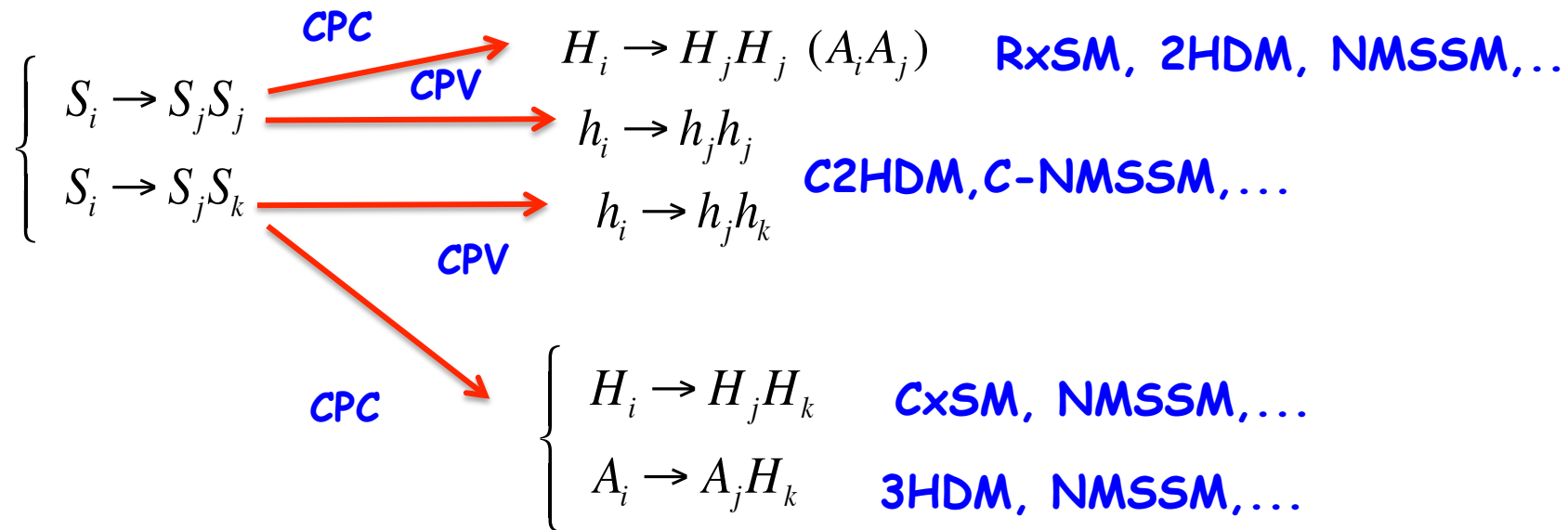
# Searches roadmap

$$CP(H_i) = 1; \quad CP(A_i) = -1$$

$h_i$  (no definite  $CP$ )



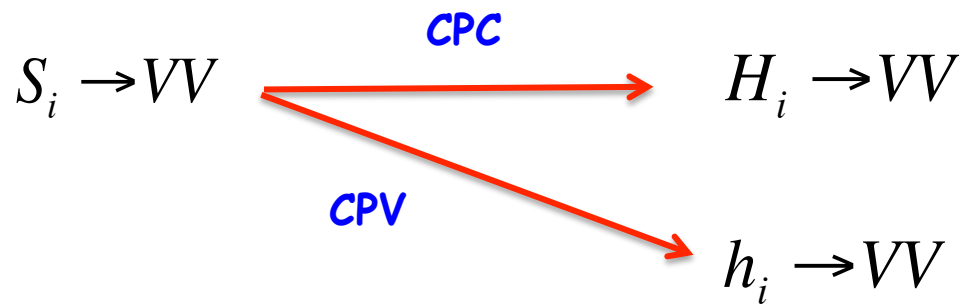
•  $H \rightarrow AZ, A \rightarrow ZH$  and  $A \rightarrow Zh_{125}$ , already studied by ATLAS and CMS



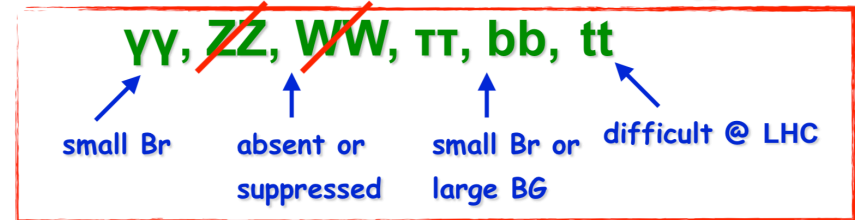
•  $h_{125} \rightarrow AA$  and  $H \rightarrow h_{125} h_{125}$  already studied by ATLAS and CMS



# Searches roadmap



For the 2HDM



$$h_1 \rightarrow ZZ + h_2 \rightarrow ZZ + h_2 \rightarrow h_1 Z$$

Combinations of three decays

$$h_1 \rightarrow ZZ \iff \text{CP}(h_1) = 1 \quad h_3 \rightarrow h_2 h_1 \implies \text{CP}(h_3) = \text{CP}(h_2) \text{CP}(h_1) = \text{CP}(h_2)$$

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

## Searches roadmap

$$\begin{cases} S_i \rightarrow f_j \bar{f}_j \\ S_i \rightarrow f_j \bar{f}_k \end{cases}$$

FC



$$H/A \rightarrow \tau^+ \tau^-$$

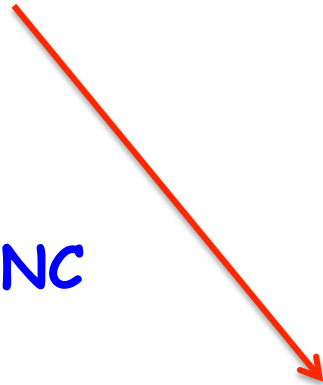
$$H/A \rightarrow \mu^+ \mu^-$$

$$H/A \rightarrow t \bar{t}$$

$$H/A \rightarrow b \bar{b}$$

Done...

FCNC



$$h_{125} \rightarrow \tau \mu, e \mu, e \tau$$

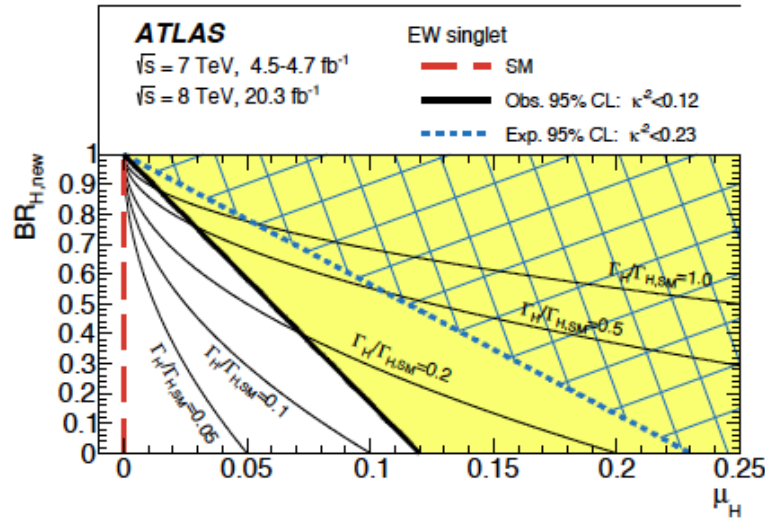
$$t \rightarrow c h_{125}$$

Still, the CP-nature of the Higgs not probed. Attempts in  $t\bar{t}h$  (production) and  $\tau\tau h$  (decay) starting (many theory papers).

$S_i$  (any neutral scalar)

## 2.a) $H_{125}$ couplings - The Real Singlet

ATLAS 1509.00672

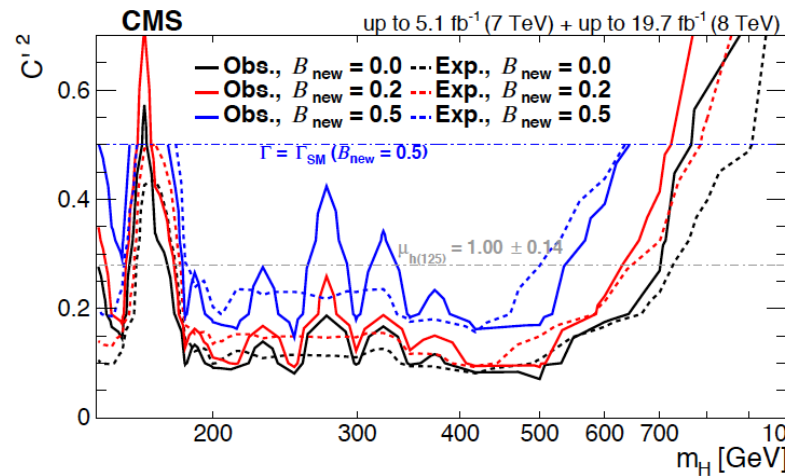


$$\mu_h = \frac{\sigma_h \times BR_h}{(\sigma_h \times BR_h)_{SM}} = \kappa^2$$

$$\mu_H = \frac{\sigma_H \times BR_H}{(\sigma_H \times BR_H)_{SM}} = \kappa'^2 (1 - BR_{H,new})$$

$$\kappa'^2 = 1 - \mu_h$$

Real singlet plus SM.  
 Also any portal model  
 with a singlet in the  
 broken phase.

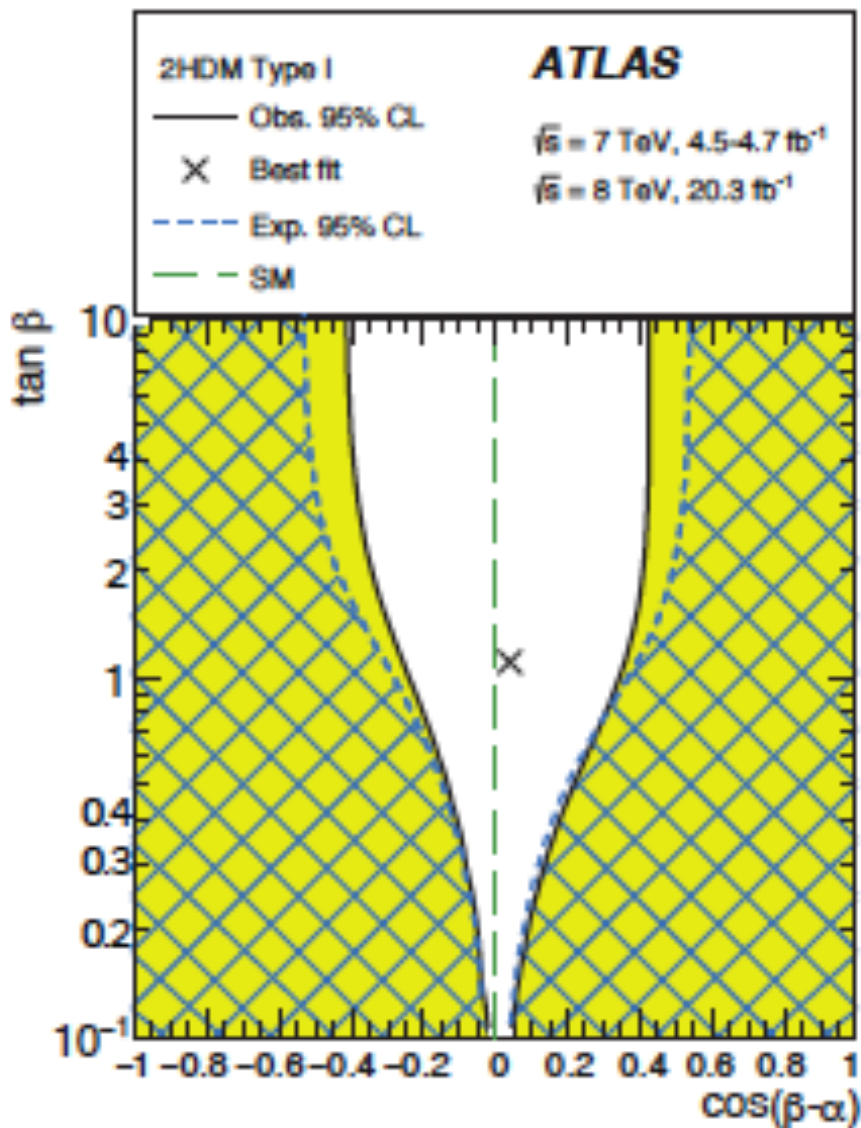


CMS 1504.00936

$$\mu' = C'^2 (1 - B_{new})$$

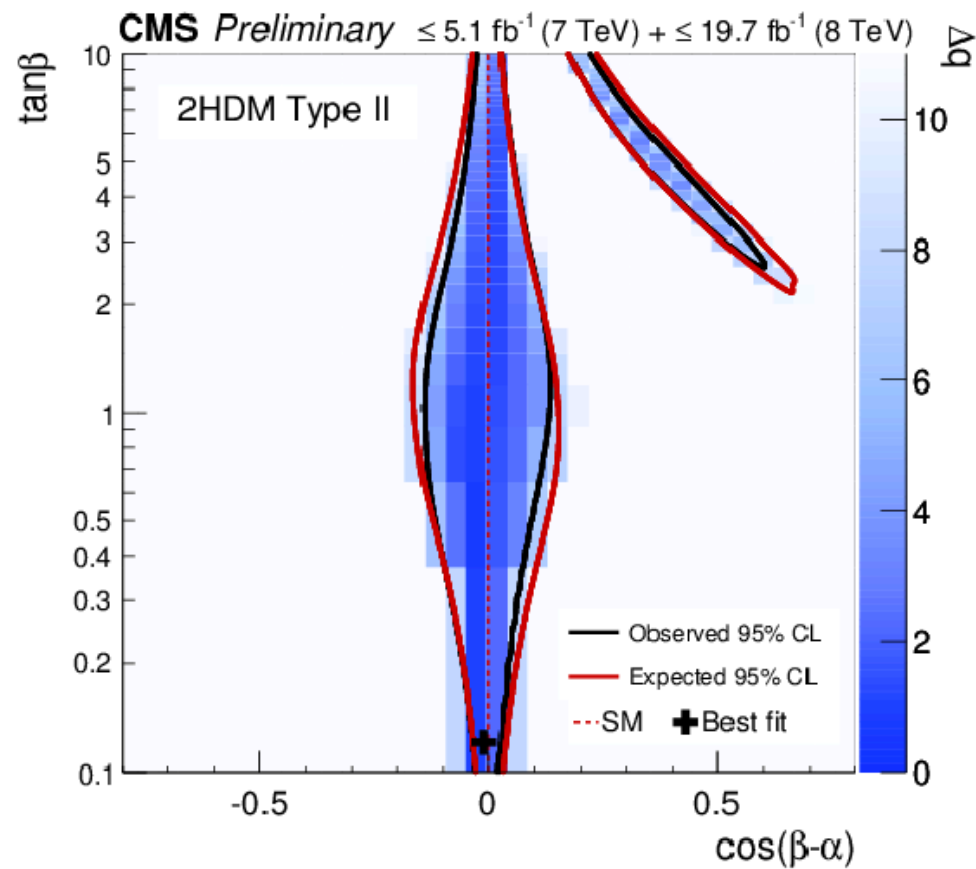
$$\Gamma' = \Gamma_{SM} \frac{C'^2}{1 - B_{new}}$$

## 2.a) b) $H_{125}$ couplings - The 2HDM (CP-conserving and no tree-level FCNC)



(a) Type I

ATLAS 1509.00672



CMS-PAS-HIG-16-007

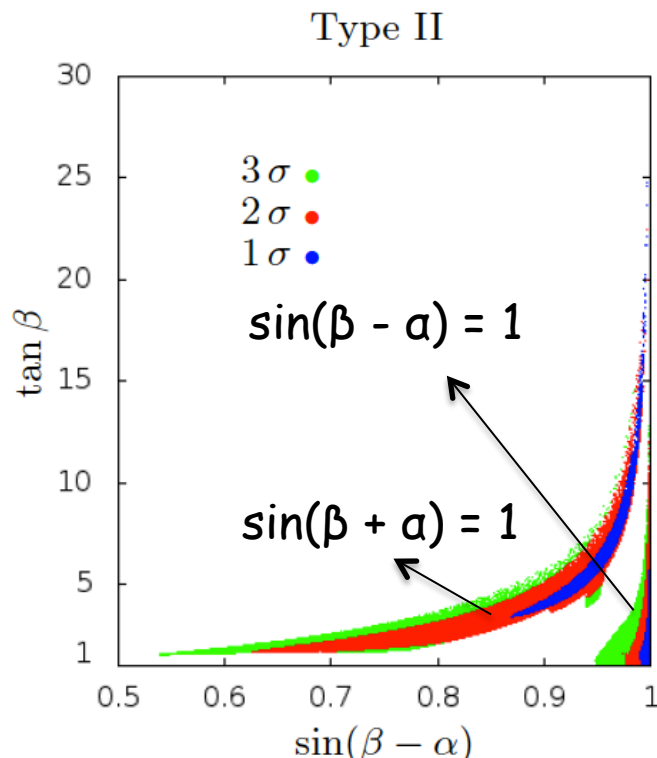
For the 2HDM the results obtained by ATLAS and CMS can be understood in terms of the Higgs couplings in the Alignment and Wrong-sign Yukawa limits

The Alignment (SM-like) limit - all tree-level couplings to fermions and gauge bosons are the SM ones.

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

Wrong-sign Yukawa coupling - at least one of the couplings of  $h$  to down-type and up-type fermion pairs is opposite in sign to the corresponding coupling of  $h$  to  $VV$  (in contrast with SM).

$$\kappa_D \kappa_W < 0 \quad \text{or} \quad \kappa_U \kappa_W < 0$$



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

at tree-level

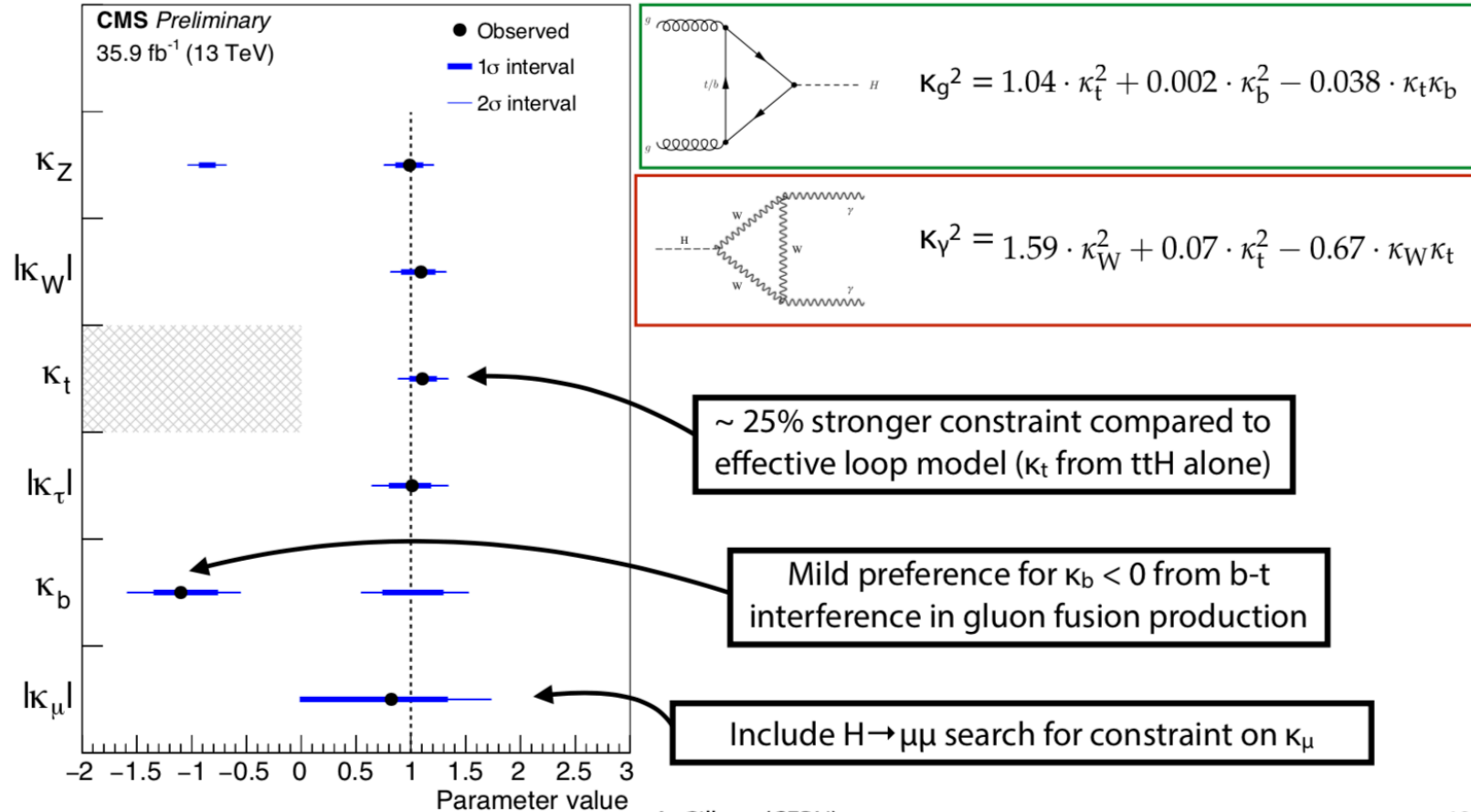
$$\kappa_i^2 = \frac{\Gamma^{2HDM}(h \rightarrow i)}{\Gamma^{SM}(h \rightarrow i)}$$

The actual sign of each  $\kappa_i$  depends on the chosen range for the angles.

FERREIRA, GUNION, HABER, RS, PRD89 (2014) 11, 115003

FERREIRA, GUEDES, SAMPAIO, RS, JHEP 1412 (2014) 067

# The wrong-sign strikes back!



A. Gilbert (CERN)

48

# Lightest Higgs couplings to gauge bosons

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

$V = W, Z$

$\left( \begin{array}{c} \\ \end{array} \right) \left( \begin{array}{c} \\ \end{array} \right) \left( \begin{array}{c} \\ \end{array} \right)$

$$g_{C2HDM}^{hVV} = \cos(\alpha_2) g_{2HDM}^{hVV}$$

**CP-VIOLATING 2HDM**

→ "PSEUDOSCALAR" COMPONENT (DOUBLET)

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

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

$$g_{N2HDM}^{hVV} = \cos(\alpha_2) g_{2HDM}^{hVV}$$

SINGLET COMPONENT

**2HDM + REAL SINGLET**

$$g_{RxSM}^{hVV} = \cos(\alpha_1) g_{SM}^{hVV}$$

**2HDM + COMPLEX SINGLET**

$$g_{CxSM}^{hVV} = \cos(\alpha_1) \cos(\alpha_2) g_{SM}^{hVV}$$

$\left( \begin{array}{c} \\ \end{array} \right) (a + ib)$

REAL COMPONENT

IMAGINARY COMPONENT

## Lightest Higgs Yukawa couplings

<b>Type I</b>	$\kappa_U^I = \kappa_D^I = \kappa_L^I = \frac{\cos \alpha}{\sin \beta}$	
<b>Type II</b>	$\kappa_U^{II} = \frac{\cos \alpha}{\sin \beta}$	$\kappa_D^{II} = \kappa_L^{II} = -\frac{\sin \alpha}{\cos \beta}$
<b>Type F/Y</b>	$\kappa_U^F = \kappa_L^F = \frac{\cos \alpha}{\sin \beta}$	$\kappa_D^F = -\frac{\sin \alpha}{\cos \beta}$
<b>Type LS/X</b>	$\kappa_U^{LS} = \kappa_D^{LS} = \frac{\cos \alpha}{\sin \beta}$	$\kappa_L^{LS} = -\frac{\sin \alpha}{\cos \beta}$

2HDM

$$Y_{CxSM} \equiv c_1 c_2 Y_{SM}$$



SINGLET  
EXTENSION

$$Y_{N2HDM} \equiv c_2 Y_{2HDM} \quad \text{CP-CONSERVING N2HDM}$$

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

when  $s_2 \rightarrow 0$

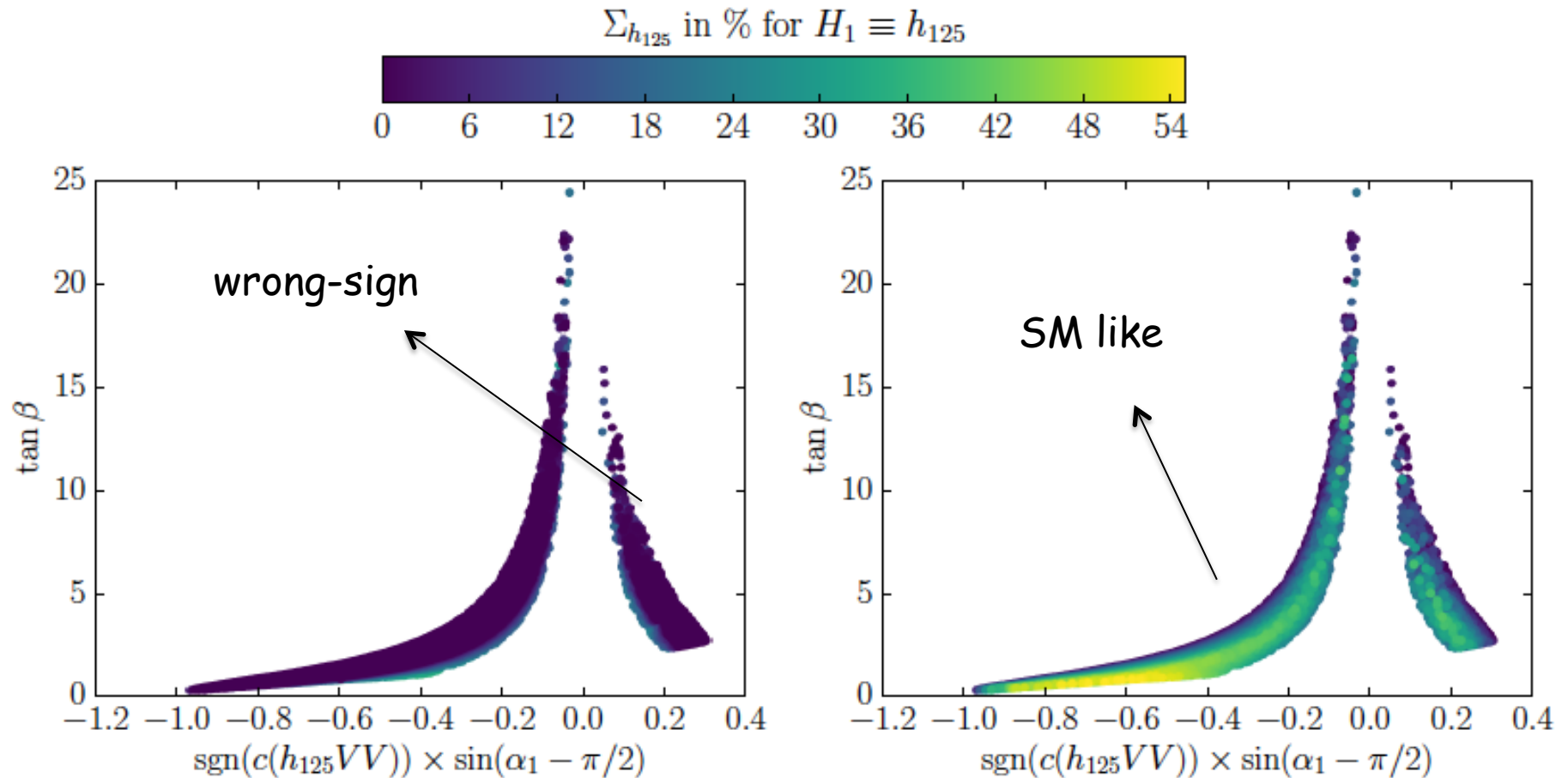
$$Y_{C2HDM} \equiv Y_{N2HDM} \equiv Y_{2HDM}$$

Independent of the Yukawa type



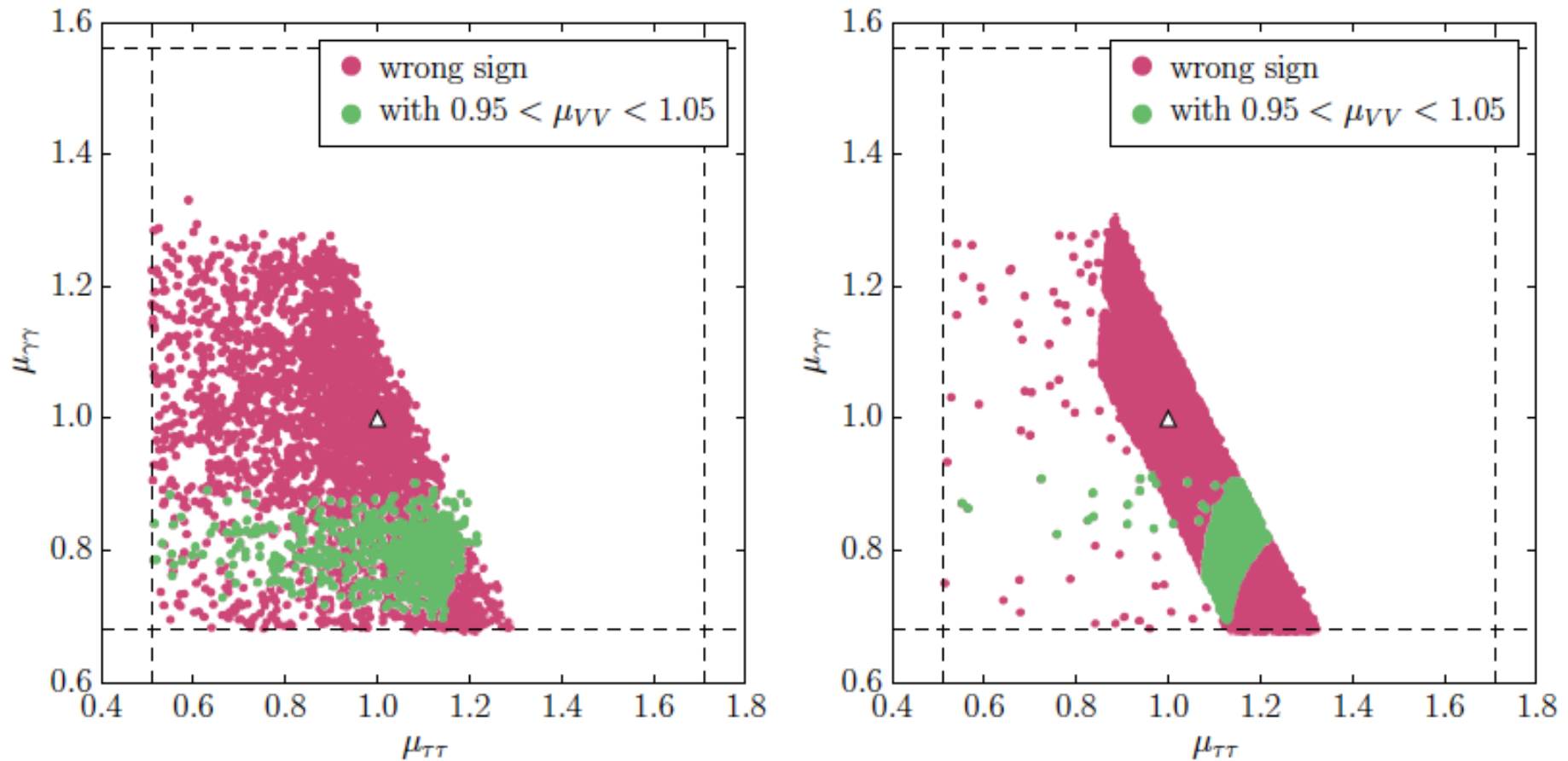
So, the allowed region looks very much like 2HDM one

$\Sigma_i^{N2HDM} = (R_{i3})^2$  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 %.

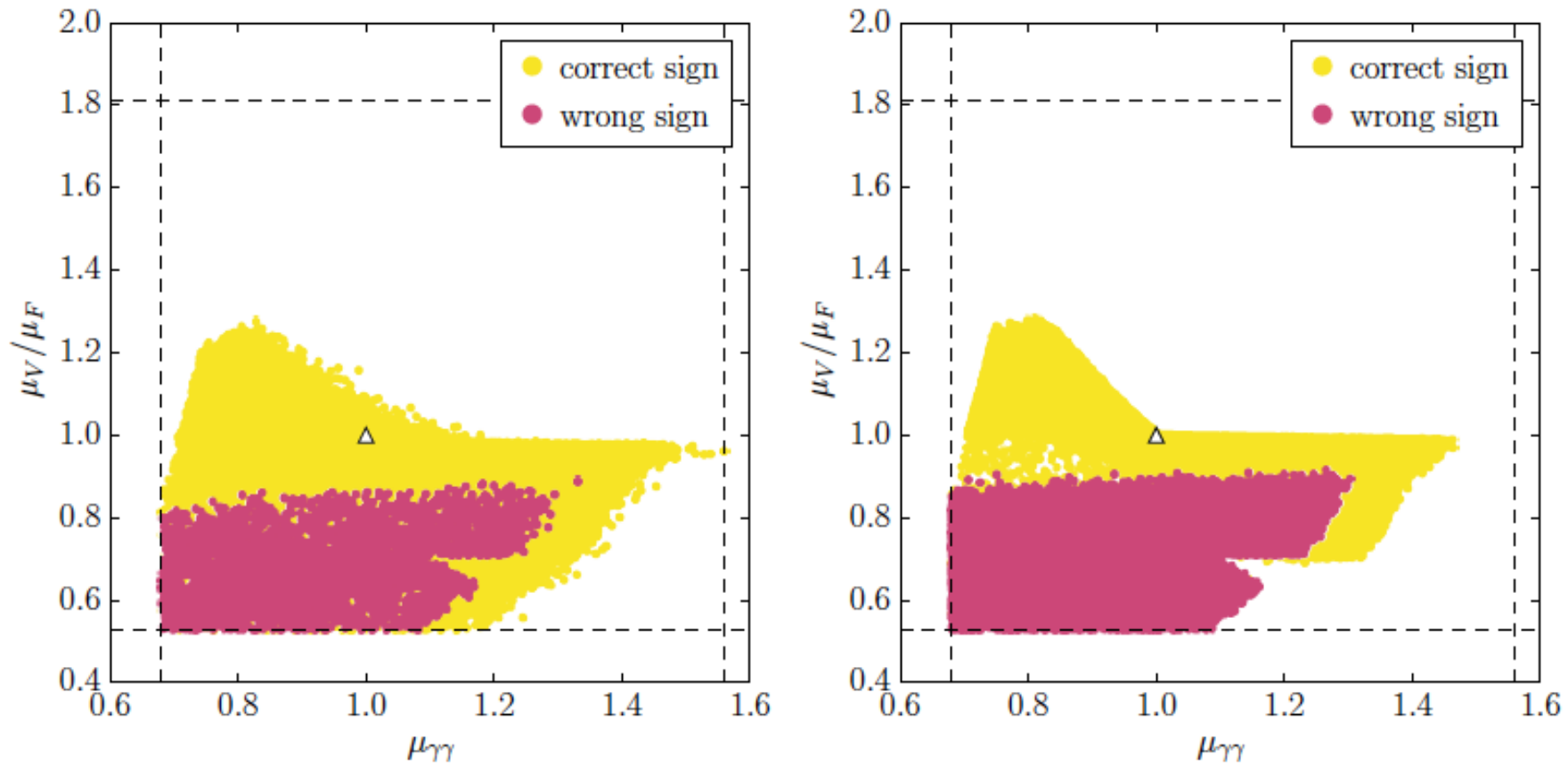
# Wrong sign can be probed in the 2HDM and N2HDM with the same measurements



$\mu_{\gamma\gamma}$  vs  $\mu_{\tau\tau}$  (only wrong sign points) in type II 2HDM (left) and N2HDM (right) - in "pink" all points and in green points where  $\mu_{ZZ}$  is measured within 5% of the SM value. Dashed lines are current limits.

Very similar behaviors in the two models.

## Wrong sign in the 2HDM and N2HDM

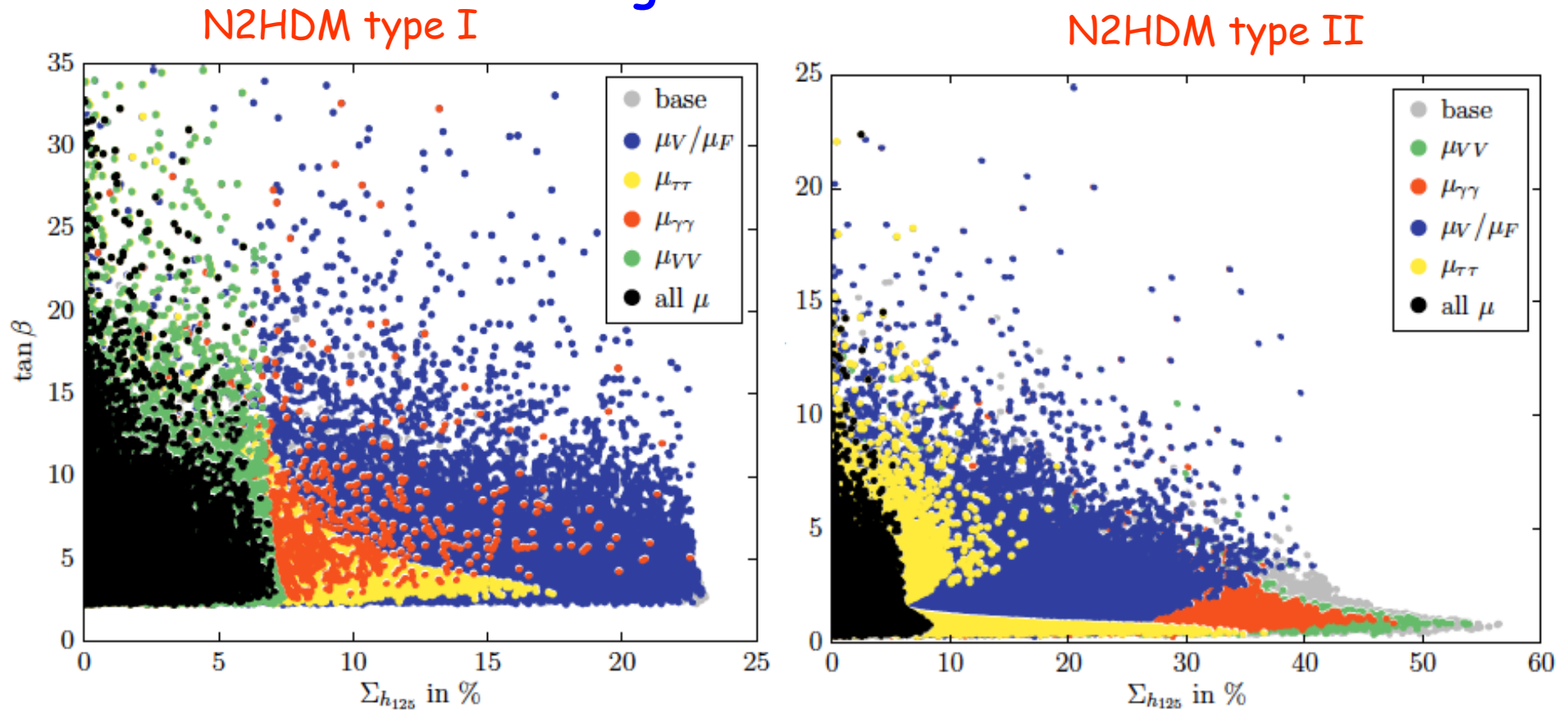


$\mu_V/\mu_F$  vs  $\mu_\gamma$  in type II 2HDM (left) and N2HDM (right) - in yellow the "right sign" and in pink the wrong sign points. Dashed lines are current limits.

The  $h_{125}$  can be any of the  $H_i$  in the N2HDM and  $h$  or  $H$  in the 2HDM.

**New variable that can be used to probe the wrong sign limit.**

## Singlet admixture



MUHLLEITNER, SAMPAIO, RS, WITTBRODT, JHEP 1703 (2017) 094

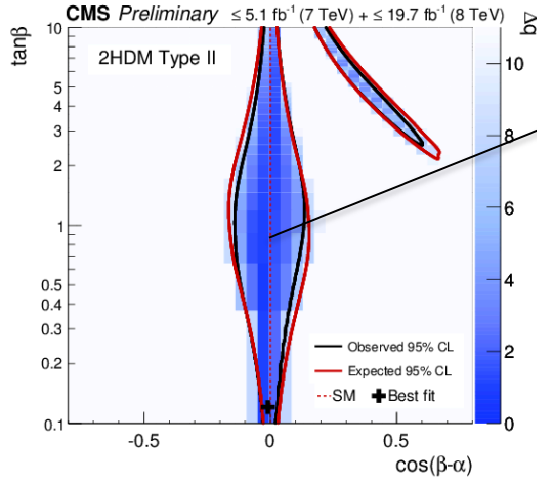
tan $\beta$  as a function of the singlet admixture for type I N2HDM (left) and type II N2HDM (right) - in grey all points with constraints; the remaining colours denote  $\mu$  values measured within 5 % of the SM. In black all  $\mu$ 's. Singlet admixture slightly below 10 % almost independently of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

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

# Back to The alignment limit in the 2HDM

What about  $\tan\beta$ ? All couplings of  $h_{125}$  with the other SM particles are SM-like (even  $h h h$ ).

$$\begin{pmatrix} \phantom{v} \\ \phantom{v} \\ \phantom{v} \\ v_1 \end{pmatrix} \quad \begin{pmatrix} \phantom{v} \\ \phantom{v} \\ \phantom{v} \\ v_2 \end{pmatrix}$$

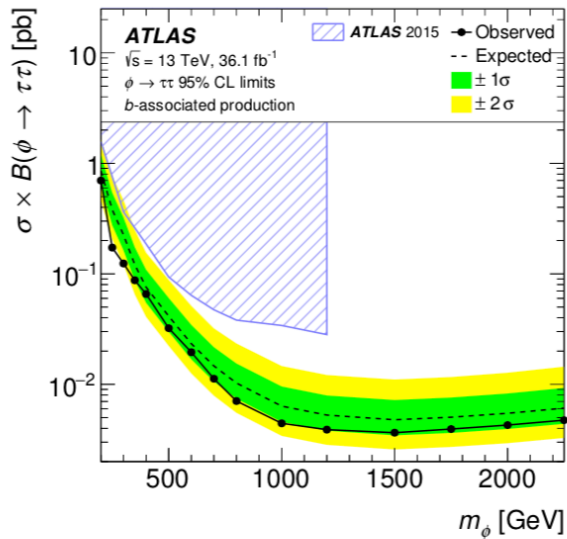


**EVEN IF IN THE END WE WILL HAVE A LINE ONLY, THE MIXING BETWEEN VEVS CAN ONLY BE SEEN WITH NEW PHYSICS.**

**TWO EXAMPLES:**

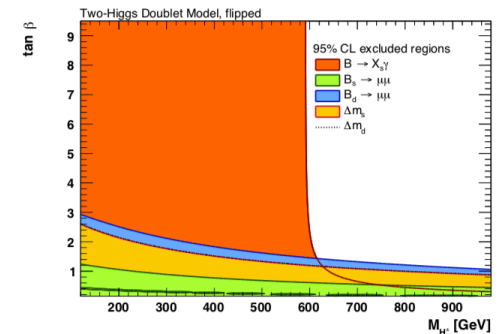
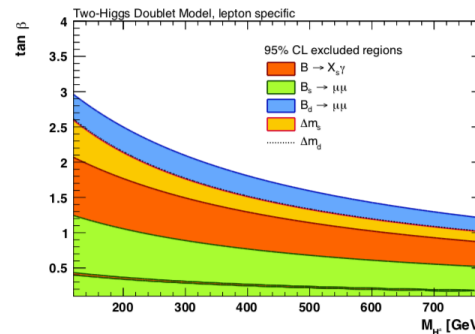
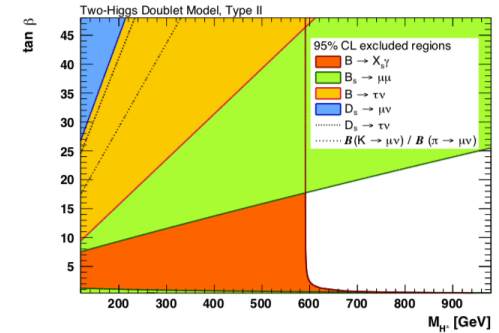
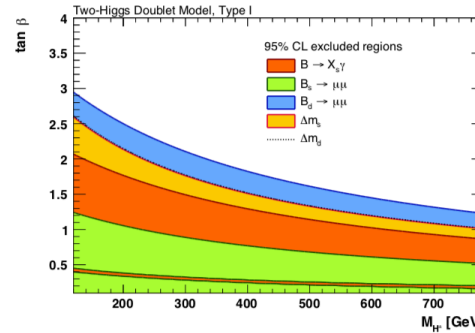
**HALLER, HOECKER, KOGLER, PEIFFER, STELZER 1803.01853**

From the LHC: limit on the pseudoscalar mass,  $\tan\beta$  plane.



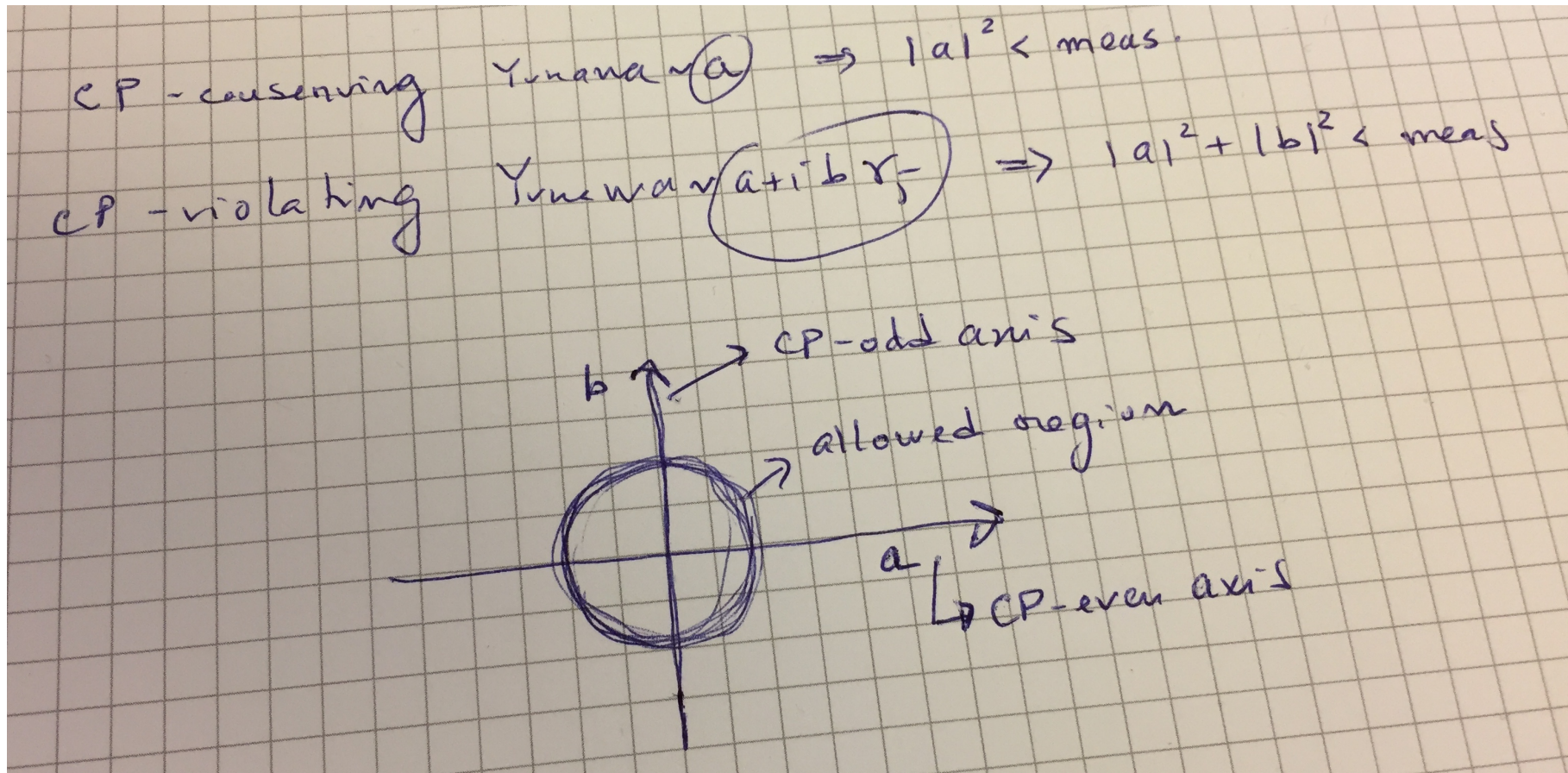
(b)  $\phi \rightarrow \tau\tau$  ( $b$ -associated production).

**ATLAS, JHEP01(2018)055**



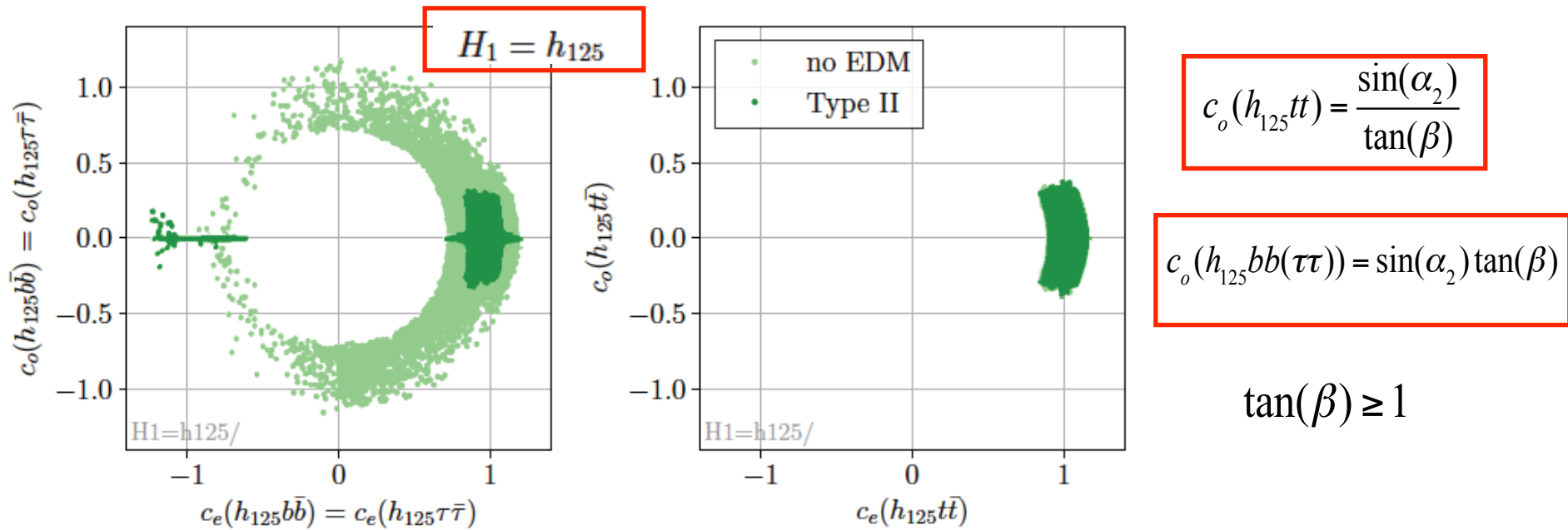
From B-physics: Charged Higgs loops – constraint in the charged Higgs mass,  $\tan\beta$  plane

## And now for some complex 2HDM - C2HDM



$$Y_{C2HDM}^{\text{Type II}} \equiv c_2 Y_{2HDM}^{\text{Type II}} + i\gamma_{52} s_2 t_\beta$$

## The allowed parameter space in type II C2HDM



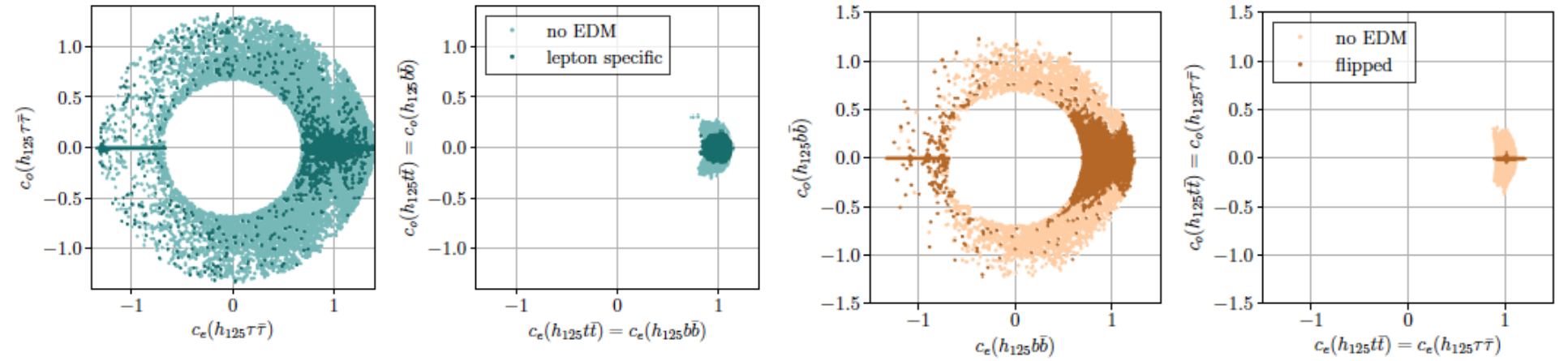
Bounds are stronger for the up-quarks couplings. They come from  $\mu_{VV}$  and the bound on  $\tan\beta$ . In type I all couplings are very constrained.

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

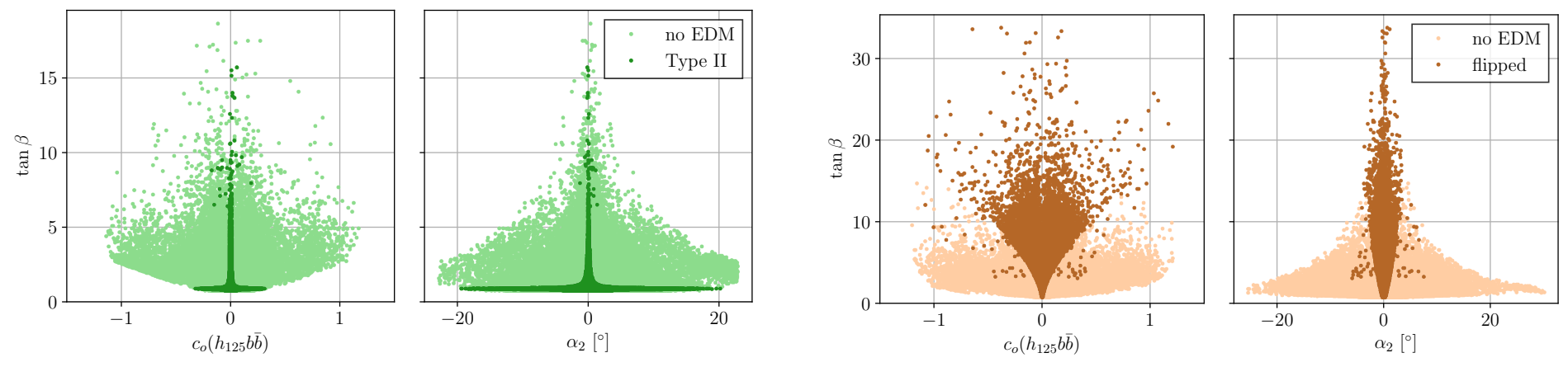
and the remaining  $h_1$  couplings to up-type quarks and gauge bosons are

$$\left\{ \begin{array}{l} a_U^2 = (1 - s_2^4) = (1 - 1/t_\beta^4) \\ b_U^2 = s_2^4 = 1/t_\beta^4 \end{array} \right. \quad \left( \frac{g_{C2HDM}^{hVV}}{g_{SM}^{hVV}} \right)^2 = C^2 = \frac{t_\beta^2 - 1}{t_\beta^2 + 1} = \frac{1 - s_2^2}{1 + s_2^2}$$

**EDMs constraints completely kill large pseudoscalar components in Type II.  
Not true in Flipped and Lepton Specific.**



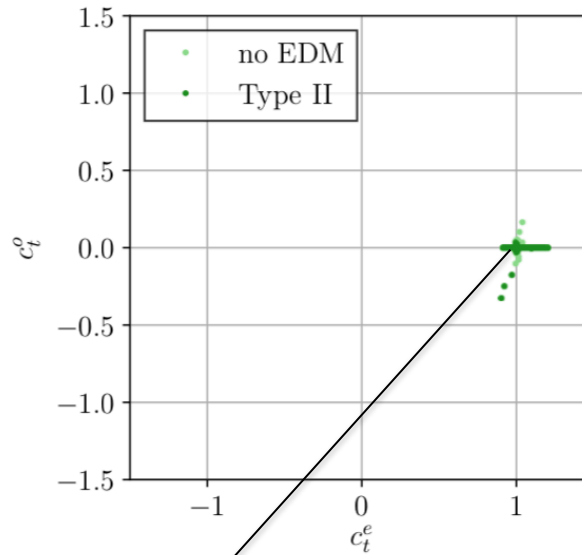
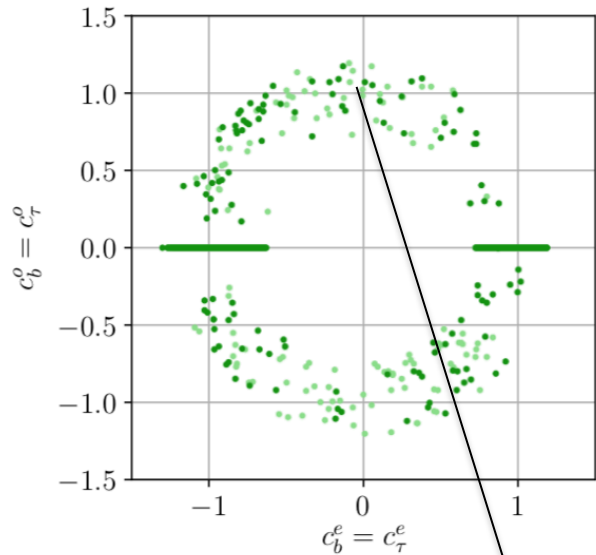
CP-odd coupling proportional to  $\sin\alpha_2 \tan\beta$



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**

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

**and the other decaying to taus as CP-odd**

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

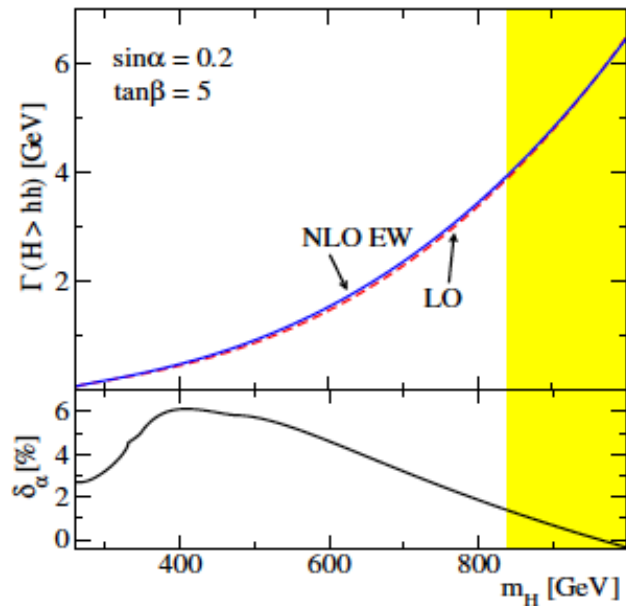
**Probing one Yukawa coupling is not enough!**

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
$\text{Re}(m_{12}^2)$	24017	7658	46784
$\alpha_1$	-0.1468	-0.14658	-0.089676
$\alpha_2$	-0.75242	-0.35712	-1.0694
$\alpha_3$	-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
$\mu_V/\mu_F$	0.899	0.959	0.837
$\mu_{VV}$	0.976	1.056	1.122
$\mu_{\gamma\gamma}$	0.852	0.935	0.959
$\mu_{\tau\tau}$	1.108	1.013	1.084
$\mu_{bb}$	1.101	1.012	1.069

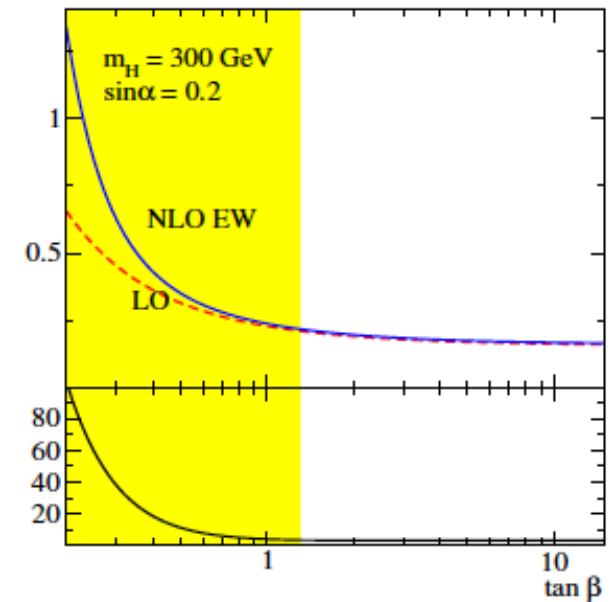
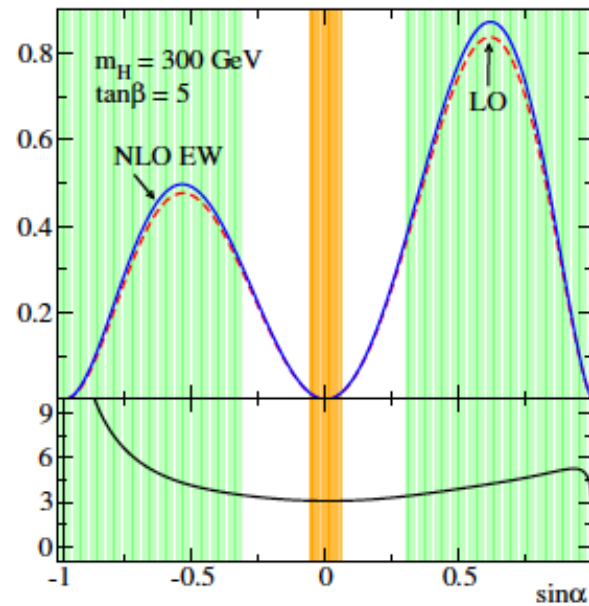
## 2.c) What are radiative corrections good for?

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

### Real Singlet model

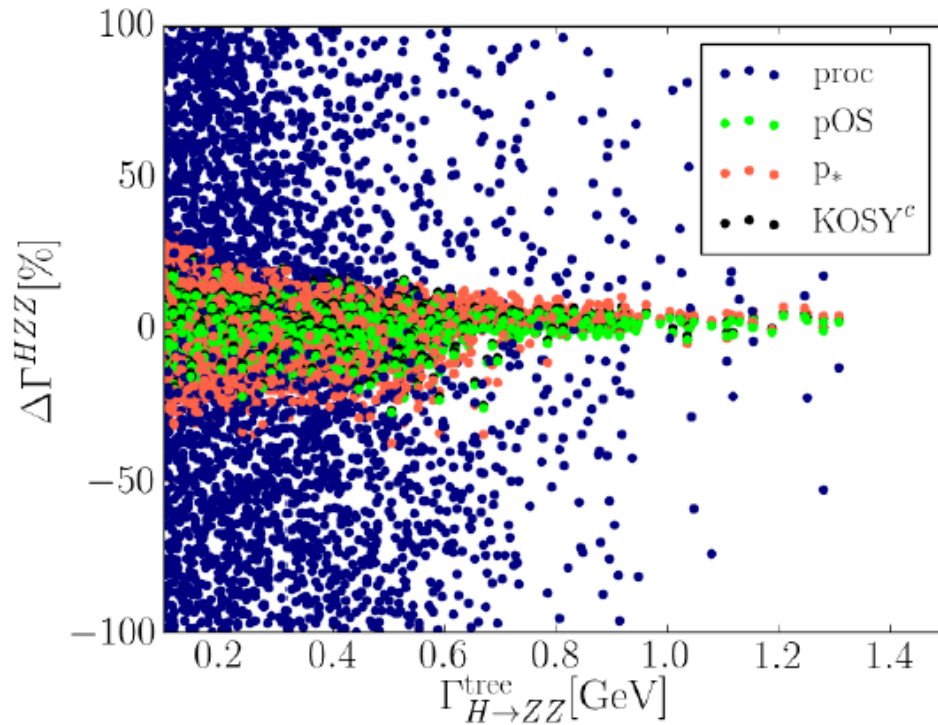


$H \rightarrow hh$



NLO Corrections shown  
to be only a few percent

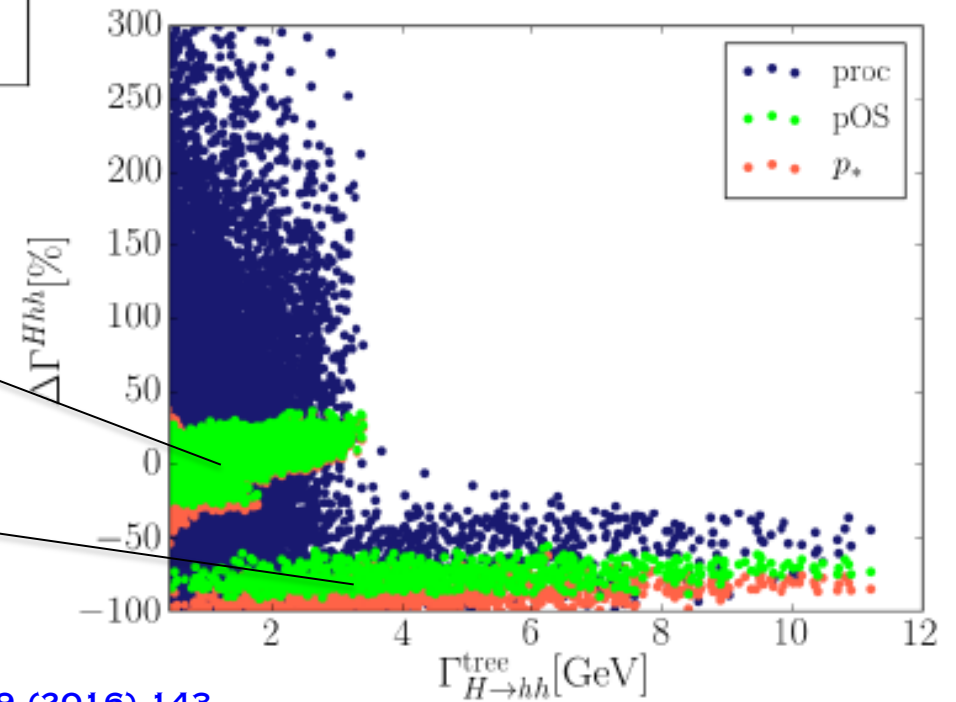
# Real 2HDM



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



# N2HDM

	BRH2ZZhigh	BRH3ZZhigh	BRH2ZZlow	BRH3ZZlow
$m_{H_1}$	125.09	125.09	125.09	125.09
$m_{H_2}$	673.70	600.76	657.07	283.53
$m_{H_3}$	692.22	713.74	658.28	751.72
$m_A$	669.07	743.00	543.62	763.09
$m_{H^\pm}$	679.76	695.73	528.76	733.05
$t_\beta$ (pOS <sup>c</sup> )	6.12	8.39	4.79	3.53
$\alpha_1$ (pOS)	-1.513	-1.526	-1.489	1.318
$\alpha_2$ (pOS)	0.098	-0.308	0.225	0.0362
$\alpha_3$ (pOS)	-0.495	-1.421	-1.001	1.504
$m_{12}^2$	74518.4	60125.0	87240.8	143579.0
$v_s$	305.48	854.50	834.33	219.29
$\Gamma_H$	2.946	2.241	2.990	2.746
BR	0.327	0.329	0.010	0.010

Table 6: Input parameters for the N2HDM benchmark scenarios used in the numerical analysis of the decay processes  $H_{2/3} \rightarrow ZZ$ . In round brackets we specify the scheme in which  $\alpha$  and  $\beta$  are defined. All masses and  $v_s$  are given in GeV. The LO total width (also given in GeV) and individual branching fractions in the last two rows correspond to the Higgs state and decay each benchmark is named after, and have been generated with N2HDECAY.

## Corrections of heavy Higgs to ZZ in different scenarios.

		pOS <sup>c</sup>	pOS <sup>o</sup>	p <sup>c</sup> *	p <sup>o</sup> *
BRH2ZZhigh	$\Gamma^{\text{LO}}(H_2 \rightarrow ZZ)$	0.989	0.989	1.008	1.008
	$\Gamma^{\text{NLO}}(H_2 \rightarrow ZZ)$	1.120	1.122	1.142	1.148
	$\Delta\Gamma^{H_2ZZ}$ [%]	13.2	13.4	13.3	14.0
BRH3ZZhigh	$\Gamma^{\text{LO}}(H_3 \rightarrow ZZ)$	0.755	0.755	0.782	0.782
	$\Gamma^{\text{NLO}}(H_3 \rightarrow ZZ)$	0.872	0.867	0.890	0.889
	$\Delta\Gamma^{H_3ZZ}$ [%]	15.6	14.9	13.9	13.7
BRH2ZZlow	$\Gamma^{\text{LO}}(H_2 \rightarrow ZZ)$	$3.130 \times 10^{-2}$	$3.130 \times 10^{-2}$	$2.529 \times 10^{-2}$	$2.533 \times 10^{-2}$
	$\Gamma^{\text{NLO}}(H_2 \rightarrow ZZ)$	$3.042 \times 10^{-2}$	$3.040 \times 10^{-2}$	$2.840 \times 10^{-2}$	$2.745 \times 10^{-2}$
	$\Delta\Gamma^{H_2ZZ}$ [%]	-2.8	-2.9	12.3	8.4
BRH3ZZlow	$\Gamma^{\text{LO}}(H_3 \rightarrow ZZ)$	$2.870 \times 10^{-2}$	$2.869 \times 10^{-2}$	$3.430 \times 10^{-2}$	$3.418 \times 10^{-2}$
	$\Gamma^{\text{NLO}}(H_3 \rightarrow ZZ)$	$2.990 \times 10^{-2}$	$3.011 \times 10^{-2}$	$3.593 \times 10^{-2}$	$3.738 \times 10^{-2}$
	$\Delta\Gamma^{H_3ZZ}$ [%]	4.2	5.0	4.8	9.3

Table 7: Higgs decay widths (in GeV) at LO and NLO EW accuracy as well as the relative corrections for the N2HDM benchmarks presented in Table 6 and four different renormalization schemes.

What can we do with all this?

a) New scalar is found - include the corrections and go home. They are probably too small anyway to be sure which model it is.

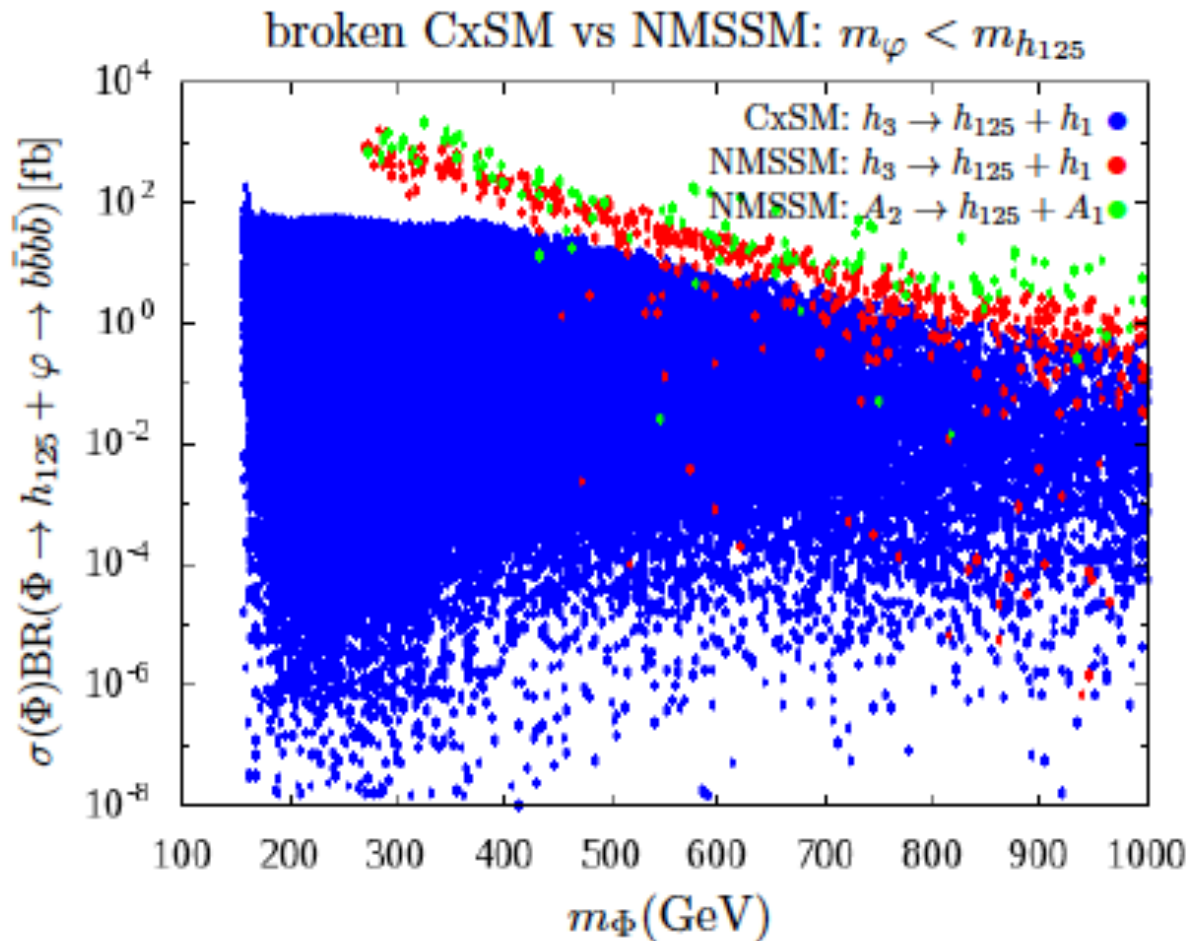
b) Nothing new is found but there is a deviation - check for the thousand parameter combinations that can explain the deviation. Maybe you're lucky!... Not likely...

c) None of the above - do nothing!

### 3. Distinguishing models

### The decay

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

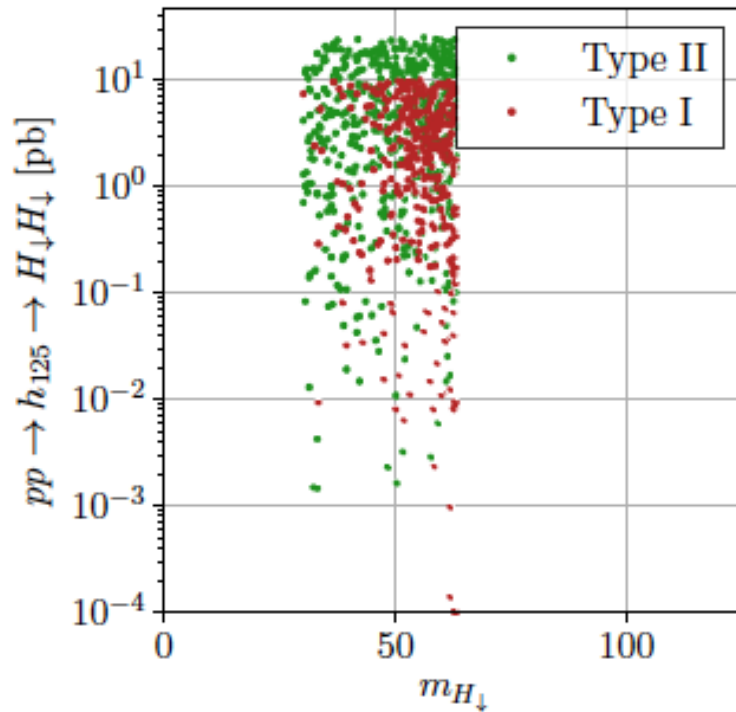


A comparison between the NMSSM and the broken Complex Singlet extension of the SM for final states with two scalars with different masses.

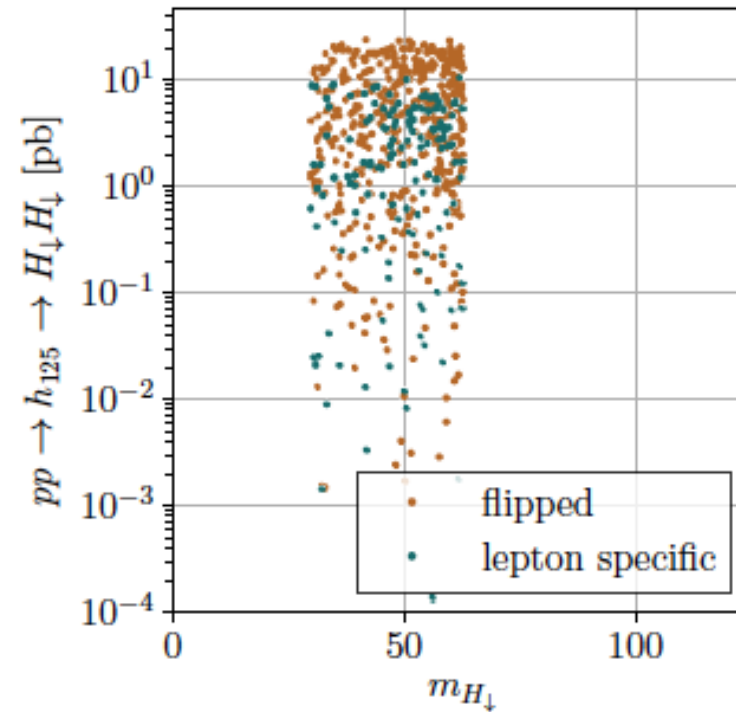
The models can be distinguished in some regions of the parameter space.

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

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



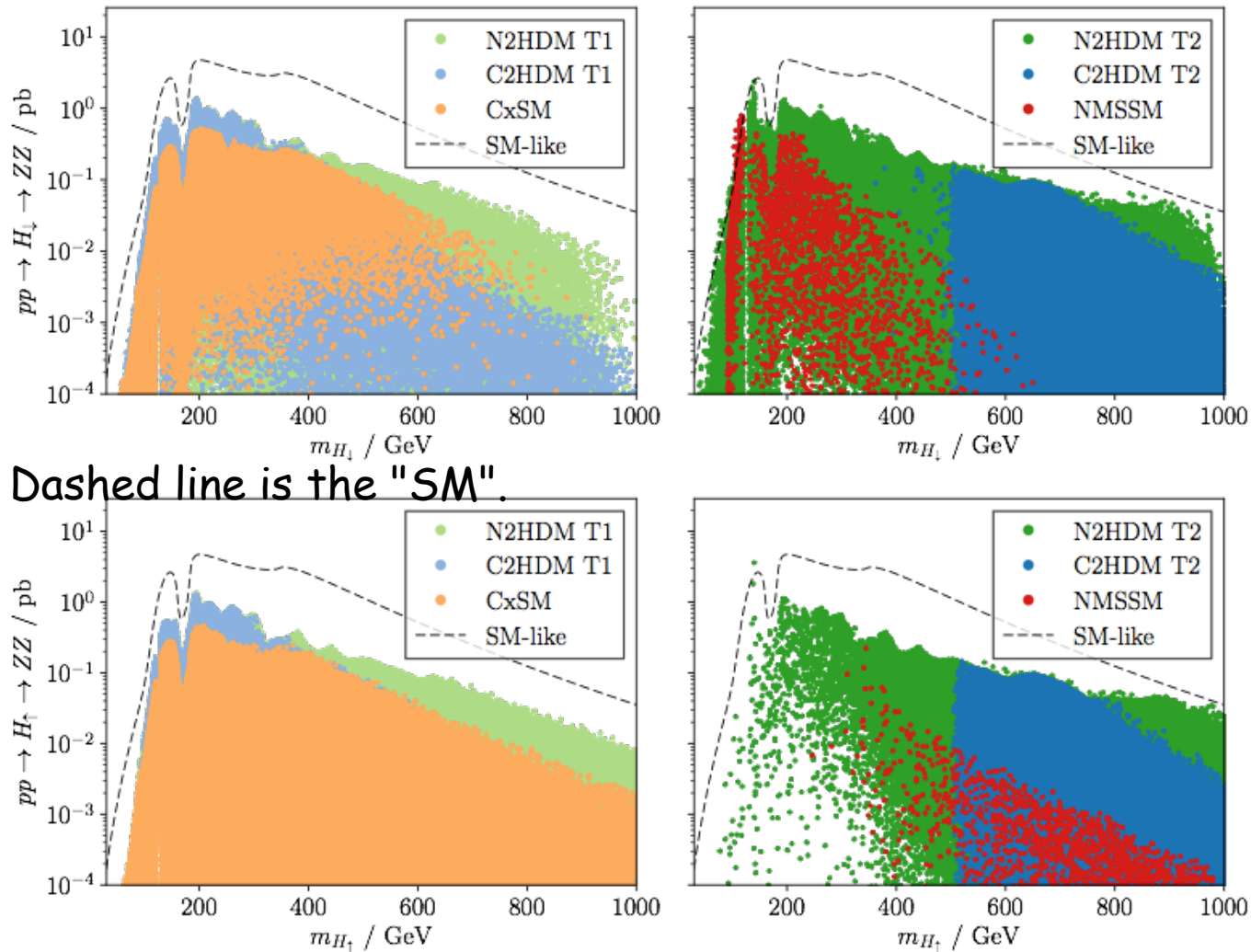
**Left** - Signal rates for the production of  $h_{125}$  decaying to  $H_{\downarrow}H_{\downarrow}$  for 13 TeV as a function of  $m_{H_{\downarrow}}$  for Types I and II



**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 CP-even to ZZ in different models



Signal rates for the production of  $H_{\downarrow}$  (upper) and  $H_{\uparrow}$  (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.

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

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

## 4. The right of a theorist to party



### Vacuum structure

▶ CP CONSERVING

$$\Phi_1 = \begin{pmatrix} 0 \\ v_1 \end{pmatrix}; \Phi_2 = \begin{pmatrix} 0 \\ v_2 \end{pmatrix}$$

▶ CHARGE BREAKING (CB)

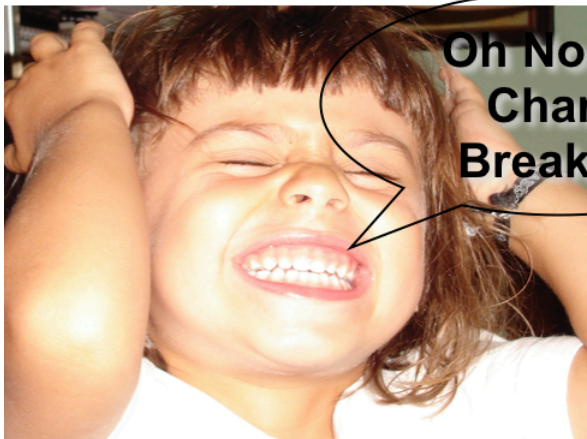
$$\Phi_1 = \begin{pmatrix} 0 \\ v'_1 \end{pmatrix}; \Phi_2 = \begin{pmatrix} \alpha \\ v'_2 \end{pmatrix}$$

▶ CP BREAKING (CP)

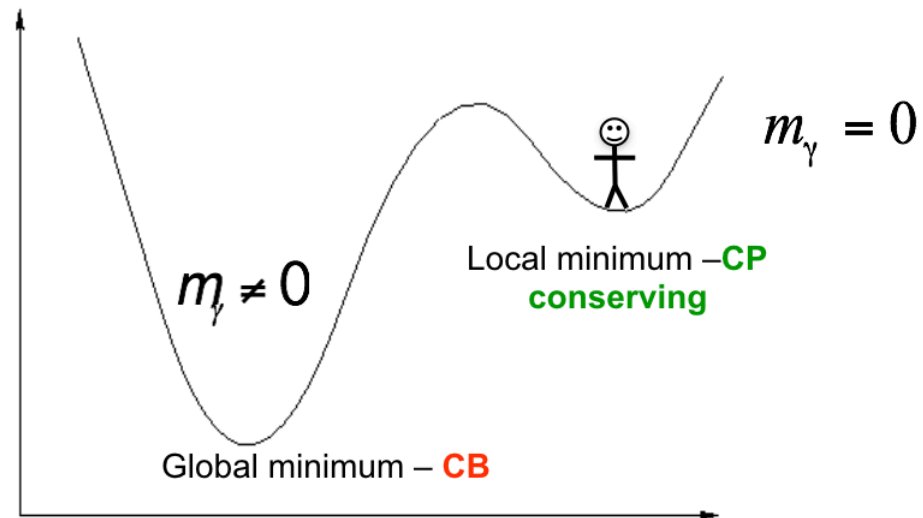
$$\Phi_1 = \begin{pmatrix} 0 \\ v'_1 + i\delta \end{pmatrix}; \Phi_2 = \begin{pmatrix} 0 \\ v'_2 \end{pmatrix}$$

Can the potential have a N and a CB minimum simultaneously?

CB is possible in 2HDMs!  
Suppose we live in a 2HDM,  
are we in DANGER?



Oh No! Not Charge Breaking!





# Vacuum structure of 2HDMs

The tree-level global picture for spontaneously broken symmetries (2HDM)

1. 2HDM have at most two minima
2. Minima of different nature never coexist
3. Unlike Normal, CB and CP minima are uniquely determined
4. If a 2HDM has only one normal minimum then this is the absolute minimum - all other SP if they exist are saddle points
5. If a 2HDM has a CP breaking minimum then this is the absolute minimum - all other SP if they exist are saddle points

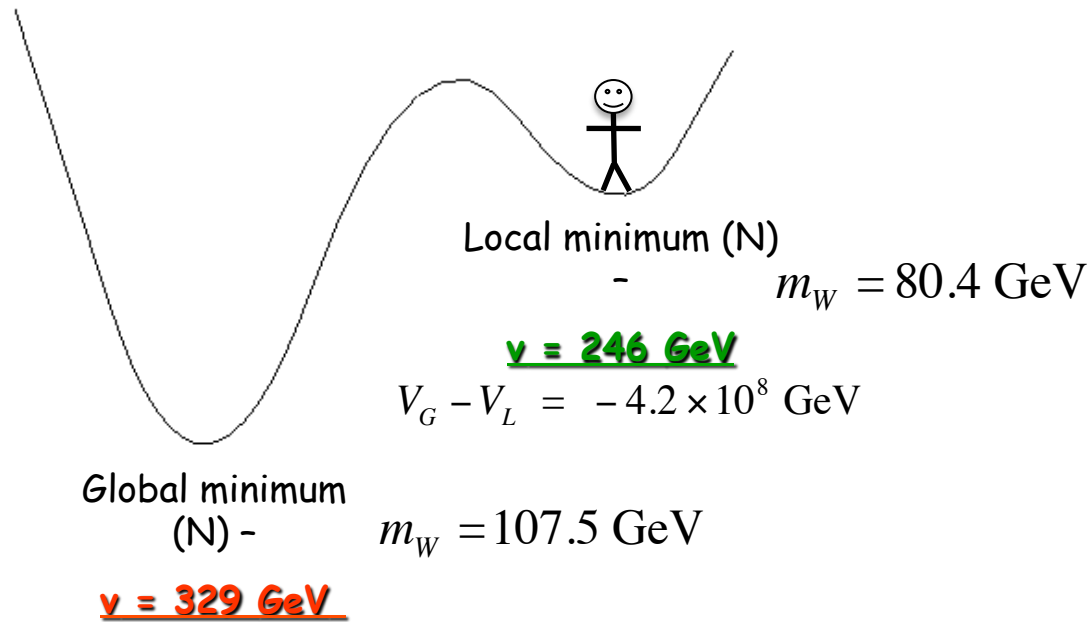
The tree-level global picture for explicit CP

6. An explicitly CP-violating 2HDM potential can have two non-degenerate minima

BARROSO, FERREIRA, RS  
IVANOV, MANIATIS, VON  
MANTEUFFEL, NACHTMANN,  
NAGEL (2004...)

**No longer true for the N2HDM – charge breaking minimum can be deeper than a CP conserving minimum.**

## Two normal minima - potential with the soft breaking term



**THE PANIC VACUUM!**  
 and this is one that can actually occur...

However, two CP-conserving minima can coexist - we can force the potential to be in the global one by using a simple condition.

$$D = m_{12}^2 \left( m_{11}^2 - k^2 m_{22}^2 \right) (\tan \beta - k) \quad k = \left( \frac{\lambda_1}{\lambda_2} \right)^{1/4}$$

$$D = \frac{1}{8v^8 s_\beta^4 c_\beta^2} (-a_1 \mu^2 + b_1) (a_2 \mu^2 - 2b_2)$$

*Our vacuum is the global minimum of the potential if and only if  $D > 0$ .*

$$\begin{aligned} a_1 &= s_\beta^2 [m_{12}^2 s_\beta^2 + (m_{21}^2 s_\beta^2 + m_{13}^2 c_\beta^2)] , \\ b_1 &= c_\beta^2 [c_{12} s_2 (-m_{11}^2 + m_{21}^2 s_\beta^2 + m_{13}^2 c_\beta^2) + s_{12} s_3 c_3 (m_{21}^2 - m_{13}^2)]^2 , \\ a_2 &= 2m_{12}^2 c_{12}^2 c_{13}^2 + (m_{21}^2 + m_{13}^2) (1 - c_{12}^2 c_{13}^2) \\ &\quad + (m_{21}^2 - m_{13}^2) [\cos(2\alpha_3) (c_{11}^2 + s_\beta^2 - c_{11}^2 c_{13}^2) + \sin(2\alpha_3) s_2 \sin(2\alpha_1 + 2\beta)] , \\ b_2 &= (m_{21}^2 s_\beta^2 + m_{13}^2 c_\beta^2) m_{12}^2 c_\beta^2 + m_{21}^2 m_{13}^2 s_\beta^2 . \end{aligned}$$

**BARROSO, FERREIRA, IVANOV, RS (2013)**

**IVANOV, SILVA (2015)**

# Workshop on Multi-Higgs Models

4-7 September 2018

Lisbon - Portugal

This Workshop brings together those interested in the theory and phenomenology of Multi-Higgs models. The program is designed to include talks given by some of the leading experts in the field, and also ample time for discussions and collaboration between researchers. A particular emphasis will be placed on identifying those features of the models which are testable at the LHC.

For registration and/or to propose a talk, send an email to:

[2hdmwork@cftp.tecnico.ulisboa.pt](mailto:2hdmwork@cftp.tecnico.ulisboa.pt)

Web Page : <http://cftp.tecnico.ulisboa.pt/~2hdmwork/>

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5<sup>th</sup> Edition of a  
classical workshop  
in a great city!

The end

**Extra slides**

**Tools available for scans and  
decay rates**

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- [Downloads](#)
- [Contact](#)

# 2HDMC

2HDMC is a general-purpose calculator for the two-Higgs doublet model. It allows parametrization of the Higgs potential in many different ways, convenient specification of generic Yukawa sectors, the evaluation of decay widths (including higher-order QCD corrections), theoretical constraints and much more.

## 2HDMC material

- [Latest version](#)
- [Physics and Manual](#)

2HDMC - Two-Higgs-Doublet Model Calculator  
D. Eriksson, J. Rathsman, O. Stål  
Comput.Phys.Commun.181:189-205 (2010);  
Comput.Phys.Commun.181:833-834 (2010)  
[\[arXiv:0902.0851\]](#)

Recommendations for evaluation of Higgs production cross sections and branching ratios at the LHC in the 2HDM  
R. Harlander, M. Mühlleitner, J. Rathsman, M. Spira, O. Stål  
[\[arXiv:1312.5571\]](#)

## Release history

1.7.0	2015-08-28	Included new interface for <a href="#">HiggsBounds</a> and <a href="#">HiggsSignals</a> . Included support for input in hybrid basis as defined in <a href="#">[1507.04281]</a> . Improved treatment of off-shell H <sup>±</sup> decays. Thanks to R. Hansen Addition of FCNC top decays. Thanks to L. Zethraeus Clean-up of obsolete features.
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<https://2hdmc.hepforge.org/>

# GMCALC

## A calculator for the Georgi-Machacek model

### Description:

The Georgi-Machacek model adds scalar triplets to the Standard Model Higgs sector in such a way as to preserve custodial SU(2) symmetry in the scalar potential. This allows the triplets to have a non-negligible vacuum expectation value while satisfying constraints from the rho parameter. Depending on the parameters, the 125 GeV neutral Higgs particle can have couplings to WW and ZZ larger than in the Standard Model due to mixing with the triplets. The model also contains singly- and doubly-charged Higgs particles that couple to vector boson pairs at tree level (WZ and like-sign WW, respectively).

GMCALC is a FORTRAN program that, given a set of input parameters, calculates the particle spectrum and tree-level couplings, checks theoretical and indirect constraints on the model, and computes the branching ratios and total widths of the scalars. It also generates a param\_card.dat file for MadGraph5 (both LO and NLO versions) to be used with the corresponding [FeynRules model implementation](#).

The full functionality of GMCALC v1.3.0 and higher requires an installation of the [LoopTools package](#). There is an option to compile GMCALC v1.3.0 and higher without LoopTools, but if this is done then the loop-induced decays of  $H_{5^0}$  to Z gamma and  $H_{3^+}$ ,  $H_{5^+}$  to  $W^+$  gamma will not be computed.

---

### Authors:

- Celine Degrande, Katy Hartling, Kunal Kumar, Heather E. Logan, and Andrea D. Peterson (v1.3.x)
- Katy Hartling, Kunal Kumar, Heather E. Logan, and Andrea D. Peterson (v1.2.x)
- Katy Hartling, Kunal Kumar, and Heather E. Logan (v1.0.x, 1.1.x)

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### Downloads:

- [GMCALC v1.3.0](#) (.tar.gz, includes manual and changes log)
- [Manual](#) (pdf)
- Log of [changes](#) (txt)

<http://people.physics.carleton.ca/~logan/gmcalc/>

---

### If you use this program to write a paper, please cite:

- K. Hartling, K. Kunal, and H. E. Logan, "GMCALC: a calculator for the Georgi-Machacek model," [arXiv:1412.7387 \[hep-ph\]](#) [[InSPIRE record](#)].

---

### The physics that went into this code is described in more detail in the following references:

- K. Hartling, K. Kunal, and H. E. Logan, "The decoupling limit in the Georgi-Machacek model," [Phys. Rev. D 90, 015007 \(2014\)](#) [[arXiv:1404.2640 \[hep-ph\]](#)] [[InSPIRE record](#)].
- K. Hartling, K. Kunal, and H. E. Logan, "Indirect constraints on the Georgi-Machacek model and implications for Higgs couplings," [Phys. Rev. D 91, 015013 \(2015\)](#) [[arXiv:1410.5538 \[hep-ph\]](#)] [[InSPIRE record](#)].
- C. Degrande, K. Hartling, and H. E. Logan, "Scalar decays to gamma gamma, Z gamma, and W gamma in the Georgi-Machacek model," [arXiv:1708.08753 \[hep-ph\]](#) [[InSPIRE record](#)].

---

### Requests and bug reports:

Contact Heather Logan at [logan@physics.carleton.ca](mailto:logan@physics.carleton.ca).

# Scanners

## Scanners allows general scalar potential with automatic:

- Analysis of tree level **local minimum/stability**
- **Detection** of tree level **scalar spectrum and mixing**
- **Tree level unitarity** test

## Interfaces to:

- HDECAY, sHDECAY, N2HDECAY, C2HDECAY
- HIGGSBOUNDS/SIGNALS (**collider** bounds/measurements)
- MICROMEGAS (**dark matter** observables)
- SUSHi (+ internal numerical tables for **gluon fusion**)
- SUPERISO (**flavour physics** observables)

## User/model defined functions to:

- Check **boundedness from below**
- Check **global stability**
- Implement **phenomenological analysis** for each point

## BSMPT - Beyond the Standard Model Phase Transitions – A Tool for the Electroweak Phase Transition in Extended Higgs Sectors

BASLER, MUHLLEITNER; 1803.02846

## ■ Real and Complex Scalar Singlet Extensions:

R. Costa, M. Mühlleitner, M.O.P. Sampaio, R. Santos, JHEP 1606 (2016) 034 + see YR4  
R. Coimbra, M.O.P. Sampaio, R. Santos, EPJ C73 (2013) 2428  
R. Costa, A. Morais, M.O.P. Sampaio, R. Santos, Phys.Rev. D92 (2015) 2, 025024

- **RxSM-dark**: 1 Higgs + 1 Dark ( $\mathbb{Z}_2$ )
- **RxSM-broken**: 2 Higgs mixing ( $\mathbb{Z}_2$  spont.broken)
- **CxSM-dark**: 2 Higgs mixing + 1 Dark
- **CxSM-broken**: 3 Higgs mixing

**New:** Input files allow *Scan* or *Check* point mode.  
see → *How to run scalar singlet extensions in Scanners*  
([indico.cern.ch/event/640710](http://indico.cern.ch/event/640710))

## ■ Scalar Doublet Extensions

- **2HDM**: *Scan* or *Check* point modes available.  
P.M. Ferreira, R. Guedes, M.O.P. Sampaio, R. Santos, JHEP 12 (2014) 067
- **N2HDM-broken**: 2HDM + Real singlet  $\mathbb{Z}_2$  spont. broken.  
*Scan* mode (*Check* mode available soon ...)  
M.M. Mühlleitner M.O.P. Sampaio, R. Santos, J. Wittbrodt, JHEP 1703 (2017) 094
- **N2HDM-dark**: 2HDM + Real singlet  $\mathbb{Z}_2$  (under dev.)
- **C2HDM**: To be publicly released soon.  
M.M. Mühlleitner M.O.P. Sampaio, R. Santos, J. Wittbrodt, arXiv:1703.07750

<https://scanners.hepforge.org/>

Determines the global minimum of BSM Higgs models at NLO and to extract the NLO triple Higgs couplings.



- **General:** Based on implementation in HDECAY

[Douadi,Spira,Kalinowski+Muhlleitner(2010), Comput.Phys.Commun. 108 (1998) 56]

- **Features:** Stand-alone codes; inclusion of relevant QCD corrections and off-shell decays, EW corrections consistently neglected **(includes 2HDM)**

- **sHDECAY**

<http://www.itp.kit.edu/~maggie/sHDECAY/>

[R.Costa,M.Muhlleitner,M.O.P.Sampaio,R.Santos, JHEP 06 (106) 034]

- ★ Real-extended SM in symmetric (dark) phase, RxSM-dark: 1 Higgs + 1 Dark ( $\mathbb{Z}_2$ )
- ★ Real-extended SM in broken phase, RxSM-broken: 2 mixing Higgs bosons ( $\mathbb{Z}_2$  spont. broken)
- ★ Complex-extended SM in symmetric (dark) phase, CxSM-dark: 2 mixing Higgs + 1 Dark
- ★ Complex-extended SM in broken phase, CxSM-broken: 3 mixing Higgs bosons

- **N2HDECAY for N2HDM**

<http://www.itp.kit.edu/~maggie/N2HDECAY/>

[M.Muhlleitner,M.O.P.Sampaio,R.Santos,J.Wittbrodt, JHEP 1703 (2017) 094]

- ★ 2DHM + real singlet  $\mathbb{Z}_2$  spont. broken: 3 scalars  $H_{1,2,3}$ , 1 pseudocalar  $A$ , charged pair  $H^\pm$
- ★ 2HDM + real singlet  $\mathbb{Z}_2$ : in preparation

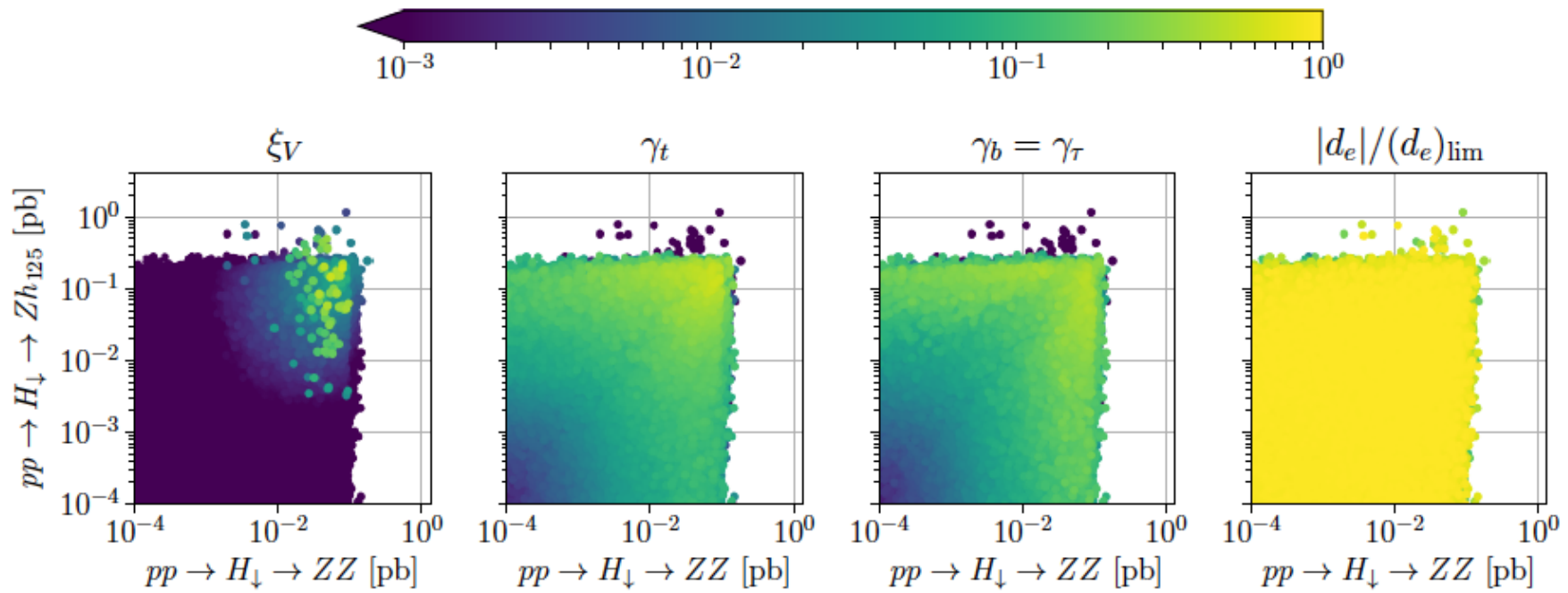
- **C2HDECAY**

- ★ CP-violating 2DHM: 3 CP-mixing scalars  $H_{1,2,3}$ , charged Higgs pair  $H^\pm$

<https://www.itp.kit.edu/~maggie/C2HDM/>

[M. Mühlleitner, J.C. Romão, R. Santos, J.P. Silva, J. Wittbrodt, JHEP 1802 (2018) 073]

Results for Type II (where some correlation seems to exist)



But in most cases there is no correlation.

We define the following admixtures

$$\sum_i^{\text{CxSM}} = (R_{i2})^2 + (R_{i3})^2, \quad \text{CxSM - SUM OF REAL AND COMPLEX COMPLEX SINGLET COMPONENTS}$$

$$\Psi_i^{\text{C2HDM}} = (R_{i3})^2 \quad \text{C2HDM - "PSEUDOSCALAR" COMPONENT}$$

$$\sum_i^{\text{N2HDM}} = (R_{i3})^2 \quad \text{N2HDM AND NMSSM - SINGLET COMPONENT}$$

In the *CxSM* all couplings to the *SM* particles are rescaled by one common factor. The maximum allowed singlet admixture in the *CxSM* is given by the lower bound on the global signal strength  $\mu$  and amounts to

$$\sum_{\text{max}}^{\text{CxSM}} \approx 1 - \mu_{\text{min}} \approx 11\%$$

## The CxSM

SM plus  $S = (S + iA)/\sqrt{2}$ ,

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

soft breaking terms

Model	Phase	VEVs at global minimum
U(1)	Higgs+2 degenerate dark	$\langle S \rangle = 0$
	2 mixed + 1 Goldstone	$\langle A \rangle = 0$ (U(1) $\rightarrow$ Z' <sub>2</sub> )
Z <sub>2</sub> × Z' <sub>2</sub>	Higgs + 2 dark	$\langle S \rangle = 0$
	2 mixed + 1 dark	$\langle A \rangle = 0$ (Z <sub>2</sub> × Z' <sub>2</sub> $\rightarrow$ Z' <sub>2</sub> )
Z' <sub>2</sub>	2 mixed + 1 dark	$\langle A \rangle = 0$
	3 mixed	$\langle S \rangle \neq 0$ (Z' <sub>2</sub> )

$$S \rightarrow S^* \Rightarrow A \rightarrow -A$$

## The CxSM

SM plus  $\mathbb{S} = (S + iA)/\sqrt{2}$ , with residual  $\mathbb{Z}_2$  symmetry  $A \rightarrow -A$

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

$$\begin{pmatrix} h_1 \\ h_2 \\ h_{DM} \end{pmatrix} = \begin{pmatrix} \cos \alpha & -\sin \alpha & 0 \\ \sin \alpha & \cos \alpha & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} h \\ s \\ A \end{pmatrix}$$

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

$$\begin{pmatrix} h_1 \\ h_2 \\ h_3 \end{pmatrix} = \begin{pmatrix} R_{1h} & R_{1S} & R_{1A} \\ R_{2h} & R_{2S} & R_{2A} \\ R_{3h} & R_{3S} & R_{3A} \end{pmatrix} \begin{pmatrix} h \\ s \\ a \end{pmatrix}$$

## Parameters

→  $\tan \beta = \frac{v_2}{v_1}$  ratio of vacuum expectation values

→ 2 charged,  $H^\pm$ , and 3 neutral

CP-conserving -  $h$ ,  $H$  and  $A$

CP-violating -  $h_1$ ,  $h_2$  and  $h_3$

→ rotation angles in the neutral sector

CP-conserving -  $\alpha$

CP-violating -  $\alpha_1$ ,  $\alpha_2$  and  $\alpha_3$

→ soft breaking parameter

CP-conserving -  $m_{12}^2$

CP-violating -  $\text{Re}(m_{12}^2)$

## The N2HDM

$$\Phi_1 \rightarrow \Phi_1, \quad \Phi_2 \rightarrow -\Phi_2, \quad \Phi_S \rightarrow \Phi_S \quad \text{Explicitly broken}$$

$$\Phi_1 \rightarrow \Phi_1, \quad \Phi_2 \rightarrow \Phi_2, \quad \Phi_S \rightarrow -\Phi_S \quad \text{Spontaneously broken}$$

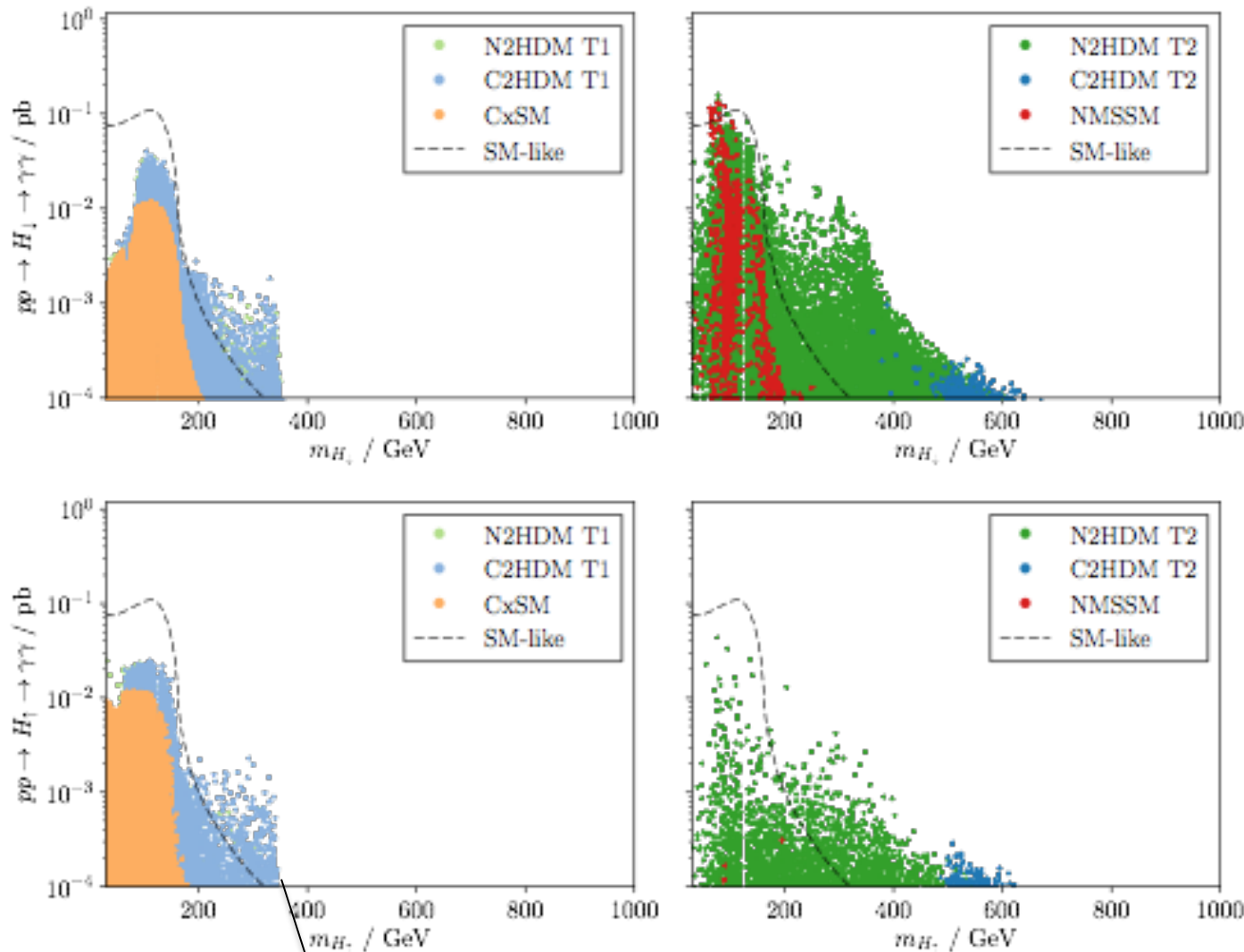
$$\begin{aligned} V = & m_{11}^2 |\Phi_1|^2 + m_{22}^2 |\Phi_2|^2 - m_{12}^2 (\Phi_1^\dagger \Phi_2 + h.c.) + \frac{\lambda_1}{2} (\Phi_1^\dagger \Phi_1)^2 + \frac{\lambda_2}{2} (\Phi_2^\dagger \Phi_2)^2 \\ & + \lambda_3 (\Phi_1^\dagger \Phi_1) (\Phi_2^\dagger \Phi_2) + \lambda_4 (\Phi_1^\dagger \Phi_2) (\Phi_2^\dagger \Phi_1) + \frac{\lambda_5}{2} [(\Phi_1^\dagger \Phi_2)^2 + h.c.] \\ & + \frac{1}{2} u_S^2 \Phi_S^2 + \frac{\lambda_6}{8} \Phi_S^4 + \frac{\lambda_7}{2} (\Phi_1^\dagger \Phi_1) \Phi_S^2 + \frac{\lambda_8}{2} (\Phi_2^\dagger \Phi_2) \Phi_S^2. \end{aligned}$$

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

$$\tan \beta = \frac{v_2}{v_1}$$

$$R = \begin{pmatrix} c_{\alpha_1} c_{\alpha_2} & s_{\alpha_1} c_{\alpha_2} & s_{\alpha_2} \\ -(c_{\alpha_1} s_{\alpha_2} s_{\alpha_3} + s_{\alpha_1} c_{\alpha_3}) & c_{\alpha_1} c_{\alpha_3} - s_{\alpha_1} s_{\alpha_2} s_{\alpha_3} & c_{\alpha_2} s_{\alpha_3} \\ -c_{\alpha_1} s_{\alpha_2} c_{\alpha_3} + s_{\alpha_1} s_{\alpha_3} & -(c_{\alpha_1} s_{\alpha_3} + s_{\alpha_1} s_{\alpha_2} c_{\alpha_3}) & c_{\alpha_2} c_{\alpha_3} \end{pmatrix} \begin{pmatrix} H_1 \\ H_2 \\ H_3 \end{pmatrix} = R \begin{pmatrix} \rho_1 \\ \rho_2 \\ \rho_S \end{pmatrix}$$

# Non-125 to $\gamma\gamma$



Signal rates for the production of  $H_{\downarrow}$  (upper) and  $H_{\uparrow}$  (lower) for 13 TeV as a function of  $m_{H_1}$ . Dashed line is the "SM".

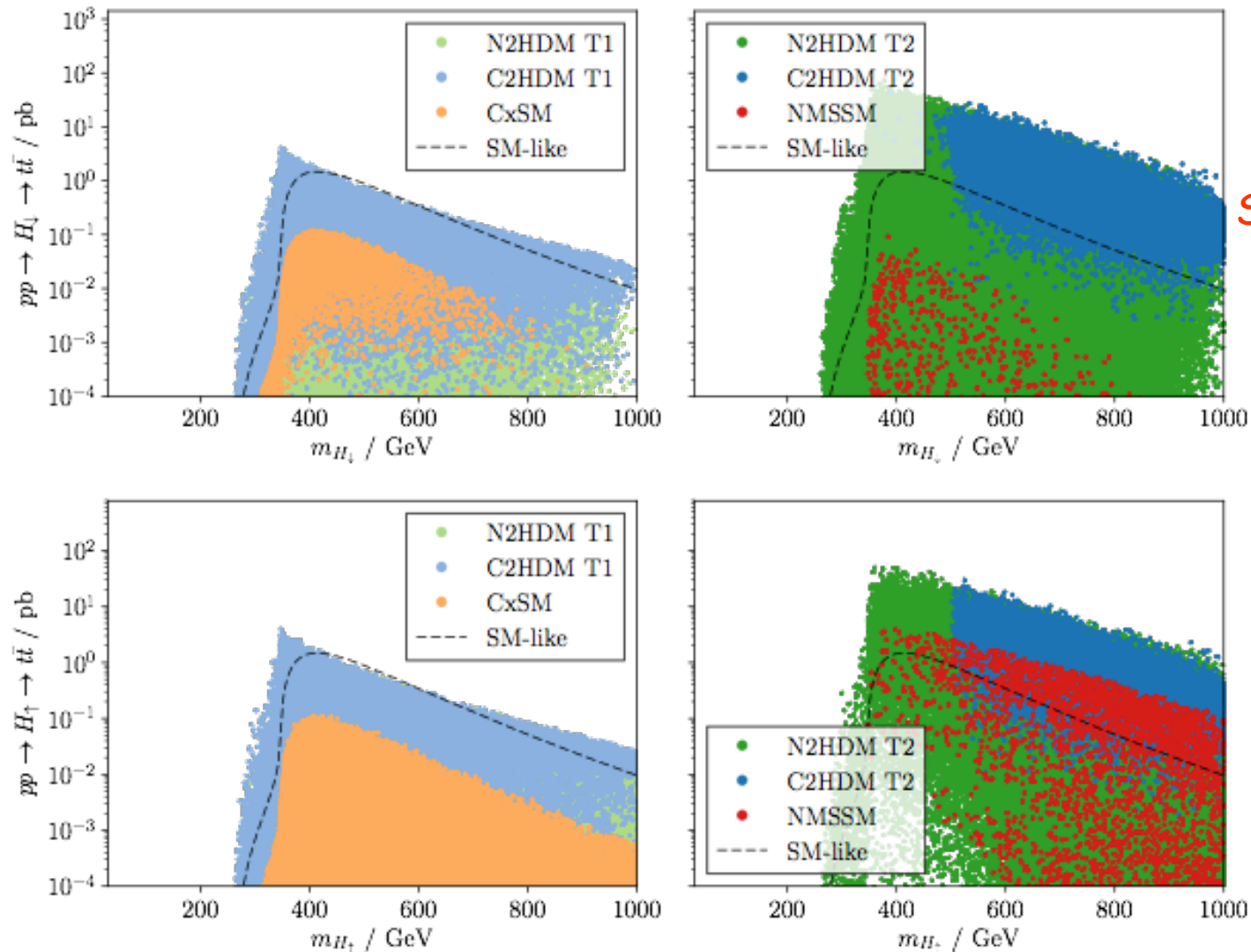
MUHLLEITNER, SAMPAIO, RS, WITTBRODT, JHEP 1708 (2017) 132

h to  $t\bar{t}$  threshold

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

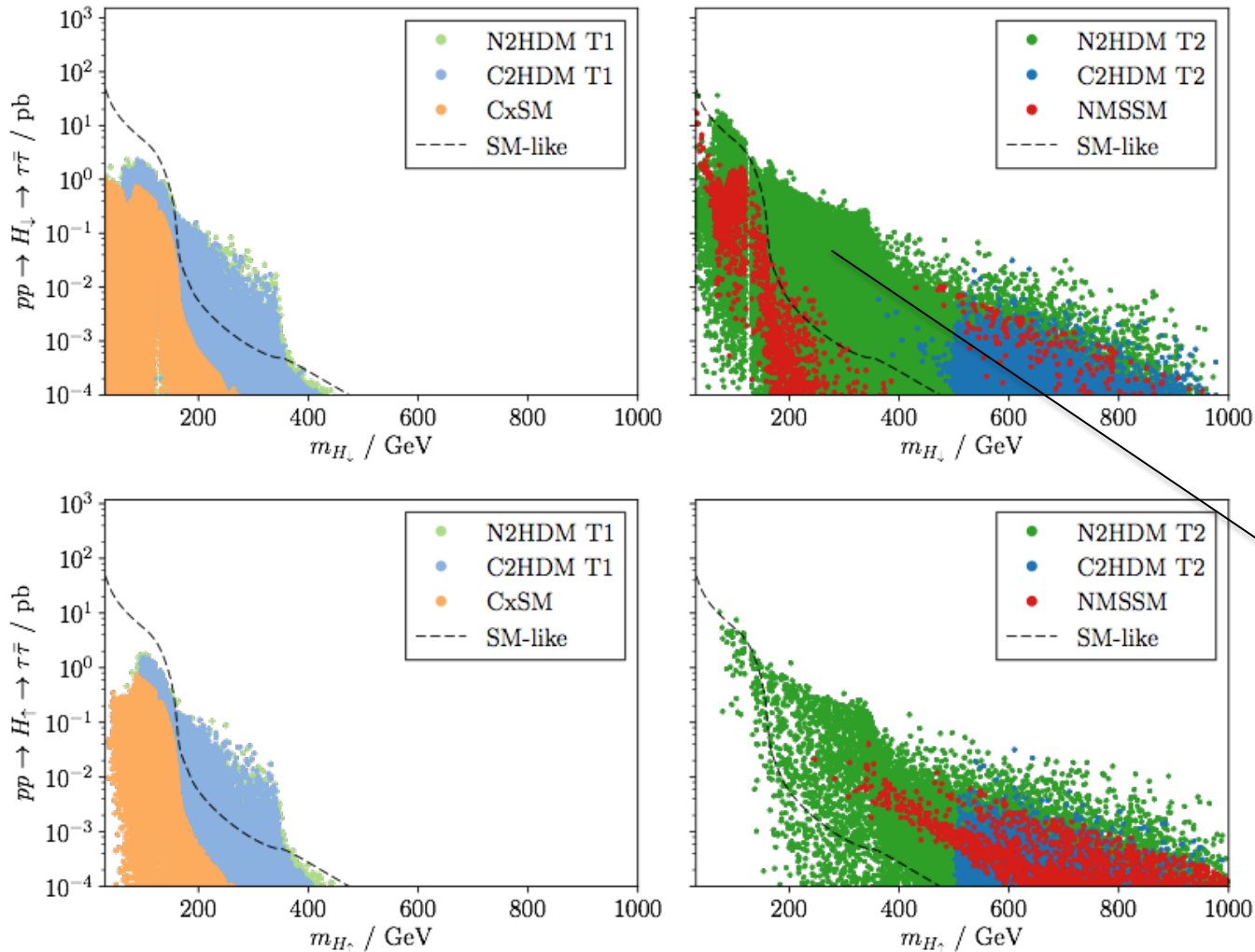


## Non-125 to $t\bar{t}$



Signal rates for the production of  $H_1$  (upper) and  $H_2$  (lower) for 13 TeV as a function of  $m_{H_i}$ . Dashed line is the "SM".

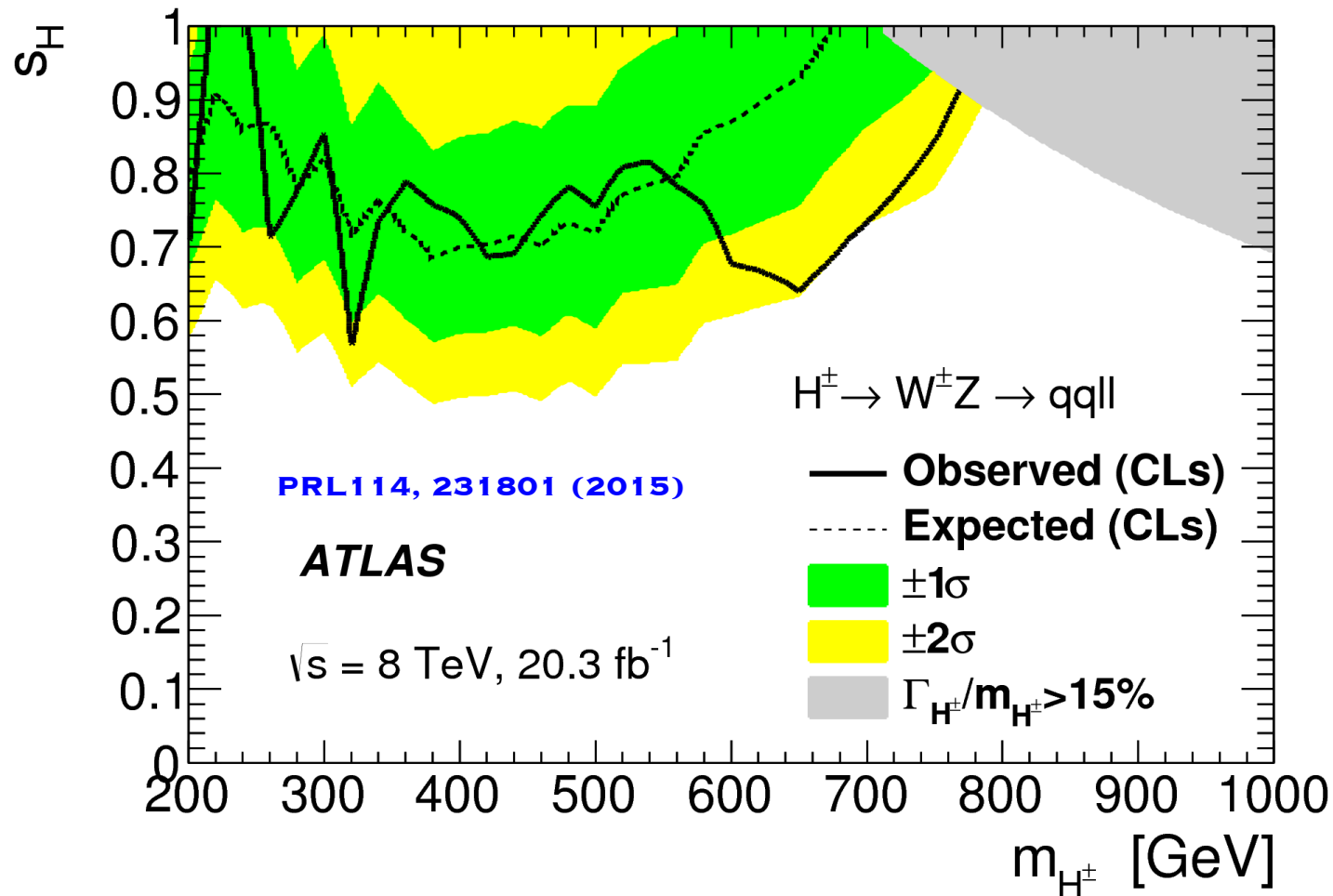
# Non-125 to $\tau\tau$



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".

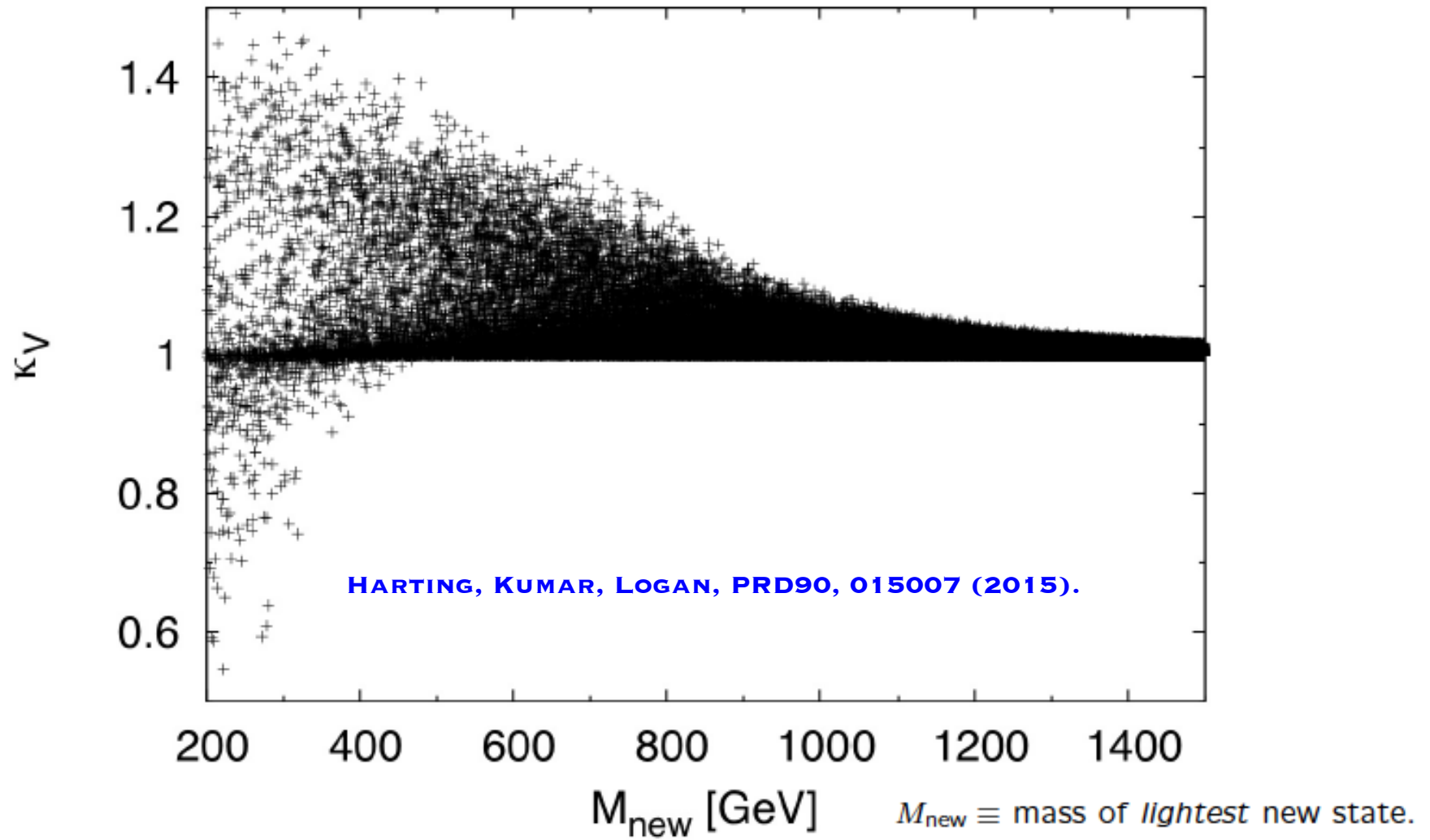
Region where only the N2hDM II survives.

# The GM Model



Exclusion limits at the 95% CL for  $s_H$  versus  $m_{H^\pm}$  in the Georgi-Machacek Higgs Triplet Model. Also included on the plot are the median,  $\pm 1\sigma$  and  $\pm 2\sigma$  values within which the limit is expected to lie in the absence of a signal.

Numerical results:  $hVV$  coupling enhancement can be quite large!



## Georgi-Machacek model (custodial-symmetric triplet scalars)

Georgi & Machacek 1985; Chanowitz & Golden 1985

- Two custodial singlets  $\rightarrow h^0, H^0$   $m_h, m_H$   $\leftarrow$  very similar
- Custodial triplet  $\rightarrow (H_3^+, H_3^0, H_3^-)$   $m_3$   $\leftarrow$  to 2HDM
- Custodial fiveplet  $(H_5^{++}, H_5^+, H_5^0, H_5^-, H_5^{--})$   $m_5$   $\leftarrow$  new!

$\rightarrow$  Focus on direct searches for  $H_5$  states

In YR4: [H. Logan and M. Zaro]

- H5plane benchmark for direct  $H_5$  searches (200–3000 GeV)
- Tables of VBF  $\rightarrow H_5$  cross sections (NNLO QCD, LO EW, onshell  $H_5$ ) and  $H_5$  decay widths (LO doubly offshell)

Details are in talk by Rui Santos at January 2016 meeting

## And for the GM model

Consider the  $hWW$  coupling:

- SM:  $i\frac{g^2v}{2}g_{\mu\nu}$  ( $v \simeq 246$  GeV)

- 2HDM:  $i\frac{g^2v}{2}g_{\mu\nu} \sin(\beta - \alpha)$

Extended Higgs sectors with isospin doublets or singlets always have hVV couplings **less than or equal** to those in the SM.

- SM + some multiplet  $X$ :  $i\frac{g^2v_X}{2}g_{\mu\nu} \cdot 2 \left[ T(T + 1) - \frac{Y^2}{4} \right]$  ( $Q = T^3 + Y/2$ )

The only way to enhance the hWW (hZZ) coupling above its SM value is through a scalar with isospin  $\geq 1$  that has a non-negative vev and mixes into the observed Higgs h (triplets benchmark).

## Georgi-Machacek model (custodial-symmetric triplet scalars)

Georgi & Machacek 1985; Chanowitz & Golden 1985

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Details are in talk by Rui Santos at January 2016 meeting

## Models with triplets: focus on Georgi-Machacek model ( $\rho = 1$ )

Georgi & Machacek 1985; Chanowitz & Golden 1985

SM Higgs (bi-)doublet + two isospin-triplets in a **bi-triplet**:

$$\Phi = \begin{pmatrix} \phi^{0*} & \phi^+ \\ -\phi^{+*} & \phi^0 \end{pmatrix} \quad X = \begin{pmatrix} \chi^{0*} & \xi^+ & \chi^{++} \\ -\chi^{+*} & \xi^0 & \chi^+ \\ \chi^{++*} & -\xi^{+*} & \chi^0 \end{pmatrix}$$

under a global  $SU(2)_L \times SU(2)_R$

### Physical spectrum:

- Two custodial singlets  $\rightarrow h^0, H^0$   $m_h, m_H$   $\leftarrow$  very similar
- Custodial triplet  $\rightarrow (H_3^+, H_3^0, H_3^-)$   $m_3$   $\leftarrow$  to 2HDM
- Custodial fiveplet  $(H_5^{++}, H_5^+, H_5^0, H_5^-, H_5^{--})$   $m_5$   $\leftarrow$  new!

$\rightarrow$  Focus on direct searches for fermiophobic  $H_5$  states



Focus for YR4:

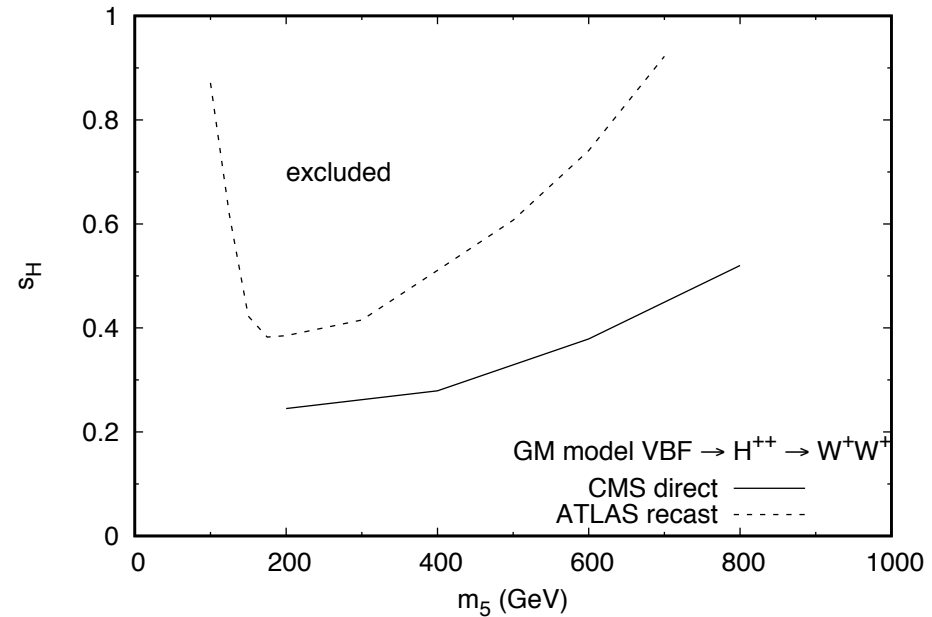
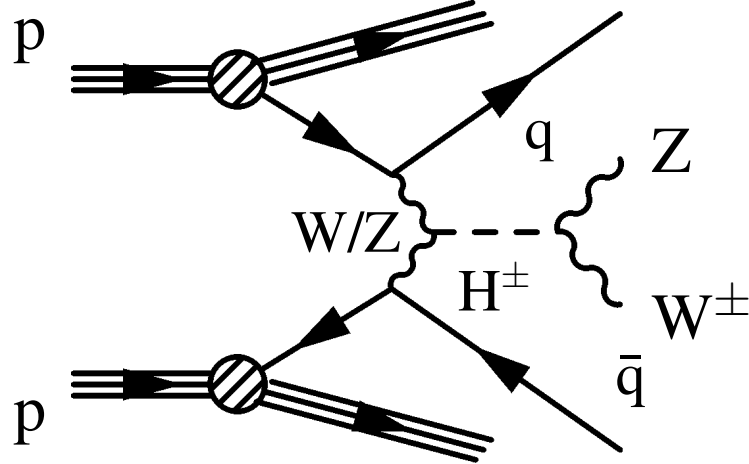
$$\text{VBF} \rightarrow H_5^{\pm\pm} \rightarrow W^\pm W^\pm$$

VBF + like-sign dileptons + MET

$$\text{VBF} \rightarrow H_5^\pm \rightarrow W^\pm Z$$

VBF +  $qqll$ ; VBF +  $3l$  + MET

$m_5 \geq 200$  GeV (for on-shell  $W/Z$  pairs)



VBF cross sections  $\propto s_H^2 = 8v_\chi^2/v_{\text{SM}}^2 \equiv$  fraction of  $M_W^2, M_Z^2$  due to exotic scalars

## New activities:

### 1) Low mass $m_5 < 200$ GeV

( $m_5 \gtrsim 75$  GeV from recasting ATLAS like-sign dimuons search)

→ go below threshold for decays to  $W/Z$  pairs:

Significant BRs for loop-induced decays  $H_5^0 \rightarrow \gamma\gamma$ ,  $H_5^\pm \rightarrow W^\pm\gamma$

(remember  $H_5$  is fermiophobic)

To do: release UFO model with EFT couplings for loop decays;  
develop priority list of interesting modes

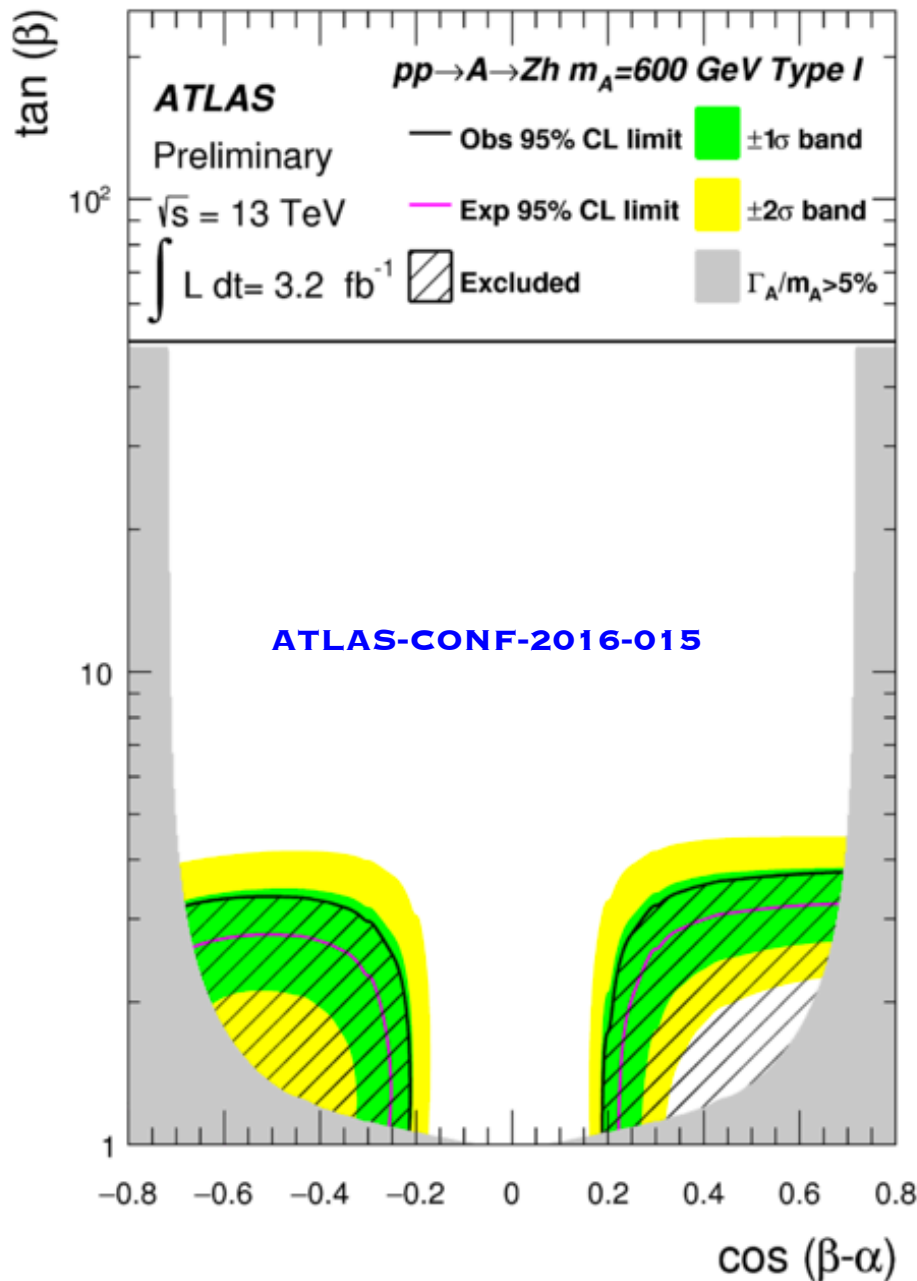
### 2) Drell-Yan production $pp \rightarrow H_5^i H_5^j$

→ large cross sections at low mass

→ only production mode that's not suppressed in alignment limit

(may also be interesting for  $m_5 > 200$  GeV, depending on decay modes)

To do: provide Drell-Yan production cross sections



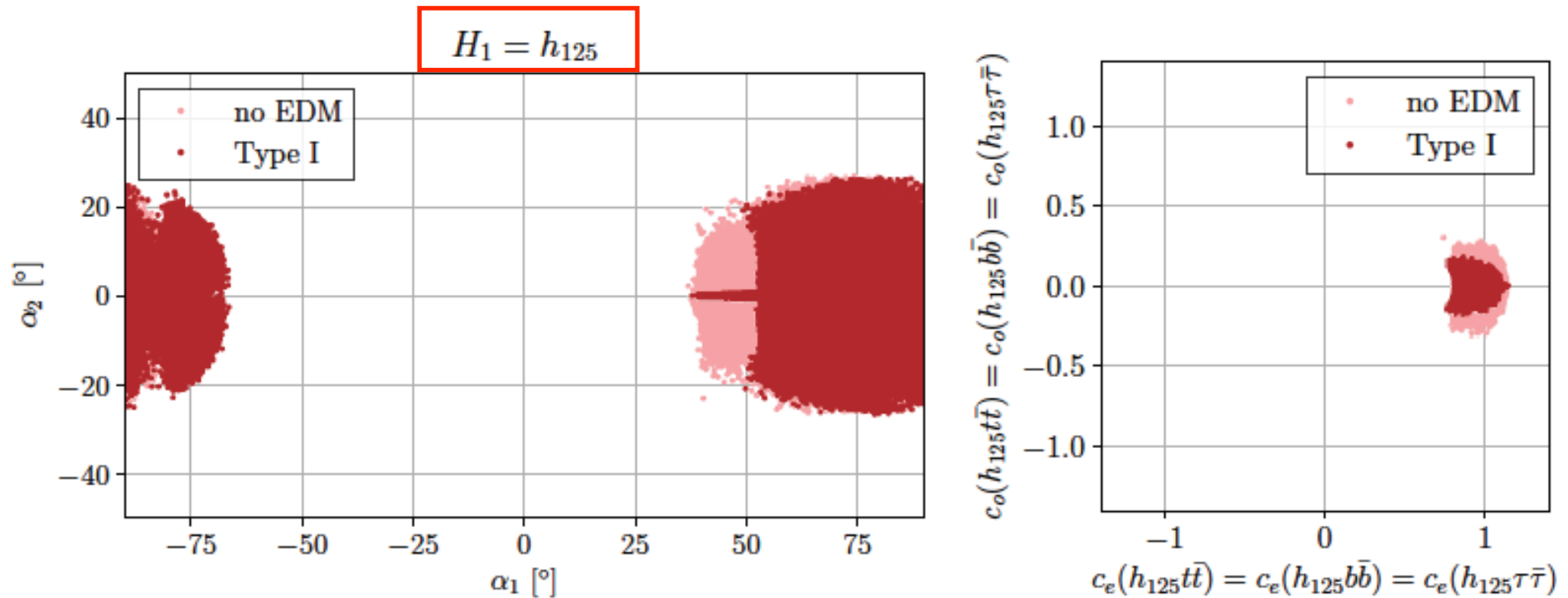
## 2. non- $H_{125}$ searches

### - The 2HDM

(CP-conserving and no tree-level FCNC)

The interpretation of the cross section limits in the context of a Type-I 2HDM as a function of the parameters  $\tan\beta$  and  $\cos(\beta - \alpha)$  for  $m_A = 600 \text{ GeV}$ . Variations of the natural width up to  $\Gamma_A/m_A = 5\%$  and different mixtures of gluon-fusion and b-quark-associated production are taken into account. Only points in parameter space where  $\Gamma_A/m_A < 5\%$  are considered.

## The allowed parameter space in type I



$$\mu_{VV} \geq 0.79 \Rightarrow \cos(\alpha_2) \geq 0.89 \Rightarrow \alpha_2 \leq 27^\circ \quad \text{and} \quad \tan(\beta) \geq 1$$

$$\alpha_2 \leq 27^\circ \Rightarrow \sin(\alpha_2) \leq 0.46 \Rightarrow c_o = \frac{\sin(\alpha_2)}{\tan(\beta)} \leq 0.46$$

All Yukawa couplings are the same - the bounds apply equally to all of them.

# Searches roadmap

$$H^\pm \rightarrow W^\pm V$$

Triplets

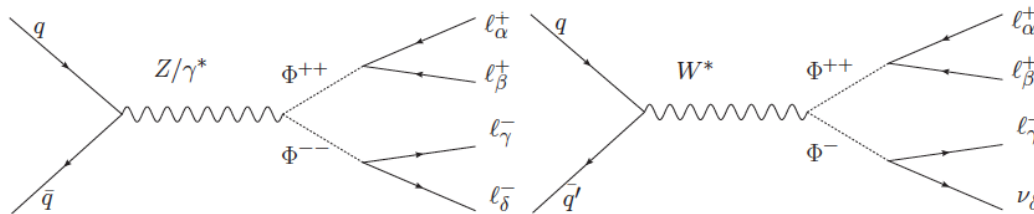
$$H^\pm \rightarrow W^\pm Z$$

Done by ATLAS

$$H^\pm \rightarrow W^\pm S$$

So far there seems to be no concrete plans even for  $H^+ \rightarrow W^+ h_{125}$

Main decays for CPC and CPV 2HDM are the same.



Doubly charged Higgs have been searched for in leptons and WW.