1. Higgs couplings in Extended Higgs sectors

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Multi-Higgs day @ LIP

11 June 2018

LHC - Two approaches to the research programme

Goal – Try to understand (some) of the outstanding problems in particle physics or just find a new particle

- You come up with a "great model"

A complete programme was devised to search for supersymmetry at the LHC

- You don't come up with a "great model"

- Perform ad-hoc extension of the SM with the goal (see above) and look for signals of the model at the LHC

- Do EFT

LHC - Two approaches to the research programme

TWiki > LHCPhysics Web > LHCHXSWG > LHCHXSWG3 (2016-09-25, RompotisNikolaos)

LHC HXSWG for BSM Higgs (WG3)

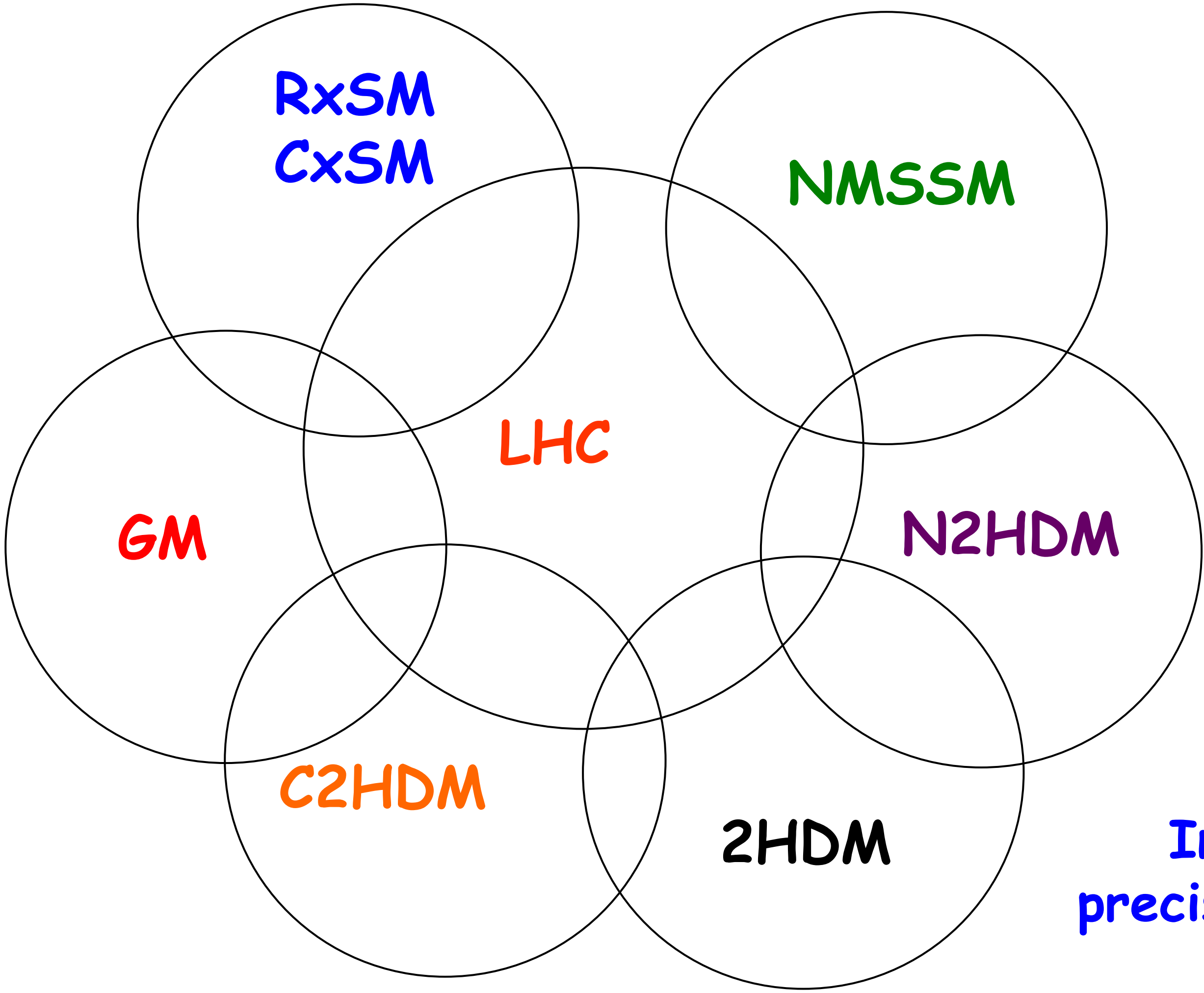
LHCHXSWG3 is responsible to provide support and recommendations for BSM Higgs related issues.

Working Group 3: Sub-group - Extended Scalars

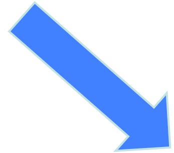
Interaction between experimentalists and theorists to look for signals of extended scalar sectors

Yellow Report 4: sets the stage for the searches in the LHC Run 2

BSM-EHS – What are they good for?



Motivate searches



New scalar?

Discovered Higgs
very SM-like

Information from
precision measurements?

WHICH BSM MODELS SHOULD WE GO FOR?

Extensions of the scalar sector - some guiding principles

- **Should contain a SM-like Higgs boson**
- **Electroweak ρ parameter should be close to 1**

$$\rho_{exp} = 1.0004^{+0.0003}_{-0.0004}$$

$$\rho \equiv \frac{m_W^2}{m_Z^2 \cos^2\theta_W} = \frac{\sum_i \left[4T_i\left(T_i+1\right) - Y_i^2\right] |v_i|^2 c_i}{\sum_i 2Y_i^2 |v_i|^2}$$

T_i $SU(2)_L$ Isospin

Y_i Hypercharge

v_i vev

c_i 1 (1/2) for complex (real) representations

$$Q = T_3 + Y/2$$

Extensions of the scalar sector - some guiding principles

For the SM we have

$$T = 1/2; \quad Y = 1 \Rightarrow \rho_{tree-level} = 1$$

One additional scalar field has to satisfy the relation

$$4T(T+1) = 3Y^2$$

$T = 0;\ Y = 0$ Singlet

$T = 1/2;\ |Y| = 1$ Doublet

$T = 3;\ |Y| = 4$ Septet

....

The simplest models that satisfy this relation are

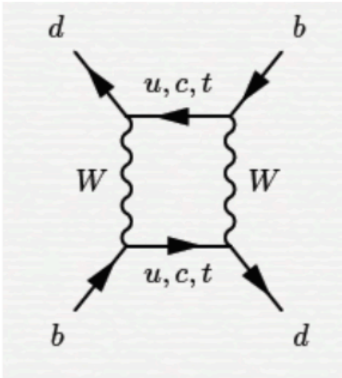
SM + any number of doublets + any number of neutral singlets

Other studied models fine-tuned to have $\rho \approx 1$ include the SM + triplet

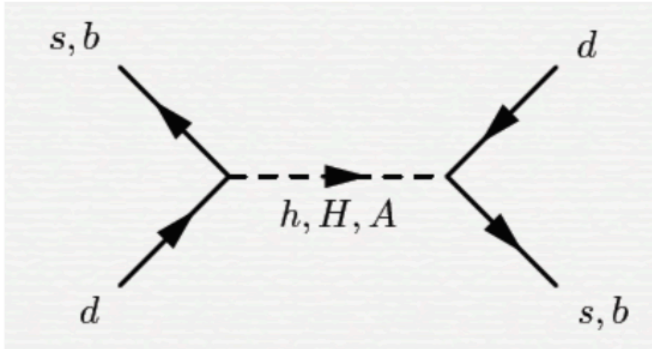
$$v_\Delta << v \;\Rightarrow\; \rho_{tree} = \frac{1+2v_\Delta^2/v^2}{1+4v_\Delta^2/v^2} \approx 1 - 2v_\Delta^2/v^2$$

FCNC constraints in 2HDM

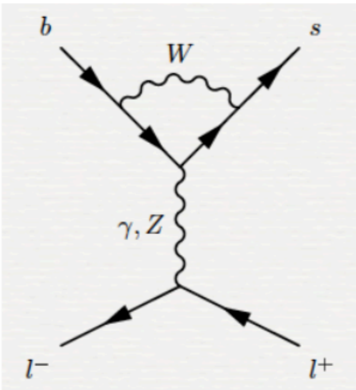
➡ B_d^0–$\overline{B}_d^0$ and B_s^0–$\overline{B}_s^0$ mixing

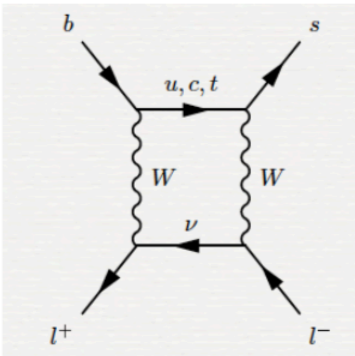


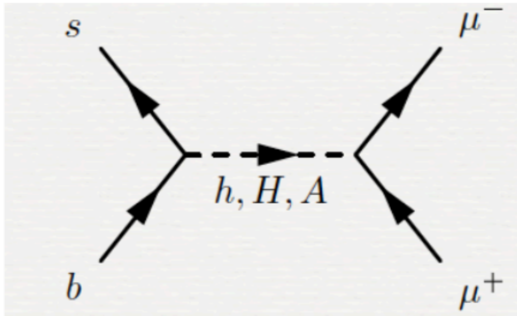
New tree-level FCNC diagrams



➡ Rare B decays







SM Yukawa Lagrangian

$$L_Y = \begin{bmatrix} \bar{U} & \bar{D} \end{bmatrix}_L \Phi Y_d\, D_R + \begin{bmatrix} \bar{U} & \bar{D} \end{bmatrix}_L \tilde{\Phi}\, Y_u U_R + \begin{bmatrix} \bar{N} & \bar{E} \end{bmatrix}_L \Phi\, Y_e E_R + \text{h.c.}$$

where the gauge eigenstates are

$$U = \begin{bmatrix} u_g & c_g & t_g \end{bmatrix};\; D = \begin{bmatrix} d_g & s_g & b_g \end{bmatrix};\; N = \begin{bmatrix} \nu_e & \nu_\mu & \nu_\tau \end{bmatrix};\; E = \begin{bmatrix} e & \mu & \tau \end{bmatrix}$$

and Y are matrices in flavour space. To get the mass terms we just need the vacuum expectation values of the scalar fields

$$L_Y^{\text{mass}} = \frac{v}{\sqrt{2}}\, \bar{U}_L Y_u U_R + \frac{v}{\sqrt{2}}\, \bar{D}_L Y_d D_R + \frac{v}{\sqrt{2}}\, \bar{E}_L Y_e E_R + \text{h.c.}$$

which have to be diagonalised.

SM Yukawa Lagrangian

So we define

$$D_R \to N_R^{-1} D_R \,;\, D_L \to N_L^{-1} D_L \,;\, U_R \to K_R^{-1} U_R \,;\, U_L \to K_L^{-1} U_L$$

and the mass matrices are

$$-\frac{v}{\sqrt{2}} N_L^{\dagger} Y_d N_R = M_d \,; \qquad -\frac{v}{\sqrt{2}} K_L^{\dagger} Y_u K_R = M_u$$

and the interaction term is proportional to the mass term (just D terms)

$$L_Y^{interactions} = \frac{h}{\sqrt{2}} \bar{D}_L Y_d D_R \propto \frac{v}{\sqrt{2}} \bar{D}_L Y_d D_R$$

<u>No scalar induced tree-level FCNCs</u>

2HDM Yukawa Lagrangian

However in 2HDMs

$$\Phi_1 = \begin{pmatrix} - \\ (h_1 + v_1)/\sqrt{2} \end{pmatrix}; \quad \Phi_2 = \begin{pmatrix} - \\ (h_2 + v_2)/\sqrt{2} \end{pmatrix}$$

$$L_Y^{mass} = \frac{v_1}{\sqrt{2}} \bar{U}_L Y_u^1 U_R + \frac{v_1}{\sqrt{2}} \bar{D}_L Y_d^1 D_R + \frac{v_2}{\sqrt{2}} \bar{U}_L Y_u^2 U_R + \frac{v_2}{\sqrt{2}} \bar{D}_L Y_d^2 D_R + \ldots$$

$$= \frac{1}{\sqrt{2}} \bar{U}_L \left(v_1 Y_u^1 + v_2 Y_u^2\right) U_R + \frac{1}{\sqrt{2}} \bar{D}_L \boxed{\left(v_1 Y_d^1 + v_2 Y_d^2\right)} D_R + \ldots$$

$$-\frac{1}{\sqrt{2}} N_L^\dagger \boxed{\left(v_1 Y_d^1 + v_2 Y_d^2\right)} N_R = M_d; \qquad -\frac{1}{\sqrt{2}} K_L^\dagger \left(v_1 Y_u^1 + v_2 Y_u^2\right) K_R = M_u$$

$$L_Y^{interactions} = \frac{h_1}{\sqrt{2}} \bar{U}_L Y_u^1 U_R + \frac{h_1}{\sqrt{2}} \bar{D}_L Y_d^1 D_R + \frac{h_2}{\sqrt{2}} \bar{U}_L Y_u^2 U_R + \frac{h_2}{\sqrt{2}} \bar{D}_L Y_d^2 D_R + \ldots$$

$$= \frac{h}{\sqrt{2}} \bar{U}_L \left(\cos\alpha Y_u^1 + \sin\alpha Y_u^2\right) U_R + \frac{H}{\sqrt{2}} \bar{D}_L \boxed{\left(-\sin\alpha Y_d^1 + \cos\alpha Y_d^2\right)} D_R + \ldots$$

h, H are the mass eigenstates (a is the rotation angle in the CP-even sector)

2HDM Yukawa Lagrangian

How can we avoid large tree-level FCNCs?

1. **Fine tuning** – for some reason the parameters that give rise to tree-level FCNC are small

Example: Type III models   CHENG, SHER (1987)

2. **Flavour alignment** – for some reason we are able to diagonalise simultaneously both the mass term and the interaction term

Example: Aligned models   PICH, TUZON (2009)

$$\boxed{Y_d^2 \propto Y_d^1}$$ (for down type)

2HDM Yukawa Lagrangian

3. Use symmetries- for some reason the L is invariant under some symmetry

3.1 Naturally small tree-level FCNCs

Example: BGL Models BRANCO, GRIMUS, LAVOURA (2009)

3.2 No tree-level FCNCs

Example: Type I 2HDM Z_2 symmetries GLASHOW, WEINBERG; PASCHOS (1977)
BARGER, HEWETT, PHILLIPS (1990)

$$L_Y = \sum_i \left[\bar{U} \quad \bar{D}\right]_L \Phi_i Y_d^i D_R + \left[\bar{U} \quad \bar{D}\right]_L \tilde{\Phi}_i Y_u^i U_R + \left[\bar{N} \quad \bar{E}\right]_L \Phi_i Y_e^i E_R + h.c.$$

$$\Phi_1 \to \Phi_1; \Phi_2 \to -\Phi_2 \qquad D_R \to -D_R; E_R \to -E_R; U_R \to -U_R$$

$$L_Y^I = \left[\bar{U} \quad \bar{D}\right]_L \Phi_2 Y_d^2 D_R + \left[\bar{U} \quad \bar{D}\right]_L \tilde{\Phi}_2 Y_u^2 U_R + \left[\bar{N} \quad \bar{E}\right]_L \Phi_2 Y_e^2 E_R + h.c.$$

NOW, WHAT ARE THEY GOOD FOR?

Extended scalars programme: SM + singlets/doublets/triplet or combinations thereof.

But what about the physics?

Singlets and 2HDMs as benchmark models

1. 2HDM Inert and Singlet – Dark matter candidate;
2. 2HDM and singlet – Could help explain baryon asymmetry;
3. 2HDM and singlet – Improve stability of the SM at high energies;
4. 2HDM – Rich phenomenology (charged scalars in 2HDM);
5. 2HDM fermiophobic – Decoupling from fermions (heavy scalars);
6. 2HDM – Wrong sign limit (Yukawas) and non-decoupling effects;
7. C2HDM – Large pseudo-scalar components in Yukawa couplings;
8. C2HDM – Probe CP-violation in a combination of 3 scalar decays;
9. 2HDM BGL – Controlled flavour changing neutral currents… **and more**

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 $\begin{pmatrix} \\ v \end{pmatrix}$ $\left(v_S\right)$

  Scalar sector – 2 CP-even neutral scalars (broken phase)

  → SM+complex singlet - CxSM

- Two-Higgs Doublet Model (Real – one extra doublet) – 2HDM → 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

Models

The CxSM (or RxSM) - Singlet

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

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

Model	Phase	VEVs at global minimum
$\mathbb{U}(1)$	Higgs+2 degenerate dark	$\langle \mathbb{S} \rangle = 0$
	2 mixed + 1 Goldstone	$\langle A \rangle = 0$ ($\not{\mathbb{U}}(1) \to \mathbb{Z}_2'$)
$\mathbb{Z}_2 \times \mathbb{Z}_2'$	Higgs + 2 dark	$\langle \mathbb{S} \rangle = 0$
	2 mixed + 1 dark	$\langle A \rangle = 0$ ($\not{\mathbb{Z}}_2 \times \mathbb{Z}_2' \to \mathbb{Z}_2'$)
$\mathbb{Z}_2'$	2 mixed + 1 dark	$\langle A \rangle = 0$
	3 mixed	$\langle \mathbb{S} \rangle \neq 0$ ($\not{\mathbb{Z}}_2'$)

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

The CxSM

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

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

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

- $\not{\mathbb{Z}}_2$ phase ($v_S \neq 0, v_A \neq 0$): 3 Higgs mix

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

Once a scalar is chosen to be the 125 GeV all couplings to other SM particles are modified by the same factor R_{ih}!

Softly broken Z_2 symmetric Higgs potential

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

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^2_{12} and λ_5 real** — **potential is CP-conserving (2HDM)**
- **m^2_{12} and λ_5 complex** — **potential is explicitly CP-violating (C2HDM)**

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

The N2HDM

$$\Phi_1 \to \Phi_1\,, \quad \Phi_2 \to -\Phi_2\,, \quad \Phi_S \to \Phi_S$$ Explicitly broken

$$\Phi_1 \to \Phi_1\,, \quad \Phi_2 \to \Phi_2\,, \quad \Phi_S \to -\Phi_S$$ Spontaneously broken

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

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

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

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

Couplings

Lightest Higgs couplings to gauge bosons

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

$V = W, Z$

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

$(a + ib)$

2HDM + REAL SINGLET

$$g^{hVV}_{RxSM} = \cos(\alpha_1)\; g^{hVV}_{SM}$$

2HDM + COMPLEX SINGLET

$$g^{hVV}_{CxSM} = \cos(\alpha_1)\; \cos(\alpha_2)\; g^{hVV}_{SM}$$

REAL COMPONENT

IMAGINARY COMPONENT

Lightest Higgs Yukawa couplings

Yukawa couplings (lightest scalar) (no FCNC at tree-level)

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

at tree-level

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

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

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…

Lightest Higgs Yukawa couplings

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

↓

SINGLET EXTENSION

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

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

2HDM

$$Y_{N2HDM} \equiv c_2 Y_{2HDM}$$

CP-CONSERVING N2HDM

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

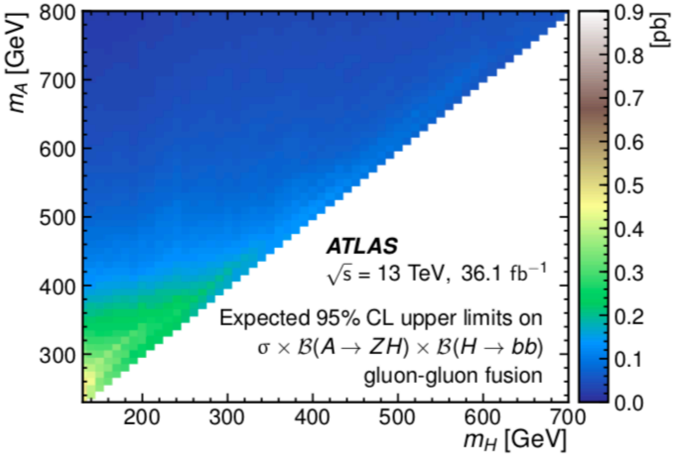
CP-VIOLATING 2HDM

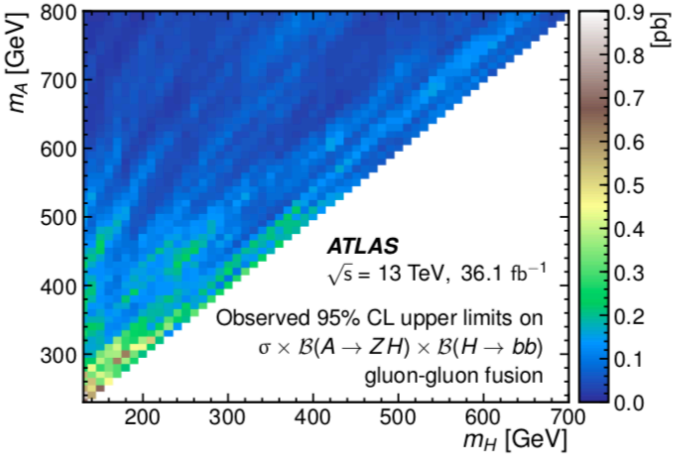
when $s_2 \to 0$

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

Independent of the Yukawa type

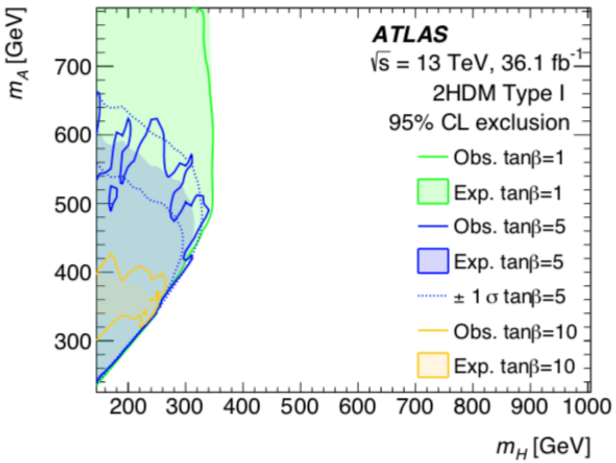
The 2HDM (CP-conserving and no tree-level FCNC)

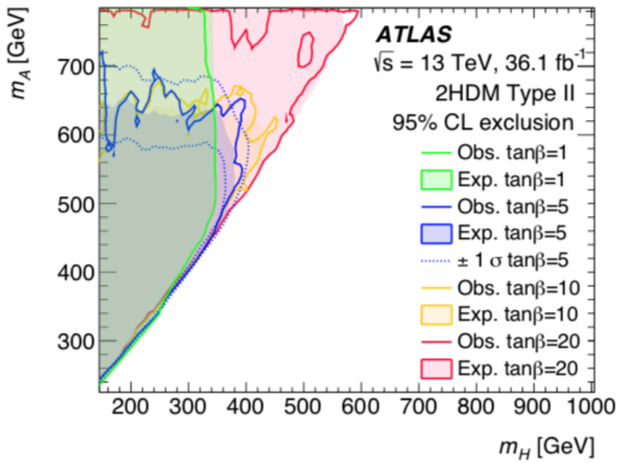




Upper bounds at 95% CL on the production cross-section times the branching ratio Br(A ⟶ ZH)×Br(H ⟶ bb) in pb for gluon–gluon fusion. Left: expected; right: observed.

ATLAS 1804.01126v1





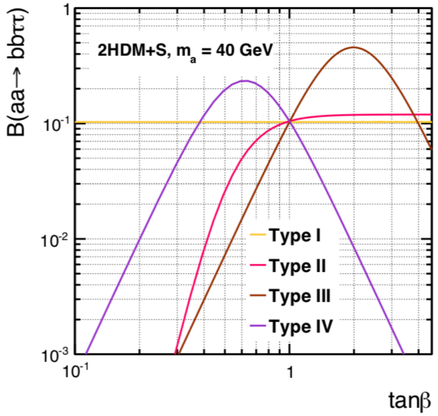
Observed and expected 95% CL exclusion regions in the (m_A, m_H) plane for various tan β values for Type I (left), and Type II (right).

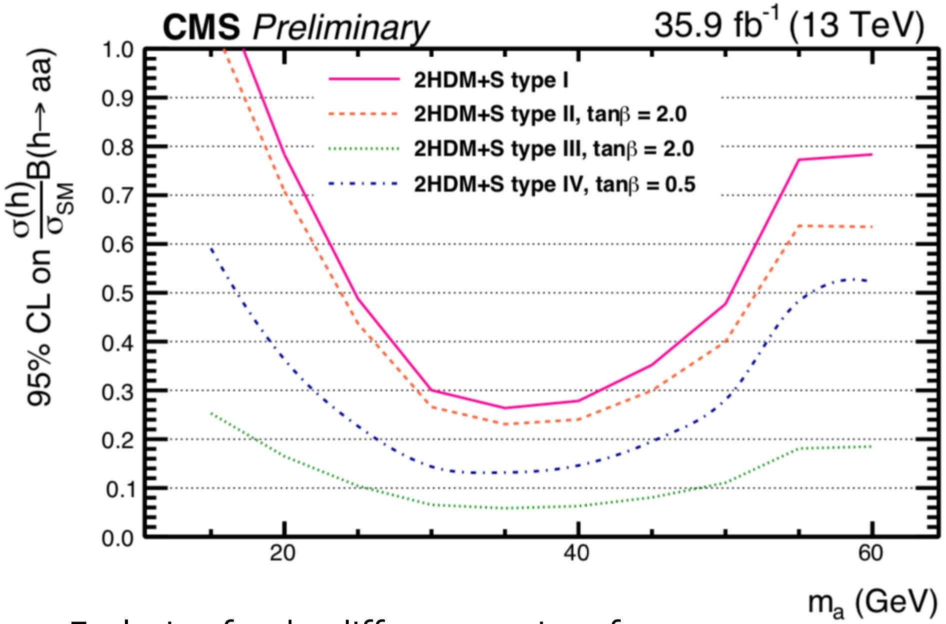
Assumptions: aligment, lightest Higgs 125 GeV, $m_{H+} = m_A$, U(1) symmetry (fixes m_{12}^2).

The N2HDM (CP-conserving and no tree-level FCNC)

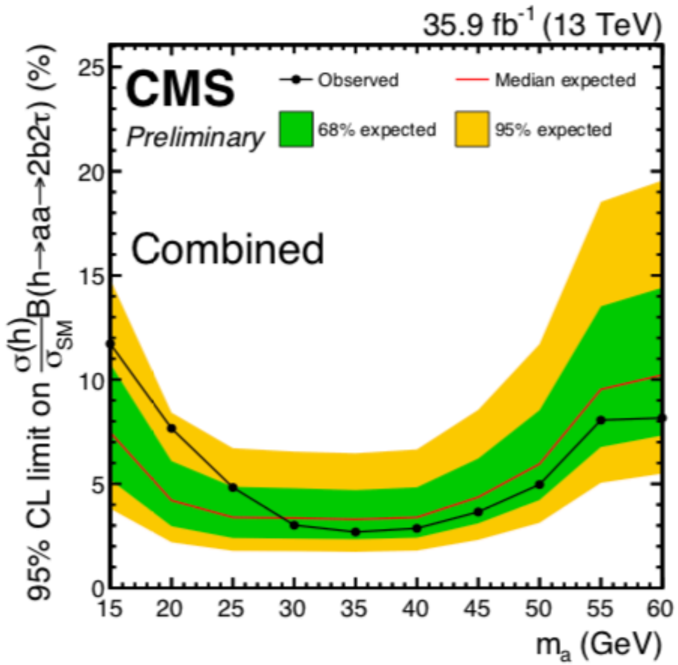
CMS PAS HIG-17-024

BRs for the 4 different versions of the model.





Exclusion for the different versions for 2 values of 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

Searches roadmap

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

h_i (no definite CP)

$S_i \to S_j V$

CPC: $H_i \to A_i V \ (A_i \to H_i V)$ 2HDM,...

CPV: $h_1 \to h_2 V$ C2HDM,...

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

$$\begin{cases} S_i \to S_j S_j \\ S_i \to S_j S_k \end{cases}$$

CPC: $H_i \to H_j H_j \ (A_i A_j)$ RxSM, 2HDM, NMSSM,..

CPV: $h_i \to h_j h_j$, $h_i \to h_j h_k$ C2HDM,C-NMSSM,...

CPC:
$$\begin{cases} H_i \to H_j H_k \\ A_i \to A_j H_k \end{cases}$$

$H_i \to H_j H_k$: CxSM, NMSSM,...

$A_i \to A_j H_k$: 3HDM, NMSSM,...

- $h_{125} \longrightarrow AA$ and $H \longrightarrow h_{125}\, h_{125}$ already studied by ATLAS and CMS

Searches roadmap

$$S_i \to VV \quad \xrightarrow{\text{CPC}} \quad H_i \to VV$$

$$S_i \to VV \quad \xrightarrow{\text{CPV}} \quad h_i \to VV$$

For the 2HDM

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

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

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

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

C2HDM – Fontes, Romão, RS, Silva, PRD92 (2015) 5, 055014
CNMSSM – King, Mühlleitner, Nevzorov, Walz; NPB901 (2015) 526-555

Searches roadmap

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

FC

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

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

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

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

Done...

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

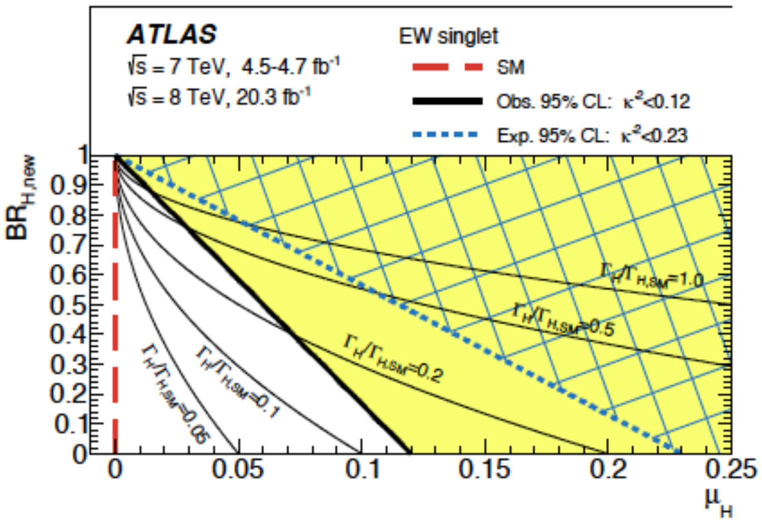
FCNC

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

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

S_i (any neutral scalar)

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



Limits as a function of the non-125 Higgs. Taking the largest point in μ_H to be the exclusion limit, the result does not depend on the H mass and width.

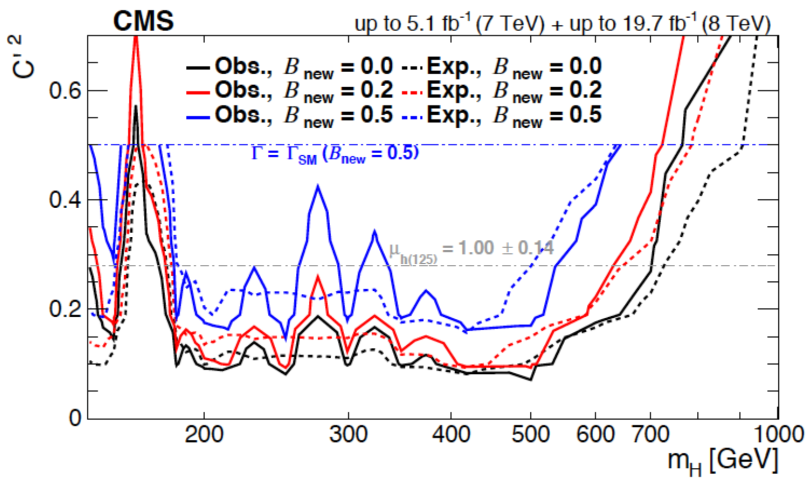
ATLAS 1509.00672

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

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

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

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

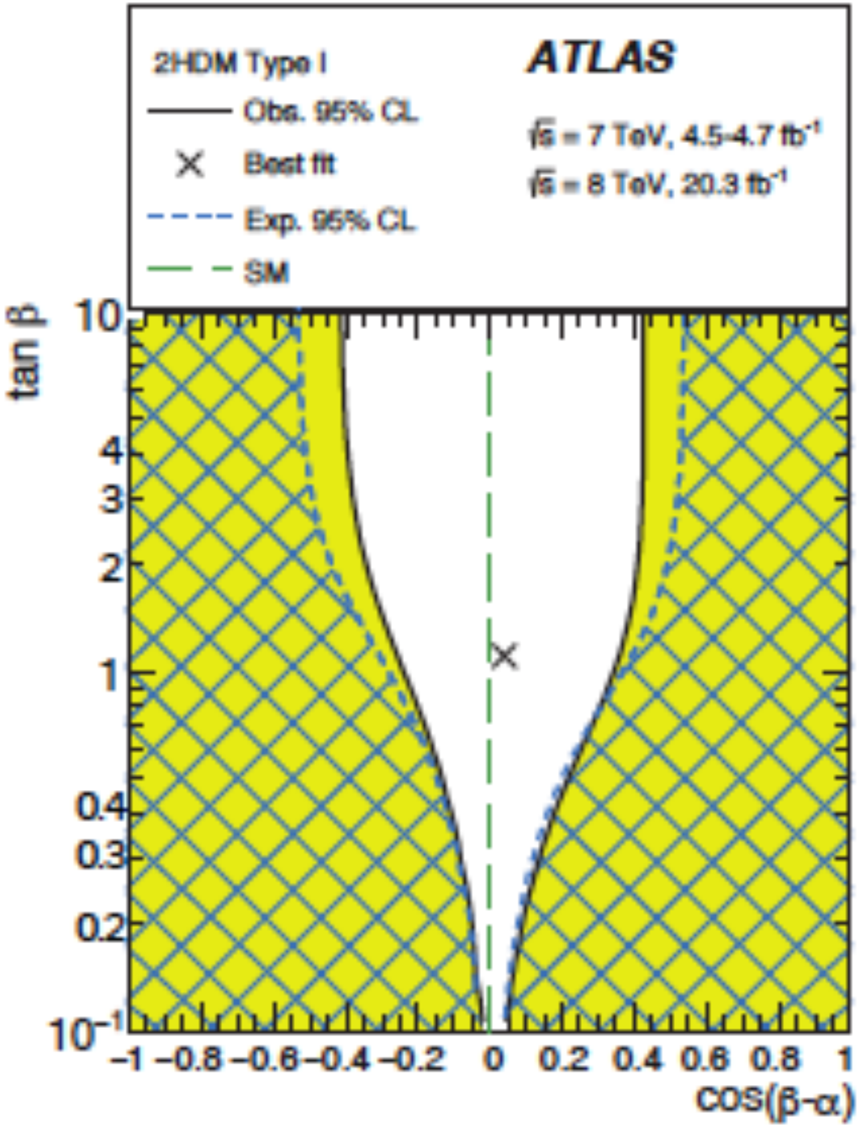


CMS 1504.00936

$$\mu' = C'^2\,(1 - \mathcal{B}_{\mathrm{new}})$$

$$\Gamma' = \Gamma_{\mathrm{SM}}\,\frac{C'^2}{1 - \mathcal{B}_{\mathrm{new}}}$$

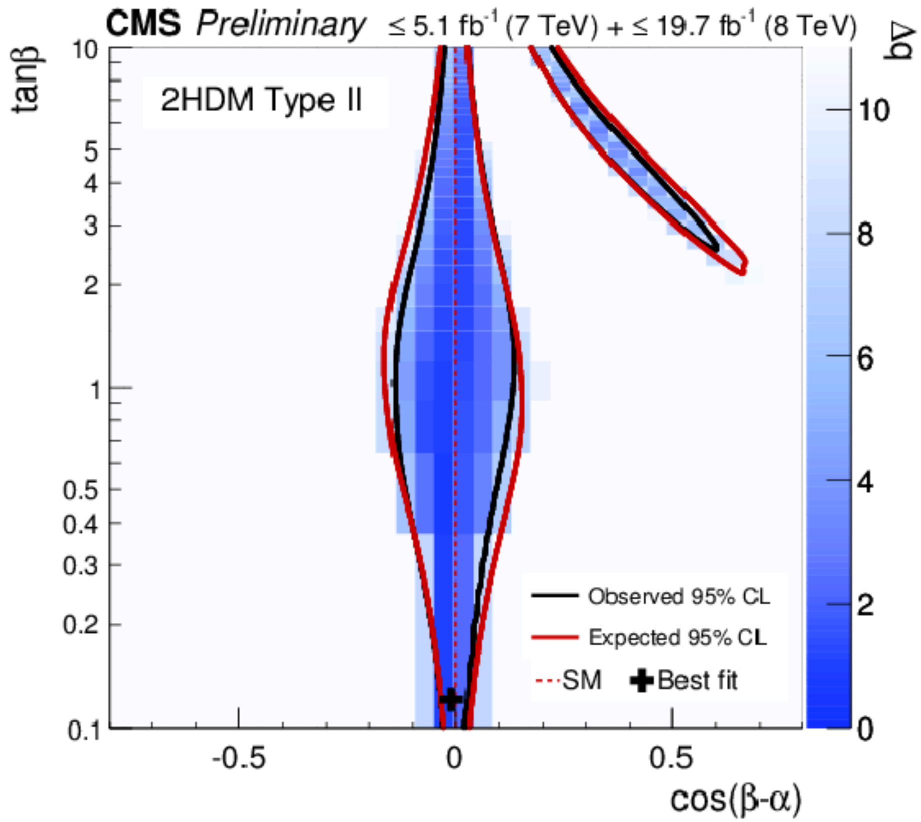
2.a) b) H_{125} couplings - The 2HDM (CP-conserving and no tree-level FCNC)



(a) Type I

ATLAS 1509.00672

CMS-PAS-HIG-16-007

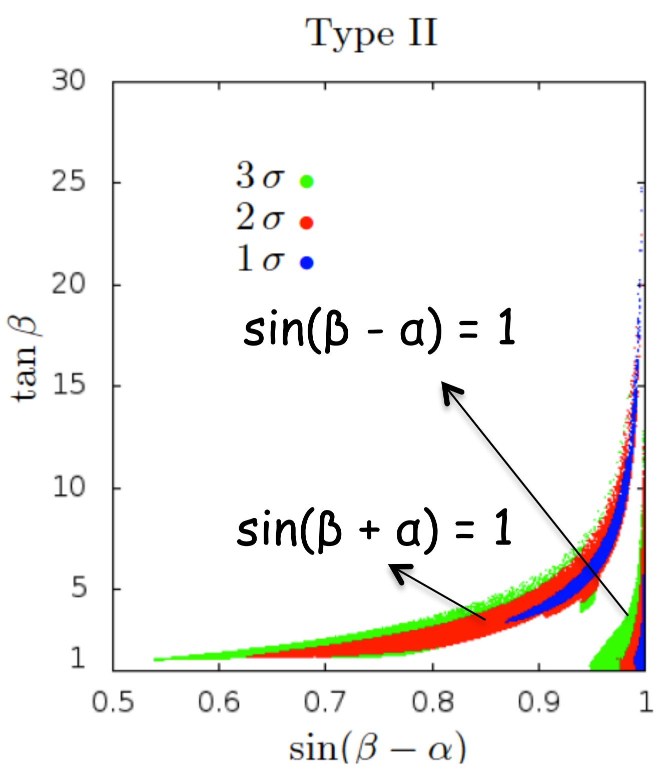


ATLAS and CMS allowed regions in type I and type II for the CP-conserving 2HDM. The central region is the SM-like limit (or alignment) where the Higgs couplings to the other SM particles are just the SM ones. The extra leg on the right has the wrong sign in the b/tau couplings relative to SM ones.

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.

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



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

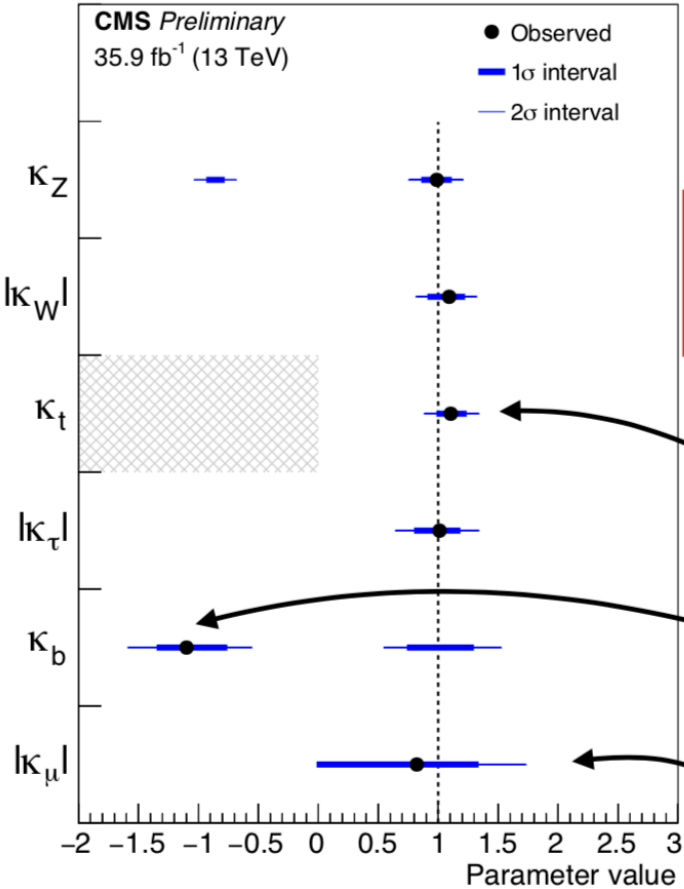
$$\kappa_i^2=\frac{\Gamma^{2HDM}(h\to i)}{\Gamma^{SM}(h\to i)}$$

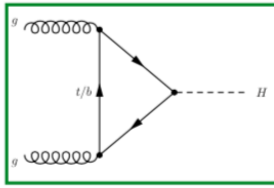
The actual sign of each κ_i depends on the chosen range for the angles.

Ferreira, Gunion, Haber, RS, PRD89 (2014) 11, 115003

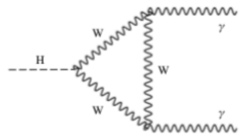
Ferreira, Guedes, Sampaio, RS, JHEP 1412 (2014) 067

The wrong-sign strikes back!





$$\kappa_g^2 = 1.04 \cdot \kappa_t^2 + 0.002 \cdot \kappa_b^2 - 0.038 \cdot \kappa_t \kappa_b$$

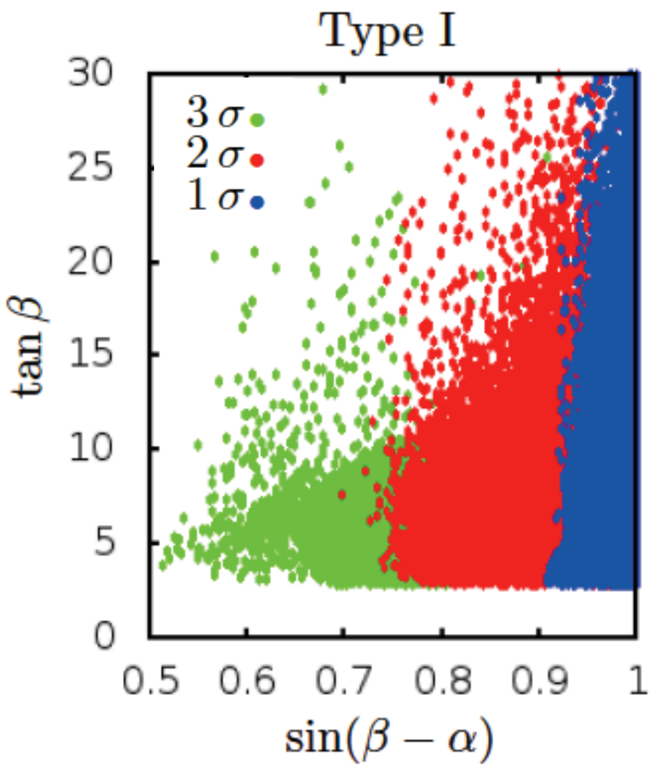


$$\kappa_\gamma^2 = 1.59 \cdot \kappa_W^2 + 0.07 \cdot \kappa_t^2 - 0.67 \cdot \kappa_W \kappa_t$$

~ 25% stronger constraint compared to effective loop model (κ_t from ttH alone)

Mild preference for $\kappa_b < 0$ from b-t interference in gluon fusion production

Include H→μμ search for constraint on κ_μ



The shape of type I

$$\kappa_F \approx \kappa_V = \sin(\beta - \alpha)$$

Cross sections and widths are like in the SM+singlet for "large" tanβ. Only Higgs self-couplings are different.

Using the same approx as in type II

$$\mu_{VV} \approx \mu_{\tau\tau} \approx \sin^2(\beta - \alpha)$$

$$\sin^2(\beta - \alpha) = 0.8 \Rightarrow$$

$$\sin(\beta - \alpha) = 0.89$$

Except for h -> γγ

$$\mu_{\gamma\gamma} \approx \kappa_\gamma^2$$

Which is close to 1.

Therefore bounds are almost independent of tanβ

Also there is just one "leg" (next slide).

$$\kappa_U = \kappa_D = \kappa_L = \frac{\cos\alpha}{\sin\beta} = \sin(\beta - \alpha) + \cos(\beta - \alpha)\cot\beta$$

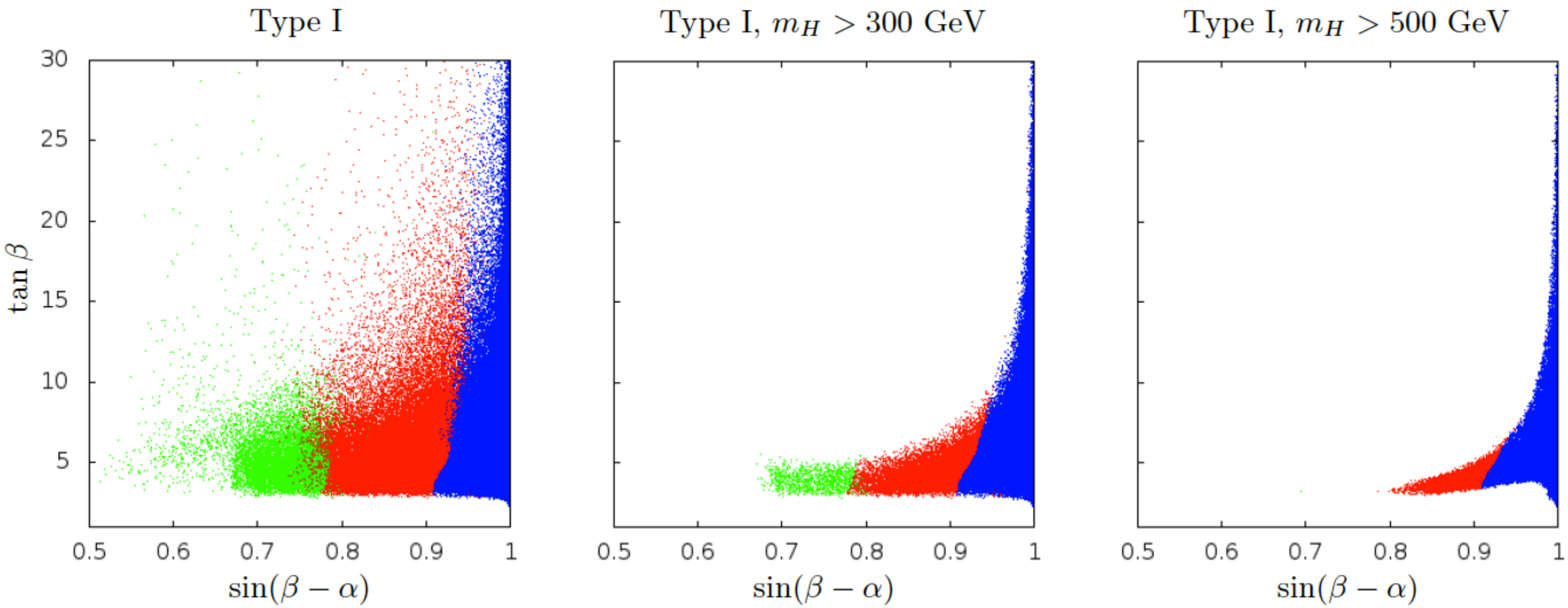
Type I

$$\kappa_U = \kappa_D = \frac{\cos\alpha}{\sin\beta} = \sin(\beta+\alpha) + \cos(\beta+\alpha)\cot\beta$$

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

$$\sin(\beta-\alpha) = \frac{\tan^2\beta - 1}{\tan^2\beta + 1} \quad \Rightarrow \quad \kappa_V \le 0 \;\; \text{if} \;\; \tan\beta \le 1$$

Because constraints force tanβ to be order 1 or larger, "there is no wrong-sign Yukawa coupling" in Type I (more about this later).

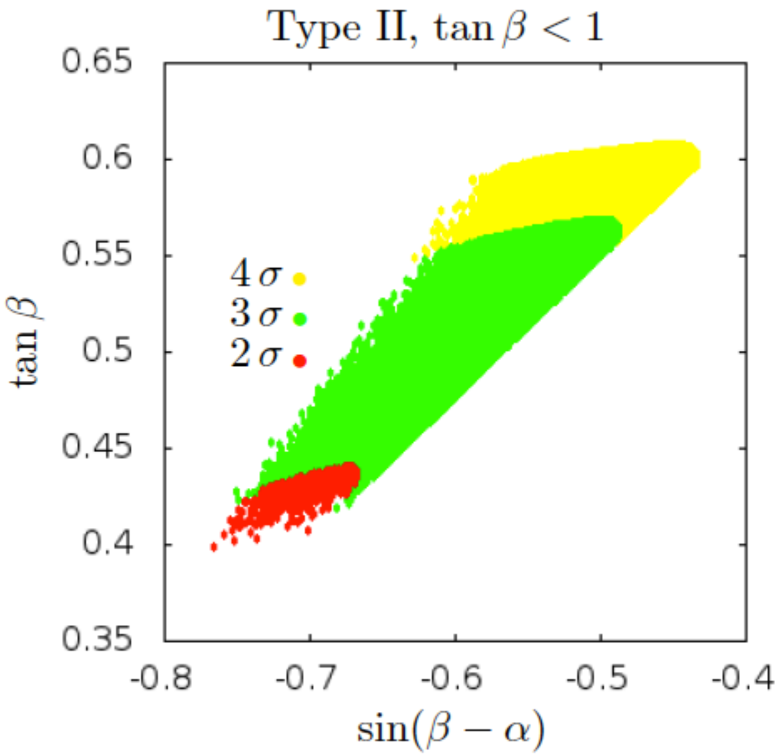


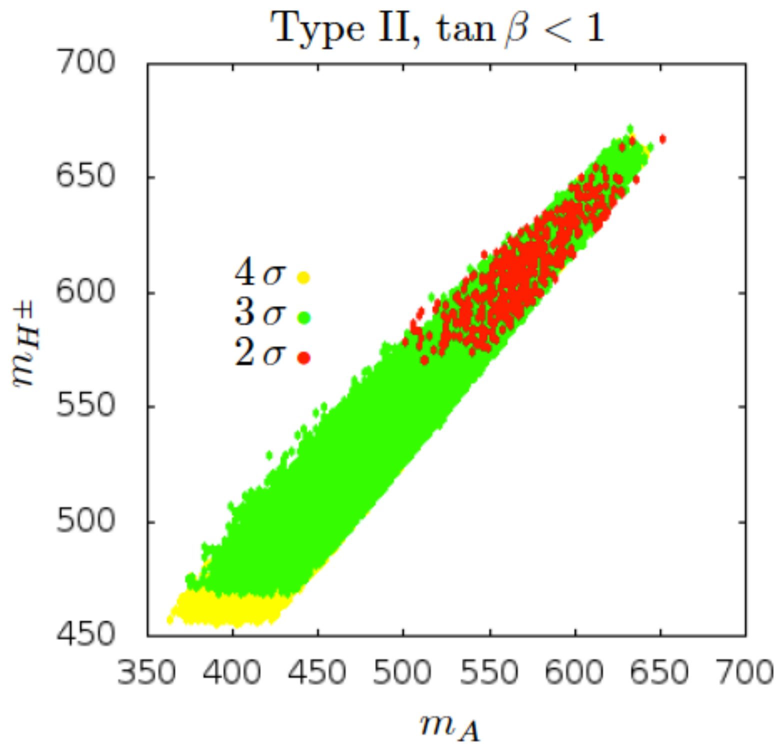
The dark side of the wrong sign scenario

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

$$\sin(\beta-\alpha)=\frac{\tan^2\beta-1}{\tan^2\beta+1} \quad \Rightarrow \quad \kappa_V \leq 0 \ \text{ if } \ \tan\beta \leq 1$$

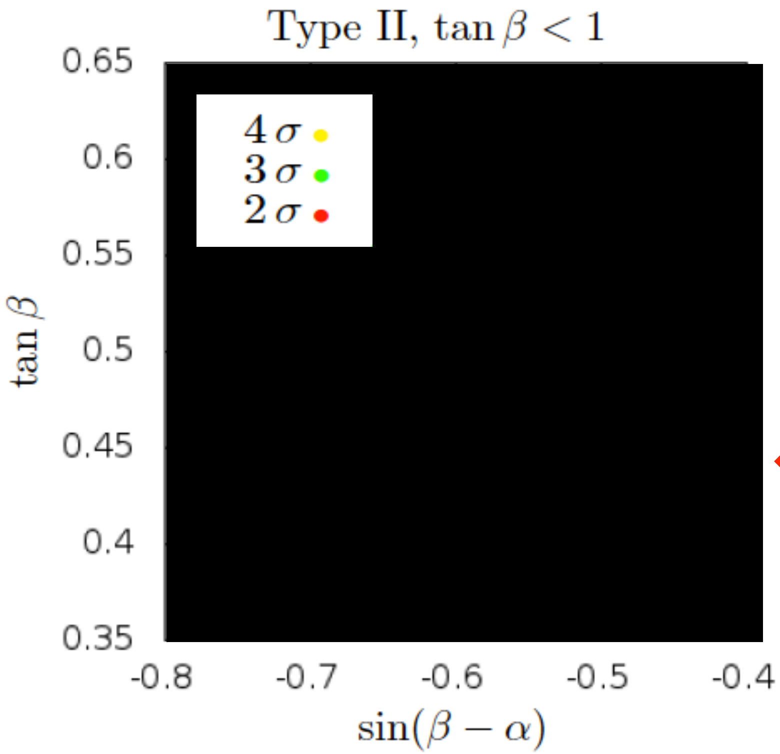
Possible in all types.

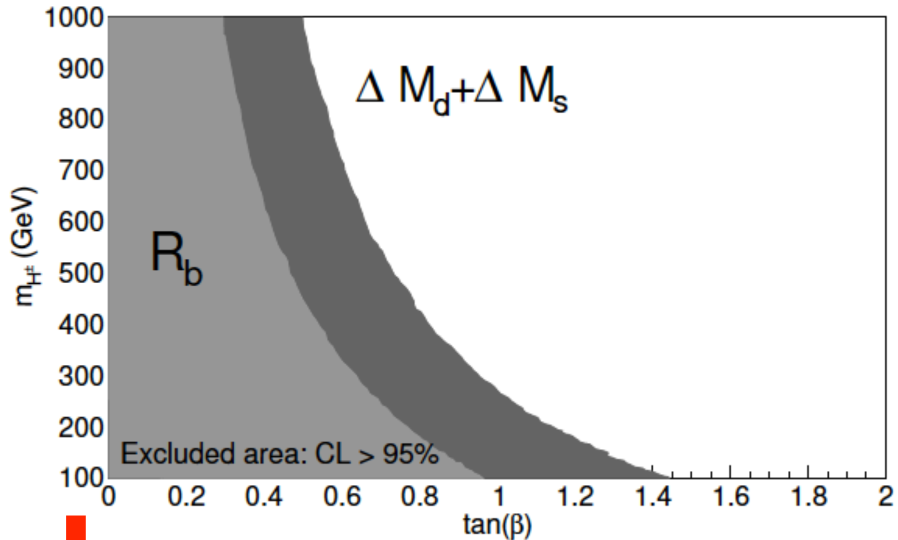




Z-> bb and b -> s γ included.

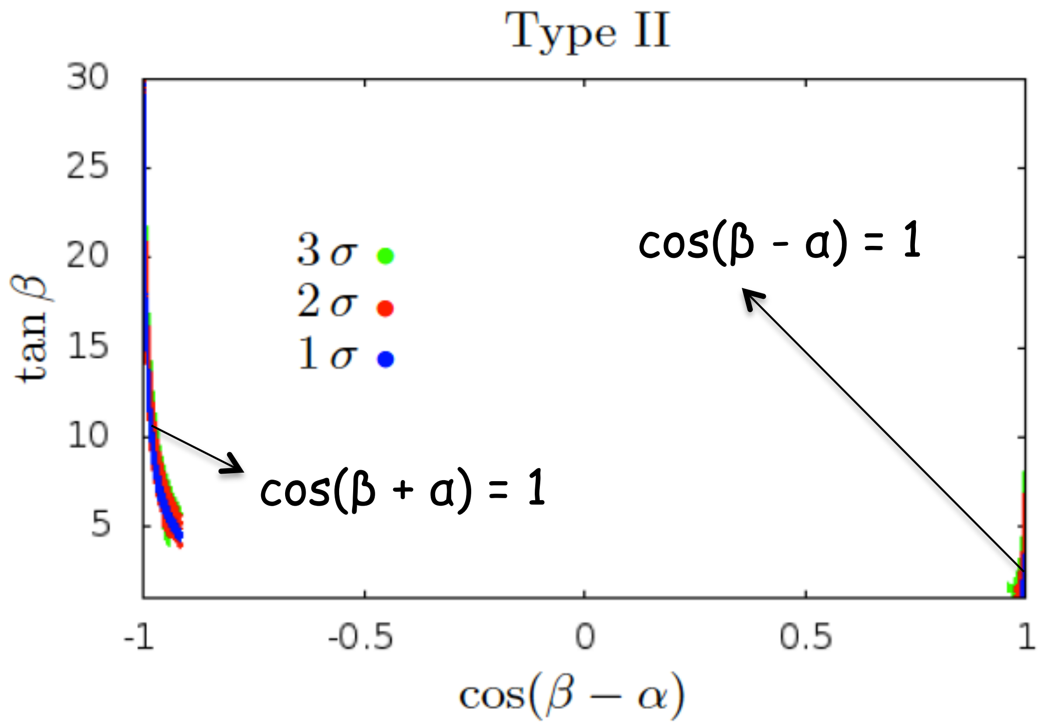
The dark side of the wrong sign scenario





Deschamps, Descotes-Genon, Monteil, Niess, T'Jampens, Tisserand, 2010

Final results when the limits from BB mixing are included.



Heaviest CP-even scalar as the SM-like Higgs

$$\begin{cases} \sin(\beta-\alpha) \to \text{sign}(\alpha)\cos(\beta-\alpha) \\ \cos(\beta-\alpha) \to -\text{sign}(\alpha)\sin(\beta-\alpha) \end{cases}$$

The SM-like limit

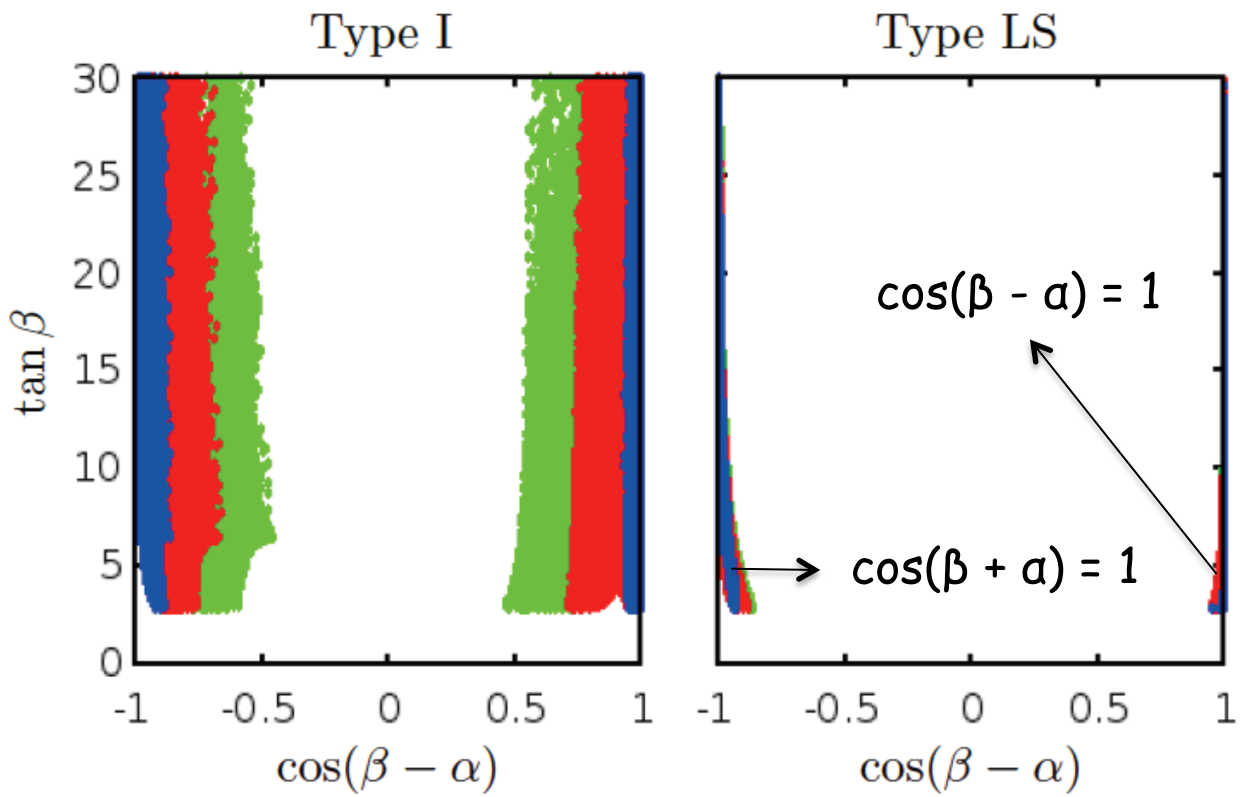
$$\cos(\beta-\alpha)=1 \;\Rightarrow$$
$$\Rightarrow \;\; \kappa_F = 1; \;\; \kappa_V = 1$$

Wrong-sign limit

$$\kappa_D \kappa_V < 0$$

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

$$\cos(\beta-\alpha) = -\frac{\tan^2\beta-1}{\tan^2\beta+1} \;\Rightarrow\; \kappa_V \le 0 \;\text{ if }\; \tan\beta \ge 1$$



Type I and LS

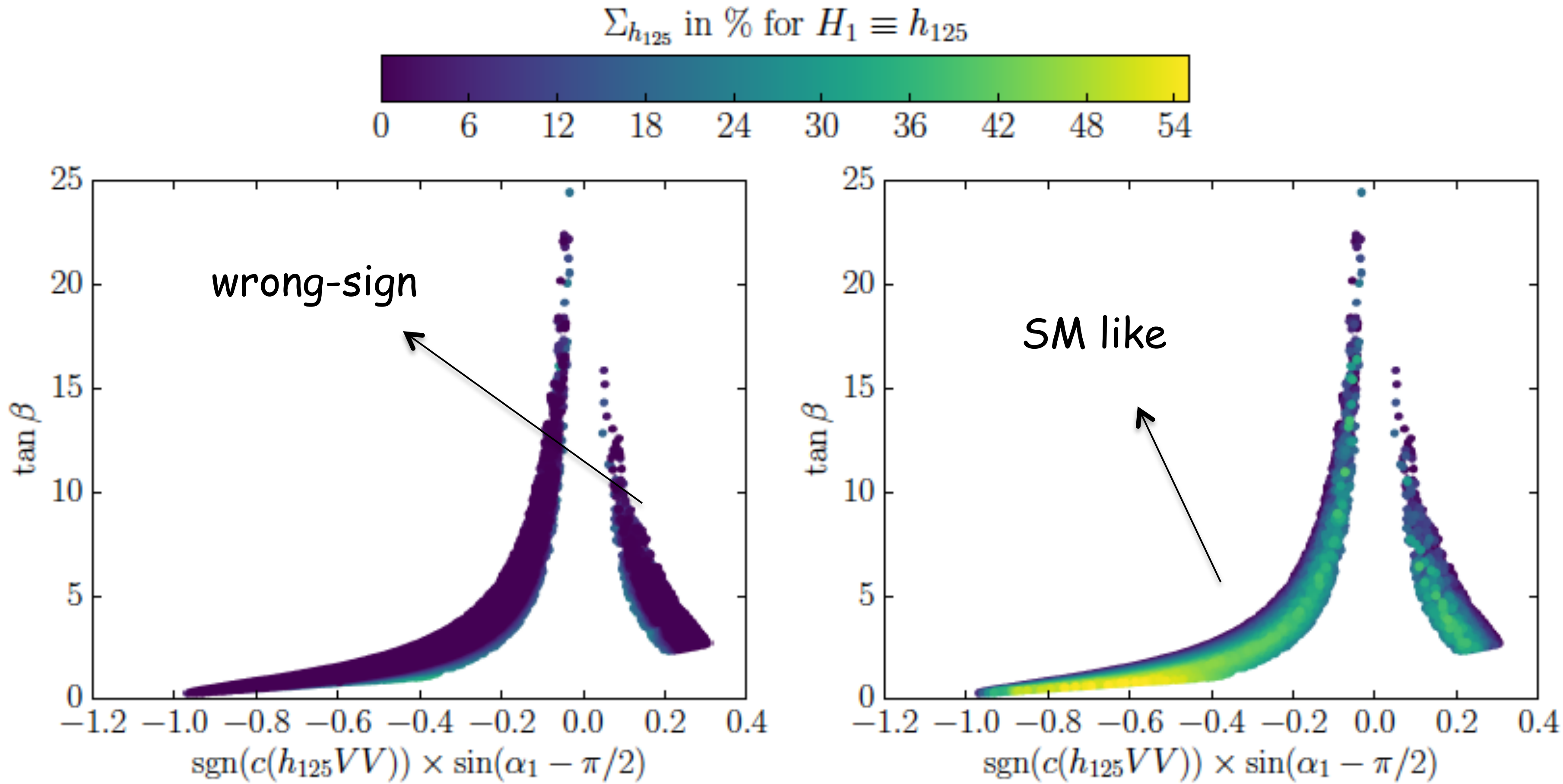
$$\cos(\beta+\alpha)=1 \quad \Rightarrow \quad \kappa_D = \kappa_U = -1$$

$$\cos(\beta-\alpha) = -\frac{\tan^2\beta-1}{\tan^2\beta+1} \quad \Rightarrow \quad \kappa_V \le 0 \ \text{ if } \ \tan\beta \ge 1$$

All couplings change sign – same conclusions as for the light scenario.

N2HDM - Without the colour bar this is just the 2HDM

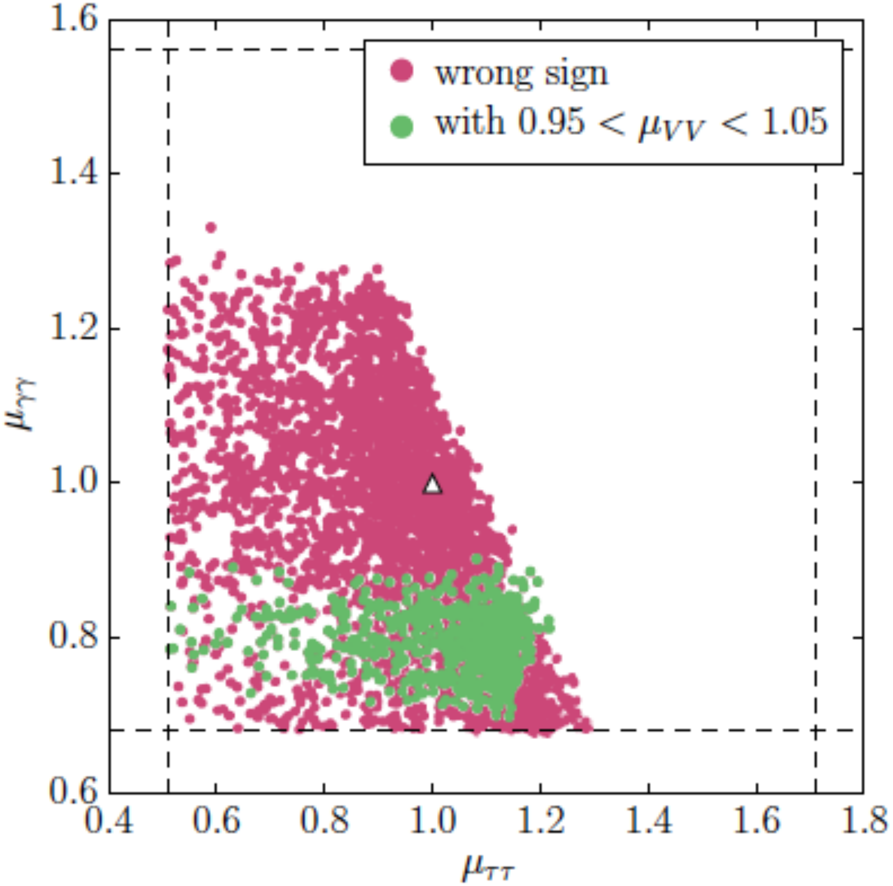
$\Sigma_i^{\mathrm{N2HDM}} = (R_{i3})^2$ singlet admixture of H_i (measure the singlet weight of H_i)

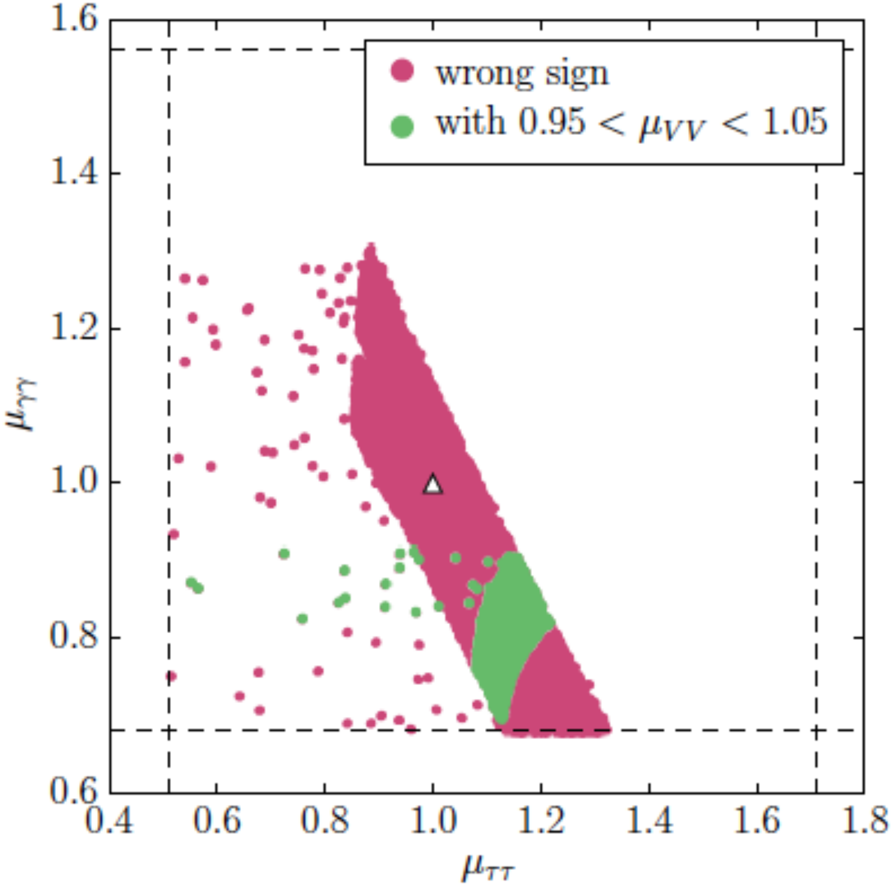


SM-like and wrong-sign limit in the N2HDM type II – the interesting fact is that in the alignment limit the singlet admixture can go up to 54 %.

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

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



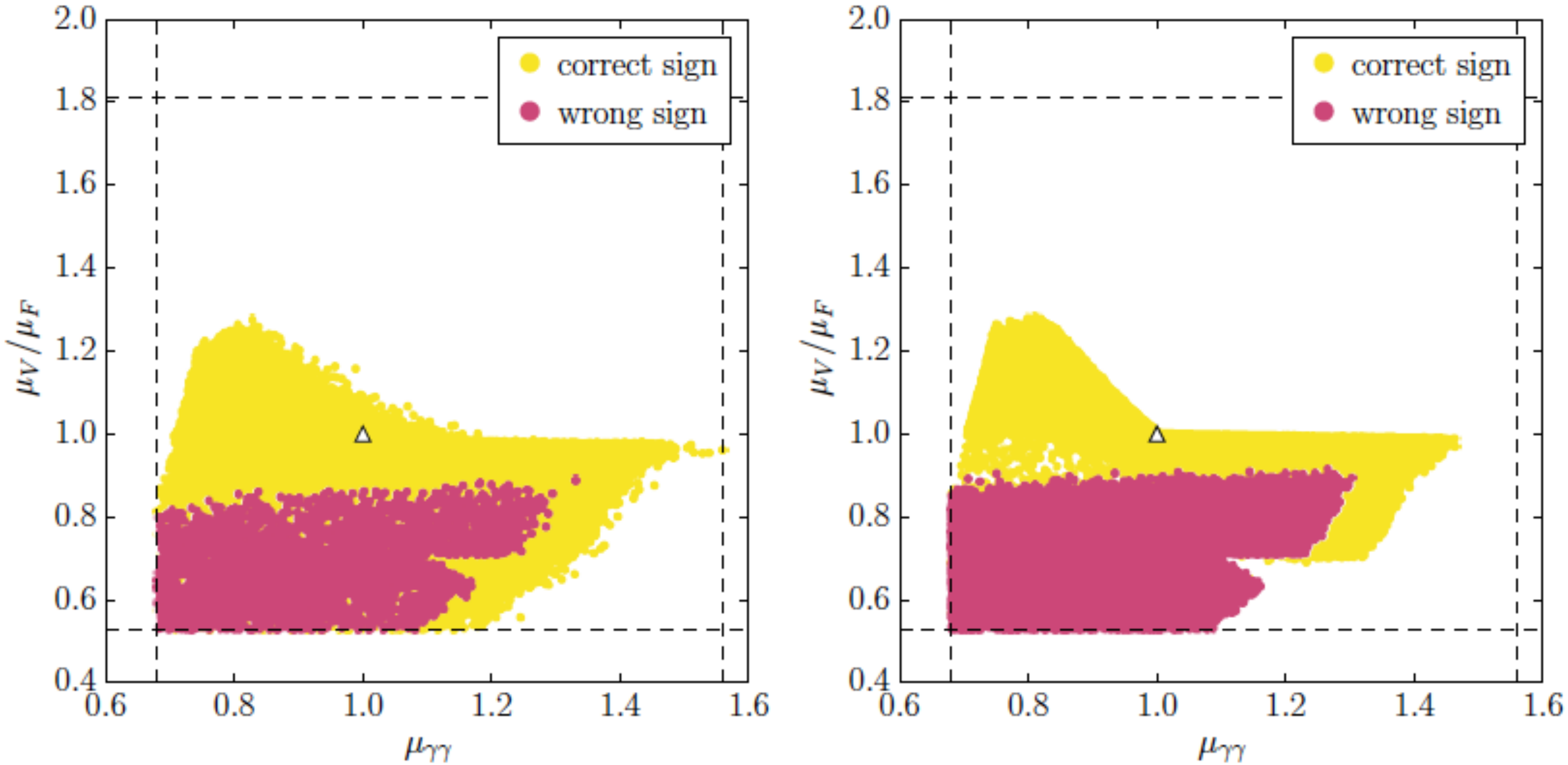


$\mu_{\gamma\gamma}$ vs $\mu_{\tau\tau}$ (only wrong sign points) in type II 2HDM (left) and N2HDM (right) – in "pink" all points and in green points where μ ZZ is measured within 5% of the SM value. Dashed lines are current limits.

Very similar behavior in the two models.

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

Wrong sign in the 2HDM and N2HDM

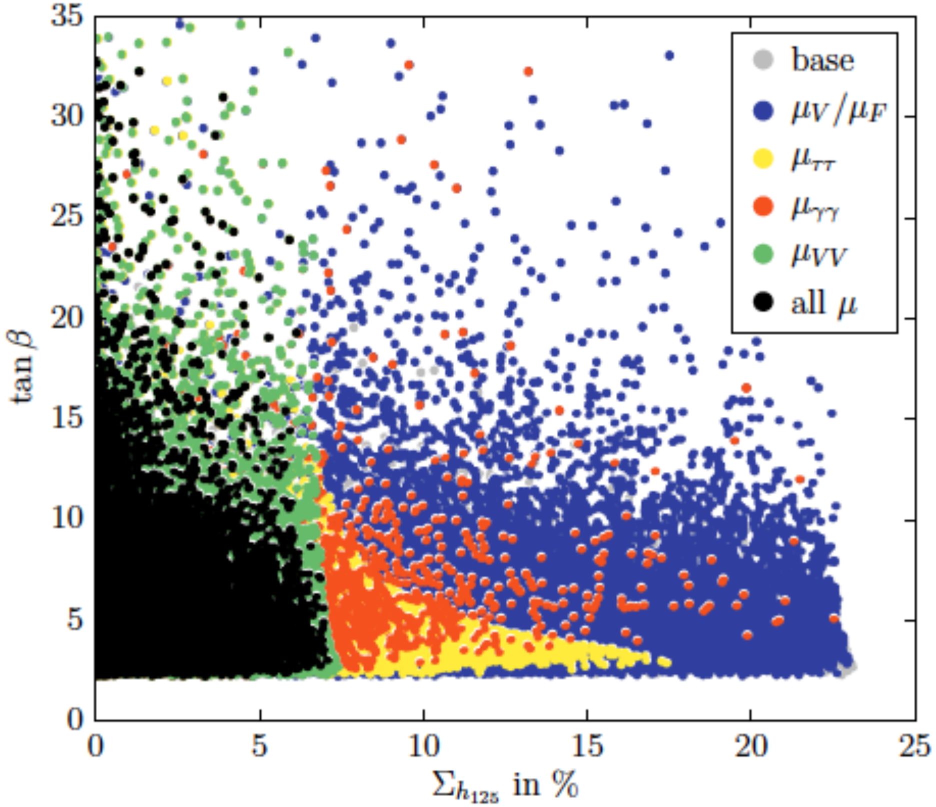


μ_V/μ_F vs $\mu_{\gamma\gamma}$ in type II 2HDM (left) and N2HDM (right) – in yellow the "right sign" and in pink the wrong sign points. Dashed lines are current limits. The h_{125} can be any of the H_i in the N2HDM and h or H in the 2HDM.

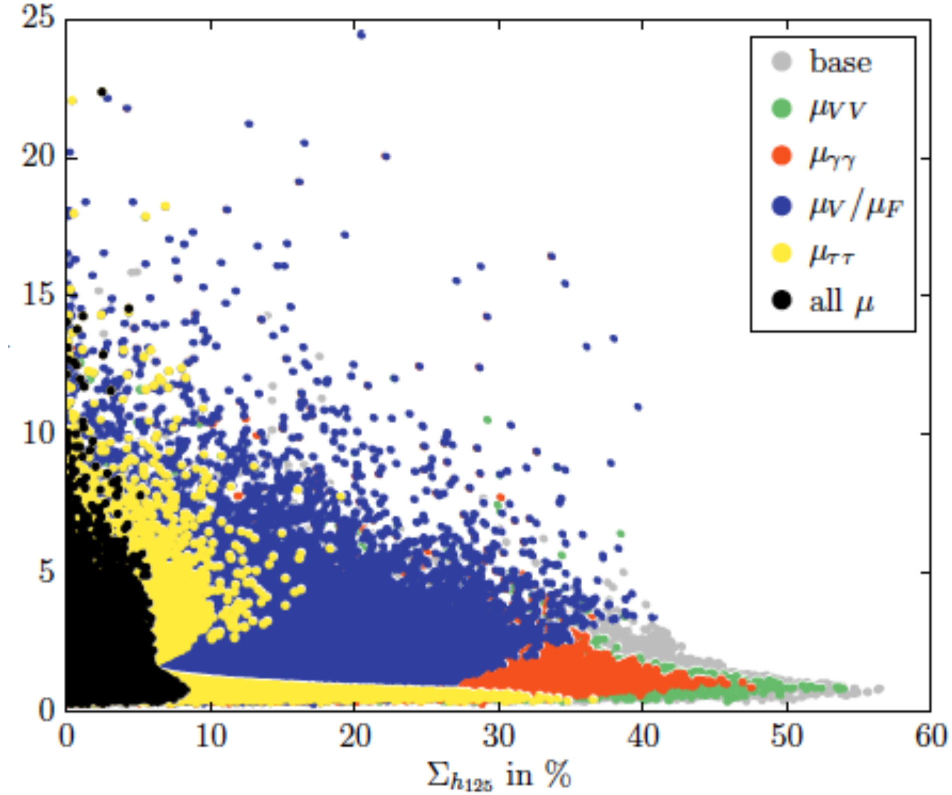
New variable that can be used to probe the wrong sign limit.

Singlet admixture

N2HDM type I



N2HDM type II



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

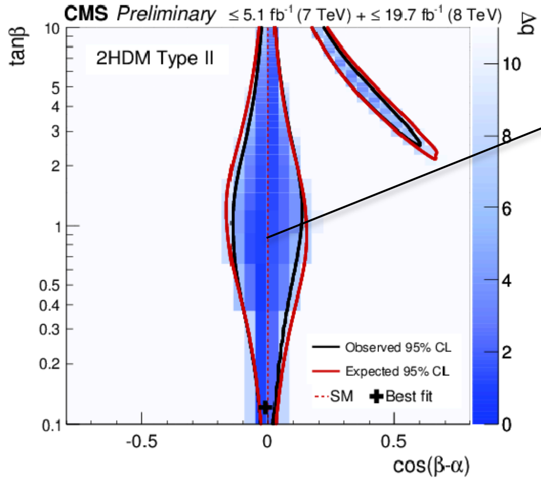
tanβ as a function of the singlet admixture for type I N2HDM (left) and type II N2HDM (right) – in grey all points with constraints; the remaining colours denote μ values measured within 5 % of the SM. In black all μ's. Singlet admixture slightly below 10 % almost independently of tanβ.

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

Back to The alignment limit in the 2HDM

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

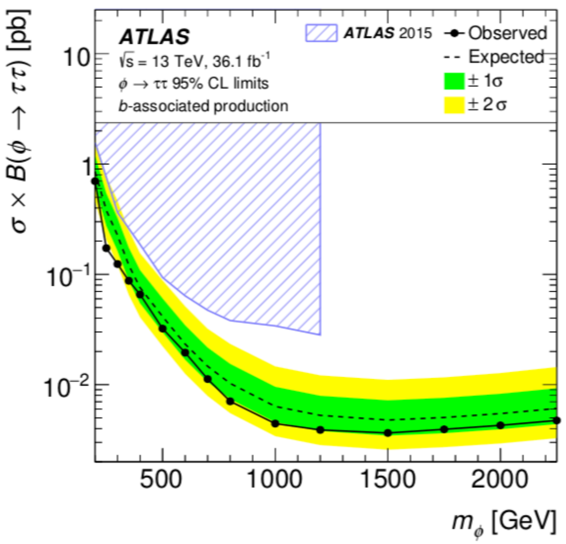
What about tanβ? All couplings of h125 with the other SM particles are SM-like (even hhh).



Even if in the end we will have a line only, the mixing between vevs can only be seen with new physics.

Two examples:

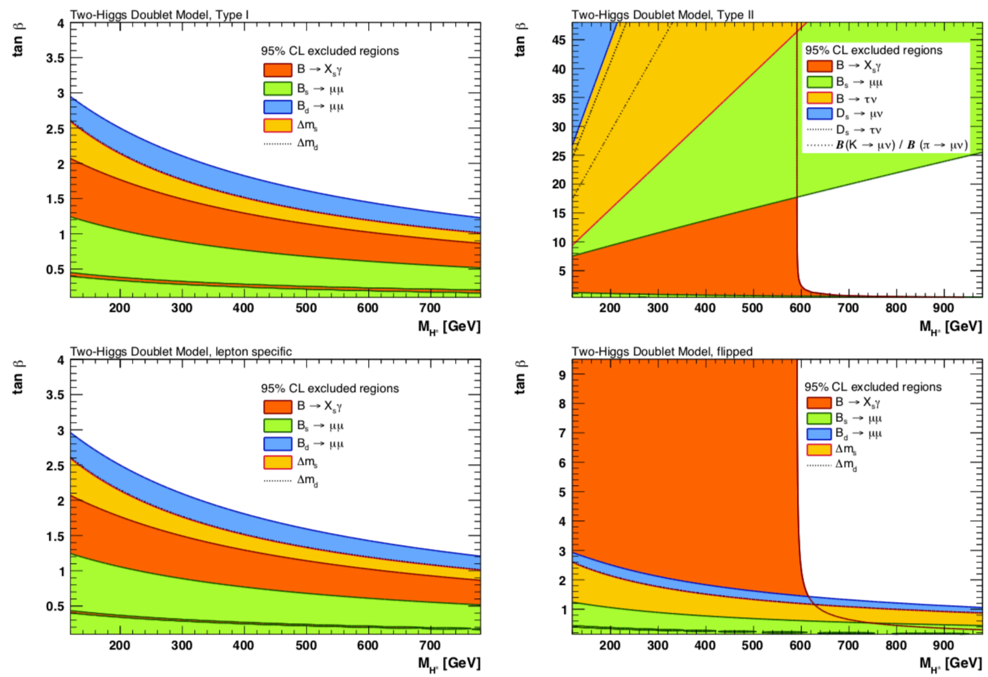
Haller, Hoecker, Kogler, Peiffer, Stelzer 1803.01853



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

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

ATLAS, JHEP01(2018)055

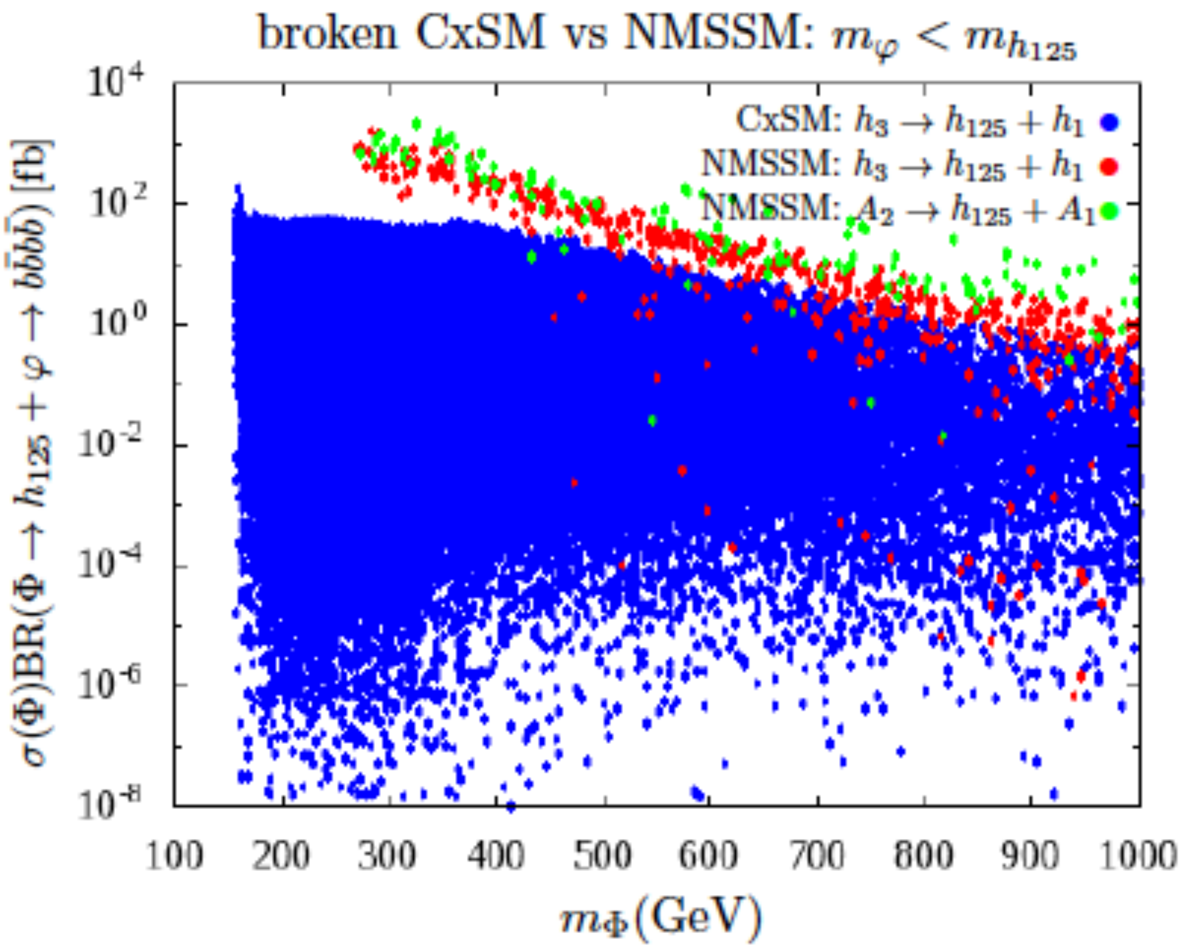


From B-physics: Charged Higgs loops – constraint in the charged Higgs mass, tanβ plane

3. Distinguishing models

The decay

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



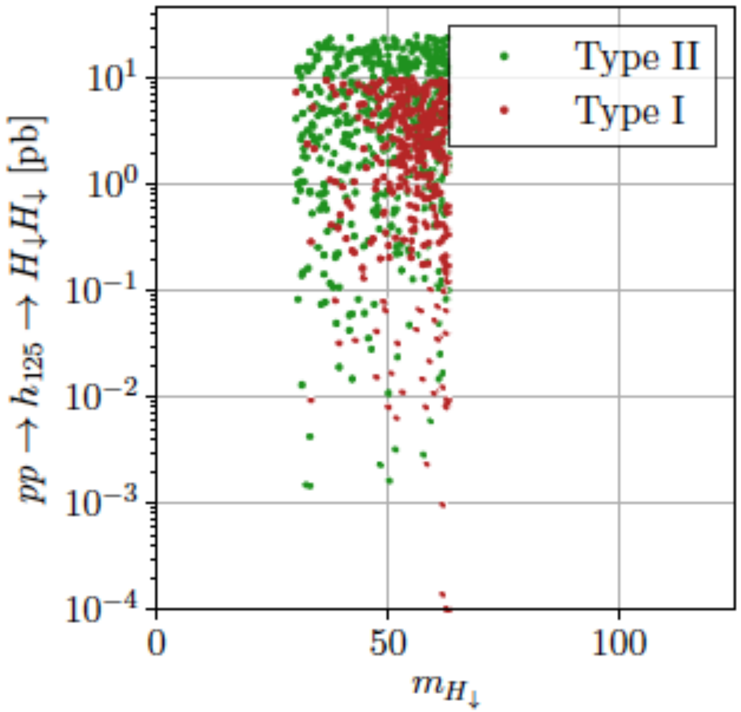
$\Phi \to h_{125} + \varphi$ found to be distinctive

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

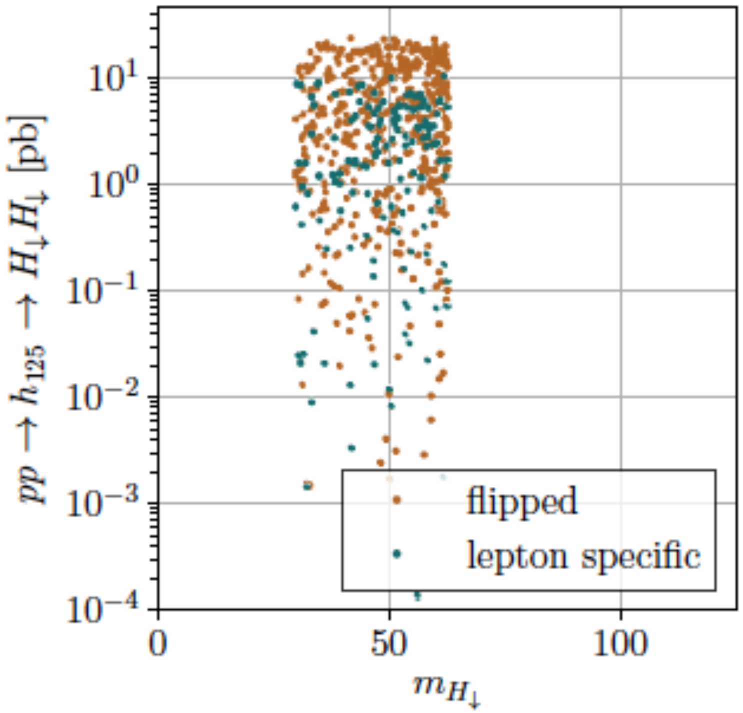
The models can be distinguished in some regions of the parameter space.

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

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



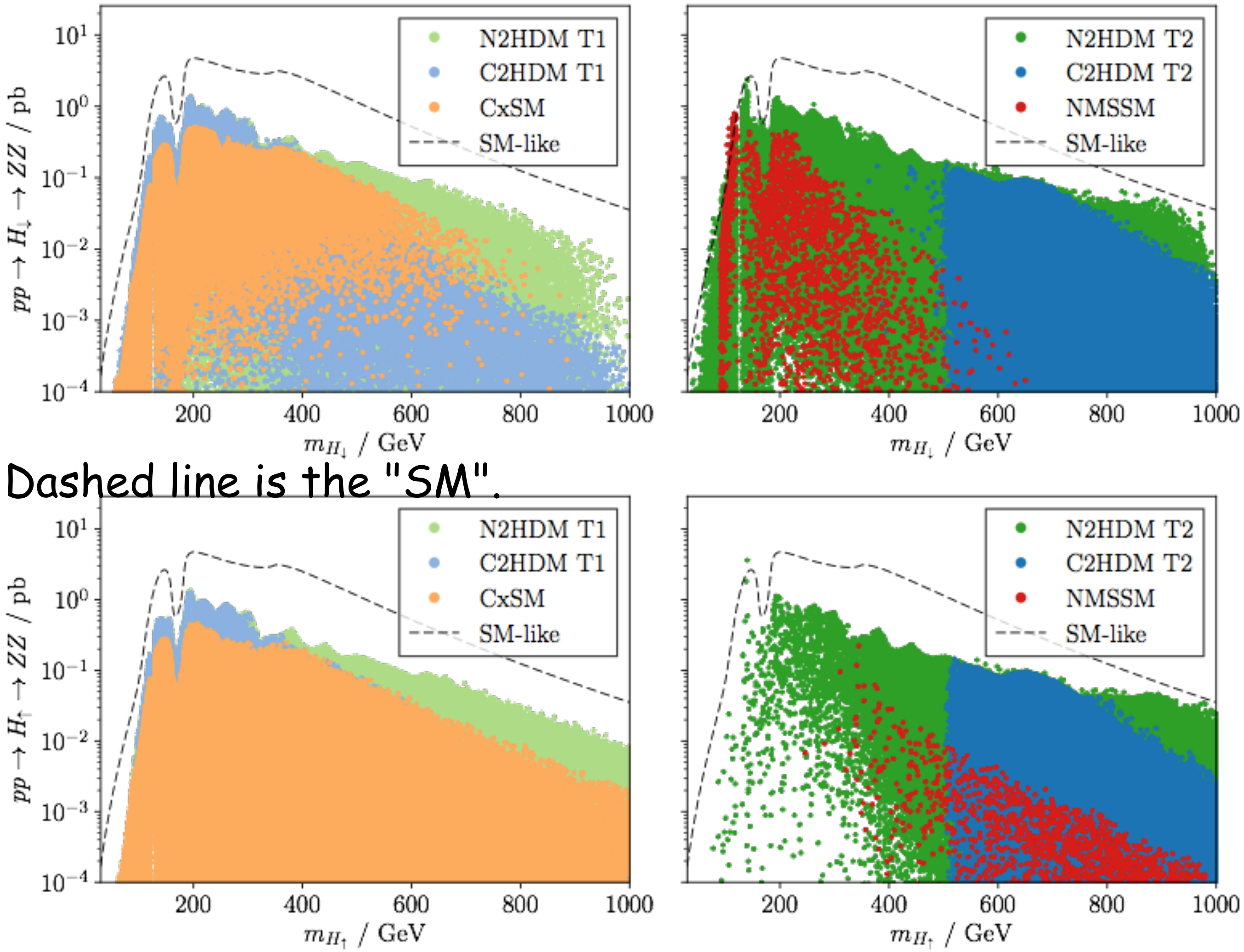
Left - Signal rates for the production of h_{125} decaying to $H_\downarrow H_\downarrow$ for 13 TeV as a function of m_H for Types I and II



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 CP-even to ZZ in different models



Dashed line is the "SM".

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.

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.

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:

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

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

And for the GM model

Consider the hWW coupling:

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

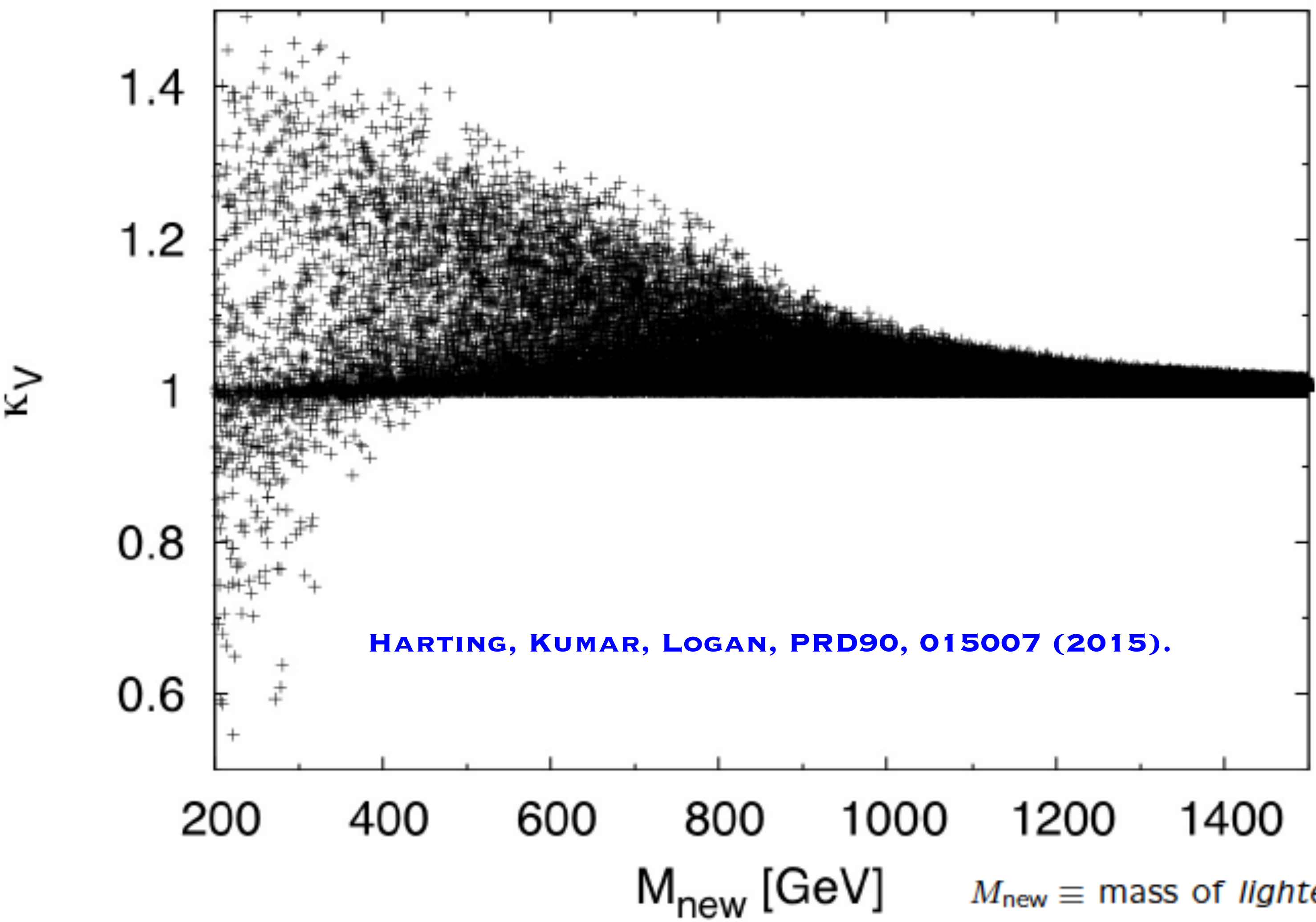
- 2HDM: $i\frac{g^2 v}{2} g_{\mu\nu} \sin(\beta - \alpha)$

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

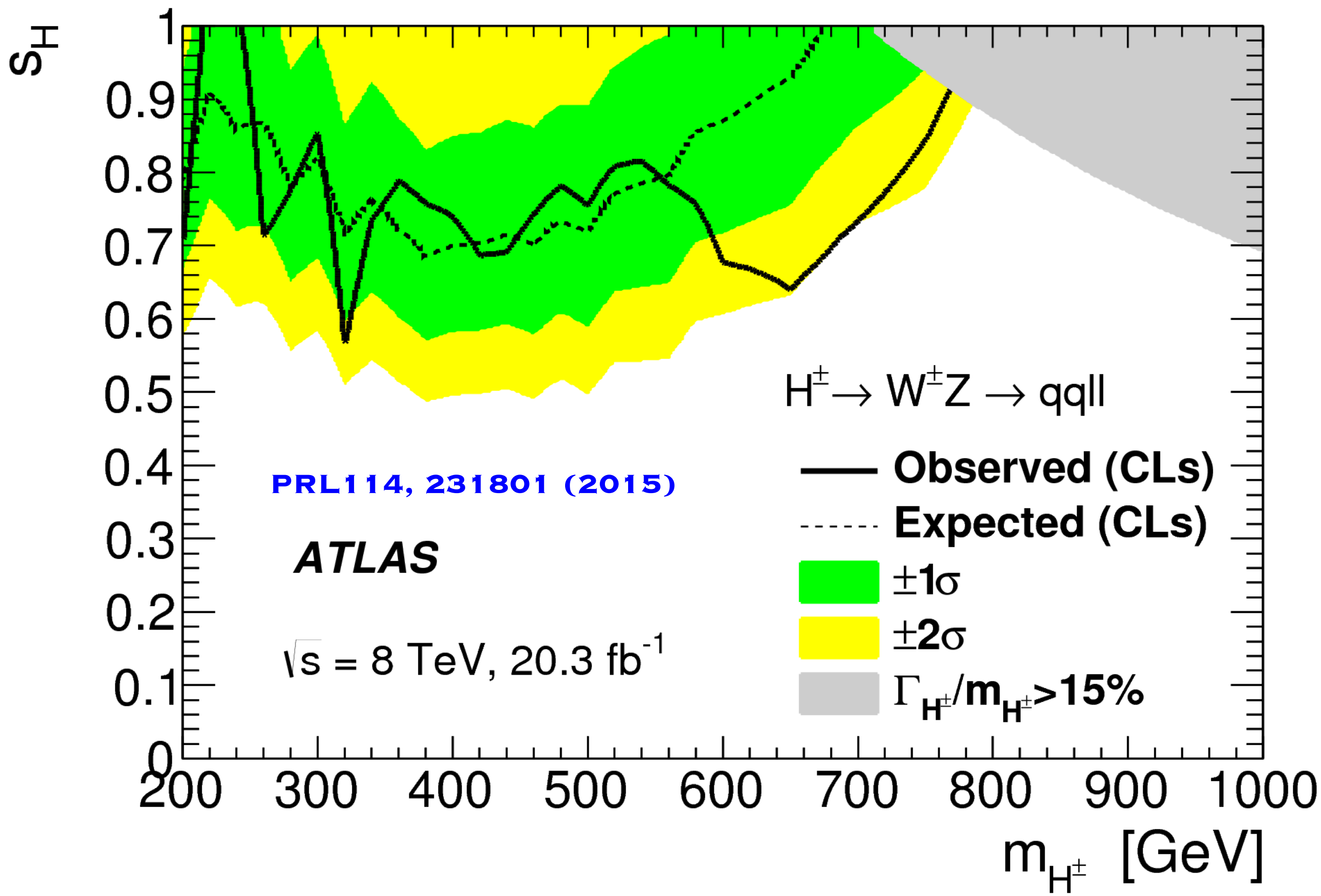
The only way to enhance the hWW (hZZ) coupling above its SM value is through a scalar with isospin ≥ 1 that has a non-negative vev and mixes into the observed Higgs h (triplets benchmark).

Numerical results: hVV coupling enhancement can be quite large!



$M_{new} \equiv$ mass of *lightest* new state.

The GM Model



Exclusion limits at the 95% CL for sH versus mH±in the Georgi-Machacek Higgs Triplet Model. Also included on the plot are the median, ± 1 σ and ± 2 σ values within which the limit is expected to lie in the absence of a signal.

Tools available for scans and decay rates

- Home
- 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 HiggsBounds and HiggsSignals. Included support for input in hybrid basis as defined in [1507.04281]. Improved treatment of off-shell H+ decays. Thanks to R. Hansen Addition of FCNC top decays. Thanks to L. Zethraeus Clean-up of obsolete features.

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)

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.

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

- 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`)

- 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/

BSMPT - Beyond the Standard Model Phase Transitions –

A Tool for the Electroweak Phase Transition in Extended Higgs Sectors

BASLER, MUHLLEITNER; 1803.02846

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]

The end and
Extra slides

We define the following admixtures

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

CxSM - SUM OF REAL AND COMPLEX COMPLEX SINGLET COMPONENTS

$$\Psi_i^{\rm C2HDM} = (R_{i3})^2$$

C2HDM – "PSEUDOSCALAR" COMPONENT

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

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 μ and amounts to

$$\Sigma_{\rm max}^{\rm CxSM} \approx 1 - \mu_{\rm min} \approx 11\%$$

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 – α

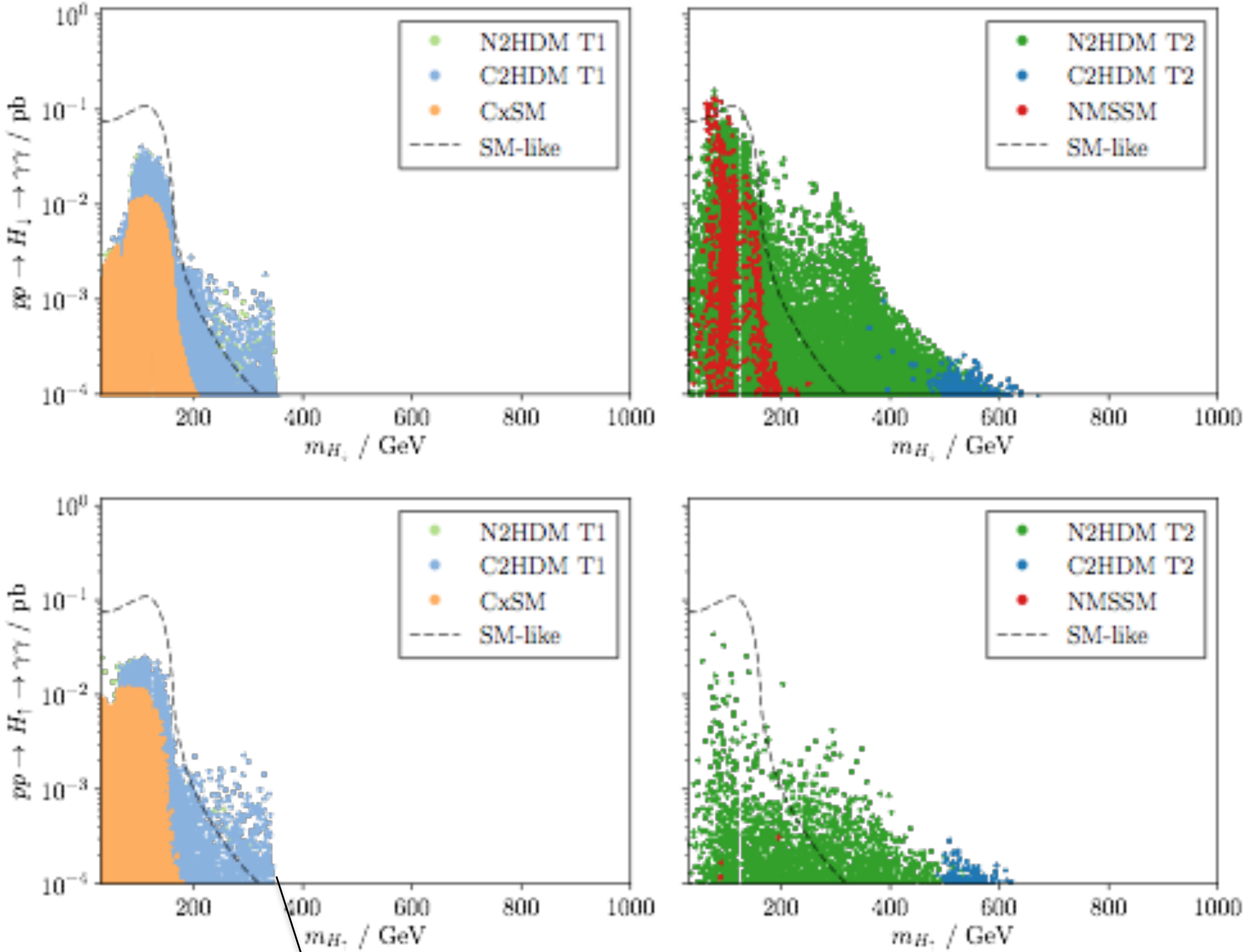
  CP-violating - α_1, α_2 and α_3

- soft breaking parameter

  CP-conserving – m^2_{12}

  CP-violating – $Re(m^2_{12})$

Non-125 to γγ



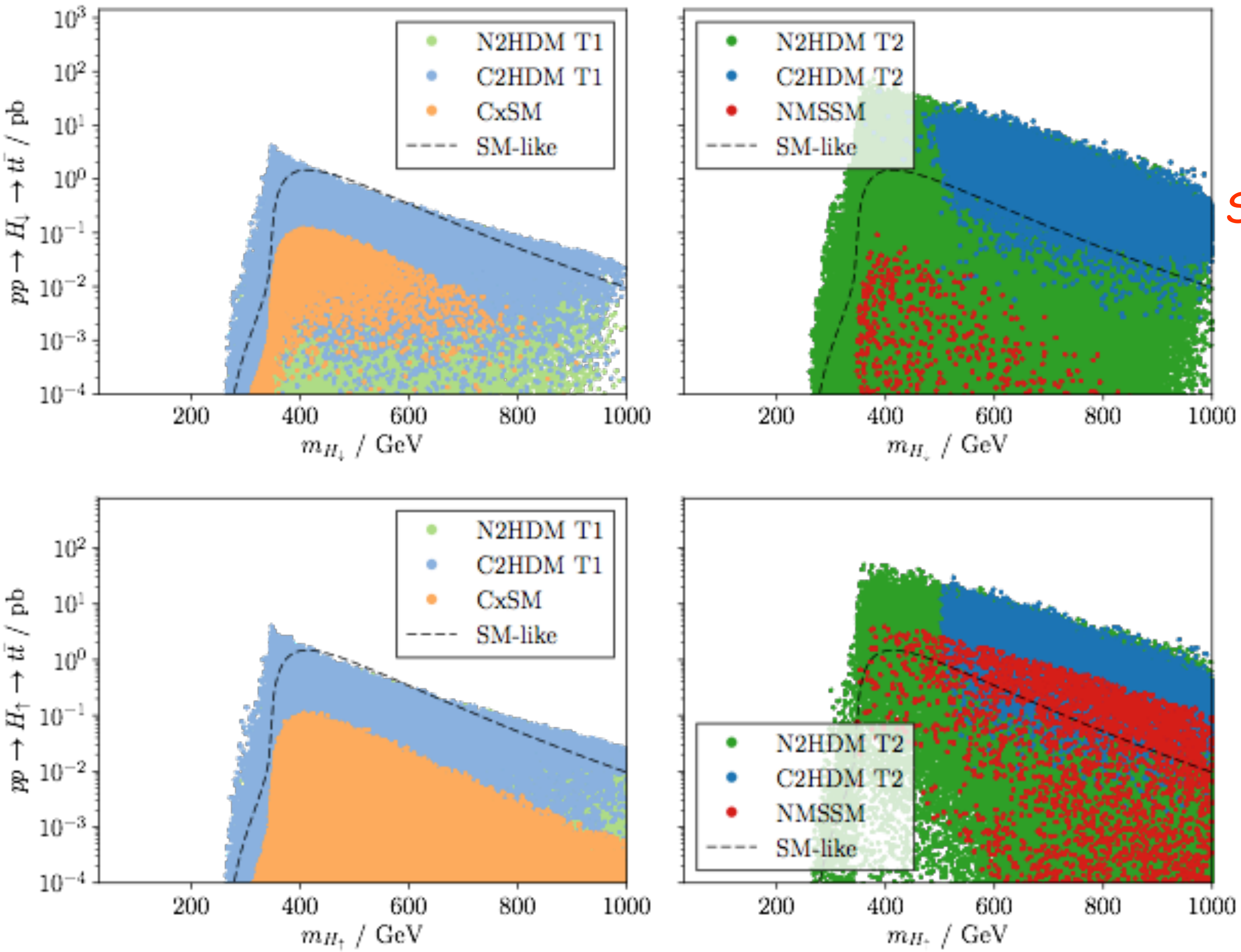
Signal rates for the production of H↓ (upper) and H↑ (lower) for 13 TeV as a function of m_H.
Dashed line is the "SM".

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

h to tt threshold

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

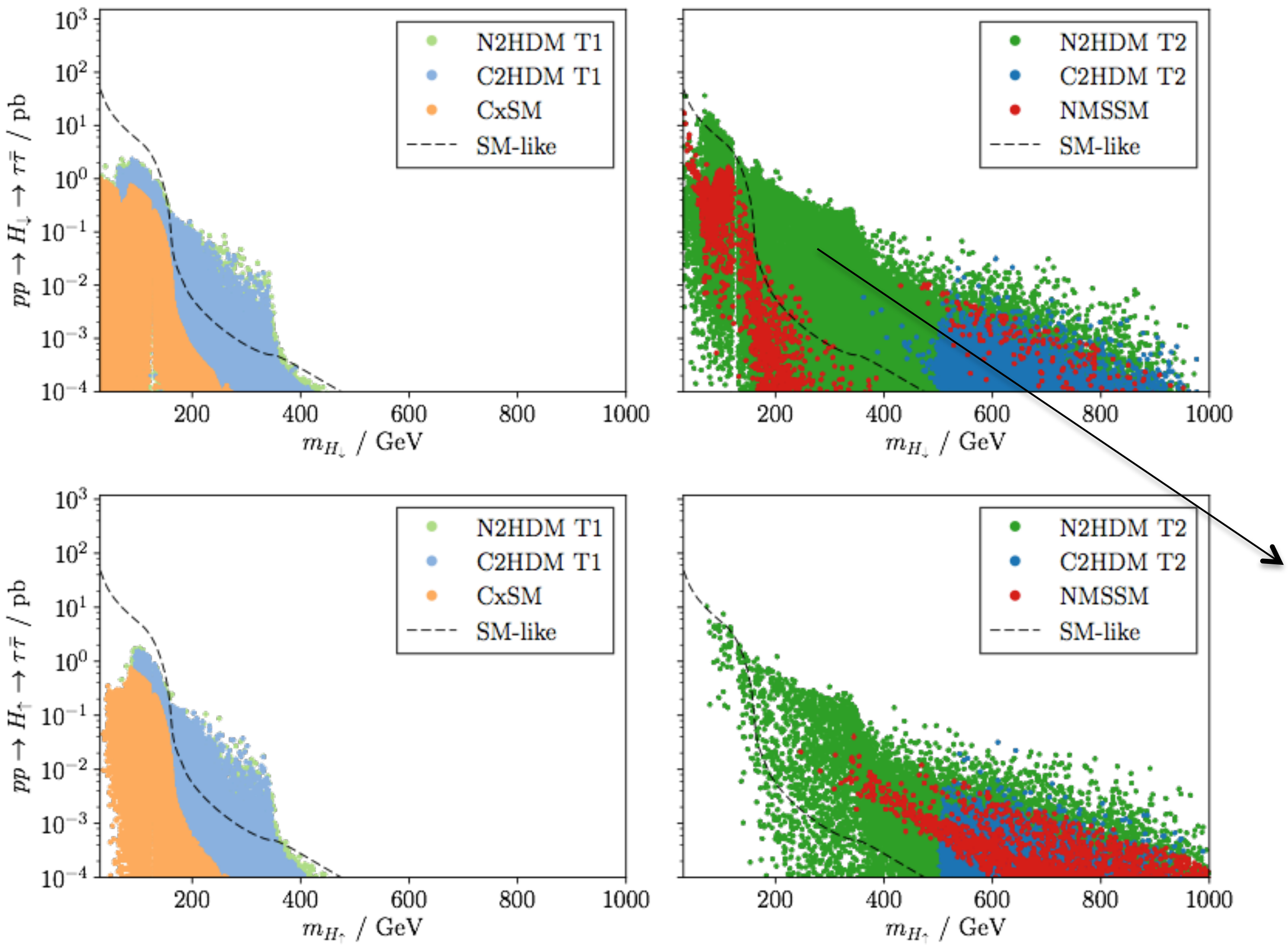
Non-125 to tt



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

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

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:

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

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!

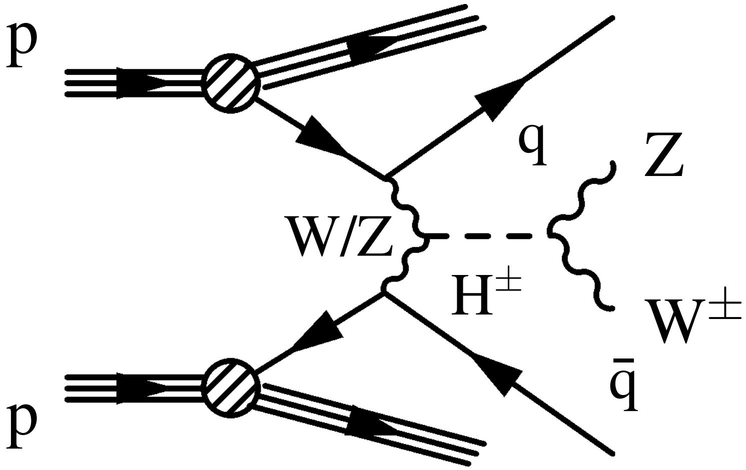
$\rightarrow$ Focus on direct searches for fermiophobic H_5 states

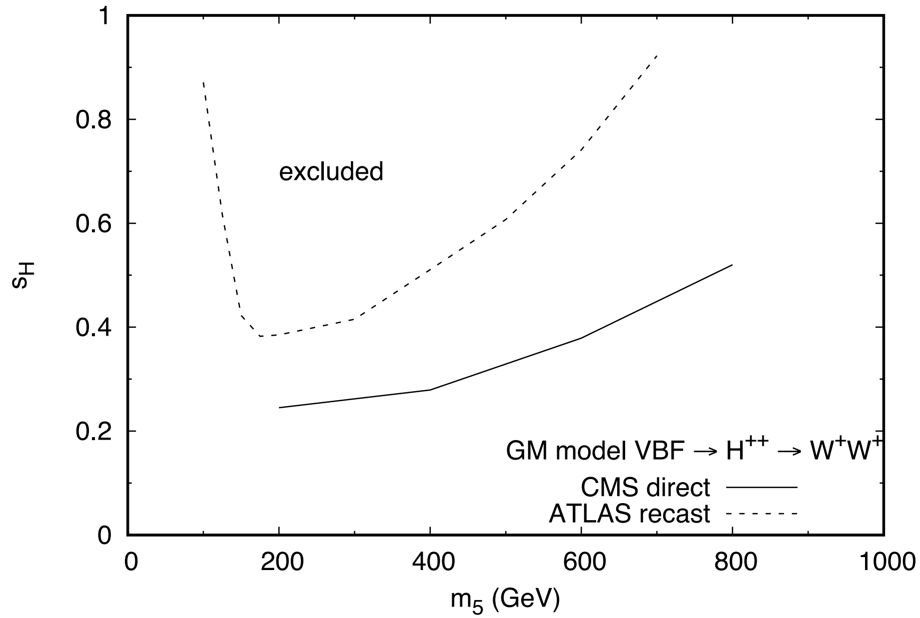
Focus for YR4:

VBF $\rightarrow H_5^{\pm\pm} \rightarrow W^\pm W^\pm$ — VBF + like-sign dileptons + MET

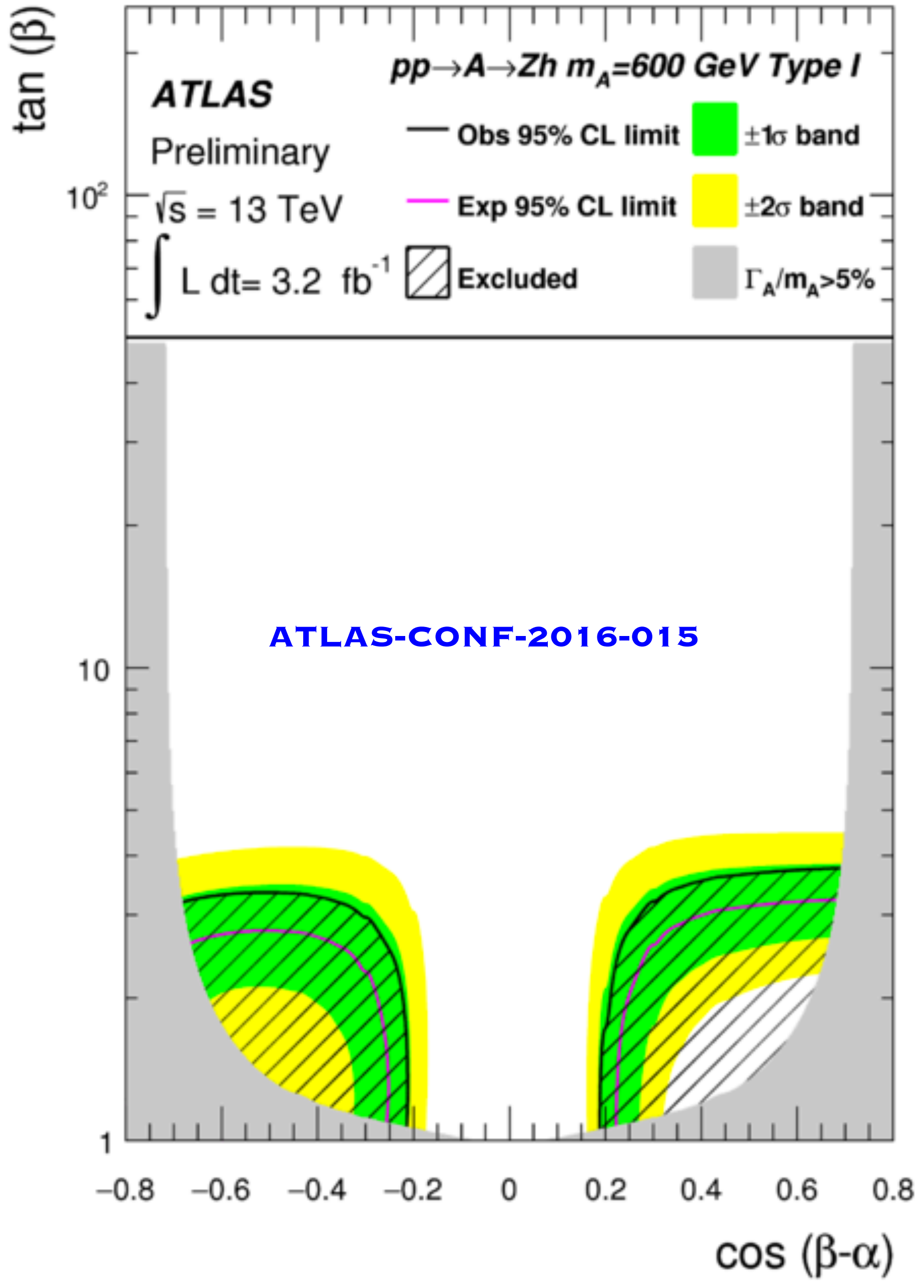
VBF $\rightarrow H_5^{\pm} \rightarrow W^\pm Z$ — VBF + $qq\ell\ell$; VBF + 3ℓ + MET

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





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



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 tanβ and cos(β - α) for mA = 600GeV. Variations of the natural width up to ΓA/mA=5% and different mixtures of gluon-fusion and b-quark-associated production are taken into account. Only points in parameter space where ΓA/mA < 5% are considered.

Searches roadmap

$H^{\pm} \to W^{\pm} V$

Triplets

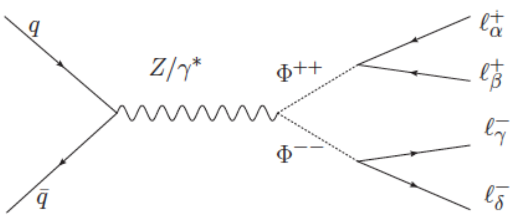
$H^{\pm} \to W^{\pm} Z$

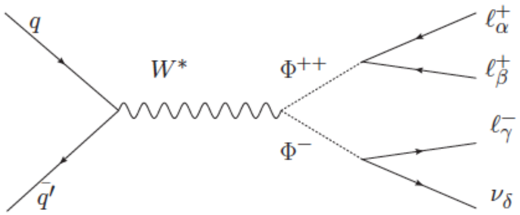
Done by ATLAS

$H^{\pm} \to W^{\pm} S$

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

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



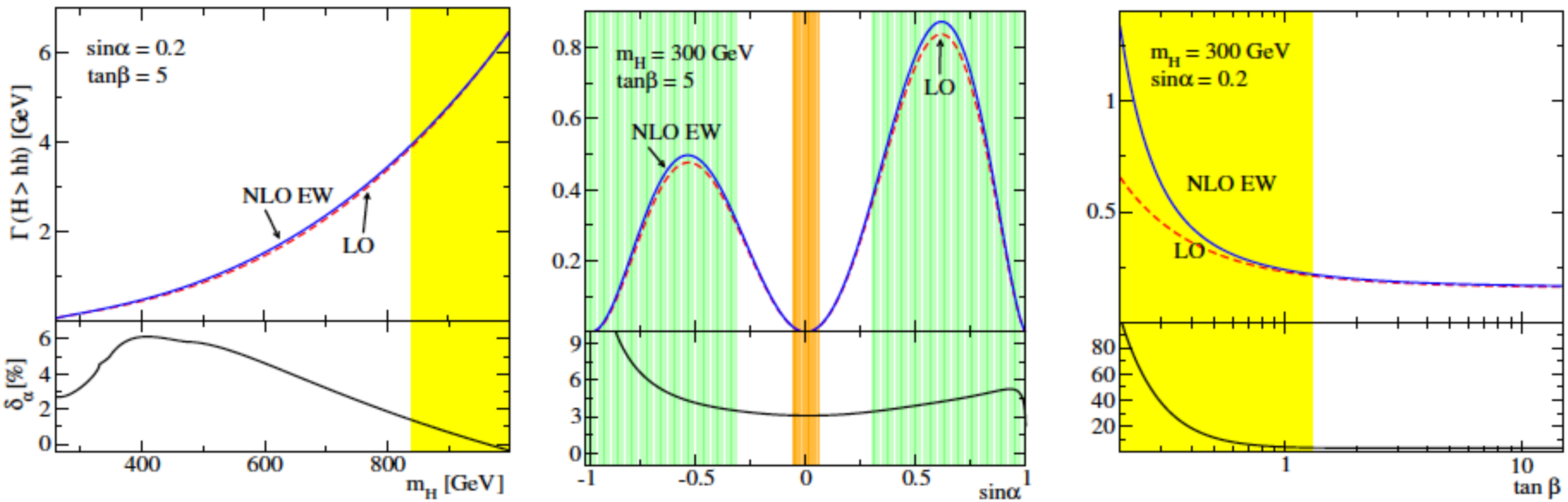


<u>Doubly charged Higgs</u> have been searched for in leptons and WW.

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

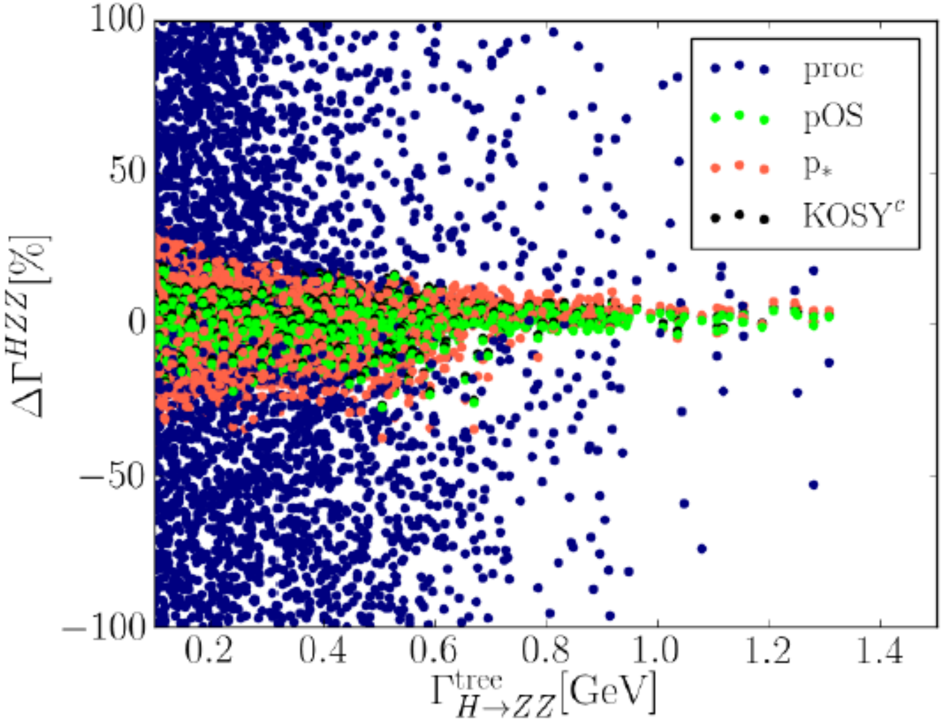


$H \to hh$

NLO Corrections shown to be only a few percent

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

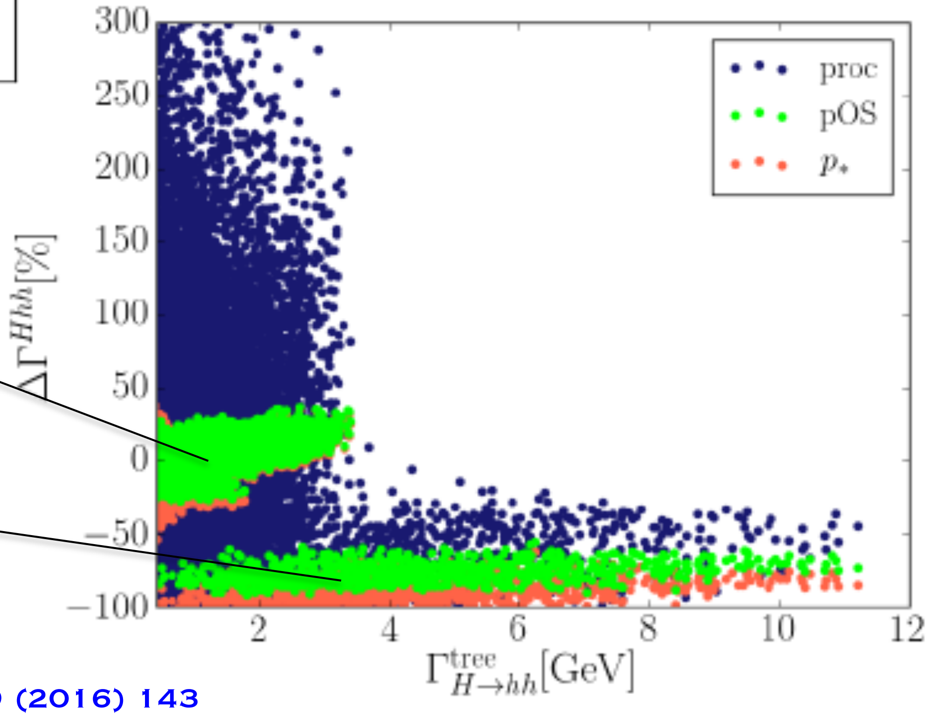
Real 2HDM



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

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_β (pOS^c)	6.12	8.39	4.79	3.53
α_1 (pOS)	-1.513	-1.526	-1.489	1.318
α_2 (pOS)	0.098	-0.308	0.225	0.0362
α_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
Γ_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 $H_{2/3} \to ZZ$. In round brackets we specify the scheme in which α and β 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^c	pOS^o	p$^c_\star$	p$^o_\star$
BRH2ZZhigh	$\Gamma^{\rm LO}(H_2 \to ZZ)$	0.989	0.989	1.008	1.008
	$\Gamma^{\rm NLO}(H_2 \to ZZ)$	1.120	1.122	1.142	1.148
	$\Delta\Gamma^{H_2ZZ}$ [%]	13.2	13.4	13.3	14.0
BRH3ZZhigh	$\Gamma^{\rm LO}(H_3 \to ZZ)$	0.755	0.755	0.782	0.782
	$\Gamma^{\rm NLO}(H_3 \to ZZ)$	0.872	0.867	0.890	0.889
	$\Delta\Gamma^{H_3ZZ}$ [%]	15.6	14.9	13.9	13.7
BRH2ZZlow	$\Gamma^{\rm LO}(H_2 \to ZZ)$	3.130×10^{-2}	3.130×10^{-2}	2.529×10^{-2}	2.533×10^{-2}
	$\Gamma^{\rm NLO}(H_2 \to ZZ)$	3.042×10^{-2}	3.040×10^{-2}	2.840×10^{-2}	2.745×10^{-2}
	$\Delta\Gamma^{H_2ZZ}$ [%]	-2.8	-2.9	12.3	8.4
BRH3ZZlow	$\Gamma^{\rm LO}(H_3 \to ZZ)$	2.870×10^{-2}	2.869×10^{-2}	3.430×10^{-2}	3.418×10^{-2}
	$\Gamma^{\rm NLO}(H_3 \to ZZ)$	2.990×10^{-2}	3.011×10^{-2}	3.593×10^{-2}	3.738×10^{-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.

KRAUSE, LOPEZ-VAL, MUHLLEITNER, RS, JHEP1712 (2017) 077

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!