Comparing extended scalar sectors at the LHC

R. Santos

ISEL & CFTC-UL & LIP-Braga

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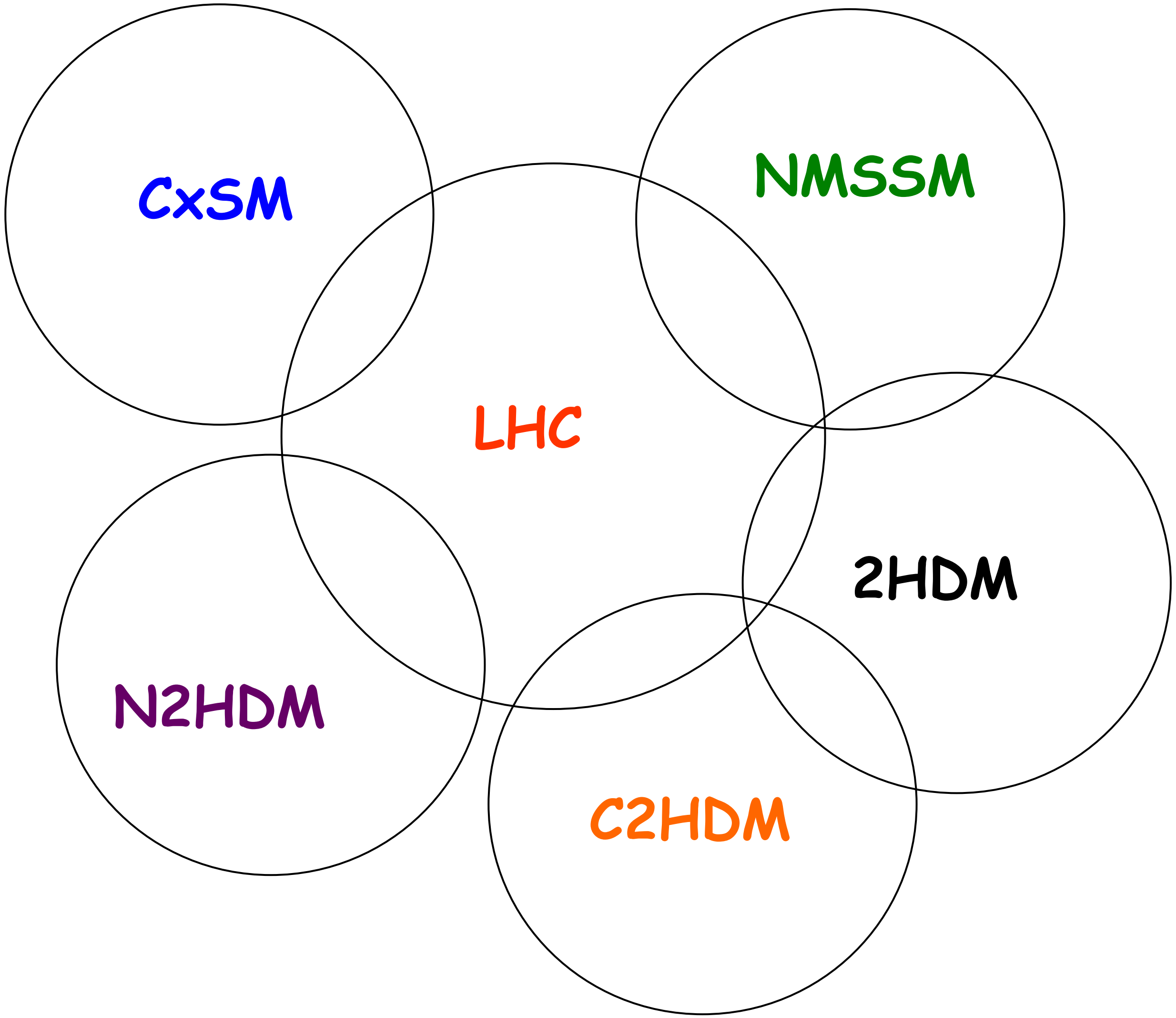
M. Mühlleitner, M. Sampaio, J. Wittbrodt (JHEP 1703 (2017) 094
and arXiv:1703.07750)

We have chosen some of the simplest extensions of the scalar sector and the NMSSM and try to find ways to distinguish them...



... if a scalar is found.

... with precision measurements.

- So far no new particles
- Discovered Higgs very SM-like

Already started

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.

- ↓ LHC HXSWG for BSM Higgs (WG3)
- ↓ Group organization
- ↓ Svn repository and tools
- ↓ Meetings
- ↓ Mailing lists
- ↓ WG3 related documentation
- ↓ General documentation

Working Group 3: Sub-group – Neutral 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

arXiv:1610.07922v1

Can the LHC Higgs phenomenology and in particular signal rates and coupling measurements be used to distinguish models with extended Higgs sectors?

How efficiently can the parameter space of the models be constrained through measurements of the Higgs properties?

The models

- **Complex Singlet Extension of the SM - CxSM**

  Scalar sector – 3 CP-even neutral scalars

- **Two-Higgs Doublet Model (Real) – 2HDM**

  Scalar sector – 2 CP-even and 1 CP-odd neutral scalars plus 2 charged scalars

- **Two-Higgs Doublet Model (Complex) – C2HDM**

  Scalar sector – 3 neutral scalars plus 2 charged scalars

- **Next-to-Minimal 2HDM (Real) – N2HDM**

  Scalar sector – 3 CP-even and 1 CP-odd neutral scalars plus 2 charged scalars

- **NMSSM**

  Scalar sector – 3 CP-even and 2 CP-odd neutral scalars plus 2 charged scalars

ScannerS

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Home

ScannerS is a C++ tool for scanning the parameter space of arbitrary scalar extensions of the Standard Model (SM), which is designed for an easy implementation of experimental results/bounds by the user. The code also contains various example implementations such as the Two Higgs Doublet Model (2HDM) and a complex singlet extension with or without dark matter (xSM) -- See References.

The code provides a convenient way to perform parameter space scans while applying phenomenological bounds using various interfaces to codes such as HiggsBounds/Signals, Superiso, SusHi, Hdecay and MicrOmegas.

Currently the code contains several core routines to numerically generate (on each scanning step) a local minimum (vacuum) from an arbitrary scalar potential expression. The potential and various options are specified by the user in a Mathematica notebook. The notebook generates an input file which is used in the main C++ code where the scanning analysis is specified. The core code contains routines to: test tree level unitarity; detect symmetries for the mixing matrix; detect flat directions and degenerate states; and various template functions to test the stability of the potential as well as to impose constraints (see comments in the code and the manual for more information).

Please contact us if you have problems and/or suggestions.

R. Coimbra, M. O. P. Sampaio and R. Santos,"ScannerS: Constraining the phase diagram of a complex scalar singlet at the LHC", Eur. Phys. J. C (2013) 73:2428, arXiv:1301.2599 [hep-ph]

P.M. Ferreira, Renato Guedes, Marco O. P. Sampaio, Rui Santos, "Wrong sign and symmetric limits and non-decoupling in 2HDMs", arXiv:1409.6723 [hep-ph]

sHDECAY

The program sHDECAY is a modified version of the latest release of HDECAY 6.50.
It allows for the calculation of the partial decay widths and branching ratios of the
Higgs bosons in the real and in the complex singlet extensions of the Standard Model,
both in the broken and the dark matter phase of the models.

Released by: Raul Costa, Margarete Mühlleitner, Marco Sampaio and Rui Santos
Program: sHDECAY obtained from extending HDECAY 6.50

When you use this program, please cite the following references:

sHDECAY:	R. Costa, M. Mühlleitner, M. Sampaio, R. Santos, JHEP 06 (2016) 034, arXiv 1512.05355
HDECAY:	A. Djouadi, J. Kalinowski, M. Spira, Comput. Phys. Commun. 108 (1998) 56
An update of HDECAY:	A. Djouadi, J. Kalinowski, Margarete Muhlleitner, M. Spira, in arXiv:1003.1643

Informations on the Program:

- Short explanations on the program are given here.
- To be advised about future updates or important modifications, send an E-mail to margarete.muehlleitner@kit.edu.
- NEW: Modifs/corrected bugs are indicated explicitly in this file (10 Oct 2016).

Downloading the files needed for sHDECAY:

- shdecay.tar.gz contains the program package files: the input file shdecay.in; shdecay.f, dmb.f, elw.f, feynhiggs.f, haber.f, hgaga.f, hgg.f, hsqsq.f, susylha.f.
- makefile for the compilation.

Example for an output file:

The input file shdecay.in provides the output files br.rb11, br.rb12, br.rb13, br.rb21, br.rb22, br.rb23, br.rd11, br.rd12, br.rd13, br.cb11, br.cb12, br.cb13, br.cb21, br.cb22, br.cb23, br.cb31, br.cb32, br.cb33, br.cd11, br.cd12, br.cd13, br.cd21, br.cd22, and br.cd23.

N2HDECAY

The program N2HDECAY is a modified version of HDECAY 6.51.
It allows for the calculation of the partial decay widths and branching ratios of the Higgs bosons of the N2HDM, i.e. the CP-conserving 2HDM extended by a real scalar singlet field.

Released by: Margarete Mühlleitner, Marco Sampaio, Rui Santos and Jonas Wittbrodt
Program: N2HDECAY obtained from extending HDECAY 6.51

When you use this program, please cite the following references:

N2HDECAY:	M. Mühlleitner, M. Sampaio, R. Santos, J. Wittbrodt, arXiv 1611.xxyyz
HDECAY:	A. Djouadi, J. Kalinowski, M. Spira, Comput. Phys. Commun. 108 (1998) 56
An update of HDECAY:	A. Djouadi, J. Kalinowski, Margarete Muhlleitner, M. Spira, in arXiv:1003.1643

Informations on the Program:

- Short explanations on the program are given here.
- To be advised about future updates or important modifications, send an E-mail to jonas.wittbrodt@desy.de, margarete.muehlleitner@kit.edu.
- NEW: Modifs/corrected bugs are indicated explicitly in this file.

Downloading the files needed for N2HDECAY:

- n2hdecayfiles.tar.gz contains the program package files: the input file n2hdecay.in; n2hdecay.f, dmb.f, elw.f, feynhiggs.f, haber.f, hgaga.f, hgg.f, hsqsq.f, susylha.f.
- makefile for the compilation.

Example for an output file:

The input file n2hdecay.in provides the output files br.H1_N2HDM_a, br.H1_N2HDM_b, br.H1_N2HDM_c, br.H2_N2HDM_a, br.H2_N2HDM_b, br.H2_N2HDM_c, br.H3_N2HDM_a, br.H3_N2HDM_b, br.H3_N2HDM_c, br.H3_N2HDM_d, br.A_N2HDM_a, br.A_N2HDM_b, br.A_N2HDM_c, br.H+_N2HDM_a, br.H+_N2HDM_b and br.H+_N2HDM_c

The CxSM

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	$\langle A \rangle = 0$ ($\cancel{\mathbb{U}}(1) \to \mathbb{Z}_2'$)
$\mathbb{Z}_2 \times \mathbb{Z}_2'$	Higgs + 2 dark	$\langle \mathbb{S} \rangle = 0$
	2 mixed + 1 dark	$\langle A \rangle = 0$ ($\cancel{\mathbb{Z}_2} \times \mathbb{Z}_2' \to \mathbb{Z}_2'$)
$\mathbb{Z}_2'$	2 mixed + 1 dark	$\langle A \rangle = 0$
	3 mixed	$\langle \mathbb{S} \rangle \neq 0$ ($\cancel{\mathbb{Z}_2'}$)

$$\mathbb{S} \to \mathbb{S}^* \Rightarrow A \to -A$$

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

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

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

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

The (C)2HDM

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

Softly broken Z_2 symmetric

we choose a vacuum configuration

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

- 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)

Parameters

- $\boxed{\tan\beta = \frac{v_2}{v_1}}$ 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 – $\mathrm{Re}(m^2_{12})$

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

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

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

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

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

Lightest Higgs couplings to gauge bosons

$$\boxed{\alpha_1 = \alpha + \pi/2}$$

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

$$\boxed{g_{C2HDM}^{hVV} = (c_\beta R_{11} + s_\beta R_{12})\ g_{SM}^{hVV} = \cos(\alpha_2)\cos(\beta-\alpha_1)\ g_{SM}^{hVV} = \cos(\alpha_2) g_{2HDM}^{hVV}}$$

$$\boxed{g_{N2HDM}^{hVV} = (c_\beta R_{11} + s_\beta R_{12})\ g_{SM}^{hVV} = \cos(\alpha_2)\cos(\beta-\alpha_1)\ g_{SM}^{hVV} = \cos(\alpha_2) g_{2HDM}^{hVV}}$$

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

Real component (singlet)

Imaginary component (singlet)

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

Lightest Higgs couplings to gauge bosons

$$\boxed{\alpha_1 = \alpha + \pi/2}$$

$$\boxed{g^{hVV}_{C2HDM} = (c_\beta R_{11} + s_\beta R_{12})\ g^{hVV}_{SM} = \cos(\alpha_2)\cos(\beta - \alpha_1)\ g^{hVV}_{SM} = \cos(\alpha_2) g^{hVV}_{2HDM}}$$

"Pseudoscalar" component (doublet)

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

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

CP-violating

$$\boxed{g^{hVV}_{N2HDM} = (c_\beta R_{11} + s_\beta R_{12})\ g^{hVV}_{SM} = \cos(\alpha_2)\cos(\beta - \alpha_1)\ g^{hVV}_{SM} = \cos(\alpha_2) g^{hVV}_{2HDM}}$$

CP-conserving

singlet component

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

Lightest Higgs Yukawa couplings

- No FCNC at tree-level - all come in four version except CxSM

2HDM AND C2HDM

$$\boxed{\Phi_1 \to \Phi_1\,, \quad \Phi_2 \to -\Phi_2}$$

N2HDM

	Φ_1	Φ_2	Φ_S
$\mathbb{Z}_2$ (explicitly broken, softly)	$+$	$-$	$+$
$\mathbb{Z}'_2$ (spontaneously broken)	$+$	$+$	$-$

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

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

Type F/Y $\quad \kappa_U^F = \kappa_L^F = \dfrac{\cos\alpha}{\sin\beta} \qquad \kappa_D^F = -\dfrac{\sin\alpha}{\cos\beta}$

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

2HDM

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

Lightest Higgs Yukawa couplings

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

CP-CONSERVING

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

CP-VIOLATING

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

when $s_2 \to 0$

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

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

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

The N2HDM
singlet admixture and
wrong-sign Yukawa

$$30 \text{ GeV} \leq m_{H_i \neq m_{h_{125}}}, m_A \leq 1 \text{ TeV}$$

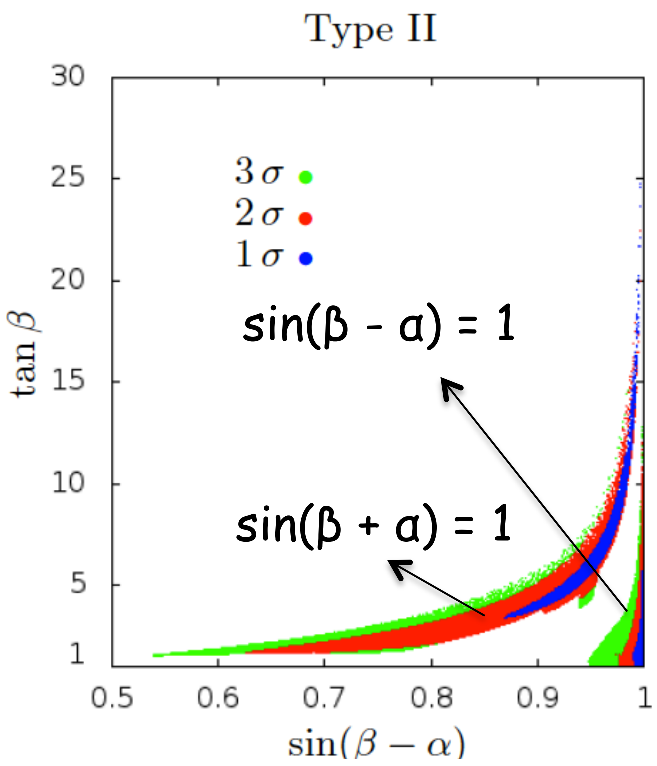
$$80 \text{ GeV} \leq m_{H^\pm} < 1 \text{ TeV (type I)} \qquad 560 \text{ GeV} \leq m_{H^\pm} < 1 \text{ TeV (type II)}$$

Alignment and wrong-sign Yukawa

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

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

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).



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

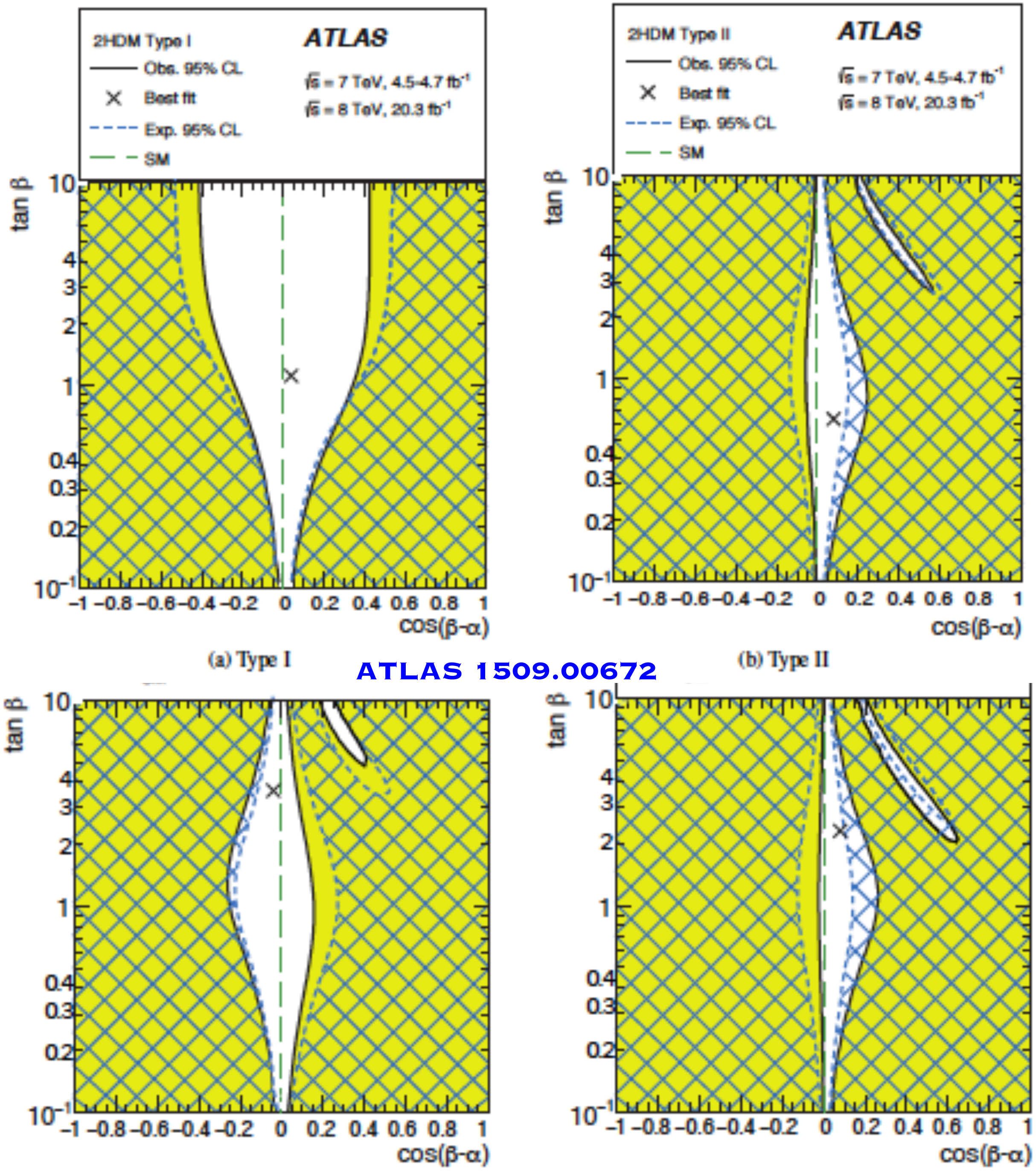
at tree-level

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

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

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

The 2HDM



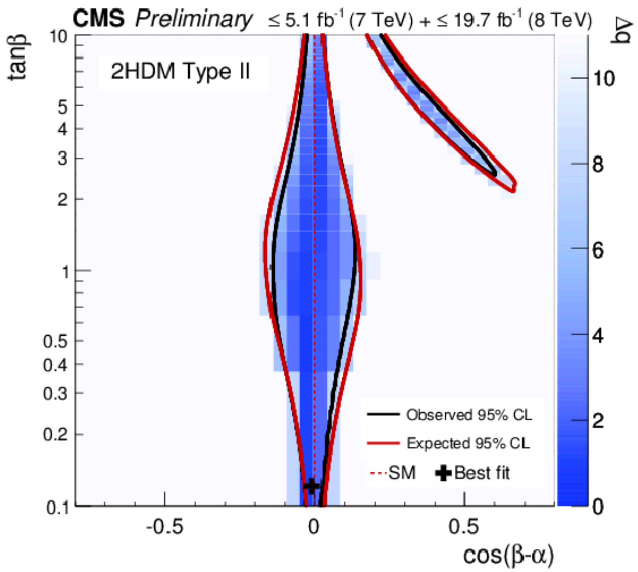
(a) Type I

(b) Type II

(c) Lepton-specific

(d) Flipped

ATLAS 1509.00672



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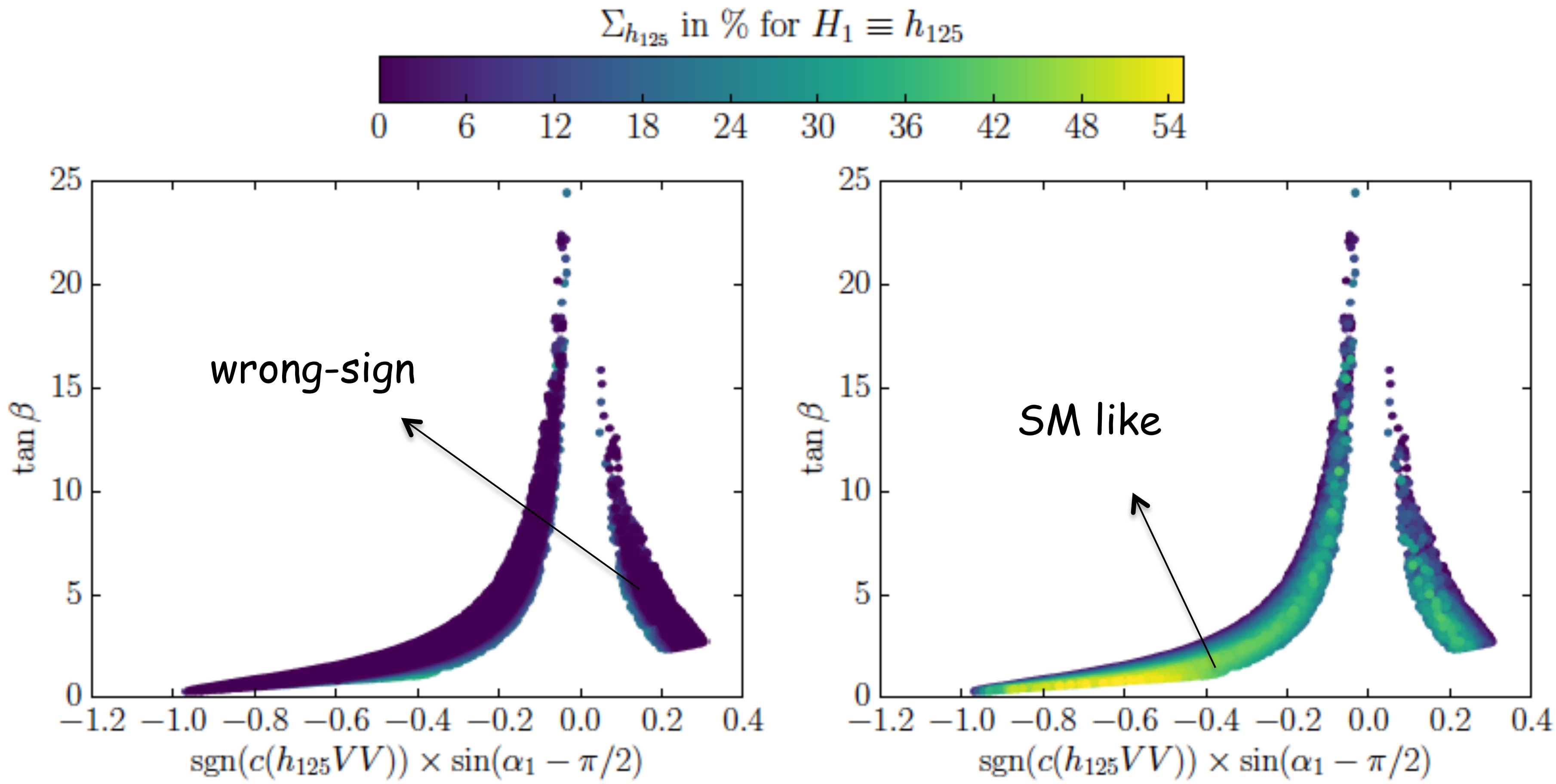
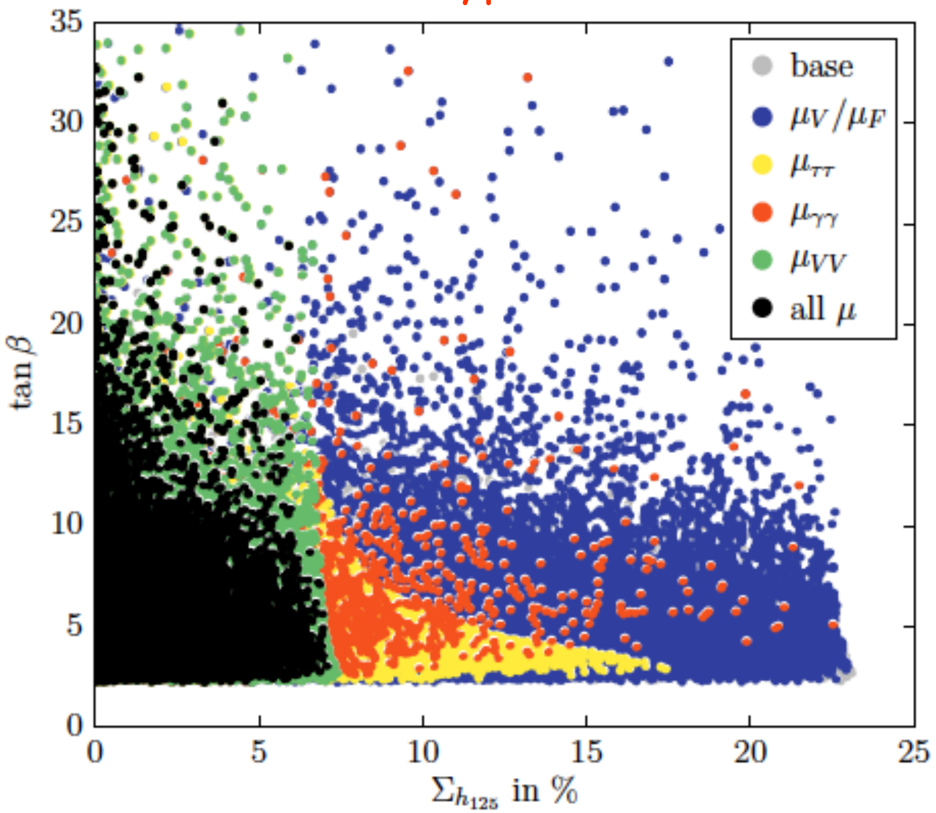
Singlet admixture



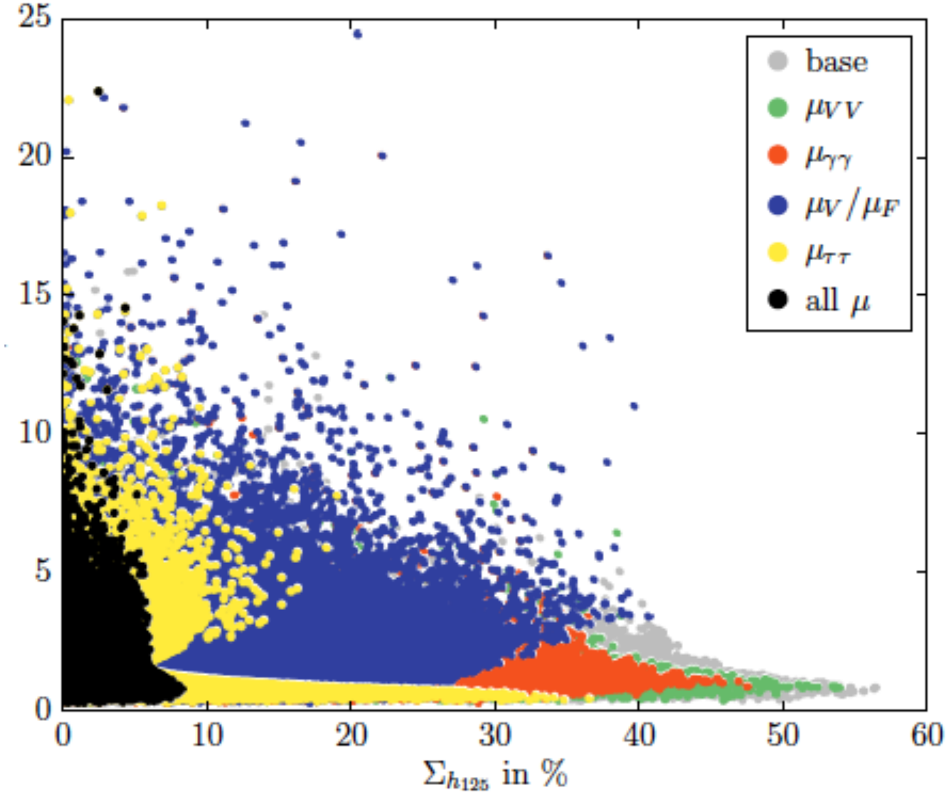
SM-like and wrong-sign limit in the N2HDM type II – the interesting fact is that in the alignment limit the singlet admixture can go up to 54 %.

Singlet admixture

N2HDM type I

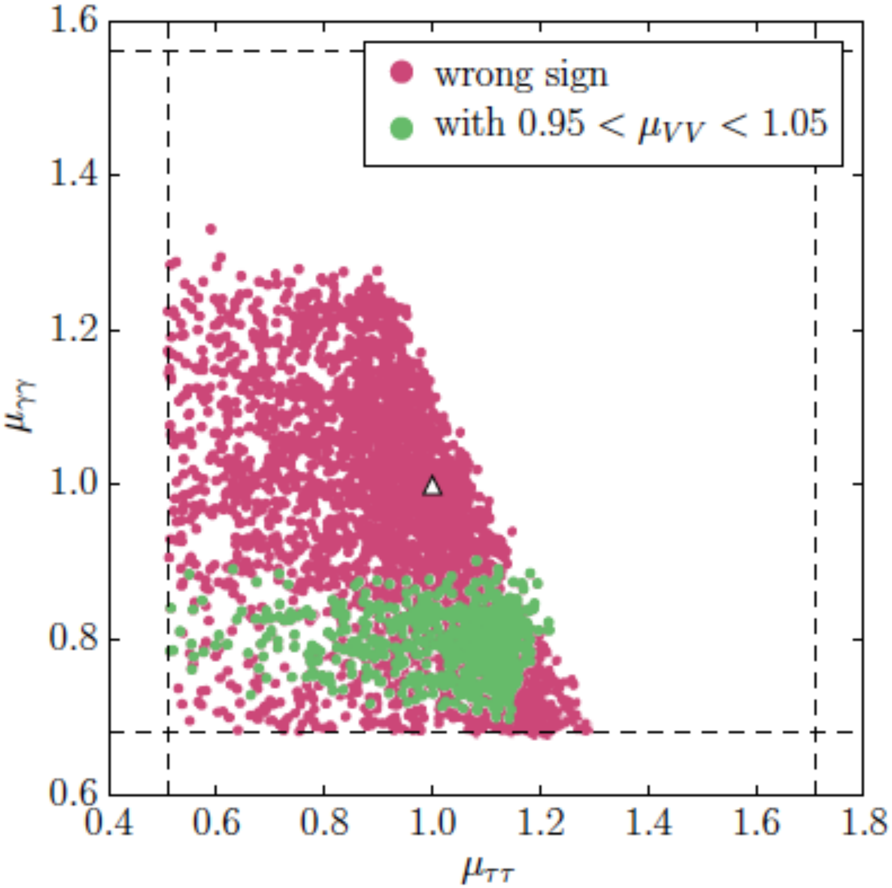


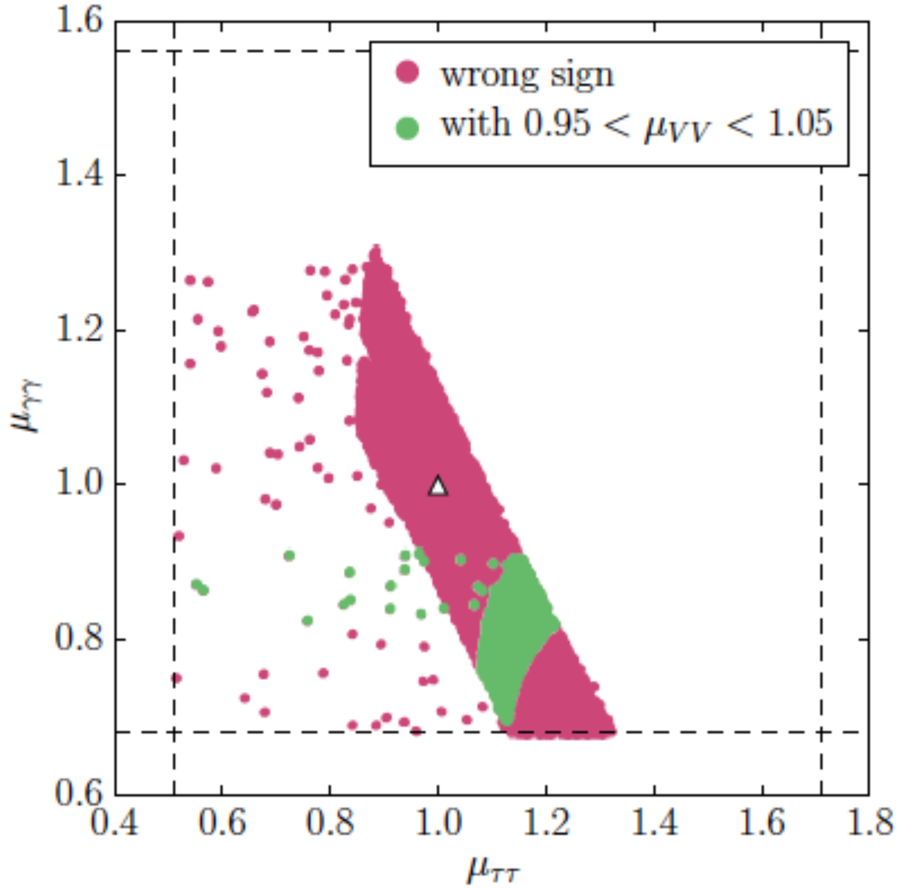
N2HDM type II



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.

Wrong sign in the 2HDM and N2HDM



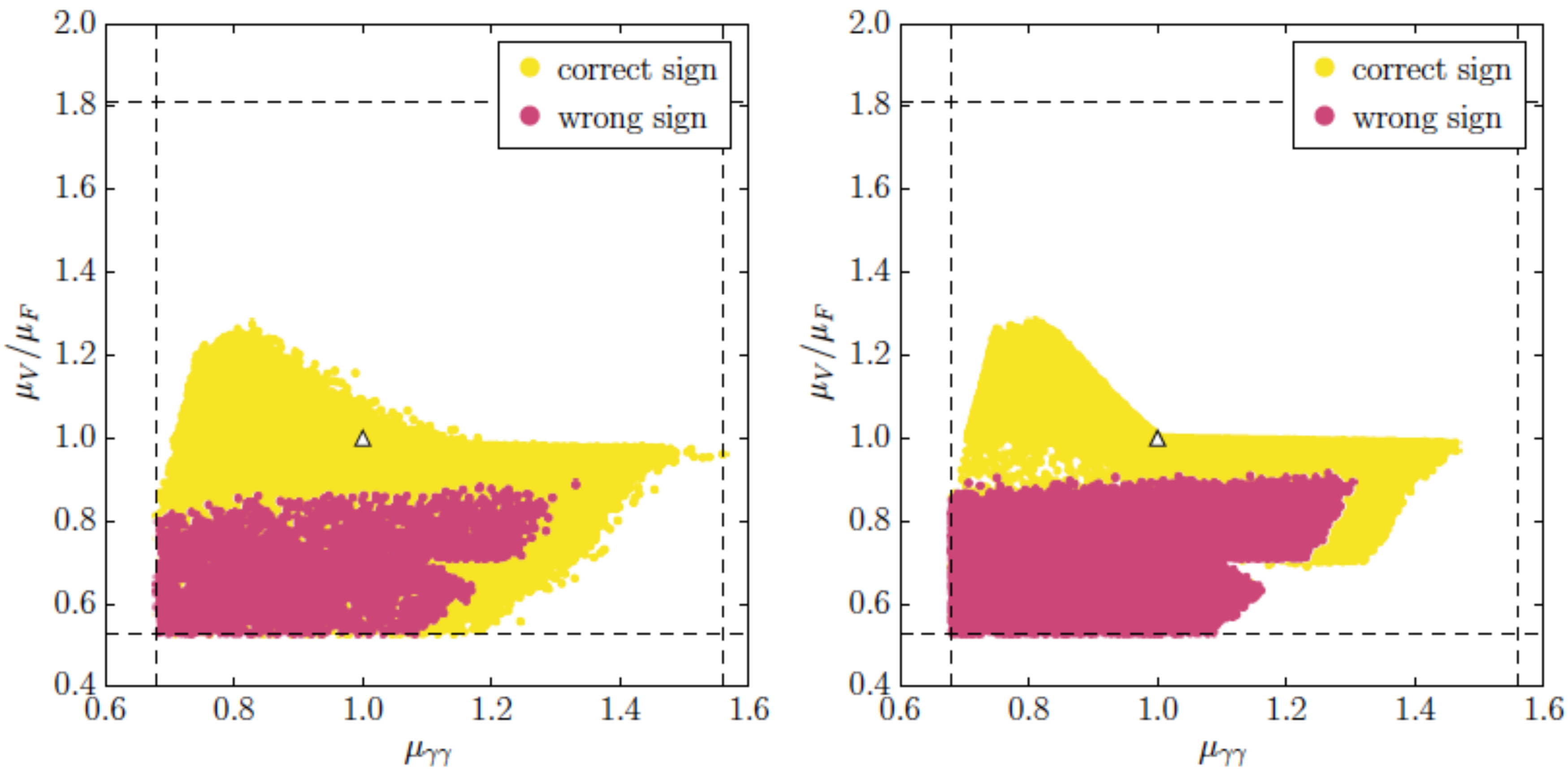


$\mu_{\gamma\gamma}$ vs $\mu_{\tau\tau}$ (only wrong sign points) in type II 2HDM (left) and N2HDM (right) – in "pink" all points and in green points where μ ZZ is measured within 5% of the SM value. Dashed lines are current limits.

Very similar behaviors in the two models.

2HDM wrong- sign previously discussed: Ferreira, Gunion, Haber, RS

Wrong sign in the 2HDM and N2HDM

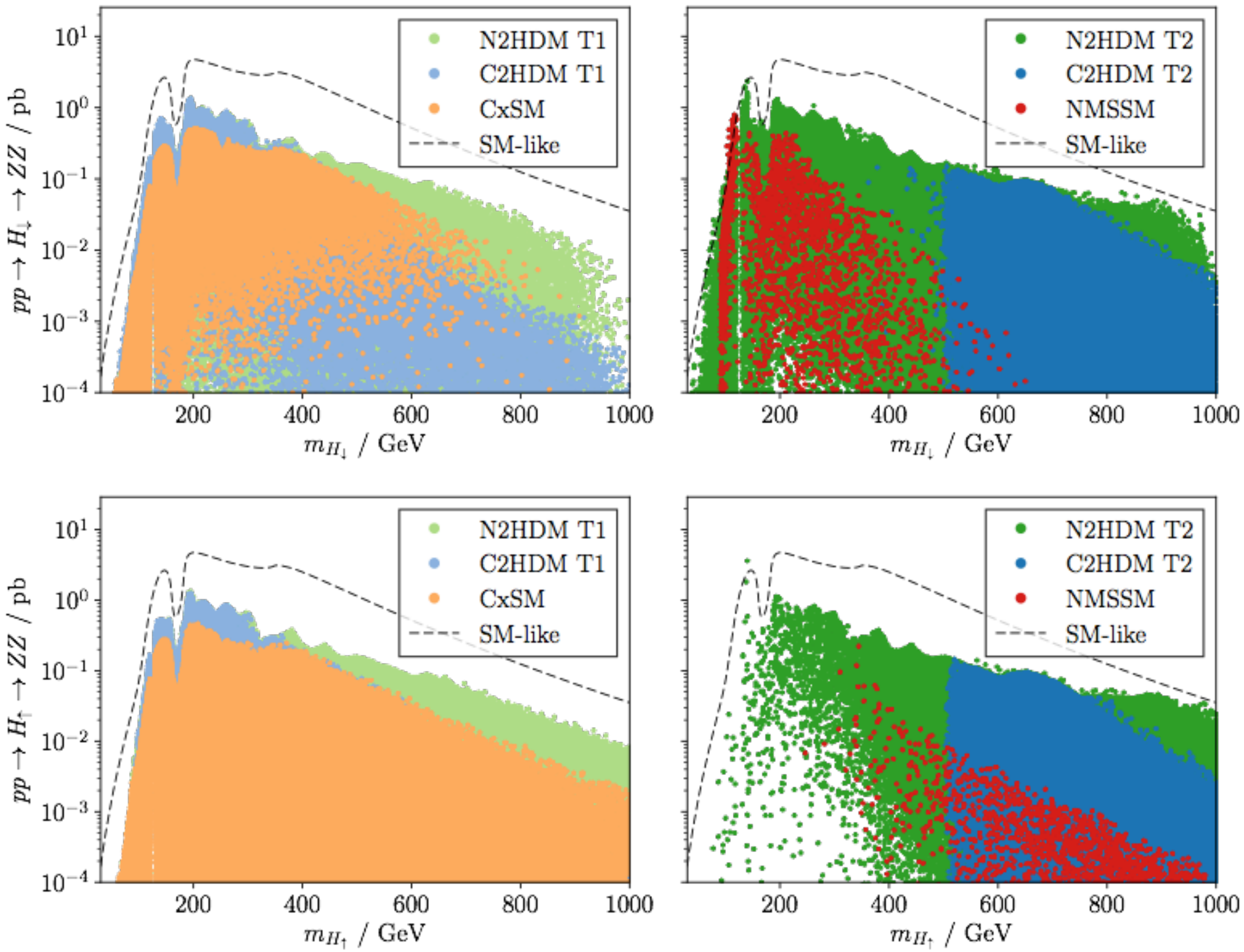


μ_V/μ_F vs $\mu_{\gamma\gamma}$ in type II 2HDM (left) and N2HDM (right) – in yellow the "right sign" and in pink the wrong sign points. Dashed lines are current limits. The h_{125} can be any of the H_i in the N2HDM and h or H in the 2HDM.

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

Comparing models
(just rates)

Non-125 to ZZ



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

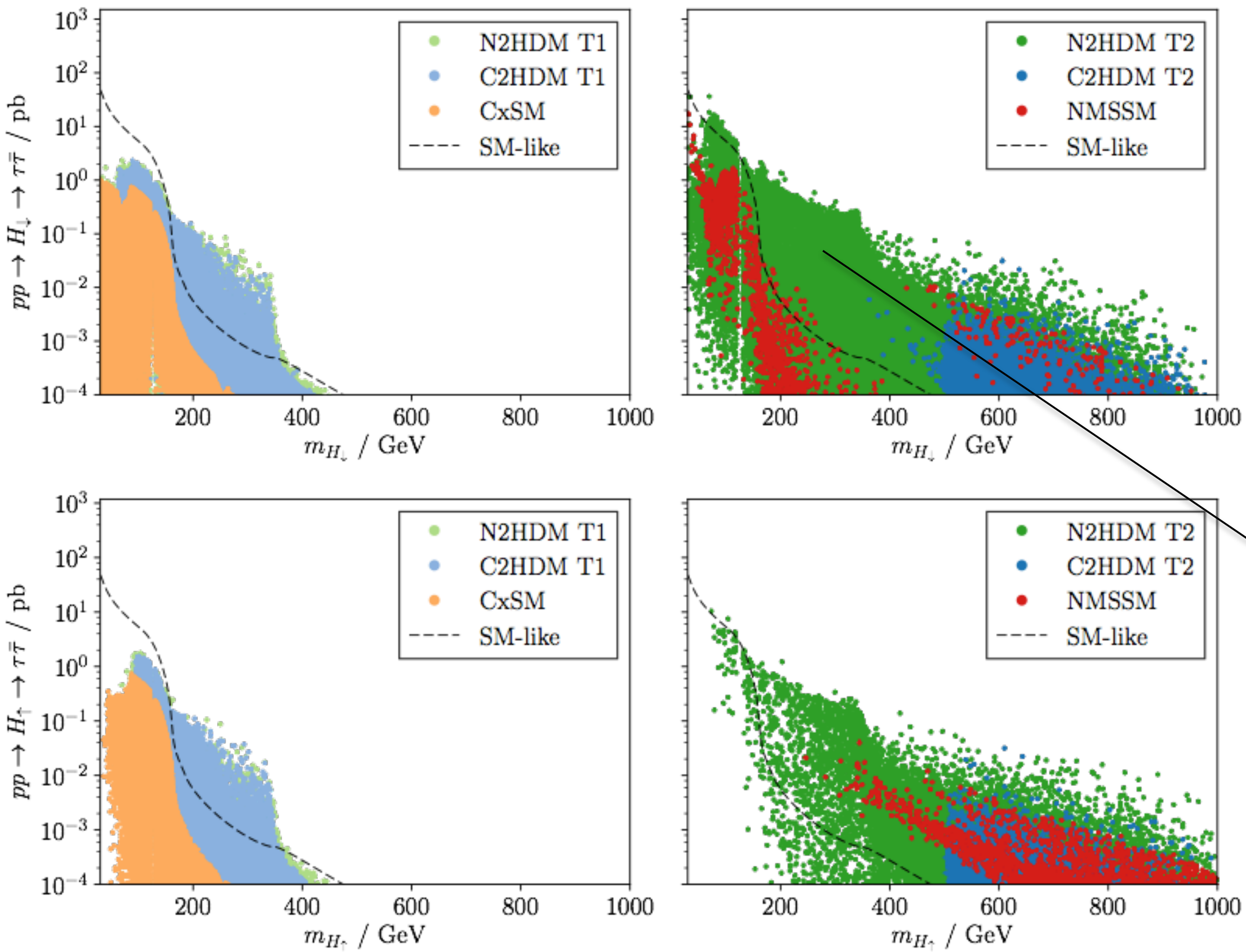
Dashed line is the "SM".

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

Rates for CxSM always well bellow the SM line. Discovery more likely via Higgs to Higgs decays for the heavier ones.

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

Non-125 to ττ

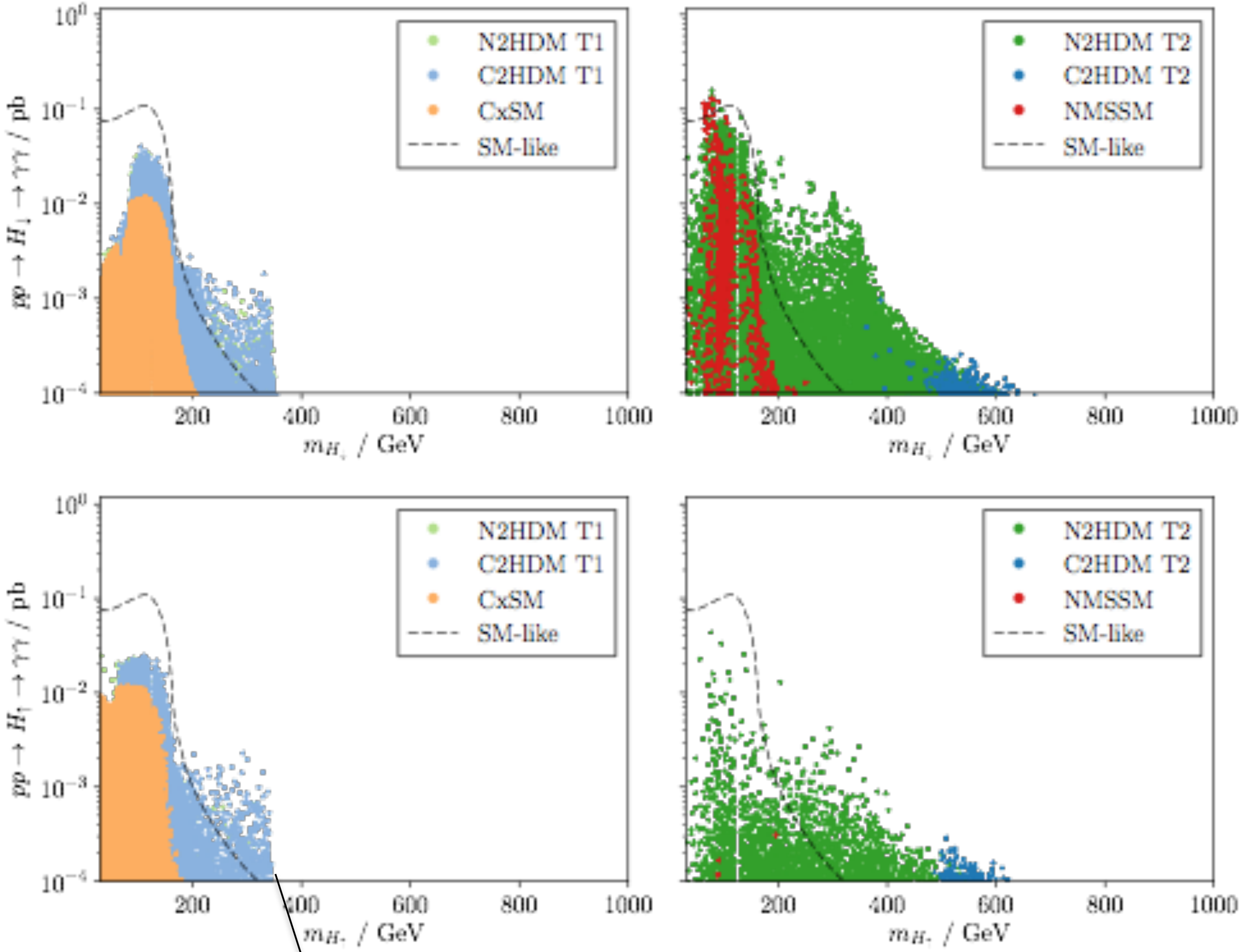


Signal rates for the production of H↓ (upper) and H↑ (lower) for 13 TeV as a function of m_H.

Dashed line is the "SM".

Region where only the N2hDM II survives.

Non-125 to γγ



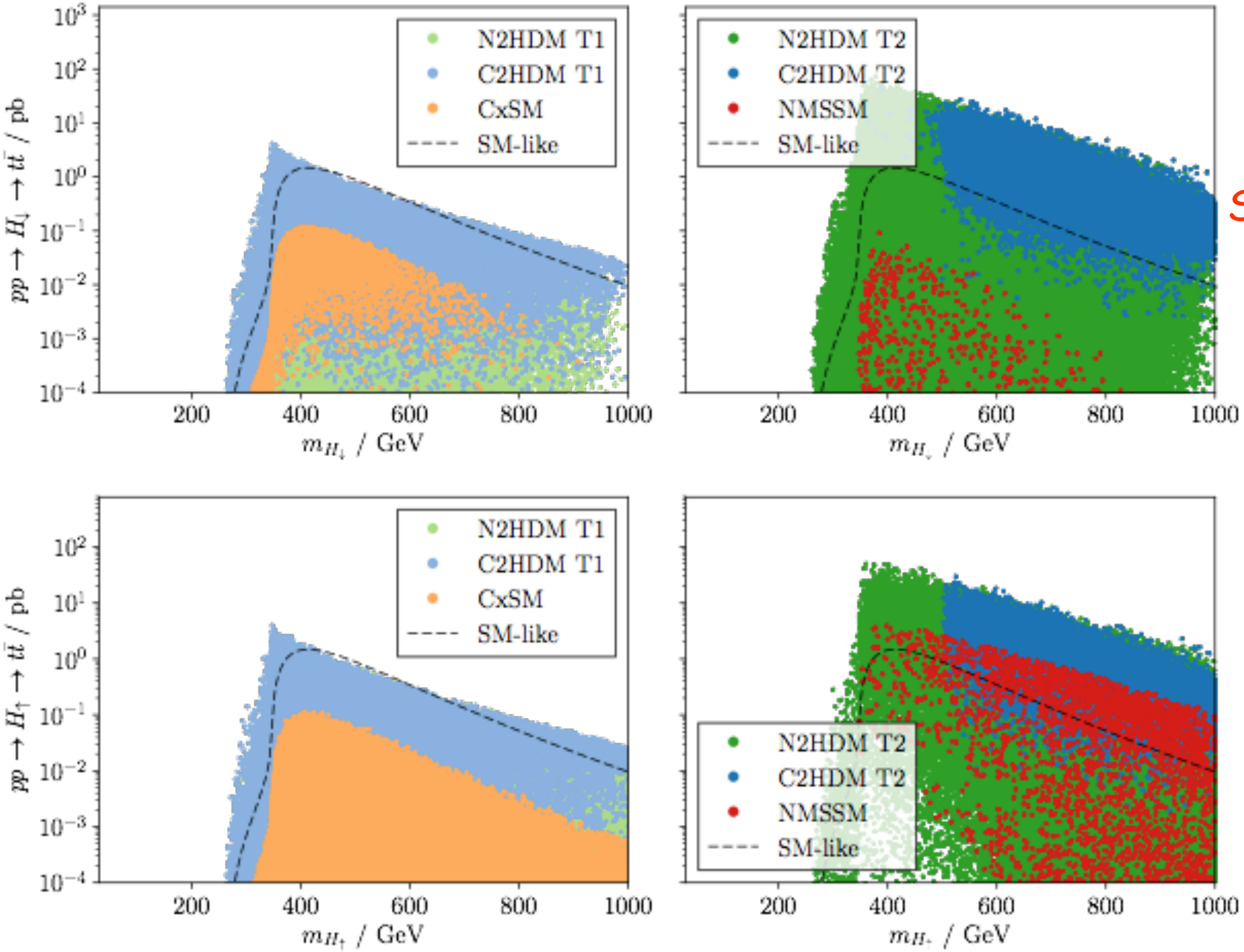
Signal rates for the production of $H_\downarrow$ (upper) and $H_\uparrow$ (lower) for 13 TeV as a function of m_H.

Dashed line is the "SM".

h to tt threshold

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

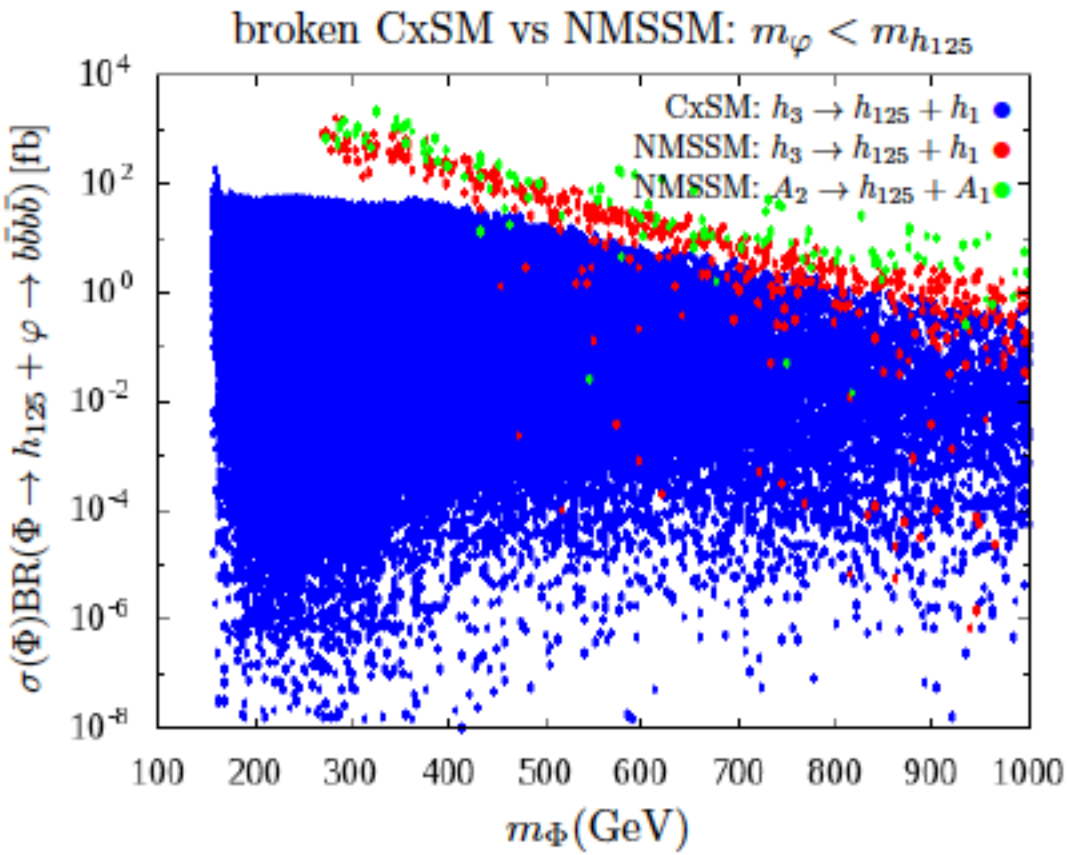
Non-125 to tt



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".

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

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



$\Phi \to h_{125} + \varphi$ 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 (2016)

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

Hint for CP violation? Combinations of three decays

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

Already observed

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

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

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

Comparing models
(sum rules)

Sum rules

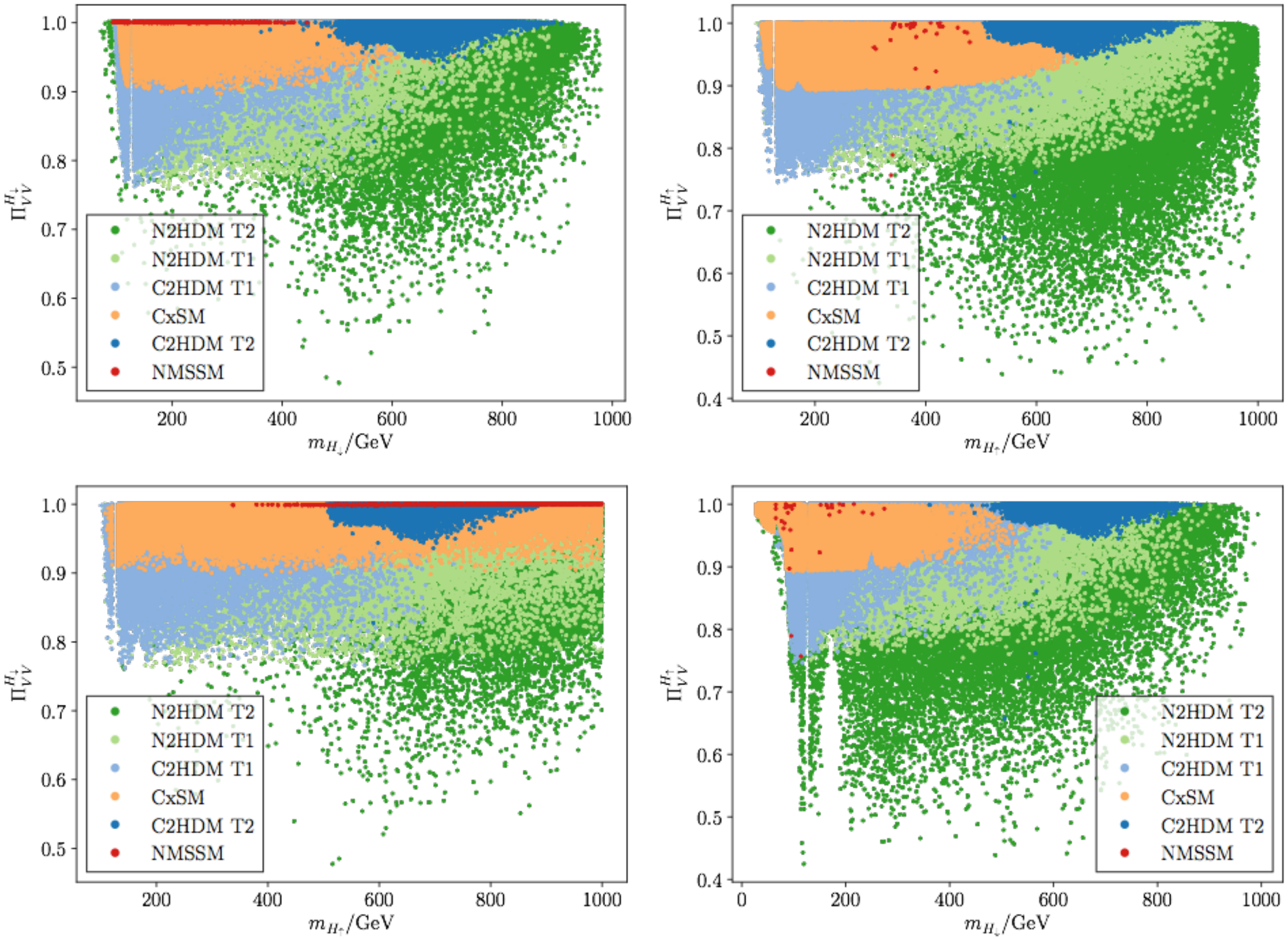
$$\Pi^i_{VV} = \sum_{j=1}^{i} |c(H_j VV)|^2$$

Couplings to gauge bosons

- Assuming that only two neutral (dominantly) CP-even Higgs bosons have been found, can we decide based on the sum rule if the CP-even Higgs sector is complete (like *e.g.* in the MSSM or CP-conserving 2HDM that incorporate only two CP-even Higgs bosons) or if we are missing the discovery of the remaining Higgs bosons of an extended Higgs sector?
- If this is possible, does the inspection of the pattern of the sum rule allow us to draw conclusions on the mass scale of the missing Higgs boson?
- Can we furthermore distinguish between the various models investigated here on the basis of the sum rule distributions?

$$ggF \to H_{\downarrow/\uparrow} \to ZZ > 10 \text{ fb}$$

Gauge bosons sum rules



Partial gauge boson sum rule including h125 and H↓ (left) and H↑ (right) as a function of respective mass (upper) and the other mass (lower).

$$\Pi^3_{VV} = 1 \quad \text{for the CxSM, N2HDM, NMSSM, C2HDM}$$

$$\Pi^2_{VV} = 1 \quad \text{for the MSSM and the CP-conserving 2HDM}$$

The last slide

- We collected a few models and compared them.

- Rates to SM particles can sometimes help distinguishing the models.

- Higgs to Higgs decays too. A scalar decaying to two other scalars with different masses looks promising.

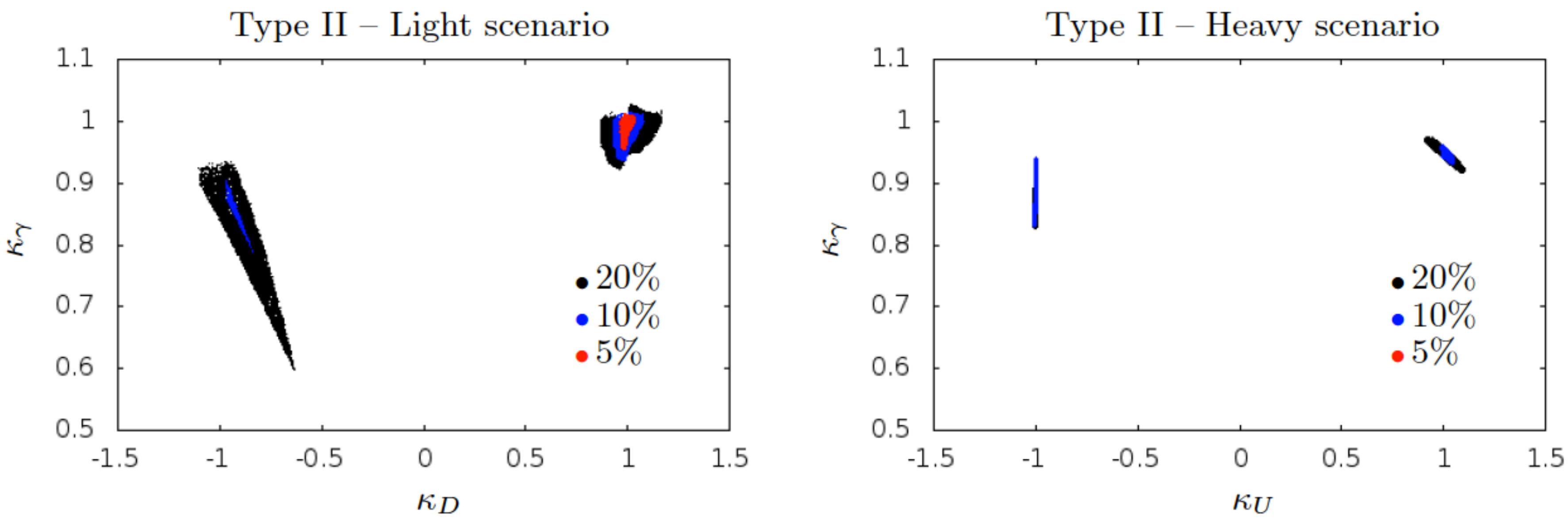
- These type of decay combined with other decays can also be used to probe CP-violation.

Thank you

Extra Slides

Non-decoupling effects

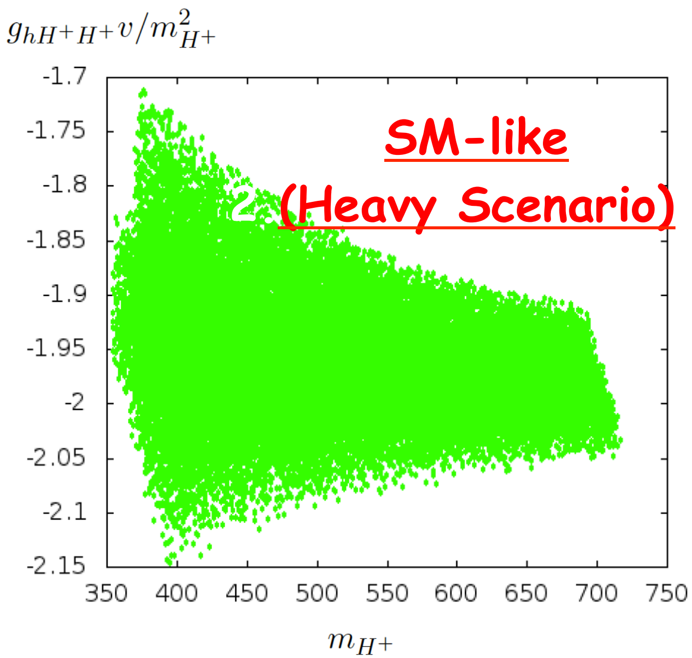
Because $m_h < m_H$ (by construction), if m_H = 125 GeV, m_h is light and there is no decoupling limit.

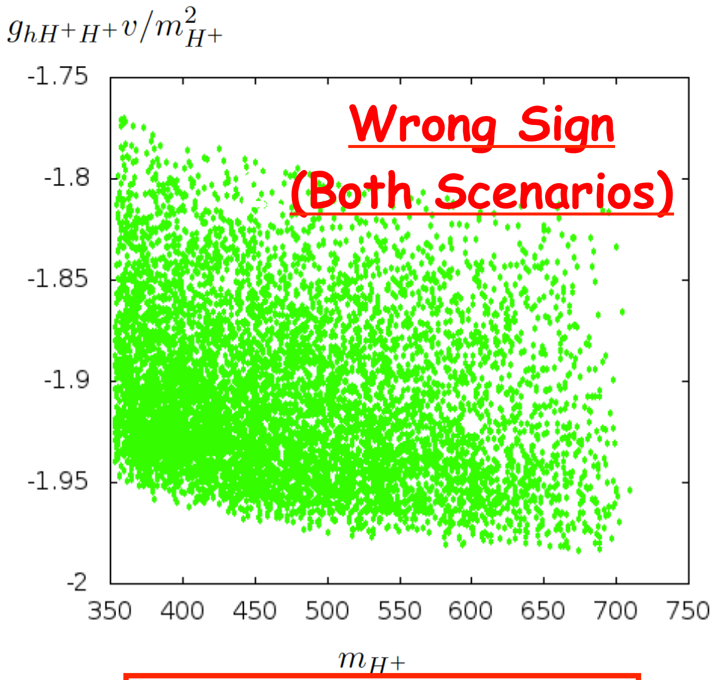


5% accuracy in the measurement of the **gamma gamma rate** could probe the wrong sign in both scenarios but also the SM-like limit in the heavy scenario due to the effect of charged Higgs loops + theoretical and experimental constraints.

FERREIRA, GUEDES, SAMPAIO, RS (2014).

How come we have no points at 5 %?





Considering only gauge bosons and fermion loops we should find points at 5 % for the wrong-sign scenario.

$$\boxed{g^{SM-like}_{HH^+H^-} \approx -\frac{2m^2_{H^\pm} - m^2_H - 2M^2}{v^2}}$$

$$\boxed{g^{Wrong\ Sign}_{HH^+H^-} \approx -\frac{2m^2_{H^\pm} - m^2_H}{v^2}}$$

In fact, if the charged Higgs loops were absent, changing the sign of κ_D would imply a change in κ_γ of less than 1 %.

Boundness from below

$$M < \sqrt{m^2_H + m^2_h/\tan^2\beta}$$

b -> s γ

$$m^2_{H^\pm} > 340 \ \ \mathrm{GeV}\ (\rightarrow 500\ \mathrm{GeV})$$

The relative negative values (and almost constant) contribution from the charged Higgs loops forces the wrong sign $\mu_{\gamma\gamma}$ to be below 1.

It is an indirect effect.

Updated in Misiak eal (2015).

Why is it not excluded yet?

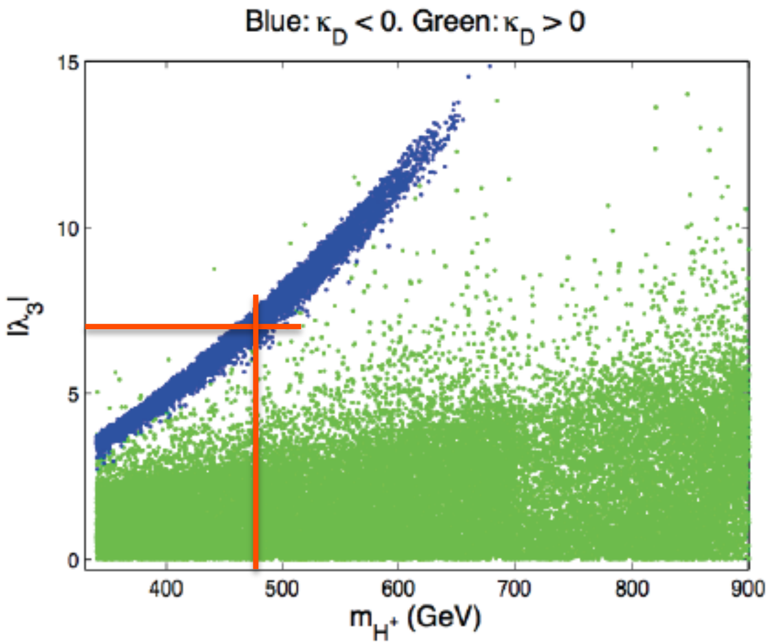
SM-like limit

$$\kappa_D \to 1 \qquad (\sin(\beta-\alpha) \to 1)$$

Wrong sign

$$\kappa_D \to -1 \qquad (\sin(\beta+\alpha) \to 1)$$

$$\begin{cases} \kappa_V \to 1 & (\sin(\beta-\alpha) \to 1) \\ \kappa_V \to \dfrac{\tan^2\beta - 1}{\tan^2\beta + 1} & (\sin(\beta+\alpha) \to 1) \end{cases}$$



Defining

$$\kappa_D = -\frac{\sin\alpha}{\cos\beta} = -1 + \varepsilon$$

$$\boxed{\sin(\beta+\alpha) - \sin(\beta-\alpha) = \frac{2(1-\varepsilon)}{1+\tan^2\beta} << 1} \qquad (\tan\beta >> 1)$$

Difference decreases with tan β

The NMSSM scan

For the NMSSM parameter scan we follow the procedure described in [56, 59] and briefly summarise the main features. The `NMSSMTools` package [100–105] is used to compute the spectrum of the Higgs and SUSY particles including higher order corrections and check for vacuum stability, the constraints from low-energy observables and compute the input required by `HiggsBounds` to verify compatibility with the exclusion bounds from Higgs searches. The Higgs branching ratios of `NMSSMTools` are cross-checked against `NMSSMCALC` [106]. The relic density is obtained via an interface with `micrOMEGAS` [105] and required not to exceed the value measured by the PLANCK collaboration [107]. Only those parameter points are retained that feautre a neutral CP-even Higgs boson with mass between 124 and 126 GeV. For this Higgs boson agreement with the signal strength fit of [92] is required at the $2 \times 1\sigma$. level. For the gluon fusion cross section the ratio between the NMSSM Higgs decay width into gluons and the corresponding

	t_β	λ	κ	M_1	M_2	M_3	A_t	A_b	A_τ	$m_{\tilde{Q}_3}$	$m_{\tilde{L}_3}$	A_λ	A_κ	$\mu_{\rm eff}$
				in GeV										
min	1	0	-0.7	0.1	0.2	1.3	-2	-2	-2	0.6	0.6	-2	-2	-1
max	30	0.7	0.7	1	1	3	2	2	2	3	3	2	2	1

Table 3: Input parameters for the NMSSM scan. All parameters have been varied independently between the given minimum and maximum values.

SM decay width at the same mass value is multiplied with the SM gluon fusion cross section. The branching rations are taken from NMSSMTools at NLO QCD, whereas the SM cross section was calculated at NNLO QCD with `HIGLU` [108]. The cross section for $b\bar{b}$ annihilation is obtained from the muliplication of the SM cross section with the effective squared $b\bar{b}$ coupling of `NMSSMTools`. For the cross section values we use the data from [109] produced with the code `SusHi` [93, 94]. The obtained parameter points are furthermore checked for compatibility with the SUSY searches at LHC [110–123] and the lower bound on the charged Higgs mass [124, 125].

The NMSSM

The ranges applied in our parameter scan are summarise in table 3. In order to ensure perturbativity we apply the rough constraint

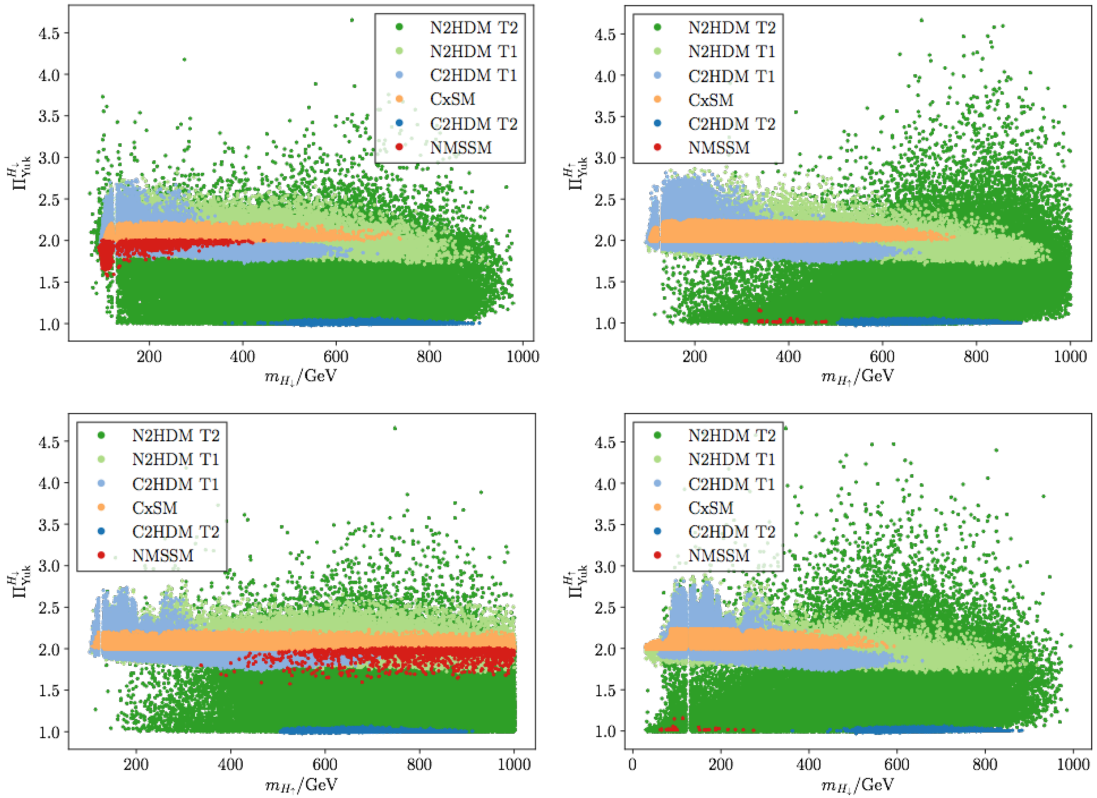
$$\lambda^2 + \kappa^2 < 0.7^2 \; . \tag{4.74}$$

The remaining mass parameters of the third generation sfermions not listed in the table are chosen as

$$m_{\tilde{t}_R} = m_{\tilde{Q}_3} \; , \quad m_{\tilde{\tau}_R} = m_{\tilde{L}_3} \quad \text{and} \;\; m_{\tilde{b}_R} = 3 \text{ TeV} \; . \tag{4.75}$$

The mass parameters of the first and second generation sfermions are set to 3 TeV. For consistency with the parameter ranges of the other models we kept only points with all Higgs masses between 30 GeV and 1 TeV.

Yukawa sum rule



In the NMSSM the partial Yukawa sum shows strong violations of more than 50% up to 100% if the additionally discovered Higgs boson is the lighter one, while it is bound to values close to 1 in case it is the heavier one.
If it is the NMSSM! we can see which of the two non-SM-like Higgs bosons has been discovered,

NMSSM is excluded if sum is above 2. If H↓ is discovered the constraints restrict tan β to small values. The next heavier CP-even Higgs boson is dominantly CP-even. While h_{125} carries most of the top-Yukawa coupling to comply with the Higgs data, the non-discovered H↑ is very doublet-like with a large coupling component to the down-type fermions. Its non-discovery leads to the observed large violations in $\Pi^2_{\rm Yuk}$.

The situation is reversed if H↑ is discovered. In this case, however, large violations in the partial gauge sum may appear if h_{125} and H↓ have similar masses.

Overview of the tool

Doublets, complex, reals, etc ... $\rightarrow$ Decompose n reals

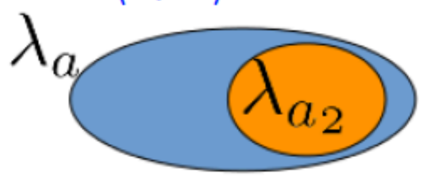
$$V(H, S, \phi, \chi, \ldots) \rightarrow \begin{matrix} H, H^\dagger \\ \mathbb{S}, \mathbb{S}^\star \\ \phi, \chi \\ \ldots \end{matrix} \rightarrow \begin{pmatrix} \phi_0 \\ \phi_1 \\ \ldots \\ \phi_n \end{pmatrix} \rightarrow V = V_a(\phi_i)\lambda_a$$

Numeric VEV

$\phi_i = \mathbf{v_i} + \delta\phi_i$

Min. Conditions

$\Rightarrow \langle \partial_i V \rangle_a \lambda_a = 0$



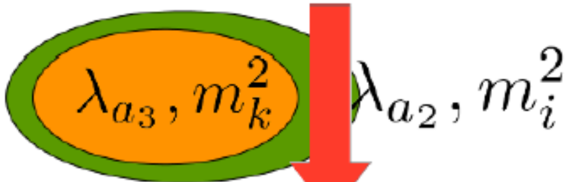
Block Detection

$\mathbf{M.M^T = 1}$

Quadratic Min. Cond.

$\left\langle \widehat{\partial}^2 V \right\rangle_{a_2} \lambda_{a_2} = diag[m_i^2]$

Indep. $\{v_i, M_{ij}, \lambda_{a_3}, m_k^2\}$



Local Minimum Generated!

$\rightarrow$ Check Tree level Unitarity

$\rightarrow$ Check Global Stability

$\rightarrow$ Boundedness from below

User Analysis

$\rightarrow$ Interfaces: Superiso, SuShi, MicrOmegas, HBounds/Signals.

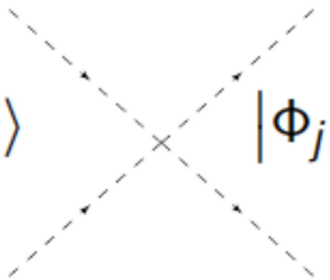
$\rightarrow$ Tables & User def. analysis.

Include theoretical bounds

Tree level unitarity

$$\left(\ldots,\ |\Phi_i\rangle\ ,\ \ldots\right) \equiv \left(\frac{1}{\sqrt{2!}}\,|\phi_1\phi_1\rangle\ ,\ldots,\ \frac{1}{\sqrt{2!}}\,|\phi_N\phi_N\rangle\ ,|\phi_1\phi_2\rangle\ ,\ldots,|\phi_{N-1}\phi_N\rangle\right)$$

Tree level unitarity in $2 \to 2$ **high energy scattering:**



$$|\Phi_i\rangle \quad |\Phi_j\rangle\ ,\ \Re\{a_{ij}^{(0)}\} < \frac{1}{2}\ ,\ \ a_{ij}^{(0)} = \frac{\langle\Phi_i|\,i\mathbf{T}^{(0)}\,|\Phi_j\rangle}{16\pi} \sim \sum_{a_4}\cdots\lambda_{a_4}$$

Lee, Quigg, Thacker; PRD16, Vol.5 (1977)

- In SM, the **2-particle** states are w^+w^-, hh, zz, hz
  $\Rightarrow$ constrains quartic coupling λ, $\Rightarrow$ $\mathbf{m_h^2 < 700\ GeV}$
- In BSM $\Rightarrow$ bounds on combinations of quartic λ_{a_4}

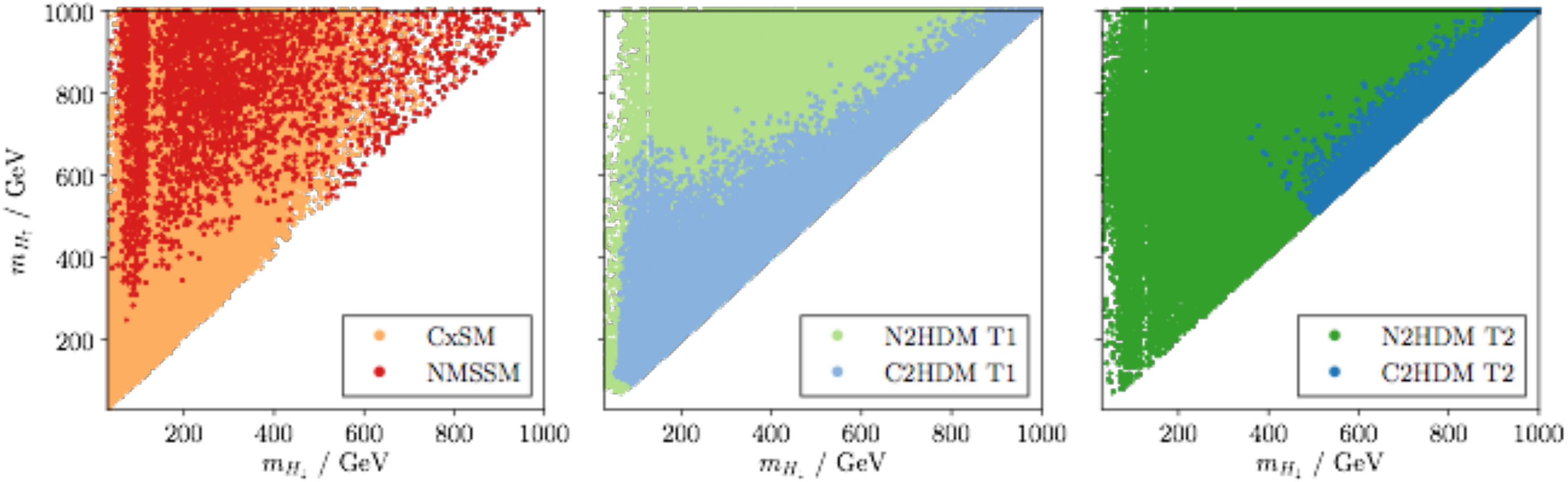
Higgs to Higgs decays

- **Assumptions:**
  - ∗ Ony subset of Higgs bosons common in CxSM and NMSSM has been found
  - ∗ *No* non-SM final state signature discovered so far
  - ∗ *No* observation of final state signatures unique to the model
  - ∗ *No* information on CP properties of Higgs bosons so far

Question: Focussing on Higgs-to-Higgs decays only in final states common to both models - Is it possible to tell the CxSM-broken from the NMSSM based on the total rates?

- **Scans in CxSM and NMSSM parameter spaces:**
  - ◇ CxSM constraints: theoretical (boundedness from below, global minimum, perturbative unitarity), DM constraints, EWPO, Higgs data (discovery & exclusion)
  - ◇ NMSSM constraints: DM, Higgs data, SUSY exclusion limits, low-energy observables
  - ◇ In both models degenerate Higgs signals discarded
- **Among the various Higgs-to-Higgs decays:** $\Phi \to h_{125} + \varphi$ found to be distinctive

The mass spectrum



- Gaps at 125 GeV due to mass window around h_{125} in order to avoid degenerate Higgs signals.

- In all models but the C2HDM type II we find points with $m_{H\downarrow} < m_{h125}$.

- In the N2HDM, the CxSM and C2HDM type I, we have points where $m_{H\uparrow} < m_{h125}$ (h125 is the heaviest CP-even Higgs) not possible in the NMSSM because of supersymmetric relations.

- N2HDM and NMSSM have additionally pseudoscalars that can also be lighter than 125 GeV.

- CxSM, N2HDM, NMSSM and C2HDM type I cover almost the whole mass region

- In contrast to the C2HDM type II, where the H↑ is always heavier than about 400 GeV.
T –parameter - one of the neutral Higgs bosons close in mass of the charged Higgs (560 GeV).
EDMs – neutral scalar masses close.

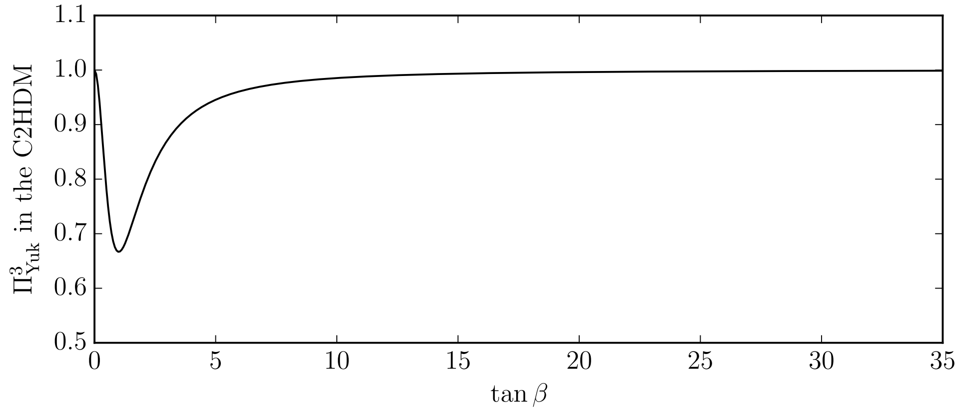
- In the CxSM (no charged Higgs) there is no constraint. N2HDM and NMSSM the additional pseudoscalars can help to fulfil this constraint.

Yukawa sum rules

$$\Pi^3_{\mathrm{Yuk}} = 2$$ **CxSM**

$$\Pi^3_{\mathrm{Yuk}} = 1$$ **NMSSM and type II N2HDM**

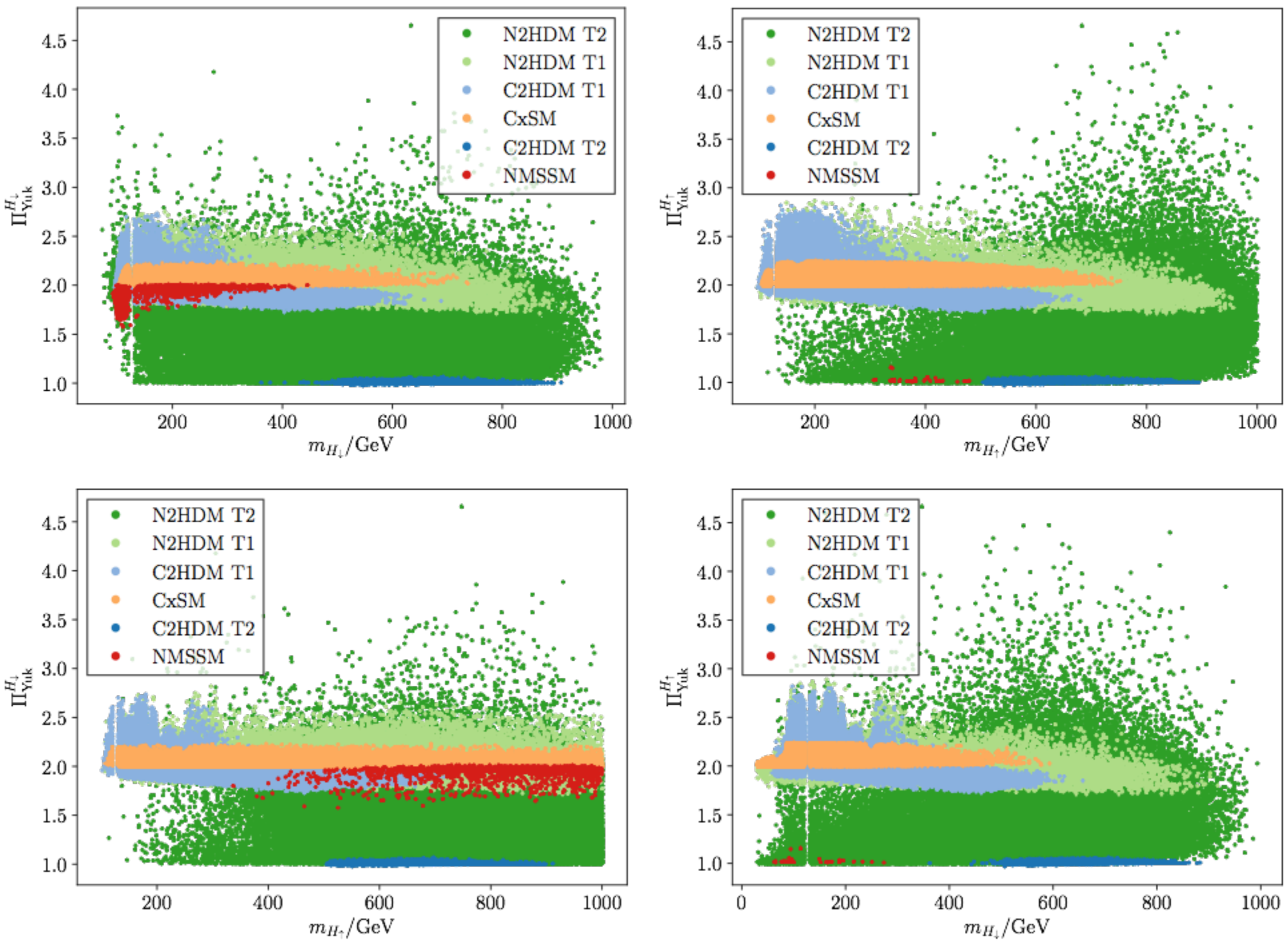
$$\Pi^3_{\mathrm{Yuk}} = 2\left(\frac{24}{17-\cos(4\beta)} - 1\right)$$



$$\Pi^3_{\mathrm{Yuk}} = 2\sin^2\beta \approx 2$$ **type I N2HDM**

$$\Pi^3_{\mathrm{Yuk}} = \frac{2\tan^2\beta}{2+\tan^2\beta}$$ **type I C2HDM**

Yukawa sum rules



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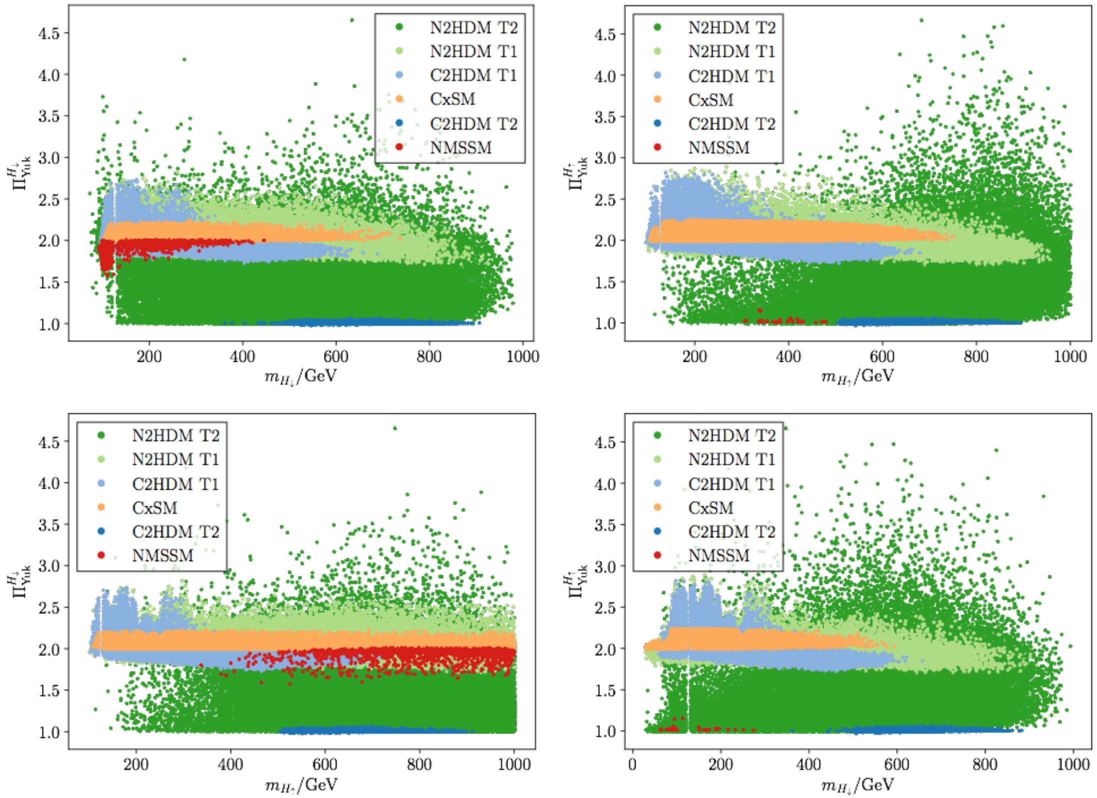
Yukawa sum rules



A measurement of the sum rule violation below 2 would immediately exclude the CxSM.

A measurement of $\Pi^2_{\rm Yuk} < 1$ is only possible in the C2HDM type II. The C2HDM type II is ruled out if deviations beyond 7% from 1 are measured.

The C2HDM type I the values of the partial Yukawa sum are distributed between about 1.7 and 2.8. The lower limit is due to the lower bound on tan β imposed by the other constraints.

This also applies for the N2HDM type I where the maximum deviations range between the partial sum values 1.7 and 2.85.

The N2HDM type II can violate the sum rule by a factor of almost 5. Any measurement of $\Pi^2_{\rm Yuk}$ above about 2.9 identifies the N2HDM type II among our models.

Sum rules correlation