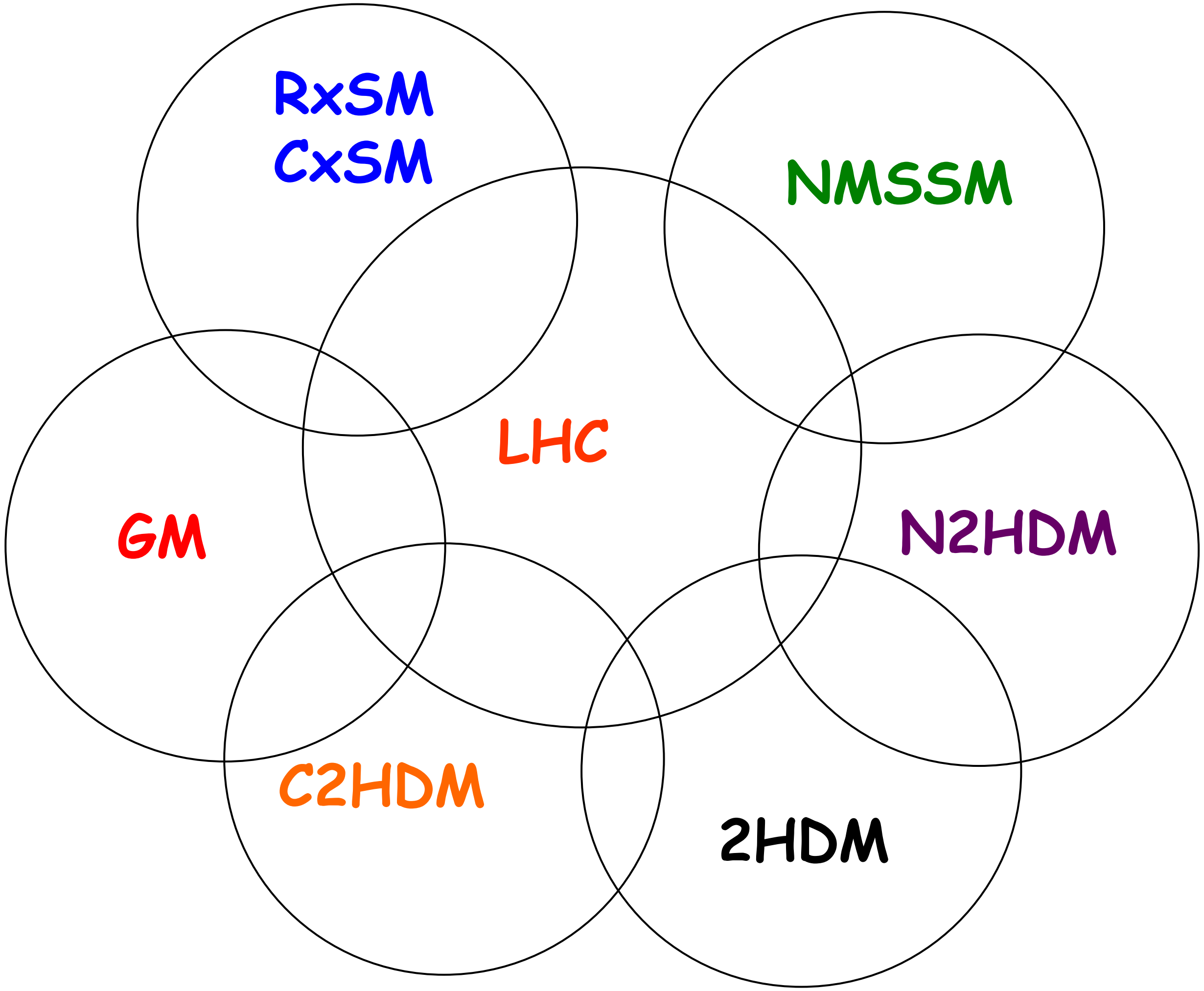
WG3 Neutral Extended Scalars Status Report

R. Santos
(for the WG3 NES)

LHCHXSWG
14th General Assembly Meeting

27 March 2018

Plenty of models. Which searches are common?



New scalar?

Precision measurements?

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

Benchmark models already being used by ATLAS and CMS

- **Real Singlet Extension of the SM (one extra real singlet) - RxSM**

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

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

  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

- **Georgi-Machacek model (two extra $SU(2)_L$ triplet scalars) – GM**

  Scalar sector – 3 CP-even, 4 charged scalars and 2 doubly charged scalars

Working Group 3: Sub-group – Neutral Extended Scalars

1. H_{125} couplings measurements (sure-fire investment)

a) How efficiently can the parameter space of the models be constrained through measurements of the Higgs properties?
b) Higher order corrections?

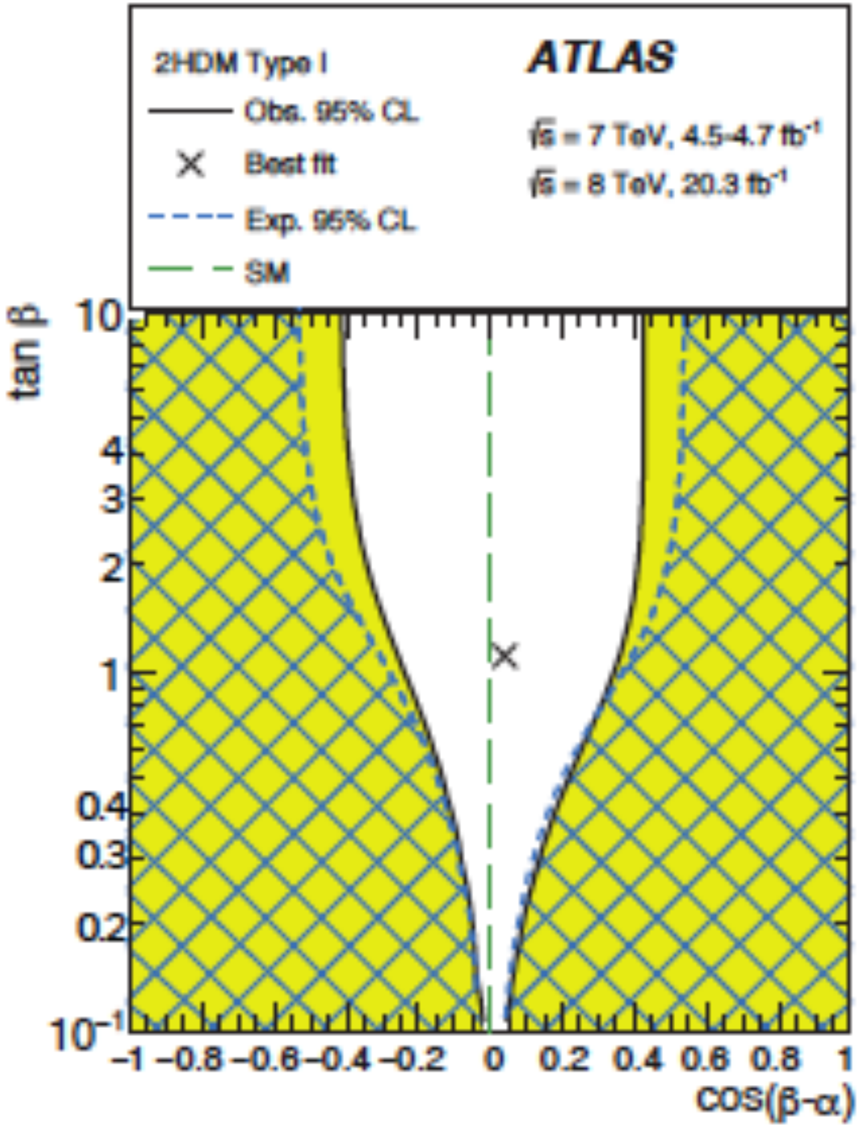
2. Look for new scalars in simple extensions of the scalar sector.

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

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

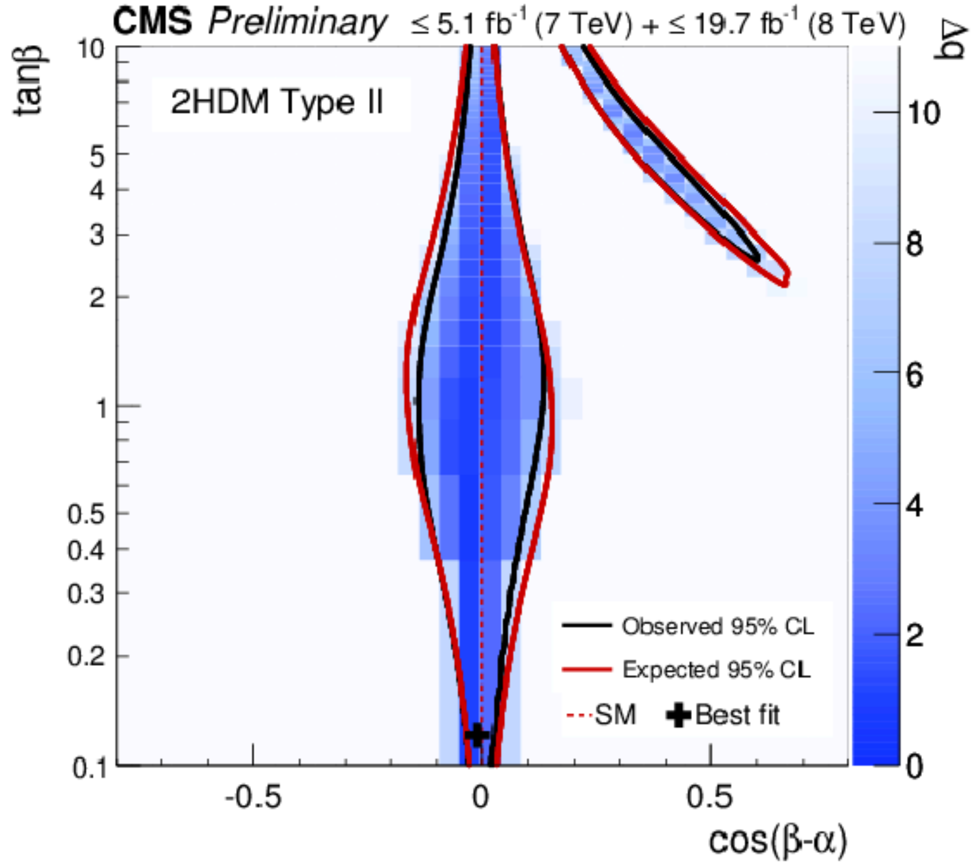
arXiv:1610.07922v1

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



(a) Type I

ATLAS 1509.00672



CMS-PAS-HIG-16-007

Lightest Higgs couplings to gauge bosons

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

$V = W, Z$

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

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

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

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

REAL COMPONENT (SINGLET)

IMAGINARY COMPONENT (SINGLET)

Lightest Higgs Yukawa couplings

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

SINGLET EXTENSION

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

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

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 $s_2 \rightarrow 0$

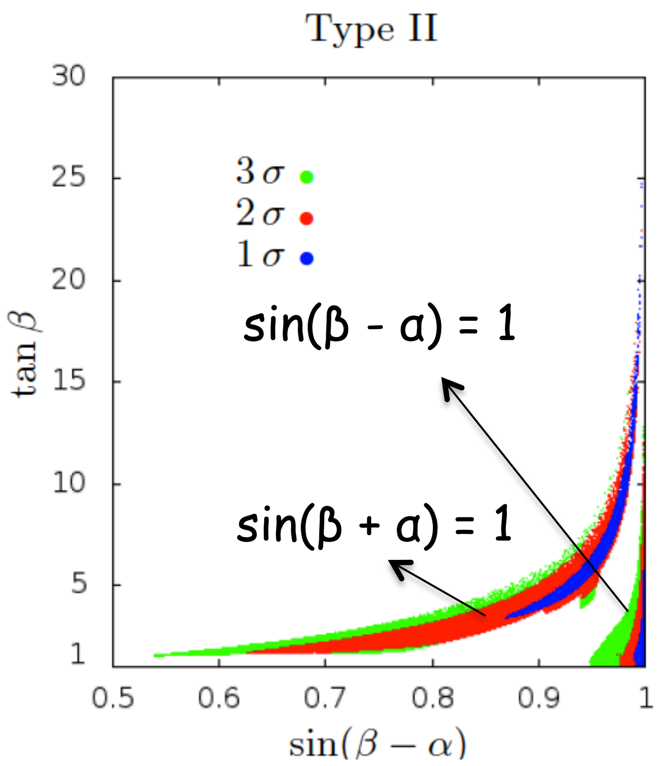
$$Y_{C2HDM} \equiv Y_{N2HDM} \equiv Y_{2HDM}$$

Independent of the Yukawa type

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).

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

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

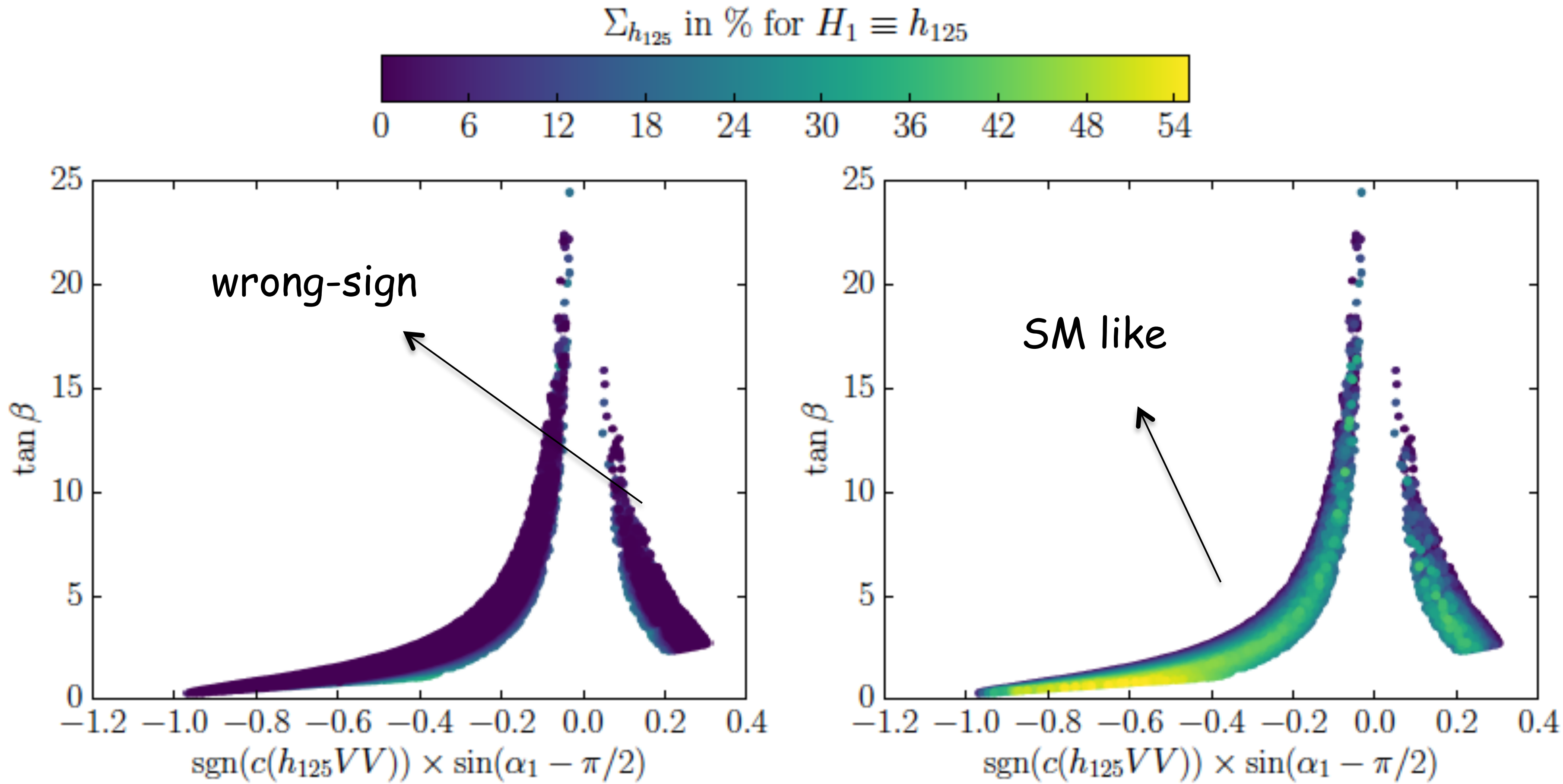
at tree-level

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

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

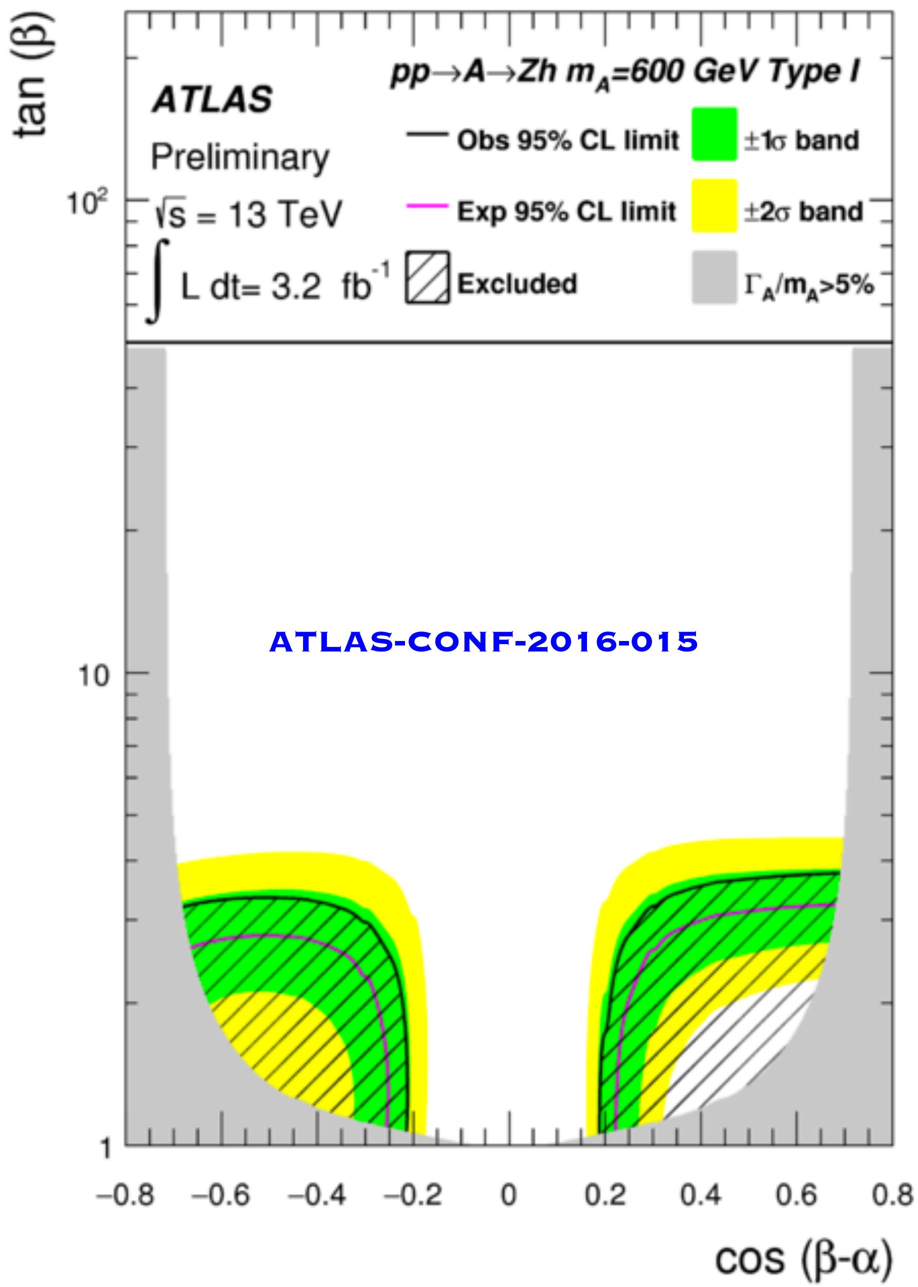
And lead to a very similar plot for the N2HDM

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



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

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 %.



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.

Search for Heavy Higgses

- Direct Search for extra Higgses
  - ➡ direct evidence for BSM new physics
- Conventional search channel (even for non-SM Higgs):

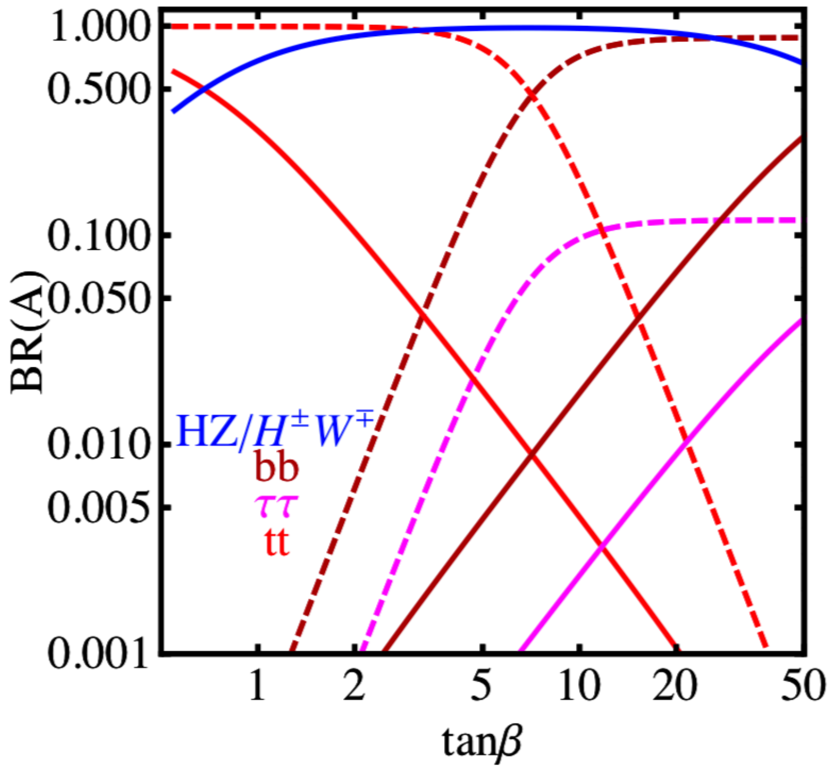
$\gamma\gamma$, ~~ZZ~~, ~~WW~~, $\tau\tau$, bb, tt

- $\gamma\gamma$: small Br
- ZZ, WW: absent or suppressed
- $\tau\tau$, bb: small Br or large BG
- tt: difficult @ LHC

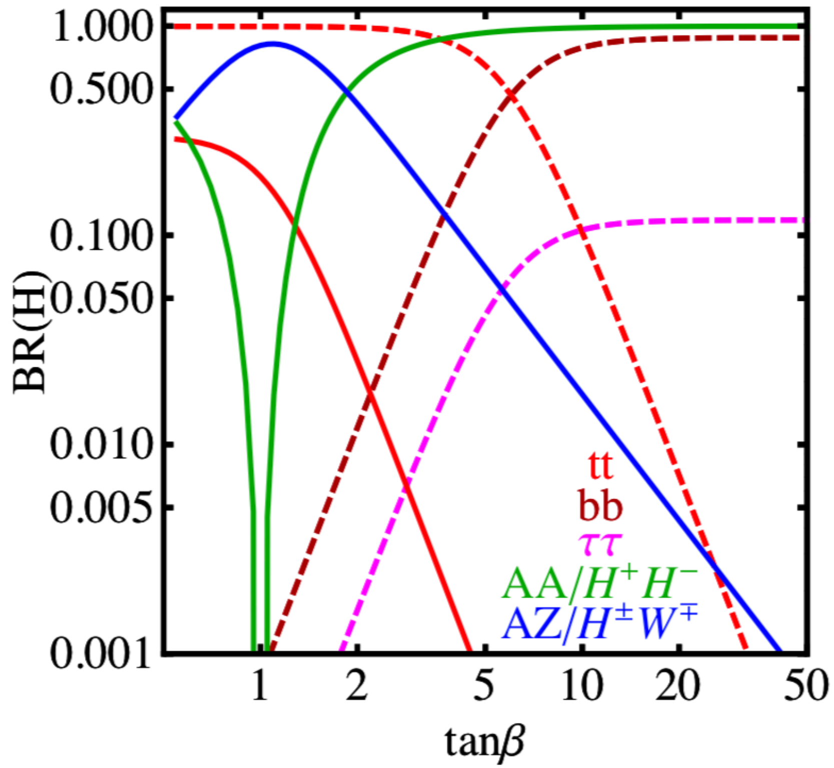
- Charged Higgs is challenge!
- New Higgs decay modes open for (non-)SM Higgs decay
  - ➡ relax the current search bounds
  - ➡ offer new discovery channels

Exotic Decay Branching Ratios

◉ A decay



◉ H^0 decay



500 GeV parent particle

200 GeV daughter particle

Searches roadmap

$S_i \to S_j V$ —CPC→ $H_i \to A_i V \ (A_i \to H_i V)$ 2HDM, ...

$S_i \to S_j V$ —CPV→ $h_1 \to h_2 V$ C2HDM, ...

- $H^0 \to ZA^0$, $A^0 \to ZH^0$, Zh^0
  - already studied @ ATLAS, CMS. ATLAS fixed daughter to be 125 GeV SM-like Higgs — Relax mass window.

h_i (no definite CP)

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

Analysis are assumed to be independent of particles CP.

Searches roadmap

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

- CPC: $H_i \to H_j H_j \ (A_i A_j)$ — RxSM, 2HDM, NMSSM
- CPV: $h_i \to h_j h_j$ — C2HDM, C-NMSSM
- CPV: $h_i \to h_j h_k$ — C2HDM, C-NMSSM
- CPC:
  - $H_i \to H_j H_k$ — CxSM, NMSSM
  - $A_i \to A_j H_k$ — NMSSM, 3HDM

- $H^0 \to A^0 A^0$, $h^0 h^0$, $h^0 \to A^0 A^0$
  - H^0 decay already studied @ ATLAS, CMS with daughter to be 125 GeV SM-like Higgs — Relax mass window.

Searches roadmap

$S_i \to VV$

CPC: $H_i \to VV$

CPV: $h_i \to VV$

Done.

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

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

Combinations of three decays

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.

Searches roadmap

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

FC

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

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

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

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

Being Done for couplings.

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)

ATLAS and CMS use the 8 TeV data set to search for LFV decays of $H \to e\mu$, $e\tau$ [158] and $\mu\tau$ [159, 160], leading to upper limits at 95% CL on the branching fraction, $\mathrm{BR}(H \to e\mu) < 0.036\%$, $\mathrm{BR}(H \to e\tau) < 0.7\%$, and $\mathrm{BR}(H \to \mu\tau) < 1.51\%$.

Searches roadmap

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

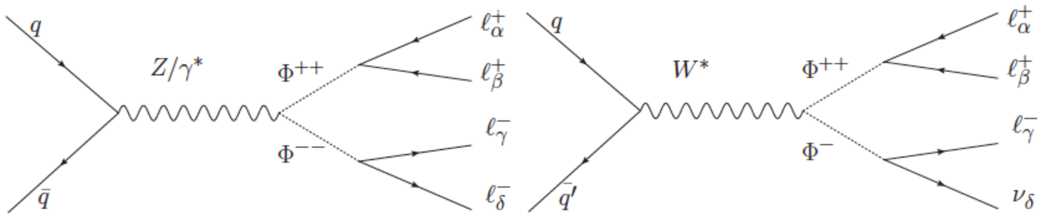
$H^{\pm} \to W^{\pm} Z$

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.



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

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)$_L$×SU(2)$_R$

Physical spectrum:

- Two custodial singlets $\to h^0$, H^0 m_h, m_H ← very similar
- Custodial triplet $\to (H_3^+, H_3^0, H_3^-)$ m_3 ← to 2HDM

- Custodial fiveplet $(H_5^{++}, H_5^{+}, H_5^{0}, H_5^{-}, H_5^{--})$ m_5 ← new!

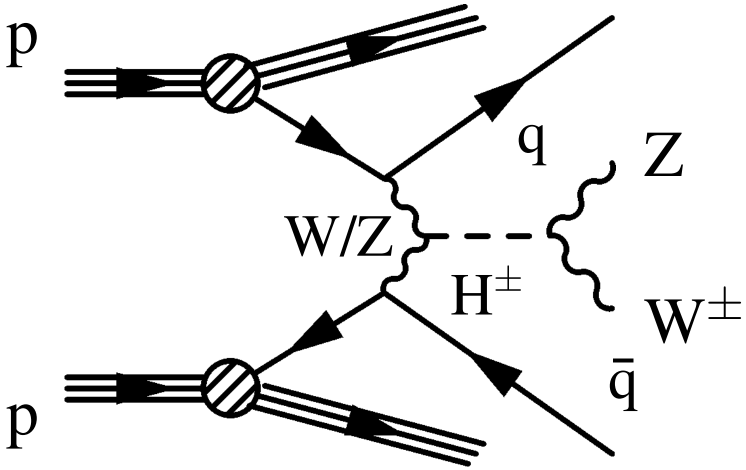
→ Focus on direct searches for fermiophobic H_5 states

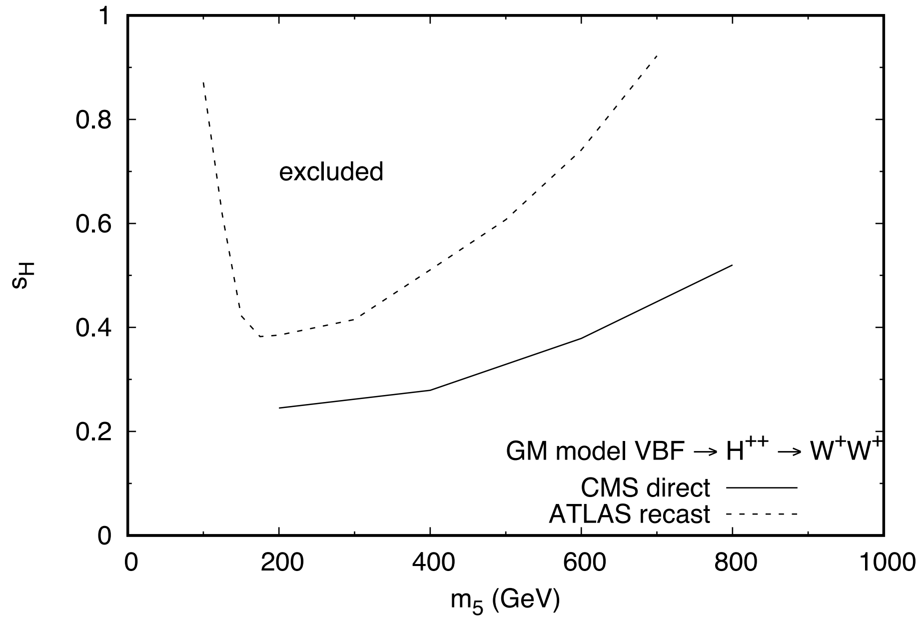
Focus for YR4:

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

VBF $\to H_5^{\pm} \to W^\pm Z$ — 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

New activities:

1) Low mass $m_5 < 200$ GeV

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

$\rightarrow$ 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 $pp \rightarrow H_5^i H_5^j$

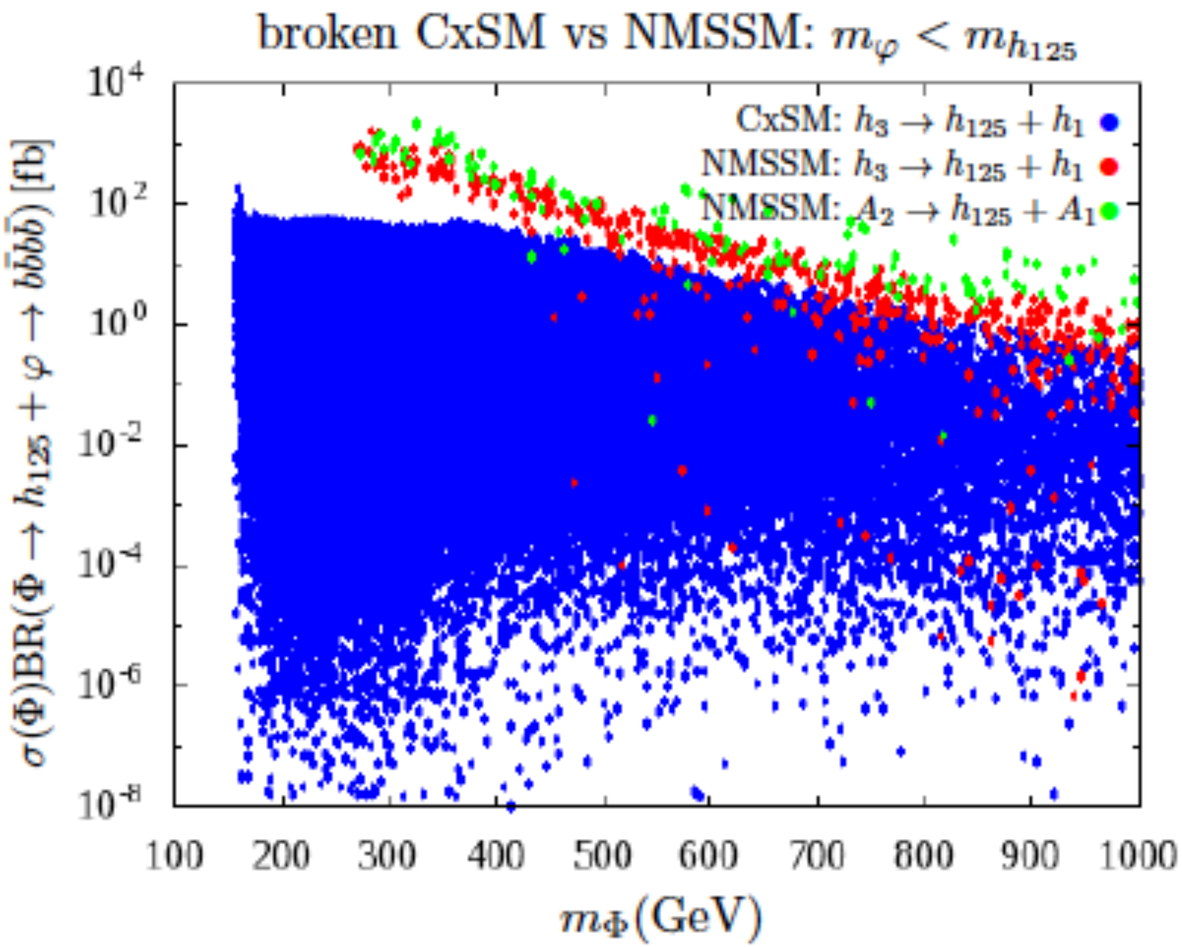
$\rightarrow$ large cross sections at low mass
$\rightarrow$ only production mode that's not suppressed in alignment limit
(may also be interesting for $m_5 > 200$ GeV, depending on decay modes)

To do: provide Drell-Yan production cross sections

3. Comparing models

The decay

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



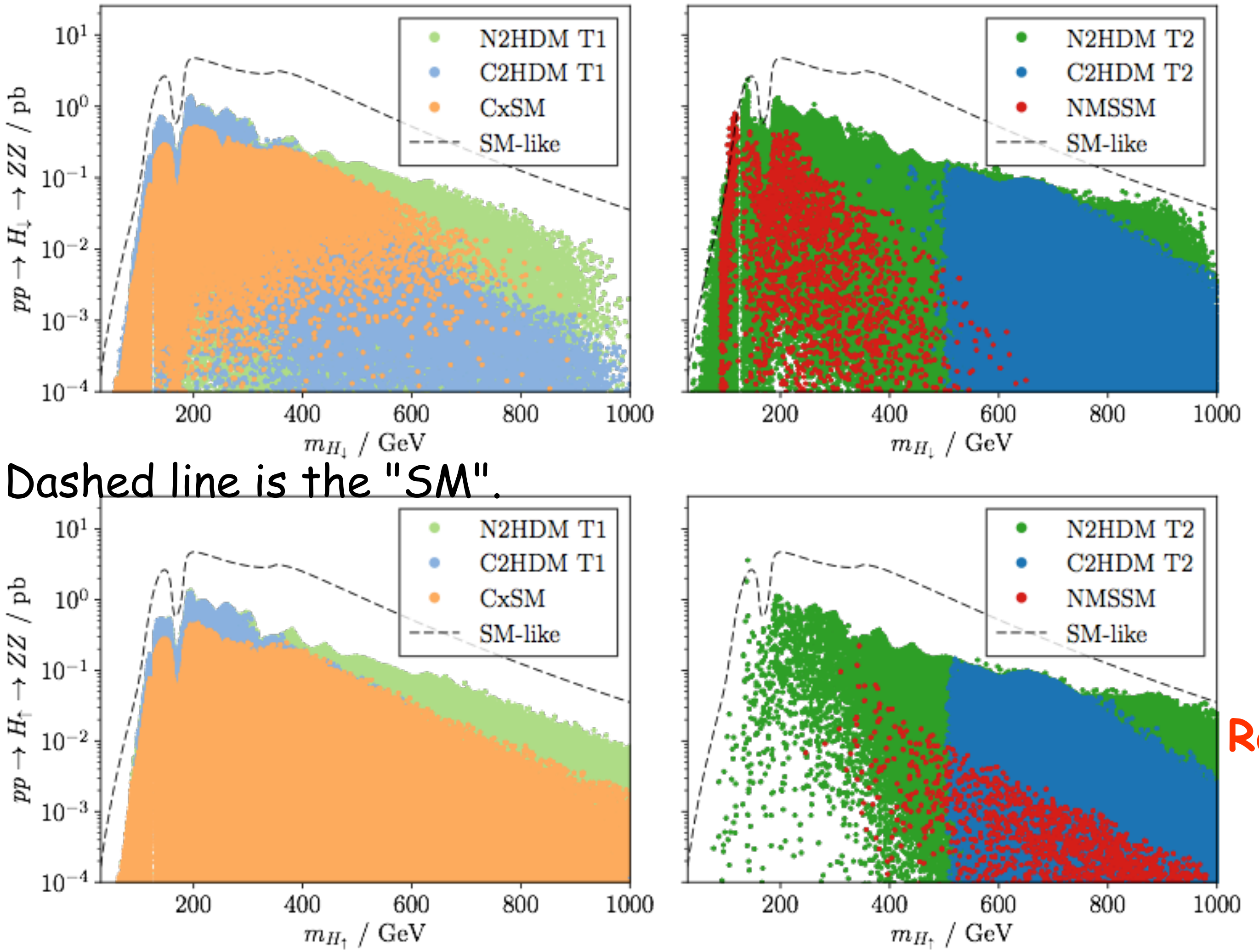
$\Phi \to h_{125} + \varphi$ found to be distinctive

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

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

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

Non-125 to ZZ



Dashed line is the "SM".

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

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

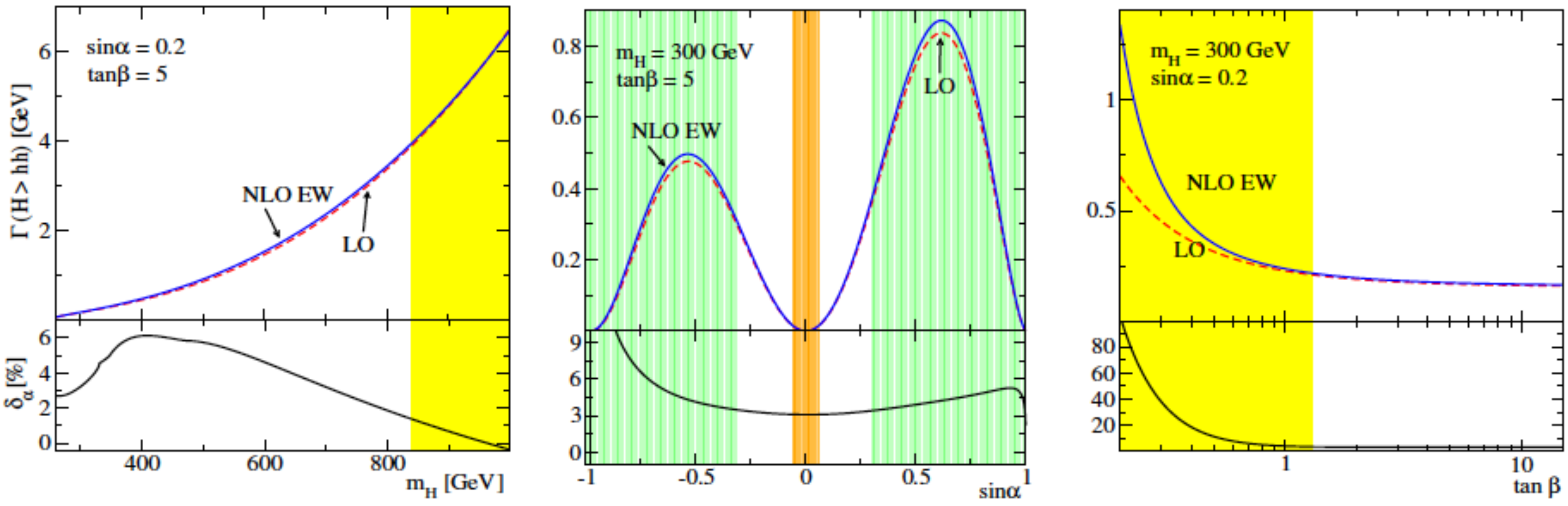
h_{125} takes most of the hVV coupling. Yukawa couplings can be different and lead to enhancements relative to the SM.

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.

1.b) Radiative corrections

Real Singlet model

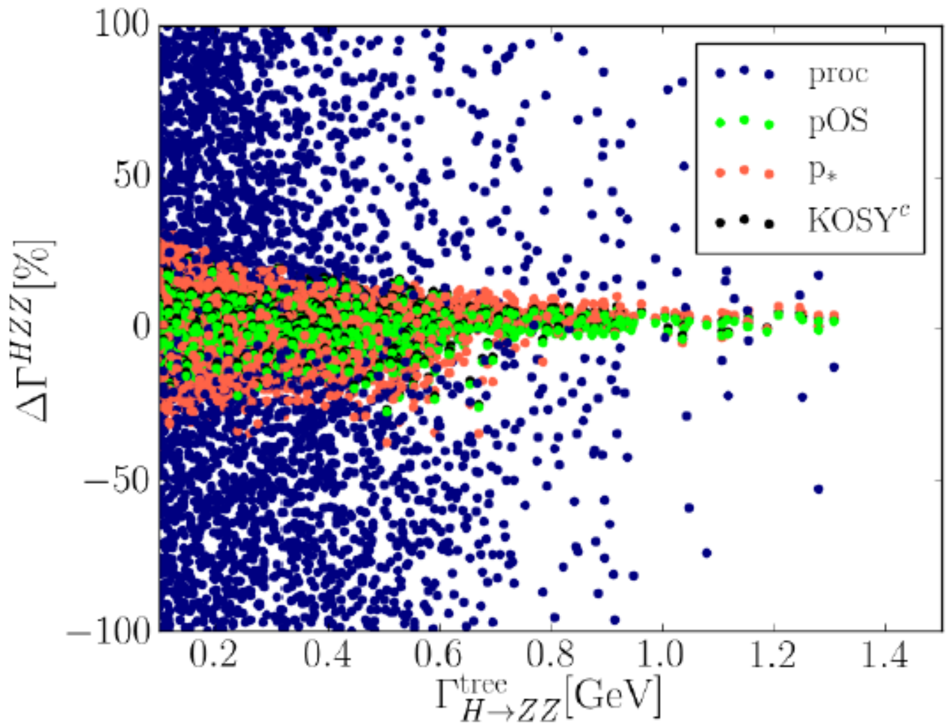


$H \rightarrow hh$

NLO Corrections shown
to be only a few percent

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

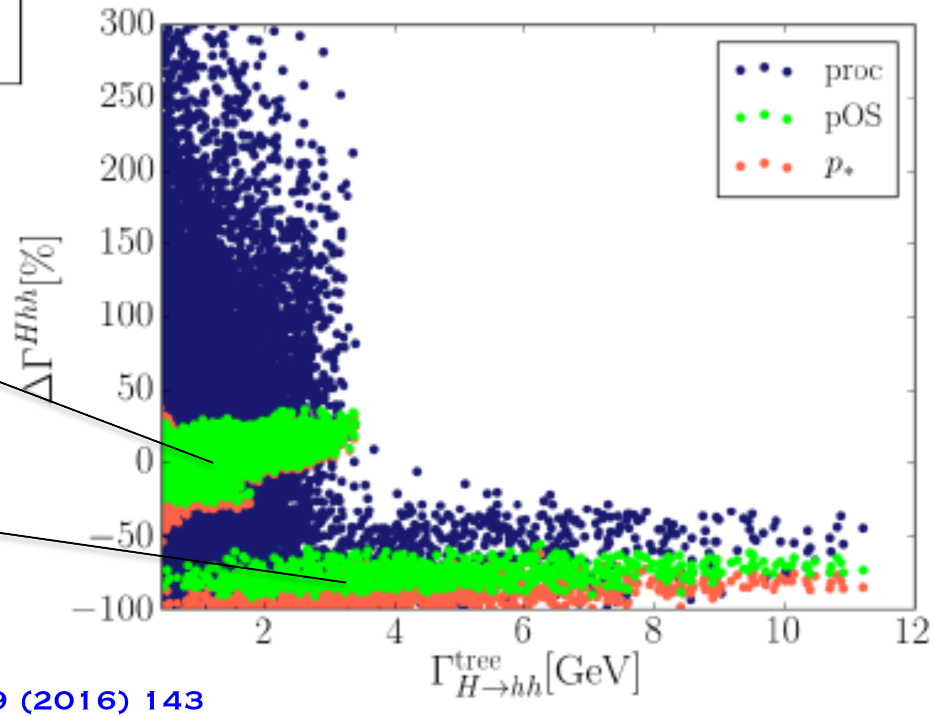
Real 2HDM



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

SM-like limit
sin(β - α) = 1

Wrong sign
sin(β + α) = 1



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

	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

Real N2HDM

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`.

		pOS^c	pOS^o	p$_\star^c$	p$_\star^o$
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

Corrections of heavy Higgs to ZZ
in different scearios.

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

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

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

Extra slides

We define the following admixtures

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

CxSM - sum of real and complex complex singlet components

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

C2HDM – "pseudoscalar" component

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

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

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

The CxSM

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

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

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

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

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 (<u>2HDM</u>)

- m^2_{12} and λ_5 complex — potential is explicitly CP-violating (<u>C2HDM</u>)

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 – $\mathrm{Re}(m^2_{12})$

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

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

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

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

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

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

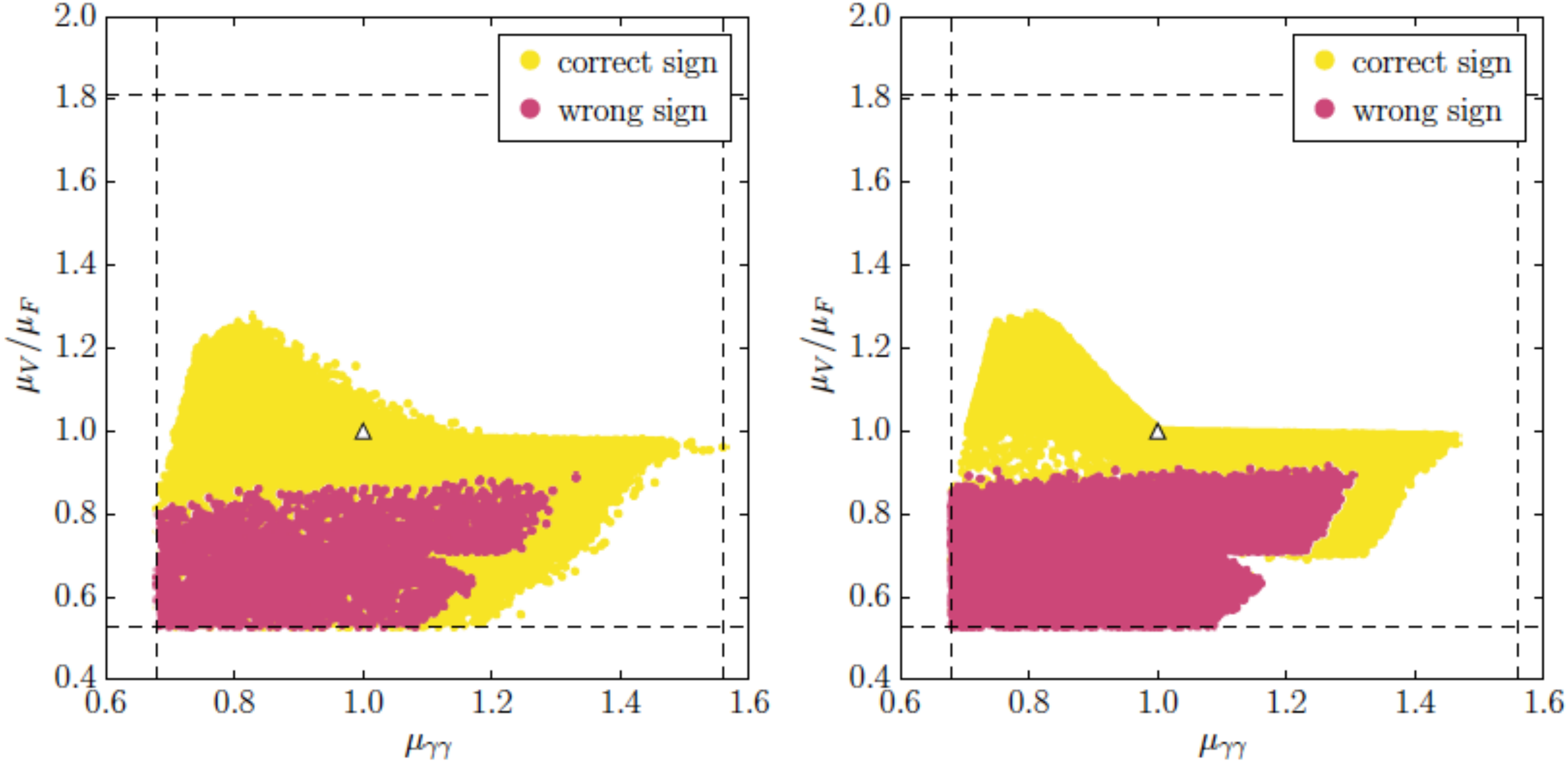
In YR4: [H. Logan and M. Zaro]

- **`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

Wrong sign in the 2HDM and N2HDM

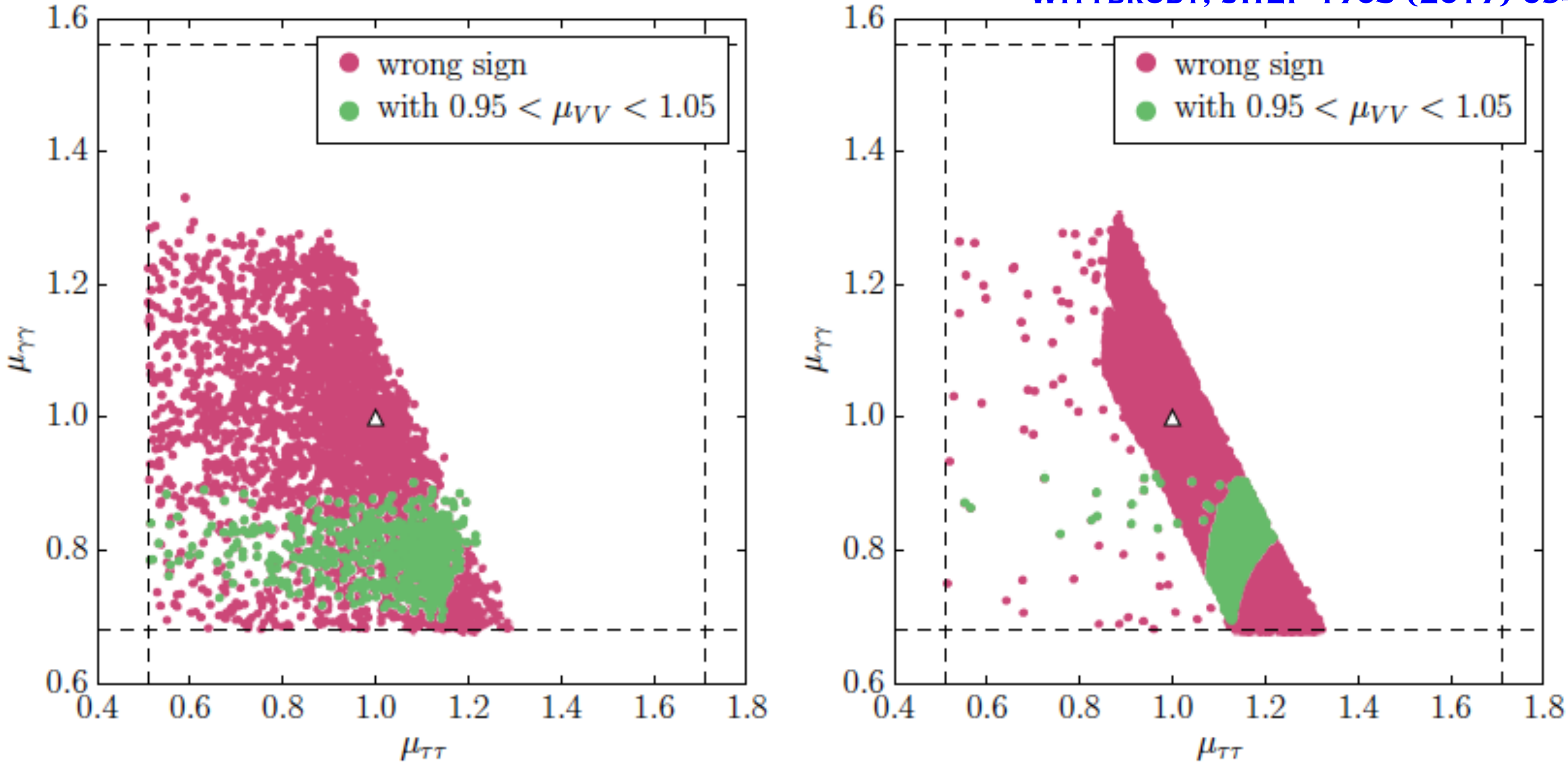


μ_V/μ_F vs $\mu_{\gamma\gamma}$ in type II 2HDM (left) and N2HDM (right) – in yellow the "right sign" and in pink the wrong sign points. Dashed lines are current limits. The h_{125} can be any of the H_i in the N2HDM and h or H in the 2HDM.

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

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

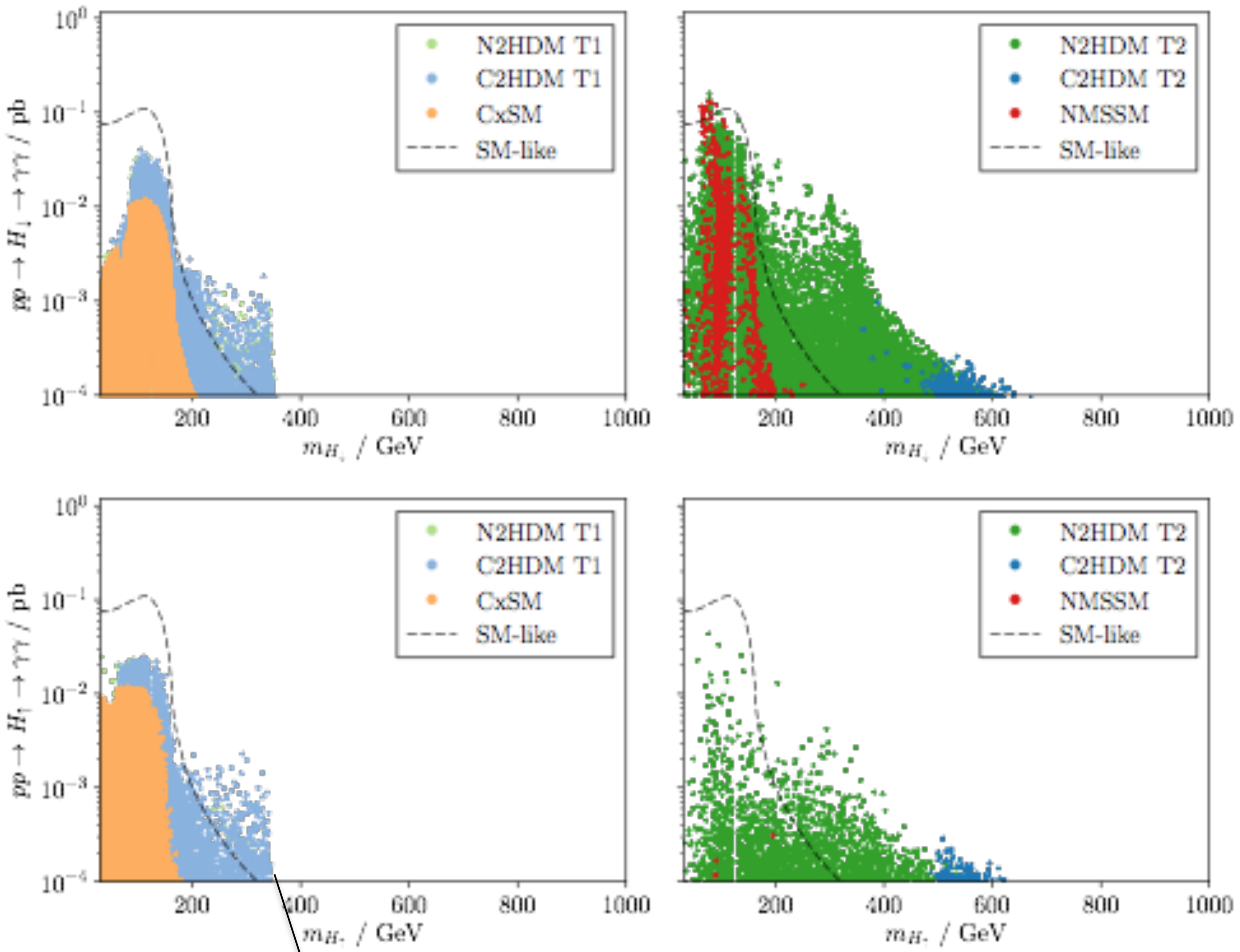
Muhlleitner, Sampaio, Santos, Wittbrodt, JHEP 1703 (2017) 094



$\mu_{\gamma\gamma}$ 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.

Non-125 to γγ



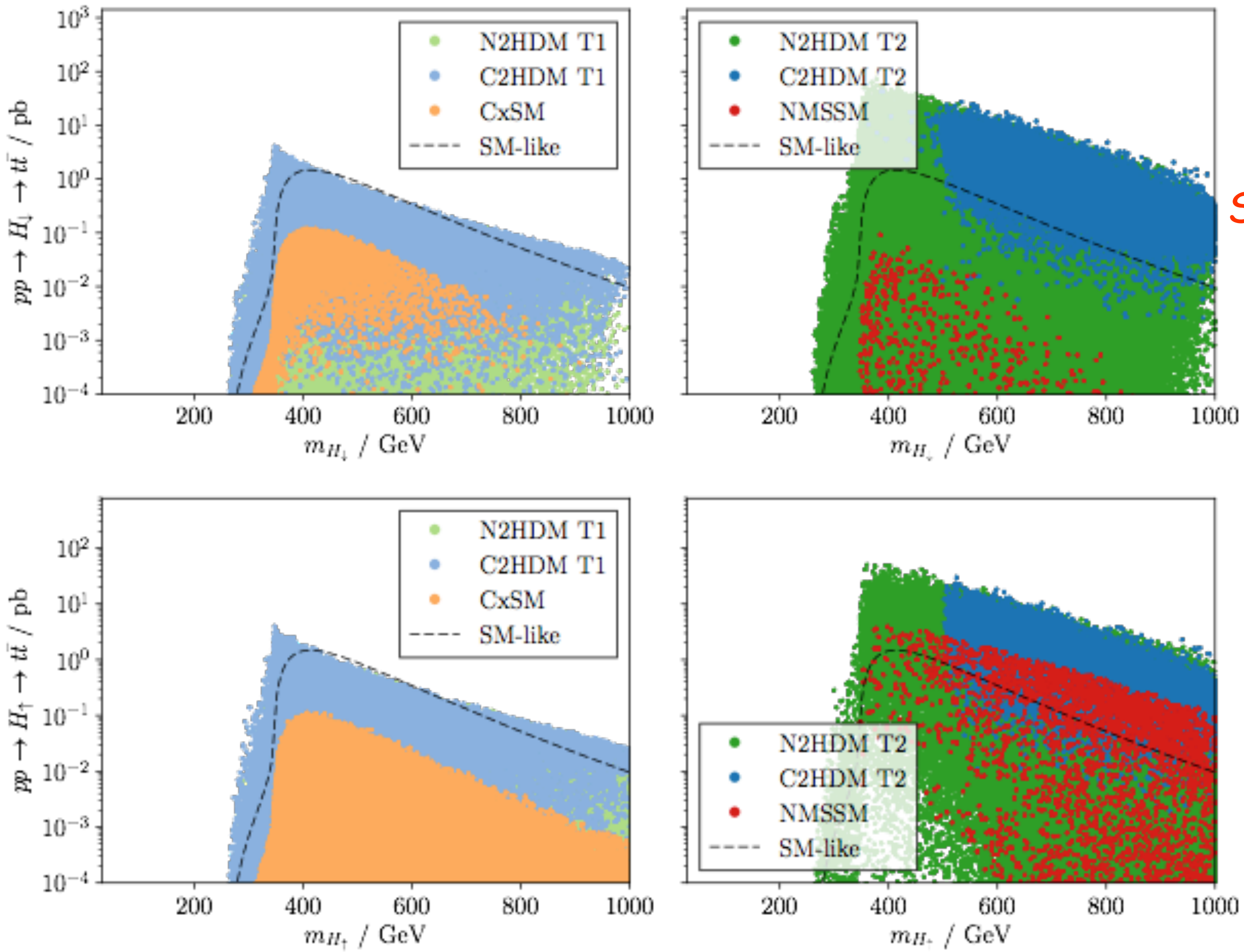
Signal rates for the production of H↓ (upper) and H↑ (lower) for 13 TeV as a function of m_H.
Dashed line is the "SM".

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

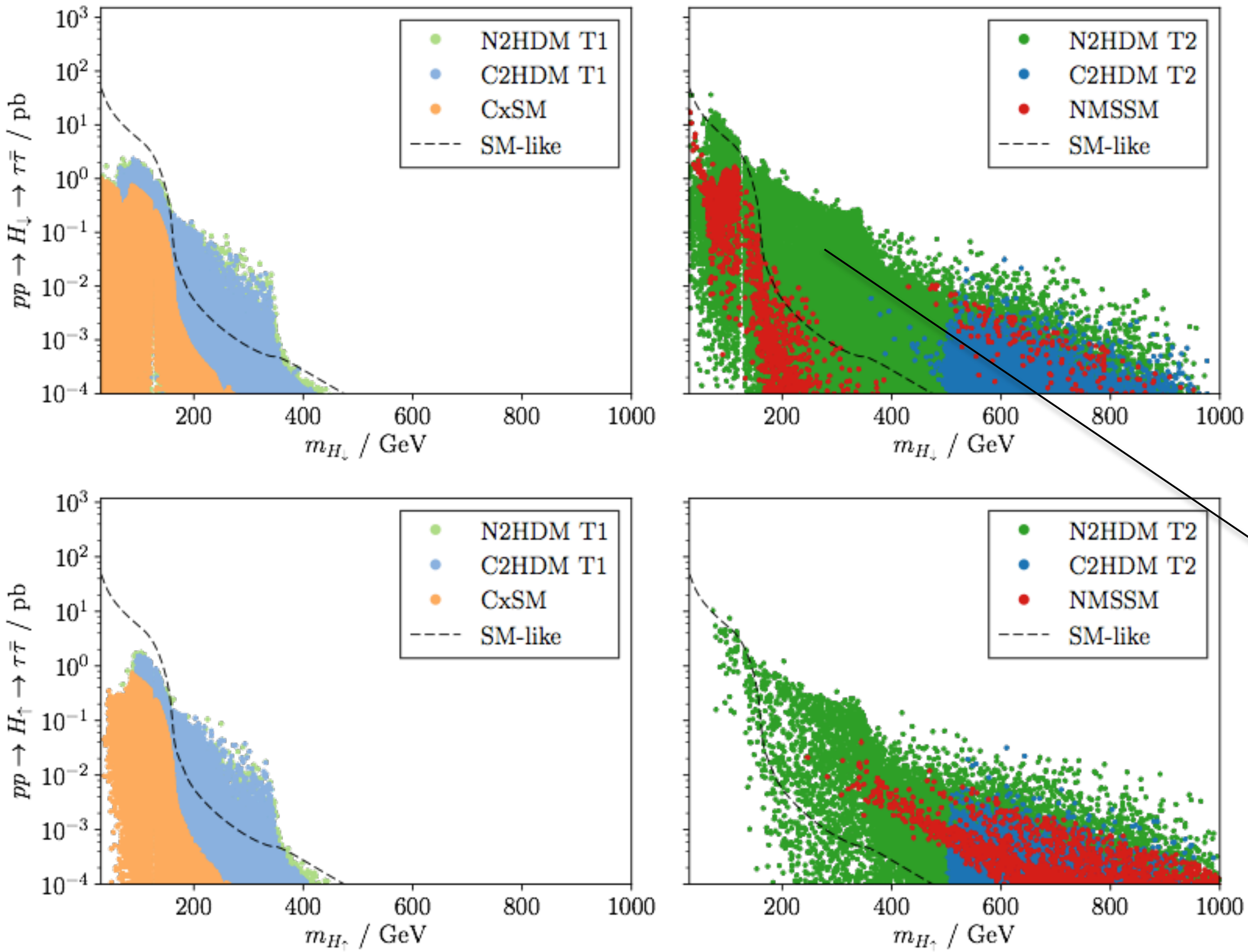


Signal rates for the production of H↓ (upper) and H↑ (lower) for 13 TeV as a function of m_H.

Dashed line is the "SM".

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

Non-125 to ττ



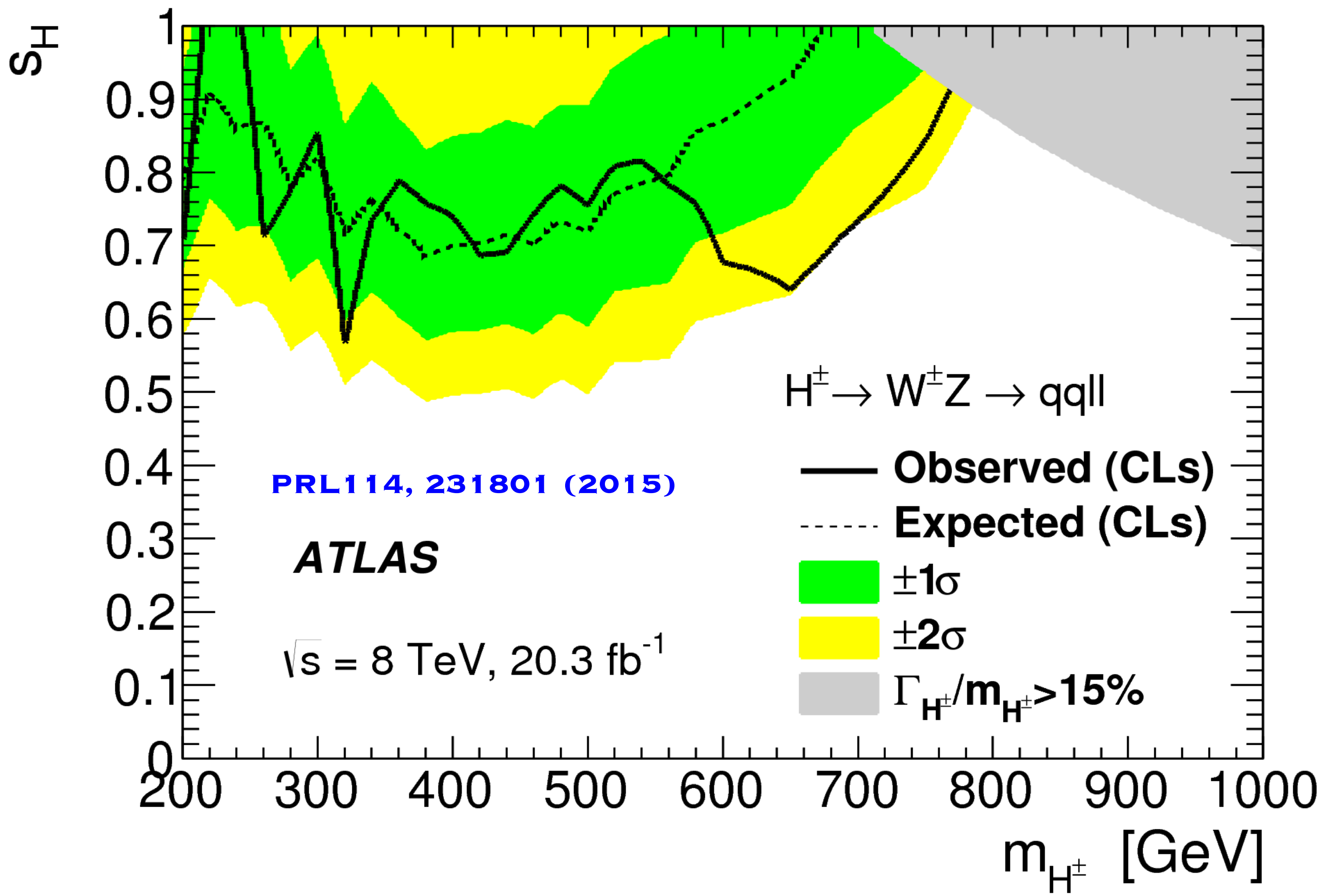
Signal rates for the production of H↓ (upper) and H↑ (lower) for 13 TeV as a function of m_H.

Dashed line is the "SM".

Region where only the N2hDM II survives.

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

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.

The simplest extensions can easily be related in many cases because the couplings to gauge bosons and fermions are similar. Sometimes, it is easy to perform the interpretation of the Higgs couplings in the framework of different models.

Such is the case of the CxSM, 2HDM, C2HDM, N2HDM and they can be compared with other models as for instance the NMSSM.

In the next slides we show how the lightest Higgs couplings to gauge bosons and fermions are related in the different models.

Lightest Higgs Yukawa couplings

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

2HDM AND C2HDM

$$\Phi_1 \to \Phi_1 \,, \quad \Phi_2 \to -\Phi_2$$

N2HDM

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

With these broken symmetries the model has three CP-even scalars and no dark matter candidate.

2HDM

Type I

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

Type II

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

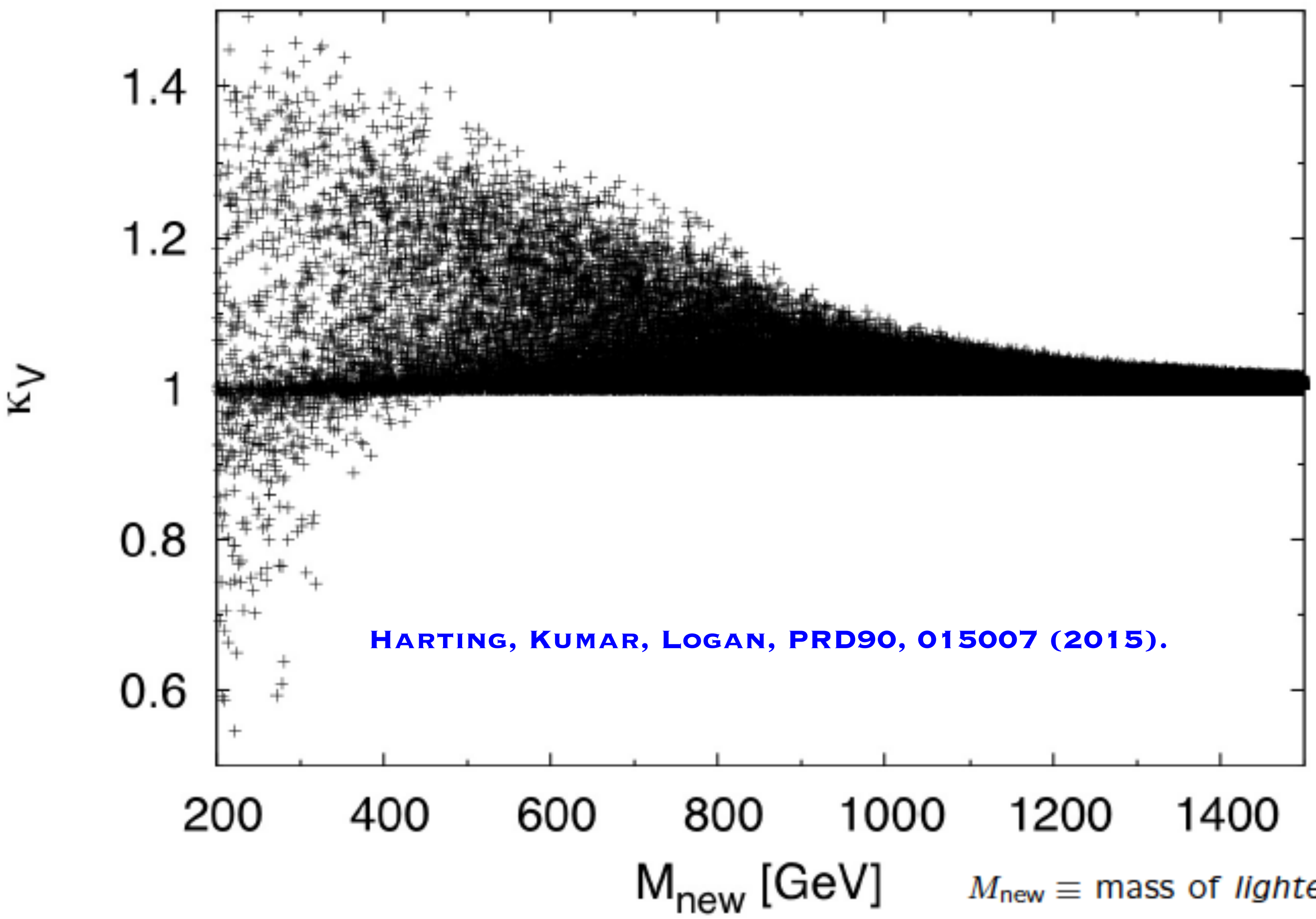
Type F/Y

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

Type LS/X

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

Numerical results: hVV coupling enhancement can be quite large!



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

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).

Searches involving neutral scalars

$$\begin{cases} S_i \to S_j S_j \to b\bar{b}b\bar{b} \\ S_i \to S_j S_j \to b\bar{b}\gamma\gamma \end{cases}$$

Resonant S_i (need to check final staes)

Vardan Khachatryan et al. Search for resonant pair production of Higgs bosons decaying to two bottom quark-antiquark pairs in proton-proton collisions at 8 TeV. Phys. Lett., B749:560–582, 2015.

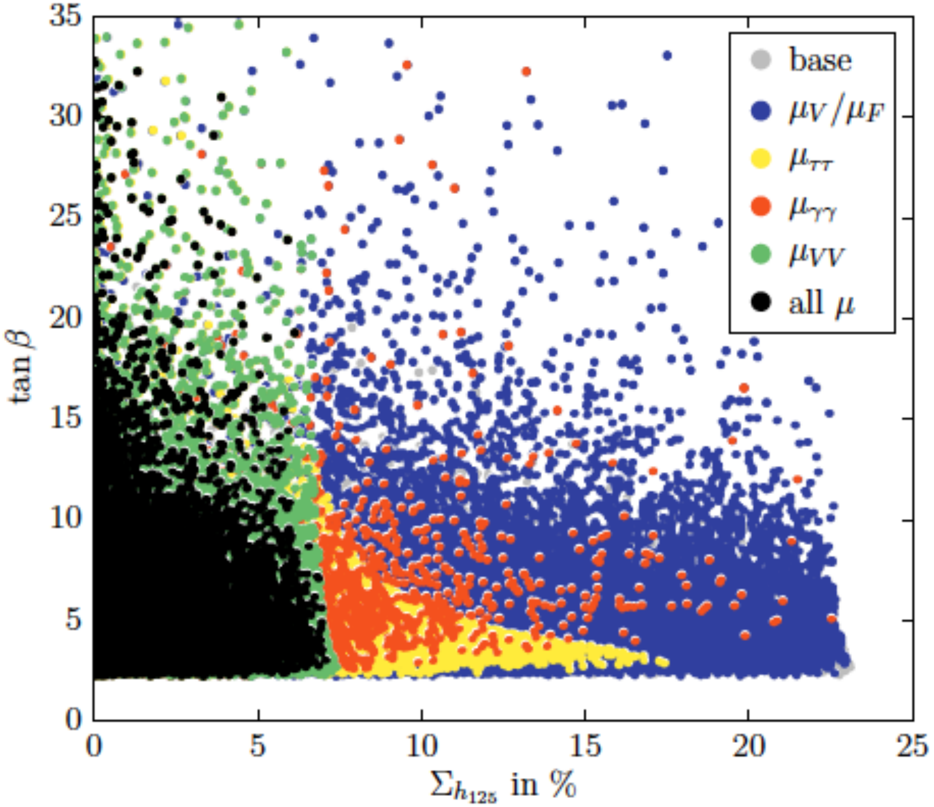
The ATLAS collaboration. A search for resonant Higgs-pair production in the bbbarbbarb final state in pp collisions at √s = 8 TeV. 2014.

G. Aad et al. Search For Higgs Boson Pair Production in the γγbbarb Final State using pp Collision Data at √s = 8 TeV from the ATLAS Detector. Phys.Rev.Lett., 114(8):081802, 2015.

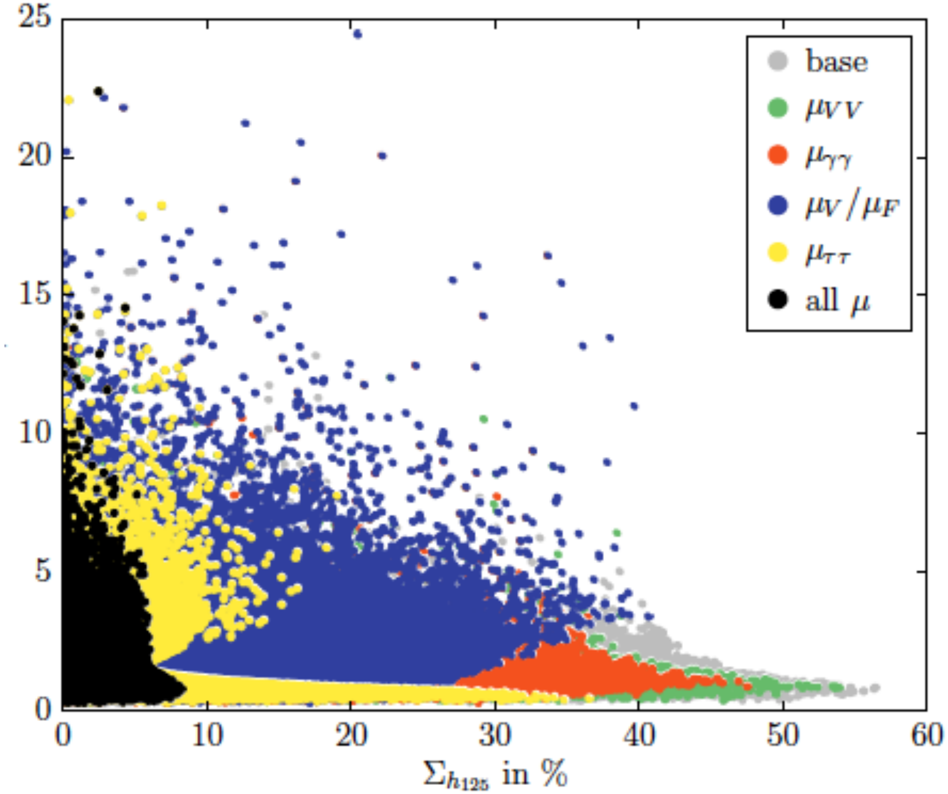
CMS Collaboration. Search for the resonant production of two Higgs bosons in the final state with two photons and two bottom quarks. 2014.

Singlet admixture

N2HDM type I



N2HDM type II



Muhlleitner, Sampaio, Santos, 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.