BSM Higgs sectors - non-SUSY (T)

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The High-Energy LHC –
Interplay between Precision Measurements
and Searches for New Physics

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LHC - Two approaches to the research programme

<u>Goal</u> – 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.

- ↓ 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 - 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

Extensions of the scalar sector - some guiding principles

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

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

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

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

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

$$\begin{array}{ll} T = 0;\ Y = 0 & \text{Singlet} \\ T = 1/2;\ |Y| = 1 & \text{Doublet} \\ T = 3;\ |Y| = 4 & \text{Septet} \\ \ldots\ldots\ldots\ldots\ldots & \end{array}$$

The simplest models that satisfy this relation are

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

Other studied models with $\rho \approx 1$ include the SM + triplet

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

Extensions of the scalar sector - some guiding principles

- **Control scalar induced tree-level FCNC**

SM Yukawa Lagrangian

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

SM + singlet (s)

Y are matrices in flavour space.

SM + doublet

$$L_Y^{mass} = \frac{1}{\sqrt{2}} \bar{D}_L \left(v_1 Y_d^1 + v_2 Y_d^2 \right) D_R + \ldots$$

$$L_Y^{interactions} = \frac{H}{\sqrt{2}} \bar{D}_L \left(-\sin\alpha Y_d^1 + \cos\alpha Y_d^2 \right) D_R + \ldots$$

cannot be diagonalised simultaneously

How to avoid large tree-level FCNCs in SM + doublet?

Extensions of the scalar sector - some guiding principles

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)

$$\boxed{\mathrm{Y}_{\mathrm{d}}^{2} \propto \mathrm{Y}_{\mathrm{d}}^{1}}$$ (for down type)

Extensions of the scalar sector - some guiding principles

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)

$$Y^U_{qt}(d_\rho) = -V_{q\rho}V^*_{t\rho}\,\frac{m_t}{v}\,c_{\beta\alpha}(t_\beta + t_\beta^{-1})\,, \quad q = u, c\,.$$

3.2 No tree-level FCNCs

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

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

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

$$L_Y^I = \begin{bmatrix}\bar{U} & \bar{D}\end{bmatrix}_L \Phi_2 Y_d^2\, D_R + \begin{bmatrix}\bar{U} & \bar{D}\end{bmatrix}_L \tilde{\Phi}_2\, Y_u^2 U_R + \begin{bmatrix}\bar{N} & \bar{E}\end{bmatrix}_L \Phi_2\, Y_e^2 E_R + \text{h.c.}$$

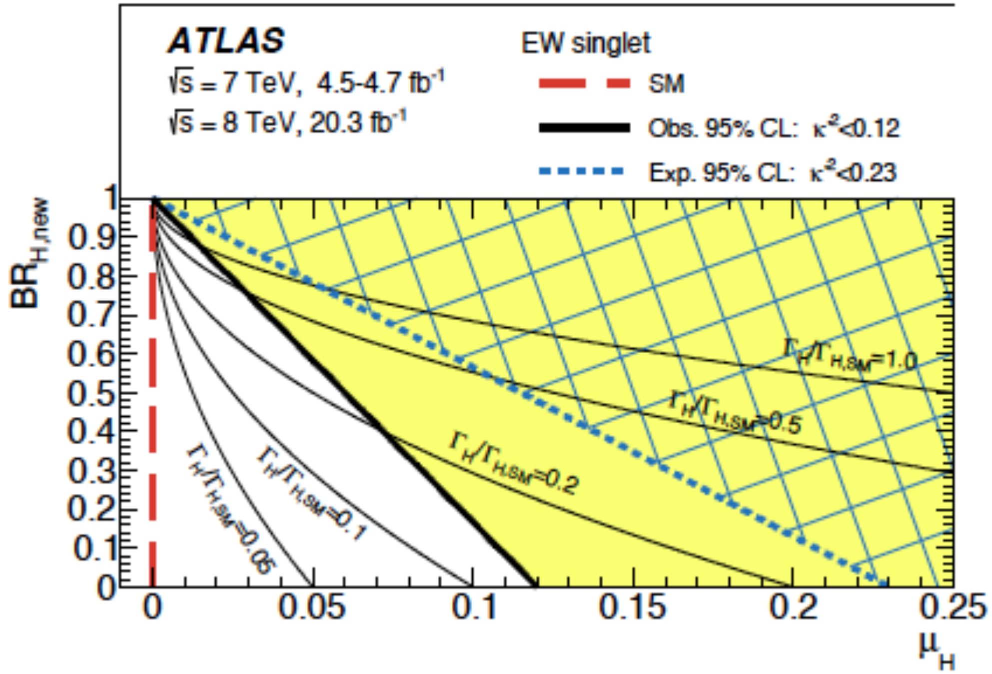
Extended scalars programme: SM + singlets/doublets/triplet or combinations thereof.

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**

The Real Singlet



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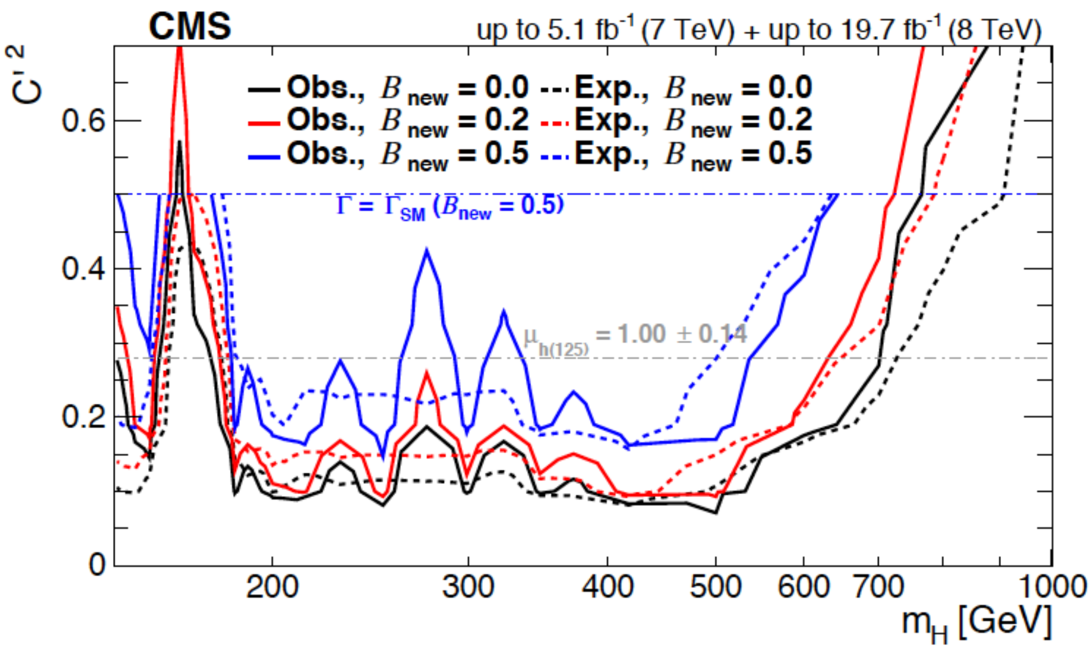
$$\mu_h = \frac{\sigma_h \times \mathrm{BR}_h}{(\sigma_h \times \mathrm{BR}_h)_{\mathrm{SM}}} = \kappa^2$$

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

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



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

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

CxSM: Phase classification for three possible models

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	$\langle \mathbb{S} \rangle \neq 0$ ($\cancel{\mathbb{Z}}_2'$)

CxSM: Minimal model with dark mater + 1/2 new Higgs

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

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

Barger, Langacker, McCaskey, Ramsey-Musolf, Shaughnessy (2009) ...
Costa, Morais, Sampaio, RS (2015)

RxSM: Minimal model with dark mater or new Higgs

SM plus S (real field) $\mathbb{Z}_2$ symmetry $S \to -S$

$$V = \frac{m^2}{2} H^\dagger H + \frac{\lambda}{4}(H^\dagger H)^2 + \frac{\lambda_{HS}}{2} H^\dagger H S^2 + \frac{m_S^2}{2} S^2 + \frac{\lambda_S}{4!} S^4$$

- $\mathbb{Z}_2$ phase ($v_S = 0$): dark matter

$$\begin{pmatrix} h_1 \\ h_{DM} \end{pmatrix} = \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix} \begin{pmatrix} h \\ S \end{pmatrix}$$

- $\cancel{\mathbb{Z}_2}$ phase ($v_S \neq 0$): 2 Higgs mix

$$\begin{pmatrix} h_1 \\ h_2 \end{pmatrix} = \begin{pmatrix} \cos\alpha & -\sin\alpha \\ \sin\alpha & \cos\alpha \end{pmatrix} \begin{pmatrix} h \\ S \end{pmatrix}$$

Datta, Raychaudhuri (1998)
Shabinger, Wells (2005) ...

Constraints

- Theoretical

ScannerS.hepforge.org

Global minimum, perturbative unitarity, potential bounded from below

- Experimental

Electroweak precision – STU

Collider Data (LEP, Tevatron, LHC) HiggsBounds/Signals

Dark matter relic density below Planck measurement &
bounds from LUX on σ_{SI} (micrOMEGAs)

Decay widths – adaptation of HDECAY (sHDECAY)
(www.itp.kit.edu/~maggie/sHEDECAY
- EW corrections consistently off
- includes both CxSM and RxSM)

CP and the CxSM

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

$$S \to S^* \Rightarrow A \to -A$$ which is a CP-transformation

so, what if A gets a vev, is CP is broken? No.

The crucial point is the following: V has two CP symmetries

$$H \to H^*;\ S \to S^* \qquad (1) \qquad H \to H^*;\ S \to S \qquad (2)$$

Symmetry (2) can be seen as a CP symmetry as long as new fermions are not added to the theory.

Therefore even if (1) is broken there is still one unbroken CP symmetry (2) and the model is CP-conserving.

Transformation (2) ceases to be a CP transformation with e.g. the introduction of vector-like quarks.

Branco, Lavoura, Silva (1999)

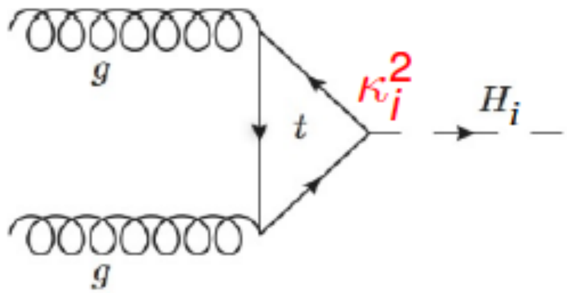
Bento, Branco (1990)

Simples changes relative to the SM

In singlet models, various LO (in EW corrections) observables, related to SM by a factor of κ^2:

- **Production cross sections:**

  $$\sigma_i = \kappa_i^2 \sigma_{SM}$$



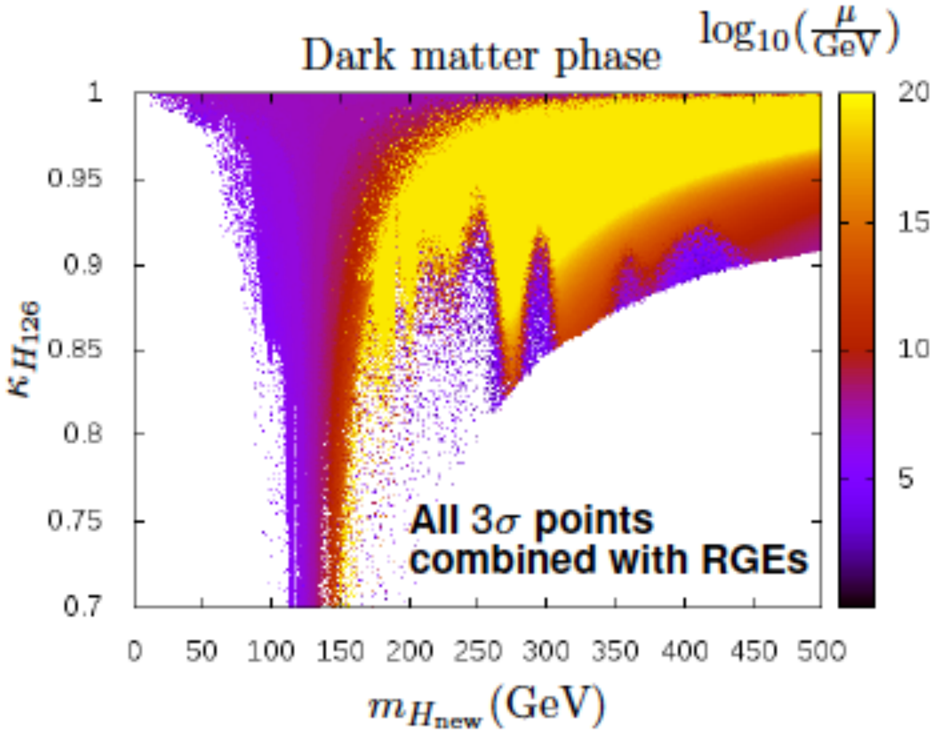
- **Decay widths to SM particles:**

  $$\Gamma_i = \kappa_i^2 \Gamma_{SM}$$

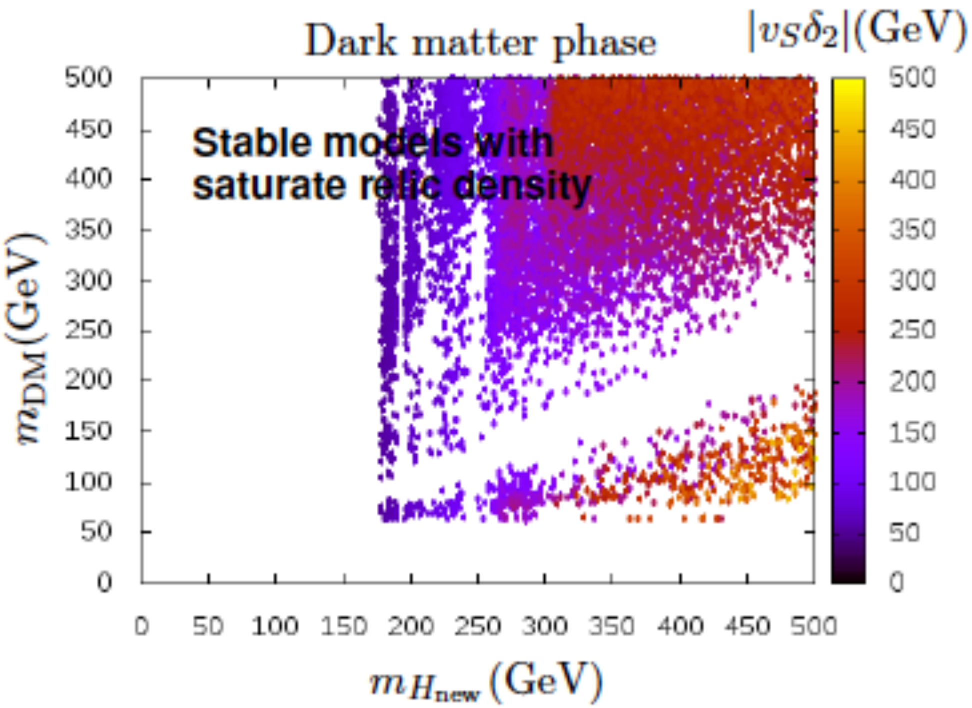
- **Total decay width:**

  $$\Gamma_i^{total} = \kappa_i^2 \Gamma_{SM}^{total} + \sum_{jk} \Gamma_{i \to jk}$$

RGE stability + Phenomenology

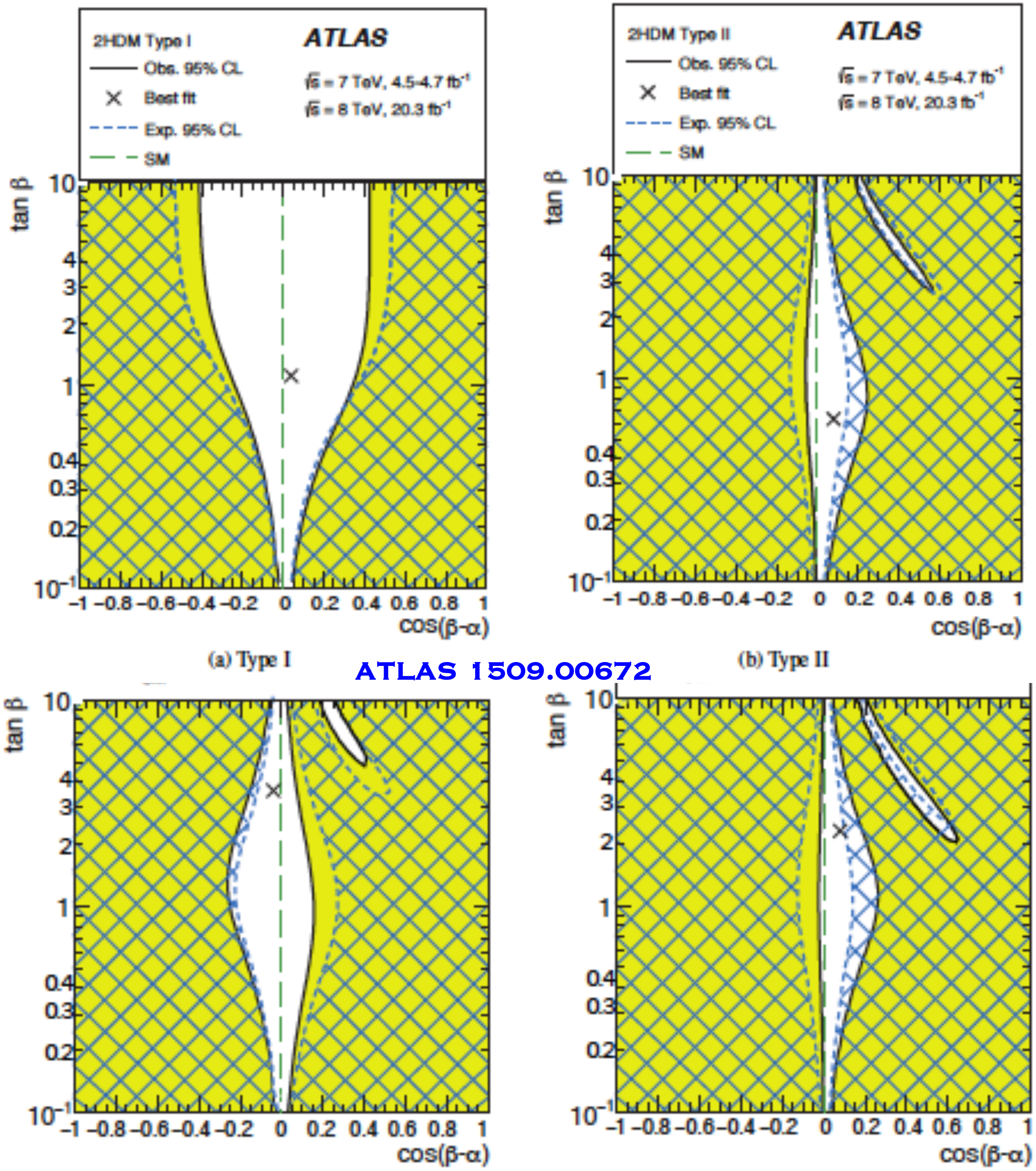


Lower bound m_{Hnew} = 170 GeV from the combination of all imposed constraints. Lower bound on the dark matter particle mass just below mDM = $\frac{1}{2}$ m_{125} and an excluded wedge around mDM = $\frac{1}{2}$ m_{Hnew}



These correspond to regions where the annihilation channels AA → Hi (to visible Higgses) are very efficient in reducing the relic density so it becomes difficult to saturate the measured Ωc.

The 2HDM



(a) Type I

(b) Type II

(c) Lepton-specific

(d) Flipped

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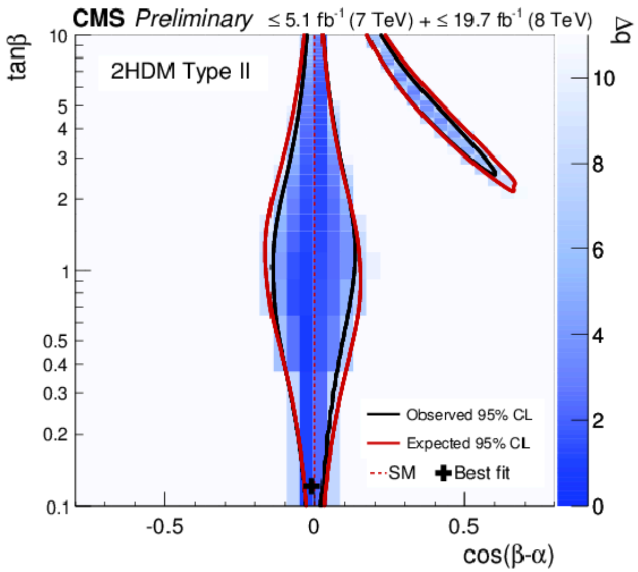

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2HDM particle content

SM $\rightarrow$ 4 degrees of freedom ⇨ 2HDM $\rightarrow$ 8 degrees of freedom

- All symmetries broken $\rightarrow$ 4 GB + 4 scalar bosons (charge breaking)
- $U(1)_{em}$ unbroken; CP broken $\rightarrow$ 3 GB + 5 scalar bosons (2 charged, $H^{\pm}$, and 3 neutral, h_1, h_2 and h_3)
- $U(1)_{em}$ unbroken; CP conserved $\rightarrow$ 3 GB + 5 scalar bosons (2 charged, $H^{\pm}$, and 3 neutral, h, H and A)

The softly broken Z_2 (U(1)) symmetric 2HDM potential

$$\boxed{\phi_1 \rightarrow \phi_1 \qquad \phi_2 \rightarrow -\phi_2}$$

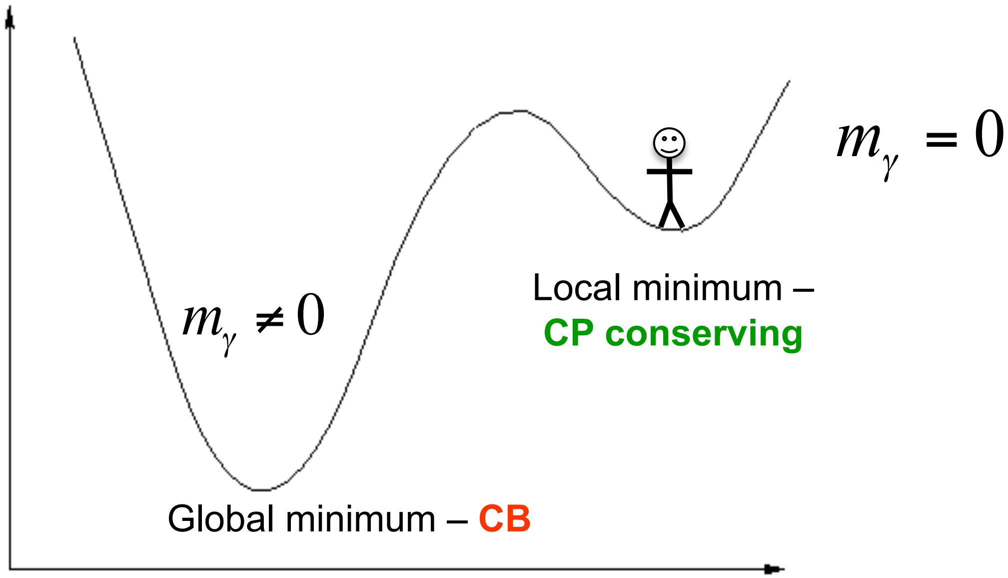
$$\begin{aligned} V(\Phi_1, \Phi_2) \;&=\; m_1^2 \Phi_1^\dagger \Phi_1 + m_2^2 \Phi_2^\dagger \Phi_2 - (m_{12}^2 \Phi_1^\dagger \Phi_2 + \mathrm{h.c}) + \frac{1}{2}\lambda_1 (\Phi_1^\dagger \Phi_1)^2 + \frac{1}{2}\lambda_2 (\Phi_2^\dagger \Phi_2)^2 \\ &+\; \lambda_3 (\Phi_1^\dagger \Phi_1)(\Phi_2^\dagger \Phi_2) + \lambda_4 (\Phi_1^\dagger \Phi_2)(\Phi_2^\dagger \Phi_1) + \frac{1}{2}\lambda_5 [(\Phi_1^\dagger \Phi_2)^2 + \mathrm{h.c.}] \end{aligned}$$

Vacuum structure

- CP CONSERVING (N) $\Phi_1 = \begin{pmatrix} 0 \\ v_1 \end{pmatrix} \; ; \; \Phi_2 = \begin{pmatrix} 0 \\ v_2 \end{pmatrix}$
- CHARGE BREAKING (CB) $\Phi_1 = \begin{pmatrix} 0 \\ v'_1 \end{pmatrix} \; ; \; \Phi_2 = \begin{pmatrix} \alpha \\ v'_2 \end{pmatrix}$
- CP BREAKING (CP) $\Phi_1 = \begin{pmatrix} 0 \\ v'_1 + i\delta \end{pmatrix} \; ; \; \Phi_2 = \begin{pmatrix} 0 \\ v'_2 \end{pmatrix}$

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

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



Vacuum structure of 2HDMs

The tree-level global picture for spontaneously broken symmetries

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

Barroso, Ferreira, RS (2004, 2006, 2007)

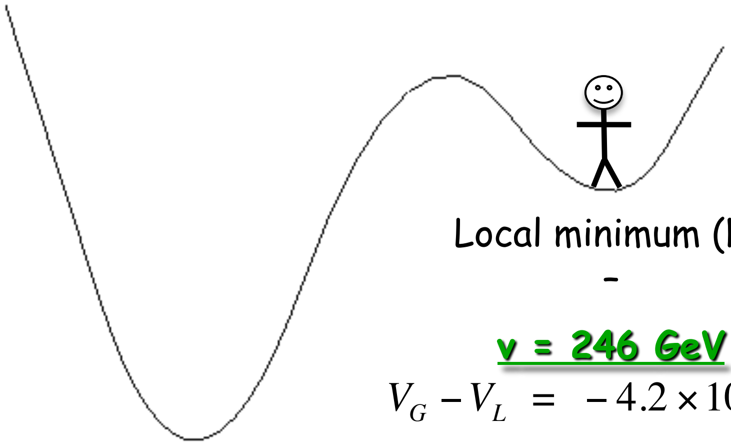
Maniatis, von Manteuffel, Nachtmann, Nagel (2006)

The tree-level global picture for explicit CP

6. An explicitly CP-violating 2HDM potential can have two non-degenerate minima
7. If they exist they must be non-degenerate

Ivanov (2007, 2008)

Two normal minima - potential with the soft breaking term



Local minimum (N) - $m_W = 80.4$ GeV

v = 246 GeV

$$V_G - V_L = -4.2 \times 10^8 \text{ GeV}$$

Global minimum (N) - $m_W = 107.5$ GeV

v = 329 GeV

THE PANIC VACUUM!

and this is one that can actually occur...

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

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

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

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

$$\begin{aligned}
a_1 &= s_\beta^2 \left[m_1^2 s_2^2 + \left(m_2^2 s_3^2 + m_3^2 c_3^2\right) c_2^2\right] \ , \\
b_1 &= c_2^2 \left[c_1 s_2 \left(-m_1^2 + m_2^2 s_3^2 + m_3^2 c_3^2\right) + s_1 s_3 c_3 \left(m_2^2 - m_3^2\right)\right]^2 \ , \\
a_2 &= 2 m_1^2 c_2^2 c_{\alpha_1+\beta}^2 + \left(m_2^2 + m_3^2\right)\left(1 - c_2^2 c_{\alpha_1+\beta}^2\right) \\
&\quad + \left(m_2^2 - m_3^2\right)\left[\cos(2\alpha_3)\left(s_{\alpha_1+\beta}^2 - c_{\alpha_1+\beta}^2 s_2^2\right) + \sin(2\alpha_3) s_2 \sin(2\alpha_1 + 2\beta)\right] \ , \\
b_2 &= \left(m_2^2 c_3^2 + m_3^2 s_3^2\right) m_1^2 c_2^2 + m_2^2 m_3^2 s_2^2 \ .
\end{aligned}$$

BARROSO, FERREIRA, IVANOV, RS (2013)

IVANOV, SILVA (2015)

Softly broken Z_2 symmetric Higgs potential

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

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)

Ginzburg, Krawczyk, Osland (2002).

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 – $\mathrm{Re}(m^2_{12})$

Lightest Higgs couplings

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

to gauge bosons

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

$$\kappa^h_V = \sin(\beta - \alpha)$$

$$\kappa^H_V = \cos(\beta - \alpha)$$

CP-conserving

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

CP-violating

$$\boxed{g^{hVV}_{C2HDM} = \cos(\alpha_2)\ g^{hVV}_{2HDM}}$$

$$C \equiv c_\beta R_{11} + s_\beta R_{12}$$

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

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

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

Lightest Higgs couplings

$$\alpha_1 = \alpha + \pi / 2$$
$$c_2 = \cos(\alpha_2)$$
$$t_\beta = \tan\beta$$

Yukawa couplings

CP-CONSERVING

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

CP-VIOLATING

$$\equiv a_F + i\gamma_5 b_F$$

Φ_2 always couples to up-type quarks

Type I	Φ_2 to leptons and to down quarks
Type II	Φ_1 to leptons and to down quarks
Type F=X=III	Φ_2 to leptons Φ_1 to down quarks
Type LS=Y=IV	Φ_1 to leptons Φ_2 to down quarks

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

Status of the CP-conserving 2HDM

Experimental

All models

- B_d^0–$\overline{B}_d^0$ and B_s^0–$\overline{B}_s^0$ mixing
- $R_b \equiv \Gamma(Z \to b\bar{b})/\Gamma(Z \to \mathrm{hadrons})$

$$\boxed{\tan\beta \gtrsim 1}$$

- Precision Electroweak

Theoretical

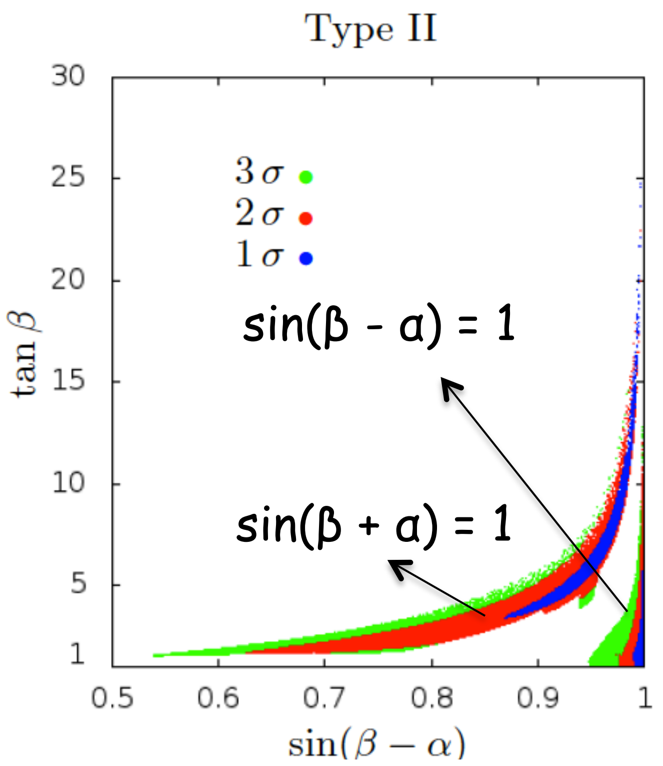
- Vacuum Stability
- Perturbative Unitarity
- Global minimum (discriminant)

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

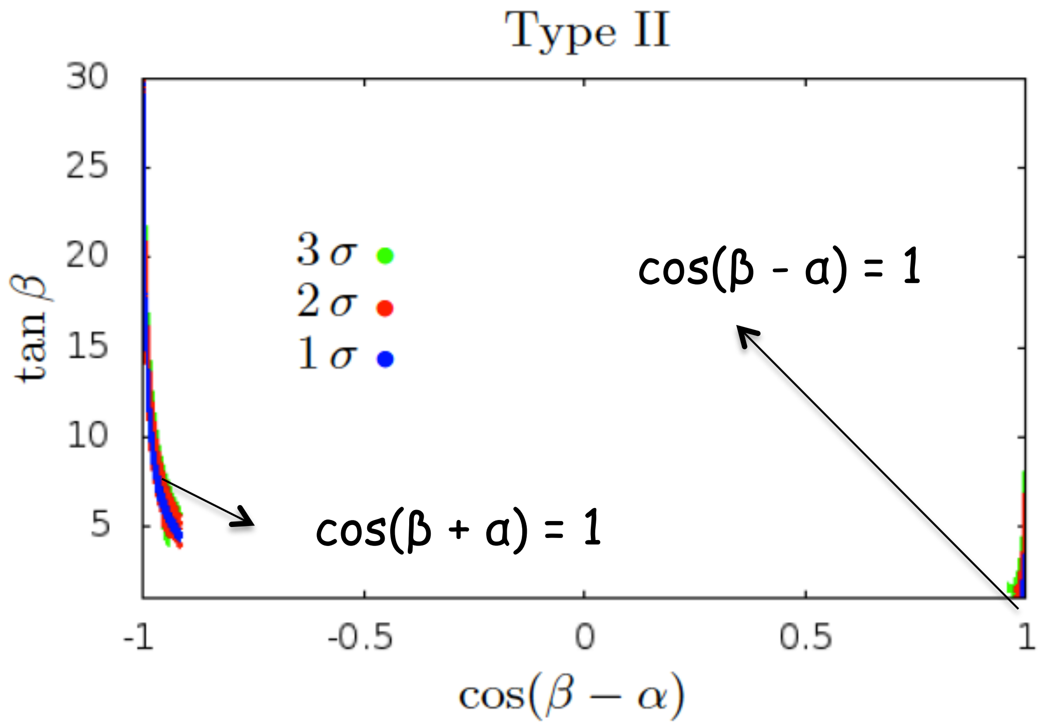
$$\kappa_i^2 = \frac{\Gamma^{2HDM}(h \to i)}{\Gamma^{SM}(h \to i)}$$

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

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

$$\boxed{125\ \text{GeV} = m_h \leq m_H \leq 900\ \text{GeV}}$$

The heavy scenario ($m_h < m_H = 125$ GeV)



The Alignment limit

$$\boxed{\begin{array}{l}\cos(\beta-\alpha)=1 \quad \Rightarrow \\ \Rightarrow \quad \kappa_F=-1; \quad \kappa_V=-1\end{array}}$$

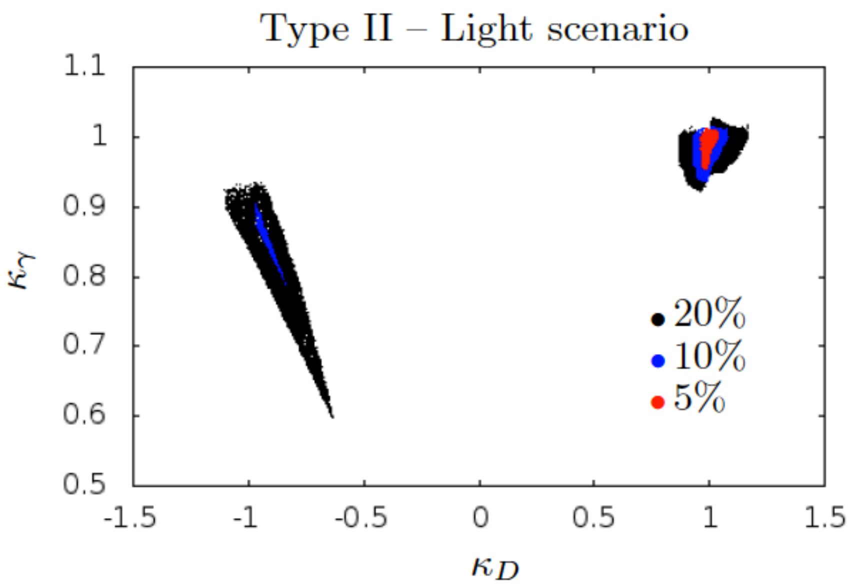
but no decouupling

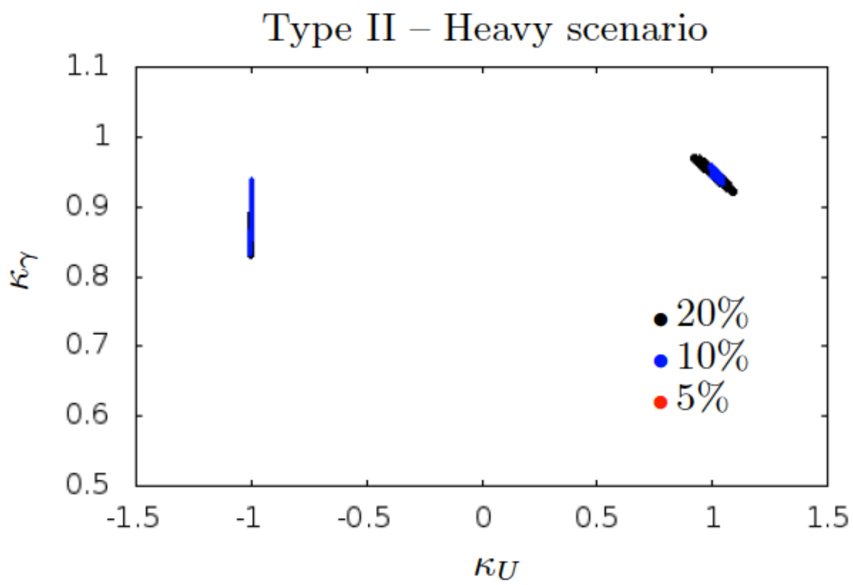
Wrong-sign limit $\boxed{\kappa_D \kappa_V < 0}$

$$\boxed{\begin{array}{l}\cos(\beta+\alpha)=1 \quad \Rightarrow \quad \kappa_D=1 \quad (\kappa_U=-1) \\ \qquad \cos(\beta-\alpha)=-\dfrac{\tan^2\beta-1}{\tan^2\beta+1} \quad \Rightarrow \quad \kappa_V \le 0 \;\; \text{if} \;\; \tan\beta \ge 1\end{array}}$$

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.

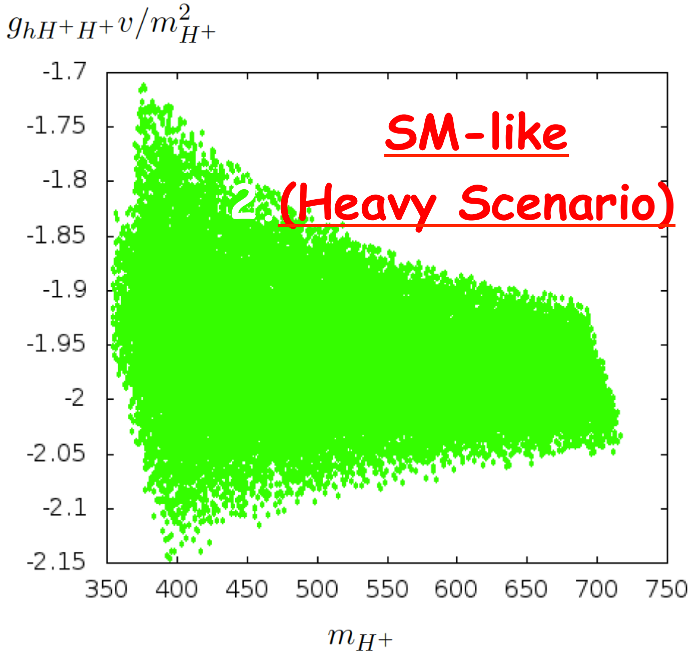


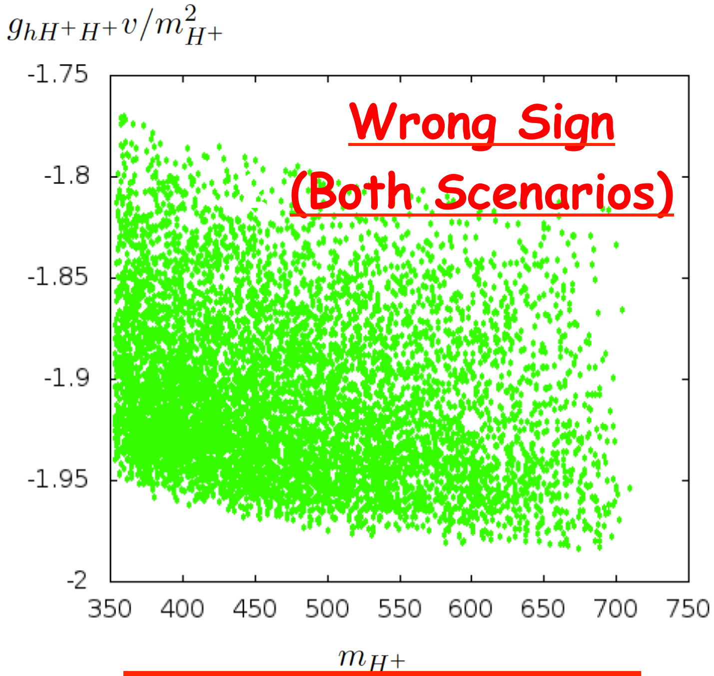


5% accuracy in the measurement of the **gamma gamma rate** could probe the wrong sign in both scenarios but also the SM-like limit in the heavy scenario due to the effect of charged Higgs loops + theoretical and experimental constraints.

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

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

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?

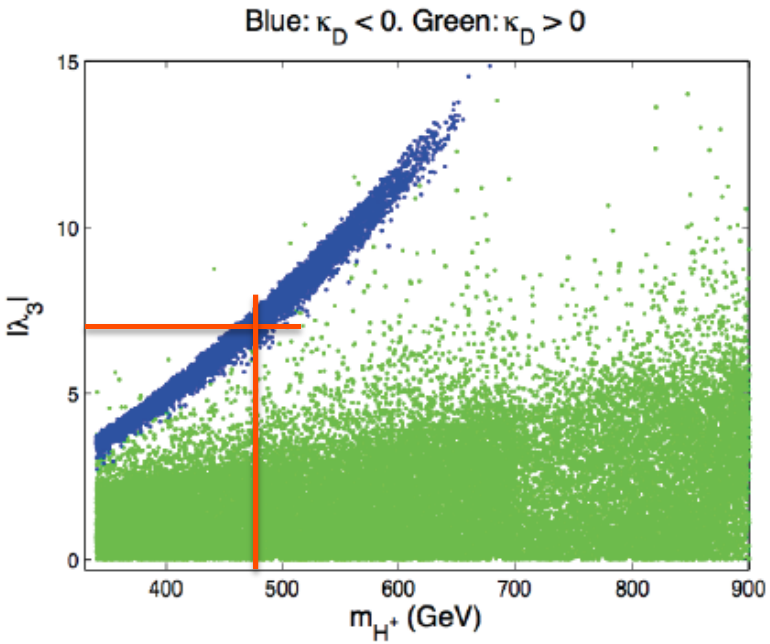
SM-like limit

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

Wrong sign

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

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



Defining

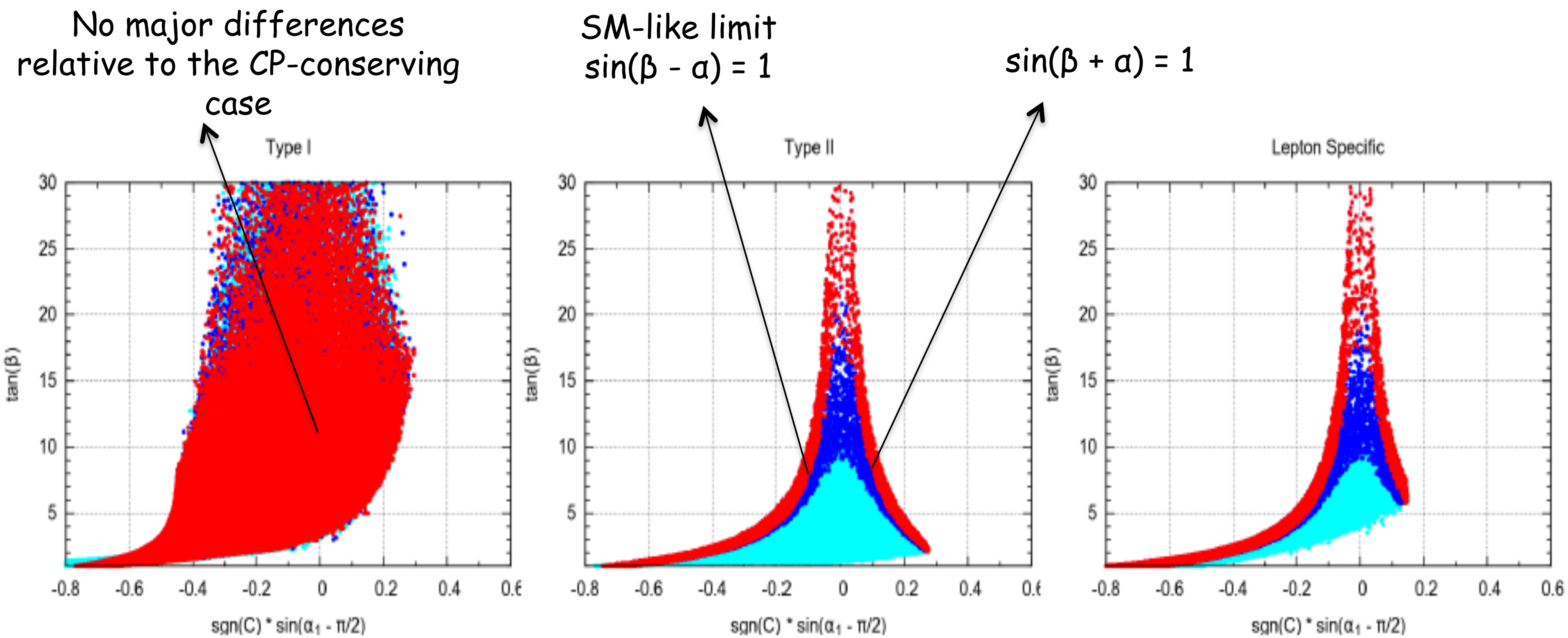
$$\kappa_D = -\frac{\sin\alpha}{\cos\beta} = -1 + \varepsilon$$

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

Difference decreases with tan β

… and three quick slides about the status of the CP-violating C2HDM

Results after run 1



tanβ as a function of $\sin(\alpha_1 - \pi/2)$ for Type I, Type II and LS. Full range (cyan), $s_2 < 0.1$ (blue) and $s_2 < 0.05$ (red).

Fontes, Romão, Silva (2014)
Fontes, Romão, RS, Silva (2015)

Scalar or pseudo-scalar?

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

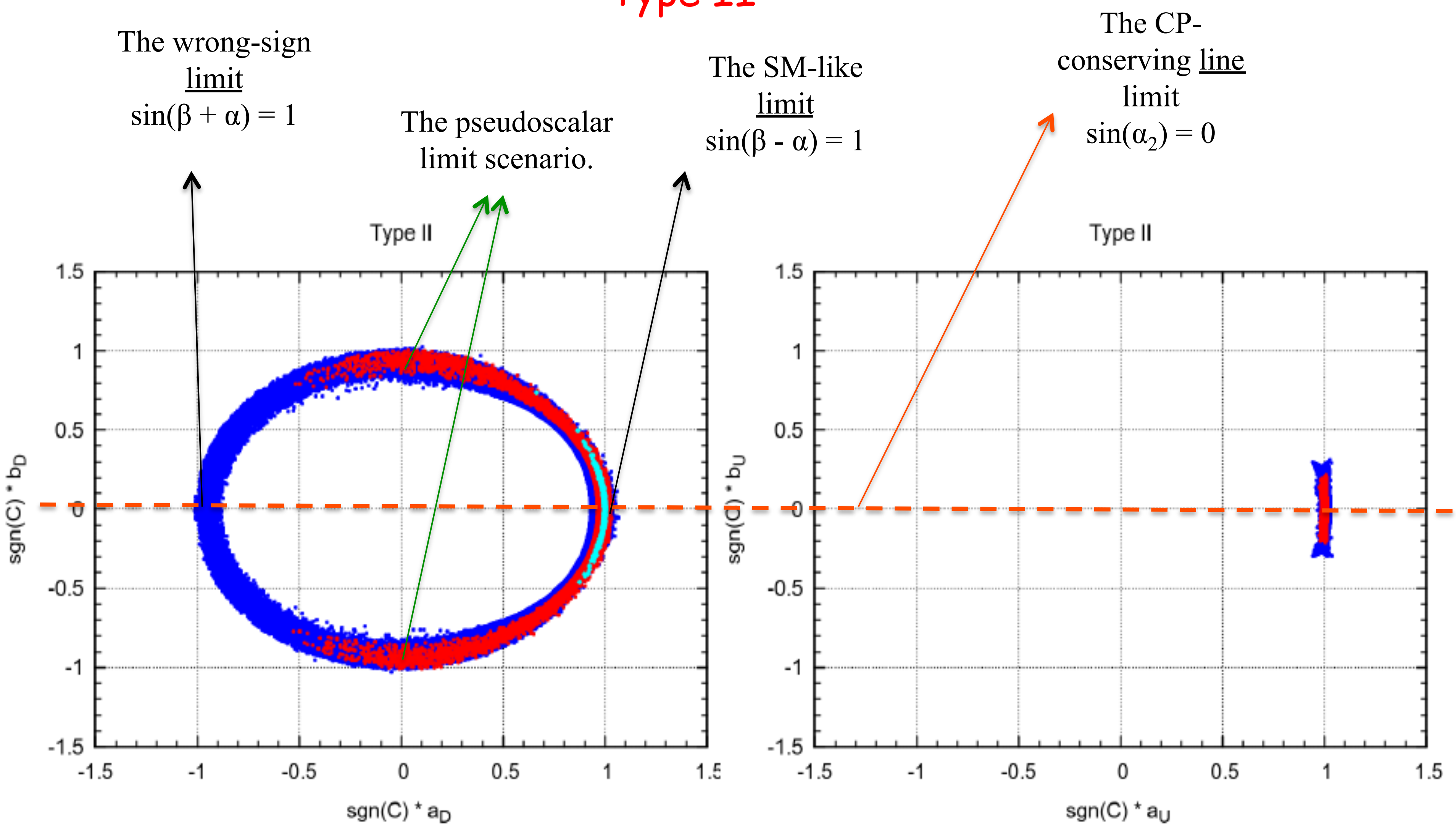
$$b_U = 0 \quad \text{and} \quad a_D = 0\,?$$

Find a 750 GeV scalar decaying to tops $\quad h_1 = H \rightarrow t\bar{t}$

Find a 750 GeV pseudoscalar decaying to taus $\quad h_1 = A \rightarrow \tau^+\tau^-$

<u>It's CP-violation!</u>

Type II



Left: sgn(C) b_D (or b_L) as a function of sgn(C) a_D (or a_L) for Type II, 13 TeV, with rates at 10% (blue), 5% (red) and 1% (cyan) of the SM prediction.
Right: same but for up-type quarks.

EDMs kill most of the parameter space with large b_D

BSM Higgs at Run 2

The future of BSM Higgs

- CP violation

  Example: scalar vs. pseudoscalars components in conection to Higgs decays in $\tau\tau h$ and tth

- EW corrections to important observables in BSM Higgs sectors

  Example: corrections to Higgs decays in singlet and 2HDM extensions.

- Make a stronger case for specific searches

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

- Tools (improve/new)

- Discuss other extensions like 3HDM (with symmetries), N2HDM, etc, if they lead to phenomenological differences.

CP-violation at the LHC

CP - what have ATLAS and CMS measured so far?

Correlations in the momentum distributions of leptons produced in the decays

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

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

Choi, Miller, Muhlleitner, Zerwas, (2003).

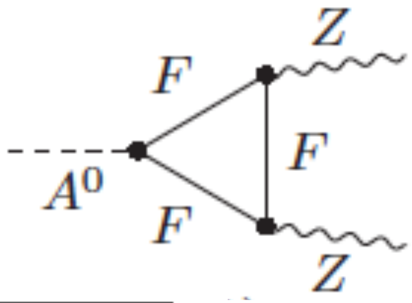
Buszello, Fleck, Marquard, van der Bij, (2004)

The results from these studies can be applied to specific classes of models

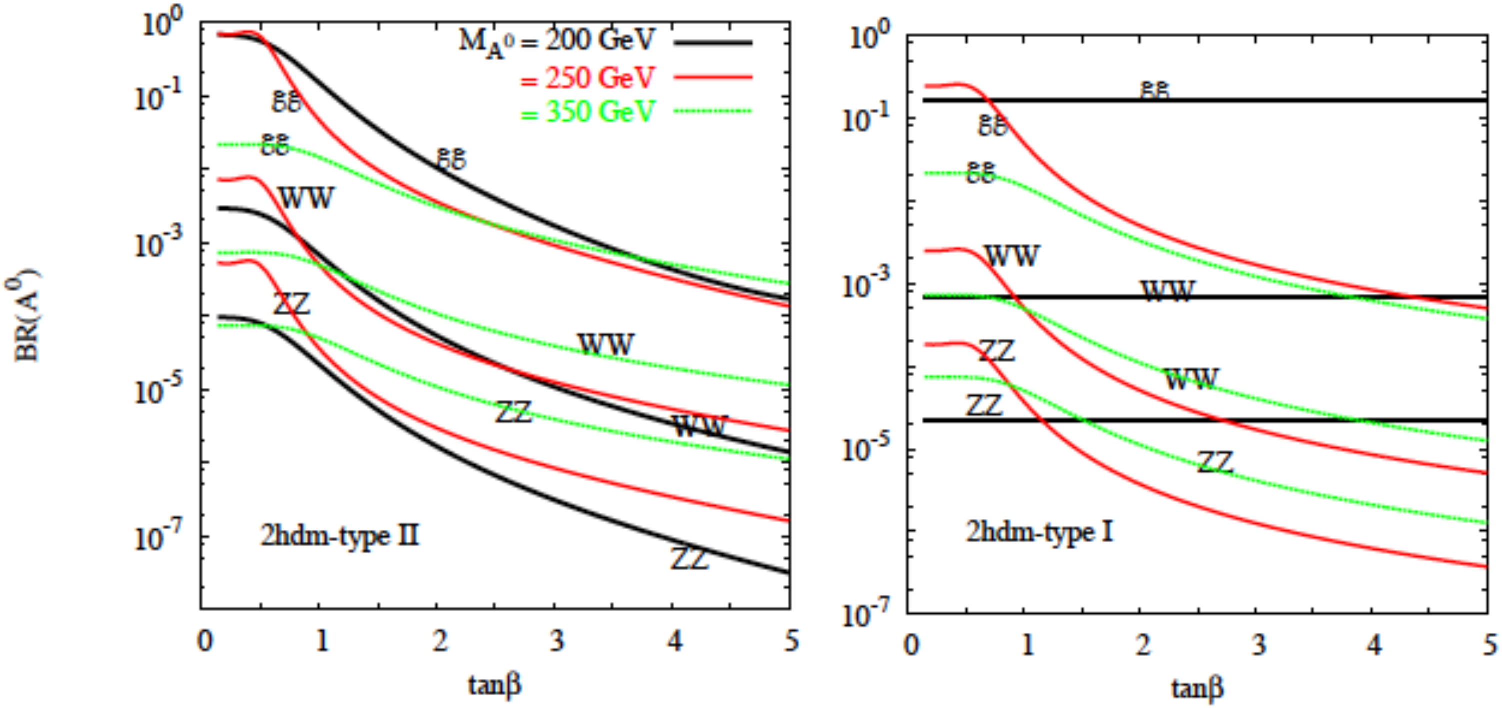
$$\mathcal{L}_{HZZ} \sim \kappa \frac{m_Z^2}{v} H Z^\mu Z_\mu + \frac{\alpha}{v} H Z^\mu \Box Z_\mu + \frac{\beta}{v} H Z^{\mu\nu} Z_{\mu\nu} + \frac{\gamma}{v} H Z^{\mu\nu} \tilde{Z}_{\mu\nu}$$

In models with <u>only one</u> SM-like Higgs boson, radiative corrections can generate different HVV terms. This is also possible in extensions of the scalar sector like for instance in the 2HDM. ATLAS and CMS results <u>have shown that if these corrections exist they are small</u>.

For each particular model one should check



$$A \rightarrow ZZ\ (W^{+}W^{-})$$



Arhrib, Benbrik, Field (2006).

In the C2HDM h has a SM-like coupling to vector bosons

In the complex 2HDM the three neutral scalars have indefinite CP.

The interaction of each scalar with the Z bosons comes exactly from the same kinetic term as the SM one

$$g_{C2HDM}^{hVV} = \cos(\alpha_2)\cos(\beta - \alpha_1)\; g_{SM}^{hVV}$$

Therefore the analysis of the correlations in momenta in

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

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

will not allow to draw any conclusion on the scalar's CP.

Again, they show however that any radiate contribution to CP-violating terms in hZZ(WW) is small.

Direct probing of pseudoscalar to scalar component

Using again the C2HDM as a benchmark, if all neutral scalars have indefinite CP it is likely that we get the first hints in the study of the process

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

Berge, Bernreuther, Ziethe (2008)
Berge, Bernreuther, Niepelt, Spiesberger, (2011)
Berge, Bernreuther, Kirchner (2014)

And later (in luminosity) possibly also using

$$pp \to h(\to b\bar{b})t\bar{t}$$

Gunion, He 1996
Boudjema, Godbole, Guadagnoli, Mohan 2015
Amor dos Santos *eal* 2015

Hint for CP violation in $H_i \to H_j H_k \qquad j \neq k$

a 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, R. Santos, J.P. Silva; PRD92 (2015) 5, 055014.

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

Classes of CP-violating processes

- ON GOING SEARCHES

Classes	C_1	C_2	C_3	C_4	C_5
Decays	$h_3 \to h_2 Z$ $h_2 \to h_1 Z$ $h_3 \to h_1 Z$	$h_2 \to h_1 Z$ $h_1 \to ZZ$ $h_2 \to ZZ$	$h_3 \to h_1 Z$ $h_1 \to ZZ$ $h_3 \to ZZ$	$h_3 \to h_2 Z$ $h_2 \to ZZ$ $h_3 \to ZZ$	$h_3 \to ZZ$ $h_2 \to ZZ$ $h_1 \to ZZ$

IN 2HDMS ONLY

ONLY TWO TO GO

Classes	C_6	C_7
Decays	$h_3 \to h_2 h_1$ $h_3 \to h_2 Z$ $h_1 \to ZZ$	$h_{2,3} \to h_1 h_1$ $h_{2,3} \to h_1 Z$ $h_1 \to ZZ$

CLASSES INVOLVING SCALAR TO TWO SCALARS DECAYS

FONTES, ROMÃO, RS, SILVA (2015).

TABLE VIII. Predictions for $\sigma \times \mathrm{BR}$ at $\sqrt{s} = 13$ TeV for the benchmark points $P5$ (Type I) and $P6$ (lepton specific).

	$P5$	$P6$
$\sigma(h_1)$ 13 TeV	55.144 [pb]	53.455 [pb]
$\sigma(h_1)\mathrm{BR}(h_1 \to W^*W^*)$	10.657 [pb]	11.069 [pb]
$\sigma(h_1)\mathrm{BR}(h_1 \to Z^*Z^*)$	1.093 [pb]	1.136 [pb]
$\sigma(h_1)\mathrm{BR}(h_1 \to bb)$	33.118 [pb]	32.152 [pb]
$\sigma(h_1)\mathrm{BR}(h_1 \to \tau\tau)$	3.825 [pb]	2.845 [pb]
$\sigma(h_1)\mathrm{BR}(h_1 \to \gamma\gamma)$	119.794 [fb]	122.579 [fb]
$\sigma_2 \equiv \sigma(h_2)$ 13 TeV	1.620 [pb]	4.920 [pb]
$\sigma_2 \times \mathrm{BR}(h_2 \to WW)$	1.032 [pb]	0.542 [pb]
$\sigma_2 \times \mathrm{BR}(h_2 \to ZZ)$	0.427 [pb]	0.232 [pb]
$\sigma_2 \times \mathrm{BR}(h_2 \to bb)$	0.012 [pb]	0.097 [pb]
$\sigma_2 \times \mathrm{BR}(h_2 \to \tau\tau)$	0.001 [pb]	0.109 [pb]
$\sigma_2 \times \mathrm{BR}(h_2 \to \gamma\gamma)$	0.123 [fb]	0.344 [fb]
$\sigma_2 \times \mathrm{BR}(h_2 \to h_1 Z)$	0.140 [pb]	0.075 [pb]
$\sigma_2 \times \mathrm{BR}(h_2 \to h_1 Z \to bbZ)$	0.084 [pb]	0.045 [pb]
$\sigma_2 \times \mathrm{BR}(h_2 \to h_1 Z \to \tau\tau Z)$	9.683 [fb]	3.982 [fb]
$\sigma_2 \times \mathrm{BR}(h_2 \to h_1 h_1)$	0.000 [fb]	3772.577 [fb]
$\sigma_2 \times \mathrm{BR}(h_2 \to h_1 h_1 \to bbbb)$	0.000 [fb]	1364.787 [fb]
$\sigma_2 \times \mathrm{BR}(h_2 \to h_1 h_1 \to bb\tau\tau)$	0.000 [fb]	241.505 [fb]
$\sigma_2 \times \mathrm{BR}(h_2 \to h_1 h_1 \to \tau\tau\tau\tau)$	0.000 [fb]	10.684 [fb]
$\sigma_3 \equiv \sigma(h_3)$ 13 TeV	9.442 [pb]	10.525 [pb]
$\sigma_3 \times \mathrm{BR}(h_3 \to WW)$	0.638 [pb]	0.945 [pb]
$\sigma_3 \times \mathrm{BR}(h_3 \to ZZ)$	0.293 [pb]	0.406 [pb]
$\sigma_3 \times \mathrm{BR}(h_3 \to bb)$	0.004 [pb]	0.422 [pb]
$\sigma_3 \times \mathrm{BR}(h_3 \to \tau\tau)$	0.432 [fb]	407.337 [fb]
$\sigma_3 \times \mathrm{BR}(h_3 \to \gamma\gamma)$	0.140 [fb]	2.410 [fb]
$\sigma_3 \times \mathrm{BR}(h_3 \to h_1 Z)$	0.383 [pb]	0.691 [pb]
$\sigma_3 \times \mathrm{BR}(h_3 \to h_1 Z \to bbZ)$	0.230 [pb]	0.416 [pb]
$\sigma_3 \times \mathrm{BR}(h_3 \to h_1 Z \to \tau\tau Z)$	26.554 [fb]	36.779 [fb]
$\sigma_3 \times \mathrm{BR}(h_3 \to h_2 Z)$	2.495 [pb]	0.000 [pb]
$\sigma_3 \times \mathrm{BR}(h_3 \to h_2 Z \to bbZ)$	0.019 [pb]	0.000 [pb]
$\sigma_3 \times \mathrm{BR}(h_3 \to h_2 Z \to \tau\tau Z)$	2.188 [fb]	0.000 [fb]
$\sigma_3 \times \mathrm{BR}(h_3 \to h_1 h_1)$	433.402 [fb]	6893.255 [fb]
$\sigma_3 \times \mathrm{BR}(h_3 \to h_1 h_1 \to bbbb)$	156.329 [fb]	2493.740 [fb]
$\sigma_3 \times \mathrm{BR}(h_3 \to h_1 h_1 \to bb\tau\tau)$	36.111 [fb]	441.277 [fb]
$\sigma_3 \times \mathrm{BR}(h_3 \to h_1 h_1 \to \tau\tau\tau\tau)$	2.085 [fb]	19.521 [fb]
$\sigma_3 \times \mathrm{BR}(h_3 \to h_2 h_1)$	0.000 [fb]	0.000 [fb]
$\sigma_3 \times \mathrm{BR}(h_3 \to h_2 h_1 \to bbbb)$	0.000 [fb]	0.000 [fb]
$\sigma_3 \times \mathrm{BR}(h_3 \to h_2 h_1 \to bb\tau\tau)$	0.000 [fb]	0.000 [fb]
$\sigma_3 \times \mathrm{BR}(h_3 \to h_2 h_1 \to \tau\tau\tau\tau)$	0.000 [fb]	0.000 [fb]

Class C7

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

$$h_3 \to h_1 Z \quad \Rightarrow \quad \mathrm{CP}(h_3) = -\,\mathrm{CP}(h_1) = -1$$

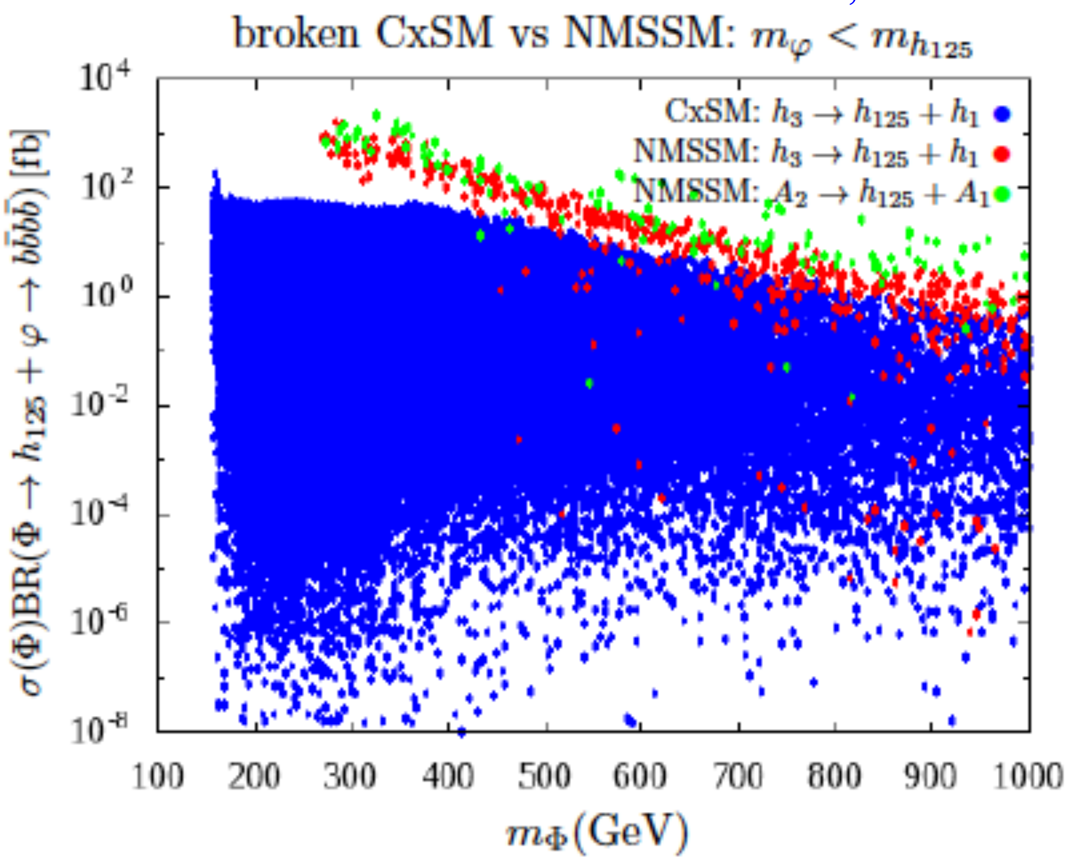
$$h_3 \to h_1 h_1 \quad \Leftarrow \quad \mathrm{CP}(h_3) = 1$$

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

To distinguish between models

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

COSTA, MUEHLEITNER, SAMPAIO RS (2016)



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.

Radiative corrections to BSM models

A new renormalization procedure for the 2HDM that is gauge independent, process independent and stable

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

Barroso, RS (1997)

Kanemura, Okada, Senaha, Yuan, Yamada, Lopez-Val Sola, Pilaftsis, Freitas, Stöckinger
Boudjema, Baro, Denner, Jenniches, Lang, Sturm, ...

Process dependent – On-shell plus two particular processes to renormalize the angles and/or soft breaking parameter

Process independent – On-shell plus conditions for the angles based on the mixing matrix properties plus MS for the soft breaking parameter

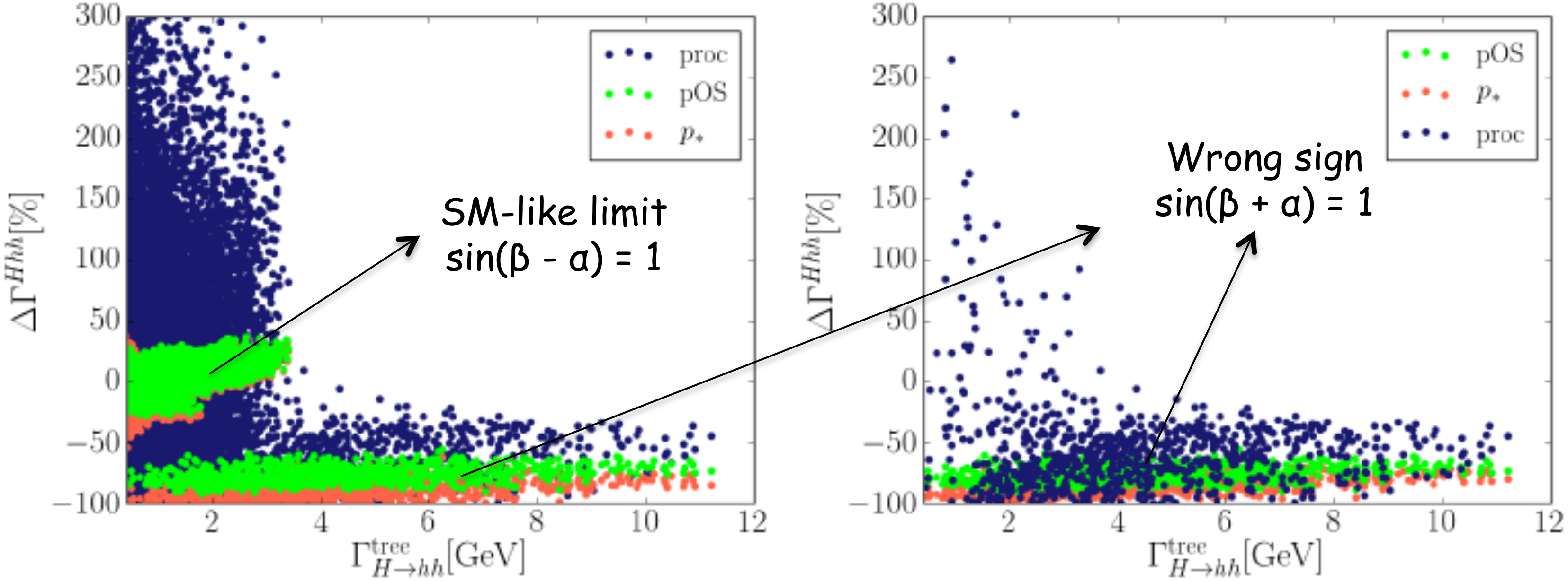
$$\delta O_{ij} = \frac{1}{4}(\delta Z_{il} - \delta Z_{li})O_{lj}$$

Pilaftsis (1997)

Kanemura, Okada, Senaha, Yuan (2004)

Input parameters: $m_h,\ m_H,\ m_A,\ m_{H^\pm},\ T_1,\ T_2,\ \alpha,\ \tan\beta,\ m_{12}^2,\ M_W^2,\ M_Z^2,\ e,\ m_f$

2HDM



Scatter plot same data, but with following restrictions:

(i) The parameter sets are chosen such that the decay $H \to hh$ is kinematically possible,

$$\textit{Condition (i):} \quad M_H \overset{!}{\geq} 2M_h$$

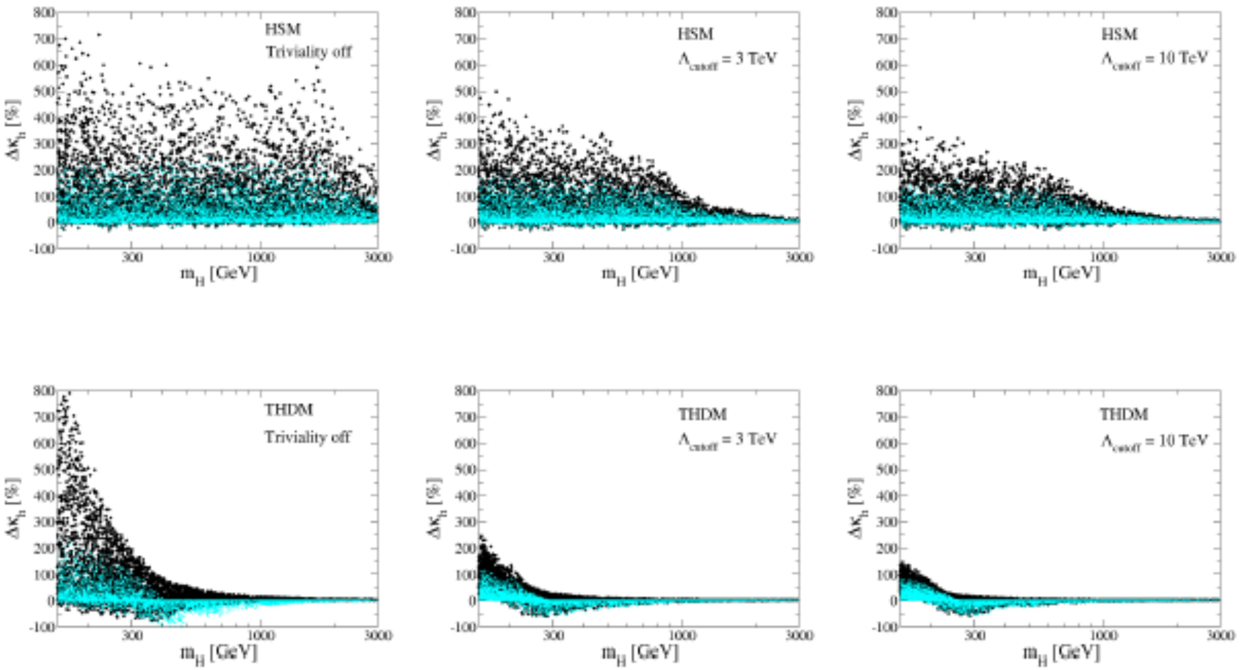
(ii) The parameter sets are chosen such that the decay $H \to hh$ is kinematically possible. Additionally, we require the heavy Higgs boson masses to maximally deviate by $\pm 5\%$ from M, with $M^2 \equiv m_{12}^2/(s_\beta c_\beta)$. We hence have

$$\textit{Condition (ii):} \quad M_H \overset{!}{\geq} 2M_h \qquad \text{and}$$
$$m_{\phi_{\text{heavy}}} \overset{!}{=} M \pm 5\% \,, \quad \text{with } m_{\phi_{\text{heavy}}} \in \{m_H, m_A, m_{H^\pm}\}$$

In these scenarios the non-SM Higgs bosons are approximately mass degenerate and of the order of the $\mathbb{Z}_2$ breaking scale.

Real Singlet model

$$V(\Phi, S) = (m_\Phi^2 + \mu_{\Phi S}\, v'_S + \lambda_{\Phi S} v'^2_S)|\Phi|^2 + \lambda|\Phi|^4$$
$$+ (\mu_{\Phi S} + 2\lambda_{\Phi S} v'_S)|\Phi|^2 S + \lambda_{\Phi S}|\Phi|^2 S^2 + (t_S + 2m_S^2 v'_S + 3\mu_S v'^2_S + 4\lambda_S v'^3_S)S$$
$$+ (m_S^2 + 3\mu_S v'_S + 6\lambda_S v'^2_S)S^2 + (\mu_S + 4\lambda_S v'_S)S^3 + \lambda_S S^4.$$



Kanemura, Kikuchi, Yagyu (2015, 2016)

FIG. 4: Scatter plot on the m_H-$\Delta\kappa_h$ plane in the HSM (upper panels) and the Type-I THDM with $\tan\beta = 1$ (lower panels). Each black (light blue) dot is the prediction allowed by theoretical constraints at the one-loop (tree) level. In the left panels, we do not impose the triviality bound, and impose the vacuum stability bound without the scale dependence. In the center and right panel, we impose all the theoretical constraints using $\Lambda_{\rm cutoff} = 3$ and 10 TeV, respectively.

Link to outstanding issues - the Inert 2HDM and dark matter

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

The first doublet contains the SM-like Higgs boson h, and the second doublet contains four dark (inert) scalars H, A and H±.

H is taken to be the lightest scalar (stable).

$$pp \to AH \to ZHH \to Z + \mathrm{MET} \qquad \text{plane: } (m_A,\, m_H)$$

$$pp \to H^\pm H^\mp \to W^\pm W^\mp HH \to W^\pm W^\mp MET \quad \text{plane: } (m_{H^\pm},\, m_H)$$

cross sections reach 350 fb (first) and 90 fb (second) at 13 TeV with BRs close to 100%

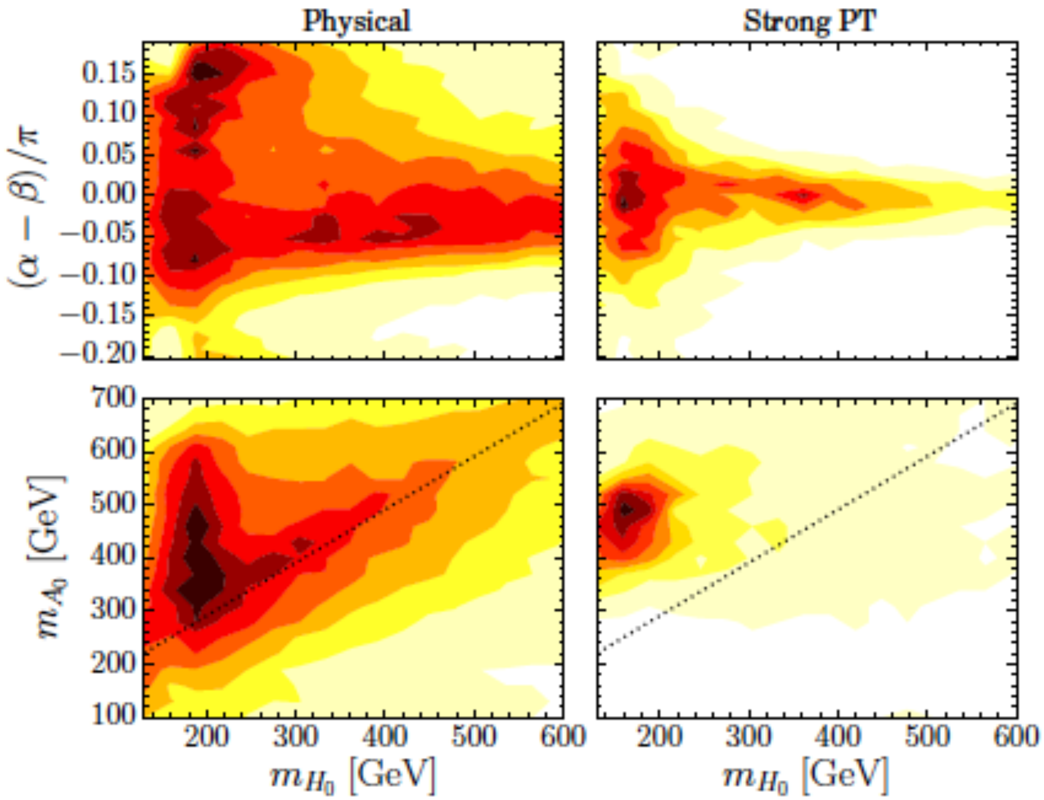
Ilnicka, Krawczyk, Robens, (2016)

Link to outstanding issues - baryogenesis

Scalar to one scalar and one gauge boson (m_h = 125 GeV)

$H \to AZ;\ A \to HZ$ plane: (m_H, m_A); $(m_{H(A)}, \cos(\beta - \alpha))$

Baryogenesis $m_A - m_H \approx v$ and light m_H



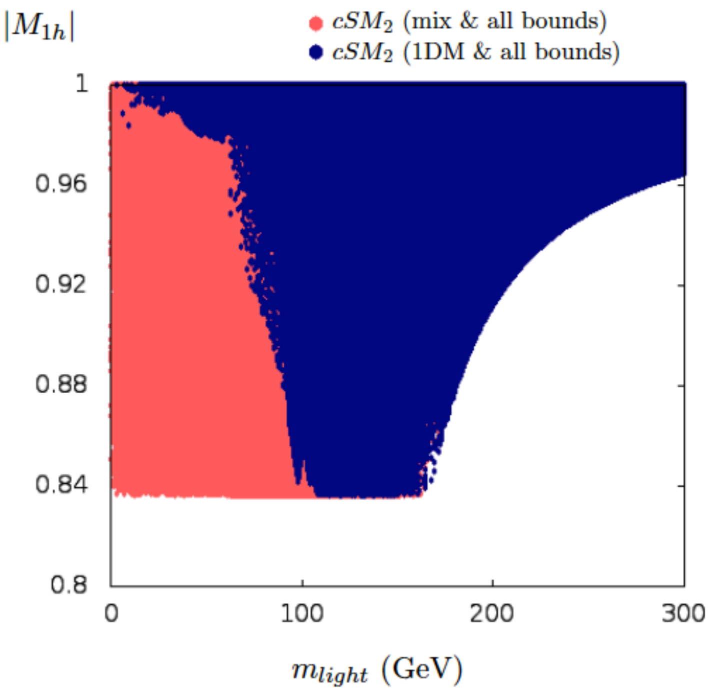
large Br($A \to HZ$)

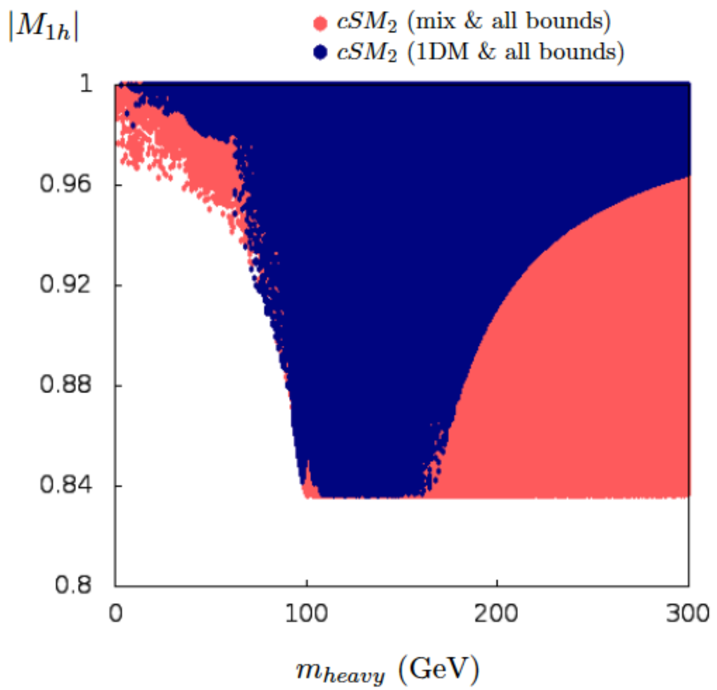
Dorsch, Huber, Mimasu, No (2014)

Thank you for your attention

Extra Slides

The two phases of CxSM at the LHC





- We can say if we are observing the lighter or the heavier scalar given a measurement of M_{1h} and the mass of a new scalar in a region exclusively of the "mix" phase (in pink), excluding the DM phase.

$\mathbb{Z}_2'$	2 mixed Higgs + 1 DM	$\langle A = 0 \rangle$
$(a_1 \in \mathbb{R})$	3 mixed	$\langle \mathbb{S} \neq 0 \rangle$

- By measuring physical particle masses and mixing angles we found that
  - identification of the phase that is realized in Nature is possible in some cases,
  - we can exclude the dark matter phase with a simultaneous measurement of the mass of a non-dark matter scalar together with its mixing angle
  - we can say whether the new scalar is the lightest or the heaviest.

Direct probing of Yukawa couplings – C2HDM as a benchmark model

Direct probing at the LHC

- For the C2HDM we need three independent measurements

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

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

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

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

Direct probing at the LHC (ττh)

$$\boxed{pp \to h \to \tau^+\tau^-}$$

Berge, Bernreuther, Ziethe 2008
Berge, Bernreuther, Niepelt, Spiesberger, 2011
Berge, Bernreuther, Kirchner 2014

- A measurement of the angle

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

can be performed with the accuracies

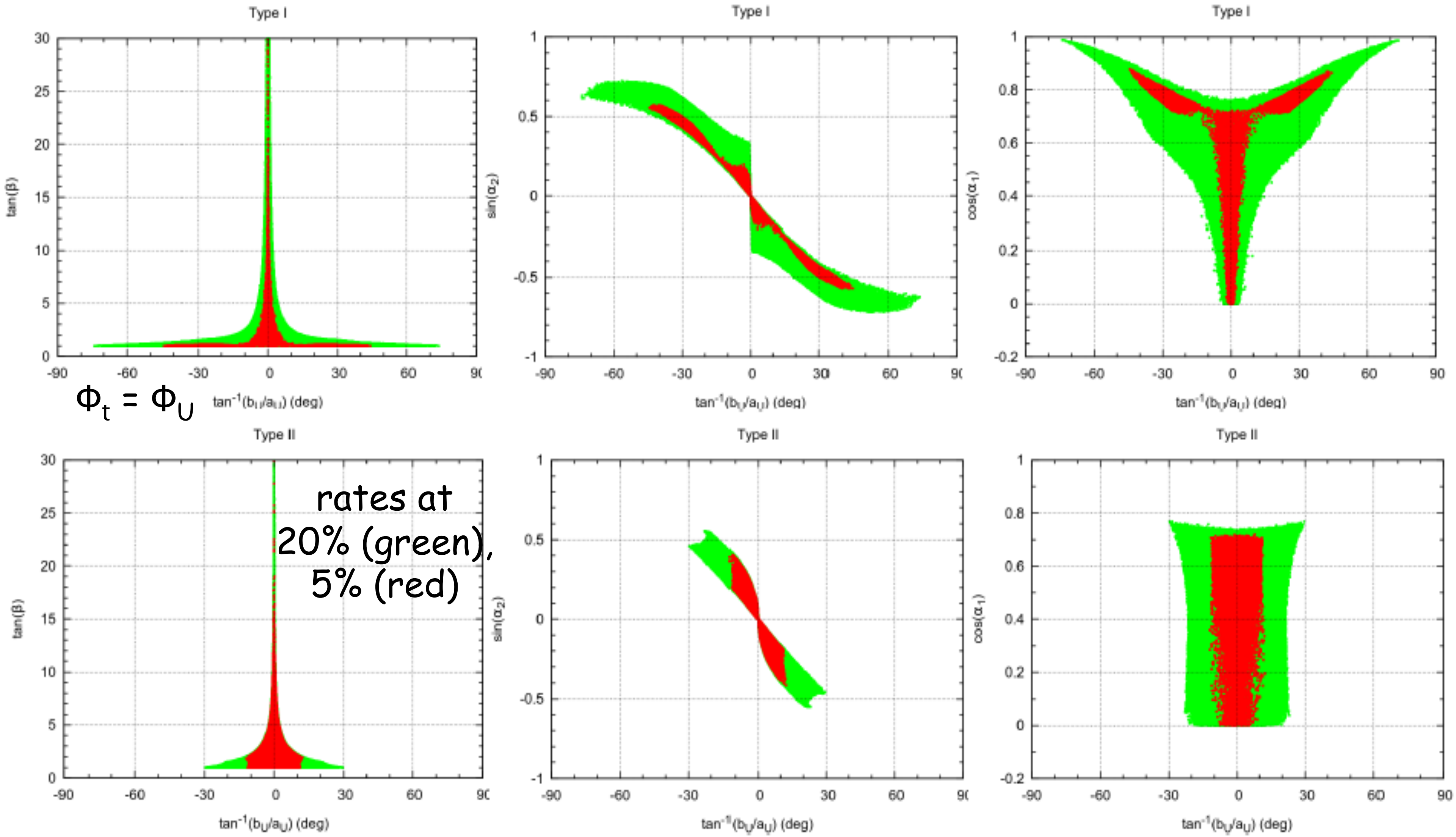
$$\begin{cases} \Delta\phi_\tau = 40^\circ & 150\ \mathrm{fb}^{-1} \\ \Delta\phi_\tau = 25^\circ & 500\ \mathrm{fb}^{-1} \end{cases}$$

Numbers from: Berge, Bernreuther, Kirchner, EPJC74, (2014) 11, 3164.

$$\tan\phi_\tau = -\frac{s_\beta}{c_1}\tan\alpha_2 \quad \Rightarrow \quad \tan\alpha_2 = -\frac{c_1}{s_\beta}\tan\phi_\tau$$

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

Limits on Φ_t based on the rates only

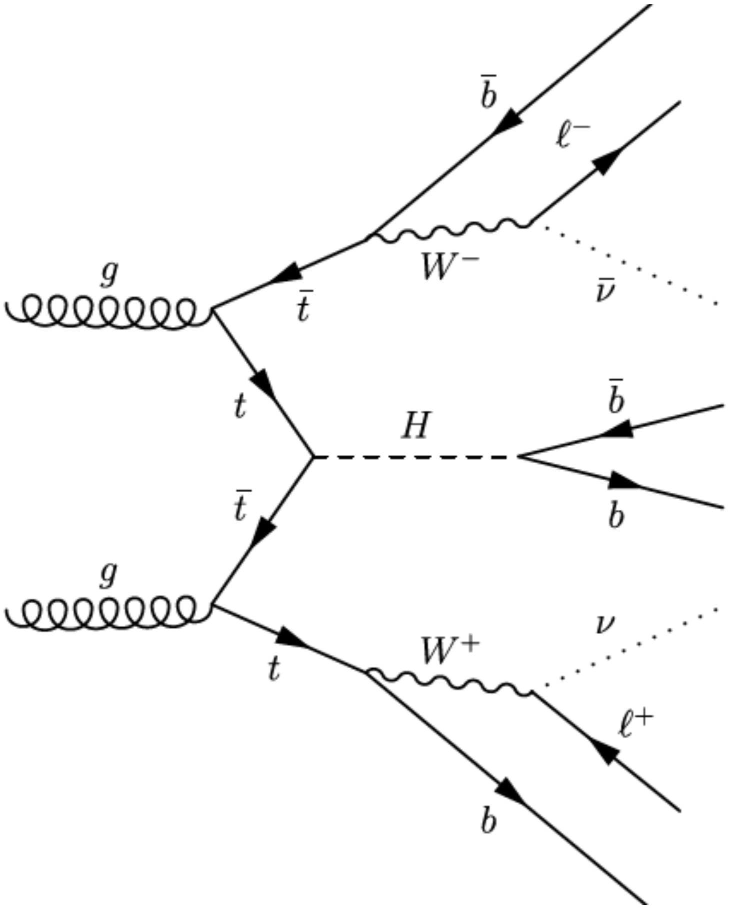


Competitive for Type I but not for Type II

Direct probing at the LHC (tth)

$$\boxed{pp \to h(\to b\bar{b})t\bar{t}}$$

Gunion, He 1996
Boudjema, Godbole, Guadagnoli, Mohan 2015
Amor dos Santos *eal* 2015



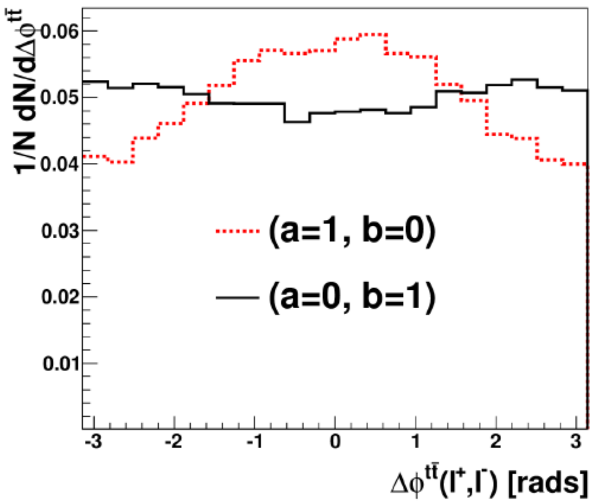
$$\mathcal{L}_{Hf\bar{f}} = -\frac{y_f}{\sqrt{2}}\bar{\psi}_f(a_f + ib_f\gamma_5)\psi_f h$$

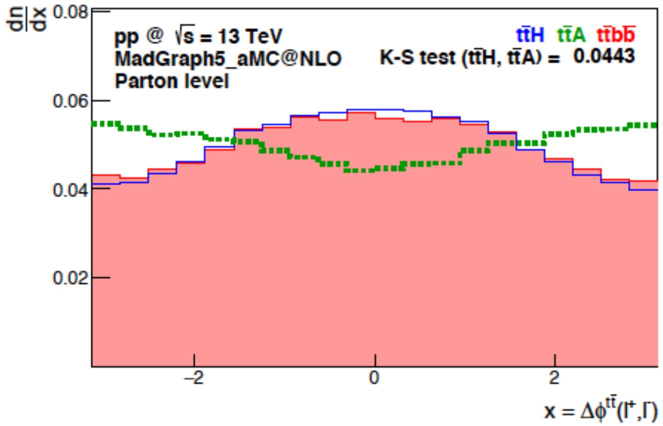
Signal: tt fully leptonic and H -> bb

Background: most relevant is the irreducible tt background

Review of tth

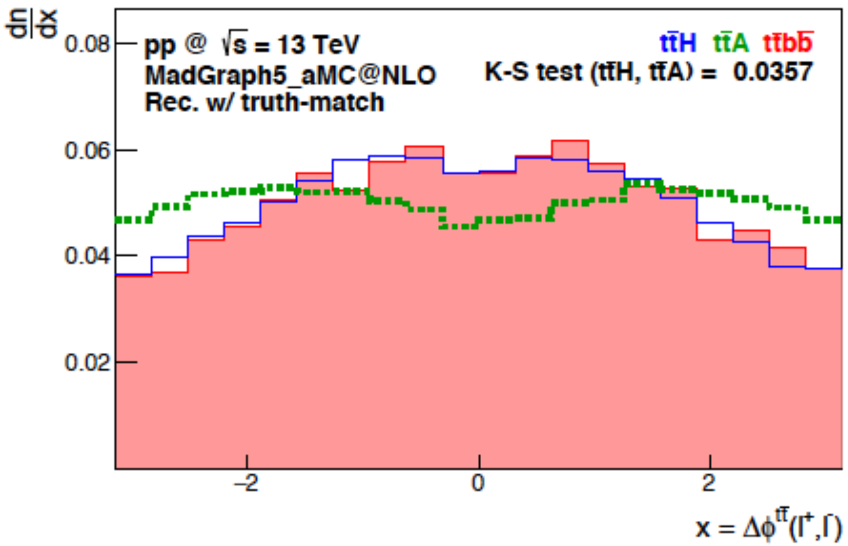
$$\mathcal{L}_{Hf\bar{f}} = -\frac{y_f}{\sqrt{2}}\bar{\psi}_f(a_f + ib_f\gamma_5)\psi_f h$$

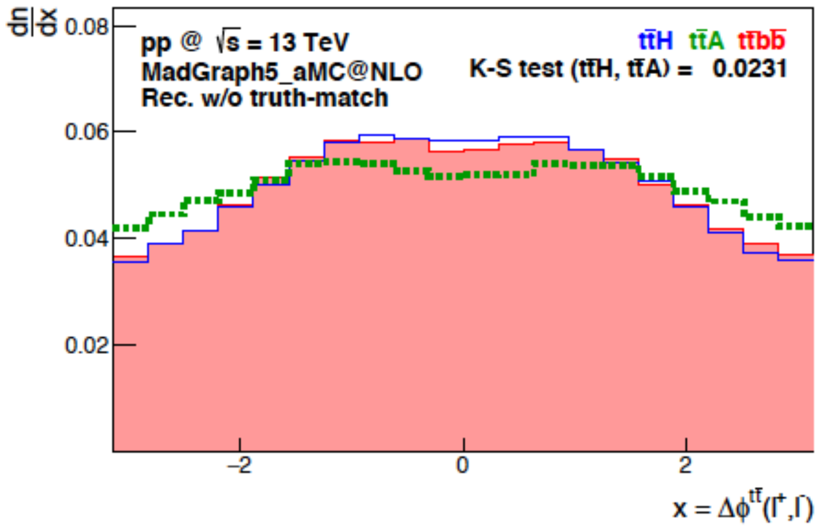




BOUDJEMA, GODBOLE, GUADAGNOLI, MOHAN 2015

Azimuthal difference between l^+ in the t rest frame and l^- in the tbar rest frame



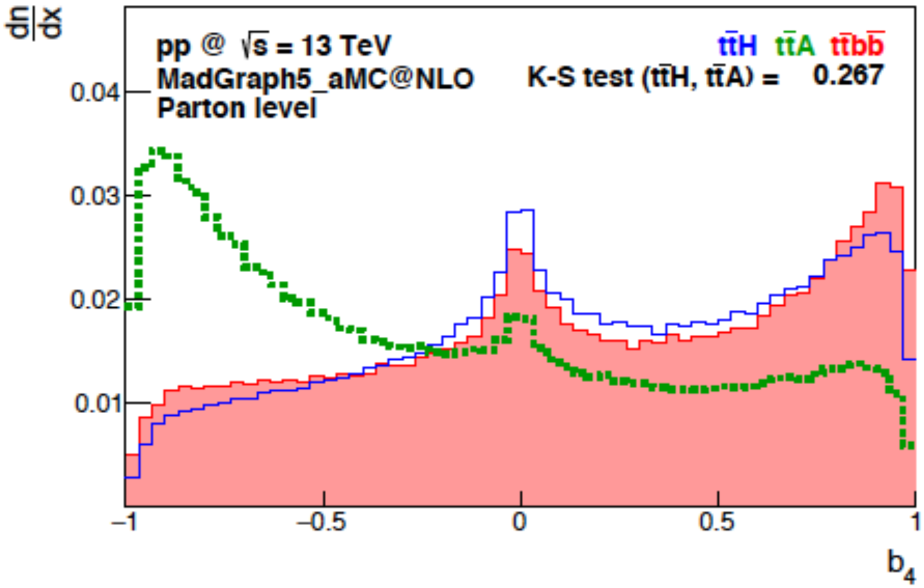


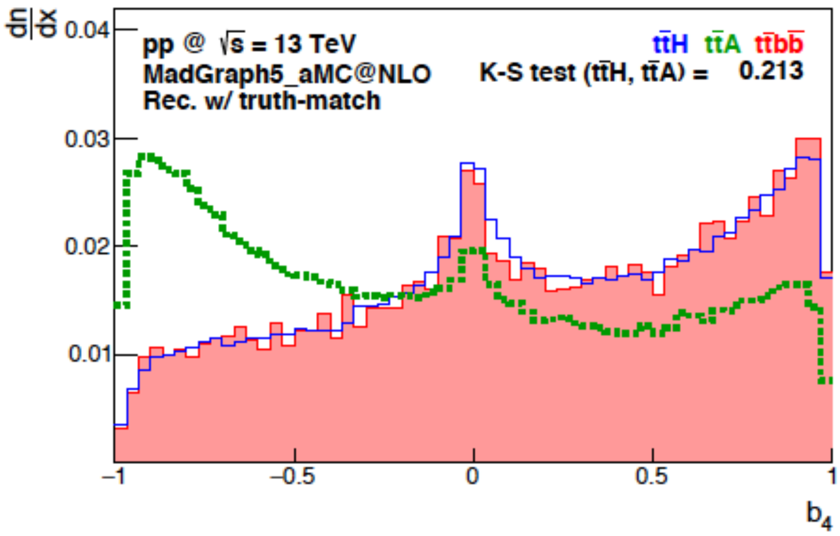
Review of tth

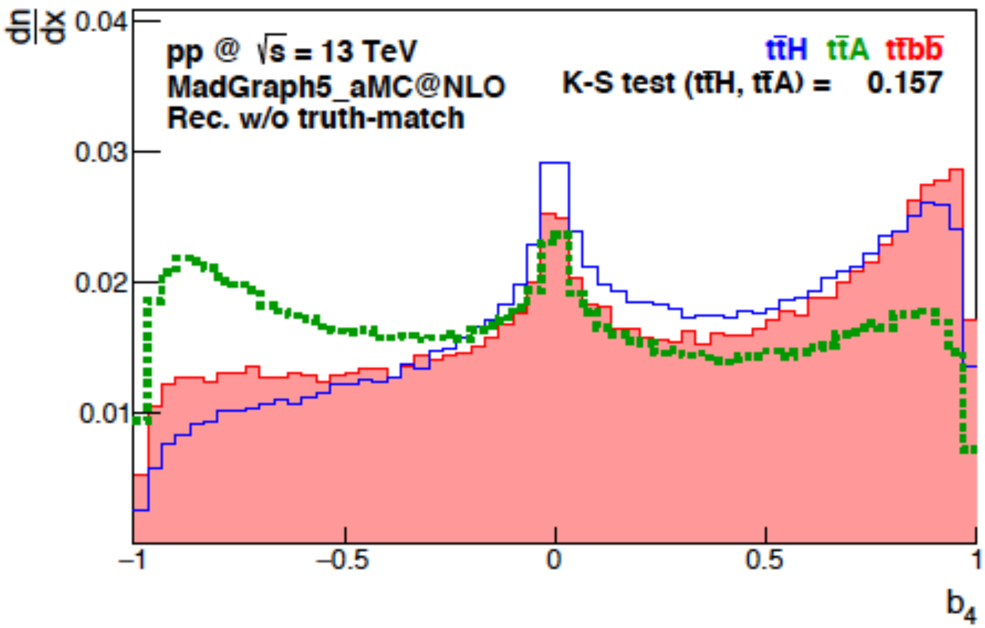
$$\mathcal{L}_{Hf\bar{f}} = -\frac{y_f}{\sqrt{2}}\bar{\psi}_f(a_f + ib_f\gamma_5)\psi_f h$$

Gunion, He 1996

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







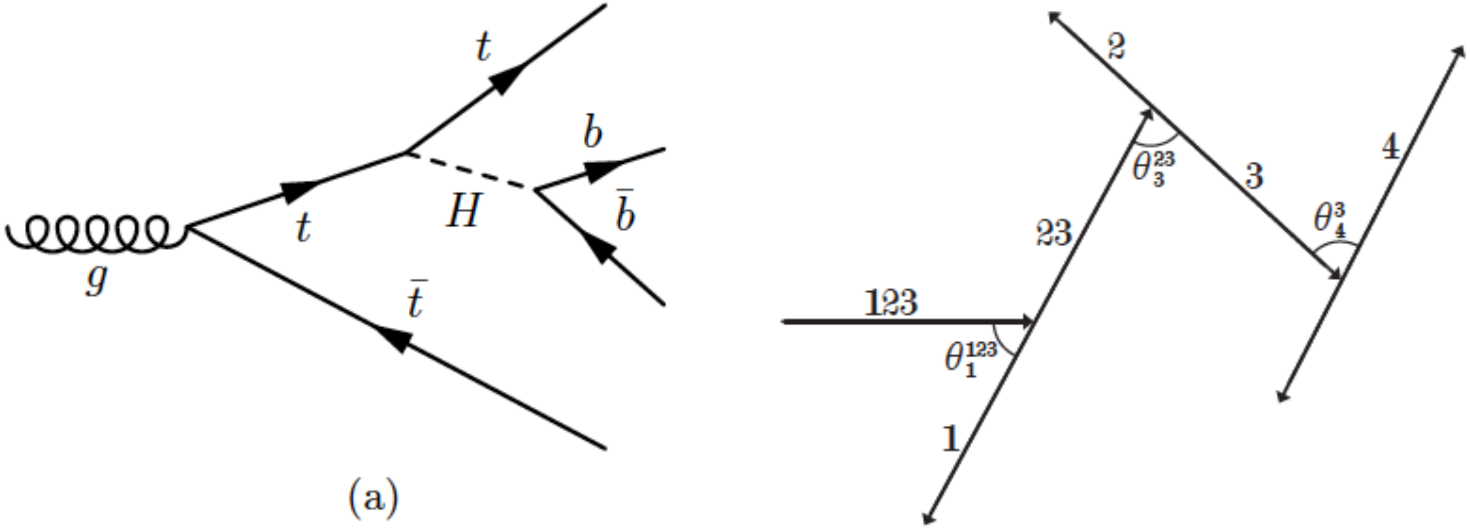


Figure 32: **Left:** $t\bar{t}H$ production through an s-channel gluon, which splits into a $\bar{t}$ and a t. In its turn, the t radiates a Higgs boson, which decays into $b\bar{b}$. **Right:** General decay chain with particles labeled 1, 2, 3 and 4.

Define the angles

θ_1^{123} : system 123 in lab frame and 1 in frame 123

θ_3^{23} : system 23 in frame 123 and 3 in frame 23

θ_4^{3} : 3 in frame 23 and 4 in frame 3

Build functions of the angles

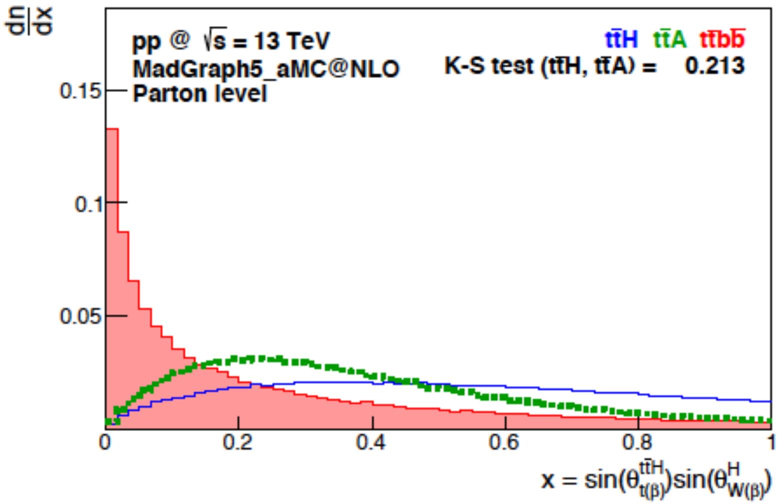
1, 2 and 3 are any permutation of t $\bar{t}$ or H

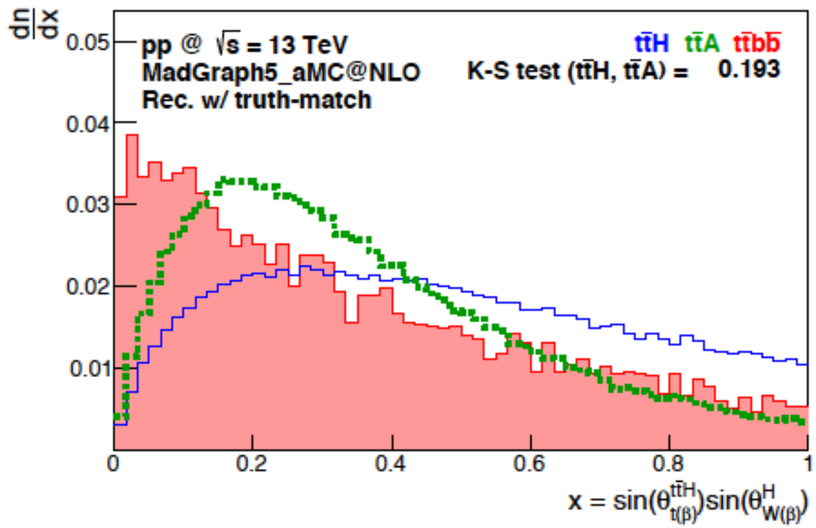
4 is a particle decaying from t $\bar{t}$ or H

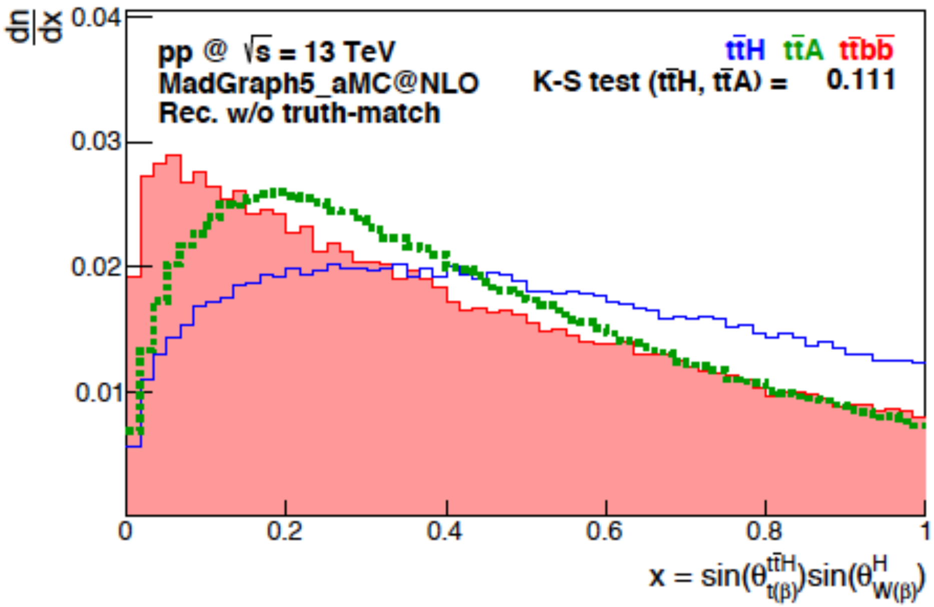
Review of tth

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

AMOR DOS SANTOS *EAL* 2015



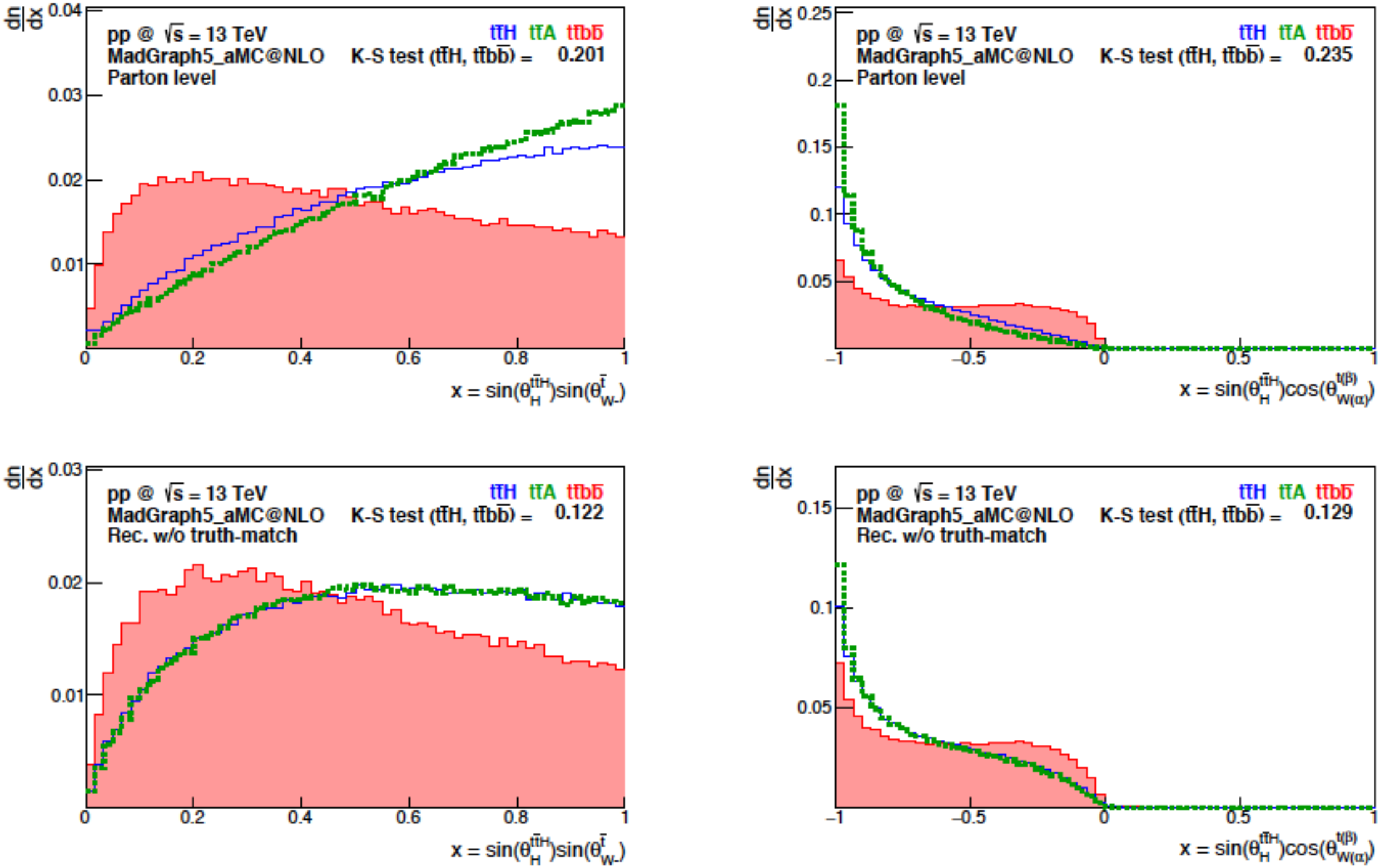




Combinatorial background plays a very important role.

Some variables are also good discriminants between ttΦ and ttbb

Amor dos Santos *eal* 2015



Higgs production mechanisms - new scalars - charged Higgs

Only "model independent" bounds come from lepton colliders

$$\boxed{e^+e^- \rightarrow \gamma, Z \rightarrow H^+H^-}$$

no Yukawa dependence (except for the decays)

ALEPH, DELPHI, L3 and OPAL Collaborations
The LEP working group for Higgs boson searches[1]

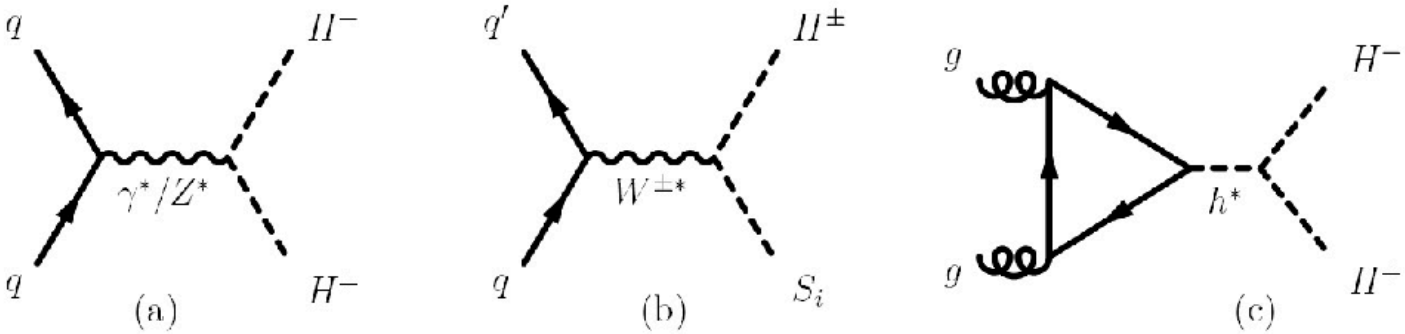
arXiv:1301.6065v1

Any $BR(H^+ \to \tau^+\nu)$ $\boxed{m_{H^\pm} \gtrsim 80\ GeV}$

$BR(H^+ \to \tau^+\nu) \approx 1$ $\boxed{m_{H^\pm} \gtrsim 94\ GeV}$ **Type LS (X)**

bound is roughly half the energy of the collider except if decays are very non-standard

Dark scalars production mechanisms



"dark"
charged Higgs

Inert

$$pp \to AH \to ZHH \to Z + \mathrm{MET}$$

$$pp \to H^\pm H^\mp \to W^\pm W^\mp HH \to W^\pm W^\mp MET$$

cross sections reach 350 fb (first) and 90 fb (second) at 13 TeV with BRs close to 100%

Fermiophobic

$$pp \to AH \to AVV$$

most promising but still with very small cross section (< 2fb)

Searches involving charged scalars

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

Triplets

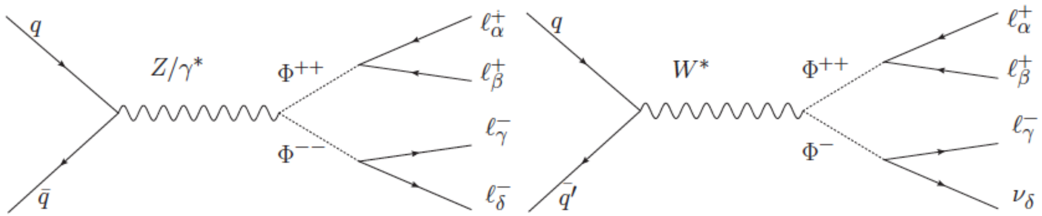
$H^{\pm} \rightarrow W^{\pm} Z$

Done by ATLAS

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

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

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



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

2HDMs

Scan

- Set m_{h1} = 125 GeV.

- Generate random values for potential's parameters such that,

$$-\pi/2 < \alpha_{1,2,3} \leq \pi/2$$

$$1 \leq \tan\beta \leq 30$$

$$m_1 \leq m_2 \leq 900\,\mathrm{GeV}$$

$$100\,\mathrm{GeV} \leq m_{H^\pm} \leq 900\,\mathrm{GeV}$$

$$m_{H^\pm} \gtrsim 340\ \mathrm{GeV}$$

$$-(900\,\mathrm{GeV})^2 \leq Re[m_{12}^2] \leq (900\,\mathrm{GeV})^2$$

- Impose pre-LHC experimental constraints,

- Impose theoretical constraints: perturbative unitarity, potential bounded from below.

ScannerS

a tool for multi-Higgs calculations

- Tool to **Scan** parameter space of **Scalar** sectors.
- **Automatise** scans for tree level renormalisable V_{scalar}.
- **Generic** routines, **flexible** user analysis & **interfaces**.

ScannerS.hepforge.org

ScannerS

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- Download
- Manual
- References
- ChangeLog
- Contact

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]

Overview of the tool

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

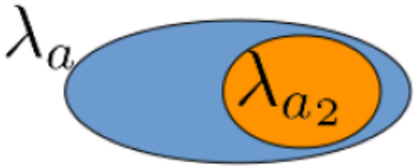
$$V(H, S, \phi, \chi, \ldots) \rightarrow \begin{matrix} H, H^\dagger \\ \mathbb{S}, \mathbb{S}^\star \\ \phi, \chi \\ \ldots \end{matrix} \rightarrow \begin{pmatrix} \phi_0 \\ \phi_1 \\ \ldots \\ \phi_n \end{pmatrix} \rightarrow V = V_a(\phi_i)\lambda_a$$

Numeric VEV

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

Min. Conditions

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



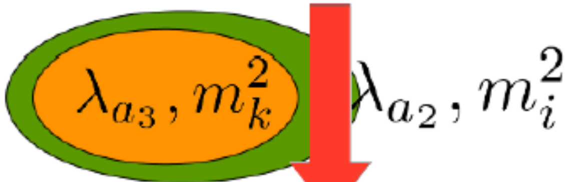
Block Detection

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

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.

The status of the singlet – scan boxes

Input parameter	Broken phase Min	Broken phase Max
$m_{h_{125}}$ (GeV)	125.1	125.1
$m_{h_{\rm other}}$ (GeV)	30	1000
v (GeV)	246.22	246.22
v_S (GeV)	1	1000
α_1	$-\pi/2$	$\pi/2$
α_2	$-\pi/2$	$\pi/2$
α_3	$-\pi/2$	$\pi/2$

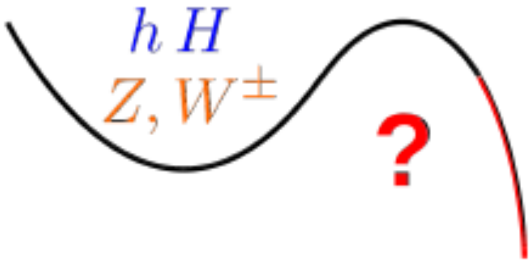
Input parameter	Dark phase Min	Dark phase Max
$m_{h_{125}}$ (GeV)	125.1	125.1
$m_{h_{\rm other}}$ (GeV)	30	1000
m_A (GeV)	30	1000
v (GeV)	246.22	246.22
v_S (GeV)	1	1000
α_1	$-\pi/2$	$\pi/2$
$a_1(\mathrm{GeV}^3)$	-10^8	0

Scan parameter	Broken phase Min	Broken phase Max
$m_{h_{125}}$ (GeV)	125.1	125.1
$m_{h_{(\rm other)}}$ (GeV)	30	1000
v (GeV)	246.22	246.22
v_S (GeV)	1	1000
α	$-\pi/2$	$\pi/2$

Stability conditions under RGE evolution

Stability conditions (imposed also in evolution):

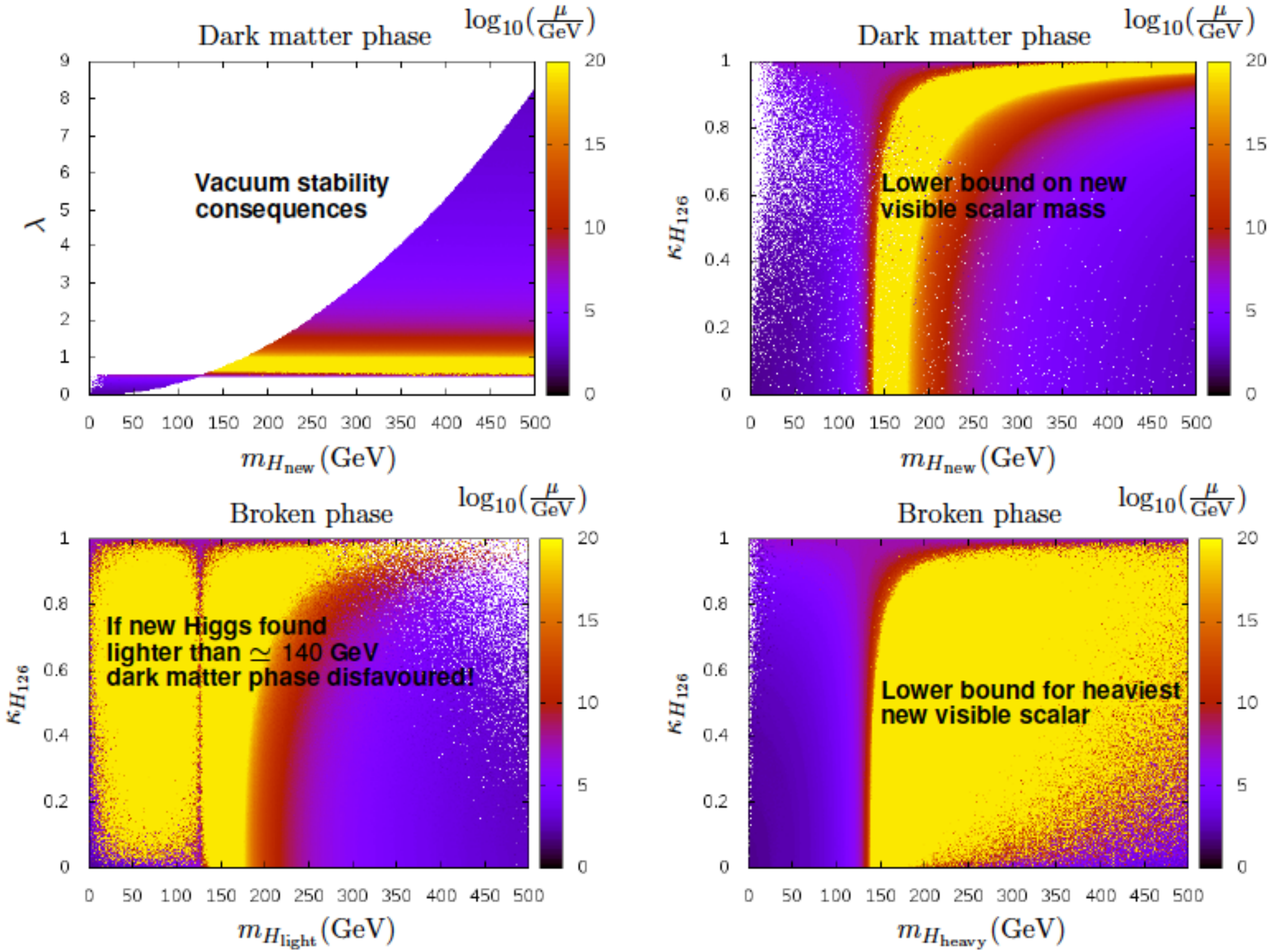
- Boundedness from below: $\lambda > 0 \;\wedge\; d_2 > 0 \;\wedge\; \delta_2 > -\sqrt{\lambda d_2}$



- Perturbative unitarity:

$$\left\{ |\lambda| \,,\; |d_2| \,,\; |\delta_2| \,,\; \left| \tfrac{3}{2}\lambda + d_2 \pm \sqrt{\left(\tfrac{3}{2}\lambda + d_2\right)^2 + d_2^2} \right| \right\} \le 16\pi$$

RGE stability bands – no Phenomenology

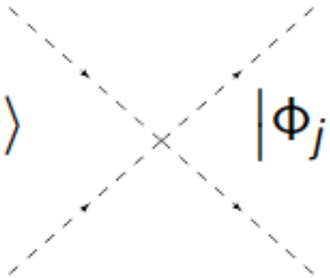


Tree level unitarity

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

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

$|\Phi_i\rangle$



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

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}

Global minimum and boundedness from below

- $H = 0$, $A = 0$ and the following cubic equation must be solved
$$S(b_1 + b_2 + d_2 S^2) + 2a_1 = 0$$
- $H = 0$, $S = -a_1/b_1$ and
$$A^2 = \frac{b_1^2(b_1 - b_2) - d_2 a_1^2}{d_2 b_1^2}$$
- $A = 0$, $H^\dagger H = -\frac{m^2+\delta_2 S^2}{\lambda}$ and the following cubic equation must be solved $\rightarrow 2a$
$$S\left[b_1 + b_2 - \frac{\delta_2 m^2}{\lambda} + \left(d_2 - \frac{\delta_2^2}{\lambda}\right) S^2\right] + 2a_1 = 0$$
- $S = -a_1/b_1$, $H^\dagger H = -\frac{m^2+\delta_2(S^2+A^2)}{\lambda}$ and $\rightarrow 2b$
$$A^2 = \frac{b_1^2(\lambda(b_1 - b_2) + m^2\delta_2) - d_2 a_1^2\lambda + \delta_2^2 a_1^2}{d_2 b_1^2 \lambda - \delta_2^2 b_1^2}$$

$$\lambda > 0 \quad \wedge \quad d_2 > 0 \quad \wedge \quad (\delta_2^2 < \lambda d_2 \ \text{ if } \ \delta_2 < 0)$$

sHDECAY

The program sDHECAY 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, 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.

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.

For additional information, comments, complaints or suggestions please e-mail to: Raul Costa, Margarete Mühlleitner, Marco Sampaio, Rui Santos

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