2HDMs as benchmark models at run 2

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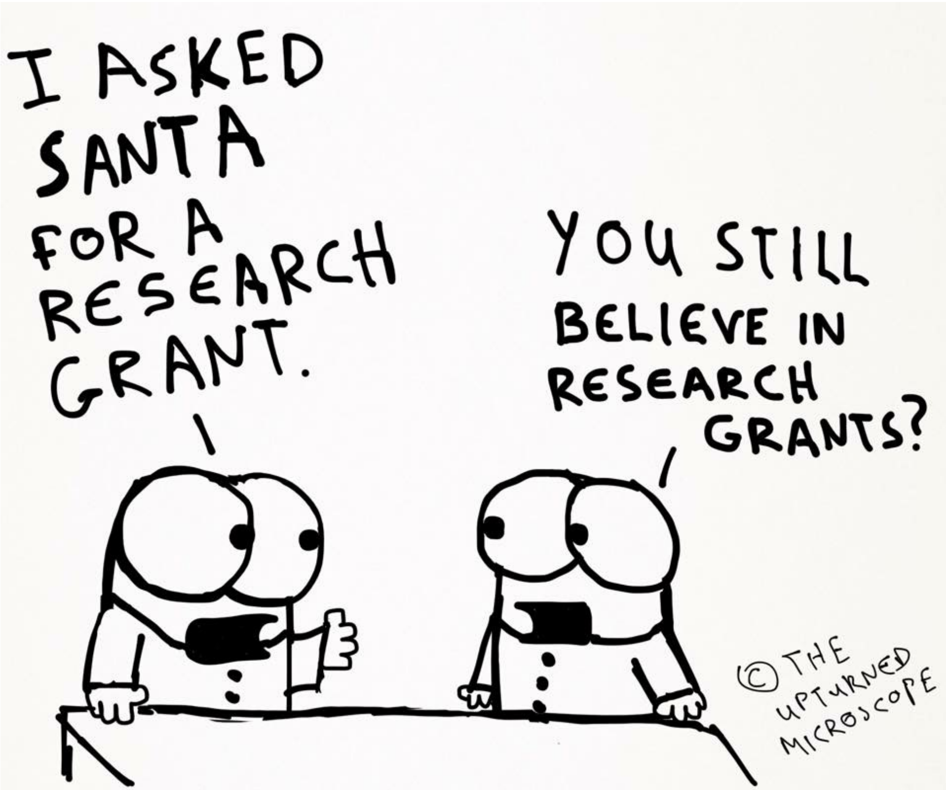

Scalars 2015, Warsaw

7 December 2015

Outlook

Z2 symmetric softly broken 2HDMs

My Highlights of the CP conserving case

Benchmark Fever in the Extended Scalar Sector

CP-violaton

Scalar or pseudoscalar?

Three decays

The 2HDMs

2HDMs Higgs Potential and the vacuum

2HDMs are stable at tree-level – once you are in a CP-conserving minimum, charge breaking and CP-breaking stationary points are saddle point above it.

Barroso, Ferreira, RS (2006)

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

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

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

Barroso, Ferreira, Ivanov, RS (2012)

In the case of explicit CP-breaking 2HDMs two minima can also coexist. In that case the condition is:

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

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

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

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

$$\kappa_V^h = \sin(\beta - \alpha)$$

$$\kappa_V^H = \cos(\beta - \alpha)$$

CP-CONSERVING

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

CP-VIOLATING

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

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

$$|s_2| = 0 \ \Rightarrow\ h_1 \text{ is a pure scalar,}$$
$$|s_2| = 1 \ \Rightarrow\ h_1 \text{ is a pure pseudoscalar}$$

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

Lightest Higgs couplings

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

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

CP-conserving

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).

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

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

Wrong-sign limit (type II and F)

Ginzburg, Krawczyk, Osland 2001

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

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

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

Ferreira, Gunion, Haber, RS (2014).

Ferreira, Guedes, Sampaio, RS (2014).

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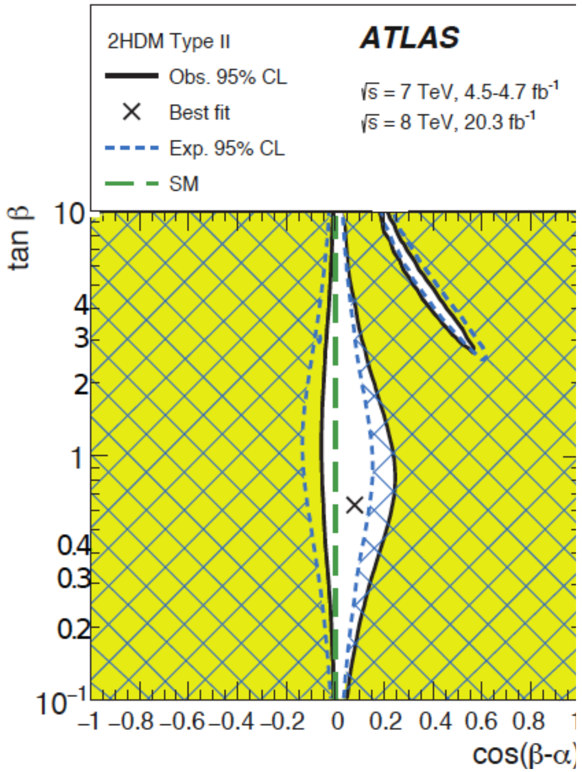
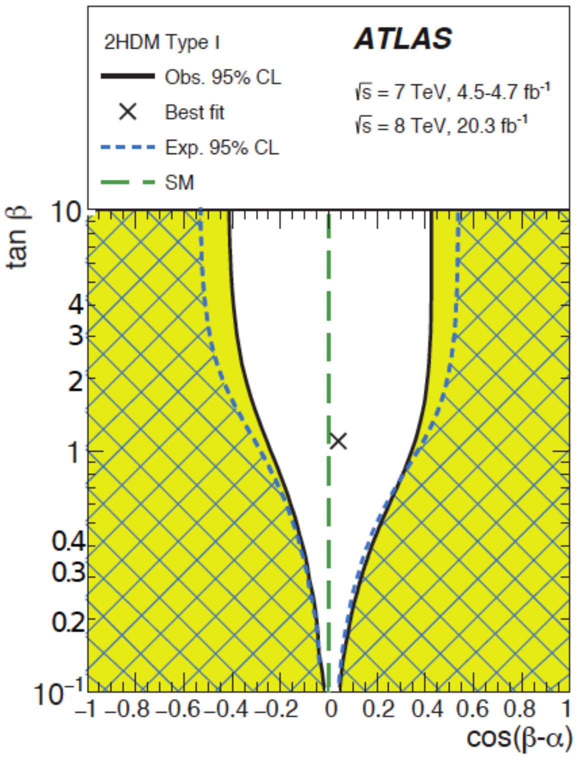
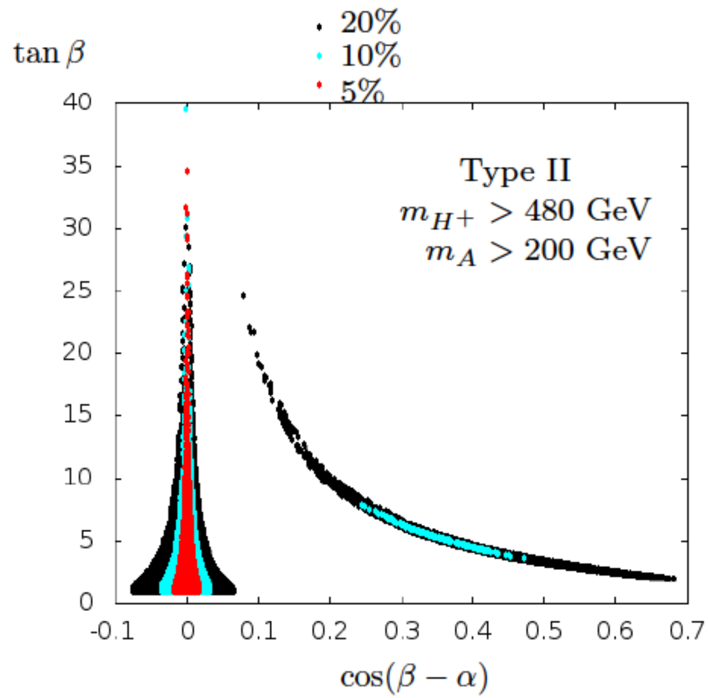
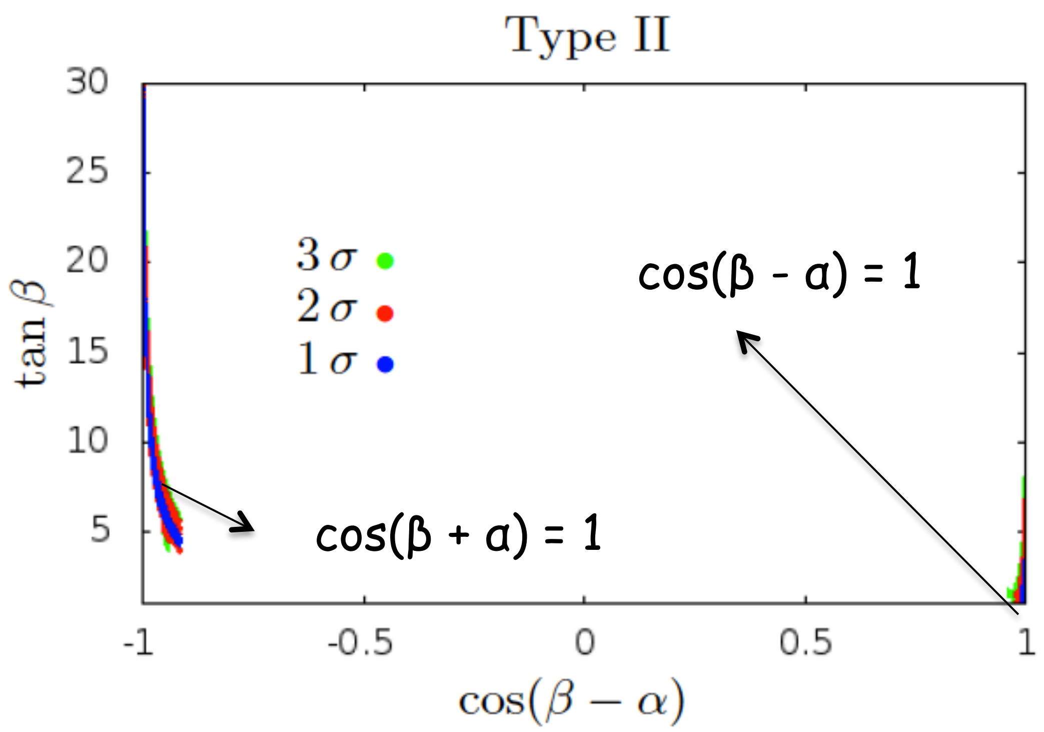






The heavy scenario ($m_h < m_H = 125$ GeV)



The Alignment limit

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

but no decouupling

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

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

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

Why is it not excluded yet?

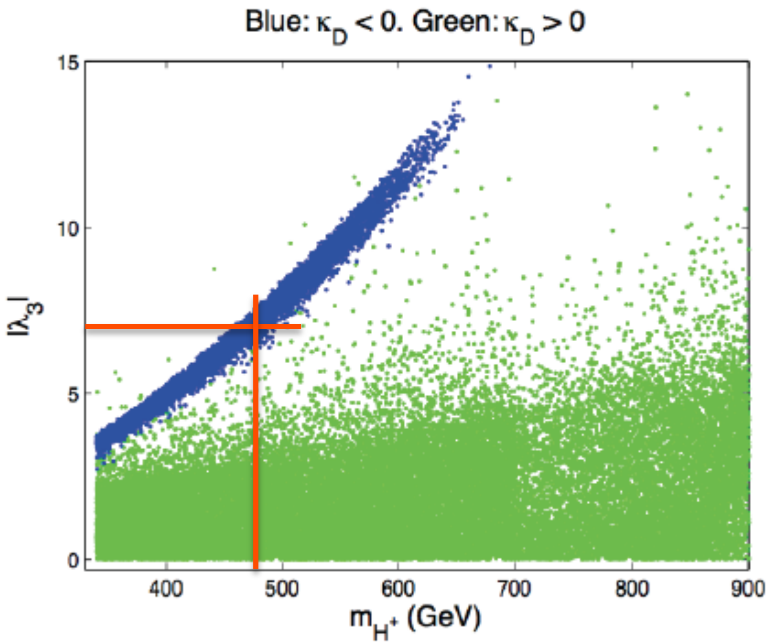
SM-like limit

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

Wrong sign

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

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



Defining

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

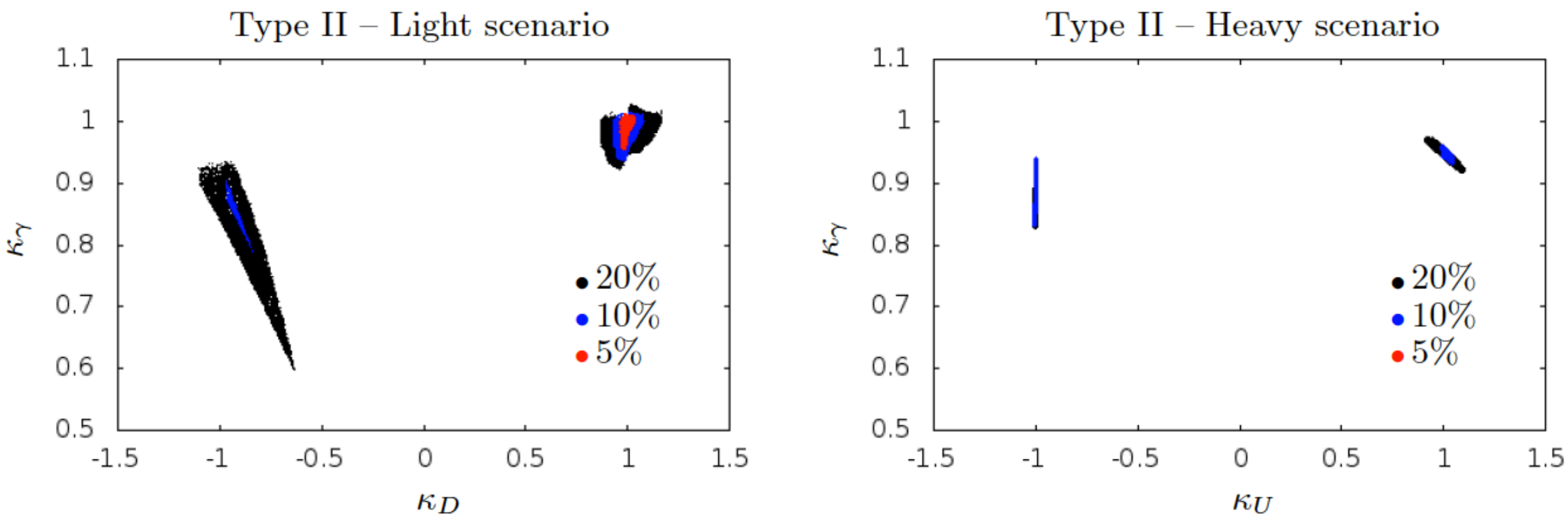
$$\boxed{\sin(\beta+\alpha) - \sin(\beta-\alpha) = \frac{2(1-\varepsilon)}{1+\tan^2\beta} << 1} \qquad (\tan\beta >> 1)$$

Difference decreases with tan β

Probing Wrong-sign limit and SM-like limit in Heavy Scenario

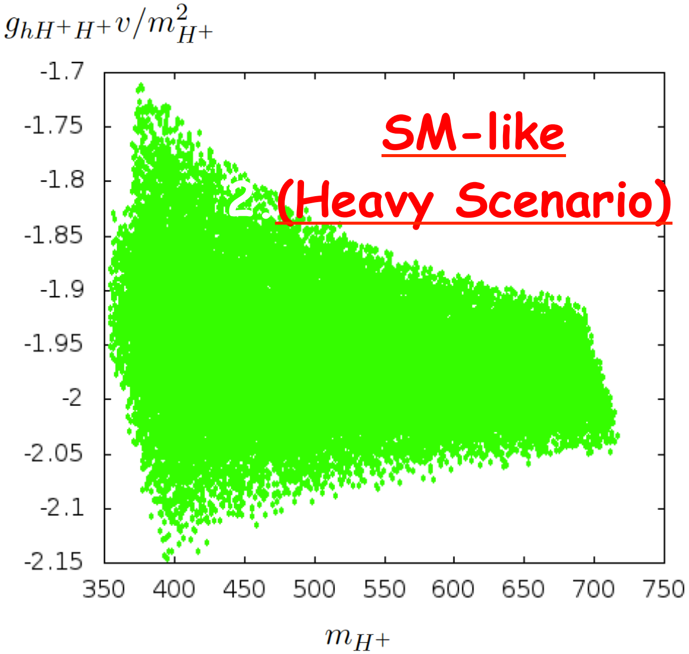
Ferreira, Guedes, Sampaio, RS (2014).

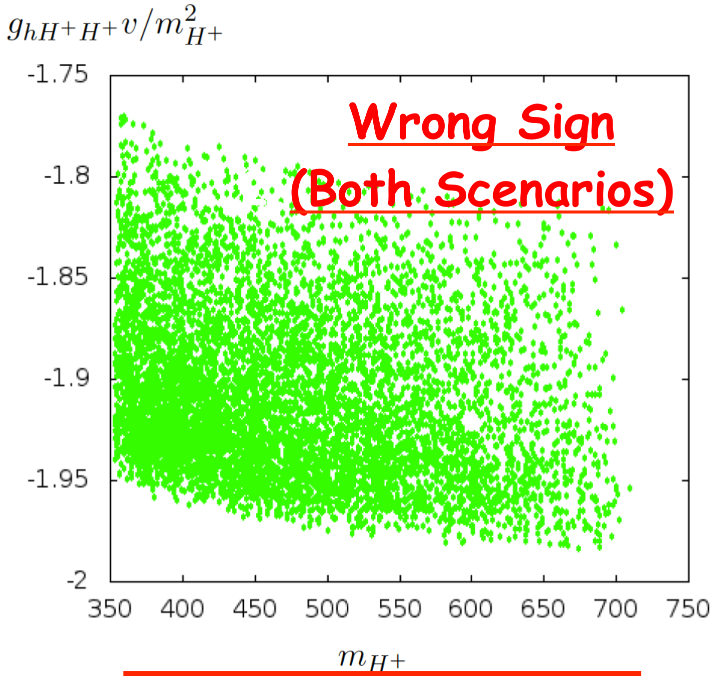
Because $m_h < m_H$ (by construction), if m_H = 125 GeV, m_h is light and there is no decoupling limit.



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.

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

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

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).

Benchmark Fever in the Scalar Sector

BP1: CP-conserving 2HDM with softly-broken Z2-symmetry. [*Howard Haber, Oscar Stål*]
https://twiki.cern.ch/twiki/pub/LHCPhysics/LHCHXSWG3Benchmarks2HDM/HH_OS_2HDM_Benchmarks.pdf

BP2: **:** CP-conserving 2HDM with softly-broken Z2-symmetry. [*Felix Kling, Shufang Su*]
https://twiki.cern.ch/twiki/pub/LHCPhysics/LHCHXSWG3Benchmarks2HDM/Exotic_Benchmarks.pdf

BP3: **:** CP-conserving 2HDM with softly-broken Z2-symmetry.[*Glauber Dorsch, Stephan Huber, Ken Mimasu, Jose Miguel No*]
https://twiki.cern.ch/twiki/pub/LHCPhysics/LHCHXSWG3Benchmarks2HDM/2HDM_Cosmic_Benchmarks.pdf

BP4: **:** CP-conserving 2HDM with softly-broken Z2-symmetry. [*Robin Aggleton, Daniele Barducci, Alexandre Nikitenko, Stefano Moretti, Claire Shepherd-Themistocleous*]
https://twiki.cern.ch/twiki/pub/LHCPhysics/LHCHXSWG3Benchmarks2HDM/2HDM_WG-final.pdf

BP5: Inert 2HDM. [Agnieszka Ilnicka, Maria Krawczyk, Tania Robens]
https://twiki.cern.ch/twiki/pub/LHCPhysics/LHCHXSWG3Benchmarks2HDM/IDM_benchmarks.pdf

BP6: Fermiophobic 2HDM. [David Lopez-Val]
https://twiki.cern.ch/twiki/pub/LHCPhysics/LHCHXSWG3Benchmarks2HDM/fermiophobic.pdf

BP7 Georgi-Machacek model benchmark *[H. Logan]*
https://twiki.cern.ch/twiki/pub/LHCPhysics/LHCHXSWG3BenchmarksNon2HDM/h5plane-benchmark.pdf

BP8 Complex 2HDM benchmarks *[D. Fontes, J.C. Romao, R. Santos and J.P. Silva]*
https://twiki.cern.ch/twiki/pub/LHCPhysics/LHCHXSWG3BenchmarksNon2HDM/benchmark-C2HDM.pdf

BP9 Flavour-changing 2HDM benchmarks *[F.J. Botella, G.C. Branco, M. Nebot and M. Rebelo]*
https://twiki.cern.ch/twiki/pub/LHCPhysics/LHCHXSWG3BenchmarksNon2HDM/benchmark-FCNC2HDM.pdf

BP10 Real and complex singlet benchmarks *[R. Costa, M. Muhlleitner, M.O.P. Sampaio and R. Santos]*
https://twiki.cern.ch/twiki/pub/LHCPhysics/LHCHXSWG3BenchmarksNon2HDM/BenchmarksCxSM_and_RxSM.pdf

BP11 Singlet benchmarks *[T. Robens and T.Stefaniak]*
https://twiki.cern.ch/twiki/pub/LHCPhysics/LHCHXSWG3BenchmarksNon2HDM/benchmarks_robens_stefaniak.pdf

Planned searches for run 2

CPC

$S_i \to ZZ$ $\qquad$ $H_i \to ZZ$

CPV $\qquad$ $h_i \to ZZ$

$S_i \to S_j Z$ $\qquad$ CPC

$H_i \to A_i Z \ (A_i \to H_i Z)$

CPV $\qquad$ 2HDM, ...

h_i (no CP)

$h_1 \to h_2 Z$

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

C2HDM, ...

No charged scalars considered

Planned searches for run 2?

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

CPC

$$H_i \to H_j H_j \;\; (A_i A_j)$$

RxSM, 2HDM, NMSSM

CPV

$$h_i \to h_j h_j$$

$$h_i \to h_j h_k$$

CPV

C2HDM, C-NMSSM

CPC

$$\begin{cases} H_i \to H_j H_k & \text{CxSM, NMSSM} \\ A_i \to A_j H_k & \text{NMSSM} \end{cases}$$

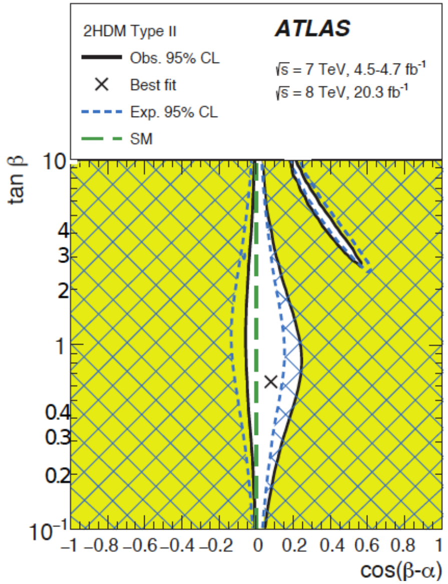
$$\boxed{h_i \text{ (no } CP)}$$

$$\boxed{CP(H_i) = 1; \;\; CP(A_i) = -1}$$

No charged scalars considered

Just different numbers for the different final states.

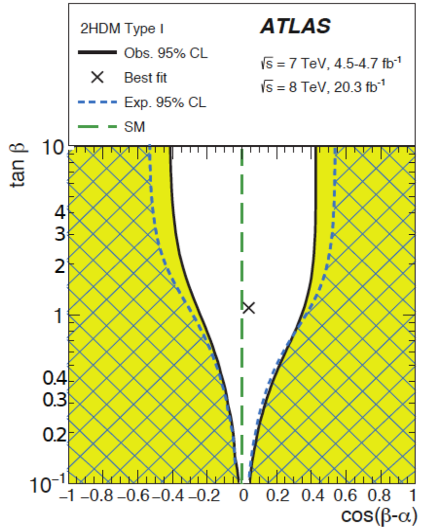
Planes to choose?



Scalar to two gauge bosons

$$H \to W^+W^-(ZZ) \quad \text{plane: } (m_H,\ \cos(\beta-\alpha); \tan\beta)$$

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



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

$$H \to H^{\pm}W^{\mp} \quad \text{plane: } (m_H,\ m_{H^{\pm}});\ (m_{H(H^{\pm})},\ \cos(\beta-\alpha); \tan\beta)$$

masses vs masses; mass vs cos(β-α);tanβ;
tanβ preferred since cos(β-α) close to zero

Cascades and Scenarios

Long Cascade

$$pp \to A \to H^{\pm}W^{\mp} \to HW^{\pm}W^{\mp} \to (H \to)W^{\pm}W^{\mp}$$

$$\text{plane: } (m_A,\, m_H);\ (m_A,\ \cos(\beta-\alpha));\ (m_A,\ \tan\beta)$$

Scenarios vs. Benchmarks?

The wrong sign scenario

Scenario F (Flipped Yukawa)								
	m_h (GeV)	m_H (GeV)	$c_{\beta-\alpha}$	Z_4	Z_5	Z_7	$\tan\beta$	Type
F2	125	$150 \ldots 600$	$\sin 2\beta$	-2	-2	0	$5 \ldots 50$	II

As in Scenario A, we take $m_h < m_H < m_A = m_{H^\pm}$. However, we fix $c_{\beta-\alpha} = s_{2\beta}$ so that

$$\frac{g_{hbb}}{g_{hbb}^{\rm SM}} = s_{\beta-\alpha} - c_{\beta-\alpha}\tan\beta = -1.$$

Specific signatures

Inert

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

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

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

Fermiophobic

$$pp \to AH \to AVV$$

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

CP-violating

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 600 GeV scalar decaying to tops $\qquad h_1 = H \to t\bar{t}$

Find a 600 GeV pseudoscalar decaying to taus $\qquad h_1 = A \to \tau^+\tau^-$

It's CP-violation!

The zero scalar scenarios

Taking

$$c_1 = 0 \quad \Rightarrow \quad R_{11} = 0$$

and

$$a_U^2 = \frac{c_2^2}{s_\beta^2}; \quad b_U^2 = \frac{s_2^2}{t_\beta^2}; \quad C^2 = s_\beta^2 c_2^2$$

Type I $\quad a_U = a_D = a_L = \frac{c_2}{s_\beta} \qquad b_U = -b_D = -b_L = -\frac{s_2}{t_\beta}$

Type II $\quad a_D = a_L = 0 \qquad b_D = b_L = -s_2 t_\beta$

Type F $\quad a_D = 0 \qquad b_D = -s_2 t_\beta$

Type LS $\quad a_L = 0 \qquad b_L = -s_2 t_\beta$

Even if the CP-violating parameter is small, large tanβ can lead to large values of b.

The zero scalar scenarios

In Type II, if

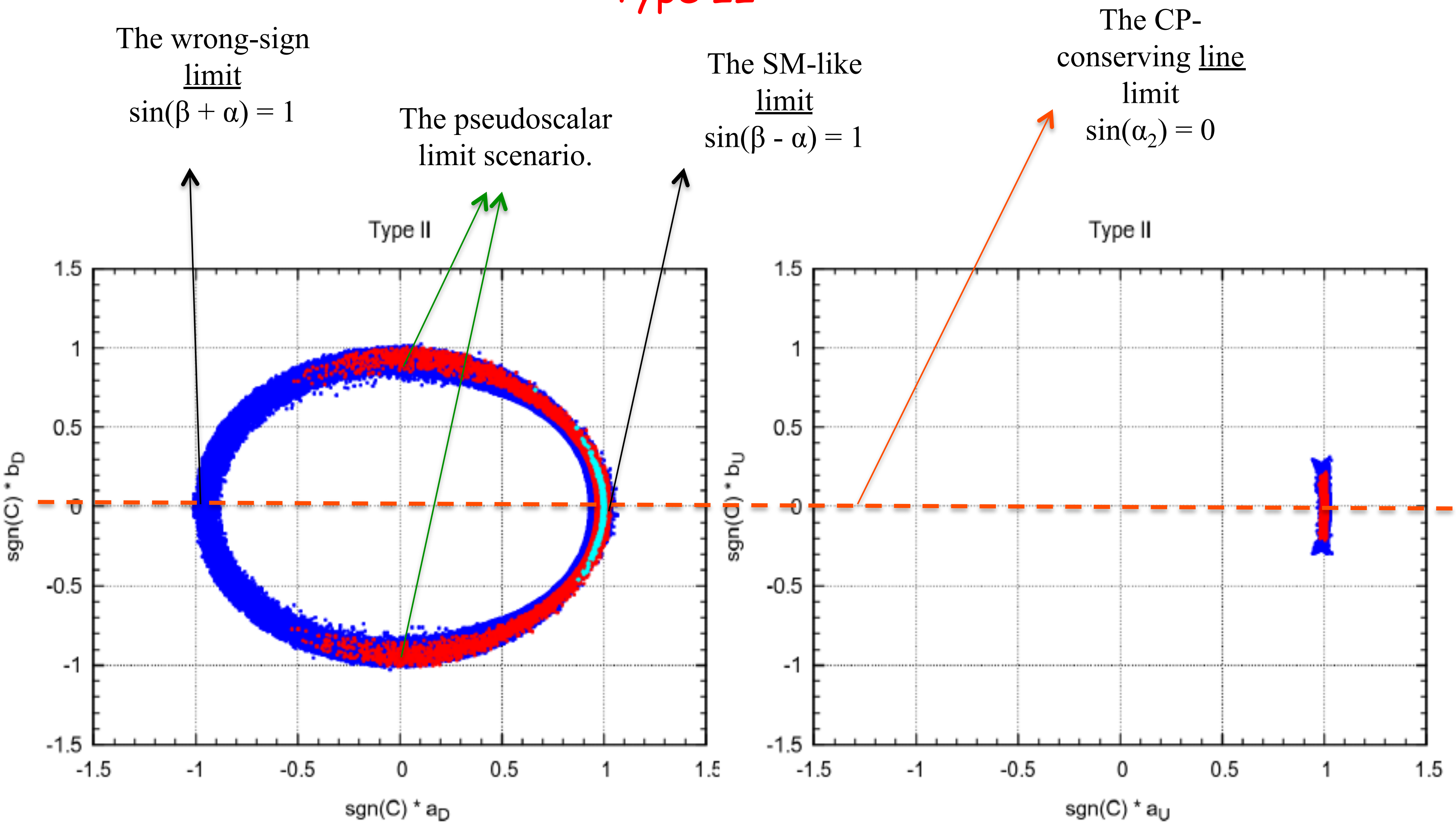
$$a_D = a_L \approx 0 \quad \Rightarrow \quad \mathrm{b}_D = \mathrm{b}_L \approx 1$$

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

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

This means that the h_1 couplings to up-type quarks and to gauge bosons have to be very close to the SM Higgs ones.

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.

So what about EDMs?

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 measurement of the CP-violating angle α_2.

CP-violation with a combination of three decays

CP, the Higgs and the LHC

see Ilya Ginzburg talk from yesterday!

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

Obtained 95% CL intervals on the *allowed* couplings of alternative, not SM-like, spin-zero states with respect to those of the SM scalar state.

		α/κ	β/κ	γ/κ
H→ZZ→4l	ATLAS	not tested	$[-2.5, 0.75]$	$[-0.95, 2.9]$
	CMS	$[-1.2, 1.5]$	$[-\infty, 0.69]$ $[1.9, 2.3]$	$[-2.2, 2.1]$
H→WW→2l2ν	ATLAS	not tested	$[-0.4, 0.85]$ $[1, 2.2]$	$[-5, 6]$
	CMS	$[-\infty, +\infty]$	$[-\infty, 0.71]$ $[1.2, +\infty]$	$[-\infty, +\infty]$
combined, assuming that ratios of "couplings" are the same for ZZ and WW	ATLAS	not tested	$[-0.63, 0.73]$	$[-0.83, 2.2]$
	CMS	$[-1.7, 1.6]$	$[-0.76, 0.58]$	$[-1.6, 1.5]$

α/κ, β/κ, γ/κ < 1-2

If CP(H)=1, coupling is constant relative to the SM one, reverse not true!

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

Combinations of three decays

Already observed

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

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

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...

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).

CP-violating class C2 (and C3 and C4)

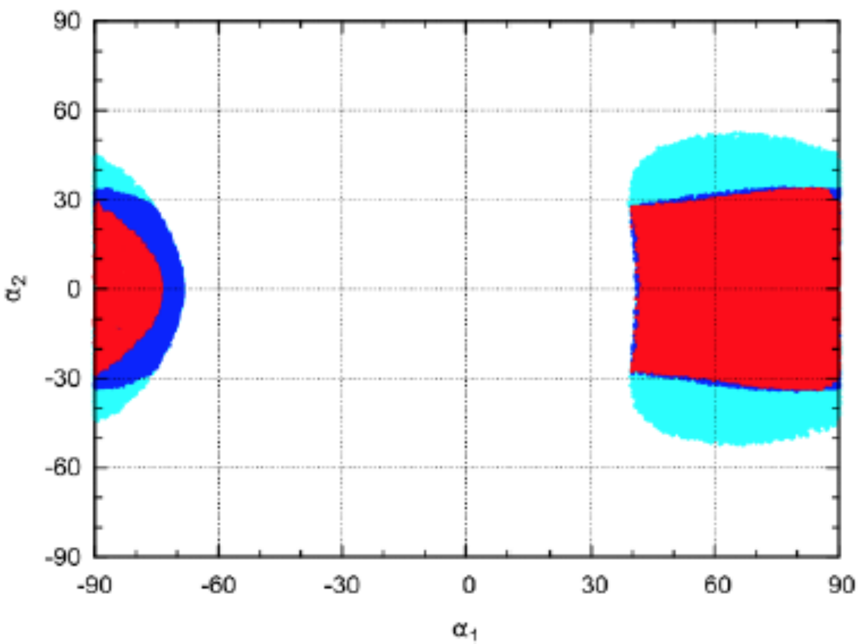
$$h_2 \to h_3 \quad h_1 \to h_2$$

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

$$h_2 \to ZZ \quad \Leftarrow \quad \mathrm{CP}(h_2) = 1$$

$$h_2 \to h_1 Z \quad \Rightarrow \quad \mathrm{CP}(h_1) \neq \mathrm{CP}(h_2)$$

Observing the three decays constitutes a "model independent" sign of CP-violation.



$$\chi = \frac{BR(h_2 \to ZZ)}{BR(h_2 \to h_1 Z)}$$

The benchmark plane is (m_2, χ)

α_2 is already constrained by the first decay. The constraints from the other two decays could be combined in a (m_2, $\sin\alpha_2$) plane.

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]	$\boxed{1.136\ [\text{pb}]}$
$\sigma(h_1)\mathrm{BR}(h_1 \to bb)$	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

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

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

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

Workshop on

Multi-Higgs Models

6-9 September 2016

Lisbon - Portugal

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

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See you all in Lisbon!

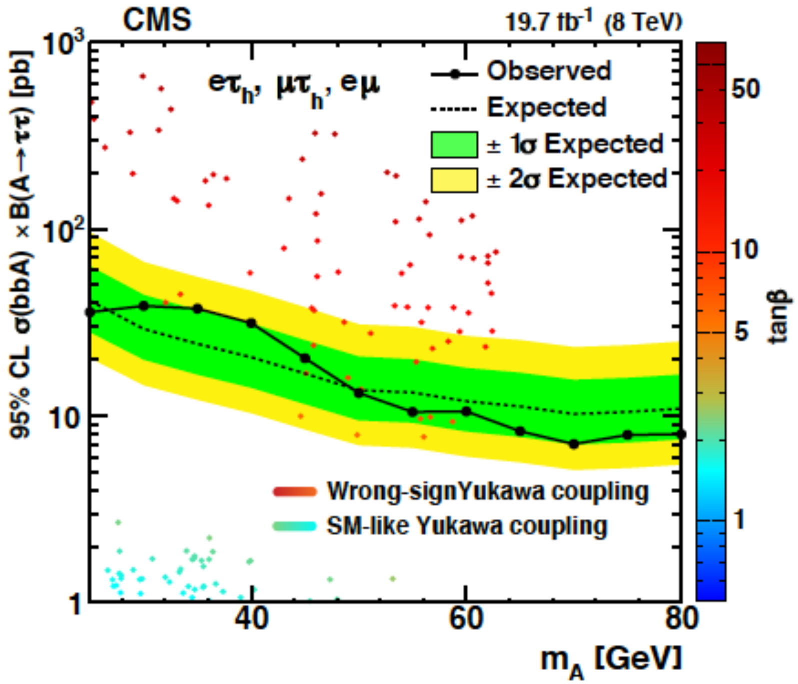


Figure 3: Expected cross sections for Type II 2HDM, superimposed on the expected and observed combined limits from this search. Cyan and green points, indicating small values of $\tan\beta$ as shown in the colour scale, have $\sin(\beta-\alpha) \approx 1$, $\cos(\beta-\alpha) > 0$, and low m_{12}^2, and correspond to models with SM-like Yukawa coupling, while red and orange points, with large $\tan\beta$, have $\sin(\beta+\alpha) \approx 1$, small $\cos(\beta-\alpha) < 0$, and $\tan\beta > 5$, and correspond to the models with a "wrong sign" Yukawa coupling. Theoretically viable points are shown only up to $m_A = m_h/2$ [19].

Constraints

- We take the lightest neutral scalar, h_1, to have a mass of 125 GeV in agreement with the latest results from ATLAS [28] and CMS [29].

- The accuracies in the measurements of the signal strengths in the processes $pp \to h_1 \to WW(ZZ)$, $pp \to h_1 \to \gamma\gamma$ and $pp \to h_1 \to \tau^+\tau^-$ are about 20% at 1σ [29, 30]. As shown in [9], imposing these run 1 constraints guarantees that the C2HDM automatically obeys all other run 1 constraints on the 125 GeV Higgs decays in this model. We will thus force μ_{VV}, $\mu_{\gamma\gamma}$ and $\mu_{\tau\tau}$ to be within 20% of the expected SM value

- The LHC results also allow us to put bounds on the heavier scalars h_2 and h_3. We impose the results on μ_{VV} [31] in the range [145, 1000] GeV and on $\mu_{\tau\tau}$ [32] in the range [100, 1000] GeV. We also use the results on $h_i \to ZZ \to 4l$ from [33] in the range [124, 150] GeV and from [31] in the range [150, 990] GeV, and on $h \to \gamma\gamma$ from [34, 35]. Finally we also impose the constraints stemming from the results based on the searches $h_i \to Zh_1 \to Zb\bar{b}(\tau^+\tau^-)$ [36] and $h_i \to Zh_1 \to llb\bar{b}$ [37].

- We consider the constraints on the charged Higgs Yukawa vertices that depend only on the charged Higgs mass and on $\tan\beta$. There is a new bound on $b \to s\gamma$, in Type II/F [38] of $m_{H^\pm} \geq 480$ GeV at 95% C.L.. Putting together all the constraints from B-physics [39, 40] and also from the $R_b \equiv \Gamma(Z \to b\bar{b})/\Gamma(Z \to \text{hadrons})$ [41] measurement, we can state that roughly $\tan\beta \gtrsim 1$ for all models. LEP searches on $e^+e^- \to H^+H^-$ [42] and the LHC searches on $pp \to \bar{t}\,t(\to H^+\bar{b}$ [43, 44]) lead us to roughly consider $m_{H^\pm} \geq 100$ GeV in Type I/LS.

Constraints

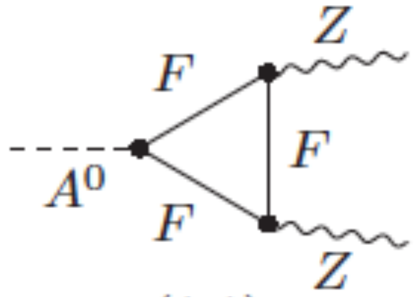
- We consider the following theoretical constraints: the potential has to be bounded from below [45], perturbative unitarity is required [46–48] and all allowed points comply with the oblique radiative parameters [49–51].

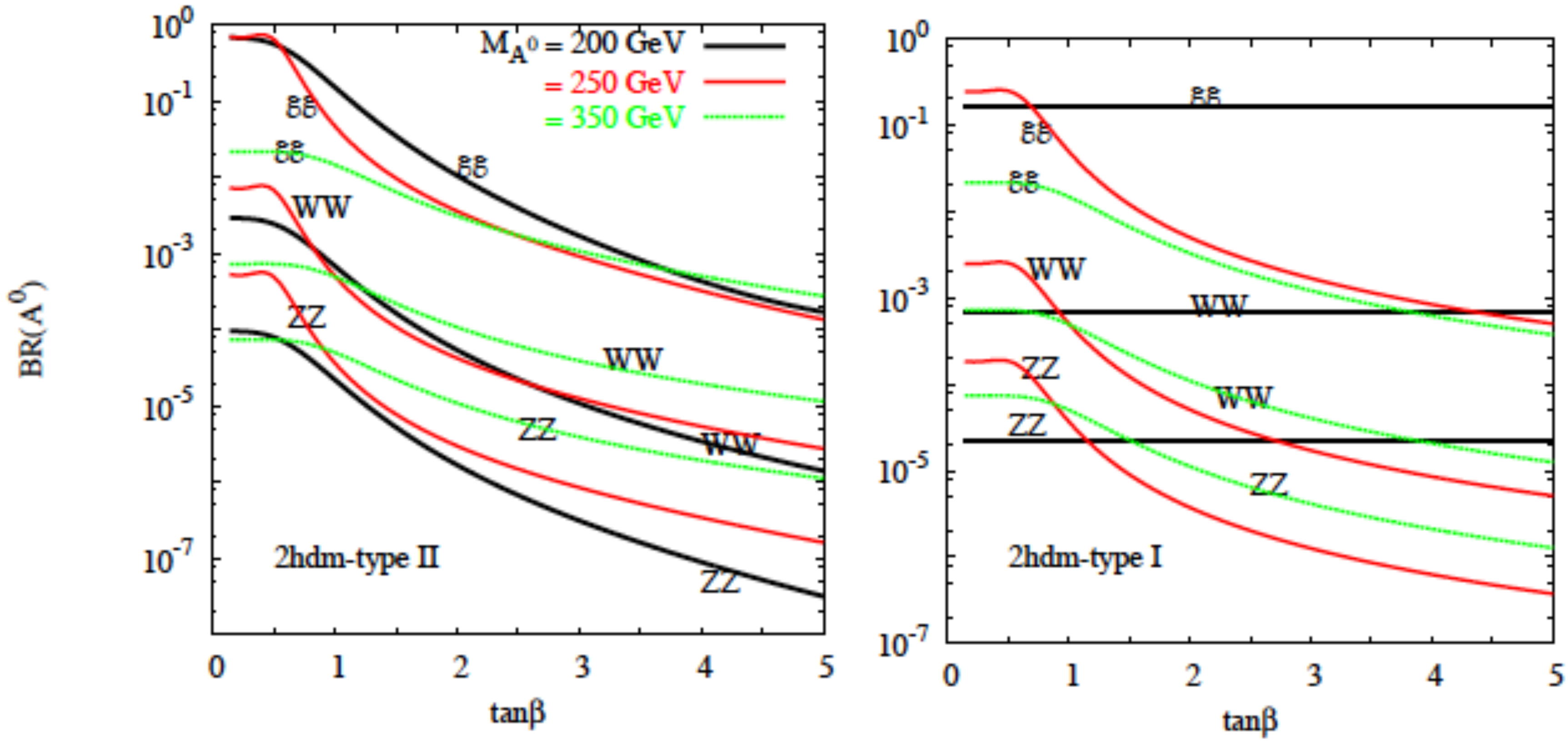
- The scenarios we will present in the next section are a clear signal of CP-violation in models with an extended scalar sector. Models with a CP-violating scalar sector are constrained by bounds from electric dipole moments (EDMs) measurements. Although the search for the proposed final states should be performed from a model independent perspective, we will nevertheless estimate the most important constraints on the CP-violating phases in the context of the C2HDM [7, 52–56].

  The most stringent bound [7] comes from the ACME [57] results on the ThO molecule EDM. In order to have points with EDMs of an order of magnitude that conforms to the ACME result, we have computed the Barr-Zee diagrams with fermions in the loop. As we will see, the ACME bound can only be evaded by either going to the limit of the CP-conserving model or in scenarios where cancellations [55, 56] among the neutral scalars occur. These cancellations are due to orthogonality of the R matrix in the case of almost degenerate scalars [9]. We should finally point out that ref. [55] argues that the extraction of the electron EDM from the data is filled with uncertainties and an order of magnitude larger EDM than that claimed by ACME should be allowed for.

For each particular model one should check

$$A \to ZZ\ (W^+W^-)$$





Arhrib, Benbrik, Field (2006).