Higgs Physics at Hadron Colliders (I)

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IBS-Honam Focus Program on
Particle Physics Phenomenology

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The strike

Many thanks to Shinya for replacing me in the last minute. A beer is due!

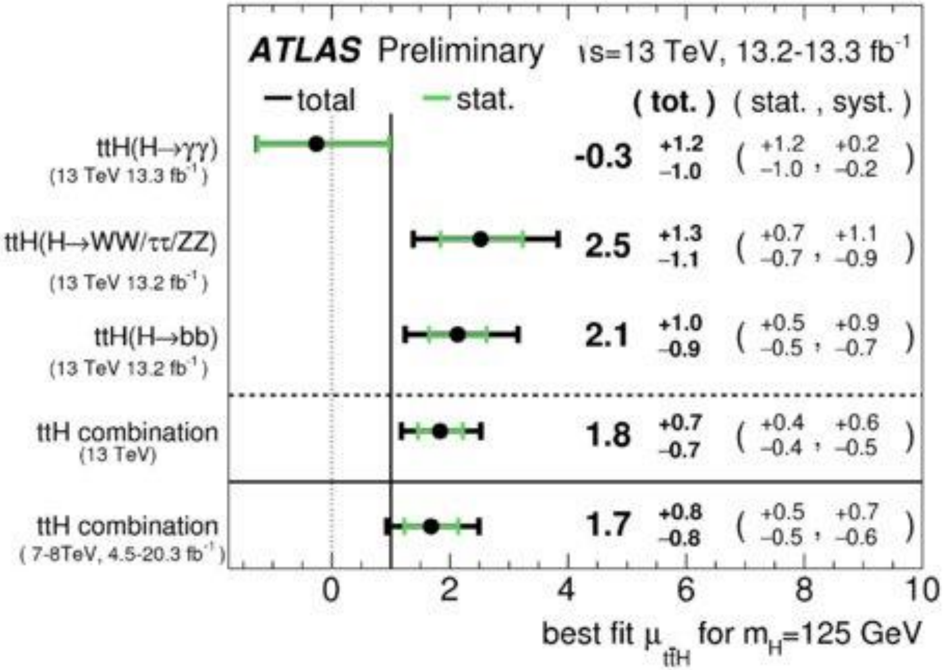
- Summary of the searches (involving scalars) that are being performed – new particles and new searches?

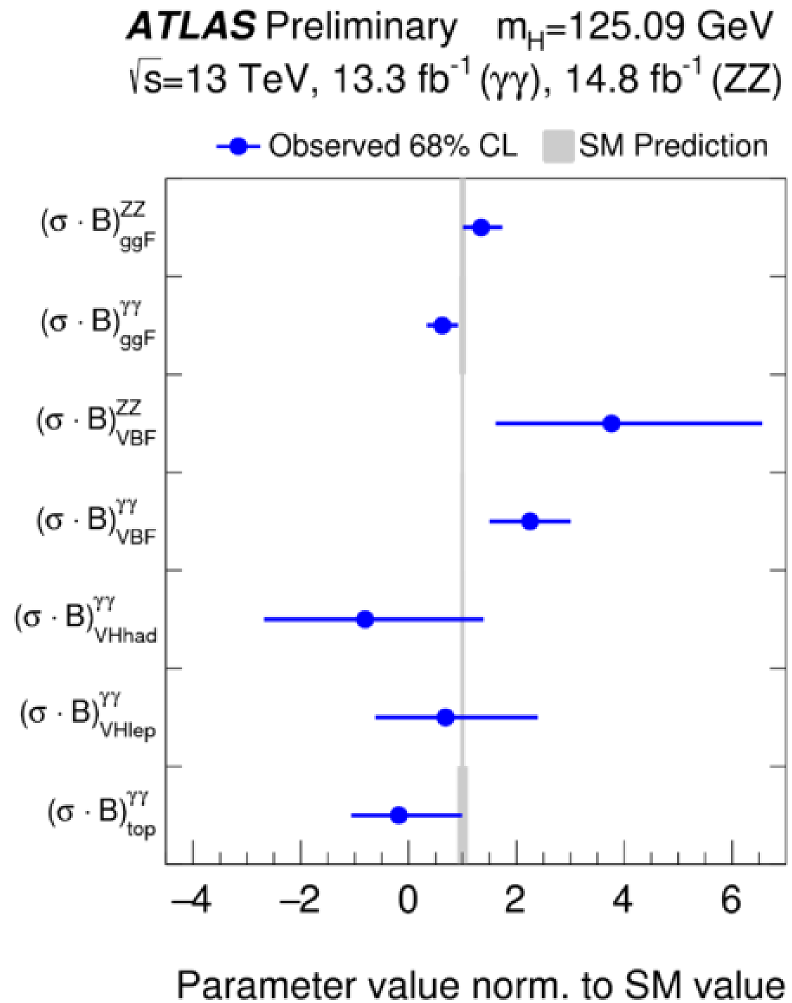
- The simplest extensions of the scalar sector as benchmark models

    - The singlet extension RxSM and CxSM
    - 2HDMs
    - 3HDMs – Ivanov and Silva's Half CP

Disclaimer: this lecture is about scalars and there is no supersymmetry involved

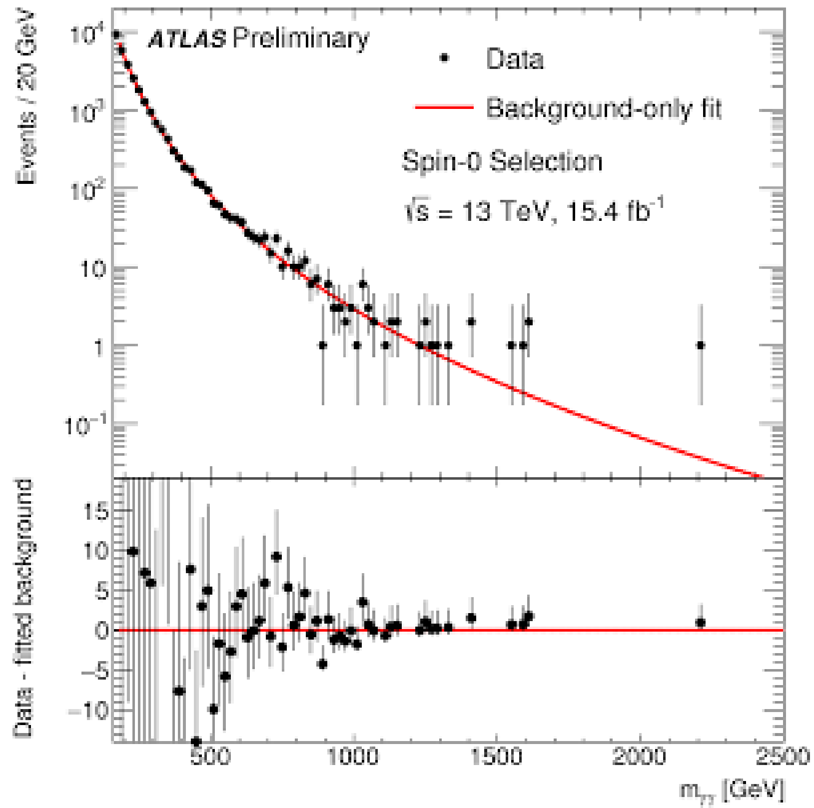
Results for couplings after ICHEP





no combinations yet
with run 1 and run 2 data

The 750 GeV turmoil



A very interesting and useful exercise for model builders and phenomenologists!

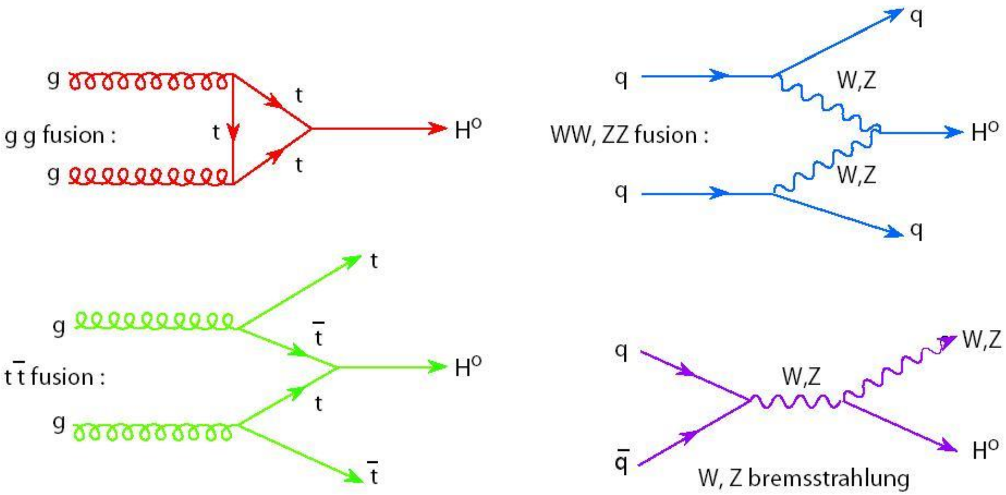
More details - Hyun Min Lee talk

The 750 GeV turmoil

total results from
resonaances.blogspot.pt

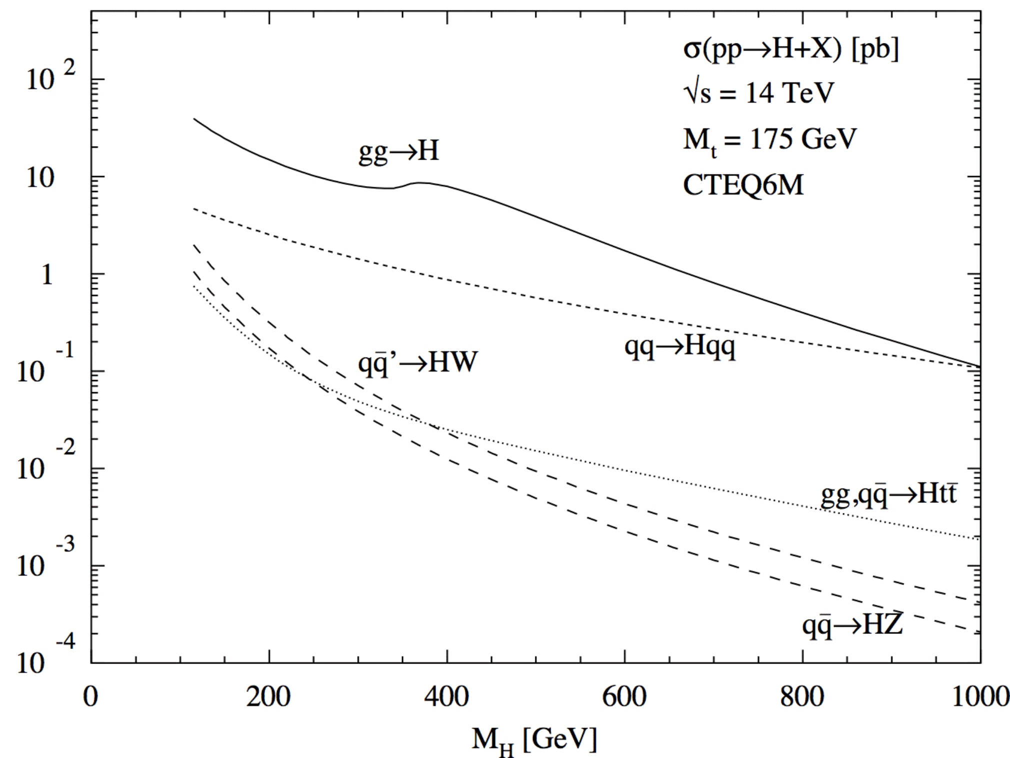
h-index results from
resonaances.blogspot.pt

Higgs production mechanisms



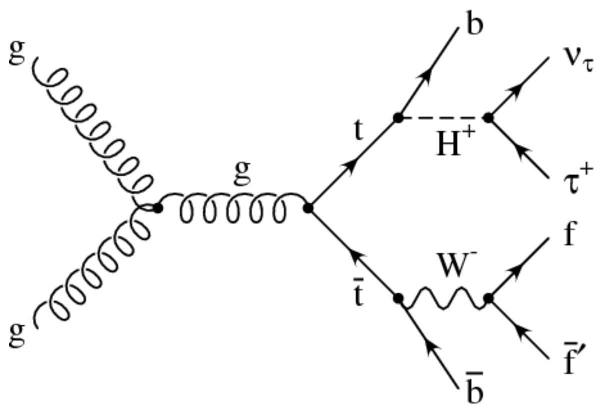
Main diagrams for a Higgs with "reasonable" couplings to fermions and gauge bosons.

Values for the production cross sections of a SM-like Higgs boson



Higgs production mechanisms – new scalars – charged Higgs

"main" process below the top threshold



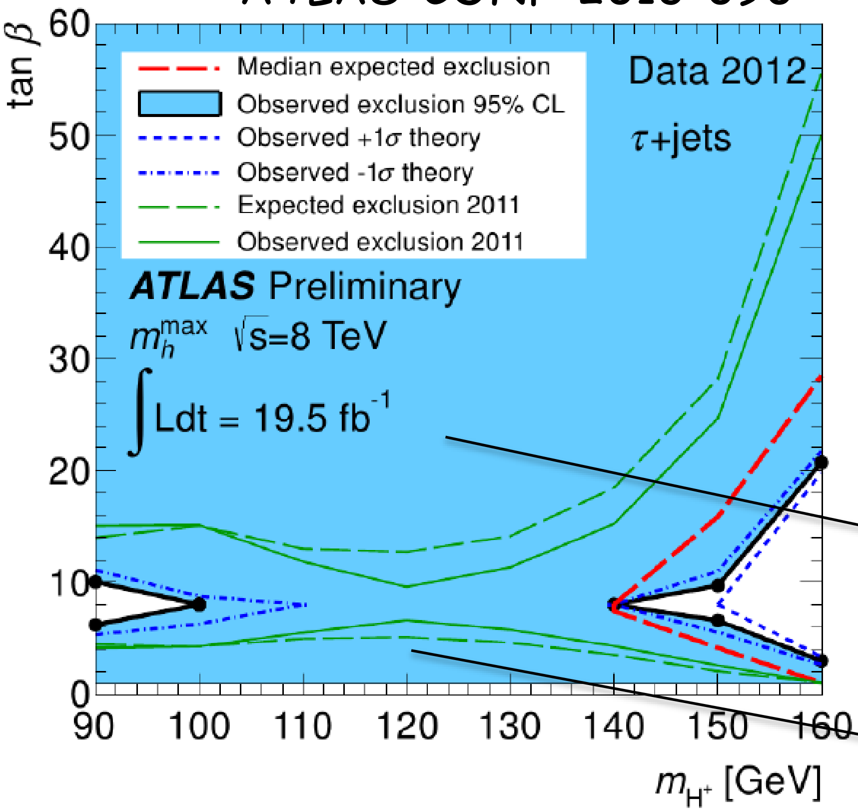
"main" processes above the top threshold

still, cross sections could be negligible

Experimental (LHC)

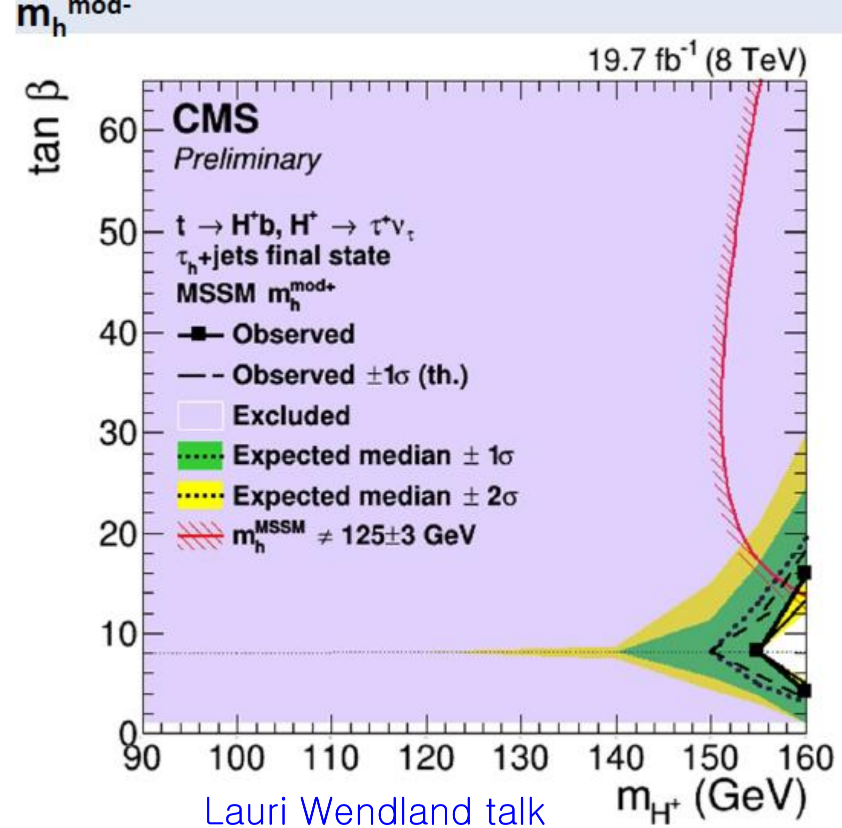
$$pp \to t\bar{t} \to b\,bW^{+}H^{-}$$

ATLAS-CONF-2013-090



$$m_b \tan b$$

$$\frac{m_t}{\tan b}$$



Lauri Wendland talk
AT Charged2014

G. Aad *et al.* [ATLAS Collaboration], JHEP **1206** (2012) 039

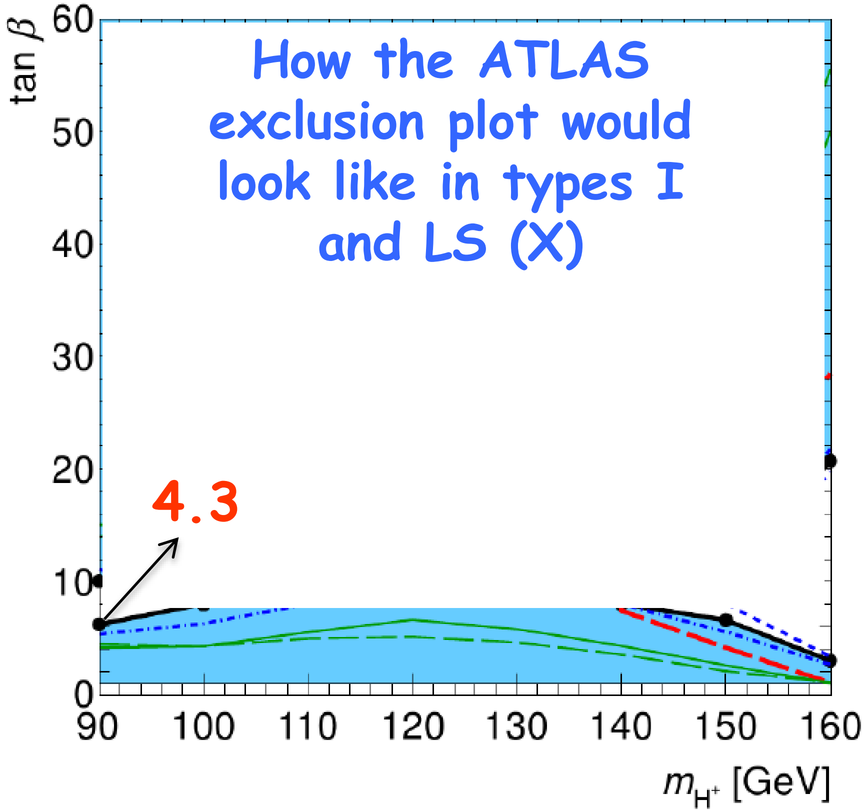
S. Chatrchyan *et al.* [CMS Collaboration], JHEP **1207** (2012) 143

Corrected for

$$BR(H^{-} \to \tau\bar{\nu})$$

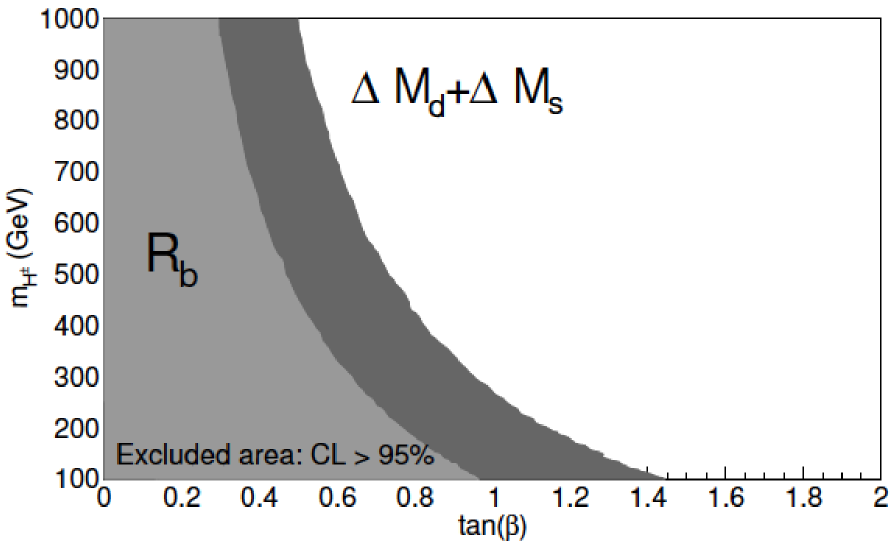
$m_{H^+} = 90$ GeV	I	II	F	LS
$\tan b$	4.3	6.4	3.2	5.2

Experimental constraints on the charged Higgs mass vs. tanβ



small tanβ excluded for this mass region

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



$$\tan\beta \gtrsim 1$$

Higgs production mechanisms - new scalars - charged Higgs

Only "model independent" bounds come from lepton colliders

$$e^+e^- \rightarrow \gamma, Z \rightarrow H^+H^-$$

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

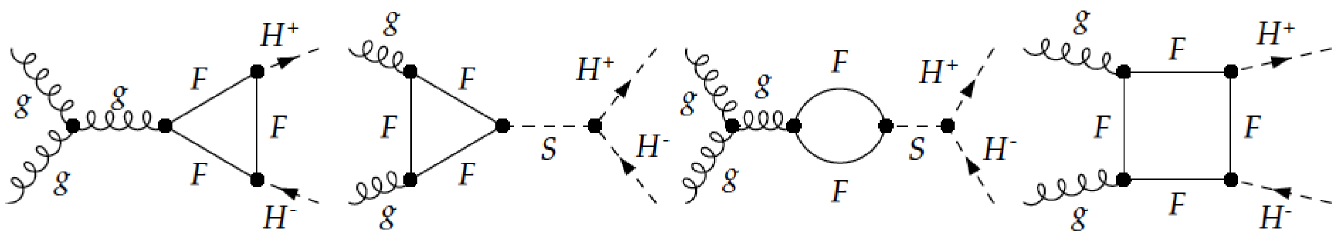
Any $BR(H^+ \to \tau^+\nu)$ $m_{H^\pm} \gtrsim 80\ GeV$

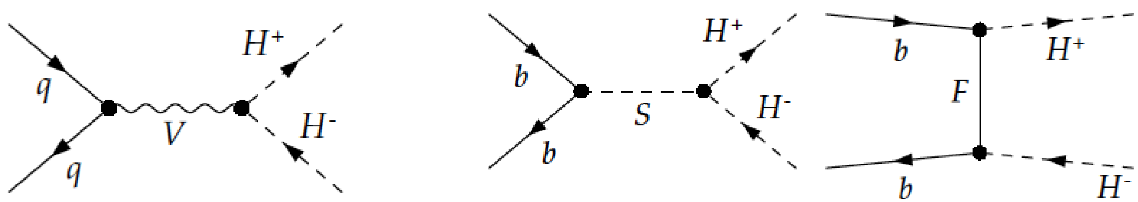
$BR(H^+ \to \tau^+\nu) \approx 1$ $m_{H^\pm} \gtrsim 94\ GeV$ Type LS (X)

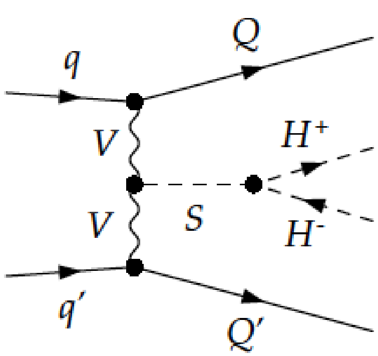
bound is roughly half the energy of the collider except if decays are very non-standard

Higgs production mechanisms - new scalars - charged Higgs

charged Higgs pair production - only interesting when resonant



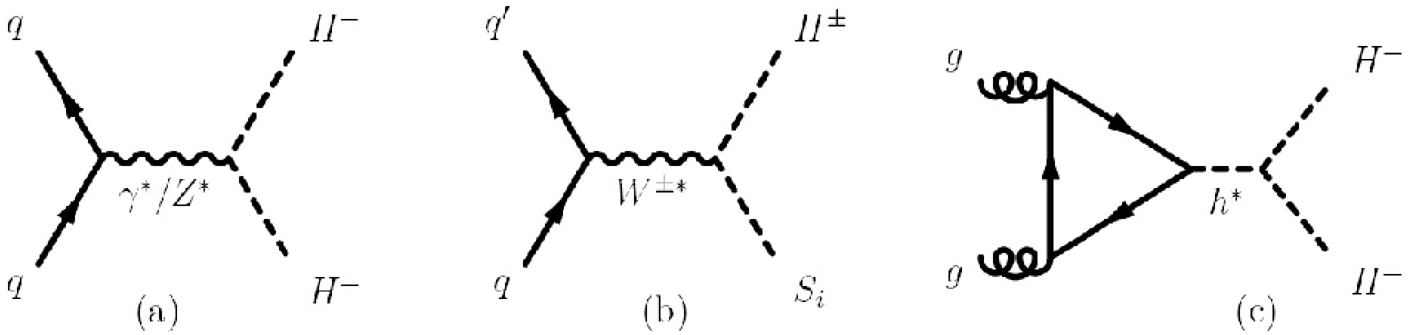




similar modes for HW production

Aoki, Guedes, Kanemura, Moretti, RS, Yagyu (2011)

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 neutral scalars

$S_i \rightarrow VV$

CPC $\rightarrow$ $H_i \rightarrow VV$

CPV $\rightarrow$ $h_i \rightarrow VV$

In run 1 searches were performed in
WW, ZZ, γγ and Zγ.
Searches will continue in run 2. There is some discussion whether Zγ
is interesting at all at high scalar masses, if there is anything experimentalists would be happy to hear.

h_i (no definite CP)

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

Analysis are assumed to be independent of particles CP.

Searches involving neutral scalars

$S_i \to S_j V$

CPC

$H_i \to A_i V \; (A_i \to H_i V)$

2HDM, ...

CPV

$h_1 \to h_2 V$

C2HDM, ...

A->Zh_{125} was done in run 1.
A->ZH is done for CMS and is being started in ATLAS.

h_i (no definite CP)

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

Analysis are assumed to be independent of particles CP.

Searches involving charged scalars

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

Triplets

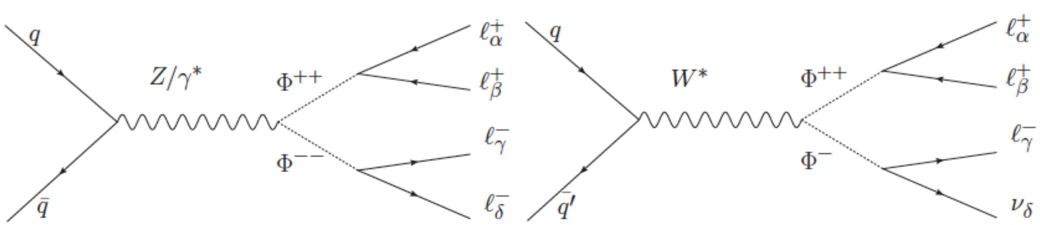
$H^{\pm} \to W^{\pm} Z$

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.

Searches involving neutral scalars

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

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:

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

h_i (no definite CP)

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

So far only H -> hh.
However it covers all cases except final states with different masses – more later.

Searches involving neutral scalars

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

Resonant S_i

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.

Searches involving scalars

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

FC

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

$H/A \to \mu^+\mu^-$ Done and new analysis being prepared

$H/A \to t\bar{t}$ Done for 8 TeV. Being done for run 2.

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

FCNC

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

$t \to ch_{125}$

There are also ttH and bbH production with H->ttbar planned as well.

S_i (any scalar)

No charged scalars considered

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 involving charged scalars

$H^{\pm} \to \tau\nu$ Done in tt production (mass below the tb threshold)

$H^{\pm} \to tb$ Done (above the tb threshold)

$H^{\pm} \to cb$

$H^{\pm} \to \mathrm{cs}$

Done in tt production
a long time ago – no updates.
(mass below the tb threshold)

Other exotic searches that were not covered here can be found in the review

LHC searches for exotic new particles
Tobias Golling, Prog.Part.Nucl.Phys. 90 (2016) 156-200

Singlet – RxSM and CxSM

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

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

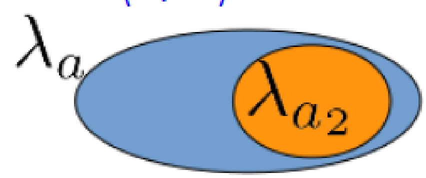
$$V(H, S, \phi, \chi, \ldots) \rightarrow \begin{matrix} H, H^\dagger \\ \mathbb{S}, \mathbb{S}^\star \\ \phi, \chi \\ \ldots \end{matrix} \rightarrow \begin{pmatrix} \phi_0 \\ \phi_1 \\ \ldots \\ \phi_n \end{pmatrix} \rightarrow V = V_a(\phi_i)\lambda_a$$

Numeric VEV

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

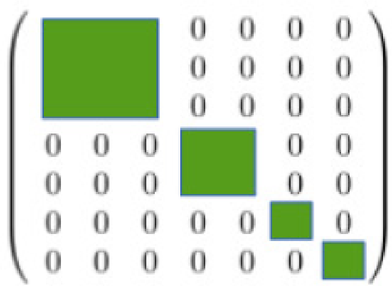
Min. Conditions

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



Block Detection

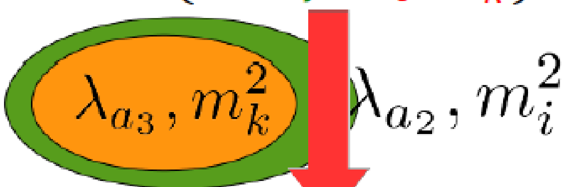
$\mathbf{M}.\mathbf{M}^\mathbf{T} = \mathbf{1}$



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 singlet

a) Provide dark matter candidates

Silveira, Zee (i985)

b) Improve stability of the SM at high energies

Costa, Morais, Sampaio, Santos (2015)

c) Help explain the baryon asymmetry of the Universe

Profumo, Ramsey-Musolf, Shaughnessy (2007)

d) Rich phenomenology with Higgs to Higgs decays

LHC run 2 -> probe extended sectors

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

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

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

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

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

Barger, Langacker, McCaskey, Ramsey-Musolf, Shaughnessy (2009) and many more...
Coimbra, Sampaio, Santos (2013)
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

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

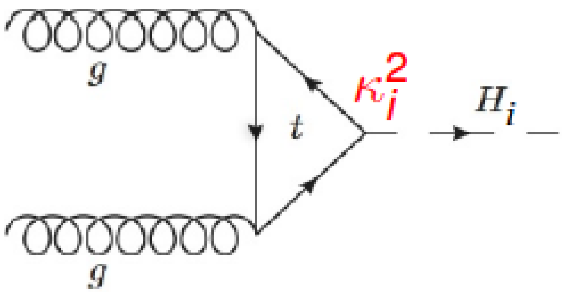
- $\not{\mathbb{Z}}_2$ phase ($v_S \neq 0$): 2 Higgs mix

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

Datta, Raychaudhuri (1998)
Shabinger, Wells (2005) and many more...

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:**

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

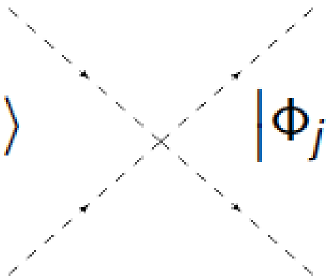
- **Total decay width:**

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

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:

$|\Phi_i\rangle$  $|\Phi_j\rangle$

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

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

- In SM, the **2-particle** states are w^+w^-, hh, zz, hz
  $\Rightarrow$ constrains quartic coupling λ, $\Rightarrow$ $\mathbf{m_h^2} < \mathbf{700\ GeV}$
- 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
$$S(b_1+b_2+d_2S^2)+2a_1=0$$
- $H=0$, $S=-a_1/b_1$ and
$$A^2=\frac{b_1^2(b_1-b_2)-d_2a_1^2}{d_2b_1^2}$$
- $A=0$, $H^\dagger H=-\frac{m^2+\delta_2S^2}{\lambda}$ and the following cubic equation must be solved $\rightarrow 2a$
$$S\left[b_1+b_2-\frac{\delta_2m^2}{\lambda}+\left(d_2-\frac{\delta_2^2}{\lambda}\right)S^2\right]+2a_1=0$$
- $S=-a_1/b_1$, $H^\dagger H=-\frac{m^2+\delta_2(S^2+A^2)}{\lambda}$ and $\rightarrow 2b$
$$A^2=\frac{b_1^2(\lambda(b_1-b_2)+m^2\delta_2)-d_2a_1^2\lambda+\delta_2^2a_1^2}{d_2b_1^2\lambda-\delta_2^2b_1^2}$$

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

Phenomenological constraints imposed using `ScannerS`:

`scanners.hepforge.org`

- Electroweak precision observables – STU
- Collider data (LEP, Tevatron, LHC) HiggsBounds/Signals
- Dark matter relic density below Planck measurement & bounds from LUX on σ_{SI} (micrOMEGAs)

$\Rightarrow$ **Decay widths – adaptation of HDECAY $\rightarrow$ sHDECAY.**

`www.itp.kit.edu/~maggie/sHDECAY/`

- EW corrections consistently off
- CxSM and also RxSM

$\Rightarrow$ **We also turned EW off for 13 TeV** $\sigma(gg \rightarrow h_i)$

We define global signal rate for direct channels

$$\mu_i = R_{ih}^2 \sum_{X_{\rm SM}} {\rm BR}(h_i \rightarrow X_{\rm SM})$$

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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Last modified: Wed Dec 16 09:45:24 CET 2015

CP and the CxSM

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

This is a CP-transformation

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

so, if *A* gets a vev, CP is broken, right? Wrong!

The model has two phases, one with a dark matter candidate and one where the three neutral scalars mix.

In any case the model is always CP-conserving. The phases only play a role if new particles are added to the theory.

CP and the CxSM

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

$$H \rightarrow H^*;\ S \rightarrow S^* \qquad (1)$$

$$H \rightarrow H^*;\ S \rightarrow S \qquad (2)$$

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

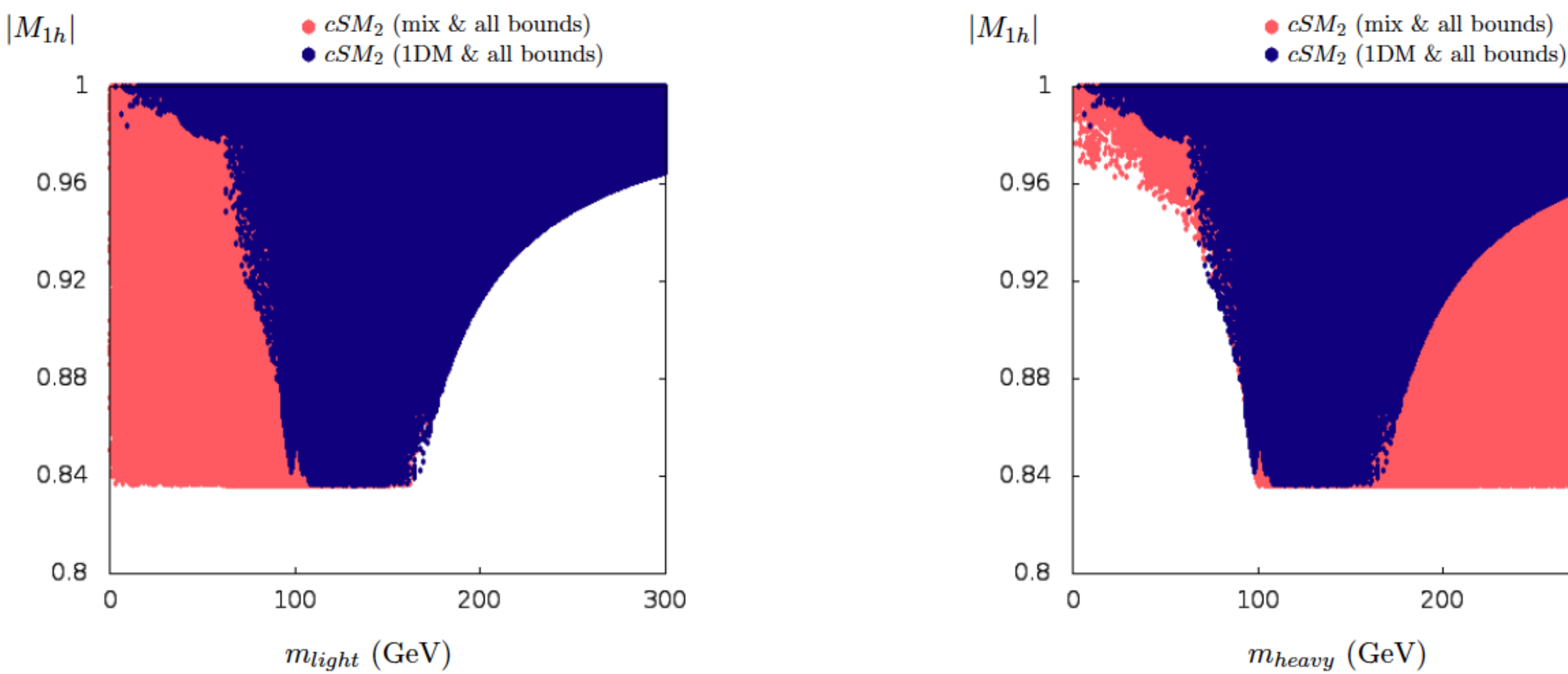
Therefore even if (1) is broken there is still one unbroken *CP* symmetry (2) and the model is *CP*-conserving.

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

Branco, Lavoura, Silva (1999)

Bento, Branco (1990)

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.

The status of the singlet – scan boxes

Input parameter	Broken phase Min	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	$-\pi/2$	$\pi/2$

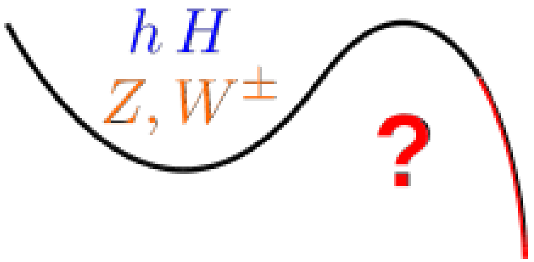
Input parameter	Dark phase Min	Max
$m_{h_{125}}$ (GeV)	125.1	125.1
$m_{h_{\rm other}}$ (GeV)	30	1000
m_A (GeV)	30	1000
v (GeV)	246.22	246.22
v_S (GeV)	1	1000
α_1	$-\pi/2$	$\pi/2$
$a_1(\rm GeV^3)$	-10^8	0

Scan parameter	Broken phase Min	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):

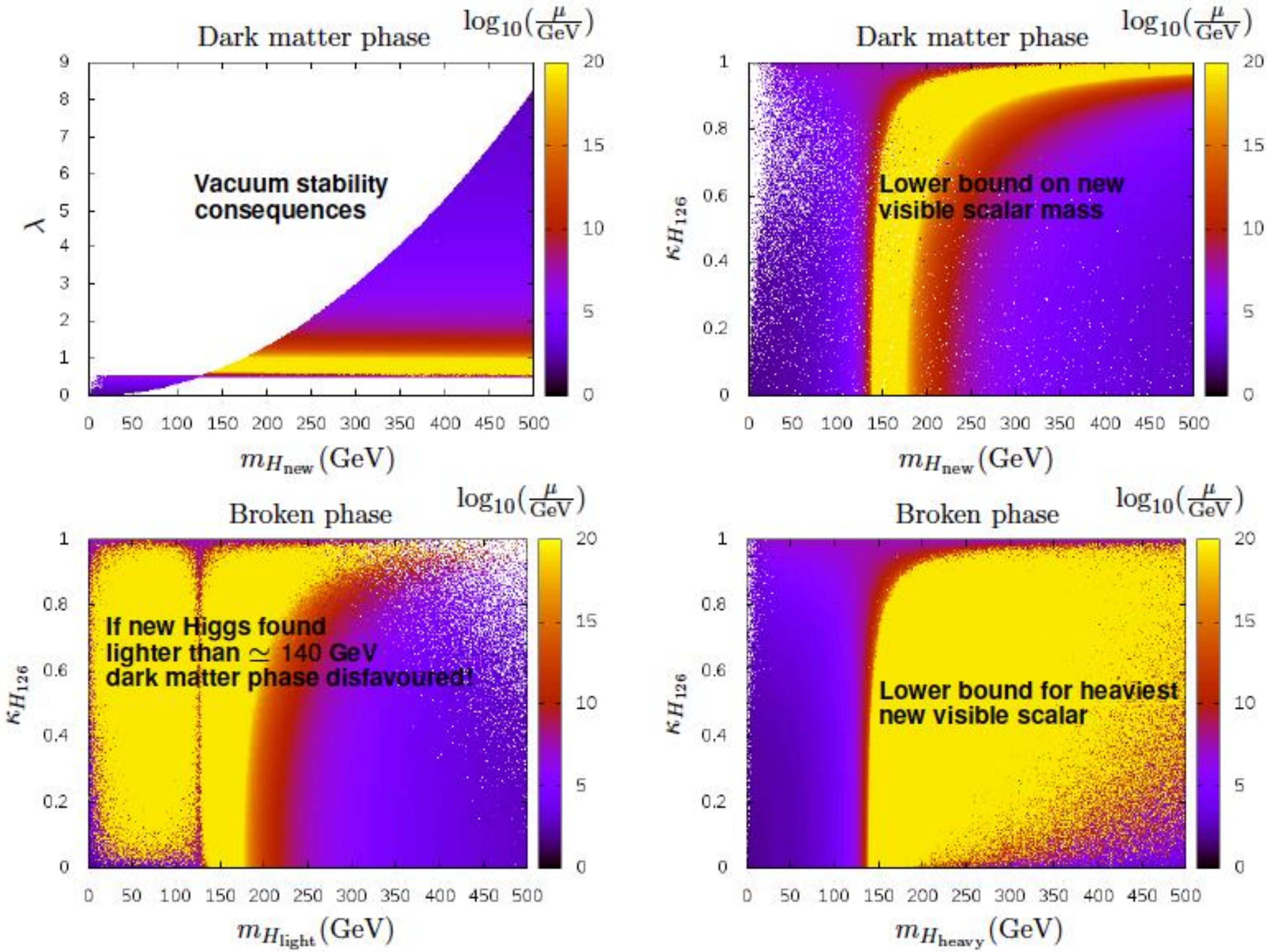
- Boundedness from below: $\lambda > 0 \ \wedge\ d_2 > 0 \ \wedge\ \delta_2 > -\sqrt{\lambda d_2}$



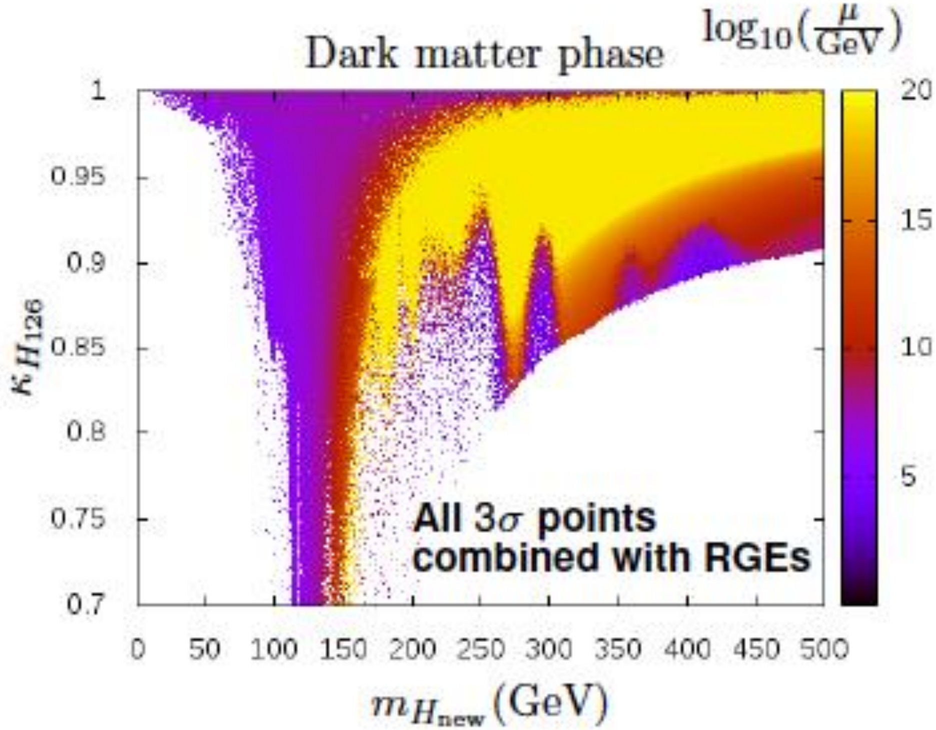
- Perturbative unitarity:

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

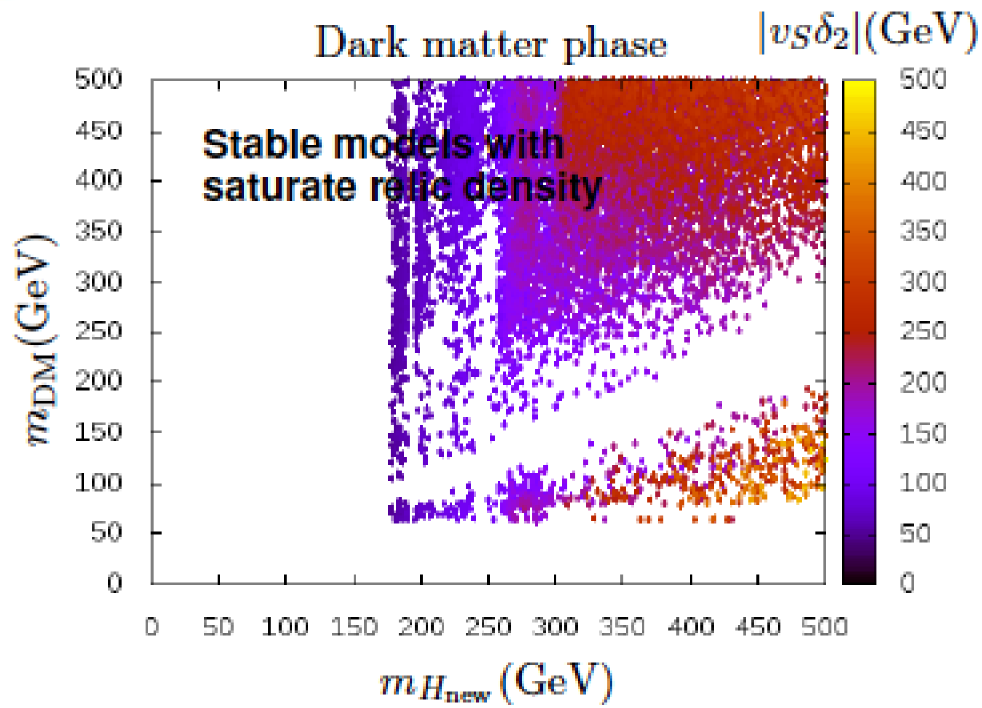
RGE stability bands – no Phenomenology



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 = ½ m_{125} and an excluded wedge around mDM = ½ 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.

2HDMs

The 2HDMs

a) Also provide dark matter candidates

b) Also improve stability of the SM at high energies

c) Also help to explain the baryon asymmetry of the Universe

d) Also richer phenomenology with Higgs to Higgs decays

e) New types of particles: charged Higgs and pseudo-scalars

f) CP-violation in the scalar sector

2HDM particle content

SM → 4 degrees of freedom ⇨ 2HDM → 8 degrees of freedom

- All symmetries broken → 4 GB + 4 scalar bosons (➡ CB)
- $U(1)_{em}$ unbroken but not CP → 3 GB + 5 scalar bosons (2 charged, $H^{\pm}$, and 3 neutral, h_1, h_2 and h_3)
- $U(1)_{em}$ and CP unbroken → 3 GB + 5 scalar bosons (2 charged, $H^{\pm}$, and 3 neutral, h, H and A)
- All symmetries unbroken → 8 scalar bosons

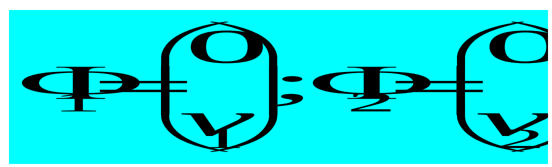
The softly broken Z_2 (U(1)) symmetric 2HDM potential

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

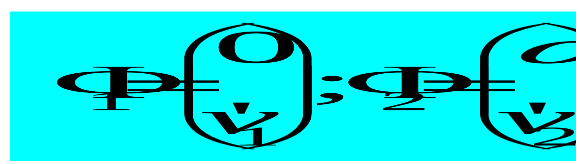
$$\phi_1 \to \phi_1 \qquad \phi_2 \to -\phi_2$$

Different models are obtained by tuning m^2_{12} and λ_5 together with the possible vacuum configurations (all other parameters real - hermiticity)

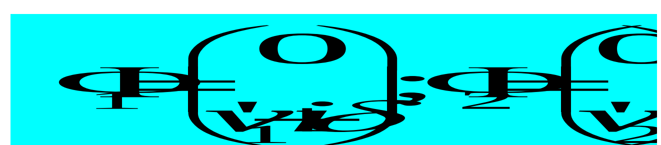
- NORMAL (N)



- CHARGE BREAKING (CB)

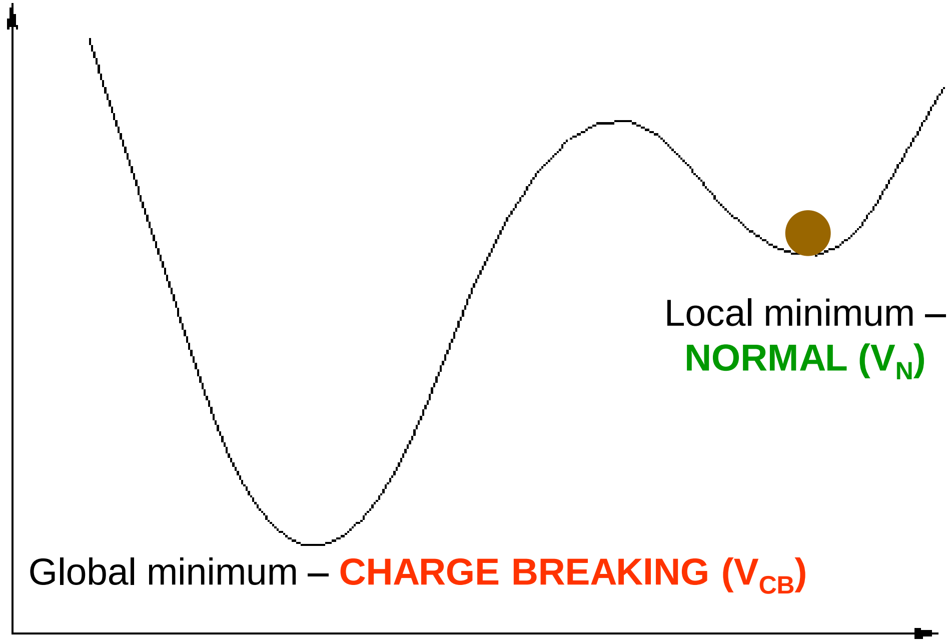


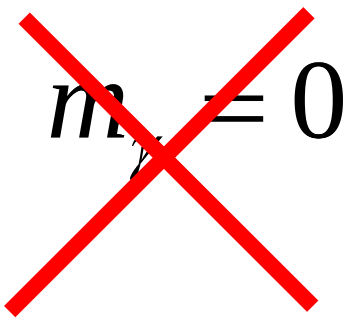
- CP BREAKING (CP)



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

Can one potential have a Normal and a CB minimum simultaneously?





$$m_\gamma \neq 0 \ !$$


Oh No! Not Charge Breaking!

For a safer 2HDM

$$V_{CB} - V_N = \frac{M^2_{H^\pm}}{2v^2}\left[\left(v'_1 v_2 - v'_2 v_1\right)^2 + a^2 v_1^2\right]$$

$\frac{M^2_{H^\pm}}{2v^2}$ ⇨ **Calculated at the Normal stationary point.**

V_N is a MINIMUM ⇨ $\frac{M^2_{H^\pm}}{2v^2} > 0$ ⇨ $V_N < V_{CB}$

The Normal minimum is below the CB SP. The CB SP is a saddle point.

Valid for the most general 2HDM but not for 3HDM!

Some beautiful relations

For charge breaking

$$V_{CB} - V_N = \frac{M_{H^\pm}^2}{2v^2}\left[\left(v'_1 v_2 - v'_2 v_1\right)^2 + a^2 v_1^2\right]$$

For CP breaking

$$V_{CP} - V_N = \frac{M_A^2}{2v^2}\left[\left(v''_1 v_2 - v''_2 v_1\right)^2 + d^2 v_1^2\right]$$

For 2 competing normal minima

$$V_{N_2} - V_{N_1} = \frac{1}{2}\left\{\left(\frac{M_{H^\pm}^2}{v^2}\right)_{N_1} - \left(\frac{M_{H^\pm}^2}{v^2}\right)_{N_2}\right\}\left[\left(v''_1 v_2 - v''_2 v_1\right)^2 + \delta^2 v_1^2\right]$$

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

The tree-level global picture

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

A. Barroso, P. Ferreira, RS

PLB603(2004), PLB632(2006), PLB652(2007)

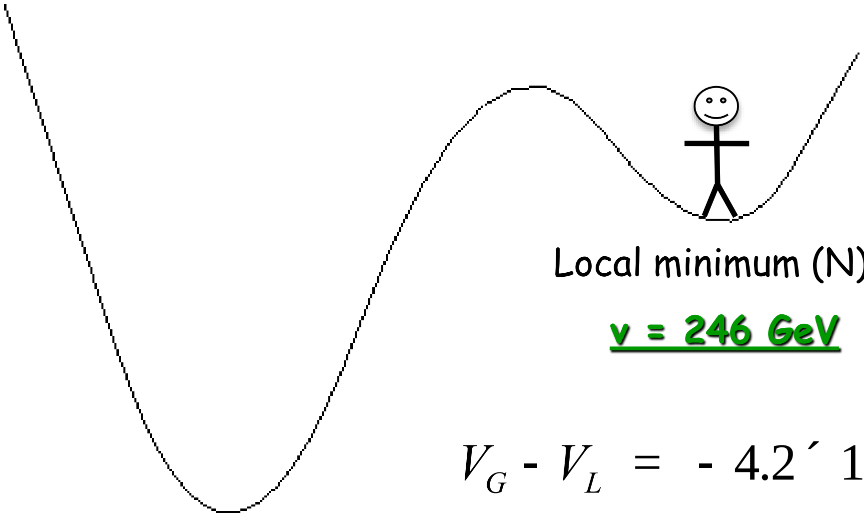
M. Maniatis, A. von Manteuffel, O. Nachtmann and F. Nagel

EPJC48(2006)805

I. Ivanov

PRD75(2007)035001, PRD77(2008)15017, PRE79(2008)021116

Two normal minima - <u>potential with the soft breaking term</u>



Local minimum (N) -

<u>v = 246 GeV</u> $m_W = 80.4\ \text{GeV}$

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

Global minimum (N) -

<u>v = 329 GeV</u> $m_W = 107.5\ \text{GeV}$

THE PANIC VACUUM!

and this is one that can actually occur...

A. Barroso, P.M. Ferreira, I.P. Ivanov, RS, JHEP06 (2013) 045.

A. Barroso, P.M. Ferreira, I.P. Ivanov, RS, J.P. Silva, Eur. Phys. J. C73 (2013) 2537.

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.

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

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:

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

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

Ivanov, Silva (2015)

Softly broken Z_2 symmetric Higgs potential

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

we choose a vacuum configuration

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

- **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

- $\tan b = \frac{v_2}{v_1}$ 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

$$a_1 = a + p/2$$

to gauge bosons

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

$$k_V^h = \sin(b - a)$$

$$k_V^H = \cos(b - a)$$

CP-conserving

$$g_{C2HDM}^{hVV} = C\, g_{SM}^{hVV} = (c_b R_{11} + s_b R_{12})\, g_{SM}^{hVV} = \cos(a_2)\cos(b - a_1)\, g_{SM}^{hVV}$$

CP-violating

$$g_{C2HDM}^{hVV} = \cos(a_2)\, g_{2HDM}^{hVV}$$

$$C \equiv c_b R_{11} + s_b R_{12}$$

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

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

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

SM Yukawa Lagrangian

[illegible]

where the gauge eigenstates are

[illegible]

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

[illegible]

which have to be diagonalised.

SM Yukawa Lagrangian

So we define

[illegible]

and the mass matrices are

[illegible]

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

[illegible]

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

2HDM Yukawa Lagrangian

However in 2HDMs

$$\Phi_1 = \begin{pmatrix} \phi_1^+ \\ \frac{v_1 + h_1 + i\eta_1}{\sqrt{2}} \end{pmatrix} \quad \Phi_2 = \begin{pmatrix} \phi_2^+ \\ \frac{v_2 + h_2 + i\eta_2}{\sqrt{2}} \end{pmatrix}$$

$$-\mathcal{L}_Y = \frac{v_1}{\sqrt{2}} \bar{u}_L Y_u^1 u_R + \frac{v_1}{\sqrt{2}} \bar{d}_L Y_d^1 d_R + \frac{v_2}{\sqrt{2}} \bar{u}_L Y_u^2 u_R + \frac{v_2}{\sqrt{2}} \bar{d}_L Y_d^2 d_R$$

$$= \frac{1}{\sqrt{2}} \bar{u}_L (v_1 Y_u^1 + v_2 Y_u^2) u_R + \frac{1}{\sqrt{2}} \bar{d}_L (v_1 Y_d^1 + v_2 Y_d^2) d_R$$

$$= \frac{1}{\sqrt{2}} \bar{u}_L M_u u_R + \frac{1}{\sqrt{2}} \bar{d}_L M_d d_R$$

$$-\mathcal{L}_Y^{h,H} = \frac{h_1}{\sqrt{2}} \bar{u}_L Y_u^1 u_R + \frac{h_1}{\sqrt{2}} \bar{d}_L Y_d^1 d_R + \frac{h_2}{\sqrt{2}} \bar{u}_L Y_u^2 u_R + \frac{h_2}{\sqrt{2}} \bar{d}_L Y_d^2 d_R$$

$$= \frac{h}{\sqrt{2}} \bar{u}_L (\cos\alpha\, Y_u^1 - \sin\alpha\, Y_u^2) u_R + \frac{H}{\sqrt{2}} \bar{d}_L (\sin\alpha\, Y_d^1 + \cos\alpha\, Y_d^2) d_R$$

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

2HDM Yukawa Lagrangian

How can we avoid large tree-level FCNCs?

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

Example: Type III models Cheng, Sher (1987)

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

Example: Aligned models Pich, Tuzon (2009)

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

2HDM Yukawa Lagrangian

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

3.1 Naturally small tree-level FCNCs

Example: BGL Models   Branco, Grimus, Lavoura (2009)

3.2 No tree-level FCNCs

Example: Type I 2HDM Z_2 symmetries   Glashow, Weinberg; Paschos (1977)
Barger, Hewett, Phillips (1990)

[illegible]

[illegible]

[illegible]

Lightest Higgs couplings

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

$$c_2 = \cos(\alpha_2)$$

$$t_\beta = \tan\beta$$

Yukawa couplings

CP-conserving

CP-violating

$$Y_{C2HDM} \equiv c_2 Y_{2HDM} \pm i\gamma_5 s_2 \left\{ \begin{array}{c} t_\beta \\ 1/t_\beta \end{array} \right.$$

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

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

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

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

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

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
- $R_b \equiv \Gamma(Z \to b\bar{b})/\Gamma(Z \to \text{hadrons})$

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

- Precision Electroweak

Theoretical

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

Scan (light scenario)

- Set m_h = 125 GeV.

- Generate random values for potential's parameters such that

$$90\ Gev \leqslant m_{H^\pm}, m_A \leqslant 900\ GeV$$

$$1 \leqslant \tan\beta \leqslant 40$$

$$125\ \text{GeV} = m_h \pounds\, m_H \pounds\, 900\ \text{GeV}$$

$$-\frac{\pi}{2} \leqslant \alpha \leqslant \frac{\pi}{2}$$

$$-(900)^2\ Gev^2 \leqslant m_{12}^2 \leqslant 900^2\ GeV^2$$

- Impose all experimental and theoretical constraints previously described.

- Calculate all branching ratios and production rates at the LHC.

$$\mu_{XX} = \frac{\sigma^{2HDM}(pp \to h) \times BR^{2HDM}(h \to XX)}{\sigma^{SM}(pp \to h) \times BR^{SM}(h \to XX)}$$

- Impose ATLAS and CMS results.

Scan (heavy scenario)

- Set m_H = 125 GeV.

- Generate random values for potential's parameters such that

$$90\ Gev \leqslant m_{H^\pm},\ m_A \leqslant 900\ GeV$$

$$m_h \text{ £ } m_H = 125\ \text{GeV}$$

$$-(900)^2\ Gev^2 \leqslant m_{12}^2 \leqslant 900^2\ GeV^2$$

$$1 \leqslant \tan\beta \leqslant 40$$

$$-\frac{\pi}{2} \leqslant \alpha \leqslant \frac{\pi}{2}$$

- Impose all experimental and theoretical constraints previously described.

- Calculate all branching ratios and production rates at the LHC.

$$\mu_{XX} = \frac{\sigma^{2HDM}(pp \to h) \times BR^{2HDM}(h \to XX)}{\sigma^{SM}(pp \to h) \times BR^{SM}(h \to XX)}$$

- Impose ATLAS and CMS results.

Alignment and wrong-sign Yukawa

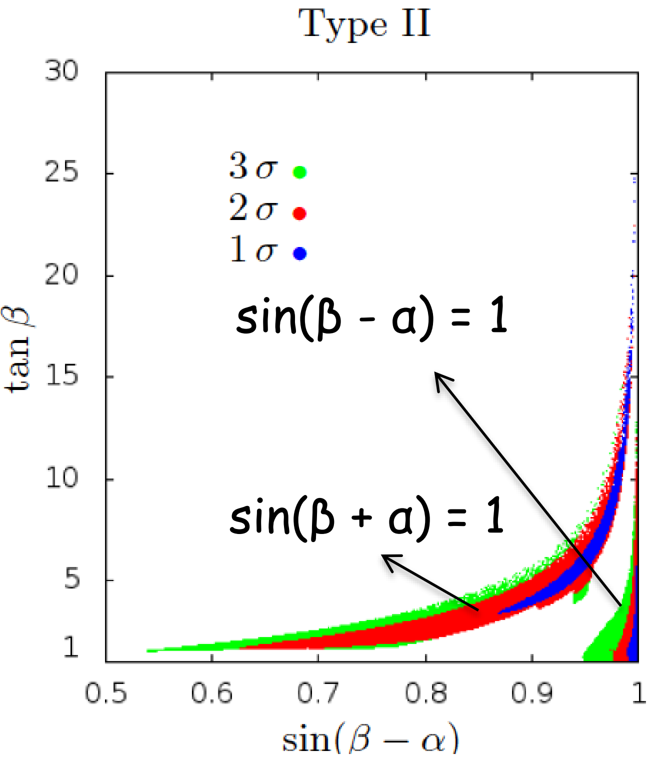
The Alignment (SM-like) limit – all tree-level couplings to fermions and gauge bosons are the SM ones.

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

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).

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

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



Results after run 1 for the CP-conserving case

The SM-like limit (alignment)

$$\sin(b - a) = 1 \quad Þ \quad k_F = 1; \quad k_V = 1$$

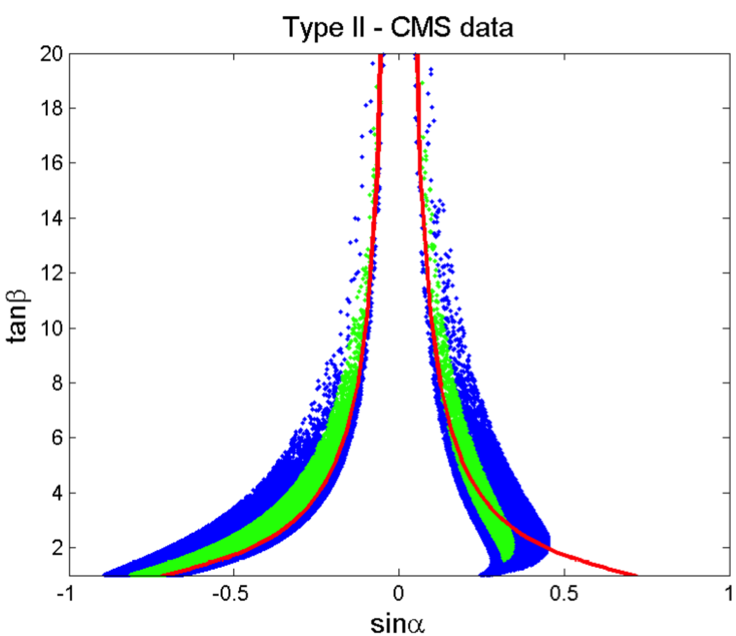
$$k_i = \frac{g_{2HDM}}{g_{SM}}$$

at tree-level

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

Wrong-sign limit

$$k_D k_V < 0 \quad \text{or} \quad k_U k_V < 0$$



OLD PLOT – just to show the behaviour with sinα

Wrong-sign limit (type II and F)

Ginzburg, Krawczyk, Osland 2001

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

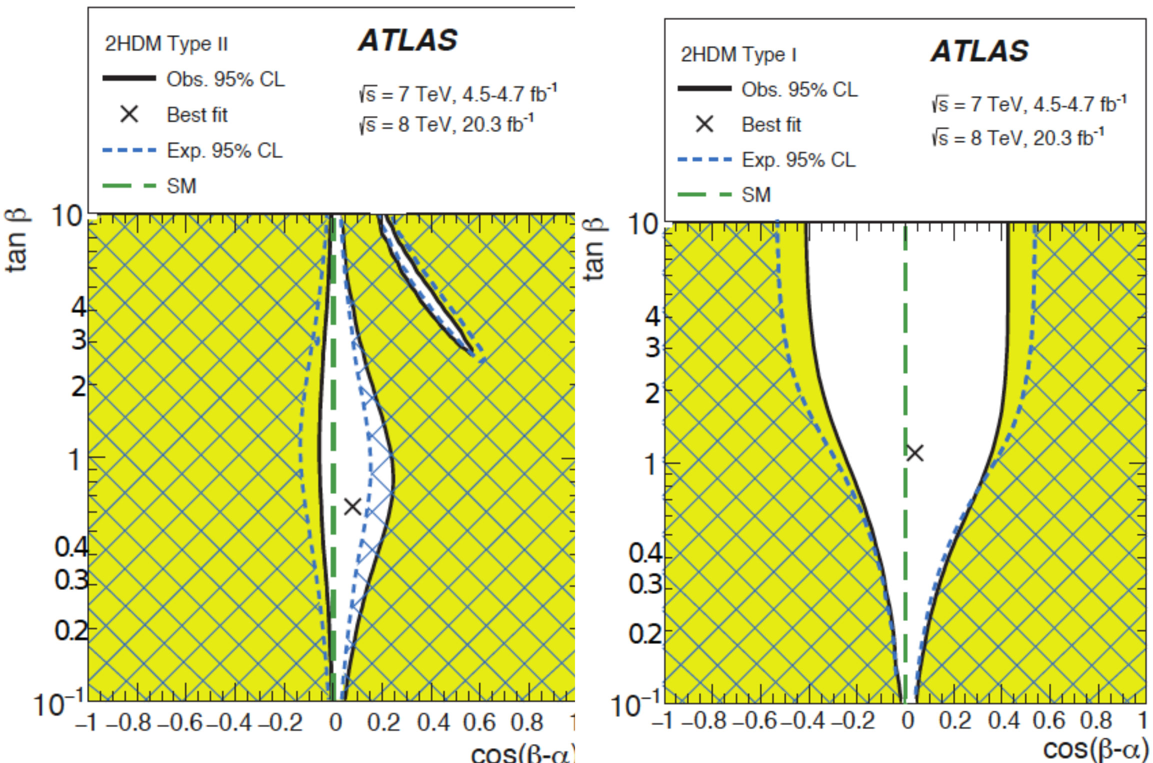
$$\sin(\beta-\alpha)=\frac{\tan^2\beta-1}{\tan^2\beta+1} \Rightarrow \kappa_V \geq 0 \text{ if } \tan\beta \geq 1$$

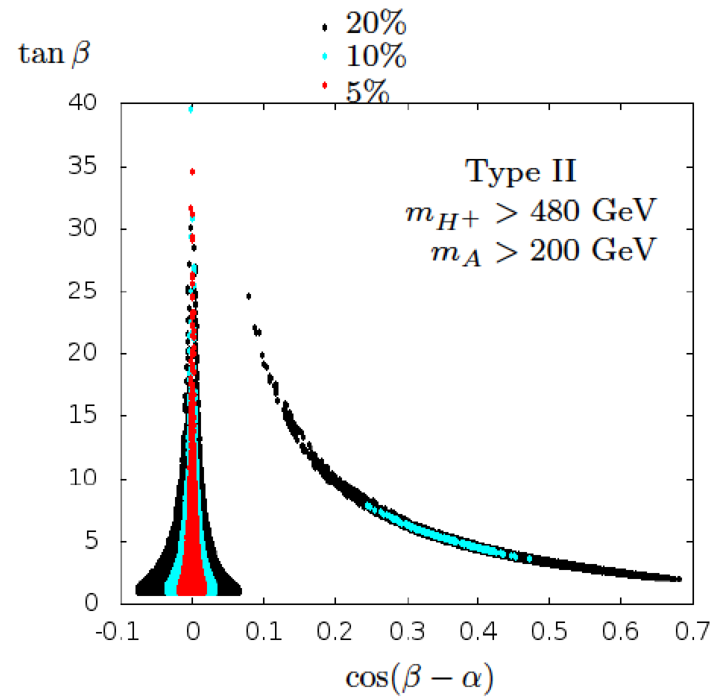
$$\kappa_D\kappa_V<0 \quad \text{or} \quad \kappa_U\kappa_V<0$$

Ferreira, Gunion, Haber, RS (2014).

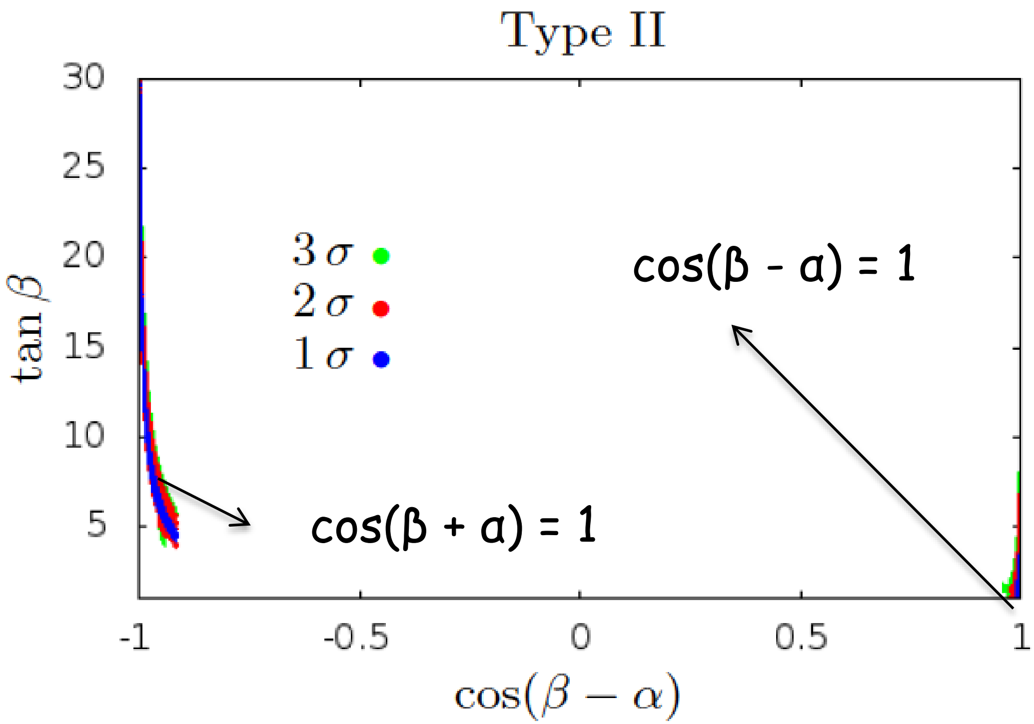
Ferreira, Guedes, Sampaio, RS (2014).

1509.00672





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



The Alignment limit

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

but no decouupling

Wrong-sign limit

$$\kappa_D \kappa_V < 0$$

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

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

Why is it not excluded yet?

SM-like limit

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

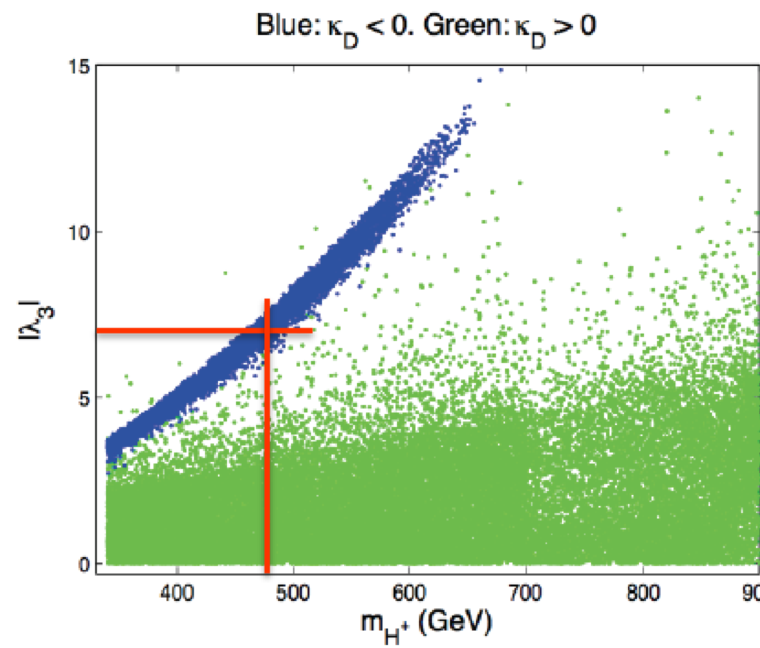
Wrong sign

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

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

Defining

$$k_D = -\frac{\sin a}{\cos b} = -1+\epsilon$$



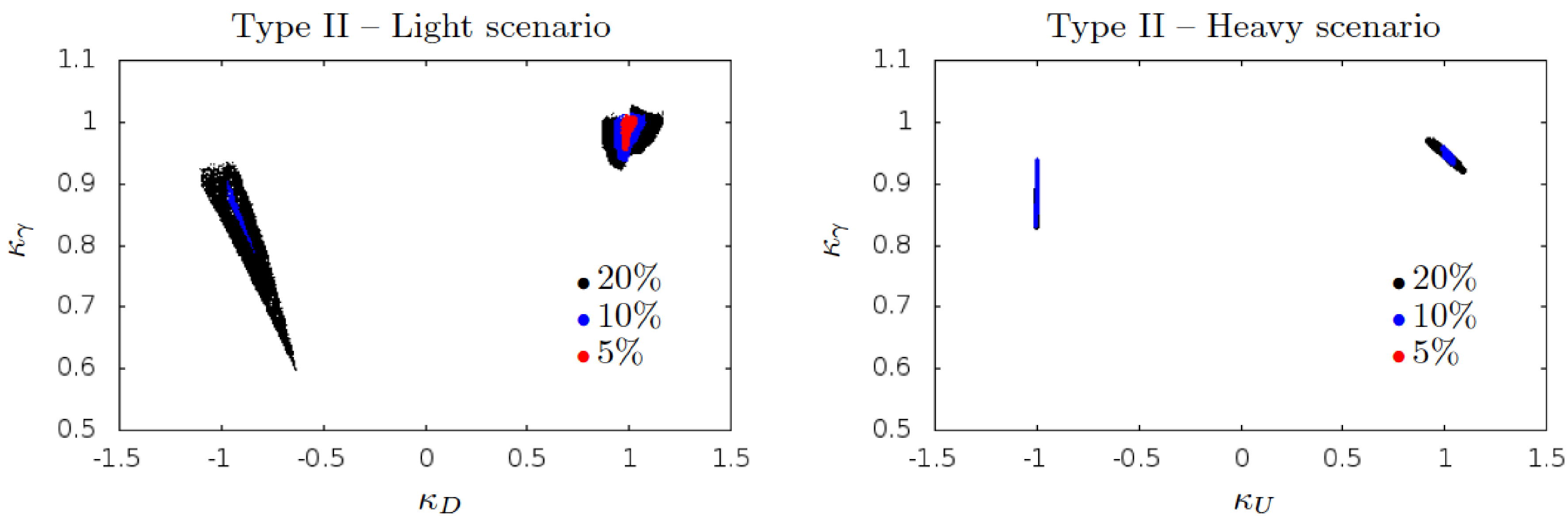
$$\sin(b+a) - \sin(b-a) = \frac{2(1-e)}{1+\tan^2 b} << 1 \qquad (\tan b >> 1)$$

Difference decreases with tan β

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

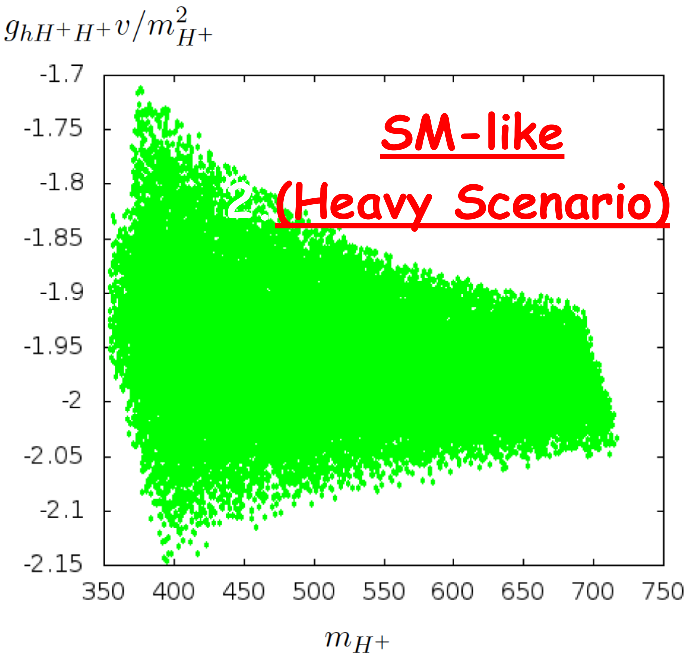
Ferreira, Guedes, Sampaio, RS (2014).

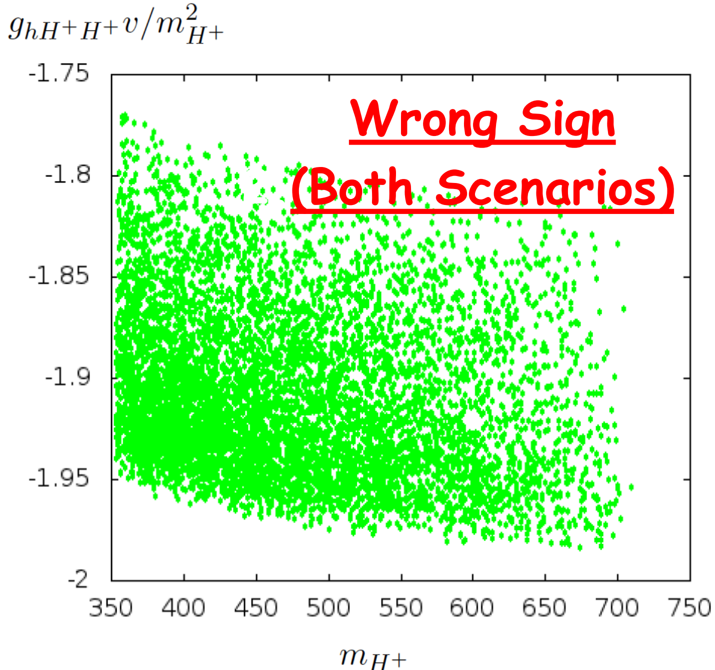
Because $m_h < m_H$ (by construction), if m_H = 125 GeV, m_h is light and there is no decoupling limit.



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.

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

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

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

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

b -> s γ

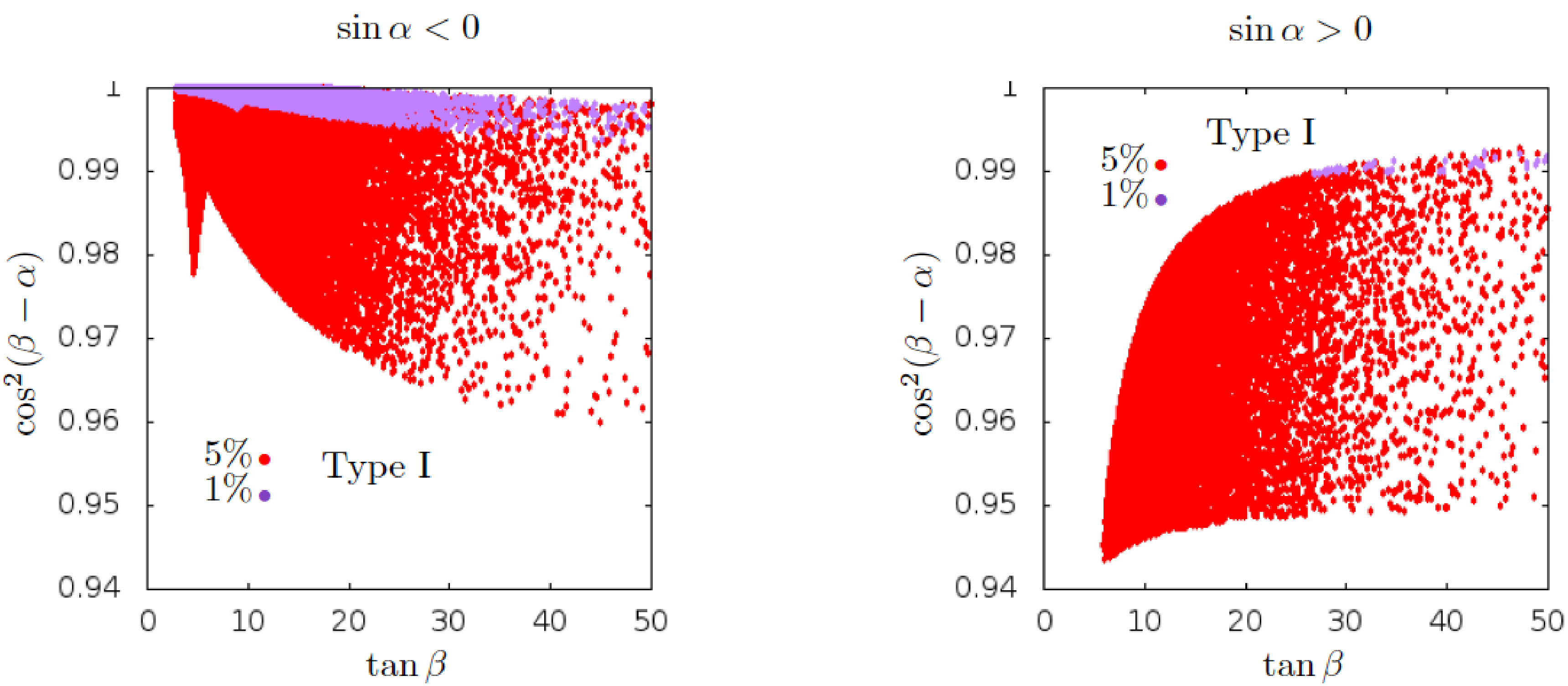
$$m^2_{H^\pm} > 340\ \ \text{GeV}\ (\to 500\ \text{GeV})$$

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).

Heavy scenario for type I



The two scenarios (distinguished by the sign of sin) can be distinguished in all models but sometimes very precise measurements are needed

Status of a CP-violating 2HDM – the C2HDM

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

Scan

• Set m_{h1} = 125 GeV.

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

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

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

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

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

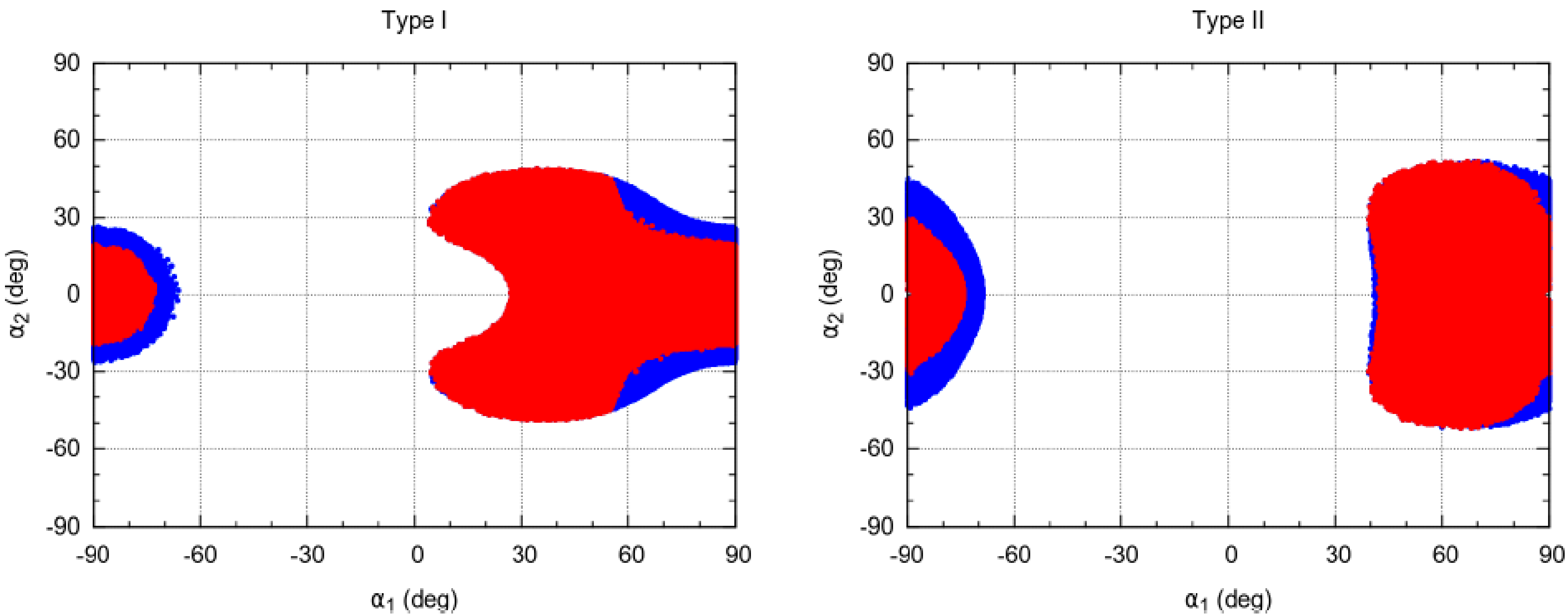
$$100\,\mathrm{GeV} \leq m_{H^\pm} \leq 900\,\mathrm{GeV}$$

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

• Impose pre-LHC experimental constraints,

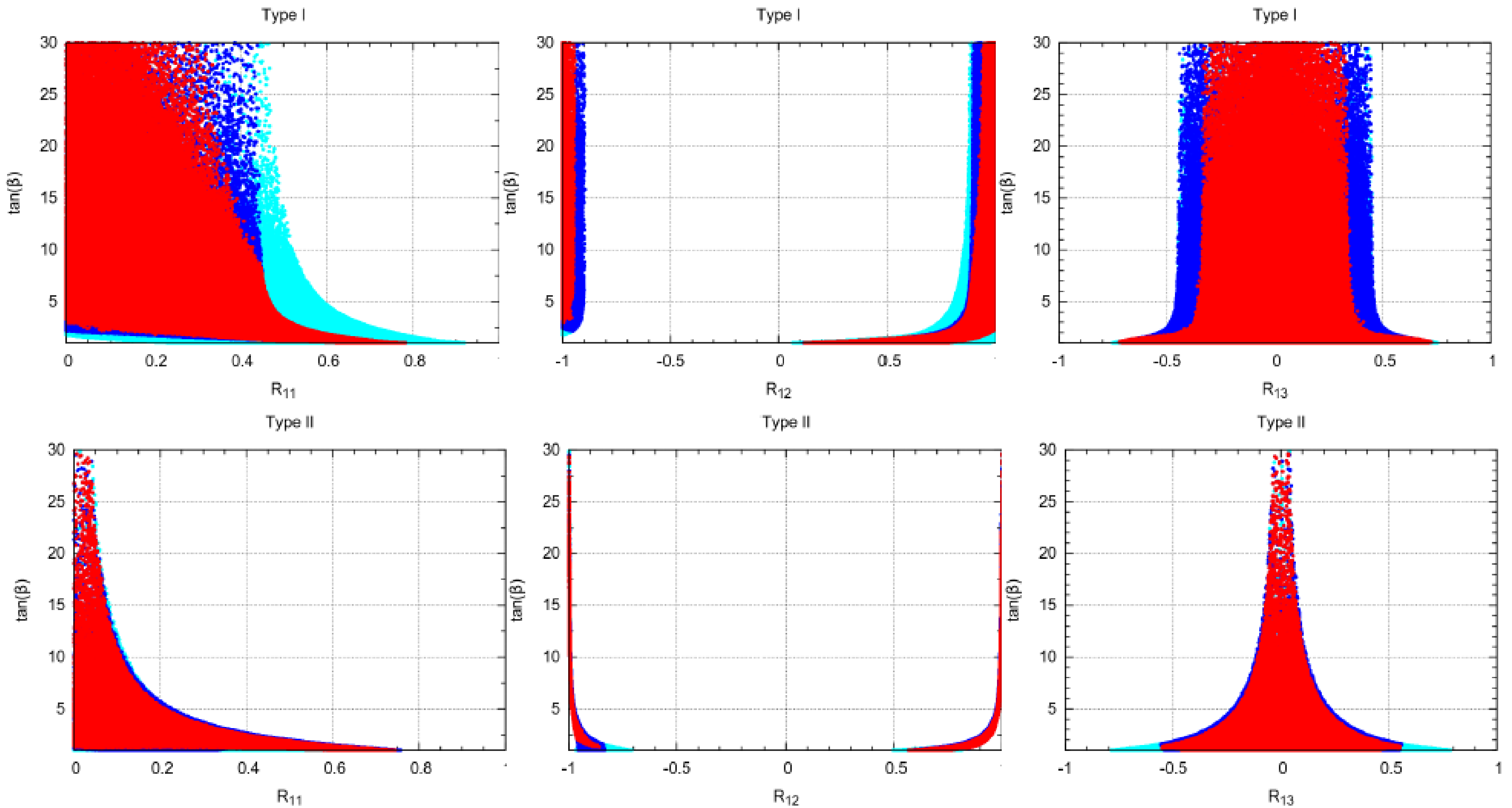
• Impose theoretical constraints: perturbative unitarity, potential bounded from below.

Results after run 1



α_1 vs. α_2
for Type I and Type II. The rates are taken to be within 20% of the SM predictions. The colours are superimposed; cyan for μ_{VV}, blue for $\mu_{\tau\tau}$ and red for $\mu_{\gamma\gamma}$.

Results after run 1



tanβ as a function of R_{11}, R_{12} and R_{13} for Type I and Type II. Same colour code.

	Type I	Type II	Lepton Specific	Flipped
Up	$\frac{R_{12}}{s_\beta} - ic_\beta \frac{R_{13}}{s_\beta}$	$\frac{R_{12}}{s_\beta} - ic_\beta \frac{R_{13}}{s_\beta}$	$\frac{R_{12}}{s_\beta} - ic_\beta \frac{R_{13}}{s_\beta}$	$\frac{R_{12}}{s_\beta} - ic_\beta \frac{R_{13}}{s_\beta}$
Down	$\frac{R_{12}}{s_\beta} + ic_\beta \frac{R_{13}}{s_\beta}$	$\frac{R_{11}}{c_\beta} - is_\beta \frac{R_{13}}{c_\beta}$	$\frac{R_{12}}{s_\beta} + ic_\beta \frac{R_{13}}{s_\beta}$	$\frac{R_{11}}{c_\beta} - is_\beta \frac{R_{13}}{c_\beta}$
Leptons	$\frac{R_{12}}{s_\beta} + ic_\beta \frac{R_{13}}{s_\beta}$	$\frac{R_{11}}{c_\beta} - is_\beta \frac{R_{13}}{c_\beta}$	$\frac{R_{11}}{c_\beta} - is_\beta \frac{R_{13}}{c_\beta}$	$\frac{R_{12}}{s_\beta} + ic_\beta \frac{R_{13}}{s_\beta}$

The zero scalar scenarios

- There is only one way to make the pseudoscalar component to vanish

$$R_{13} = 0 \quad \text{Þ} \quad s_2 = 0$$

and they all vanish (for all types and all fermions).

- There are two ways of making the scalar component to vanish

$$R_{11} = 0 \quad \text{Þ} \quad c_1 c_2 = 0$$

$c_2 = 0$ Þ $g_{h1VV} = 0$ **excluded**

$c_1 = 0$ **allowed**

$$R_{12} = 0 \quad \text{Þ} \quad s_1 c_2 = 0$$

excluded

	Type I	Type II	Lepton Specific	Flipped
Up	$\frac{R_{12}}{s_\beta} - ic_\beta \frac{R_{13}}{s_\beta}$	$\frac{R_{12}}{s_\beta} - ic_\beta \frac{R_{13}}{s_\beta}$	$\frac{R_{12}}{s_\beta} - ic_\beta \frac{R_{13}}{s_\beta}$	$\frac{R_{12}}{s_\beta} - ic_\beta \frac{R_{13}}{s_\beta}$
Down	$\frac{R_{12}}{s_\beta} + ic_\beta \frac{R_{13}}{s_\beta}$	$\frac{R_{11}}{c_\beta} - is_\beta \frac{R_{13}}{c_\beta}$	$\frac{R_{12}}{s_\beta} + ic_\beta \frac{R_{13}}{s_\beta}$	$\frac{R_{11}}{c_\beta} - is_\beta \frac{R_{13}}{c_\beta}$
Leptons	$\frac{R_{12}}{s_\beta} + ic_\beta \frac{R_{13}}{s_\beta}$	$\frac{R_{11}}{c_\beta} - is_\beta \frac{R_{13}}{c_\beta}$	$\frac{R_{11}}{c_\beta} - is_\beta \frac{R_{13}}{c_\beta}$	$\frac{R_{12}}{s_\beta} + ic_\beta \frac{R_{13}}{s_\beta}$

The zero scalar scenarios

- So, taking

$$c_1 = 0 \quad Þ \quad R_{11} = 0$$

and

$$a_U^2 = \frac{c_2^2}{s_b^2}; \quad b_U^2 = \frac{s_2^2}{t_b^2}; \quad C^2 = s_b^2 c_2^2$$

Type I $\quad a_U = a_D = a_L = \frac{c_2}{s_b} \qquad b_U = - b_D = - b_L = - \frac{s_2}{t_b}$

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

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

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

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

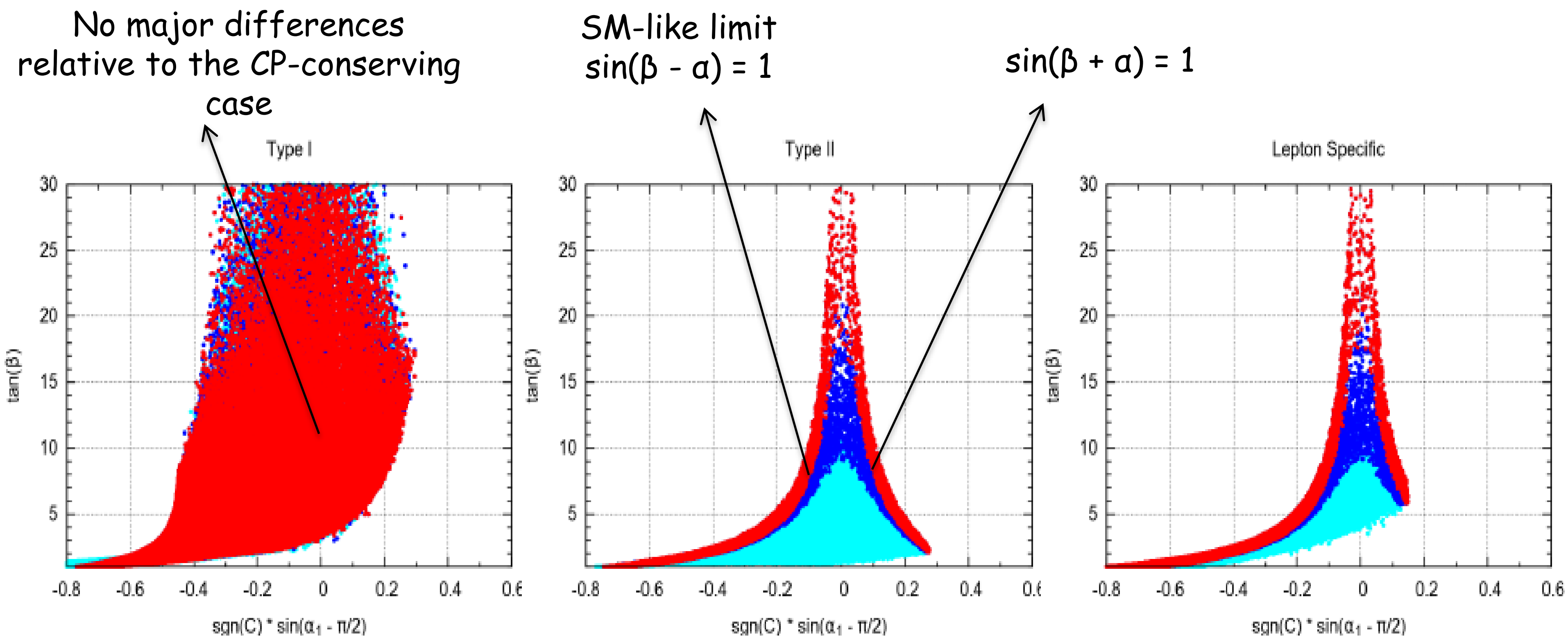
$$a_D = a_L \approx 0 \quad \Rightarrow \quad b_D = b_L \approx 1$$

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

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

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.

Results after run 1



$\tan\beta$ 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).

$$\mu_{VV}^{II} \approx \frac{\cos^2\alpha_2\,\cos^2(\beta-\alpha_1)}{\tan^2\beta}\;\frac{\sin^2\alpha_1\,\cos^2\alpha_2+\sin^2\alpha_2\,\cos^2\beta}{\cos^2\alpha_1\,\cos^2\alpha_2+\sin^2\alpha_2\,\sin^2\beta}$$

Scalar or pseudo-scalar?

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

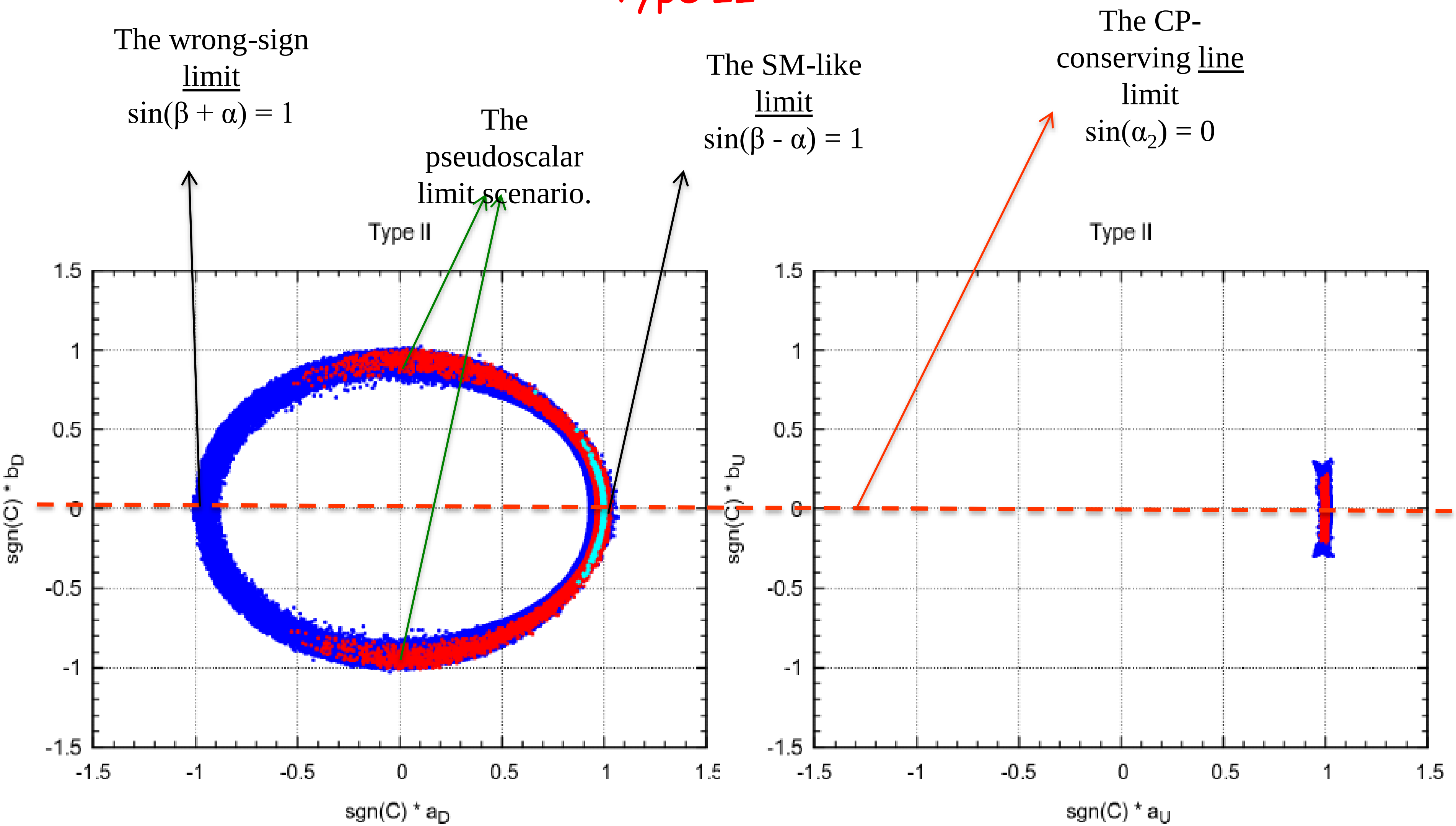
$$b_U = 0 \quad \text{and} \quad a_D = 0?$$

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

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

<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.

So what about EDMs?

Direct probing at the LHC (ττh)

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

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.

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

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

More later!

CP-violation with a combination of three decays

Combinations of three decays

Already observed

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

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

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

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)

$h_2 \to h_3 \;\; h_1 \to h_2$

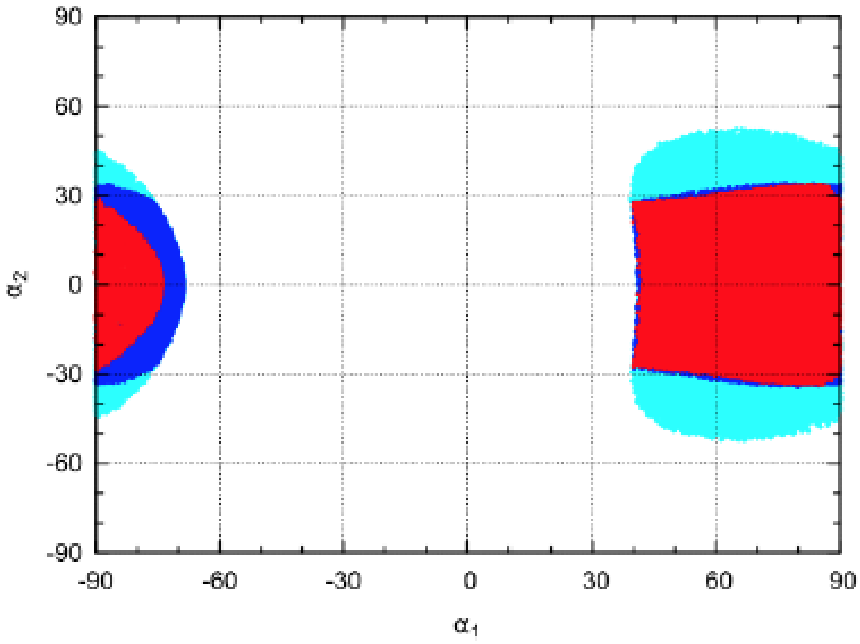
$$h_1 \to ZZ \quad \Leftarrow \quad \mathrm{CP}(h_1) = 1$$

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

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

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

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



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]	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

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

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

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

a special 3HDM

Consider 3HDM with the following potential $V = V_0 + V_1$ (notation: $i \equiv \phi_i$):

$$V_0 = -m_{11}^2(1^\dagger 1) - m_{22}^2(2^\dagger 2 + 3^\dagger 3) + \lambda_1(1^\dagger 1)^2 + \lambda_2\left[(2^\dagger 2)^2 + (3^\dagger 3)^2\right]$$
$$+\lambda_3(1^\dagger 1)(2^\dagger 2 + 3^\dagger 3) + \lambda_3'(2^\dagger 2)(3^\dagger 3) + \lambda_4\left[(1^\dagger 2)(2^\dagger 1) + (1^\dagger 3)(3^\dagger 1)\right] + \lambda_4'(2^\dagger 3)(3^\dagger 2)\,,$$

with all parameters real, and

$$V_1 = \lambda_5(3^\dagger 1)(2^\dagger 1) + \frac{\lambda_6}{2}\left[(2^\dagger 1)^2 - (3^\dagger 1)^2\right] + \lambda_8(2^\dagger 3)^2 + \lambda_9(2^\dagger 3)\left[(2^\dagger 2) - (3^\dagger 3)\right] + h.c.$$

with real $\lambda_{5,6}$ and complex $\lambda_{8,9}$. It is invariant under order-4 gCP:

$$J:\ \phi_i \mapsto X_{ij}\phi_j^*\,, \quad X = \begin{pmatrix} -1 & 0 & 0 \\ 0 & 0 & i \\ 0 & -i & 0 \end{pmatrix}.$$

Its square, $J^2 = \mathrm{diag}(1, -1, -1)$, and $J^4 = \mathbb{I}$.
This model has no other symmetries [Ivanov, Keus, Vdovin, 2012].

The model is similar to the usual Inert Doublet Model (IDM) but with elaborate interaction pattern within the inert sector.

$$V_1 = \underbrace{\lambda_5(3^\dagger 1)(2^\dagger 1) + \frac{\lambda_6}{2}\left[(2^\dagger 1)^2 - (3^\dagger 1)^2\right]}_{\text{similar to } \lambda_5(\phi_2^\dagger \phi_1)^2} + \underbrace{\lambda_8(2^\dagger 3)^2 + \lambda_9(2^\dagger 3)\left[(2^\dagger 2) - (3^\dagger 3)\right]}_{\text{new}} + h.c.$$

- Extending J to the entire lagrangian: $\phi_{2,3}$ decouple from fermions, the J-symmetric minimum is $(v, 0, 0)$, inert scalars protected from decay to SM fields.
- The scalar spectrum is exactly IDM-like: a pair of degenerate $H^\pm$, and two pairs of degenerate neutrals.

Possible to diagonalize the mass matrix staying within complex neutral fields

$$\begin{pmatrix} \Phi \\ \varphi \end{pmatrix} = \begin{pmatrix} c_\gamma & s_\gamma \\ -s_\gamma & c_\gamma \end{pmatrix} \frac{1}{\sqrt{2}} \begin{pmatrix} \phi_2^0 + \phi_3^{0*} \\ \phi_3^0 - \phi_2^{0*} \end{pmatrix} .$$

with $\tan 2\gamma = -\lambda_6/\lambda_5$. Complex fields Φ and φ are eigenstates of mass,

$$M^2,\, m^2 = -m_{22}^2 + \frac{v^2}{2}\left(\lambda_3 + \lambda_4 \pm \sqrt{\lambda_5^2 + \lambda_6^2}\right) ,$$

and are also eigenstates of J with charges $q = +1$:

$$J: \quad \Phi \mapsto i\Phi\,, \quad \varphi \mapsto i\varphi\,.$$

The real complex fields Φ, φ have weird CP-properties:

$$J: \quad \Phi \mapsto i\Phi\,, \quad \varphi \mapsto i\varphi\,.$$

They are neither CP-even nor CP-odd but are half-CP-odd.

NB: J, which was antiunitary in the ϕ_i doublet space, becomes unitary in (Φ, φ)-space!

Conserved quantum number: not $\mathbb{Z}_2$-parity but the charge q defined modulo 4.

The map from (ϕ_2^0, ϕ_3^0) to (Φ, φ) conserves the norm implying

$$|\partial_\mu \phi_2^0|^2 + |\partial_\mu \phi_3^0|^2 = |\partial_\mu \Phi|^2 + |\partial_\mu \varphi|^2\,,$$

while the interaction potential contains only combinations

$$\varphi^*\varphi\,, \quad \varphi^4\,, \quad (\varphi^*)^4\,, \quad \varphi^2(\varphi^*)^2\,, \quad \text{where } \varphi \text{ stands for } \Phi \text{ or } \varphi,$$

all of which conserve q. Transitions $\varphi^* \to \varphi\varphi\varphi$, $\varphi\varphi \to \varphi^*\varphi^*$, or loop-induced $\varphi \leftrightarrow \Phi$ as possible, while $\varphi \to \varphi^*$ are forbidden by q conservation.

Instead of ZHA vertex in CP-conserving 2HDM, with H and A of opposite CP-parities, we have $Z\Phi\varphi$ vertex, with two scalars of the same CP-properties:

$$\text{instead of} \quad (+1)\cdot(-1) = -1 \quad \text{we have} \quad i \cdot i = -1\,.$$

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END of Part I