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

ATLAS Preliminary  $m_H = 125.09$ GeV  
$\sqrt{s} = 13$ TeV, 13.3 fb$^{-1}$ ($\gamma\gamma$), 14.8 fb$^{-1}$ (ZZ)

- 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 resonances.blogspot.pt

h-index results from resonances.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

\[
\sigma(pp\rightarrow H+X) [pb] \\
\sqrt{s} = 14 \text{ TeV} \\
M_t = 175 \text{ GeV} \\
\text{CTEQ6M}
\]
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)

\[ pp \rightarrow \bar{t}t \rightarrow bbW^+H^- \]

**ATLAS-CONF-2013-090**

\[ \int L dt = 19.5 \text{ fb}^{-1} \]

**ATLAS Preliminary**

\[ m^\text{max}_h \sqrt{s} = 8 \text{ TeV} \]

**Corrected for**

\[ BR(H^- \rightarrow \tau \bar{\nu}) \]

\[ m_{H^+} = 90 \text{ GeV} \]

<table>
<thead>
<tr>
<th></th>
<th>I</th>
<th>II</th>
<th>F</th>
<th>LS</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\tan)</td>
<td>4.3</td>
<td>6.4</td>
<td>3.2</td>
<td>5.2</td>
</tr>
</tbody>
</table>

G. Aad *et al.* [ATLAS Collaboration], JHEP **1206** (2012) 039
S. Chatrchyan *et al.* [CMS Collaboration], JHEP **1207** (2012) 143

Lauri Wendland talk
AT Charged2014

\[ m_{H^+} = 90 \text{ GeV} \]

**ATLAS**

**Data 2012**

\[ \tau + \text{jets} \]

**Observed**

- Observed exclusion 95% CL
- Observed -1σ theory
- Expected exclusion 2011

**MSSM**

-\(--\)
- Expected median ± 1σ
- Expected median ± 2σ

**AT Charged2014**

\[ m_{H^+} = 90 \text{ GeV} \]

**Corrected for**

\[ BR(H^- \rightarrow \tau \bar{\nu}) \]

<table>
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**CMS**

**Preliminary**

- Observed ±1σ (th.)
- Excluded
How the ATLAS exclusion plot would look like in types I and LS (X)

4.3

small $\tan \beta$ 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\(^1\)

\[
\begin{align*}
\text{Any } & \quad BR(H^+ \rightarrow \tau^+ \nu) \cdot m_{H^\pm} \gtrsim 80 \text{ GeV} \\
BR(H^+ \rightarrow \tau^+ \nu) & \approx 1 \quad m_{H^\pm} \gtrsim 94 \text{ GeV}
\end{align*}
\]

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

Aoki, Guedes, Kanemura, Moretti, RS, Yagyu (2011)
Dark scalars production mechanisms

Inert

$pp \rightarrow AH \rightarrow ZHH \rightarrow Z + \text{MET}$

$pp \rightarrow H^\pm H^\mp \rightarrow W^\pm W^\mp HH \rightarrow W^\pm W^\mp \text{MET}$

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

Fermiophobic

$pp \rightarrow AH \rightarrow AVV$  

most promising but still with very small cross section (< 2fb)
Searches involving neutral scalars

\[ S_i \rightarrow VV \quad H_i \rightarrow VV \quad h_i \rightarrow VV \]

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

\[ h_i \text{ (no definite } CP) \]

\[ CP(H_i) = 1; \quad CP(A_i) = 1 \]

Analysis are assumed to be independent of particles CP.
Searches involving neutral scalars

\[ S_i \rightarrow S_j V \]

**CPC**

\[ H_i \rightarrow A_i V \ (A_i \rightarrow H_i V) \]

2HDM, …

\[ h_1 \rightarrow h_2 V \]

C2HDM, …

\[ A \rightarrow Zh_{125} \] was done in run 1.
\[ A \rightarrow ZH \] is done for CMS and is being started in ATLAS.

\[ h_i \text{ (no definite } CP) \]

\[ CP(H_i) = 1; \ CP(A_i) = 1 \]

Analysis are assumed to be independent of particles CP.
 Searches involving charged scalars

\[ H^\pm \rightarrow W^\pm V \]

\[ H^\pm \rightarrow W^\pm S \]

\[ H^\pm \rightarrow W^\pm Z \]

Done by ATLAS

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.

Doubly charged Higgs have been searched for in leptons and WW.
Searches involving neutral scalars

\[ H_i \rightarrow H_j H_j \ (A_i A_j) \]

\[ h_i \rightarrow h_j h_j \]

\[ h_i \rightarrow h_j h_k \]

\[ H_i \rightarrow H_j H_k \] \( \text{C}x\text{SM, NMSSM} \)

\[ A_i \rightarrow A_j H_k \] \( \text{NMSSM} \)

\( h_i \) (no definite CP)

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

So far only \( H \rightarrow hh \).

However it covers all cases except final states with different masses - more later.
Searches involving neutral scalars

\[
\begin{align*}
S_i & \rightarrow S_j S_j \rightarrow b\bar{b}b\bar{b} \\
S_i & \rightarrow S_j S_j \rightarrow b\bar{b} \gamma\gamma
\end{align*}
\]

Resonant $S_i$


The ATLAS collaboration. A search for resonant Higgs-pair production in the $b\bar{b}b\bar{b}b\bar{b}$ final state in pp collisions at $\sqrt{s} = 8$ TeV. 2014.

G. Aad et al. Search For Higgs Boson Pair Production in the $\gamma\gamma b\bar{b}b\bar{b}$ Final State using pp Collision Data at $\sqrt{s} = 8$ 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.
No charged scalars considered

SI \quad (\text{any scalar})

FC

\begin{align*}
S_i & \rightarrow f_j \bar{f}_j \\
S_i & \rightarrow f_j \bar{f}_k
\end{align*}

FCNC

$S_i \rightarrow c h_{125}$

Searches involving scalars

\begin{align*}
H/A & \rightarrow \tau^+\tau^- \\
H/A & \rightarrow \mu^+\mu^- \\
H/A & \rightarrow t\bar{t} \\
H/A & \rightarrow b\bar{b}
\end{align*}

Done

Done and new analysis being prepared

Done for 8 TeV. Being done for run 2.

Being done

There are also $ttH$ and $bbH$ production with $H \rightarrow tt\bar{t}$ planned as well.

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

\[ H^\pm \rightarrow \tau \nu \] Done in \( tt \) production (mass below the \( tb \) threshold)

\[ H^\pm \rightarrow tb \] Done (above the \( tb \) threshold)

\[ H^\pm \rightarrow cb \] Done in \( tt \) production a long time ago - no updates.

\[ H^\pm \rightarrow cs \] (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 $V_{\text{scalar}}$.
- **Generic** routines, **flexible** user analysis & **interfaces**.

[Scanners-hepforge.org](http://Scanners-hepforge.org)
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.


Overview of the tool

Doublets, complex, reals, etc ... → Decompose $n$ reals

\[ V(H, S, \phi, \chi, \ldots) \rightarrow \begin{align*}
H, H^\dagger \\
S, S^* \\
\phi, \chi \\
\ldots
\end{align*} \rightarrow \begin{pmatrix}
\phi_0 \\
\phi_1 \\
\ldots \\
\phi_n
\end{pmatrix} \rightarrow V = V_a(\phi_i)\lambda_a \]

### Quadratic Min. Cond.

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

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

\[ \lambda_{a_3}, m_k^2 \]

\[ \lambda_{a_2}, m_i^2 \]

### Block Detection

\[ M.M^T = 1 \]

### Numeric VEV

\[ \phi_i = V_i + \delta \phi_i \]

Min. Conditions

\[ \Rightarrow \left\langle \partial_i V \right\rangle_{a\lambda} = 0 \]

\[ \lambda_a \]

\[ \lambda_{a_2} \]

### Local Minimum Generated!

→ Check Tree level Unitarity
→ Check Global Stability
→ Boundedness from below

### User Analysis

→ Interfaces: Superiso, SuShi, MicrOmegas, HBounds/Signals.
→ Tables & User def. analysis.
The singlet

a) Provide dark matter candidates

Silveira, Zee (1985)

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

25
**CxSM: Phase classification for three possible models**

\[ SM \text{ plus } S = \frac{(S + iA)}{\sqrt{2}}, \]

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

- **U(1)**
  - **Phase**: Higgs + 2 degenerate dark
  - **VEVs at global minimum**: \( \langle S \rangle = 0 \), \( \langle A \rangle = 0 \) \((U(1) \rightarrow \mathbb{Z}_2')\)

- **\(\mathbb{Z}_2 \times \mathbb{Z}_2'\)**
  - **Phase**: Higgs + 2 dark
  - **VEVs at global minimum**: \( \langle S \rangle = 0 \), \( \langle A \rangle = 0 \) \((\mathbb{Z}_2 \times \mathbb{Z}_2' \rightarrow \mathbb{Z}_2')\)

- **\(\mathbb{Z}_2'\)**
  - **Phase**: 2 mixed + 1 dark
  - **3 mixed**
  - **VEVs at global minimum**: \( \langle A \rangle = 0 \), \( \langle S \rangle \neq 0 \) \((\mathbb{Z}_2')\)

**Soft breaking terms**
CxSM: Minimal model with dark mater + 1/2 new Higgs

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

- $\mathbb{Z}_2$ phase ($v_S \neq 0, v_A = 0$): 2 Higgs mix + 1 dark

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

- $\mathbb{Z}_2$ 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 \( S \rightarrow -S \)**

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

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

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

- **\( \mathbb{Z}_2 \) 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 $\kappa_i^2$:

- **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:**
  \[ \Gamma_i^{total} = \kappa_i^2 \Gamma_{SM}^{total} + \sum_{jk} \Gamma_{i \rightarrow jk} \]
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:**

\[ |\Phi_i\rangle \times |\Phi_j\rangle, \Re \{ a_{ij}^{(0)} \} < \frac{1}{2}, \quad a_{ij}^{(0)} = \frac{\langle \Phi_i |iT^{(0)}|\Phi_j \rangle}{16\pi} \sim \sum a_4 \ldots \lambda a_4 \]

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

- **In SM**, the 2-particle states are \( w^+ w^-, hh, zz, hz \)
  \( \Rightarrow \) constrains quartic coupling \( \lambda \), \( \Rightarrow m_h^2 < 700 \text{ GeV} \)

- **In BSM** \( \Rightarrow \) bounds on combinations of quartic \( \lambda a_4 \)
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
  \[ \rightarrow 2b \]
  \[ A^2 = \frac{b_1^2(\lambda(b_1 - b_2) + m^2 \delta_2) - d_2 a_1^2 \lambda + \delta_2^2 a_1^2}{d_2 b_1^2 \lambda - \delta_2^2 b_1^2} \]

- $\lambda > 0 \land d_2 > 0 \land (\delta_2^2 < \lambda d_2$ 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 $\sigma_{Sl}$ (micrOMEGAs)

$\Rightarrow$ **Decay widths – adaptation of HDECAy → sHDECAy.**
www.itp.kit.edu/~maggie/sHDECAY/

- EW corrections consistently off
- CxSM and also RxSM

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

We define global signal rate for direct channels

$$\mu_i = R_{ih}^2 \sum_{X_{SM}} BR(h_i \to X_{SM})$$
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 Mühleitner, 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. Mühleitner, M. Sampaio, R. Santos, arXiv 1512.05335

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 margeart.e.muehleitner@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, hsga.f, hgg.f, hsqsf.f, susylha.f.
- makefile for the compilation.

Example for an output file:

The input file shdecay.in provides the output files brz11, brz12, brz13, brz21, brz22, brz23, brz31, brz32, brz33, brz34, brz41, brz42, brz43, brz44, brz51, brz52, brz53, brz54, and brz55.

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

Last modified: Wed Dec 16 09:45:24 CET 2015
CP and the CxSM

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

This is a CP-transformation

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

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

\[
H \rightarrow H^*; \quad S \rightarrow S^* \quad (1) \\
H \rightarrow H^*; \quad S \rightarrow S \quad (2)
\]

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.

<table>
<thead>
<tr>
<th>$Z'_2$</th>
<th>2 mixed Higgs + 1 DM</th>
<th>$\langle A = 0 \rangle$</th>
<th>$\langle S \neq 0 \rangle$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$a_1 \in \mathbb{R}$</td>
<td>3 mixed</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
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

<table>
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<tr>
<th>Input parameter</th>
<th>Broken phase Min</th>
<th>Max</th>
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<tr>
<td>( m_{h_{125}} ) (GeV)</td>
<td>125.1</td>
<td>125.1</td>
</tr>
<tr>
<td>( m_{h_{\text{other}}} ) (GeV)</td>
<td>30</td>
<td>1000</td>
</tr>
<tr>
<td>( \nu ) (GeV)</td>
<td>246.22</td>
<td>246.22</td>
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<tr>
<td>( \nu_S ) (GeV)</td>
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<td>1000</td>
</tr>
<tr>
<td>( \alpha_1 )</td>
<td>(-\pi/2)</td>
<td>(\pi/2)</td>
</tr>
<tr>
<td>( \alpha_2 )</td>
<td>(-\pi/2)</td>
<td>(\pi/2)</td>
</tr>
<tr>
<td>( \alpha_3 )</td>
<td>(-\pi/2)</td>
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<table>
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<th>Max</th>
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</tr>
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<td>30</td>
<td>1000</td>
</tr>
<tr>
<td>( m_A ) (GeV)</td>
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<td>1000</td>
</tr>
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<td>( \nu ) (GeV)</td>
<td>246.22</td>
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<td>1000</td>
</tr>
<tr>
<td>( \alpha_1 )</td>
<td>(-\pi/2)</td>
<td>(\pi/2)</td>
</tr>
<tr>
<td>( a_1 ) (GeV^3)</td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>Scan parameter</th>
<th>Broken phase Min</th>
<th>Max</th>
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</tr>
<tr>
<td>( \nu_S ) (GeV)</td>
<td>1</td>
<td>1000</td>
</tr>
<tr>
<td>( \alpha )</td>
<td>(-\pi/2)</td>
<td>(\pi/2)</td>
</tr>
</tbody>
</table>
Stability conditions under RGE evolution:

**Stability conditions** (imposed also in evolution):

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

- **Perturbative unitarity:**

$$\left\{ \left| \lambda \right|, |d_2|, |\delta_2|, \left| \frac{3}{2} \lambda + d_2 \pm \sqrt{\left( \frac{3}{2} \lambda + d_2 \right)^2 + d_2^2} \right| \right\} \leq 16\pi$$
RGE stability bands - no Phenomenology

Vacuum stability consequences

If new Higgs found lighter than \( \sim 140 \ \text{GeV} \) dark matter phase disfavoured.

Lower bound on new visible scalar mass

Lower bound for heaviest new visible scalar
Lower bound $m_{H_{\text{new}}} = 170$ GeV from the combination of all imposed constraints. Lower bound on the dark matter particle mass just below $m_{\text{DM}} = \frac{1}{2} m_{125}$ and an excluded wedge around $m_{\text{DM}} = \frac{1}{2} m_{H_{\text{new}}}$.

These correspond to regions where the annihilation channels $AA \rightarrow H_{i}$ (to visible Higgses) are very efficient in reducing the relic density so it becomes difficult to saturate the measured $\Omega c$. 

RGE stability + Phenomenology
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 $\rightarrow$ 4 degrees of freedom $\rightarrow$ 2HDM $\rightarrow$ 8 degrees of freedom

- All symmetries broken $\rightarrow$ 4 GB + 4 scalar bosons ($\rightarrow$ CB)

- $U(1)_{em}$ unbroken but not CP $\rightarrow$ 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 $\rightarrow$ 3 GB + 5 scalar bosons (2 charged, $H^\pm$, and 3 neutral, $h$, $H$ and $A$)

- All symmetries unbroken $\rightarrow$ 8 scalar bosons
The softly broken $Z_2$ ($U(1)$) symmetric 2HDM potential

$$V(\Phi_1, \Phi_2) = m_{12}^2 \Phi_1^\dagger \Phi_1 + m_2^2 \Phi_2^\dagger \Phi_2 - (m_{12}^2 \Phi_1^\dagger \Phi_2 + \text{h.c.}) + \frac{1}{2} \lambda_1 (\Phi_1^\dagger \Phi_1)^2 + \frac{1}{2} \lambda_2 (\Phi_2^\dagger \Phi_2)^2$$

$$+ \lambda_3 (\Phi_1^\dagger \Phi_1)(\Phi_2^\dagger \Phi_2) + \lambda_4 (\Phi_1^\dagger \Phi_2)(\Phi_2^\dagger \Phi_1) + \frac{1}{2} \lambda_5 [(\Phi_1^\dagger \Phi_2)^2 + \text{h.c.}]$$

$$\phi_1 \rightarrow \phi_1, \quad \phi_2 \rightarrow -\phi_2$$

Different models are obtained by tuning $m_{12}^2$ and $\lambda_5$ together with the possible vacuum configurations (all other parameters real - hermiticity)

- NORMAL (N)
- CHARGE BREAKING (CB)
- CP BREAKING (CP)
Can one potential have a Normal and a CB minimum simultaneously?

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

\[ m_\gamma \neq 0 \]
Oh No! Not Charge Breaking!
For a safer 2HDM

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

\[ \frac{M_{H^\pm}^2}{2v^2} \quad \text{Calculated at the Normal stationary point.} \]

\[ V_N \text{ is a MINIMUM} \quad \frac{M_{H^\pm}^2}{2v^2} > 0 \quad \rightarrow \quad V_N < V_C \]

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

\[
\begin{align*}
V_{CB} & \quad V_N = \frac{M_{H^\pm}^2}{2v^2} \left[ \left( v'_1 v_2 \quad v'_2 v_1 \right)^2 + \frac{2v_1^2}{2} \right] \\
V_{CP} & \quad V_N = \frac{M_A^2}{2v^2} \left[ \left( v''_1 v_2 \quad v''_2 v_1 \right)^2 + \frac{2v_1^2}{2} \right]
\end{align*}
\]

For charge breaking

For CP breaking

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
M. Maniatis, A. von Manteuffel, O. Nachtman and F. Nagel
EPJC48(2006)805
I. Ivanov
PRD75(2007)035001,
PRD77(2008)15017,
PRE79(2008)021116
Two normal minima - potential with the soft breaking term

Global minimum (N) - 
\[ v = 329 \text{ GeV} \]
\[ m_W = 107.5 \text{ GeV} \]

Local minimum (N) - 
\[ v = 246 \text{ GeV} \]
\[ m_W = 80.4 \text{ GeV} \]

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

THE PANIC VACUUM!
and this is one that can actually occur...

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.

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

\[ D = m_{12}^2 \left( m_{11}^2 - k^2 m_{22}^2 \right) (\tan k) \]

\[ k = \frac{1}{2} \tan^{-1} \left( \frac{1}{2} \right) \]

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

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

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

\[ a_1 = s_\beta^2 \left[ m_1^2 s_3^2 + (m_2^2 s_3^2 + m_3^2 c_3^2) c_3^2 \right] \]
\[ b_1 = c_3^2 \left[ c_2 c_1 s_2 \left( -m_1^2 + m_2^2 s_3^2 + m_3^2 c_3^2 \right) + s_1 s_3 c_3 \left( m_2^2 - m_3^2 \right) \right]^2 \]
\[ a_2 = 2m_3^2 c_2 c_{\alpha_1+\beta} + (m_2^2 + m_3^2) (1 - c_2^2 c_{\alpha_1+\beta}) \]
\[ + \left( m_2^2 - m_3^2 \right) \left[ \cos (2\alpha_3) (s_{\alpha_1+\beta} + c_{\alpha_1+\beta} s_2^2) + \sin (2\alpha_3) s_2 \sin (2\alpha_1 + 2\beta) \right] \]
\[ b_3 = (m_2^2 c_3^2 + m_3^2 s_3^2) \left( m_1^2 c_2^2 + m_2^2 m_3^2 s_3^2 \right) \]
Softly broken $Z_2$ symmetric Higgs potential

$$V(F_1, F_2) = m_1^2 F_1^2 + m_2^2 F_2^2 + (m_{12}^2 F_1 F_2 + \text{h.c.}) + \frac{1}{2} (F_1^2 + F_2^2) + \frac{2}{2} (F_1 F_2)^2 + \text{h.c.}$$

we choose a vacuum configuration

$$\langle 1 \rangle = \frac{1}{\sqrt{2}} \begin{array}{c} 0 \\ \nu_1 \end{array}, \quad \langle 2 \rangle = \frac{1}{\sqrt{2}} \begin{array}{c} 0 \\ \nu_2 \end{array}$$

- $m_{12}^2$ and $\lambda_5$ real potential is CP-conserving (2HDM)
- $m_{12}^2$ and $\lambda_5$ complex potential is explicitly CP-violating (C2HDM)

Ginzburg, Krawczyk, Osland (2002).
Parameters

- $\tan \theta = \frac{v_2}{v_1}$ 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** - $\alpha$
  - **CP-violating** - $\alpha_1$, $\alpha_2$ and $\alpha_3$

- soft breaking parameter
  - **CP-conserving** - $m_{12}^2$
  - **CP-violating** - $\text{Re}(m_{12}^2)$
Lightest Higgs couplings to gauge bosons

\[ g_{2_{HDM}}^{hVV} = \sin(b - a) \frac{g_{SM}^{hVV}}{g_{SM}^{hVV}} \quad V = W, Z \]

\[ h_{V}^{h} = \sin(\quad) \]

\[ h_{V}^{H} = \cos(\quad) \]

\[ g_{C2_{HDM}}^{hVV} = C \frac{g_{SM}^{hVV}}{g_{SM}^{hVV}} = (c_{1} R_{11} + s_{1} R_{12}) \frac{g_{SM}^{hVV}}{g_{SM}^{hVV}} = \cos(2) \cos(1) g_{SM}^{hVV} \]

\[ C \quad c_{1} R_{11} + s_{1} R_{12} \]

\[ |s_{2}| = 0 \Rightarrow h_{1} \text{ is a pure scalar,} \]

\[ |s_{2}| = 1 \Rightarrow h_{1} \text{ is a pure pseudoscalar} \]

\[ R = \begin{pmatrix} c_{1}c_{2} & s_{1}c_{2} & s_{2}c_{3} \\ c_{1}s_{2}s_{3} + s_{1}c_{3} & c_{1}c_{3} & s_{1}s_{2}s_{3} \\ c_{1}s_{2}c_{3} + s_{1}s_{3} & (c_{1}s_{3} + s_{1}s_{2}c_{3}) & 55c_{2}s_{3} \end{pmatrix} \]
where the gauge eigenstates are

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

which have to be diagonalised.
SM Yukawa Lagrangian

So we define

and the mass matrices are

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

No scalar induced tree-level FCNCs
However in 2HDMs

$h, H$ are the mass eigenstates ($\alpha$ 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


\[ Y_d^2 \mu Y_d^1 \] (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)
Yukawa couplings

\[ Y_{C2HDM} \quad c_2 Y_{2HDM} \pm i \sin 5s_2 \]

Lightest Higgs couplings

\[ a_F + i \sin 5b_F \]

**Yukawa couplings**

- Type I: \[ I_U = I_D = I_L = \frac{\cos}{\sin} \]
- Type II: \[ II_U = \frac{\cos}{\sin} \quad II_D = II_L = \frac{\sin}{\cos} \]
- Type F/Y: \[ F_U = F_L = \frac{\cos}{\sin} \quad F_D = \frac{\sin}{\cos} \]
- Type LS/X: \[ LS_U = LS_D = \frac{\cos}{\sin} \quad LS_L = \frac{\sin}{\cos} \]

- \( c_2 = \cos(\angle) \)
- \( t = \tan \)

\( 1 = + \quad \frac{1}{2} \)
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
- $R_b \equiv \Gamma(Z \to b\bar{b})/\Gamma(Z \to \text{hadrons})$

\[ \tan \beta \gtrsim 1 \]

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

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

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

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

$$1 \leq \tan \beta \leq 40$$

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

- Impose all experimental and theoretical constraints previously described.

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

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

- Impose ATLAS and CMS results.
• Set $m_H = 125$ GeV.

• Generate random values for potential’s parameters such that

\[
90 \text{ Gev} \leq m_{H^\pm}, m_A \leq 900 \text{ GeV}
\]

\[
m_h, m_H = 125 \text{ GeV}
\]

\[-(900)^2 \text{ Gev}^2 \leq m_{12}^2 \leq 900^2 \text{ GeV}^2
\]

\[1 \leq \tan \beta \leq 40
\]

\[\frac{-\pi}{2} \leq \alpha \leq \frac{\pi}{2}
\]

• Impose all experimental and theoretical constraints previously described.

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

\[
\mu_{XX} = \frac{\sigma^{2HDM} (pp \rightarrow h) \times BR^{2HDM} (h \rightarrow XX)}{\sigma^{SM} (pp \rightarrow h) \times BR^{SM} (h \rightarrow XX)}
\]

• 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.

\[
\sin(b - a) = 1 \quad D = 1; \quad U = 1; \quad W = 1
\]

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).

\[
D \ W < 0 \quad \text{or} \quad U \ W < 0
\]

The actual sign of each \( \kappa_i \) depends on the chosen range for the angles.
Results after run 1 for the CP-conserving case

**The SM-like limit (alignment)**

\[
\sin(\beta - \alpha) = 1 \quad F = 1; \quad V = 1
\]

Wrong-sign limit

\[
D \; V < 0 \quad \text{or} \quad U \; V < 0
\]

Old plot – just to show the behaviour with \( \sin \alpha \)
Wrong-sign limit (type II and F)

\[
\sin(b + a) = 1 \quad \Rightarrow \quad k_D = -1 \quad (k_U = 1)
\]

\[
\sin(b - a) = \frac{\tan^2 b - 1}{\tan^2 b + 1} \quad \Rightarrow \quad k_V \geq 0 \quad \text{if} \quad \tan b \geq 1
\]

Ferrare, Gunion, Haber, RS (2014).
Ferrare, Guedes, Sampaio, RS (2014).
Ferngberg, Krawczyk, Osland 2001
The heavy scenario ($m_h < m_H = 125$ GeV)

**Type II**

\[
\begin{align*}
\cos(\beta - \alpha) &= 1 \\
\cos(\beta + \alpha) &= 1
\end{align*}
\]

**The Alignment limit**

\[
\begin{align*}
\cos(\beta - \alpha) &= 1 \\
F &= 1; \quad V = 1
\end{align*}
\]

**Wrong-sign limit**

\[
\begin{align*}
D \cdot V < 0
\end{align*}
\]

\[
\begin{align*}
\cos(\beta + \alpha) &= 1 \\
D &= 1 \quad (U = 1) \\
\cos(\beta - \alpha) &= \frac{\tan^2 \beta}{\tan^2 \alpha + 1} \\
V &= 0 \text{ if } \tan \alpha 1
\end{align*}
\]

but no decoupling
Why is it not excluded yet?

**SM-like limit**

\[ \kappa_D \rightarrow 1 \quad (\sin(\beta - \alpha) \rightarrow 1) \]

**Wrong sign**

\[ \kappa_D \rightarrow -1 \quad (\sin(\beta + \alpha) \rightarrow 1) \]

\[ \kappa_V \rightarrow 1 \quad (\sin(\beta - \alpha) \rightarrow 1) \]

\[ \kappa_V \rightarrow \frac{\tan^2 \beta - 1}{\tan^2 \beta + 1} \quad (\sin(\beta + \alpha) \rightarrow 1) \]

Defining

\[ \kappa_D = \frac{\sin(\beta + \alpha)}{\cos(\beta + \alpha)} = 1 + \]

\[ \sin(\beta + \alpha) \sin(\beta - \alpha) = \frac{2(1 - \tan^2 \beta)}{1 + \tan^2 \beta} \ll 1 \quad (\tan \beta \gg 1) \]

Difference decreases with \( \tan \beta \)
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 \textit{gamma gamma rate} could probe the \textit{wrong sign in both scenarios} but also the SM-like limit in the \textit{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.

In fact, if the charged Higgs loops were absent, changing the sign of $\kappa_D$ would imply a change in $\kappa_\gamma$ of less than 1 %.

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.

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)
• Set $m_{h1} = 125$ GeV.

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

\[-\frac{\pi}{2} < \alpha_{1,2,3} \leq \frac{\pi}{2}\]

\[1 \leq \tan \beta \leq 30\]

\[m_1 \leq m_2 \leq 900 \text{ GeV}\]

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

\[100 \text{ GeV} \leq m_{H^\pm} \leq 900 \text{ GeV}\]

\[m_{H^\pm} \gtrsim 340 \text{ GeV}\]

• Impose pre-LHC experimental constraints,

• Impose theoretical constraints: perturbative unitarity, potential bounded from below.
Results after run 1

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

$\alpha_1$ vs. $\alpha_2$
\( \tan \beta \) as a function of \( R_{11} \), \( R_{12} \) and \( R_{13} \) for Type I and Type II. Same colour code.
The zero scalar scenarios

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

\[ R_{13} = 0 \quad s_2 = 0 \]

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

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

\[ R_{11} = 0 \quad c_1 c_2 = 0 \]
\[ R_{12} = 0 \quad s_1 c_2 = 0 \]

\[ c_2 = 0 \quad g_{h1VV} = 0 \quad \text{excluded} \]
\[ c_1 = 0 \quad \text{allowed} \]

<table>
<thead>
<tr>
<th>Type I</th>
<th>Type II</th>
<th>Lepton Specific</th>
<th>Flipped</th>
</tr>
</thead>
<tbody>
<tr>
<td>Up</td>
<td>( \frac{R_{12}}{s_\beta} - i c_\beta \frac{R_{13}}{s_\beta} )</td>
<td>( \frac{R_{12}}{s_\beta} - i c_\beta \frac{R_{13}}{s_\beta} )</td>
<td>( \frac{R_{12}}{s_\beta} - i c_\beta \frac{R_{13}}{s_\beta} )</td>
</tr>
<tr>
<td>Down</td>
<td>( \frac{R_{12}}{s_\beta} + i c_\beta \frac{R_{13}}{s_\beta} )</td>
<td>( \frac{R_{11}}{c_\beta} - i s_\beta \frac{R_{13}}{c_\beta} )</td>
<td>( \frac{R_{12}}{s_\beta} + i c_\beta \frac{R_{13}}{s_\beta} )</td>
</tr>
<tr>
<td>Leptons</td>
<td>( \frac{R_{12}}{s_\beta} + i c_\beta \frac{R_{13}}{s_\beta} )</td>
<td>( \frac{R_{11}}{c_\beta} - i s_\beta \frac{R_{13}}{c_\beta} )</td>
<td>( \frac{R_{11}}{c_\beta} - i s_\beta \frac{R_{13}}{c_\beta} )</td>
</tr>
</tbody>
</table>
The zero scalar scenarios

• So, taking
\[ c_1 = 0 \quad \text{and} \quad R_{11} = 0 \]

and
\[ a_U^2 = \frac{c_2^2}{s^2}; \quad b_U^2 = \frac{s_2^2}{t^2}; \quad C^2 = s^2 c_2^2 \]

Type I
\[ a_U = a_D = a_L = \frac{c_2}{s} \]
\[ b_U = b_D = b_L = \frac{s_2}{t} \]

Type II
\[ a_D = a_L = 0 \]
\[ b_D = b_L = s_2t \]

Even if the CP-violating parameter is small, large $\tan \beta$ can lead to large values of $b$.

Type F
\[ a_D = 0 \]
\[ b_D = s_2t \]

Type LS
\[ a_L = 0 \]
\[ b_L = s_2t \]
The zero scalar scenarios

In Type II, if

\[ a_D = a_L \neq 0 \quad b_D = b_L = 1 \]

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

\[ a_U^2 = (1, s_2^4) = (1, 1/t^4) \quad g_{C2HDM}^{hVV} : = C^2 = \frac{t^2}{t^2 + 1} = \frac{1}{1 + s_2^2} \]

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

No major differences relative to the CP-conserving case

SM-like limit
\[ \sin(\beta - \alpha) = 1 \]
\[ \sin(\beta + \alpha) = 1 \]

\( \tan\beta \) 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).

\[
\mu_{VV}^H \approx \frac{\cos^2 \alpha_2 \cos^2(\beta - \alpha_1)}{\tan^2 \beta} \cdot \frac{\sin^2 \alpha_1 \cos^2 \alpha_2 + \sin^2 \alpha_2 \cos^2 \beta}{\cos^2 \alpha_1 \cos^2 \alpha_2 + \sin^2 \alpha_2 \sin^2 \beta}
\]
Scalar or pseudo-scalar?

\[ Y_{C2HDM} \quad a_F + i \ 5b_F \]

\[ b_U = 0 \quad \text{and} \quad a_D = 0? \]

Find a 750 GeV scalar decaying to tops

\[ h_1 = H \rightarrow t\bar{t} \]

Find a 750 GeV pseudoscalar decaying to taus

\[ h_1 = A \rightarrow + \]

It's CP-violation!
Type II

The wrong-sign limit
\( \sin(\beta + \alpha) = 1 \)

The SM-like limit
\( \sin(\beta - \alpha) = 1 \)

The CP-conserving line limit
\( \sin(\alpha_2) = 0 \)

The pseudoscalar limit scenario.

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

So what about EDMs?
Direct probing at the LHC ($\tau\tau h$)

$$pp \rightarrow h \rightarrow^+$$

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

• A measurement of the angle

$$\tan \left( \frac{b_L}{a_L} \right)$$

can be performed with the accuracies

\[
\begin{align*}
\tan &= \frac{s}{c_1} \tan_2 \\
\tan_2 &= \frac{c_1}{s} \tan
\end{align*}
\]

\[
\begin{align*}
\theta &= 40^\circ \quad 150 \text{ fb}^{-1} \\
\theta &= 25^\circ \quad 500 \text{ fb}^{-1}
\end{align*}
\]

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

• It is not a measurement of the CP-violating angle $\alpha_2$.

More later!
CP-violation with a combination of three decays
Combinations of three decays

Already observed

\[ h_1 \rightarrow ZZ \quad \iff \quad CP(h_1) = 1 \]

\[ h_3 \rightarrow h_2 h_1 \quad \Rightarrow \quad CP(h_3) = CP(h_2) \quad CP(h_1) = CP(h_2) \]

<table>
<thead>
<tr>
<th>Decay</th>
<th>CP eigenstates</th>
<th>Model</th>
</tr>
</thead>
<tbody>
<tr>
<td>( h_3 \rightarrow h_2 Z ) ( CP(h_3) = CP(h_2) )</td>
<td>None</td>
<td>C2HDM, other CPV extensions</td>
</tr>
<tr>
<td>( h_2(3) \rightarrow h_1 Z ) ( CP(h_2(3)) = 1 )</td>
<td>2 CP-odd; None</td>
<td>C2HDM, NMSSM, 3HDM...</td>
</tr>
<tr>
<td>( h_2 \rightarrow ZZ ) ( CP(h_2) = 1 )</td>
<td>3 CP-even; None</td>
<td>C2HDM, cxSM, NMSSM, 3HDM...</td>
</tr>
</tbody>
</table>
Classes of CP-violating processes

- on going searches

<table>
<thead>
<tr>
<th>Classes</th>
<th>$C_1$</th>
<th>$C_2$</th>
<th>$C_3$</th>
<th>$C_4$</th>
<th>$C_5$</th>
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<tbody>
<tr>
<td>Decays</td>
<td>$h_3 \to h_2 Z$</td>
<td>$h_2 \to h_1 Z$</td>
<td>$h_3 \to h_1 Z$</td>
<td>$h_3 \to h_2 Z$</td>
<td>$h_3 \to ZZ$</td>
</tr>
<tr>
<td>$h_2 \to h_1 Z$</td>
<td>$h_1 \to ZZ$</td>
<td>$h_1 \to ZZ$</td>
<td>$h_2 \to ZZ$</td>
<td>$h_2 \to ZZ$</td>
<td></td>
</tr>
<tr>
<td>$h_3 \to h_1 Z$</td>
<td>$h_2 \to ZZ$</td>
<td>$h_3 \to ZZ$</td>
<td>$h_3 \to ZZ$</td>
<td>$h_1 \to ZZ$</td>
<td></td>
</tr>
</tbody>
</table>

In 2HDMs only

only two to go

<table>
<thead>
<tr>
<th>Classes</th>
<th>$C_6$</th>
<th>$C_7$</th>
</tr>
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<tbody>
<tr>
<td>Decays</td>
<td>$h_3 \to h_2 h_1$</td>
<td>$h_{2,3} \to h_1 h_1$</td>
</tr>
<tr>
<td>$h_3 \to h_2 Z$</td>
<td>$h_{2,3} \to h_1 Z$</td>
<td></td>
</tr>
<tr>
<td>$h_1 \to ZZ$</td>
<td>$h_1 \to ZZ$</td>
<td></td>
</tr>
</tbody>
</table>

Classes involving scalar to two scalars decays

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

\[ h_2 \rightarrow h_3 \quad h_1 \rightarrow h_2 \]

\[ h_1 \rightarrow ZZ \quad \Longleftrightarrow \quad \text{CP}(h_1) = 1 \]

\[ h_2 \rightarrow ZZ \quad \Longleftrightarrow \quad \text{CP}(h_2) = 1 \]

\[ h_2 \rightarrow h_1Z \quad \Rightarrow \quad \text{CP}(h_1) \neq \text{CP}(h_2) \]

\[ c = \frac{\text{BR}(h_2 \rightarrow ZZ)}{\text{BR}(h_2 \rightarrow h_1Z)} \]

The benchmark plane is \((m_2, \chi)\)

\(\alpha_2\) 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 $\sigma \times BR$ at $\sqrt{s} = 13$ TeV for the benchmark points $P5$ (Type I) and $P6$ (lepton specific).

<table>
<thead>
<tr>
<th></th>
<th>$P5$</th>
<th>$P6$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sigma(h_1)$ 13 TeV</td>
<td>55.144 [pb]</td>
<td>53.455 [pb]</td>
</tr>
<tr>
<td>$\sigma(h_1)BR(h_1 \rightarrow W^<em>W^</em>)$</td>
<td>10.657 [pb]</td>
<td>11.069 [pb]</td>
</tr>
<tr>
<td>$\sigma(h_1)BR(h_1 \rightarrow Z^<em>Z^</em>)$</td>
<td>1.093 [pb]</td>
<td>1.136 [pb]</td>
</tr>
<tr>
<td>$\sigma(h_1)BR(h_1 \rightarrow bb)$</td>
<td>33.118 [pb]</td>
<td>32.152 [pb]</td>
</tr>
<tr>
<td>$\sigma(h_1)BR(h_1 \rightarrow \tau\tau)$</td>
<td>3.825 [pb]</td>
<td>2.845 [pb]</td>
</tr>
<tr>
<td>$\sigma(h_1)BR(h_1 \rightarrow \gamma\gamma)$</td>
<td>119.794 [fb]</td>
<td>122.579 [fb]</td>
</tr>
<tr>
<td>$\sigma_2 \equiv \sigma(h_2)$ 13 TeV</td>
<td>1.620 [pb]</td>
<td>4.920 [pb]</td>
</tr>
<tr>
<td>$\sigma_2 \times BR(h_2 \rightarrow WW)$</td>
<td>1.032 [pb]</td>
<td>0.542 [pb]</td>
</tr>
<tr>
<td>$\sigma_2 \times BR(h_2 \rightarrow ZZ)$</td>
<td>0.427 [pb]</td>
<td>0.232 [pb]</td>
</tr>
<tr>
<td>$\sigma_2 \times BR(h_2 \rightarrow bb)$</td>
<td>0.012 [pb]</td>
<td>0.097 [pb]</td>
</tr>
<tr>
<td>$\sigma_2 \times BR(h_2 \rightarrow \tau\tau)$</td>
<td>0.001 [pb]</td>
<td>0.109 [pb]</td>
</tr>
<tr>
<td>$\sigma_2 \times BR(h_2 \rightarrow \gamma\gamma)$</td>
<td>0.123 [fb]</td>
<td>0.344 [fb]</td>
</tr>
<tr>
<td>$\sigma_2 \times BR(h_2 \rightarrow h_1Z)$</td>
<td>0.140 [pb]</td>
<td>0.075 [pb]</td>
</tr>
<tr>
<td>$\sigma_2 \times BR(h_2 \rightarrow h_1Z \rightarrow bbZ)$</td>
<td>0.084 [pb]</td>
<td>0.045 [pb]</td>
</tr>
<tr>
<td>$\sigma_2 \times BR(h_2 \rightarrow h_1Z \rightarrow \tau\tau Z)$</td>
<td>9.683 [fb]</td>
<td>3.982 [fb]</td>
</tr>
<tr>
<td>$\sigma_2 \times BR(h_2 \rightarrow h_1h_1)$</td>
<td>0.000 [fb]</td>
<td>3772.577 [fb]</td>
</tr>
<tr>
<td>$\sigma_2 \times BR(h_2 \rightarrow h_1h_1 \rightarrow bbb)$</td>
<td>0.000 [fb]</td>
<td>1364.787 [fb]</td>
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<tr>
<td>$\sigma_2 \times BR(h_2 \rightarrow h_1h_1 \rightarrow bb\tau\tau)$</td>
<td>0.000 [fb]</td>
<td>241.505 [fb]</td>
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<tr>
<td>$\sigma_2 \times BR(h_2 \rightarrow h_1h_1 \rightarrow \tau\tau\tau)$</td>
<td>0.000 [fb]</td>
<td>10.684 [fb]</td>
</tr>
<tr>
<td>$\sigma_3 \equiv \sigma(h_3)$ 13 TeV</td>
<td>9.442 [pb]</td>
<td>10.525 [pb]</td>
</tr>
<tr>
<td>$\sigma_3 \times BR(h_3 \rightarrow WW)$</td>
<td>0.638 [pb]</td>
<td>0.945 [pb]</td>
</tr>
<tr>
<td>$\sigma_3 \times BR(h_3 \rightarrow ZZ)$</td>
<td>0.293 [pb]</td>
<td>0.406 [pb]</td>
</tr>
<tr>
<td>$\sigma_3 \times BR(h_3 \rightarrow bb)$</td>
<td>0.004 [pb]</td>
<td>0.422 [pb]</td>
</tr>
<tr>
<td>$\sigma_3 \times BR(h_3 \rightarrow \tau\tau)$</td>
<td>0.432 [fb]</td>
<td>407.337 [fb]</td>
</tr>
<tr>
<td>$\sigma_3 \times BR(h_3 \rightarrow \gamma\gamma)$</td>
<td>0.140 [fb]</td>
<td>2.410 [fb]</td>
</tr>
<tr>
<td>$\sigma_3 \times BR(h_3 \rightarrow h_1Z)$</td>
<td>0.383 [pb]</td>
<td>0.691 [pb]</td>
</tr>
<tr>
<td>$\sigma_3 \times BR(h_3 \rightarrow h_1Z \rightarrow bbZ)$</td>
<td>0.230 [pb]</td>
<td>0.416 [pb]</td>
</tr>
<tr>
<td>$\sigma_3 \times BR(h_3 \rightarrow h_1Z \rightarrow \tau\tau Z)$</td>
<td>26.554 [fb]</td>
<td>36.779 [fb]</td>
</tr>
<tr>
<td>$\sigma_3 \times BR(h_3 \rightarrow h_1Z \rightarrow h_2Z)$</td>
<td>2.495 [fb]</td>
<td>0.000 [fb]</td>
</tr>
<tr>
<td>$\sigma_3 \times BR(h_3 \rightarrow h_1Z \rightarrow h_2Z \rightarrow bbZ)$</td>
<td>0.019 [fb]</td>
<td>0.000 [fb]</td>
</tr>
<tr>
<td>$\sigma_3 \times BR(h_3 \rightarrow h_1Z \rightarrow h_2Z \rightarrow \tau\tau Z)$</td>
<td>2.188 [fb]</td>
<td>0.000 [fb]</td>
</tr>
<tr>
<td>$\sigma_3 \times BR(h_3 \rightarrow h_1h_1)$</td>
<td>433.402 [fb]</td>
<td>6893.255 [fb]</td>
</tr>
<tr>
<td>$\sigma_3 \times BR(h_3 \rightarrow h_1h_1 \rightarrow bbb)$</td>
<td>156.329 [fb]</td>
<td>2493.740 [fb]</td>
</tr>
<tr>
<td>$\sigma_3 \times BR(h_3 \rightarrow h_1h_1 \rightarrow bb\tau\tau)$</td>
<td>36.111 [fb]</td>
<td>441.277 [fb]</td>
</tr>
<tr>
<td>$\sigma_3 \times BR(h_3 \rightarrow h_1h_1 \rightarrow \tau\tau\tau)$</td>
<td>2.085 [fb]</td>
<td>19.521 [fb]</td>
</tr>
</tbody>
</table>

Class C7

\[ h_1 \rightarrow ZZ \quad \Leftrightarrow \quad \text{CP}(h_1) = 1 \]

\[ h_3 \rightarrow h_1 Z \quad \Rightarrow \quad \text{CP}(h_3) = \text{CP}(h_1) = 1 \]

\[ h_3 \rightarrow h_1 h_1 \quad \Leftrightarrow \quad \text{CP}(h_3) = 1 \]
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:

$$J : \phi_i \mapsto X_{ij} \phi_j^*,$$

$$X = \begin{pmatrix}
-1 & 0 & 0 \\
0 & 0 & i \\
0 & -i & 0
\end{pmatrix}.$$ 

Its square, $J^2 = \text{diag}(1, -1, -1)$, 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.

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

- Extending $J$ to the entire lagrangian: $\phi_{2,3}$ decouple from fermions, the $J$-symmetric minimum is $(\nu, 0, 0)$, 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 \(\Phi\) and \(\varphi\) are eigenstates of mass,

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

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 $\Phi$, $\varphi$ 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 $\phi_i$ doublet space, becomes unitary in $(\Phi, \varphi)$-space!

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

The map from $(\phi_2^0, \phi_3^0)$ to $(\Phi, \varphi)$ 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 $\varphi^* \to \varphi \varphi$, $\varphi \varphi \to \varphi^* \varphi^*$, 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:

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

I. P. Ivanov and J. P. Silva, PRD 93, 095014 2016
END of Part I