Theory and Phenomenology of Composite 2-Higgs Doublet Models

Stefania De Curtis
and Dept. of Physics and Astronomy, Florence University, Italy


637. Wilhelm und Else Heraeus-Seminar
UNDERSTANDING THE LHC
Physikzentrum Bad Honnef, Germany, Feb. 12-15, 2017
Motivations and Outline

- The search for additional Higgses is one of the most important tasks of the LHC. Moreover, extra spineless states can induce sizeable effects in the couplings of the discovered one.

- From a theoretical point of view, extra Higgses do not give an explanation for naturalness. Their pNGB nature can link them to natural theories at the weak scale.

- Focus on Composite Two Higgs Doublet Models (C2HDMs) emerging from specific symmetry breaking patterns. Results for $SO(6) \rightarrow SO(4) \times SO(2)$.

- Perturbative unitarity and vacuum stability properties of the C2HDM.

- Phenomenology at the LHC of the different Yukawa Type C2HDMs and comparison with the Elementary 2HDM predictions.

- Phenomenology at future $e^+e^-$ colliders (preliminary).
Generalities on Extended Composite Higgs Models

Models with a larger Higgs structure with respect to the SM have been proposed —→ 2HDMs offer a rich phenomenology in EW and flavour physics

In 2HDMs, as in the SM, the Higgs sector is very sensitive to UV physics —→ Hierarchy problem

Is it Naturalness a good guideline?
The most popular solution, Supersymmetry, requires two Higgs doublets with specific Yukawa and potential terms

A natural alternative is to consider the Higgs bosons as composite states from a strong sector. They can be lighter than the strong scale if they are pNGBs of G/H

![Diagram showing SM elementary fields and G/H strong sector](image)
Higgs as a Composite Pseudo Goldstone Boson

The basic idea

- Higgs as Goldstone Boson of $G/H$ in a strong sector
- An idea already realized for pions in QCD

How to get an Higgs mass?

- $G$ is only an approximate global symmetry $g_0 \to V(h)$
- EWSB as in the SM

- And the hierarchy problem?
  no Higgs mass term at tree level

$$\delta m_h^2 \sim \frac{g_0^2}{16\pi^2} \Lambda_{com}^2$$

$$l \sim 1/\Lambda_{com}$$
Characteristics of a Composite Higgs

It is not a true (SM-like) Higgs...

\[
\mathcal{L} = \frac{1}{2} (\partial_\mu h)^2 + V(h) + \frac{v^2}{4} \text{Tr} [(D_\mu \Sigma) \dagger (D^\mu \Sigma)] \left( 1 + 2a \frac{h}{v} + b \frac{h^2}{v^2} + \cdots \right)
- \frac{v}{\sqrt{2}} \sum_{i,j} (\bar{u}^i_L \bar{d}^j_L ) \Sigma \begin{pmatrix}
\lambda^{u}_{ij} & u^j_R \\
\lambda^{d}_{ij} & d^j_R
\end{pmatrix} \left( 1 + c \frac{h}{v} + \cdots \right) + \mathcal{L}_{SM,h}
\]

- SM Higgs for a \( a = b = c = 1 \)
- GB Higgs \( a = \sqrt{1 - v^2/f^2}, \ b = 1 - 2 \frac{v^2}{f^2} \) \( \text{SM limit } f \to \infty \)
- Composite Higgs only partly unitarizes WW scattering \( A(s, t, u) \sim \frac{s + t}{f^2} \)
- Up to effects \( v^2/f^2 \), the scalar \( h \) behaves as the SM Higgs
- Technicolor limit \( f = v \)
Extended Composite Higgs Models

We characterise models where EWSB is driven by 2 Higgs doublets as pNGBs of new dynamics above the weak scale.

We focus on models based on \( \text{SO}(6)/\text{SO}(4) \times \text{SO}(2) \). The unbroken group contains the custodial \( \text{SO}(4) \). The spectrum of the GBs is completely fixed by the coset and it is given by 2 Higgs 4-plets.

The low-energy effective Lagrangian stands on few specific assumptions about the strong sector: the global symmetries, the SSB pattern, the sources of explicit breaking. At the leading 2-derivative order, the non-linear \( \sigma \)-model interactions are fixed in terms of a unique parameter \( f \) (compositeness scale).

Elementary fields are linearly coupled to the strong sector (partial compositeness):
\[
\mathcal{L}_{\text{mix}} = g_0 \left( \psi_{\text{SM}} \mathcal{O} \right) \quad \psi_{\text{SM}} = (A_\mu, f) \quad g_0 = g, y
\]

The SM fields have a degree of mixing \( \sim g_0/g_\rho \). Realistic models \( g_0 < g_\rho < 4\pi \).

\( \mathcal{L}_{\text{mix}} \) breaks the global symm. of the strong sector, the Higgses become pNGBs and acquire a potential.
Extended Composite Higgs Models

- Crucial property is the presence of discrete symmetries in addition to the custodial SO(4), to control the T-parameter (this because in non-minimal models, even though the non-linear interactions satisfy SO(4), a contribution to T can arise for a generic vacuum structure J.Mrazek et al.1105.5403)

- Discrete symmetries also protect from Higgs-mediated Flavour Changing Neutral Currents

- Besides CP, impose a C\(_2\) discrete symmetry (J.Mrazek et al.1105.5403) distinguishes the 2 Higgs doublets and restricts the form of the Higgs potential and the Yukawa couplings (analogous of Z\(_2\) in E2HDM)

- Two classes of models: 1) exact discrete C\(_2\) symmetry (inert case) — the second Higgs does not couple to the SM fields 2) softly-broken C\(_2\) symmetry (active case) which controls the T parameter and FCNC
The model - 2 Higgs Doublets as pNGBs

J. Mrazek et al. 1105.5403; DC, Moretti, Yagyu, Yildirim 1602.06437

Analogue of the construction in non-linear sigma models developed by Callan-Coleman-Wess-Zumino (CCWZ)

The kinetic Lagrangian invariant under the SO(6) is:

\[ \mathcal{L}_{\text{kin}} = \frac{f^2}{4} (d_{\alpha}^a)_{\mu} (d_{\alpha}^a)_{\mu} \]

\[ (d_{\alpha}^a)_{\mu} = i \text{ tr}(U^\dagger D_{\mu} U T^a_{\alpha}) \]

\[ \Pi \equiv \sqrt{2} h_{\alpha}^a T^a = -i \begin{pmatrix} 0_{4 \times 4} & h_1^a & h_2^a \\ -h_1^a & 0 & 0 \\ -h_2^a & 0 & 0 \end{pmatrix} \]

\[ \Phi_{\alpha} \equiv \frac{1}{\sqrt{2}} \begin{pmatrix} h_{\alpha}^2 + ih_{\alpha}^1 \\ h_{\alpha}^4 - ih_{\alpha}^3 \end{pmatrix} \]

\[ h_{\alpha}^4 = \tilde{h}_{\alpha} = h_{\alpha} + v_{\alpha} \]

GB matrix

\[ \alpha = 1, 2 \quad a = 1, \ldots, 4 \]

are the 8 broken SO(6) generators

covariant derivative:

\[ D_\mu = \partial_\mu - ig T^a_{\mu} W^a_\mu - ig' Y B_\mu \]

the gauge boson masses are generated by the VEVs of the fourth components of the Higgs fields

\[ m_W^2 = \frac{g_2^2}{4} f^2 \sin^2 \frac{v}{f} \]

\[ v^2_{\text{SM}} \equiv v_1^2 + v_2^2 \]
The model - 2 Higgs Doublets as pNGBs

Similarly to E2HDM, define the **Higgs basis**: only one doublet contains $v$ and the NGs of $W, Z$

$$
\begin{pmatrix}
\Phi_1 \\
\Phi_2
\end{pmatrix} = \begin{pmatrix}
\cos \beta & -\sin \beta \\
\sin \beta & \cos \beta
\end{pmatrix}
\begin{pmatrix}
\Phi \\
\Psi
\end{pmatrix}, \quad \Phi = \begin{pmatrix}
G^+ \\
\frac{v+h'_1+iG^0}{\sqrt{2}}
\end{pmatrix}, \quad \Psi = \begin{pmatrix}
H^+ \\
\frac{h'_2+iA}{\sqrt{2}}
\end{pmatrix}
$$

$\tan \beta = v_2/v_1$

By expanding the kinetic term up to $O(1/f^2)$ we get **non canonical** forms for $G_0, G^\pm, h'_2$

we rescale according to:

$$
G^+ \to \left(1 - \frac{\xi}{3}\right)^{-1/2} G^+, \quad G^0 \to \left(1 - \frac{\xi}{3}\right)^{-1/2} G^0, \quad h'_2 \to \left(1 - \frac{\xi}{3}\right)^{-1/2} h'_2
$$

The mass eigenstates of the CP-even scalars are defined by introducing the mixing angle $\Theta$

$$
\begin{pmatrix}
h'_1 \\
h'_2
\end{pmatrix} = \begin{pmatrix}
\cos \theta & -\sin \theta \\
\sin \theta & \cos \theta
\end{pmatrix}
\begin{pmatrix}
h \\
H
\end{pmatrix}
$$

identified with the Higgs discovered at the LHC determined by the mass matrix from the Higgs potential

$A$ CP-odd

$h'_{1,2}$ CP-even

$\xi = \frac{v^2_{SM}}{f^2}$
Higgs potential in C2HDM

- The Higgs potential is generated at loop level
  - gauge boson loops give a positive squared-mass term
  - fermion loops can provide a negative squared-mass term and trigger EWSB

- Studied by J. Mrazek et al. 1105.5403 in the SO(6)/SO(4)xSO(2) model for several reps. of fermion fields assuming that all the explicit breaking is associated with the couplings of the strong sector to the SM fields due to Yukawa (y) and gauge (g) couplings (by relaxing this hypothesis the parameter space could be enlarged)

- They obtain the general E2HDM potential with parameters expressed in terms of those in the strong sector and the explicit breaking ones (at each order in y and g, it is parameterized by a limited number of coefficients which depend on the fermion representation)

\[
V(\Phi_1, \Phi_2) = \frac{1}{2} m_{11}^2 \text{Tr}[\Phi_1^\dagger \Phi_1] + \frac{1}{2} m_{22}^2 \text{Tr}[\Phi_2^\dagger \Phi_2] + \frac{1}{2} \text{Tr}[\Phi_1^\dagger \Phi_2 (m_{12}^2 + i m_{12}^2 \sigma_3)] \\
+ \frac{1}{4} \lambda_1 \text{Tr}^2[\Phi_1^\dagger \Phi_1] + \frac{1}{4} \lambda_2 \text{Tr}^2[\Phi_2^\dagger \Phi_2] + \frac{1}{4} \lambda_3 \text{Tr}[\Phi_1^\dagger \Phi_1] \text{Tr}[\Phi_2^\dagger \Phi_2] \\
+ \frac{1}{4} \lambda_4 \text{Tr}^2[\Phi_1^\dagger \Phi_2] + \frac{1}{4} \lambda_4 \text{Tr}^2[\Phi_2^\dagger \Phi_2 \sigma_3] + i \frac{1}{4} \lambda_5 \text{Tr}[\Phi_1^\dagger \Phi_2] \text{Tr}[\Phi_1^\dagger \Phi_2 \sigma_3] \\
+ \frac{1}{4} \text{Tr}[\Phi_1^\dagger \Phi_1] \text{Tr}[\Phi_1^\dagger \Phi_2 (\lambda_6 + i \lambda_6 \sigma_3)] + \frac{1}{4} \text{Tr}[\Phi_2^\dagger \Phi_2] \text{Tr}[\Phi_1^\dagger \Phi_2 (\lambda_7 + i \lambda_7 \sigma_3)]
\]
Contribution to the parameters of the general C2HDM potential from fermions in the $6$

The result depends on:

- the fermionic repr.
- the explicit breaking assumption
- the order of the expansion in the degree of mixing $g_0/g_\rho$ with $g_0 = g, g', Y_L Y_R$
Here we assume the most general CP-conserving E2HDM form for the potential. The masses and couplings of the Higgses are free parameters.

We will however highlight parameter space regions where differences can be found between E2HDM and C2HDM (the compositeness implemented in the kinetic terms and interactions with SM fields).

To avoid FCNC’s at tree level we impose a discrete $C_2$ symmetry $(\Phi_1, \Phi_2) \rightarrow (+\Phi_1, -\Phi_2)$ which could be exact (inert case) or softly broken (active case).

$$V(\Phi_1, \Phi_2) = m_1^2 \Phi_1^\dagger \Phi_1 + m_2^2 \Phi_2^\dagger \Phi_2 - m_3^2 (\Phi_1^\dagger \Phi_2 + h.c.) + \frac{1}{2} \lambda_1 (\Phi_1^\dagger \Phi_1)^2 + \frac{1}{2} \lambda_2 (\Phi_2^\dagger \Phi_2)^2$$

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

$m_3^2$ and $\lambda_5$ are real, $M$ defined by $M^2 = \frac{m_3^2}{s_\beta c_\beta}$ is the soft-breaking $C_2$ parameter.

(The $C_2$ symm. also avoids anomalous contributions to the $T$ parameter from dim-6 operators E.Bertuzzo et al 1206.2623)
Mass spectrum for the Active C2HDM

The mass matrices for charged states and the CP-odd scalars are diagonalised by a $\beta$-angle rotation

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

$$m_{H^\pm}^2 = M^2 - \frac{v^2}{2}(\lambda_4 + \lambda_5), \quad m_A^2 = M^2 - v^2\lambda_5$$

The mass matrix for the CP-even scalars is diagonalised by a $\Theta$-angle rotation

$$\tan 2\theta = \frac{2(M_{\text{even}})^2_{12}}{(M_{\text{even}})^2_{11} - (M_{\text{even}})^2_{22}}$$

$$(M_{\text{even}})_{11}^2 = v^2(\lambda_1 c_\beta^4 + \lambda_2 s_\beta^4 + 2\lambda_{345} c_\beta^2 s_\beta^2),$$

$$(M_{\text{even}})_{22}^2 = \left(1 + \frac{\xi}{3}\right)[M^2 + v^2(\lambda_1 + \lambda_2 - 2\lambda_{345}) s_\beta^2 c_\beta^2],$$

$$(M_{\text{even}})_{12}^2 = v^2 \left(1 + \frac{\xi}{6}\right)[-\lambda_1 c_\beta^2 + \lambda_2 s_\beta^2 + c_\beta^2 \lambda_{345}] s_\beta c_\beta$$

$$\lambda_{345} = \lambda_3 + \lambda_4 + \lambda_5.$$

$$m_h^2 = c_\theta^2 (M_{\text{even}})_{11}^2 + s_\theta^2 (M_{\text{even}})_{22}^2 + 2s_\theta c_\theta (M_{\text{even}})_{12}^2,$$

$$m_{H}^2 = s_\theta^2 (M_{\text{even}})_{11}^2 + c_\theta^2 (M_{\text{even}})_{22}^2 - 2s_\theta c_\theta (M_{\text{even}})_{12}^2$$

Decoupling limit for large $M$: the extra Higgses get degenerate with $M$ and $\Theta \to 0$

(the usual 2HDM notation is recovered with $\Theta = \alpha - \beta - \pi/2$)
\( \lambda_i \) parameters in terms of the masses of the physical Higgs bosons

\[
\begin{align*}
\lambda_1 &= \frac{1}{v^2 c^2_\beta} \left[ m_h^2 c^2_{\beta+\theta} + m_H^2 s^2_{\beta+\theta} - M^2 s^2_\beta + \frac{\xi}{3} s_\beta (m_h^2 c_{\beta+\theta} s_\theta - m_H^2 s_{\beta+\theta} c_\theta) \right], \\
\lambda_2 &= \frac{1}{v^2 s^2_\beta} \left[ m_h^2 s^2_{\beta+\theta} + m_H^2 c^2_{\beta+\theta} - M^2 c^2_\beta - \frac{\xi}{3} c_\beta \left( m_h^2 s_{\beta+\theta} s_\theta + m_H^2 c_{\beta+\theta} c_\theta \right) \right], \\
\lambda_3 &= \frac{1}{v^2} \left[ \frac{2s_{\beta+\theta}c_{\beta+\theta}}{s^2_\beta} (m_h^2 - m_H^2) + 2m_{H^\pm}^2 - M^2 - \frac{\xi}{3s^2_\beta} \left( m_H^2 s_{\beta+\theta} c_\theta s_{2\beta+\theta} - m_H^2 c_\theta s_{2\beta+\theta} \right) \right], \\
\lambda_4 &= \frac{1}{v^2} (M^2 + m_A^2 - 2m_{H^\pm}^2), \\
\lambda_5 &= \frac{1}{v^2} (M^2 - m_A^2).
\end{align*}
\]

\( m_H = 125 \text{GeV}, \quad v = 245 \text{GeV} \)

Total of 7 free parameters:

- \( m_H, m_A, m_{H^+}, \sin \Theta, \tan \beta, M, \xi \) (or \( f \))

Mass spectrum for the Inert C2HDM

\[
\begin{align*}
m_{H^\pm}^2 &= m_2^2 + \frac{v^2}{2} \lambda_3, \\
m_H^2 &= \left( 1 + \frac{\xi}{3} \right) \left( m_2^2 + \frac{v^2}{2} \lambda_{345} \right), \\
m_A^2 &= m_2^2 + \frac{v^2}{2} (\lambda_3 + \lambda_4 - \lambda_5), \\
m_h^2 &= \lambda_1 v^2.
\end{align*}
\]

\( m_3 = M = 0 \) (C\(_2\) symm) and \( \langle \Phi_2 \rangle = 0 \), \( m_2 \) sets the scale for the mass of the inert Higgs \( \Phi_2 \equiv H \) possible candidate for composite neutral dark matter
Trilinear Higgs self-coupling - role of $M$

$$\lambda_{hhh} = \frac{1}{4v_{SM}s_{2\beta}} \left[ (s_{2\beta+3\theta} - 3s_{2\beta+\theta})m_h^2 + 4s_{2\beta+\theta}M^2 \right] + \frac{\xi}{12v_{SM}} \left[ c_{\theta}m_h^2 + 2s_{\theta}M^2(c_{\theta} + 2s_{\theta}\cot\beta) \right] + \mathcal{O}(\xi^2)$$

$\tan\beta = 1$ (nearly independent of $\tan\beta$ for small $\Theta$)

$\xi = 0, 0.04, 0.08$

$M = 300 GeV$

$M = 200 GeV$

$M = 0$
The quantum effect of additional particles in loop diagrams for $\lambda_{hhh}$ can be enhanced when they show the non-decoupling property and can become as large as plus 100% for $M \ll m_\Phi$.

Under control in the decoupling limit $M \approx m_\Phi = m_H = m_{H^+} = m_A$.

Deviations $\sim 10\%$ for $M = 0.8 \, m_\Phi$ and $m_\Phi = 300 \text{GeV}$. Lower for larger masses.

We will set $M = 0.8 \, m_\Phi$ in our analysis.
C2HDM coupling deviations

Even without introducing fermions, the pattern of deviations from the SM-like properties can be different between C2HDMs and E2HDMs.

Introduce a scaling factor $k_X$ for the $hXX$ couplings as $\kappa_X = \frac{g_{hXX}^{NP}}{g_{hXX}^{SM}}$.

- In the C2HDM, at the first order in $\xi$ we get $\kappa_V = (1 - \xi/2)c_\theta$ (V=W,Z).
- E2HDM is obtained with $\xi=v^2/f^2 \to 0$ or $f \to \infty$, while SM has $\kappa_X = 1$.
- Two sources giving $\kappa_X \neq 1$ in C2HDM: non zero value of $\xi$ and/or $\theta$.
- Conversely, only $\theta \neq 0$ gives $\kappa_X \neq 1$ in E2HDM.

Therefore, for a given value of $k_X$, the value of $\theta$ is determined in E2HDM while only the combination $(\theta, \xi)$ is determined in C2HDM.
C2HDM coupling deviations

Contours for the deviations in the $hVV$ coupling

$$\Delta \kappa_V = \kappa_V - 1$$

$$\kappa_V = g_{hVV}/g_{hVV}^{SM} = (1 - \xi/2)c_\theta$$

Ex. $\Delta \kappa_V = -2\%$ corresponds to $\sin \theta = 0.2$ in the E2HDM but can be reproduced by $(\sin \theta, \xi) = (0, 0.04)$ in the C2HDM

Even in the case of no-mixing between $h$ and $H$, a non-zero deviation in $hVV$ coupling is present in the C2HDM

Coefficients of the scalar-scalar-gauge type vertices

<table>
<thead>
<tr>
<th>Vertex</th>
<th>Coefficient</th>
</tr>
</thead>
<tbody>
<tr>
<td>$H^\pm \partial_\mu AW^{\mp\mu}$</td>
<td>$\frac{g}{2}$</td>
</tr>
<tr>
<td>$H^\pm \partial_\mu h W^{\mp\mu}$</td>
<td>$\mp i \frac{g}{2} (1 - \frac{5}{6} \xi) \sin \theta$</td>
</tr>
<tr>
<td>$h \partial_\mu H^{\pm W^{\mp\mu}}$</td>
<td>$\pm i \frac{g}{2} (1 - \frac{5}{6} \xi) \sin \theta$</td>
</tr>
<tr>
<td>$A \partial_\mu H^{\pm W^{\mp\mu}}$</td>
<td>$- \frac{g}{2} (1 - \frac{5}{6} \xi) \cos \theta$</td>
</tr>
<tr>
<td>$h \partial_\mu AZ^{\mu}$</td>
<td>$\frac{g}{2} (1 - \frac{5}{6} \xi) \sin \theta$</td>
</tr>
<tr>
<td>$A \partial_\mu H Z^{\mu}$</td>
<td>$- \frac{g}{2} (1 - \frac{5}{6} \xi) \cos \theta$</td>
</tr>
<tr>
<td>$H \partial_\mu AZ^{\mu}$</td>
<td>$\frac{g}{2} (1 - \frac{5}{6} \xi) \cos \theta$</td>
</tr>
<tr>
<td>$H^+ \partial_\mu H^{- Z^{\mu}}$</td>
<td>$- i \frac{g}{2} c_{2W}$</td>
</tr>
<tr>
<td>$H^+ \partial_\mu H^{- A^{\mu}}$</td>
<td>$- ie$</td>
</tr>
</tbody>
</table>
Perturbative Unitarity in C2HDM

The s-wave amplitudes $A(V_L V_L \rightarrow V_L V_L)$ grow with energy due to the modified $hVV$ coupling and lead to perturbative unitarity violation

$$a_0(W_L^+ W_L^- \rightarrow W_L^+ W_L^-) = \frac{s}{32\pi v^2_{SM}} \xi - \frac{1}{8\pi v^2_{SM}} \left( m_h^2 c_\theta^2 + m_H^2 s_\theta^2 \right) (1 - \xi) + O(g^2, s^{-1}).$$

The study of unitarity bounds gives an indication of the scale at which effects of the strong sector become relevant

Use of the Equivalence Theorem

$|a_0| < 1/2$ gives a unitarity cut-off on energy

Ex: $f=1\text{TeV}$ ($\xi=0.06$) $\Lambda \sim 7\text{TeV}$
Perturbative Unitarity in C2HDM

\[ \mathcal{M}(H^+H^- \rightarrow H^+H^-) = \frac{s}{2v_{SM}^2} \xi(1 + c_\phi) - \frac{m_{H^\pm}^2}{v_{SM}^2} \xi \left( \frac{2}{3} + 4c_\phi \right) + \lambda_{H^+H^-H^+H^-} + O(s^{-1}) \]

- from kinetic term due to NGB nature
- from kinetic term and potential
- from potential

Unitarity bound from the requirement
|a_0(H^+H^- \rightarrow H^+H^-)| < 1/2

for \( M = mA = mH = mH^+ = m\Phi \)

- dashed lines neglecting \( O(s^0\xi) \) terms

\( O(s^0\xi) \) contributions are not so important as long as we consider \( m\Phi \lesssim 1 \text{ TeV} \)

Neglecting \( O(s^0\xi) \) makes the calculation of all the 2→2 body scattering amplitudes simpler and it is safe in the parameter region relevant for the phenomenology at the LHC.
Perturbative Unitarity in C2HDM from G+G→G+G-

grey regions: exact formulae
green regions: neglecting $O(1/s)$ terms

$m_H=m_A=m_{H^+}=M=m_{\Phi}$
$\cos\Theta=0.99$, $\tan\beta=1$

• The results are in good agreement for $\sqrt{s}>m_\Phi$
• The region $\sqrt{s}=m_\Phi$ is excluded due to the resonant effects

Compare C2HDM (left, center) with E2HDM (right):
• Energy cut-off $\sim 20\text{TeV}$ for $f=3\text{TeV}$ in C2HDM
• Below the cut-off the bound on the mass is less stringent in the C2HDM due to a partial cancellation between the $s$ term and the $m_{H^2}$ one
We calculate all the $2 \rightarrow 2$ body elastic (pseudo)scalar scattering amplitudes in the C2HDM. There are 14 neutral, 8 singly charged and 3 double charged states.

We also impose the vacuum stability condition (scalar potential bounded from below in any direction):

$$\lambda_1 > 0, \quad \lambda_2 > 0, \quad \sqrt{\lambda_1 \lambda_2 + \lambda_3 + \text{MIN}(0, \lambda_4 \pm \lambda_5)} > 0$$

E2HDM corresponds to $f \rightarrow \infty$ (indistinguishable from $f=3000\text{GeV}$).

More parameter space becomes available to the C2HDM with respect to the E2HDM for smaller $f$ values.
Perturbative Unitarity and Vacuum Stability in C2HDM outside the alignment limit $\sin \theta \rightarrow 0$

$m_{H^+} = m_A = m_H$

$M/m_A = 1, 0.8, 0.6$

below solid (dashed) lines: allowed by vacuum stability (unitarity)

C2HDM bounds are for $\sqrt{s} = 1000$ GeV and $f = 1250(850)$ GeV corresponding to $\xi = 0.04(0.08)$

E2HDM corresponds to $f \rightarrow \infty$ ($\xi = 0$)

for $m_{\Phi} = 500$ GeV, $M = 0.8 m_A$, $\tan \beta = 1, 2$

$-0.2 < \sin \theta < 0.2$ is allowed

larger $\tan \beta$ values require lower $m_{\Phi}$
The kinetic term of the pNGB is uniquely determined by the structure of the global symmetry breaking \( SO(6)/SO(4) \times SO(2) \).

For the Yukawa sector we need to assume the embedding for SM fermions into \( SO(6) \) multiplets. It is justified by the partial compositeness assumption where the SM fermions mix with the composite ones in a \( SU(2) \times U(1) \) invariant form. The low-energy Lagrangian is obtained after integrating out the composite fermions.

We use here the 6-plet reprs of \( SO(6) \) for SM quarks and leptons:

\[
\begin{align*}
(\Psi_{2/3})_L &\equiv Q^u_L = (-id_L, -d_L, -iu_L, u_L, 0, 0)^T, \\
(\Psi_{-1/3})_L &\equiv Q^d_L = (-iu_L, u_L, id_L, d_L, 0, 0)^T, \\
(\Psi_{2/3})_R &\equiv U_R = (0, 0, 0, 0, 0, u_R)^T, \\
(\Psi_{-1/3})_R &\equiv D_R = (0, 0, 0, 0, 0, d_R)^T, \\
(\Psi_{-1})_L &\equiv L_L = (-i\nu_L, \nu_L, ie_L, e_L, 0, 0)^T, \\
(\Psi_{-1})_R &\equiv E_R = (0, 0, 0, 0, 0, e_R)^T.
\end{align*}
\]

In order to reproduce the correct electric charge we have added an additional \( U(1)_X \) symmetry.
Effective Yukawa Lagrangian for C2HDM

The Yukawa Lagrangian is given in terms of $\Sigma$, the 15-plet of pNGB, SO(6) adjoint, the 6-plet of fermions

$$\mathcal{L}_Y = f \left[ \bar{Q}^u_L (a_u \Sigma - b_u \Sigma^2) U_R + \bar{Q}^d_L (a_d \Sigma - b_d \Sigma^2) D_R + \bar{L}_L (a_e \Sigma - b_e \Sigma^2) E_R \right] + \text{h.c.}$$

$\Sigma = U \Sigma_0 U^T$

transforms linearly under SO(6)

$\Sigma \rightarrow g \Sigma g^T$

$U = \text{pNGB matrix}$

$\Sigma_0 = \begin{pmatrix} 0_{4 \times 4} & 0_{4 \times 2} \\ 0_{2 \times 4} & i \sigma_2 \end{pmatrix}$

$a_f$ and $b_f$ are 3x3 complex matrices in the flavor space

Masses of fermions (at the first order in $\xi$) →

$$m_f = v_{SM} \left[ a_f c_\beta + b_f s_\beta \left( 1 - \frac{\xi}{2} \right) \right]$$

In general FCNCs appear at tree level due to the existence of two independent Yukawa couplings $a_f$ and $b_f$ (both doublets couple to each fermion type).

To avoid it, impose a $C_2$ discrete symmetry (J. Mrazek et al. 1105.5403)

$U(\pi_1^\phi, \pi_2^\phi) \rightarrow C_2 U(\pi_1^\phi, \pi_2^\phi) C_2 = U(\pi_1^\phi, -\pi_2^\phi)$

$C_2 = \text{diag}(1, 1, 1, 1, 1, -1)$

$\pi_1^\phi$ is $C_2$-even

$\pi_2^\phi$ is $C_2$-odd

Depending on the $C_2$ charge of the right-handed fermions, we define 4-independent Types of Yukawa interactions, like the $Z_2$ symm. in E2HDM
Effective Yukawa Lagrangian for C2HDM

\[
\mathcal{L}_Y = \sum_{f=u,d,e} \frac{m_f}{v_{\text{SM}}} f \left( \bar{X}_f^h h + \bar{X}_f^H H - 2iI_f \bar{X}_f^A \gamma_5 A \right) f + \frac{\sqrt{2}}{v_{\text{SM}}} \bar{u} V_{ud} (m_d \bar{X}_d^A P_R - m_u \bar{X}_u^A P_L) d^+ H^+ + \frac{\sqrt{2}}{v_{\text{SM}}} \bar{v} m_e \bar{X}_e P_R e^+ H^+ + h.c.
\]

\[\bar{X}_f^\phi \text{ are diagonal in the mass eigenbasis of fermions}\]

<table>
<thead>
<tr>
<th>Type</th>
<th>(U_R)</th>
<th>(D_R)</th>
<th>(E_R)</th>
<th>(a_u, b_u)</th>
<th>(a_d, b_d)</th>
<th>(a_e, b_e)</th>
<th>(\bar{X}_u^h)</th>
<th>(\bar{X}_d^h)</th>
<th>(\bar{X}_e^h)</th>
<th>(\bar{X}_u^H)</th>
<th>(\bar{X}_d^H)</th>
<th>(\bar{X}_e^H)</th>
<th>(\bar{X}_u^A)</th>
<th>(\bar{X}_d^A)</th>
<th>(\bar{X}_e^A)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type-I</td>
<td>(-)</td>
<td>(-)</td>
<td>(-)</td>
<td>(0, \sqrt{\xi})</td>
<td>(0, \sqrt{\xi})</td>
<td>(0, \sqrt{\xi})</td>
<td>(\zeta_h)</td>
<td>(\zeta_h)</td>
<td>(\zeta_h)</td>
<td>(\zeta_H)</td>
<td>(\zeta_H)</td>
<td>(\zeta_H)</td>
<td>(\zeta_A)</td>
<td>(\zeta_A)</td>
<td>(\zeta_A)</td>
</tr>
<tr>
<td>Type-II</td>
<td>(-)</td>
<td>(+)</td>
<td>(+)</td>
<td>(0, \sqrt{\xi})</td>
<td>(\sqrt{\xi}, 0)</td>
<td>(\sqrt{\xi}, 0)</td>
<td>(\zeta_h)</td>
<td>(\xi_h)</td>
<td>(\xi_h)</td>
<td>(\xi_H)</td>
<td>(\xi_H)</td>
<td>(\xi_H)</td>
<td>(\zeta_A)</td>
<td>(\xi_A)</td>
<td>(\zeta_A)</td>
</tr>
<tr>
<td>Type-X</td>
<td>(-)</td>
<td>(-)</td>
<td>(+)</td>
<td>(0, \sqrt{\xi})</td>
<td>(0, \sqrt{\xi})</td>
<td>(\sqrt{\xi}, 0)</td>
<td>(\zeta_h)</td>
<td>(\zeta_h)</td>
<td>(\xi_h)</td>
<td>(\zeta_H)</td>
<td>(\zeta_H)</td>
<td>(\zeta_H)</td>
<td>(\zeta_A)</td>
<td>(\zeta_A)</td>
<td>(\zeta_A)</td>
</tr>
<tr>
<td>Type-Y</td>
<td>(+)</td>
<td>(-)</td>
<td>(-)</td>
<td>(0, \sqrt{\xi})</td>
<td>(\sqrt{\xi}, 0)</td>
<td>(0, \sqrt{\xi})</td>
<td>(\zeta_h)</td>
<td>(\xi_h)</td>
<td>(\zeta_h)</td>
<td>(\xi_H)</td>
<td>(\xi_H)</td>
<td>(\xi_H)</td>
<td>(\zeta_A)</td>
<td>(\zeta_A)</td>
<td>(\zeta_A)</td>
</tr>
</tbody>
</table>

\[\zeta_h = -\frac{1 - \frac{3}{2} \xi}{c_\theta + s_\theta \cot \beta}, \quad \xi_h = \frac{1 - \xi}{c_\theta - s_\theta \tan \beta}, \quad \zeta_H = -\frac{1 - \frac{3}{2} \xi}{s_\theta + c_\theta \cot \beta}, \quad \xi_H = -\frac{1 - \xi}{s_\theta - c_\theta \tan \beta}, \quad \zeta_A = \frac{1 + \frac{\xi}{2} \cot \beta}, \quad \xi_A = -\frac{1 - \frac{\xi}{2}}{\tan \beta}.
\]

Ex. in all Types:

\[\kappa_t = g_{htt}^{\text{SM}} / g_{htt} = \bar{X}_u^h = \zeta_h\]

Corrections \(O(\xi)\) are predominately negative.
Present collider bounds for the C2HDM Type-I and Type-II

$m_A = m_{H^+} = m_H = M = 500\,\text{GeV}$ \hspace{1cm} $m_h = 125\,\text{GeV}$

- **Type-I** reveals a better compliance with the LHC data
- **Type-II** disfavoured for $|\sin\theta| > 0.2$ and $\tan\beta > 10$
- **Type-X** and **Type-Y** very similar to **Type-II**

Choose: $\xi \lesssim 0.08$ \hspace{0.5cm} $|\sin\theta| \lesssim 0.2$ and small $\tan\beta$

also compliant with unitarity and stability bounds with $m_\Phi = 500\,\text{GeV}$

---

green/red regions are 95%CL allowed/excluded from LEP, Tevatron, LHC data by using HiggsBounds package

- 68%CL
- 95%CL
- 99%CL

$\Delta \chi^2$-contours by HiggsSignal package
Deviations in Higgs boson couplings

\[ \Delta \kappa_X = \frac{g_{hXX}}{g_{hXX}^{SM}} - 1 \]

DC, Moretti, Yagyu, Yildirim 1610.02087

Suppose a deviation \( \Delta k_V \) is measured at the LHC, it is an indirect evidence for a non-minimal Higgs sector.

If \( |\Delta k_V| \leq 2\% \), by looking at the pattern of the deviations in \( \Delta k_E \) and \( \Delta k_D \) we can discriminate between E2HDM and C2HDM and among the four Types of Yukawa interactions.

Ex: if \( \Delta k_V = -2\% \), \( \Delta k_D = -10\% \), \( \Delta k_E = 20\% \) then \( \rightarrow \) Type-X C2HDM with \( \tan \beta = 2 \) and \( \xi = 0.03 \).

Dots on the lines refer to \( \tan \beta = 1 \) to 10 with steps of 1 away from (0,0).
Decays of the extra-Higgs boson $H$

$m_\Phi = m_H = m_{H^+} = m_A$
$M = 0.8 mA, \tan \beta = 2$

Below the $tt$ threshold, $H \rightarrow hh, WW, ZZ$ are the dominant channels in E2CHM while they are absent in the C2HDM with $\sin \Theta = 0$ (in all the 4 Yukawa Types)

$\Delta k_V = -2\%$

E2HDM
($\sin \Theta = -0.2, \xi = 0$)

C2HDM
($\sin \Theta = 0, \xi = 0.04$)
Decays of the extra-Higgs boson $A$

$m_\Phi=m_H=m_{H^+}=m_A$

$M=0.8m_A$, $\tan\beta=2$  

the three body decay $A\rightarrow Z^*h\rightarrow ffh$ is taken into account for $mA<mZ+mh$

$\Delta k_V = -2\%$

$E2HDM$  

$(\sin\Theta=-0.2, \xi=0)$

$C2HDM$  

$(\sin\Theta=0, \xi=0.04)$

Below the $tt$ threshold, $A\rightarrow Zh$ can be the dominant channels in $E2HDM$ while it is absent in the $C2HDM$ with $\sin\Theta=0$ (in all the 4 Yukawa Types)
Productions of the extra-Higgs bosons at the LHC

$$\sigma \left( gg \rightarrow H/A \right)$$

$$\sigma(gg \rightarrow \phi^0) = \frac{\Gamma(\phi^0 \rightarrow gg)}{\Gamma(h_{SM} \rightarrow gg)} \times \sigma(gg \rightarrow h_{SM}), \quad (\phi^0 = H \text{ or } A).$$

with the mass of $h_{SM}$ artificially set at $m_{\phi^0}$

E2HDM: BP1($\sin \Theta = -0.2$, $\xi = 0$)

C2HDM: BP2($\sin \Theta = -0.1$, $\xi = 0.03$), BP3($\sin \Theta = 0$, $\xi = 0.04$)

Sizeable differences between E2HDM and C2HDM in gluon fusion H production

For the A production the differences are marginal mainly due to the $\sin \Theta$ dependence in the top Yukawa couplings

$$\zeta_H = - \left(1 - \frac{3}{2} \xi \right) s_\theta + c_\theta \cot \beta$$

$$\zeta_A = \left(1 + \frac{\xi}{2}\right) \cot \beta.$$

$\sqrt{s} = 13 \text{ TeV}$
**SCENARIO 1:** A deviation in the hVV and/or hff couplings is established during the Run2 of the LHC, then an investigation of the 2HDM is called for

- If $|\Delta k_V| > 2\%$ then E2HDM unlikely could explain it because of the theor. and exp. bounds on $\sin\Theta$, but it could be possible within the C2HDM.
- If $|\Delta k_V| \lesssim 2\%$ a dedicated scrutiny of the decay patterns of all potentially accessible heavy Higgs states could enable to separate the E2HDM from the C2HDM through the combination of the differences in the BRs and production cross sections.

**SCENARIO 2:** 😞 No additional Higgs states will have been discovered at the LHC, neither after 3000 fb$^{-1}$, nor deviations in the Higgs couplings.

- e+e- colliders will have a great task. The Higgs boson $h$ discovered at the LHC will be produced in single-mode (via Higgs-strahlung $ee \rightarrow Zh$, Vector Boson Fusion $ee \rightarrow eeh$ and associated production via top quarks $ee \rightarrow tth$) and double-mode (via $ee \rightarrow Zhh$, $ee \rightarrow eehh$, $ee \rightarrow tthh$).
- Because of the small background, the Higgs boson couplings will be measured with an extremely good accuracy $\sim 0.5\%(2.5\%)$ for $hZZ(htt)$ at ILC(500,500).

Future e+e- machines will have the potential to discriminate between the E2HDM and C2HDM by studying the SM-h cross-sections.
Present and future LHC bounds for the C2HDM Type-I

$m_A = m_{H^+} = m_H = 500 \text{GeV} \quad M = 0.8 m_A \quad m_h = 125 \text{GeV}$

$\tan\beta = 1 \quad \tan\beta = 2 \quad \tan\beta = 3$

$\ast \ast \ast$ = regions 95%CL allowed by current collider data (HiggsBounds tool)

compatibility with the observed Higgs signals (SM) extrapolated at $300 \text{fb}^{-1}$ $3000 \text{fb}^{-1}$ contours of $|\Delta k_V| = |g_{hvVV}^{C2HDM} / g_{hvVV}^{SM} - 1|$
Same analysis for the C2HDM Type-II

Assumption: no new Higgs boson detected and the properties of SM-like one are greatly constrained

After HL-LHC there remains scope to distinguish C2HDM from E2HDM ($\xi=0$) at future $e^+e^-$ colliders
Associated Higgs Boson production with top quarks
\[ e^+e^- \rightarrow t\bar{t}h \]

At \( \sqrt{s} = 1,2 \text{ TeV} \) the on-shell production of \( A \) is realised and the cross section gets enhanced. The \( \xi \) dependence acts like an overall rescaling with negative deviations >20% for \( \xi = 0.08 \).

The C2HDM predicts cross sections for \( e^+e^- \rightarrow t\bar{t}h \) that cannot be realised in the E2HDM.
Differences in $e^+e^- \rightarrow t\bar{t}h$ cross-section for fixed $k_V^2 = 0.99, 0.98$

$\sqrt{s} = 1000\text{GeV}$, $m_{A}=m_{H^{\pm}}=m_H=500\text{GeV}$ $M = 0.8 \, m_A$ $m_h = 125\text{GeV}$

$$\Delta \sigma = (\sigma_{C2HDM}/\sigma_{E2HDM} - 1)$$

$k_V = g_{hVV}/g_{hVV}^{SM}$

$\Delta k_V = -0.5\%$

$\Delta k_V = -1\%$

$\sin \Theta < 0$

$\sin \Theta > 0$

the sign of $\sin \Theta$ not determined by measuring $k_V$

the lines correspond to values of Type-I C2HDM parameters allowed by unitarity and stability bounds and after $3000 \, \text{fb}^{-1}$ at the LHC

Even with very small deviations in $k_V$ precisely determined via HS and VBF, the differences between E2HDM and C2HDM in $e^+e^- \rightarrow t\bar{t}h$ cross section can be $\sim 15\%$
Double Higgs Boson production: $e^+e^-\rightarrow Zhh$

sensitive to triple-Higgs couplings and to the extra Higgs boson exchanges

At $\sqrt{s}=1,2\text{TeV}$ the on-shell production of $H,A$ is realised, followed by $H\rightarrow hh$ and $A\rightarrow Zh$ respectively, both proportional to $\sin \Theta$

The $\xi$ dependence remains comparable at all energies being in the 20-30% range

$M=0.8m_\Phi \tan \beta=2$

$m_\Phi=400\text{GeV}$

$m_\Phi=500\text{GeV}$

$m_\Phi=500\text{GeV}$
Differences in cross section for $e^+e^-\rightarrow Zhh$

$\sqrt{s}=1000\text{GeV}$  \(m_A=m_{H^+}=m_{H}=500\text{GeV}\)  \(M=0.8\text{ mA}\)  \(m_h=125\text{GeV}\)

$$\Delta \sigma = \left( \frac{\sigma_{\text{C}_2\text{HDM}}}{\sigma_{\text{E}_2\text{HDM}}} - 1 \right)$$

$$k_V = \frac{g_{hVV}}{g_{hVV}^{\text{SM}}}$$

- $\sin\Theta > 0$  \(\Delta k_V = -0.5\%\)
- $\sin\Theta < 0$  \(\Delta k_V = -1\%\)

the lines correspond to values of Type-I C2HDM parameters allowed by unitarity and stability bounds and after 3000 fb$^{-1}$ at the LHC

Large negative differences between C2HDM and E2HDM are predicted also for $\lesssim 1\%$ deviations in the $hVV$ coupling
Summary and Conclusions

☑ C2HDM amplitudes grow with $\sqrt{s}$ in bosonic scattering processes. Perturbative unitarity is broken at a certain energy scale depending on the compositeness scale $f$. However for LHC ($e^+e^-$) energies and $m_\Phi \lesssim 500\text{GeV}$, UV completion is not necessary for Higgs studies.

☑ In presence of a deviation in $hVV$ couplings from SM prediction, E2HDM would require non-zero mixing case, while C2HDM could achieve this with zero mixing case.

☑ If deviations are measured at collider experiments, we have indirect evidence for a non-minimal Higgs sector possible belonging to a E2HDM or C2HDM.

☑ Differences in the decay BR’s and production cross sections for the extra Higgs bosons could enable us to distinguish a C2HDM from E2HDM at both hadron and lepton colliders.
BACKUP SLIDES
**Spectrum:**

\[ m_{\rho} = g_{\rho} f \]

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

\[ m_W = 80 \text{ GeV} \]

\[ 0 \]

---

**Strong sector:** resonances + Higgs bound state

**Extra particle content:**
- Spin 1 resonances
- Spin 1/2 resonances

---

**Linear elementary-composite couplings (partial compositeness):**

\[ \Delta_R Q_R O_L + \Delta_L Q_L O_R + Y \bar{O}_L H O_R \]

\[ y_{SM} = \epsilon_L \cdot Y \cdot \epsilon_R \]

\[ \epsilon = \frac{\Delta}{m_Q} \]

\[ m_t \sim \frac{v}{\sqrt{2}} \frac{\Delta_{tL}}{m_\psi} \frac{\Delta_{tR}}{m_X} \frac{Y_T}{f} \]

---

SM hierarchies are generated by the mixings:
- light quarks elementary, top strongly composite
And the Higgs mass?

Integrate out the composite sector and get a low-energy Lagrangian with form-factors

Contribution from the gauge loops subleading

\[ m_H \sim 0.3 \, y_t \frac{m}{f} v \]
In the inert model (C\textsubscript{2} symm) there is no m\textsubscript{3} term in the potential (M=0) and \langle\Phi\rangle=0. H is the inert Higgs, not coupled to quarks and leptons.

A different choice of parameters leading to a different mass spectrum with m\textsubscript{H}<m\textsubscript{h} is possible. Ex. for m\textsubscript{H}=m\textsubscript{2}=100GeV the upper limit from unitarity on m\textsubscript{H}+=m\textsubscript{A} is about 700GeV.

A dark-matter-motivated scenario is available as it is consistent with the unitarity bounds derived.
Constraints on 2HDM from $B \rightarrow X_s \gamma$

Predictions for $\text{Br}(B \rightarrow X_s \gamma)$ at NLO QCD within the SM and the 2HDM for $\tan\beta = 1, 3, 30$

The red lines delimit the $2\sigma$ allowed region from exp. results

95%CL bounds from NNLO calculation ($M. Misiak$ et al. 1503.01789)

Type-I (Type-X): $M_{H^+} > 100(200)$ GeV for $\tan\beta = 2.5(2)$, no bound for $\tan\beta > 3$

Type-II (Type-Y): $M_{H^+} > 480$ GeV for $\tan\beta > 2$

Loose bounds on $m_{H^+}$ in Type-I for $\tan\beta \gtrsim 2$
Trilinear $Hhh$ coupling

\[
\lambda_{Hhh} = \frac{s_\theta}{2v_{SM} s_\beta} \left[ -s_2(\beta+\theta) (2m_h^2 + m_H^2) + (s_2 + 3s_2(\beta+\theta)) M^2 \right] + \frac{\xi}{12v_{SM}} s_\theta \left[ m_H^2 - 2m_h^2 + (1 + 3c_2\theta + 6 \cot 2\beta s_2) M^2 \right] + \mathcal{O}(\xi^2)
\]

nearly independent on $\tan\beta$ for small $\Theta$

$\tan\beta = 1$

$\xi = 0, 0.04, 0.08$

$m_H = 400\text{GeV}$

$M = 300\text{GeV}$

$M = 200\text{GeV}$

$M = 0$
Decays of the extra-Higgs boson $H^+$

$\Delta k_V = -2\%$

$E2HDM$
$(\sin\Theta = -0.2, \xi = 0)$

$C2HDM$
$(\sin\Theta = 0, \xi = 0.04)$

$H^+ \rightarrow W^+ h$ is a relevant channel in E2ChM while it is absent in the C2HDM with $\sin\Theta = 0$
(in all the 4 Yukawa Types)
Productions of the extra-Higgs bosons at the LHC

\[ \sigma (gg \to bbH/A) \quad \text{and} \quad \sigma (gb \to tH^+) \]

\( \sqrt{s} = 13 \text{ TeV} \)

E2HDM: BP1\((\sin \Theta = -0.2, \xi = 0)\)

C2HDM: BP2\((\sin \Theta = -0.1, \xi = 0.03)\), BP3\((\sin \Theta = 0, \xi = 0.04)\)

Relevant differences between E2HDM and C2HDM only for H production

(for all Types and all \( \tan \beta \) values)