The HL-LHC and HE-LHC scope in testing compositeness of 2HDMs

Luigi Delle Rose

In collaboration with S. De Curtis, S. Moretti, A. Tesi, K. Yagyu
Q. Is the discovered Higgs the SM one?

Q. Is it elementary or composite?

Q. Any other scalar accompanying it? 
*minimality is not always a good guiding principle*

Q. Which is the mechanism behind EWSB?

Q. How can we address the hierarchy problem?

Q. Do we really understand it?

Q. ...? ...? ...? ...?
### INTRODUCTION - Q&A

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  (minimality is not always a good guiding principle) |
| Q. | Which is the mechanism behind EWSB?| A. | we don’t know |
| Q. | How can we address the hierarchy problem? | A. | Susy and compositeness are the best-known paradigms |
| Q. | Do we really understand it?        | A. | probably not  |
| Q. | ... ? ... ? ... ? ... ?            | A. | we don’t know |

*LHC is doing a great job in helping us answering these questions and it will do much much much better*
we consider a realisation of ESWB achieved with 2 Higgs doublets as (pseudo) Nambu Goldstone bosons of a new strong dynamics

*a composite 2HDM is the simplest natural 2HDM alternative to SUSY that also addresses the hierarchy problem*

*Mrazek, Pomarol, Rattazzi, Redi, Serra, Wulzer, 2011*

The phenomenology is very rich and interesting: effects in the Higgs couplings, extended scalar sector, new resonances

*(strong correlations among different observables)*
Symmetry fixes (almost) everything

we borrow this idea from QCD
Nature has already realised this mechanism

do the coset delivers a set of states at a common mass scale \( m^* \)

a large separation with the Higgs can be achieved if we identify it with a NGB state

the mixing breaks the global symmetry and generates a one-loop effective potential
the coset delivers 8 NGBs (2 Higgs doublets)

spin 1/2 and 1 resonances

<table>
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<tr>
<th>G</th>
<th>H</th>
<th>N_G</th>
<th>NGBs rep.[H] = rep.[SU(2) × SU(2)]</th>
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<tr>
<td>SO(7)</td>
<td>G_2</td>
<td>7</td>
<td>7 = (1, 3) + (2, 2)</td>
</tr>
<tr>
<td>SO(7)</td>
<td>SO(5) × SO(2)</td>
<td>10</td>
<td>10_0 = (3, 1) + (1, 3) + (2, 2)</td>
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<tr>
<td>SO(7)</td>
<td>[SO(3)]^3</td>
<td>12</td>
<td>(2, 2, 3) = 3 × (2, 2)</td>
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<td>Sp(6)</td>
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<td>SU(5)</td>
<td>SO(5)</td>
<td>14</td>
<td>14 = (3, 3) + (2, 2) + (1, 1)</td>
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Mrazek et al., 2011
Cooking recipe

- **G/H** \( \text{SO(6)}/\text{SO(4)} \times \text{SO(2)} \)
  - The coset delivers 8 NGBs (2 Higgs doublets)
  - Spin 1/2 and 1 resonances

- **elementary/composite mixing**
  - No freedom in the gauge sector
  - Partial compositeness among fermions (different reps. under G)

- **discrete symmetries**
  - \( CP, \ C_2 \)

- **constraints**
  - Calculability of the effective potential, absence of FCNC, constraints from flavour observables, Higgs data and direct searches
Partial compositeness

linear interactions between composite and elementary operators

\[ \mathcal{L}_{\text{int}} = g J_\mu W^\mu \]
\[ \mathcal{L}_{\text{int}} = y_L q_L \mathcal{O}_L + y_R t_R \mathcal{O}_R \]

in the IR \(-\mathcal{L} = m^* \bar{T} T + y f \bar{t} T\) \(\rightarrow\) \textit{partial compositeness}

In our scenario with G/H = SO(6)/SO(4)xSO(2) and fermions in the 6 of SO(6):

\[ \mathcal{L}_{\text{mix}} + \mathcal{L}_{\text{strong}} = \Delta_L^I \bar{q}_L^6 \Psi_R^I + \Delta_R^I \bar{t}_R^6 \Psi_L^I \]
\[ + \bar{\Psi}^I i \gamma^5 \Psi^I - \bar{\Psi}_L^I M_{\Psi}^{IJ} \Psi_R^J - \bar{\Psi}_L^I \left( Y_1^{IJ} \Sigma + Y_2^{IJ} \Sigma^2 \right) \Psi_R^J \]

at least 2 heavy resonances are needed for a UV finite potential

\[ \Sigma = U i \sigma_2 U^T \quad U = \exp(i \frac{\Pi}{f}) \]
\[ \Pi = \sqrt{2} h_\alpha \hat{T}_\alpha = -i \begin{pmatrix} 0_{4 \times 4} & h_1^a & h_2^a \\ -h_1^a & 0 & 0 \\ -h_2^a & 0 & 0 \end{pmatrix} \]
\[ v^2 = v_1^2 + v_2^2 \]
\[ m_W^2 = \frac{g^2}{4} f^2 \sin^2 \frac{v}{f} \]
Custodial symmetry

The predicted leading order correction to the T parameter arises from the non-linearity of the GB lagrangian. In the SO(6)/SO(4)xSO(2) model is

\[ \hat{T} \propto 16 \times \frac{v^2}{f^2} \times \frac{\text{Im}[\langle H_1 \rangle^\dagger \langle H_2 \rangle]^2}{(|\langle H_1 \rangle|^2 + |\langle H_2 \rangle|^2)^2} \]

no freedom in the coefficient, fixed by the coset

possible solutions:

- CP
- C_2: (H_1 \rightarrow H_1, H_2 \rightarrow -H_2) which forbids H_2 to acquire a vev

FCNC

FCNC mediated by the heavy resonances

for example, for \( \Delta S = 2 \), \( \sim \frac{1}{m^*} \frac{m_d m_s}{v v} \)

\[ \sim \epsilon^i L \epsilon^j R \epsilon^k L \epsilon^l R \left( \frac{g^*}{m^*} \right)^2 a^{ijkl}, \quad a^{ijkl} \sim O(1) \]

- does not require an excessive and unnatural tuning of the parameters.
- flavour symmetries can also help to control these observables.
An issue with Higgs-mediated FCNC

the most general lagrangian is built from the H invariants in $\mathbf{r}_L \times \mathbf{r}_R$

$$-\mathcal{L}_{\text{yuk}} = a_{ij}^A (q_L^i \mathbf{r}_L^A U P A U^\dagger t_R^j \mathbf{r}_R^A + \text{h.c.})$$

$$U \equiv \exp(i \frac{\Pi}{f})$$

FCNC may arise if there are
- several non trivial invariants in the product $\mathbf{r}_L \times \mathbf{r}_R$
- multiple embeddings of the SM fermions in $\mathbf{r}_{L,R}$

For instance, $\mathbf{6} = \mathbf{4} + \mathbf{2}$, provides three invariants ($\mathbf{4} \cdot \mathbf{4}$, $\mathbf{2} \cdot \mathbf{2}$, $\mathbf{2} \wedge \mathbf{2}$) in $\mathbf{6} \times \mathbf{6}$ and two independent embeddings for $t_R$
An issue with Higgs-mediated FCNC

The most general lagrangian is built from the H invariants in $r_L \times r_R$

$$-\mathcal{L}_{\text{yuk}} = a_{ij}^A (\bar{q}_L^i r_L U P_A U^\dagger (t_R^j r_R) + \text{h.c.}$$

$$U \equiv \exp(i \frac{\Pi}{f})$$

FCNC may arise if there are
- several non trivial invariants in the product $r_L \times r_R$
- multiple embeddings of the SM fermions in $r_L, r_R$

For instance, $6 = 4 + 2$, provides three invariants $(4 \cdot 4, 2 \cdot 2, 2 \wedge 2)$ in $6 \times 6$ and two independent embeddings for $t_R$

FCNC can be removed by
1. assuming $C_2$ in the strong sector and in the mixings $\text{inert C2HDM}$
2. requiring (flavour) alignment in the Yukawa couplings $Y_1^{IJ} \propto Y_2^{IJ}$

$$Y_u^{ij} Q^i u^j (a_{1u} H_1 + a_{2u} H_2) + Y_d^{ij} Q^i d^j (a_{1d} H_1 + a_{2d} H_2) + Y_e^{ij} L^i e^j (a_{1e} H_1 + a_{2e} H_2) + \text{h.c.}$$

The ratio $a_1/a_2$ is predicted by the strong dynamics.
The effective potential

\[ V = m_1^2 H_1^+ H_1 + m_2^2 H_2^+ H_2 - \left[ m_3^2 H_1^+ H_2 + \text{h.c.} \right] + \frac{\lambda_1}{2} (H_1^+ H_1)^2 + \frac{\lambda_2}{2} (H_2^+ H_2)^2 + \lambda_3 (H_1^+ H_1)(H_2^+ H_2) + \lambda_4 (H_1^+ H_2)(H_2^+ H_1) + \frac{\lambda_5}{2} (H_1^+ H_2)^2 + \lambda_6 (H_1^+ H_1)(H_1^+ H_2) + \lambda_7 (H_2^+ H_2)(H_1^+ H_2) + \text{h.c.} \]

the entire effective potential is fixed by the parameters of the strong sector
and the scalar spectrum is fully predicted by the strong dynamics

without any tuning, the
minimum of the potential is \( v \sim f \)
\[ m_{\Pi}^2 \sim \frac{g^*}{16\pi^2} y^2 f^2 \]

while, in the tuned direction,
\[ m_h^2 \sim \frac{g^*}{16\pi^2} y^2 v^2 \]

\( m_3^2 \neq 0, \lambda_6 \neq 0, \lambda_7 \neq 0 \)
\[ \lambda_6 = \lambda_7 = \frac{5}{3} \frac{m_3^2}{f^2} \]

C\(_2\) breaking in the strong sector induces:
it is not possible to realise a 2HDM-like scenario with a softly broken Z\(_2\)
Sampling the parameter space

**C2HDM**: we adopt the L-R structure based on the 2-site models which represents the minimal choice for a realistic and calculable effective potential

\[
X = f, Y_1, Y_2, M_\Psi, \Delta_L, \Delta_R
\]

\[
600 \text{ GeV} < f < 3000 \text{ GeV} \quad |X| < 10f
\]

reconstruction of \(m_h\) and \(m_{\text{top}}\)

the output of the scan is tested against present experimental measurements

- HiggsBounds (*void Higgs boson searches*) and
- HiggsSignals (*parameter determinations from the discovered Higgs state*)
- $\tan \beta$ is predicted by the strong sector
- $m_h$ and $m_{\text{top}}$ require $\tan \beta \sim O(1-10)$
- Larger tuning at large $f$

- $m_H, m_A, m_{H^+}$ grow with $f$ (and $\tan \beta$)

\[
\mathcal{M}^2 = \begin{pmatrix}
\Lambda_1 v^2 & \Lambda_6 v^2 \\
\Lambda_6 v^2 & \mathcal{M}_{22}^2
\end{pmatrix}
\]

fixed by minimisation of $V$

unconstrained $\mathcal{M}_{22} \sim f$

- In the limit $f \to \infty$ (+ EWSB), we recover the SM (not the E2HDM)
the SM-like Higgs coupling to $W,Z$ \[ \kappa_V = \left( 1 - \frac{\xi}{2} \right) \cos \theta, \quad \xi \equiv \frac{\nu_{SM}^2}{f^2} \]

the alignment limit is approached more slowly in the C2HDM than in an elementary 2HDM (e.g. MSSM) a relevant deviation is present even for no mixing
Phenomenology of $H$

the coupling of the heavy Higgs $H$ to the SM top quark is controlled by

$$
\zeta_t = \frac{\tilde{\zeta}_t - \tan \beta}{1 + \tilde{\zeta}_t \tan \beta} \quad \tilde{\zeta}_t = \frac{Y_1^t}{Y_2^t}
$$

the $Htt$ and $Hhh$ couplings are strongly correlated and carry the imprint of compositeness

$H \to tt$ represents the main decay mode

below the $tt$ threshold, $H \to hh$ dominates ($BR(H \to hh) \sim 80\%, BR(H \to VV) \sim 20\%$)
interplay between indirect and direct searches
\[ gg \rightarrow H \rightarrow hh \rightarrow bb\gamma\gamma \]

end of Run 3

HL-LHC and HE-LHC

colour legend:
- **green**: points that pass present constraints at 13 TeV
- **red**: points that have \( \kappa_v, \kappa_\gamma \) and \( \kappa_\xi \) within 95% CL projected uncertainty at \( L = 300 \text{ fb}^{-1} \) (left) and \( L = 3000 \text{ fb}^{-1} \) (right) (arXiv:1307.7135)
- **orange**: points that are 95% CL excluded by direct search at \( L = 300 \text{ fb}^{-1} \) (left) and \( L = 3000 \text{ fb}^{-1} \) (right) (CMS PAS HIG-17-008)
- **yellow**: points that are 95% CL excluded by direct search at the HE-LHC (right)
interplay between indirect and direct searches
gg → H → tt (semileptonic)

end of Run 3

HL-LHC

colour legend:
- **green**: points that pass present constraints at 13 TeV
- **red**: points that have $\kappa_V$, $\kappa_\gamma$ and $\kappa_\xi$ within 95% CL projected uncertainty at $L = 300 \text{ fb}^{-1}$ (left) and $L = 3000 \text{ fb}^{-1}$ (right)  (arXiv:1307.7135)
- **blue**: points that are 95% CL excluded by direct search at $L = 300 \text{ fb}^{-1}$ (left) and $L = 3000 \text{ fb}^{-1}$ (right)  (arXiv:1804.10823)
a C2HDM is the simplest natural 2HDM alternative to SUSY

we considered the SO(6)/SO(4)xSO(2) scenario with a broken C\textsubscript{2} which realises a (type-III) Composite 2HDM

nice interplay between indirect and direct searches (involving \(H\)) that can be exploited during the upgraded phases of the LHC

other interesting scenarios: exact C\textsubscript{2}, spontaneously broken C\textsubscript{2}, broken CP

other interesting channels: A and H\(^+\) production and decay modes