Aligned two-doublet model

Alejandro Celis

Ludwig-Maximilians-Universität München

50th Rencontres de Moriond EW 2015
Contents

- Motivations to consider an enlarged scalar sector
- A scalar sector with two doublets
  - Tree-level FCNCs and Yukawa alignment
  - Flavour and collider phenomenology
- Conclusions
Motivations

**ATLAS and CMS combined mass**

M. Duehrssen talk

\[ m_H = 125.09 \pm 0.24 \text{ GeV (0.19\% precision!)} \]
\[ = 125.09 \pm 0.21(\text{stat.}) \pm 0.11(\text{syst.}) \text{ GeV} \]

The 125 GeV boson data is in good agreement with the SM
Flavour exp. & EWPD also agree with the SM picture of EWSB

\[ \text{SU}(2)_L \times \text{U}(1)_Y \rightarrow \text{U}(1)_{\text{em}} \]
due to the vev of a scalar doublet

**considering an extended scalar sector**

Dark matter, the BAU, the strong CP problem, \( \nu \) masses, \ldots

adding scalar singlets and doublets

\[ \Rightarrow \rho_{\text{tree}} = \frac{M_W^2}{M_Z^2 c_W^2} = \frac{\sum_i [T_i (T_i + 1) - Y_i^2]}{2 \sum_i Y_i^2 v_i^2} \]

\[ = 1 \]

P. Langacker (1981)
Adding a second scalar doublet

\[ \langle \phi_i^0 \rangle = v_i / \sqrt{2} \quad (i = 1, 2) \quad v = \sqrt{v_1^2 + v_2^2}, \quad \tan \beta = v_2 / v_1 \]

5 scalar fields: \( H^\pm, \phi_i^0 = (h, H, A) \)  \([3 \times 3 \text{ mixing } \mathcal{R}_{ij}]\)

(M\(_h\) \leq M_H)

In the CP-conserving limit:

\[
\mathcal{R} = \begin{bmatrix}
\cos \tilde{\alpha} & \sin \tilde{\alpha} & 0 \\
-\sin \tilde{\alpha} & \cos \tilde{\alpha} & 0 \\
0 & 0 & 1
\end{bmatrix}, \quad \kappa_{\phi_i^0} = g_{\phi_i^0VV} / g_{\text{SM}VV} = \mathcal{R}_{i1}
\]

\((VV = W^+W^-, ZZ)\)

\(\text{tree-level unitarity sum-rule}\)

\[(\kappa_{hV}^2 + (\kappa_{HV}^2) = 1\]

Assuming \( h \) is the observed scalar boson

The scalar \( h \) plays a major role in the restoration of perturbative unitarity in \( W_LW_L \) scattering
Yukawa sector

\[ \mathcal{L}_Y = -\bar{Q}_L (\Gamma_1 \phi_1 + \Gamma_2 \phi_2) d'_R \cdots \Rightarrow -\frac{\sqrt{2}}{v} \bar{Q}_L (M'_d \Phi_1 + Y'_d \Phi_2) d'_R \cdots \]

(same for \(u_R\) and \(\ell_R\) Yukawas)

\[ \langle \Phi_1^0 \rangle = v/\sqrt{2}, \quad \langle \Phi_2^0 \rangle = 0 \]

\(M'_f\) \& \(Y'_f\) unrelated \quad \text{(not simultaneously diagonal)} \Rightarrow \quad \text{FCNCs}

Solutions:

• **Natural Flavour Conservation** \quad \text{Glashow-Weinberg, Paschos (77)}

  \[ \Gamma_1 = 0 \text{ or } \Gamma_2 = 0 \quad (\mathcal{Z}_2 \text{ models}) \]

• **Yukawa Alignment** \quad \text{Pich-Tuzon (09)}

  \[ \Gamma_1 \propto \Gamma_2 \Rightarrow Y_{d,l} = \varsigma_{d,l} M_{d,l}, \quad Y_u = \varsigma_u^* M_u \]

\(\varsigma_f\) : family universal complex parameters \quad \text{(new sources of CP-violation beyond CKM)}

• **BGL models** “controlled” FCNCs \quad \text{symmetries} \quad \text{Branco-Grimus-Lavoura (96)}
\( \mathcal{Z}_2 \) models

Yukawas: (SM units)

\[
y_{d,l}^\phi_0 = R_{i1} + (R_{i2} + iR_{i3}) \varsigma_{d,l}
y_{u}^\phi_0 = R_{i1} + (R_{i2} - iR_{i3}) \varsigma_u^*
\]

Usual \( \mathcal{Z}_2 \) models recovered in particular (CP-conserving) limits of the Aligned two-doublet model

<table>
<thead>
<tr>
<th>Model</th>
<th>( \varsigma_d )</th>
<th>( \varsigma_u )</th>
<th>( \varsigma_l )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type I</td>
<td>( \cot \beta )</td>
<td>( \cot \beta )</td>
<td>( \cot \beta )</td>
</tr>
<tr>
<td>Type II</td>
<td>( -\tan \beta )</td>
<td>( \cot \beta )</td>
<td>( -\tan \beta )</td>
</tr>
<tr>
<td>Type X</td>
<td>( \cot \beta )</td>
<td>( \cot \beta )</td>
<td>( -\tan \beta )</td>
</tr>
<tr>
<td>Type Y</td>
<td>( -\tan \beta )</td>
<td>( \cot \beta )</td>
<td>( \cot \beta )</td>
</tr>
</tbody>
</table>

Implications of \( h(125) \) data for \( \mathcal{Z}_2 \) models

Bernon-Dumont-Kraml (14); Ferreira et al, Eberhardt-Nierste-Wiebusch,...
Yukawa Alignment

Constraints from tree-level flavour processes

\[ \mathcal{L} \supset -\frac{\sqrt{2}}{\nu} H^+ \{ \bar{u} [\zeta_d V_{CKM} M_d \mathcal{P}_R - \zeta_u M_u V_{CKM} \mathcal{P}_L] d + \zeta_l \bar{\nu} M_l \mathcal{P}_R l \} + \text{h.c.} \]

\[ R(D^{(*)}) = \frac{\Gamma(B \rightarrow D^{(*)} \tau - \bar{\nu}_\tau)}{\Gamma(B \rightarrow D^{(*)} \ell - \bar{\nu}_\ell)} \]

BaBar (2012) (Belle results using full data sample not available yet)

\( R(D) \) & \( R(D^*) \) show 2.0\( \sigma \) and 2.7\( \sigma \) excess with respect to the SM

The excess in \( R(D^*) \) cannot be accommodated within the A2HDM  

AC-Jung-Li-Pich (13)
Yukawa Alignment

Constraints from loop-induced processes

• $|\varsigma_d|$ and $|\varsigma_l|$ not strongly constrained from flavour observables.

• $Z \rightarrow \bar{b}b \ (R_b) \Rightarrow |\varsigma_u| \lesssim 2$ for $M_{H^\pm} \leq 500 \text{ GeV}$

• Constraints on the $\varsigma_u - \varsigma_d$ plane from $\bar{B} \rightarrow X_s \gamma$

95% CL, $M_{H^\pm} \in [80, 500] \text{ GeV}$

Jung-Pich-Tuzon (10)

For type II:

$\varsigma_d = -\varsigma_u^{-1} = - \tan \beta$

$M_{H^+} > 480 \text{ GeV} \ (95\% \text{ CL})$

Misiak et al. (15)

CP-violating phases are strongly constrained by EDM experiments

Jung-Pich (14)
Yukawa Alignment

Rich phenomenology at the LHC

Altmannshofer et al., Barger et al., AC-Ilisie-Pich, Cervero-Gerard, Lopez-Val et al...

LHC measurements of $h(125)$ properties imply strong bounds on the couplings of additional scalars

$$|\kappa^h V| > 0.80 \Rightarrow |\kappa^H V| < 0.6 \quad (90\% \text{ CL}) \quad \text{AC-Ilisie-Pich (13)}$$

*tree-level unitarity sum-rules*

$$|y^h_f|^2 + |y^H_f|^2 - |y^A_f|^2 = 1, \quad \kappa^h V y^h_f + \kappa^H V y^H_f = 1$$

Gunion-Haber-Wudka (91), Grzadkowski-Gunion-Kalinowski (00), Ginzburg-Krawczyk (05), AC-Ilisie-Pich (13)

$$\Rightarrow |y^H_u|^2 - |y^A_u|^2 \in [-0.6, 0.5], \quad \kappa^H V y^H_u \in [-0.17, 0.5]$$

$$|y^H_d|^2 - |y^A_d|^2 \in [-1.2, 0.9], \quad \kappa^H V y^H_d \in [-0.3, 0.7] \cup [1.3, 2.5]$$

(similar bounds for charged leptons)

These sum-rules are useful handles to test the scalar sector if additional scalars are discovered at the LHC
Yukawa Alignment

Interplay between $h(125)$ measurements and flavour constraints

- $|\varsigma_d|$ and $|\varsigma_l|$ not strongly constrained from flavour observables.

- Measurements of $h(125)$ properties imply strong bounds on $|\varsigma_d|$ and $|\varsigma_l|$ for $\kappa_h^V < 1$

$LHC \ & \ Tevatron \ data \implies |y_d^h| \sim 1$ with $y_d^h = \cos \tilde{\alpha} + \sin \tilde{\alpha} \varsigma_d$

similar bounds for charged leptons

(flipped sign-Yukawa region)

Yukawas of additional neutral scalars:

$$y_d^H = -\sin \tilde{\alpha} + \cos \tilde{\alpha} \varsigma_d \quad , \quad y_d^A = i\varsigma_d$$
Yukawa Alignment

Direct searches for a charged scalar at colliders

\[ M_{H^\pm} \gtrsim 80 \text{ GeV (95\% CL)} \quad \text{LEP} \]

Search for a light charged scalar via top decay at the LHC

\[ t \rightarrow bH^+ \ (M_{H^\pm} < m_t - m_b) \]

- \[ \Gamma(H^+ \rightarrow \bar{c} \bar{b}) \sim \Gamma(H^+ \rightarrow c\bar{s}, \tau^+ \nu_\tau) \] for \[ |\varsigma_d| \gg |\varsigma_u|, |\varsigma_l| \]

Strong bounds on the alignment parameters, complementary to flavour constraints
Flavour-violating top decays

Loop-level processes in the SM with strong GIM and CKM suppression

the top quark decays dominantly into $t \rightarrow W^+ b$, with $\Gamma(t \rightarrow W^+ b)/m_t \sim 1\%$

<table>
<thead>
<tr>
<th>Observable</th>
<th>SM prediction</th>
<th>Exp. Limit</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\text{Br}(t \rightarrow c\gamma)$</td>
<td>$\sim 4 \times 10^{-14}$</td>
<td>$&lt; 1.8 \times 10^{-3}$ CMS</td>
</tr>
<tr>
<td>$\text{Br}(t \rightarrow cZ)$</td>
<td>$\sim 10^{-14}$</td>
<td>$&lt; 5 \times 10^{-4}$ CMS</td>
</tr>
<tr>
<td>$\text{Br}(t \rightarrow ch)$</td>
<td>$\sim 3 \times 10^{-15}$</td>
<td>$&lt; 5.6 \times 10^{-3}$ CMS</td>
</tr>
</tbody>
</table>

\[
\frac{\text{Br}(t \rightarrow uX)}{\text{Br}(t \rightarrow cX)} \simeq |V_{ub}/V_{cb}|^2 \\
\quad \sim 7 \times 10^{-3}
\]

very large enhancements possible for $t \rightarrow ch$ from intermediate $H^\pm$

Eilam-Hewett-Soni (91), Bejar-Guasch-Sola (01), Arhrib (05)

\[
\mathcal{A}_{t \rightarrow ch} \propto \xi_2^2 \lambda_{H^+H^-}^h \\
\text{Flavour and } h(125) \text{ constraints} \\
\Rightarrow t \rightarrow ch \text{ beyond reach of high-luminosity phase of the LHC}
\]

Abbas-AC-Li-Lu-Pich (in preparation)
Conclusions

Testing extended scalar sectors involves a rich interplay between $h(125)$ coupling measurements, searches for additional scalars, EWPD and flavour experiments

The Aligned two-doublet model:

- General setting without FCNCs & new sources of CP violation
- Rich phenomenology at the LHC $H^\pm$, $\varphi_i^0 = (h, H, A)$
- Usual $\mathbb{Z}_2$ models recovered in particular (CP-conserving) limits

Constraints from $h(125)$ data on the properties of additional scalars are manifest in the form of unitarity sum rules
The speaker’s attendance at this conference was sponsored by the Alexander von Humboldt Foundation.

http://www.humboldt-foundation.de