Aligned two-doublet model

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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

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

The 125 GeV boson data is in good agreement with the SM

Flavour exp. & EWPD also agree with the SM picture of EWSB

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

considering an extended scalar sector

Dark matter, the BAU, the strong CP problem, ν masses, ...

adding scalar singlets and doublets

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

P. Langacker (1981)

Adding a second scalar doblet

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

5 scalar fields: $H^\pm,\ \varphi_i^0 = (h, H, A)$ $\qquad$ [3×3 mixing $\mathcal{R}_{ij}$]

$(M_h \leq M_H)$

In the CP-conserving limit:

$$\mathcal{R} = \begin{bmatrix} \cos\tilde{\alpha} & \sin\tilde{\alpha} & 0 \\ -\sin\tilde{\alpha} & \cos\tilde{\alpha} & 0 \\ 0 & 0 & 1 \end{bmatrix}\,, \qquad \kappa_V^{\varphi_i^0} \equiv g_{\varphi_i^0 VV}/g_{hVV}^{\mathsf{SM}} = \mathcal{R}_{i1}$$

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

tree-level unitarity sum-rule

$$(\kappa_{\mathbf{V}}^{\mathbf{h}})^{\mathbf{2}} + (\kappa_{\mathbf{V}}^{\mathbf{H}})^{\mathbf{2}} = \mathbf{1}$$

Assuming h is the observed scalar boson

The scalar h plays a major role in the restoration of perturbative unitarity in $W_L W_L$ scattering

Yukawa sector

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

(same for u_R and ℓ_R Yukawas) $\langle\Phi_1^0\rangle = v/\sqrt{2}\,,\ \ \langle\Phi_2^0\rangle = 0$

$\mathbf{M'_f}$ & $\mathbf{Y'_f}$ **unrelated** (not simultaneously diagonal) $\Rightarrow$ **FCNCs**

Solutions:

- **Natural Flavour Conservation** Glashow-Weinberg, Paschos (77)

  $\Gamma_1 = 0$ or $\Gamma_2 = 0$ ($\mathcal{Z}_2$ models)

- **Yukawa Alignment** Pich-Tuzon (09)

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

ς_f : family universal complex parameters (new sources of CP-violation beyond CKM)

- **BGL models** "controlled" FCNCs (symmetries) Branco-Grimus-Lavoura (96)

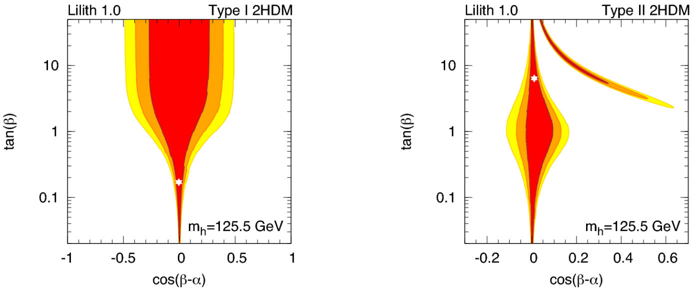
$\mathcal{Z}_2$ models

Yukawas: (SM units)

$$y_{d,l}^{\varphi_i^0} = \mathcal{R}_{i1} + (\mathcal{R}_{i2} + i\mathcal{R}_{i3})\,\varsigma_{d,l}$$
$$y_u^{\varphi_i^0} = \mathcal{R}_{i1} + (\mathcal{R}_{i2} - i\mathcal{R}_{i3})\,\varsigma_u^*$$

Model	ς_d	ς_u	ς_l
Type I	$\cot\beta$	$\cot\beta$	$\cot\beta$
Type II	$-\tan\beta$	$\cot\beta$	$-\tan\beta$
Type X	$\cot\beta$	$\cot\beta$	$-\tan\beta$
Type Y	$-\tan\beta$	$\cot\beta$	$\cot\beta$

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



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

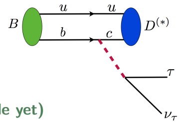
Bernon-Dumont-Kraml (14); Ferreira et al, Eberhardt-Nierste-Wiebusch,...

Yukawa Alignment

Constraints from tree-level flavour processes

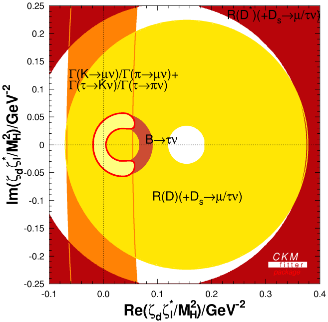
$$\mathcal{L} \supset -\frac{\sqrt{2}}{v}\, H^+ \left\{ \bar{u} \left[\varsigma_d\, V_{\text{CKM}} M_d \mathcal{P}_R - \varsigma_u\, M_u V_{\text{CKM}} \mathcal{P}_L \right] d + \varsigma_l\, \bar{\nu} M_l \mathcal{P}_R l \right\} + \text{h.c.}$$

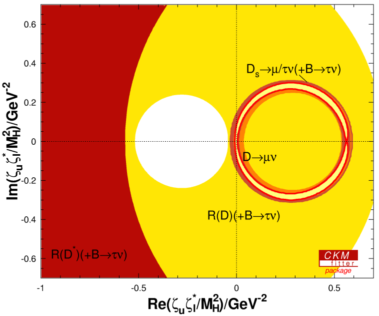
$$R(D^{(*)}) = \frac{\Gamma(\bar{B}\to D^{(*)}\tau^-\bar{\nu}_\tau)}{\Gamma(\bar{B}\to D^{(*)}\ell^-\bar{\nu}_\ell)}$$



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

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



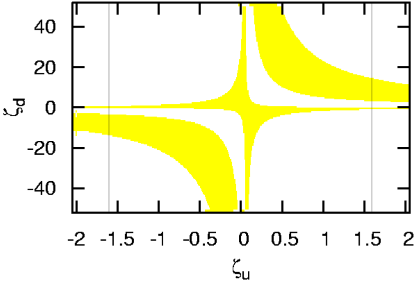


The excess in $R(D^*)$ cannot be accommodated within the A2HDM **AC-Jung-Li-Pich (13)**

Yukawa Alignment

Constraints from loop-induced processes

- $|\varsigma_d|$ and $|\varsigma_l|$ not strongly constrained from flavour observables.
- $Z \to \bar{b}b$ $(R_b) \Rightarrow |\varsigma_u| \lesssim 2$ for $M_{H^\pm} \leq 500$ GeV
- Constraints on the $\varsigma_u - \varsigma_d$ plane from $\bar{B} \to X_s \gamma$



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

Jung-Pich-Tuzon (10)

For type II:

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

$M_{H^+} > 480$ GeV (95% 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 $\mathrm{h}(125)$ properties imply strong bounds on the couplings of additional scalars

$|\kappa_V^h| > 0.80 \Rightarrow |\kappa_V^H| < 0.6$ (90% CL) AC-Ilisie-Pich (13)

tree-level unitarity sum-rules

$$|\mathbf{y_f^h}|^2 + |\mathbf{y_f^H}|^2 - |\mathbf{y_f^A}|^2 = \mathbf{1}\,, \qquad \kappa_\mathbf{V}^\mathbf{h}\,\mathbf{y_f^h} + \kappa_\mathbf{V}^\mathbf{H}\,\mathbf{y_f^H} = \mathbf{1}$$

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

$$\Rightarrow \quad |y_u^H|^2 - |y_u^A|^2 \in [-0.6, 0.5]\,, \qquad \kappa_V^H\, y_u^H \in [-0.17, 0.5]$$

$$|y_d^H|^2 - |y_d^A|^2 \in [-1.2, 0.9]\,, \qquad \kappa_V^H\, y_d^H \in [-0.3, 0.7] \cup [1.3, 2.5]$$

(similar bounds for charged leptons)

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

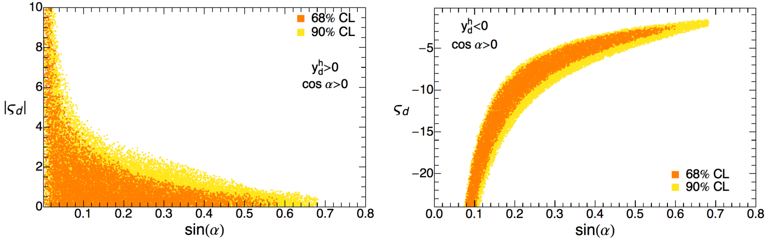
Yukawa Alignment

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

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

- **Measurements of $\mathbf{h(125)}$ properties imply strong bounds on $|\varsigma_d|$ and $|\varsigma_l|$ for $\kappa_{\mathbf{V}}^{\mathbf{h}} < 1$**

LHC & Tevatron data $\Rightarrow |\mathbf{y_d^h}| \sim \mathbf{1}$ with $\mathbf{y_d^h} = \cos\tilde{\alpha} + \sin\tilde{\alpha}\,\varsigma_{\mathbf{d}}$



similar bounds for charged leptons (flipped sign-Yukawa region)

Yukawas of additional neutral scalars:

$$y_d^H = -\sin\tilde{\alpha} + \cos\tilde{\alpha}\,\varsigma_d \;, \qquad y_d^A = i\varsigma_d$$

Yukawa Alignment

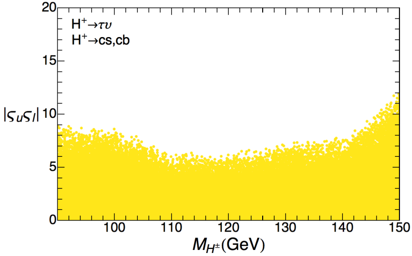
Direct searches for a charged scalar at colliders

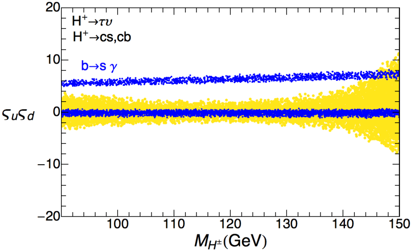
$M_{H^\pm} \gtrsim 80$ GeV (95% CL) LEP

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

$\mathbf{t \to bH^+}$ $(M_{H^\pm} < m_t - m_b)$

- $\Gamma(H^+ \to c\bar{b}) \sim \Gamma(H^+ \to c\bar{s}, \tau^+\nu_\tau)$ 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

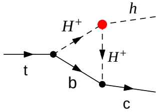
the top quark decays dominantly into $t \to W^+ b$, with $\mathbf{\Gamma(t \to W^+ b)/m_t \sim 1\%}$

Observable	SM prediction	Exp. Limit
$\mathrm{Br}(t \to c\gamma)$	$\sim 4 \times 10^{-14}$	$< 1.8 \times 10^{-3}$ CMS
$\mathrm{Br}(t \to cZ)$	$\sim 10^{-14}$	$< 5 \times 10^{-4}$ CMS
$\mathrm{Br}(t \to ch)$	$\sim 3 \times 10^{-15}$	$< 5.6 \times 10^{-3}$ CMS

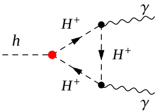
$$\frac{\mathrm{Br}(t \to uX)}{\mathrm{Br}(t \to cX)} \simeq |V_{ub}/V_{cb}|^2 \sim 7 \times 10^{-3}$$

very large enhancements possible for $\mathrm{t \to ch}$ from intermediate $H^\pm$

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



$\mathcal{A}_{t\to ch} \propto \varsigma_{\mathbf{d}}^{\mathbf{2}}\, \lambda^{\mathbf{h}}_{\mathbf{H^+H^-}}$



$|\lambda^{\mathbf{h}}_{\mathbf{H^+H^-}}|$ constrained by $h \to \gamma\gamma$

Flavour and $h(125)$ constraints

$\Rightarrow$ $t \to ch$ 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 $\mathrm{h}(125)$ 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 $\mathcal{Z}_2$ models recovered in particular (CP-conserving) limits**

Constraints from $\mathrm{h}(125)$ data on the properties of additional scalars are manifest in the form of unitarity sum rules

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http://www.humboldt-foundation.de