Status of the Aligned two Higgs doublet model in the low mass region

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Based on: Upcoming paper

ICHEP2024, Prague
17th - 24th July, 2024

Motivation

➠ **2HDM:** SM + another scalar doublet.

➠ **Prospects:** New sources of CP violation, Axion-like phenomenology, Dark matter aspects, Electroweak Baryogenesis, Stability of scalar potential till Planck scale, EFT for SUSY, etc.

➠ **Problems:** **FCNC**

➠ **Solutions:** 1) Additional $\mathcal{Z}_2$ symmetry, 2) **A2HDM**

➠ **A2HDM:** The Yukawa matrices corresponding to two scalars are proportional to each other.

➠ **Advantages:** 1) More generic framework to study 2HDM.
2) There could be additional sources of CP violation.
3) Rich phenomenology.

Pich, Tuzon PRD 80 (2009) 091702; Ferreira, Lavoura, Silva PLB 688 (2010) 341; Jung, Pich, Tuzon JHEP 11 (2010) 003; Braeuninger, Ibarra, Simonetto PLB 692 (2010) 189; Bijnens, Lu, Rathsman JHEP 05 (2012) 118; Li, Lu, Pich JHEP 06 (2014) 022; Abbas, et al. JHEP 06 (2015) 005; Botella, et al. EPJC 75 (2015) 286; Gori, Haber, Santos JHEP 06 (2017) 110; Kanemura, Mondal, Yagyu JHEP 02 (2023) 237; etc...

➠ **This talk:** **Possibility of light scalars**

➠ **Heavy case:** Karan, Miralles, Pich PRD 109 (2024) 3; Eberhardt, Peñuelas, Pich JHEP 05 (2021) 005

The Model: A2HDM

Scalar Potential

$$\phi_a : \langle 0 | \, \phi_a^T \, | 0 \rangle = (0, v_a e^{i\theta_a}) \quad a \in \{1, 2\}$$

Global $SU(2)$ $\Longrightarrow$ "Higgs basis"

$$\Phi_a : \quad \Phi_1 = \frac{1}{\sqrt{2}} \begin{pmatrix} \sqrt{2}\, G^+ \\ S_1 + v + i\, G^0 \end{pmatrix}, \quad \Phi_2 = \frac{1}{\sqrt{2}} \begin{pmatrix} \sqrt{2}\, H^+ \\ S_2 + i\, S_3 \end{pmatrix}$$

Goldstone: G^+, G^0 — Charged: H^+ — CP-even: S_1, S_2 — CP-odd: S_3

$$\begin{pmatrix} h \\ H \end{pmatrix} = \begin{pmatrix} \cos\tilde{\alpha} & \sin\tilde{\alpha} \\ -\sin\tilde{\alpha} & \cos\tilde{\alpha} \end{pmatrix} \begin{pmatrix} S_1 \\ S_2 \end{pmatrix} \quad \text{and} \quad A = S_3 \,.$$

✏ **Scalar Potential:**

$$V = \mu_1 \Phi_1^\dagger \Phi_1 + \mu_2 \Phi_2^\dagger \Phi_2 + \left[\boldsymbol{\mu_3} \Phi_1^\dagger \Phi_2 + h.c. \right] + \frac{\lambda_1}{2} (\Phi_1^\dagger \Phi_1)^2 + \frac{\lambda_2}{2} (\Phi_2^\dagger \Phi_2)^2 + \lambda_3 (\Phi_1^\dagger \Phi_1)(\Phi_2^\dagger \Phi_2)$$
$$+ \lambda_4 (\Phi_1^\dagger \Phi_2)(\Phi_2^\dagger \Phi_1) + \left[\left(\frac{\boldsymbol{\lambda_5}}{2} \Phi_1^\dagger \Phi_2 + \boldsymbol{\lambda_6} \Phi_1^\dagger \Phi_1 + \boldsymbol{\lambda_7} \Phi_2^\dagger \Phi_2 \right) (\Phi_1^\dagger \Phi_2) + \mathrm{h.c.} \right].$$

✏ **Gauge-Higgs Coupling:**

$$C_{hVV} = \cos\tilde{\alpha}\; C_{hVV}^{SM}\,, \quad C_{HVV} = -\sin\tilde{\alpha}\; C_{hVV}^{SM}\,, \quad C_{AVV} = 0\,, \quad VV \equiv (W^+W^-,\, ZZ)$$

Fermionic interaction

- **Yukawa interaction:**

$$-\mathcal{L}_Y = \left(1+\frac{S_1}{v}\right)\left\{\bar{u}_L\, M_u\, u_R + \bar{d}_L\, M_d\, d_R + \bar{\ell}_L\, M_\ell\, \ell_R\right\} + \frac{1}{v}\,(S_2 + iS_3)\left\{\bar{u}_L\, Y_u\, u_R + \bar{d}_L\, Y_d\, d_R + \bar{\ell}_L\, Y_\ell\, \ell_R\right\} + \frac{\sqrt{2}}{v}\, H^+ \left\{\bar{u}_L\, V\, Y_d\, d_R - \bar{u}_R\, Y_u^\dagger\, V\, d_L + \bar{\nu}_L\, Y_\ell\, \ell_R\right\} + \mathrm{h.c.}\,,$$

- **Alignment:** $Y_u = \varsigma_u^*\, M_u$ and $Y_{d,\ell} = \varsigma_{d,\ell}\, M_{d,\ell}\,,$

$$-\mathcal{L}_Y = \sum_{i,f}\left(\frac{y_f^{\varphi_i^0}}{v}\right)\varphi_i^0\left[\bar{f}M_f\mathcal{P}_R f\right] + \left(\frac{\sqrt{2}}{v}\right)H^+\left[\bar{u}\left\{\varsigma_d V M_d \mathcal{P}_R - \varsigma_u M_u^\dagger V \mathcal{P}_L\right\} d + \varsigma_\ell\,\bar{\nu} M_\ell \mathcal{P}_R \ell\right] + \mathrm{h.c.}$$

$$y_u^H = -\sin\tilde{\alpha} + \varsigma_u^*\,\cos\tilde{\alpha}\,,\qquad y_u^h = \cos\tilde{\alpha} + \varsigma_u^*\,\sin\tilde{\alpha}\,,\qquad y_u^A = -i\varsigma_u^*\,,$$
$$y_{d,\ell}^H = -\sin\tilde{\alpha} + \varsigma_{d,\ell}\,\cos\tilde{\alpha}\,,\qquad y_{d,\ell}^h = \cos\tilde{\alpha} + \varsigma_{d,\ell}\,\sin\tilde{\alpha}\,,\qquad y_{d,\ell}^A = i\varsigma_{d,\ell}.$$

Type I: $\varsigma_u = \varsigma_d = \varsigma_\ell = \cot\beta$, **Type II:** $\varsigma_u = -\frac{1}{\varsigma_d} = -\frac{1}{\varsigma_\ell} = \cot\beta\,,$ **Inert:** $\varsigma_u = \varsigma_d = \varsigma_\ell = 0\,,$

Type X: $\varsigma_u = \varsigma_d = -\frac{1}{\varsigma_\ell} = \cot\beta$ and **Type Y:** $\varsigma_u = -\frac{1}{\varsigma_d} = \varsigma_\ell = \cot\beta\,.$

Constraints

1. Stability of Scalar Potential

- **Z_2-sym cases:** $\lambda_{1,2} > 0, \quad \lambda_3 + \sqrt{\lambda_1\lambda_2} > 0, \quad \lambda_3 + \lambda_4 - |\lambda_5| + \sqrt{\lambda_1\lambda_2} > 0.$

- **Bounded from below:** $V = -\,\mathtt{M}_\mu\,\mathtt{r}^\mu + \frac{1}{2}\,\Lambda^\mu{}_\nu\,\mathtt{r}_\mu\,\mathtt{r}^\nu\,,$ where,

$$\mathtt{M}_\mu = \left(-\frac{\mu_1+\mu_2}{2},\, -\mathrm{Re}\,\mu_3,\, \mathrm{Im}\,\mu_3,\, -\frac{\mu_1-\mu_2}{2}\right),$$

$$\mathtt{r}^\mu = \left(|\Phi_1|^2 + |\Phi_2|^2,\, 2\,\mathrm{Re}(\Phi_1^\dagger\Phi_2),\, 2\,\mathrm{Im}(\Phi_1^\dagger\Phi_2),\, |\Phi_1|^2 - |\Phi_2|^2\right),$$

$$\Lambda^\mu{}_\nu = \frac{1}{2}\begin{pmatrix} \frac{1}{2}(\lambda_1+\lambda_2)+\lambda_3 & \mathrm{Re}(\lambda_6+\lambda_7) & -\mathrm{Im}(\lambda_6+\lambda_7) & \frac{1}{2}(\lambda_1-\lambda_2) \\ -\mathrm{Re}(\lambda_6+\lambda_7) & -\lambda_4-\mathrm{Re}\lambda_5 & \mathrm{Im}\lambda_5 & -\mathrm{Re}(\lambda_6-\lambda_7) \\ \mathrm{Im}(\lambda_6+\lambda_7) & \mathrm{Im}\lambda_5 & -\lambda_4+\mathrm{Re}\lambda_5 & \mathrm{Im}(\lambda_6-\lambda_7) \\ -\frac{1}{2}(\lambda_1-\lambda_2) & -\mathrm{Re}(\lambda_6-\lambda_7) & \mathrm{Im}(\lambda_6-\lambda_7) & -\frac{1}{2}(\lambda_1+\lambda_2)+\lambda_3 \end{pmatrix}.$$

✓ ***The necessary & sufficient conditions for bounded below potential :***

1. All the eigenvalues ($\Lambda_{0,1,2,3}$) of $\Lambda^\mu{}_\nu$ are real.
2. $\Lambda_0 > 0$ with $\Lambda_0 > \Lambda_i \ \forall\, i \in \{1,2,3\}$.

For several necessary conditions:

H. Bahl, et al., JHEP 03 (2023) 165

- **Absolute stability:** $D = Det[\xi\,\mathbb{I}_4 - \Lambda^\mu{}_\nu] = -\prod_{k=0}^{3}(\xi - \Lambda_k)$ with $\xi = \frac{m_{H^\pm}^2}{v^2}$.

✓ ***The conditions for global minimum :*** 1) $D > 0$, or 2) $D < 0$ with $\xi > \Lambda_0$.

Ivanov, PRD 75 (2007) 035001; Ivanov and Silva, PRD 92 (2015) 055017

2. LO Perturbativity

❍ **Tree-level partial-wave amplitudes:** $(\mathcal{A}_0)_{i,f} = \frac{1}{16\pi s}\int_{-s}^{0} dt\, \mathcal{M}_{i\to f}(s,t)$

❍ **Eigenvalues in the j th partial wave:** $(a_0^j)^2 \leq 1/4$

❍ There are fourteen neutral, eight single-charged and three doubly-charged two-body scalar $2 \to 2$ scattering states. $\Longrightarrow$ $a_0^{(0,+1,+2)} = \frac{1}{16\pi}\left(\oplus \{X_{Y,\sigma}\}\right)$

$$X_{(1,0)} = \lambda_3 - \lambda_4\,,$$

$$X_{(1,1)} = \begin{pmatrix} \lambda_1 & \lambda_5 & \sqrt{2}\lambda_6 \\ \lambda_5^* & \lambda_2 & \sqrt{2}\lambda_7^* \\ \sqrt{2}\lambda_6^* & \sqrt{2}\lambda_7^* & \lambda_3+\lambda_4 \end{pmatrix}, \quad X_{(0,1)} = \begin{pmatrix} \lambda_1 & \lambda_4 & \lambda_6 & \lambda_6^* \\ \lambda_4 & \lambda_2 & \lambda_7 & \lambda_7^* \\ \lambda_6^* & \lambda_7^* & \lambda_3 & \lambda_5^* \\ \lambda_6 & \lambda_7 & \lambda_5 & \lambda_3 \end{pmatrix},$$

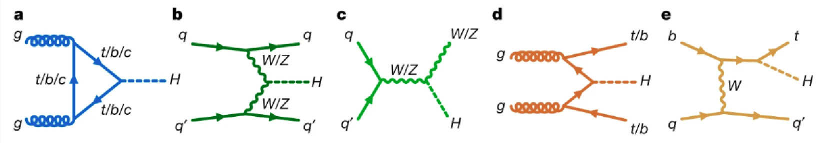
$$X_{(0,0)} = \begin{pmatrix} 3\lambda_1 & 2\lambda_3+\lambda_4 & 3\lambda_6 & 3\lambda_6^* \\ 2\lambda_3+\lambda_4 & 3\lambda_2 & 3\lambda_7 & 3\lambda_7^* \\ 3\lambda_6^* & 3\lambda_7^* & \lambda_3+2\lambda_4 & 3\lambda_5^* \\ 3\lambda_6 & 3\lambda_7 & 3\lambda_5 & \lambda_3+2\lambda_4 \end{pmatrix}.$$

❍ **Eigenvalues of $X_{(a,b)}$:** $|e_i| < 8\pi$

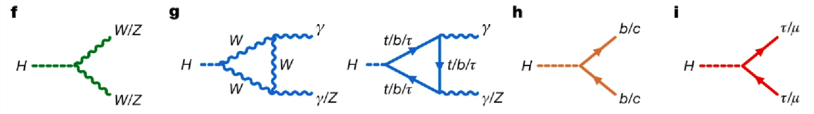
Ginzburg, Ivanov, PRD 72 (2005) 115010; H. Bahl, et al., JHEP 03 (2023) 165

❍ **Charged scalar coupling to fermions:** $\sqrt{2}\,|\varsigma_f| m_f/v < 1$

3. Signal Strength



SM Higgs Production channels at LHC



SM Higgs Decay channels

ATLAS, Nature 607(2022) 52–59

Signal strength: $\mu_{XY} = \dfrac{\sigma(pp \to h)\ Br(h \to XY)}{[\sigma(pp \to h)\ Br(h \to XY)]_{SM}}$

Modifications: $C_{hVV} \to \cos\tilde{\alpha}\ C^{SM}_{hVV}$ and $C_{hff} \to y^h_f\ C^{SM}_{hff} \to \hat{f}(\varsigma_f, \tilde{\alpha})\ C^{SM}_{hff}$

Data: ATLAS and CMS (8 TeV and 13 TeV)

4. EWPO & Flavour Observables

➠ **EWPO:** We remove $R_b = \frac{\Gamma(Z \to b\bar{b})}{\Gamma(Z \to hadrons)}$ from the global fit of EW precision data to fit S,T,U.

➠ **Loop Processes:** ΔM_{B_s}, $B \to X_s \gamma$, $B_s \to \mu\mu$ (and R_b)

➠ **Tree level Processes:** $B \to \tau\nu$, $D_{(s)} \to \tau\nu$, $D_{(s)} \to \mu\nu$, $\frac{\Gamma(K \to \mu\nu)}{\Gamma(\pi \to \mu\nu)}$, $\frac{\Gamma(\tau \to K\nu)}{\Gamma(\tau \to \pi\nu)}$

Data: PDG Phys. Rev. D 110, 030001 (2024)

We fit the CKM parameters form the observables that are not contaminated by the presence of additional scalars.

5. Collider Searches

Scalar production: cern twiki

Scalar Decay: HDECAY

Pseudoscalar: Madgraph5_aMC@NLO, HIGLU, HDECAY

Data: CMS & ATLAS (8 TeV & 13 TeV)

Light Scalars

- $pp \to h \to \phi_i \phi_i$
- $pp \to h \to \phi_i Z$
- $pp \to \phi_i b\bar{b}$
- $pp \to \phi_i t\bar{t}$
- $pp \to \phi_i \to \gamma\gamma$
- $pp \to \phi_i \to f\bar{f}$
- $pp \to t \to H^+ b$

Heavy Scalars

- $pp \to \phi_i \to hh$
- $pp \to \phi_i \to hZ$
- $pp \to \phi_i \to \phi_j Z$
- $pp \to \phi_i \to VV$
- $pp \to \phi_i \to Z\gamma$
- $pp \to \phi_i \to f\bar{f}$
- $pp \to H^+ \to f'\bar{f}$

LEP data

- $e^+e^- \to Z^* \to \phi_i Z$
- $e^+e^- \to Z^* \to \phi_i \phi_j$
- $e^+e^- \to Z^* \to H^+ H^-$

Invisible width

h,Z,W

Global Fits

(preliminary result)

Fit Set Up

- **Generic Scenario:**

☆ **Parameters:** $\varsigma_{u,d,l}, \mu_1, \mu_2, \mu_3, \lambda_{1,2,3,4}, \lambda_{5,6,7} \implies (6+14)$ parameters.

☆ **Minimization Condition:** $v^2 = -\frac{2\mu_1}{\lambda_1} = -\frac{2\mu_3}{\lambda_6}$

☆ **Independent parameters:** $\varsigma_{u,d,l}$, v, μ_2, $\lambda_{1,2,3,4}$, $|\lambda_{5,6,7}|$, two rel. phases $[\lambda_{5,6,7}]$.
$\implies (6+11)$ parameters.

- **CP conserving case:**

☆ **Parameters:** $(3+9)$ parameters.

☆ **Masses:** $M^2_{H\pm} = \mu_2 + \frac{\lambda_3}{2} v^2$, $\quad M^2_{h,H} = \frac{1}{2}(\Sigma \mp \Delta)$, $\quad M^2_A = M^2_{H\pm} + \frac{v^2}{2}(\lambda_4 - \lambda_5)$,
with $\quad \Sigma = M^2_{H\pm} + \left(\lambda_1 + \frac{\lambda_4}{2} + \frac{\lambda_5}{2}\right) v^2 \quad$ and $\quad \Delta = \sqrt{\left(\Sigma - 2\lambda_1 v^2\right)^2 + 4\,\lambda_6^2\, v^4}$.

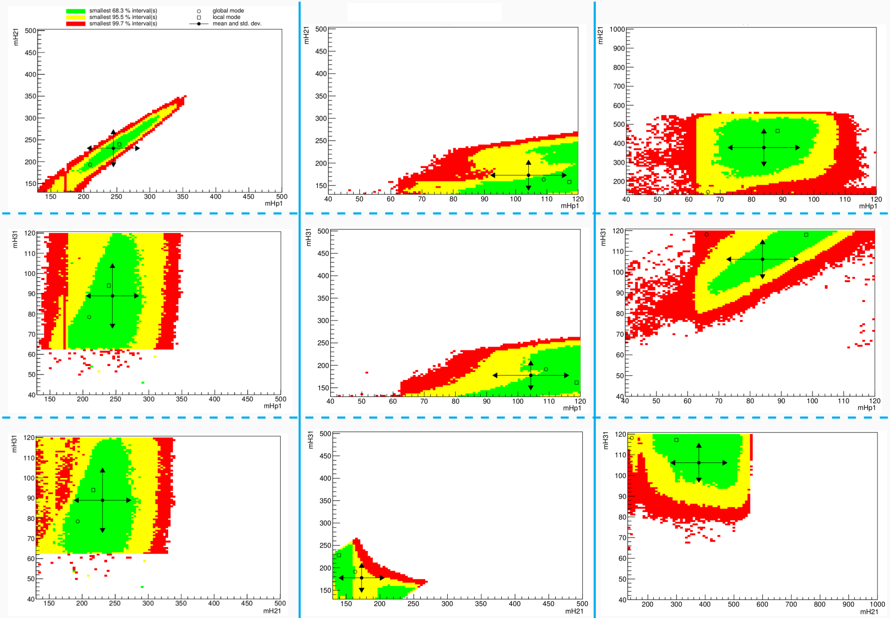
☆ **Mixing angle:** $\tan\tilde{\alpha} = \frac{M_h^2 - v^2\,\lambda_1}{v^2\,\lambda_6} = \frac{v^2\,\lambda_6}{v^2\,\lambda_1 - M_H^2}$.

☆ **Final Parameters:** ~~v~~, ~~M_h~~, $M_{H\pm}$, M_H, M_A, $\tilde{\alpha}$, λ_2, λ_3, λ_7 and $\varsigma_{u,d,l}$
$\implies (3+7)$ parameters.

- **Package:** `HEPfit` **(Bayesian approach)** de Blas et al., Eur.Phys.J.C 80 (2020) 5, 456

- **Scenarios:** 1) Light A, 2) Light H^+, 3) Light A and H^+

mH21$\equiv M_H$, mH31$\equiv M_A$, mHp1$\equiv M_{H^\pm}$

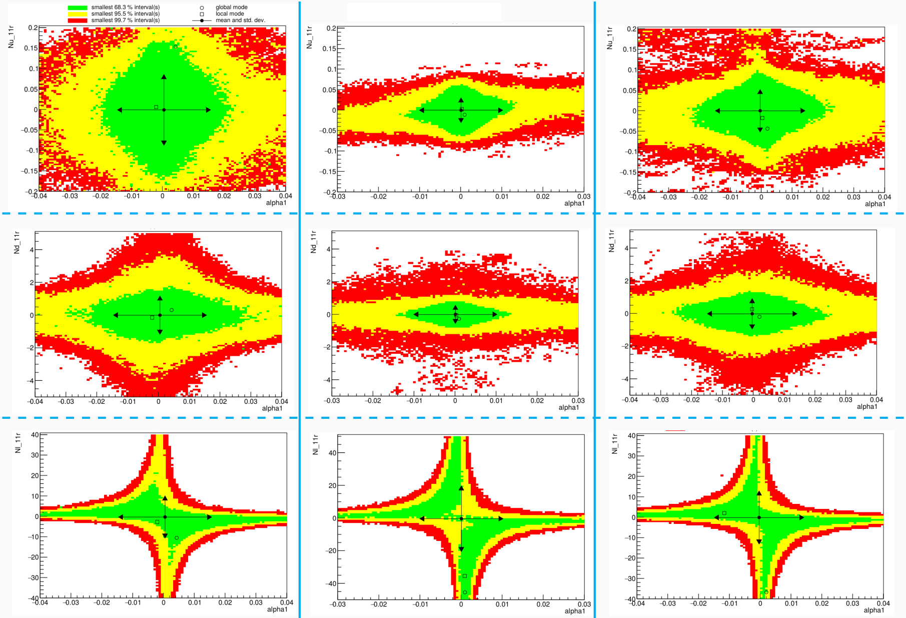


Light A

Light H^+

Light A & H^+

alpha1 $\equiv \tilde{\alpha}$, $Nf\_11r \equiv \varsigma_f$



Light A | **Light H^+** | **Light A & H^+**

Take home message

It seems that there exist viable regions of parameter-space allowed by different theoretical and experimental bounds below 125 GeV of mass for the three scenarios: 1) Light A, 2) Light H^+, 3) Light A and H^+ in A2HDM.

Thank you for your attention!!