Extensions of the Standard Model scalar sector

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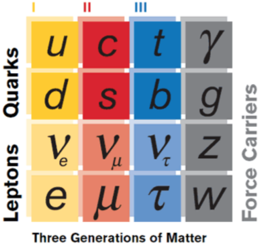
Introduction. Standard Model

- The SM is the theory better describing elementary particles and their interactions



- Local gauge invariance under $SU(3)_C \otimes SU(2)_L \otimes U(1)_Y \Rightarrow$ massless particles

- To generate masses $\Rightarrow$ spontaneously symmetry breaking
- We introduce the complex doublet
$$\phi(x) = \begin{bmatrix} \phi^{(+)}(x) \\ \phi^{(0)}(x) \end{bmatrix}$$
- Minimum of the potential for
$$\begin{bmatrix} 0 \\ \sqrt{\frac{-\mu^2}{2h}} \end{bmatrix} = \begin{bmatrix} 0 \\ \frac{v}{\sqrt{2}} \end{bmatrix}$$
- $\rightarrow \phi(x) = \frac{1}{\sqrt{2}} \begin{bmatrix} 0 \\ v + H(x) \end{bmatrix}$

Introduction. Motivation

- The Higgs mechanism is the simplest to generate masses in the SM

- Different alternatives would both reproduce the content of the SM as well as including some new ingredients

$$\rho = \frac{M_W^2}{M_Z^2 \cos^2\theta_{\rm w}} = \sum_i \frac{v_i^2[T_i(T_i+1) - Y_i^2]}{2\sum_i v_i^2 Y_i^2} = 1\,,$$

Introduction. Motivation

- The experimental data will be connected through μ

$$\mu = \frac{\sigma(pp \to h_2 Y)}{\sigma(pp \to HY)_{SM}} \frac{\mathrm{BR}(h_2 \to X)}{\mathrm{BR}(H \to X)_{SM}}$$

- The χ^2 function will be minimized

$$\chi^2(\varphi_i^0) = \sum_k \frac{\left(\mu_k^{\varphi_i^0} - \mu_k\right)^2}{\sigma_k^2},$$

Overview

Higgs singlet extension. The model

- Simplest extension of the SM: A real bosonic singlet invariant under all the quantum numbers of the SM is added (φ)

doing $\varphi \to \varphi + \langle\varphi\rangle$

$$V(\phi,\varphi) = \mu^2(\phi^\dagger\phi) + h(\phi^\dagger\phi)^2 + (a\varphi + b\varphi^2 + c\varphi^3 + d\varphi^4) \\ +(\phi^\dagger\phi)(A\varphi + B\varphi^2) + V_0$$

with $h > 0, d > 0, B > 0$ (increasing), $\det H > 0$ (bounded) i $\mu^2 < 0$

$$\langle 0|\,\phi\,|0\rangle = \begin{bmatrix} 0 \\ \frac{v}{\sqrt{2}} \end{bmatrix}, \qquad \langle 0|\,\varphi\,|0\rangle = 0\,.$$

$$\phi(x) = e^{i\frac{\sigma_i}{2}\theta^i(x)}\frac{1}{\sqrt{2}}\begin{bmatrix} 0 \\ v + H(x) \end{bmatrix} \xrightarrow{\text{unitary gauge}} \frac{1}{\sqrt{2}}\begin{bmatrix} 0 \\ v + H(x) \end{bmatrix},$$

$$\varphi(x) \xrightarrow{\text{unitary gauge}} \varphi(x)\,.$$

Higgs singlet extension. The model

$$V = \underbrace{-\frac{1}{4}hv^4 + V_0' +}_{V_0} \underbrace{(hvH^3 + \frac{h}{4}H^4)}_{\text{Higgs self-interactions}} + \underbrace{(c\varphi^3 + d\varphi^4)}_{\varphi \text{ self-interactions}}$$

$$+ \underbrace{\frac{1}{2}M_H^2 H^2 + \frac{1}{2}M_\varphi^2 \varphi^2 + Av\varphi H}_{\text{mass terms}} + \underbrace{Bv\varphi^2 H + \frac{1}{2}AH^2\varphi + \frac{1}{2}BH^2\varphi^2}_{\text{H-}\varphi \text{ interactions}},$$

$$\begin{bmatrix} h_1 \\ h_2 \end{bmatrix} = \begin{bmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{bmatrix} \begin{bmatrix} H \\ \varphi \end{bmatrix}, \qquad m^2_{h_{1,2}} = \frac{M_H^2 + M_\varphi^2}{2} \pm \frac{|M_H^2 - M_\varphi^2|}{2}\sqrt{1 + \tan^2 2\theta}\,.$$

Phenomenology and fits

$$\mathcal{L}_{\mathrm{Y}} = -\frac{1}{\sqrt{2}}\left(1 + \frac{h_1 \cos\theta - h_2 \sin\theta}{v}\right)\left(c_2 \overline{d} d + c_2 \overline{u} u + c_3 \overline{e} e\right).$$

- Reduction of the couplings with respect to the SM

$$\kappa_V^{h_1} \equiv g_{h_1 VV} / g_{HVV}^{SM} = \cos\theta\,, \qquad \kappa_f^{h_1} \equiv y_{h_1 ff} / y_{Hff}^{SM} = \cos\theta\,,$$
$$\kappa_V^{h_2} \equiv g_{h_2 VV} / g_{HVV}^{SM} = -\sin\theta\,, \qquad \kappa_f^{h_2} \equiv y_{h_2 ff} / y_{Hff}^{SM} = -\sin\theta\,.$$

$$\Gamma_{h_1} = \Gamma_{SM} \cos^2\theta + \underbrace{\Gamma_{h_1 \to h_2 h_2}}_{\text{if allowed}}\,,$$
$$\Gamma_{h_2} = \Gamma_{SM} \sin^2\theta\,.$$

$$\Gamma_{h_1 \to h_2 h_2} = \frac{|\widetilde{\mu}|^2}{8\pi m_{h_1}} \sqrt{1 - \frac{4 m_{h_2}^2}{m_{h_1}^2}}\,,$$

Phenomenology and fits. Heavy scenario

- The cross sections

$$\frac{\sigma(pp \to h_2 Y)}{\sigma(pp \to HY)_{SM}} = \sin^2\theta\,.$$

- For the branching ratios

$$\frac{\mathrm{BR}(h_2 \to X)}{\mathrm{BR}(H \to X)_{SM}} = \frac{\Gamma(h_2 \to X)}{\Gamma_{h_2}} \frac{\Gamma_{H,SM}}{\Gamma(H \to X)_{SM}} = \frac{\sin^2\theta}{1}\frac{1}{\sin^2\theta} = 1\,.$$

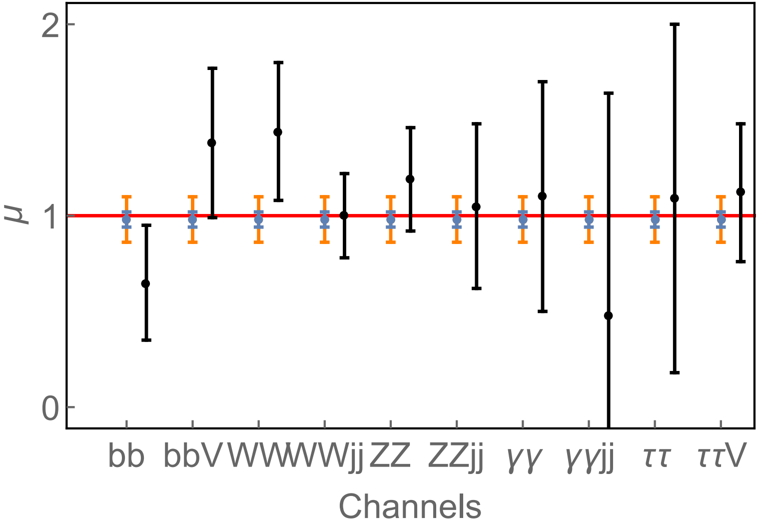
- All the strengths are identical

$$\mu = \sin^2\theta$$

Results of the fit (χ^2)

$$\sin\theta = 0.99 \pm 0.01\,, \qquad \chi^2/\text{d.o.f.} = 0.55$$

Phenomenology and fits. Heavy scenario



Phenomenology and fits. Light scenario

- The cross sections

$$\frac{\sigma(pp \to h_1 Y)}{\sigma(pp \to HY)_{SM}} = \cos^2\theta\,.$$

- For the branching ratios, with the additional decay

$$\frac{\mathrm{BR}(h_1 \to X)}{\mathrm{BR}(H \to X)_{SM}} = \frac{\Gamma_{h_1 \to X}}{\Gamma_{h_1}}\,\frac{\Gamma_{H,SM}}{\Gamma_{H\to X,SM}}$$

$$= \frac{\cos^2\theta\Gamma_{H,SM}}{\cos^2\theta\Gamma_{H,SM} + \Gamma_{h_1\to h_2 h_2}} = \frac{1}{1 + \frac{\Gamma_{h_1\to h_2h_2}}{\cos^2\theta\Gamma_{H,SM}}}\,.$$

- All the strengths are identical

$$\mu = \cos^2\theta \times \frac{1}{1 + \frac{\Gamma_{h_1\to h_2h_2}}{\cos^2\theta\Gamma_{H,SM}}} = \frac{\cos^4\theta}{\cos^2\theta + \frac{\Gamma_{h_1\to h_2h_2}}{\Gamma_{H,SM}}}\,.$$

Results of the fit (χ^2)

$$\cos\theta = 0.99 \pm 0.01\,, \quad \Gamma_{h_1\to h_2h_2} = 0\,, \qquad \chi^2/\text{d.o.f.} = 0.55$$

Overview

A2HDM. Scalar potential and symmetry breaking

- A doublet with the same quantum numbers of the SM one is added

$$\phi_1 = \begin{bmatrix} \phi_1^{(+)} \\ \phi_1^{(0)} \end{bmatrix}, \qquad \phi_2 = \begin{bmatrix} \phi_2^{(+)} \\ \phi_2^{(0)} \end{bmatrix}.$$

- General form of the vev

$$\langle 0|\, \phi_1 \,|0\rangle = \frac{1}{\sqrt{2}} \begin{bmatrix} 0 \\ v_1 e^{i\theta_1} \end{bmatrix}, \qquad \langle 0|\, \phi_2 \,|0\rangle = \frac{1}{\sqrt{2}} \begin{bmatrix} 0 \\ v_2 e^{i\theta_2} \end{bmatrix}.$$

- $U(1)$ transformation to eliminate one of the phases

$$\langle 0|\, \phi_1 \,|0\rangle = \frac{1}{\sqrt{2}} \begin{bmatrix} 0 \\ v_1 \end{bmatrix}, \qquad \langle 0|\, \phi_2 \,|0\rangle = \frac{1}{\sqrt{2}} \begin{bmatrix} 0 \\ v_2 e^{i\theta_2 - \theta_1} \end{bmatrix} = \frac{1}{\sqrt{2}} \begin{bmatrix} 0 \\ v_2 e^{i\varepsilon} \end{bmatrix}.$$

A2HDM. Scalar potential and symmetry breaking

- $SU(2)$ transformation in the scalar space $(\phi_1, \phi_2) \rightarrow$ just one of the doublets acquire a vev

$$\begin{bmatrix} \Phi_1 \\ -\Phi_2 \end{bmatrix} = \frac{1}{v} \begin{bmatrix} v_1 & v_2 \\ v_2 & -v_1 \end{bmatrix} \begin{bmatrix} \phi_1 \\ e^{-i\varepsilon}\phi_2 \end{bmatrix} = \frac{1}{v} \begin{bmatrix} v_1\phi_1 + e^{-i\varepsilon} v_2\phi_2 \\ v_2\phi_1 - e^{-i\varepsilon} v_1\phi_2 \end{bmatrix},$$

with $v^2 = v_1^2 + v_2^2$.

- Excitations over the vacuum

$$\Phi_1 = \begin{bmatrix} G^+ \\ \frac{1}{\sqrt{2}}(v + S_1 + iG^0) \end{bmatrix}, \qquad \Phi_2 = \begin{bmatrix} H^+ \\ \frac{1}{\sqrt{2}}(S_2 + iS_3) \end{bmatrix}.$$

$$\begin{aligned} V &= \mu_1^2(\Phi_1^\dagger\Phi_1) + \mu_2^2(\Phi_2^\dagger\Phi_2) + [\mu_3\Phi_1^\dagger\Phi_2 + \mu_3^*\Phi_2^\dagger\Phi_1] \\ &+\lambda_1(\Phi_1^\dagger\Phi_1)^2 + \lambda_2(\Phi_2^\dagger\Phi_2)^2 + \lambda_3(\Phi_1^\dagger\Phi_1)(\Phi_2^\dagger\Phi_2) + \lambda_4(\Phi_1^\dagger\Phi_2)(\Phi_2^\dagger\Phi_1) \\ &+\Big[(\lambda_5\Phi_1^\dagger\Phi_2 + \lambda_6\Phi_1^\dagger\Phi_1 + \lambda_7\Phi_2^\dagger\Phi_2)(\Phi_1^\dagger\Phi_2) + \mathrm{h.c.}\Big]. \end{aligned}$$

A2HDM. Scalar potential and symmetry breaking

- Mass terms

$$V_2 = M_{H^\pm}^2 H^+ H^- + \frac{1}{2} \begin{bmatrix} S_1, & S_2, & S_3 \end{bmatrix} \mathcal{M} \begin{bmatrix} S_1 \\ S_2 \\ S_3 \end{bmatrix} ,$$

- Mass matrix

$\lambda_i^I \equiv \Im(\lambda_i),\ \lambda_i^R \equiv \Re(\lambda_i)$

$$\mathcal{M} = \begin{bmatrix} 2\lambda_1 v^2 & v^2 \lambda_6^R & -v^2 \lambda_6^I \\ v^2 \lambda_6^R & M_{H^\pm}^2 + v^2 (\frac{\lambda_4}{2} + \lambda_5^R) & -v^2 \lambda_5^I \\ -v^2 \lambda_6^I & -v^2 \lambda_5^I & M_{H^\pm}^2 + v^2 \left(\frac{\lambda_4}{2} - \lambda_5^R \right) \end{bmatrix} .$$

$$\begin{bmatrix} h \\ H \\ A \end{bmatrix} = \mathcal{R} \begin{bmatrix} S_1 \\ S_2 \\ S_3 \end{bmatrix} \xrightarrow[\lambda_i^I = 0]{\text{CP-conserving limit}} \begin{bmatrix} h \\ H \end{bmatrix} = \begin{bmatrix} \cos\tilde{\alpha} & \sin\tilde{\alpha} \\ -\sin\tilde{\alpha} & \cos\tilde{\alpha} \end{bmatrix} \begin{bmatrix} S_1 \\ S_2 \end{bmatrix} ,$$

$$A = S_3 .$$

A2HDM. Yukawa sector

- The new doublet has the same quantum numbers as the one of the SM $\Rightarrow$ more terms in the Yukawa Lagrangian

$$\mathcal{L}_Y = -\bar{\mathbf{Q}}'_L(\mathbf{\Gamma}_1\phi_1 + \mathbf{\Gamma}_2\phi_2)\mathbf{d}'_R - \bar{\mathbf{Q}}'_L(\mathbf{\Delta}_1\tilde{\phi}_1 + \mathbf{\Delta}_2\tilde{\phi}_2)\mathbf{u}'_R$$
$$- \bar{\mathbf{L}}'_L(\mathbf{\Pi}_1\phi_1 + \mathbf{\Pi}_2\phi_2)\mathbf{l}'_R + \mathrm{h.c.}$$

- In the Higgs basis

$$\mathcal{L}_Y = -\frac{\sqrt{2}}{v}\Big(\bar{\mathbf{Q}}'_L(\mathbf{M}'_d\Phi_1 + \mathbf{Y}'_d\Phi_2)\mathbf{d}'_R - \bar{\mathbf{Q}}'_L(\mathbf{M}'_u\tilde{\Phi}_1 + \mathbf{Y}'_u\tilde{\Phi}_2)\mathbf{u}'_R$$
$$-\bar{\mathbf{L}}'_L(\mathbf{M}'_l\Phi_1 + \mathbf{Y}'_l\Phi_2)\mathbf{l}'_R + \mathrm{h.c}\Big)$$

- $\mathbf{M}'_a$ can be diagonalized by performing transformations in the fields and introducing the CKM matrix
- Nothing guarantees us that the matrices $\mathbf{Y}'_a$ will be diagonal $\Rightarrow$ it can give flavour changing neutral currents (FCNC)

A2HDM. Yukawa sector

- To avoid FCNC we require that $\mathbf{Y}'_a$ and $\mathbf{M}'_a$ are aligned in flavour space

$$\Gamma_2 = \varepsilon_d e^{-i\varepsilon}\Gamma_1\,, \qquad \Delta_2 = \varepsilon_u^* e^{i\varepsilon}\Delta_1\,, \qquad \Pi_2 = \varepsilon_l e^{-i\varepsilon}\Pi_1\,.$$

- And we have

$$\mathbf{Y}'_a = \varsigma_a^{(*)}\mathbf{M}'_a\,,$$

- Yukawa Lagrangian

$$\mathcal{L}_Y = -\frac{\sqrt{2}}{v}H^+\left\{\bar{u}(x)[\varsigma_d V\mathbf{M}_d\mathcal{P}_R - \varsigma_u\mathbf{M}_u^\dagger V\mathcal{P}_L]d(x) + \varsigma_l\bar{\nu}(x)\mathbf{M}_l\mathcal{P}_R l(x)\right\}$$
$$-\frac{1}{v}\sum_{\varphi_i^0,f} y_f^{\varphi_i^0}\varphi_i^0[\bar{f}(x)\mathbf{M}_f\mathcal{P}_R f(x)] + \mathrm{h.c.}\,.$$

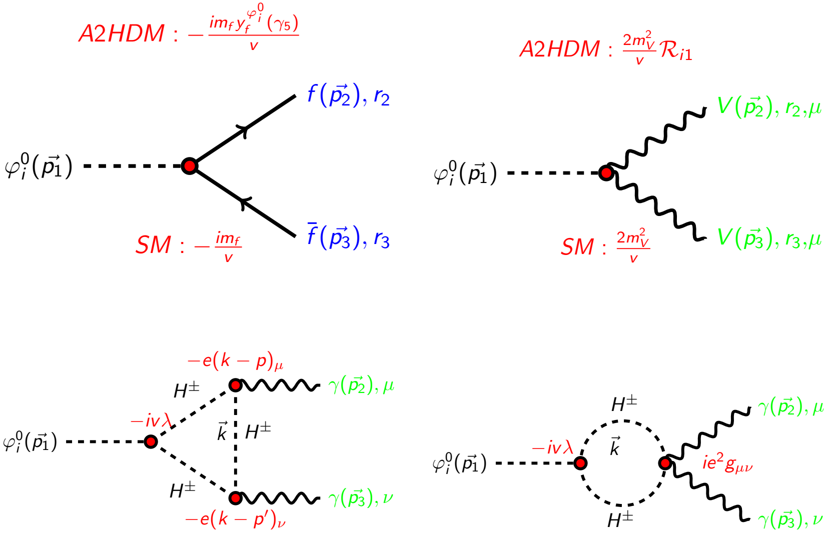
A2HDM. Yukawa Sector

Consequences of the alignment

- All the couplings scalars-fermions are proportional to the masses
- The Yukawas are diagonal in flavour

- The only contribution to interactions changing flavour is given by the CKM matrix
- There is only three new parameters, ς_f (in general complex)
- The couplings satisfy universality among generations

A2HDM. Phenomenology and Higgs signal strengths



A2HDM. Fit of light CP-even Higgs with $H^\pm$ loop

- With the signs of yu and $\cos\tilde{\alpha}$ chosen as in the SM and in the CP-conserving limit

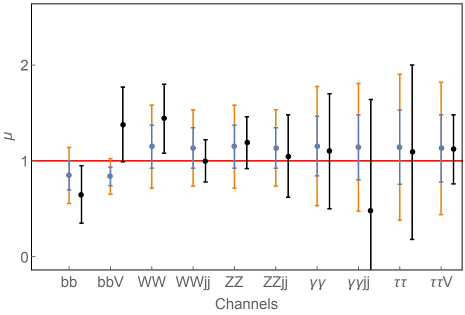
Results of the fit

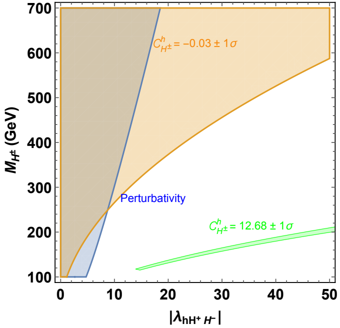
$$\cos\tilde{\alpha} = 0.98^{+0.02}_{-0.05}\,, \qquad \mathcal{C}^h_{H^\pm} = (-0.03^{+0.70}_{-0.61} \cup 12.68^{+0.70}_{-0.67})\,,$$
$$y^h_u = 0.98 \pm 0.08\,, \quad |y^h_d| = 0.84^{+0.08}_{-0.09}\,, \quad |y^h_l| = 0.97^{+0.14}_{-0.16}\,.$$

with $\chi^2/\text{d.o.f} = 0.59$

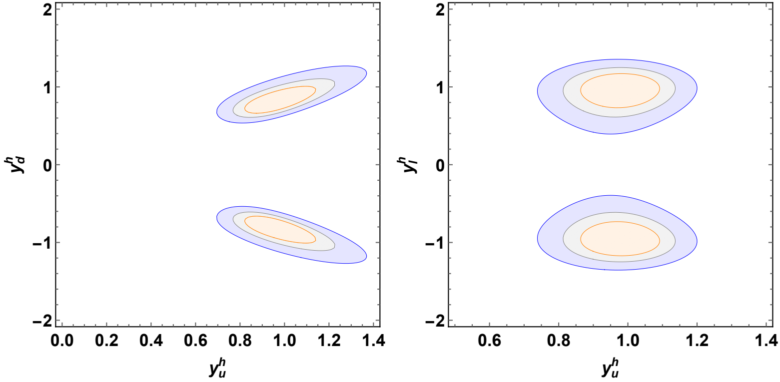
$$\mathcal{C}^{\varphi^0_i}_{H^\pm} = \frac{v^2}{2M^2_{H_\pm}} \lambda_{\varphi^0_i H^+ H^-} \mathcal{A}(x_{H_\pm})\,.$$

A2HDM. Fit of light CP-even Higgs with $H^{\pm}$ loop





A2HDM. Fit of light CP-even Higgs with $H^{\pm}$ loop



A2HDM. Fit of light CP-odd Higgs

- $\mathcal{R}_{31} = 0$ so A does not couple to bosons at tree level
- $\mu^A_{bbV} = \mu^A_{\tau\tau V} = \mu^A_{\gamma\gamma jj} = \mu^A_{VV} = \mu^A_{VVjj} = 0$

Results of the fit

$$|y_u^A| = 0.84 \pm 0.07\,, \quad |y_d^A| = 0.34^{+0.10}_{-0.08}\,, \quad |y_l^h| = 0.35^{+0.09}_{-0.12}\,.$$

with $\chi^2/\text{d.o.f.} = 11.6$

Overview

Conclusions

- Motivation for the study of extensions $\rightarrow$ aspects of nature not explained only by the SM + freedom to extend the scalar sector
- Singlet extension: A real bosonic singlet invariant under all the SM quantum number $\rightarrow$ 2 scalars (Higgs-like)
- A2HDM: Two doublets with the same quantum numbers as the Higgs doublet$\rightarrow$ 3 scalar neutral particles ($\{S_i\}_{i=1,2,3}$) + 2 charged particles $H^{\pm}$
- Statistical analysis of the models with the LHC data. Best fit A2HDM, CP-even
- Interesting aspects of the models: CP-violation, dark matter...

A2HDM. Yukawa sector

- $y_f^{\varphi^0}$ are the couplings for the physical fields

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

- With the relations

$$\sum_{i=1}^{3} (y_f^{\varphi_i^0})^2 = 1\,, \quad \sum_{i=1}^{3} |y_f^{\varphi_i^0}|^2 = 1 + 2|\varsigma_f|^2\,, \quad \sum_{i=1}^{3} y_f^{\varphi_i^0}\mathcal{R}_{i1} = 1\,,$$

$$\sum_{i=1}^{3} y_{d,l}^{\varphi_i^0}\mathcal{R}_{i2} = \varsigma_{d,l}\,, \qquad \sum_{i=1}^{3} y_u^{\varphi_i^0}\mathcal{R}_{i2} = \varsigma_u^*\,,$$

$$\sum_{i=1}^{3} y_{d,l}^{\varphi_i^0}\mathcal{R}_{i3} = i\varsigma_{d,l}\,, \qquad \sum_{i=1}^{3} y_u^{\varphi_i^0}\mathcal{R}_{i3} = -i\varsigma_u^*\,.$$

A2HDM. Phenomenology and Higgs signal strengths

$$\mu_{bb}^{\varphi_i^0} = C_{gg}^{\varphi_i^0} \left[\Re(y_d^{\varphi_i^0})^2 + \Im(y_d^{\varphi_i^0})^2 \beta_b^{-2} \right] \rho(\varphi_i^0)^{-1},$$

$$\mu_{\gamma\gamma}^{\varphi_i^0} = C_{gg}^{\varphi_i^0} C_{\gamma\gamma}^{\varphi_i^0} \rho(\varphi_i^0)^{-1},$$

$$\mu_{\tau\tau}^{\varphi_i^0} = C_{gg}^{\varphi_i^0} \left[\Re(y_l^{\varphi_i^0})^2 + \Im(y_l^{\varphi_i^0})^2 \beta_\tau^{-2} \right] \rho(\varphi_i^0)^{-1},$$

$$\mu_{\gamma\gamma jj}^{\varphi_i^0} = (\mathcal{R}_{i1})^2 C_{\gamma\gamma}^{\varphi_i^0} \rho(\varphi_i^0)^{-1},$$

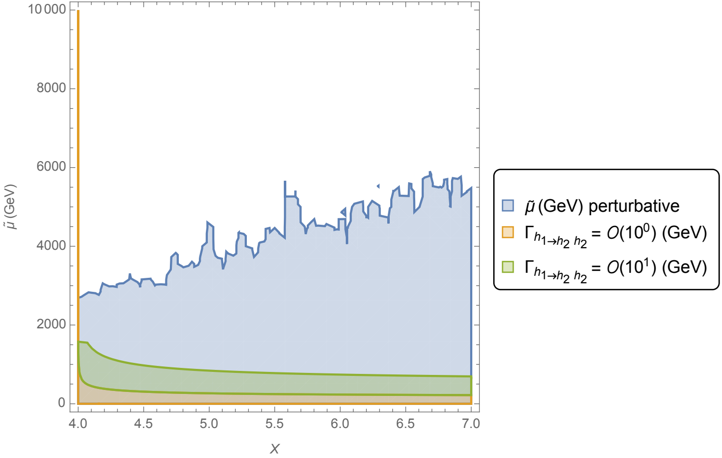
$$\mu_{bbV}^{\varphi_i^0} = (\mathcal{R}_{i1})^2 \left[\Re(y_d^{\varphi_i^0})^2 + \Im(y_d^{\varphi_i^0})^2 \beta_b^{-2} \right] \rho(\varphi_i^0)^{-1},$$

$$\mu_{VV}^{\varphi_i^0} = C_{gg}^{\varphi_i^0} (\mathcal{R}_{i1})^2 \rho(\varphi_i^0)^{-1},$$

$$\mu_{\tau\tau V}^{\varphi_i^0} = (\mathcal{R}_{i1})^2 \left[\Re(y_l^{\varphi_i^0})^2 + \Im(y_l^{\varphi_i^0})^2 \beta_\tau^{-2} \right] \rho(\varphi_i^0)^{-1},$$

$$\mu_{VVjj}^{\varphi_i^0} = (\mathcal{R}_{i1})^4 \rho(\varphi_i^0)^{-1},$$

Phenomenology and fits. Heavy scenario



A2HDM. Fit light CP-even Higgs without $H^{\pm}$ loop

Fit results $yu > 0$ and $\cos\tilde{\alpha} > 0$

$$\cos\tilde{\alpha} = 0.98^{+0.02}_{-0.06}\,,\; y_u^h = 0.98 \pm 0.08\,,\; |y_d^h| = 0.84^{+0.08}_{-0.09}\,,\; |y_l^h| = 0.97^{+0.14}_{-0.16}\,,$$

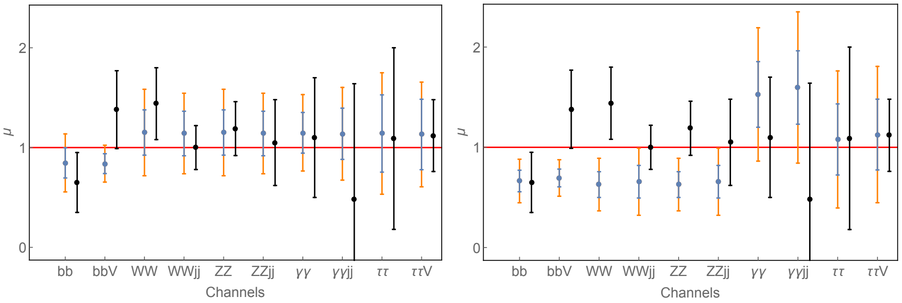
amb $\chi^2/\text{d.o.f} = 0.47.$

Fit results $yu < 0$ i $\cos\tilde{\alpha} > 0$

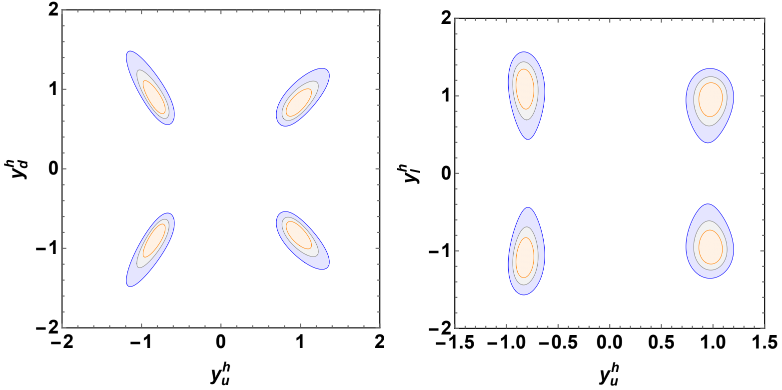
$$\cos\tilde{\alpha} = 0.83 \pm 0.06\,,\; y_u^h = -0.83 \pm 0.06\,,\; |y_d^h| = 0.87^{+0.08}_{-0.09}\,,\; |y_l^h| = 1.12^{+0.15}_{-0.18}\,,$$

amb $\chi^2/\text{d.o.f} = 2.96.$

A2HDM. Fit light CP-even Higgs without $H^{\pm}$ loop



A2HDM. Fit light CP-even Higgs without $H^{\pm}$ loop



A2HDM. Discrete $\mathcal{Z}_2$ symmetries

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	$-\tan\beta$	$\cot\beta$	$\cot\beta$
Inert	0	0	0

Table : CP-conserving 2HDMs based on discrete $\mathcal{Z}_2$ symmetries, being $\tan\beta \equiv v_2/v_1$