MODEL S 2 HIGGSOVA DUBLETA (2HDM)

- IDENTIFICIRANJE FIZIKALNIH POLJA
- MASE BAŽDARNIH BOZONA
- VEZANJA NEUTRALNIH SKALARA
- ELIMINIRANJE FCNC

Podvostručenje dubleta (2HDM)

$$\Phi_1 = \begin{pmatrix} \phi_1^+ \\ (h_1 + v_1 + ia_1)/\sqrt{2} \end{pmatrix}, \qquad \Phi_2 = \begin{pmatrix} \phi_2^+ \\ (h_2 + v_2 + ia_2)/\sqrt{2} \end{pmatrix}$$

- Oba VEV u neutralnim komp. za neslomljenu bažd. simetriju EM
- Uz realnost oba VEV izjegnuto je narušenje CP u skalarnom sektoru

Najopćenitiji (ne-SuSy) 2HDM uz potencijal koji čuva CP

$$\Phi_1 = \frac{1}{\sqrt{2}} \begin{pmatrix} \sqrt{2}\left(G^+ \cos\beta - H^+ \sin\beta\right) \\ v_1 - h\sin\alpha + H\cos\alpha + \mathrm{i}\left(G\cos\beta - A\sin\beta\right) \end{pmatrix}$$

$$\Phi_2 = \frac{1}{\sqrt{2}} \begin{pmatrix} \sqrt{2}\left(G^+ \sin\beta + H^+ \cos\beta\right) \\ v_2 + h\cos\alpha + H\sin\alpha + \mathrm{i}\left(G\sin\beta + A\cos\beta\right) \end{pmatrix}$$

$$\begin{aligned} \mathcal{V}_{\rm 2HDM} &= m_{11}^2 \Phi_1^\dagger \Phi_1 + m_{22}^2 \Phi_2^\dagger \Phi_2 - [m_{12}^2 \Phi_1^\dagger \Phi_2 + \text{ h.c.}] \\ &+ \tfrac{1}{2}\lambda_1 (\Phi_1^\dagger \Phi_1)^2 + \tfrac{1}{2}\lambda_2 (\Phi_2^\dagger \Phi_2)^2 + \lambda_3 (\Phi_1^\dagger \Phi_1)(\Phi_2^\dagger \Phi_2) + \lambda_4 (\Phi_1^\dagger \Phi_2)(\Phi_2^\dagger \Phi_1) \\ &+ \left\{ \tfrac{1}{2}\lambda_5 (\Phi_1^\dagger \Phi_2)^2 + \left[\lambda_6 (\Phi_1^\dagger \Phi_1) + \lambda_7 (\Phi_2^\dagger \Phi_2)\right] \Phi_1^\dagger \Phi_2 + \text{ h.c.} \right\} . \end{aligned}$$

- Izbjegavanje FCNC uz "natural flavor cons"

impose a Z_2 symmetry so that each type of fermion only couples to one of the doublets (forcing $\lambda_6 = \lambda_7 = 0$)

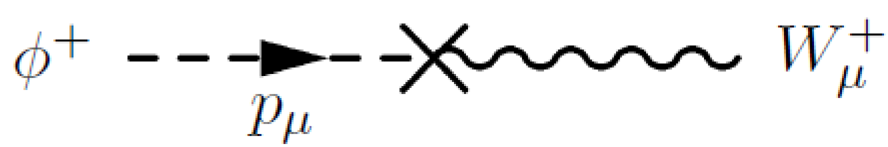
Identificiranje "Goldstoneova"

- **Podsjetnik na eliminaciju neželjenog (annoying) člana za Higgs SM-a**

$$\mathcal{L} \supset (\mathcal{D}_\mu \Phi)^\dagger (\mathcal{D}^\mu \Phi), \qquad \Phi = \begin{pmatrix} \phi^+ \\ (h + v + ia)/\sqrt{2} \end{pmatrix}$$

$$\mathcal{D}_\mu = \partial_\mu - i\frac{g}{\sqrt{2}}(W_\mu^+ \sigma^+ + W_\mu^- \sigma^-) - i\frac{e}{s_W c_W} Z_\mu (T^3 - s_W^2 Q) - ieA_\mu Q$$

$$\mathcal{L} \supset -i\frac{g}{\sqrt{2}} v \partial_\mu \phi^- W^{+\mu} + i\frac{g}{\sqrt{2}} v \partial_\mu \phi^+ W^{-\mu} + \frac{e}{\sqrt{2} s_W c_W} v \partial_\mu a Z^\mu$$



Goldstoneova stanja u 2HD iz

$$\mathcal{L} \supset -i\frac{g}{\sqrt{2}}\partial_\mu(v_1\phi_1^- + v_2\phi_2^-)W^{+\mu} + \text{h.c.} + \frac{e}{\sqrt{2}s_W c_W}\partial_\mu(v_1 a_1 + v_2 a_2)Z^\mu$$

Stanja iz nefizikalnih interakcija s W i Z su Goldstoneova (normirana) $\tan\beta \equiv v_2/v_1$

$$G^\pm = \frac{v_1}{\sqrt{v_1^2+v_2^2}}\phi_1^\pm + \frac{v_2}{\sqrt{v_1^2+v_2^2}}\phi_2^\pm \equiv \cos\beta\,\phi_1^\pm + \sin\beta\,\phi_2^\pm$$

$$G^0 = \frac{v_1}{\sqrt{v_1^2+v_2^2}}a_1 + \frac{v_2}{\sqrt{v_1^2+v_2^2}}a_2 \equiv \cos\beta\,a_1 + \sin\beta\,a_2,$$

Ortogonalna stanja – nabijeno i CP neparno i dva neutralna:

$$H^\pm = -\sin\beta\,\phi_1^\pm + \cos\beta\,\phi_2^\pm$$

$$A^0 = -\sin\beta\,a_1 + \cos\beta\,a_2$$

$$h^0 = -\sin\alpha\,h_1 + \cos\alpha\,h_2$$

$$H^0 = \cos\alpha\,h_1 + \sin\alpha\,h_2$$

Mase baždarnih bozona u 2HDM

$$\mathcal{L} \supset (\mathcal{D}_\mu \Phi_1)^\dagger (\mathcal{D}^\mu \Phi_1) + (\mathcal{D}_\mu \Phi_2)^\dagger (\mathcal{D}^\mu \Phi_2)$$

involving only h^0, H^0, and the vevs

$$\begin{aligned} \mathcal{L} \quad \supset \quad & \frac{1}{2}(\partial_\mu h_1)(\partial^\mu h_1) + \frac{1}{2}(\partial_\mu h_2)(\partial^\mu h_2) \\ & + \frac{1}{4} g^2 \left[(h_1 + v_1)^2 + (h_2 + v_2)^2 \right] W_\mu^+ W^{-\mu} \\ & + \frac{1}{8}(g^2 + g'^2) \left[(h_1 + v_1)^2 + (h_2 + v_2)^2 \right] Z_\mu Z^\mu \end{aligned}$$

- **Mase:**

$$\begin{aligned} M_W^2 &= \frac{g^2}{4}(v_1^2 + v_2^2) = \frac{g^2 v_{\mathrm{SM}}^2}{4}, \\ M_Z^2 &= \frac{g^2 + g'^2}{4}(v_1^2 + v_2^2) = \frac{(g^2 + g'^2) v_{\mathrm{SM}}^2}{4} \end{aligned}$$

Vezanja CP-parnih neutralnih skalara: hhVV su kao u SM

$$\begin{aligned}\mathcal{L} \;&\supset\; \frac{g^2}{4}\left[h_1^2 + h_2^2\right] W_\mu^+ W^{-\mu} + \frac{(g^2+g'^2)}{8}\left[h_1^2 + h_2^2\right] Z_\mu Z^\mu \\ &=\; \frac{g^2}{4}\left[(h^0)^2 + (H^0)^2\right] W_\mu^+ W^{-\mu} + \frac{(g^2+g'^2)}{8}\left[(h^0)^2 + (H^0)^2\right] Z_\mu Z^\mu\end{aligned}$$

- Vezanja hVV imaju dodatni faktor - iz

$$\mathcal{L} \supset \frac{g^2}{2}\left[h_1 v_1 + h_2 v_2\right] W_\mu^+ W^{-\mu} + \frac{(g^2+g'^2)}{4}\left[h_1 v_1 + h_2 v_2\right] Z_\mu Z^\mu$$

Uz:

$$v_1 = v_{\rm SM}\cos\beta, \qquad v_2 = v_{\rm SM}\sin\beta,$$

$$h_1 = -\sin\alpha\, h^0 + \cos\alpha\, H^0, \qquad h_2 = \cos\alpha\, h^0 + \sin\alpha\, H^0$$

$$\begin{aligned}\left[h_1 v_1 + h_2 v_2\right] &= v_{\rm SM} h^0(-\sin\alpha\cos\beta + \cos\alpha\sin\beta) + v_{\rm SM} H^0(\cos\alpha\cos\beta + \sin\alpha\sin\beta) \\ &= v_{\rm SM} h^0 \sin(\beta-\alpha) + v_{\rm SM} H^0 \cos(\beta-\alpha).\end{aligned}$$

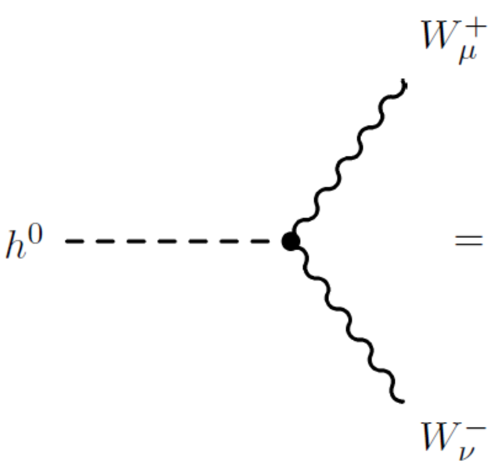
Feynmanova pravila

$$h^0 W_\mu^+ W_\nu^- : \qquad 2i \frac{M_W^2}{v_{\mathrm{SM}}} \sin(\beta - \alpha) g_{\mu\nu},$$

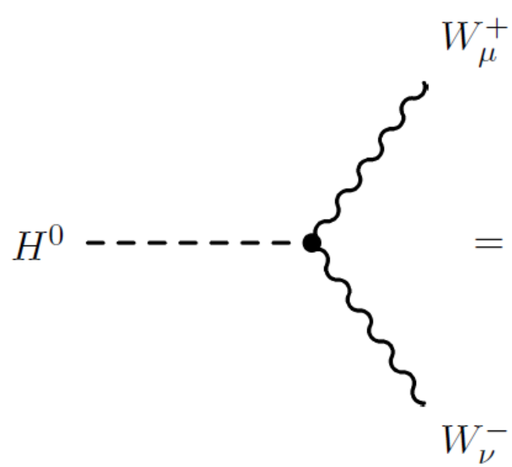
$$h^0 Z_\mu Z_\nu : \qquad 2i \frac{M_Z^2}{v_{\mathrm{SM}}} \sin(\beta - \alpha) g_{\mu\nu},$$

$$H^0 W_\mu^+ W_\nu^- : \qquad 2i \frac{M_W^2}{v_{\mathrm{SM}}} \cos(\beta - \alpha) g_{\mu\nu},$$

$$H^0 Z_\mu Z_\nu : \qquad 2i \frac{M_Z^2}{v_{\mathrm{SM}}} \cos(\beta - \alpha) g_{\mu\nu}.$$



$$= 2i \frac{M_W^2}{v_{\mathrm{SM}}} \sin(\beta - \alpha) g_{\mu\nu}$$



$$= 2i \frac{M_W^2}{v_{\mathrm{SM}}} \cos(\beta - \alpha) g_{\mu\nu}$$

"Higgsova baza" 1) za $(\beta-\alpha)=\pi/2$: $\sin(\beta-\alpha)=1$

$$\begin{aligned} h^0 &= -\sin\alpha\, h_1 + \cos\alpha\, h_2 \\ &= -\sin\left(\beta-\frac{\pi}{2}\right) h_1 + \cos\left(\beta-\frac{\pi}{2}\right) h_2 \\ &= \cos\beta\, h_1 + \sin\beta\, h_2. \end{aligned}$$

$$\begin{aligned} \Phi_H &\equiv \cos\beta\,\Phi_1 + \sin\beta\,\Phi_2 = \begin{pmatrix} G^+ \\ (h^0 + v_{\rm SM} + iG^0)/\sqrt{2} \end{pmatrix} \\ \Phi_0 &\equiv -\sin\beta\,\Phi_1 + \cos\beta\,\Phi_2 = \begin{pmatrix} H^+ \\ (H^0 + iA^0)/\sqrt{2} \end{pmatrix}. \end{aligned}$$

- 2) za $(\beta-\alpha)\neq\pi/2$

$$\begin{aligned} \Phi_H &= \begin{pmatrix} G^+ \\ \left[h^0\sin(\beta-\alpha) + H^0\cos(\beta-\alpha) + v_{\rm SM} + iG^0\right]/\sqrt{2} \end{pmatrix} \\ \Phi_0 &= \begin{pmatrix} H^+ \\ \left[-h^0\cos(\beta-\alpha) + H^0\sin(\beta-\alpha) + iA^0\right]/\sqrt{2} \end{pmatrix}. \end{aligned}$$

Pojavljivanje i eliminiranje FCNC

$$\begin{aligned}\mathcal{L}_{\text{Yukawa}} \;=\;& -y_{ij}^{\ell 1}\bar{e}_{Ri}\Phi_1^\dagger L_{Lj} - y_{ij}^{d1}\bar{d}_{Ri}\Phi_1^\dagger Q_{Lj} - y_{ij}^{u1}\bar{u}_{Ri}\tilde{\Phi}_1^\dagger Q_{Lj} + \text{h.c.}\\ & -y_{ij}^{\ell 2}\bar{e}_{Ri}\Phi_2^\dagger L_{Lj} - y_{ij}^{d2}\bar{d}_{Ri}\Phi_2^\dagger Q_{Lj} - y_{ij}^{u2}\bar{u}_{Ri}\tilde{\Phi}_2^\dagger Q_{Lj} + \text{h.c.}\end{aligned}$$

- **Na primjeru vezanja u Higgsovoj bazi**

$$\left(y_{ij}^{d1}\Phi_1^\dagger + y_{ij}^{d2}\Phi_2^\dagger\right)\bar{d}_{Ri}Q_{Lj} + \text{h.c.}$$

$$\left(y_{ij}^{d1}\frac{v_1}{\sqrt{2}} + y_{ij}^{d2}\frac{v_2}{\sqrt{2}}\right)\bar{d}_{Ri}d_{Lj} + \text{h.c.}$$

$$\mathcal{M}_{ij}^d = \left(y_{ij}^{d1}\frac{v_1}{\sqrt{2}} + y_{ij}^{d2}\frac{v_2}{\sqrt{2}}\right)$$

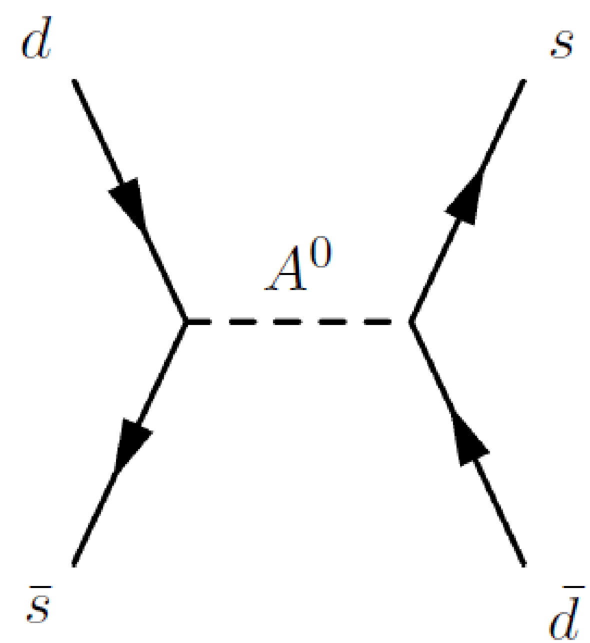
Diagonalizing $\mathcal{M}_{ij}^d$ diagonalizes $\;y_{ij}^{d1}\cos\beta + y_{ij}^{d2}\sin\beta$,
the coefficient of the down-type quark coupling to Φ_H in the Higgs basis.
does *not* in general diagonalize the orthogonal $-y_{ij}^{d1}\sin\beta + y_{ij}^{d2}\cos\beta$,
the coefficient of the down-type quark coupling to Φ_0 in the Higgs basis.

FC-vezanje na donje fermione

any neutral scalars that live in Φ_0 will have

Primjer miješanja neutralnih kaona od vrha Asd – dvije metode eliminiranja:

- Prirodno očuvanje okusa
- Yukawino poravnanje (alignment)



Prirodno očuvanje okusa

- **Tip I:** $u_R, d_R, e_R \to -u_R, -d_R, -e_R$
- **Tip I:** $u_R \to -u_R$ and $d_R, e_R \to d_R, e_R$
- **Tip I:** $u_R, d_R \to -u_R, -d_R$ and $e_R \to e_R$
- **Tip I:** $u_R, e_R \to -u_R, -e_R$ and $d_R \to d_R$

TABLE I. Four types of the charge assignment of the Z_2 symmetry.

	Φ_1	Φ_2	u_R	d_R	ℓ_R	Q_L, L_L
Type-I	+	−	−	−	−	+
Type-II	+	−	−	+	+	+
Type-X	+	−	−	−	+	+
Type-Y	+	−	−	+	−	+

Tip I: Svi R-fermioni su vezani na Φ_2

$$\mathcal{L}_\Phi^F = -y_{ij}^{\ell 2}\bar{e}_{Ri}\Phi_2^\dagger L_{Lj} - y_{ij}^{d2}\bar{d}_{Ri}\Phi_2^\dagger Q_{Lj} - y_{ij}^{u2}\bar{u}_{Ri}\tilde{\Phi}_2^\dagger Q_{Lj} + \text{h.c.} \qquad \text{(Type I)}$$

- **Mase fermiona – Yukawina matrica**

$$m_f = \frac{y_f v_2}{\sqrt{2}} = \frac{y_f v_{\rm SM}}{\sqrt{2}}\sin\beta, \qquad y_f = \frac{\sqrt{2}m_f}{v_{\rm SM}}\frac{1}{\sin\beta}$$

perturbative y_t a lower bound on $\sin\beta$; i.e., v_2 cannot be too small

the Feynman rules for

$$h^0 f\bar{f}: \qquad -i\frac{m_f}{v_{\rm SM}}\frac{\cos\alpha}{\sin\beta} = -i\frac{m_f}{v_{\rm SM}}\left[\sin(\beta-\alpha) + \cot\beta\cos(\beta-\alpha)\right],$$

$$H^0 f\bar{f}: \qquad -i\frac{m_f}{v_{\rm SM}}\frac{\sin\alpha}{\sin\beta} = -i\frac{m_f}{v_{\rm SM}}\left[-\cot\beta\sin(\beta-\alpha) + \cos(\beta-\alpha)\right]$$

neither the h^0 nor H^0 coupling to fermions can be significantly enhanced over the corresponding SM Higgs coupling

Tip II: R-up-kvarkovi su vezani na Φ_2

appears in the Higgs sector of the Minimal Supersymmetric Standard Model

$$\mathcal{L}_\Phi^F = -y_{ij}^{\ell 1}\bar{e}_{Ri}\Phi_1^\dagger L_{Lj} - y_{ij}^{d1}\bar{d}_{Ri}\Phi_1^\dagger Q_{Lj} - y_{ij}^{u2}\bar{u}_{Ri}\tilde{\Phi}_2^\dagger Q_{Lj} + \text{h.c.} \qquad \text{(Type II)}$$

- **Mase fermiona – perturbativnost Yukawe:**

$$m_u = \frac{y_u v_2}{\sqrt{2}} = \frac{y_u v_{\text{SM}}}{\sqrt{2}}\sin\beta, \qquad m_{d,\ell} = \frac{y_{d,\ell} v_1}{\sqrt{2}} = \frac{y_{d,\ell} v_{\text{SM}}}{\sqrt{2}}\cos\beta$$

$$y_u = \frac{\sqrt{2}m_u}{\ }\,\frac{1}{\ } \qquad y_{d,\ell} = \frac{\sqrt{2}m_{d,\ell}}{\ }\,\frac{1}{\ }$$

$$h^0 u\bar{u}: \quad -i\frac{m_u}{v_{\text{SM}}}\frac{\cos\alpha}{\sin\beta} = -i\frac{m_u}{v_{\text{SM}}}\left[\sin(\beta-\alpha) + \cot\beta\cos(\beta-\alpha)\right],$$

$$h^0 d\bar{d}: \quad -i\frac{m_d}{v_{\text{SM}}}\frac{-\sin\alpha}{\cos\beta} = -i\frac{m_d}{v_{\text{SM}}}\left[\sin(\beta-\alpha) - \tan\beta\cos(\beta-\alpha)\right],$$

$$H^0 u\bar{u}: \quad -i\frac{m_u}{v_{\text{SM}}}\frac{\sin\alpha}{\sin\beta} = -i\frac{m_f}{v_{\text{SM}}}\left[-\cot\beta\sin(\beta-\alpha) + \cos(\beta-\alpha)\right],$$

$$H^0 d\bar{d}: \quad -i\frac{m_d}{v_{\text{SM}}}\frac{\cos\alpha}{\cos\beta} = -i\frac{m_d}{v_{\text{SM}}}\left[\tan\beta\sin(\beta-\alpha) + \cos(\beta-\alpha)\right].$$

Feynmanova pravila

$$h^0 u\bar{u}: \qquad -i\frac{m_u}{v_{\rm SM}}\frac{\cos\alpha}{\sin\beta} = -i\frac{m_u}{v_{\rm SM}}\left[\sin(\beta-\alpha)+\cot\beta\cos(\beta-\alpha)\right],$$

$$h^0 d\bar{d}: \qquad -i\frac{m_d}{v_{\rm SM}}\frac{-\sin\alpha}{\cos\beta} = -i\frac{m_d}{v_{\rm SM}}\left[\sin(\beta-\alpha)-\tan\beta\cos(\beta-\alpha)\right],$$

$$H^0 u\bar{u}: \qquad -i\frac{m_u}{v_{\rm SM}}\frac{\sin\alpha}{\sin\beta} = -i\frac{m_f}{v_{\rm SM}}\left[-\cot\beta\sin(\beta-\alpha)+\cos(\beta-\alpha)\right],$$

$$H^0 d\bar{d}: \qquad -i\frac{m_d}{v_{\rm SM}}\frac{\cos\alpha}{\cos\beta} = -i\frac{m_d}{v_{\rm SM}}\left[\tan\beta\sin(\beta-\alpha)+\cos(\beta-\alpha)\right].$$

- **Fenomenologija Tipa II 2HDM**

in the limit $\sin(\beta-\alpha)\to 1$, the couplings of h^0 reduce to those of the SM Higgs boson

the scalar couplings to down-type quarks and charged leptons contain a factor of $\tan\beta$

by replacing $m_d \to m_\ell$

the phenomenology of the Type II 2HDM when $\tan\beta$ is large

Tip III/"Flipped"
R-donji kvarkovi vezani na Φ_1

$$\mathcal{L}_\Phi^F = -y_{ij}^{\ell 2}\bar{e}_{Ri}\Phi_2^\dagger L_{Lj} - y_{ij}^{d1}\bar{d}_{Ri}\Phi_1^\dagger Q_{Lj} - y_{ij}^{u2}\bar{u}_{Ri}\tilde{\Phi}_2^\dagger Q_{Lj} + \text{h.c.} \qquad \text{(Flipped)}$$

The Higgs couplings to quarks are the same as in the Type II 2HDM, while the couplings to leptons

$$h^0\ell\bar{\ell}: \qquad -i\frac{m_\ell}{v_{\rm SM}}\frac{\cos\alpha}{\sin\beta} = -i\frac{m_\ell}{v_{\rm SM}}\left[\sin(\beta-\alpha)+\cot\beta\cos(\beta-\alpha)\right],$$

$$H^0\ell\bar{\ell}: \qquad -i\frac{m_\ell}{v_{\rm SM}}\frac{\sin\alpha}{\sin\beta} = -i\frac{m_\ell}{v_{\rm SM}}\left[-\cot\beta\sin(\beta-\alpha)+\cos(\beta-\alpha)\right]$$

- **FenomenologijaTipa III**

The perturbativity constraints on $\tan\beta$ are the same as in the Type II 2HDM couplings to down-type quarks can be quite significantly enhanced

scalar couplings to charged leptons contain a factor of $\cot\beta$ and cannot be significantly enhanced compared to SM Higgs couplings

Tip IV/"Lepton-specific"/Tip X:
R-nabijeni leptoni vezani na Φ_1

$$\mathcal{L}_\Phi^F = -y_{ij}^{\ell 1}\bar{e}_{Ri}\Phi_1^\dagger L_{Lj} - y_{ij}^{d2}\bar{d}_{Ri}\Phi_2^\dagger Q_{Lj} - y_{ij}^{u2}\bar{u}_{Ri}\tilde{\Phi}_2^\dagger Q_{Lj} + \text{h.c.} \qquad \text{(Lepton specific)}$$

The Higgs couplings to quarks are the same as in the Type I 2HDM, while the couplings to leptons

$$h^0\ell\bar{\ell}: \qquad -i\frac{m_\ell}{v_{\rm SM}}\frac{-\sin\alpha}{\cos\beta} = -i\frac{m_\ell}{v_{\rm SM}}\left[\sin(\beta-\alpha) - \tan\beta\cos(\beta-\alpha)\right],$$

$$H^0\ell\bar{\ell}: \qquad -i\frac{m_\ell}{v_{\rm SM}}\frac{\cos\alpha}{\cos\beta} = -i\frac{m_\ell}{v_{\rm SM}}\left[\tan\beta\sin(\beta-\alpha) + \cos(\beta-\alpha)\right].$$

- **FenomenologijaTipa X**

$\tan\beta$ can be large as 200 before the tau Yukawa coupling becomes nonperturbative, so that the scalar couplings to leptons can be quite significantly enhanced

The Hunt for the Rest of the Higgs Bosons: Type I, II

In theories with two Higgs doublets Φ_1, Φ_2 and the most general renormalizable CP-conserving potential, there are nine free parameters that remain after minimizing the potential and fixing the symmetry breaking vev $v^2 = v_1^2 + v_2^2 = (246\,\mathrm{GeV})^2$. There are various possible parameterizations. Here we use the conventions of [14], taking for the free parameters the ratio $\tan\beta = |\langle\Phi_2^0\rangle/\langle\Phi_1^0\rangle|$, the mixing angle α that diagonalizes the neutral scalar mass matrix, the four physical masses $\{m_h, m_H, m_A, m_{H^\pm}\}$, and the dimensionless couplings $\lambda_{5,6,7}$.

The coupling of the physical states $h, H, A, H^\pm$ to SM fermions and gauge bosons are fully determined by the angles α and β, while the renormalizable couplings involving three or four physical Higgs bosons depend on the additional parameters of the potential. The couplings of physical scalars to SM fermions and gauge bosons as a function of α and β in Type 1 and Type 2 2HDM are summarized in table 1. In this work we will assume that the observed 125 GeV Higgs is the CP-even scalar h with SM-like Higgs couplings, with the additional Higgs scalars $H, A, H^\pm$ parametrically heavier. The case of additional scalars lighter than the 125 GeV Higgs is also quite interesting but qualitatively distinct.

- N.Craig et al./arXiv:1504.04630

$y_{2\mathrm{HDM}}/y_{\mathrm{SM}}$	Type 1	Type 2
hVV	$s_{\beta-\alpha}$	$s_{\beta-\alpha}$
hQu	$s_{\beta-\alpha} + c_{\beta-\alpha}/t_\beta$	$s_{\beta-\alpha} + c_{\beta-\alpha}/t_\beta$
hQd	$s_{\beta-\alpha} + c_{\beta-\alpha}/t_\beta$	$s_{\beta-\alpha} - t_\beta c_{\beta-\alpha}$
hLe	$s_{\beta-\alpha} + c_{\beta-\alpha}/t_\beta$	$s_{\beta-\alpha} - t_\beta c_{\beta-\alpha}$
HVV	$c_{\beta-\alpha}$	$c_{\beta-\alpha}$
HQu	$c_{\beta-\alpha} - s_{\beta-\alpha}/t_\beta$	$c_{\beta-\alpha} - s_{\beta-\alpha}/t_\beta$
HQd	$c_{\beta-\alpha} - s_{\beta-\alpha}/t_\beta$	$c_{\beta-\alpha} + t_\beta s_{\beta-\alpha}$
HLe	$c_{\beta-\alpha} - s_{\beta-\alpha}/t_\beta$	$c_{\beta-\alpha} + t_\beta s_{\beta-\alpha}$
AVV	0	0
AQu	$1/t_\beta$	$1/t_\beta$
AQd	$-1/t_\beta$	t_β
ALe	$-1/t_\beta$	t_β

Table 1: The coupling of Higgs bosons h, H, A to SM bosons and fermions as a function of the angles α and β, expressed in terms of the alignment parameter $c_{\beta-\alpha} \equiv \cos(\beta - \alpha)$, and $t_\beta \equiv \tan\beta$. The coupling dependence of the charged scalars $H^\pm$ is the same as the pseudo-scalar A.

Single Heavy Higgs Strong Production	$\mathcal{O}(g_s^4\lambda_f^2)$	$gg \to H\,,\ A$
Single Heavy Higgs Associated Strong Production	$\mathcal{O}(g_s^4\lambda_f^2)$	$gg \to bbH\,,\ bbA\,,\ tbH^{\pm}\,,\ ttH\,,\ ttA$
Single Heavy Higgs Associated Weak Production	$\mathcal{O}(g_s^2 g_w^4\lambda_f^2)$	$gq \to bq'\,bH^{\pm}\,,\ bq\,tH\,,\ bq\,tA$
Double Heavy Higgs Weak Production	$\mathcal{O}(g_w^4)$	$q\bar{q} \to HA\,,\ HH^{\pm}\,,\ AH^{\pm}\,,\ H^+H^-$
Light + Heavy Higgs Strong Production	$\mathcal{O}(g_s^4\lambda_f^4)$	$gg \to hH\,,\ hA$
Double Heavy Higgs Strong Production	$\mathcal{O}(g_s^4\lambda_f^4)$	$gg \to HH\,,\ HA\,,\ AA\,,\ H^+H^-$

Table 2: Hierarchy of heavy Higgs leading LHC production channels that do not vanish in the 2HDM alignment limit.

In table 2 we summarize the the leading LHC production channels for heavy Higgs bosons in 2HDM that are non-vanishing in the alignment limit, ordered by their relative size at LHC energies. These include resonant production of heavy neutral Higgses by gluon fusion; single production of heavy neutral or charged Higgses in association with top and bottom quarks; heavy Higgs pair production via Drell-Yan processes; heavy-light Higgs boson production via gluon fusion; and heavy Higgs pair production via gluon fusion. Other production modes that vanish in the alignment limit are *significantly* suppressed near the alignment limit, rendering them unpromising in the parameter space currently allowed by Higgs coupling fits. We likewise summarize the Standard Model decay channels of heavy Higgs bosons in table 3. In contrast with production modes, decay modes that vanish near the alignment limit may still be appreciable near the alignment limit, given the relatively small partial widths of competing decays.

		H	A	$H^\pm$
Standard Model	WW, ZZ	–		
Decay Channels	$tt, bb, \tau\tau, \mu\mu$	✓	✓	
	$\gamma\gamma$	✓	✓	
	Zh		–	
	hh	–		
	Wh			–
	$tb, \tau\nu$			✓

Table 3: Standard Model decay channels of 2HDM heavy Higgs bosons. A checkmark indicates that the partial decay width approaches a constant in the alignment limit, while a dash indicates that the decay width vanishes in the alignment limit.

The Hunt for Flipped (III)

- Rare t-decay t->c gamma (Gaitan et al./1503.04391)
- h->tau mu (Dorsner et al./1502.07784, Omura et al./1502.07824)

The Hunt for Charged Higgs in Lepton specific (2HDM-IV)

- Logan, McLennan/0903.2246
- Aoki et al. CKP

Yukawino poravnanje ("alignment") zahtijeva proporcionalnost matrica

$$\begin{aligned}\mathcal{L}_{\text{Yukawa}} &= -y_{ij}^{\ell 1}\bar{e}_{Ri}\Phi_1^\dagger L_{Lj} - y_{ij}^{d1}\bar{d}_{Ri}\Phi_1^\dagger Q_{Lj} - y_{ij}^{u1}\bar{u}_{Ri}\tilde{\Phi}_1^\dagger Q_{Lj} + \text{h.c.}\\ &\quad -y_{ij}^{\ell 2}\bar{e}_{Ri}\Phi_2^\dagger L_{Lj} - y_{ij}^{d2}\bar{d}_{Ri}\Phi_2^\dagger Q_{Lj} - y_{ij}^{u2}\bar{u}_{Ri}\tilde{\Phi}_2^\dagger Q_{Lj} + \text{h.c.}\end{aligned}$$

$$y_{ij}^{\ell 1} = z_\ell y_{ij}^{\ell 2}, \qquad y_{ij}^{d1} = z_d y_{ij}^{d2}, \qquad y_{ij}^{u1} = z_u y_{ij}^{u2}$$

$\tan\beta$ can be absorbed into the definitions of $z_{\ell,d,u}$

CP-conserving A2HDM

has separate parameters for the up-type quarks, the down-type quarks and the leptons, usually denoted by β^U, β^D and β^L

- **A2DM u Higgsovoj bazi (samo jedan VEV)**

input parameters include $\sin\alpha$ diagonalises the CP-even Higgs-sector

λ_2, λ_3, λ_7 and the above-mentioned alignment angles $\beta^{U,D,L}$

Nabijeni Higgsevi

- Kanal W higgs na LHC-u (Enberg et al.)

	2HDM-I	2HDM-II	A2HDM
$g^2_{qH^\pm}$	$m_b^2 \cot^2\beta + m_t^2 \cot^2\beta$	$m_b^2 \tan^2\beta + m_t^2 \cot^2\beta$	$m_b^2 \tan^2\beta^D + m_t^2 \tan^2\beta^U$

$g^2_{qH^\pm}$ in the 2HDM-II is identical to the one in the SUSY