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TÉCNICO LISBOA

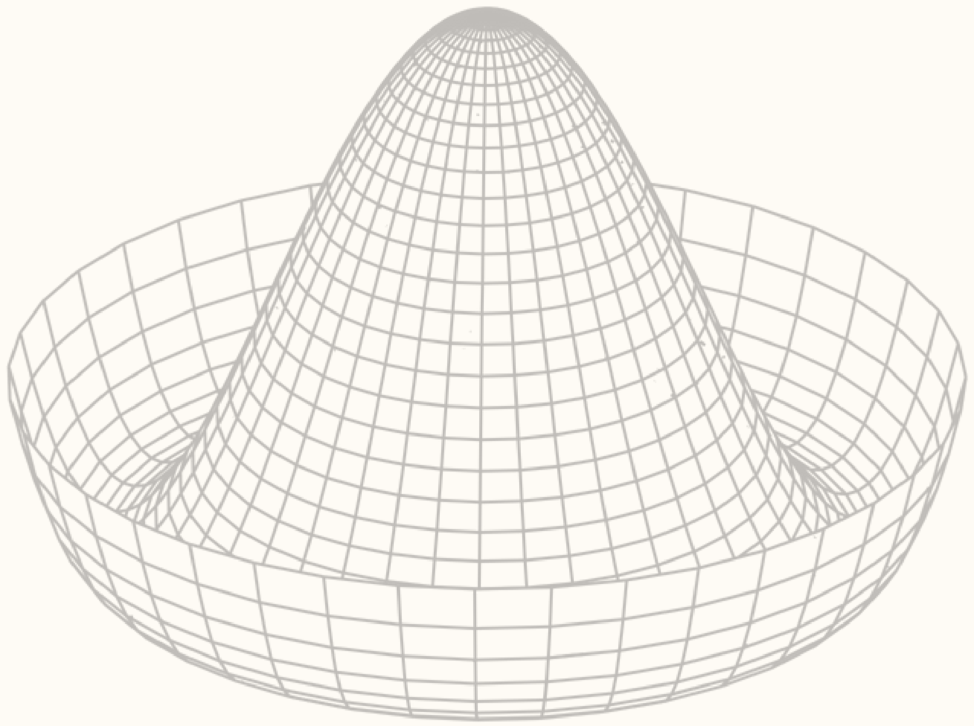
Fundação para a Ciência e a Tecnologia

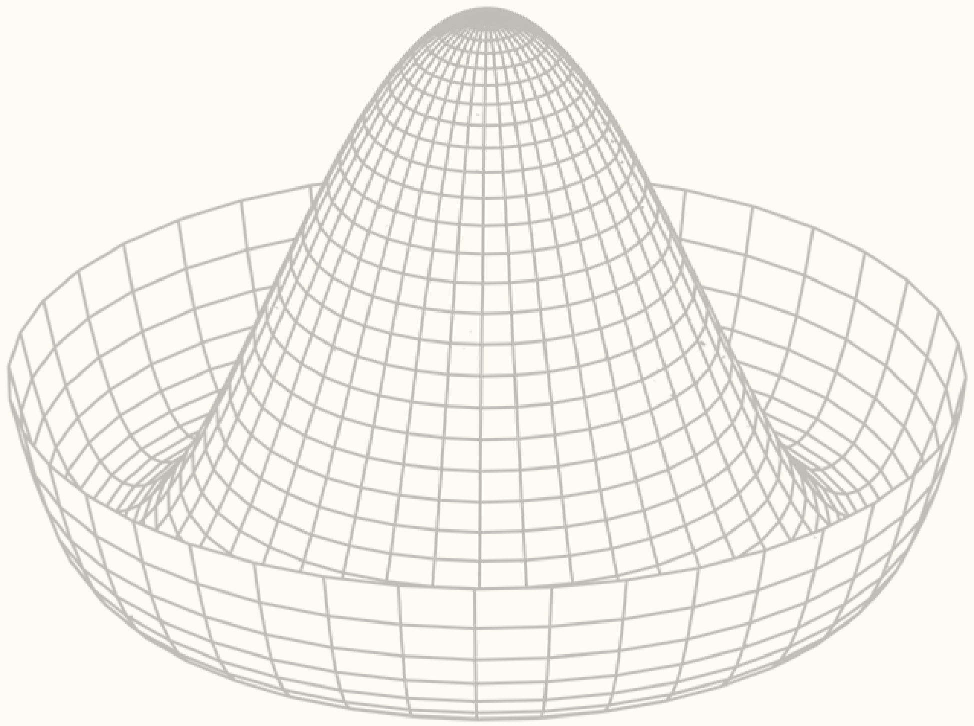
Yukawa Couplings in 3HDM

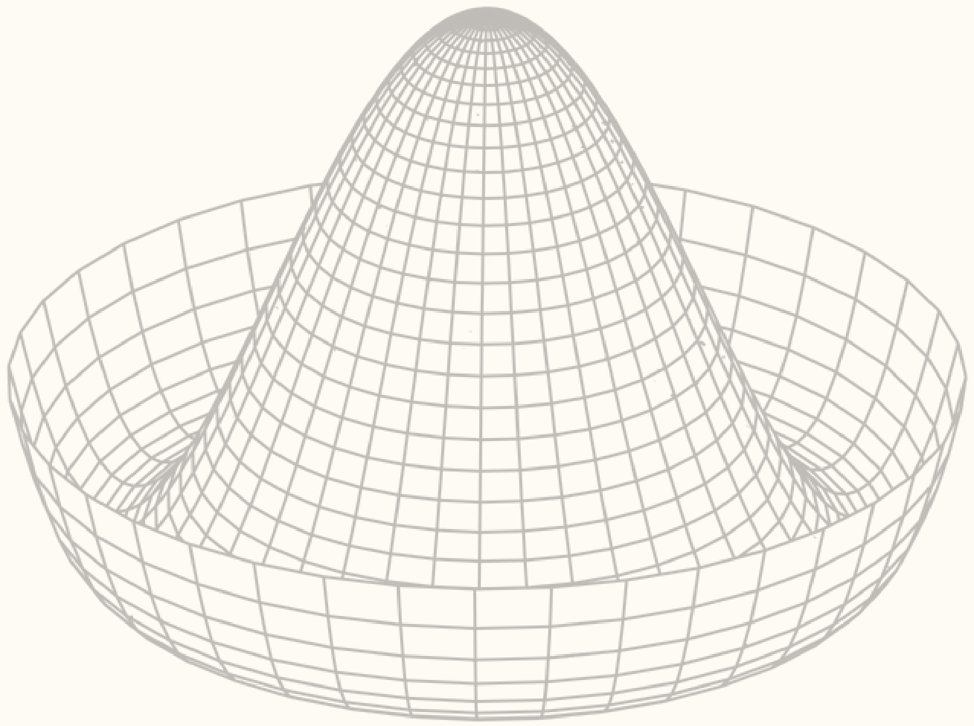
2nd Cycle Integrated Project in Engineering Physics

Duarte Dâmaso Correia | 102791 | duarte.d.correia@tecnico.ulisboa.pt

Supervisors: João Paulo Silva | Jorge Crispim Romão







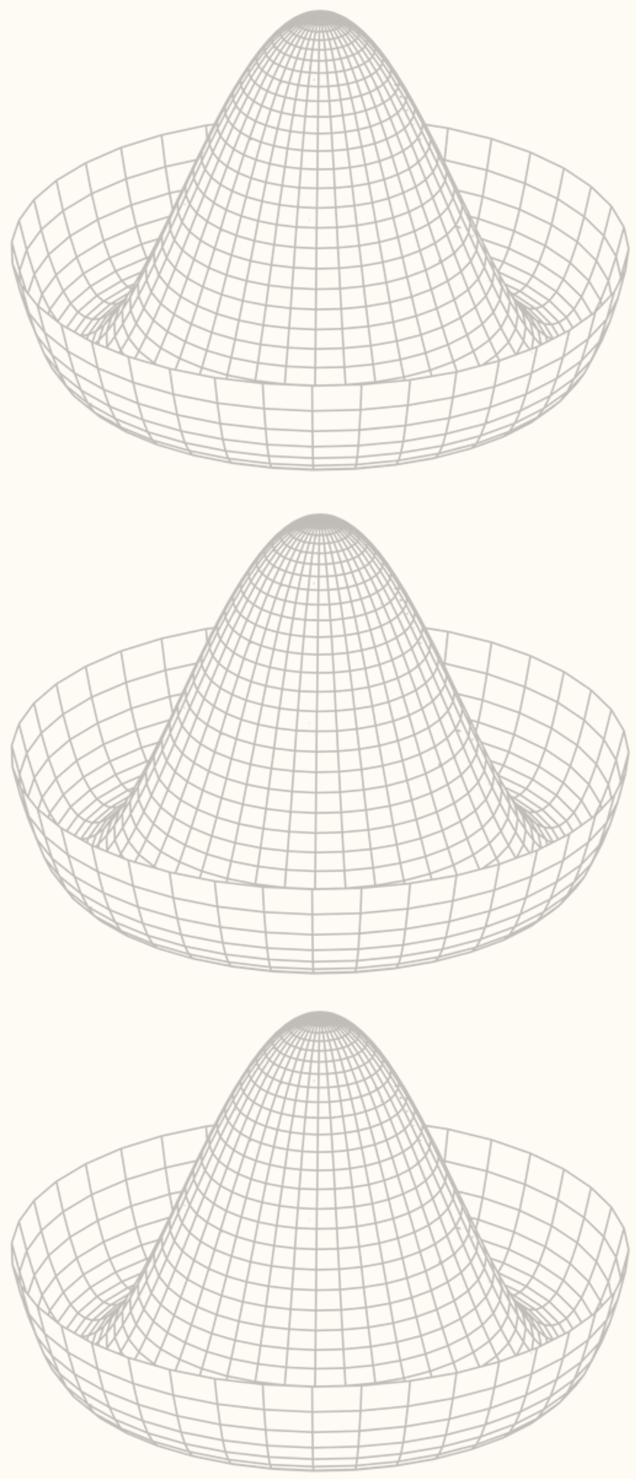
Introduction

- The Standard Model is our most successful theory of the fundamental building blocks of the Universe, however it is still incomplete.

- Natural extensions to the SM include the addition of scalar fields, named NHDM. In this work we studied a 3HDM and imposed invariance under a GCP transformation.

- We start by introducing 3 Higgs-doublets, of the same hypercharge:

$$\Phi_i = \begin{pmatrix} \phi_i^+ \\ \phi_i^0 \end{pmatrix} \xrightarrow{SSB} \langle \Phi_i \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v_i \end{pmatrix}$$



Lagrangian

Scalar Potential

$$V_H = Y_{ij}(\Phi_i^\dagger \Phi_j) + Z_{ij,kl}(\Phi_i^\dagger \Phi_j)(\Phi_k^\dagger \Phi_l)$$

- $Y_{ij} = Y_{ji}^*$
- $Z_{ij,kl} = Z_{kl,ij} = Z_{ji,lk}^* = Z_{lk,ji}^*$

CKM Matrix

- $V \equiv U_{u_L}^\dagger U_{d_L}$
- $\mathrm{Tr}[H_u, H_d]^3 = 6i(m_t^2 - m_c^2)(m_t^2 - m_u^2) \times (m_c^2 - m_u^2)(m_b^2 - m_s^2) \times (m_b^2 - m_d^2)(m_s^2 - m_d^2) J_{CP}$
- $J_{CP} = \mathrm{Im}(V_{us} V_{cb} V_{ub}^* V_{cs}^*) = (3.12^{+0.13}_{-0.12}) \times 10^{-5}$

Yukawa Sector

$$-\mathcal{L}_Y = \overline{q}_L \left(\sum_{k=1}^{3} \Gamma_k \Phi_k \right) n_R + \overline{q}_L \left(\sum_{k=1}^{3} \Delta_k \tilde{\Phi}_k \right) p_R + \mathrm{H.c.}$$

SSB ↓

$$-\mathcal{L}_{mass} = \overline{n}_L M_d n_R + \overline{p}_L M_u p_R + \mathrm{H.c.}$$

- $M_d \equiv \sum_k v_k \Gamma_k / \sqrt{2}$
- $M_u \equiv \sum_k v_k^* \Delta_k / \sqrt{2}$
- $H_d \equiv M_d M_d^\dagger = U_{d_L} D_d^2 U_{d_L}^\dagger$
- $H_u \equiv M_u M_u^\dagger = U_{u_L} D_u^2 U_{u_L}^\dagger$

GCP Transformation

GCP

Scalar GCP: $\Phi_a \to (X_\theta)_{ab}\Phi_b^*$

Quark GCP: $\begin{cases} q_L \to X_\alpha \gamma^0 C(\overline{q}_L)^\top \\ n_R \to X_\beta \gamma^0 C(\overline{n}_R)^\top \\ p_R \to X_\gamma \gamma^0 C(\overline{p}_R)^\top \end{cases}$

- $X \in SU(3)$

Invariance Conditions

- $Y_{ab}^* = X_{\alpha a}^* Y_{\alpha\beta} X_{\beta b}$
- $Z_{ab,cd}^* = X_{\alpha a}^* X_{\gamma c}^* Z_{\alpha\beta,\gamma\delta} X_{\beta b} X_{\delta d}$
- $\Gamma_b^* = X_\alpha^\dagger (X_\theta)_{ab} (\Gamma_a) X_\beta$
- $\Delta_b^* = X_\alpha^\dagger (X_\theta)_{ab}^* (\Delta_a) X_\gamma$

- In a 2HDM, there is only one non-trivial, GCP-symmetric model that respects all experimental constraints. However, the model **could not fit** the SM.
- We studied this same model in a 3HDM. Its transformations are given by:

$$(\theta, \alpha, \beta, \gamma) = \left(\frac{\pi}{3}, \frac{\pi}{3}, \frac{\pi}{3}, \frac{\pi}{3}\right)$$

- $$X_{\theta,\alpha,\beta,\gamma} = \begin{bmatrix} \cos\frac{\pi}{3} & \sin\frac{\pi}{3} & 0 \\ -\sin\frac{\pi}{3} & \cos\frac{\pi}{3} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

Yukawa Textures

$$(\theta,\alpha,\beta,\gamma)=\left(\frac{\pi}{3},\frac{\pi}{3},\frac{\pi}{3},\frac{\pi}{3}\right)$$

$$\Rightarrow\ \Gamma_1=\begin{pmatrix} ia_{11} & ia_{12} & a_{13}\\ ia_{12} & -ia_{11} & a_{23}\\ a_{31} & a_{32} & 0\end{pmatrix};\ \Gamma_2=\begin{pmatrix} ia_{12} & -ia_{11} & -a_{23}\\ -ia_{11} & -ia_{12} & a_{13}\\ -a_{32} & a_{31} & 0\end{pmatrix};\ \Gamma_3=\begin{pmatrix} c_{11} & c_{12} & 0\\ -c_{12} & c_{11} & 0\\ 0 & 0 & c_{33}\end{pmatrix};$$

$$\Delta_1=\begin{pmatrix} ib_{11} & ib_{12} & b_{13}\\ ib_{12} & -ib_{11} & b_{23}\\ b_{31} & b_{32} & 0\end{pmatrix};\ \Delta_2=\begin{pmatrix} ib_{12} & -ib_{11} & -b_{23}\\ -ib_{11} & -ib_{12} & b_{13}\\ -b_{32} & b_{31} & 0\end{pmatrix};\ \Delta_3=\begin{pmatrix} d_{11} & d_{12} & 0\\ -d_{12} & d_{11} & 0\\ 0 & 0 & d_{33}\end{pmatrix};$$

$$a_{ij}\,,b_{ij}\,,c_{ij}\,,d_{ij}\in\mathbb{R}$$

Fitting Procedure

VEV Parametrization

$$\vec{v} = (v_1, v_2, v_3)$$
$$= v\,(c_{\beta_1} s_{\beta_2}, s_{\beta_1} s_{\beta_2} e^{i\delta_2}, c_{\beta_2} e^{i\delta_3})$$

CKM Entries

$$\mathrm{Tr}\left(H_u^a H_d^b\right) \equiv L_{ab} = \sum_{k,i} U_{ki} (D_u^2)^a_{kk} (D_d^2)^b_{ii}$$
$$U_{ki} \equiv |V_{ki}|^2$$

- V is unitary, thus U has only 4 independent entries.
- These equations are linear in U_{ki}, and thus invertible.
- With just 4 CKM magnitudes, it is possible to determine the Jarlskog Invariant, up to its sign.

Jarslkog Invariant

$$R \equiv \mathrm{Re}(V_{11} V_{23} V_{13}^* V_{21}^*)$$
$$= \frac{1}{2}(1 - U_{11} - U_{13} - U_{21} - U_{23} + U_{11}U_{23} + U_{13}U_{21})$$
$$J_{CP}^2 = [\mathrm{Im}(V_{11} V_{23} V_{13}^* V_{21}^*)]^2 = U_{11}U_{23}U_{13}U_{23} - R^2$$

Fitting Results

Fit Parameters

$a_{11} = -3.97098074673 \times 10^{-3}$	$a_{12} = -1.52242815681 \times 10^{-3}$	$a_{13} = 5.34797946049 \times 10^{-5}$
$a_{23} = 3.73091195042 \times 10^{-4}$	$a_{31} = 1.33396458400 \times 10^{-2}$	$a_{32} = -1.89244229504 \times 10^{-2}$
$b_{11} = 2.48770399447 \times 10^{-3}$	$b_{12} = -1.06333634693 \times 10^{-4}$	$b_{13} = -1.36846732240 \times 10^{-2}$
$b_{23} = -0.394235334214$	$b_{31} = 1.72455632323 \times 10^{-3}$	$b_{32} = 3.07496958514 \times 10^{-2}$
$c_{11} = -1.52943935326 \times 10^{-2}$	$c_{12} = -1.01596106071 \times 10^{-2}$	$c_{33} = -3.61156633985 \times 10^{-3}$
$d_{11} = -1.01285923590 \times 10^{-2}$	$d_{12} = 1.46042064639 \times 10^{-3}$	$d_{33} = -3.94605049199$

$\beta_1 = 6.63958460053 \times 10^{-2}$	$\beta_2 = 1.33694986953$
$\delta_2 = 3.58094815748$	$\delta_3 = 4.68064054215$

Model Predictions

$v_1 = 238.777$ GeV	$v_2 = 15.877$ GeV	$v_3 = 57.003$ GeV
$m_u = 2.160$ MeV	$m_c = 1273.000$ MeV	$m_t = 172.570028$ GeV
$m_d = 4.700$ MeV	$m_s = 93.500$ MeV	$m_b = 4182.998$ MeV

$\lvert V_{11}\rvert = 0.97435$	$\lvert V_{13}\rvert = 0.00373202$
$\lvert V_{21}\rvert = 0.22487$	$\lvert V_{23}\rvert = 0.0418298$
$J_{CP} = 3.15490 \times 10^{-5}$	$\chi^2 = 3.910 \times 10^{-7}$

Conclusions

- We studied a 3HDM, while imposing invariance under GCP transformations.

- While analogous GCP-symmetric 2HDM were shown to be overly restrictive and phenomenologically excluded, the extension to 3HDM allows for realistic quark masses and mixing.

- The model is invariant under a CPc scalar potential and contains a total of 22 parameters in the Yukawa sector. The fit shows excellent agreement between prediction and experimental data.

- An analysis of the scalar mass spectrum, vacuum stability, flavor-changing neutral couplings and perturbative unitarity constraints would further test the viability of our model.

- This work will be published in an upcoming article.

Thank You