NTNU

Norwegian University of Science and Technology

Light states from weak CP violation in the aligned Weinberg 3HDM

Robin Plantey
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Scalar spectrum of the Weinberg potential

A theoretical and phenomenological study of Weinberg's 3HDM close to alignment

- CP violation
- scalar masses and gauge couplings

Based on an ongoing project

Scalar spectrum of the Weinberg potential (in preparation)
R. Plantey, O. M. Ogreid, P. Osland, M. N. Rebelo, M. Aa. Solberg.

Contents

Motivations for 3HDMs

- 2HDMs with Natural Flavour Conservation (NFC) are CP-conserving
- 3HDMs with NFC can accommodate both explicit and spontaneous CP violation [1]
- Aesthetic appeal: Same generation structure for Higgs and Fermion sector

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[1] Weinberg, 1976. Branco, 1980.

Weinberg’s 3HDM: Scalar Potential

$\mathbb{Z}_2 \times \mathbb{Z}_2$-symmetric potential

$$
\begin{aligned}
V &= V_2 + V_0 + V_{\text{ph}} \\
V_2 &= -m_{11}^2 \phi_1^\dagger \phi_1 - m_{22}^2 \phi_2^\dagger \phi_2 - m_{33}^2 \phi_3^\dagger \phi_3 \\
V_0 &= \lambda_{11} (\phi_1^\dagger \phi_1)^2 + \lambda_{12} (\phi_1^\dagger \phi_1)(\phi_2^\dagger \phi_2) + \lambda_{13} (\phi_1^\dagger \phi_1)(\phi_3^\dagger \phi_3) + \lambda_{22} (\phi_2^\dagger \phi_2)^2 \\
&\quad + \lambda_{23} (\phi_2^\dagger \phi_2)(\phi_3^\dagger \phi_3) + \lambda_{33} (\phi_3^\dagger \phi_3)^2 \\
&\quad + \lambda'_{12} (\phi_1^\dagger \phi_2)(\phi_2^\dagger \phi_1) + \lambda'_{13} (\phi_1^\dagger \phi_3)(\phi_3^\dagger \phi_1) + \lambda'_{23} (\phi_2^\dagger \phi_3)(\phi_3^\dagger \phi_2) \\
V_{\text{ph}} &= \lambda_1 (\phi_2^\dagger \phi_3)^2 + \lambda_2 (\phi_3^\dagger \phi_1)^2 + \lambda_3 (\phi_1^\dagger \phi_2)^2 + \text{h.c.}
\end{aligned}
$$

- No explicit CP violation: $\lambda_1, \lambda_2, \lambda_3 \in \mathbb{R}$

Weinberg's 3HDM: scalar sector

Doublets

$$\phi_i = \begin{pmatrix} \phi_i^+ \\ (w_i + \eta_i + i\chi_i)/\sqrt{2} \end{pmatrix}, \quad i = 1, 2, 3,$$

- $w_i = v_i e^{i\theta_i}$ (without loss of generality $\theta_1 = 0$)
- $\theta_2 \neq 0$ and $\theta_3 \neq 0$
- Eliminate λ_2 and λ_3 with minimization equations

$$\lambda_2 = \frac{\lambda_1 v_2^2 \sin(2\theta_2 - 2\theta_3)}{v_1^2 \sin 2\theta_3}, \qquad \lambda_3 = -\frac{\lambda_1 v_3^2 \sin(2\theta_2 - 2\theta_3)}{v_1^2 \sin 2\theta_2}.$$

Weinberg's 3HDM: scalar sector

Spontaneous CP violation

In general, no generalized CP transformation preserves both $\mathcal{L}$ and the vacuum[2]

$$U_{ij} w_j^* \neq w_i$$

After EWSB,

$$V_{\text{ph}} = \lambda_1 (\phi_2^\dagger \phi_3)^2 + \lambda_2 (\phi_3^\dagger \phi_1)^2 + \lambda_3 (\phi_1^\dagger \phi_2)^2 + \text{h.c.}$$

introduces CP violating terms in $\mathcal{L}$

Spectrum

- 5 physical neutral scalars
- 2 physical charged scalars
- **Not CP eigenstates**

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[2] Branco, 1983

Weinberg's 3HDM: Yukawa sector

Natural Flavour Conservation with $\mathbb{Z}_2 \times \mathbb{Z}_2$ charges

$$\begin{array}{lll} \phi_1 : (-1,1) & \phi_2 : (1,1) & \phi_3 : (1,-1) \\ u_R : (-1,1) & d_R : (1,1) & l_R : (1,-1) \end{array}$$

$$\mathcal{L}_Y = Y^U Q_L \tilde{\phi}_1 u_R + Y^D Q_L \phi_2 d_R + Y^L E_L \phi_3 l_R$$

$$M^U = v_1 Y^U \quad M^D = v_2 e^{i\theta_2} Y^D \quad M^L = v_3 e^{i\theta_3} Y^L$$

- Does not generate complex CKM entries (unless generation dep. $\mathbb{Z}_2 \times \mathbb{Z}_2$ charges)
- Scalar mixing is the only source of CP violation

Limit of weak scalar CP violation

$$V_{\text{ph}} = \lambda_1(\phi_2^\dagger\phi_3)^2 + \lambda_2(\phi_3^\dagger\phi_1)^2 + \lambda_3(\phi_1^\dagger\phi_2)^2 + \text{h.c.}$$

In the limit $\lambda_1, \lambda_2, \lambda_3 \to 0$

- scalar CP eigenstates do not mix, no scalar CP violation
- $\mathbb{Z}_2 \times \mathbb{Z}_2$ symmetry enhanced to $U(1) \times U(1) \implies$ 2 Goldstone bosons

λ_1 controls the strength of CP violation and masses of 2 lightest neutral states

Parameter space scans

Numerical exploration of the model's phenomenology close to the alignment limit

- One SM-like 125 GeV neutral scalar h_{SM} in the spectrum
- Input set (neutral sector)
  $\{v_2, v_3, \theta_2, \theta_3, (\mathcal{M}^2_{\text{neut}})_{11}, (\mathcal{M}^2_{\text{neut}})_{12}, (\mathcal{M}^2_{\text{neut}})_{13}, \lambda_{11}, \lambda_{22}, \lambda_{33}, \lambda_1\}$

Alignment in a CP violating 3HDM

- $\phi_1^{\text{HB}} = \begin{pmatrix} \varphi_1^{+\text{HB}} \\ \frac{1}{\sqrt{2}}(v + \eta_1^{\text{HB}} + i\chi_1^{\text{HB}}) \end{pmatrix}$
- $\eta_1^{\text{HB}} = h_{SM}$ with $m = 125$ GeV
- $g_{VVh} = (g_{VVh})^{SM}$
- CP even

$$\mathcal{M}^2_{\text{neut}} \sim \left(\begin{array}{c|cccc} \star & \star & \star & 0 & 0 \\ \hline \star & & & & \\ \star & & & & \\ 0 & & (4 & \times & 4) \\ 0 & & & & \end{array}\right) \overset{!}{=} \left(\begin{array}{c|cccc} m_h^2 & \mathbf{0} & \mathbf{0} & 0 & 0 \\ \hline \mathbf{0} & & & & \\ \mathbf{0} & & & & \\ 0 & & (4 & \times & 4) \\ 0 & & & & \end{array}\right)$$

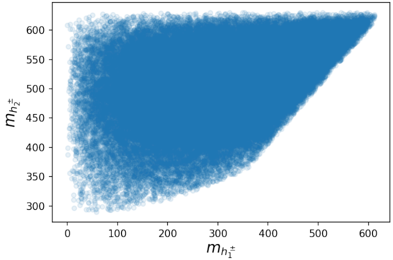
Charged Sector

The charged spectrum can be varied independently of the neutral spectrum

All points with $\lambda'_{12} + \lambda_{12} = cst\,,\ \lambda'_{13} + \lambda_{13} = cst\,,\ \lambda'_{23} + \lambda_{23} = cst$ have the same neutral spectrum

Scan over a benchmark neutral sector point

$m_{h_1} = 11.4$ GeV, $m_{h_2} = 84.1$ GeV, $m_{h_3} = 125.0$ GeV, $m_{h_4} = 187.2$ GeV, $m_{h_5} = 809.4$ GeV



- $m_{h^\pm} \lesssim 650$ GeV from perturbativity constraint $|\lambda| < 4\pi$

Parameter space scans

Observation

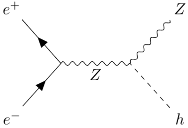
- At least one state lighter than h_{SM} in most of the parameter space (>90%)

Do such light states rule out most of the parameter space?

Not necessarily...

Close to alignment: ZZh coupling is suppressed for non-SM scalars

- Production via Bjorken mechanism suppressed
- Could have escaped detection at LEP



Final words

Summary

- Weakly CP violating Weinberg 3HDM typically contains light states
- The same parameter λ_1 controls:
  - masses of light states
  - strength of scalar CP violation
- These light states decouple in the alignment limit so could have gone undetected

Future directions

- Compute more observables in this model (SARAH, CalcHEP)
- Relate λ_1 to CP violating observables
- Apply more experimental constraints (HiggsBounds, HiggsSignal)