Light States in Weinberg's Potential with Spontaneous CP Violation

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Scalar spectrum of the Weinberg potential

Phenomenological study of a model of spontaneous CPV and Natural Flavour Conservation (NFC)

- How is the scalar spectrum of the model when basic experimental constraints are applied?
  - BSM Masses
  - CP Properties

Based on arxiv:2022.13594
Weinberg's 3HDM potential with spontaneous CP violation
R. Plantey, O. M. Ogreid, P. Osland, M. N. Rebelo, M. Aa. Solberg.

The $\mathbb{Z}_2 \times \mathbb{Z}_2$-symmetric 3HDM

- 3HDM with an exact $\mathbb{Z}_2 \times \mathbb{Z}_2$ symmetry
- Can accomodate both Spontaneous CPV and NFC
- Scalar spectrum:
  - 5 Neutral scalars h_i (not CP eigenstates)
  - 2 Charged scalars h_j^+

$$V = V_{U(1)\times U(1)} + V_{ph}$$

- After minimization of V, only one independent coupling in V_{ph}
- $\rightarrow$ large fraction of parameter space yields a $U(1) \times U(1)$ symmetric model
- $\rightarrow$ (pseudo-)Goldstone bosons when V is (approx.) $U(1) \times U(1)$-invariant

CP content of the neutral scalars

Neutral physical scalars are not CP eigenstates

How to quantify how "close" a particle is from CP-even/odd in a CP violating model?

- Compare couplings with the corresponding CP-conserving model
- Two examples: Zh_ih_j and Yukawa couplings

Gauge couplings: Zh_ih_j

In a CP conserving model these vanish if the product h_ih_j is CP-even

Can be expressed in terms of the neutral scalar mixing matrix O

$$\kappa_{Zh_ih_j} = -\frac{g}{2\cos\theta_W}\left(O_{i2}O_{j4} + O_{i3}O_{j5} - (i \leftrightarrow j)\right) \equiv -\frac{g}{2\cos\theta_W}P_{ij} \qquad (1)$$

P_{ij} measures the relative CP of h_i and h_j

Yukawa couplings

$$\mathcal{L}_Y = Y^u \bar{Q}_L \tilde{\phi}_1 u_R + Y^d \bar{Q}_L \phi_2 d_R + Y^e \bar{E}_L \phi_3 e_R + \text{h.c.} \tag{2}$$

CP violating theory $\rightarrow$ Neutral scalars couple to both CP-even and CP-odd fermion currents

$$\mathcal{L}_{h_i ff} = \frac{m_f}{v} h_i (\kappa^{h_i ff} \bar{f} f + i \tilde{\kappa}^{h_i ff} \bar{f} \gamma_5 f) \tag{3}$$

The ratio $\frac{\tilde{\kappa}}{\kappa} \equiv \tan\alpha$ measures the absolute CP profile of h_i

- $\alpha = 0 \quad \rightarrow \quad h_i$ CP-even
- $\alpha = \frac{\pi}{2} \quad \rightarrow \quad h_i$ CP-odd

$$\alpha^{h_i ff} = \arg(Z_i^{(k)}) \tag{4}$$

$$Z_i^{(k)} = \tilde{\mathcal{R}}_{1k} O_{i1} + \tilde{\mathcal{R}}_{2k} (O_{i2} + i O_{i4}) + \tilde{\mathcal{R}}_{3k} (O_{i3} + i O_{i5}). \tag{5}$$

Parameter space scans

How do experimental Higgs measurements constrain the scalar spectrum?

- Masses
- CP properties

Uniform parameter space scan ($\approx$ 1M points)

- Discovered Higgs/alignment limit implemented numerically by uniform rescaling of the quartic couplings

Results

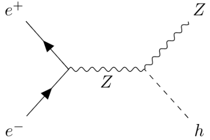
99.7% of the sampled viable parameter space contains lighter states than $m_h = 125$ GeV

h_1	h_2	h_3	h_4	h_5
0.3	38.1	28.2	22.8	10.6

Table: Fraction of occurence for each case $h_j = h_{SM}$, with the physical states h_j ordered by increasing mass $m_1 < m_2 < m_3 < m_4 < m_5$.

These light neutral scalars do not necessarily rule out the model

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



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Results: Yukawa couplings $h_i\tau\tau$

Averages over parameter space

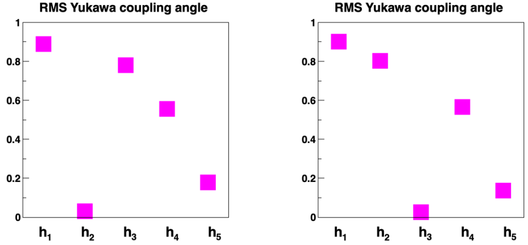

Figure: RMS of the angle $\alpha^{h_i\tau\tau}$ (in units of $\pi/2$) which measures the CP-odd content of the Yukawa couplings to $\tau\bar{\tau}$ for $h_2 = h_{\rm SM}$ (left) and $h_3 = h_{\rm SM}$ (right).

$$\mathcal{L}_{h_i\tau\tau} = \frac{m_\tau}{v} h_i\left(\kappa^{h_i\tau\tau}\bar{\tau}\tau + i\tilde{\kappa}^{h_i\tau\tau}\bar{\tau}\gamma_5\tau\right) \qquad \frac{\tilde{\kappa}}{\kappa} \equiv \tan\alpha^{h_i\tau\tau}$$

In general, the states lighter than h_{SM} have large CP-odd couplings

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Conclusion and Outlook

- Frequent light states in the $\mathbb{Z}_2 \times \mathbb{Z}_2$-symmetric 3HDM
  - mostly CP-odd nature
  - decouple from main production channel, could have gone undetected

- Improvement: relate VEVs phases to the CKM complex phase $\rightarrow$ relax NFC