Geometrical CP violation and nonstandard Higgs decays

Gautam Bhattacharyya

Saha Institute of Nuclear Physics, Kolkata

G.B., Ivo de M. Varzielas, Philipp Leser, arXiv:1210.0545 [hep-ph]

Phys. Rev. Lett. 109 (2012) 241603

Introduction

- Spontaneous CP violation is an interesting idea. The origin is in complex VEVs of neutral scalars.
- Start with a Lagrangian that conserves CP, i.e. parameters in the potential are all real. CPV occurs when $\mathrm{SU(2)_L \times U(1)_Y \to U(1)_Q}$ by complex VEVs.
- Just the presence of complex VEVs does not guarantee that CP is violated. If

$$< \phi_i >^* = U_{ij} < \phi_j > \qquad \text{and} \qquad \mathcal{L}(U\phi) = \mathcal{L}(\phi)$$

  then CP is preserved even in the presence of complex VEVs.
- Geometrical phase solution requires more than 2 Higgs doublets and non-abelian symmetries, otherwise it is always possible to find an U which is a symmetry of the potential [Branco, Gerard, Grimus, 1984].
- For phases to be 'calculable', they should have only 'geometrical' values independent of arbitrary parameters of the scalar potential [Varzielas, Emmanuel-Costa, 2011].
- Parameters of the potential should either related, or many of them should be absent due to some symmetry.
- Smallest discrete group that leads to spontaneous CPV is $\Delta(27)$.

Basics of $\Delta(27)$

- $\Delta(27)$ is a finite subgroup of SU(3) [Luhn et al 2007, Ishimori et al 2010].
- Consider two independent diagonal matrices

$$\begin{pmatrix} \beta & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & \bar{\beta} \end{pmatrix} \qquad \begin{pmatrix} \bar{\gamma} & 0 & 0 \\ 0 & \gamma & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

where $\beta^n = \gamma^n = 1$. This generates $Z_n \times Z_n$. When entries are permuted by S_3, we get $\Delta(6n^2) \equiv (Z_n \times Z_n) \rtimes S_3$. When the diagonal entries are permuted by Z_3,

$$\Delta(3n^2) \equiv (Z_n \times Z_n) \rtimes Z_3$$

- $\Delta(3n^2)$ has 3 generators: 'a' generates Z_3 with $a^3 = 1$. 'c' and 'd' generate $Z_n \times Z_n$ with $c^n = d^n = 1$ and $cd = dc$. Z_3 acts on $Z_n \times Z_n$ by conjugation:

$$aca^{-1} = c^{-1}d^{-1}, \;\; ada^{-1} = c$$

- Any group element $g \in \Delta(3n^2)$ can be written as $g = a^\alpha c^\gamma d^\delta$, where $\alpha = 0, 1, 2$ and . $\gamma, \delta = 0, 1, 2, \cdots, n-1$.

Representations of $\Delta(27)$

- $\Delta(27)$ has 9 singlets $\mathbf{1}_{rs}$: $a = \omega^r,\ c = d = \omega^s,\ (r, s = 0, 1, 2)$, and 2 triplets $\mathbf{3}_{01}$ and $\mathbf{3}_{02}$, where $\omega = \exp(2\pi i/3)$,

$$C_{01} = \begin{pmatrix} \omega^0 & 0 & 0 \\ 0 & \omega^1 & 0 \\ 0 & 0 & \omega^{-1} \end{pmatrix} \qquad a = \begin{pmatrix} 0 & 1 & 0 \\ 0 & 0 & 1 \\ 1 & 0 & 0 \end{pmatrix}$$

  Representations obtained by conjugation by a and a^2 are ‘equivalent’.

- **Some Tensor products:** $\mathbf{3} \times \mathbf{3} = \bar{\mathbf{3}} + \bar{\mathbf{3}} + \bar{\mathbf{3}}$, $\mathbf{3} \times \bar{\mathbf{3}} = \sum \mathbf{1}_{rs}\ (r, s = 0, 1, 2)$.
- If $(H_1, H_2, H_3)^T = \mathbf{3_{01}}$, then $(H_1^\dagger, H_2^\dagger, H_3^\dagger)^T = \mathbf{3_{02}}$

$$a(H_1, H_2, H_3) = (H_2, H_3, H_1)$$

$$c(H_1, H_2, H_3) = (H_1, \omega H_2, \omega^2 H_3)$$

$$c(H_1^\dagger, H_2^\dagger, H_3^\dagger) = (H_1^\dagger, \omega^2 H_2^\dagger, \omega H_3^\dagger)$$

Crucial term in scalar potential

$$V \supset \lambda_3 \left(H_1 H_2^\dagger H_1 H_3^\dagger + \text{h.c.} \right) + \text{c.p}$$

Other terms giving phases in a general 3HDM potential are removed by $\Delta(27)$ symmetry.
Only VEVs with calculable phases are

$$< H >^T = \frac{v}{\sqrt{3}} \left(1, \omega, \omega^2\right)$$

$$\boxed{< H >^T = \frac{v}{\sqrt{3}} \left(\omega, 1, 1\right)}$$

The first solution does not produce spontaneous CPV as one can find a symmetry transformation U that can relate $< H >$ with $< H >^*$. The second solution does give spontaneous CPV.

Quark masses and $\cdots$

Yukawa: QH_id^c, $QH^{i\dagger}u^c$, where $H_i = \mathbf{3_{01}}$ and $H^{i\dagger} = \mathbf{3_{02}}$.

Option-I: Q is a triplet, then this forces d^c to be a triplet. Or, Q is an anti-triplet, which forces u^c to be anti-triplet. Then, in at least one sector,

$$\mathbf{3_{0i}} \otimes \mathbf{3_{0i}} \otimes \mathbf{3_{0i}}$$

which yields degenerate quark masses. Ruled out by data.

Option-II: Q is singlet, and u^c, d^c are triplet/anti-triplet. Yukawa structure

$$\mathbf{1_{ij}} \otimes (\mathbf{3_{01}} \otimes \mathbf{3_{02}})$$

The only choice that works is $(Q_1, Q_2, Q_3) = \mathbf{1_{00}}, \mathbf{1_{00}}, \mathbf{1_{01}}$.

$$M_d = v \begin{pmatrix} y_1\omega & y_1 & y_1 \\ y_2\omega & y_2 & y_2 \\ y_3 & y_3 & y_3\omega \end{pmatrix} \quad , \quad M_d M_d^\dagger = 3v^2 \begin{pmatrix} y_1^2 & y_1y_2 & 0 \\ y_1y_2 & y_2^2 & 0 \\ 0 & 0 & y_3^2 \end{pmatrix}$$

Only two non-zero masses, but importantly, complex phase is absent.

$\cdots$ and CKM mixing

Add a driving field $\phi = \mathbf{1_{01}}$. Additional Yukawa term $QH_i d^{cj}\phi$. This gives

$$M_\phi = v\begin{pmatrix} y_{\phi 1} & y_{\phi 1}\omega & y_{\phi 1} \\ y_{\phi 2} & y_{\phi 2}\omega & y_{\phi 2} \\ y_{\phi 3}\omega & y_{\phi 3} & y_{\phi 3} \end{pmatrix}$$

From $M_d M_\phi^\dagger + M_d^\dagger M_\phi$ we get the required off-diagonal elements. But, still no phases!

Construct another Yukawa term with higher powers of H, namely, $QH_i d^{cj}\left(H_k H^{\dagger l}\right)$.

$$M_H = v\begin{pmatrix} y_{H1} & y_{H1}\omega^2 & y_{H1}\omega^2 \\ y_{H2} & y_{H2}\omega^2 & y_{H2}\omega^2 \\ y_{H3}\omega^2 & y_{H3}\omega^2 & y_{H3} \end{pmatrix}$$

Interference term $M_d M_H^\dagger + M_H M_d^\dagger$ yields phases!

$$\boxed{\mathcal{L}_{\rm Yuk} = Q\left(H^{\dagger i}u_j^c + H_i d^{cj} + H_i d^{cj}\phi + H_i d^{cj}(H_k H^{\dagger l})\right)}$$

CKM parameters and data

$$\lambda^{\text{exp}} = 0.22535 \pm 0.00065 \qquad \lambda = 0.22534,$$

$$A^{\text{exp}} = 0.811\begin{matrix}+0.022\\-0.012\end{matrix} \qquad A = 0.810,$$

$$\bar{\rho}^{\,\text{exp}} = 0.131\begin{matrix}+0.026\\-0.013\end{matrix} \qquad \bar{\rho} = 0.129,$$

$$\bar{\eta}^{\,\text{exp}} = 0.345\begin{matrix}+0.013\\-0.014\end{matrix} \qquad \bar{\eta} = 0.344.$$

- Total 13 Yukawa parameters (9 in down sector, 4 in up sector). There are 10 experimental points (6 quark masses, 4 mixing parameters).
- We have not done any fit, we simply reproduced the quark masses and mixing.
- Only two sets of irreducible representations broadly worked, one of them is ruled out by precision flavor data.

Extended scalar sector

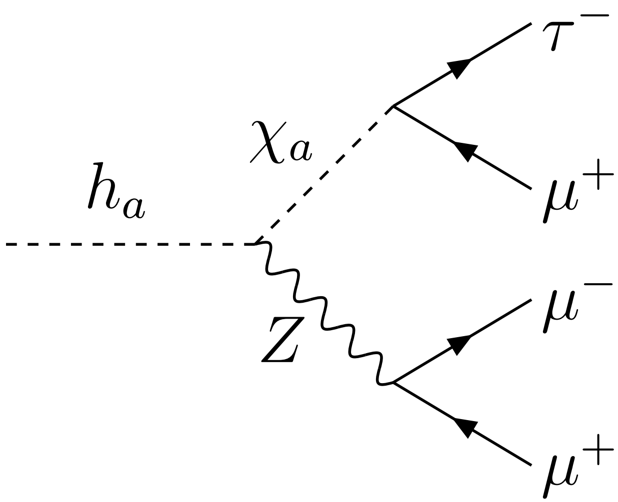
$$V(H,\phi) = m_1^2 \left[H_1 H_1^\dagger\right] + m_2^2 \phi\phi^\dagger + m_3(\phi^3 + \text{h.c.})$$
$$+ \lambda_1 \left[(H_1 H_1^\dagger)^2\right] + \lambda_2 \left[H_1 H_1^\dagger H_2 H_2^\dagger\right] + \lambda_3 \left[H_1 H_2^\dagger H_1 H_3^\dagger + \text{h.c.}\right]$$
$$+ \lambda_4 (\phi\phi^\dagger)^2 + \lambda_5 \left[\phi(H_1 H_2^\dagger) + \text{h.c.}\right] + \lambda_6 \left[\phi\phi(H_1 H_3^\dagger) + \text{h.c.}\right] ,$$

- Assume the ϕ field to weigh beyond 1 TeV, then it decouples from the doublets.
- Three CP-even neutral scalars (h_a, h_b, h_c), two CP-odd neutral scalars (χ_a, χ_b), and two sets of charged scalars $(h_a^\pm, h_b^\pm)$.
- h_b and h_c have roughly SM Higgs-like couplings. h_b can have a mass $\sim$ 125 GeV.
- h_a and χ_a have no 3-point couplings with ZZ or WW. They can evade LEP2 and EWPT bounds - hence, can be very light.

  Reason: Scalar mass-squared matrix has the following structure, which always yields an eigenvector $(-1, 1, 0)$.

$$\begin{pmatrix} A & B & B \\ B & C & D \\ B & D & C \end{pmatrix}$$

Collider signatures of h_a



- Production of h_a primarily through $h_a uc$ interaction and $t \to h_a c$.
- $\mathrm{Br}\,(h_a \to \chi_a Z)$ can be rather large (almost 100%) due to dominance of gauge coupling.
- $\mathrm{Br}\,(\chi_a \to \mu\tau)$ can be large.
- Multi-leptons of different flavors can be a testable signal at LHC.

Similar to what we found with S_3: G.B., P. Leser, H. Päs, 2010, 2012

Outlook

- Spontaneous CPV with calculable phases implemented for the first time in a viable quark mass / CKM mixing scheme.
- What about the leptons? Less constrained than the quark sector. Type of see-saw mechanism employed for neutrino mass generation decides the choice of invariants for charged leptons [Varzielas et al 2011]. A lepton model based on $\mathbf{3_{0i}} \otimes \mathbf{3_{0i}} \otimes \mathbf{3_{0i}}$ has been discussed [Ma 2006].
- Flavor changing Higgs decays at LHC constitute smoking gun signals!
- Falsifiability? If the current LHC lower limit of 650 GeV on any other SM-like Higgs goes further up (say 1 TeV), some λ_i couplings have to go up from π to 2π. Still, for those heavy states there are enough independent combination of quartic couplings, so it does not give more fine-tuning.
- Proliferation of scalar states around 1 TeV would affect the energy growth of $W_L W_L$ scattering whose quantitative implication may 'possibly' be studied in super-LHC.
- Testing 'successful' flavor groups against the Higgs data is an important exercise.