Geometrical CP violation

Ivo de Medeiros Varzielas

University of Basel

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Outline

Spontaneous CP violation

Complex VEVs not sufficient. CP conserved if:

$$H_i \longrightarrow H'_i = U_{ij} H_j \, ,$$

$$U_{ij} \langle H_j \rangle^* = \langle H_i \rangle \, ,$$

while U leaves the Lagrangian invariant.

Calculable phases

Branco, Gérard, Grimus (1984) PLB
(Geometrical T violation)

- Phases have geometrical values independent of couplings.
- >2 Higgs doublets and non-Abelian symmetries.
- Interesting $\Delta(27)$ example found.

$\Delta(27)$ calculable phase

$\Delta(27)$: Det $= 1$; cyclic generator; phase generator ($e^{i2\pi/3}$)

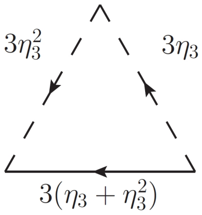
$$V(H) \sim \lambda_3 (H_1^\dagger H_2 H_1^\dagger H_3 + H_2^\dagger H_3 H_2^\dagger H_1 + H_3^\dagger H_1 H_3^\dagger H_2) + \text{h.c.}$$

$$V \propto \lambda_3 v^4 (e^{iA_1} + e^{iA_2} + e^{iA_3} + h.c.)\,, \quad A_i = -2\alpha_i + \alpha_j + \alpha_k$$

$$(\sum A_i = 0)$$

Geometrical (complex) VEV solution

$$V \propto \lambda_3 v^4 (e^{iA_1} + e^{iA_2} + e^{iA_3} + h.c.)\,, \quad A_i = -2\alpha_i + \alpha_j + \alpha_k$$



$$(\eta_3 = \omega = e^{i2\pi/3}, \omega^3 = 1)$$

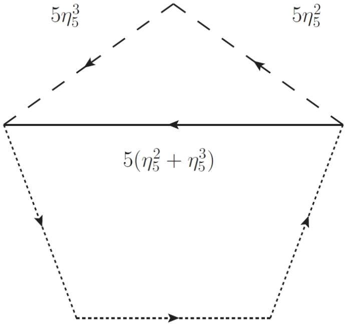
Geometrical (complex) VEVs

Phases depend on the sign of λ_3 and for $\lambda_3 > 0$

$$\langle H \rangle = \frac{v}{\sqrt{3}} (\omega, 1, 1) \,, A_i = 2\pi/3$$

Geometrical (complex) VEVs - see also

IdMV (2012) JHEP 1205.3780
Holthausen, Lindner, Schmidt (2012) JHEP 1211.6953
Ivanov, Lavoura (2013) EPJ 1302.3656
IdMV (2013) Discrete 2012 Proceedings 1302.3991



Fermions: $\Delta(27)$

IdMV, Emmanuel-Costa (2011) PLB 1106.5477
(Geometrical CP Violation)

$QH^\dagger u^c$, QHd^c and Q_i as...

- triplet: 1 sector $\mathbf{3_{0i}} \times \mathbf{3_{0i}} \times \mathbf{3_{0i}}$.
  Already pointed out as not viable.
- singlets: Both sectors $\mathbf{1_{rs}} \times \mathbf{3_{01}} \times \mathbf{3_{02}}$
  can get:
  rank 1 mass matrices or
  (M_d) one generation decoupled or
  "diagonal" matrices with three distinct eigenvalues.

Singlets on the left

$(Hd^c) \to 1_{rs}$: $H_1 d^{c1} + c.p.$ (1_{00})
$H_1 d^{c2} + c.p.$ or $H_1 d^{c3} + c.p.$ (1_{02} and 1_{01})

Q_1 and Q_2 as 1_{00};
Q_3 as 1_{02} (combines with $H_1 d^{c3} + c.p.$):

$$M_d = v \begin{pmatrix} y_1\omega & y_1 & y_1 \\ y_2\omega & y_2 & y_2 \\ y_3 & y_3 & y_3\omega \end{pmatrix}$$

No CKM

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

$$(1 + \omega + \omega^2 = 0)$$

Off-diagonal entries

Bhattacharyya, IdMV, Leser (2012) PRL 1210.0545
Add θ, in the irrep $\mathbf{1}_{01}$. Get $QH_i d^{cj} \theta$

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

Obtain the required off-diagonal entries...
But no complex phase.

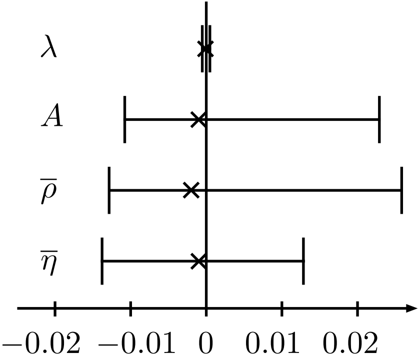
Complex phase

Use $QH_i d^{cj}(H_k H^{\dagger l})$

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

$M_d + M_\theta + M_H$: everything needed to account for observations!

Observations



Potential

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

λ_5, λ_6 problematic

What next?

Explaining the hierarchies?
Safeguard potential?
Leptons?

Potential and Hierarchies

IdMV, Pidt (2013) JPG, 1307.0711

Solve simultaneously, single symmetry:

1. Charge 1_{0i} scalar, force $\lambda_5 = \lambda_6 = 0$.
2. Must keep the 1_{0i} in the Yukawa sector... Use 1_{0i} as FN field.

Leptons

IdMV, Pidt (2013) JHEP, 1307.6545

If we have $LLH^\dagger H^\dagger$ invariants and H as 3_{0i}
LHl^c is $\mathbf{3_{0i}} \times \mathbf{3_{0i}} \times \mathbf{3_{0i}}$.

Our solution: separate ϕ ($\Delta(27)$ triplet with GCPV) and H.

See also: Ma (2013) 1304.1603
additional $SU(2)$ doublet scalars ζ, $LLH^\dagger \zeta$
(issues with potential!)

Complete fermion sector

Charged leptons: singlets on the right

$$H\left(y_3(L\phi^\dagger)_{01}\tau^c + y_2(L\phi^\dagger)_{02}\mu^c(\theta^2) + y_1(L\phi^\dagger)_{00}e^c(\theta^3)\right).$$

$$V_l = \frac{1}{\sqrt{3}}\begin{pmatrix}\omega^2 & \omega & 1\\ 1 & \omega & \omega^2\\ 1 & 1 & 1\end{pmatrix}.$$

No free parameters, y_i set to get masses.

Neutrino invariants

$$H^\dagger H^\dagger \left(A(L\phi^\dagger)_{00}(L\phi^\dagger)_{00} + B(L\phi^\dagger)_{01}(L\phi^\dagger)_{02} \right)$$

$$\begin{aligned} &H^\dagger H^\dagger \xi \left(z_1 (L_i L_i \phi_i)_{00} + z_4 (L_i L_j \phi_k)_{00} \right) \\ &H^\dagger H^\dagger \xi' \left(z_2 (L_i L_i \phi_i)_{02} + z_5 (L_i L_j \phi_k)_{02} \right) \\ &H^\dagger H^\dagger \xi'' \left(z_3 (L_i L_i \phi_i)_{01} + z_6 (L_i L_j \phi_k)_{01} \right) , \end{aligned}$$

ξ, ξ', ξ'' are 1_{00}, 1_{01}, 1_{02} spurion fields
Made from combinations of FN fields φ (1_{00}) and θ (1_{0i}).

One type of model with $\xi \sim \theta^3$ and $\xi' \sim \theta^2 \varphi^2$ (no z_3, z_6).
Another type of model has the h.c. assignments (no z_2, z_5).

Complete potential

$$
\begin{aligned}
V(H,\phi,\varphi,\theta) &= m_H^2 HH^\dagger + m_\varphi^2 \varphi\varphi^\dagger + m_\theta^2 \theta\theta^\dagger \\
&+ \lambda_H (HH^\dagger)^2 + \lambda_\varphi (\varphi\varphi^\dagger)^2 + \lambda_\theta (\theta\theta^\dagger)^2 + \lambda_{\varphi\theta} (\varphi\varphi^\dagger)(\theta\theta^\dagger) \\
&+ \left(\lambda_{\varphi H} \varphi\varphi^\dagger + \lambda_{\theta H} \theta\theta^\dagger\right) \left(HH^\dagger\right) \\
&+ m_\phi^2 \left[\phi_i \phi_i^\dagger\right] + \lambda_1 \left[(\phi_i \phi_i^\dagger)^2\right] + \lambda_2 \left[\phi_1 \phi_1^\dagger \phi_2 \phi_2^\dagger\right] \\
&+ \lambda_3 \left[\phi_1 \phi_2^\dagger \phi_1 \phi_3^\dagger + \text{h.c.}\right] \\
&+ \left(\lambda_{H\phi} HH^\dagger + \lambda_{\varphi\phi} \varphi\varphi^\dagger + \lambda_{\theta\phi} \theta\theta^\dagger\right) \left[\phi_i \phi_i^\dagger\right] .
\end{aligned}
$$

Geometrical CP violation with complete fermion sector

Conclusions

- First time GCPV with viable fermions.
- Precision data restricts viable irrep. choices.
- Additional symmetry safeguards potential.
- Same symmetry alleviates mass hierarchies.
- Constructed compatible lepton models.