# Fermion mixing with geometrical CP violation and its tests at the LHC

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# Outline

# Spontaneous CP violation

Complex VEVs not sufficient. CP conserved if:

$$H_i \longrightarrow H'_i = U_{ij} H_j \,, \tag{1}$$

$$U_{ij} \langle H_j \rangle^* = \langle H_i \rangle \,, \tag{2}$$

while $U$ leaves the Lagrangian invariant.

# Calculable phases

Branco, Gérard, Grimus (1979, PLB)

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

# CP and discrete symmetries

Recent work:

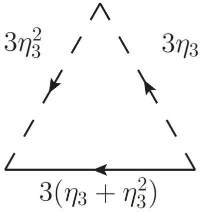
Feruglio, Hagedorn, Ziegler (arXiv:1211.5560, plenary talk)

Holthausen, Lindner, Schmidt (arXiv:1211.6953)

# $\Delta(27)$ calculable phase

$$V(H) \sim \lambda_3 (H_1^\dagger H_2 H_1^\dagger H_3 + H_2^\dagger H_3 H_2^\dagger H_1 + H_3^\dagger H_1 H_3^\dagger H_2) + \text{H.c.} \quad (3)$$

$$V \propto v^4 (e^{iA_1} + e^{iA_2} + e^{A_3} + H.c.) \,, \quad A_i = 2\alpha_i - \alpha_j - \alpha_k$$




Generalisations: IdMV (arXiv:1205.3780, JHEP)

# Geometrical (complex) VEVs

VEVs depend on the sign of $\lambda_3$ ($\eta_3 = \omega = e^{i2\pi/3}$, $\omega^3 = 1$):

$$\langle H \rangle = v\,(1, \omega, \omega^2)\,, \tag{4a}$$

$$\langle H \rangle = v\,(\omega, 1, 1) \tag{4b}$$

# Fermions: $\Delta(27)$

IdMV, Emmanuel-Costa (arXiv:1106.5477, PLB)

**$QH^\dagger u^c$, $QHd^c$ 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 (not shown) or
  one generation decoupled or ($M_d$)
  "diagonal" matrices with three distinct eigenvalues ($\tilde{M}_d$).

# Singlets on the left

$$\tilde{M}_d = v \begin{pmatrix} y_1\omega & y_1 & y_1 \\ y_2 & y_2\omega & y_2 \\ y_3 & y_3 & y_3\omega \end{pmatrix} \tag{5}$$

$$M_d = v \begin{pmatrix} y_1\omega & y_1 & y_1 \\ y_2\omega & y_2 & y_2 \\ y_3 & y_3 & y_3\omega \end{pmatrix} \tag{6}$$

# No CKM

$$\tilde{M}_d \tilde{M}_d^\dagger = 3v^2 \begin{pmatrix} y_1^2 & 0 & 0 \\ 0 & y_2^2 & 0 \\ 0 & 0 & y_3^2 \end{pmatrix} \tag{7}$$

$$M_d M_d^\dagger = 3v^2 \begin{pmatrix} y_1^2 & y_1 y_2 & 0 \\ y_1 y_2 & y_2^2 & 0 \\ 0 & 0 & y_3^2 \end{pmatrix} \tag{8}$$

# Off-diagonal entries

Bhattacharyya, IdMV, Leser (arXiv:1210.0545, PRL)
Add $\phi$, in the irrep $\mathbf{1}_{01}$. Get $QHd^c\phi$

$$M_\phi = v \begin{pmatrix} y_{\phi 1} & y_{\phi 1}\omega & y_{\phi 1} \\ y_{\phi 2} & y_{\phi 2}\omega & y_{\phi 2} \\ y_{\phi 3}\omega & y_{\phi 3} & y_{\phi 3} \end{pmatrix} \tag{9}$$

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

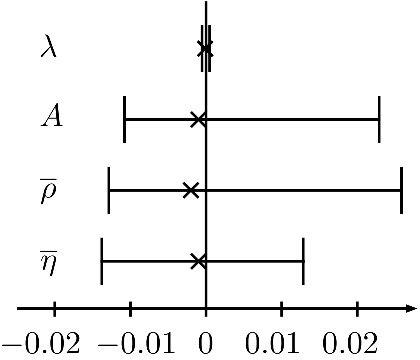
# Complex phase

Use $QHd^c(HH^\dagger)$

$$M_H = v \begin{pmatrix} y_{H1} & y_{H1}\omega^2 & y_{H1}\omega^2 \\ y_{H2} & y_{H2}\omega^2 & y_{H2}\omega^2 \\ y_{H3}\omega^2 & y_{H3}\omega^2 & y_{H3} \end{pmatrix} \tag{10}$$

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

# Observations



# Lagrangian and results

$$\mathcal{L} = Q\left(H^\dagger u^c + H d^c + H d^c \phi + H d^c (H H^\dagger)\right) . \qquad (11)$$

$$\begin{aligned}
\lambda^{\text{exp}} &= 0.22535 \pm 0.00065 & \lambda &= 0.22534, \\
A^{\text{exp}} &= 0.811 {}^{+0.022}_{-0.012} & A &= 0.810, \\
\bar{\rho}^{\,\text{exp}} &= 0.131 {}^{+0.026}_{-0.013} & \bar{\rho} &= 0.129, \\
\bar{\eta}^{\,\text{exp}} &= 0.345 {}^{+0.013}_{-0.014} & \bar{\eta} &= 0.344.
\end{aligned} \qquad (12)$$

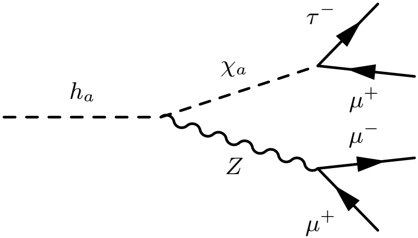
# Potential

$$
\begin{aligned}
V(H,\phi) = {} & m_1^2 \left[ H_1 H_1^\dagger \right] + m_2^2 \phi\phi^\dagger + m_3(\phi^3 + \text{h.c.}) \\
& + \lambda_1 \left[ (H_1 H_1^\dagger)^2 \right] + \lambda_2 \left[ H_1 H_1^\dagger H_2 H_2^\dagger \right] + \lambda_3 \left[ H_1 H_2^\dagger H_1 H_3^\dagger + \text{h.c.} \right] \\
& + \lambda_4 (\phi\phi^\dagger)^2 + \lambda_5 \left[ \phi (H_1 H_2^\dagger) + \text{h.c.} \right] + \lambda_6 \left[ \phi\phi (H_1 H_3^\dagger) + \text{h.c.} \right] ,
\end{aligned}
\tag{13}
$$

$\lambda_5, \lambda_6$ must be suppressed (natural, and a $Z_4$ can enforce it).

# LHC tests

In the $\phi$ decoupling limit, similar to $S_3$ case
Bhattacharyya, Leser, Päs (arXiv:1206.4202, PRD)
CP even state $h_a \sim H_2 - H_3$
No $h_a VV$; $h_a$ ($\chi_a$) couples off-diagonal to fermions ($h_a uc$, $h_a ct$)



# Conclusions

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- First time GCP with viable fermions.
- Precision data restricts viable irrep. choices.
- Scalar sector inherits symmetries and can be tested at LHC.