Three Higgs doublet models with S_3 Symmetry and Dark matter candidates

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From Higgs to Dark Matter

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Motivation for three Higgs doublets

Three fermion generations may suggest three doublets

Interesting scenario for dark matter

Possibility of having a discrete symmetry and still having spontaneous CP violation

Rich phenomenology

Motivation for imposing discrete symmetries

Symmetries reduce the number of free parameters leading to (testable) predictions

Symmetries help to control HFCNC

Example: NFC, no HFCNC due to Z_2 symmetry(ies)

Example: MFV suppression of HFCNC, BGL models

Symmetries are needed to stabilise dark matter

Three Higgs doublet models with S_3 Symmetry

(extended to flavour)

Despite

many works aiming at explaining neutrino masses and leptonic mixing

Ma, Koide, Kubo, Mondragon, Rodriguez-Jauregui, Chen, Wolfenstein, Mohapatra, Nasri, Yu, Harrison, Scott, Frigerio, Grimus, Lavoura, Branco, Silva-Marcos…

several works addressing masses and mixing in the quark sector

Harari, Haut, Weyers, Meloni, Teshima, Melic, Canales, S Salazar, Velasco-Sevilla ,…

a lot of work already done analysing the Higgs potential

Derman, Tsao, Pakvasa, Sugawra, Wyler, Branco, Gerard, Grimus, Das, Dey, Bhattacharyya, Leser, Pas, Ivanov, Nishi…

inert dark matter candidates from S_3 3HDM considered

Fortes, Machado, Montano, Pleitez…

Interesting open questions still remain!

The Scalar potential

S_3 is the permutation group involving three objects, ϕ_1, ϕ_2, ϕ_3

$$V_2 = -\lambda \sum_i \phi_i^\dagger \phi_i + \frac{1}{2}\gamma \sum_{i<j} [\phi_i^\dagger \phi_j + \mathrm{hc}]$$

$$V_4 = A \sum_i (\phi_i^\dagger \phi_i)^2 + \sum_{i<j} \{ C(\phi_i^\dagger \phi_i)(\phi_j^\dagger \phi_j) + \bar{C}(\phi_i^\dagger \phi_j)(\phi_j^\dagger \phi_i) + \frac{1}{2} D[(\phi_i^\dagger \phi_j)^2 + \mathrm{hc}]\}$$
$$+ \frac{1}{2} E_1 \sum_{i\neq j} [(\phi_i^\dagger \phi_i)(\phi_i^\dagger \phi_j) + \mathrm{hc}] + \sum_{i\neq j\neq k\neq i, j<k} \{ \frac{1}{2} E_2 [(\phi_i^\dagger \phi_j)(\phi_k^\dagger \phi_i) + \mathrm{hc}]$$
$$+ \frac{1}{2} E_3 [(\phi_i^\dagger \phi_i)(\phi_k^\dagger \phi_j) + \mathrm{hc}] + \frac{1}{2} E_4 [(\phi_i^\dagger \phi_j)(\phi_i^\dagger \phi_k) + \mathrm{hc}]\}$$

Derman, 1979

here all fields appear on equal footing

this representation is not irreducible, for instance, the combination

$$\phi_1 + \phi_2 + \phi_3$$

remains invariant, it splits into two irreducible representations,

doublet and singlet: $\begin{pmatrix} h_1 \\ h_2 \end{pmatrix}, \quad h_S$

Decomposition into these two irreducible representations

$$\begin{pmatrix} h_1 \\ h_2 \\ h_S \end{pmatrix} = \begin{pmatrix} \frac{1}{\sqrt{2}} & -\frac{1}{\sqrt{2}} & 0 \\ \frac{1}{\sqrt{6}} & \frac{1}{\sqrt{6}} & -\frac{2}{\sqrt{6}} \\ \frac{1}{\sqrt{3}} & \frac{1}{\sqrt{3}} & \frac{1}{\sqrt{3}} \end{pmatrix} \begin{pmatrix} \phi_1 \\ \phi_2 \\ \phi_3 \end{pmatrix}$$

This definition does not treat equally ϕ_1, ϕ_2, ϕ_3 **, they could be interchanged**

Notice similarity with tribimaximal mixing: Harrison, Perkins and Scott, 1999

$$(F =) \begin{pmatrix} -\frac{2}{\sqrt{6}} & \frac{1}{\sqrt{3}} & 0 \\ \frac{1}{\sqrt{6}} & \frac{1}{\sqrt{3}} & \frac{1}{\sqrt{2}} \\ \frac{1}{\sqrt{6}} & \frac{1}{\sqrt{3}} & -\frac{1}{\sqrt{2}} \end{pmatrix}$$

The matrix F diagonalizes the democratic matrix , Δ

$$F'^T \begin{pmatrix} 1 & 1 & 1 \\ 1 & 1 & 1 \\ 1 & 1 & 1 \end{pmatrix} F' = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 3 \end{pmatrix} \qquad \Delta = \begin{pmatrix} 1 & 1 & 1 \\ 1 & 1 & 1 \\ 1 & 1 & 1 \end{pmatrix}$$

The democratic mass matrix can be obtained from S_3 flavour symmetries

S_{3L} x S_{3R}: $M_l = \lambda' \ \Delta \quad ; \qquad M_D = \lambda \ \Delta \quad ; \qquad M_R = \mu \ (\Delta + a \ 1\!\!1)$

Very interesting alternative, democratic with phases (USY)

The scalar potential in terms of fields from irreducible representations

$$V_2 = \mu_0^2 h_S^\dagger h_S + \mu_1^2 (h_1^\dagger h_1 + h_2^\dagger h_2),$$

$$\begin{aligned} V_4 = {} & \lambda_8 (h_S^\dagger h_S)^2 + \lambda_5 (h_S^\dagger h_S)(h_1^\dagger h_1 + h_2^\dagger h_2) + \lambda_1 (h_1^\dagger h_1 + h_2^\dagger h_2)^2 \\ & + \lambda_2 (h_1^\dagger h_2 - h_2^\dagger h_1)^2 + \lambda_3 [(h_1^\dagger h_1 - h_2^\dagger h_2)^2 + (h_1^\dagger h_2 + h_2^\dagger h_1)^2] \\ & + \lambda_6 [(h_S^\dagger h_1)(h_1^\dagger h_S) + (h_S^\dagger h_2)(h_2^\dagger h_S)] \\ & + \lambda_7 [(h_S^\dagger h_1)(h_S^\dagger h_1) + (h_S^\dagger h_2)(h_S^\dagger h_2) + \text{h.c.}] \\ & + \lambda_4 [(h_S^\dagger h_1)(h_1^\dagger h_2 + h_2^\dagger h_1) + (h_S^\dagger h_2)(h_1^\dagger h_1 - h_2^\dagger h_2) + \text{h.c.}] \end{aligned}$$

Das and Dey

no symmetry under the interchange of h_1 and h_2

however there is symmetry for $h_1 \to -h_1$

equivalent doublet representation $\begin{pmatrix} \chi_1 \\ \chi_2 \end{pmatrix} = \frac{1}{\sqrt{2}} \begin{pmatrix} i & 1 \\ -i & 1 \end{pmatrix} \begin{pmatrix} h_1 \\ h_2 \end{pmatrix}$

now there is symmetry for $\chi_1 \leftrightarrow \chi_2$

In the special case $\lambda_4 = 0$ **the potential has SO(2) symmetry:**

$$\begin{pmatrix} h_1' \\ h_2' \end{pmatrix} = \begin{pmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} h_1 \\ h_2 \end{pmatrix}$$

Danger: massless scalar!

Alternative choice of irreducible representations

S_3 has three irreducible representations, doublet, singlet and pseudo singlet, h_A

Take S_3 doublet and h_A

No direct translation into initial fields Φ_1, Φ_2, Φ_3

New potential (only term in λ_4 changes):

$$V_2 = \mu_0^2 h_A^\dagger h_A + \mu_1^2 (h_1^\dagger h_1 + h_2^\dagger h_2), \tag{2.75a}$$

$$\begin{aligned} V_4 &= \lambda_1 (h_1^\dagger h_1 + h_2^\dagger h_2)^2 + \lambda_2 (h_1^\dagger h_2 - h_2^\dagger h_1)^2 + \lambda_3 [(h_1^\dagger h_1 - h_2^\dagger h_2)^2 + (h_1^\dagger h_2 + h_2^\dagger h_1)^2] \\ &+ \lambda_4 [(h_A^\dagger h_2)(h_1^\dagger h_2 + h_2^\dagger h_1) - (h_A^\dagger h_1)(h_1^\dagger h_1 - h_2^\dagger h_2) + \mathrm{h.c.}] + \lambda_5 (h_A^\dagger h_A)(h_1^\dagger h_1 + h_2^\dagger h_2) \\ &+ \lambda_6 [(h_A^\dagger h_1)(h_1^\dagger h_A) + (h_A^\dagger h_2)(h_2^\dagger h_A)] + \lambda_7 [(h_A^\dagger h_1)(h_A^\dagger h_1) + (h_A^\dagger h_2)(h_A^\dagger h_2) + \mathrm{h.c.}] \\ &+ \lambda_8 (h_A^\dagger h_A)^2. \end{aligned} \tag{2.75b}$$

reduces to the same potential we had before with h_1 and h_2 interchanged, no new physics!

Minimisation of the scalar potential:

The vacuum conditions give μ_0^2 and μ_1^2 in terms of the quartic coefficients:

$$\mu_0^2 = \frac{1}{2w_S}\left[\lambda_4(w_2^2 - 3w_1^2)w_2 - (\lambda_5 + \lambda_6 + 2\lambda_7)(w_1^2 + w_2^2)w_S - 2\lambda_8 w_S^3\right],$$

$$\mu_1^2 = -\frac{1}{2}\left[2(\lambda_1 + \lambda_3)(w_1^2 + w_2^2) + 6\lambda_4 w_2 w_S + (\lambda_5 + \lambda_6 + 2\lambda_7)w_S^2\right],$$

$$\mu_1^2 = -\frac{1}{2}\left[2(\lambda_1 + \lambda_3)(w_1^2 + w_2^2) - 3\lambda_4(w_2^2 - w_1^2)\frac{w_S}{w_2} + (\lambda_5 + \lambda_6 + 2\lambda_7)w_S^2\right].$$

The second and third equations are not automatically consistent

consistency requires:

$$\lambda_4(3w_2^2 - w_1^2)w_S = 0.$$

leading to:

- Case I. $\lambda_4 = 0$
- Case II. $v_1^2 = 3v_2^2$
- Case III. $w_S = 0$.

The scalar mass spectrum of cases I and II is computed in Das and Dey

Phys.Rev. D89 (2014) 9, 095025

SSB, real vacua, residual symmetries

Derman, Tsao Phys. Rev. D20 (1979) 1207:

(x, x, x) S_3 ; (x, x, y) S_2 ; (x, y, z) = (x, -x, 0) S_2 $\lambda_4 \neq 0$

Translation into doublet singlet notation

(x, x, x) $\longrightarrow$ (0,0, ω_S) $\omega_1 = \sqrt{3}\omega_2$ (two zeros)

(x, -x, 0) $\longrightarrow$ $(\omega_1, 0, 0)$ $\omega_S = 0$ (two zeros)

(x, 0, -x) $\longrightarrow$ $(\omega_1, \omega_2, 0)$ $\omega_S = 0$

(0,x, -x) $\longrightarrow$ $(\omega_1, \omega_2, 0)$ $\omega_S = 0$

(x, x, y) $\longrightarrow$ (o, w_2, w_S) would require $\lambda_4 = 0$

(x, y, x) $\longrightarrow$ $(\omega_1, -\sqrt{3}\omega_1, \omega_S)$ $\omega_1 = -\sqrt{3}\omega_2$

(y, x, x) $\longrightarrow$ $(\omega_1, \sqrt{3}\omega_1, \omega_S)$ $\omega_1 = \sqrt{3}\omega_2$

For $\lambda_4 = 0$ SO(2) symmetry implies (x, y, z) possible solution

Complex vacua, Spontaneous CP violation

$\langle\phi_1\rangle_0 = \xi_1 \cos\alpha\, e^{i\psi}$, $\quad \langle\phi_2\rangle_0 = \xi_1 \sin\alpha\, e^{i\phi}$, $\quad \langle\phi_0\rangle_0 = \xi_0$, for a given region of parameter space

with $\alpha = \pi/4$, $\phi + \psi = 0$, and $\cos 2\phi = -(\xi_0/\xi_1)^2 f'/(d+g)$, Pakvasa, Sugawara,1978

here ϕ_O denotes the singlet the two other fields are in the doublet

see also: Wyler, 1979

Another possible solution: complex, geometrical (calculable) phases

$$\langle 0|\phi_k^0|0\rangle = \exp\left[i\tfrac{2}{3}\pi(k-1)\right]v\,, \quad k = 1, 2, 3\,.$$

No spontaneous CP violation $\quad U_{ij}^*\langle 0|\phi_j|0\rangle^* = \langle 0|\phi_i|0\rangle\,.$ $\quad U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & 0 & 1 \\ 0 & 1 & 0 \end{pmatrix},$

Branco, Gerard, Grimus1984

Also $\quad (v_1,\, v_2 e^{i\xi_2},\, v_2 e^{i\xi_2}).$ Ivanov and Nishi 2014

Different Residual Symmetries for different cases

Systematic study under way

Inert Higgs

Initial proposal: 2 Higgs doublets, Unbroken Z_2 symmetry $\Phi_2 \to -\Phi_2$

all other Standard Model particles are invariant under Z_2

R. Barbieri, L. J. Hall, and V. S. Rychkov, 2006

Φ_2- , the inert Higgs, does not couple to matter and acquires no vev, NFC

Notice that this is different from going to the Higgs basis

The Z_2 symmetry is left unbroken, as a result the lightest inert particle will be stable and will contribute to dark matter density

Inert scalars can be produced at colliders through their couplings to the EW gauge bosons subject to Z_2 constraints and participate in cubic and quartic Higgs couplings

Our Aims

Determine whether Spontaneous CP violation in S_3 is compatible with a good inert dark matter candidate and what are their properties

Challenges:

Determine necessary and sufficient vacuum stability conditions

No breaking of electric charge

Obey unitarity constraints for the potential

Obtain correct dark matter density

Possibility of generating complex V_{CKM}

NFC does not generate complex V_{CKM} from complex vacua   **Branco, 1980**

Phenomenologically realistic implementation

with the possibility of being tested at the LHC

Conclusions

Models with S_3 symmetry look very promising

We are still at an early stage of our work

Hopefully LHC will find extra scalars