State of the Art of the Minimal S_3-Invariant Extension of the Standard Model

U. J. Saldaña Salazar
A. Mondragón M. Mondragón

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A Global Overview

1. Stage I: Some quick motivations.
   - The Standard Model (SM) and what it lacks
   - "A Bottom-Up Approach"
     - Flavour Symmetries

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     - Justification
     - Construction
     - Background Work

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The Standard Model (SM)

The gauge group that describes the particles interactions is given by:

$$G_{SM} = SU(3)_C \otimes SU(2)_L \otimes U(1)_Y$$

Some unsolved problems of the SM...

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- etc...

Discrete flavour symmetries

Discrete groups

Discrete flavour symmetries

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We avoid the introduction of Goldstone bosons and flavons after the flavour symmetry breaking.

Discrete flavour symmetries

Abelian groups

Discrete flavour symmetries

Abelian groups

Barbieri et al showed that under the gauge group $SU(2)_L \otimes U(1)_Y$ of the standard model, it is not posible under any abelian discrete group and an arbitrary number of Higgs and families to reproduce the Cabibbo Angle in terms of quark mass ratios. [Phys. Lett. **74B**, 344 (1978)]

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Non-Abelian groups

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Non-Abelian groups

- D. Wyler showed that by using a non-abelian discrete symmetry and by introducing at least 3 Higgs weak doublets, then it becomes possible to express the Cabibbo angle in terms of quark mass ratios. [Phys. Rev. **D19**, 330 (1979)]

Discrete flavour symmetries

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- D. Wyler showed that by using a non-abelian discrete symmetry and by introducing at least 3 Higgs weak doublets, then it becomes possible to express the Cabibbo angle in terms of quark mass ratios. [Phys. Rev. **D19**, 330 (1979)]
- In multi-Higgs models, the Higgs potential may become invariant under a larger class of symmetries. [P.M. Ferreira et al Phys. Rev. **D78**, 116007 (2008)]

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Justification of the Model

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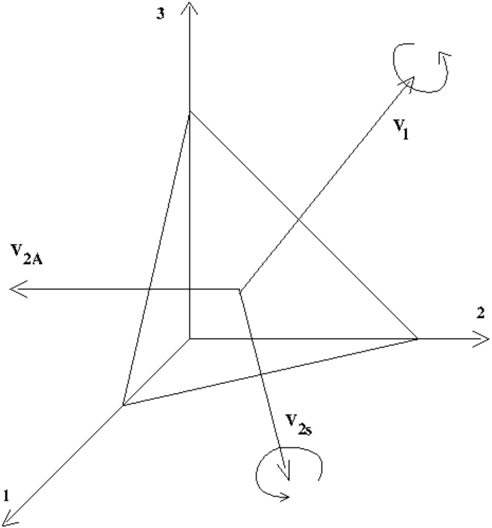
- The scalar sector is minimally extended by adding two more Higgs weak-doublets.
  - The concept of flavour is taken to a more fundamental level.
  - By having a multiHiggs model there is no need to break the flavour symmetry by hand.
- An abelian Z_2 symmetry is added in the leptonic sector to achieve a further reduction in the number of parameters.

MS3IESM - Construction of the Model

The S_3 Group: Permutations of 3 objects.



MS3IESM - Construction of the Model

Permutations		Rotations
$\begin{pmatrix} 1 & 2 & 3 \\ 3 & 1 & 2 \end{pmatrix}$	$\Longleftrightarrow$	a rotation of 120° around the invariant vector $\mathbf{V}_1$
$\begin{pmatrix} 1 & 2 & 3 \\ 2 & 1 & 3 \end{pmatrix}$	$\Longleftrightarrow$	a rotation of 180° around the invariant vector $\mathbf{V}_{2S}$

MS3IESM - Construction of the Model

The irreps of the group are:

- 1 Dimension: $\mathbf{1}_A$, $\mathbf{1}_S$
- 2 Dimensions: $\mathbf{2}$

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The direct products between irreps are:

- $\mathbf{1}_S \otimes \mathbf{1}_S = \mathbf{1}_S$
- $\mathbf{1}_A \otimes \mathbf{1}_A = \mathbf{1}_S$
- $\mathbf{1}_A \otimes \mathbf{1}_S = \mathbf{1}_A$
- $\mathbf{1}_S \otimes \mathbf{2} = \mathbf{2}$
- $\mathbf{1}_A \otimes \mathbf{2} = \mathbf{2}$
- $\mathbf{2} \otimes \mathbf{2} = \mathbf{2} + \mathbf{1}_S + \mathbf{1}_A$

MS3IESM - Construction of the Model

The tensor product of two doublets:

$$\mathbf{p_D} = \begin{pmatrix} p_{D1} \\ p_{D2} \end{pmatrix} \qquad \textit{and} \qquad \mathbf{q}_D = \begin{pmatrix} q_{D1} \\ q_{D2} \end{pmatrix}$$

we have two singlets, r_S y r_A, and one doublet $\mathbf{r}_D$, where:

$r_S = p_{D1}q_{D1} + p_{D2}q_{D2}$ is invariant, $r_A = p_{D1}q_{D2} - p_{D2}q_{D1}$ is not invariant

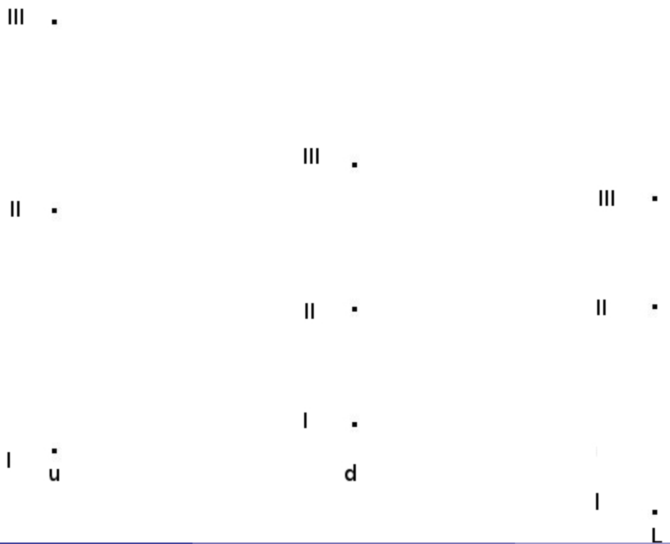
and

$$\mathbf{r}_D = \begin{pmatrix} p_{D1}q_{D2} + p_{D2}q_{D1} \\ p_{D1}q_{D1} - p_{D2}q_{D2} \end{pmatrix}$$

is invariant.

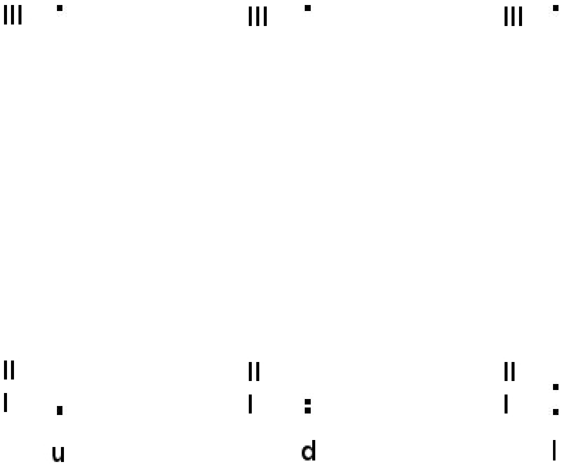
MS3IESM - Construction of the Model

Logarithmic scale of fundamental known fermion masses



MS3IESM - Construction of the Model

Natural scale of fundamental fermion mass ratios



MS3IESM - Construction of the Model

Assignments of fields and irreps:

$$\Phi \to H = (\Phi_1, \Phi_2, \Phi_3)^T$$

H is a reducible representation $\mathbf{1_S} \oplus \mathbf{2}$ of S_3

$$H_s = \frac{1}{\sqrt{3}}\Big(\Phi_1 + \Phi_2 + \Phi_3\Big)$$

$$H_D = \begin{pmatrix} \frac{1}{\sqrt{2}}(\Phi_1 - \Phi_2) \\ \\ \frac{1}{\sqrt{6}}(\Phi_1 + \Phi_2 - 2\Phi_3) \end{pmatrix}$$

The quark, lepton and Higgs fields are

$$Q^T = (u_L, d_L), u_R, d_R, \qquad L^\dagger = (\nu_L, e_L), e_R, \nu_R, \qquad H.$$

All these fields have 3 species (flavours) and they belong to a reducible rep. $\mathbf{1_S} \oplus \mathbf{2}$ of S_3.

MS3IESM - Construction of the Model

The most general S_3 invariant renormalizable Yukawa interactions:

$$\mathcal{L}_Y = \mathcal{L}_{Y_D} + \mathcal{L}_{Y_u} + \mathcal{L}_{Y_E} + \mathcal{L}_{Y_\nu}$$

Quarks

$$\begin{aligned}\mathcal{L}_{Y_D} &= -Y_1^d \overline{Q}_I H_S d_{IR} - Y_3^d \overline{Q}_3 H_S d_{3R} \\ &- Y_2^d [\overline{Q}_I \kappa_{IJ} H_1 d_{JR} + \overline{Q}_I \eta_{IJ} H_2 d_{JR}] \\ &- Y_4^d \overline{Q}_3 H_I d_{IR} - Y_5^d \overline{Q}_I H_I d_{3R} + h.c.,\end{aligned}$$

$$\begin{aligned}\mathcal{L}_{Y_U} &= -Y_1^U \overline{Q}_I (i\sigma_2) H_S^* u_{IR} - Y_3^u \overline{Q}_3 (i\sigma_2) H_S^* u_{3R} \\ &- Y_2^u [\ \overline{Q}_I \kappa_{IJ} (i\sigma_2) H_1^* u_{JR} + \overline{Q}_I \eta_{IJ} (i\sigma_2) H_2^* u_{JR}\ ] \\ &- Y_4^u \overline{Q}_3 (i\sigma_2) H_I^* u_{IR} - Y_5^u \overline{Q}_I (i\sigma_2) H_I^* u_{3R} + h.c.\end{aligned}$$

The flavour doublets carry index $I, J = 1, 2$

$$\kappa = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix}; \qquad \eta = \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}$$

The flavour singlets carry the index S or 3.

MS3IESM - Construction of the Model

Leptons

$$\begin{aligned}\mathcal{L}_{Y_E} &= -Y_1^e \overline{L}_I H_S e_{IR} - Y_3^e \overline{L}_3 H_S e_{3R} - Y_2^e [\, \overline{L}_I \kappa_{IJ} H_1 e_{JR} + \overline{L}_I \eta_{IJ} H_2 e_{JR} \,] \\ &- Y_4^e \overline{L}_3 H_I e_{IR} - Y_5^e \overline{L}_I H_I e_{3R} + h.c.,\end{aligned}$$

$$\begin{aligned}\mathcal{L}_{Y_\nu} &= -Y_1^\nu \overline{L}_I (i\sigma_2) H_S^* \nu_{IR} - Y_3^\nu \overline{L}_3 (i\sigma_2) H_S^* \nu_{3R} \\ &- Y_2^\nu [\, \overline{L}_I \kappa_{IJ} (i\sigma_2) H_1^* \nu_{JR} + \overline{L}_I \eta_{IJ} (i\sigma_2) H_2^* \nu_{JR} \,] \\ &- Y_4^\nu \overline{L}_3 (i\sigma_2) H_I^* \nu_{IR} - Y_5^\nu \overline{L}_I (i\sigma_2) H_I^* \nu_{3R} + h.c.\end{aligned}$$

$$\kappa = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix}; \qquad \eta = \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix} \qquad I, J = 1, 2$$

Moreover, the Majorana terms for the right-handed neutrinos are

$$\mathcal{L}_M = -M_1 \nu_{IR}^T C \nu_{IR} - M_3 \nu_{3R}^T C \nu_{3R},$$

C is the charge conjugation matrix.

MS3IESM - Construction of the Model

Generic mass matrix for Dirac fermions

Assuming that $< H_1 >=< H_2 >\neq 0$, [S. Pakvasa et al, Phys. Lett. 73B, 61 (1978)], and $< H_3 >\neq 0$ the generic mass matrix, under the S_3 flavour symmetry, is given by: [E. Derman, Phys. Rev. D19, 317 (1979)],[R. Yahalom, Phys. Rev. D29, 536 (1984)]

$$\mathcal{M} = \begin{pmatrix} \mu_1 + \mu_2 & \mu_2 & \mu_5 \\ \mu_2 & \mu_1 - \mu_2 & \mu_5 \\ \mu_4 & \mu_4 & \mu_3 \end{pmatrix}$$

where, in addition to, the following relation is fulfilled:

$$< H_3 >^2 + < H_{D1} >^2 + < H_{D2} >^2 \approx \left(\frac{246}{\sqrt{2}} GeV\right)^2$$

The Majorana massses for ν_L are obtained from the See-saw Mechanism:

$$M_\nu = M_{\nu_D} \tilde{\mathrm{M}}^{-1} (M_{\nu_D})^T \qquad \text{with} \qquad \tilde{\mathrm{M}} = \mathrm{diag}(M_1, M_1, M_3)$$

MS3IESM - Background Work

Some references of works with an S_3 symmetry...

- S. Pakvasa et al, Phys. Lett. 73B, 61 (1978)
- E. Derman, Phys. Rev. D19, 317 (1979)
- D. Wyler, Phys. Rev. D19, 330 (1979)
- R. Yahalom, Phys. Rev. D29, 536 (1984)
- A. Mondragón et al, Phys. Rev. D59, 093009, (1999)
- J. Kubo et al, Prog. Theor. Phys. 109, 795 (2003)
- J. Kubo et al, Phys. Rev. D70, 036007 (2004)
- A. Mondragon et al, Phys. Rev. D76, 076003, (2007)
- D. Meloni et al, Nucl. Part. Phys. 38 015003, (2011)
- T. Teshima et al, arXiv:1103.6127 (2011)
- G. Bhattacharyya et al, Phys. Rev. D83, 011701 (2011)
- And many more... I apologize for those references I don't include.

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Some highlights of the published work...

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- Numerical analysis of the quark mixing matrix, without introducing a Z_2 symmetry, is in good agreement with experimental data. [J. Kubo et al, Prog. Theor. Phys. 109, 795 (2003), T. Teshima et al, arXiv:1103.6127 (2011)]

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- The leptonic mixing angles were successfully expressed as lepton mass ratios. [A. Mondragón et al, AIP Conf. Proc. 1026, 164 (2008), 0712.2488]

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- The leptonic mixing angles were successfully expressed as lepton mass ratios. [A. Mondragón et al, AIP Conf. Proc. 1026, 164 (2008), 0712.2488]
- It predicts an inverted hierarchy between massive neutrinos. [A. Mondragón et al, AIP Conf. Proc. 1026, 164 (2008), 0712.2488]

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- The FCNC contribution, δa_μ, to the anomaly of the muon's magnetic moment is smaller than or of the order of 6% of the discrepancy Δa_μ, between the experimental value and the SM prediction. ($\frac{\delta a_\mu}{\Delta a_\mu} \approx 0.06$) [A. Mondragón et al, J. Phys. A41, 304035 (2008), 0712.1799]

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- Branching ratios were computed for leptonic processes via FCNC as $\mu \to e\gamma$ and $\mu \to 3e$ and it gave for these particular processes 2.42×10^{-20} and 2.53×10^{-16}, respectively. [A. Mondragón et al, J. Phys. Conf. Ser. 171, 012081 (2009)]

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- The observed baryon asymmetry of the universe can be reproduced by the implied leptogenesis of the MS3IESM with S_3 softly broken. [T. Araki et al, Eur. Phys. J. C45, 465 (2006), hep-ph/0502164]

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The Quark Sector

Analysis of the Yukawa couplings under $< H_1 > \neq < H_2 >$

$$\mathbf{M}_f = \begin{pmatrix} -2Y_1 v_s - 2Y_2 v_2 & -2Y_1 v_1 & -2Y_5 v_1 \\ -2Y_1 v_1 & -2Y_1 v_s + 2Y_2 v_2 & -2Y_5 v_2 \\ -2Y_4 v_1 & -2Y_4 v_2 & -2Y_3 v_s \end{pmatrix}$$

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- We then found all the possible textures under a $S_3 \otimes Z_2$ symmetry.

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- There's no texture that contains the Cabibbo Angle, neither eigenvector components with a dominant mass ratio nature.

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- We studied their interdependence under an abelian Z_2 symmetry, in such a way that whenever we forbid one as a consequence another was canceled.
- We then found all the possible textures under a $S_3 \otimes Z_2$ symmetry.
- There's no texture that contains the Cabibbo Angle, neither eigenvector components with a dominant mass ratio nature.
- And moreover, the *CKM* matrix is not reproduced.

The Quark Sector

Analysis of the Yukawa couplings under $< H_1 > \neq < H_2 >$

What do we conclude?

The Quark Sector

Analysis of the Yukawa couplings under $< H_1 > \neq < H_2 >$

What do we conclude?

- The Z_2 symmetry is overconstraining the quark sector.

The Higgs Potential

Some references of works with an S_3 invariant potential...

- S. Pakvasa and H. Sugawara, Phys. Lett. 73B, 61 (1978)
- E. Derman, Phys. Rev. D19, 317 (1979)
- D. Wyler, Phys. Rev. D19, 330 (1979)
- R. Yahalom, Phys. Rev. D29, 536 (1984)
- Y. Koide, Phys. Rev. D60, 077301 (1999)
- J. Kubo et al, Phys. Rev. D70, 036007 (2004)
- S. Chen et al, Phys. Rev. D70, 073008 (2004)
- O. Félix-Beltrán et al, J. Phys.: Conf. Ser. 171 012028 (2009)
- D. Meloni et al, Nucl. Part. Phys. 38 015003, (2011)
- G. Bhattacharyya et al, Phys. Rev. D83, 011701 (2011)
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  - 2. $SU(2)$ scalar.

The Higgs Potential

How did we construct it?

- Each term must be invariant under $S_3 \otimes G_{SM}$.
- The latter is carefully done by steps:
  - 1. S_3 invariant.
  - 2. $SU(2)$ scalar.
- We assign a different coupling to each different direct product of irreps.

The Higgs Potential

Lets see an example...

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- $(\mathbf{2} \otimes \mathbf{2})_{\mathbf{S}} \otimes (\mathbf{2} \otimes \mathbf{2})_{\mathbf{S}} = \mathbf{1}_{\mathbf{S_3}}$

The Higgs Potential

Lets see an example...

- $(\mathbf{2} \otimes \mathbf{2})_\mathbf{S} \otimes (\mathbf{2} \otimes \mathbf{2})_\mathbf{S} = \mathbf{1}_{\mathbf{S_3}}$
    - $(\mathbf{2_w} \otimes \mathbf{2_w})_\mathbf{S} \otimes (\mathbf{2_{w'}} \otimes \mathbf{2_{w'}})_\mathbf{S} = \mathbf{1}_{\mathbf{S_3 \otimes G_{SM}}}$
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  - $\frac{1}{2}[(H_{1w}^{\dagger} H_{1w})^2 + (H_{2w}^{\dagger} H_{2w})^2 + (H_{1w}^{\dagger} H_{2w})^2 + (H_{2w}^{\dagger} H_{1w})^2]$

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- These 3 terms will have the same coupling.

The Higgs Potential

The most general S_3 invariant Higgs potential is:

$$V = V_{2H} + V_{4H}$$

where:

$$\mathrm{V}_{2H} = \mu_S^2(H_S^\dagger H_S) + \mu_D^2(H_1^\dagger H_1 + H_2^\dagger H_2)$$

$$V_{4H} = a(H_S^\dagger H_S)^2 + bf_{ijk}[(H_S^\dagger H_i)(H_j^\dagger H_k) + h.c.] + c[(H_S^\dagger H_1)(H_1^\dagger H_S) + (H_S^\dagger H_2)(H_2^\dagger H_S)] + d[(H_1^\dagger H_1 - H_2^\dagger H_2)^2 + (H_1^\dagger H_2 + H_2^\dagger H_1)^2] + e[(H_S^\dagger H_1)^2 + (H_S^\dagger H_2)^2 + h.c.] + f[(H_1^\dagger H_1)^2 + (H_2^\dagger H_2)^2 + (H_1^\dagger H_2)^2 + (H_2^\dagger H_1)^2] + \frac{f+4d}{2}(H_1^\dagger H_1 + H_2^\dagger H_2)^2 + \frac{g-4d}{2}(H_1^\dagger H_2 - H_2^\dagger H_1)^2$$

where $f_{112} = f_{121} = f_{211} = -f_{222} = 1$ and a, b, c, d, e, f, g are the seven independent couplings.

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  - The most general S_3 invariant Higgs potential has seven independent couplings.

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  - The scalar sector is now ready for a phenomenological study.

Thanks for your attention. Any Questions?

At last, the mystery of the Mayan calendar revealed.