S3-3H MODELS: YUKAWA, HIGGS AND NEUTRINO SECTORS

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SOME ASPECTS OF THE FLAVOUR PROBLEM

- Quark and charged lepton masses very different, very hierarchical

$$m_u : m_c : m_t \sim 10^{-6} : 10^{-3} : 1$$

$$m_d : m_s : m_b \sim 10^{-4} : 10^{-2} : 1$$

$$m_e : m_\mu : m_\tau \sim 10^{-5} : 10^{-2} : 1$$

- Neutrino masses unknown, only difference of squared masses.
- Type of hierarchy (normal or inverted) also unknown
- Higgs sector under study

- Quark mixing angles

$$\theta_{12} \approx 13.0^o$$
$$\theta_{23} \approx 2.4^o$$
$$\theta_{13} \approx 0.2^o$$

?

- Neutrino mixing angles

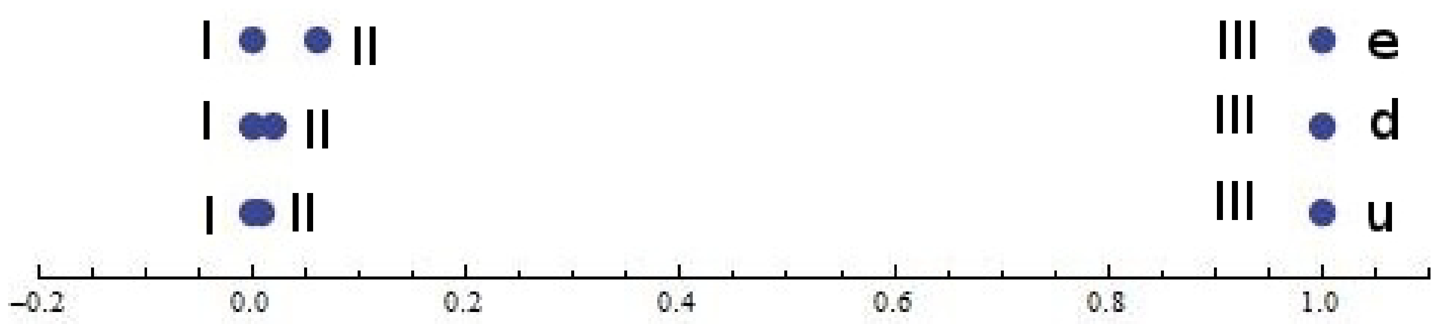
$$\Theta_{12} \approx 33.8^\circ$$
$$\Theta_{23} \approx 49.6^\circ$$
$$\Theta_{13} \approx 8.6^\circ$$

- Small mixing in quarks, large mixing in neutrinos. Very different
- Is there an underlying symmetry?

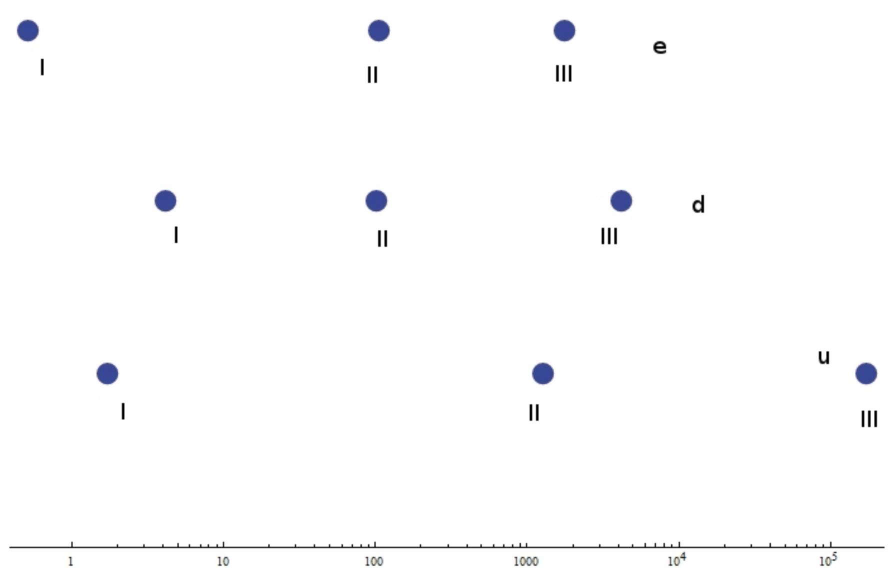
HOW DO WE CHOOSE A FLAVOUR SYMMETRY?

- Several ways:
- Look for inspiration in a high energy extension of SM, i.e. strings or GUTs (see S. King talk)
- Look at low energy phenomenology
- At some point they should intersect…
- In here:
  - Find the smallest flavour symmetry suggested by data
  - Explore how generally it can be applied (universally)
  - Follow it to the end
  - Compare it with the data

Logarithmic plot of masses



Plot of mass ratios

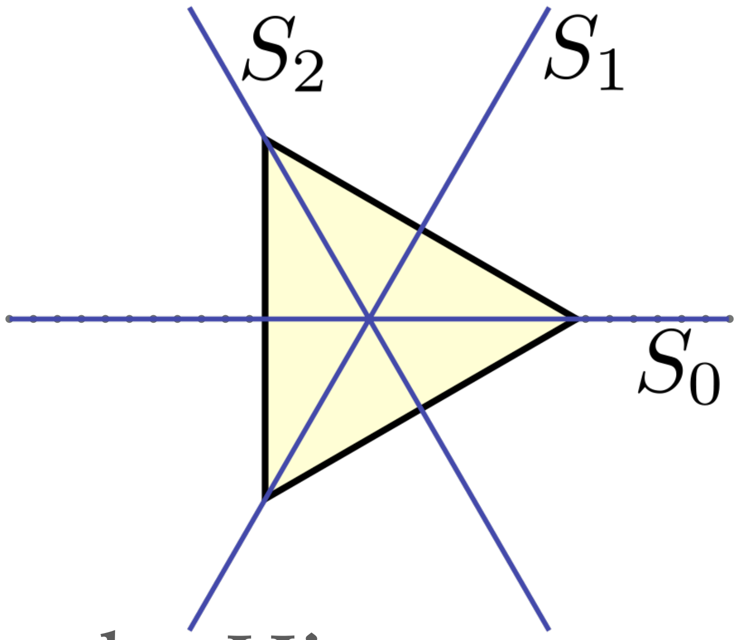


Suggests a 2⊕1 structure

3HDM

- Without symmetry $\Longrightarrow$ 54 real parameters in potential
- Complemented with additional symmetry(ies)
- Studies started in the 70's, hope to find global symmetry that explains the mass and mixing patterns
- The first symmetries to be added were the permutational groups S3 and S4
- Different modern versions of these models exist

3HDM WITH S3



- Low-energy model
- Extend the concept of flavour to the Higgs sector by adding two more eW doublets
- Add symmetry: permutation symmetry of three objects, symmetry operations (reflections and rotations) that leave an equilateral triangle invariant
- 3HDM with symmetry S3:
  8 couplings in the Higgs potential

A sample of S3 models

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. Mondragon et al, Phys. Rev. D59, 093009, (1999)

J. Kubo, A. Mondragon, et al, Prog. Theor. Phys. 109, 795 (2003)

J. Kubo et al, Phys. Rev. D70, 036007 (2004)

S. Chen, M. Frigerio and E. Ma, Phys. Rev. D70, 073008 (2004)

A. Mondragon et al, Phys. Rev. D76, 076003, (2007)

S. Kaneko et al, hep-ph/0703250, (2007)

D. Meloni et al, Nucl. Part. Phys. 38 015003, (2011)

T. Teshima et al, Phys.Rev. D84 (2011) 016003 Phys.Rev. D85 105013 (2012)

F. Gonzalez Canales, A&M. Mondragon Fort. der Physik 61, Issue 4-5 (2013)

H.B. Benaoum, Phys. RevD.87.073010 (2013)

E. Ma and B. Melic, arXiv:1303.6928

F. Gonzalez Canales, A. &M Mondragon, U. Salda~na, L. Velasco, arXiv:1304.6644

R. Jora et al, Int.J.Mod.Phys. A28 (2013),1350028

A. E. Cárcamo Hernández, E. Cataño Mur, R. Martinez, Phys.Rev. D90 (2014) no.7, 073001

A.E. Cárcamo, I. de Medeiros E. Schumacheet, Phys.Rev. D93 (2016) no.1, 016003

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. Felix-Beltran, M.M., 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)

D. Meloni, JHEP 1205 (2012) 124

S. Dev et al, Phys.Lett. B708 (2012) 284-289

S. Zhou, Phys.Lett. B704 (2011) 291-295

E. Barradas et al, 2014

P. Das et al, 2014, 2016

Just a sample, there are many more…
I apologise for those not included

- Smallest non-Abelian discrete group
- Has irreducible representations, 2, 1_S and 1_A
- We add three right-handed neutrinos to implement the see-saw mechanism
- We apply the symmetry “universally” to quarks, leptons and Higgs-es
    - First two families in the doublet
    - Third family in symmetric singlet
- Three sectors related, we treat them simultaneously

PREDICTIONS, ADVANTAGES?

- Possible to reparametrize mixing matrices in terms of mass ratios, successfully
- CKM has NNI and Fritzsch textures
- PMNS → fix one mixing angle, predictions for the other two within experimental range
- Reactor mixing angle $\theta_{13} \neq 0$
- Some FCNCs suppressed by symmetry
- Higgs potential has 8 couplings
- Underlying symmetry in quark, leptons and Higgs → residual symmetry of a more fundamental one?
- Lots of Higgses: 3 neutral, 4 charged, 2 pseudoscalars
- Further predictions will come from Higgs sector: decays, branching ratios

A. Mondragón, M. M., F. González, E. Peinado, U. Saldaña, O. Félix, E. Rodríguez, A. Pérez, H. Reyes...; Das, Dey et al; Teshima et al;

FERMION MASSES

- The Lagrangian of the model

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

- The general form of the fermion mass matrices in the symmetry adapted basis is

$$\mathbf{M} = \begin{pmatrix} m_1 + m_2 & m_2 & m_5 \\ m_2 & m_1 - m_2 & m_5 \\ m_4 & m_4 & m_3 \end{pmatrix}.$$

where $m_{1,3} = Y_{1,3}\, v_3$ and $m_{1,2,4,5} = Y_{1,2,4,5}\, (v_1 \text{ or } v_2)$

QUARKS

3HDM: $G_{SM} \otimes S_3$

	ψ^f_L	ψ^f_R	Mass matrix	Possible mass textures	
A	$\mathbf{2}$, $1_{\mathbf{S}}$	$\mathbf{2}$, $1_{\mathbf{S}}$	$\begin{pmatrix} \mu^f_1+\mu^f_2 & \mu^f_4 & \mu^f_6 \\ \mu^f_4 & \mu^f_1-\mu^f_2 & \mu^f_7 \\ \mu^f_8 & \mu^f_9 & \mu^f_3 \end{pmatrix}$	$\begin{pmatrix} 0 & \mu^f_2 sc\,(3-t^2) & 0 \\ \mu^f_2 sc\,(3-t^2) & -2\mu^f_2 c^2\,(1-3t^2) & \mu^f_7/c \\ 0 & \mu^{f*}_7/c & \mu^f_3-\mu^f_1-\mu^f_2 c^2(1-3t^2) \end{pmatrix}$	
$A^{'}$				$\begin{pmatrix} 0 & \frac{2}{\sqrt{3}}\mu^f_2 & 0 \\ \frac{2}{\sqrt{3}}\mu^f_2 & 0 & \frac{2}{\sqrt{3}}\mu^f_7 \\ 0 & \frac{2}{\sqrt{3}}\mu^f_9 & \mu^f_3-\mu^f_1 \end{pmatrix}$	*NNI*
B	$\mathbf{2}$, $1_{\mathbf{A}}$	$\mathbf{2}$, $1_{\mathbf{A}}$	$\begin{pmatrix} \mu^f_1+\mu^f_2 & \mu^f_4 & \mu^f_7 \\ \mu^f_4 & \mu^f_1-\mu^f_2 & -\mu^f_6 \\ -\mu^f_9 & \mu^f_8 & \mu^f_3 \end{pmatrix}$	$\begin{pmatrix} 0 & -\mu^f_4 c^2\,(1-3t^2) & 0 \\ -\mu^f_4 c^2\,(1-3t^2) & 2\mu^f_4 sc\,(3-t^2) & -\mu^f_6/c \\ 0 & -\mu^{f*}_6/c & \mu^f_3-\mu^f_1+\lvert\mu^f_4 sc(3-t^2) \end{pmatrix}$	
$B^{'}$				$\begin{pmatrix} 0 & -2\mu^f_4 & 0 \\ -2\mu^f_4 & 0 & -2\mu^f_6 \\ 0 & 2\mu^f_8 & \mu^f_3-\mu^f_1 \end{pmatrix}$	*NNI*

Table 2: Mass matrices in S_3 family models with three Higgs $SU(2)_L$ doublets: H_1 and H_2, which occupy the S_3 irreducible representation $\mathbf{2}$, and H_S, which transforms as $1_{\mathbf{S}}$ for the cases when both the left- and right-handed fermion fields are in the same assignment. The mass matrices shown here follow a normal ordering of their mass eigenvalues (m^f_1, m^f_2, m^f_3). We have denoted $s = \sin\theta$, $c = \cos\theta$ and $t = \tan\theta$. The third column of this table corresponds to the general case, while the fourth column to a case where we have rotated the matrix to a basis where the elements $(1,1)$, $(1,3)$ and $(3,1)$ vanish. The primed cases, A' or B', are particular cases of the unprimed ones, A or B, with $\theta = \pi/6$ or $\theta = \pi/3$, respectively.

Mass matrices reproduce the NNI or the Fritzsch forms (rotation + shift)

F. González et al, Phys.Rev. D88 (2013) 096004

HIGGS SECTOR – TESTS FOR THE MODEL

General Potential:

$$
\begin{aligned}
V \;=\;& \mu_1^2\left(H_1^\dagger H_1 + H_2^\dagger H_2\right) + \mu_0^2\left(H_s^\dagger H_s\right) + a\left(H_s^\dagger H_s\right)^2 + b\left(H_s^\dagger H_s\right)\left(H_1^\dagger H_1 + H_2^\dagger H_2\right) \\
&+c\left(H_1^\dagger H_1 + H_2^\dagger H_2\right)^2 + d\left(H_1^\dagger H_2 - H_2^\dagger H_1\right)^2 + e f_{ijk}\left(\left(H_s^\dagger H_i\right)\left(H_j^\dagger H_k\right) + h.c.\right) \\
&+f\left\{\left(H_s^\dagger H_1\right)\left(H_1^\dagger H_s\right) + \left(H_s^\dagger H_2\right)\left(H_2^\dagger H_s\right)\right\} + g\left\{\left(H_1^\dagger H_1 - H_2^\dagger H_2\right)^2 + \left(H_1^\dagger H_2 + H_2^\dagger H_1\right)^2\right\} \\
&+h\left\{\left(H_s^\dagger H_1\right)\left(H_s^\dagger H_1\right) + \left(H_s^\dagger H_2\right)\left(H_s^\dagger H_2\right) + \left(H_1^\dagger H_s\right)\left(H_1^\dagger H_s\right) + \left(H_2^\dagger H_s\right)\left(H_2^\dagger H_s\right)\right\} \qquad (1)
\end{aligned}
$$

Derman and Tsao (1979); Sugawara and Pawasa (1978); Kubo et al (2004); Felix-Beltrán, Rodríguez-Jáuregui, M.M (2009), Das and Dey (2014), Barradas et al (2014), Costa, Ogreid, Osland and Rebelo (2016), etc

- *The minimum of potential can be parameterised in spherical coordinates, two angles and v*
- *Minimisation fixes* $v_1^2 = 3v_2^2$
- *e = 0 massless scalar, residual continuous S2 symmetry*
- *Conditions for normal vacuum already studied, also for CP breaking ones*

Felix-Beltrán, Rodríguez-Jáuregui, M.M; Costa et al

$$v_1 = v\cos\varphi\sin\theta, \quad v_2 = v\sin\varphi\sin\theta \quad v_3 = v\cos\theta.$$

$$\tan\varphi = 1/\sqrt{3} \quad\Rightarrow\quad \sin\varphi = \frac{1}{2} \quad \& \quad \cos\varphi = \frac{\sqrt{3}}{2}$$

$$\tan\theta = \frac{2v_2}{v_3} \quad\Rightarrow\quad \sin\theta = \frac{2v_2}{v} \quad \& \quad \cos\theta = \frac{v_3}{v}$$

STABILITY CONDITIONS

$$\lambda_8 > 0$$
$$\lambda_1 + \lambda_3 > 0$$
$$\lambda_5 > -2\sqrt{(\lambda_1 + \lambda_3)\lambda_8}$$
$$\lambda_5 + \lambda_6 - 2|\lambda_7| > \sqrt{(\lambda_1 + \lambda_3)\lambda_8}$$
$$\lambda_1 - \lambda_2 > 0$$
$$\lambda_1 + \lambda_3 + \mid 2\lambda_4 \mid + \lambda_5 + 2\lambda_7 + \lambda_8 > 0$$
$$\lambda_{13} > 0$$
$$\lambda_{10} > -2\sqrt{(\lambda_1 + \lambda_3)\lambda_{13}}$$
$$\lambda_{10} + \lambda_{11} - 2|\lambda_{12}| > \sqrt{(\lambda_1 + \lambda_3)\lambda_{13}}$$
$$\lambda_{14} > -2\sqrt{\lambda_8\lambda_{13}}.$$

Das and Dey (2014)

UNITARITY CONDITIONS

$$a_1^{\pm} = (\lambda_1 - \lambda_2 + \frac{\lambda_5 + \lambda_6}{2}) \pm \sqrt{(\lambda_1 - \lambda_2 + \frac{\lambda_5 + \lambda_6}{2})^2 - 4[(\lambda_1 - \lambda_2)(\frac{\lambda_5 + \lambda_6}{2}) - \lambda_4^2]}$$
$$a_2^{\pm} = (\lambda_1 + \lambda_2 + 2\lambda_3 + \lambda_8) \pm \sqrt{(\lambda_1 + \lambda_2 + 2\lambda_3 + \lambda_8)^2 - 4[\lambda_8(\lambda_1 + \lambda_2 + 2\lambda_3) - 2\lambda_7^2]}$$
$$a_3^{\pm} = (\lambda_1 - \lambda_2 + 2\lambda_3 + \lambda_8) \pm \sqrt{(\lambda_1 - \lambda_2 + 2\lambda_3 + \lambda_8)^2 - 4[\lambda_8(\lambda_1 + \lambda_2 + 2\lambda_3) - \frac{\lambda_6^2}{2}]}$$
$$a_4^{\pm} = (\lambda_1 + \lambda_2 + \frac{\lambda_5}{2} + \lambda_7) \pm \sqrt{(\lambda_1 + \lambda_2 + \frac{\lambda_5}{2} + \lambda_7)^2 - 4[(\lambda_1 - \lambda_2)(\frac{\lambda_5}{2} + \lambda_7) - \lambda_4^2]}$$

$$a_5^{\pm} = (5\lambda_1 - \lambda_2 + 2\lambda_3 + 3\lambda_8) \pm \sqrt{(5\lambda_1 - \lambda_2 + 2\lambda_3 + 3\lambda_8)^2 - 4[3\lambda_8(5\lambda_1 - \lambda_2 + 2\lambda_3) - \frac{1}{2}(2\lambda_5 + \lambda_6)^2]}$$
$$a_6^{\pm} = (\lambda_1 + \lambda_2 + 4\lambda_3 + \frac{\lambda_5}{2} + \lambda_6 + 3\lambda_7) \pm ((\lambda_1 + \lambda_2 + 4\lambda_3 + \frac{\lambda_5}{2} + \lambda_6 + 3\lambda_7)^2 - 4[(\lambda_1 + \lambda_2 + 4\lambda_3)(\frac{\lambda_5}{2} + \lambda_6 + 3\lambda_7) - 9\lambda_4^2])^{1/2}$$

$$b_1 = \lambda_5 + 2\lambda_6 - \lambda_7$$
$$b_2 = \lambda_5 - 2\lambda_7$$
$$b_3 = 2(\lambda_1 - 5\lambda_1 - 2\lambda_3)$$
$$b_4 = 2(\lambda_1 - \lambda_1 - 2\lambda_3)$$
$$b_5 = 2(\lambda_1 + \lambda_1 - 2\lambda_3)$$
$$b_6 = \lambda_5 - \lambda_6.$$

HIGGS MASSES

- After electroweak symmetry breaking (Higgs mechanism) we are left with 9 massive particles

doesn't couple to gauge bosons Z2 symmetry
massless when e=0, S2 symmetry

$$m^2_{h_0} = -9ev^2 \sin\theta\cos\theta$$

$$m^2_{H_1,H_2} = (M_a^2 + M_c^2) \pm \sqrt{(M_a^2 - M_c^2)^2 + (M_b^2)^2}$$

H2 is the SM Higgs boson

$$M_a^2 = \left[2(c+g)v^2\sin^2\theta + \frac{3}{2}ev^2\sin\theta\cos\theta\right]$$

$$M_b^2 = \left[3ev^2\sin^2\theta + 2(b+f+2h)v^2\sin\theta\cos\theta\right]$$

$$M_c^2 = 2av^2\cos^2\theta - \frac{ev^2\tan\theta\sin^2\theta}{2}$$

$$m^2_{A_1} = -v^2\left[2(d+g)\sin^2\theta + 5e\cos\theta\sin\theta + 2h\cos^2\theta\right]$$

$$m^2_{A_2} = -v^2(e\tan\theta + 2h)$$

$$m^2_{H_1^\pm} = -v^2\left[5e\sin\theta\cos\theta + (f+h)\cos^2\theta + 2g\sin^2\theta\right]$$

$$m^2_{H_2^\pm} = -v^2\left[e\tan\theta + (f+h)\right]$$

Das and Dey (2014)
Barradas et al (2014)

RESIDUAL Z2 SYMMETRY

- After eW symmetry breaking, S3 breaks -> residual Z2 symmetry

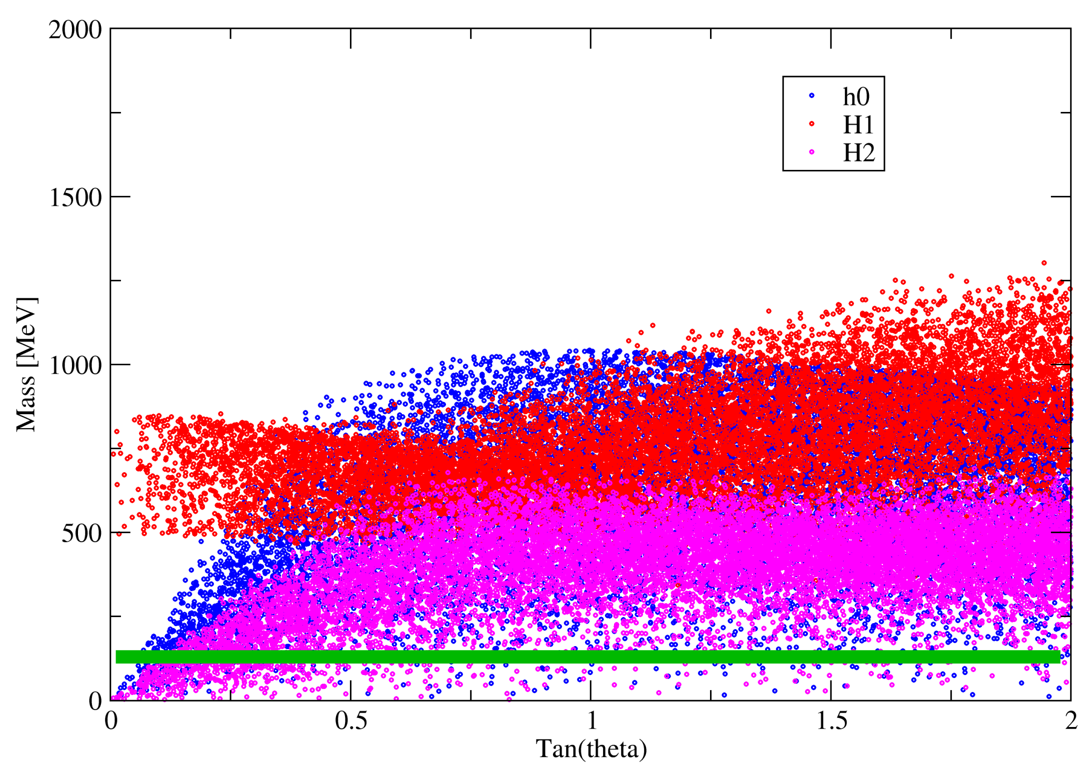
  Das and Dey (2014), Ivanov (2017)

- h0 decoupled from gauge bosons
- There is a "decoupling" limit, where H2 is the SM Higgs boson
  H1 also decoupled from the gauge bosons
- h_0, A_1, $H_1^{\pm}$ have Z_2 parity -1,
  H_1, H_2 +1 parity +1
  $H_2^{\pm}$, A_2 parity +1

  Das and Dey (2014)

- This forbids certain couplings

NEUTRAL SCALAR MASSES



S3-3H Neutral scalar masses with stability and unitarity bounds only

Pink will be constrained to be SM Higgs

Red neutral H1

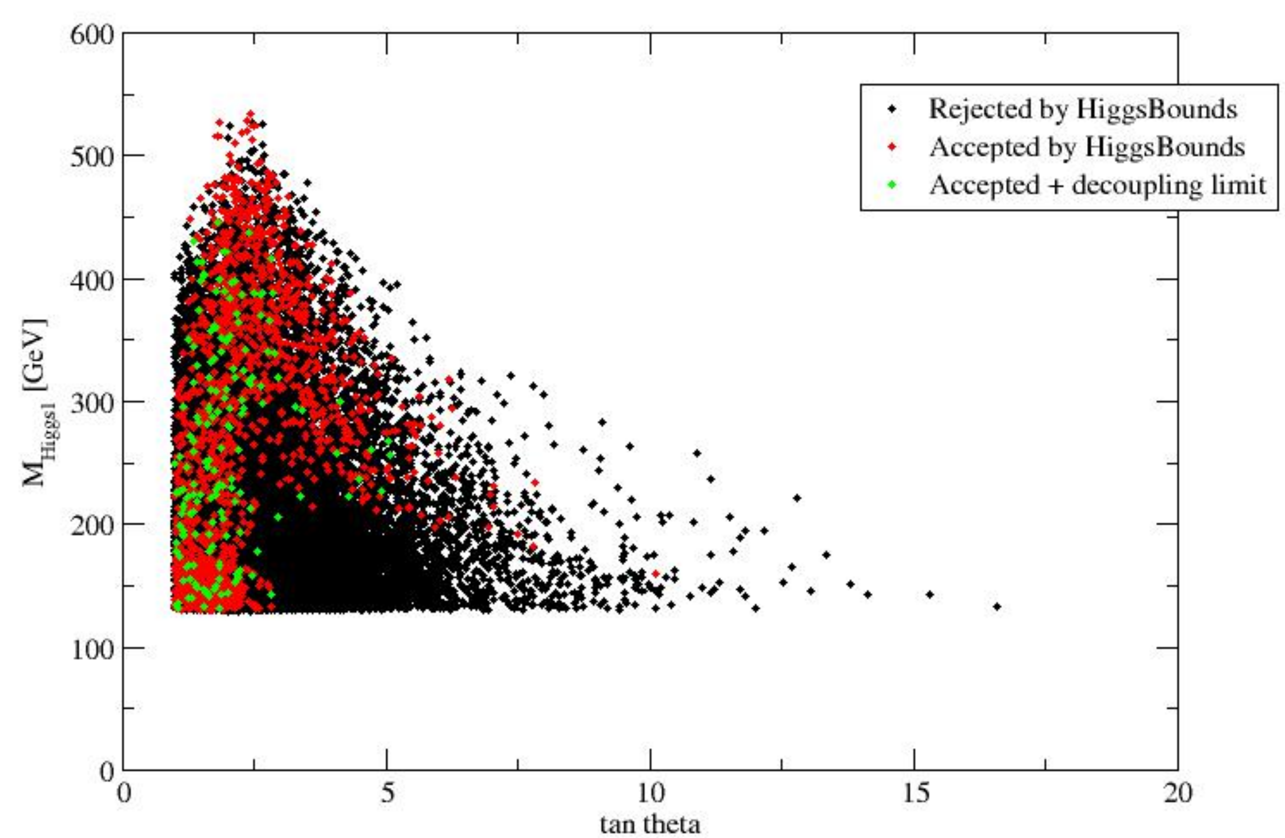
Blue h0 decoupled from gauge bosons

S3-4H *See Catalina Espinoza talk on Friday*

H2 constrained to be SM-H

Shown H1 vs tan θ

Green passes unitarity, stability and HiggsBounds + *decoupling limit* $\Longrightarrow$ *small tan* θ



HIGGS BASIS AND TRILINEAR COUPLINGS

- In the Higgs basis

$$\begin{pmatrix} H_1 \\ H_2 \\ H_3 \end{pmatrix} = \begin{pmatrix} \cos\varphi\sin\theta & -\sin\varphi & -\cos\varphi\cos\theta \\ \sin\varphi\sin\theta & \cos\varphi & -\sin\varphi\cos\theta \\ \cos\theta & 0 & \sin\theta \end{pmatrix} \begin{pmatrix} \phi_{vev} \\ \psi_1 \\ \psi_2 \end{pmatrix}$$

$$\phi_{vev} = \begin{pmatrix} G^\pm \\ \frac{1}{\sqrt{2}}(v + \widetilde{h} + iG_0) \end{pmatrix}, \quad \psi_1 = \begin{pmatrix} H_1^\pm \\ \frac{1}{\sqrt{2}}(\widetilde{H_1} + iA_1) \end{pmatrix}, \quad \psi_2 = \begin{pmatrix} H_2^\pm \\ \frac{1}{\sqrt{2}}(\widetilde{H_2} + iA_2) \end{pmatrix}$$

$$\begin{pmatrix} \widetilde{h} \\ \widetilde{H_1} \\ \widetilde{H_2} \end{pmatrix} = \begin{pmatrix} \cos(\alpha-\theta) & 0 & \sin(\alpha-\theta) \\ 0 & 1 & 0 \\ -\sin(\alpha-\theta) & 0 & \cos(\alpha-\theta) \end{pmatrix} \begin{pmatrix} H_1 \\ h_0 \\ H_2 \end{pmatrix}$$

TRILINEAR HIGGS-GAUGE COUPLINGS

- In the decoupling limit only H2 has couplings to the gauge bosons

$\cos(\alpha-\theta)$	$\sin(\alpha-\theta)$
$H_1 W^+ W^-$	$H_2 W^+ W^-$
$H_1 Z Z$	$H_2 Z Z$
$Z A_2 H_2$	$Z A_2 H_1$
$W^\pm H_2^\mp H_2$	$W^\pm H_2^\mp H_1$
$Z W^\pm H_2^\mp H_2$	$Z W^\pm H_2^\mp H_1$
$\gamma W^\pm H_2^\mp H_2$	$\gamma W^\pm H_2^\mp H_1$

- h0 has no trilinear gauge couplings, only:

$$Z A_1 h_0,\ Z W^\pm H_1^\mp h_0,\ W^\pm H_1^\mp h_0 \text{ y } \gamma W^\pm H_1^\mp h_0$$

In accordance with Z2 symmetry

SCALAR COUPLINGS

$$h_0 h_0 h_0 = 0 \qquad A_1 A_1 A_1 = 0$$

$$H_2 H_2 H_2 = -\frac{1}{144 v \sin\theta \cos^3\theta}\big(3(4m_{h_0}^2 + 9m_{H_1}^2)\cos(\alpha-\theta) + (4m_{h_0}^2 + 9m_{H_1}^2)\cos(3(\alpha-\theta)) + 9m_{H_1}^2(2\cos(3\alpha-\theta) + 6\cos(\alpha+\theta) + \cos(3\alpha+\theta) + 3\cos(\alpha+3\theta))\big)$$

$$H_1 H_1 H_1 = -\frac{1}{144 v \sin\theta \cos^3\theta}\big(3(4m_{h_0}^2 + 9m_{H_2}^2)\sin(\alpha-\theta) - (4m_{h_0}^2 + 9m_{H_2}^2)\sin(3(\alpha-\theta)) - 9m_{H_2}^2(2\sin(3\alpha-\theta) - 6\sin(\alpha+\theta) + \sin(3\alpha+\theta) - 3\sin(\alpha+3\theta))\big)$$

$$h_0 h_0 H_1 = \frac{1}{v}(m_{h_0}^2 \frac{\cos\alpha}{\cos\theta} + \frac{\sin\alpha}{\sin\theta}(m_{h_0}^2 + m_{H_2}^2))$$

Differs from Barradas et al, consistent with Z2 symmetry

$$h_0 h_0 H_2 = \frac{1}{v}(m_{h_0}^2 \frac{\sin\alpha}{\cos\theta} - \frac{\cos\alpha}{\sin\theta}(m_{h_0}^2 + m_{H_1}^2))$$

$$H_1 H_1 H_2 = \frac{\sin(\alpha-\theta)}{12 v \sin\theta \cos^3\theta}\big(2m_{h_0}^2\cos(2\alpha)\sin(2\theta) - \sin(2\alpha)(\cos(2\theta)(2m_{h_0}^2 + 3m_{H_1}^2 + 6m_{H_2}^2) + 3(m_{H_1}^2 + 2m_{H_2}^2)\big)$$

$$H_1 H_2 H_2 = \frac{\cos(\alpha-\theta)}{12 v \sin\theta \cos^3\theta}\big(-2m_{h_0}^2\cos(2\alpha)\sin(2\theta) + \sin(2\alpha)(\cos(2\theta)(2m_{h_0}^2 + 3m_{H_2}^2 + 6m_{H_1}^2) + 3(m_{H_2}^2 + 2m_{H_1}^2)\big)$$

ONE-LOOP CORRECTIONS TO V

- $V = V_{\text{Tree}} + V_{\text{one-loop}}$

$$V_1 = \frac{1}{64\pi^2} \sum_\alpha n_\alpha \, m_\alpha^4(\varphi_i) \left[\log\left(\frac{m_\alpha^2(\varphi_i)}{\mu^2} \right) - \frac{3}{2} \right]$$

$$\frac{\partial V}{\partial \varphi_i} = \frac{\partial V_0}{\partial \varphi_i} + \frac{1}{32\pi^2} \sum_\alpha n_\alpha m_\alpha^2 \frac{\partial m_\alpha^2}{\partial \varphi_i} \left[\log\left(\frac{m_\alpha^2}{\mu^2} \right) - 1 \right]$$

sum runs over all scalar eigenstates and fermions, n degrees of freedom

- Changes mass matrices and Higgs mixing angles
- Will have impact on masses and trilinear couplings
- Important for determining deeper vacua

Work in progress

IN YUKAWA SECTOR

- The Z2 symmetry will lead to zeroes in the CKM matrix

Das, Dey, Pal (2015)

- To recover the good features of the symmetry:
  - Add S3 singlet — Brown, Deshpande,Sugawara, Pakwasa 1984
  - Break very softly the S3 symmetry with mass terms

    e.g., Kubo, Okada, Sakamaki (2004), Das, Dey, Pal (2015)
  - Consider CP violation — Costa, Ogreid, Osland, Rebelo(2014)
  - Higher order interactions
  - All of the above

QUARK MASS MATRICES

- Possible to add soft breaking terms and recover the original fermion mass matrix form

Kubo et al (2004)

- From our parameterization

$$\mathbf{M} = \begin{pmatrix} m_1 + m_2 & m_2 & m_5 \\ m_2 & m_1 - m_2 & m_5 \\ m_4 & m_4 & m_3 \end{pmatrix}.$$

$$v_1 = \frac{\sqrt{3}}{2} \sin\theta$$

$$v_2 = \frac{1}{2} \sin\theta$$

$$v_3 = v \cos\theta$$

$$m_3 = Y_S v_3 = Y_S v \cos\theta$$

- From Higgs analysis $\Longrightarrow$ restriction on $\boldsymbol{\theta}$ and Y's to keep hierarchical structure

Work in progress

- Recover solution $v_1 = v_2$, now without massless scalar

LEPTONS x Z2

- Extra Z2 symmetry added in the leptonic sector (by hand…)

$-$	$+$
H_S, ν_{3R}	$H_I, L_3, L_I, e_{eR}, e_{IR}.\nu_{IR}$

Table 1: Z2 assignment in the leptonic sector.

- Charged leptons can be also parameterized successfully, no extra free parameters
- Neutrinos: Fixing one mixing angle we obtain the other two in experimental range

Peinado, Mondragón, MM

- Neutrinos: S3 predicts $\Theta_{13} \neq 0$
  M_1 and M_2 equal → Θ_{13} too small
  M_1 and M_2 different → Θ_{13} in experimental range

González-Canales, Mondragón, MM

- Mass matrices of charged leptons and neutrinos are parameterised in terms of physical masses

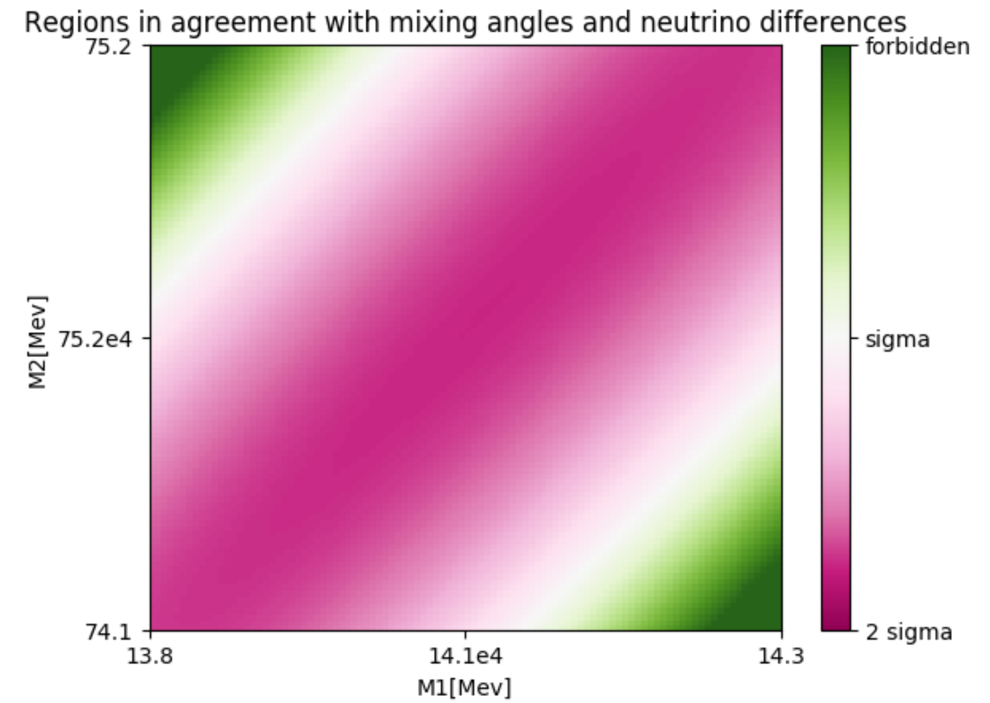
$$M_e \simeq m_\tau \begin{pmatrix} \frac{1}{\sqrt{2}}\frac{\tilde{m_\mu}}{\sqrt{1+x^2}} & \frac{1}{\sqrt{2}}\frac{\tilde{m_\mu}}{\sqrt{1+x^2}} & \frac{1}{\sqrt{2}}\frac{\sqrt{1+x^2-\tilde{m_\mu^2}}}{\sqrt{1+x^2}} \\ \frac{1}{\sqrt{2}}\frac{\tilde{m_\mu}}{\sqrt{1+x^2}} & -\frac{1}{\sqrt{2}}\frac{\tilde{m_\mu}}{\sqrt{1+x^2}} & \frac{1}{\sqrt{2}}\frac{\sqrt{1+x^2-\tilde{m_\mu^2}}}{\sqrt{1+x^2}} \\ \frac{\tilde{m_e}(1+x^2)}{\sqrt{1+x^2-\tilde{m_\mu^2}}}e^{i\delta_e} & \frac{\tilde{m_e}(1+x^2)}{\sqrt{1+x^2-\tilde{m_\mu^2}}}e^{i\delta_e} & 0 \end{pmatrix}.$$

$$\tilde{m_i} = m_i/m_\tau, \quad x^4 = (m_e/m_\tau)^4$$

Similarly for the Majorana neutrino mass matrix —
μ function of the masses, Majorana phases ϕ and Dirac phase δ

$$M_\nu = M_{\nu D}\tilde{M}^{-1}(M_{\nu D})^T = \begin{pmatrix} (\frac{1}{M_1}+\frac{1}{M_2})\mu_2^2 & (\frac{1}{M_1}-\frac{1}{M_2})\mu_2^2 & (\frac{1}{M_1}+\frac{1}{M_2})\mu_2\mu_4 \\ (\frac{1}{M_1}-\frac{1}{M_2})\mu_2^2 & (\frac{1}{M_1}+\frac{1}{M_2})\mu_2^2 & (\frac{1}{M_1}-\frac{1}{M_2})\mu_2\mu_4 \\ (\frac{1}{M_1}+\frac{1}{M_2})\mu_2\mu_4 & (\frac{1}{M_1}-\frac{1}{M_2})\mu_2\mu_4 & \frac{\mu_4^2}{M_2}+\frac{\mu_3^2}{M_3} \end{pmatrix}$$

Simultaneous fit of masses and mixings — New parameterization of neutrino masses

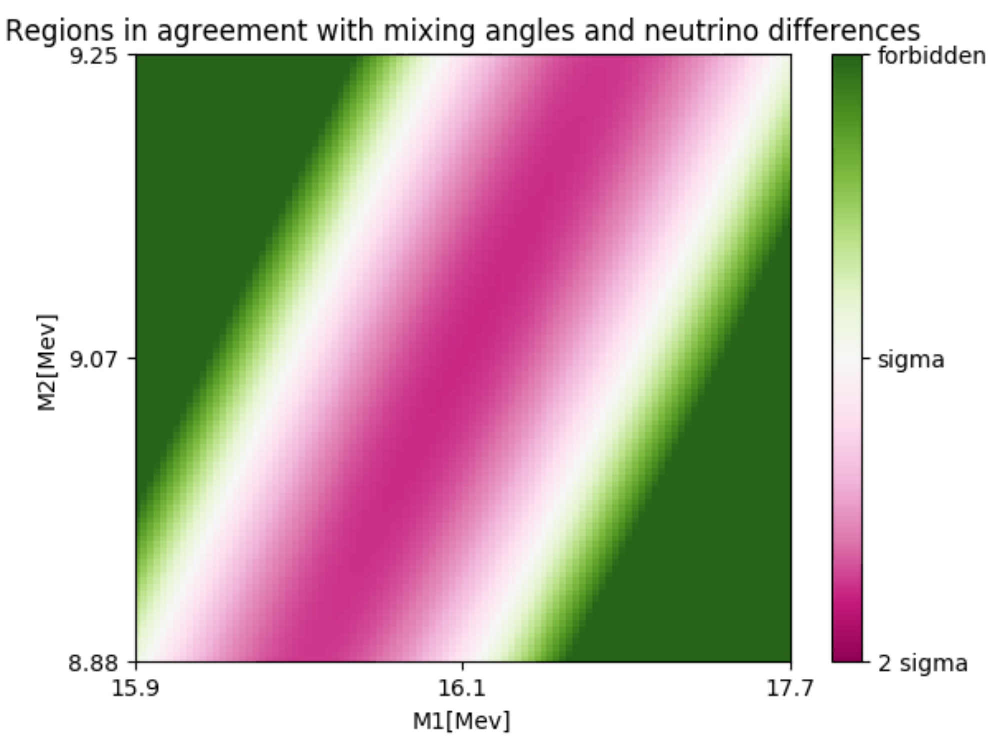


Inverted hierarchy
Best values

$m_3 = 2.97\ 10^{-5}\ eV$
$m_2 = 1.84\ 10^{-5}\ eV$
$m_1 = 8.95\ 10^{-6}\ eV$

$M_3 = 9.99\ 10^5\ GeV$
$M_2 = 141.39\ GeV$
$M_1 = 75.24\ GeV$

Green - discarded by exp values
Magenta- best fit of χ^2



Normal hierarchy
Best values

$m_3 = 2.97\ 10^{-5}\ eV$
$m_2 = 1.84\ 10^{-5}\ eV$
$m_1 = 8.95\ 10^{-6}\ eV$

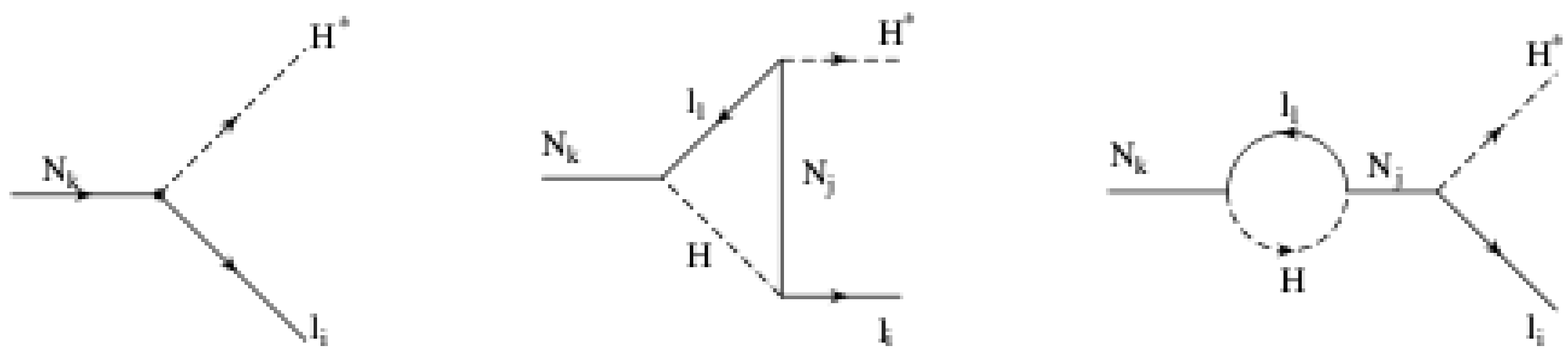
$M_3 = 1.00\ 10^4\ GeV$
$M_2 = 9.07\ GeV$
$M_1 = 16.16\ GeV$

A.Alvarez, M.M. update of arXiv:1701.07929

LEPTOGENESIS IN S3-3H

- The model lends itself naturally to leptogenesis and associated baryogenesis:
  - Heavy right handed neutrinos
  - Majorana neutrinos
  - Decay of right-handed neutrinos into the left-handed ones

$$\epsilon_1 = \frac{\sum_\alpha \Gamma(N_1 \to \ell_\alpha H) - \Gamma(N_1 \to \overline{\ell}_\alpha \overline{H})}{\sum_\alpha \Gamma(N_1 \to \ell_\alpha H) + \Gamma(N_1 \to \overline{\ell}_\alpha \overline{H})}.$$



(a) (b) (c)

$$\epsilon \simeq -\frac{3}{8\pi}\frac{1}{(h_\nu h_\nu^\dagger)}\sum_{i=2,3}\mathrm{Im}\{(h_\nu h_\nu^\dagger)^2_{1i}\}[f(\frac{M_i^2}{M_1^2})+g(\frac{M_i^2}{M_1^2})].$$

$$f(x)=\sqrt{x}[1-(1+x)\ln(\frac{1+x}{x})] \qquad g(x)=\frac{\sqrt{x}}{1-x}$$

Asymmetry depends on the right- and left-handed neutrino masses, as well as the phases

Mi, right handed neutrinos

hν mass matrices for Yukawa couplings of Dirac neutrinos

SOLVING BOLTZMANN EQUATIONS

$$\epsilon = \frac{\text{Im}[e^{2i\delta^*} M_2 m_3 \frac{\sqrt{M_2(m_2-m_3)(m_3-m_1)}}{\sqrt{m_3}}](f[\frac{M_3^2}{M_1^2}] + g[\frac{M_3^2}{M_1^2}])}{8\pi|M_2 m_3|} \;.$$

$$Y_B = aY_{B-L} = \frac{a}{a-1} Y_L \qquad\qquad a = (8N_f + 4N_H)/(22N_f + 13N_H),$$

δ = Dirac phase, $Y_{L,B}$ = baryon, lepton asymmetry, $N_{f,H}$= number of families and Higgs doublets

Asymmetry for the degenerate case M_1=M_2
Only inverted hierarchy for light neutrinos possible

For the non-degenerate case it depends also on the phases μ_{ia} , $\mu_i = |\mu_i| e^{i\mu_{ia}}$
both hierarchies possible

Work in progress

Preliminary

update of arXiv:1701.07929 A.Alvarez, M.M.

New parameterization of neutrino mass matrix $\Longrightarrow$

less liberty, more predictive, contribution to leptogenesis

GOING UP?

- You can embed the model (or a version of it) in a SUSY model with Q6 symmetry

- Grand Unified SU(5) x Q6 model already studied, preserves the nice features of S3 in quarks and leptons. Mixing angles in good agreement with experiment, both hierarchies allowed.
  J.C. Gómez-Izquierdo, F. González-Canales, M.M. (2014)

- Possible to have different assignments of Q6 in leptonic sector
  $\Longrightarrow$ breaking of mu-tau symmetry

  J.C. Gómez-Izquierdo, M.M. (2017)

CONCLUSIONS

- Multi-Higgs models with S3 symmetry consistent with CKM and PMNS
  - symmetry softly broken, possible to recover S3 mass matrix
  - new parameterization in neutrino sector allows for a very good fit of masses and mixings
  - contribution to leptogenesis $\Longrightarrow$ baryogenesis
- Models have to be consistent from the SM point of view $\rightarrow$ extra Higgses sufficiently decoupled or inert possible
- Vacuum much more complicated than in SM, all checks necessary: pass stability and perturbative unitarity,
  Need to add one-loop corrections

Work in progress