

# S3 – 3H AND 4H: DARK MATTER AND LEPTOGENESIS

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# SOME ASPECTS OF THE FLAVOUR PROBLEM

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- 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

$$\theta_{12} \approx 13.0^\circ$$

$$\theta_{23} \approx 2.4^\circ$$

$$\theta_{13} \approx 0.2^\circ$$

► 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

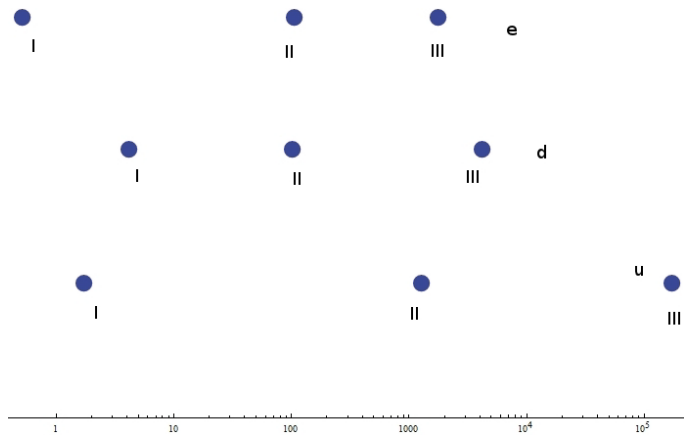
► Is there an underlying symmetry?

# HOW DO WE CHOOSE A FLAVOUR SYMMETRY?

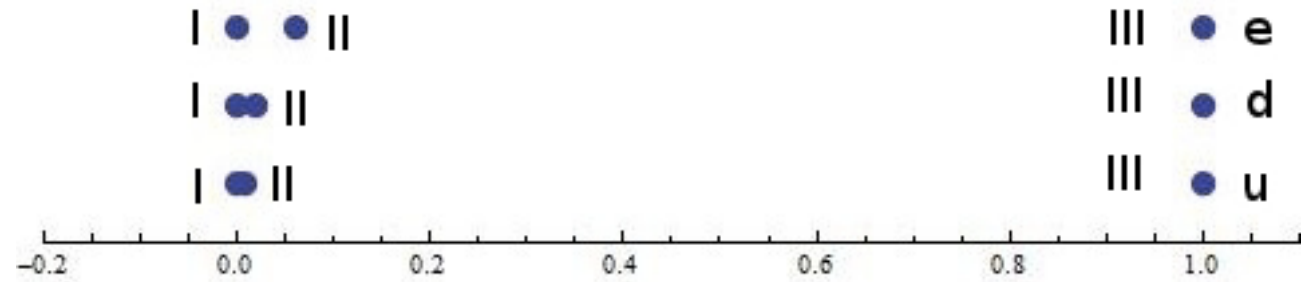
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- Several ways:
- Look for inspiration in a high energy extension of SM, i.e. strings or GUTs
- Look at low energy phenomenology
- At some point they should intersect...
- In here:
  - Find the smallest flavour symmetry suggested by data
  - Explore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





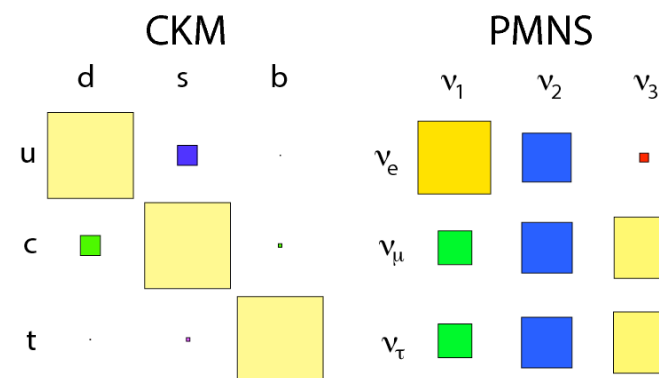
*Plot of mass ratios*



*Logarithmic plot of quark masses*

$$\begin{bmatrix} |V_{ud}| & |V_{us}| & |V_{ub}| \\ |V_{cd}| & |V_{cs}| & |V_{cb}| \\ |V_{td}| & |V_{ts}| & |V_{tb}| \end{bmatrix} \approx \begin{bmatrix} 0.974 & 0.225 & 0.003 \\ 0.225 & 0.973 & 0.041 \\ 0.009 & 0.040 & 0.999 \end{bmatrix},$$

Suggests a  $2 \oplus 1$  structure

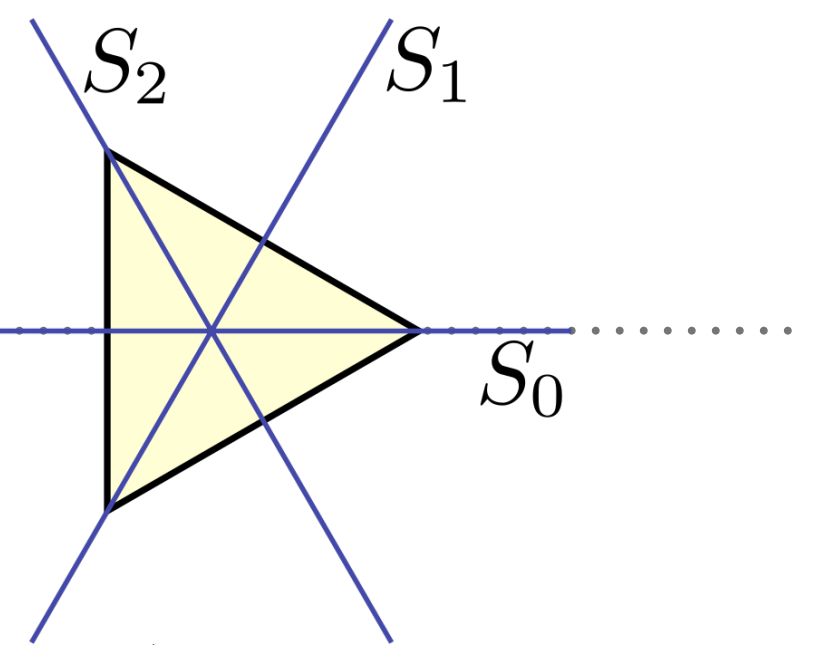


# 3HDM

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- Without symmetry  $\implies$  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  $S_3$  and  $S_4$
- Different modern versions of these models exist

## 3HDM WITH $S_3$



- 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  $S_3$ :  
8 couplings in the Higgs potential

## A sample of S3 models

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

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

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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

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D. Meloni, JHEP 1205 (2012) 124

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

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

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

E. Ma and B. Melic, Phys.Lett. B725 (2013)

E. Barradas et al, 2014

P. Das et al, 2014, 2016

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

# S3

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- 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?

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- 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

# FERMION MASSES

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- 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:  $G_{SM} \otimes S_3$

	$\psi_L^f$	$\psi_R^f$	Mass matrix	Possible mass textures	
$A$	$\mathbf{2}, 1_S$	$\mathbf{2}, 1_S$	$\begin{pmatrix} \mu_1^f + \mu_2^f & \mu_4^f & \mu_6^f \\ \mu_4^f & \mu_1^f - \mu_2^f & \mu_7^f \\ \mu_8^f & \mu_9^f & \mu_3^f \end{pmatrix}$	$\begin{pmatrix} 0 & \mu_2^f sc(3-t^2) & 0 \\ \mu_2^f sc(3-t^2) & -2\mu_2^f c^2(1-3t^2) & \mu_7^f/c \\ 0 & \mu_7^{f*}/c & \mu_3^f - \mu_1^f - \mu_2^f c^2(1-3t^2) \end{pmatrix}$	
$A'$				$\begin{pmatrix} 0 & \frac{2}{\sqrt{3}}\mu_2^f & 0 \\ \frac{2}{\sqrt{3}}\mu_2^f & 0 & \frac{2}{\sqrt{3}}\mu_7^f \\ 0 & \frac{2}{\sqrt{3}}\mu_9^f & \mu_3^f - \mu_1^f \end{pmatrix}$	NNI
$B$	$\mathbf{2}, 1_A$	$\mathbf{2}, 1_A$	$\begin{pmatrix} \mu_1^f + \mu_2^f & \mu_4^f & \mu_7^f \\ \mu_4^f & \mu_1^f - \mu_2^f & -\mu_6^f \\ -\mu_9^f & \mu_8^f & \mu_3^f \end{pmatrix}$	$\begin{pmatrix} 0 & -\mu_4^f c^2(1-3t^2) & 0 \\ -\mu_4^f c^2(1-3t^2) & 2\mu_4^f sc(3-t^2) & -\mu_6^f/c \\ 0 & -\mu_6^{f*}/c & \mu_3^f - \mu_1^f +  \mu_4^f sc(3-t^2)  \end{pmatrix}$	
$B'$				$\begin{pmatrix} 0 & -2\mu_4^f & 0 \\ -2\mu_4^f & 0 & -2\mu_6^f \\ 0 & 2\mu_8^f & \mu_3^f - \mu_1^f \end{pmatrix}$	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  $1_S$  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  $(m_1^f, m_2^f, m_3^f)$ . 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)*



# HIGGS SECTOR – TESTS FOR THE MODEL

*General Potential:*

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

*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*

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

$$\begin{aligned}
 \tan \varphi = 1/\sqrt{3} & \Rightarrow \sin \varphi = \frac{1}{2} \quad \& \quad \cos \varphi = \frac{\sqrt{3}}{2} \\
 \tan \theta = \frac{2v_2}{v_3} & \Rightarrow \sin \theta = \frac{2v_2}{v} \quad \& \quad \cos \theta = \frac{v_3}{v}
 \end{aligned}$$

# STABILITY CONDITIONS

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

Das and Dey (2014)

# UNITARITY CONDITIONS

$$\begin{aligned} a_1^\pm &= (\lambda_1 - \lambda_2 + \frac{\lambda_5 + \lambda_6}{2}) \\ &\pm \sqrt{(\lambda_1 - \lambda_2 + \frac{\lambda_5 + \lambda_6}{2})^2 - 4[(\lambda_1 - \lambda_2)(\frac{\lambda_5 + \lambda_6}{2}) - \lambda_4^2]} \\ a_2^\pm &= (\lambda_1 + \lambda_2 + 2\lambda_3 + \lambda_8) \\ &\pm \sqrt{(\lambda_1 + \lambda_2 + 2\lambda_3 + \lambda_8)^2 - 4[\lambda_8(\lambda_1 + \lambda_2 + 2\lambda_3) - 2\lambda_7^2]} \\ a_3^\pm &= (\lambda_1 - \lambda_2 + 2\lambda_3 + \lambda_8) \\ &\pm \sqrt{(\lambda_1 - \lambda_2 + 2\lambda_3 + \lambda_8)^2 - 4[\lambda_8(\lambda_1 + \lambda_2 + 2\lambda_3) - \frac{\lambda_6^2}{2}]} \\ a_4^\pm &= (\lambda_1 + \lambda_2 + \frac{\lambda_5}{2} + \lambda_7) \\ &\pm \sqrt{(\lambda_1 + \lambda_2 + \frac{\lambda_5}{2} + \lambda_7)^2 - 4[(\lambda_1 - \lambda_2)(\frac{\lambda_5}{2} + \lambda_7) - \lambda_4^2]} \\ a_5^\pm &= (5\lambda_1 - \lambda_2 + 2\lambda_3 + 3\lambda_8) \\ &\pm \sqrt{(5\lambda_1 - \lambda_2 + 2\lambda_3 + 3\lambda_8)^2 - 4[3\lambda_8(5\lambda_1 - \lambda_2 + 2\lambda_3) - \frac{1}{2}(2\lambda_5 + \lambda_6)^2]} \\ a_6^\pm &= (\lambda_1 + \lambda_2 + 4\lambda_3 + \frac{\lambda_5}{2} + \lambda_6 + 3\lambda_7) \pm ((\lambda_1 + \lambda_2 + 4\lambda_3 + \frac{\lambda_5}{2} + \lambda_6 + 3\lambda_7)^2 - \\ &4[(\lambda_1 + \lambda_2 + 4\lambda_3)(\frac{\lambda_5}{2} + \lambda_6 + 3\lambda_7) - 9\lambda_4^2])^{1/2} \end{aligned}$$

$$\begin{aligned} b_1 &= \lambda_5 + 2\lambda_6 - \lambda_7 \\ b_2 &= \lambda_5 - 2\lambda_7 \\ b_3 &= 2(\lambda_1 - 5\lambda_1 - 2\lambda_3) \\ b_4 &= 2(\lambda_1 - \lambda_1 - 2\lambda_3) \\ b_5 &= 2(\lambda_1 + \lambda_1 - 2\lambda_3) \\ b_6 &= \lambda_5 - \lambda_6. \end{aligned}$$

# 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*

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

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

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

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

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

*H2 is the SM Higgs boson*

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

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

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

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

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

# RESIDUAL Z2 SYMMETRY

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- After eW symmetry breaking,  $S_3$  breaks  $\rightarrow$  residual  $Z_2$  symmetry

Das and Dey (2014), Ivanov (2017)

- $h_0$  decoupled from gauge bosons

- There is an “alignment” limit, where  $H_2$  is the SM Higgs boson  $\rightarrow H_1$  also decoupled from the gauge bosons

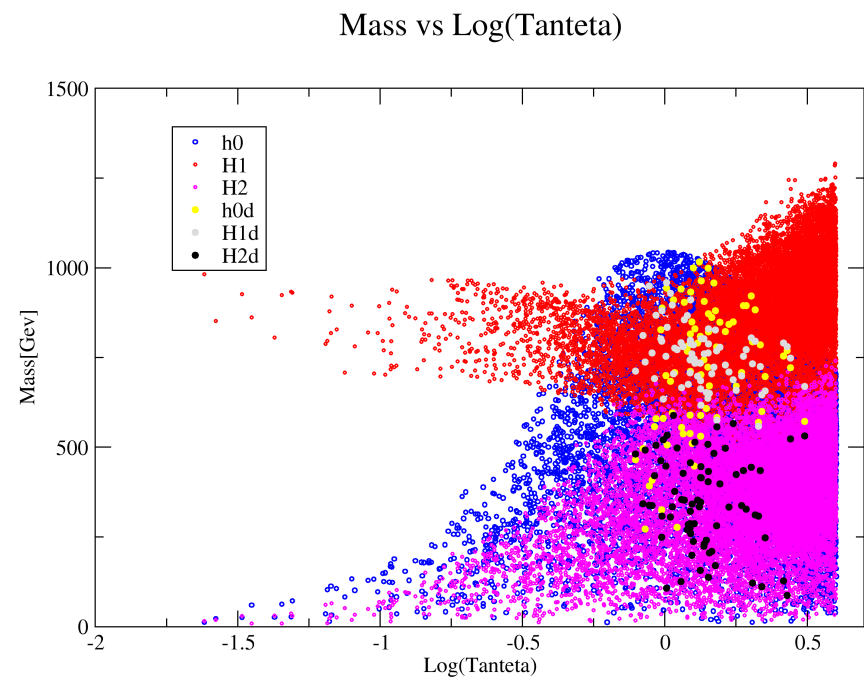
- $h_0, A_1, H_{1\pm}$  have  $Z_2$  parity  $-1$ ,  
 $H_1, H_2$  parity  $+1$   
 $H_{2\pm}, A_2$  parity  $+1$

Das and Dey (2014)

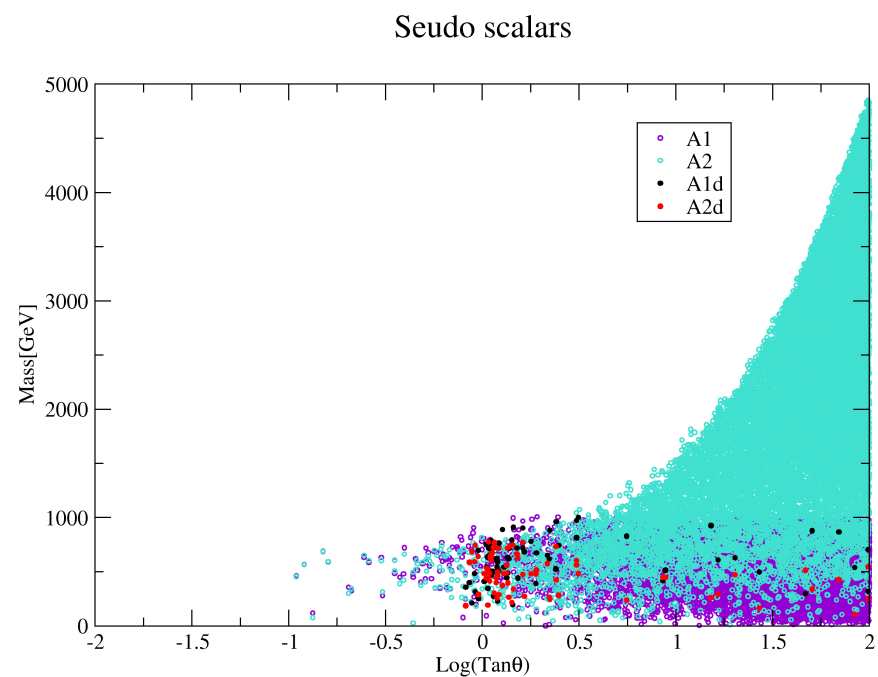
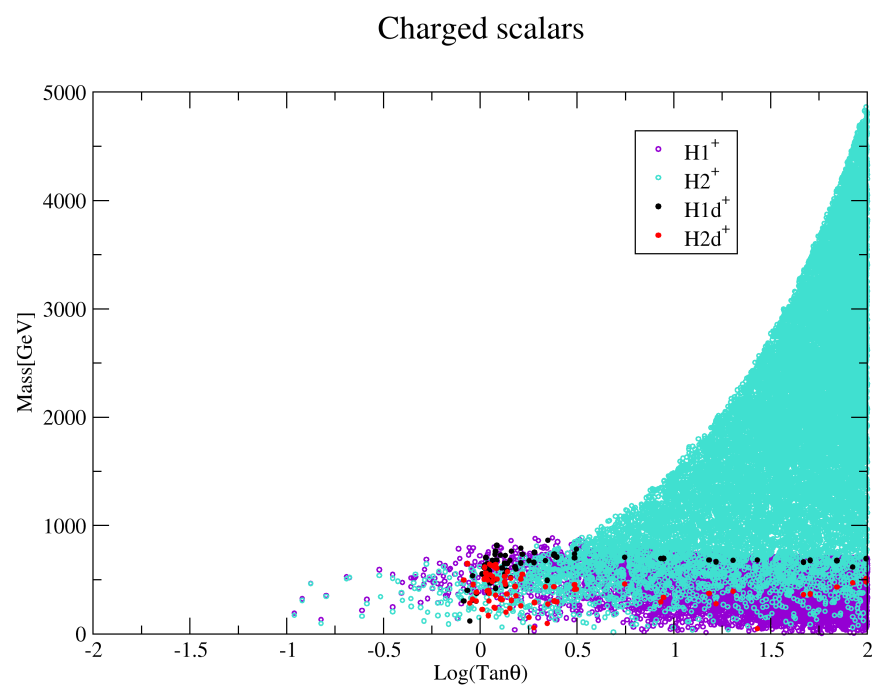
- This forbids certain couplings

# NEUTRAL SCALAR MASSES

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- All points satisfy stability and unitarity bounds
- Dark points satisfy alignment limit  
→ upper bound to the scalar masses  
consistent with Das & Day (2014)
- Radiative corrections will shift the values



# HIGGS BASIS AND TRILINEAR COUPLINGS

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► In the Higgs basis

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

$$\phi_{vev} = \begin{pmatrix} G^\pm \\ \frac{1}{\sqrt{2}}(v + \tilde{h} + iG_0) \end{pmatrix}, \quad \psi_1 = \begin{pmatrix} H_1^\pm \\ \frac{1}{\sqrt{2}}(\tilde{H}_1 + iA_1) \end{pmatrix}, \quad \psi_2 = \begin{pmatrix} H_2^\pm \\ \frac{1}{\sqrt{2}}(\tilde{H}_2 + iA_2) \end{pmatrix}$$

$$\begin{pmatrix} \tilde{h} \\ \tilde{H}_1 \\ \tilde{H}_2 \end{pmatrix} = \begin{pmatrix} \cos(\alpha - \theta) & 0 & \sin(\alpha - \theta) \\ 0 & 1 & 0 \\ -\sin(\alpha - \theta) & 0 & \cos(\alpha - \theta) \end{pmatrix} \begin{pmatrix} H_1 \\ h_0 \\ H_2 \end{pmatrix}$$

# TRILINEAR HIGGS-GAUGE COUPLINGS

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

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

- 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 TRILINEAR COUPLINGS

$$h_0 h_0 h_0 = 0$$

$$A_1 A_1 A_1 = 0$$

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

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

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

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

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

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

*Differs from Barradas et al,  
consistent with Z2 symmetry*



# QUARTIC SCALAR COUPLINGS

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$$\begin{aligned}
 H_2 H_2 H_1 H_1 &= \frac{1}{8v^2 \sin^2 2\theta} \left\{ \frac{-2m_{h_0}^2}{3 \cos^2 \theta} (2 \cos(4\alpha - 2\theta) + \cos 4(\alpha - \theta) - 2 \cos 2\theta - 1) \right. \\
 &\quad + m_{H_1}^2 \sin 2\alpha (-3 \sin(4\alpha - 2\theta) + 6 \sin 2\alpha + \sin 2\theta) \\
 &\quad \left. + m_{H_2}^2 \sin 2\alpha (3 \sin(4\alpha - 2\theta) + 6 \sin 2\alpha + \sin 2\theta) \right\} \quad (97)
 \end{aligned}$$

$$\begin{aligned}
 H_2 H_2 H_2 H_2 &= \frac{1}{v^2 \sin^2 2\theta} \left\{ m_{h_0}^2 \cos^3(\alpha - \theta) \frac{(\cos(\alpha - \theta) + 2 \cos(\alpha + \theta))}{9 \cos^2 \theta} \right. \\
 &\quad \left. + m_{H_1}^2 \frac{\sin^2 2\alpha \cos^2(\alpha - \theta)}{4} + m_{H_2}^2 \frac{(\cos(3\alpha - \theta) + 3 \cos(\alpha + \theta))^2}{16} \right\} \quad (98)
 \end{aligned}$$

$$\begin{aligned}
 H_2 H_2 h_0 h_0 &= \frac{1}{2v^2 \cos \theta} \left\{ \frac{m_{h_0}^2}{3} \left( \frac{\sin^2 \alpha}{\cos \theta} + \frac{\cos^2 \alpha}{\tan \theta \sin \theta} - \frac{2 \sin 2\alpha}{\sin \theta} \right) + \right. \\
 &\quad \left. + m_{H_1}^2 \frac{\sin^2 \alpha \cos \alpha \cos(\alpha - \theta)}{\sin^2 \theta} + m_{H_2}^2 \frac{\cos \alpha}{4 \sin^2 \theta} (\cos(3\alpha - \theta) + 3 \cos(\alpha + \theta)) \right\} \quad (99)
 \end{aligned}$$

...and so on, lengthy expressions

# ONE-LOOP CORRECTIONS TO HIGGS MASS

---

- We can calculate the one-loop corrections to SM Higgs (H2)

$$\begin{aligned}\Sigma^\phi m_{H_2}^2 &= \sum_i \frac{g_{H_2 H_2 \phi_i^0 \phi_i^0}}{16\pi^2} A_0(m_{\phi_i^0}^2) + \sum_i \frac{g_{H_2 \phi_i^0 \phi_i^0}^2}{8\pi^2} B_0(p^2, m_{\phi_i^0}^2, m_{\phi_i^0}^2) \\ &+ \sum_j \frac{g_{H_2 H_j^\pm H_j^\mp}^2}{8\pi^2} B_0(p^2, m_{H_j^\pm}^2, m_{H_j^\pm}^2)\end{aligned}$$

with  $\phi_i^0 = h_0, H_1, H_2, A_1, A_2$  and  $j = 1, 2$

$$\Sigma^{top} m_{H_2}^2 = -\frac{m_t^2}{2\pi^2 v^2} \frac{\cos^2 \alpha}{\sin^2 \beta} \left[ \frac{\sin^2 \beta}{\cos^2 \alpha} v^2 B_0(0, m_t^2, m_t^2) + A_0(m_t^2) + m_t^2 B_0(0, m_t^2, m_t^2) \right]$$

with opposite signs, plus the ones from the gauge bosons

*Work in progress*

# 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

► Important for determining deepest vacuum

*Work in progress*

# IN YUKAWA SECTOR

---

- The Higgs  $Z_2$  symmetry will lead to zeroes in the CKM matrix

Das, Dey, Pal (2015)

- To recover the good features of the symmetry:

- Add  $S_3$  singlet

Brown, Deshpande, Sugawara, Pakwasa 1984

- Break very softly the  $S_3$  symmetry with mass terms, recover original structure

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  $\implies$  restriction on  $\theta$  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...)
- Charged leptons can be also parameterized successfully, no extra free parameters when  $v_1 = v_2$
- “Classical” type I seesaw mechanism for neutrino mass generation
- Neutrinos: Fixing one mixing angle we obtain the other two

Peinado, Mondragón, MM

- Neutrinos:  $S_3$  predicts  $\theta_{13} \neq 0$   
 $M_1 = M_2 \rightarrow \theta_{13}$  too small  
 $M_1 \neq M_2 \rightarrow \theta_{13}$  in experimental range

González-Canales, Mondragón, MM

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

Table 1: Z2 assignment in the leptonic sector.

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

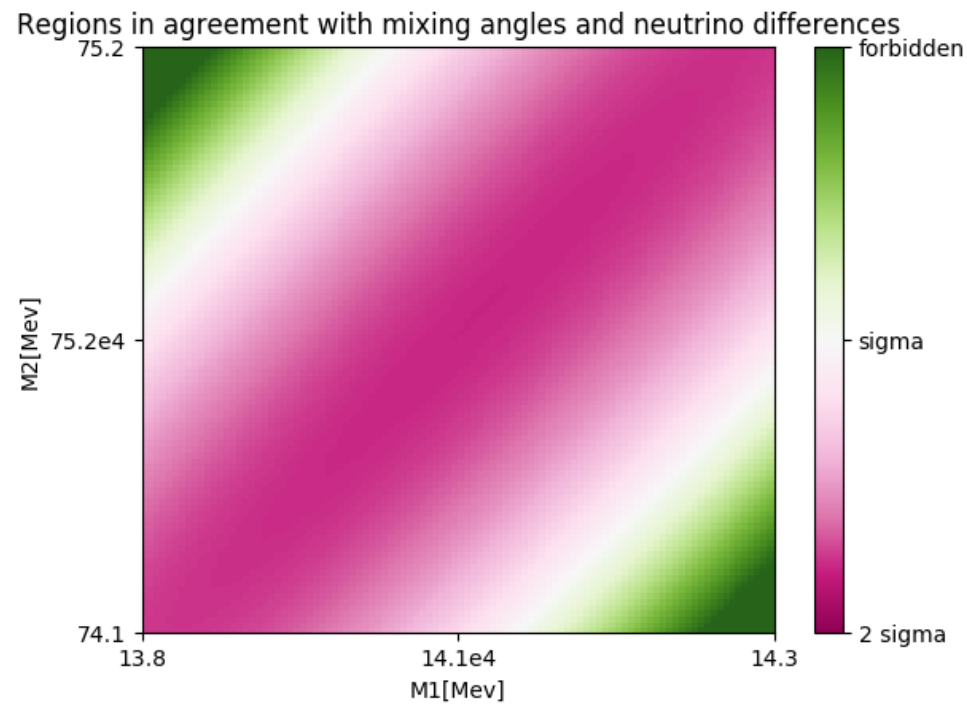
$$M_e \simeq m_\tau \begin{pmatrix} \frac{1}{\sqrt{2}} \frac{\tilde{m}_\mu}{\sqrt{1+x^2}} & \frac{1}{\sqrt{2}} \frac{\tilde{m}_\mu}{\sqrt{1+x^2}} & \frac{1}{\sqrt{2}} \frac{\sqrt{1+x^2-\tilde{m}_\mu^2}}{\sqrt{1+x^2}} \\ \frac{1}{\sqrt{2}} \frac{\tilde{m}_\mu}{\sqrt{1+x^2}} & -\frac{1}{\sqrt{2}} \frac{\tilde{m}_\mu}{\sqrt{1+x^2}}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

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

Similarly for the Majorana neutrino mass matrix —  
 $\mu$  function of the masses, Majorana phases  $\phi$  and Dirac phase  $\delta$

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

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



*Inverted hierarchy*  
*Best values*

$$m_3 = 2.7 \times 10^{-4} \text{ eV}$$

$$m_2 = 1.57 \times 10^{-4} \text{ eV}$$

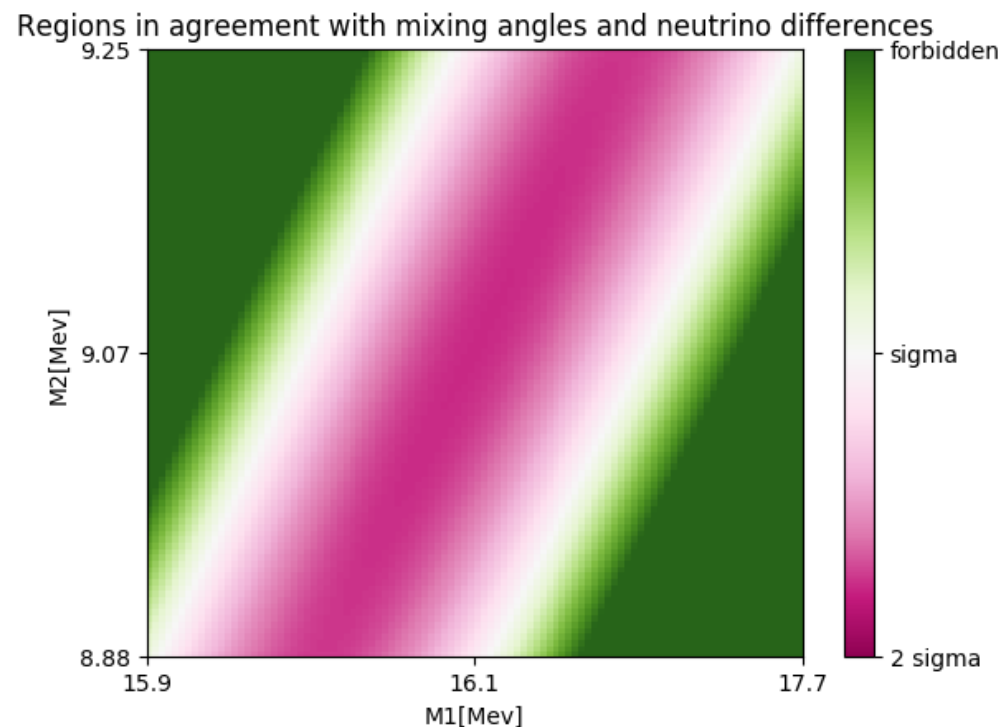
$$m_1 = 7.53 \times 10^{-4} \text{ eV}$$

$$M_3 = 9.99 \times 10^5 \text{ GeV}$$

$$M_2 = 141.39 \text{ GeV}$$

$$M_1 = 75.24 \text{ GeV}$$

Green - discarded by exp values  
Magenta- best fit of  $\chi^2$



*Normal hierarchy*  
*Best values*

$$m_3 = 2.97 \times 10^{-5} \text{ eV}$$

$$m_2 = 1.84 \times 10^{-5} \text{ eV}$$

$$m_1 = 8.95 \times 10^{-6} \text{ eV}$$

$$M_3 = 1.00 \times 10^4 \text{ GeV}$$

$$M_2 = 9.07 \text{ GeV}$$

$$M_1 = 16.16 \text{ GeV}$$

*Work in progress*



# LEPTONIC SECTOR: THE GENERAL CASE

- We extend the analysis for the leptonic sector taking into account the minimization of the potential  $v_1^2 = 3v_2^2$ , and the more general case  $M_1 \neq M_2$
- We reparameterize the charged lepton mass matrix in terms of the physical masses and the potential parameters  
 $\implies$  only one free parameter  $\tan \theta$

$$M_e M_e^\dagger = \begin{pmatrix} 4((v_1^2 + v_2^2)|Y_2|^2 + v_1^2|Y_5|^2) & 4v_1 v_2 |Y_5|^2 & 8v_1 v_2 Y_2 Y_4^* \\ 4v_1 v_2 |Y_5|^2 & 4((v_1^2 + v_2^2)|Y_2|^2 + v_2^2|Y_5|^2) & 4(v_1^2 - v_2^2)Y_2 Y_4^* \\ 8v_1 v_2 Y_4 Y_2^* & 4(v_1^2 - v_2^2)Y_4 Y_2^* & 4(v_1^2 + v_2^2)|Y_4|^2 \end{pmatrix}$$

$$Y_5^2 = \sqrt{-4B + A^2} + Y_4^2$$

$$0 = -2Y_4^6 + (A - 3\sqrt{A^2 - 4B})Y_4^4 + (-A + A\sqrt{(A - 4B) + 4B})Y_4^2 - C$$

$$Y_2^2 = \frac{A - Y_5^2 - Y_4^2}{2}$$

$$A = \frac{m_e^2 + m_\mu^2 + m_\tau^2}{4(v_1^2 + v_2^2)}$$

$$B = \frac{m_e^2 m_\mu^2 + m_\mu^2 m_\tau^2 + m_e^2 m_\tau^2}{16(v_1^2 + v_2^2)^2}$$

$$C = \frac{m_e^2 m_\mu^2 m_\tau^2}{64v_2^2(-3v_1^2 + v_2^2)^2}$$

# NEUTRINO MASSES

- For the general case

$$M_{\nu D} = \begin{pmatrix} -2Y_2 v_2 & -2Y_2 v_2 & 0 \\ -2Y_2 v_2 & 2Y_2 v_2 & 0 \\ -2Y_4 v_1 & -2Y_4 v_2 & -2Y_3 v_3 \end{pmatrix}$$

- Again, in terms of the potential parameters

$$M_{\nu} = M_{\nu D} \tilde{M}^{-1} (M_{\nu D})^T = \begin{pmatrix} \frac{4(M_1 v_1^2 + M_2 v_2^2) Y_2^2}{M_1 M_2} & -\frac{4(M_1 - M_2) v_1 v_2 Y_2^2}{M_1 M_2} & \frac{4(M_1 + M_2) v_1 v_2 Y_2 Y_4}{M_1 M_2} \\ -\frac{4(M_1 - M_2) v_1 v_2 Y_2^2}{M_1 M_2} & \frac{4(M_2 v_1^2 + M_1 v_2^2) Y_2^2}{M_1 M_2} & -\frac{4(-M_2 v_1^2 + M_1 v_2^2) Y_2 Y_4}{M_1 M_2} \\ \frac{4(M_1 + M_2) v_1 v_2 Y_2 Y_4}{M_1 M_2} & -\frac{4(-M_2 v_1^2 + M_1 v_2^2) Y_2 Y_4}{M_1 M_2} & \frac{4(M_1 M_2 \mu_3^2 + M_2 v_1^2 Y_4^2 + M_1 v_2^2 Y_4^2)}{M_1 M_2} \end{pmatrix}$$

$$\mu_3 = \frac{v_s Y_3}{\sqrt{M_3}}.$$

- We obtain the theoretical expression for  $V_{\text{PMNS}}$  and compare to the experimental one (PDG)

# FIT TO MASSES AND MIXINGS

- ▶ We fix  $\tan \theta$  and use the experimental values as constraints:
  - three mixing angles
  - difference of squared masses
  - sum of neutrino masses
- ▶ Obtain the right-handed and left-handed neutrino masses
- ▶ We find different regions with good results, but so far only for normal ordering, and small values of  $\tan \theta$ 
  - consistent with Higgs sector

$$\delta_{CP} \approx 276$$

$$\tan \theta = 1$$

$$m_3 = 4.33 \times 10^{-3} \text{eV}$$

$$m_2 = 9.6 \times 10^{-3} \text{eV}$$

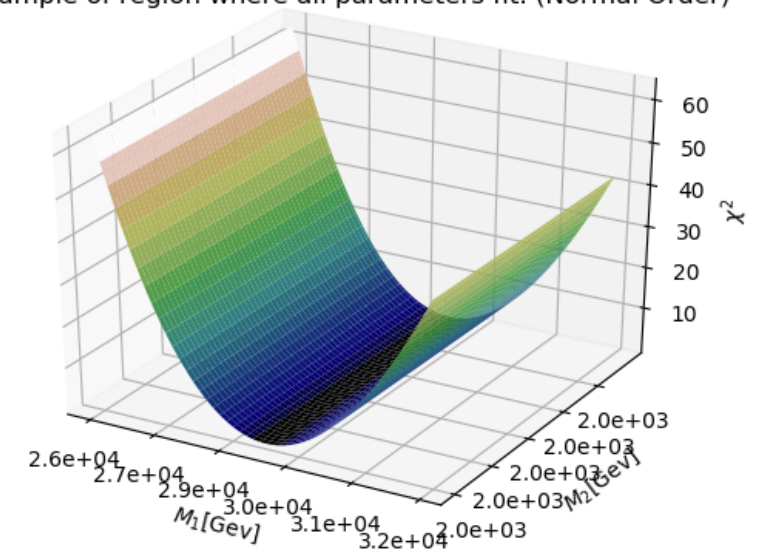
$$m_1 = 5.03 \times 10^{-2} \text{eV}$$

$$M_3 = \text{free}$$

$$M_2 = 1.96 \text{ TeV}$$

$$M_1 = 29.20 \text{ TeV}$$

Example of region where all parameters fit. (Normal Order)



**Preliminary** *Work in progress*

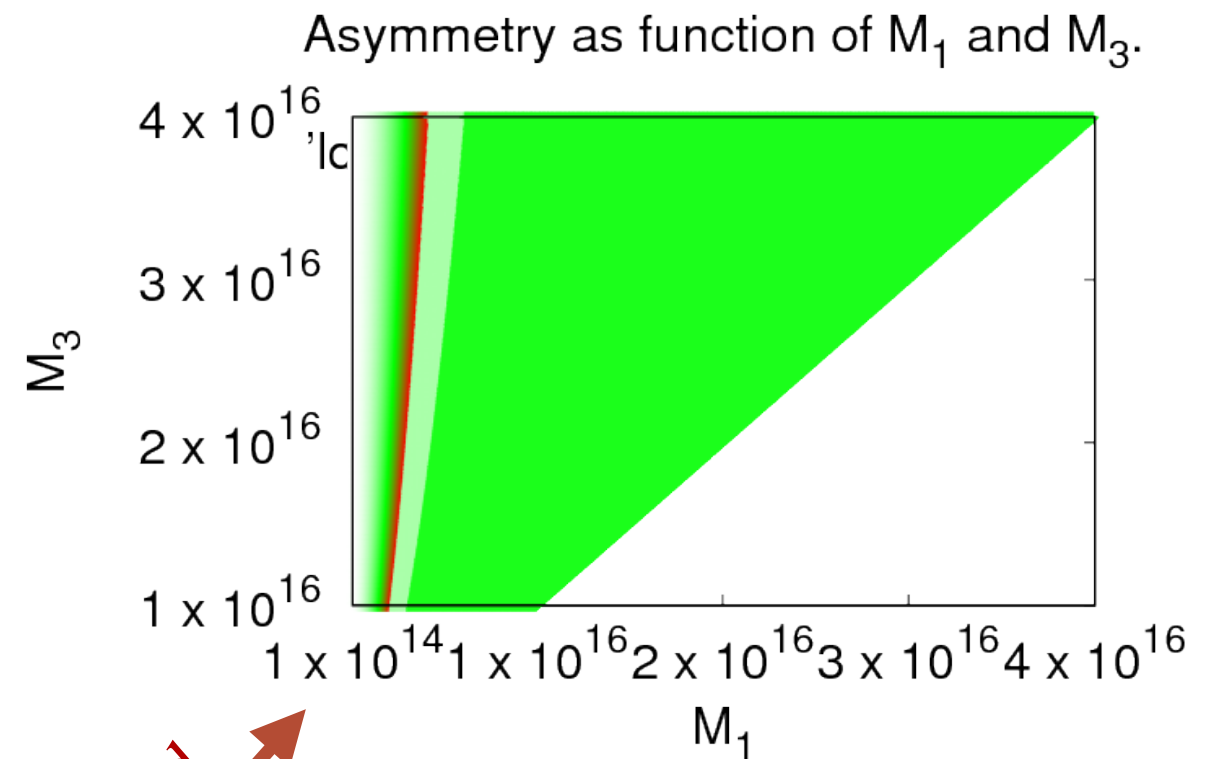
# LEPTOGENESIS IN S3-3H

- 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



old

*Previously: enough leptogenesis possible*

*arXiv:1701.07929 A.Alvarez, M.M*

*The regions change in new parameterization, but contribution to leptogenesis still there*

**Red - too much baryon asymmetry**  
**Darker shades of green - more asymmetry but not yet saturated**

# SOLVING BOLTZMANN EQUATIONS

---

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

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

$\delta =$  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, found only normal hierarchy*

*Work in progress*

## Preliminary

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

New parameterization of neutrino mass matrix  $\implies$  less liberty, more predictive,  
contribution to leptogenesis

Solving Boltzmann eqs shifts parameter space, but not drastically

# 4HDM -S3 WITH DM

---

- We add another doublet, inert, to have a DM candidate. We assign it to the  $1^A$ , and thus “saturate” the irreps
- First two generations in a flavour doublet, third in a singlet, extra anti-symmetric singlet is inert → DM candidates
- A lot of Higgses (13), but the good features of 3H-S3 remain  
Quark and lepton sectors remain unchanged  
DM candidate in inert sector
- Add a  $Z_2$  symmetry to prevent the DM candidate to decay
- $S_3$  symmetry constrains strongly the allowed couplings

C. Espinoza, E. Garcés, M.M., H. Reyes (2019)

# HIGGS POTENTIAL 4H-S3

- We need to find the minima of the potential S3xZ2, which satisfy the stability and unitarity conditions

$$\begin{aligned}
 V_4 = & \mu_0^2 H_s^\dagger H_s + \mu_1^2 (H_1^\dagger H_1 + H_2^\dagger H_2) + \mu_2^2 H_a^\dagger H_a \\
 & + \lambda_1 (H_1^\dagger H_1 + H_2^\dagger H_2)^2 + \lambda_2 (H_1^\dagger H_2 - H_2^\dagger H_1)^2 \\
 & + \lambda_3 [(H_1^\dagger H_1 - H_2^\dagger H_2)^2 + (H_1^\dagger H_2 + H_2^\dagger H_1)^2] \\
 & + \lambda_4 [(H_s^\dagger H_1)(H_1^\dagger H_2 + H_2^\dagger H_1) + (H_s^\dagger H_2)(H_1^\dagger H_1 - H_2^\dagger H_2) + \text{h.c.}] \\
 & + \lambda_5 (H_s^\dagger H_s)(H_1^\dagger H_1 + H_2^\dagger H_2) \\
 & + \lambda_6 [(H_s^\dagger H_1)(H_1^\dagger H_s) + (H_s^\dagger H_2)(H_2^\dagger H_s)] \\
 & + \lambda_7 [(H_s^\dagger H_1)(H_s^\dagger H_1) + (H_s^\dagger H_2)(H_s^\dagger H_2) + \text{h.c.}] \\
 & + \lambda_8 (H_s^\dagger H_s)^2 \\
 & ~~+ \lambda_9 [(H_a^\dagger H_2)(H_1^\dagger H_2 + H_2^\dagger H_1) - (H_a^\dagger H_1)(H_1^\dagger H_1 - H_2^\dagger H_2) + \text{h.c.}]~~ \\
 & + \lambda_{10} (H_a^\dagger H_a)(H_1^\dagger H_1 + H_2^\dagger H_2) \\
 & + \lambda_{11} [(H_a^\dagger H_1)(H_1^\dagger H_a) + (H_a^\dagger H_2)(H_2^\dagger H_a)] \\
 & + \lambda_{12} [(H_a^\dagger H_1)(H_a^\dagger H_1) + (H_a^\dagger H_2)(H_a^\dagger H_2) + \text{h.c.}] \\
 & ~~+ \lambda_{13} (H_a^\dagger H_a)^2 + \lambda_{14} (H_s^\dagger H_a H_a^\dagger H_s) + \lambda_{15} [(H_1^\dagger H_s)(H_2^\dagger H_a) + \text{h.c.}]~~
 \end{aligned}$$

# MASSES

---

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

13 massive particles!

- One has to be the SM Higgs boson, same as in S3-3H
- Two can be DM particles
- Check lightest one of neutral scalars

$$m_{HS}^2 = \begin{pmatrix} m_{h_s^n h_s^n} & m_{h_1^n h_s^n} & m_{h_2^n h_s^n} & 0 \\ m_{h_s^n h_1^n} & m_{h_1^n h_1^n} & m_{h_2^n h_1^n} & 0 \\ m_{h_s^n h_2^n} & m_{h_1^n h_2^n} & m_{h_2^n h_2^n} & 0 \\ 0 & 0 & 0 & m_{h_a^n h_a^n} \end{pmatrix}$$



And the corresponding eigenvalues are:

$$m_{h_s^n}^2 = -18\lambda_4 v_0 v_2$$

$$m_{h_a^n}^2 = \mu_2^2 + \lambda_{14} v_0^2 + 4(\lambda_{10} + \lambda_{11} + 2\lambda_{12}) v_2^2$$

$$m_{h_1^n}^2 = \left(\frac{1}{v_0}\right)(2\lambda_8 v_0^3 + v_2(3\lambda_4 v_0^2 + 8(\lambda_1 + \lambda_3)v_0 v_2 - 4\lambda_4 v_2^2) +$$

$$((4\lambda_8^2 v_0^6 - 12\lambda_4 \lambda_8 v_0^5 v_2 + (9\lambda_4^2 +$$

$$16((\lambda_5 + \lambda_6 + 2\lambda_7)^2 - 2(\lambda_1 + \lambda_3)\lambda_8))v_0^4 v_2^2 +$$

$$16\lambda_4(3(\lambda_1 + \lambda_3 + 2(\lambda_5 + \lambda_6 + 2\lambda_7)) - \lambda_8)v_0^3 v_2^3 +$$

$$8(8(\lambda_1 + \lambda_3)^2 + 21\lambda_4^2)v_0^2 v_2^4 + 64(\lambda_1 + \lambda_3)\lambda_4 v_0 v_2^5 +$$

$$16\lambda_4^2 v_2^6))^{1/2}$$

$$m_{h_2^n}^2 = \left(\frac{1}{v_0}\right)(2\lambda_8 v_0^3 + v_2(3\lambda_4 v_0^2 + 8(\lambda_1 + \lambda_3)v_0 v_2 - 4\lambda_4 v_2^2) -$$

$$(4\lambda_8^2 v_0^6 - 12\lambda_4 \lambda_8 v_0^5 v_2 + (9\lambda_4^2 +$$

$$16((\lambda_5 + \lambda_6 + 2\lambda_7)^2 - 2(\lambda_1 + \lambda_3)\lambda_8))v_0^4 v_2^2 +$$

$$16\lambda_4(3(\lambda_1 + \lambda_3 + 2(\lambda_5 + \lambda_6 + 2\lambda_7)) - \lambda_8)v_0^3 v_2^3 +$$

$$8(8(\lambda_1 + \lambda_3)^2 + 21\lambda_4^2)v_0^2 v_2^4 + 64(\lambda_1 + \lambda_3)\lambda_4 v_0 v_2^5 +$$

$$16\lambda_4^2 v_2^6))^{1/2}.$$

$$m_{h_s^p}^2 = 0$$

$$m_{h_a^p}^2 = \mu_2^2 + \lambda_{14} v_0^2 + 4(\lambda_{10} + \lambda_{11} - 2\lambda_{12}) v_2^2$$

$$m_{h_1^p}^2 = -\frac{2(2\lambda_7 v_0^3 + 5\lambda_4 v_0^2 v_2 + 8\lambda_2 v_0 v_2^2 + 8\lambda_3 v_0 v_2^2)}{v_0}$$

$$m_{h_2^p}^2 = -\frac{2(2\lambda_7 v_0 + \lambda_4 v_2)(v_0^2 + 4v_2^2)}{v_0}.$$

$$m_{h_s^\pm} = 0$$

$$m_{h_a^\pm} = \mu_2^2 + 4\lambda_{10} v_2^2$$

$$m_{h_1^\pm} = -(\lambda_6 + 2\lambda_7)v_0^2 - 10\lambda_4 v_0 v_2 - 16\lambda_3 v_2^2$$

$$m_{h_2^\pm} = -\frac{(\lambda_6 v_0 + 2\lambda_7 v_0 + 2\lambda_4 v_2)(v_0^2 + 4v_2^2)}{v_0}.$$

We choose the neutral scalar

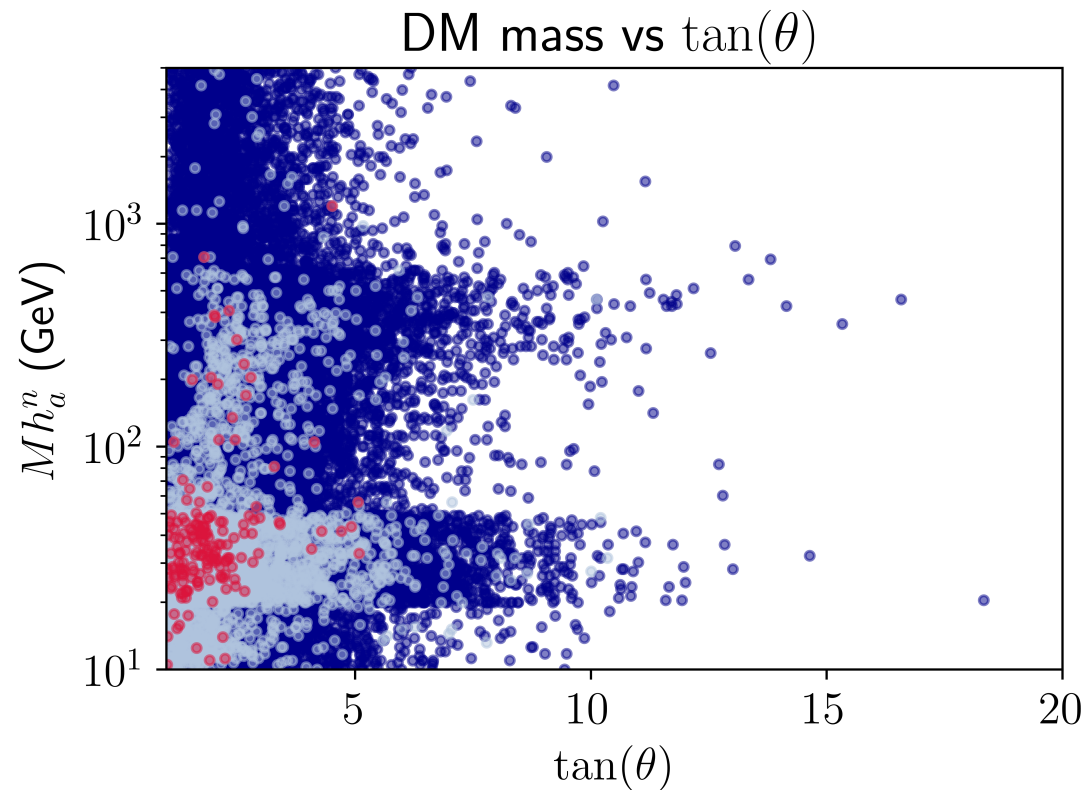
# CONSTRAINTS

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- In the Yukawa sector assume SM limit
- Several constraints are imposed over the parameter space:
- Usual vacuum stability conditions
- Unitarity conditions for large  $s$  (LQT conditions)
- Unitarity conditions for finite  $s$
- SM Higgs boson mass within  $25 \text{ pm } 3 \text{ GeV}$
- Limits for Higgs searches at LEP, Tevatron and LHC

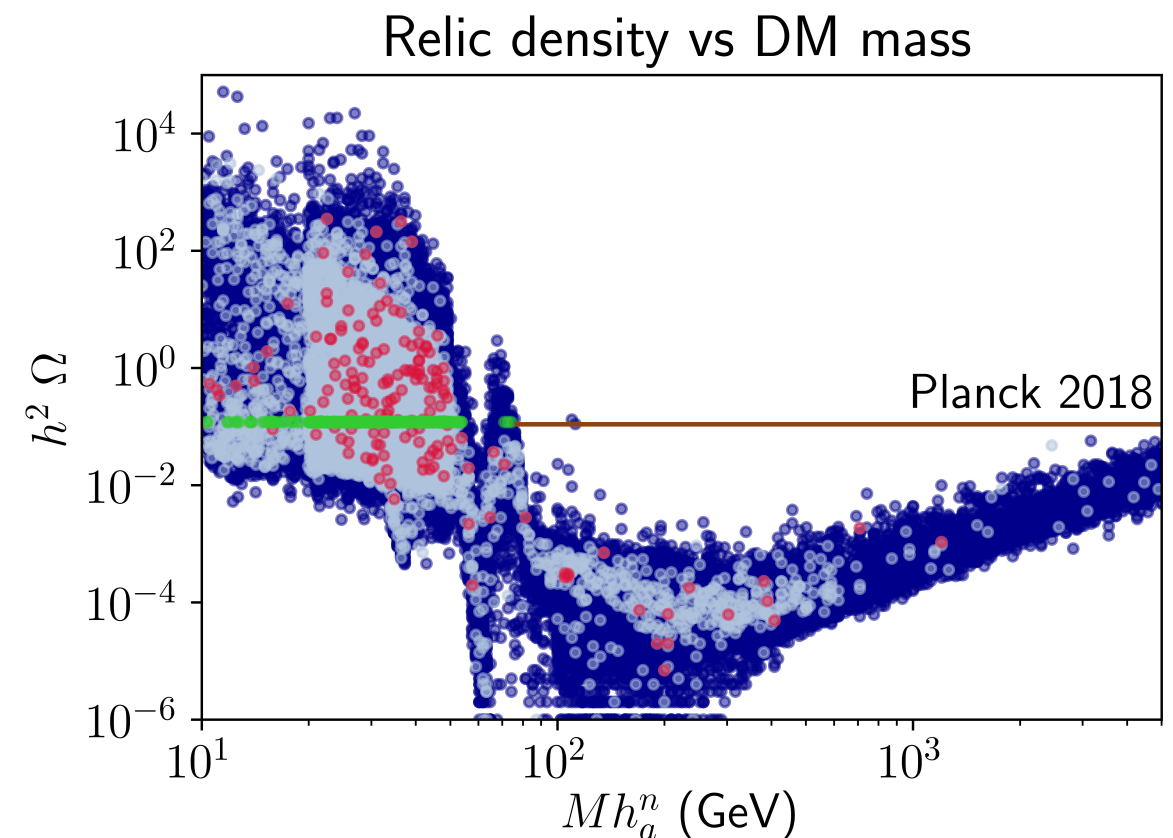
Constraints implemented using FeynArts, FormCalc, SARAH+SPheno, HiggsBounds, MicrOmegas

# DM MASS AND RELIC DENSITY

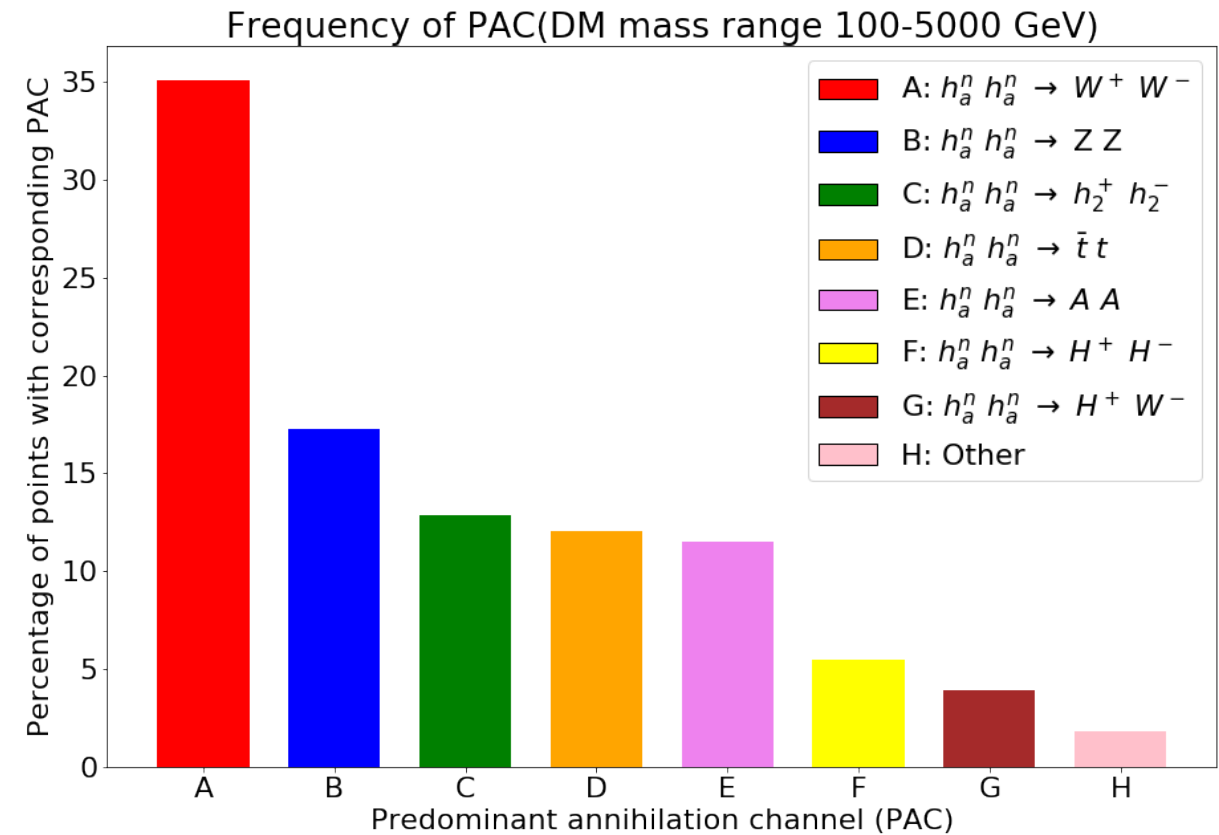
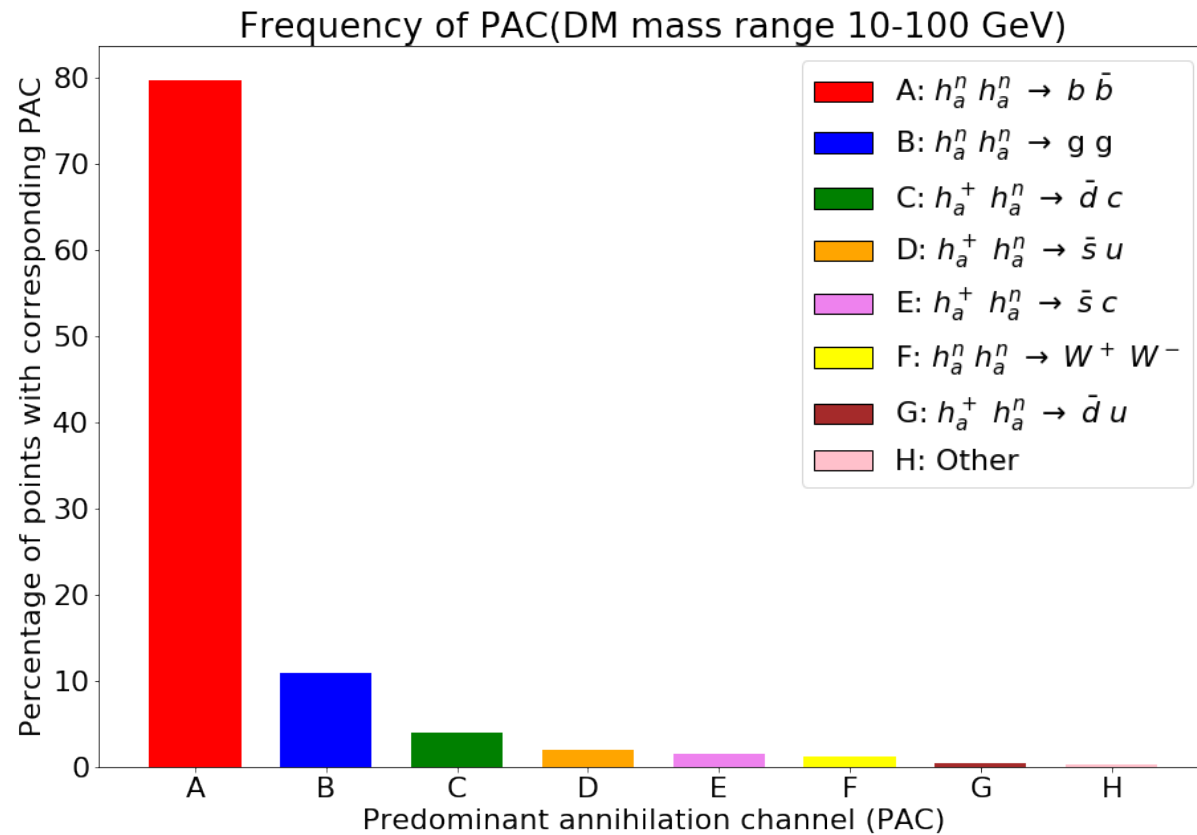


Blue points  $\rightarrow$  stability and unitarity  
Light blue  $\rightarrow$  also Higgs bounds  
Red points  $\rightarrow$  also alignment limit  
*The bounds apply to S3-3H too*

Green points  $\rightarrow$  DM Planck limits  
Small values of  $\tan\theta$  preferred



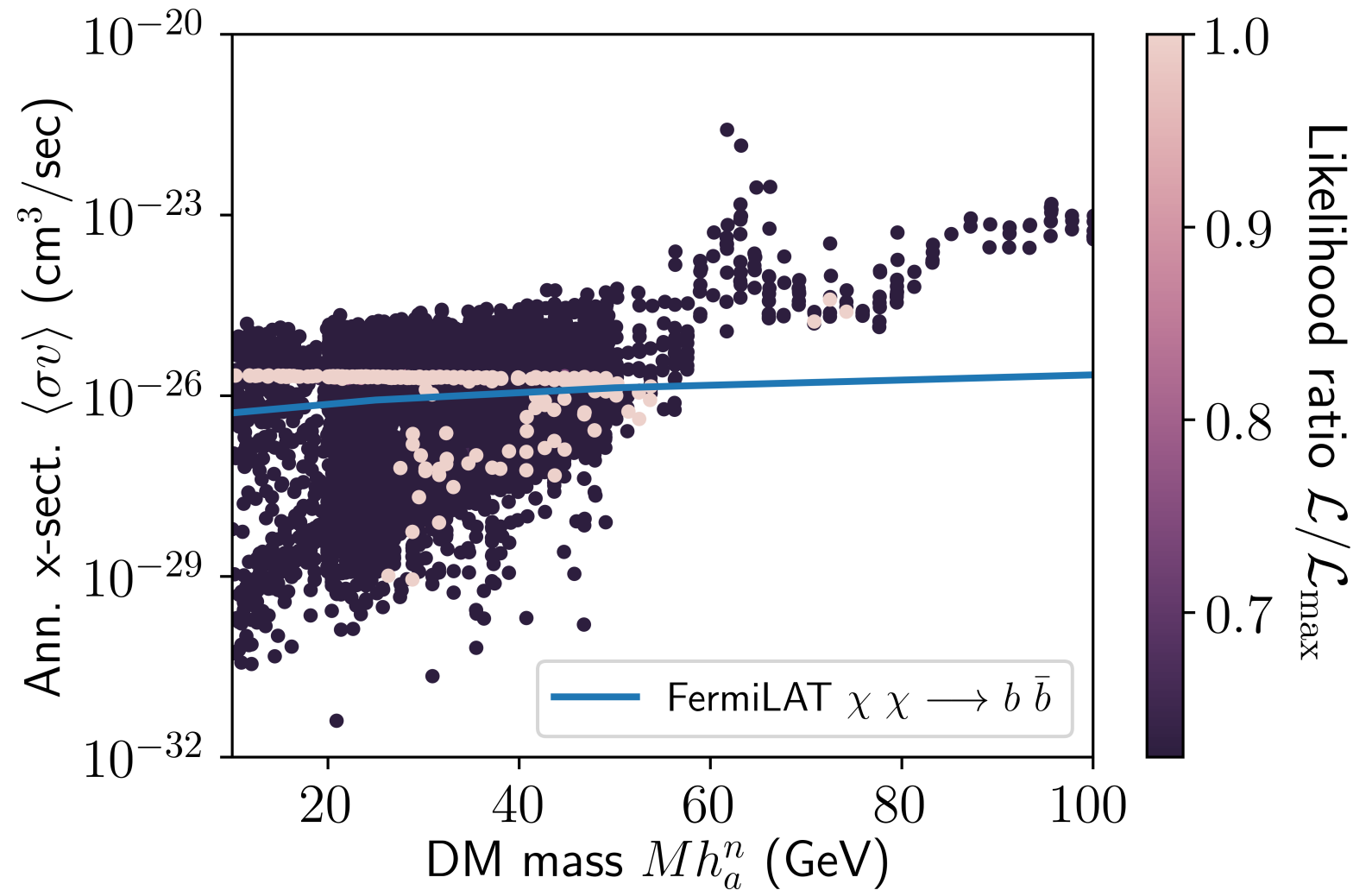
# DM ANNIHILATION CHANNELS



- Frequency of dominant annihilation channels that contribute to DM relic density
- All points below or at Planck limit
- Similar to i2HDM

# ANNIHILATION CROSS SECTION

- Annihilation cross section vs DM mass → relevant for indirect detection experiments
- Likelihood function with respect to Planck limits
- Pink points have relic density within experimental bounds



*There are points in parameter space which survive all constraints  
Tree level: results will shift with radiative corrections*

# 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)  
Neutrino masses: add singlets or non-renormalizable interactions or radiatively
- Possible to have different assignments of Q6 in leptonic sector  $\implies$  **breaking of mu-tau symmetry** J.C. Gómez-Izquierdo, M.M. (2017)
- Flavour structure in trilinear soft SUSY breaking terms  $\rightarrow$  LFV  $\tau \rightarrow \mu + \gamma$ , g-2 contributions through LFV in leptonic sector  
F. Flores-Báez, M. Gómez-Bock, M.M. (2018)
- Non-SUSY B-L model with S3, also breaking of mu-tau symmetry  
J.C. Gómez-Izquierdo, M.M. (2019)



# CONCLUSIONS

---

- $S_3$  is a small symmetry that goes a long way
- $S_3$ -3H models consistent with CKM and PMNS  
 $\theta_{13} \neq 0$  naturally  
Possible to find all neutrino masses and mixings,  $\delta_{CP}$
- Simultaneous study of Higgs and fermionic sector shows model is self-consistent:  
 **$\tan\theta$  small solutions appear both in Higgs and neutrino sectors**
- Regions of parameter space that pass all Higgs bounds:  
Extra Higgses sufficiently decoupled or inert possible
- Good DM candidate(s)
- Leptogenesis possible
- Vacuum much more complicated than in SM, all checks necessary:  
**Need to add one-loop corrections**