

arXiv [hep-ph]: 1304.6644, 1210.0288 + to appear

Mexican Grants: PAPIIT-IN113712 and CONACyT-132059



A four Higgs doublets S3 flavour model

Workshop on Higgs and BSM Physics at the LHC
ICTP, Trieste, Italy
June 26, 2013

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(IF-UNAM)

In collaboration with:
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L. Velasco-Sevilla, F. González-Canales

Outline

- I. Main motivation
- II. 4H-S3 flavour model
- III. Results



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A photograph showing a group of penguins on a large, white, textured iceberg. In the foreground, a killer whale (Orcinus orca) is partially visible in the water, its dark back contrasting with the light ice. Another penguin is seen leaping from the water towards the right side of the frame. The background consists of more icebergs under a clear blue sky.

Which penguin are we?





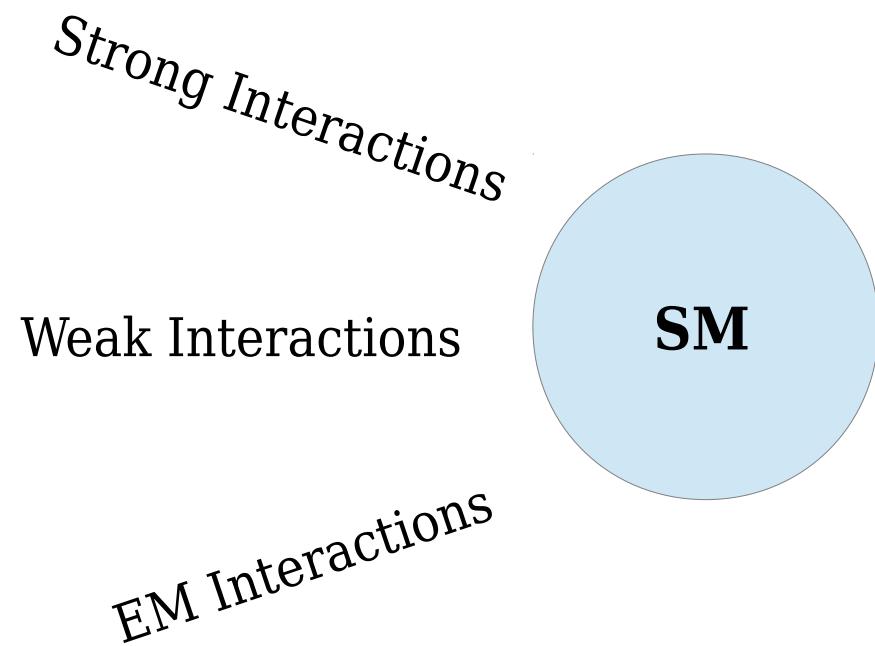


Main motivation



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Main motivation

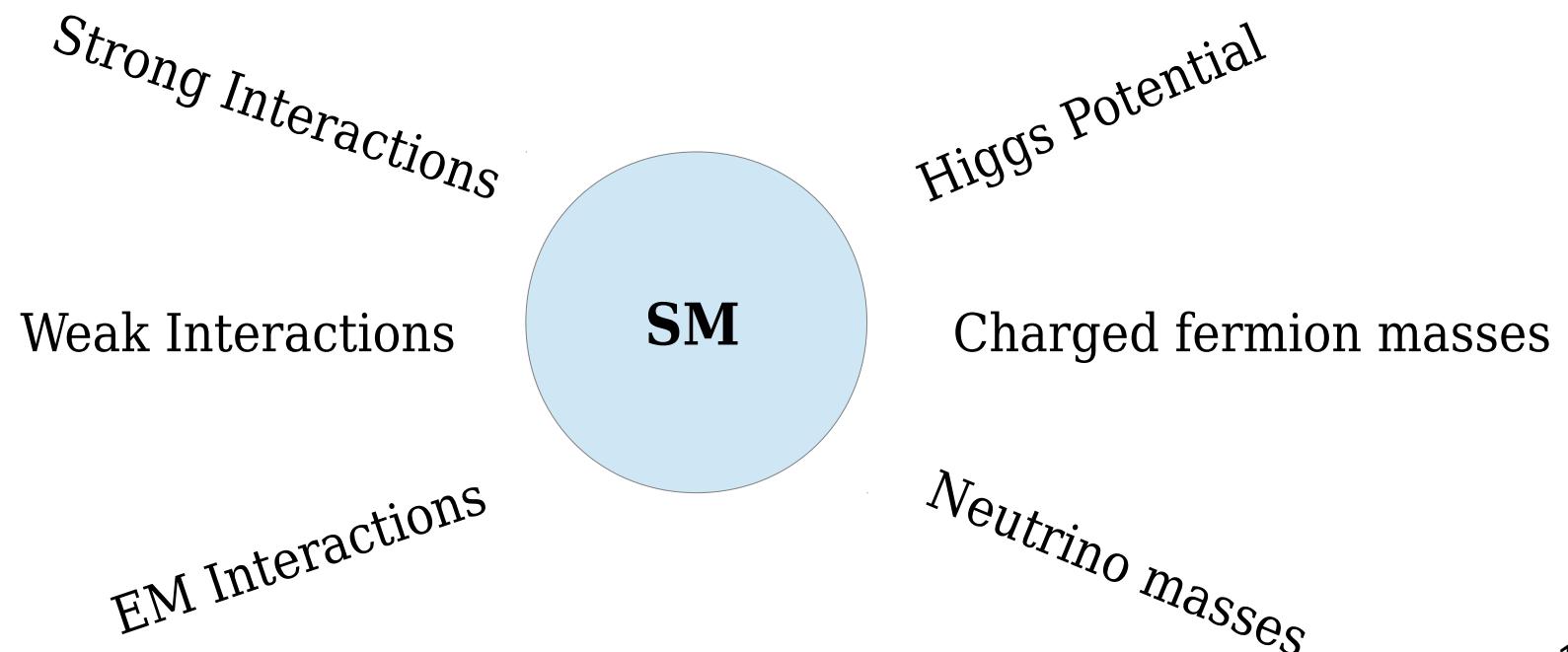


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Main motivation

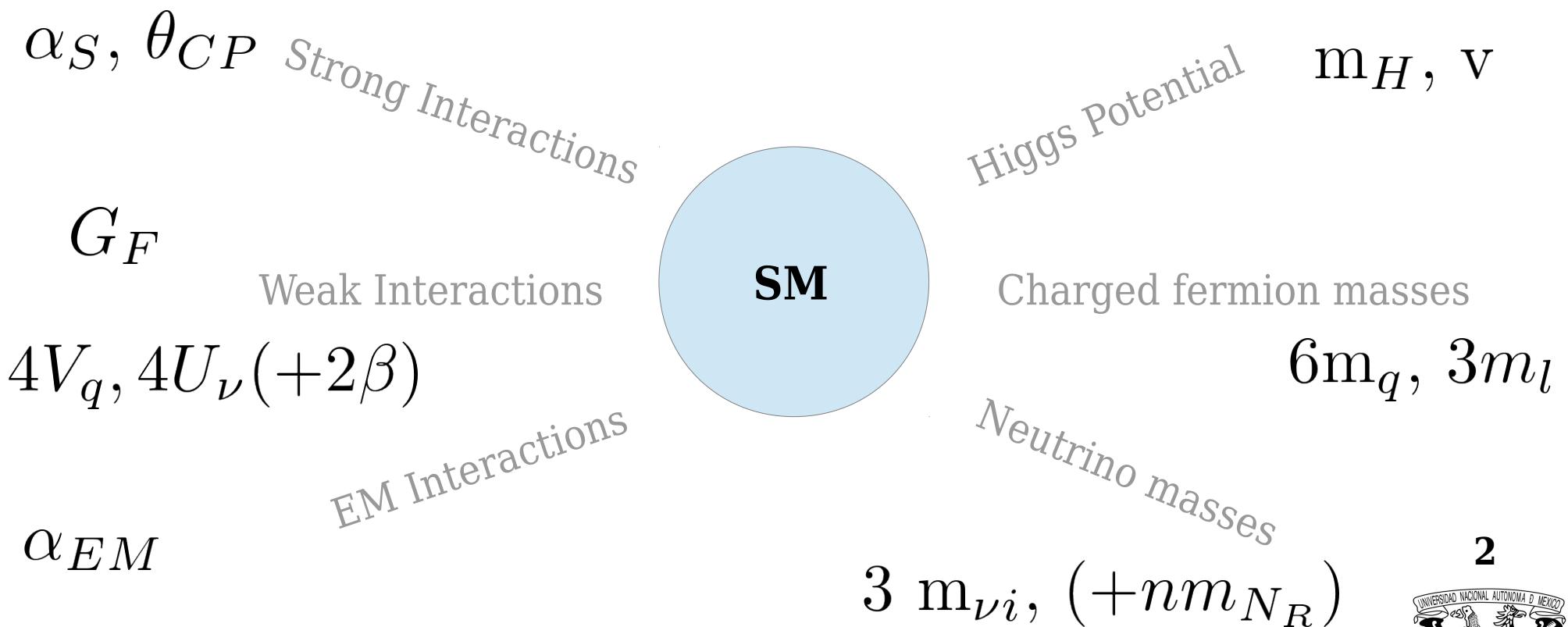


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Main motivation



2



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Main motivation

$$\theta_C \approx \sqrt{\frac{m_d}{m_s}}$$

Gatto, Sartori, and Tonin; Cabibbo and Maiani. (1968)
Pagels; Weinberg; Wilczek and Zee; Fritzsch; (75-79)
Ebrahim; Mohapatra and Senjanovic;
Pakvasa and Sugawara; Derman; Wyler; Frere.

3

Recent reviews: Fritzsch and Xing (2000);
Gupta and Ahuja (2011); Hirsch et al (2012);
Ishimori et al (2010); Altarelli and Feruglio (2010).



Main motivation

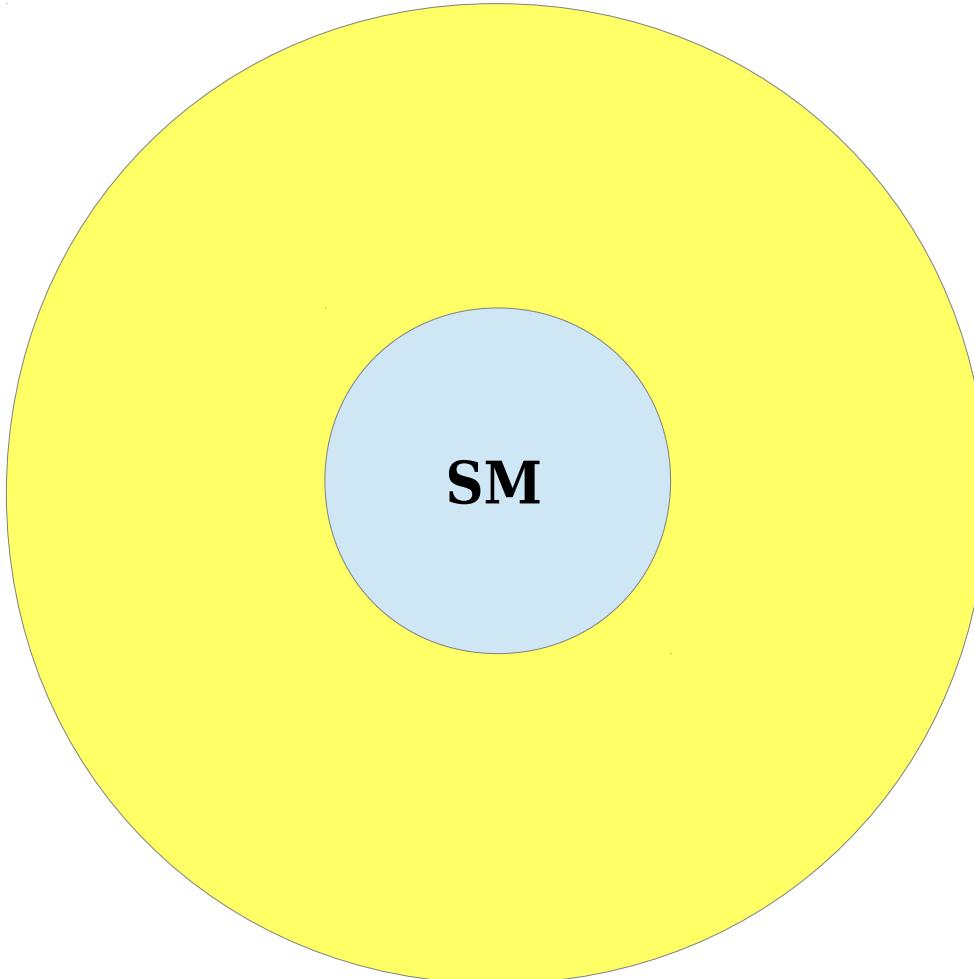
SM

4



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Main motivation



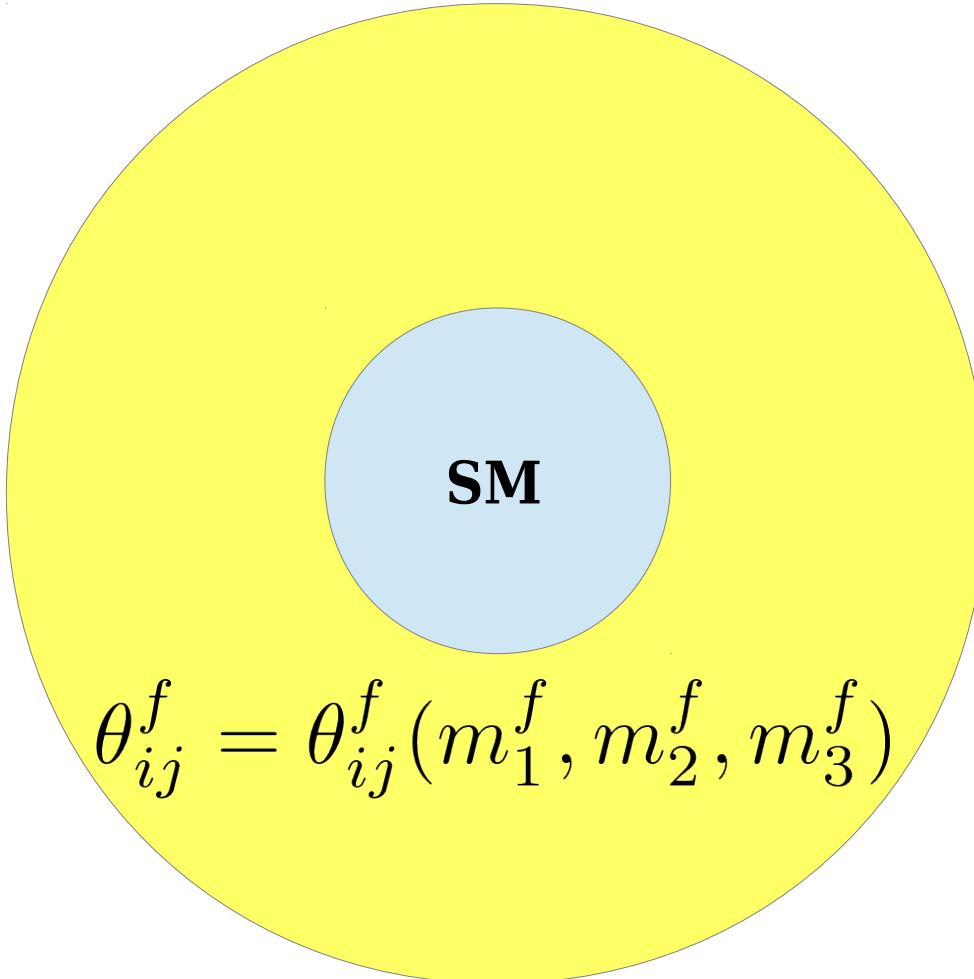
SM

4



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Main motivation



SM

$$\theta_{ij}^f = \theta_{ij}^f(m_1^f, m_2^f, m_3^f)$$

4



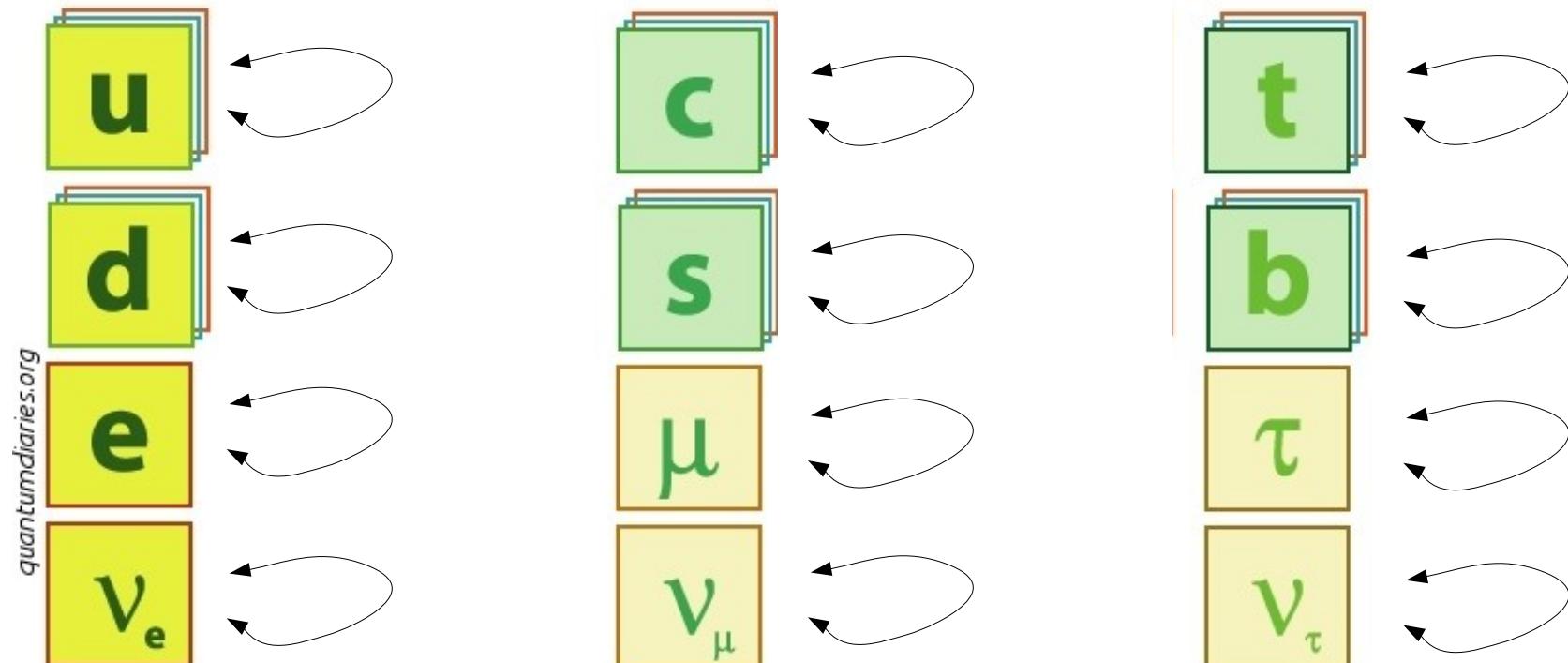
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4H-S3 flavour model



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4H-S3 flavour model



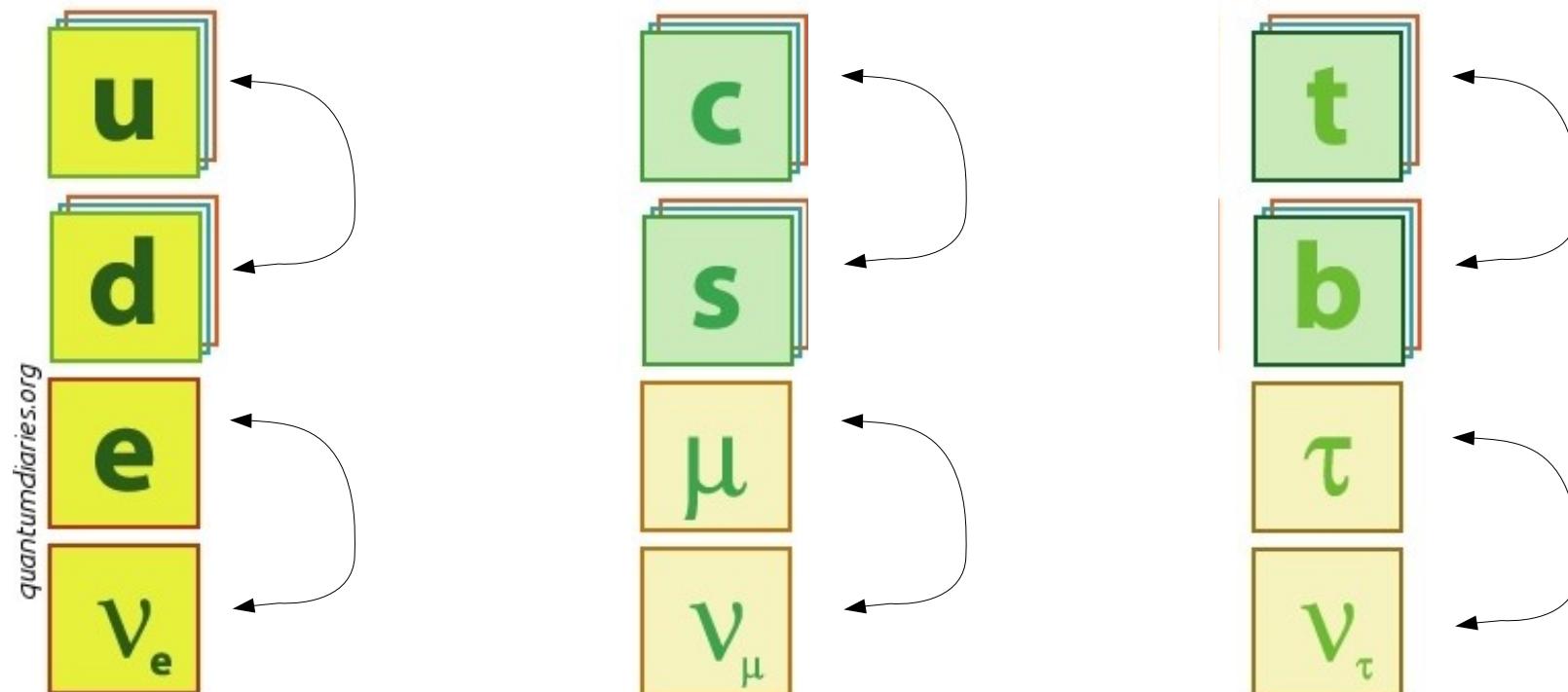
5

Z^0, γ, G_a



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4H-S3 flavour model



W^\pm (Weak-B)

6



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4H-S3 flavour model

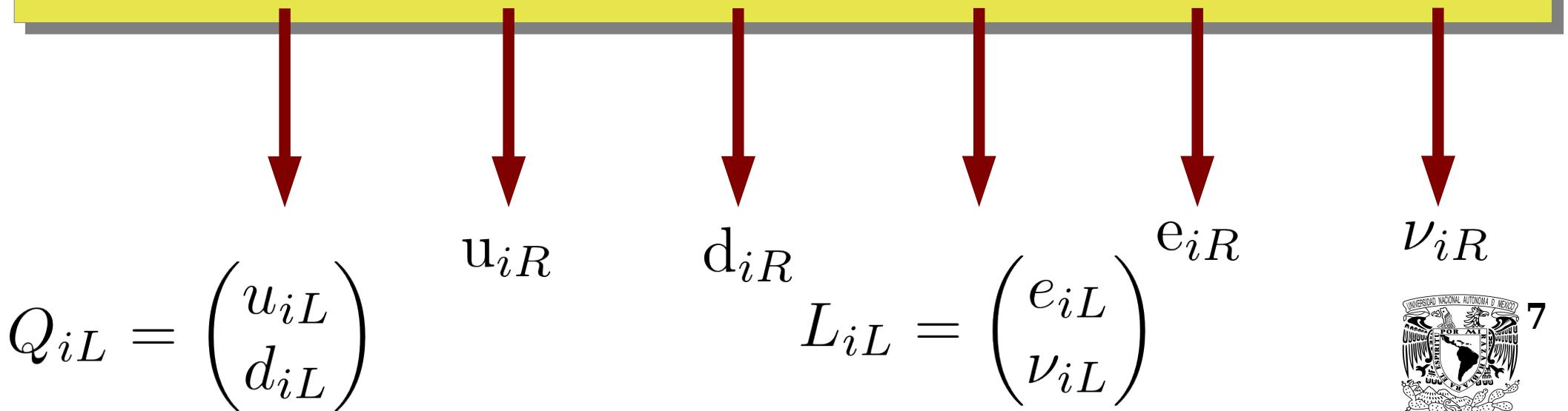
$$L_f = i\bar{\psi}_{f,i} \gamma_\mu \mathcal{D}_f^\mu \psi_{f,i}$$

$$G_F = U(3)_L^Q \otimes U(3)_R^u \otimes U(3)_R^d \otimes U(3)_L^l \otimes U(3)_R^e \otimes U(3)_R^\nu$$

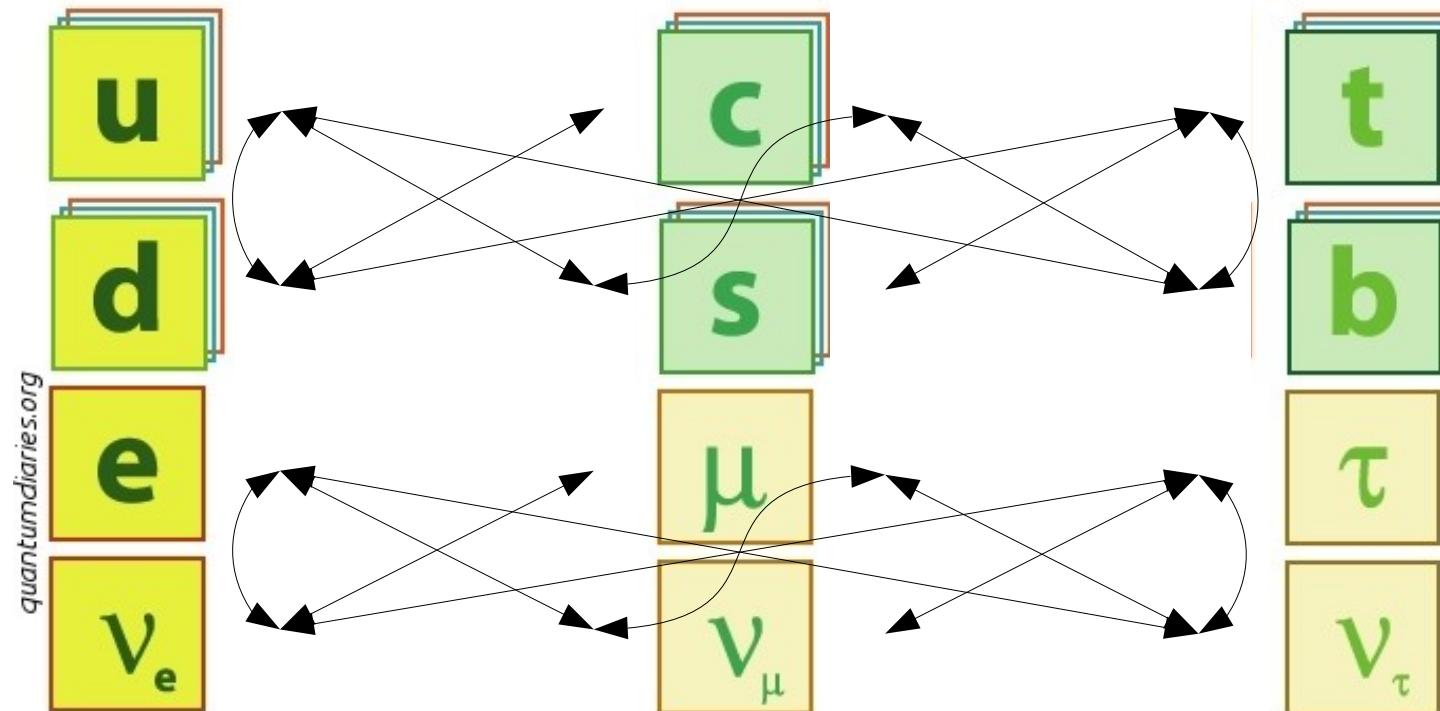
4H-S3 flavour model

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4H-S3 flavour model



8

W^\pm (Mass-B)



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4H-S3 flavour model

$$L_f = i\bar{\psi}_{f,i} \gamma_\mu \mathcal{D}_f^\mu \psi_{f,i} - \sum_{ij} Y_f^{ij} \bar{\psi}_{f,i}^L H \psi_{f,i}^R + h.c.$$

$$G_F \rightarrow U(1)_B \otimes U(1)_L$$

Yukawa param. - # Broken G. = # Phys. Param.

9

$$4(9 + 9) - [6(9) - 2] = 2(10)$$



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4H-S3 flavour model

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4H-S3 flavour model

But,

- Which symmetry?
- How should we search for it?
- What facts do we already know?

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4H-S3 flavour model

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4H-S3 flavour model

- What facts do we already know?
 1. Discrete and a subgroup of U(3).
 2. It acts independently on each fermion specie.
 3. It acts independently on each handedness.

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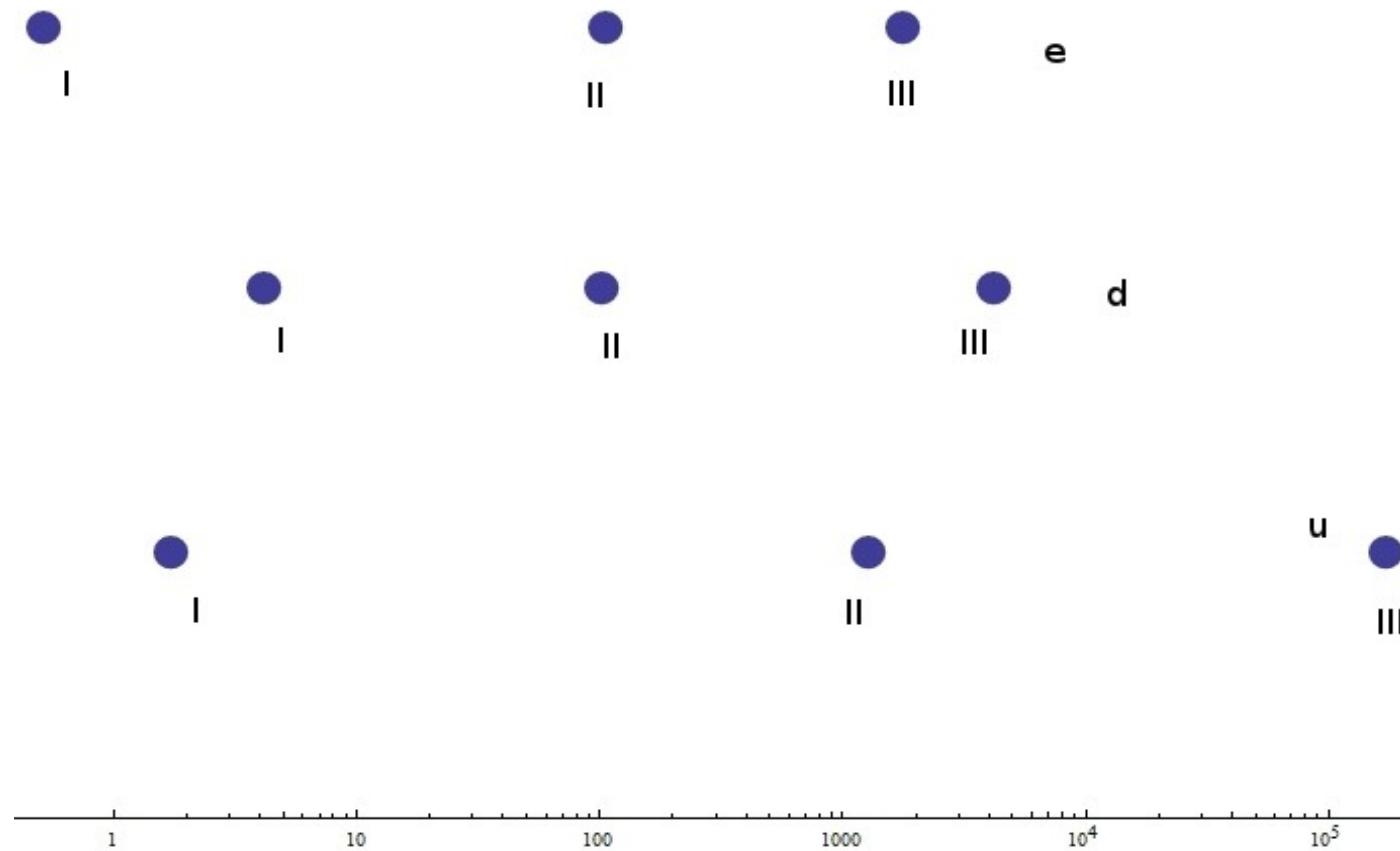
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4H-S3 flavour model

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 1. Mass spectra
 2. In the kinetic terms of the Lagrangian

4H-S3 flavour model

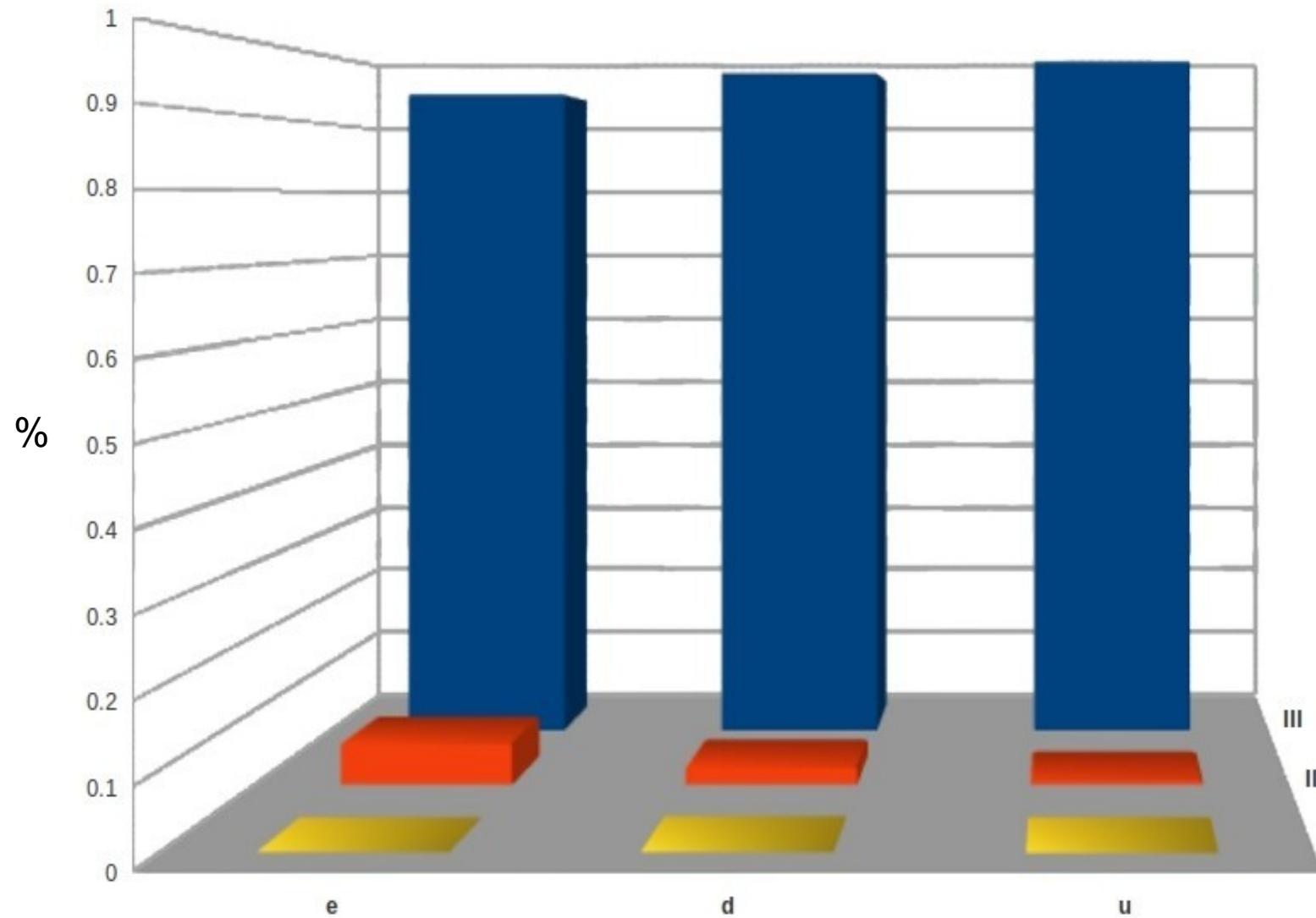


13



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4H-S3 flavour model

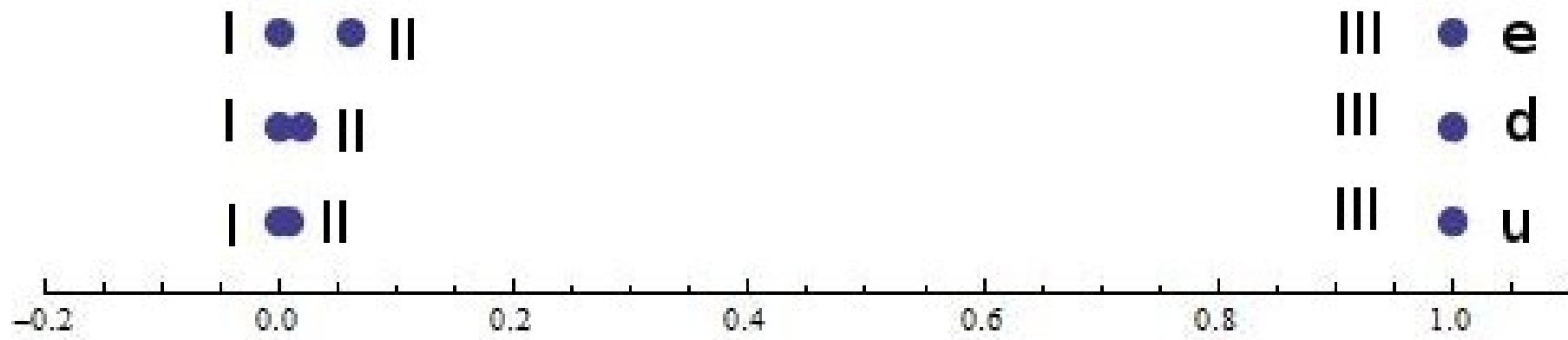


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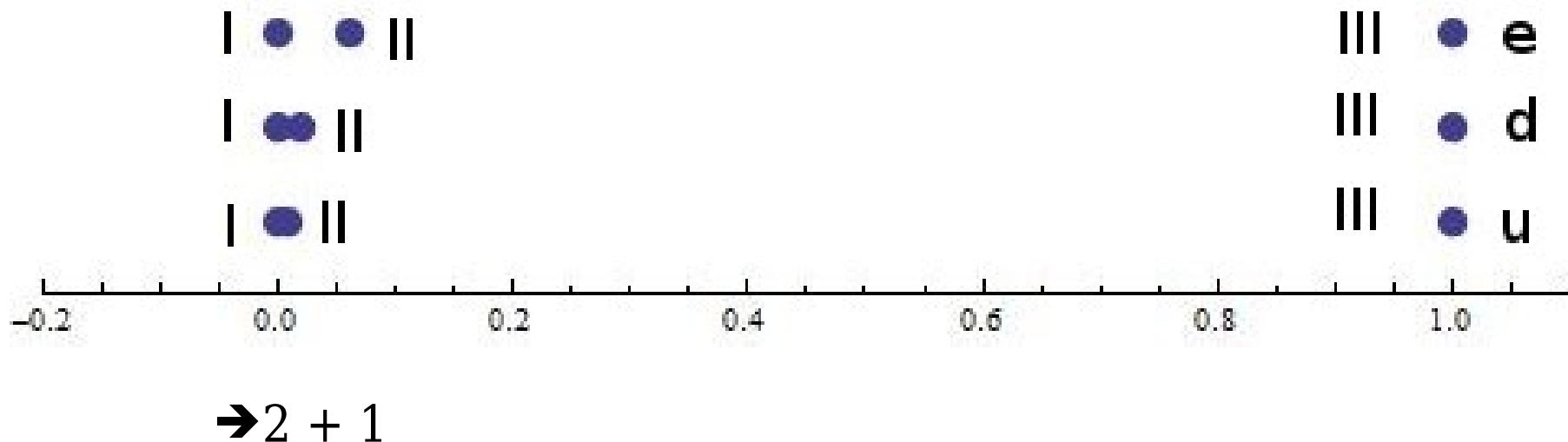
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4H-S3 flavour model



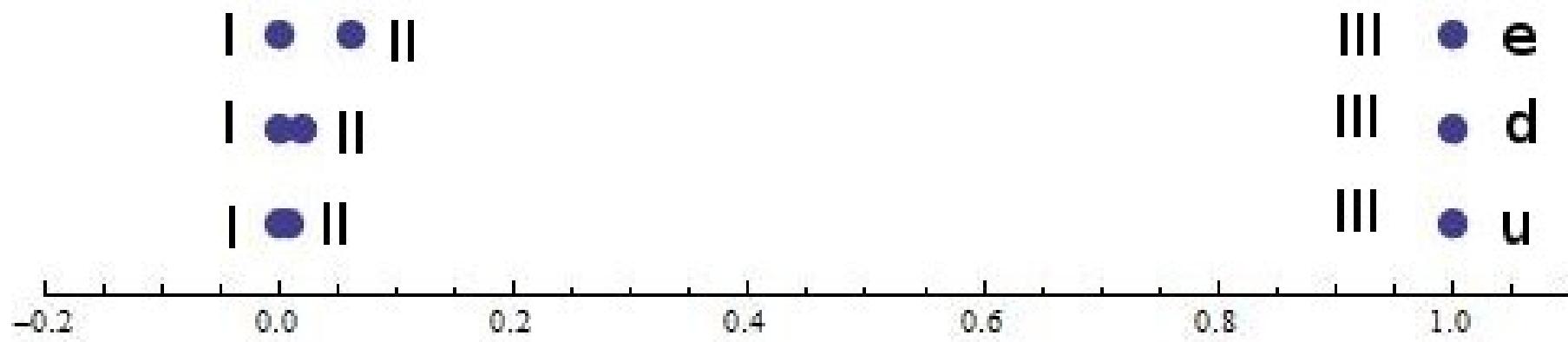
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4H-S3 flavour model



15

4H-S3 flavour model

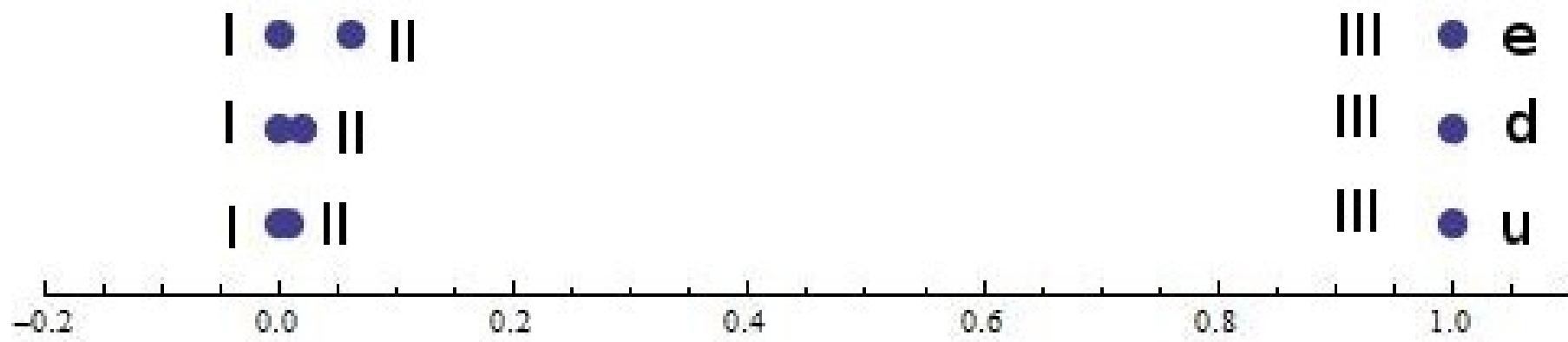


→ 2 + 1

→ Preserved after the EWSB

15

4H-S3 flavour model



→ 2 + 1

→ Preserved after the EWSB

→ Non-Abelian Symmetry Group

15



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4H-S3 flavour model

- Which symmetry?
 1. A non-Abelian discrete subgroup of U(3)
 2. Preserved after the EWSB
 3. $3 \rightarrow 2 + 1$



4H-S3 flavour model

- How should we search for it?
 1. Mass spectra
 2. In the kinetic terms of the Lagrangian

4H-S3 flavour model

$$L_f = i\bar{\psi}_{f,i} \gamma_\mu \mathcal{D}_f^\mu \psi_{f,i} - \sum_{ij} Y_f^{ij} \bar{\psi}_{f,i}^L H \psi_{f,i}^R + h.c.$$

$$L_f = i\bar{\psi}_{f,i} \gamma_\mu \mathcal{D}_f^\mu \psi_{f,i}$$

4H-S3 flavour model

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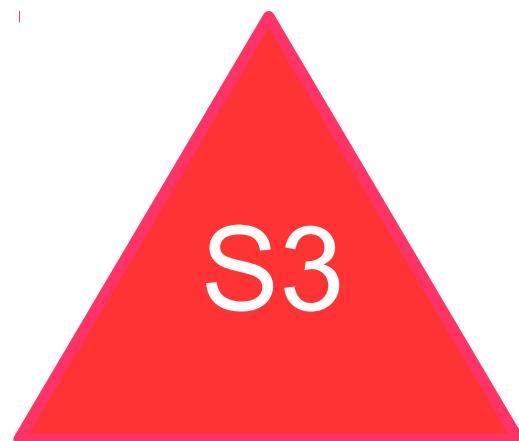
$$L_f = i\bar{\psi}_{f,i} \gamma_\mu \mathcal{D}_f^\mu \psi_{f,i} \quad L'_f = L_f(1 \leftrightarrow 2 \leftrightarrow 3)$$

4H-S3 flavour model

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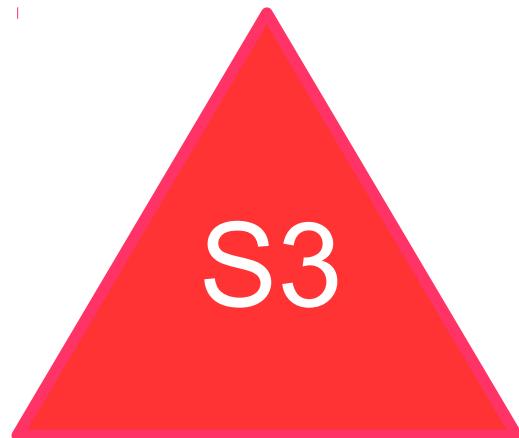
17



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4H-S3 flavour model

?



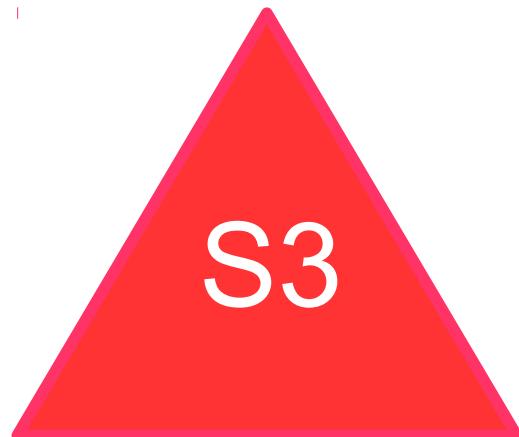
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4H-S3 flavour model

- ✓ A non-Abelian discrete subgroup of U(3)
- ✓ Preserved after the EWSB
- ✓ $3 \rightarrow 2 + 1$



18



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4H-S3 flavour model

$$L_f = i\bar{\psi}_{f,i} \gamma_\mu \mathcal{D}_f^\mu \psi_{f,i} - \sum_{ij} Y_f^{ij} \bar{\psi}_{f,i}^L H \psi_{f,i}^R + h.c.$$

$$L_Y = - \sum_{ij} Y_f^{ij} \bar{\psi}_{f,i}^L H \psi_{f,i}^R$$

$$L'_Y = L_Y(1 \leftrightarrow 2 \leftrightarrow 3)$$



?

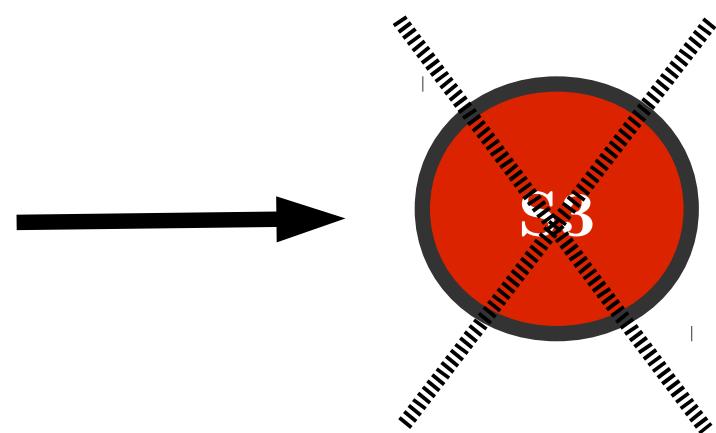
19



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4H-S3 flavour model

1 Higgs \longrightarrow $m_1 = m_2 \neq m_3$
 $V = I_{3 \times 3}$



- Mondragon et al, Phys. Rev. D59, 093009
- Mondragon et al, Phys. Rev. D61, 113002
- Barranco et al, Phys. Rev. D82, 073010
- Feruglio et al, Nucl. Phys. B800, 77
- Kobayashi et al, Phys. Rev. D78, 115006
- Jora et al, Phys. Rev. D80, 093007
- Xing et al, Phys. Lett. B690, 204
- ...

20

4H-S3 flavour model



4H-S3 flavour model

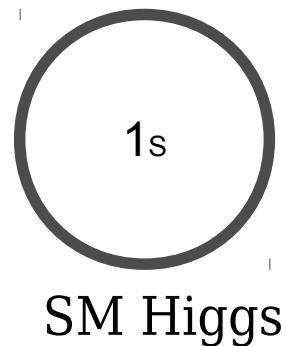


Is this our end?

4H-S3 flavour model



4H-S3 flavour model

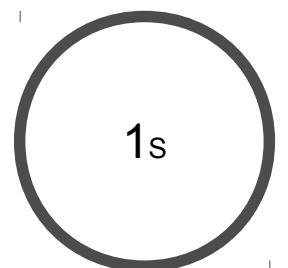


21



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4H-S3 flavour model



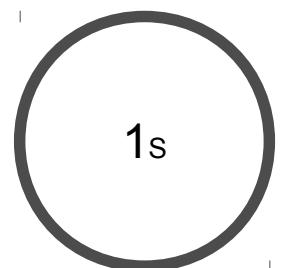
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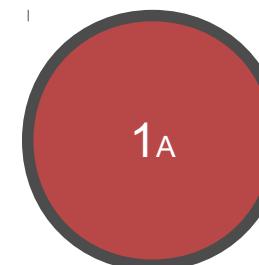
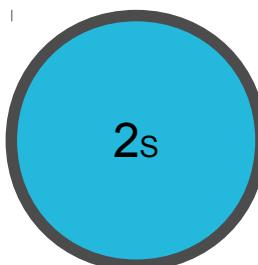
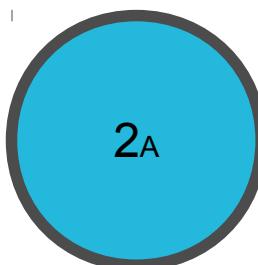
4H-S3 flavour model



SM Higgs

+

3 Higgs

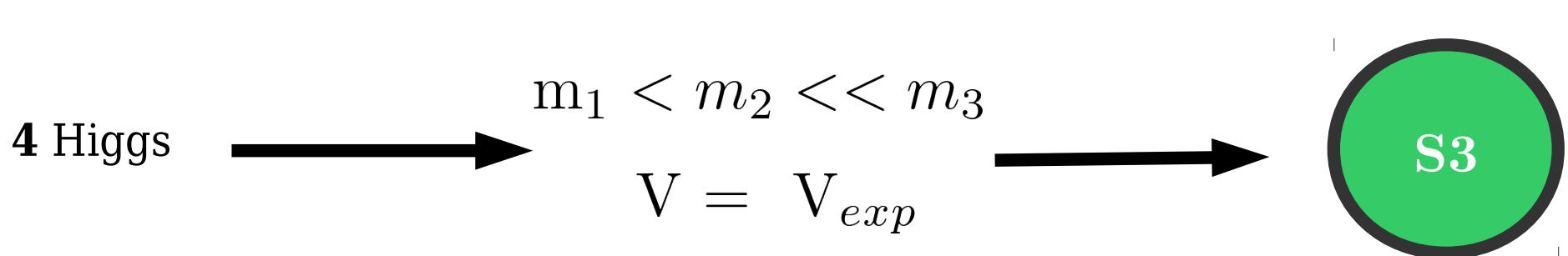


21



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4H-S3 flavour model



S3 preserved + **4H**:

- Yahalom, Phys. Rev. D29, 536
- **Mondragon et al, arXiv:1304.6644

S3 preserved + **3H**:

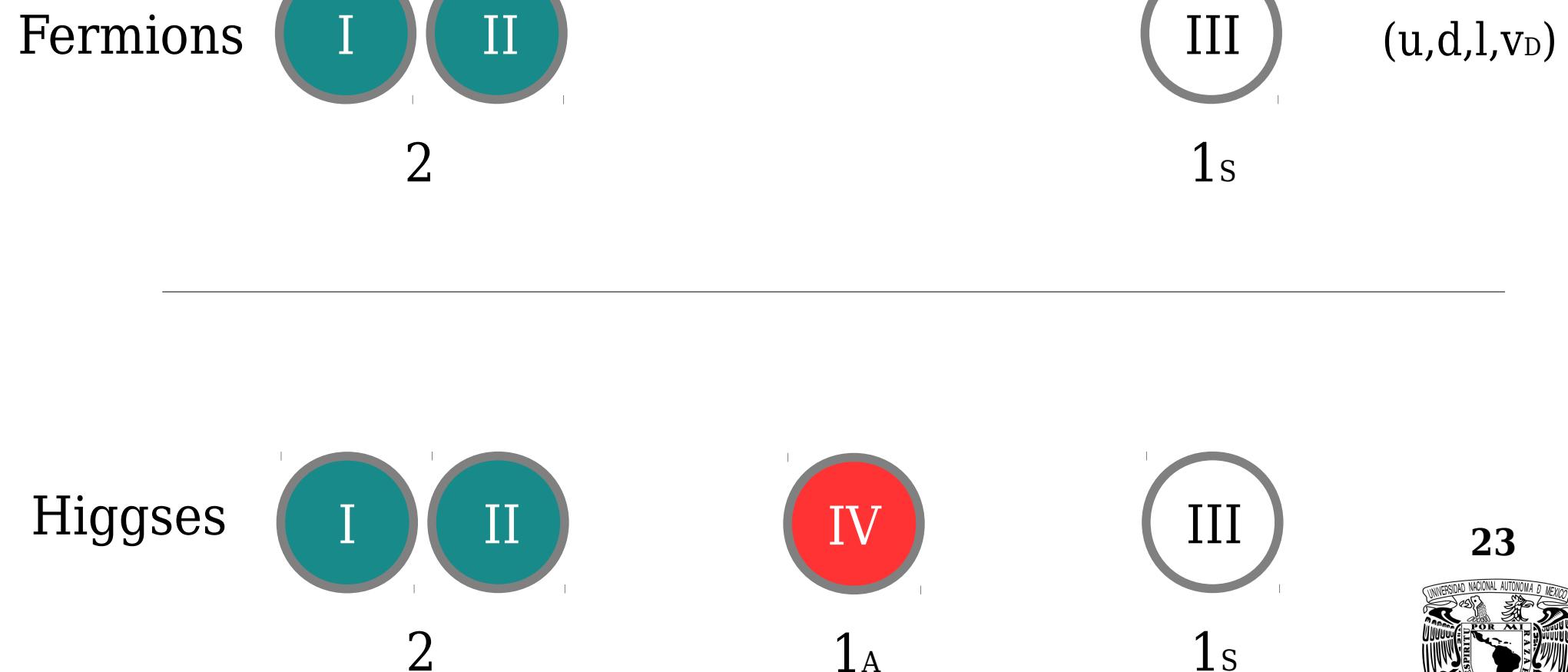
- Pakvasa et al, Phys. Lett. B73, 61
- Derman, Phys. Rev. D19, 317
- Kubo et al, Prog. Theor. Phys. 109, 795
- Gonzalez Canales et al, Fortschritte der Physik, arXiv:1205.4755

22

4H-S3 flavour model



4H-S3 flavour model



4H-S3 flavour model

How to achieve $\theta_{ij} = \theta_{ij}(m_f)$?

24



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4H-S3 flavour model

$$\mathcal{M}_f^{S3} = \begin{pmatrix} \mu_1^f + \mu_2^f & \mu_4^f + \mu_5^f & \mu_6^f \\ \mu_4^f - \mu_5^f & \mu_1^f - \mu_2^f & \mu_7^f \\ \mu_8^f & \mu_9^f & \mu_3^f \end{pmatrix} \longrightarrow$$



4H-S3 flavour model

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↑

25



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Many parameters!

25



4H-S3 flavour model

- Hermiticity
- 2x2 Rotation
- The angle should satisfy:

$$\tan(\alpha) = \frac{w_1}{w_2}$$

26



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4H-S3 flavour model

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26



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4H-S3 flavour model

$$\hat{\mathcal{M}}_f^{S_3} = \begin{pmatrix} |\mu_1^f| + |\mu_2^f|c^2(1 - 3t^2) & |\mu_2^f|sc(3 - t^2) + i|\mu_5^f| & 0 \\ |\mu_2^f|sc(3 - t^2) - i|\mu_5^f| & |\mu_1^f| - |\mu_2^f|c^2(1 - 3t^2) & \mu_7^f/c \\ 0 & \mu_7^{f*}/c & |\mu_3^f| \end{pmatrix}$$

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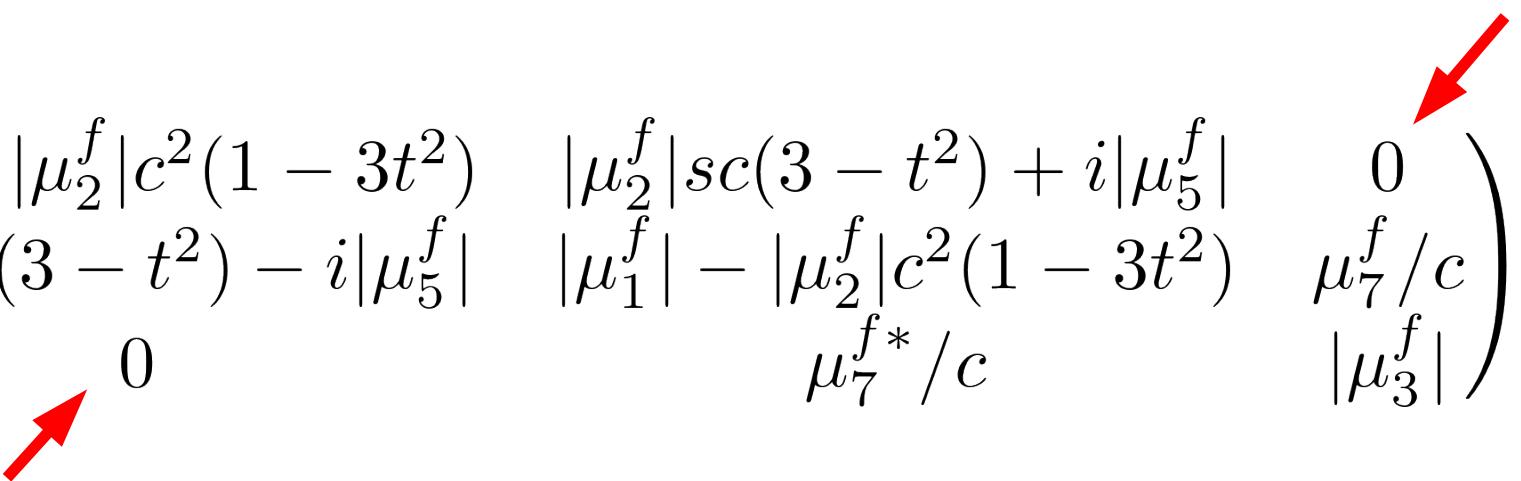
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26



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4H-S3 flavour model

$$\mathcal{U} \mathcal{A}_{n \times n} \mathcal{U}^{-1} = \text{diag}(a_1, a_2, \dots, a_n),$$



4H-S3 flavour model

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$$\mathcal{U}\bar{A}_{n \times n}\mathcal{U}^{-1} = \text{diag}(a_1 - \Delta, a_2 - \Delta, \dots, a_n - \Delta),$$

4H-S3 flavour model

$$\bar{\mathcal{M}}_f^{S_3} = \begin{pmatrix} 0 & \sqrt{\frac{\tilde{\sigma}_1^f \tilde{\sigma}_2^f}{1-\delta_f}} & 0 \\ \sqrt{\frac{\tilde{\sigma}_1^f \tilde{\sigma}_2^f}{1-\delta_f}} & \tilde{\sigma}_1^f - \tilde{\sigma}_2^f + \delta_f & \sqrt{\frac{\delta_f}{1-\delta_f}} \xi_1^f \xi_2^f \\ 0 & \sqrt{\frac{\delta_f}{1-\delta_f}} \xi_1^f \xi_2^f & 1 - \delta_f \end{pmatrix}$$

$$\xi_1^f \equiv 1 - \tilde{\sigma}_1^f - \delta_f, \quad \xi_2^f \equiv 1 + \tilde{\sigma}_2^f - \delta_f$$

28



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4H-S3 flavour model

$$\overline{\mathcal{M}}_f^{S3} = \begin{pmatrix} 0 & |\mu_2^f|sc(3-t^2) + i|\mu_5^f| & 0 \\ |\mu_2^f|sc(3-t^2) - i|\mu_5^f| & -2|\mu_2^f|c^2(1-3t^2) & \mu_7^f/c \\ 0 & \mu_7^{f*}/c & |\mu_3^f| - \Delta_f \end{pmatrix}$$

$$\mathcal{M} = \begin{pmatrix} 0 & A & 0 \\ A^* & |B| & C \\ 0 & C^* & |D| \end{pmatrix} \text{ (Two texture zeroes)}$$

$$\mathcal{M} = \begin{pmatrix} 0 & A & 0 \\ \pm A & 0 & B_1 \\ 0 & B_2 & C \end{pmatrix} \text{ (Nearest Neighbour Interaction)}$$

29



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Results



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Results

$$V_{ud}^{th} = \sqrt{\frac{\tilde{\sigma}_c \tilde{\sigma}_s \xi_1^u \xi_1^d}{\mathcal{D}_{1u} \mathcal{D}_{1d}}} + \sqrt{\frac{\tilde{\sigma}_u \tilde{\sigma}_d}{\mathcal{D}_{1u} \mathcal{D}_{1d}}} \left(\sqrt{(1 - \delta_u)(1 - \delta_d)} \xi_1^u \xi_1^d + \sqrt{\delta_u \delta_d \xi_2^u \xi_2^d} e^{i\phi_2} \right) e^{i\phi_1},$$

$$V_{us}^{th} = -\sqrt{\frac{\tilde{\sigma}_c \tilde{\sigma}_d \xi_1^u \xi_2^d}{\mathcal{D}_{1u} \mathcal{D}_{2d}}} + \sqrt{\frac{\tilde{\sigma}_u \tilde{\sigma}_s}{\mathcal{D}_{1u} \mathcal{D}_{2d}}} \left(\sqrt{(1 - \delta_u)(1 - \delta_d)} \xi_1^u \xi_2^d + \sqrt{\delta_u \delta_d \xi_2^u \xi_1^d} e^{i\phi_2} \right) e^{i\phi_1},$$

$$V_{ub}^{th} = \sqrt{\frac{\tilde{\sigma}_c \tilde{\sigma}_d \tilde{\sigma}_s \delta_d \xi_1^u}{\mathcal{D}_{1u} \mathcal{D}_{3d}}} + \sqrt{\frac{\tilde{\sigma}_u}{\mathcal{D}_{1u} \mathcal{D}_{3d}}} \left(\sqrt{(1 - \delta_u)(1 - \delta_d)} \delta_d \xi_1^u - \sqrt{\delta_u \xi_2^u \xi_1^d \xi_2^d} e^{i\phi_2} \right) e^{i\phi_1},$$

$$V_{cd}^{th} = -\sqrt{\frac{\tilde{\sigma}_u \tilde{\sigma}_s \xi_2^u \xi_1^d}{\mathcal{D}_{2u} \mathcal{D}_{1d}}} + \sqrt{\frac{\tilde{\sigma}_c \tilde{\sigma}_d}{\mathcal{D}_{2u} \mathcal{D}_{1d}}} \left(\sqrt{(1 - \delta_u)(1 - \delta_d)} \xi_2^u \xi_1^d + \sqrt{\delta_u \delta_d \xi_1^u \xi_2^d} e^{i\phi_2} \right) e^{i\phi_1},$$

$$V_{cs}^{th} = \sqrt{\frac{\tilde{\sigma}_u \tilde{\sigma}_d \xi_2^u \xi_2^d}{\mathcal{D}_{2u} \mathcal{D}_{2d}}} + \sqrt{\frac{\tilde{\sigma}_c \tilde{\sigma}_s}{\mathcal{D}_{2u} \mathcal{D}_{2d}}} \left(\sqrt{(1 - \delta_u)(1 - \delta_d)} \xi_2^u \xi_2^d + \sqrt{\delta_u \delta_d \xi_1^u \xi_1^d} e^{i\phi_2} \right) e^{i\phi_1}, \quad (38)$$

$$V_{cb}^{th} = -\sqrt{\frac{\tilde{\sigma}_u \tilde{\sigma}_d \tilde{\sigma}_s \delta_d \xi_2^u}{\mathcal{D}_{2u} \mathcal{D}_{3d}}} + \sqrt{\frac{\tilde{\sigma}_c}{\mathcal{D}_{2u} \mathcal{D}_{3d}}} \left(\sqrt{(1 - \delta_u)(1 - \delta_d)} \delta_d \xi_2^u - \sqrt{\delta_u \xi_1^u \xi_1^d \xi_2^d} e^{i\phi_2} \right) e^{i\phi_1},$$

$$V_{td}^{th} = \sqrt{\frac{\tilde{\sigma}_u \tilde{\sigma}_c \tilde{\sigma}_s \delta_u \xi_1^d}{\mathcal{D}_{3u} \mathcal{D}_{1d}}} + \sqrt{\frac{\tilde{\sigma}_d}{\mathcal{D}_{3u} \mathcal{D}_{1d}}} \left(\sqrt{\delta_u (1 - \delta_u)(1 - \delta_d)} \xi_1^d - \sqrt{\delta_d \xi_1^u \xi_2^u \xi_2^d} e^{i\phi_2} \right) e^{i\phi_1},$$

$$V_{ts}^{th} = -\sqrt{\frac{\tilde{\sigma}_u \tilde{\sigma}_c \tilde{\sigma}_d \delta_u \xi_2^d}{\mathcal{D}_{3u} \mathcal{D}_{2d}}} + \sqrt{\frac{\tilde{\sigma}_s}{\mathcal{D}_{3u} \mathcal{D}_{2d}}} \left(\sqrt{\delta_u (1 - \delta_u)(1 - \delta_d)} \xi_2^d - \sqrt{\delta_d \xi_1^u \xi_2^u \xi_1^d} e^{i\phi_2} \right) e^{i\phi_1},$$

$$V_{tb}^{th} = \sqrt{\frac{\tilde{\sigma}_u \tilde{\sigma}_c \tilde{\sigma}_d \tilde{\sigma}_s \delta_u \delta_d}{\mathcal{D}_{3u} \mathcal{D}_{3d}}} + \left(\sqrt{\frac{\xi_1^u \xi_2^u \xi_1^d \xi_2^d}{\mathcal{D}_{3u} \mathcal{D}_{3d}}} + \sqrt{\frac{\delta_u \delta_d (1 - \delta_u)(1 - \delta_d)}{\mathcal{D}_{3u} \mathcal{D}_{3d}}} e^{i\phi_2} \right) e^{i\phi_1},$$

$$\begin{aligned} \xi_1^{u,d} &= 1 - \tilde{\sigma}_{u,d} - \delta_{u,d}, & \xi_2^{u,d} &= 1 + \tilde{\sigma}_{c,s} - \delta_{u,d}, \\ \mathcal{D}_{1(u,d)} &= (1 - \delta_{u,d})(\tilde{\sigma}_{u,d} + \tilde{\sigma}_{c,s})(1 - \tilde{\sigma}_{u,d}), \\ \mathcal{D}_{2(u,d)} &= (1 - \delta_{u,d})(\tilde{\sigma}_{u,d} + \tilde{\sigma}_{c,s})(1 + \tilde{\sigma}_{c,s}), \\ \mathcal{D}_{3(u,d)} &= (1 - \delta_{u,d})(1 - \tilde{\sigma}_{u,d})(1 + \tilde{\sigma}_{c,s}). \end{aligned}$$

Mondragón et al,
arXiv:1304.6644

30

Results

Parameter	Central value	χ^2	Values with restricted precision	χ^2
Fit using the 2012 values of the parameters \tilde{m}_i				
$\tilde{\sigma}_u(M_Z)$	2.08977×10^{-6}		$(2.09 \pm 0.19) \times 10^{-6}$	
$\tilde{\sigma}_c(M_Z)$	3.93180×10^{-3}		$(3.93 \pm 0.007) \times 10^{-3}$	
$\tilde{\sigma}_d(M_Z)$	1.35949×10^{-3}		$(1.36 \pm 0.004) \times 10^{-3}$	
$\tilde{\sigma}_s(M_Z)$	2.08443×10^{-2}		$(2.08 \pm 0.02) \times 10^{-2}$	
δ_u	3.96726×10^{-2}		$(3.97 \pm 0.35) \times 10^{-2}$	
δ_d	5.29260×10^{-2}		$(5.29 \pm 0.41) \times 10^{-2}$	
$\cos \phi_2$	8.48776×10^{-1}	3.3×10^{-4}	$(8.49 \pm 0.22) \times 10^{-1}$	3.9×10^{-1}
Fit using the 2012 values of the parameters \tilde{m}_i (with \tilde{m}_s^{th})				
$\tilde{\sigma}_u(M_Z)$	2.17737×10^{-6}		$(2.18 \pm 0.35) \times 10^{-6}$	
$\tilde{\sigma}_c(M_Z)$	3.94×10^{-3}		$(3.94 \pm 0.007) \times 10^{-3}$	
$\tilde{\sigma}_d(M_Z)$	1.19392×10^{-3}		$(1.19 \pm 0.009) \times 10^{-3}$	
$\tilde{\sigma}_s(M_Z)$	1.82432×10^{-2}		$(1.82 \pm 0.02) \times 10^{-3}$	
δ_u	6.12747×10^{-2}		$(6.13 \pm 0.41) \times 10^{-2}$	
δ_d	8.36979×10^{-2}		$(8.37 \pm 0.64) \times 10^{-2}$	
$\cos \phi_2$	9.23028×10^{-1}	3.3×10^{-4}	$(9.23 \pm 0.11) \times 10^{-1}$	7.3×10^{-2}

Table 9: Results of the fits for Cases II and III, that is the case of an SM invariant under an unbroken S_3 symmetry. Note that when we restrict the precision of the fitted values, we observe a significant change in the value of χ^2 .

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31



Summary



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Simplest extension to the SM

33



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Summary

Simplest extension to the SM

Predicts mixing parameters



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Introduction of a non-Abelian discrete symmetry



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Mixing matrix elements as
function of the masses...

33



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Thanks for your attention.

