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The Higgs as a window into flavor symmetries at the LHC

based on

G. Bhattacharyya, P.L. and H. Päs, *arXiv:1006.5597*

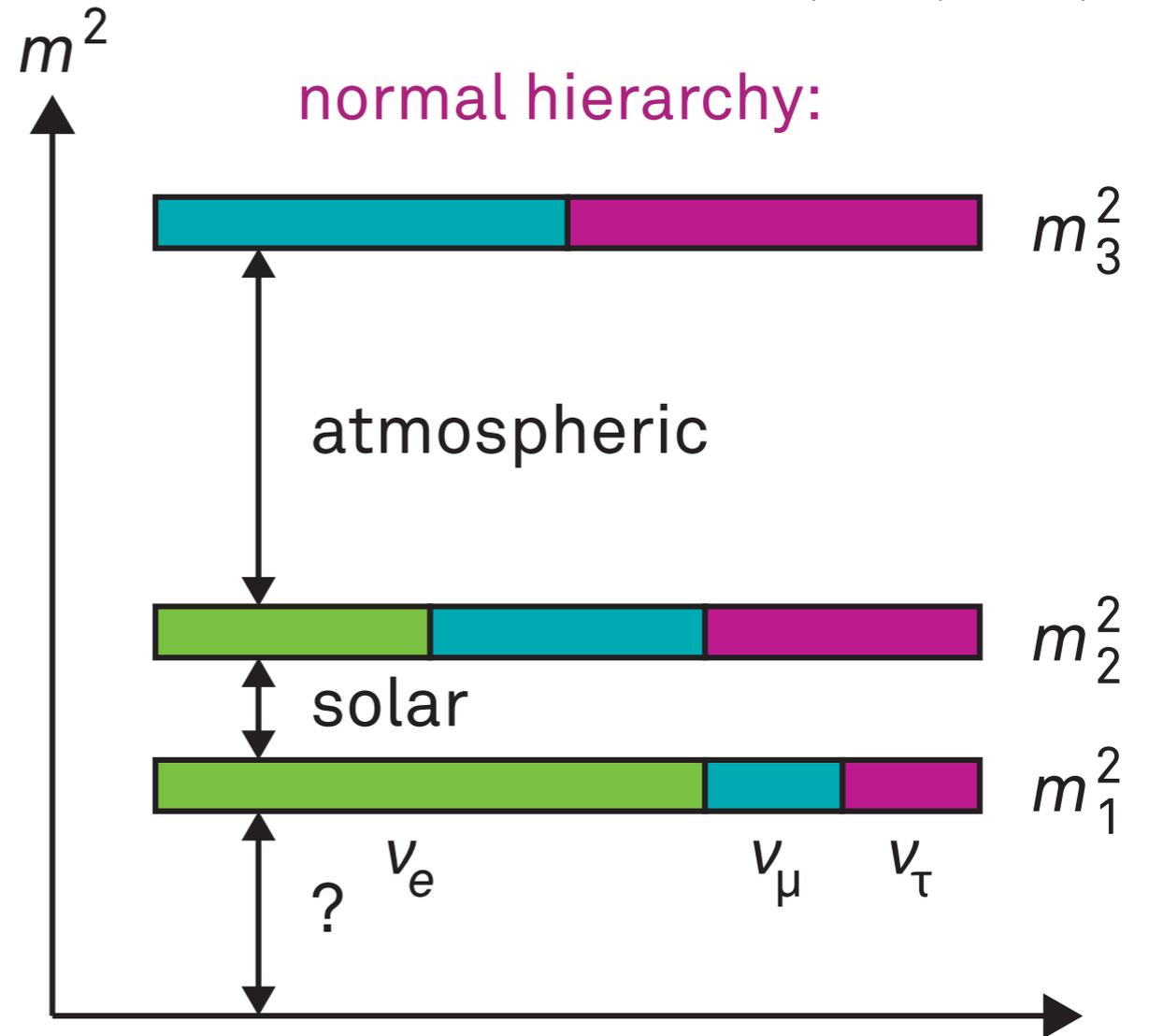
$$V_{\text{TBM}} = \begin{pmatrix} -\sqrt{\frac{2}{3}} & \sqrt{\frac{1}{3}} & 0 \\ \sqrt{\frac{1}{6}} & \sqrt{\frac{1}{3}} & \sqrt{\frac{1}{2}} \\ \sqrt{\frac{1}{6}} & \sqrt{\frac{1}{3}} & -\sqrt{\frac{1}{2}} \end{pmatrix}$$

Neutrino data

- ▶ Squared mass differences measured, absolute scale relatively unknown
- ▶ m_3^2 could be heavier than the other pair (normal hierarchy) or lighter (inverted hierarchy)
- ▶ current best fit is in normal hierarchy regime
- ▶ Significance of $\theta_{13} \neq 0$ approx. $< 2\sigma$

$$\Delta m_{21}^2 = 7.59 \pm 0.20 \begin{pmatrix} +0.61 \\ -0.69 \end{pmatrix} \times 10^{-5} \text{ eV}^2$$

$$\Delta m_{31}^2 = \begin{cases} -2.36 \pm 0.11 (\pm 0.37) \times 10^{-3} \text{ eV}^2 \\ +2.46 \pm 0.12 (\pm 0.37) \times 10^{-3} \text{ eV}^2 \end{cases}$$



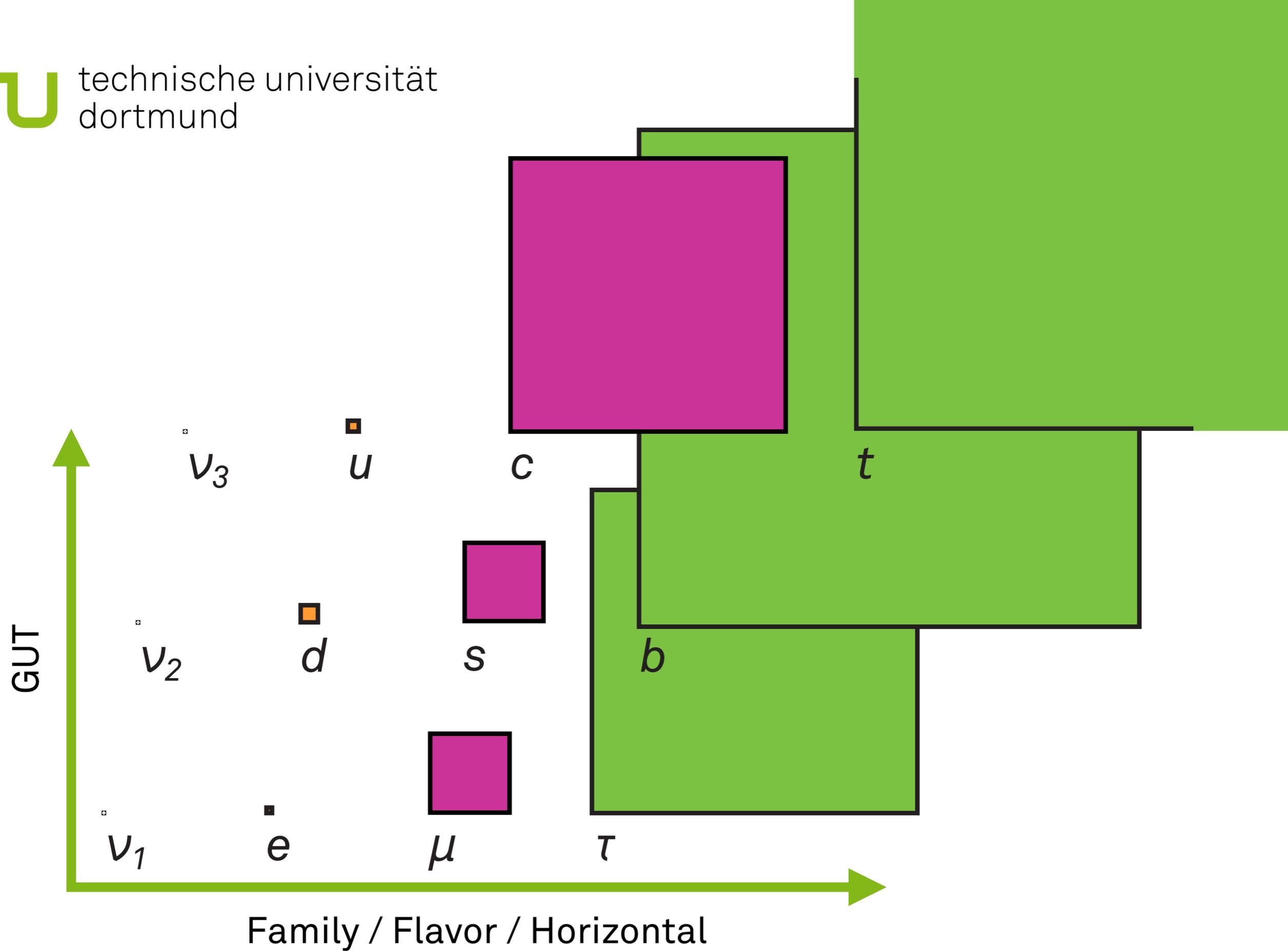
$$\theta_{12} = 34.4 \pm 1.0 \begin{pmatrix} +3.2 \\ -2.9 \end{pmatrix}^\circ$$

$$\theta_{23} = 42.8 \begin{matrix} +4.7 \\ -2.9 \end{matrix} \begin{pmatrix} +10.7 \\ -7.3 \end{pmatrix}^\circ$$

$$\theta_{13} = 5.6 \begin{matrix} +3.0 \\ -2.7 \end{matrix} (\leq 12.5)^\circ$$

Gonzalez-Garcia, Maltoni, Salvado, *arXiv:1001.4524*

Flavor symmetries

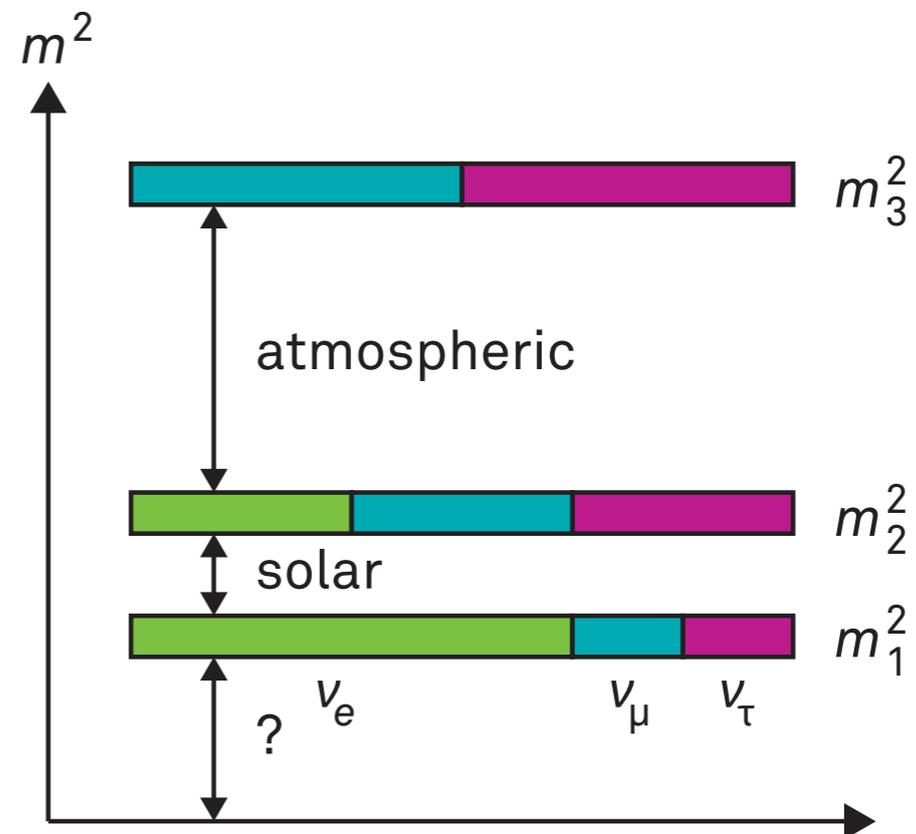


Why use horizontal symmetries?

- ▶ Horizontal symmetries have the potential to explain
 - ▶ **Masses**, mass relations
 - ▶ **Patterns** in the mixing matrices

$$V_{\text{TBM}} = \begin{pmatrix} -\sqrt{\frac{2}{3}} & \sqrt{\frac{1}{3}} & 0 \\ \sqrt{\frac{1}{6}} & \sqrt{\frac{1}{3}} & \sqrt{\frac{1}{2}} \\ \sqrt{\frac{1}{6}} & \sqrt{\frac{1}{3}} & -\sqrt{\frac{1}{2}} \end{pmatrix}$$

$$V_{\text{CKM}} \approx \begin{pmatrix} 1 & \lambda & \lambda^3 \\ -\lambda & 1 & \lambda^2 \\ \lambda^3 & -\lambda^2 & 1 \end{pmatrix}$$



What kind of symmetries?

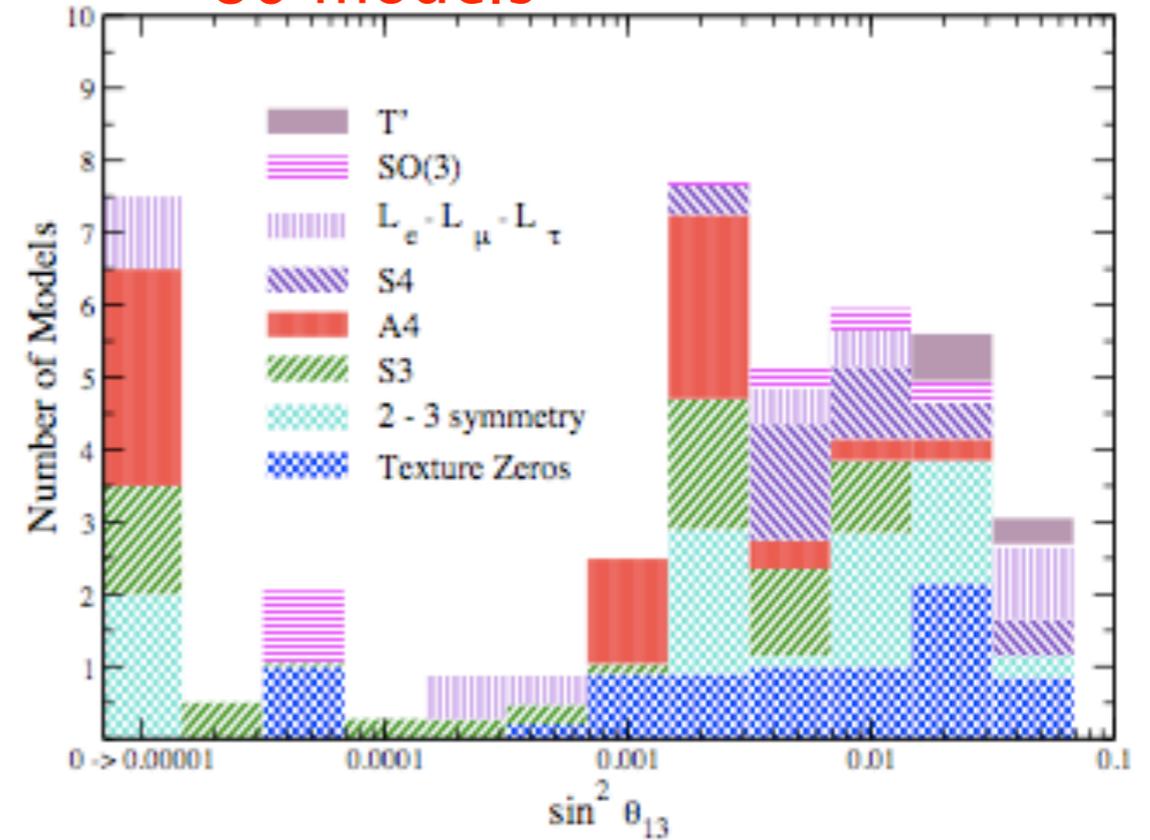
- ▶ Abelian symmetries like Froggatt-Nielsen $U(1)$, or Z_n
- ▶ All kinds of non-abelian discrete symmetries like S_3, A_4, S_4, \dots can be used to deduce some of these relations
 - ▶ through **specific choice of representations** for particle content
 - ▶ through **vacuum alignment** of extra scalars

How to discriminate?

- ▶ Huge variety of models
- ▶ A lot of them fit neutrino data reasonably well, but the allowed parameter space is large
- ▶ Search for other ways to test flavor symmetries

86 models

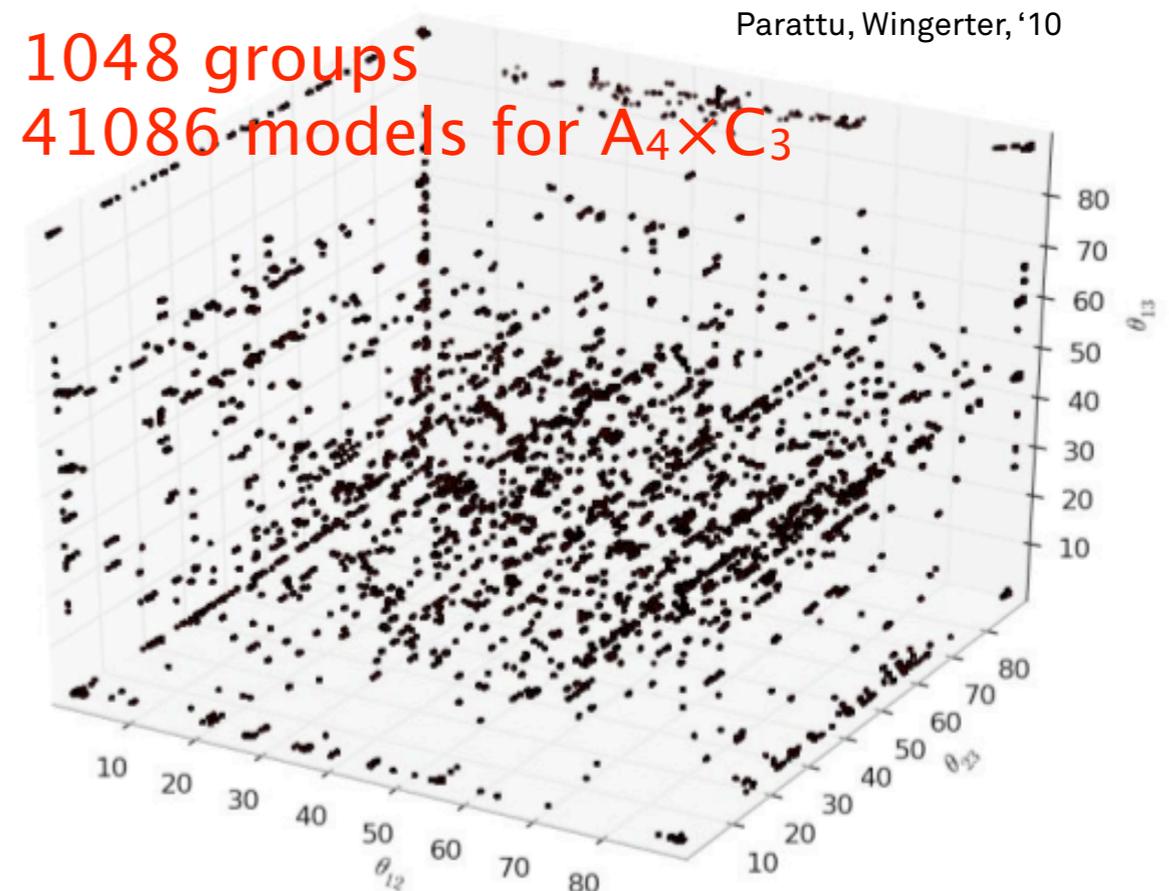
Albright, Chen, Rodejohann, '06, '08



1048 groups

41086 models for $A_4 \times C_3$

Parattu, Wingerter, '10



Phenomenology of discrete symmetries

- ▶ Typical interesting predictions:
 - ▶ sum rules / connections between lepton and quark sectors (\Rightarrow GUT embedding)
 - ▶ enlarged scalar sector (masses, mixings)
 - ▶ branching ratios of scalar decays differ from SM
 - ▶ unusual collider signatures
 - ▶ FCNCs in scalar decays

An example

The symmetry group S_3

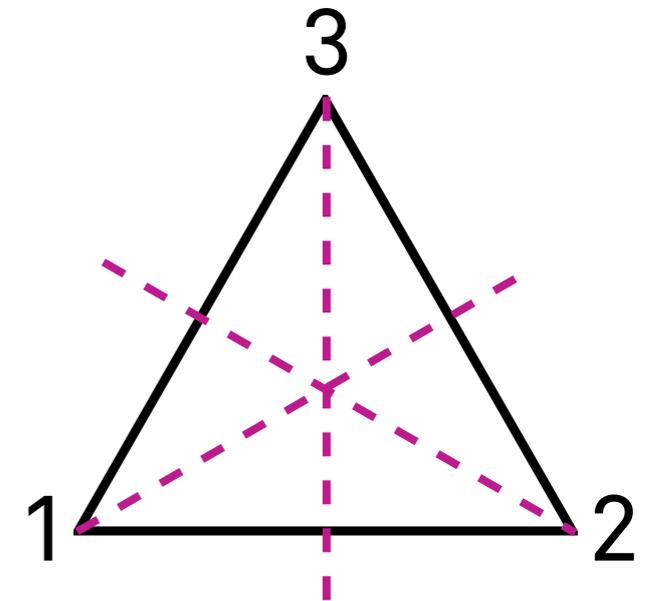
- ▶ Contains 6 elements:

▶ (123)	(312), (231)	(132), (321), (213)
id	rotation by 120°	swap two points / reflection

- ▶ 3 irreducible representations: $1, 1', 2$

- ▶ Basic multiplication rules:

▶ $1' \times 1' = 1$ and $2 \times 2 = 1 + 1' + 2$



A specific S_3 model

Chen, Frigerio, Ma, *Phys. Rev. D* **70**, 073008 (2004)

Lepton doublets

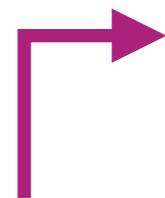


$$(L_1, L_2) \propto \mathbf{2}$$

$$(Q_1, Q_2) \propto \mathbf{2}$$

$$(\phi_1, \phi_2) \propto \mathbf{2}$$

Quark doublets



RH singlets



$$L_3, \ell_3^c, \ell_1^c \propto \mathbf{1}$$

$$Q_3, u_3^c, u_1^c, d_3^c, d_1^c \propto \mathbf{1}$$

$$\phi_3 \propto \mathbf{1}$$

$$\ell_2^c \propto \mathbf{1}'$$

$$u_2^c, d_2^c \propto \mathbf{1}'$$

- ▶ Two generations $\rightarrow S_3$ doublet; the other $\rightarrow S_3$ singlet

A specific S_3 model

Chen, Frigerio, Ma, *Phys. Rev. D* **70**, 073008 (2004)

- ▶ One scalar for each generation
- ▶ Neutrino sector separate, diagonal (See-Saw II, 2 heavy EW triplet scalars)
- ▶ Simple vacuum alignment:

$$\langle \phi_1 \rangle = \langle \phi_2 \rangle = v \quad \langle \phi_3 \rangle = v_3$$

$$2v^2 + v_3^2 = v_{SM}^2$$

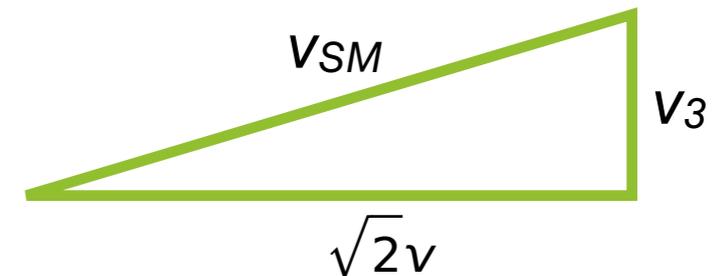
translates
directly into
PMNS matrix

$$\mathcal{M}_\ell = \begin{pmatrix} f_4 v_3 & f_5 v_3 & 0 \\ 0 & f_1 v & -f_2 v \\ 0 & f_1 v & f_2 v \end{pmatrix}$$

The scalar sector

Minimization of the potential

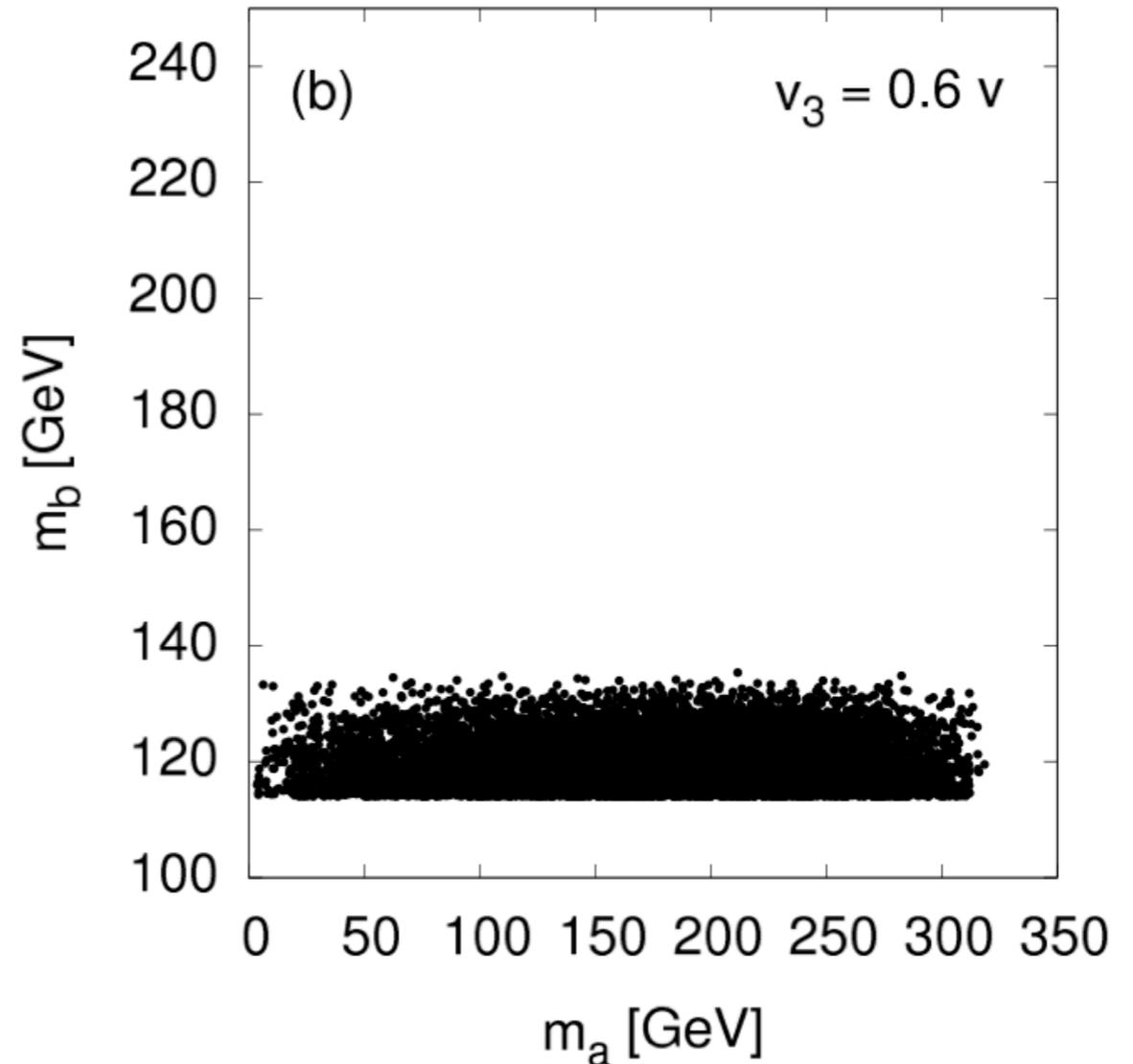
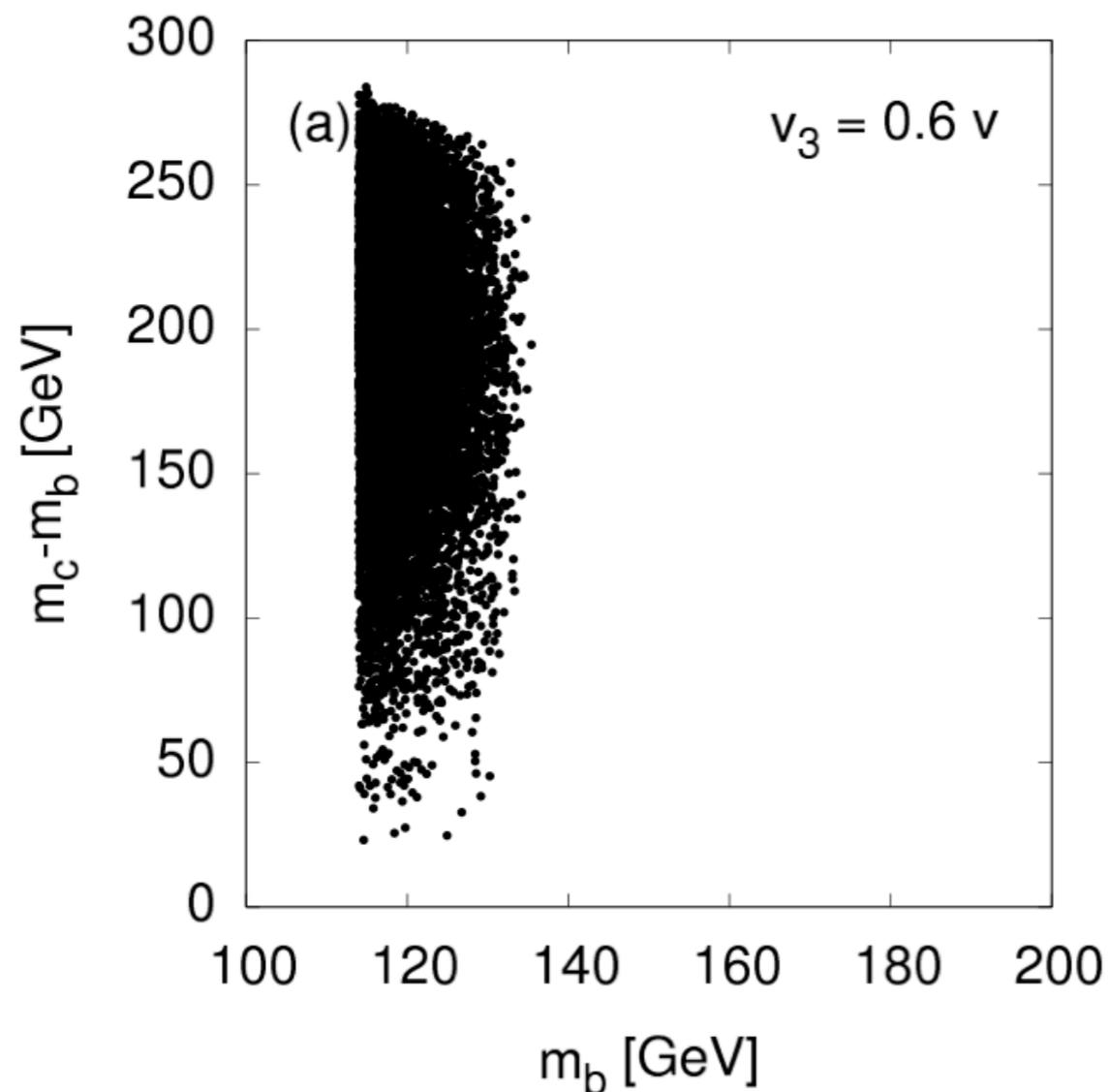
- ▶ Conditions applied for minimization
 - ▶ Wanted **vacuum alignment** $\langle \phi_1 \rangle = \langle \phi_2 \rangle = v$ must be a solution
 - ▶ It must actually be a minimum
 - ▶ Global **stability** of the solution
 - ▶ Allow fixed ratio of v_3 and v
 - ▶ We only consider real parameters



restrict parameters
of the potential, but
the parameter
space is still large

Results of parameter scan

- ▶ Physical CP-even neutral scalars:
 m_b light (< 200 GeV), m_c heavier (200 GeV $< m_c < 450$ GeV), $m_a < 350$ GeV



Scalar mixing

- ▶ Weak basis scalars $h_{1/2/3}$ are connected to physical scalars $h_{a/b/c}$ via

$$h_1 = U_b h_b + U_c h_c - \frac{1}{\sqrt{2}} h_a$$

$$h_2 = U_b h_b + U_c h_c + \frac{1}{\sqrt{2}} h_a$$

$$h_3 = U_{3b} h_b + U_{3c} h_c$$

- ▶ The U are analytically tractable but complicated functions of the parameters of the scalar potential

Couplings to gauge and matter fields

- ▶ Couplings of symmetry basis scalars h_i to W and Z are **modified by a factor** of $v_i/v_{SM} < 1$ compared to Standard Model
- ▶ In terms of physical scalars h_a, h_b and h_c :
 - ▶ **Suppression** of the couplings of h_b and h_c to gauge fields is governed by VEVs and scalar mixing parameters

h_a is special

- ▶ **h_a does not couple to W or Z via the three-point-vertex**
 - ▶ this follows because the h_a content in the symmetry basis scalars h_1 and h_2 is equal, but has opposite signs.
 - ▶ As the VEVs v_1 and v_2 are equal, the h_a coupling vanishes

Yukawa couplings

- ▶ **Identical structures** in charged lepton sector and up- / down quark sectors
- ▶ 2 scalars $h_{b,c}$ couple similarly to SM Higgs:
 - ▶ $h_{b,c} \rightarrow ee(uu, dd)$
 - $h_{b,c} \rightarrow \mu\mu(ss, cc)$
 - $h_{b,c} \rightarrow \tau\tau(bb, tt)$
- ▶ Additional FCNC coupling: $h_{b,c} \rightarrow e\mu$

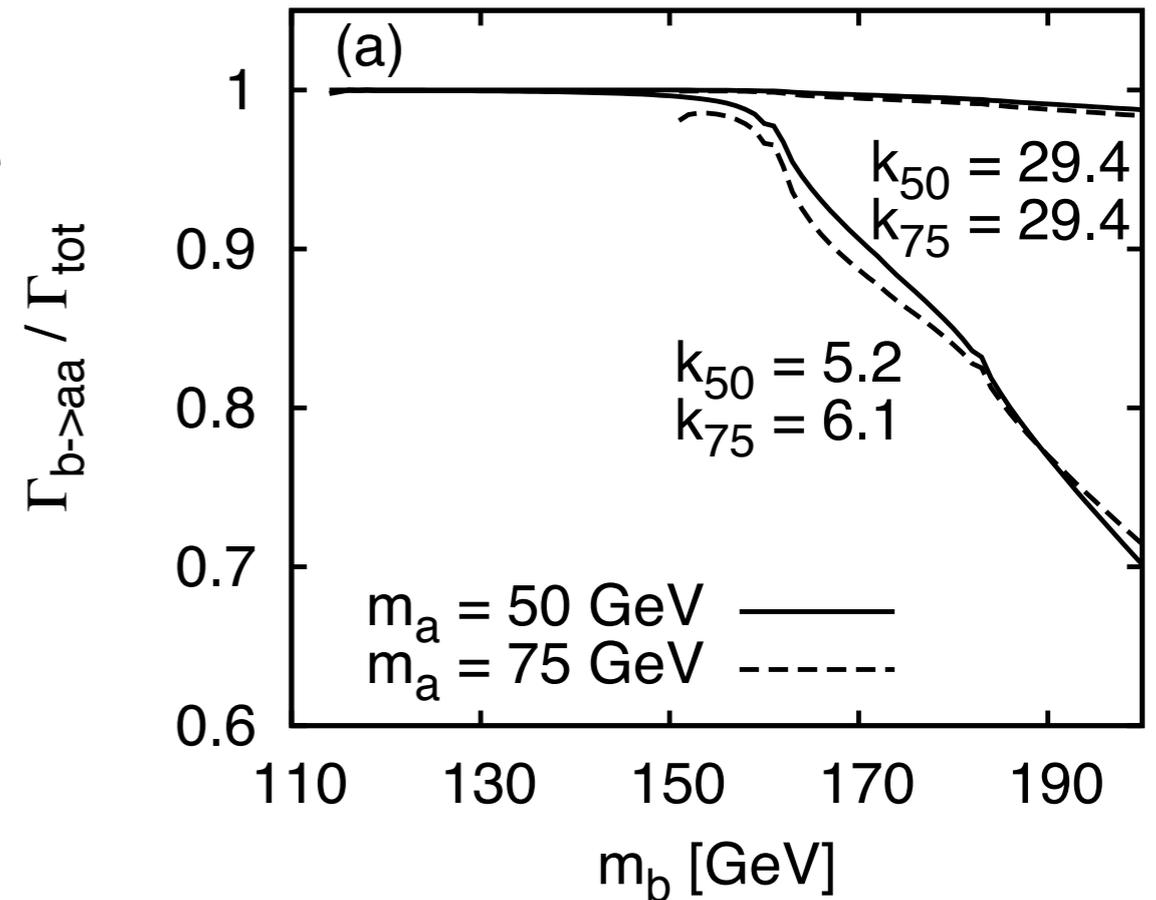
h_a is special, again

- ▶ The 3rd scalar h_a **only couples off-diagonally**, always with 3rd generation:
 - ▶ $h_a \rightarrow e\tau(db, ut)$ $h_a \rightarrow \mu\tau(sb, ct)$
- ▶ FCNC couplings are numerically small and fixed by fermion masses

$$Y_{h_a} = \begin{pmatrix} 0 & 0 & \gamma_{eL\tau R}^a \\ 0 & 0 & \gamma_{\mu L\tau R}^a \\ \gamma_{\tau L e R}^a & \gamma_{\tau L \mu R}^a & 0 \end{pmatrix}, \quad Y_{h_b} = \begin{pmatrix} \gamma_{eL e R}^b & \gamma_{eL \mu R}^b & 0 \\ \gamma_{\mu L e R}^b & \gamma_{\mu L \mu R}^b & 0 \\ 0 & 0 & \gamma_{\tau L \tau R}^b \end{pmatrix}, \quad Y_{h_c} = \begin{pmatrix} \gamma_{eL e R}^c & \gamma_{eL \mu R}^c & 0 \\ \gamma_{\mu L e R}^c & \gamma_{\mu L \mu R}^c & 0 \\ 0 & 0 & \gamma_{\tau L \tau R}^c \end{pmatrix}$$

Signatures of h_b and h_c

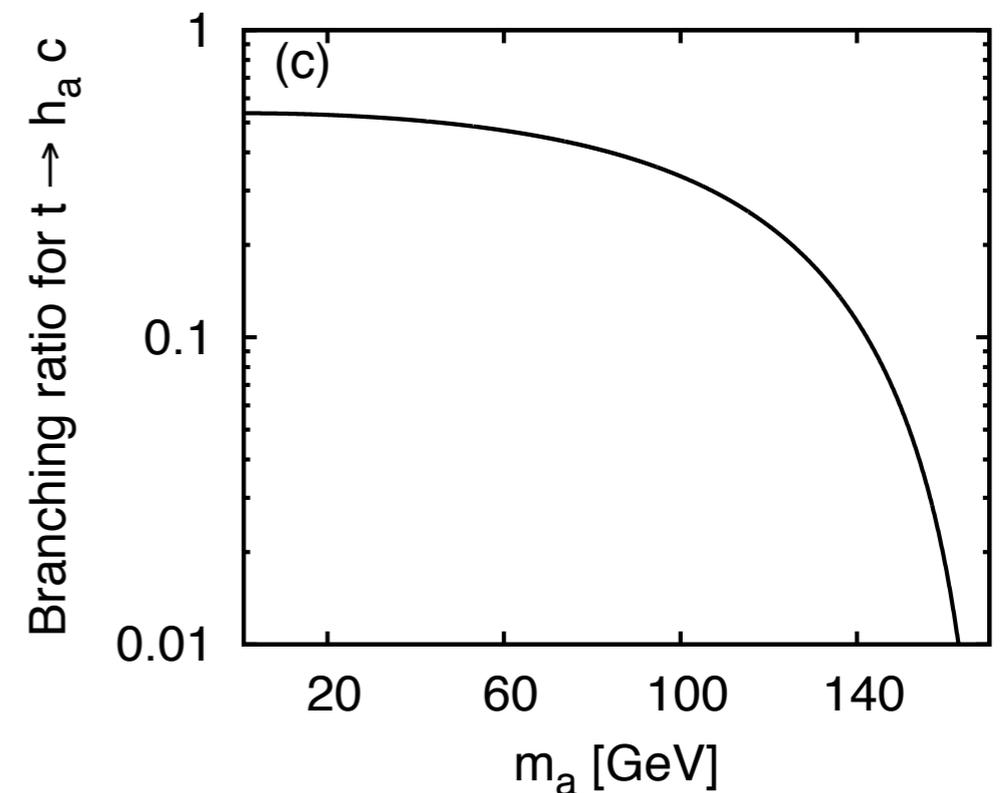
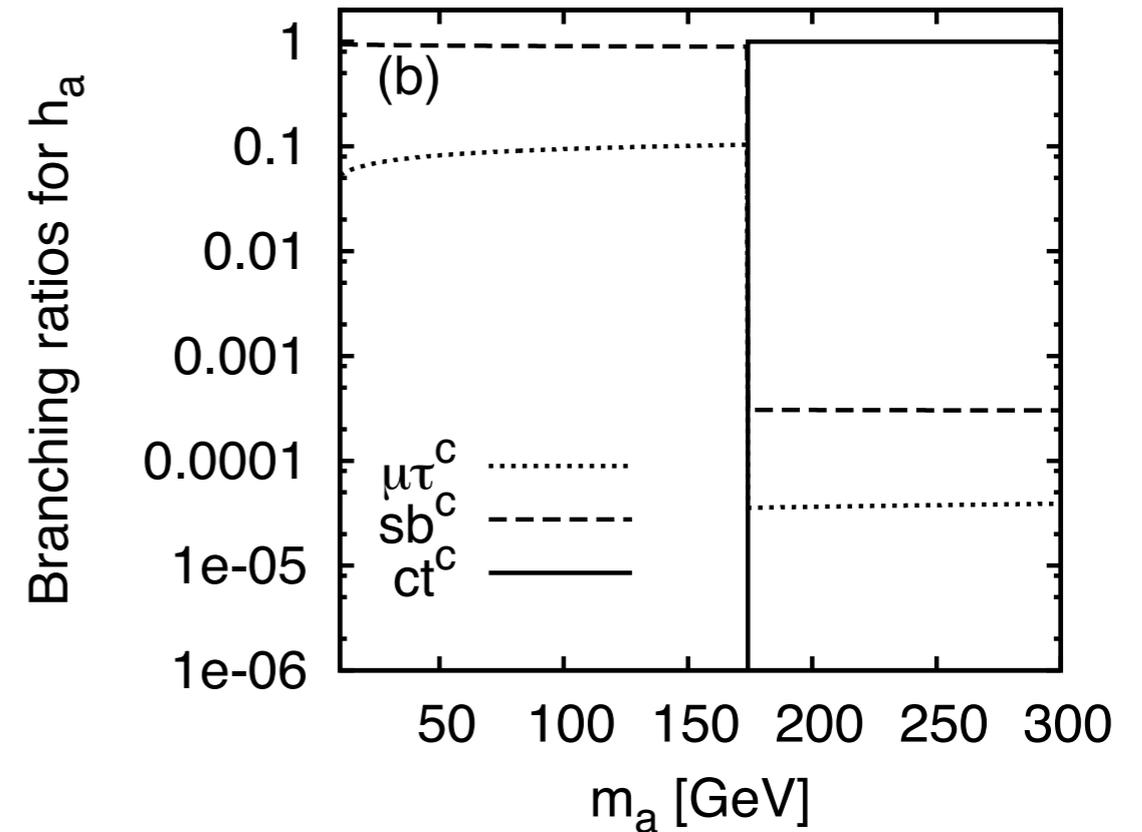
- ▶ Both can decay into usual Higgs decay modes ($ZZ, WW, b\bar{b}, \gamma\gamma, \dots$), but:
- ▶ **Dominant decay** for a light scalar h_a is three-scalar mode $h_{b/c} \rightarrow h_a h_a$
- ▶ Parameter k is the ratio between three-scalar coupling and $h_b WW$ coupling



- ▶ For $m_a = 50$ GeV, $k \approx 10$
- ▶ Compare to THDM, where it is typically $5 \lesssim k \lesssim 30$ for a 400 GeV scalar decaying into two 114 GeV scalars

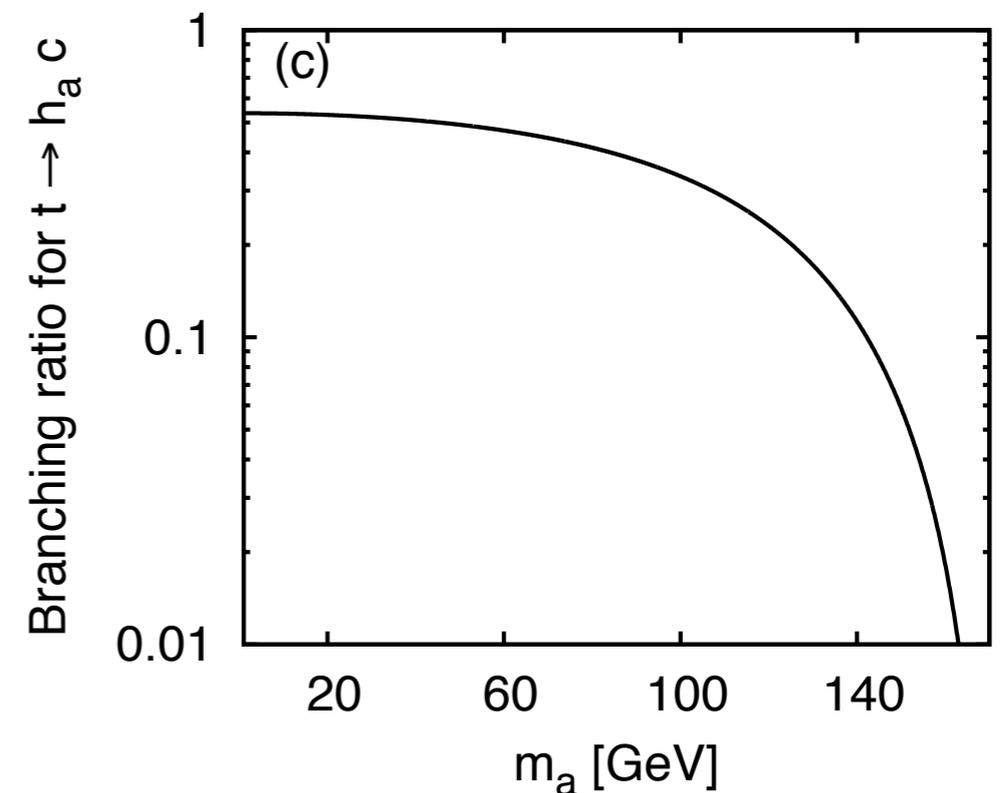
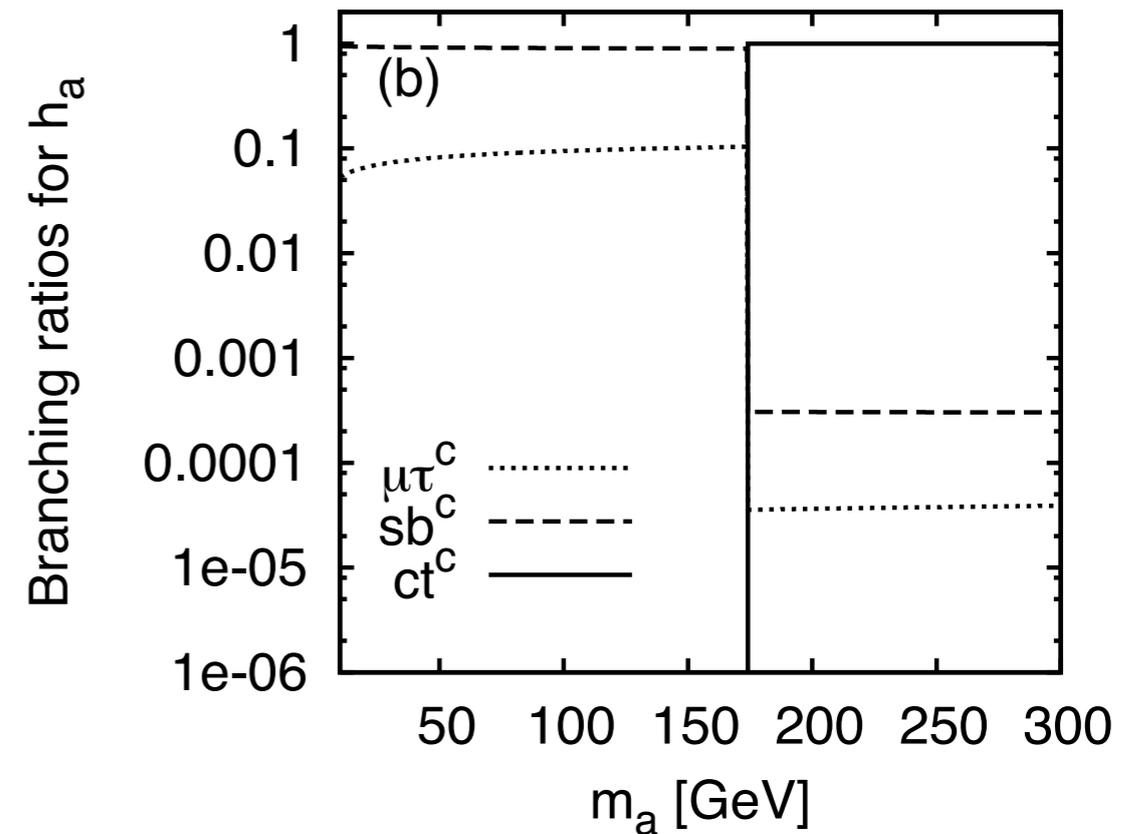
Signatures of h_a

- ▶ As long as $m_a < m_t$, the dominant decay mode is into jets
- ▶ Possibly significant decay mode into $\mu\tau$



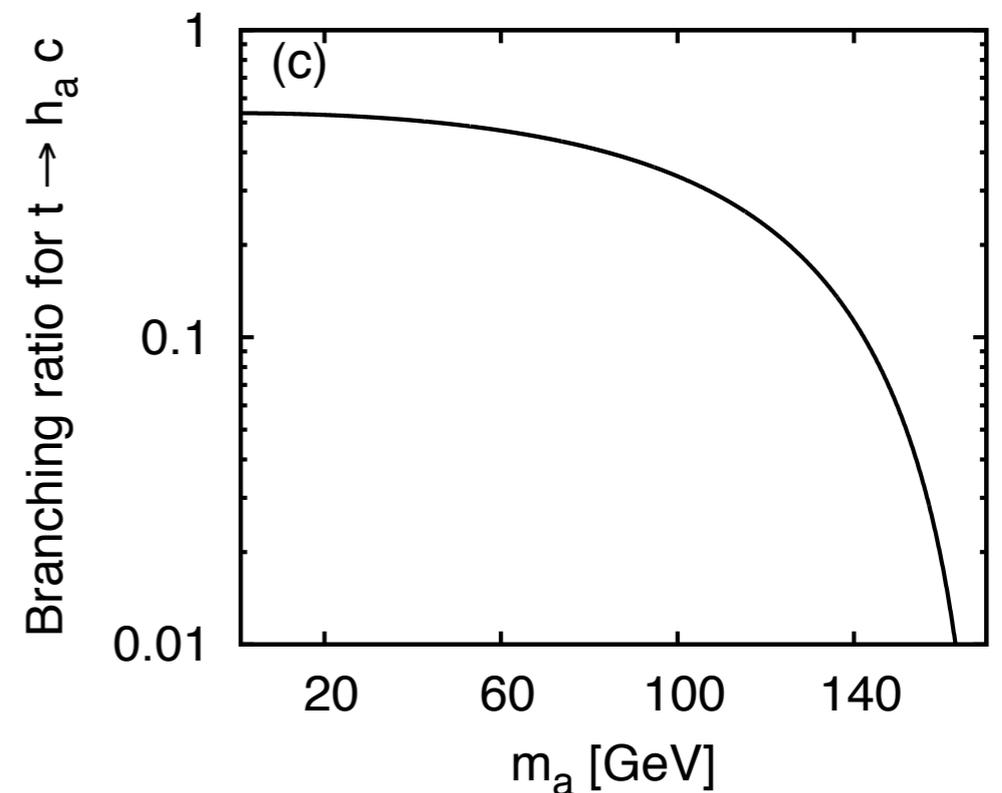
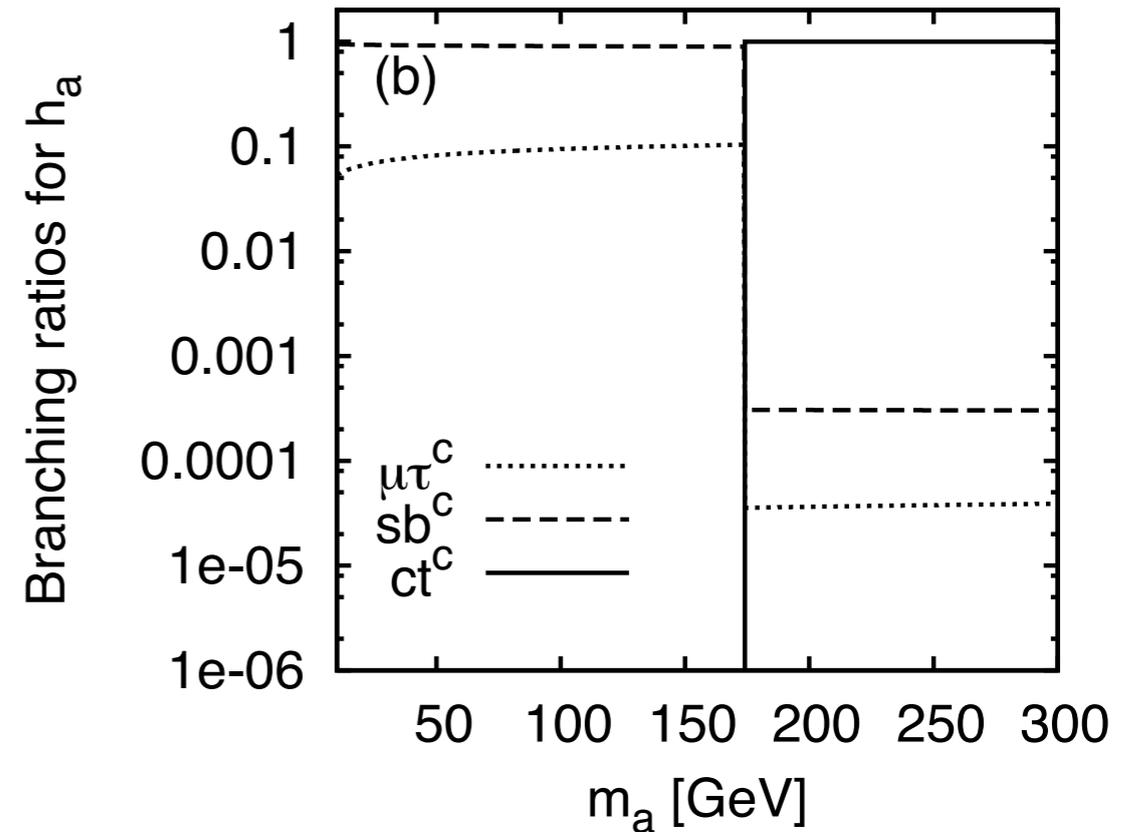
Production of h_a

- ▶ Light h_a is a decay product of $h_{b/c}$
- ▶ Production of h_a possible through **top decays** for light h_a , subsequent decay into $\mu\tau$ might be possible to detect
- ▶ For $m_a > m_t$, h_a dominantly decays off-diagonally into ct



h_a

- ▶ Dependency on vacuum alignment:
- ▶ Quark mixing requires small deviation from (1, 1, 0) vacuum alignment
- ▶ \Rightarrow some weakening of special properties of h_a , i.e. small three-vertex couplings to vector bosons



Summary

- ▶ Scalar sector is an interesting avenue to test flavor symmetries
- ▶ S_3 can **explain some mixing angles**, comes with an **enlarged scalar sector**.
- ▶ **Two SM-Higgs-like scalars** h_b and h_c . Decay dominantly into third scalar h_a
- ▶ Scalar h_a has **limited gauge interactions**
- ▶ h_a has only off-diagonal Yukawa couplings, involving a lepton or quark from the third generation
- ▶ Scalars might already be buried in existing LEP or Tevatron data
- ▶ **The enlarged Higgs sector can be a harbinger of flavor symmetries!**

Backup material

Minimization of the potential

- ▶ The conditions are met via the following parameter constraints:

$$-m^2 = (2\lambda_1 + \lambda_3)v^2 + (\lambda_5 + \lambda_6 + \lambda_7)v^2_3 + 3\lambda_8 v v_3,$$

$$-m^2_3 = \lambda_4 v^2_3 + 2(\lambda_5 + \lambda_6 + \lambda_7)v^2 + 2\lambda_8 v^3/v_3$$

$$\lambda_1 + \lambda_2 > 0, \quad \lambda_1 + \lambda_3 > \lambda_2, \quad \lambda_4 > 0,$$

$$\lambda_5 + \lambda_6 > 0, \quad \lambda_7 > 0, \quad \lambda_8 > 0$$

- ▶ The spectrum is then determined using a parameter scan in this space

Minimization of the potential

- ▶ Gives allowed vacuum alignments, masses and mixings of the scalars
- ▶ S3 invariant scalar potential (doublets, 8+2 params)

$$\begin{aligned}
 V = & m^2 (\phi_1^\dagger \phi_1 + \phi_2^\dagger \phi_2) + m_3^2 \phi_3^\dagger \phi_3 + \frac{\lambda_1}{2} (\phi_1^\dagger \phi_1 + \phi_2^\dagger \phi_2)^2 + \frac{\lambda_2}{2} (\phi_1^\dagger \phi_1 - \phi_2^\dagger \phi_2)^2 \\
 & + \lambda_3 \phi_1^\dagger \phi_2 \phi_2^\dagger \phi_1 + \frac{\lambda_4}{2} (\phi_3^\dagger \phi_3)^2 + \lambda_5 (\phi_3^\dagger \phi_3) (\phi_1^\dagger \phi_1 + \phi_2^\dagger \phi_2) + \lambda_6 \phi_3^\dagger (\phi_1 \phi_1^\dagger + \phi_2 \phi_2^\dagger) \phi_3 \\
 & + \left[\lambda_7 \phi_3^\dagger \phi_1 \phi_3^\dagger \phi_2 + \lambda_8 \phi_3^\dagger (\phi_1 \phi_2^\dagger \phi_1 + \phi_2 \phi_1^\dagger \phi_2) + \text{h. c.} \right]
 \end{aligned}$$

Scalar mixing

- ▶ One physical scalar is given by $h_a = (h_2 - h_1)/\sqrt{2}$, i.e. there is no dependence on the scalar parameters or on the VEVs.
- ▶ This happens because S_3 requires the scalar mass matrix to be of the form

$$\begin{pmatrix} a & b & c \\ b & a & c \\ c & c & d \end{pmatrix}$$

same mechanism is
responsible for maximal
mixing in lepton sector

which always yields $(-1, 1, 0)$ as one eigenvector.

Scalar masses

- The squared masses of the CP-even neutral scalars are given by

$$m_a^2 = 4\lambda_2 v^2 - 2\lambda_3 v^2 - v_3 (2\lambda_7 v_3 + 5\lambda_8 v) ,$$

$$m_b^2 = \frac{1}{2v_3} [4\lambda_1 v^2 v_3 + 2\lambda_3 v^2 v_3 + 2\lambda_4 v_3^3 - 2\lambda_8 v^3 + 3\lambda_8 v v_3^2 - \Delta m^3] ,$$

$$m_c^2 = \frac{1}{2v_3} [4\lambda_1 v^2 v_3 + 2\lambda_3 v^2 v_3 + 2\lambda_4 v_3^3 - 2\lambda_8 v^3 + 3\lambda_8 v v_3^2 + \Delta m^3] ;$$

where

$$\Delta m^3 = \left[8v v_3 \left\{ 2v v_3^3 \left(2(\lambda_5 + \lambda_6 + \lambda_7)^2 - \lambda_4(2\lambda_1 + \lambda_3) \right) + 2\lambda_8 v^4 (2\lambda_1 + \lambda_3) - 3\lambda_4 \lambda_8 v_3^4 \right. \right. \\ \left. \left. + 12\lambda_8 v^2 v_3^2 (\lambda_5 + \lambda_6 + \lambda_7) + 12\lambda_8^2 v^3 v_3 \right\} + \left\{ 2v^2 v_3 (2\lambda_1 + \lambda_3) + 2\lambda_4 v_3^3 - 2\lambda_8 v^3 + 3\lambda_8 v v_3^2 \right\}^2 \right]^{\frac{1}{2}}$$

Yukawas

Chen, Frigerio, Ma (2004)

- ▶ **Mass terms** for charged leptons (quarks are treated identically):

$$(\phi_1 L_2 + \phi_2 L_1) l_1^c \quad (\phi_1 L_2 - \phi_2 L_1) l_2^c \quad L_3 l_3^c \phi_3 \quad L_3 l_1^c \phi_3$$

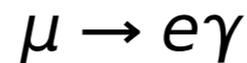
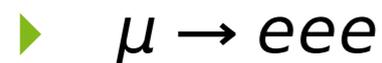
- ▶ After SSB, this leads to the **mass matrix**:

$$\mathcal{M}_\ell = \begin{pmatrix} f_4 v_3 & f_5 v_3 & 0 \\ 0 & f_1 v & -f_2 v \\ 0 & f_1 v & f_2 v \end{pmatrix}$$

- ▶ The specific alignment $\langle \phi_1 \rangle = \langle \phi_2 \rangle = v$ leads to maximal atm. mixing
- ▶ **Special vacuum alignments** like this are needed in most models based on discrete symmetries

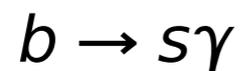
Other decays

- ▶ Other typical processes are



- ▶ All many orders of magnitude **below current bounds**
 (10^{-12} for eee , 10^{-11} for $e\gamma$)

- ▶ Due to the coupling structure, some interesting benchmark decays are **not possible** via these scalars:



- ▶ etc.

