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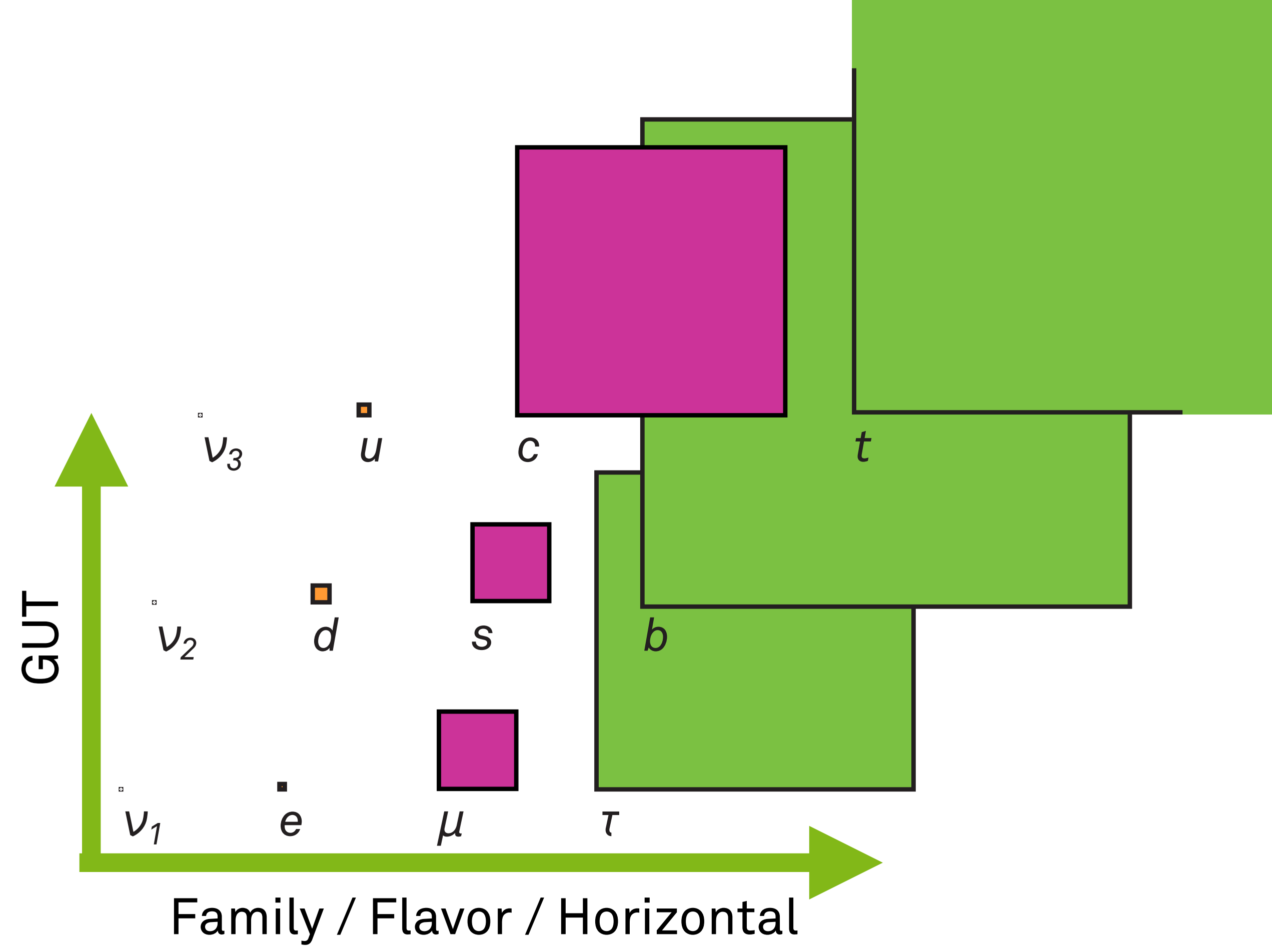
S_3 flavor symmetry at the LHC

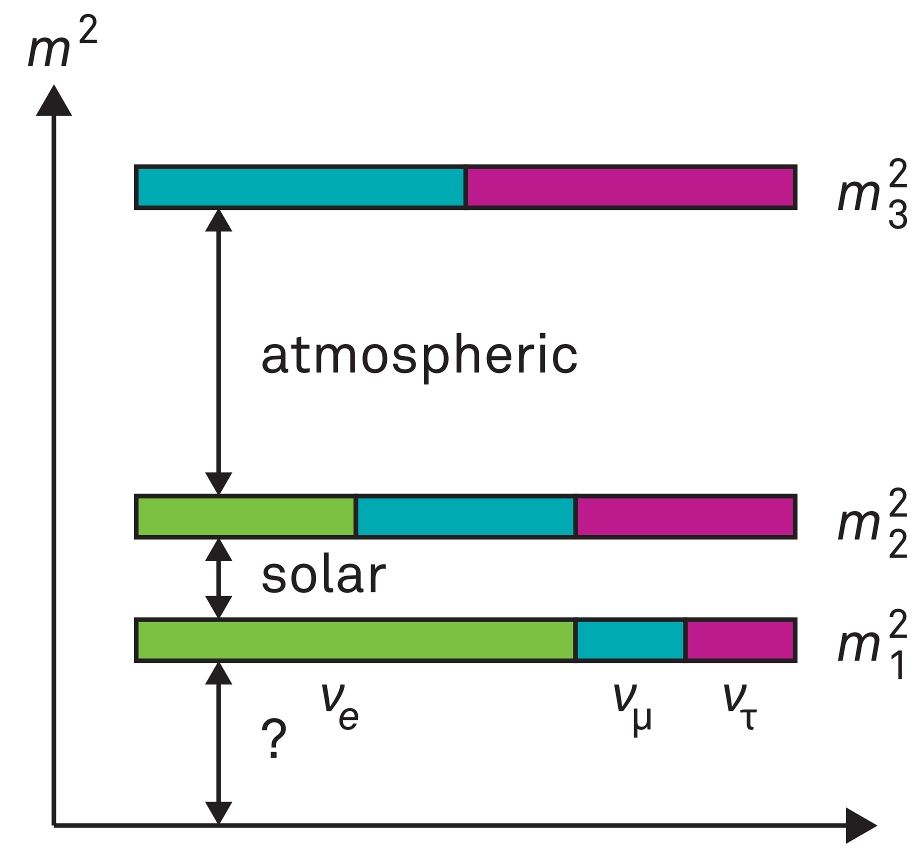
G. Bhattacharyya, P. Leser, H. Päs, Phys. Rev. **D83**, 011701 (2011)
+ work in progress

Why flavor symmetries?

- Flavor symmetries have the potential to explain:
- Masses, mass relations, hierarchies
- Patterns in the mixing matrices (CKM vs. PMNS)

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





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, ... can be used to deduce some of these relations
  - through **specific choice of representations** for particle content
  - through **vacuum alignment** of extra scalars

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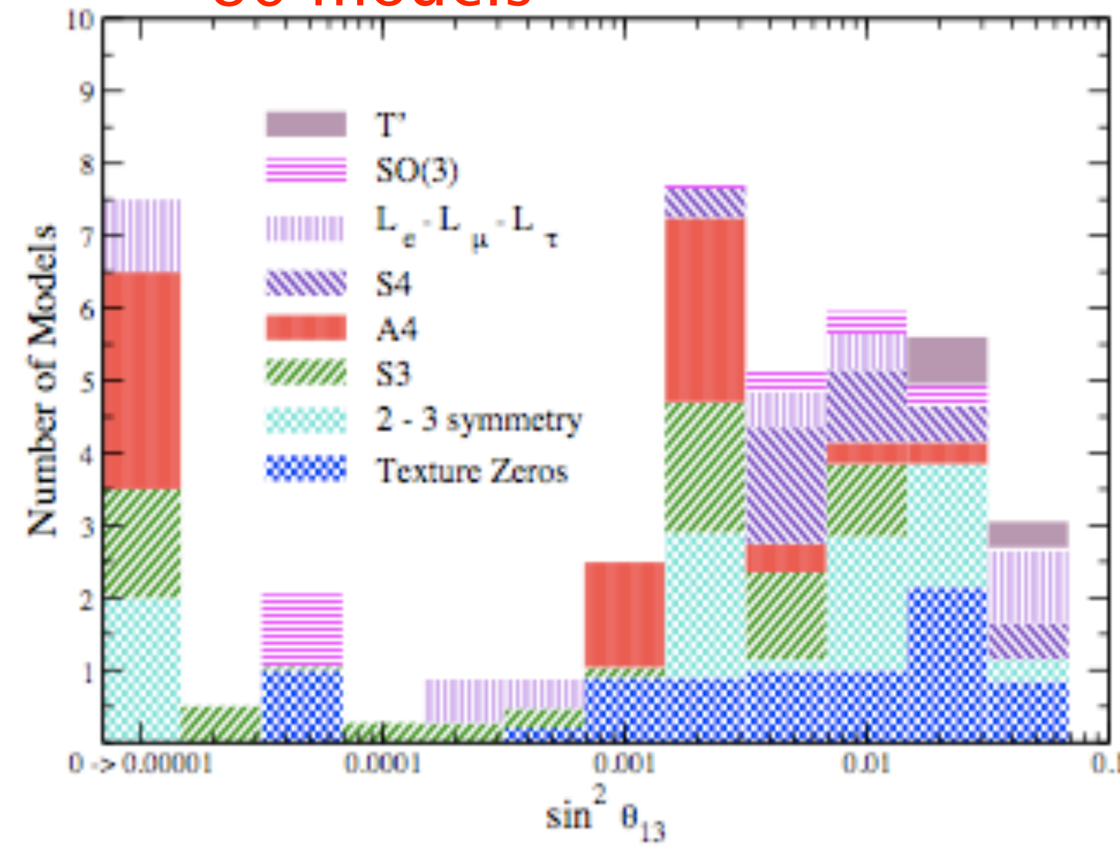
How to discriminate?

- 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

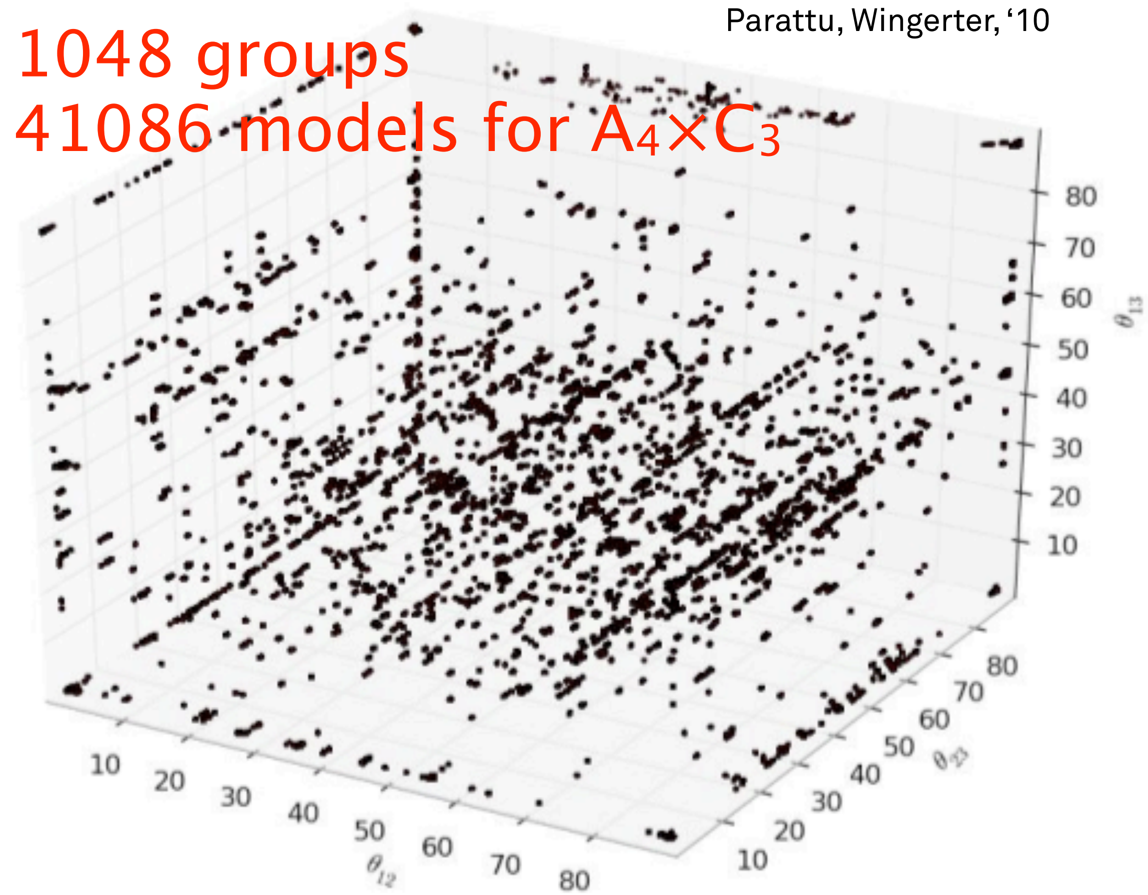
86 models

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 exemplary S_3 model

Chen, Frigerio, Ma, *Phys. Rev.* **D70**, 073008 (2004)

Lepton doublets

RH singlets

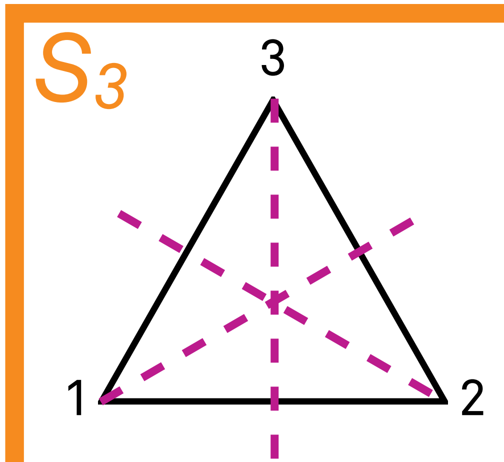
$$(L_1, L_2) \propto \mathbf{2} \qquad L_3, \ell^c_3, \ell^c_1 \propto \mathbf{1} \qquad \ell^c_2 \propto \mathbf{1'}$$

$$(Q_1, Q_2) \propto \mathbf{2} \qquad Q_3, u^c_3, u^c_1, d^c_3, d^c_1 \propto \mathbf{1} \qquad u^c_2, d^c_2 \propto \mathbf{1'}$$

$$(\phi_1, \phi_2) \propto \mathbf{2} \qquad \phi_3 \propto \mathbf{1}$$

Quark doublets

- Two generations → S_3 doublet; the other → S_3 singlet



6 elements
irreps: **1**,**1′**,**2**

A specific S_3 model

Chen, Frigerio, Ma, *Phys. Rev.* **D70**, 073008 (2004)

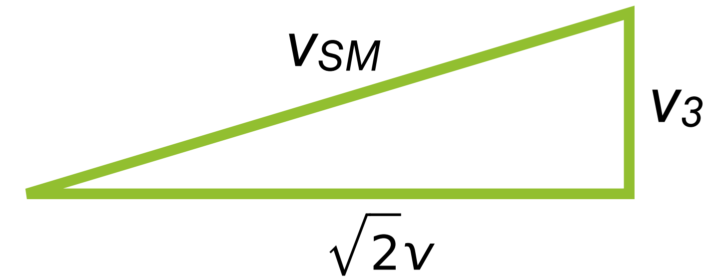
- One **scalar for each** generation
- Neutrino sector separate, diagonal
  (See-Saw II, 2 heavy EW triplet scalars)
- Simple vacuum alignment:
  $\langle\phi_1\rangle = \langle\phi_2\rangle = v \qquad \langle\phi_3\rangle = v_3$

$2v^2 + v3^2 = v_{\mathrm{SM}}^2$

translates directly into PMNS matrix

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

Minimization of the potential

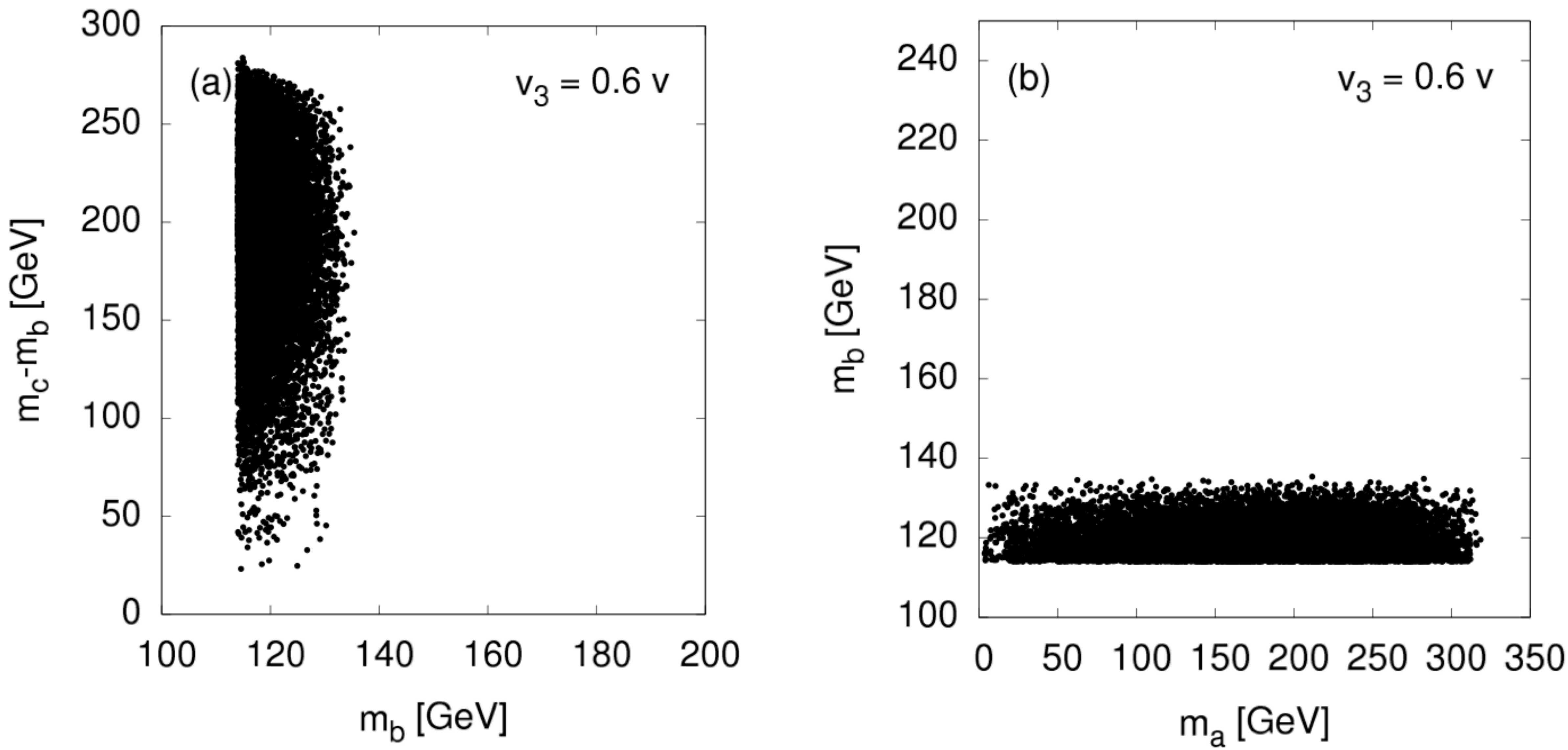


- Conditions applied for minimization
  - Wanted **vacuum alignment** $\langle\phi_1\rangle = \langle\phi_2\rangle = v$ must be a solution
  - It must actually be a minimum
  - Global **stability** of the solution
  - Allow fixed ratio of v_3 and v
  - We only consider real parameters

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

Results of parameter scan for scalars

- 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 $v_i/v_{\mathrm{SM}} < 1$ 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: $h_{b,c} \rightarrow e\mu$

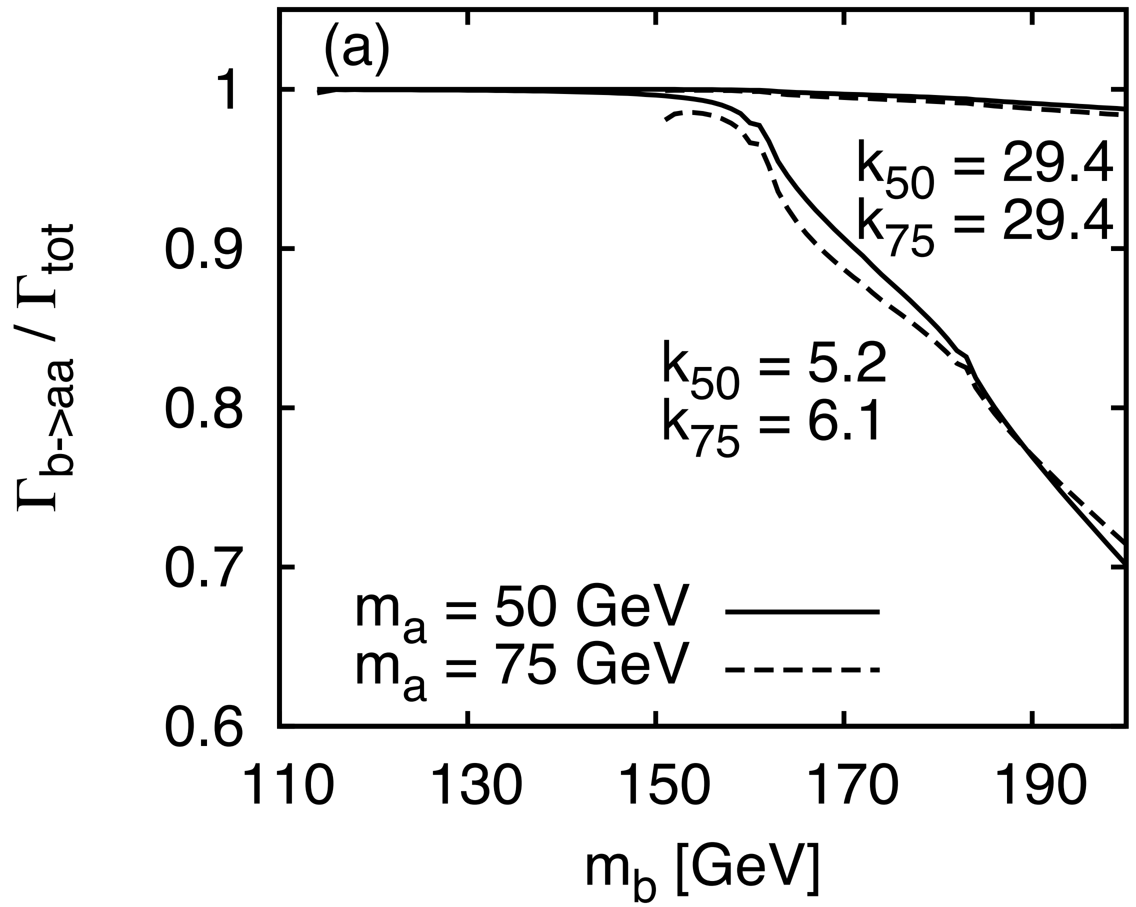
h_a is special, again

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

$$Y_{h_a} = \begin{pmatrix} 0 & 0 & Y^a_{e_L\tau_R} \\ 0 & 0 & Y^a_{\mu_L\tau_R} \\ Y^a_{\tau_L e_R} & Y^a_{\tau_L\mu_R} & 0 \end{pmatrix}, \quad Y_{h_b} = \begin{pmatrix} Y^b_{e_L e_R} & Y^b_{e_L\mu_R} & 0 \\ Y^b_{\mu_L e_R} & Y^b_{\mu_L\mu_R} & 0 \\ 0 & 0 & Y^b_{\tau_L\tau_R} \end{pmatrix}, \quad Y_{h_c} = \begin{pmatrix} Y^c_{e_L e_R} & Y^c_{e_L\mu_R} & 0 \\ Y^c_{\mu_L e_R} & Y^c_{\mu_L\mu_R} & 0 \\ 0 & 0 & Y^c_{\tau_L\tau_R} \end{pmatrix}$$

Signatures of h_b and h_c

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

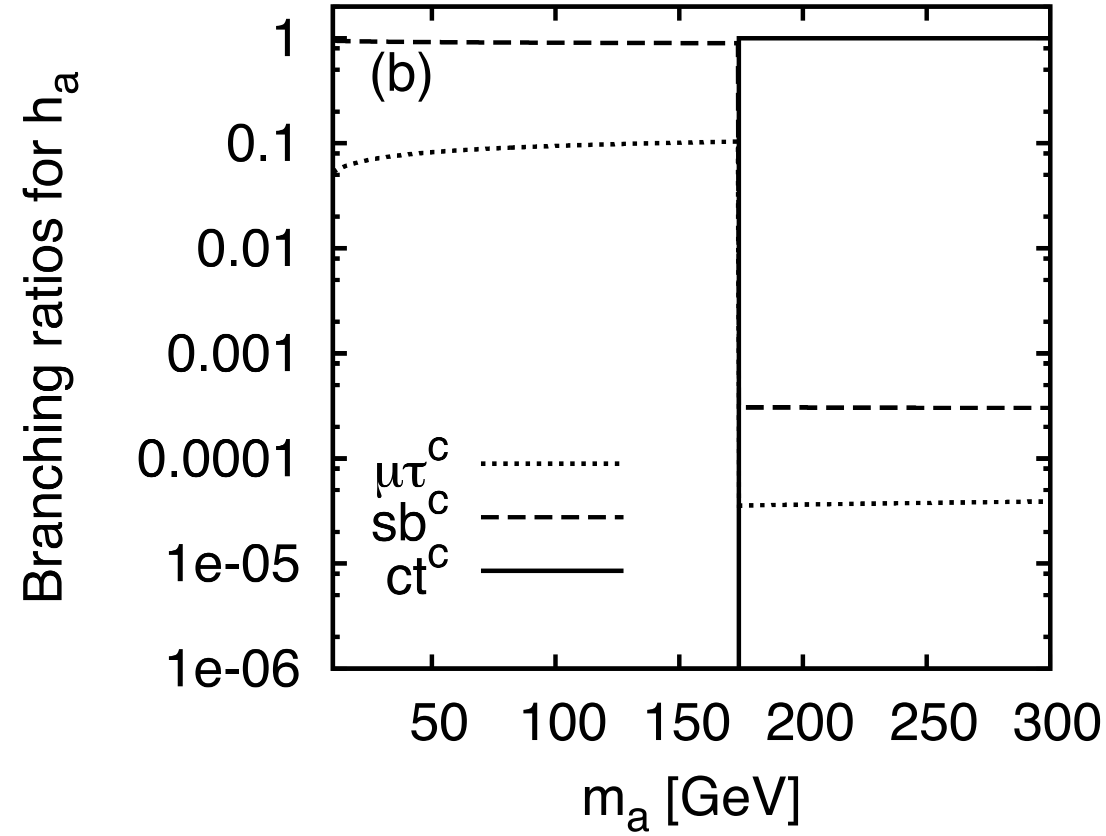


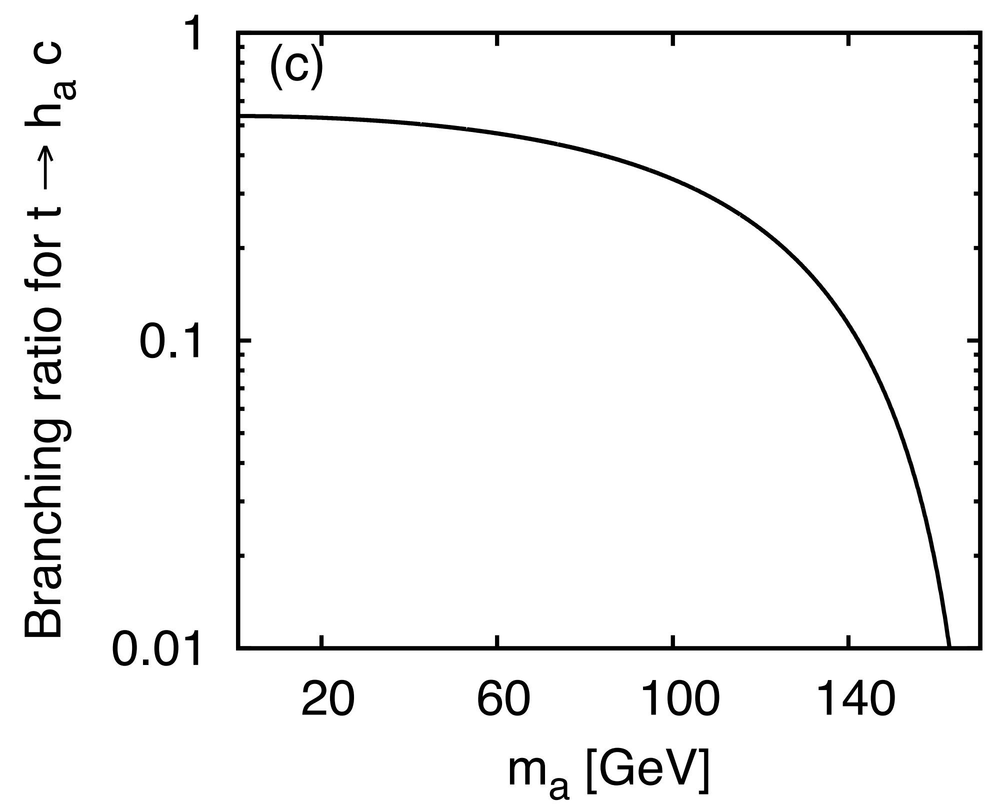
- For m_a = 50 GeV, $k \approx 10$
- Compare to THDM, where it is typically $5 \lesssim k \lesssim 30$ for a 400 GeV scalar decaying into two 114 GeV scalars

HDECAY: Djouadi, A., Kalinowski, J. and Spira, M., *Comput. Phys. Commun.* **108** 56-74 (1998)

Signatures of h_a

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





HDECAY: Djouadi, A., Kalinowski, J. and Spira, M., *Comput. Phys. Commun.* **108** 56-74 (1998)

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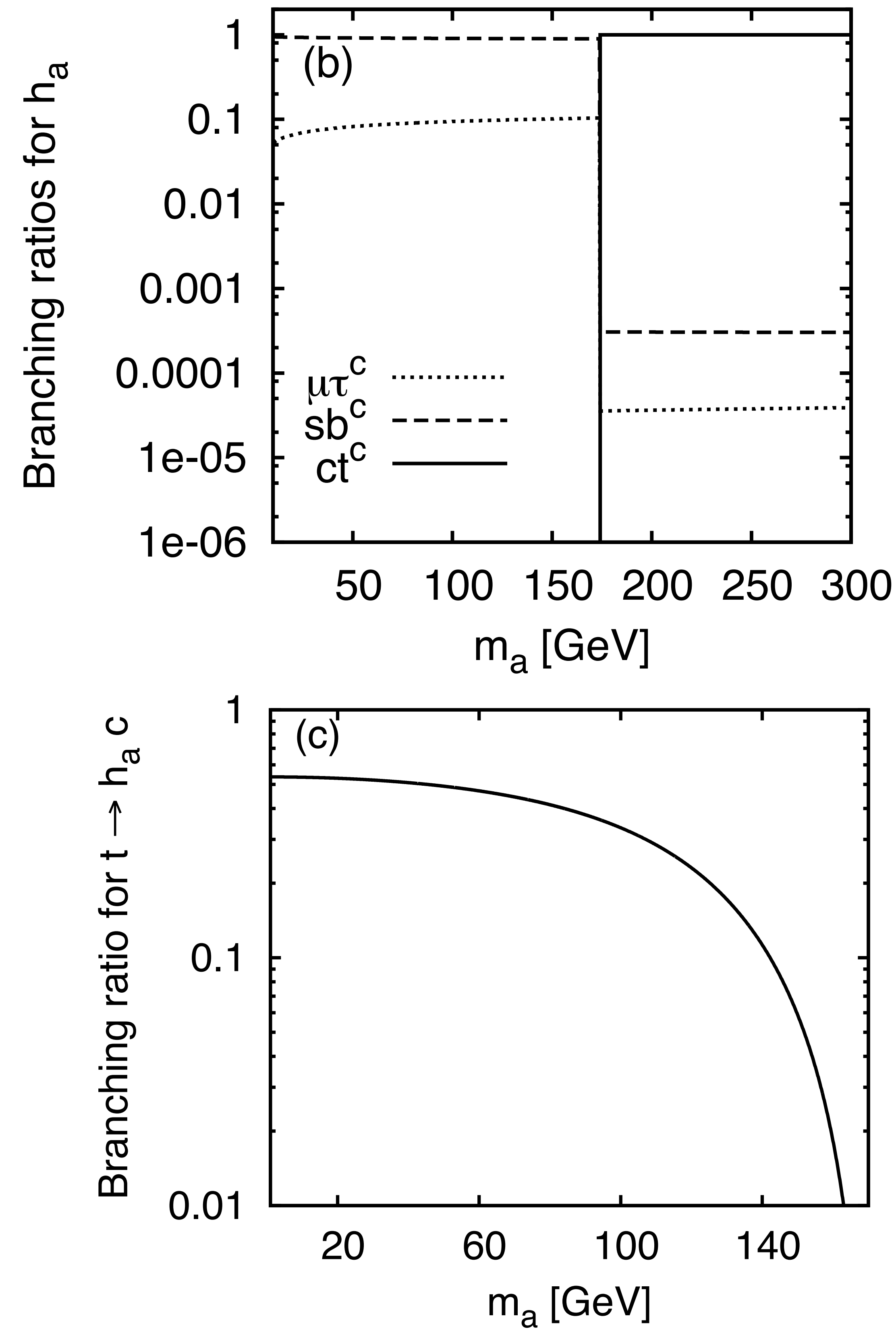
Production of h_a

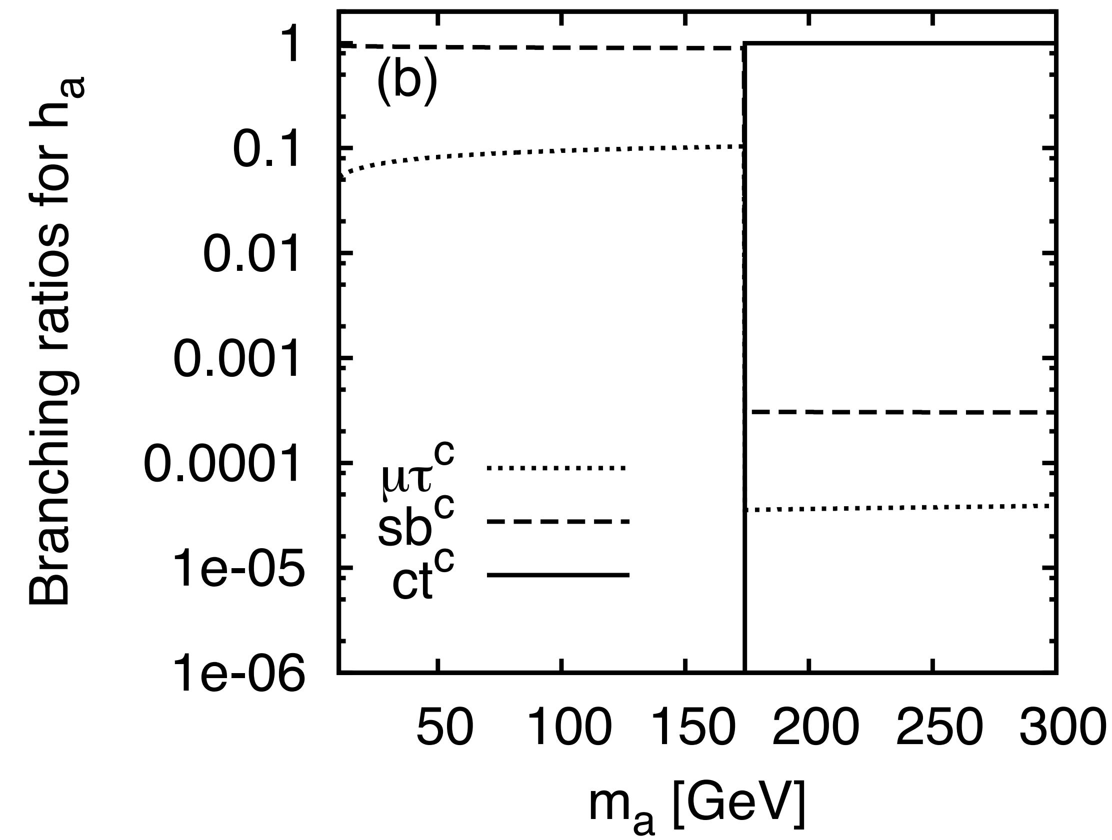
- Light h_a is a decay product of $h_{b/c}$
- Production of h_a possible through **top decays** for light h_a, subsequent decay into $\mu\tau$ might be possible to detect
- For $m_a > m_t$, h_a dominantly decays off-diagonally into ct

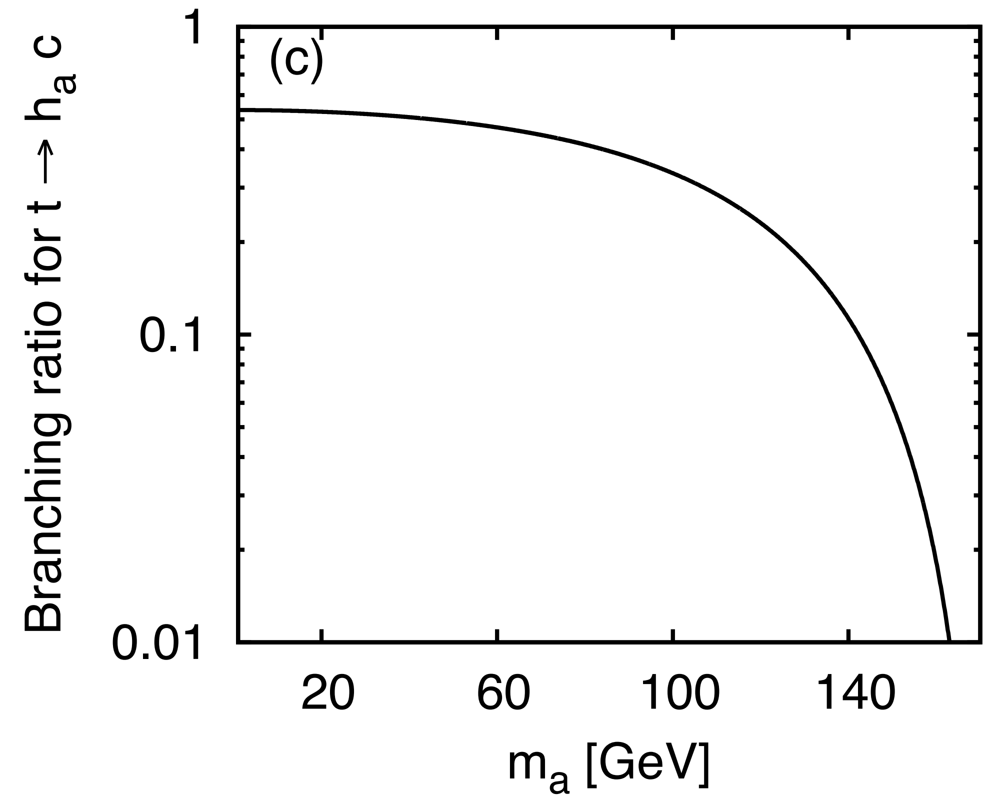


HDECAY: Djouadi, A., Kalinowski, J. and Spira, M., *Comput. Phys. Commun.* **108** 56-74 (1998)

h_a

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





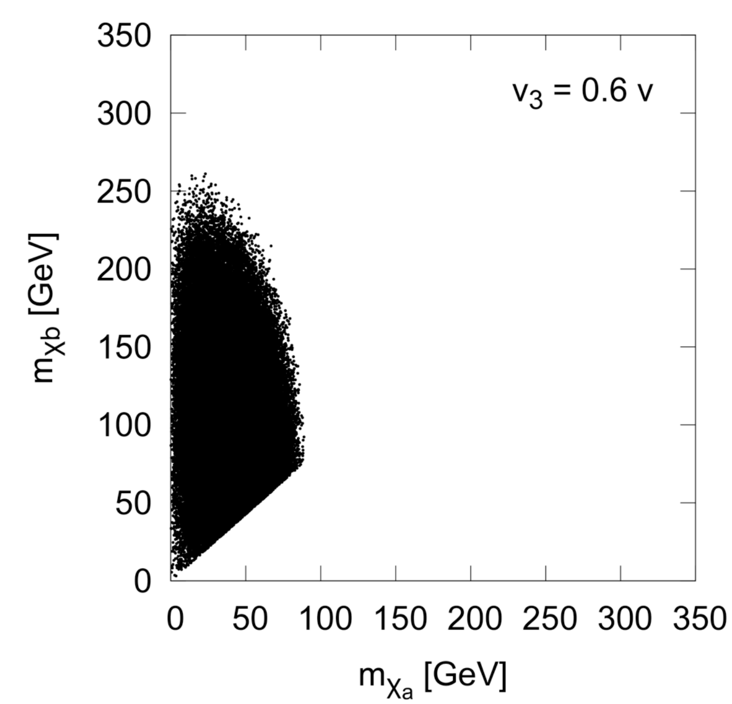
HDECAY: Djouadi, A., Kalinowski, J. and Spira, M., *Comput. Phys. Commun.* **108** 56-74 (1998)

Pseudo-scalars

- Physical pseudo-scalars χ_a and χ_b have patterns of couplings to quarks / leptons identical to h_a and h_b/h_c:

$$Y_{\chi_a} = \begin{pmatrix} 0 & 0 & Y^a_{e_L\tau_R} \\ 0 & 0 & Y^a_{\mu_L\tau_R} \\ Y^a_{\tau_L e_R} & Y^a_{\tau_L\mu_R} & 0 \end{pmatrix}, \quad Y_{\chi_b} = \begin{pmatrix} Y^b_{e_L e_R} & Y^b_{e_L\mu_R} & 0 \\ Y^b_{\mu_L e_R} & Y^b_{\mu_L\mu_R} & 0 \\ 0 & 0 & Y^b_{\tau_L\tau_R} \end{pmatrix}$$

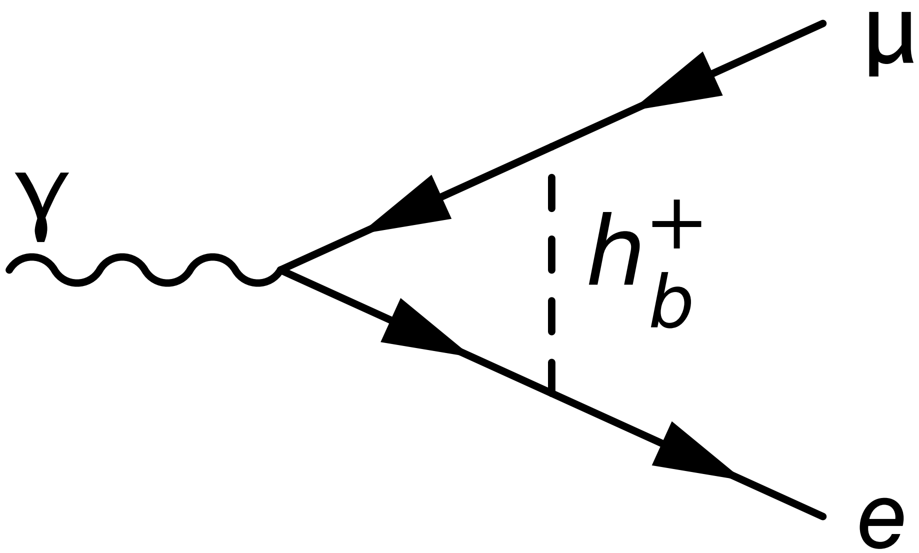
- $h_a \to \chi_a\chi_b$ is allowed for certain mass hierarchies; would change special h_a decay properties

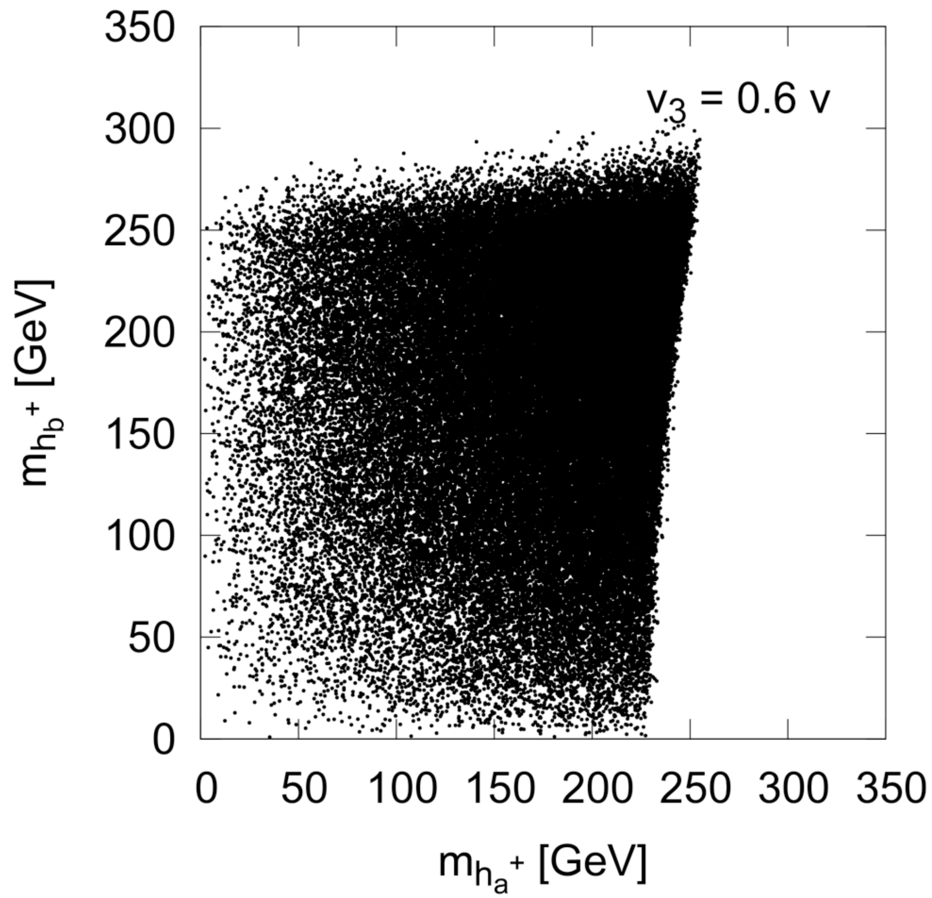


Charged scalars

$$Y_{h_a^+} = \begin{pmatrix} 0 & 0 & Y^a_{13} \\ 0 & 0 & Y^a_{23} \\ Y^a_{31} & Y^a_{32} & 0 \end{pmatrix}, \qquad Y_{h_b^+} = \begin{pmatrix} Y^b_{11} & Y^b_{12} & 0 \\ Y^b_{21} & Y^b_{22} & 0 \\ 0 & 0 & Y^b_{33} \end{pmatrix}$$

- The couplings of h_a^+ and h_b^+ to quarks and leptons follow the same pattern as pseudo-scalars.
- There is no $b \to s\gamma$.
- The off-diagonal (12) coupling of h_b^+ allows for $\mu \to e\gamma$





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 $h_a\, h_a$
- 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
- Currently expanding the analysis to include all scalar degrees of freedoms

Backup material

Minimization of the potential

- The conditions are met via the following parameter constraints:

$$-m^2 = (2\lambda_1 + \lambda_3)v^2 + (\lambda_5 + \lambda_6 + \lambda_7)v_3^2 + 3\lambda_8 v v_3\,,$$
$$-m_3^2 = \lambda_4 v_3^2 + 2(\lambda_5 + \lambda_6 + \lambda_7)v^2 + 2\lambda_8 v^3/v_3$$

$$\lambda_1 + \lambda_2 > 0, \qquad \lambda_1 + \lambda_3 > \lambda_2, \qquad \lambda_4 > 0,$$
$$\lambda_5 + \lambda_6 > 0, \qquad \lambda_7 > 0, \qquad \lambda_8 > 0$$

- 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)

$$V = m^2\left(\phi_1^\dagger\phi_1 + \phi_2^\dagger\phi_2\right) + m_3^2\phi_3^\dagger\phi_3 + \frac{\lambda_1}{2}\left(\phi_1^\dagger\phi_1 + \phi_2^\dagger\phi_2\right)^2 + \frac{\lambda_2}{2}\left(\phi_1^\dagger\phi_1 - \phi_2^\dagger\phi_2\right)^2$$

$$+\lambda_3\phi_1^\dagger\phi_2\phi_2^\dagger\phi_1 + \frac{\lambda_4}{2}(\phi_3^\dagger\phi_3)^2 + \lambda_5\left(\phi_3^\dagger\phi_3\right)\left(\phi_1^\dagger\phi_1 + \phi_2^\dagger\phi_2\right) + \lambda_6\phi_3^\dagger\left(\phi_1\phi_1^\dagger + \phi_2\phi_2^\dagger\right)\phi_3$$

$$+\left[\lambda_7\phi_3^\dagger\phi_1\phi_3^\dagger\phi_2 + \lambda_8\phi_3^\dagger\left(\phi_1\phi_2^\dagger\phi_1 + \phi_2\phi_1^\dagger\phi_2\right) + \text{h. c.}\right]$$

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

$$\begin{aligned} m_a^2 &= 4\lambda_2 v^2 - 2\lambda_3 v^2 - v_3\left(2\lambda_7 v_3 + 5\lambda_8 v\right) \,, \\ m_b^2 &= \frac{1}{2v_3}\left[4\lambda_1 v^2 v_3 + 2\lambda_3 v^2 v_3 + 2\lambda_4 v_3^3 - 2\lambda_8 v^3 + 3\lambda_8 v v_3^2 - \Delta m^3\right] \,, \\ m_c^2 &= \frac{1}{2v_3}\left[4\lambda_1 v^2 v_3 + 2\lambda_3 v^2 v_3 + 2\lambda_4 v_3^3 - 2\lambda_8 v^3 + 3\lambda_8 v v_3^2 + \Delta m^3\right] \,; \end{aligned}$$

where

$$\begin{aligned} \Delta m^3 = \Bigg[& 8 v v_3 \Bigg\{ 2 v v_3^3 \Bigg(2(\lambda_5 + \lambda_6 + \lambda_7)^2 - \lambda_4(2\lambda_1 + \lambda_3) \Bigg) + 2\lambda_8 v^4 (2\lambda_1 + \lambda_3) - 3\lambda_4\lambda_8 v_3^4 \\ & + 12\lambda_8 v^2 v_3^2 (\lambda_5 + \lambda_6 + \lambda_7) + 12\lambda_8^2 v^3 v_3 \Bigg\} + \Bigg\{ 2v^2 v_3 (2\lambda_1 + \lambda_3) + 2\lambda_4 v_3^3 - 2\lambda_8 v^3 + 3\lambda_8 v v_3^2 \Bigg\}^2 \Bigg]^{\frac{1}{2}} \end{aligned}$$

Yukawas

Chen, Frigerio, Ma (2004)

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

$$(\phi_1 L_2 + \phi_2 L_1)\ell_1^c \qquad (\phi_1 L_2 - \phi_2 L_1)\ell_2^c \qquad L_3 \ell_3^c \phi_3 \qquad L_3 \ell_1^c \phi_3$$

- 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
  - $\mu \to eee$ $\mu \to e\gamma$
- All many orders of magnitude **below current bounds** (10^{-12} for *eee*, 10^{-11} for *eγ*)
- Due to the coupling structure, some interesting benchmark decays are **not possible** via these scalars:
  - $\tau \to e\gamma$ $\tau \to \mu\gamma$ $\tau \to \mu\mu\mu$ $b \to s\gamma$
  - etc.