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Fakultät Physik
Theoretische Physik III

Philipp Leser (TU Dortmund)

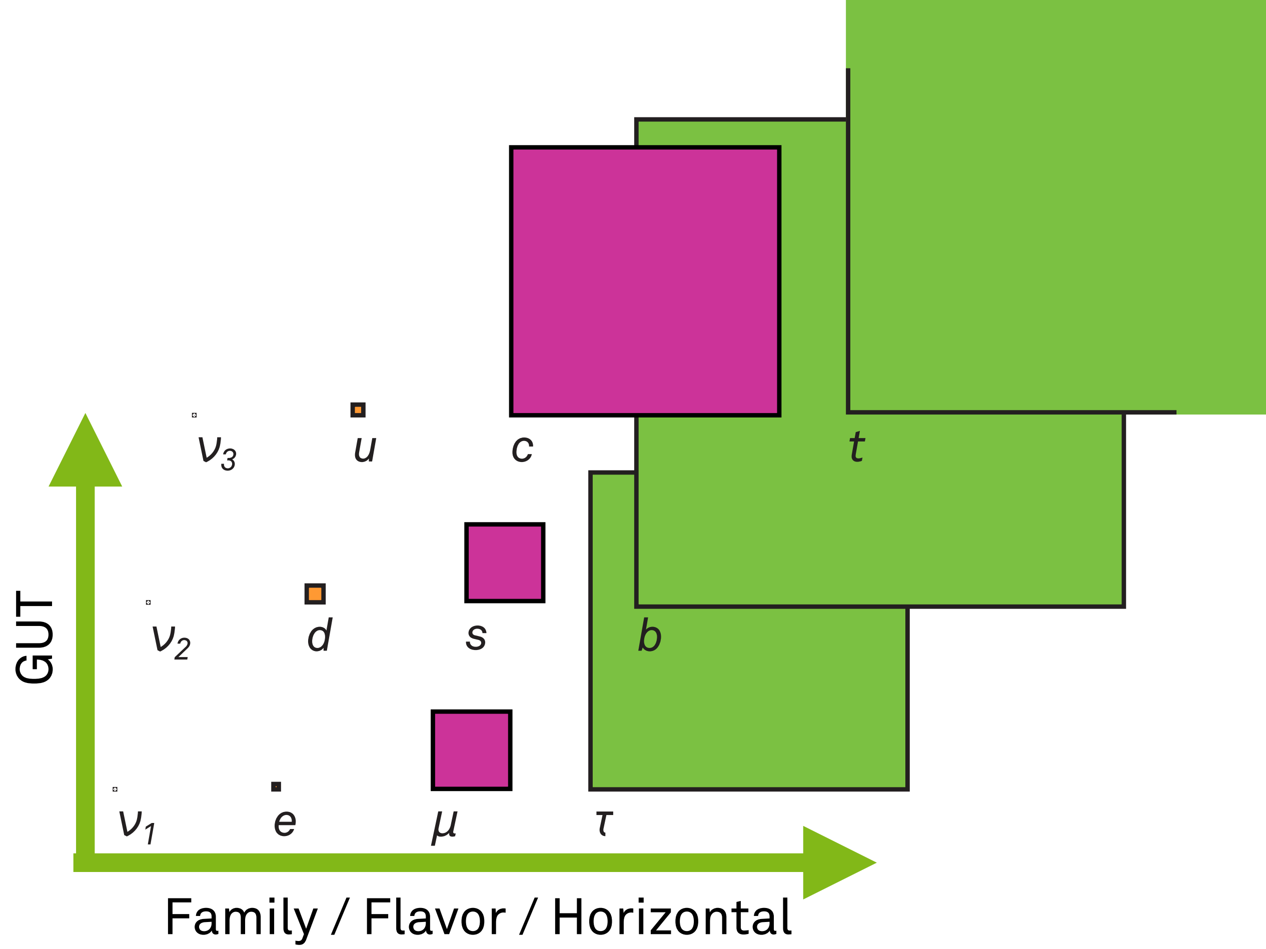
S_3 flavor symmetry at the LHC

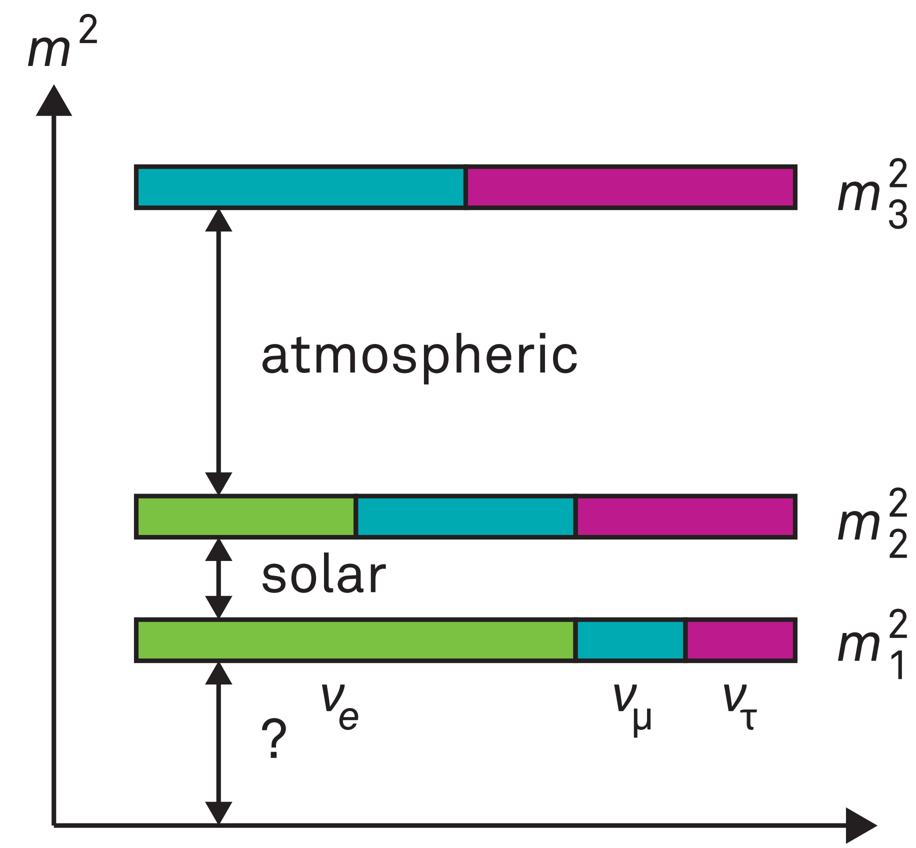
G. Bhattacharyya, P. Leser, H. Päs, Phys. Rev. **D83**, 011701 (2011)
+ work in progress

Why flavor symmetries?

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

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





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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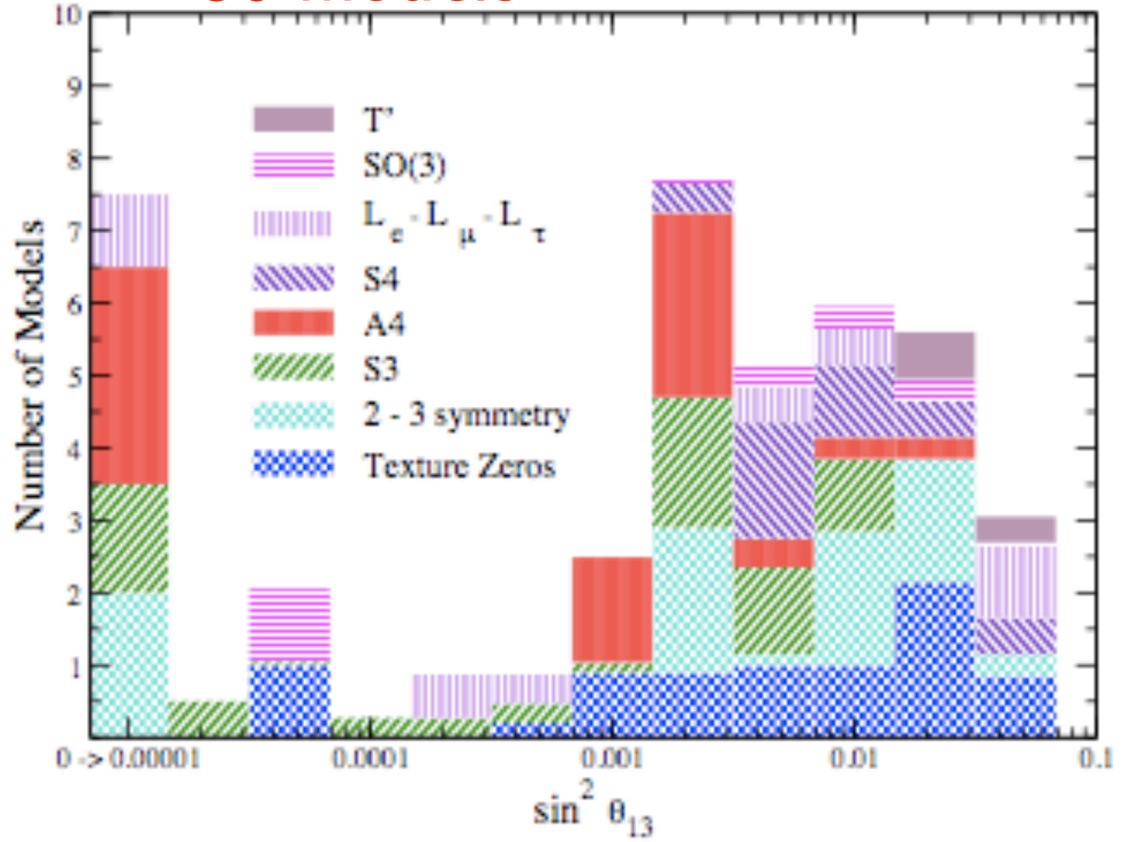
How to discriminate?

- 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

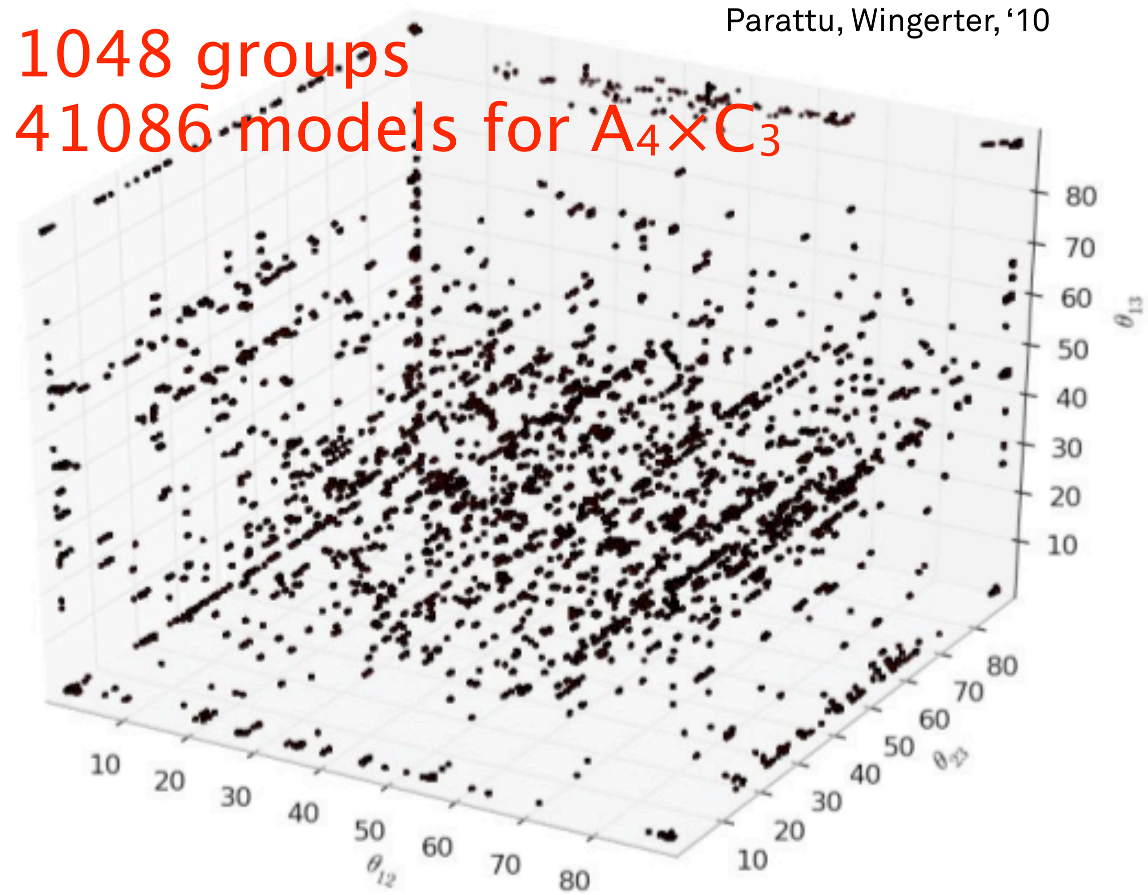
86 models

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

$(L_1, L_2) \propto \mathbf{2}$ $\quad L_3, \ell_3^c, \ell_1^c \propto \mathbf{1}$ $\quad \ell_2^c \propto \mathbf{1'}$

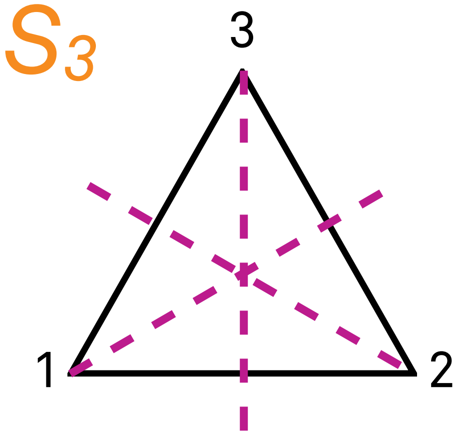
$(Q_1, Q_2) \propto \mathbf{2}$ $\quad Q_3, u_3^c, u_1^c, d_3^c, d_1^c \propto \mathbf{1}$ $\quad u_2^c, d_2^c \propto \mathbf{1'}$

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

Quark doublets

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

S_3



6 elements

irreps: $\mathbf{1}, \mathbf{1'}, \mathbf{2}$

A specific S_3 model

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

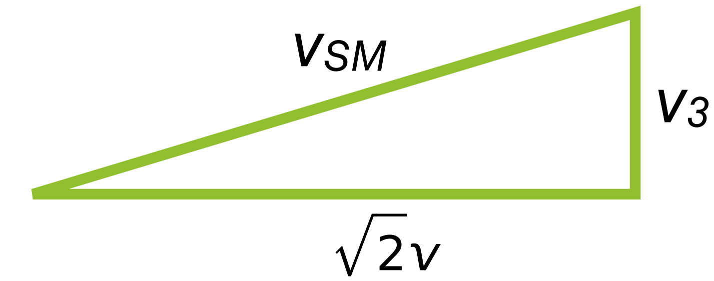
- One **scalar for each** generation
- Neutrino sector separate, diagonal
  (See-Saw II, 2 heavy EW triplet scalars)
- Simple vacuum alignment:
  $\langle \phi_1 \rangle = \langle \phi_2 \rangle = v \qquad \langle \phi_3 \rangle = v_3$

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

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

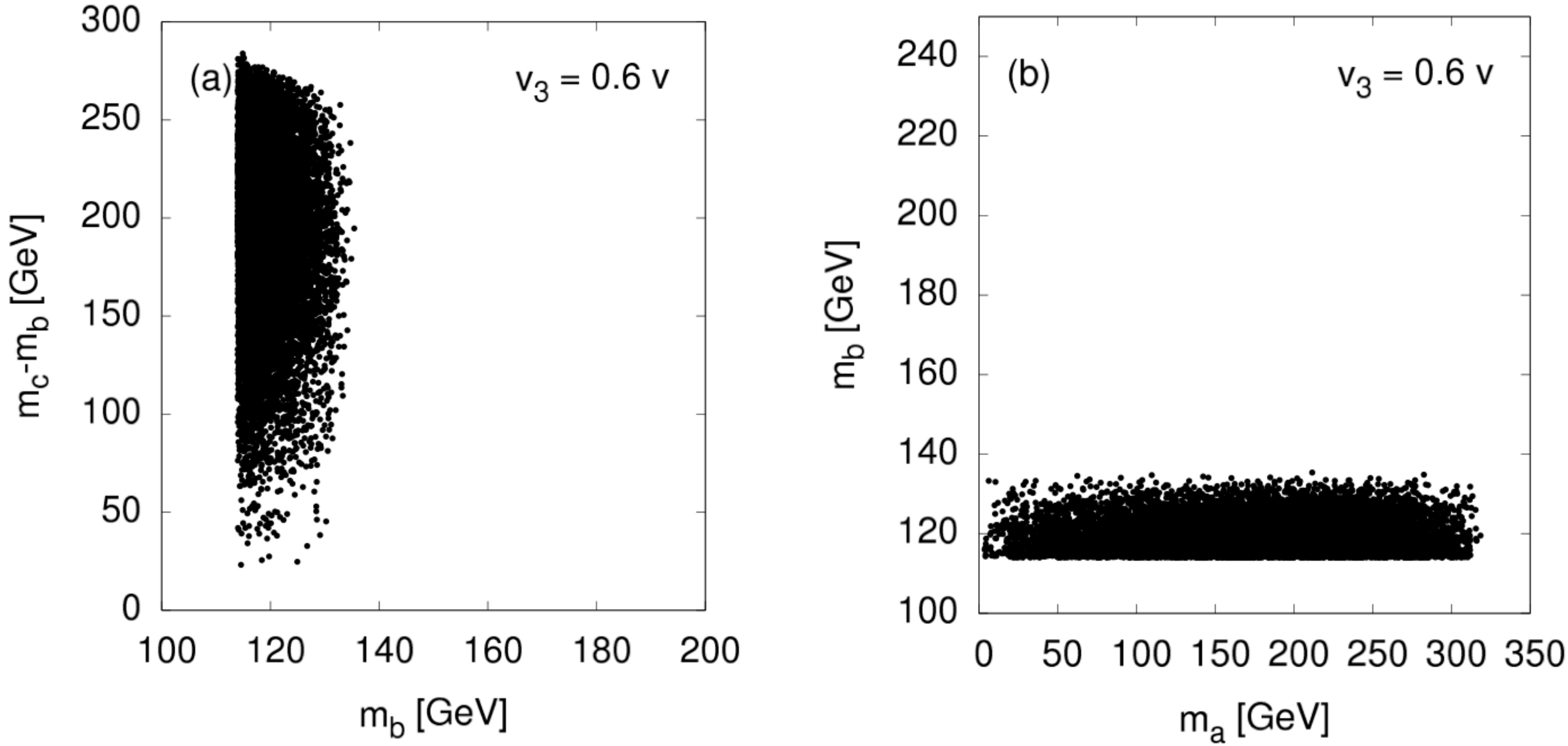


- Conditions applied for minimization
  - Wanted **vacuum alignment** $\langle\phi_1\rangle = \langle\phi_2\rangle = v$ must be a solution
  - It must actually be a minimum
  - Global **stability** of the solution
  - Allow fixed ratio of v_3 and v
  - We only consider real parameters

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 $v_i/v_{\text{SM}} < 1$ 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:
  - $h_{b,c} \to ee(uu, dd)$
    $h_{b,c} \to \mu\mu(ss, cc)$
    $h_{b,c} \to \tau\tau(bb, tt)$
  - Additional FCNC coupling: $h_{b,c} \to e\mu$

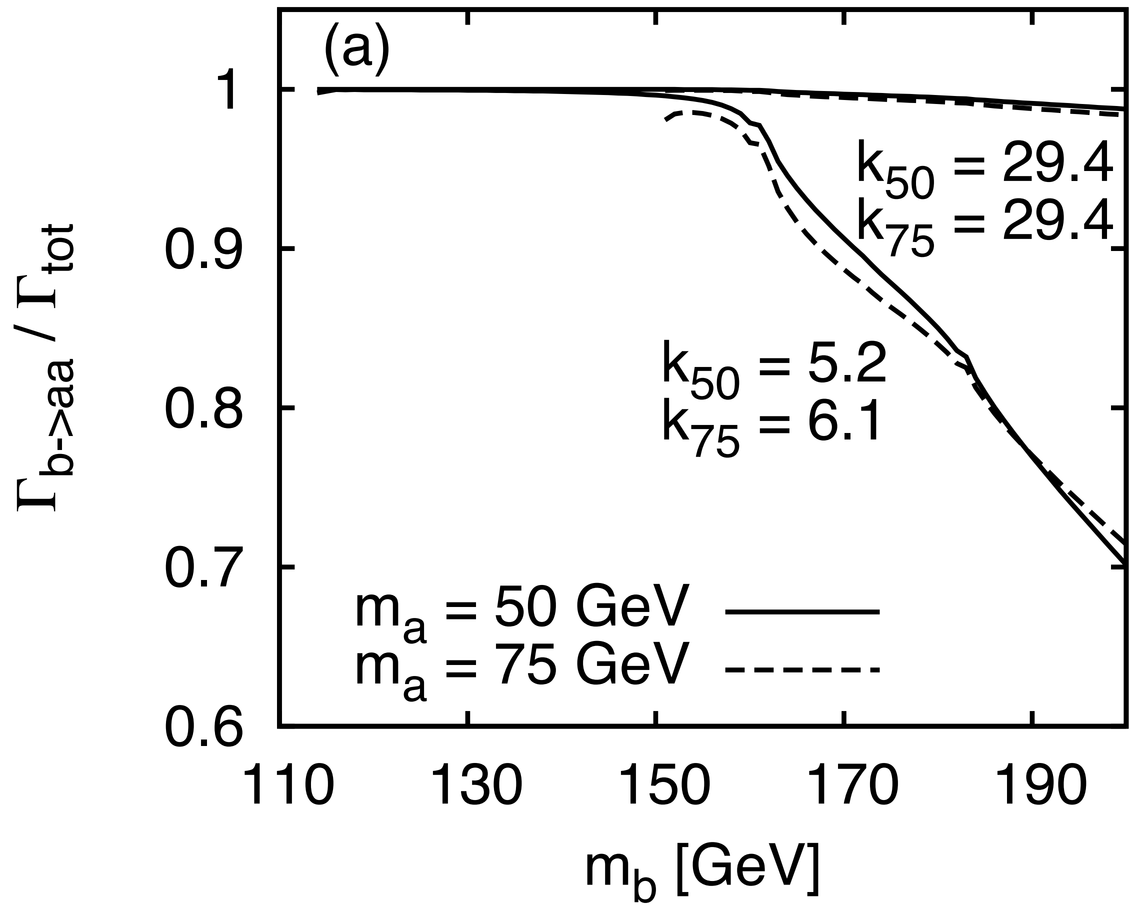
h_a is special, again

- The 3rd scalar ha **only couples off-diagonally**, always with 3rd generation:
  - $h_a \to e\tau(db, ut)$ $h_a \to \mu\tau(sb, ct)$
- 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

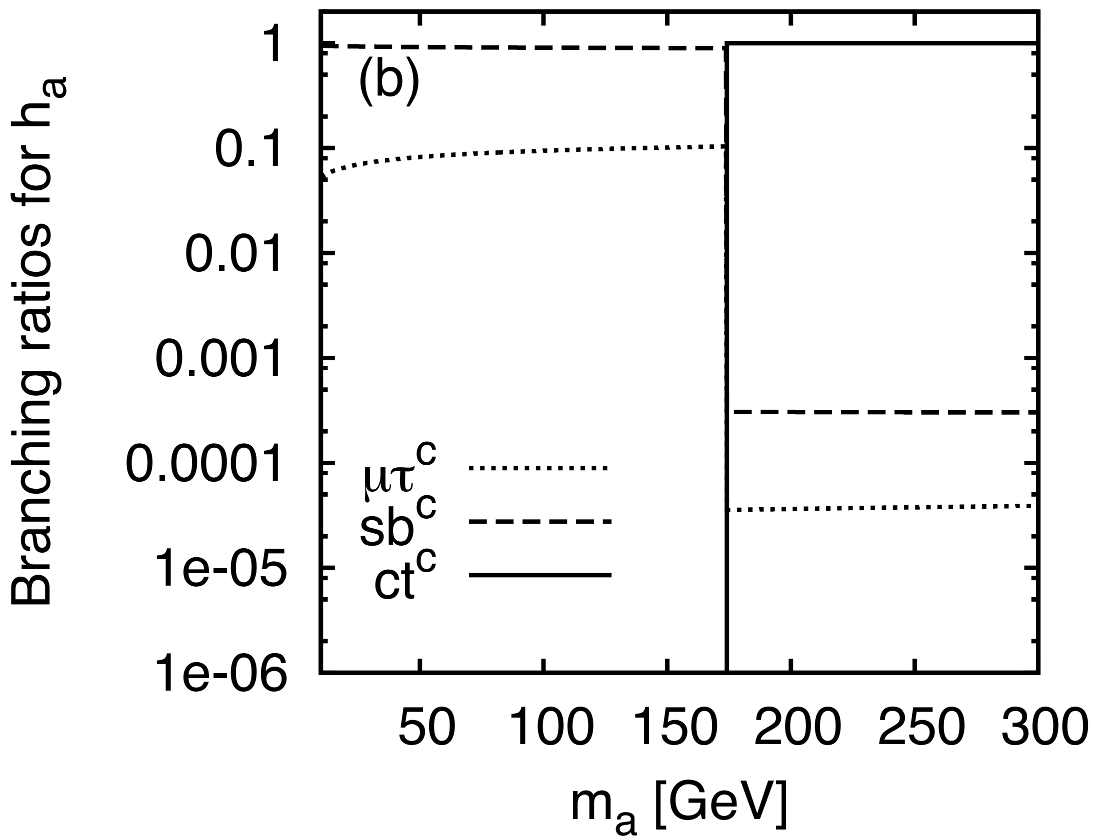


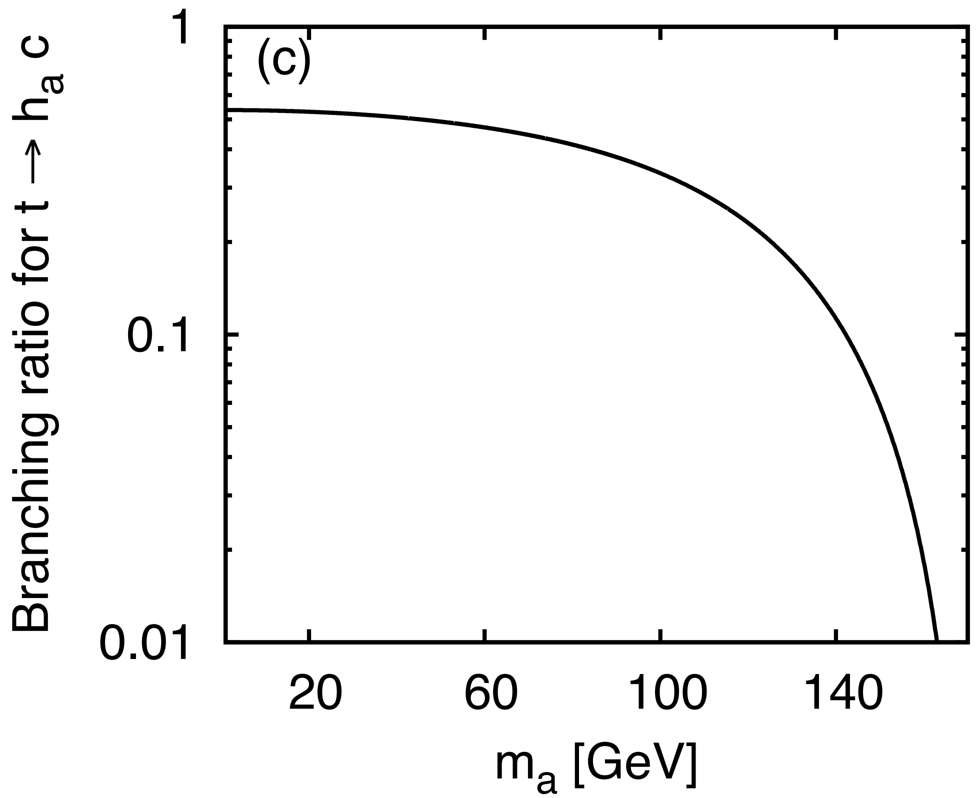
- For m_a = 50 GeV, $k \approx 10$
- Compare to THDM, where it is typically $5 \lesssim k \lesssim 30$ for a 400 GeV scalar decaying into two 114 GeV scalars

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 $\mu\tau$





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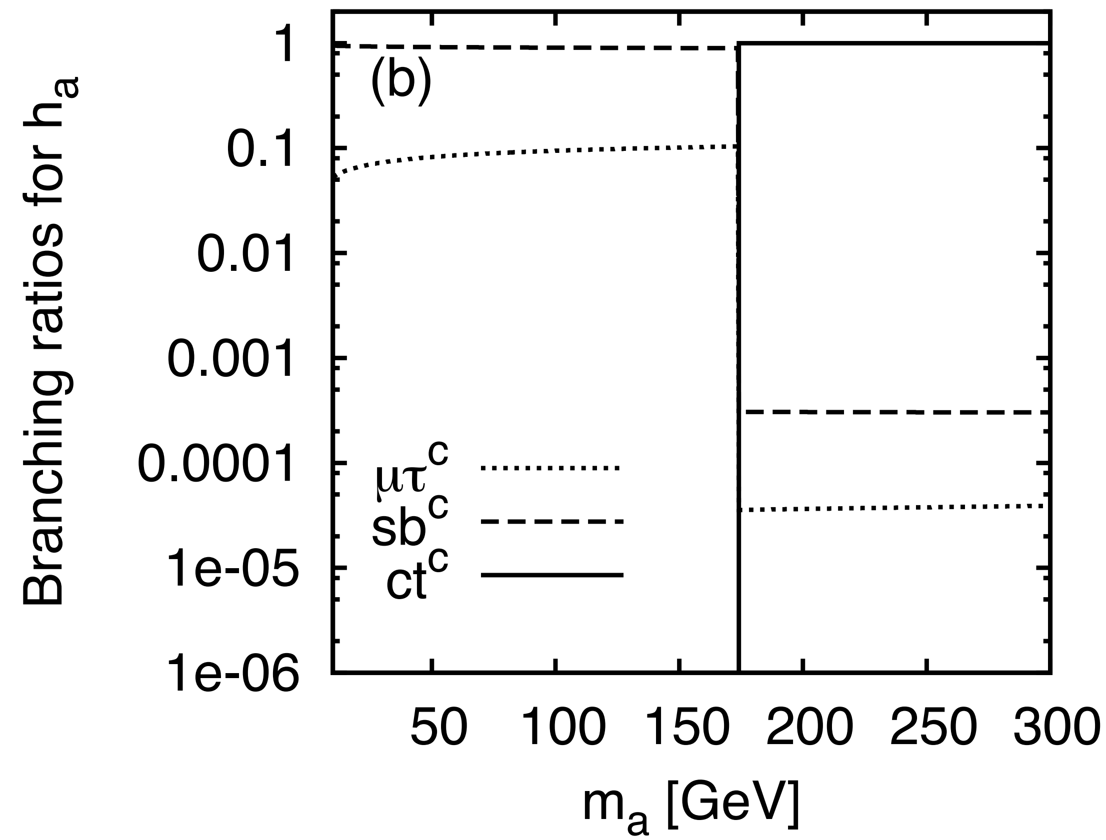
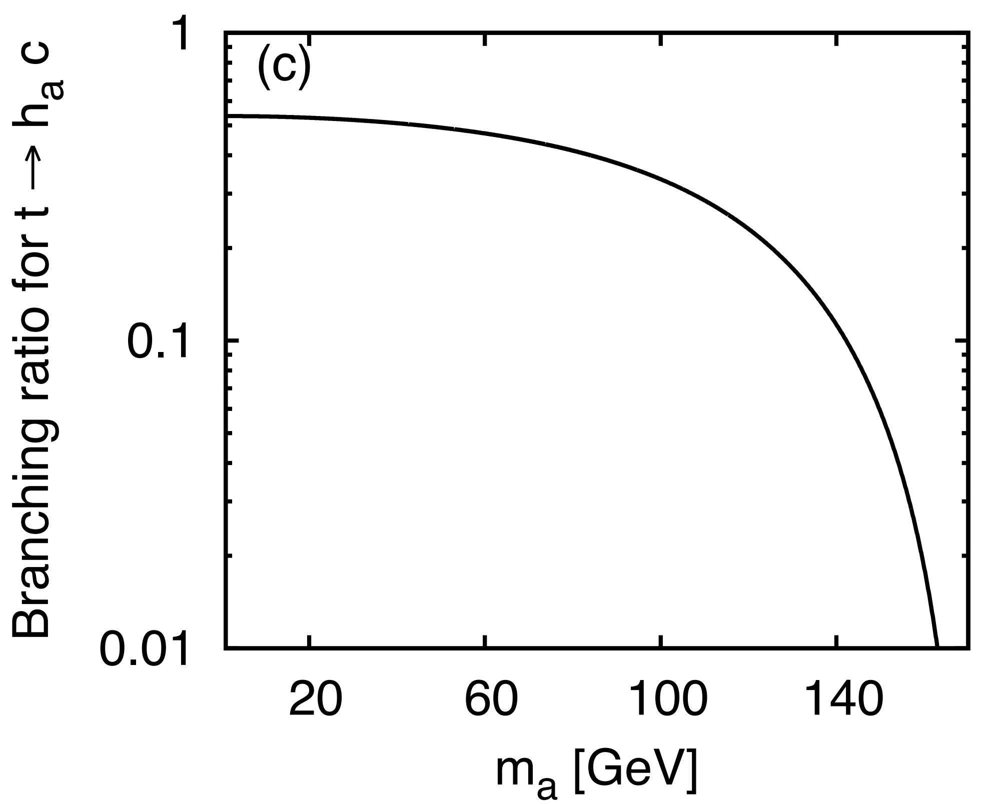
Production of h_a

- 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

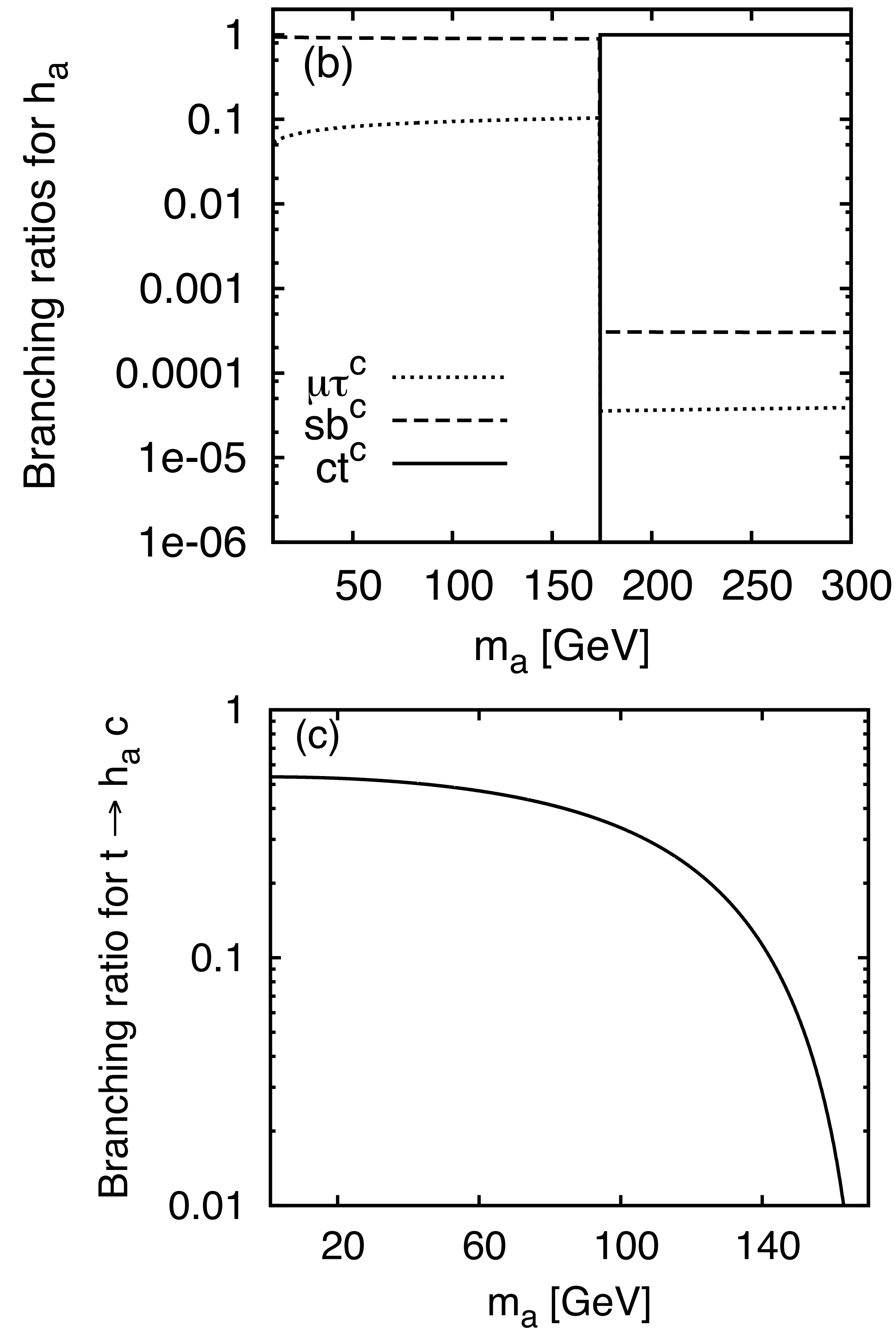




HDECAY: Djouadi, A., Kalinowski, J. and Spira, M., *Comput. Phys. Commun.* **108** 56-74 (1998)

h_a

- Dependency on vacuum alignment:
- Quark mixing requires small deviation from (1, 1, 0) vacuum alignment
- $\Rightarrow$ 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)

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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:

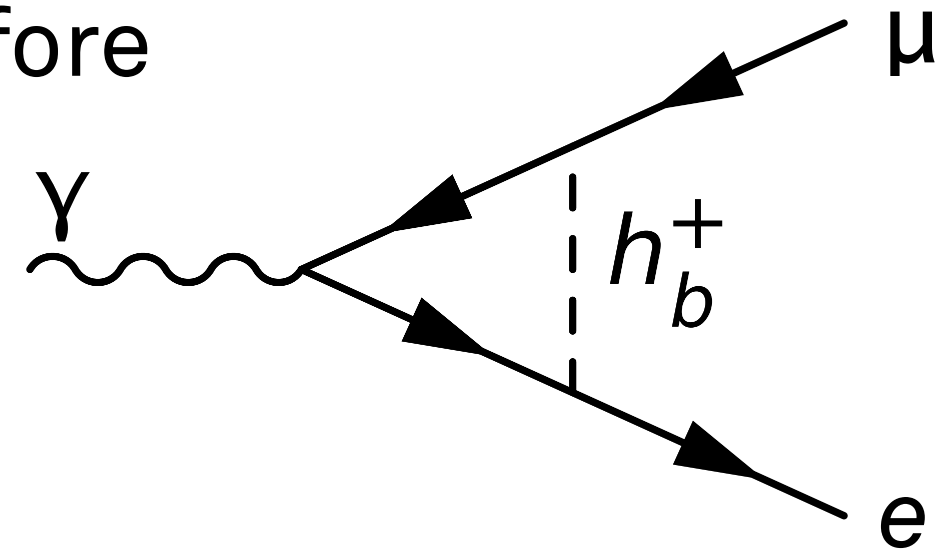
$$Y_{\chi_a} = \begin{pmatrix} 0 & 0 & Y^a_{e_L\tau_R} \\ 0 & 0 & Y^a_{\mu_L\tau_R} \\ Y^a_{\tau_L e_R} & Y^a_{\tau_L\mu_R} & 0 \end{pmatrix}, \qquad Y_{\chi_b} = \begin{pmatrix} Y^b_{e_L e_R} & Y^b_{e_L\mu_R} & 0 \\ Y^b_{\mu_L e_R} & Y^b_{\mu_L\mu_R} & 0 \\ 0 & 0 & Y^b_{\tau_L\tau_R} \end{pmatrix}$$

- In volume of parameter space where $h_a \to \chi_a\chi_b$ opens, h_a cannot be very light

Charged scalars

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

- h_a^+ has limited gauge couplings, similar to h_a: no three-vertices
- The couplings of h_a^+ and h_b^+ to quarks and leptons follow the same pattern as before
- There is no $b \to s\gamma$.
- The off-diagonal (12) coupling of h_b^+ allows for $\mu \to e\gamma$



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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