Properties and decay modes of scalars in an S_3 symmetric model

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Motivation – Horizontal symmetries

- Vast **mass hierarchy between generations** of quarks and charged leptons. Neutrino mass hierarchy can be much flatter.
- CKM matrix and neutrino mixing **angles are parameters** that are not predicted currently.
- PMNS matrix close to being **tribimaximal.**
- Horizontal symmetries have the potential to explain
  - **Masses**, mass relations → $\frac{m_\tau}{m_\mu} \approx 20 \quad \frac{m_\mu}{m_e} \approx 200$
  - **Patterns** in the mixing matrices → $(V_{\mathrm{CKM}})_{12} \approx \left(\frac{m_d}{m_s}\right)^{1/2} (V_{\mathrm{CKM}})_{23} \approx \left(\frac{m_s}{m_b}\right)$

$$\begin{pmatrix} \sqrt{2/3} & 1/\sqrt{3} & \text{small} \\ -1/\sqrt{6} & 1/\sqrt{3} & -1/\sqrt{2} \\ -1/\sqrt{6} & 1/\sqrt{3} & 1/\sqrt{2} \end{pmatrix}$$

Phenomenology of discrete symmetries

- Discrete symmetries like S_3, A_4, S_4, D_4, Q_4, D_5, D_6, Q_6, D_7,... can be used to deduce some of these relations
  - through specific choice of **representations**
  - through **vacuum alignment** of expectation values
- Typical predictions:
  - enlarged **scalar sector** (masses, mixings)
  - branching ratios of **decays** differ from SM
  - **FCNCs** (often tree-level) in scalar decays or typical signals such as

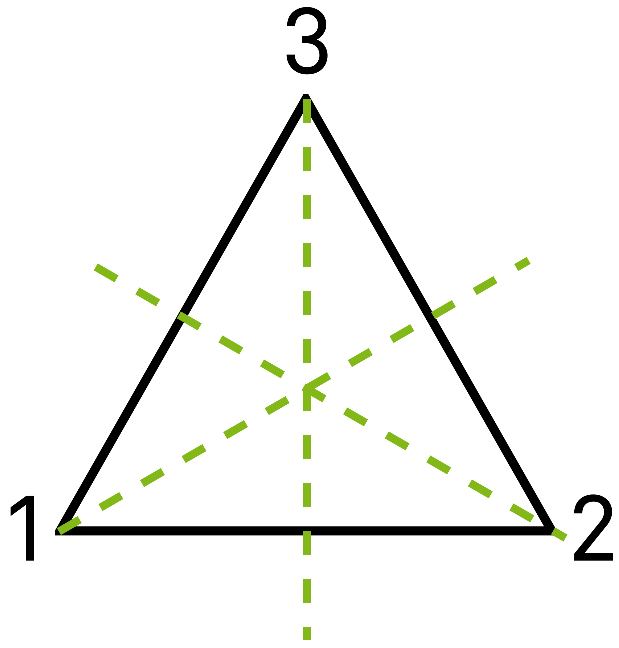
    $\mu \to e\gamma$ $\quad\quad$ $\mu \to eee$ $\quad\quad$ $\tau \to \mu\mu\mu$

The symmetry group S_3

- Symmetry group of the permutation of 3 objects.
  (equivalent to an **equilateral triangle**)
- Natural explanation of **maximal atmospheric mixing** in the neutrino sector
- Contains 6 **elements**:

id	rotation by 2π/3	swap two points / reflection
(123)	(312), (231)	(132), (321), (213)

- 3 irreducible **representations**: $\mathbf{1}, \mathbf{1'}, \mathbf{2}$
- Only $\mathbf{1}$ is an invariant, $\mathbf{1'}$ is not.
- Basic multiplication rules:
  - $\mathbf{1'} \times \mathbf{1'} = \mathbf{1}$ and $\mathbf{2} \times \mathbf{2} = \mathbf{1} + \mathbf{1'} + \mathbf{2}$



A specific S_3 model

- Assign SM particles to S_3 representations:

Quark doublets — Lepton doublets — RH singlets

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

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

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

- **3 scalars** for mass generation of quarks / charged leptons
- Neutrino sector separate (See-Saw Type II, 2 triplet scalars)
- Maximal atm. mixing originates in charged lepton sector

Chen, Frigerio, Ma (2004)

A specific S_3 model

- **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
- Simple in S_3, because model is rather simple and does „one thing well“

Chen, Frigerio, Ma (2004)

Scalar potential

- Most general S_3 invariant scalar potential (only for the doublets)

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

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

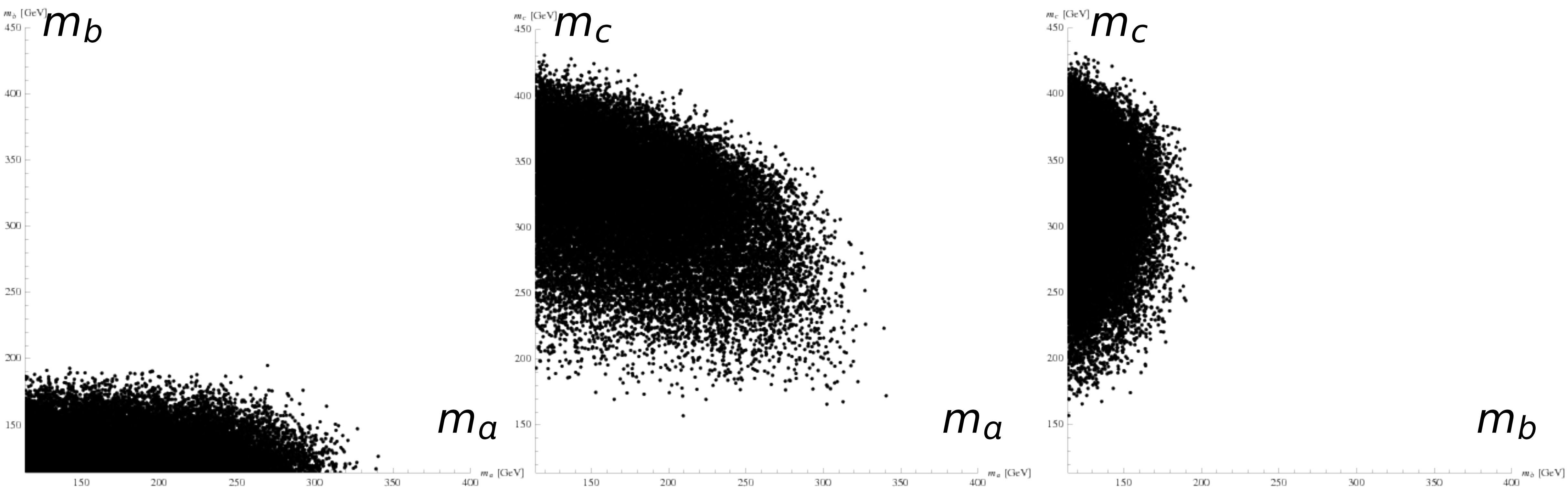
$$+\lambda_6\phi_3^\dagger(\phi_1\phi_1^\dagger+\phi_2\phi_2^\dagger)\phi_3+\left[\lambda_7\phi_3^\dagger\phi_1\phi_3^\dagger\phi_2+\lambda_8\phi_3^\dagger(\phi_1\phi_2^\dagger\phi_1+\phi_2\phi_1^\dagger\phi_2)+h.c.\right]$$

- 8 couplings and 2 mass parameters
- Parameter space constricted by conditions:
  - Real, positive masses, VEV v_3 should be larger than v, squared sum of the VEVs should be equal to squared SM Higgs VEV.

Chen, Frigerio, Ma (2004)

Scalar masses

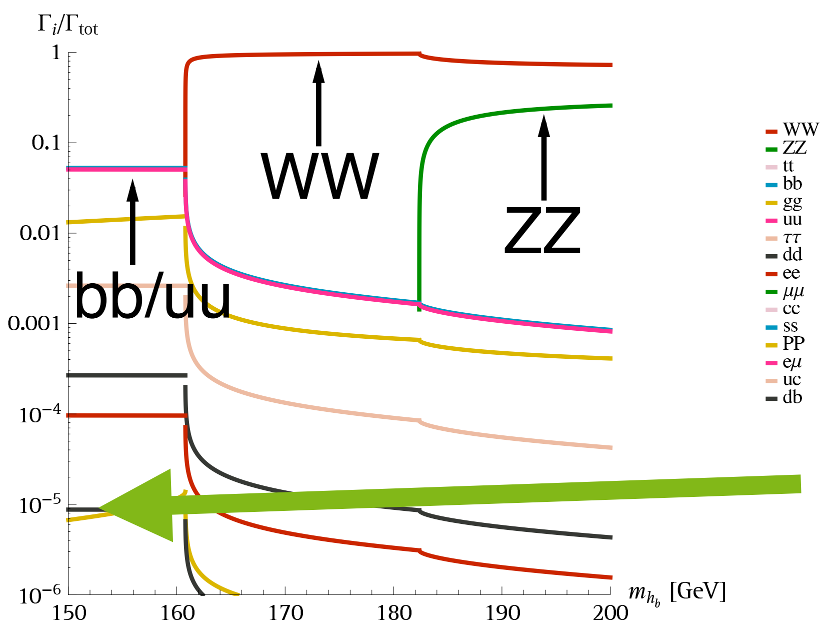
- Masses for the 3 physical scalars (after minimizing the potential and diagonalizing the scalar mass matrix)
- all below 450 GeV



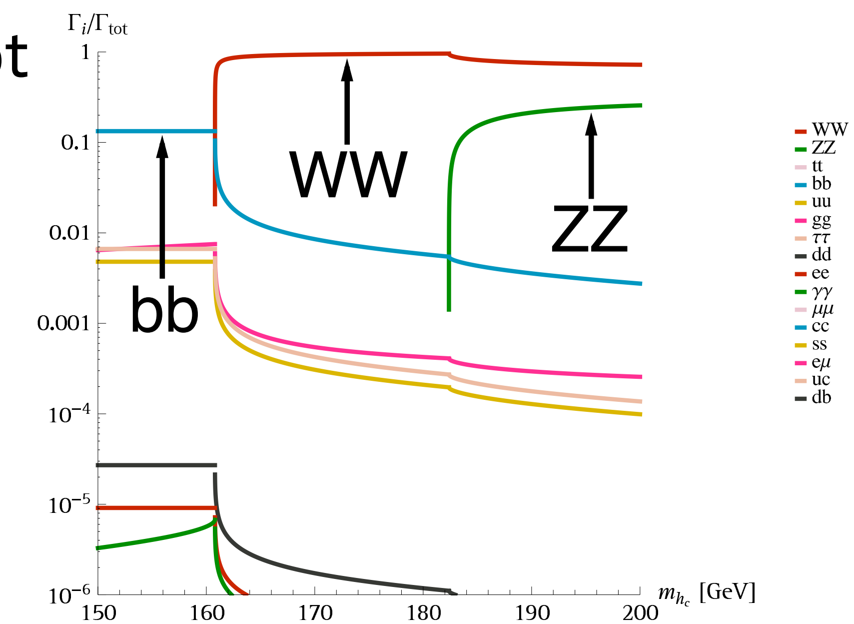
Couplings of the scalars to fermions

- After SSB the physical scalars couple through **Yukawas.**
- FCNCs on tree level emerge
- 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: $h_{b,c} \to e\mu$
- The 3rd scalar h_a **only couples off-diagonally**:
  - $h_a \to e\tau(db, ut)$ $h_a \to \mu\tau(sb, ct)$
- These channels exist in the charged lepton / up and down quark sectors

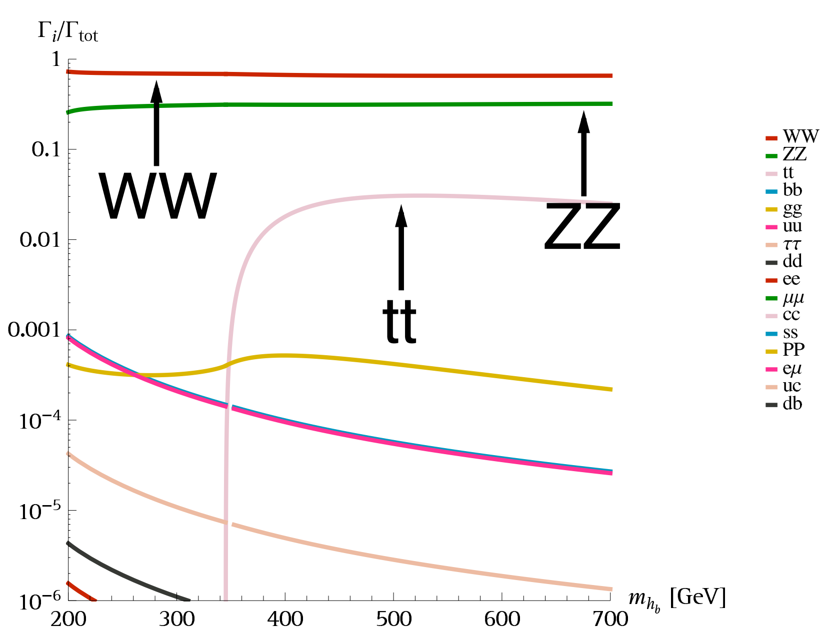
Decays of the scalars $h_{b,c}$

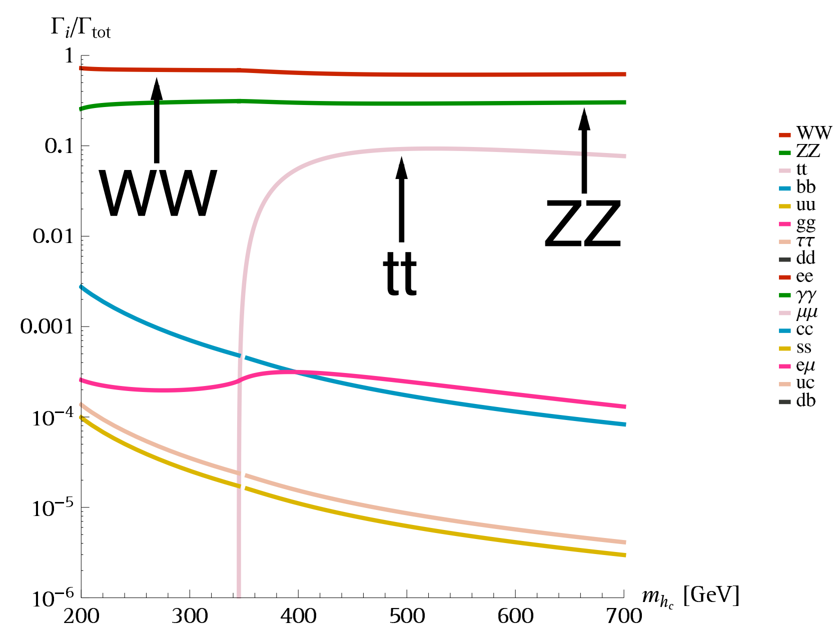


couplings not directly proportional to masses

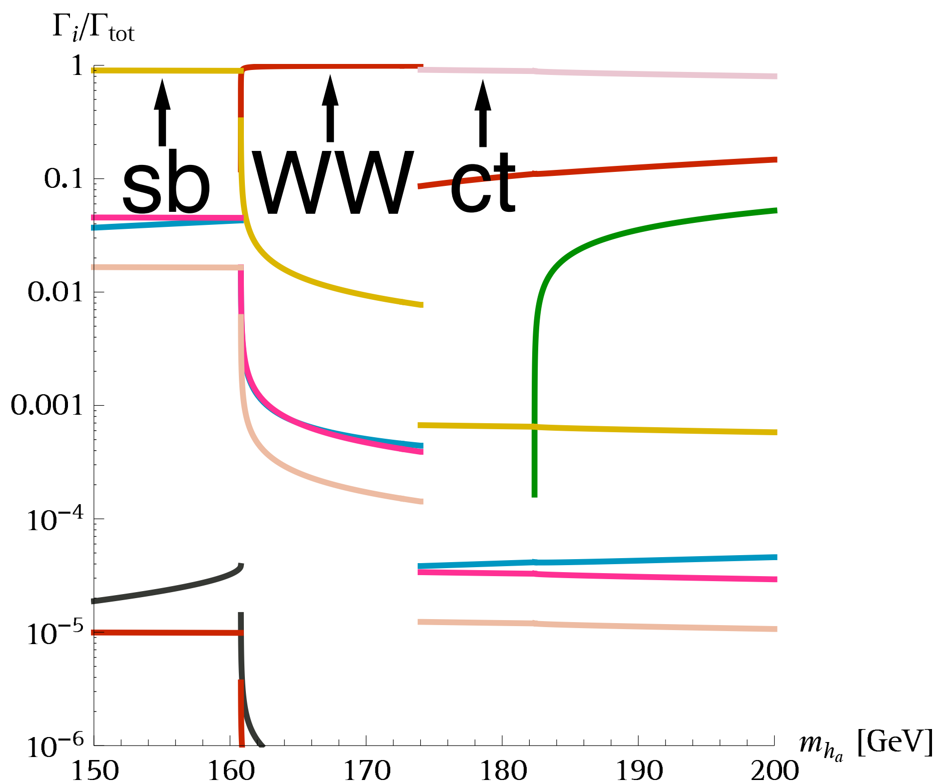


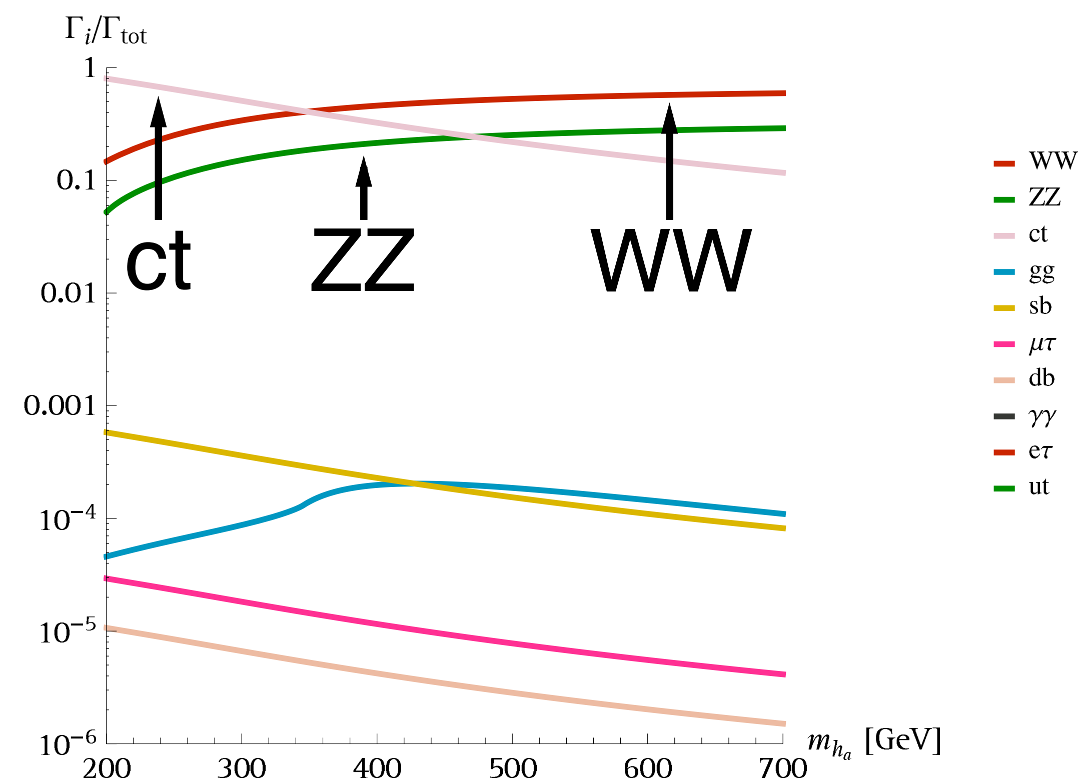
db channel at 10^{-5}





Decays of the scalar h_a





- Dominant decay into *sb* or *ct* for low masses
- *WW*/*ZZ* large for $m_a > 300$ GeV

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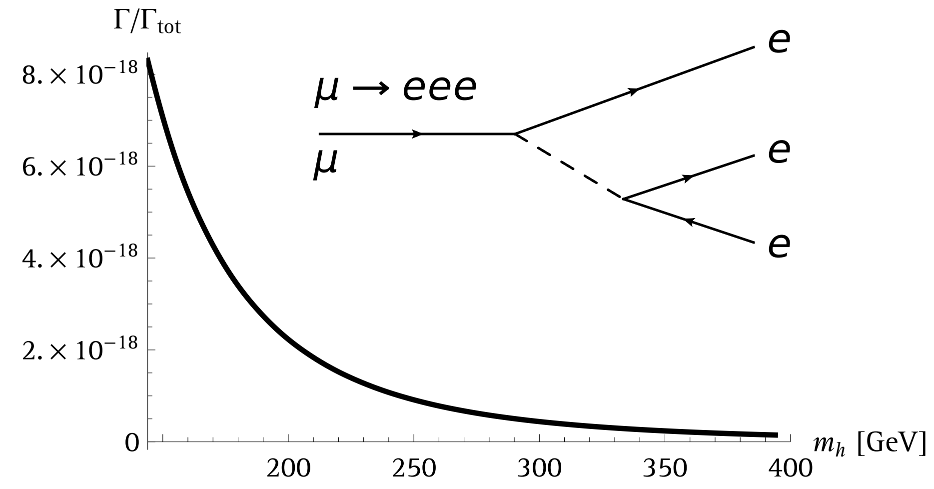
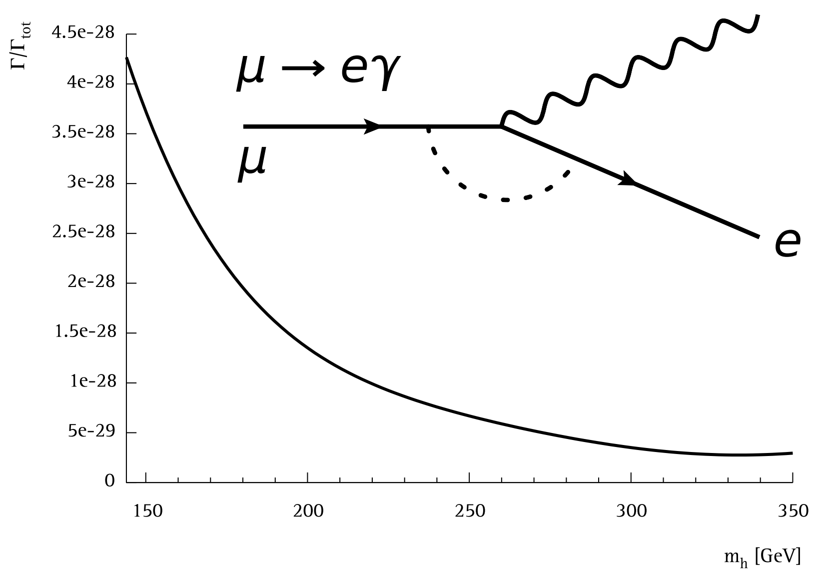
Other decays

- 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 very interesting benchmark decays are **not allowed** in this model:
  - $\tau \to e\gamma$ $\tau \to \mu\gamma$ $\tau \to \mu\mu\mu$ $b \to s\gamma$
  - etc.





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Outlook

- Many discrete symmetries on the market.
- Some are very successful in **describing mixings** of quarks and leptons.
- Most have **enlarged scalar sectors** with FCNCs.
- Scalars responsible for **neutrino mass generation** can enter observables through mixing or direct couplings.
- Specific decay patterns of scalars or processes with intermediate scalars might be observable in **collider experiments**.

Summary

- Discrete horizontal symmetries can **explain the mixing angles and masses** of the particles in the SM.
- Most horizontal symmetries come with an **enlarged scalar sector** that might be probed in colliders and which includes FCNC signals.
- A specific S_3 model was studied:
  - Explains the **close-to-maximal atmospheric** mixing angle in the neutrino sector naturally
  - Comes with scalars that decay similar to SM Higgs except for partly large **FCNC couplings**