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Fakultät Physik
Theoretische Physik III

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The Higgs as a harbinger of flavor symmetry

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

Overview

- Motivation / general phenomenological aspects
- An example: review of a specific S_3 model
  - Scalar potential and properties of physical scalars in the model
- Summary

Motivation – Horizontal symmetries

- Vast **mass hierarchy between generations** of quarks and charged leptons. Neutrino mass hierarchy could be much flatter.
- CKM matrix and neutrino mixing **angles are parameters** that are not predicted in the SM.
  - CKM mixing small, PMNS mixing large
- Horizontal symmetries have the potential to explain
  - **Masses**, mass relations $\longrightarrow$ $\dfrac{m_\tau}{m_\mu} \approx 20 \quad \dfrac{m_\mu}{m_e} \approx 200$
  - **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** for particle content
  - through **vacuum alignment** of expectation values
- Typical interesting predictions:
  - enlarged **scalar sector** (masses, mixings)
  - branching ratios of scalar **decays** differ from SM
  - unusual collider signatures
  - **FCNCs** in scalar decays

  valid for large class of models
  - sum rules and other connections between lepton and quark sectors

The symmetry group S_3

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

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

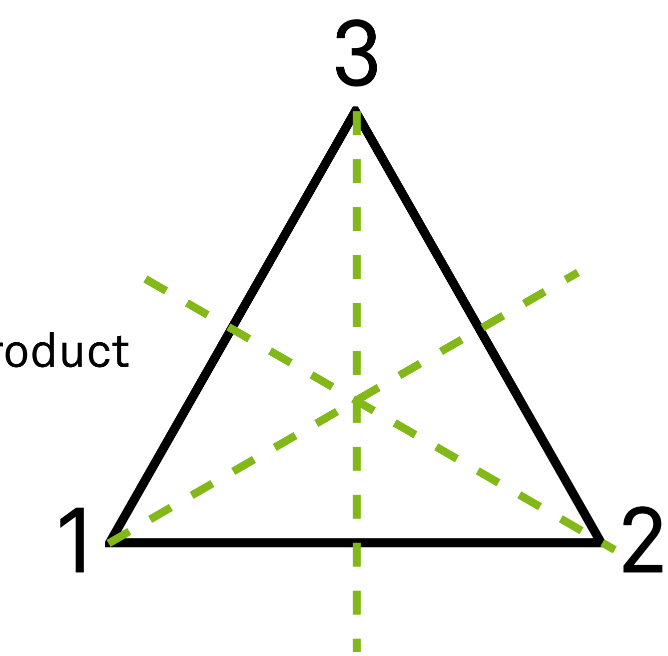
- 3 irreducible **representations**: **1, 1′, 2**

  smallest non-abelian discrete group with **2**

  e.g. norm of outer product

  e.g. inner product

- 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

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

Quark doublets Lepton doublets RH singlets

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

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

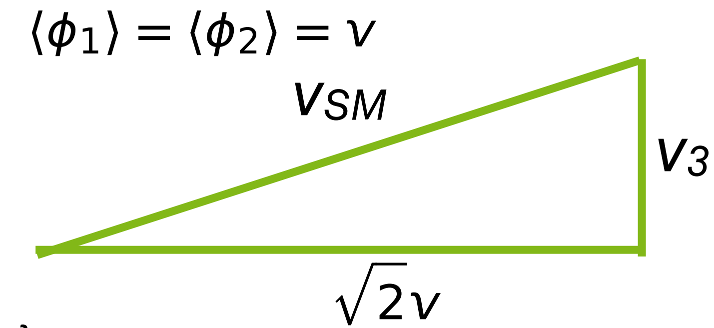
$$(\phi_1, \phi_2) \propto \mathbf{2} \qquad \phi_3 \propto \mathbf{1}$$

- Two generations → S_3 doublet; the other → S_3 singlet
- One **scalar for each** generation
- Neutrino sector separate, diagonal (See-Saw II, 2 heavy EW triplet scalars)
- After SSB and specific alignment $\langle \phi_1 \rangle = \langle \phi_2 \rangle = v$;
  maximal mixing:

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

this translates directly into PMNS matrix

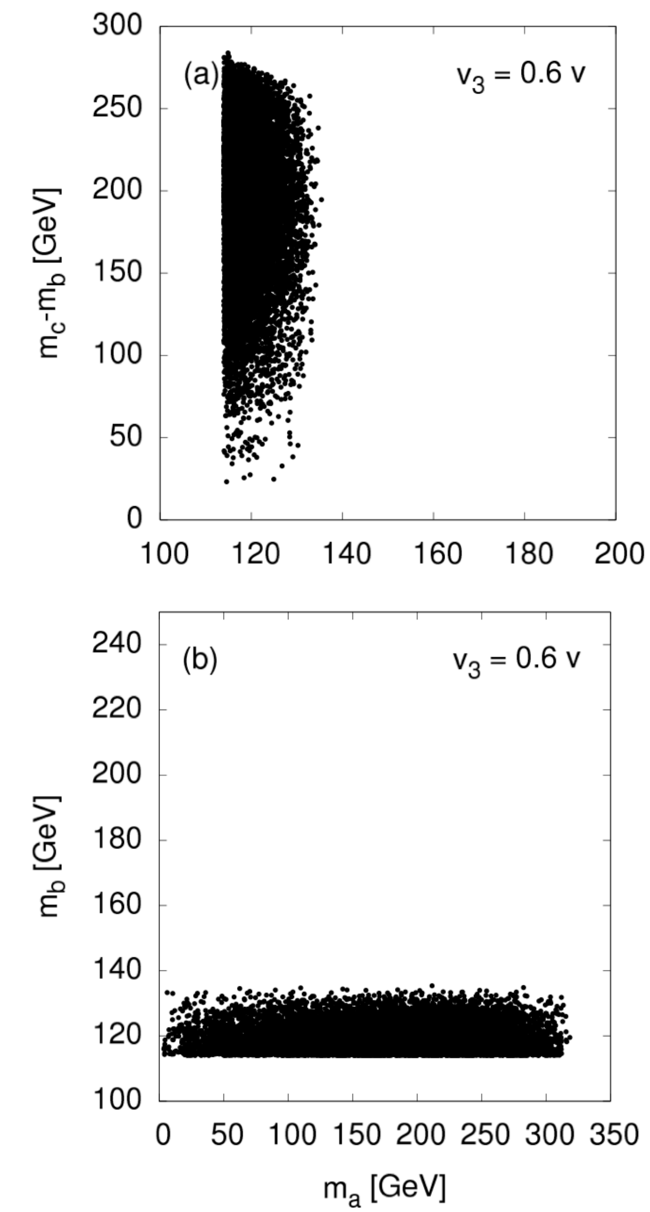
Minimization of the potential



- S_3 invariant scalar potential (doublets, 8+2 params)

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

- Parameter space reduced by conditions:
  - Vacuum state must be a (stable) **minimum of the potential** ($\langle\phi_1\rangle = \langle\phi_2\rangle = v$ is solution)
  - Real, positive masses, allow fixed ratio of v_3 and v, squared sum of the VEVs should be equal to squared SM Higgs VEV.



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

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Scalar mixing

- After diagonalization the weak basis scalars can be expressed via the physical scalars:

$$h_1 = U_{1b} h_b + U_{1c} h_c - \frac{1}{\sqrt{2}} h_a$$

$$h_2 = U_{2b} h_b + U_{2c} h_c + \frac{1}{\sqrt{2}} h_a$$

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

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

- For $v_1 = v_2$, it follows that $U_{1b} = U_{2b}$ and $U_{1c} = U_{2c}$

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 **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

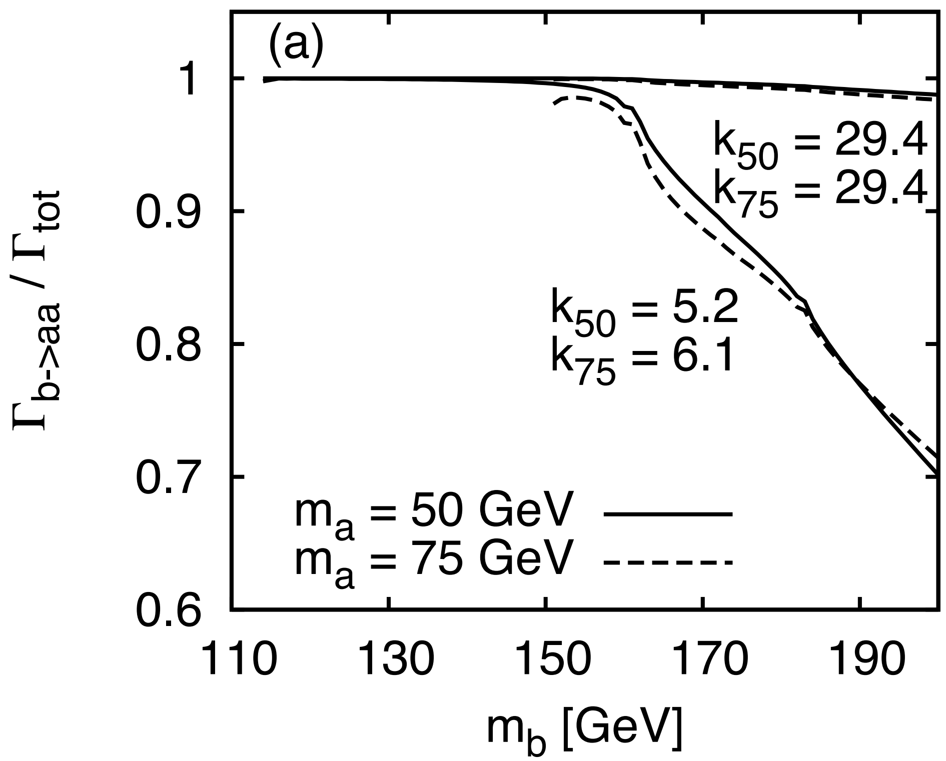
Yukawa couplings

- Identical structures in charged lepton sector and up- / down quark sectors
- 2 scalars $h_{b,c}$ couple **similarly to SM Higgs**:
  - $h_{b,c} \to ee(uu, dd)$ $\quad h_{b,c} \to \mu\mu(ss, cc)$ $\quad h_{b,c} \to \tau\tau(bb, tt)$
  - Additional **FCNC** coupling: $h_{b,c} \to e\mu$
- The 3rd scalar h_a **only couples off-diagonally**, always with 3rd generation:
  - $h_a \to e\tau(db, ut)$ $\quad h_a \to \mu\tau(sb, ct)$
- FCNC couplings are numerically small

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

Signatures of h_b and h_c

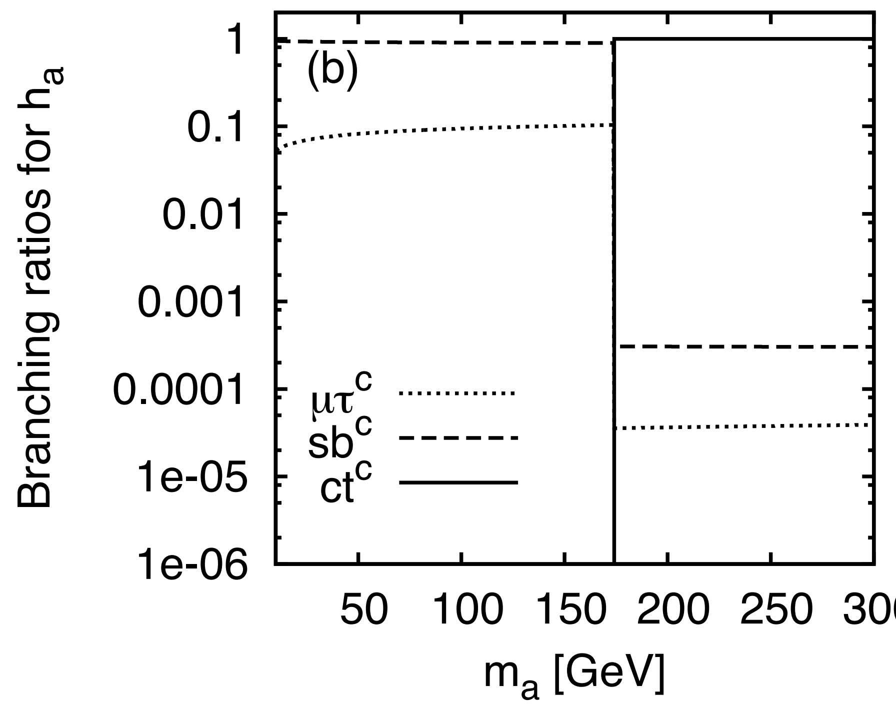
- Both can decay into usual Higgs decay modes ($ZZ, WW, b\bar{b}, \gamma\gamma, \ldots$), but:
- **Dominant decay** for a light scalar h_a is three-scalar mode $h_{b/c} \to h_a\, h_a$
- Parameter k is the ratio between three-scalar coupling and $h_b WW$ coupling
  - For m_a = 50 GeV, this can be $5 \lesssim k \lesssim 30$
  - Compare to THDM, where it is typically $k \approx 10$ for a 400 GeV scalar decaying into two 114 GeV scalars

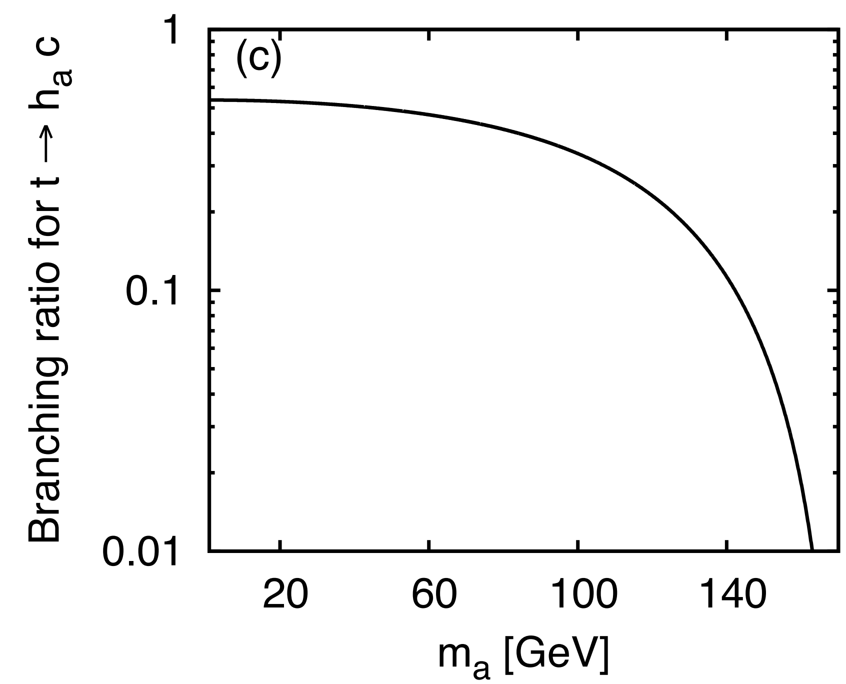


HDECAY: Djouadi, A., Kalinowski, J. and Spira, M., *Comput. Phys. Commun.* **108** 56-74 (1998)

Signatures of h_a

- As long as $m_a < m_t$, the dominant decay mode is into jets
- Possibly significant decay mode into $\mu\tau$
- **Dominant decay** for a light scalar h_a is three-scalar mode $h_{b/c} \rightarrow h_a h_a$
- 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





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Summary

- The discrete flavor symmetry S_3 can **explain the mixing angles and masses** of the particles in the SM and comes with an **enlarged scalar sector.**
- The potential has been minimized and the scalars diagonalized, yielding:
  - **two SM-Higgs-like scalars** h_b and h_c, except that each of them can decay dominantly into pairs of the third scalar h_a
  - The scalar h_a with **limited gauge interactions** although in the symmetry basis all are weak doublets
  - h_a has only off-diagonal Yukawa couplings, involving a lepton or quark from the third generation
- Due to unconventional decay channels, these scalars might already be buried in existing LEP or Tevatron data

Summary cont‘d

- This kind of analysis of the scalar sector can be relevant for discriminating between different horizontal symmetries in general:
- **The enlarged Higgs sector can be a harbinger of flavor symmetries!**

Scalar mixing cont‘d

- 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

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

which always yields (-1, 1, 0) as one eigenvector, regardless of a, b, c.

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):

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

- 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