Flavor Symmetries: Finding tests & alternatives

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Erice School on Nuclear Physics, 2013

- The Higgs as a harbinger of S3 flavor symmetry
- Novel signatures of the Higgs sector from S3 flavor symmetry

  G. Bhattacharyya, P. Leser, H.Päs, PRD 83 (2011) and PRD 86 (2012) 036009

- Knotted strings & leptonic flavor structure

  T.W. Kephart, P. Leser, H. Päs, Mod. Phys. Lett. A 27 (2012) 1250224

Puzzling Flavor structures

Fact:
- Large/Maximal lepton vs. small quark mixing
- Mild lepton vs. strong quark hierarchies

- Discrete Flavor symmetry?

  $S_3, A_4, S_4, D_4, Q_4, D_5, D_6, Q_6, D_7, \ldots$

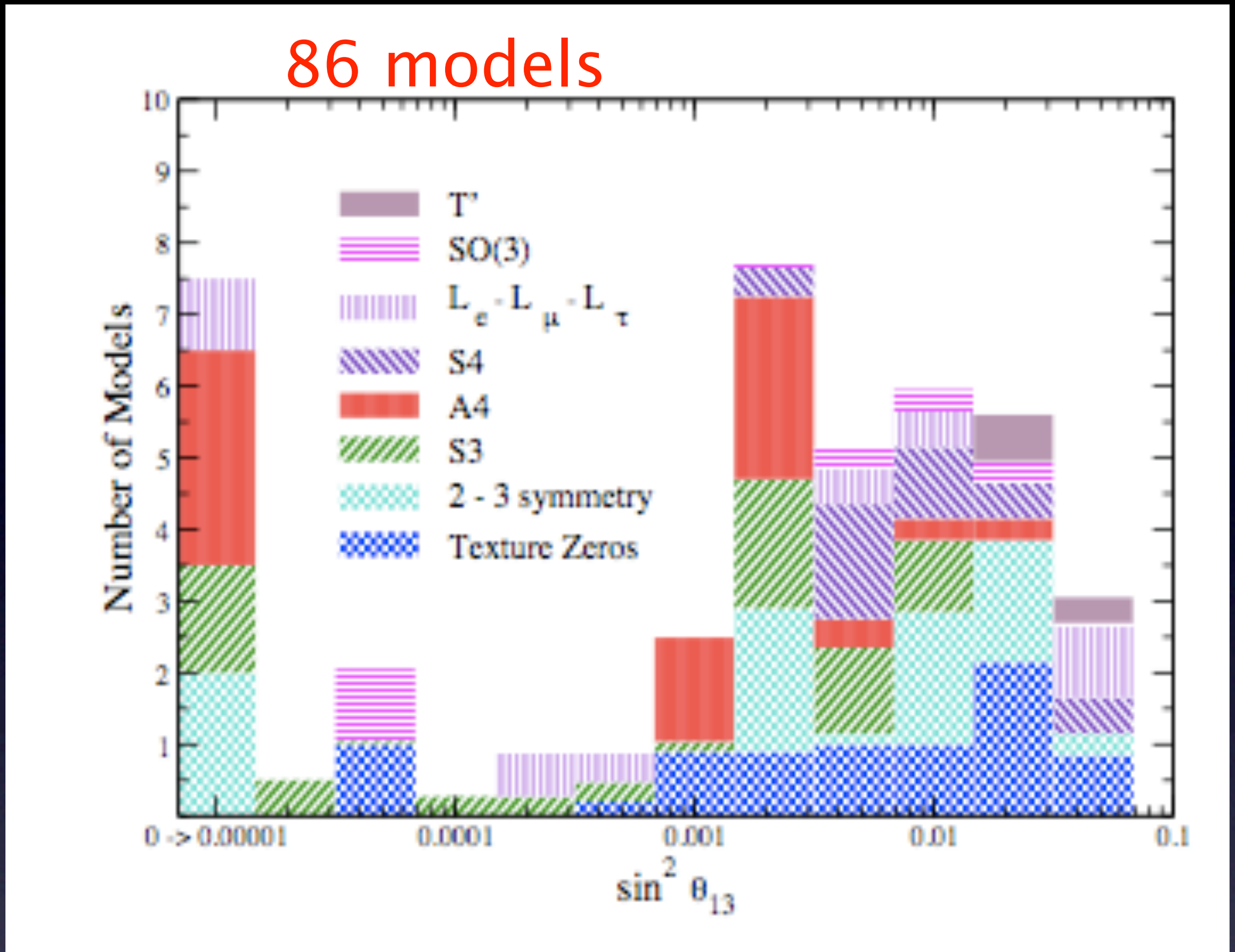
  [e.g. Ma, Altarelli, Feruglio, King, Ross, Varzielas,...]

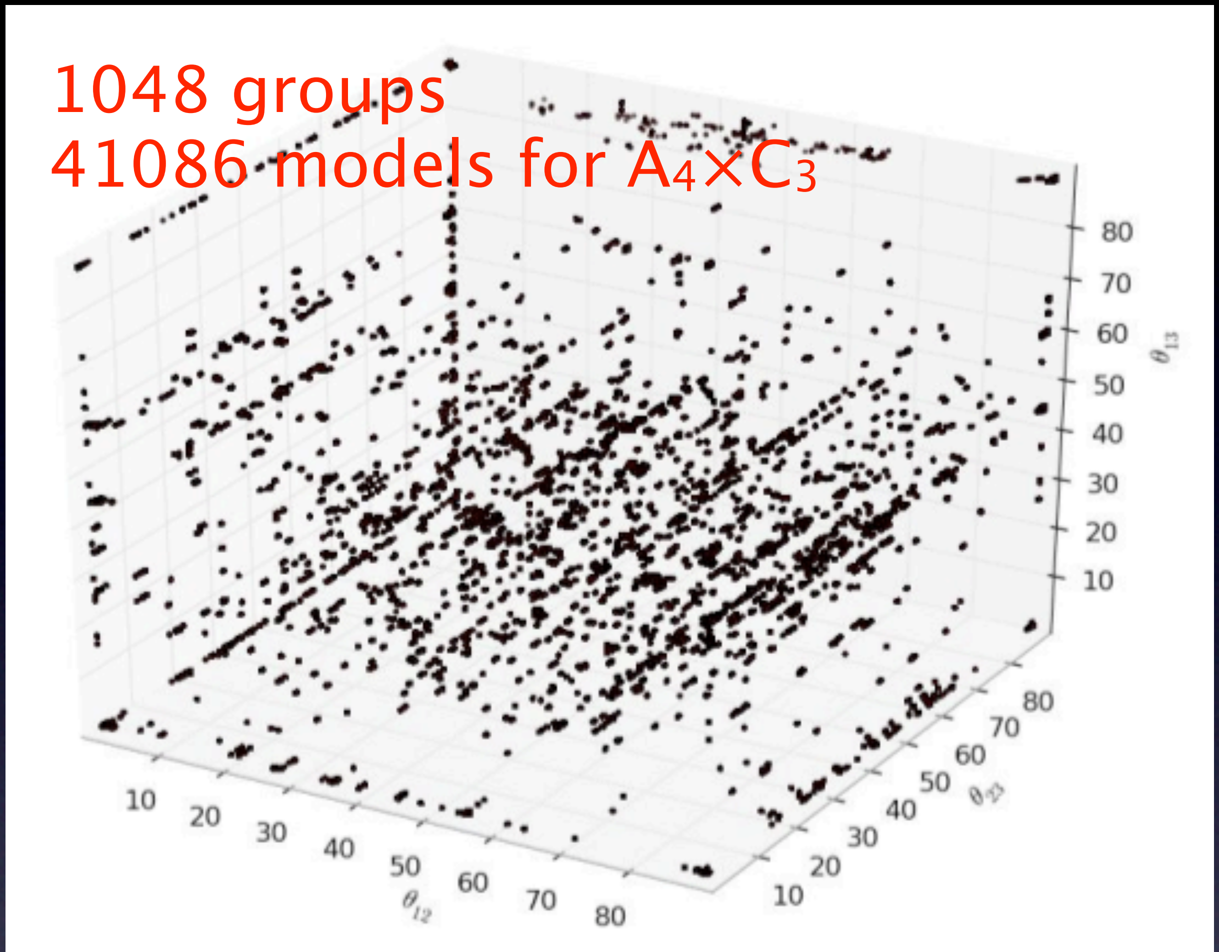
- Anarchy?

  Masses and Mixings random numbers?

  [Hall, Murayama, Weiner, Haber, de Gouvea, ’99, ’00, ’03]

A landscape of Flavor symmetry





[Albright, Chen, Rodejohann; '06,'08]

[Parattu, Wingerter, SUSY'10, FLASY'12]

- Huge variety of models
- Predictions spanning a large part of the parameter space
- Search for new tests of Flavor symmetry
- Search for alternatives of Flavor symmetry

Probing flavor symmetry models

A typical flavor model:

- Choose a symmetry group
- Assign matter to irreducible representations
- Write down Lagrangian allowed by symmetry
- Find minima of Higgs potential

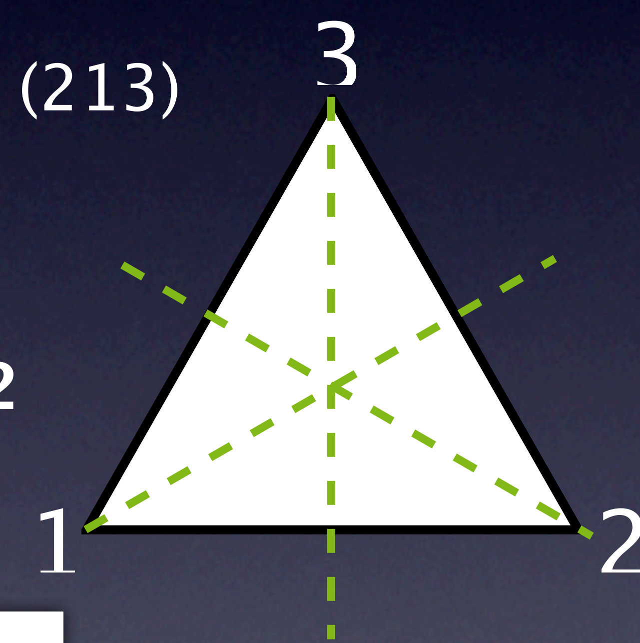
If Higgses responsible for flavor structure also break electroweak symmetry: Maximal ν mixing can translate into Higgs couplings →extraordinary Higgs phenomenology!

A prototypical flavor model based on S_3:

[Chen, Frigerio, Ma, '04]

More attractive again for sizable θ_{13}!

- Symmetry group of the permutation of 3 objects. (equivalent to symmetry group of **equilateral triangle**)
- Contains 6 **elements**: (123), (312), (231), (132), (321), (213)
- 3 irreducible **representations**: $\mathbf{1}$, $\mathbf{1'}$, $\mathbf{2}$
- Basic multiplication rules: $\mathbf{1'}\times\mathbf{1'}=\mathbf{1}$ and $\mathbf{2}\times\mathbf{2}=\mathbf{1}+\mathbf{1'}+\mathbf{2}$
- Assign matter fields to irreps as follows:



$(L_1, L_2) \propto \mathbf{2}$	$L_3, \ell^c_3, \ell^c_1 \propto \mathbf{1}$	$\ell^c_2 \propto \mathbf{1'}$
$(Q_1, Q_2) \propto \mathbf{2}$	$Q_3, u^c_3, u^c_1, d^c_3, d^c_1 \propto \mathbf{1}$	$u^c_2, d^c_2 \propto \mathbf{1'}$
$(\phi_1, \phi_2) \propto \mathbf{2}$	$\phi_3 \propto \mathbf{1}$	

Probing flavor models at the LHC

- the same Higgses breaking EWSB also break Flavor!
- 3 Higgs SU(2) doublets necessary
- Vaccum alignment $v_1 = v_2 \equiv v$ for maximal atmospheric ν mixing (extremum ✔)
- Large Flavor violating terms cancel between up and down-type quarks
- Neutrino masses generated by additional Higgs SU(2) triplet
- Large Flavor violation translates as mismatch between charged leptons and neutrinos directly into PMNS matrix

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

→Such models exhibit an extraordinary Higgs phenomenology!

S3 invariant potential:

- Correct W and Z masses
- Maximal atmospheric mixing:
- Minimize scalar potential
- Diagonalization of mass matrix

Realistic models

Consider a 125 GeV SM-like Higgs
Include the complete set of scalars and pseudoscalars

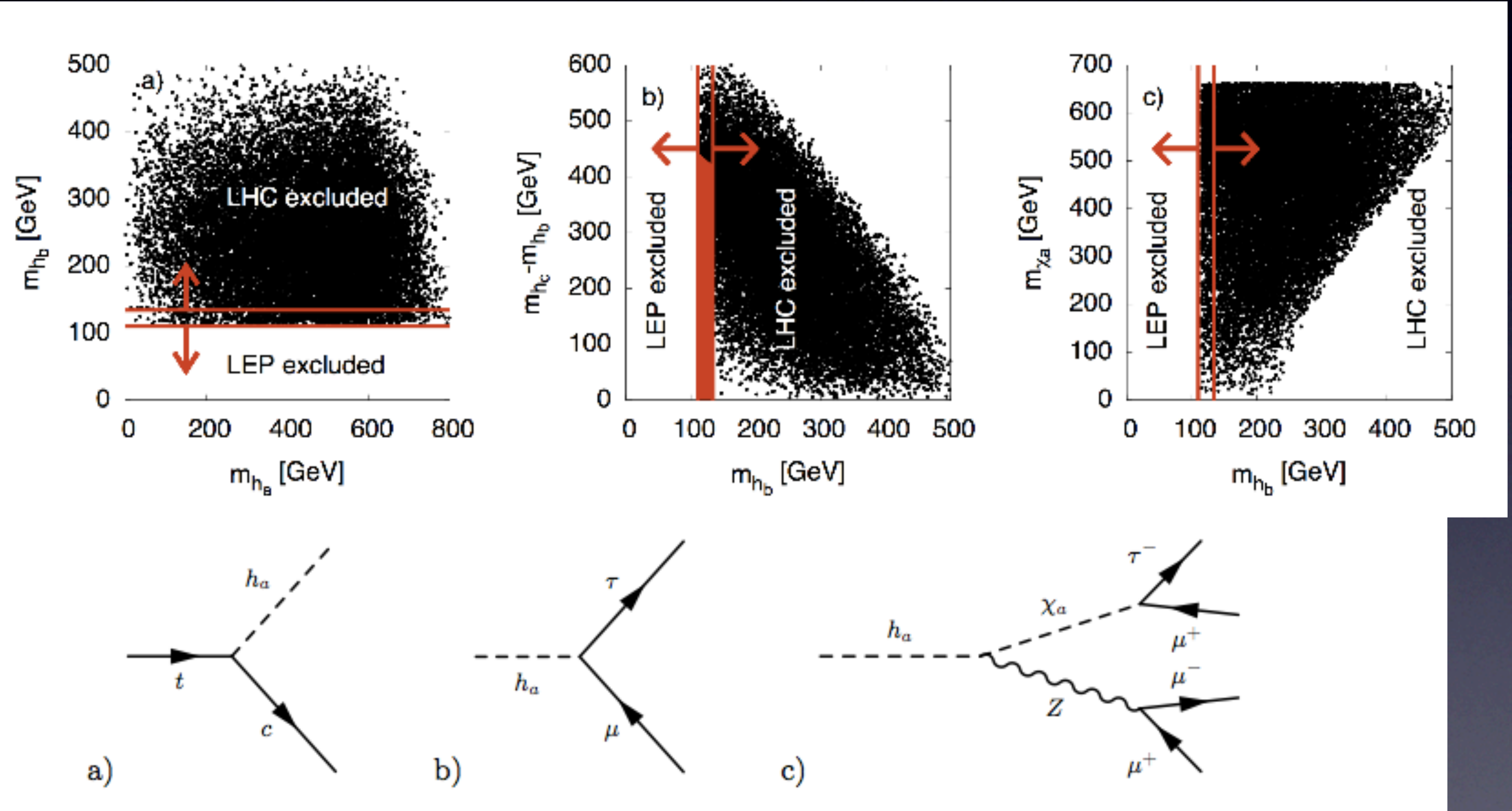
[Bhattacharyya, Leser, Päs, '12]

3 CP even, 2 CP odd and 2 charged scalars

- $h_{b,c}$ have SM–like couplings except for decay into h_a
- h_a and X_a have no WW or ZZ interactions
- h_a /X_a have only flavor off–diagonal Yukawa couplings with 3rd generation
- h_a /X_a can be hidden from standard searches and thus can be very light
- All other scalar/pseudoscalars can have masses above 550 GeV

Full scalar and pseudoscalar spectrum and couplings

[Bhattacharyya, Leser, Päs, '12]



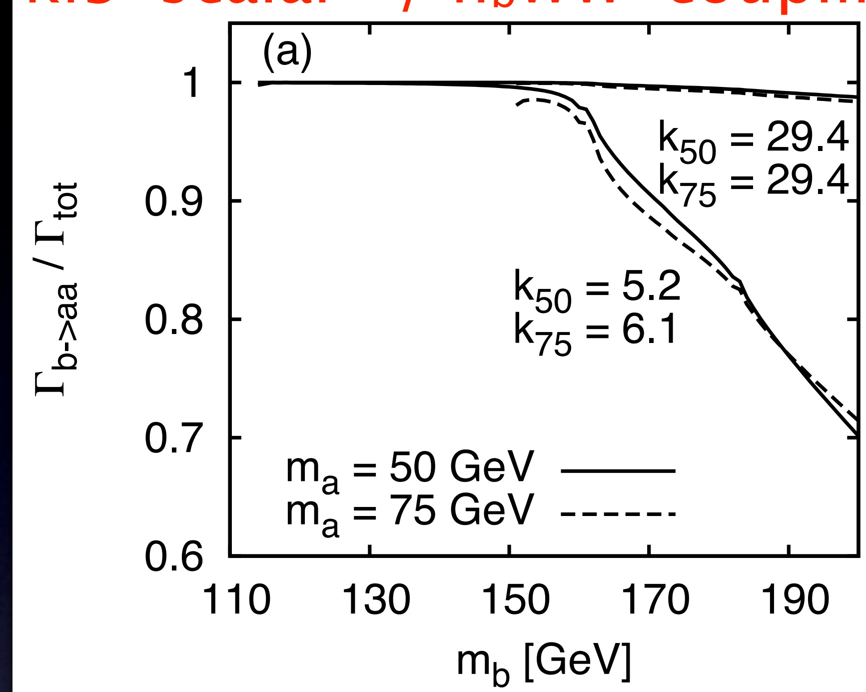
Feynman graphs for dominant sources of h_a production and decays which might be relevant at the LHC.

Phenomenology of CP-even scalars

- Dominant decay for a light h_a:
  $h_{b/c} \to h_a h_a$
- Production of h_a possible through
  $t \to h_a c$ with subsequent decay $h_a \to \mu\tau$
- h_a decays dominantly off-diagonally into jets (sb^c, $m_a < m_t$) or ct^c ($m_a > m_t$)

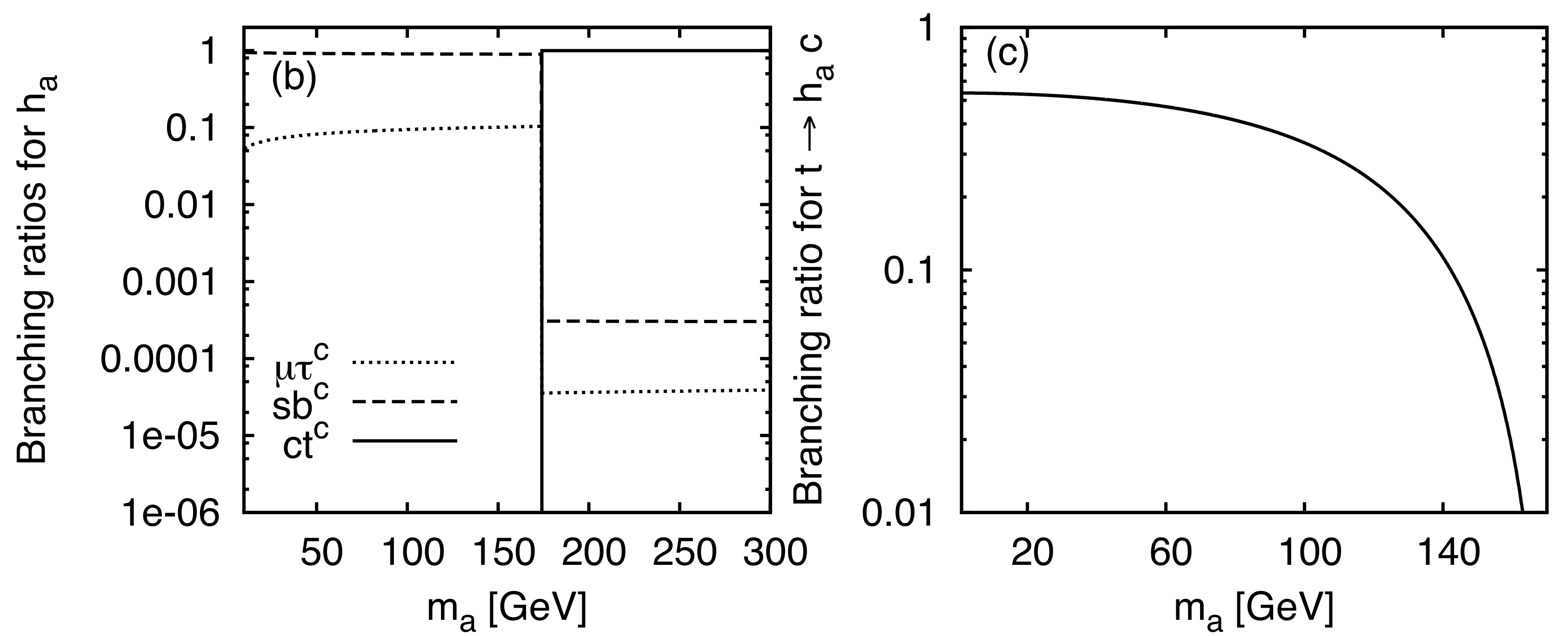
[Bhattacharyya, Leser, Päs, '10]

k:3-scalar- / h_bWW-coupling



Interesting signals at the LHC!

- h_a, h_b might already be buried in existing LEP or Tevatron data!

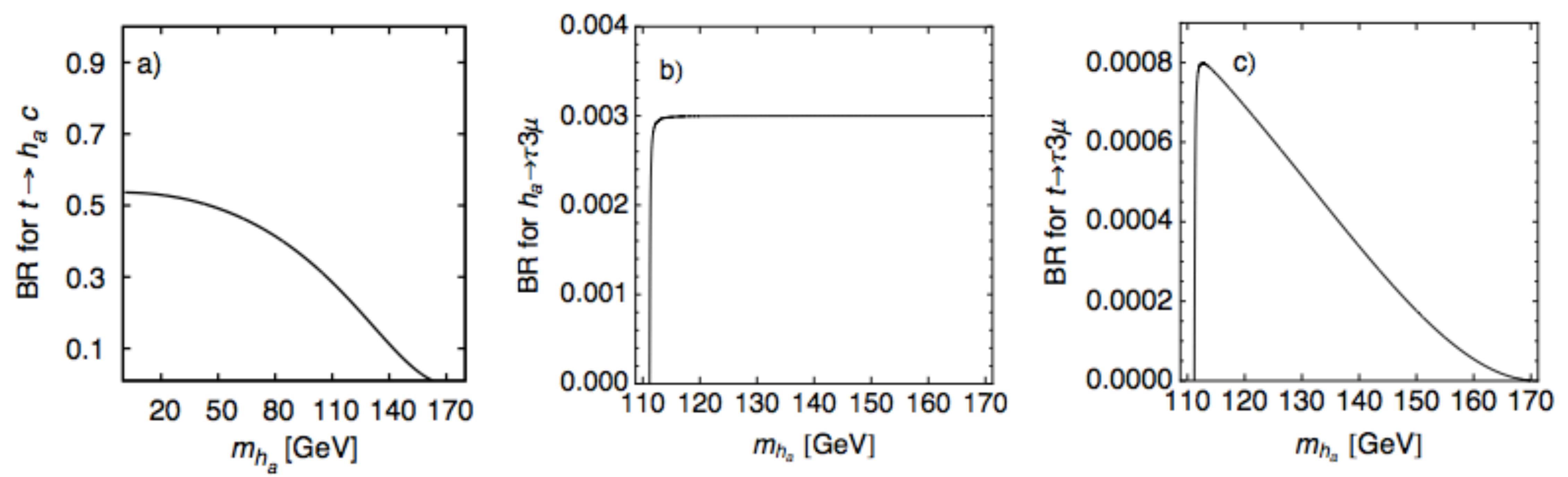


Signatures of the pseudoscalar χ_a

$h_a \to \chi_a Z$ with BR~100 % followed by

$Z \to \mu\mu$ BR of $\sim 3\%$ and $\chi_a \to \tau\mu$ with a BR of $\sim 10\%$

$\Rightarrow$ $h_a \to \chi_a Z \to \tau\mu\mu\mu$ signature



"The Higgs as a harbinger of flavor symmetry"

Discrete symmetries employed to explain flavor mixing and mass hierarchies can be associated with an enlarged scalar sector which might lead to exotic Higgs decay modes. In this paper, we explore such a possibility in a scenario

[Bhattacharyya, Leser, Päs, '10]

If neutrino tribimaximal mixing is explained by a non-Abelian discrete symmetry such as A_4, T_7, $\Delta(27)$, etc., the charged-lepton Higgs sector has a Z_3 residual symmetry (lepton flavor triality), which may be observed directly in the decay chain $H^0 \to \psi_2^0 \bar{\psi}_2^0$, then $\psi_2^0(\bar{\psi}_2^0) \to l_i^+ l_j^-$ $(i \neq j)$, where H^0 is a standard-model-like Higgs boson and ψ_2^0 is a scalar particle needed for realizing the original discrete symmetry. If kinematically allowed, this unusual and easily detectable decay is observable at the LHC with 1 fb^{-1} for $E_{\rm cm} = 7$ TeV.

[Cao, Damanik, Ma, Wegman, '11]

Alternative: Knotted strings & flavor

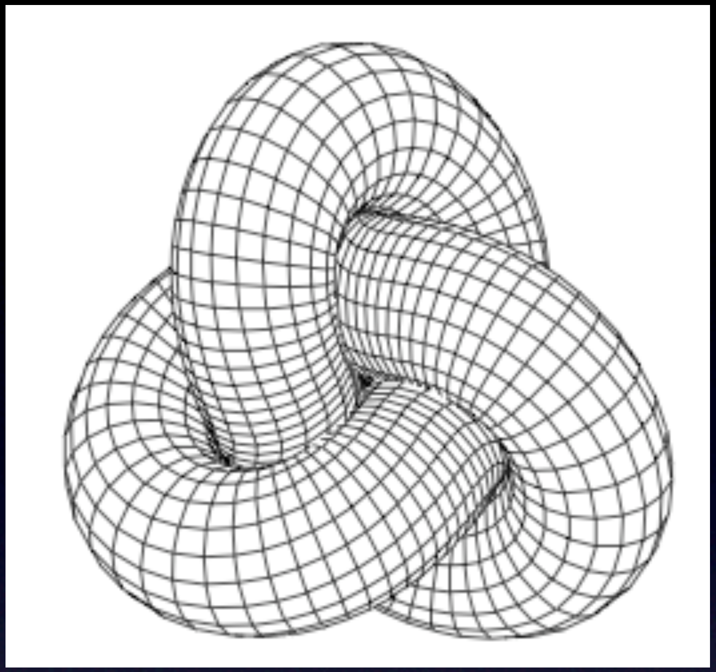
- Major achievement of Flavor models:
motivate degenerate mass matrix entries to fit TBM:

$$m_\nu = \begin{pmatrix} x & y & y \\ y & x+v & y-v \\ y & y-v & x+v \end{pmatrix}$$

[e.g. Altarelli, Feruglio]

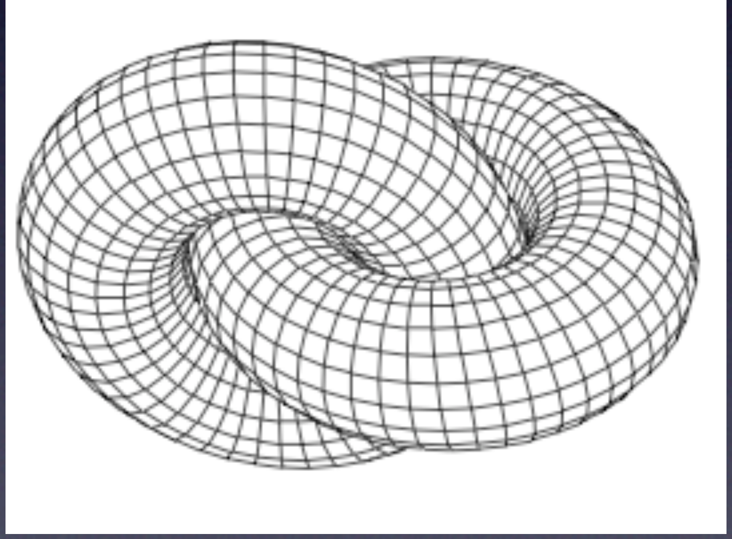
- Alternative: Anarchy....
- Anything else?
- Other phenomena in Nature with close numbers?

Alternative: Knotted strings & flavor



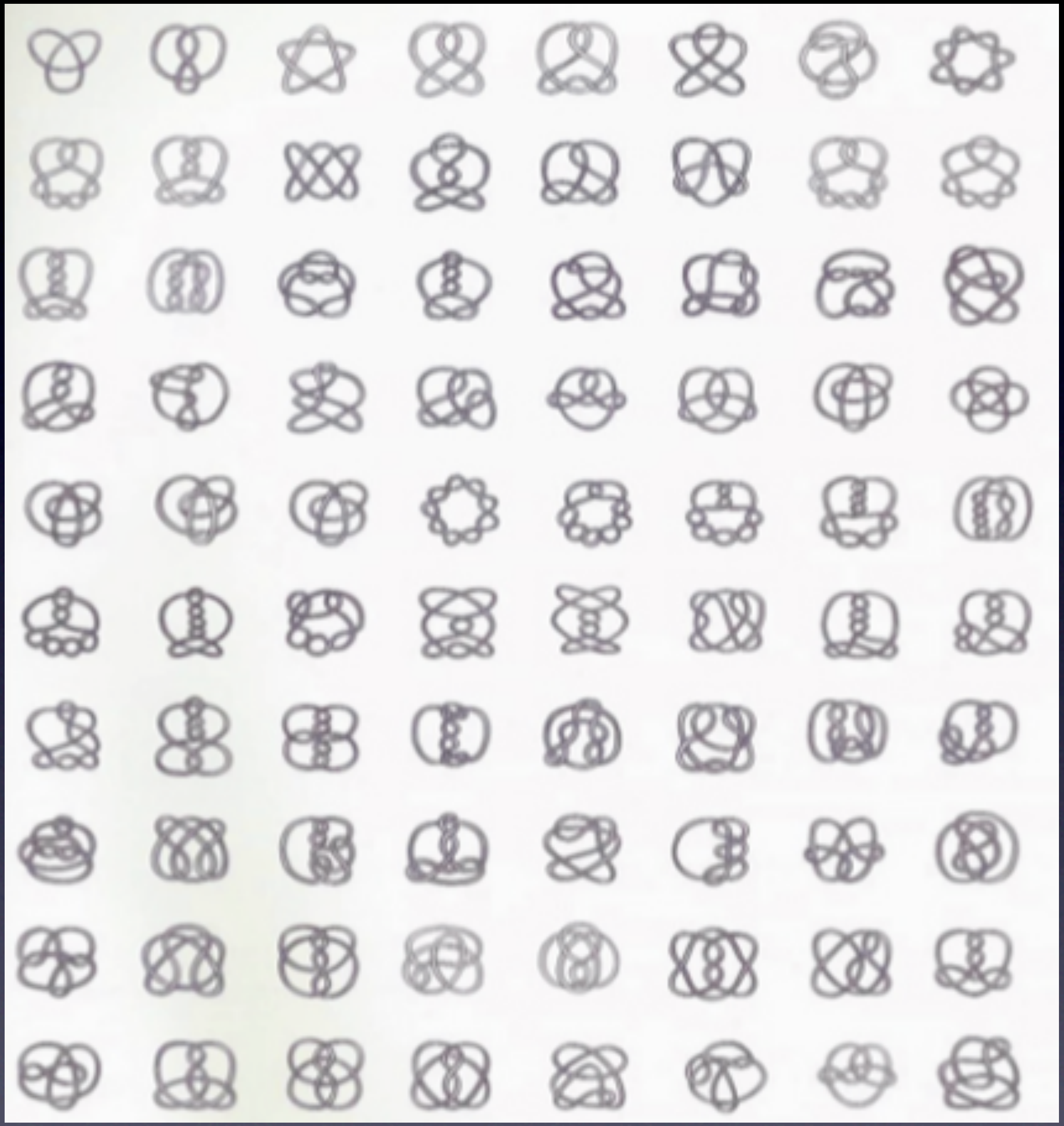
3_1 knot

(3 crossings, 1 component)



3^2_1 link (3 crossings, 2 components)

[Buniy, Kephart '03]



[Dale Rolfson: Knots and Links]

Alternative: Knotted strings & flavor

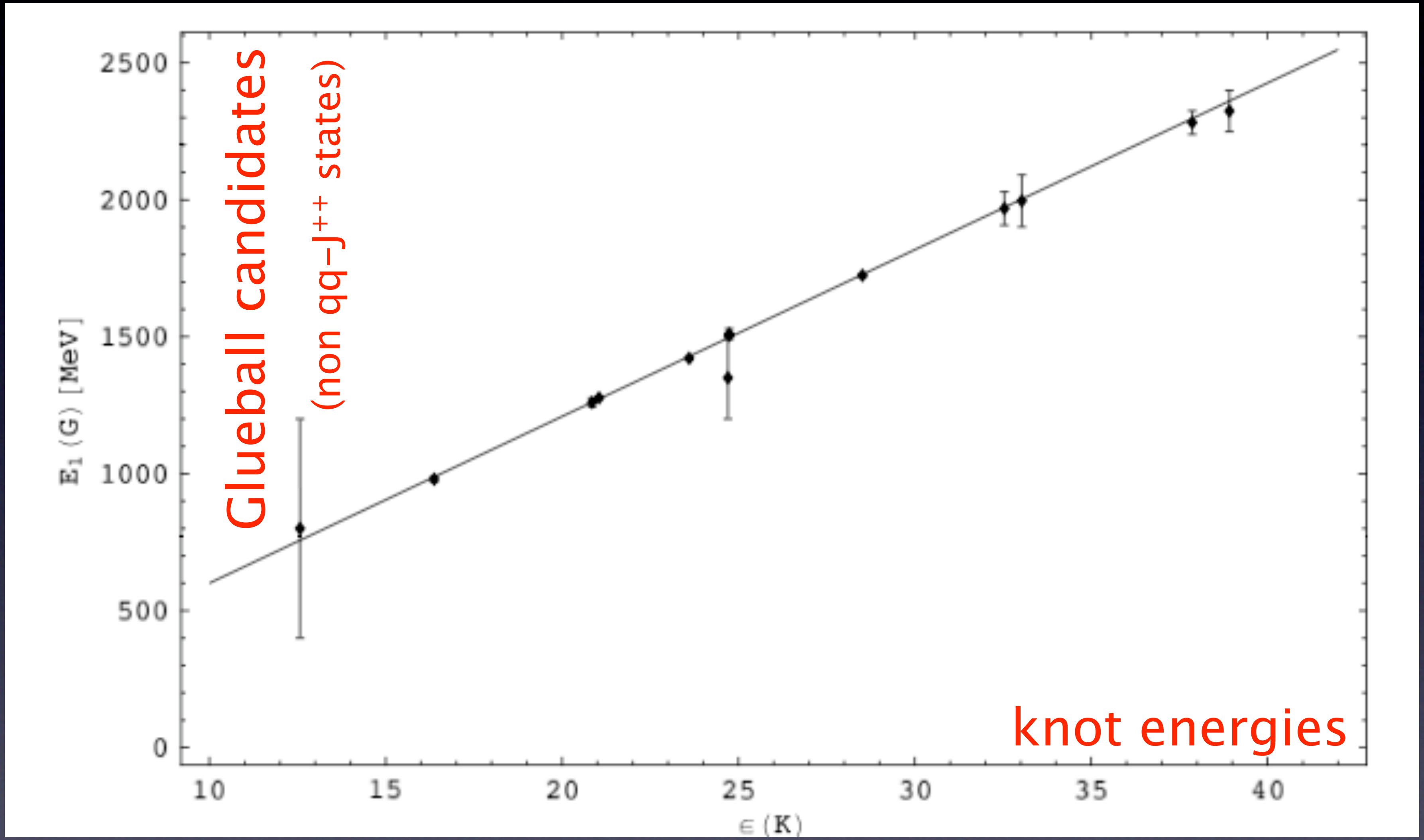
- Lengths of the smallest knots and links
- Several numbers lying closeby!
- Numerology?

Link	Rop_p	Rop
2_1^2	25.1415	25.1334
3_1	32.7437	32.7436
4_1	42.0971	42.0887
4_1^2	40.0203	40.0122
5_1	47.2149	47.2016
5_2	49.4820	49.4701
5_1^2	49.7864	49.7716
6_1	56.7178	56.7058
6_2	57.0381	57.0235
6_3	57.8531	57.8392
6_1^2	54.3919	54.3768
6_2^2	56.7087	56.7000
6_3^2	58.1142	58.1013
6_1^3	57.8286	57.8141
6_2^3	58.0112	58.0070
6_3^3	50.5602	50.5539
7_1	61.4234	61.4067
7_2	63.8684	63.8556
7_3	63.9430	63.9285
7_4	64.2836	64.2687
7_5	65.2705	65.2560
7_6	65.7068	65.6924
7_7	65.6235	65.6086

[Ashton, Cantarella, Piatek, Rawdon, arXiv:1002.1723]

Alternative: Knotted strings & flavor

- What's relating know lengths and particle physics?
- Assume knot length $\propto$ knot energy (flux tube model)



[Buniy, Kephart '03,'05; Buniy, Holmes, Kephart '09]

- Excellent fit to the spectrum of glueball candidates!

Alternative: Knotted strings & flavor

- String theory (+ AdS/QCD duality): glueballs, gravitons and modulinos are open strings
- [Arkani-Hamed, Dvali, Dimopoulos, March-Russell + some 400 cites]: Right-handed neutrinos can be closed string modulinos

→Obtain Leptonic flavor structures by assuming right-handed neutrino masses are dominated by knot and link energies?

- 6×6 seesaw matrix:

$$m_\nu = \begin{pmatrix} 0 & m_D^{\text{diag}} \\ m_D^{\text{diag}} & M_R \end{pmatrix}$$

Mixing purely from right-handed sector!

$$M_R = \begin{pmatrix} \text{knot}_1 & \text{link}_1 & \text{link}_2 \\ \text{link}_1 & \text{knot}_2 & \text{link}_3 \\ \text{link}_2 & \text{link}_3 & \text{knot}_3 \end{pmatrix}$$

[Kephart, Leser, Päs, 2011]

Comparing model with data: back on the envelope

Diagonalizing the seesaw formula:

$$M^{\nu}_{\mathrm{flv}} = m_{\mathrm{D}}^{T} M^{-1} m_{\mathrm{D}}$$

$$M^{\nu}_{\mathrm{flv}} = \frac{1}{\Delta^3} \begin{pmatrix} \left[m_2^{\mathrm{K}} m_3^{\mathrm{K}} - (m_3^{\mathrm{L}})^2\right] (m_1^{\mathrm{D}})^2 & (m_2^{\mathrm{L}} m_3^{\mathrm{L}} - m_3^{\mathrm{K}} m_1^{\mathrm{L}}) m_1^{\mathrm{D}} m_2^{\mathrm{D}} & (m_1^{\mathrm{L}} m_3^{\mathrm{L}} - m_2^{\mathrm{K}} m_2^{\mathrm{L}}) m_1^{\mathrm{D}} m_3^{\mathrm{D}} \\ (m_2^{\mathrm{L}} m_3^{\mathrm{L}} - m_3^{\mathrm{K}} m_1^{\mathrm{L}}) m_1^{\mathrm{D}} m_2^{\mathrm{D}} & \left[m_1^{\mathrm{K}} m_3^{\mathrm{K}} - (m_2^{\mathrm{L}})^2\right] (m_2^{\mathrm{D}})^2 & (m_1^{\mathrm{L}} m_2^{\mathrm{L}} - m_1^{\mathrm{K}} m_3^{\mathrm{L}}) m_2^{\mathrm{D}} m_3^{\mathrm{D}} \\ (m_1^{\mathrm{L}} m_3^{\mathrm{L}} - m_2^{\mathrm{K}} m_2^{\mathrm{L}}) m_1^{\mathrm{D}} m_3^{\mathrm{D}} & (m_1^{\mathrm{L}} m_2^{\mathrm{L}} - m_1^{\mathrm{K}} m_3^{\mathrm{L}}) m_2^{\mathrm{D}} m_3^{\mathrm{D}} & \left[m_1^{\mathrm{K}} m_2^{\mathrm{K}} - (m_1^{\mathrm{L}})^2\right] (m_3^{\mathrm{D}})^2 \end{pmatrix}$$

with

$$\Delta^3 = -m_3^{\mathrm{K}} (m_1^{\mathrm{L}})^2 + 2 m_1^{\mathrm{L}} m_2^{\mathrm{L}} m_3^{\mathrm{L}} - m_2^{\mathrm{K}} (m_2^{\mathrm{L}})^2 - m_1^{\mathrm{K}} (m_3^{\mathrm{L}})^2 + m_1^{\mathrm{K}} m_2^{\mathrm{K}} m_3^{\mathrm{K}}$$

and compare with TBM mixing for various hierarchies

Comparing model with data: back on the envelope

Normal hierarchy $\mathrm{diag}(0,0,\tilde{m})$ $\Rightarrow$ $\tilde{m}\cdot\begin{pmatrix}0 & 0 & 0\\ 0 & \frac{1}{2} & -\frac{1}{2}\\ 0 & -\frac{1}{2} & \frac{1}{2}\end{pmatrix}$

$$m_3^{\mathrm{K}}/m_2^{\mathrm{K}} = (m_2^{\mathrm{D}})^2/(m_3^{\mathrm{D}})^2,\ m_2^{\mathrm{L}}/m_1^{\mathrm{L}} = m_3^{\mathrm{D}}/m_2^{\mathrm{D}},\ m_2^{\mathrm{K}}m_2^{\mathrm{L}} = m_1^{\mathrm{L}}m_3^{\mathrm{L}}$$

$$m_1^{\mathrm{K}}m_2^{\mathrm{K}} \neq (m_1^{\mathrm{L}})^2,\ \tilde{m} = 2\,(m_3^{\mathrm{D}})^2\left((m_1^{\mathrm{L}})^2 - m_1^{\mathrm{K}}m_2^{\mathrm{K}}\right)/\Delta^3$$

m_i^{D} are assumed to be roughly equal $\Rightarrow$ with $m_i^{\mathrm{K/L}} = \ell_i^{\mathrm{K/L}}\cdot m_{\mathrm{S}}$

ℓ_i^{K} and ℓ_i^{L} are close to each other. $\Rightarrow$

Knots and links fit better than random numbers!

Comparing model with data: back on the envelope

Inverse hierarchy

$$\mathrm{diag}(\tilde{m}, \tilde{m}, 0) \Rightarrow \tilde{m} \cdot \begin{pmatrix} 1 & 0 & 0 \\ 0 & \frac{1}{2} & \frac{1}{2} \\ 0 & \frac{1}{2} & \frac{1}{2} \end{pmatrix}$$

$\Rightarrow$ can only be solved if $\tilde{m} = 0$

$\Rightarrow$ Disfavored for knots and links!

Degenerate neutrinos

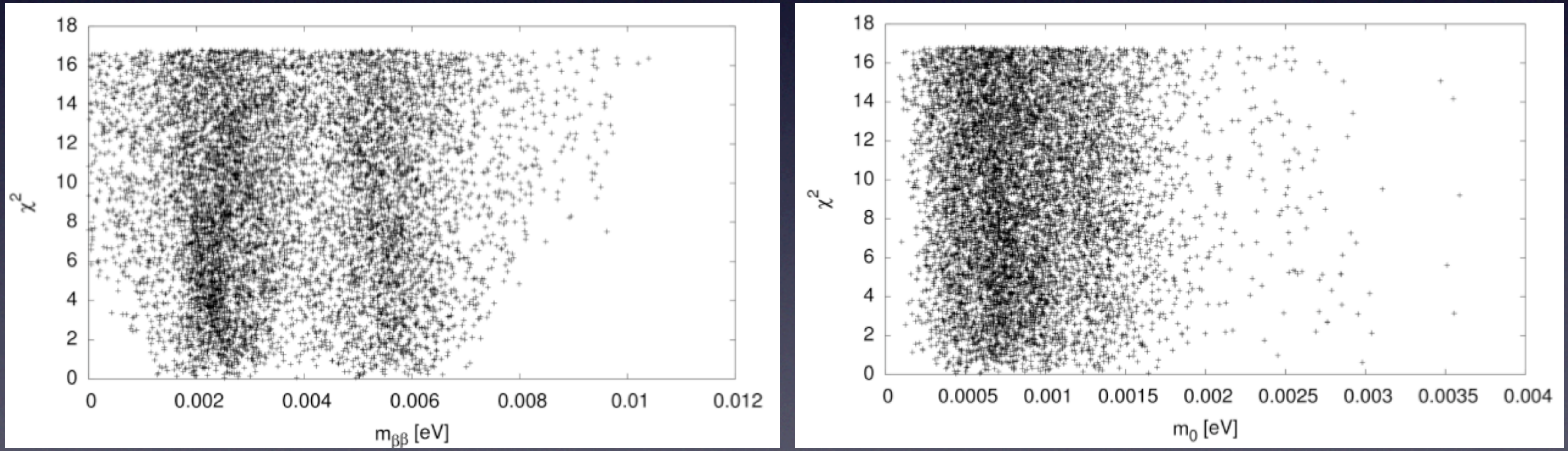
$$\mathrm{diag}(\tilde{m}, \tilde{m}, \tilde{m}) \Rightarrow m_1^{\mathrm{L}} = m_2^{\mathrm{L}} = m_3^{\mathrm{L}} = 0$$

$\Rightarrow$ Disfavored for knots and links!

Results:

To be done: implement θ_{13}

- Excellent fit: $\chi^2 \approx 0.04$
- Comparison with random numbers favorable
- Normal hierarchy preferred (bad news for $0\nu\beta\beta$ decay search)



[Kephart, Leser, Päs, 2011]

Conclusions

- Huge variety of flavor models
- Neither generic predictions nor discriminators in the ν sector
- Flavor models where the same Higgses break EW and Flavor symmetry: characteristic Higgs sectors
- Spectacular LFV signals at the LHC
- But also: Symmetry and Anarchy are not the only explanation for the leptonic Flavor structure
- Example: seesaw models with right-handed ν's as knotted strings