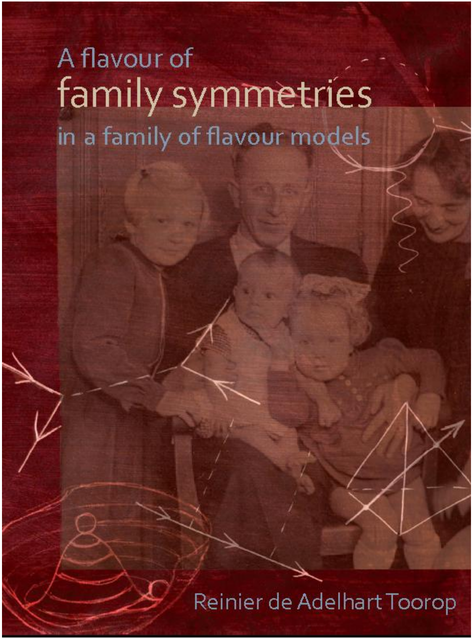
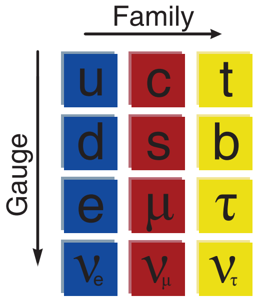

A flavour of
family symmetries
in a family of flavour models
Reinier de Adelhart Toorop

Outline

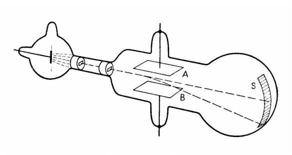
1. Motivation of family symmetries
2. A ‘vanilla’ family symmetry model
   - The Altarelli-Feruglio A_4 model
3. Non-zero θ_{13}
   - Mixing patterns of finite modular groups
   - Mixing patterns with large NLO corrections
   - Flavour symmetries at the Electroweak scale
4. conclusions

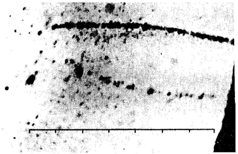
- Central theme of my thesis: family symmetries.
- Related to the existence of three families
- Motivation is threefold.
  - Structure in similarity
  - Structure in difference 1: masses
  - Structure in difference 2: mixing

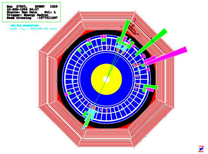


Structure in similarity

- Charged leptons of all three generations
  - Same charges
  - Same spin
- Complete generation replication quite special
  - Although partly explained by anomalies
- In the Standard Model this is considered an experimental fact...
  - ...but not explained by a deeper reason.

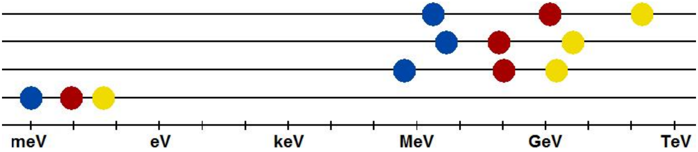






Structure in difference 1: masses

- Particles of the three generations differ in their masses.
- The masses are highly hierarchical.
- On a logarithmic scale, there might be some structure.



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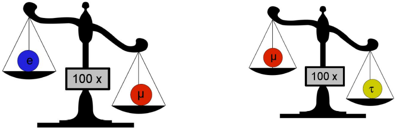

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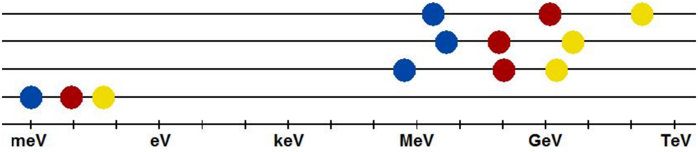

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- Mass and weak interaction eigenstates do not coincide.
  - Quarks: moderate CKM-mixing,
  - Leptons: strong PMNS-mixing.

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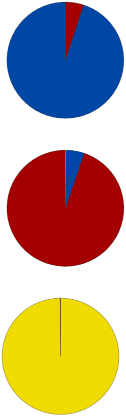

$$|(V_{CKM})_{ij}| = \begin{pmatrix} 0.97 & 0.23 & 0.0039 \\ 0.23 & 1.0 & 0.041 \\ 0.0081 & 0.038 & 1? \end{pmatrix}$$

C. Amsler et al. Review of particle physics, July 2008

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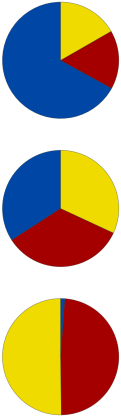
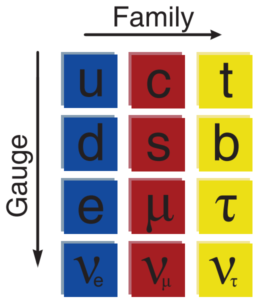


$$|(U_{PMNS})_{ij}| = \begin{pmatrix} 0.81 & 0.56 & <0.22 \\ 0.39 & 0.59 & 0.68 \\ 0.38 & 0.55 & 0.70 \end{pmatrix}$$

M.C. Gonzales Garcia Nucl. Phys. A **827** (2009) 5C

Coincidence or symmetry?

- The observed patterns might be purely coincidental.
  - 22 of 28 free parameters in SM relate to fermion mass sector.
  - Their values may just be like this.
- More interesting: the patterns follow from a symmetry principle.

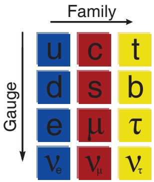


Flavour Symmetries

These structures might be explained by flavour/family symmetries

- We charge the families under a symmetry group.
- To make the Lagrangian invariant, we need to add Higgs-like fields 'flavons'.
- Structure in flavon-VEVs leads to structure in the fermion masses.
- Non-renormalizable operators often occur
    - Terms suppressed by VEV/Λ.

A very good introduction: G. Altarelli, Models of neutrino masses and mixings; hep-ph/0611117

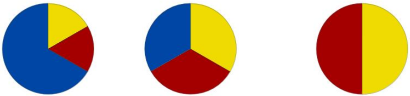


The Altarelli-Feruglio model

- We consider a model by Altarelli and Feruglio

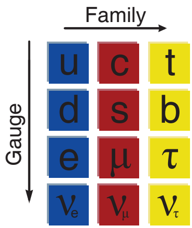
  G. Altarelli and F. Feruglio,, Nucl. Phys. **B741** (2006) 215-235. [hep-ph/0512103]

- It discusses only the lepton sector.
  - It explains charged lepton and neutrino masses.
- It reproduces tribimaximal mixing.



The group A_4 and the A-F model

- The flavour symmetry group is A_4
- The symmetry group of the tetrahedron.
  - "toprotations" 120° and 240°.
  - "axisrotations" 180°.



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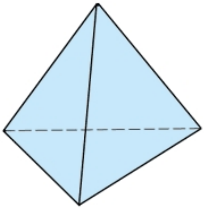

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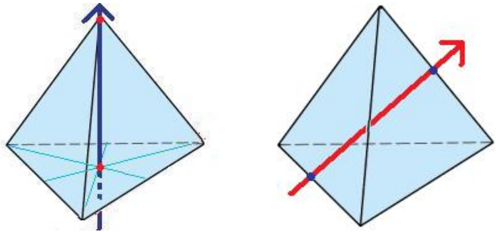
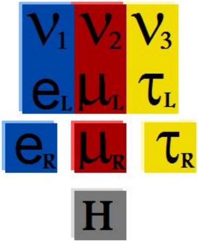


Matter in the A-F model

- The group A_4 has
  - Three 1-d irreps: 1, 1' and 1".
  - One 3-d irrep

- Matter assignment:
  - Lepton doublets in **3**
    - lefthanded electron
    - normal neutrino
  - Lepton singlets are in the three different 1-d reps.
    - righthanded electron
  - The Higgs transforms trivially under A_4.
- The model is supersymmetric for practical purposes.



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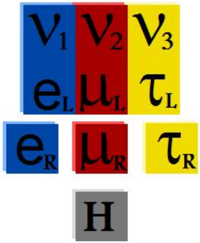

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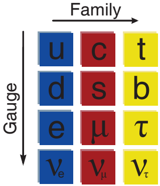
Flavons in the A-F model

- $\mathcal{L}$ is not invariant under A_4.
- Two flavons are needed.
- One couples to the neutrinos.
  - Its vacuum expectation values breaks A_4.
  - But leaves a Z_2 symmetry.
- One couples to the charged leptons.
  - It leaves a Z_3 symmetry.



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$$w_e = \frac{y_e}{\Lambda}\bar{e_R}(\varphi_T l_L)_1 h + \frac{y_\mu}{\Lambda}\bar{\mu_R}(\varphi_T l_L)_{1'} h + \frac{y_\tau}{\Lambda}\bar{\tau_R}(\varphi_T l_L)_{1''} h$$

$$w_\nu = \frac{x_a}{\Lambda}(\tilde{h}l)(\tilde{h}l) + \frac{x_a}{\Lambda^2}\varphi_S(\tilde{h}l)(\tilde{h}l)$$

$$\langle H \rangle = v, \quad \langle \varphi_T \rangle = (u,0,0)\Lambda, \quad \langle \varphi_S \rangle = (u',u',u')\Lambda$$

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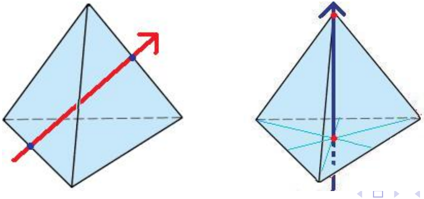

Tri-bimaximal mixing in the A-F model

- The superpotential
- Together with the vev structures
- Gives the mass matrices
- That is exactly diagonalized by the tribimaximal matrix

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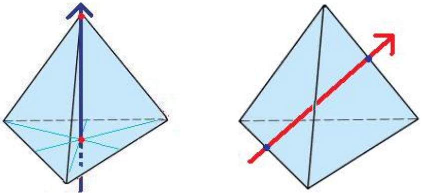

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$$M_l = \mathrm{diag}(y_e, y_\mu, y_\tau) v u$$

$$M_\nu = \begin{pmatrix} a+2b & -b & -b \\ -b & 2b & a-b \\ -b & a-b & 2b \end{pmatrix} v^2$$

Tri-bimaximal mixing in the A-F model

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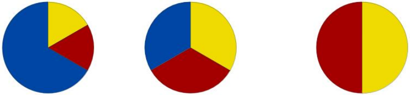
$$U_{\mathrm{TBM}}^T M_\nu U_{\mathrm{TBM}} = \begin{pmatrix} m_1 = a+b & 0 & 0 \\ 0 & m_2 = a & 0 \\ 0 & 0 & m_3 = -a+b \end{pmatrix}$$

The A-F model: conclusion

- The Altarelli-Feruglio model can reproduce tribimaximal mixing.
- The residual symmetries of the flavons were crucial.
- Basically, the Z_3 and the Z_2 give the *tri* and the *bi* of tribimaximal mixing.



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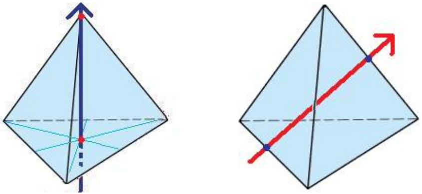

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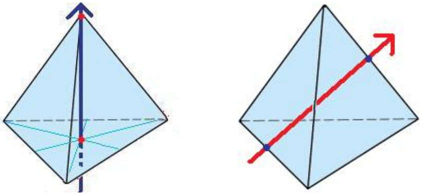


Vanishing reactor mixing angle $\theta_{13} = 0$

- The Altarelli-Feruglio model reproduces tribimaximal mixing.
- It thus gives $\theta_{13} = 0$.
  - Subleading corrections can give tiny corrections.
- Allowed at $\sim 2\sigma$ at the time of the model.

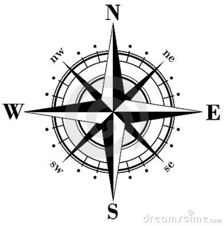

2010
2011

Non-zero reactor mixing angle $\theta_{13} \neq 0$

- Recent results of T2K, Minos, Double Chooz and (last week) Daya Bay.
- $\theta_{13} \neq 0$ at the 3-5 sigma level.
- But ‘vanilla’ flavour symmetry models predict it to be zero.

What to do?

- Directions in theory space.
  1. Give up on flavour symmetries.
  2. Work out new mixing patterns apart from TBM mixing.
  3. Build models with (T)BM and large corrections.
  4. Build models that do not predict mixing angles.
     - Keep they other good properties.
     - At the electroweak scale.



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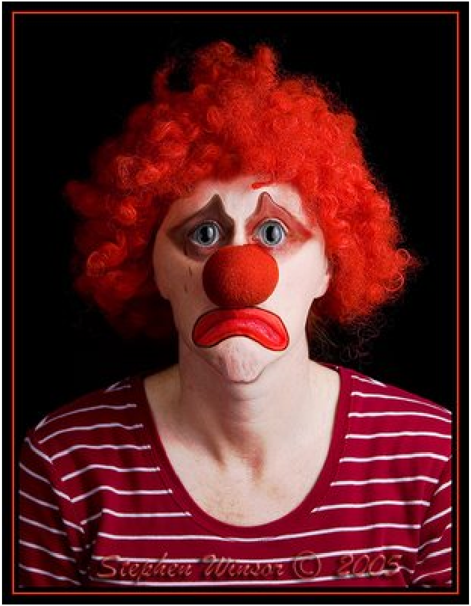
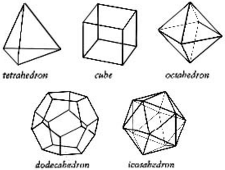

Stephen Winsor © 2005

2. Find new mixing patterns.

Modular Subgroups

Based on R. de Adelhart Toorop, F. Feruglio and C. Hagendorn Phys.Lett. B703 (2011) 447 and Nucl.Phys. B858 (2012) 437

- In the Altarelli-Feruglio model, the group A_4 reproduced tribimaximal mixing
- Many other models in the literature use the groups S_4 and A_5
- These groups have in common
  - That they are symmetry groups of Platonic solids.
  - That they are subgroups of the modular group.



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$$S^2 = 1, \qquad (S.T)^3 = 1, \qquad \begin{cases} T^3 = 1, & \text{for } A_4 \\ T^4 = 1, & \text{for } S_4 \\ T^5 = 1, & \text{for } A_5 \end{cases}$$

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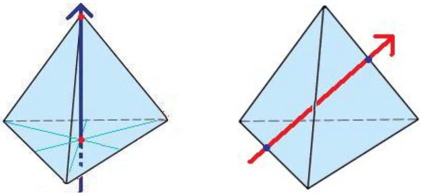
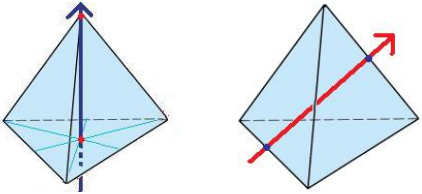


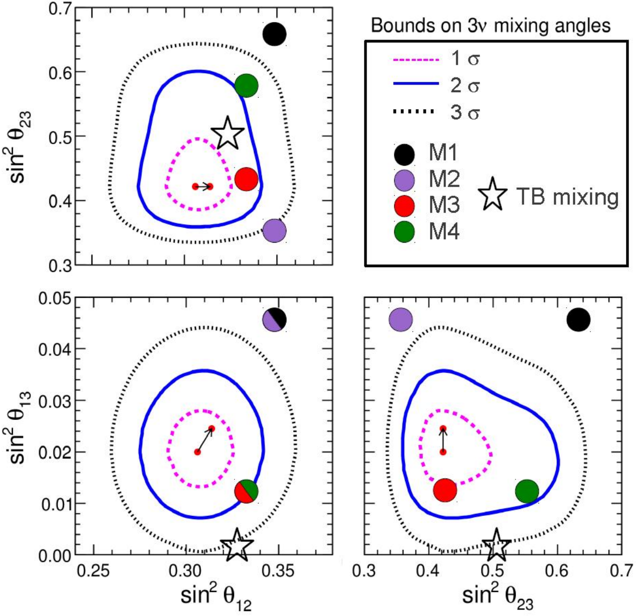
Modular Subgroups

- The second criterion easily generalizes
- If we demand three-dimensional irreps
- Three new candidate groups
  - $PSL(2,7)$ with $T^7 = 1$ (and $(ST^{-1}ST)^4 = 1$)
  - $\Delta(96)$ with $T^8 = 1$ (and $(ST^{-1}ST)^3 = 1$)
  - $\Delta(384)$ with $T^{16} = 1$ (and $(ST^{-1}ST)^3 = 1$)

Modular Subgroups

- We investigate lepton mixing patterns from these groups.
- Same assumptions as in Altarelli-Feruglio model.
  - Residual symmetries in charged lepton and neutrino sectors
- Interesting mixing patterns from $\Delta(96)$ and $\Delta(384)$



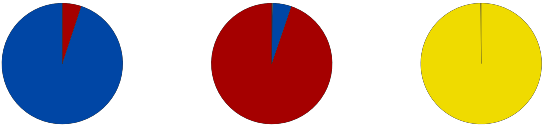

Bounds on 3ν mixing angles
1 σ
2 σ
3 σ
M1
M2
M3
M4
TB mixing
sin² θ23
sin² θ13
sin² θ12
sin² θ23
0.7
0.6
0.5
0.4
0.3
0.05
0.04
0.03
0.02
0.01
0.00
0.25
0.30
0.35
0.3
0.4
0.5
0.6
0.7

3. Mixing patterns with large corrections

Large NLO corrections

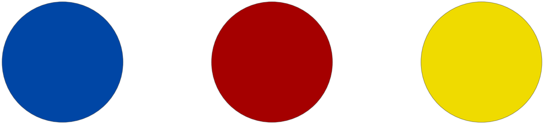
Based on R. de Adelhart Toorop, F. Bazzocchi and L. Merlo JHEP 1008 (2010) 001 (and many other papers)

- look again at quark mixing
- Only very moderate mixing.
- Even Cabibbo angle remarkably small.



Large NLO corrections

- Idea: in first approximation no mixing
- The reproduce the Cabibbo angle by NLO effects
- NLO terms have an extra flavon
  - And are thus (even more) non-renormalizable.
  - Effect suppressed by (extra) factor of VEV/$\Lambda \sim 0.2$.
- The two other (tiny) mixing follow at even higher order.



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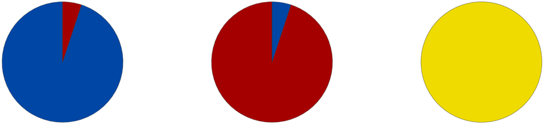

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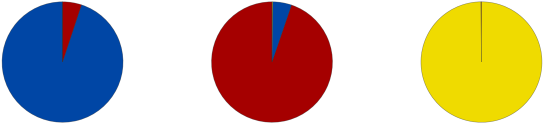
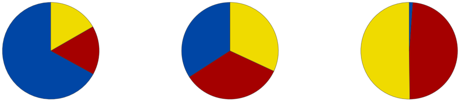


Quark-lepton complementarity

- Philosophy of the previous slide:
  - Quark sector
  - moderate corrections from LO to NLO.
- This might also be the case in the neutrino sector.
  - At LO: reproduce tribimaximal mixing
  - Or the similar bimaximal mixing
  - Large corrections then give $\theta_{13} \neq 0$.
  - In accordance with the data

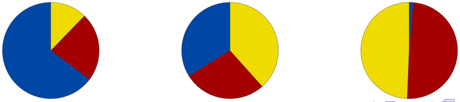
Quark-lepton complementarity

- Neutrino data



- LO approximation

- NLO approximation

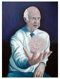


4. Flavour symmetries at the Electroweak scale

Flavour symmetries at the Electroweak scale

Based on R. de Adelhart Toorop, F. Bazzocchi, L. Merlo and A. Paris JHEP 1103 (2011) 035 and 040

- Models discussed so far: very high energy scale.
- Alternatively: at the Electroweak scale.
  - Models very predictive.
  - But not in mixing angles.
  - Non-zero θ_{13} no problem.

 = 

Problems of models with flavons

- Models with flavons can become quite baroque.
  - Model of the previous section: 10 new flavon fields.
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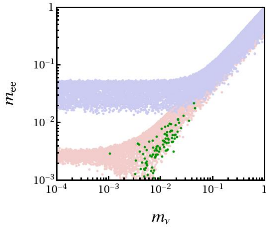

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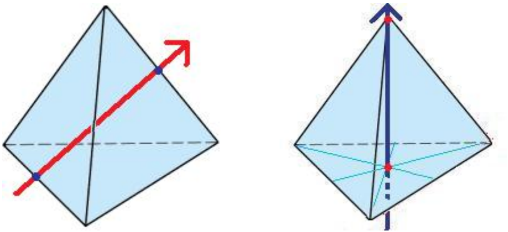
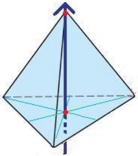


Flavo-Higgs

- Alternative: assume only one direction in flavon space.
- The SM Higgs can play the role of the flavons.
  - Much simpler models.
  - Flavour scale = Higgs scale → testable at LHC.



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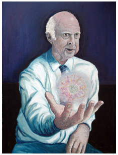

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The A_4-Higgs model

- Assume three copies of the SM Higgs field.

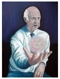
The A_4-Higgs model

- Assume three copies of the SM Higgs field.
- In a triplet of the flavour group A_4.

$$\Phi_1 \to \frac{1}{\sqrt{2}} \begin{pmatrix} \phi_1^1 \\ v_1 e^{i\omega_1} + \phi_1^0 \end{pmatrix}, \quad \Phi_2 \to \frac{1}{\sqrt{2}} \begin{pmatrix} \phi_2^1 \\ v_2 e^{i\omega_2} + \phi_2^0 \end{pmatrix},$$

$$\Phi_3 \to \frac{1}{\sqrt{2}} \begin{pmatrix} \phi_3^1 \\ v_3 e^{i\omega_3} + \phi_3^0 \end{pmatrix}.$$

- The vector of vevs $(v_1 e^{i\omega_1}, v_2 e^{i\omega_2}, v_3 e^{i\omega_3})$ serves as the flavon.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The A_4-invariant Higgs potential

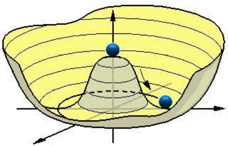
- The Higgs potential

$$
\begin{aligned}
V &= \mu^2(\Phi_1^\dagger\Phi_1 + \Phi_2^\dagger\Phi_2 + \Phi_3^\dagger\Phi_3) + \lambda_1(\Phi_1^\dagger\Phi_1 + \Phi_2^\dagger\Phi_2 + \Phi_3^\dagger\Phi_3)^2 \\
&+ \lambda_3(\Phi_1^\dagger\Phi_1\Phi_2^\dagger\Phi_2 + \Phi_1^\dagger\Phi_1\Phi_3^\dagger\Phi_3 + \Phi_2^\dagger\Phi_2\Phi_3^\dagger\Phi_3) \\
&+ \lambda_4(\Phi_1^\dagger\Phi_2\Phi_2^\dagger\Phi_1 + \Phi_1^\dagger\Phi_3\Phi_3^\dagger\Phi_1 + \Phi_2^\dagger\Phi_3\Phi_3^\dagger\Phi_2) \\
&+ \frac{\lambda_5}{2}\Bigg[e^{i\epsilon}[(\Phi_1^\dagger\Phi_2)^2 + (\Phi_2^\dagger\Phi_3)^2 + (\Phi_3^\dagger\Phi_1)^2] + \\
&\qquad e^{-i\epsilon}[(\Phi_2^\dagger\Phi_1)^2 + (\Phi_3^\dagger\Phi_2)^2 + (\Phi_1^\dagger\Phi_3)^2]\Bigg],
\end{aligned}
$$

- allows a number of minimum configurations.

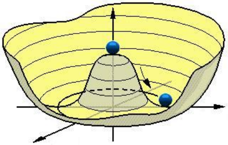
Minima of the Higgs potential

- The Higgs potential allows a number of minimum configurations.
    - If all vevs are real: CP conserving
        - (v, v, v)
        - $(v, 0, 0)$
    - If some vevs are complex: CP violating
        - $(ve^{i\omega}, rv, 0)$
        - $(ve^{i\omega}, ve^{-i\omega}, rv)$



Constraining flavo-Higgs models

- Not all parameter choices give realistic models.
- We constrain the models by
  - Positive m^2 for all 5 neutral and 2 charged Higgses
  - Unitarity constraints
  - Z- and W-decay constraints
  - Oblique parameters
  - For models with explicit fermion content
    - Rare decays
    - Meson oscillations

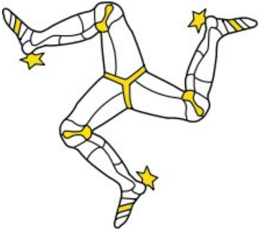


The alignment (v, v, v)

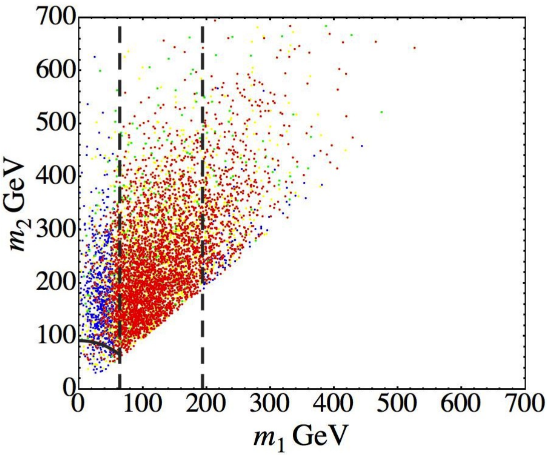
- The CP conserving alignment (v, v, v)

  E. Ma and G. Rajasekaran, Phys. Rev. D **64**, 113012 (2001)

  - Residual Z_3 symmetry
  - Higgs spectrum
    - SM Higgs boson
    - Two degenerate scalars
    - Two degenerate pseudoscalars



Fermion independent constraints



All masses ≥ 0: yellow points. Unitarity OK: blue points.

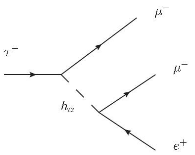
Z decay OK: green points. Oblique parameters OK: red points

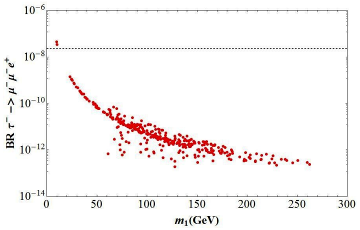
Tests

- $M^2 > 0$
- Unitarity
- Z and W
- Oblique

Fermion dependent constraints

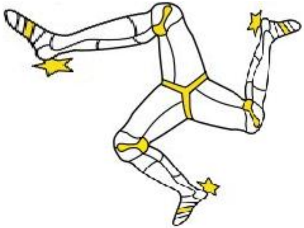
- In the Ma-Rajasekaran setup, many rare decays are indeed forbidden.
  - No $\mu^- \to e^- e^- e^+$ and $\mu^- \to e^- \gamma$
- Allowed decays are below experimental bounds.
  - $\tau^- \to \mu^- \mu^- e^+$





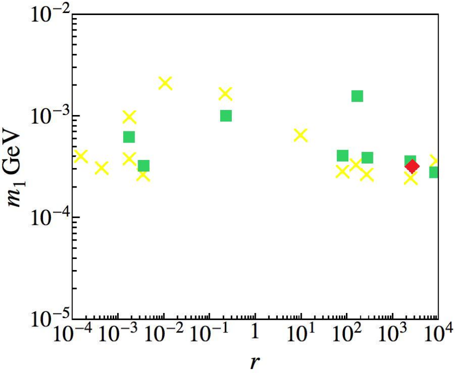
The alignment $(ve^{i\omega}, ve^{-i\omega}, rv)$

- The CP violating alignment $(ve^{i\omega}, ve^{-i\omega}, rv)$ (or permutations)
  Lepton sector: S. Morisi and E. Peinado, Phys. Rev. D **80**, 113011 (2009)
  Quark sector: L. Lavoura and H. Kuhbock, Eur. Phys. J. C **55**, 303 (2008)
  - No residual symmetry
  - Five Higgses are mixes of scalars and pseudoscalars.
  - Without softly breaking the A_4-invariant potential, not possible to have all ${m_h}^2 \geq 0$



Fermion independent constraints (with soft A_4-breaking terms)

- Scan over 100.000 points



All masses ≥ 0: yellow points. Unitarity OK: blue points.

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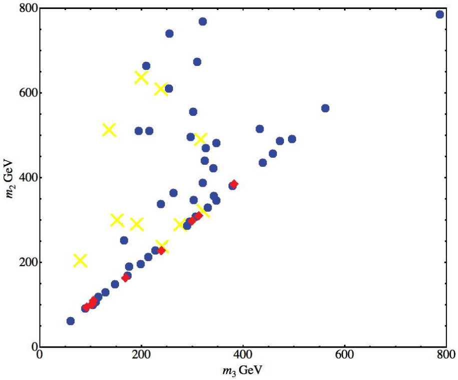
Fermion independent constraints (with soft A_4-breaking terms)

- Scan over few 1000 points; r fixed



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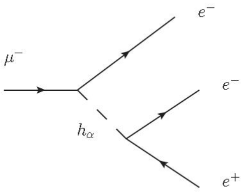
Rare fermion decays

- Rare fermion decays can be very constraining
  - $\mu^- \to e^- e^- e^+$ in Morisi and Peinaldo's model.
  - $\mu^- \to e^- \gamma$ less constraining



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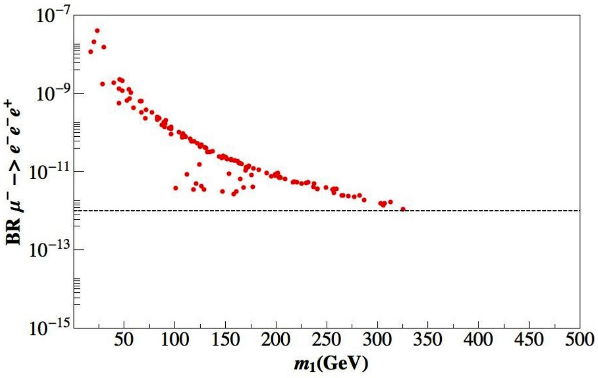

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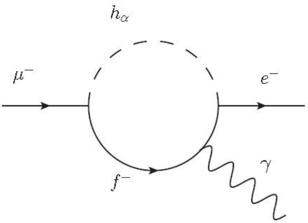

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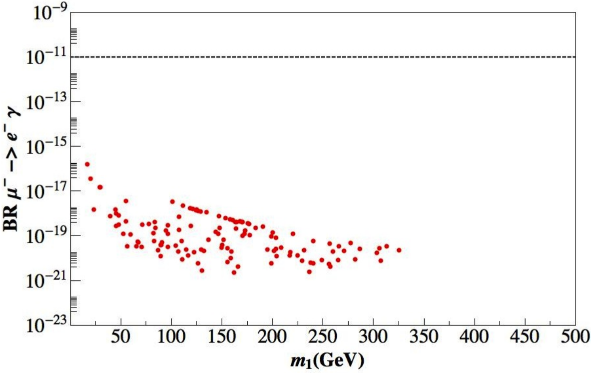
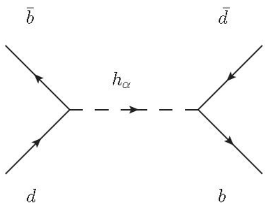


Meson oscillations

- In models with quarks, meson oscillations give very strong bounds.
  - $\Delta_{M_{B_d}}$ in $B_d \leftrightarrow {B_d}^*$ oscillations in Lavoura and Kuhbock's model.



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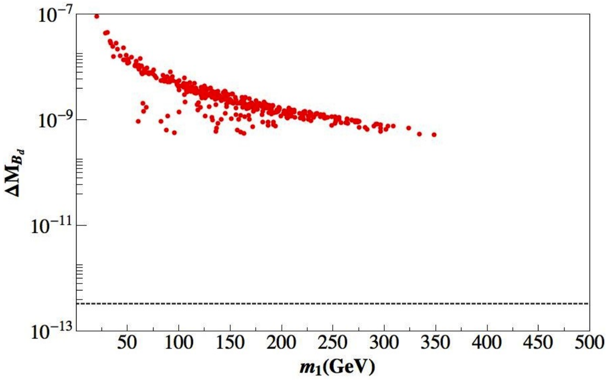

Conclusions

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    - New mixing patterns beyond tribimaximal.
    - Mixing patterns with large NLO corrections.
    - Flavour symmetries at the EW scale.
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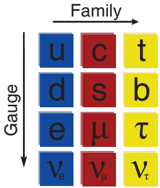

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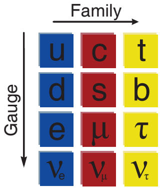

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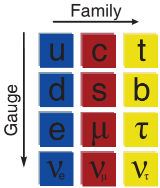

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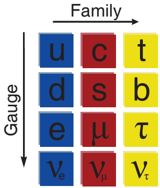

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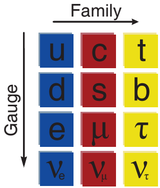

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