Quark-lepton complementarity in an S_4 Pati Salam inspired scenario

Based on work in progress with Federica Bazzocchi and Luca Merlo, hep-ph/0910.xxxx

Reinier de Adelhart Toorop, Nikhef, Amsterdam

Outline

1. Introduction: family physics
2. TriBiMaximal versus BiMaximal mixing
3. The model
4. Results and Conclusions

Family physics

- Family physics aims to explain the apparent structure in the fermion mass sector
  - Hierarchical masses
  - Quarks: moderate Cabibbo-mixing
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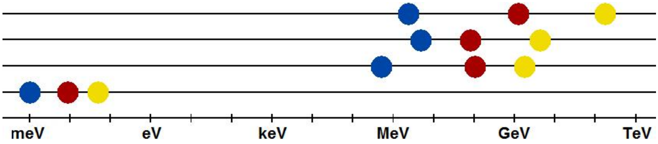

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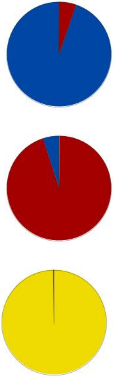

$$|(V_{CKM})_{ij}| = \begin{pmatrix} 0.97 & 0.23 & 0.0039 \\ 0.23 & 1.0 & 0.041 \\ 0.0081 & 0.038 & 1? \end{pmatrix}$$

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

Family physics

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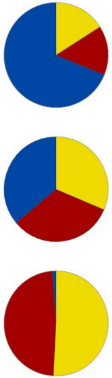
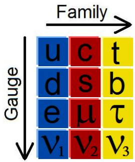
$$|(U_{PMNS})_{ij}| = \begin{pmatrix} 0.81 & 0.56 & <0.22 \\ 0.39 & 0.59 & 0.68 \\ 0.38 & 0.55 & 0.70 \end{pmatrix}$$



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

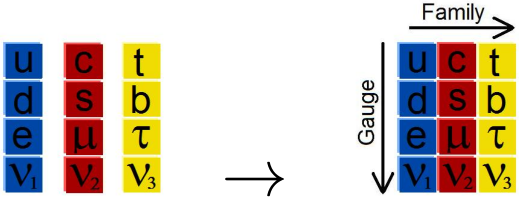
Family physics

- We charge the families under a symmetry group.
- To make the Lagrangian invariant, we need to add Higgs-like fields 'flavons'.
- Structure in the VEVs of the flavons leads to structure in the fermion masses. A very good introduction: G. Altarelli, Models of neutrino masses and mixings; hep-ph/0611117



Family Physics and Grand Unification

- Family symmetries unify the three families.
- Grand Unified Theories unify
  - The gauge couplings
  - The SM particles in fewer representations



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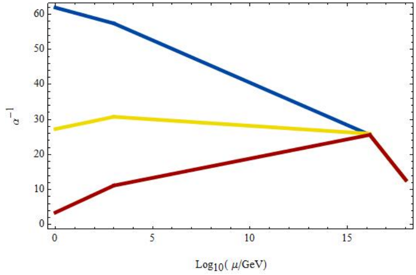

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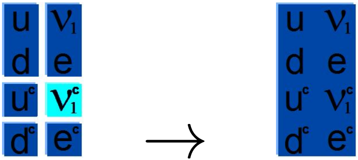

$$\left[\begin{pmatrix} u_R & u_G & u_B \\ d_R & d_G & d_B \end{pmatrix} + (u^c_R \quad u^c_G \quad u^c_B) + (d^c_R \quad d^c_G \quad d^c_B) + \begin{pmatrix} \nu \\ e \end{pmatrix} + (e^c) + (\nu^c) \right]_{\mathrm{SM}} \rightarrow$$

$$\left[(u_R \quad u_G \quad u_B \quad d_R \quad d_G \quad d_B \quad u^c_R \quad u^c_G \quad u^c_B \quad d^c_R \quad d^c_G \quad d^c_B \quad \nu \quad e \quad e^c \quad \nu^c) \right]_{\mathrm{SO(10)}}$$

Family Physics and Grand Unification

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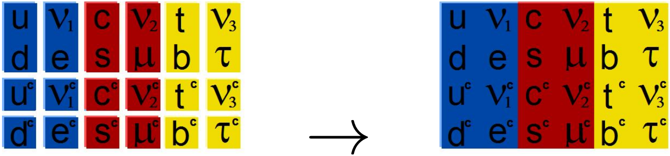
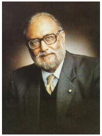
- We like to build models that combine Family Physics and Grand Unification.

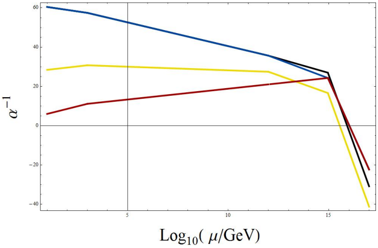


Pati-Salam

- We use Pati and Salam's $SU(4)_c \times SU(2)_L \times SU(2)_R$
  - Gauge: not quite unifying
  - All SM particles in two representations.
  - The type II seesaw can be dominant

This prevents unwanted correlations between quarks and neutrinos





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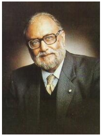

$$\left[\begin{pmatrix} u_R & u_G & u_B \\ u_R & d_G & d_B \end{pmatrix} \quad \begin{pmatrix} \nu \\ e \end{pmatrix} \right] \quad \& \quad \left[\begin{matrix} (u^c_R & u^c_G & u^c_B) \\ (d^c_R & d^c_G & d^c_B) \end{matrix} \quad \begin{matrix} (\nu^c) \\ (e^c) \end{matrix} \right]$$

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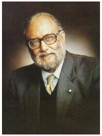


$$m_\nu^I = -m_{\text{Dir}}^T \frac{1}{M_{RR}} m_{Dir} \propto M_R^{-1}$$

$$m_\nu^{II} = M_{LL} \propto M_{3L}^{-1}$$

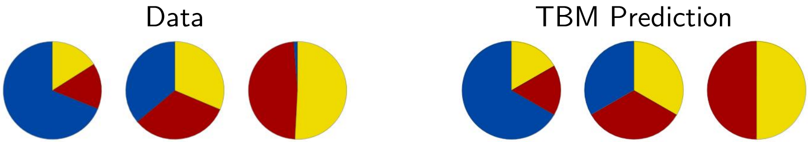
TriBiMaximal mixing

- Many models use tribimaximal mixing to model the neutrino mixing P. F. Harrison, D. H. Perkins and W. G. Scott, Phys. Lett. B **530** (2002) 167

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

$$\theta_{12} = 35^\circ, \quad \theta_{13} = 0^\circ, \quad \theta_{23} = 45^\circ.$$

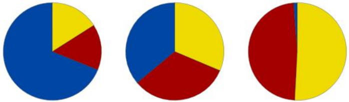
- This describes the data really well ...



- TBM mixing might describe the neutrino data a bit too well.
  - Most models describe the quark mixing poorly at Leading Order*.
  - The Cabibbo angle arises only via NLO effects.
  - Often these NLO effects influence the PMNS as well.

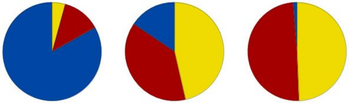
* LO is defined as having the lowest number of flavons possible; NLO has one extra flavon

Data



TBM LO

Typical TBM NLO



$\delta\theta_{12} = -0.9\theta_C, \quad \delta\theta_{13} = 0.5\theta_C$, so
$\theta_{12} = 23^\circ, \quad \theta_{13} = 7^\circ, \quad \theta_{23} = 45^\circ$, while $\delta = 0$.

BiMaximal mixing

- An alternative is BiMaximal mixing
- At leading order, two angles are maximal

$$U_{\rm BM} = \begin{pmatrix} \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & 0 \\ -\frac{1}{2} & \frac{1}{2} & -\frac{1}{\sqrt{2}} \\ -\frac{1}{2} & \frac{1}{2} & \frac{1}{\sqrt{2}} \end{pmatrix}$$

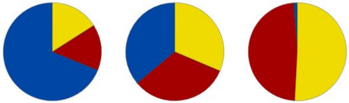
- And we can write $U_{\rm BM} =$ as the product of two maximal rotations

$$U_{\rm BM} = R_{23}(-\frac{\pi}{4}) \times R_{12}(\frac{\pi}{4})$$

- The leading order does not explain the data well.
- Via quark lepton complementarity at NLO it might.

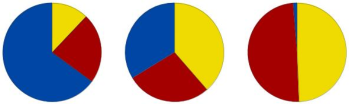
G. Altarelli, F. Feruglio and L. Merlo, JHEP **0905** (2009) 020

Data



BM LO

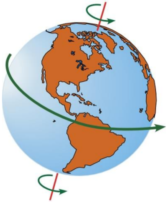
Typical BM NLO



$\delta\theta_{12} = -0.7\theta_C, \quad \delta\theta_{13} = 0.5\theta_C$, so
$\theta_{12} = 36^\circ, \quad \theta_{13} = 7^\circ, \quad \theta_{23} = 45^\circ$, while $\delta = 0$.

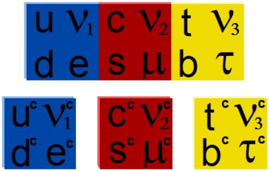
Rotations at leading order

- BiMaximal mixing models have at leading order
  - $V_{CKM} = V_u^\dagger V_d = \mathbb{1}$,
  - $U_{PMNS} = V_e^\dagger V_\nu = R_{23}(-\frac{\pi}{4}) R_{12}(\frac{\pi}{4})$
- This can be achieved if
  - M_ν^{II} is diagonalized by $V = R_{12}(\frac{\pi}{4})$
  - And $M_e M_e^\dagger$, $M_d M_d^\dagger$ and $M_u M_u^\dagger$ by $V_{e,d,u} = R_{23}(\frac{\pi}{4})$



Matter content of the model

- How to get such mass matrices?
  $\rightarrow$ Model details
  - Our family group is the discrete group S_4
  - We put the lefthanded PS multiplets F_L in a 3_a of S_4
  - We put the righthanded PS multiplets $F^c_{1,2,3}$ in 1_b, 1_b and 1_a of S_4
  - We introduce two flavons (σ, χ) in the neutrino sector
  - And two (φ, φ') for the charged particles



Neutrinos

- In the neutrino sector we introduce a singlet σ and a triplet χ

$$\chi \propto \begin{pmatrix} 0 \\ 0 \\ 1 \end{pmatrix}$$

- This gives the type II seesaw contributions

$$F_L F_L \to \begin{pmatrix} u_1 & 0 & 0 \\ 0 & u_1 & 0 \\ 0 & 0 & u_1 \end{pmatrix}, \quad F_L F_L \chi \to \begin{pmatrix} 0 & u_2 & 0 \\ u_2 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}$$

- That is indeed diagonalized by $V = R_{12}(\frac{\pi}{4})$

Charged particles

- For the charged particles we introduce a 3_a triplet φ and a 3_b triplet φ'

$$\varphi \propto \begin{pmatrix} 0 \\ 1 \\ 1 \end{pmatrix} \quad \varphi' \propto \begin{pmatrix} 0 \\ 1 \\ -1 \end{pmatrix}$$

- This leads to masses

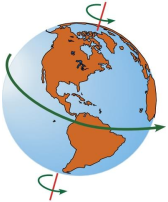
$$F_L F_3{}^c \varphi \rightarrow \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & y \\ 0 & 0 & y \end{pmatrix}, \quad F_L F_2{}^c \varphi' \rightarrow \begin{pmatrix} 0 & 0 & 0 \\ 0 & x & 0 \\ 0 & -x & 0 \end{pmatrix}$$

- The square is indeed diagonalized by $V = R_{23}(\frac{\pi}{4})$

$$MM^\dagger = \begin{pmatrix} 0 & 0 & 0 \\ 0 & y^2 + x^2 & y^2 - x^2 \\ 0 & y^2 - x^2 & y^2 + x^2 \end{pmatrix}$$

Rotations at leading order

- We indeed have at Leading order.
  - M_ν^{II} is diagonalized by $V = R_{12}(\frac{\pi}{4})$
  - And $M_e M_e^\dagger$, $M_d M_d^\dagger$ and $M_u M_u^\dagger$ by $V_{e,d,u} = R_{23}(\frac{\pi}{4})$
- So we indeed reproduce BiMaximal mixing.
  - $V_{CKM} = V_u^\dagger V_d = \mathbb{1}$,
  - $U_{PMNS} = V_e^\dagger V_\nu = R_{23}(-\frac{\pi}{4}) R_{12}(\frac{\pi}{4})$



Next-to-Leading Order

- At NLO M_ν^{II} is still diagonalized by $V = R_{12}(\frac{\pi}{4})$

$$M_\nu^{II} = \begin{pmatrix} u_1 & u_2\lambda & 0 \\ u_2\lambda & u_1 & 0 \\ 0 & 0 & u_1 + u_3\lambda^2 \end{pmatrix} \qquad \lambda \approx 0.2$$

- The charged particle mass matrices now read

$$M_x = \begin{pmatrix} 0 & \tilde{x}\lambda & \tilde{y}\lambda \\ 0 & x & y \\ 0 & -x & y \end{pmatrix}$$

Next-to-Leading Order

- $MM^\dagger$-matrices are diagonalized by

$$V_x = R_{23}(\frac{\pi}{4}) \times R_{13}(f\lambda) \times R_{12}(g_x\lambda),$$

  where $f = f_u = f_d = f_e$ and $g_u \neq g_d = g_e$ are $\mathcal{O}(1)$.

- The CKM matrix is

$$V_{CKM} = {V_u}^\dagger V_d = R_{12}((g_d - g_u)\lambda)$$

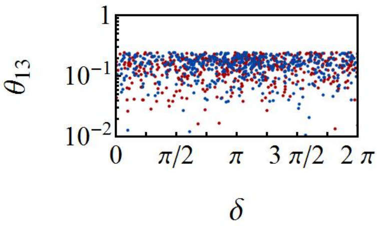
- And the PMNS matrix is

$$V_{PMNS} = {V_e}^\dagger V_\nu = R_{23}(-\frac{\pi}{4}) \times R_{13}(\tilde{f}\lambda) \times R_{12}(\frac{\pi}{4} - \tilde{g}_e\lambda)$$

Some Results

- The angle θ_{13} is predicted to be rather large and can be measured in near-future experiments.
- The neutrino masses are near-degenerate
- Neutrinoless double beta decay is in the sensitive area of near-future experiments

$$\theta_{13}^{\mathrm{PMNS}} = \tilde{f}\lambda \lesssim 0.18$$
$$\theta_{12}^{\mathrm{CKM}} = (g_d - g_u)\lambda \approx 0.23$$
$$\theta_{12}^{\mathrm{PMNS}} - \frac{\pi}{4} = -\tilde{g}_e\lambda \approx -0.17$$



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$$M_\nu^{II} = \begin{pmatrix} u_1 & u_2\lambda & 0 \\ u_2\lambda & u_1 & 0 \\ 0 & 0 & u_1 + u_3\lambda^2 \end{pmatrix}$$

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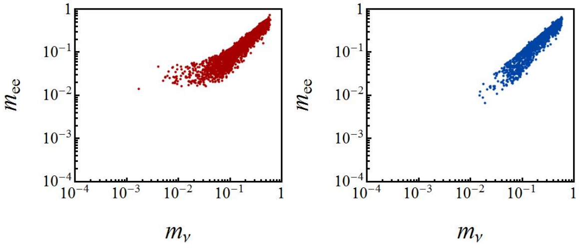

Conclusions

- Family Physics and Grand Unification both give a unified descriptions of the SM fermions.
- TriBiMaximal mixing and BiMaximal mixing patterns are both interesting.
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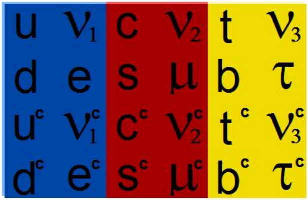
  - θ_{13} and $0\nu\beta\beta$ are expected to be measured soon.



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