A possibile common origin of quark and neutrino mixings

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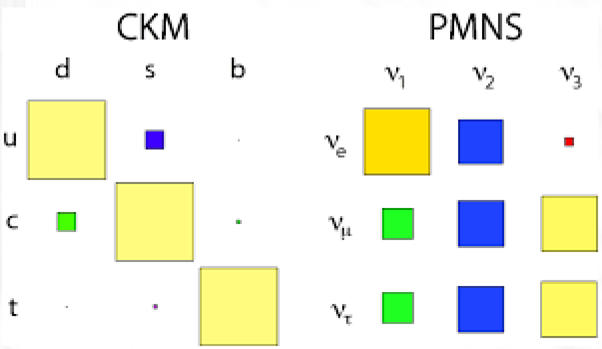
Standard oscillations

- Mixing matrix has the same structure in both contexts

$$U_{CKM,PMNS} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \times \begin{pmatrix} c_{13} & 0 & s_{13}e^{i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{-i\delta} & 0 & c_{13} \end{pmatrix} \times \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$



PMNS vs CKM

PMNS	CKM
all (but 1-3) matrix elements are of O(1)	matrix almost diagonal
one small and two large mixing angles	the three mixings are all small

In the Standard Model they do not talk to each other although the mechanism producing them is essentially the same

Mixing matrices

- U_{PMNS} and V_{CKM} have contributions from two different sectors

<u>leptons</u>

$$U_{PMNS} = U^{+l}_{j\alpha} U^{\nu}_{\alpha i}$$

<u>quarks</u>

$$V_{CKM} = U^{+d}_{j\alpha} U^{u}_{\alpha i}$$

from the diagonalisation of the charged lepton mass matrix

from the diagonalisation of the neutrino mass matrix

How to relate these two sectors ?

The need of New Physics

How to relate these two sectors ?

- Invoking GUT theories (different gauge groups):

  leptons and quarks sit in the same irreducible representations of the group

↓

Mass matrices are related

ex: SU(5)

$$\bar{5} = \begin{pmatrix} d_1^c \\ d_2^c \\ d_3^c \\ e^- \\ -\nu_e \end{pmatrix}_L \qquad m_d = m_e^T$$

ex: SO(10)

all left-handed fields in the unique 16 representation

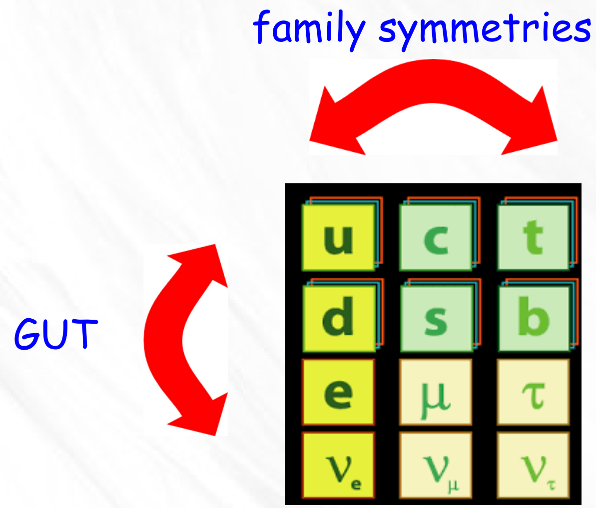
$$m_d = m_e^T$$
$$m_{up} = m_\nu^D$$

The need of New Physics

- to improve predictability: Invoke family symmetries:

different families sit in the same irreducible representations of the group

Matrix elements of mass matrices are related



GUT-A possible experimental hint

- Numerically, one sees that: $\theta_{12} + \theta_c \sim \pi/4$ → quark-lepton complementarity (QLC)

$\theta_{12} + O(\theta_c) \sim \pi/4$ is called *weak complementarity*

- Numerically, one also sees that: $\theta_{13} \sim \theta_c/\text{sqrt}[2]$

this suggests that the Cabibbo is a key-role parameter

Where θ_c enters in the lepton sector?

Nature seems to help us !

- $m_\mu/m_\tau \sim \theta^2_c$
- $m_e/m_\mu \sim \theta_c^{3\text{-}4}$

we have to deal with **mass matrices !**

GUT-A possible experimental hint

- for large fermion masses, we can use renormalizable operators (d=4):

$$\overline{\psi_L} H \psi_R$$

- to generate hierarchies, we can use non-renormalizable operators (d>=5):

$$\overline{\psi_L} H \psi_R \left(\frac{\varphi}{\Lambda}\right)^n$$

new scalar fields, with vev = $\langle\phi\rangle$

cut-off of the theory

this number should be smaller than 1

breaking of the flavor symmetry

$$\frac{\langle\varphi\rangle}{\Lambda} \sim \theta_C$$

- $m_\mu / m_\tau \sim$ (d=6) / (d=4)

Natural assumption: the vevs of the new scalar fields are all of the same order of magnitude

Getting the QLC

- The strategy:

Start with a model whose LO prediction in the neutrino sector is $\theta_{12} = \pi/4$

An easy task with family symmetries
Plethora of models in the literature

Frampton, Petcov and Rodejohann, Nucl. Phys. B687 (2004) 31
T.Ohlsson, Phys.Lett.B622, 159 (2005)
Altarelli, Feruglio and Merlo, JHEP0905, 020 (2009)
D.Meloni, JHEP1110, 010 (2011)
Altarelli, Machado and Meloni, arXiv:1504.05514 [hep-ph]

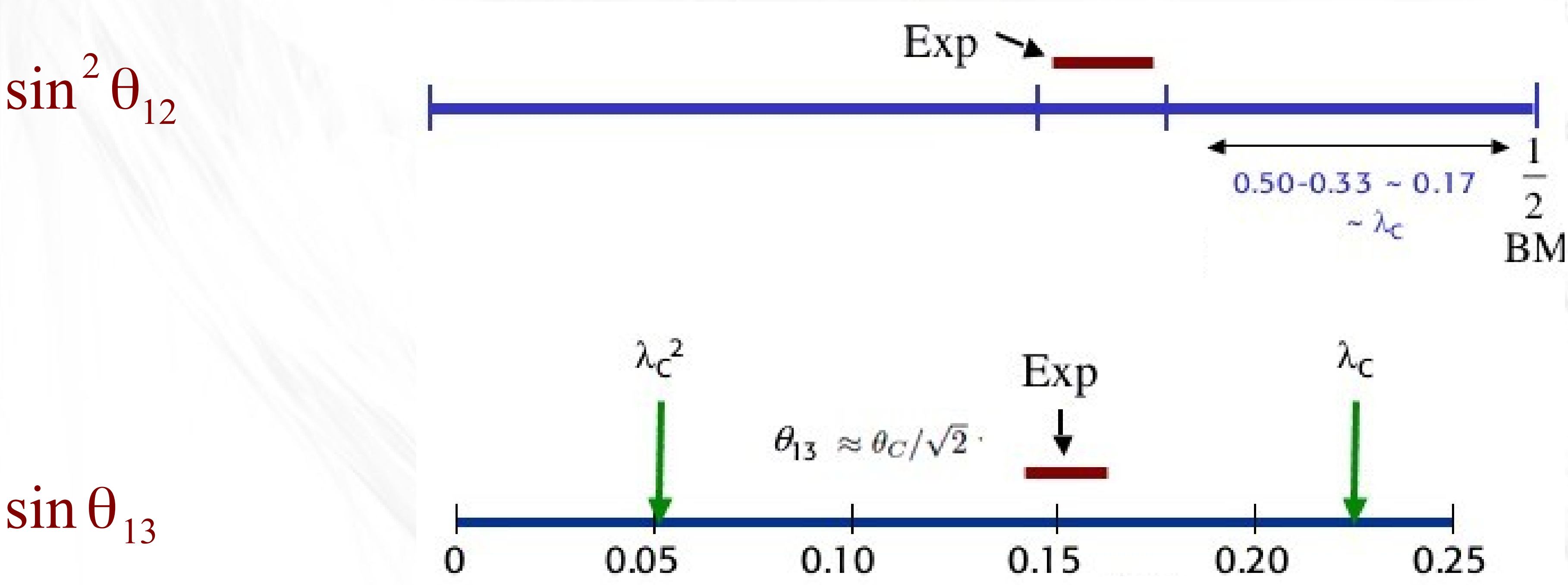
$$M_\nu = \begin{pmatrix} x & y & y \\ y & z & x-z \\ y & x-z & z \end{pmatrix} \quad \xrightarrow{\text{diagonalization}} \quad U^\nu = \begin{pmatrix} \frac{1}{\sqrt{2}} & -\frac{1}{\sqrt{2}} & 0 \\ \frac{1}{2} & \frac{1}{2} & -\frac{1}{\sqrt{2}} \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{\sqrt{2}} \end{pmatrix}$$

$$\sin^2\theta_{12} = \frac{1}{2} \quad \sin^2\theta_{23} = \frac{1}{2} \quad \sin^2\theta_{13} = 0$$

The solar angle

- The strategy:

Now needs corrections to fall on the experimental value $\theta_{12} \sim 33°$



Corrections provided by the diagonalization of the charged leptons

The solar angle

- Example restricted to the first two families:

$$m_e \sim \begin{bmatrix} a_{11}\lambda_C^2 & a_{12}\lambda_C \\ a_{21}\lambda_C & O(1) \end{bmatrix} \quad \Rightarrow \quad U_l \sim \begin{bmatrix} 1 & u_{12}\lambda_C \\ -u_{12}^*\lambda_C & 1 \end{bmatrix}$$

- a_{ij}, u_{ij} are O(1) coefficients
- u_{ij} is a linear combination of a_{ij}

this gives $\sin^2\theta_{12} = \frac{1}{2} - u_{12}\lambda_C$ which is perfectly OK

this relation is of the *weak complementarity* form **IF** the models generate Vus ~ $O(\lambda_c)$

→ link with GUT

The Vus matrix element

- SU(5)-inspired mass relation:

$$m_d = m_e^T \quad \Rightarrow \quad U_d \sim \begin{bmatrix} 1 & d_{12}\lambda_C \\ -d_{12}^*\lambda_C & 1 \end{bmatrix}$$

d_{ij} are a different combination of a_{ij}

so mixings are different but the off-diagonal elements are of $O(\lambda_c)$

(we only need to make sure that the up-quark sector does not destroy the scheme)

weak complementarity is realized in the context GUT + family symmetry

The reactor angle

- Remember that we also would like $\theta_{13} \sim \theta_C/\text{sqrt}[2]$

We have to extend the formalism to three families

$$U_l = \begin{bmatrix} 1 & u_{12}\lambda_C & u_{13}\lambda_C \\ -u_{12}^*\lambda_C & 1 & 0 \\ -u_{13}^*\lambda_C & 0 & 1 \end{bmatrix} + O\left(\lambda_C^2\right)$$

$$\sin\theta_{13} = \frac{1}{\sqrt{2}}\Re\left[u_{12}+u_{13}\right]\ \lambda_C$$

$$\sin^2\theta_{12} = \frac{1}{2} - \frac{1}{\sqrt{2}}\left|u_{12}-u_{13}\right|\ \lambda_C$$

This completes a form of connection between quarks and leptons

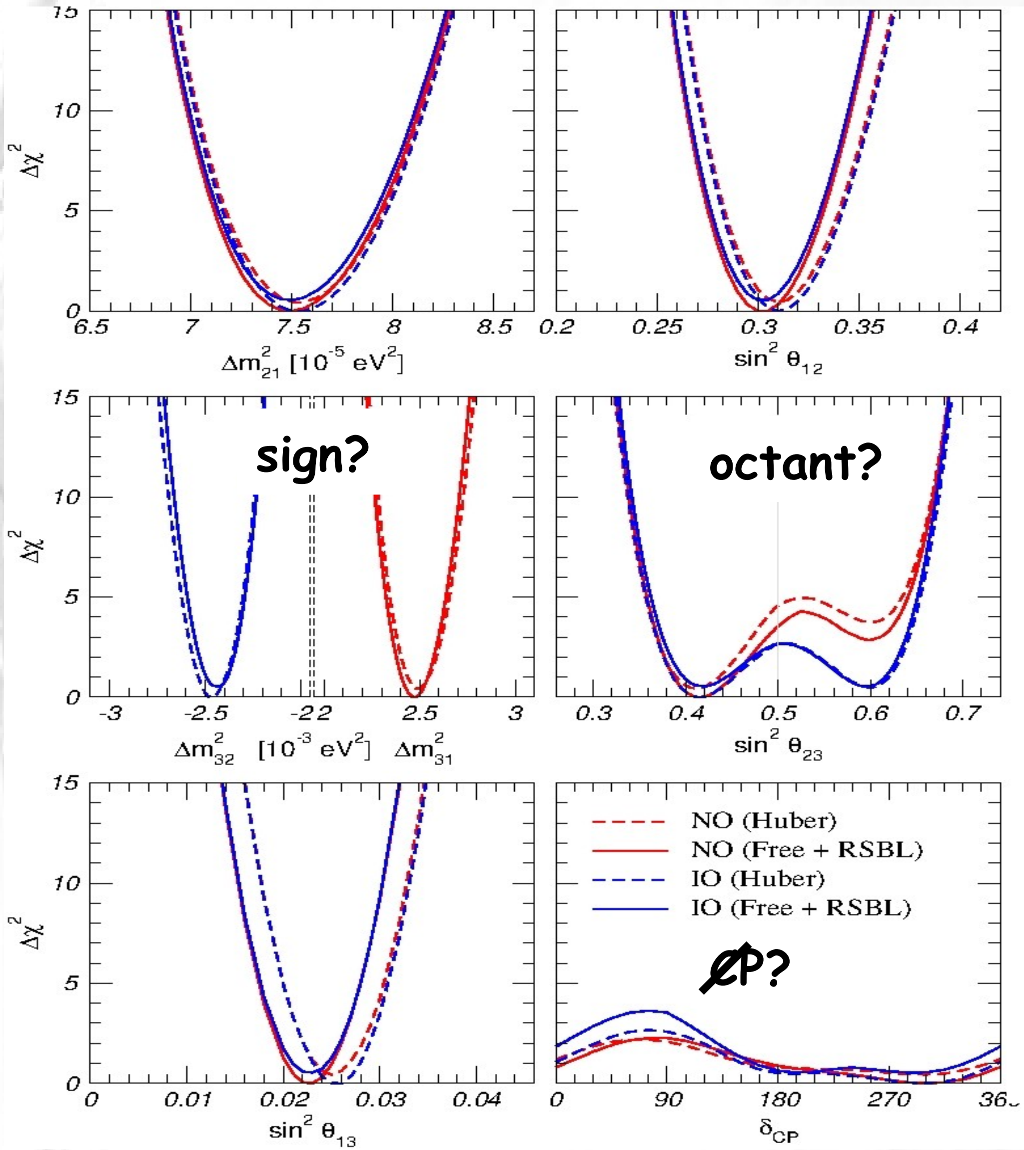
Conclusions

- It is possible that fermion masses and mixing have the same origin
- Different features are different to reconcile → needs extension of the SM
- Perhaps GUT + family symmetries is a good way to succeed

We do not know yet...

Backup

Global fit on neutrino data



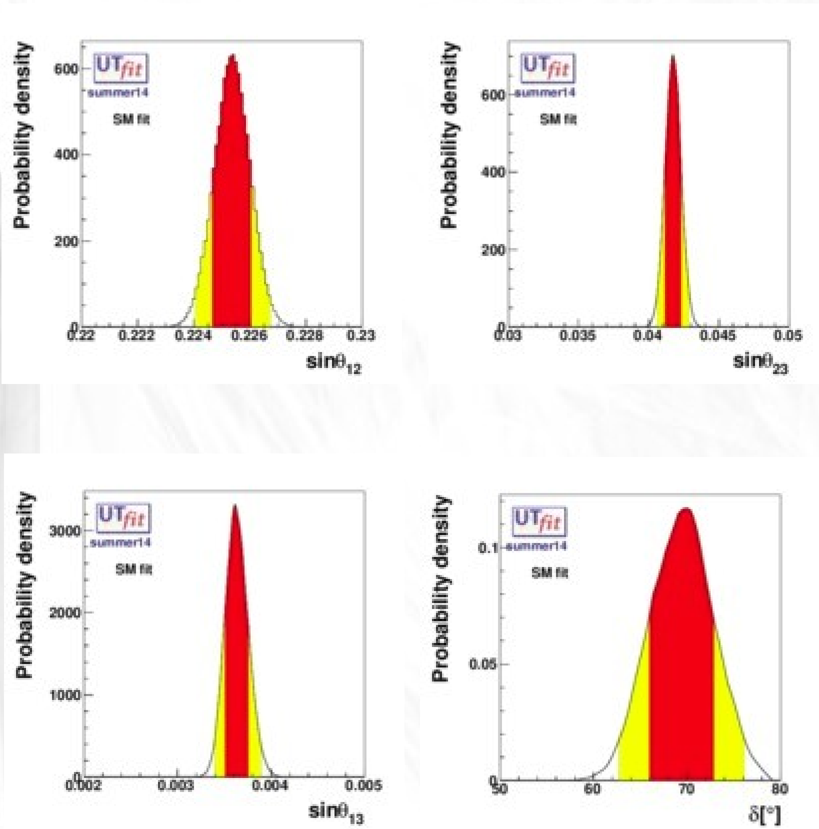
Gonzalez-Garcia et al. JHEP1212,(2012)123

Parameter	Result
θ_{12}	$33.36^{+0.81}_{-0.78}$
θ_{13}	$8.66^{+0.44}_{-0.46}$
θ_{23}	$40.0^{+2-1}_{-1.5}$
δ	300^{+66}_{-138}
Δm^2_{23} (10^{-3} eV^2)	$2.47^{+0.07}_{-0.07}$
Δm^2_{12} (10^{-5} eV^2)	$7.50^{+0.18}_{-0.19}$

$$|U| = \begin{pmatrix} 0.795 \to 0.846 & 0.513 \to 0.585 & 0.126 \to 0.178 \\ 0.205 \to 0.543 & 0.416 \to 0.730 & 0.579 \to 0.808 \\ 0.215 \to 0.548 & 0.409 \to 0.725 & 0.567 \to 0.800 \end{pmatrix}$$

PMNS mixing matrix

Global fit on quark data



http://www.utfit.org

Parameter	Result
$\sin\theta_{12}$	0.22523+-0.00065
$\sin\theta_{13}$	0.00363+-0.00012
$\sin\theta_{23}$	0.0417+-0.00057
$\delta^{(o)}$	69.4+-3.4

$$V_{CKM} = \begin{pmatrix} (0.97426 \pm 0.00015) & (0.22529 \pm 0.00061) & (0.00363 \pm 0.00012)e^{i(-69.3\pm3.3)^\circ} \\ (-0.22518 \pm 0.00066)e^{i(0.03509\pm0.00098)^\circ} & (0.97341 \pm 0.00015)e^{i(-0.00187\pm0.00005)^\circ} & (0.0417 \pm 0.00056) \\ (0.0088 \pm 0.00018)e^{i(-22.0\pm0.8)^\circ} & (-0.04092 \pm 0.00055)e^{i(1.069\pm0.042)^\circ} & (0.999119 \pm 0.000021) \end{pmatrix}$$

CKM mixing matrix