Economic models of flavor

fefo

Universidad de Colima - FC - CUICBAS - DCPIHEP

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November 28 2012

Flavor problem

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- Neutrino masses?.

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- Few oscillation parameters are well measured
- Only upper limits on the absolute mass scale
- We do not know the their *nature*

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- Oscillations are governed by a 3×3 unitary matrix and by mass differences
- The mixing angles **have been measured**
- mass differences **have been measured** (although not the hierarchy)
- CP violating phase is unknown.

Mixing parameters

- Conventional (PDG) parameterization for the mixing matrices U_{CKM} and U_{PMNS}:

"Dirac" CP phase δ

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \cdot P_{Maj}$$

(eventually)

mixing angle θ_{23} mixing angle θ_{13} mixing angle θ_{12}

θ_{13}

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$$P(\nu_\mu \to \nu_e) = \mathcal{F}(\theta_{13}, \delta_{CP})$$

- A year ago T2K presented candidates for ν_e appearance - six events (on an expected background of 1.5 ± 0.3)

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- A year ago T2K presented candidates for ν_e appearance - six events (on an expected background of 1.5 ± 0.3)
- MINOS followed with 62 events (on a background of 49.6)

Abe K *et al.*. (T2K Collaboration) 2011 PRL **107** 041801

Adamson P *et al.* (MINOS Collaboration) 2011 PRL **107** 181802

θ_{13}

- Reactor experiments:

$$P(\bar{\nu}_e \to \bar{\nu}_e) \approx 1 - \sin^2 2\theta_{\mathbf{13}} \sin^2(1.267 \Delta m^2_{13} L/E)$$

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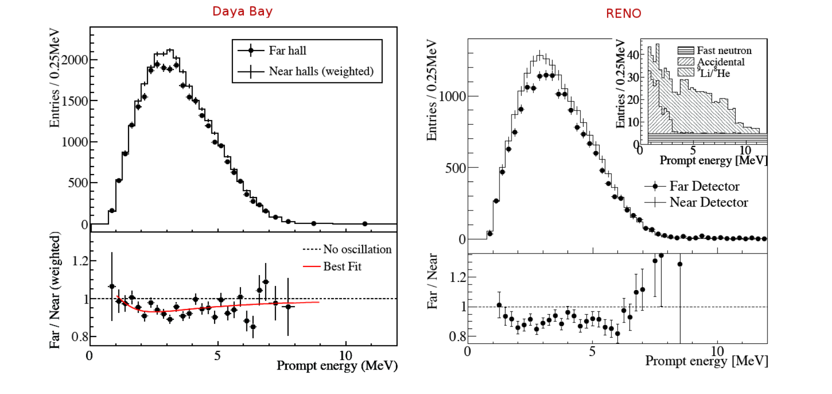
$\longrightarrow \theta_{13} \neq 0!$

An F *et al.*. (DAYA-BAY Collaboration) 2012 PRL **108** 171803

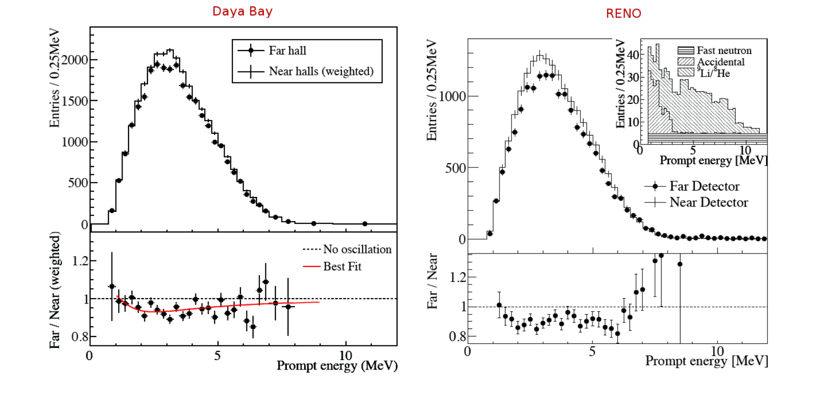
Ahn J *et al.* (RENO Collaboration) 2012 PRL **108** 191802

θ_{13}



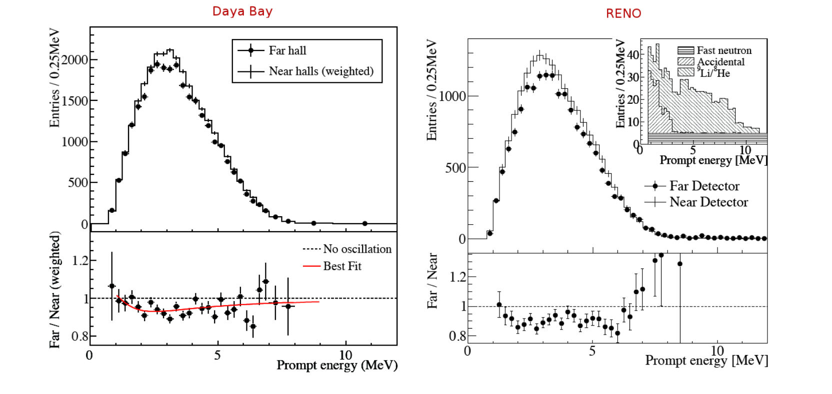
Daya Bay
RENO
Entries / 0.25MeV
Far hall
Near halls (weighted)
Far / Near (weighted)
No oscillation
Best Fit
Prompt energy (MeV)
Fast neutron
Accidental
^{9}Li/^{8}He
Prompt energy [MeV]
Far Detector
Near Detector
Far / Near

θ_{13}



Daya Bay (left): Best-fit solution with $\sin^2 2\theta_{13} = 0.089$

θ_{13}



Daya Bay (left): Best-fit solution with $\sin^2 2\theta_{13} = 0.089$

RENO (right): Best-fit solution with $\sin^2 2\theta_{13} = 0.113$

Δm^2_{21} and θ_{12}

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- Current values

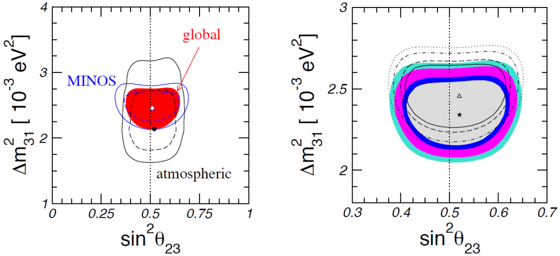
$$\Delta m^2_{21} = 7.59^{+0.20}_{-0.18} \times 10^{-5} \mathrm{eV}^2$$

$$\sin^2 \theta_{12} = 0.312^{+0.017}_{-0.015}$$

Schwetz T, Tortola M and Valle J 2011 *New J. Phys* 13 063004

$|\Delta m^2_{31}|$ and θ_{23}

$$|\Delta m^2_{31}| = \begin{cases} 2.45 \pm 0.09 & \times 10^{-3}\ \text{eV}^2 \quad (\text{NH}) \\ 2.34^{+0.10}_{-0.09} & \times 10^{-3}\ \text{eV}^2 \quad (\text{IH}) \end{cases} \quad \text{and} \quad \sin^2\theta_{23} = 0.51 \pm 0.06$$



Schwetz T, Tortola M and Valle J 2011 *New J. Phys* 13 063004

Present status: Mixing parameters

U_{PMNS}:

$\theta_{12}^{PMNS} \approx 34° \pm 1°$
$\theta_{23}^{PMNS} \approx 45° \pm 3°$
$\theta_{13}^{PMNS} \approx 9° \pm 1°$

δ^{PMNS} = unknown
($\varphi_{1,2}^{Maj}$ = unknown)

→ two large mixings
→ $\theta_{13}^{PMNS} = O(\theta_C)$
→ unknown phases

Up-type quarks — Down-type quarks

M_u ⟷ M_d

$U_{CKM} = U^{u\dagger} U^d$

Neutrinos — Charged leptons

m_ν ⟷ M_e

$U_{PMNS} = U^{e\dagger} U^\nu$

U_{CKM}:

$\theta_{12}^{CKM} \equiv \theta_C \approx 13.0°$
$\theta_{23}^{CKM} \approx 2.4°$
$\theta_{13}^{CKM} \approx 0.2°$

$\delta^{CKM} \approx 70° \pm 2°$

→ very small 2-3 and 1-3 mixings
→ only not-so-small mixing is the Cabibbo angle θ_C
→ “large” CP phase δ^{CKM}

Stolen from Stefan Antusch @ Neutrino 2012

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$\Lambda \rightarrow$ LARGE mass scale.

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Next minimal setup: Radiative masses

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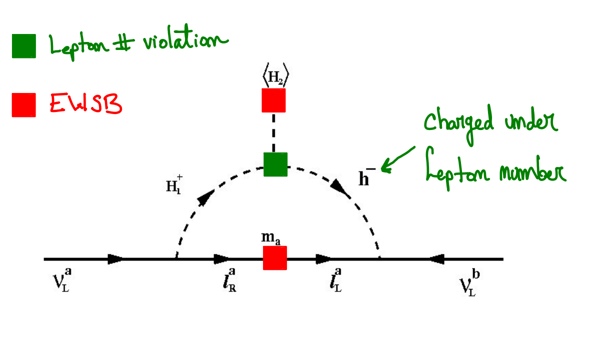
Requires introduction of new fields



$$m_{ab} = \kappa^{ab}(m_b^2 - m_a^2)\frac{\lambda_{12} v_2}{v_1} F(m_H^2, m_h^2)$$

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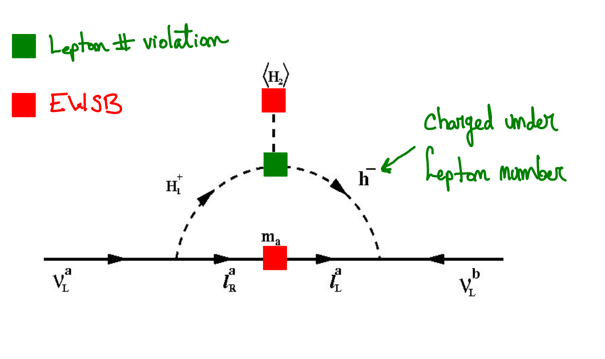

$$m_{ab} = \kappa^{ab}(m_b^2 - m_a^2)\frac{\lambda_{12} v_2}{v_1} F(m_H^2, m_h^2)$$

$m_h \to$ LARGE

A. Zee, Phys. Lett 93B, 389 (1980)

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Next possible setup: Right-handed neutrinos

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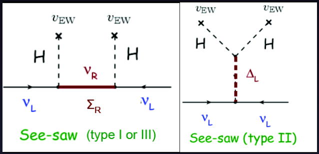
Dirac and Majorana mass terms are now possible

$$M_\nu = \begin{pmatrix} m_L & m_D \\ m_D & m_R \end{pmatrix}$$



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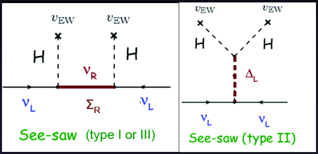

m_R must be large

$$m_\nu \sim m_D^2 / m_R$$

P. Minkowski, Mohapatra, Senjanovic, Yanagida,

Gell-Mann, Ramond, Slansky, Schechter, Valle,

....

Budget crisis?

to explain: neutrino, charged lepton and quark masses, mixing angles, hierarchy problem, dark matter, BAU, gravity, ...?

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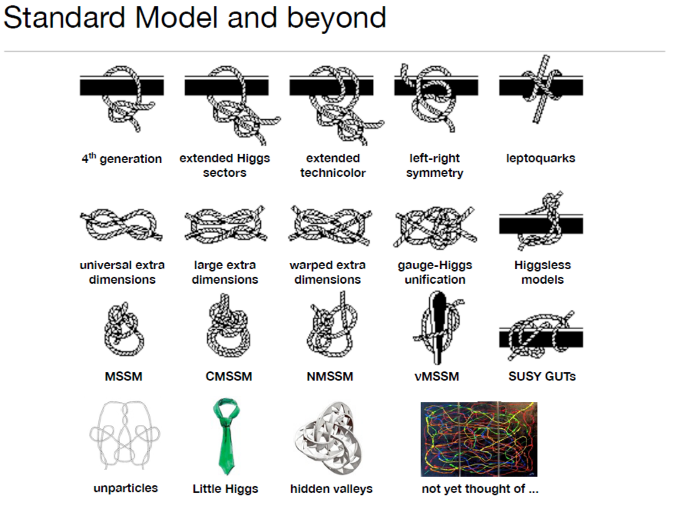

Mass in the Standard Model

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Electroweak theory: $SU(2)_W \times U(1)_Y$

Gauge invariant terms:

$$\mathcal{L} = -\frac{1}{4} F^a_{\mu\nu} F^{a\mu\nu} - i\bar{\Psi}^a D_\mu \gamma^\mu \Psi^a$$

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Not invariant!

But massive particles do exist $\rightarrow$ Higgs mechanism

Higgs mechanism

Lagrangian for a scalar field

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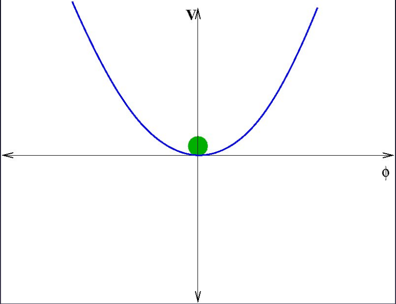
$$\mathcal{L} = \frac{1}{2} D_\mu \Phi D^\mu \Phi$$

Higgs mechanism

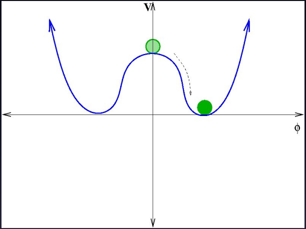
Lagrangian for a scalar field

$$\mathcal{L} = \frac{1}{2} D_\mu \Phi D^\mu \Phi - \frac{m^2}{2} \Phi^2$$



the sacalar VEV satisfies $\langle \Phi \rangle = 0$

Higgs mechanism



Lagrangian for a scalar field

$$\mathcal{L} = \frac{1}{2} D_\mu \Phi D^\mu \Phi - \frac{m^2}{2}\Phi^2 + \frac{\lambda}{4}\Phi^4$$

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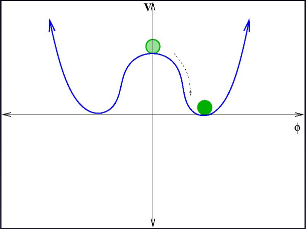


Lagrangian for a scalar field

$$\mathcal{L} = \frac{1}{2} D_\mu \Phi D^\mu \Phi - \frac{m^2}{2}\Phi^2 + \frac{\lambda}{4}\Phi^4$$

This scalar must also couple to fermions $\rightarrow \bar{\Psi}\Phi\Psi$

now the VEV satisfies $\langle \Phi \rangle \neq 0$

and we obtain $\bar{\Psi}\Phi\Psi \rightarrow \bar{\Psi}\langle\Phi\rangle\Psi \rightarrow$ Gauge symmetry has been broken spontaneously!!!

Higgs $\rightarrow$ mass

Finally

Higgs $\to$ mass

Finally

$$\mathcal{L} = -\frac{1}{4}F^a_{\mu\nu}F^{a\mu\nu} - i\bar{\Psi}^a D_\mu \gamma^\mu \Psi^a$$

Higgs $\rightarrow$ mass

Finally

$$\begin{aligned}\mathcal{L} &= -\frac{1}{4}F^a_{\mu\nu}F^{a\mu\nu} - i\bar{\Psi}^a D_\mu \gamma^\mu \Psi^a + \\ &\frac{1}{2}D_\mu \Phi D^\mu \Phi - \frac{m^2}{2}\Phi^2 + \frac{\lambda}{4}\Phi^4 - \\ &\mathbf{Y_a}\bar{\Psi}^a \Phi \Psi^a\end{aligned}$$

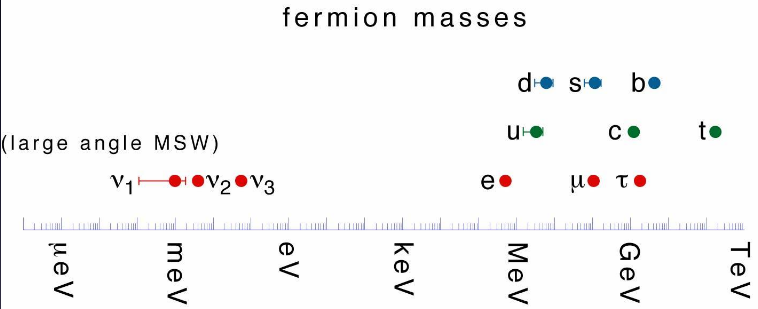
Higgs $\rightarrow$ mass

Finally

$$\mathcal{L} = -\frac{1}{4}F^a_{\mu\nu}F^{a\mu\nu} - i\bar{\Psi}^a D_\mu \gamma^\mu \Psi^a + \frac{1}{2}D_\mu \Phi D^\mu \Phi - \frac{m^2}{2}\Phi^2 + \frac{\lambda}{4}\Phi^4 - \mathbf{Y_a}\bar{\Psi}^a \Phi \Psi^a$$

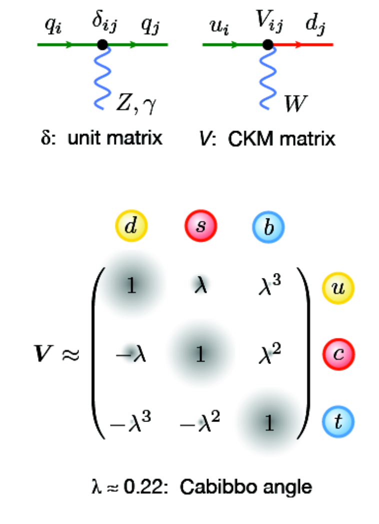
$\mathbf{Y_a}$ are the so-called *YUKAWA matrices* $\rightarrow$ completely undetermined in the SM.

Masses?



fermion masses
d
s
b
u
c
t
(large angle MSW)
ν1
ν2
ν3
e
μ
τ
μeV
meV
eV
keV
MeV
GeV
TeV

Mixing angles?



Mixing angles?

Tri-bimaximal mixing

Harrison, Perkins, Scott ('02)

$\theta_{13} = 0°$

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

$\theta_{12} = 35.3°$ $\theta_{23} = 45°$

Stolen from Stefan Antusch @ Neutrino 2012

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$$\frac{1}{\Lambda_F} \bar{\Psi}_i \Phi \xi_1 \Psi_j + \frac{1}{\Lambda'_F} \bar{\Psi}_i \Phi \xi_2 \Psi_3 + \bar{\Psi}_3 \Phi \Psi_3$$

Flavor symmetries

- When the symmetry **is** respected

$$\mathbf{Y_u} = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

Flavor symmetries

- When the symmetry **is broken** by the *second generation* field

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$$\mathbf{Y_u} = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 1 \end{pmatrix} \to \begin{pmatrix} 0 & 0 & 0 \\ 0 & \epsilon & \epsilon \\ 0 & \epsilon & 1 \end{pmatrix} \qquad \epsilon \sim \frac{\langle \xi_2 \rangle}{\Lambda'_F}$$

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- There is a remnant symmetry in the first generation.

Flavor symmetries

- When the symmetry is completely broken

$$\mathbf{Y_u} = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 1 \end{pmatrix} \rightarrow \begin{pmatrix} 0 & 0 & 0 \\ 0 & \epsilon & \epsilon \\ 0 & \epsilon & 1 \end{pmatrix}$$

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$$\epsilon' \sim \frac{\langle \xi_1 \rangle}{\Lambda_F}$$

- Could *explain* sizes and mixings
- Must find a symmetry (and model) that works!

Mixing angles?

The TBM structure *suggests* an underlying symmetry (?)

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If charged leptons are *diagonal*

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$\rightarrow$ M_ν is *magical* and $2-3$ *symmetric*

Mixing angles?

Z_2, Z_4, S_3, Q_4,

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Z_2, Z_4, S_3, Q_4, S_4,

Mixing angles?

Z_2, Z_4, S_3, Q_4, S_4, A_4,

Mixing angles?

Z_2, Z_4, S_3, Q_4, S_4, A_4, T', ...

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Z_2, Z_4, S_3, Q_4, S_4, A_4, T', ...

Altarelli, Araaki, Antusch, Bazzocchi, Bonilla, Branco, Chen, Datta, Frampton, Fukugita, Feruglio, Gupta, Gross, Hagedorn, Kim, King, Kobayashi, Kumar, Lavoura, Lam, Ma, Mohapatra, Mondragon, Morisi, Okada, Peinado, Petcov, Ramos, Romanino, Rojas, Ross, Seo, Shimizo, Takahashi, Tanimoto, Valle, Wang, Watanabe, Yanagida, Yang, Zee, ...

Mixing angles?

Z_2, Z_4, S_3, Q_4, S_4, A_4, T', ...

Altarelli, Araaki, Antusch, Bazzocchi, Bonilla, Branco, Chen, Datta, Frampton, Fukugita, Feruglio, Gupta, Gross, Hagedorn, Kim, King, Kobayashi, Kumar, Lavoura, Lam, Ma, Mohapatra, Mondragon, Morisi, Okada, Peinado, Petcov, Ramos, Romanino, Rojas, Ross, Seo, Shimizo, Takahashi, Tanimoto, Valle, Wang, Watanabe, Yanagida, Yang, Zee, ...

But $\theta_{13} \neq 0$

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Yes ...

a small step for M_ν, a giant leap for ?

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minimizing the number of scalar fields leads to the possibility of using the group Q_4 **with 4 SU(2) doublets and radiative masses for the neutrinos** (which costs an additional singlet charged scalar).

AA, Bonilla, Ramos, Rojas

Quaternion group Q_4

$$
\begin{aligned}
i^2 &= j^2 = k^2 = -1 \\
ij &= -ji = k \\
jk &= -kj = i \\
ki &= -ik = j
\end{aligned}
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representations: $\mathbf{1}^{++}, \mathbf{1}^{+-}, \mathbf{1}^{-+}, \mathbf{1}^{--}, \mathbf{2}$

Particle content of the model:

$$
\begin{aligned}
\overline{Q} &\sim \mathbf{1}^{++} \oplus \mathbf{1}^{+-} \oplus \mathbf{1}^{-+} \equiv \{\overline{Q}_1 \oplus \overline{Q}_2 \oplus \overline{Q}_3\} \\
d_R &\sim \mathbf{2} \oplus \mathbf{1}^{+-} \equiv \{(d_{R1} \;\; d_{R2}) \oplus d_{R3}\} \\
u_R &\sim \mathbf{2} \oplus \mathbf{1}^{+-} \equiv \{(u_{R2} \;\; u_{R1}) \oplus u_{R3}\} \\
\overline{L} &\sim \mathbf{2} \oplus \mathbf{1}^{+-} \equiv \{(\overline{L}_1 \;\; \overline{L}_2) \oplus \overline{L}_3\} \\
e_R &\sim \mathbf{1}^{++} \oplus \mathbf{1}^{+-} \oplus \mathbf{1}^{-+} \equiv \{e_{R1} \oplus e_{R2} \oplus e_{R3}\} \\
H &\sim \mathbf{2} \oplus \mathbf{1}^{++} \oplus \mathbf{1}^{--} \equiv \{H_D \equiv (H_1 \;\; H_2) \oplus H_3 \oplus H_4\} \\
\eta &\sim \mathbf{2} \equiv \{\eta_D \equiv (\eta_1 \;\; \eta_2)\}
\end{aligned}
$$

The mass matrices (for quarks and charged leptons) take the form

$$M_{u,d} = \begin{pmatrix} 0 & A_{u,d} & 0 \\ -A_{u,d} & 0 & B_{u,d} \\ 0 & D_{u,d} & C_{u,d} \end{pmatrix} .$$

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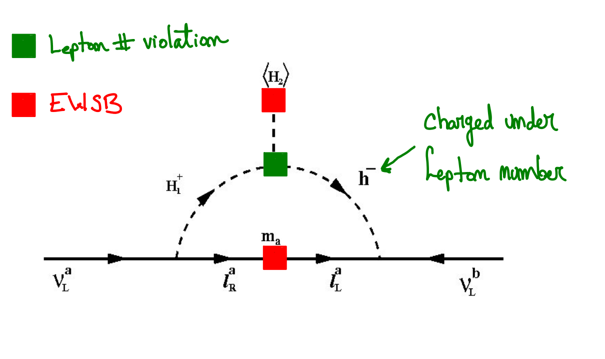
$\Longrightarrow$

$$|V_{CKM}^{th}| = \begin{pmatrix} 0.974386 & 0.224853 & 0.00363 \\ 0.224723 & 0.973587 & 0.0403354 \\ 0.00844 & 0.0396092 & 0.99918 \end{pmatrix}$$

$$\delta_{CKM}^{th} = 1.19528$$

Neutrino masses are obtained radiatively



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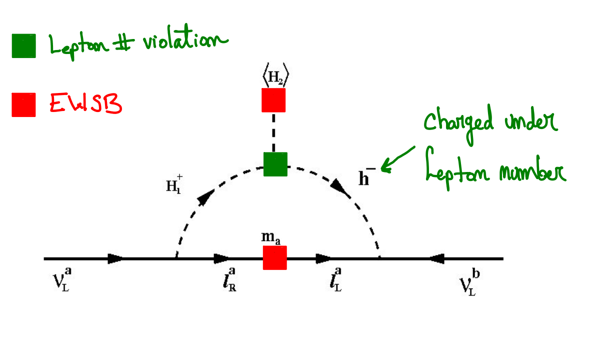

$$m_{ab} = \kappa^{ab}(m_b^2 - m_a^2)\frac{\lambda_{12} v_2}{v_1}\frac{1}{(4\pi)^2}\frac{1}{m_{H_1}^2 - m_h^2}\log\frac{m_{H_1}^2}{m_h^2}$$

$$= \kappa^{ab}(m_b^2 - m_a^2)\frac{\lambda_{12} v_2}{v_1} F(m_h^2, m_H^2)$$

with

$$F(x, y) = \frac{1}{16\pi^2}\frac{1}{x - y}\log\frac{x}{y}$$

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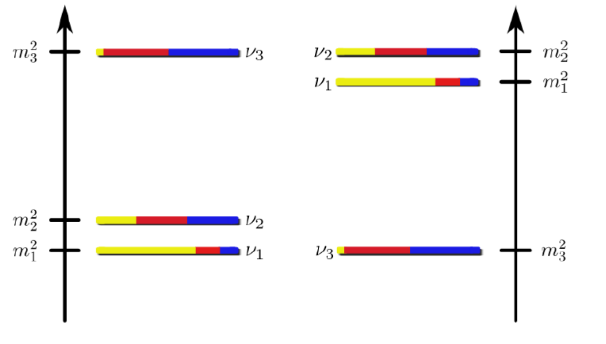
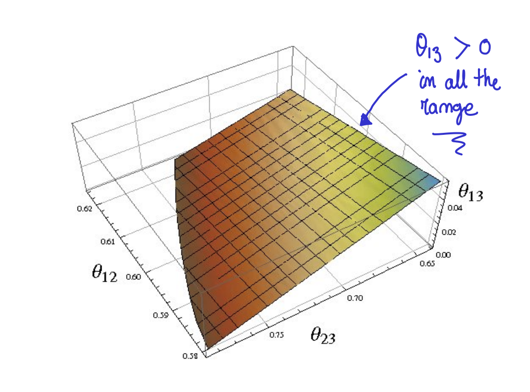
$$\begin{aligned} \Delta m^2_{21} &= 7.59^{+0.19}_{-0.21} \times 10^{-5}\ \mathrm{eV}^2 \\ \Delta m^2_{32} &= 2.43 \pm 0.13 \times 10^{-3}\ \mathrm{eV}^2 \end{aligned}$$

Only works for Inverted hierarchy





θ13 > 0
in all the
range
θ13
0.04
0.02
0.00
0.65
0.70
0.75
θ23
0.62
0.61
θ12
0.60
0.59
0.58

Majorana neutrinos $\rightarrow 0\nu\beta\beta-$decay

Decay is characterized by the (1,1) element of the neutrino mass matrix in the charged lepton mass basis:

$$\begin{aligned} m_{\beta\beta} &= e^{2i\sigma}\cos^2\theta_{12}\cos^2\theta_{13}m_1 + \\ &+ e^{2i\rho}\sin^2\theta_{12}\cos^2\theta_{13}m_2 + \sin^2\theta_{13}m_3 \end{aligned}$$

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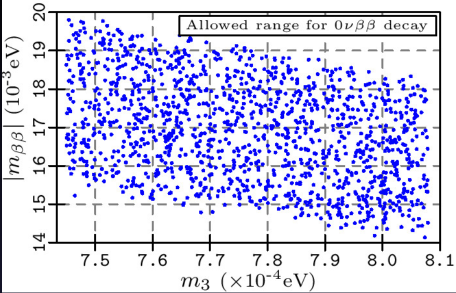
\end{aligned}
$$

Current bounds:

$$
\begin{aligned}
|m_{\beta\beta}| &< (0.20 - 0.32)\mathrm{eV} \quad (^{76}\mathrm{Ge}), \\
&< (0.30 - 0.71)\mathrm{eV} \quad (^{130}\mathrm{Te}), \\
&< (0.50 - 0.96)\mathrm{eV} \quad (^{130}\mathrm{Mo}),
\end{aligned} \tag{1}
$$

Bilenky et al.

Contribution to $0\nu\beta\beta$ decay



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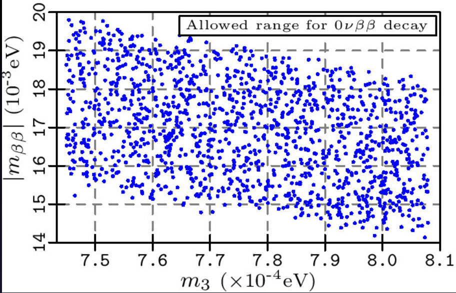

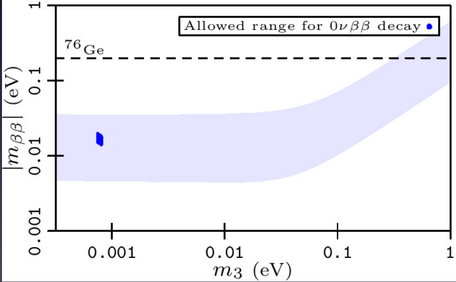

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- Finaly, they are my favorite particles!

Thank you!!

advertisement

2012
08.30

2013 DCPIHEP workshop

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Neutrino Physics

January 7 – 18 @ Colima

Invited Lectures

André de Gouvêa (Northwestern U.): **Neutrino Physics (theory)**
Stefano Morisi (IFIC – Valencia) **Neutrino mass models**
TBC: Jonathan Paley (Argonne Natl. Lab.): **Neutrino Physics (experiment)**

Preliminary Program

The purpose of the workshop is to bring together people interested in BSM physics. There will be a series of lectures and abundant time for discussion and actual work. Organization of informal seminars and talks are encouraged. If you are interested in leading a specific discussion session please send us the topic and hourly sessions needed. The time table for the lectures is shown below. Information regarding other activities will be posted as it becomes available. **Please note that some of the informal talks and discussion sessions will be organized while at the workshop.**