Seesaw with Occam’s Razor

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Five parameters in the neutrino mass and mixing are now measured :

$$\Delta m^2_{21} = 7.59^{+0.20}_{-0.18} \times 10^{-5}\,\mathrm{eV}^2\,, \qquad \Delta m^2_{31} = 2.45^{+0.09}_{-0.09} \times 10^{-3}\,\mathrm{eV}^2\,(NH)\,,$$

$$\Delta m^2_{31} = -2.34^{+0120}_{-0.09} \times 10^{-3}\,\mathrm{eV}^2\,(IH)\,,$$

For the squared mass differences

$$\sin^2\theta_{12} = 0.312^{+0.017}_{-0.015}\,, \qquad \sin^2\theta_{23} = 0.51^{+0.06}_{-0.06}\,(NH)\,, \quad \sin^2\theta_{13} = 0.023^{+0.004}_{-0.004}\,,$$

$$\sin^2\theta_{23} = 0.52^{+0.06}_{-0.06}\,(IH)\,,$$

For three mixing angles

What are m_ee   and   J_CP ?

Neutrinoless Double Beta Decay

→

CP Violation in Neutrino Oscillation

Seesaw Mechanism:

$$m_\nu = \begin{pmatrix} a & b & c \\ b & d & e \\ c & e & f \end{pmatrix}$$

Free parameters ; 12-3 = 9 > 5

Too many parameters to predict m_ee and J_CP !

Use Occam's Razor !!!

What are minimal, necessary parameters and particles ?

The Universe's Baryon Asymmetry requires at least two Right-handed heavy Majorana neutrinos

N ------> lepton + Higgs or anti-lepton + Higgs

If CP is broken in the decay processes, lepton asymmetry is created and the lepton asymmetry is converted to baryon asymmetry in the present universe …………… Leptogenesis (1986)

Talk by Buchmuller

We need at least two Right-handed neutrinos $N_{1,2}$ to have CP violation

We now assume two N_1,2, since the third one is NOT necessary

Take the diagonal mass basis : $M_R = \mathrm{diag}(M_1, M_2)$

Yukawa coupling matrix:

$$Y = \begin{pmatrix} a & b & c \\ d & e & f \end{pmatrix}$$

We still have too many free parameters
We do not need all of them

Use Occam's razor to remove unnecessary parameters !

This Occam's razor was first used on the quark mass matrix

$$m = \begin{pmatrix} 0 & a \\ a & b \end{pmatrix}$$

S. Weinberg (1977)

Two parameters are sufficient to explain two masses
for down and strange quarks

$$\theta_{\text{Cabibbo}} \simeq \sqrt{\frac{m_d}{m_s}} \simeq 0.22$$

It is very successful !!!

Three mixing angles requires at least three non-vanishing couplings

$$Y = \begin{pmatrix} a & 0 & c \\ 0 & e & 0 \end{pmatrix}$$

But, all phases of couplings can be absorbed into wave functions of three left-handed leptons

We need one more coupling to have CP violating phase

The minimal Yukawa contains four couplings

$$Y = \begin{pmatrix} a & b & 0 \\ 0 & c & d \end{pmatrix}$$

Frampton, Glashow, Yanagida (2002)

We now have four real parameters and one phase

4 + 1 = 5

We have measured three mixing angles and two mass differences

⟹ Determine all parameters and predict m_ee and J_CP

But, it is not always the case

The present model can not fit the experimental data for the normal mass hierarchy

The seesaw mechanism gives

$$(m_\nu)_{\alpha\beta} = \sum_{i=1}^{2} Y^T_{\alpha i} M_i^{-1} Y_{i\beta}\, v^2$$

The masses M_1 and M_2 can be absorbed into the definition of the Yukawa couplings

Two right-handed neutrinos ⟹ One eigenvalue = 0

Normal hierarchy : m_1=0

Inverted hierarchy : m_3=0

For normal hierarchy :

We examined all textures Y with two zeros and found no solution consistent with observed mixing angles and masses

We found S_13 = 0.08, 0.09, 0.66, 0.69, 1.0, 1.0,……

The measured S_13 = 0.12-0.18

Ibarra,Ross (2004)

This is because the dependence of the phase is suppressed by the small mass ratio of m_2 /m_3 = 0.17….

→ effectively 4 parameters

$$s_{13} = -\frac{m_2}{m_3}\frac{c_{12}c_{23}s_{12}}{s_{23}(\cos\bar{\alpha} - m_2/m_3\cos\delta)} \simeq \frac{m_2}{m_3}\frac{c_{12}c_{23}s_{12}}{s_{23}} \simeq 0.08 \; .$$

For inverted hierarchy

We found solutions !!!

Harigaya, Ibe, Yanagida at K IPMU(2012)

The contributions of the phase become large, since
there is no large mass hierarchy between m_1 and m_2

→ All 5 parameters contributes mixings

Determine the five parameters by using
the observed three mixing angles and two mass^2 differences

⇒ Predict m_ee and J_CP

We searched all Yukawa textures with two zeros

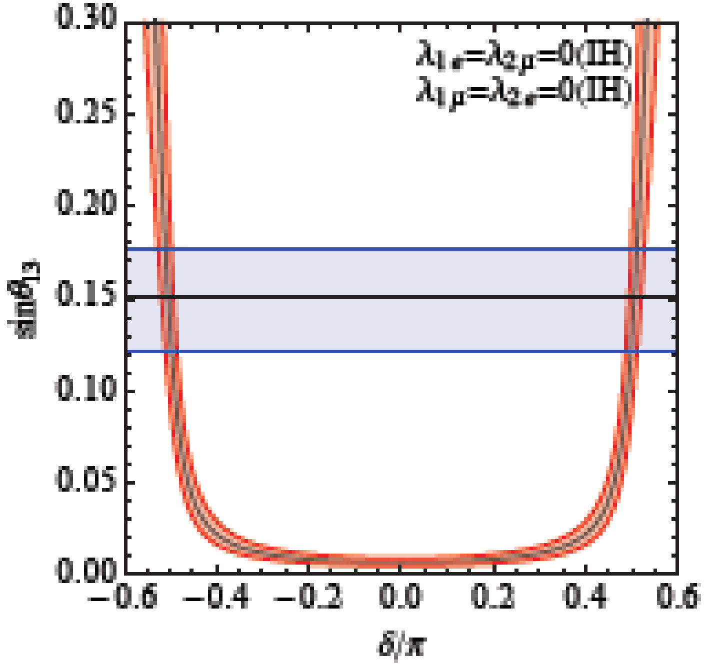
We found only two types of textures have consistent solutions

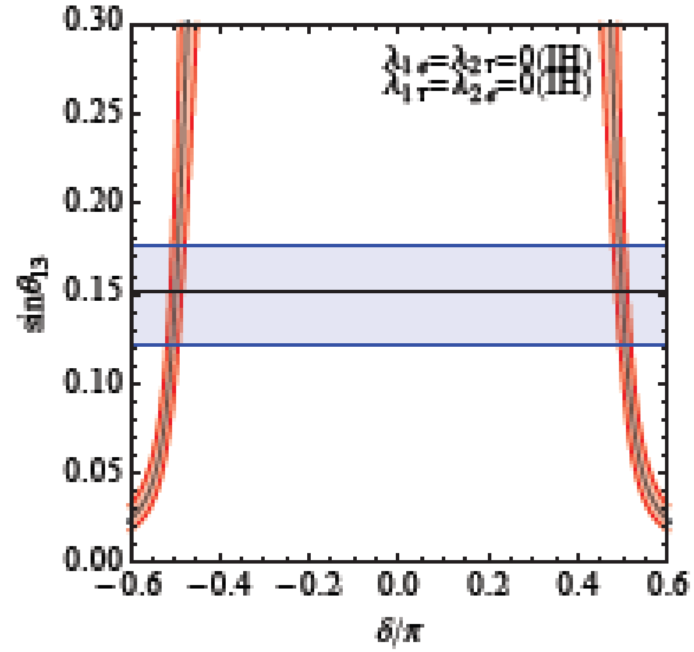
$$Y = \begin{pmatrix} a & 0 & b \\ 0 & c & d \end{pmatrix} \qquad\qquad Y = \begin{pmatrix} a & b & 0 \\ 0 & c & d \end{pmatrix}$$

Both predict

$$|\delta_{\rm CP}| = \frac{\pi}{2} \pm 0.02$$

$$m_{\rm ee} = (47 \pm 1)\ {\rm meV}$$





$$Y = \begin{pmatrix} a & 0 & b \\ 0 & c & d \end{pmatrix}$$

$$Y = \begin{pmatrix} a & b & 0 \\ 0 & c & d \end{pmatrix}$$

Connection to Universe's baryon asymmetry

FGY (2002)

The model has only one CP-violating phase and hence we can relate CP violation in neutrino oscillation to universe's baryon asymmetry

The baryon asymmetry is given by the leptogenesis

$$\eta_{B_0} = n_B/n_\gamma \simeq -3.4 \times 10^{-4} \times \varepsilon_1 \left(\frac{0.01\,\mathrm{eV}}{\tilde{m}_1}\right)^{1.16}$$

Buchmuller

$$\varepsilon_1 = -\frac{3}{16\pi}\frac{M_1}{v}\frac{\mathrm{Im}[m_1^2 s_z^2 + m_2^2 c_z^2]}{v(m_1|s_z|^2 + m_2|c_z|^2)}$$

$$\mathrm{Im}[m_1^2 s_z^2 + m_2^2 c_z^2] = \Delta m_{12}^2 \times \mathrm{Im}[c_z^2]$$

$$\mathrm{Im}[c_z^2] = \pm s_{12} c_{12} t_{23} s_{13} \sin\delta = \pm \frac{J_{CP}}{c_{13}^2 c_{23}^2}$$

The Baryon asymmetry in the present universe

⟹ Non-vanishing CP violation in neutrino oscillation

$$J_{CP} = \mathrm{Im}\left[U_{\mu 3} U_{e3}^{*} U_{e2} U_{\mu 2}^{*}\right] \simeq 0.034$$

cf. Pascoli, Petcov, Riotto (2007)

Conclusion

The seesaw with Occam's razor

Frampton, Glashow, Yanagida

CP violation in neutrino oscillation

⟺ Universe's baryon asymmetry

The normal hierarchy is excluded and
it is consistent with the inverted hierarchy !!!

It predicts

$$|\delta_{\mathrm{CP}}| = \frac{\pi}{2} \pm 0.02$$

$$m_{\mathrm{ee}} = (47 \pm 1)\ \mathrm{meV}$$

Motivation of two right-handed neutrino N_1,2

Quark mass matrix:

$$m_d = m_b \begin{pmatrix} 0 & \lambda^3 & \lambda^3 \\ \lambda^3 & \lambda^2 & \lambda^2 \\ \lambda^3 & \lambda^2 & 1 \end{pmatrix}$$

Dirac mass matrix for lepton

$$m_{\text{lepton Dirac}} = m_D \begin{pmatrix} 0 & \lambda^3 & \lambda^3 \\ \lambda^3 & \lambda^2 & \lambda^2 \\ \lambda^3 & \lambda^2 & 1 \end{pmatrix}$$

$$\underset{\theta_{23}}{\longleftrightarrow}$$

Mixing angles for lepton sector are also small !!

If M_3 >>> M_1,2, we have effectively only two N_i and the third low becomes irrelevant in the Yukawa matrix

$$m_{\text{lepton Dirac}} = m_D \begin{pmatrix} 0 & \lambda^3 & \lambda^3 \\ \lambda^3 & \lambda^2 & \lambda^2 \\ \lambda^2 & \lambda^2 & 1 \end{pmatrix}$$

↔ $\theta_{23} = O(1)$

We get a large mixing between neutrinos in the second and third generation !!!