Predictive model of inverted neutrino hierarchy and resonant leptogenesis

Hep-ph/0705??

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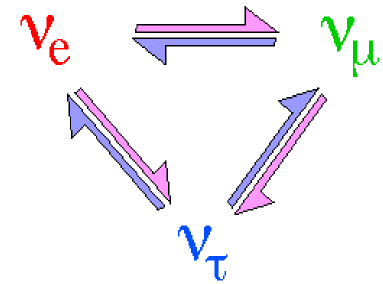
Three Neutrino Oscillations



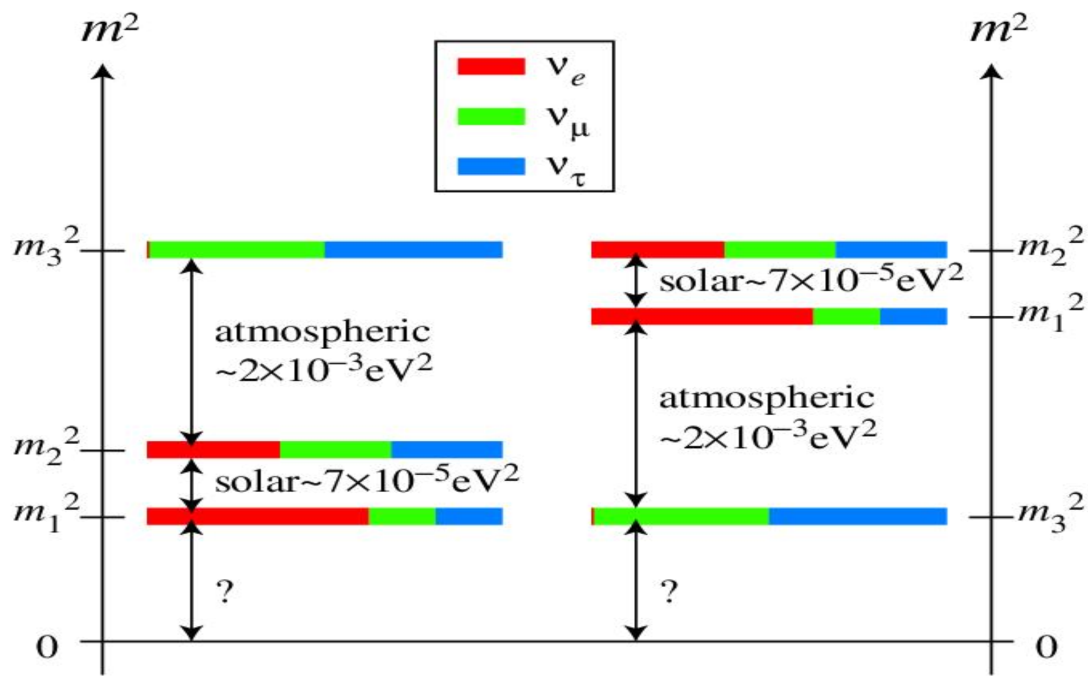
Neutrino Mixing

$$|\nu_\alpha\rangle = \sum U_{\alpha i} |\nu_i\rangle$$

Weak eigenstate **Mass eigenstate**

$$U_{PMNS} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \begin{pmatrix} \cos\theta_{13} & 0 & \sin\theta_{13} e^{-i\delta} \\ 0 & 1 & 0 \\ -\sin\theta_{13} e^{i\delta} & 0 & \cos\theta_{13} \end{pmatrix} \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \times P$$

$\mathbf{m_1 < m_2 \ll m_3}$



$\mathbf{m_1 \sim m_2 >> m_3}$

Neutrinos have tiny masses & their flavor mixing involves two large angles and one small angle:

$$36^\circ \leq \theta_{23} \leq 54^\circ$$
$$30^\circ \leq \theta_{12} \leq 38^\circ$$
$$0^\circ \leq \theta_{13} < 10^\circ$$

(at 99% confidence level)

Best fit values:

$$\Delta m_s^2 = 8.0 \times 10^{-5}\mathrm{eV}^2 \quad \Delta m_a^2 = 2.5 \times 10^{-3}\mathrm{eV}^2$$

$$\theta_{12} = 34^\circ$$

$$\theta_{23} = 45^\circ$$

$$\theta_{13} = 0^\circ$$

- Why are the two mixing angles large?

- What is the sign of Δm^2_{atm} ?
- The sign is directly linked to neutrino mass hierarchy
- The value of θ_{13} ?

(if $\theta_{13} \neq 0 \rightarrow \delta$ of CP is physical)

$\Rightarrow$ A reasonable extension of the SM should provide an understanding of this pattern

Inverted hierarchy and *L*- Symmetry

$L = L_e - L_\mu - L_\tau$

Starting from the following minimal seesaw

$$\Im = \bar{\nu}_L m_D N - \frac{1}{2} N^T M_R N$$

to ensure maximal $\nu_\mu - \nu_\tau$ mixing, impose an interchange S_2 symmetry between $\nu_\mu \leftrightarrow \nu_\tau$ $(\theta_{23} \simeq 45^\circ)$

The most general couplings (that respect ***S*₂**) is

$$Y_\nu^D = \begin{array}{c} \\ 1 \\ -1 \\ -1 \end{array} \begin{array}{c} \begin{matrix} -1 & 1 \end{matrix} \\ \begin{pmatrix} \alpha & 0 \\ \beta' & \beta \\ \beta' & \beta \end{pmatrix} \end{array}, \qquad M_R = \begin{array}{c} \\ -1 \\ 1 \end{array} \begin{array}{c} \begin{matrix} -1 & 1 \end{matrix} \\ \begin{pmatrix} -\delta_N & 1 \\ 1 & -\delta'_N \end{pmatrix} \end{array} M$$

β', δ_N and δ'_N violate $L = L_e - L_\mu - L_\tau$

using seesaw;

$$m_\nu = \begin{pmatrix} 2\delta_\nu' & \sqrt{2} & \sqrt{2} \\ \sqrt{2} & \delta_\nu & \delta_\nu \\ \sqrt{2} & \delta_\nu & \delta_\nu \end{pmatrix} \frac{m}{2}$$

$$m = \frac{\langle h_u^0 \rangle^2}{M(1-\delta_N \delta_N')} \sqrt{2}\alpha \left(\beta + \beta' \delta_N'\right)$$

$$\delta_\nu = \frac{\sqrt{2}}{\alpha} \frac{2\beta\beta' + \beta^2 \delta_N + (\beta')^2 \delta_N'}{\beta + \beta' \delta_N'} ,$$

$$\delta_\nu' = \frac{\alpha}{\sqrt{2}} \frac{\delta_N'}{\beta + \beta' \delta_N'}$$

$$|\delta_\nu|, |\delta_\nu'| \ll 1$$

(since they are proportional to *L*- symmetry breaking term, will also be responsible for the solar splitting)
If L violating term were not present, you will only generate atmospheric mass splitting

Assuming the charged lepton sector to be diagonal,

all the mixing will be contained in $U_\nu = U_{23}U_{12}$ such that

$$Diag(m_1, m_2, 0) = U_\nu^T m_\nu U_\nu$$

$$U_{23} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \frac{1}{\sqrt{2}} & -\frac{1}{\sqrt{2}} \\ 0 & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \end{pmatrix}, \quad U_{12} \simeq \begin{pmatrix} \bar{c} & -\bar{s}e^{i\rho} & 0 \\ \bar{s}e^{-i\rho} & \bar{c} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

$$\Rightarrow \quad Sin^2(\theta_{12}) \simeq \frac{1}{2}$$

corresponding to maximal mixing in the solar angle; imcompatible with experiments!!

- This picture leads to Bimaximal mixing ($\theta_{12} = \pi/4$) however, θ_{12} is significantly away from maximal mixing (Kamland & Solar)

We take a step forward to correct the situation:
The $S_2 -$ Symmetry is exact in neutrino mass matrix but broken in the charged lepton mass matrix (such that some predictions are preserved)

The charged lepton matrix will now be assumed non-diagonal,

$\Rightarrow$ Contribute to leptonic mixing

$\Rightarrow$ Use this contribution to fix the value of θ_{12}

$\Rightarrow$ Find interesting correlation between solar & reactor angles

Assume the following texture for charged lepton mass matrix:

$$Y_E = \begin{pmatrix} 0 & a' & 0 \\ a & \lambda_\mu & 0 \\ 0 & 0 & \lambda_\tau \end{pmatrix}, \quad a' = \lambda_\mu \theta_e e^{i\omega}$$

Can be diagonalized by the rotation :

$$U_e = \begin{pmatrix} c & s e^{i\omega} & 0 \\ -s e^{-i\omega} & c & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

$c \equiv \cos t$, $s \equiv \sin t$ and $\tan t = -\theta_e$

The total mixing matrix:

$$U^l = U_e^* U_\nu \ ,$$

Prediction:

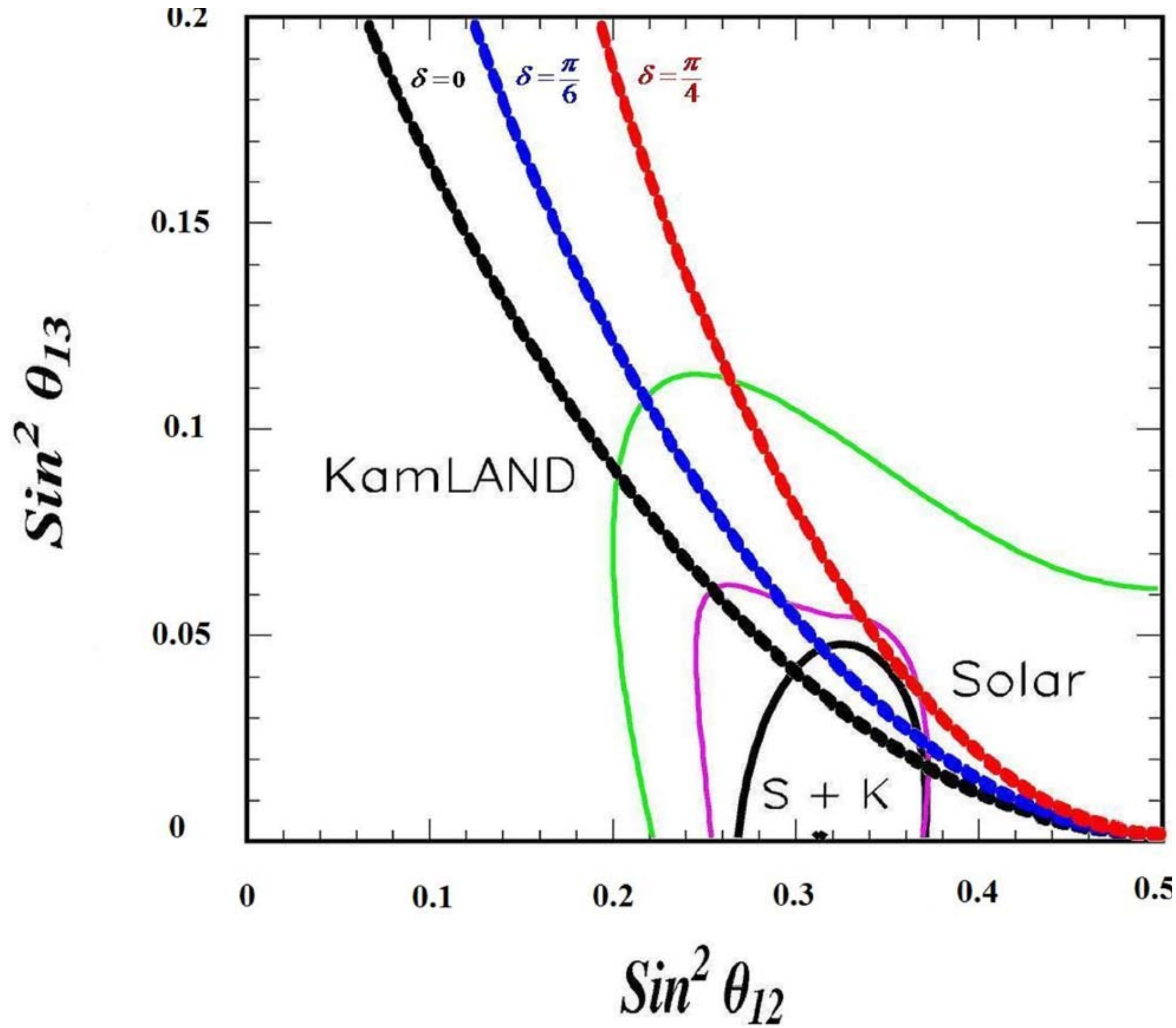
$$\sin^2\theta_{12} = \frac{1}{2} - \sqrt{1-\tan^2\theta_{13}}\,\tan\theta_{13}\cos\delta\ ,$$

$$\sin^2\theta_{23} = \frac{1}{2}\left(1-\tan^2\theta_{13}\right)$$

$\Rightarrow$ The deviation of the solar angle from its maximal value of $\frac{\pi}{4}$ is controlled by θ_{13}.

Implying several constraints:

$$0.31 \le Sin^2(\theta_{12}) \le 0.7, \ \rightarrow \ 0 \le Cos(\delta) \le 0.7, \quad \theta_{13} \ge 0.13$$



The contours represent projections of the region allowed at 2 σ

Fogli, Lisi, Marrone, and Palazzo (2005)

Resonant Leptogenesis

Our model of inverted hierarchy involves two quasi-degenerate RHN

→ Resonant enhancement of CP Violation, successfully leading to Baryon Asymmetry

$$\epsilon_1 = \frac{\mathrm{Im}(\hat{Y}_\nu^\dagger \hat{Y}_\nu)^2_{21}}{(\hat{Y}_\nu^\dagger \hat{Y}_\nu)_{11}} \frac{|\delta_N^* + \delta_N'|}{8\pi|\delta_N^* + \delta_N'|^2 + (\hat{Y}_\nu^\dagger \hat{Y}_\nu)_{22}} ,$$

Pilaftsis, 1997

Allowing for lower RHN masses, in way that avoid Gravitino problem

$$M_R \leq 10^8 GeV$$

Two cases: $8\pi|\delta_N^* + \delta_N'|^2 >> (\hat{Y}_\nu^\dagger \hat{Y}_\nu)_{22}$

Extreme resonant case ← $8\pi|\delta_N^* + \delta_N'|^2 \sim (\hat{Y}_\nu^\dagger \hat{Y}_\nu)_{22}$

Both heavy RHN equally contribute to CP asymmetry:

$$\epsilon_1 \simeq \epsilon_2 \simeq -\frac{1}{32\sqrt{2}\pi}\frac{(2-x^2)^2}{x(2+x^2)}\frac{\sqrt{\Delta m^2_{\rm atm}}M}{\langle h_u^0\rangle^2 \sin^2\beta}\frac{\sin 2r}{|\delta_N^* + \delta_N'|}$$

$$\left.\frac{n_B}{s}\right|_{x=1} \simeq 1.34\cdot 10^{-15}\left(\frac{M}{10^8\mathrm{GeV}}\right)\frac{\sin 2r}{|\delta_N^* + \delta_N'|}$$

Gives the right order for;

$$\left|\delta_N^* + \delta_N'\right| \simeq 1.5\cdot 10^{-5}\sin 2r\left(\frac{M}{10^8\mathrm{GeV}}\right)$$

Can be explained via symmetry…

Conclusion:

- Predictive model of inverted hierarchical neutrinos was presented

- New symmetries play central role for predictions
  (Can be tested in experiments)

↓

- $0.31 \leq Sin^2(\theta_{12}) \leq 0.7, \;\; 0 \leq Cos(\delta) \leq 0.7$ and $\theta_{13} \geq 0.13$, all which testable in forthcoming experiments.

- Model involves two quasi-degenerate RHNs $\rightarrow$
  succesful Baryon Asymmetry via Resonant Leptogenesis