Neutrino mass degeneracy and CP violation

Takeshi Araki (Maskawa Inst.)

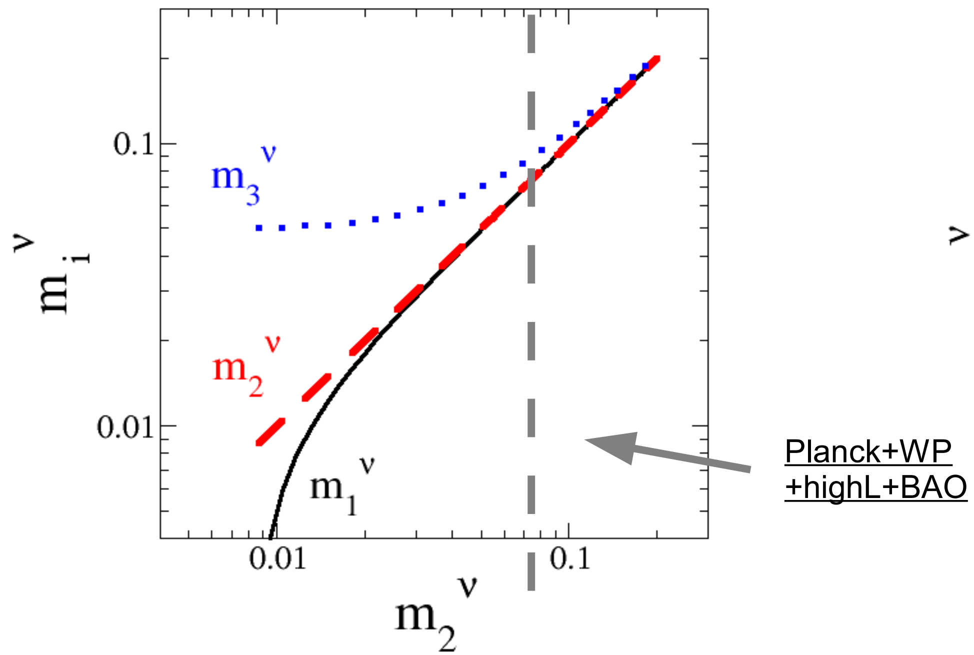
with Hiroyuki Ishida (Tohoku Univ.)
Eiichi Takasugi (Osaka Univ.)

based on arXiv:1211.4452 [hep-ph]
arXiv:1308.XXX [hep-ph].

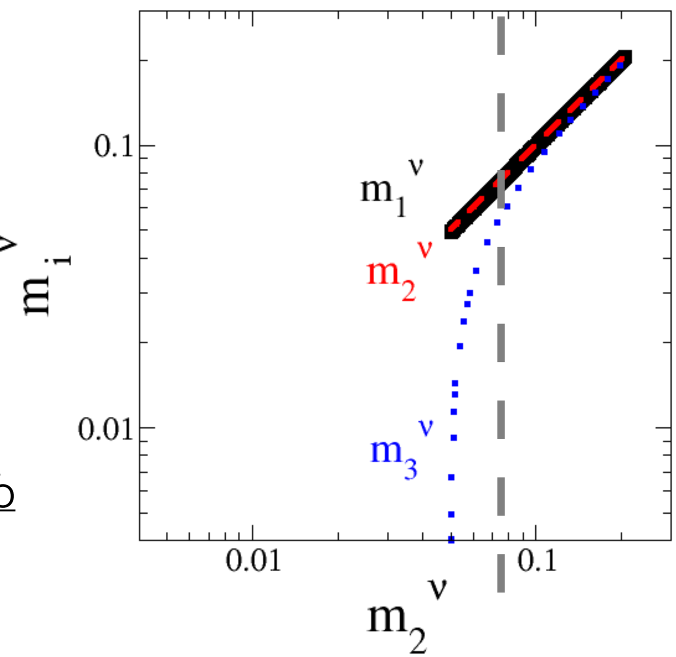
Neutrino mass hierarchy

$\Delta m^2_{12},\ \Delta m^2_{23}$ ‡ measured, m_i^{ν} ‡ undetermined.

Normal Hierarchy



Inverted Hierarchy



Strongly quasi-degenerated spectrum may be disfavored.

In most of the regions, m1 and m2 are quasi-degenerated.

By accident or design? What kind of physics behind it?

D_N model

The D_N flavor model:

$$M_\ell \sim m_\tau \begin{pmatrix} 0 & 0 & 0 \\ 0 & 1/\Lambda_F^2 & 0 \\ 0 & 0 & 1 \end{pmatrix} \Longrightarrow \frac{1}{\Lambda_F^2} \sim \frac{m_\mu}{m_\tau} \sim 0.06$$

$$M_\nu = \begin{pmatrix} m_1^0 & 0 & 0 \\ 0 & m_1^0 & 0 \\ 0 & 0 & m_3^0 \end{pmatrix} + \frac{1}{\Lambda_F^2} \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & \varepsilon_{23} \\ 0 & \varepsilon_{23} & 0 \end{pmatrix} + \frac{1}{\Lambda_F^4} \xcancel{\begin{pmatrix} 0 & 0 & 0 \\ 0 & * & * \\ 0 & * & * \end{pmatrix}}$$

$$(M_\nu)_{11} \simeq (M_\nu)_{22} \qquad \theta_{12} = \theta_{13} = 0^\circ$$

- The D_N symmetry makes m_1^ν and m_2^ν exactly degenerated.
- The degeneracy is lifted after the D_N breaking,

but $\theta_{12} = \theta_{13} = 0^\circ,\ m_e = 0$ by Z_2 of D_N.

D_N model

The D_N flavor model **after** the Z_2 symmetry breaking:

$$M_\ell = m_\tau \begin{pmatrix} 0 & 0 & 0 \\ 0 & 1/\Lambda_F^2 & 0 \\ 0 & 0 & 1 \end{pmatrix} + \mathcal{O}(m_e) \qquad \frac{1}{\Lambda_F^2} \sim \frac{m_\mu}{m_\tau} \sim 0.06$$

$$M_\nu = \begin{pmatrix} m_1^0 & 0 & 0 \\ 0 & m_1^0 & 0 \\ 0 & 0 & m_3^0 \end{pmatrix} + \frac{1}{\Lambda_F^2} \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & \varepsilon_{23} \\ 0 & \varepsilon_{23} & 0 \end{pmatrix} + \frac{1}{\Lambda_F^n} \begin{pmatrix} \varepsilon_{11} & \varepsilon_{12} & \varepsilon_{13} \\ \varepsilon_{12} & 0 & 0 \\ \varepsilon_{23} & 0 & 0 \end{pmatrix}$$

$$\frac{|\varepsilon_{23}|}{\Lambda_F^2} = m_3^0 (0.02 \sim 0.1) \qquad \frac{|\varepsilon_{23}|}{\Lambda_F^2} > \frac{|\varepsilon_{11}|, |\varepsilon_{12}|, |\varepsilon_{13}|}{\Lambda_F^n}$$

- 5 - 10% tuning is inevitable

  In order for $\theta_{23} \simeq 45°$

  $$m_1^0 - m_3^0 \sim \frac{|\varepsilon_{23}|}{\Lambda_F^2}$$

$$\begin{pmatrix} 1 & \varepsilon \\ \varepsilon & 1+\delta \end{pmatrix} \ddagger \quad \frac{2\varepsilon}{\sqrt{4\varepsilon^2 + \delta^2}} \sim 1$$

$$m_3^\nu \simeq m_1^\nu, m_2^\nu$$

Onbb

The model provides a novel prediction for m_{ee} of 0nbb.

- The phases of m_1^0 and m_3^0 can be absorbed.
- $m_i^0 \gg \varepsilon_{ij}$; the eigenvalues are dominated by m_1^0 and m_3^0.
- As a result, the Majorana phases are almost vanishing.

$$\begin{pmatrix} |m_1^0| & 0 & 0 \\ 0 & |m_1^0| & 0 \\ 0 & 0 & |m_3^0| \end{pmatrix} \Rightarrow \begin{pmatrix} m_1^\nu e^{i\alpha_1} & 0 & 0 \\ 0 & m_2^\nu e^{i\alpha_2} & 0 \\ 0 & 0 & m_3^\nu e^{i\alpha_3} \end{pmatrix}$$

where $\underline{\alpha_1 \simeq \alpha_2 \simeq \alpha_3 \simeq 0}$.

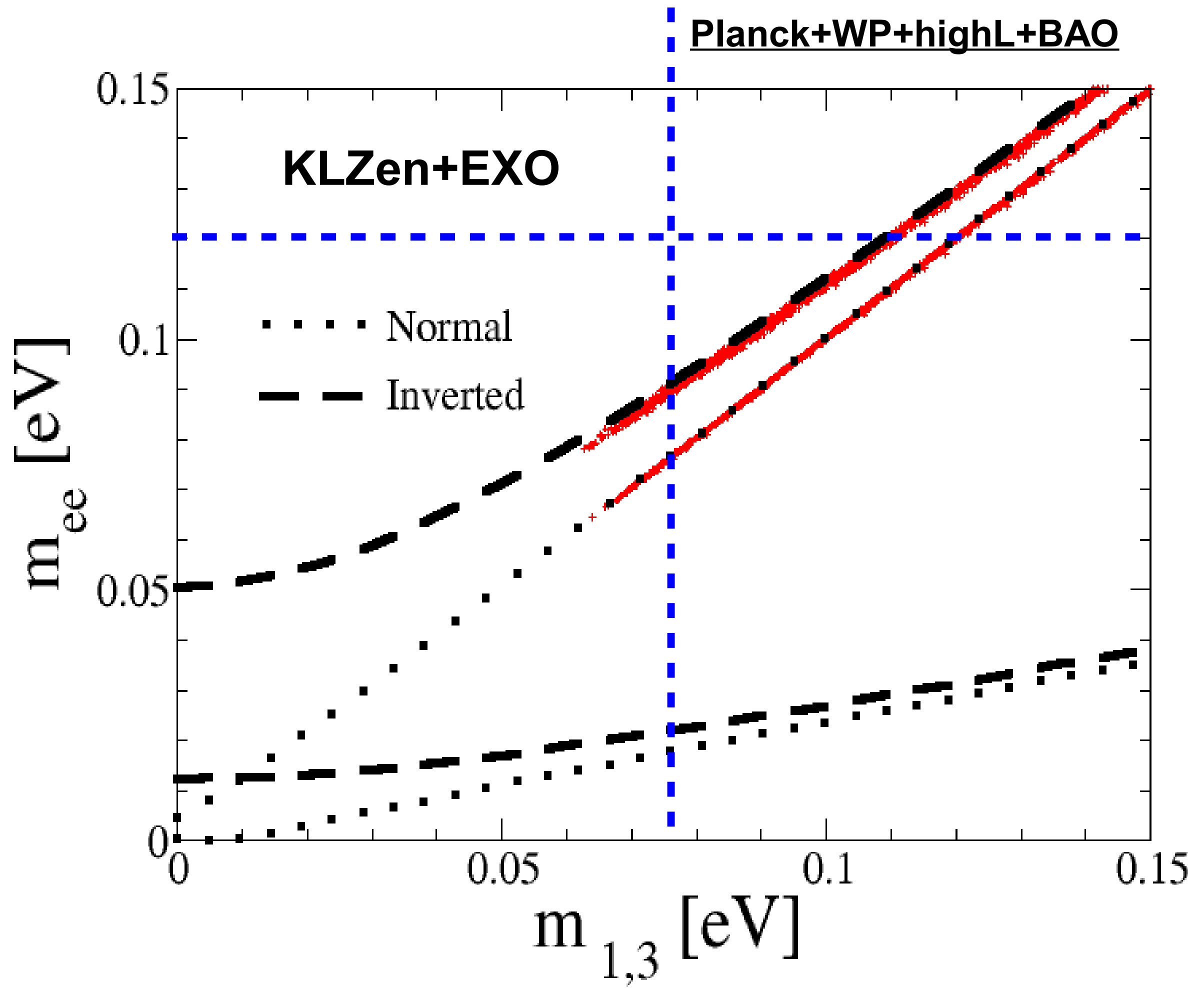
The effective of 0nbb is reduced as

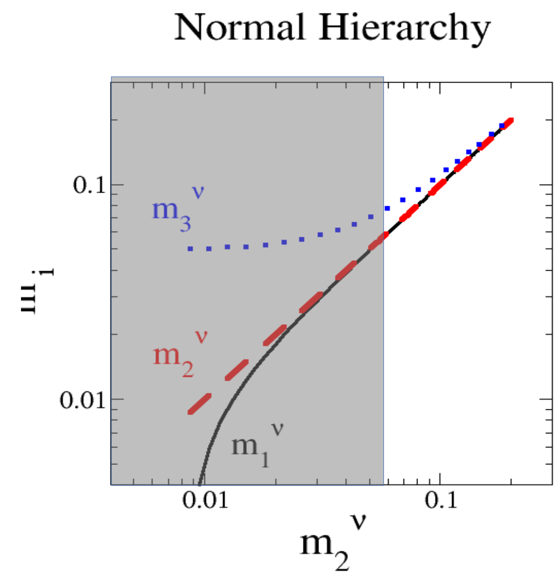
$$m_{ee} = |c_{12}^2 c_{13}^2 m_1^\nu e^{i\alpha_1} + s_{12}^2 c_{13}^2 m_2^\nu e^{i\alpha_2} + s_{13}^2 e^{-2i\delta + i\alpha_3} m_3^\nu|$$

$$\simeq |c_{12}^2 + s_{12}^2| c_{13}^2 m_1^\nu \Leftarrow \begin{array}{l} \alpha_1 \simeq \alpha_2 \simeq \alpha_3 \simeq 0 \\ s_{13}^2 \ll 1 \end{array}$$

$$\simeq m_1^\nu \ (m_2^\nu) \Leftarrow c_{13}^2 \simeq 1$$

0nbb





Conditions

$$\frac{|\varepsilon_{23}|}{\Lambda_F^2} = m_3^0(0.02 \sim 0.1)$$

$$\frac{|\varepsilon_{23}|}{\Lambda_F^2} > \frac{|\varepsilon_{11}|, |\varepsilon_{12}|, |\varepsilon_{13}|}{\Lambda_F^n}$$

$$\begin{matrix} \Delta m_{12}^2, \ \Delta m_{23}^2 \\ \theta_{12}, \ \theta_{23}, \ \theta_{13} \end{matrix} < 3\sigma$$

- CPV is small: $|J_{\rm CP}| < 0.015 \ (\delta \simeq 0, \pi)$.
- The mass ordering can be distinguished.

Modification for $\theta_{23} \simeq 45^\circ$

Let us improve the model to naturally induce a large θ_{23}.

$$M_\nu = \begin{pmatrix} m_1^0 & 0 & 0 \\ 0 & m_1^0 & 0 \\ 0 & 0 & m_3^0 \end{pmatrix} + \cdots$$

$$\begin{pmatrix} m_1^0 & 0 & 0 \\ 0 & \frac{1}{2}(m_3^0 + m_1^0) & \frac{1}{2}(m_3^0 - m_1^0) \\ 0 & \frac{1}{2}(m_3^0 - m_1^0) & \frac{1}{2}(m_3^0 + m_1^0) \end{pmatrix}$$

(Comment: S4 could derive it.)

which can be diagonalized by the maximal mixing:

$$R_{23}^T M_\nu^0 R_{23}$$
$$= \mathrm{Diag}(m_1^0, m_1^0, m_3^0)$$

$$R_{23} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1/\sqrt{2} & 1/\sqrt{2} \\ 0 & -1/\sqrt{2} & 1/\sqrt{2} \end{pmatrix}.$$

In a basis where $V^0 = R_{23}$

$$M_\nu = \begin{pmatrix} m_1^0 & 0 & 0 \\ 0 & m_1^0 & 0 \\ 0 & 0 & m_3^0 \end{pmatrix} + \frac{1}{\Lambda_F^2} \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & \varepsilon_{23} \\ 0 & \varepsilon_{23} & 0 \end{pmatrix} + \frac{1}{\Lambda_F^n} \begin{pmatrix} \varepsilon_{11} & \varepsilon_{12} & \varepsilon_{13} \\ \varepsilon_{12} & 0 & 0 \\ \varepsilon_{23} & 0 & 0 \end{pmatrix}$$

Onbb

The model still provides a novel prediction for m_{ee} of 0nbb.

- $(M_\nu)_{11} \simeq (M_\nu)_{22}$ including phases due to the symmetry.
- $m_i^0 \gg \varepsilon_{ij}$; the eigenvalues are dominated by m_1^0 and m_3^0.
- Thus, the two Majorana phases are also quasi-degenerated.

$$\begin{pmatrix} m_1^0 & 0 & 0 \\ 0 & m_1^0 & 0 \\ 0 & 0 & m_3^0 \end{pmatrix} \Rightarrow \begin{pmatrix} m_1^\nu e^{i\alpha_1} & 0 & 0 \\ 0 & m_2^\nu e^{i\alpha_2} & 0 \\ 0 & 0 & m_3^\nu e^{i\alpha_3} \end{pmatrix}$$

where $\underline{\alpha_1 \simeq \alpha_2 \cancel{\simeq \alpha_3 \simeq 0}}$.

The effective of 0nbb is reduced as

$$m_{ee} = |c_{12}^2 c_{13}^2 m_1^\nu e^{i\alpha_1} + s_{12}^2 c_{13}^2 m_2^\nu e^{i\alpha_2} + s_{13}^2 e^{-2i\delta + i\alpha_3} m_3^\nu|$$

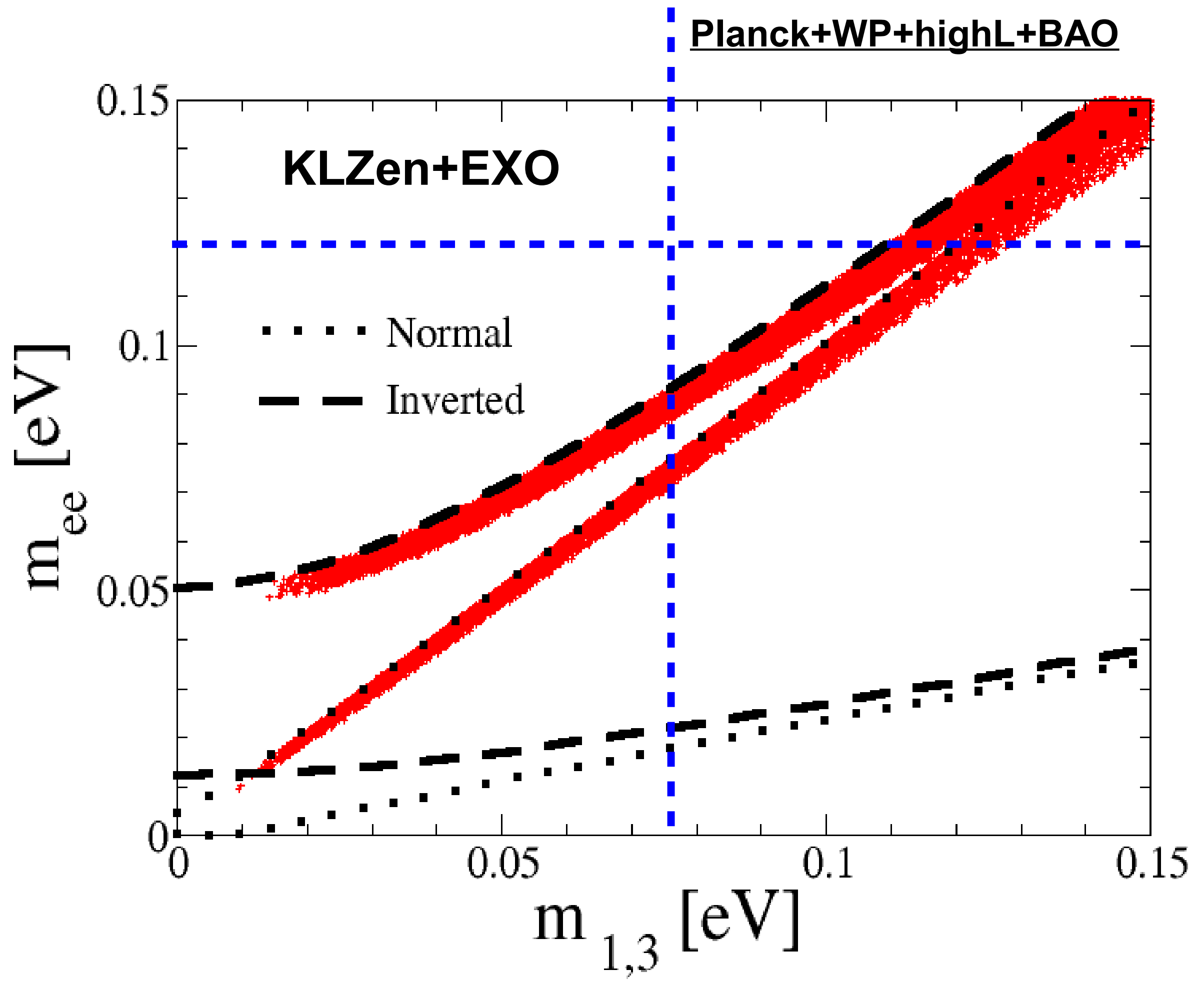
$$\simeq |c_{12}^2 + s_{12}^2| c_{13}^2 m_1^\nu$$

$\alpha_1 \simeq \alpha_2 \cancel{\simeq \alpha_3 \simeq 0}$
$s_{13}^2 \ll 1$

$$\simeq m_1^\nu \ (m_2^\nu)$$

$c_{13}^2 \simeq 1$

Onbb



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$$\begin{matrix} \Delta m_{12}^2, & \Delta m_{23}^2 & \\ \theta_{12}, & \theta_{23}, & \theta_{13} \end{matrix} < 3\sigma$$

- CPV can be large: $|J_{\rm CP}| < 0.04 \ (\delta = 0 \sim 2\pi)$.
- Distinguishable from the CP conserving case.

Summary

- $\Delta m^2_{12} \ll \Delta m^2_{23}$ $(m^\nu_1 \simeq m^\nu_2)$ may suggest

$$M_\nu = \begin{pmatrix} m^0_1 & 0 & 0 \\ 0 & m^0_1 & 0 \\ 0 & 0 & m^0_3 \end{pmatrix} + \begin{pmatrix} \varepsilon_{11} & \varepsilon_{12} & \varepsilon_{13} \\ \varepsilon_{12} & 0 & \varepsilon_{23} \\ \varepsilon_{23} & \varepsilon_{23} & 0 \end{pmatrix} \quad m^0_i \ll \varepsilon_{ij}$$

  in the diagonal basis of the charged lepton mass matrix.

- $m^0_1 = m^0_2 \to \theta^0_{12} = 0$ and $\sin\theta_{13} \ll 1 \to \theta^0_{13} \simeq 0$ may indicate

$$V^0 = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c^0_{23} & s^0_{23} \\ 0 & -s^0_{23} & c^0_{23} \end{pmatrix}.$$

- If θ^0_{23} is small, CP is almost conserved, and then $\underline{m_{ee} \simeq m^\nu_1.}$
- If θ^0_{23} is large, CPV can also be large.

  $(M_\nu)_{11} \simeq (M_\nu)_{22}$ including phases, thus $\underline{m_{ee} \simeq m^\nu_1.}$

  Testable.

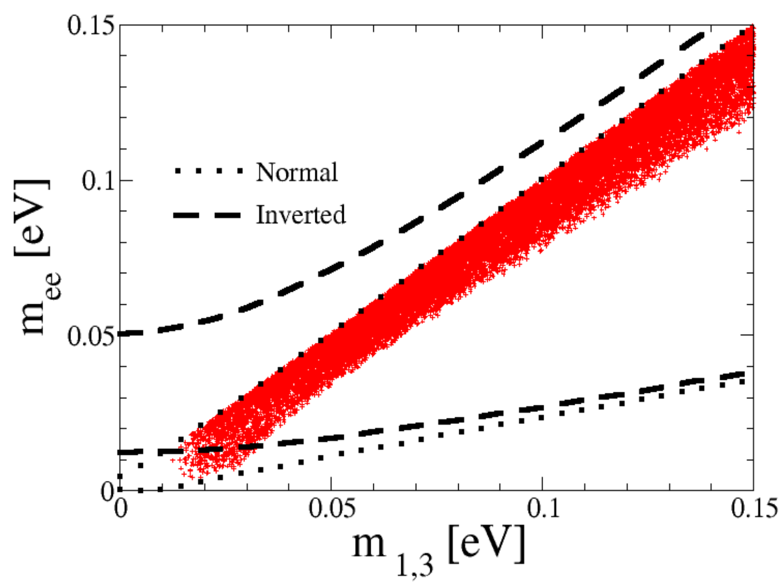
- The mass ordering can be distinguished.

Comment

- The above conclusion, $m_{ee} \simeq m_1^\nu$, is based on $m_i^0 \ll \varepsilon_{ij}$.

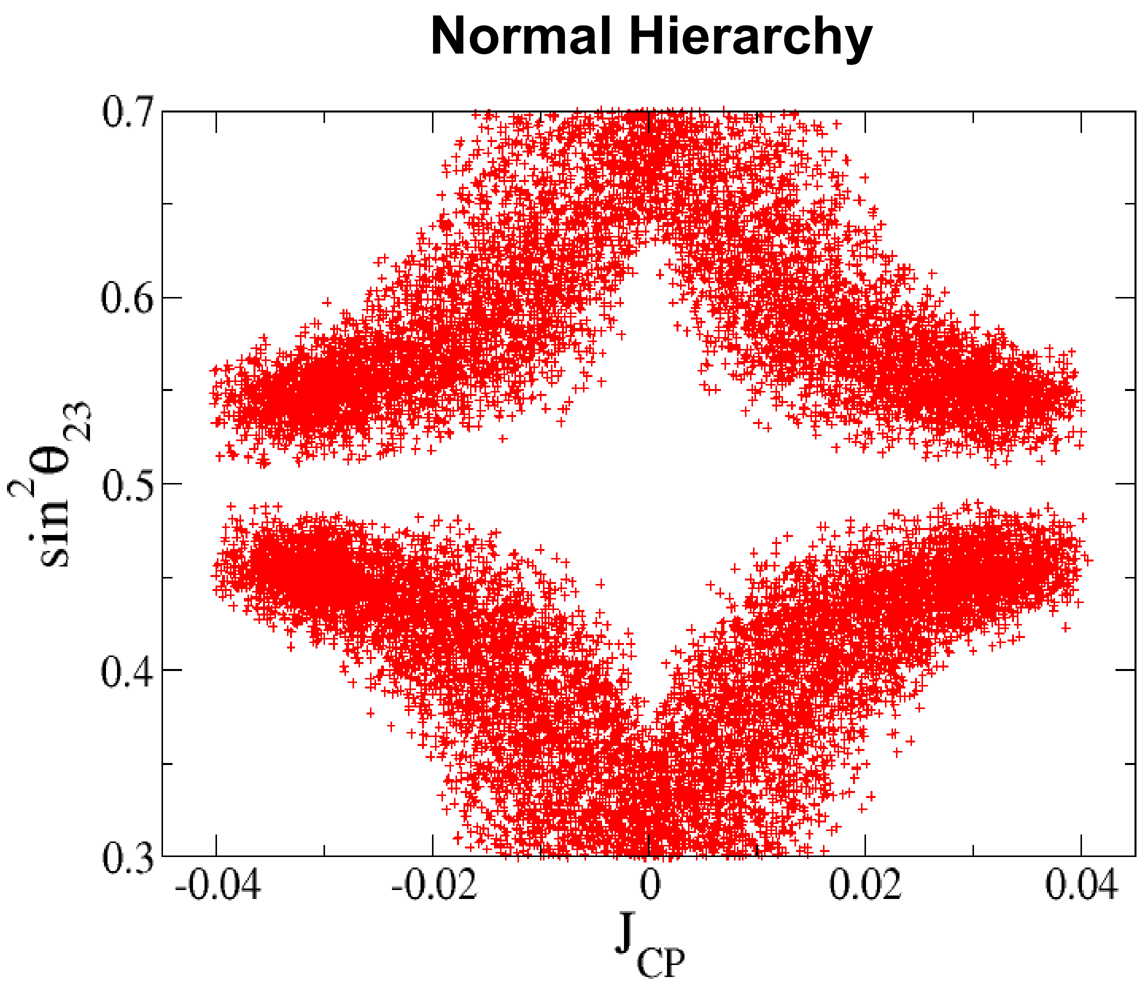
$$M_\nu = \begin{pmatrix} m_1^0 & 0 & 0 \\ 0 & m_1^0 & 0 \\ 0 & 0 & m_3^0 \end{pmatrix} + \begin{pmatrix} \varepsilon_{11} & \varepsilon_{12} & \varepsilon_{13} \\ \varepsilon_{12} & 0 & \varepsilon_{23} \\ \varepsilon_{23} & \varepsilon_{23} & 0 \end{pmatrix}$$

- For instance, if $\varepsilon_{11}, \varepsilon_{12}/m_3^0 < 0.1$ is soften to < 0.5, then



Back up

CP violation



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