

Low Energy CP-Violation in the Lepton Sector and Leptogenesis

S. T. Petcov

SISSA/INFN, Trieste, Italy, and
INRNE, Bulgarian Academy of Sciences, Sofia, Bulgaria

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Low Energy Leptonic CPV and Leptogenesis: Summary

Leptogenesis: see-saw mechanism; N_j - heavy RH ν 's;

N_j, ν_k - Majorana particles

$$N_j: M_1 \ll M_2 \ll M_3$$

The observed value of the baryon asymmetry of the Universe can be generated

A. CP-violation due to the Dirac phase δ in U_{PMNS} , no other sources of CPV (Majorana phases in U_{PMNS} equal to 0, etc.)

$m_1 \ll m_2 \ll m_3$ (NH):

$$|\sin \theta_{13} \sin \delta| \gtrsim 0.09, \quad \sin \theta_{13} \gtrsim 0.09; \quad |J_{\text{CP}}| \gtrsim 2.0 \times 10^{-2}$$

$m_3 \ll m_1 < m_2$ (IH):

$$|\sin \theta_{13} \sin \delta| \gtrsim 0.02, \quad \sin \theta_{13} \gtrsim 0.02; \quad |J_{\text{CP}}| \gtrsim 4.6 \times 10^{-3}$$

B. CP-violation due to the Majorana phases in U_{PMNS} , no other sources of CPV (Dirac phase in U_{PMNS} equal to 0, etc.)

C. CP-violation due to both Dirac and Majorana phases in U_{PMNS} , no other source of CPV.

Compelling Evidences for ν -Oscillations

$$\nu_{l\text{L}} = \sum_{j=1} U_{lj} \nu_{j\text{L}} \quad l = e, \mu, \tau. \quad (1)$$

B. Pontecorvo, 1957; 1958; 1967;
Z. Maki, M. Nakagawa, S. Sakata, 1962;

Three Neutrino Mixing

$$\nu_{lL} = \sum_{j=1}^3 U_{lj} \nu_{jL} . \quad (2)$$

U is the Pontecorvo-Maki-Nakagawa-Sakata (PMNS) neutrino mixing matrix,

$$U = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu1} & U_{\mu2} & U_{\mu3} \\ U_{\tau1} & U_{\tau2} & U_{\tau3} \end{pmatrix} \quad (3)$$

- U - $n \times n$ unitary:

	n	2	3	4
mixing angles:	$\frac{1}{2}n(n-1)$	1	3	6

CP-violating phases:

ν_j - Dirac:	$\frac{1}{2}(n-1)(n-2)$	0	1	3
ν_j - Majorana:	$\frac{1}{2}n(n-1)$	1	3	6

$n = 3$: 1 Dirac and
2 additional CP-violating phases, Majorana phases

PMNS Matrix: Standard Parametrization

$$U = V \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\frac{\alpha_{21}}{2}} & 0 \\ 0 & 0 & e^{i\frac{\alpha_{31}}{2}} \end{pmatrix} \quad (4)$$

$$V = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix} \quad (5)$$

- $s_{ij} \equiv \sin \theta_{ij}$, $c_{ij} \equiv \cos \theta_{ij}$, $\theta_{ij} = [0, \frac{\pi}{2}]$,
- δ - Dirac CP-violation phase, $\delta = [0, 2\pi]$,
- α_{21} , α_{31} - the two Majorana CP-violation phases.
- $\Delta m_{\odot}^2 \equiv \Delta m_{21}^2 \cong 8.0 \times 10^{-5} \text{ eV}^2 > 0$, $\sin^2 \theta_{12} \cong 0.30$, $\cos 2\theta_{12} \gtrsim 0.28$ (2σ),
- $|\Delta m_{\text{atm}}^2| \equiv |\Delta m_{31}^2| \cong 2.5 \times 10^{-3} \text{ eV}^2$, $\sin^2 2\theta_{23} \cong 1$,
- θ_{13} - the CHOOZ angle: $\sin^2 \theta_{13} < 0.027$ (0.041) 2σ (3σ).

A.Bandyopadhyay, S.Choubey, S.Goswami, S.T.P., D.P.Roy, hep-ph/0406328 (updated)

T. Schwetz, hep-ph/0606060.

- $\sqrt{\Delta m_{\odot}^2} \sin^2 \theta_{12} \cong 3.0 \times 10^{-3} \text{ eV}$ (\pm) $\sqrt{|\Delta m_{\text{atm}}^2|} \sin^2 \theta_{13} \lesssim 2.2 \times 10^{-3} \text{ eV}$;
- $\sqrt{|\Delta m_{\text{atm}}^2|} \cong 5 \times 10^{-2} \text{ eV}$; $\sqrt{|\Delta m_{\text{atm}}^2|} \cos 2\theta_{12} \gtrsim 1.4 \times 10^{-2} \text{ eV}$ ($\cos 2\theta_{12} \gtrsim 0.28$)
- m_0 : $m_0^2 \gg \Delta m_{\odot}^2, |\Delta m_{\text{atm}}^2|$, $m_0 \gtrsim 0.1 \text{ eV}$
- $\text{sgn}(\Delta m_{\text{atm}}^2) = \text{sgn}(\Delta m_{31}^2)$ not determined

$$\Delta m_{\text{atm}}^2 \equiv \Delta m_{31}^2 > 0, \text{ normal mass ordering}$$

$$\Delta m_{\text{atm}}^2 \equiv \Delta m_{32}^2 < 0, \text{ inverted mass ordering}$$

Convention: $m_1 < m_2 < m_3$ - **NMO**, $m_3 < m_1 < m_2$ - **IMO**

- **Majorana phases α_{21}, α_{31} :**

- $\nu_l \leftrightarrow \nu_l, \bar{\nu}_l \leftrightarrow \bar{\nu}_l$ not sensitive;

S.M. Bilenky, J. Hosek, S.T.P., 1980;
P. Langacker, S.T.P., G. Steigman, S. Toshev, 1987

- $|\langle m \rangle|$ in $(\beta\beta)_{0\nu}$ -decay depends on α_{21}, α_{31} ;
- $\Gamma(\mu \rightarrow e + \gamma)$ etc. in SUSY theories depend on $\alpha_{21,31}$;
- BAU, leptogenesis scenario: $\alpha_{21,31}$!

Future Progress

- Determination of the nature - Dirac or Majorana, of ν_j .
- Determination of $\text{sgn}(\Delta m_{\text{atm}}^2)$, type of ν - mass spectrum

$$m_1 \ll m_2 \ll m_3, \quad \text{NH,}$$

$$m_3 \ll m_1 < m_2, \quad \text{IH,}$$

$$m_1 \cong m_2 \cong m_3, \quad m_{1,2,3}^2 \gg \Delta m_{\text{atm}}^2, \quad \text{QD; } m_j \gtrsim 0.10 \text{ eV.}$$

- Determining, or obtaining significant constraints on, the absolute scale of ν_j -masses, or $\min(m_j)$.
- Status of the CP-symmetry in the lepton sector: violated due to δ (Dirac), and/or due to α_{21}, α_{31} (Majorana)?
- High precision determination of $\Delta m_{\odot}^2, \theta_{\odot}, \Delta m_{\text{atm}}^2, \theta_{\text{atm}}$.
- Measurement of, or improving by at least a factor of (5 - 10) the existing upper limit on, $\sin^2 \theta_{13}$.
- Searching for possible manifestations, other than ν_l -oscillations, of the non-conservation of $L_l, l = e, \mu, \tau$, such as $\mu \rightarrow e + \gamma, \tau \rightarrow \mu + \gamma$, etc. decays.

- Understanding at fundamental level the mechanism giving rise to the ν - masses and mixing and to the L_l -non-conservation. Includes understanding
 - the origin of the observed patterns of ν -mixing and ν -masses ;
 - the physical origin of CPV phases in U_{PMNS} ;
 - Are the observed patterns of ν -mixing and of $\Delta m_{21,31}^2$ related to the existence of a new symmetry?
 - Is there any relations between q -mixing and ν - mixing? Is $\theta_{12} + \theta_c = \pi/4$?
 - Is $\theta_{23} = \pi/4$, or $\theta_{23} > \pi/4$ or else $\theta_{23} < \pi/4$?
 - Is there any correlation between the values of CPV phases and of mixing angles in U_{PMNS} ?
- Progress in the theory of ν -mixing might lead to a better understanding of the origin of the BAU.
 - Can the Majorana and/or Dirac CPVP in U_{PMNS} be the leptogenesis CPV parameters at the origin of BAU?

Rephasing Invariants Associated with CPVP

Dirac phase δ :

$$J_{CP} = \text{Im} \{ U_{e1} U_{\mu 2} U_{e2}^* U_{\mu 1}^* \} .$$

C. Jarlskog, 1985 (for quarks)

CP-, T- violation effects in neutrino oscillations

P. Krastev, S.T.P., 1988

Majorana phases α_{21}, α_{31} :

$$S_1 = \text{Im} \{ U_{e1} U_{e3}^* \}, \quad S_2 = \text{Im} \{ U_{e2} U_{e3}^* \} \quad (\text{not unique}); \quad \text{or}$$
$$S'_1 = \text{Im} \{ U_{\tau 1} U_{\tau 2}^* \}, \quad S'_2 = \text{Im} \{ U_{\tau 2} U_{\tau 3}^* \}$$

J.F. Nieves and P. Pal, 1987, 2001

G.C. Branco et al., 1986

J.A. Aguilar-Saavedra and G.C. Branco, 2000

CP-violation: both $\text{Im} \{ U_{e1} U_{e3}^* \} \neq 0$ and $\text{Re} \{ U_{e1} U_{e3}^* \} \neq 0$.

S_1, S_2 appear in $|\langle m \rangle|$ in $(\beta\beta)_{0\nu}$ -decay.

In general, J_{CP}, S_1 and S_2 are independent.

Dirac CP-Nonconservation: δ in U_{PMNS}

Observable manifestations in

$$\nu_l \leftrightarrow \nu_{l'} , \quad \bar{\nu}_l \leftrightarrow \bar{\nu}_{l'} , \quad l, l' = e, \mu, \tau$$

- not sensitive to Majorana CPVP α_{21}, α_{31}

CP-invariance:

$$P(\nu_l \rightarrow \nu_{l'}) = P(\bar{\nu}_l \rightarrow \bar{\nu}_{l'}) , \quad l \neq l' = e, \mu, \tau$$

N. Cabibbo, 1978
S.M. Bilenky, J. Hosek, S.T.P., 1980;
V. Barger et al., 1980.

CPT-invariance:

$$P(\nu_l \rightarrow \nu_{l'}) = P(\bar{\nu}_{l'} \rightarrow \bar{\nu}_l)$$

$$l = l' : \quad P(\nu_l \rightarrow \nu_l) = P(\bar{\nu}_l \rightarrow \bar{\nu}_l)$$

T-invariance:

$$P(\nu_l \rightarrow \nu_{l'}) = P(\nu_{l'} \rightarrow \nu_l), \quad l \neq l'$$

3ν -mixing:

$$A_{\text{CP}}^{(l,l')} \equiv P(\nu_l \rightarrow \nu_{l'}) - P(\bar{\nu}_l \rightarrow \bar{\nu}_{l'}) , \quad l \neq l' = e, \mu, \tau$$

$$A_{\text{T}}^{(l,l')} \equiv P(\nu_l \rightarrow \nu_{l'}) - P(\nu_{l'} \rightarrow \nu_l), \quad l \neq l'$$

$$A_{\text{T}}^{(e,\mu)} = A_{\text{T}}^{(\mu,\tau)} = -A_{\text{T}}^{(e,\tau)}$$

In vacuum:

$$A_{\top}^{(e,\mu)} = J_{\text{CP}} F_{\text{osc}}^{\text{vac}}$$

$$J_{\text{CP}} = \text{Im} \{ U_{e1} U_{\mu 2} U_{e2}^* U_{\mu 1}^* \} = \frac{1}{8} \sin 2\theta_{12} \sin 2\theta_{23} \sin 2\theta_{13} \cos \theta_{13} \sin \delta$$

$$F_{\text{osc}}^{\text{vac}} = \sin\left(\frac{\Delta m_{21}^2 L}{2E}\right) + \sin\left(\frac{\Delta m_{32}^2 L}{2E}\right) + \sin\left(\frac{\Delta m_{13}^2 L}{2E}\right)$$

P.I. Krastev, S.T.P., 1988

In matter: Matter effects violate

$$\text{CP} : P(\nu_l \rightarrow \nu_{l'}) \neq P(\bar{\nu}_l \rightarrow \bar{\nu}_{l'})$$

$$\text{CPT} : P(\nu_l \rightarrow \nu_{l'}) \neq P(\bar{\nu}_{l'} \rightarrow \bar{\nu}_l)$$

P. Langacker et al., 1987

Can conserve the T-invariance (Earth)

$$P(\nu_l \rightarrow \nu_{l'}) = P(\nu_{l'} \rightarrow \nu_l), \quad l \neq l'$$

In matter with constant density: $A_{\top}^{(e,\mu)} = J_{\text{CP}}^{\text{mat}} F_{\text{osc}}^{\text{mat}}$

$$J_{\text{CP}}^{\text{mat}} = J_{\text{CP}}^{\text{vac}} R_{\text{CP}}$$

R_{CP} does not depend on θ_{23} and δ ; $|R_{\text{CP}}| \lesssim 2.5$

P.I. Krastev, S.T.P., 1988

HOW?

- Reactor Experiments ~ 2 km

$\sin 2\theta_{13}$

- Super Beams: $\theta_{13}, \delta, \dots$

JHF (T2K), SK (HK) 295 km

NuMI (NO ν A) ~ 800 km

SPL+ β -beams, UNO (1 megaton):
CERN-Frejus ~ 140 km

ν -Factories $\sim 3000, 7000$ km

If ν_j – Majorana particles, U_{PMNS} contains (3- ν mixing)

δ -Dirac, α_{21} , α_{31} - Majorana physical CPV phases

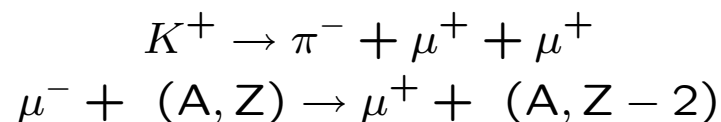
ν -oscillations $\nu_l \leftrightarrow \nu_{l'}$, $\bar{\nu}_l \leftrightarrow \bar{\nu}_{l'}$, $l, l' = e, \mu, \tau$,

- are not sensitive to the nature of ν_j ,

S.M. Bilenky et al., 1980;
P. Langacker et al., 1987

- provide information on $\Delta m_{jk}^2 = m_j^2 - m_k^2$, but not on the absolute values of ν_j masses.

The Majorana nature of ν_j can manifest itself in the existence of $\Delta L = \pm 2$ processes:



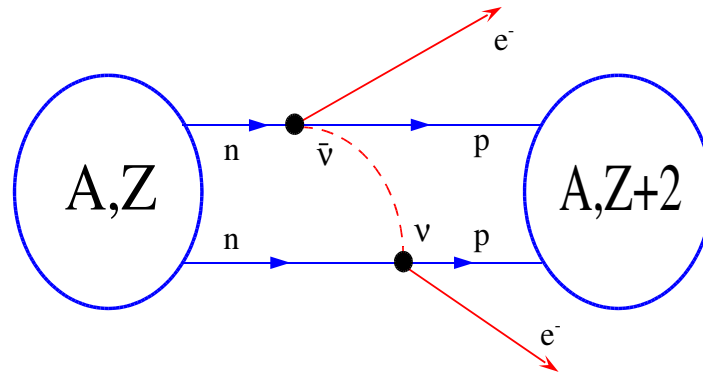
The process most sensitive to the possible Majorana nature of ν_j - $(\beta\beta)_{0\nu}$ -decay



of even-even nuclei, ^{48}Ca , ^{76}Ge , ^{82}Se , ^{100}Mo , ^{116}Cd , ^{130}Te , ^{136}Xe , ^{150}Nd .

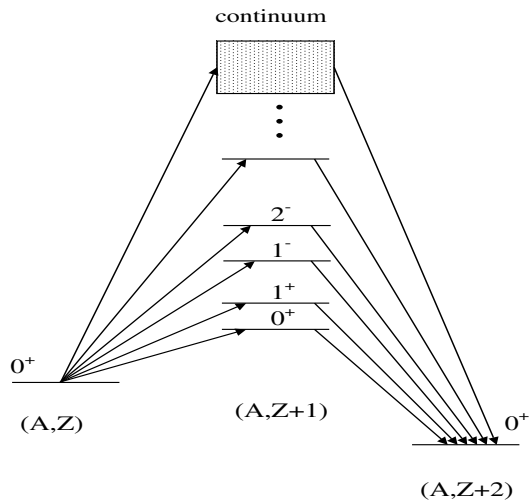
$2n$ from (A, Z) exchange a virtual Majorana ν_j (via the CC weak interaction) and transform into $2p$ of $(A, Z+2)$ and two free e^- .

Nuclear $0\nu\beta\beta$ -decay



strong in-medium modification of the basic process

$$dd \rightarrow uue^-e^-(\bar{\nu}_e\bar{\nu}_e)$$



virtual excitation
of states of all multiplicities
in $(A, Z+1)$ nucleus

$(\beta\beta)_{0\nu}$ –Decay Experiments:

- Majorana nature of ν_j
- Type of ν –mass spectrum (NH, IH, QD)
- Absolute neutrino mass scale

${}^3\text{H}$ β -decay , cosmology: m_{ν} (QD, IH)

- CPV due to Majorana CPV phases

ν_j – Dirac or Majorana particles, fundamental problem

ν_j –Dirac: **conserved lepton charge exists**, $L = L_e + L_\mu + L_\tau$, $\nu_j \neq \bar{\nu}_j$

ν_j –Majorana: **no lepton charge is exactly conserved**, $\nu_j \equiv \bar{\nu}_j$

The observed patterns of ν –mixing and of Δm_{atm}^2 and Δm_{\odot}^2 can be related to Majorana ν_j and an **approximate** symmetry:

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

S.T.P., 1982

See-saw mechanism: ν_j – Majorana

Establishing that ν_j are Majorana particles would be as important as the discovery of ν – oscillations.

$$A(\beta\beta)_{0\nu} \sim \langle m \rangle M(A,Z), \quad M(A,Z) - \text{NME},$$

$$\begin{aligned} |\langle m \rangle| &= |m_1 |U_{e1}|^2 + m_2 |U_{e2}|^2 e^{i\alpha_{21}} + m_3 |U_{e3}|^2 e^{i\alpha_{31}}| \\ &= |m_1 c_{12}^2 c_{13}^2 + m_2 s_{12}^2 c_{13}^2 e^{i\alpha_{21}} + m_3 s_{13}^2 e^{i\alpha_{31}}|, \quad \theta_{12} \equiv \theta_{\odot}, \theta_{13} - \text{CHOOZ} \end{aligned}$$

α_{21}, α_{31} - the two Majorana CPVP of the PMNS matrix.

CP-invariance: $\alpha_{21} = 0, \pm\pi, \alpha_{31} = 0, \pm\pi;$

$$\eta_{21} \equiv e^{i\alpha_{21}} = \pm 1, \quad \eta_{31} \equiv e^{i\alpha_{31}} = \pm 1$$

relative CP-parities of ν_1 and ν_2 , and of ν_1 and ν_3 .

L. Wolfenstein, 1981;

S.M. Bilenky, N. Nedelcheva, S.T.P., 1984;

B. Kayser, 1984.

$$|\langle m \rangle| : m_j, \theta_\odot \equiv \theta_{12}, \theta_{13}, \alpha_{21,31}$$

$m_{1,2,3}$ - in terms of $\min(m_j)$, Δm_{atm}^2 , Δm_\odot^2

S.T.P., A.Yu. Smirnov, 1994

Convention: $m_1 < m_2 < m_3$ - **NMO**, $m_3 < m_1 < m_2$ - **IMO**

$$\Delta m_\odot^2 \equiv \Delta m_{21}^2, \quad m_2 = \sqrt{m_1^2 + \Delta m_\odot^2},$$

while either

$$\Delta m_{\text{atm}}^2 \equiv \Delta m_{31}^2 > 0, \quad m_3 = \sqrt{m_1^2 + \Delta m_{\text{atm}}^2}, \quad \text{normal mass ordering, or}$$

$$\Delta m_{\text{atm}}^2 \equiv \Delta m_{32}^2 < 0, \quad m_1 = \sqrt{m_3^2 + |\Delta m_{\text{atm}}^2| - \Delta m_\odot^2}, \quad \text{inverted mass ordering}$$

The neutrino mass spectrum –

Normal hierarchical (NH) if $m_1 \ll m_2 \ll m_3$,

Inverted hierarchical (IH) if $m_3 \ll m_1 \cong m_2$,

Quasi-degenerate (QD) if $m_1 \cong m_2 \cong m_3 = m$, $m_j^2 \gg |\Delta m_{\text{atm}}^2|$; $m_j \gtrsim 0.1$ eV

Given $|\Delta m_{\text{atm}}^2|$, Δm_\odot^2 , θ_\odot , θ_{13} ,

$$|\langle m \rangle| = |\langle m \rangle| (m_{\text{min}}, \alpha_{21}, \alpha_{31}; S), \quad S = \text{NO(NH), IO(IH)}.$$

$$A(\beta\beta)_{0\nu} \sim \langle m \rangle M(A,Z), \quad M(A,Z) - \text{NME},$$

$$|\langle m \rangle| \cong \left| \sqrt{\Delta m_{\odot}^2} \sin^2 \theta_{12} e^{i\alpha} + \sqrt{\Delta m_{31}^2} \sin^2 \theta_{13} e^{i\beta_M} \right|, \quad m_1 \ll m_2 \ll m_3 \text{ (NH)},$$

$$|\langle m \rangle| \cong \sqrt{m_3^2 + \Delta m_{13}^2} |\cos^2 \theta_{12} + e^{i\alpha} \sin^2 \theta_{12}|, \quad m_3 < (\ll) m_1 < m_2 \text{ (IH)},$$

$$|\langle m \rangle| \cong m |\cos^2 \theta_{12} + e^{i\alpha} \sin^2 \theta_{12}|, \quad m_{1,2,3} \cong m \gtrsim 0.10 \text{ eV (QD)},$$

$$\theta_{12} \equiv \theta_{\odot}, \theta_{13}\text{-CHOOZ}; \quad \alpha \equiv \alpha_{21}, \beta_M \equiv \alpha_{31}.$$

$$\text{CP-invariance: } \alpha = 0, \pm\pi, \beta_M = 0, \pm\pi;$$

$$|\langle m \rangle| \lesssim 5 \times 10^{-3} \text{ eV, NH};$$

$$\sqrt{\Delta m_{13}^2} \cos 2\theta_{12} \cong 0.013 \text{ eV} \lesssim |\langle m \rangle| \lesssim \sqrt{\Delta m_{13}^2} \cong 0.055 \text{ eV, IH};$$

$$m \cos 2\theta_{12} \lesssim |\langle m \rangle| \lesssim m, \quad m \gtrsim 0.10 \text{ eV, QD}.$$

Best sensitivity: Heidelberg-Moscow ^{76}Ge experiment.

Claim for a positive signal at $> 3\sigma$:

H. Klapdor-Kleingrothaus et al., PL B586 (2004),

$|\langle m \rangle| = (0.1 - 0.9) \text{ eV}$ (99.73% C.L.).

IGEX ^{76}Ge : $|\langle m \rangle| < (0.33 - 1.35) \text{ eV}$ (90% C.L.).

Taking data - NEMO3 (^{100}Mo), CUORICINO (^{130}Te):

$|\langle m \rangle| < (0.7 - 1.2) \text{ eV}$, $|\langle m \rangle| < (0.18 - 0.90) \text{ eV}$ (90% C.L.).

Large number of projects: $|\langle m \rangle| \sim (0.01 - 0.05) \text{ eV}$

CUORE - ^{130}Te ,

GERDA - ^{76}Ge ,

SuperNEMO - ^{82}Se ,

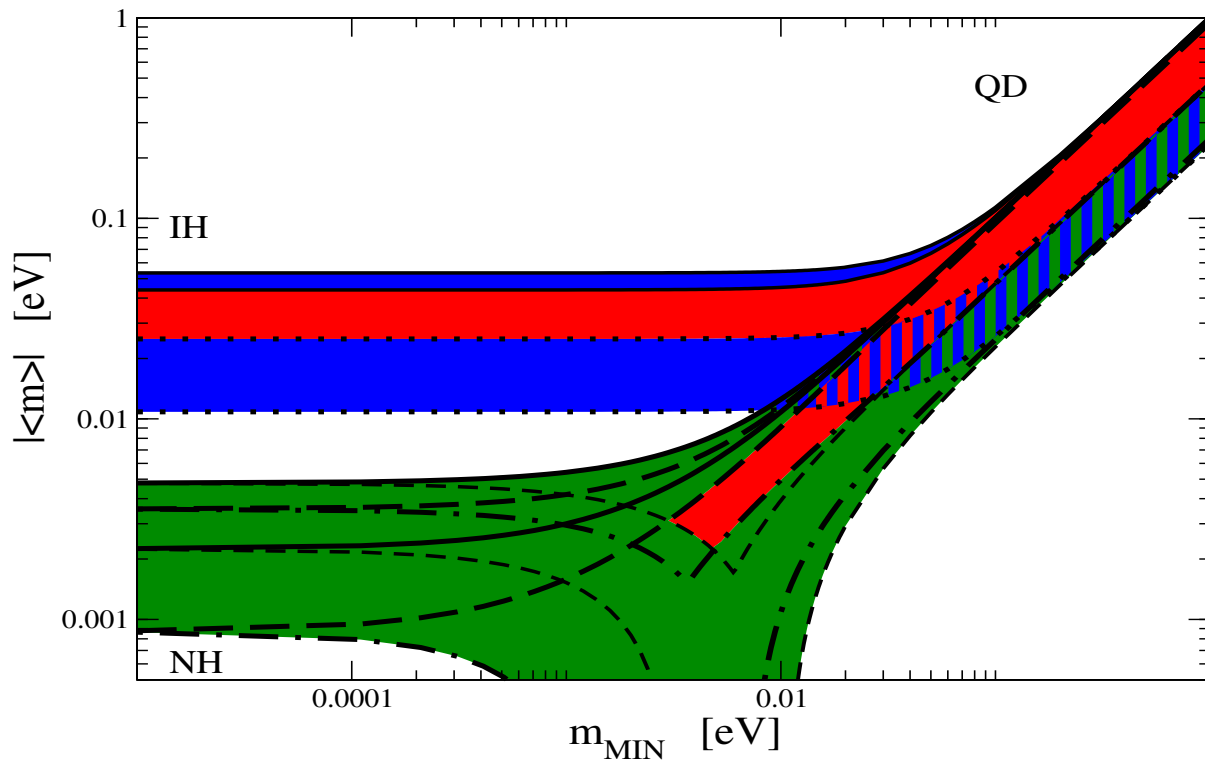
EXO - ^{136}Xe ,

MAJORANA - ^{76}Ge ,

MOON - ^{100}Mo ,

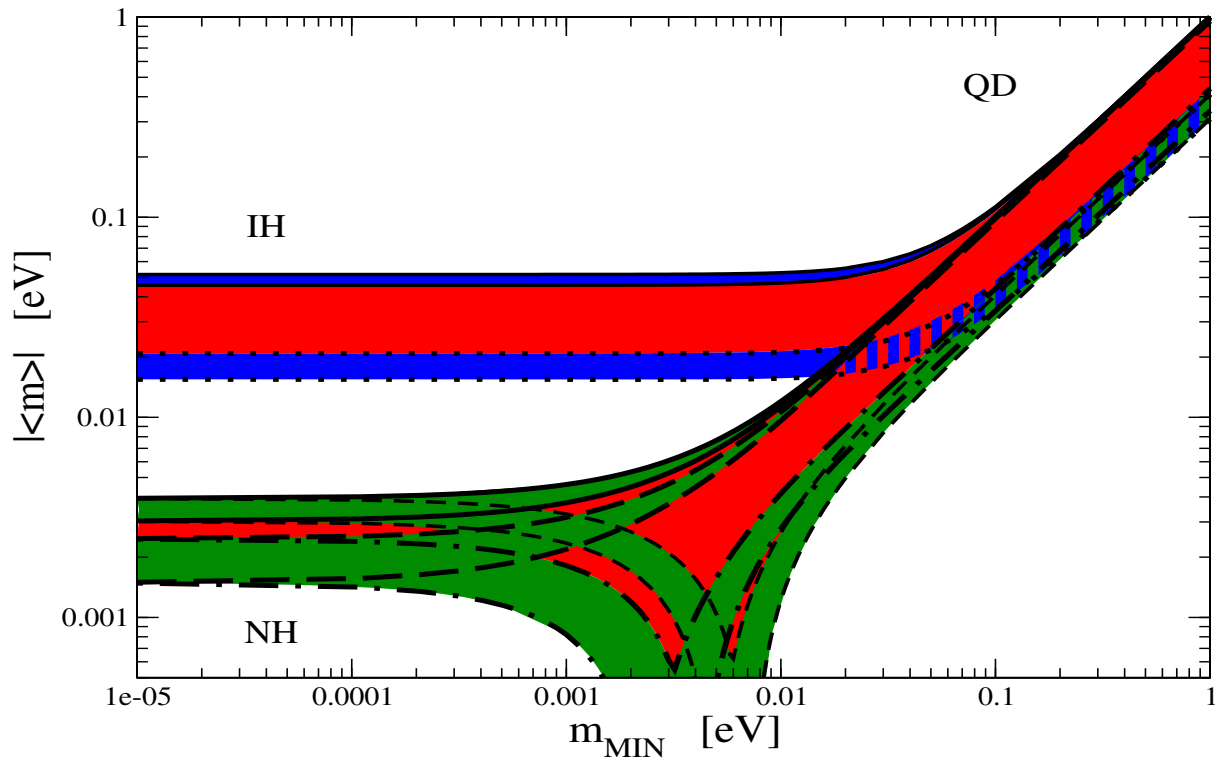
CANDLES - ^{48}Ca ,

XMASS - ^{136}Xe .



S. Pascoli, S.T.P., 2006

The current 2σ ranges of values of the parameters used.



$\sin^2 \theta_{13} = 0.015 \pm 0.006$; $1\sigma(\Delta m_{\odot}^2) = 4\%$, $1\sigma(\sin^2 \theta_{\odot}) = 4\%$, $1\sigma(|\Delta m_{\text{atm}}^2|) = 6\%$;

$2\sigma(|\langle m \rangle|)$ used.

Majorana CPV Phases and $|\langle m \rangle|$

CPV can be established provided

- $|\langle m \rangle|$ measured with $\Delta \lesssim 15\%$;
- Δm_{atm}^2 (IH) or m_0 (QD) measured with $\delta \lesssim 10\%$;
- $\xi \lesssim 1.5$;
- α_{21} (QD): in the interval $\sim [\frac{\pi}{4} - \frac{3\pi}{4}]$, or $\sim [\frac{5\pi}{4} - \frac{3\pi}{2}]$;
- $\tan^2 \theta_{\odot} \gtrsim 0.40$.

S. Pascoli, S.T.P., W. Rodejohann, 2002

S. Pascoli, S.T.P., L. Wolfenstein, 2002

S. Pascoli, S.T.P., T. Schwetz, hep-ph/0505226

No “No-go for detecting CP-Violation via $(\beta\beta)_{0\nu}$ -decay”

V. Barger *et al.*, 2002

Absolute Neutrino Mass Measurements

The Troitzk and Mainz ${}^3\text{H}$ β -decay experiments

$$m_{\nu_e} < 2.3 \text{ eV} \quad (95\% \text{ C.L.})$$

There are prospects to reach sensitivity

$$\text{KATRIN :} \quad m_{\nu_e} \sim 0.2 \text{ eV}$$

Cosmological and astrophysical data: the WMAP result combined with data from large scale structure surveys (2dFGRS, SDSS)

$$\sum_j m_j \equiv \Sigma < (0.4 - 1.7) \text{ eV}$$

The WMAP and future PLANCK experiments can be sensitive to

$$\sum_j m_j \cong 0.4 \text{ eV}$$

Data on weak lensing of galaxies by large scale structure, combined with data from the WMAP and PLANCK experiments may allow to determine

$$\sum_j m_j : \quad \delta \cong 0.04 \text{ eV.}$$

M_ν from the See-Saw Mechanism

P. Minkowski, 1977.

M. Gell-Mann, P. Ramond, R. Slansky, 1979;

T. Yanagida, 1979;

R. Mohapatra, G. Senjanovic, 1980.

- Explains the smallness of ν -masses.
- Through **leptogenesis theory** links the ν -mass generation to the generation of baryon asymmetry of the Universe Y_B .

S. Fukugita, T. Yanagida, 1986.

- In SUSY GUT's with see-saw mechanism of ν -mass generation, the LFV decays

$$\mu \rightarrow e + \gamma, \quad \tau \rightarrow \mu + \gamma, \quad \tau \rightarrow e + \gamma, \quad \text{etc.}$$

are predicted to take place with rates within the reach of present and future experiments.

F. Borzumati, A. Masiero, 1986.

- The ν_j are **Majorana particles**; $(\beta\beta)_{0\nu}$ -decay is allowed.

See-Saw: Dirac ν -mass m_D + Majorana mass M_R for N_R

The See-Saw Lagrangian

$$\mathcal{L}^{\text{lep}}(x) = \mathcal{L}_{\text{CC}}(x) + \mathcal{L}_Y(x) + \mathcal{L}_M^{\text{N}}(x),$$

$$\mathcal{L}_{\text{CC}} = -\frac{g}{\sqrt{2}} \bar{l}_L(x) \gamma_\alpha \nu_{lL}(x) W^{\alpha\dagger}(x) + h.c.,$$

$$\mathcal{L}_Y(x) = \lambda_{il} \bar{N}_{iR}(x) H^\dagger(x) \psi_{lL}(x) + Y_l H^c(x) \bar{l}_R(x) \psi_{lL}(x) + h.c.,$$

$$\mathcal{L}_M^{\text{N}}(x) = -\frac{1}{2} M_i \bar{N}_i(x) N_i(x).$$

ψ_{lL} - LH doublet, $\psi_{lL}^T = (\nu_{lL} \ l_L)$, l_R - RH singlet, H - Higgs doublet.

Basis: $M_R = (M_1, M_2, M_3)$; $D_N \equiv \text{diag}(M_1, M_2, M_3)$, $D_\nu \equiv \text{diag}(m_1, m_2, m_3)$.

m_D generated by the Yukawa interaction:

$$-\mathcal{L}_Y^\nu = \lambda_{il} \bar{N}_{iR} H^\dagger(x) \psi_{lL}(x), \quad v = 174 \text{ GeV}, \quad v \lambda = m_D - \text{complex}$$

For M_R - sufficiently large,

$$m_\nu \simeq v^2 \lambda^T M_R^{-1} \lambda = U_{\text{PMNS}}^* m_\nu^{\text{diag}} U_{\text{PMNS}}^\dagger.$$

$Y_\nu \equiv \lambda = \sqrt{D_N} R \sqrt{D_\nu} (U_{\text{PMNS}})^\dagger / v_u$, all at M_R ; R -complex, $R^T R = \mathbf{1}$.

J.A. Casas and A. Ibarra, 2001

In GUTs, $M_R < M_X$, $M_X \sim 10^{16}$ GeV;

in GUTs, e.g., $M_R = (10^9, 10^{12}, 10^{15})$ GeV, $m_D \sim 1$ GeV.

The CP-Invariance Constraints

Assume: $C(\bar{\nu}_j)^T = \nu_j$, $C(\bar{N}_k)^T = N_k$, $j, k = 1, 2, 3$.

The CP-symmetry transformation:

$$\begin{aligned} U_{\text{CP}} N_j(x) U_{\text{CP}}^\dagger &= \eta_j^{\text{NCP}} \gamma_0 N_j(x'), \quad \eta_j^{\text{NCP}} = i\rho_j^N = \pm i, \\ U_{\text{CP}} \nu_k(x) U_{\text{CP}}^\dagger &= \eta_k^{\nu\text{CP}} \gamma_0 \nu_k(x'), \quad \eta_k^{\nu\text{CP}} = i\rho_k^\nu = \pm i. \end{aligned}$$

CP-invariance:

$$\lambda_{jl}^* = \lambda_{jl} (\eta_j^{\text{NCP}})^* \eta^l \eta^{H*}, \quad j = 1, 2, 3, \quad l = e, \mu, \tau,$$

Convenient choice: $\eta^l = i$, $\eta^H = 1$ ($\eta^W = 1$):

$$\lambda_{jl}^* = \lambda_{jl} \rho_j^N, \quad \rho_j^N = \pm 1,$$

$$U_{lj}^* = U_{lj} \rho_j^\nu, \quad \rho_j^\nu = \pm 1,$$

$$R_{jk}^* = R_{jk} \rho_j^N \rho_k^\nu, \quad j, k = 1, 2, 3, \quad l = e, \mu, \tau,$$

λ_{jl} , U_{lj} , R_{jk} - either real or purely imaginary.

Relevant quantity:

$$P_{jkml} \equiv R_{jk} R_{jm} U_{lk}^* U_{lm}, \quad k \neq m,$$

$$\text{CP: } P_{jkml}^* = P_{jkml} (\rho_j^N)^2 (\rho_k^\nu)^2 (\rho_m^\nu)^2 = P_{jkml}, \quad \text{Im}(P_{jkml}) = 0.$$

$$P_{jkml} \equiv R_{jk} R_{jm} U_{lk}^* U_{lm}, \quad k \neq m,$$

$$CP: \quad P_{jkml}^* = P_{jkml} (\rho_j^N)^2 (\rho_k^\nu)^2 (\rho_m^\nu)^2 = P_{jkml}, \quad \text{Im}(P_{jkml}) = 0.$$

Consider NH N_j , NH ν_k : $P_{123\tau} = R_{12} R_{13} U_{\tau 2}^* U_{\tau 3}$

Suppose, CP-invariance holds at low E : $\delta = 0$, $\alpha_{21} = \pi$, $\alpha_{31} = 0$.

Thus, $U_{\tau 2}^* U_{\tau 3}$ - purely imaginary.

Then real $R_{12} R_{13}$ corresponds to CP-violation at "high" E .

Leptogenesis

$$Y_B = \frac{n_B - n_{\bar{B}}}{S} \sim 8.6 \times 10^{-11} \quad (n_\gamma: \sim 6.3 \times 10^{-10})$$

$$Y_B \cong -10^{-2} \quad \varepsilon \kappa$$

W. Buchmüller, M. Plümacher, 1998;

W. Buchmüller, P. Di Bari, M. Plümacher, 2004

κ - efficiency factor; $\kappa \sim 10^{-1} - 10^{-3}$: $\varepsilon \gtrsim 10^{-7}$.

ε : CP -, L - violating asymmetry generated in out of equilibrium N_{Rj} -decays in the early Universe,

$$\varepsilon_1 = \frac{\Gamma(N_1 \rightarrow \Phi^- \ell^+) - \Gamma(N_1 \rightarrow \Phi^+ \ell^-)}{\Gamma(N_1 \rightarrow \Phi^- \ell^+) + \Gamma(N_1 \rightarrow \Phi^+ \ell^-)}$$

M.A. Luty, 1992;

L. Covi, E. Roulet and F. Vissani, 1996;

M. Flanz *et al.*, 1996;

M. Plümacher, 1997;

A. Pilaftsis, 1997.

$\kappa = \kappa(\tilde{m})$, \tilde{m} - determines the rate of wash-out processes:

$\Phi^+ + \ell^- \rightarrow N_1$, $\ell^- + \Phi^+ \rightarrow \Phi^- + \ell^+$, etc.

W. Buchmüller, P. Di Bari and M. Plümacher, 2002;

G. F. Giudice *et al.*, 2004

Low Energy Leptonic CPV and Leptogenesis

Assume: $M_1 \ll M_2 \ll M_3$, $M_1 \gtrsim 10^{12}$ GeV

Individual asymmetries:

$$\varepsilon_{1l} = -\frac{3M_1}{16\pi v^2} \frac{\text{Im} \left(\sum_{j,k} m_j^{1/2} m_k^{3/2} U_{lj}^* U_{lk} R_{1j} R_{1k} \right)}{\sum_j m_j |R_{1j}|^2}, \quad v = 174 \text{ GeV}$$

$$\widetilde{m}_l \equiv \frac{|\lambda_{1l}|^2 v^2}{M_1} = \left| \sum_k R_{1k} m_k^{1/2} U_{lk}^* \right|^2, \quad l = e, \mu, \tau.$$

The “one-flavor” approximation - $\mathbf{Y}_{e,\mu,\tau}$ - “small”:

Boltzmann eqn. for $n(N_1)$ and $\Delta L = \Delta(L_e + L_\mu + L_\tau)$.

$Y_l H^c(x) \bar{l}_R(x) \psi_{lL}$ - out of equilibrium at $T \sim M_1$.

One-flavor approximation: $M_1 \sim T > 10^{12}$ GeV

$$\varepsilon_1 = \sum_l \varepsilon_{1l} = -\frac{3M_1}{16\pi v^2} \frac{\text{Im} \left(\sum_{j,k} m_j^2 R_{1j}^2 \right)}{\sum_k m_k |R_{1k}|^2},$$

$$\widetilde{m}_1 = \sum_l \widetilde{m}_l = \sum_k m_k |R_{1k}|^2.$$

At $M_1 \sim 10^{12}$ GeV: Y_τ - in equilibrium, $Y_{e,\mu}$ - not; dynamics changes: τ_R^-, τ_L^+

$\tau_R^- + N_1 \rightarrow \nu_L + \tau_R^-$, $N_1 + \nu_L \rightarrow \tau_R^- + \tau_L^+$, etc.

At $M_1 \sim 10^9$ GeV: Y_τ, Y_μ - in equilibrium, Y_e - not.

Thus, at $M_1 \sim 10^9 - 10^{12}$ GeV: $L_\tau, \Delta L_\tau$ - distinguishable;

$L_e, L_\mu, \Delta L_e, \Delta L_\mu$ - individually not distinguishable;

$L_e + L_\mu, \Delta(L_e + L_\mu)$

A. Abada et al., 2006; E. Nardi et al., 2006

A. Abada et al., 2006

Individual asymmetries:

Assume: $M_1 \ll M_2 \ll M_3$, $10^9 \lesssim M_1 \lesssim 10^{12}$ GeV,

$$\epsilon_{1l} = -\frac{3M_1}{16\pi v^2} \frac{\text{Im} \left(\sum_{j,k} m_j^{1/2} m_k^{3/2} U_{lj}^* U_{lk} R_{1j} R_{1k} \right)}{\sum_j m_j |R_{1j}|^2}$$

$$\widetilde{m}_l \equiv \frac{|\lambda_{1l}|^2 v^2}{M_1} = \left| \sum_k R_{1k} m_k^{1/2} U_{lk}^* \right|^2, \quad l = e, \mu, \tau.$$

The baryon asymmetry is

$$Y_B \simeq -\frac{12}{37g_*} \left(\epsilon_2 \eta \left(\frac{417}{589} \widetilde{m}_2 \right) + \epsilon_\tau \eta \left(\frac{390}{589} \widetilde{m}_\tau \right) \right),$$

$$\eta(\widetilde{m}_l) \simeq \left(\left(\frac{\widetilde{m}_l}{8.25 \times 10^{-3} \text{ eV}} \right)^{-1} + \left(\frac{0.2 \times 10^{-3} \text{ eV}}{\widetilde{m}_l} \right)^{-1.16} \right)^{-1}.$$

$$Y_B = -(12/37) (Y_2 + Y_\tau),$$

$$Y_2 = Y_{e+\mu}, \quad \epsilon_2 = \epsilon_{1e} + \epsilon_{1\mu}, \quad \widetilde{m}_2 = \widetilde{m}_{1e} + \widetilde{m}_{1\mu}$$

A. Abada et al., 2006; E. Nardi et al., 2006

A. Abada et al., 2006

Real (Purely Imaginary) R : $\varepsilon_{1l} \neq 0$, CPV from U

$$\varepsilon_{1e} + \varepsilon_{1\mu} + \varepsilon_{1\tau} = \varepsilon_2 + \varepsilon_{1\tau} = 0,$$

$$\begin{aligned} \varepsilon_{1\tau} &= -\frac{3M_1}{16\pi v^2} \frac{\text{Im} \left(\sum_{j,k} m_j^{1/2} m_k^{3/2} U_{\tau j}^* U_{\tau k} R_{1j} R_{1k} \right)}{\sum_j m_j |R_{1j}|^2} \\ &= -\frac{3M_1}{16\pi v^2} \frac{\sum_{j,k>j} m_j^{1/2} m_k^{1/2} (m_k - m_j) R_{1j} R_{1k} \text{Im} (U_{\tau j}^* U_{\tau k})}{\sum_j m_j |R_{1j}|^2}, R_{1j} R_{1k} = \pm |R_{1j} R_{1k}|, \\ &= \mp \frac{3M_1}{16\pi v^2} \frac{\sum_{j,k>j} m_j^{1/2} m_k^{1/2} (m_k + m_j) |R_{1j} R_{1k}| \text{Re} (U_{\tau j}^* U_{\tau k})}{\sum_j m_j |R_{1j}|^2}, R_{1j} R_{1k} = \pm i |R_{1j} R_{1k}| \end{aligned}$$

CP-Violation: $\text{Im} (U_{\tau j}^* U_{\tau k}) \neq 0$, $\text{Re} (U_{\tau j}^* U_{\tau k}) \neq 0$;

$$Y_B = -\frac{12}{37} \frac{\varepsilon_{1\tau}}{g_*} \left(\eta \left(\frac{390}{589} \widetilde{m}_\tau \right) - \eta \left(\frac{417}{589} \widetilde{m}_2 \right) \right)$$

$m_1 \ll m_2 \ll m_3, M_1 \ll M_{2,3}; R_{12}R_{13} - \text{real}; m_1 \cong 0, R_{11} \cong 0 (N_3 \text{ decoupling})$

$$\varepsilon_{1\tau} = - \frac{3M_1 \sqrt{\Delta m_{31}^2}}{16\pi v^2} \left(\frac{\Delta m_{\odot}^2}{\Delta m_{31}^2} \right)^{\frac{1}{4}} \frac{|R_{12}R_{13}|}{\left(\frac{\Delta m_{\odot}^2}{\Delta m_{31}^2} \right)^{\frac{1}{2}} |R_{12}|^2 + |R_{13}|^2} \\ \times \left(1 - \frac{\sqrt{\Delta m_{\odot}^2}}{\sqrt{\Delta m_{31}^2}} \right) \text{Im}(U_{\tau 2}^* U_{\tau 3})$$

$$\text{Im}(U_{\tau 2}^* U_{\tau 3}) = -c_{13} \left[c_{23}s_{23}c_{12} \sin\left(\frac{\alpha_{32}}{2}\right) - c_{23}^2 s_{12}s_{13} \sin\left(\delta - \frac{\alpha_{32}}{2}\right) \right]$$

$\alpha_{32} = \pi, \delta = 0: \text{Re}(U_{\tau 2}^* U_{\tau 3}) = 0, \text{CPV due to } R$

S. Pascoli, S.T.P., A. Riotto, 2006.

$$M_1 \ll M_2 \ll M_3, m_1 \ll m_2 \ll m_3 \text{ (NH)}$$

Dirac CP-violation

$$\alpha_{32} = 0 \text{ (} 2\pi \text{)}, \beta_{23} = \pi \text{ (} 0 \text{)}; \quad \beta_{23} \equiv \beta_{12} + \beta_{13} \equiv \arg(R_{12}R_{13}).$$

$$|R_{12}|^2 \cong 0.85, |R_{13}|^2 = 1 - |R_{12}|^2 \cong 0.15 - \text{maximise } |\epsilon_\tau| \text{ and } |Y_B|:$$

$$|Y_B| \cong 2.8 \times 10^{-13} |\sin \delta| \left(\frac{s_{13}}{0.2} \right) \left(\frac{M_1}{10^9 \text{ GeV}} \right).$$

$$|Y_B| \gtrsim 8 \times 10^{-11}, \quad M_1 \lesssim 5 \times 10^{11} \text{ GeV imply}$$

$$|\sin \theta_{13} \sin \delta| \gtrsim 0.11, \quad \sin \theta_{13} \gtrsim 0.11.$$

The lower limit corresponds to

$$|J_{\text{CP}}| \gtrsim 2.4 \times 10^{-2}$$

FOR $\alpha_{32} = 0 \text{ (} 2\pi \text{)}, \beta_{23} = 0 \text{ (} \pi \text{)}$:

$$|\sin \theta_{13} \sin \delta| \gtrsim 0.09, \quad \sin \theta_{13} \gtrsim 0.09; \quad |J_{\text{CP}}| \gtrsim 2.0 \times 10^{-2}$$

$$M_1 \ll M_2 \ll M_3, m_1 \ll m_2 \ll m_3 \text{ (NH)}$$

Majorana CP-violation

$$\delta = 0, \text{ real } R_{12}, R_{13} (\beta_{23} = \pi (0));$$

$$\alpha_{32} \cong \pi/2, \quad |R_{12}|^2 \cong 0.85, \quad |R_{13}|^2 = 1 - |R_{12}|^2 \cong 0.15 - \text{maximise } |\epsilon_\tau| \text{ and } |Y_B|:$$

$$|Y_B| \cong 2 \times 10^{-12} \left(\frac{\sqrt{\Delta m_{31}^2}}{0.05 \text{ eV}} \right) \left(\frac{M_1}{10^9 \text{ GeV}} \right).$$

We get $|Y_B| \gtrsim 8 \times 10^{-11}$, for $M_1 \gtrsim 3.6 \times 10^{10} \text{ GeV}$

$$M_1 \ll M_2 \ll M_3, m_3 \ll m_1 < m_2 \text{ (IH)}$$

Dirac CP-violation

$$m_3 \cong 0, R_{13} \cong 0 \text{ (} N_3 \text{ decoupling)}$$

$$\alpha_{21} = \pi; R_{11}R_{12} = i\kappa|R_{11}R_{12}|, \kappa = 1;$$

$$|R_{11}| \cong 1.07, |R_{12}|^2 = |R_{11}|^2 - 1, |R_{12}| \cong 0.38 - \text{maximise } |\epsilon_\tau| \text{ and } |Y_B|:$$

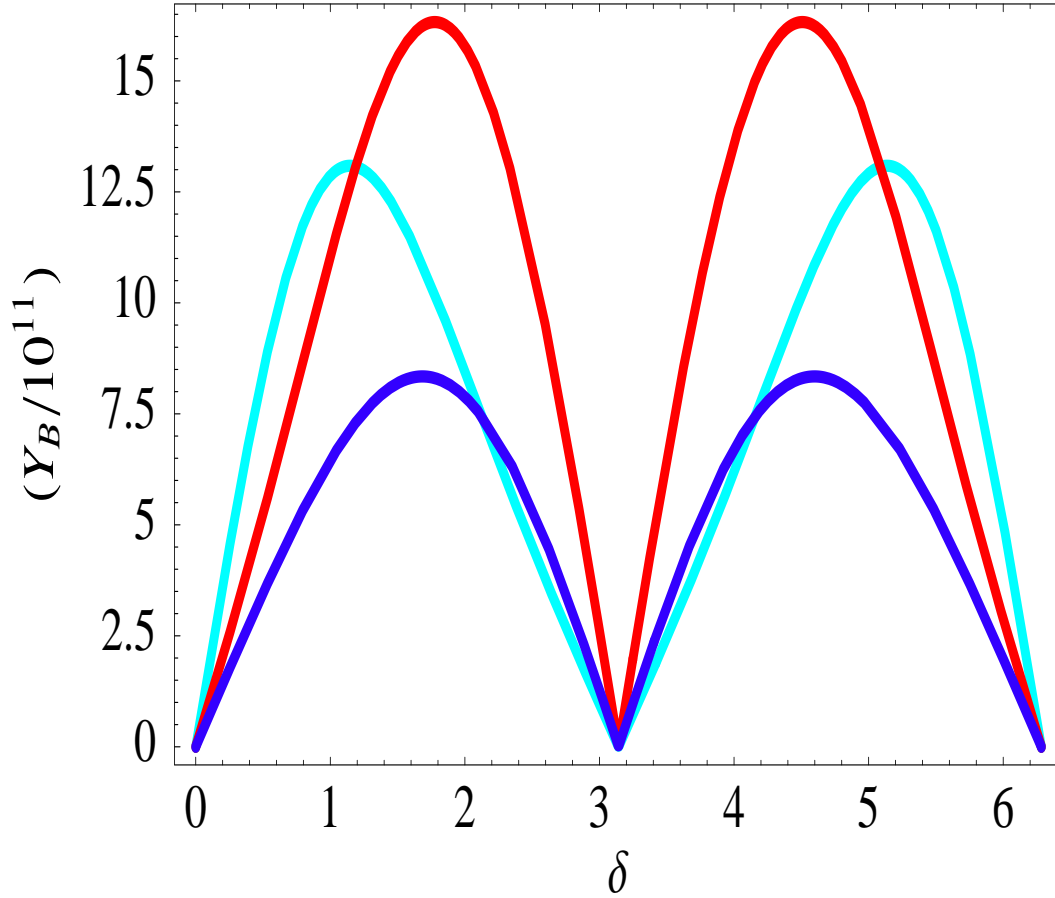
$$|Y_B| \cong 8.1 \times 10^{-12} |s_{13} \sin \delta| \left(\frac{M_1}{10^9 \text{ GeV}} \right).$$

$$|Y_B| \gtrsim 8 \times 10^{-11}, M_1 \lesssim 5 \times 10^{11} \text{ GeV imply}$$

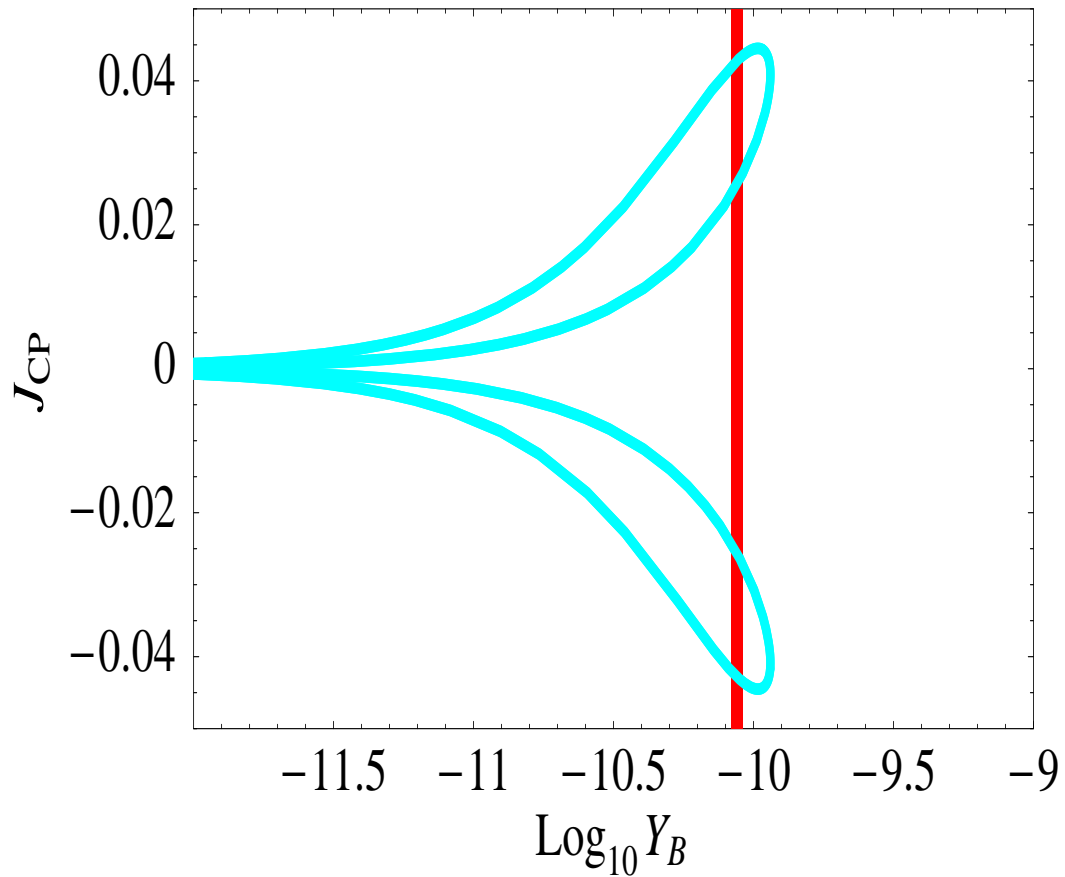
$$|\sin \theta_{13} \sin \delta| \gtrsim 0.02, \quad \sin \theta_{13} \gtrsim 0.02.$$

The lower limit corresponds to

$$|J_{\text{CP}}| \gtrsim 4.6 \times 10^{-3}$$

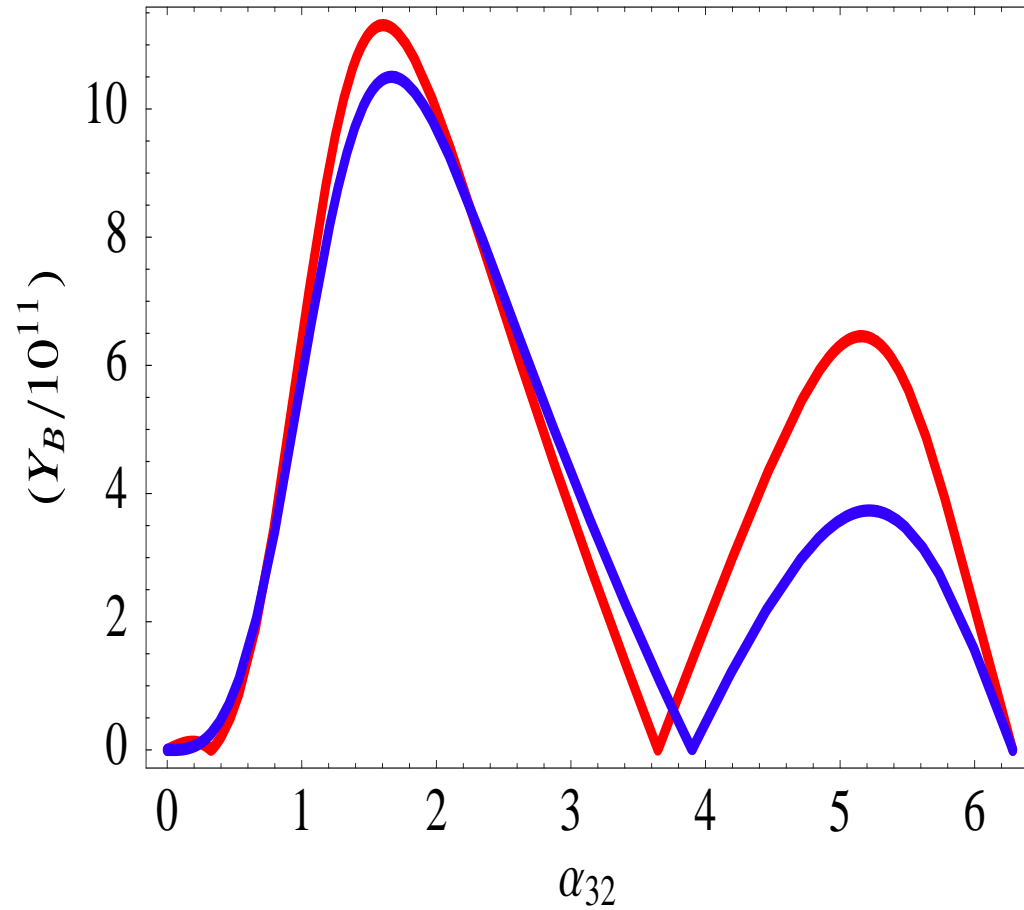


$M_1 \ll M_2 \ll M_3$, $m_1 \ll m_2 \ll m_3$; Dirac CP-violation, $\alpha_{32} = 0$; 2π ;
 real R_{12} , R_{13} , $|R_{12}|^2 + |R_{13}|^2 = 1$, $|R_{12}| = 0.86$, $|R_{13}| = 0.51$, $\text{sign}(R_{12}R_{13}) = +1$;
 i) $\alpha_{32} = 0$ ($\kappa' = +1$), $s_{13} = 0.2$ (red line) and $s_{13} = 0.1$ (dark blue line);
 ii) $\alpha_{32} = 2\pi$ ($\kappa' = -1$), $s_{13} = 0.2$ (light blue line);
 $M_1 = 5 \times 10^{11}$ GeV.



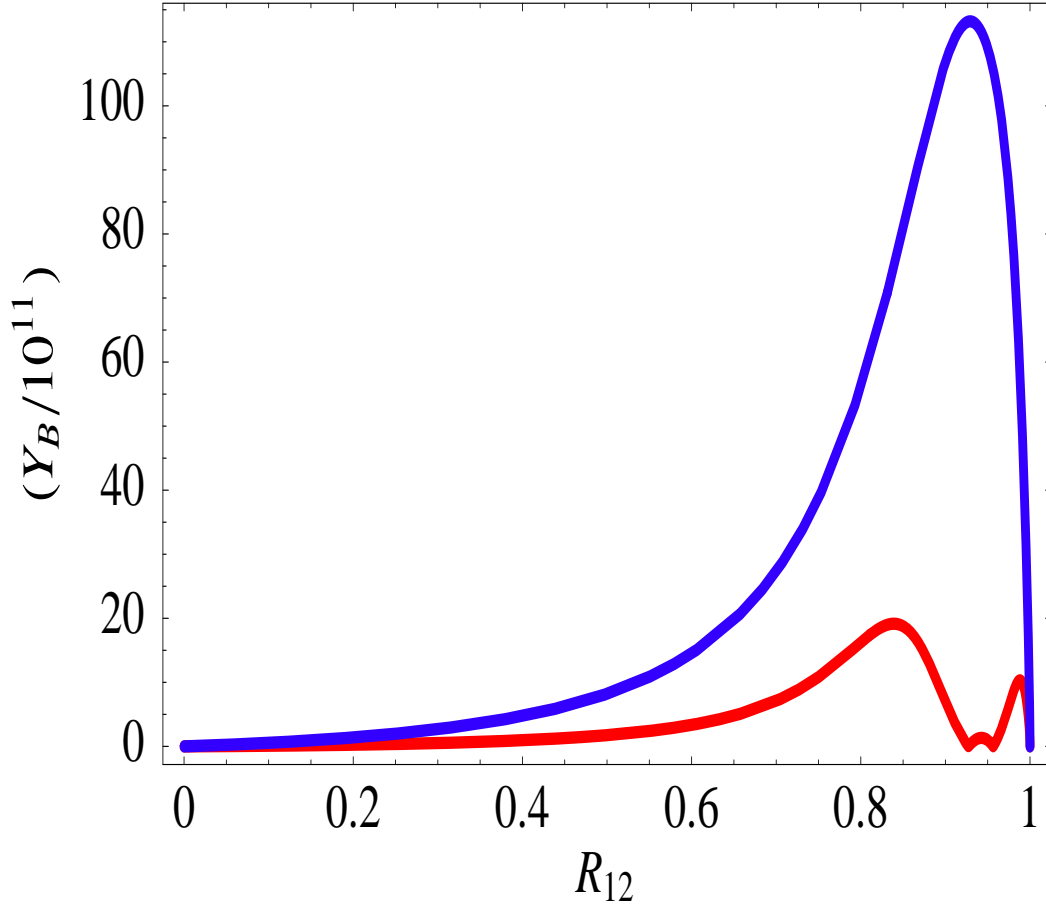
$M_1 \ll M_2 \ll M_3, m_1 \ll m_2 \ll m_3; M_1 = 5 \times 10^{11} \text{ GeV};$
 Dirac CP-violation, $\alpha_{32} = 0 \text{ (} 2\pi \text{)}$;
 $|R_{12}| = 0.86, |R_{13}| = 0.51, \text{sign}(R_{12}R_{13}) = +1 \text{ (-1)} \text{ (}\beta_{23} = 0 \text{ (}\pi\text{), } \kappa' = +1\text{)}$;
 The red region denotes the 2σ allowed range of Y_B .

S. Pascoli, S.T.P., A. Riotto, 2006.

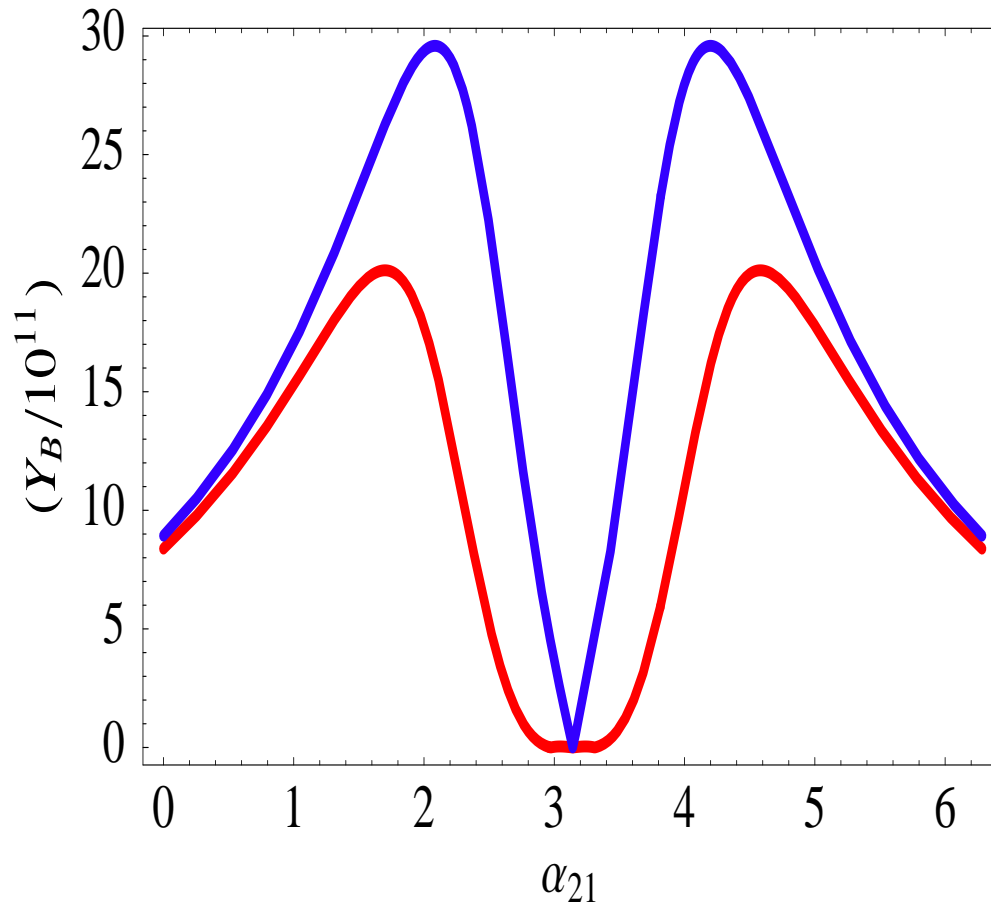


$M_1 \ll M_2 \ll M_3$, $m_1 \ll m_2 \ll m_3$; Majorana CP-violation, $\delta = 0$;
 real R_{12} , R_{13} , $|R_{12}| = 0.92$, $|R_{13}| = 0.39$, $\text{sgn}(R_{12}R_{13}) = +1$ ($\beta_{23} = 0$, $\kappa = +1$);
 $M_1 = 5 \times 10^{10}$ GeV, $s_{13} = 0$ (blue line) and 0.2 (red line).

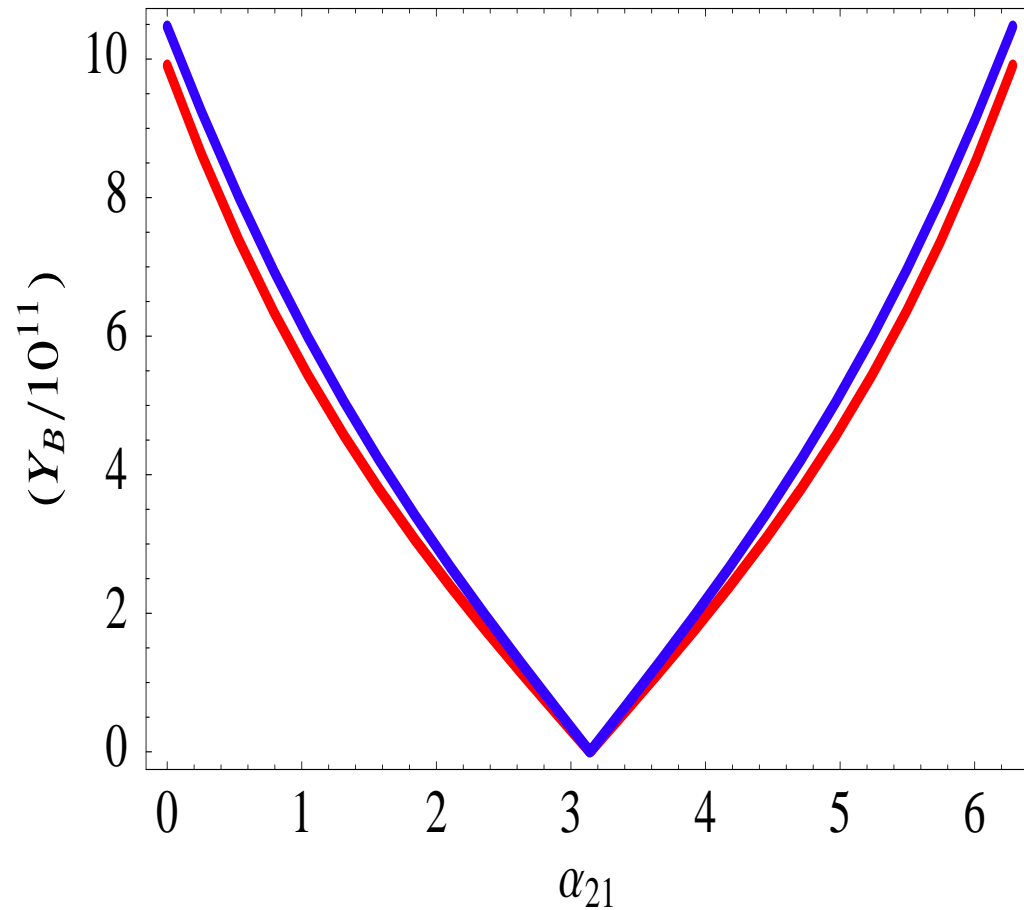
S. Pascoli, S.T.P., A. Riotto, 2006.



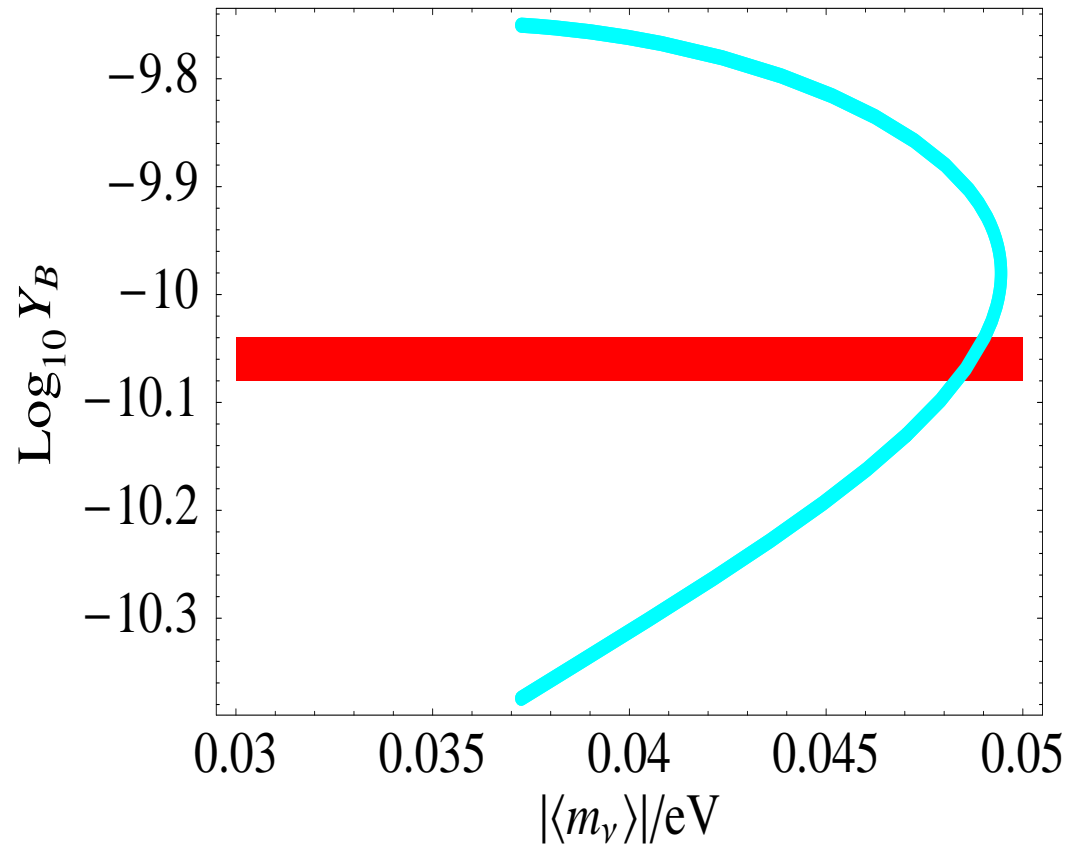
$M_1 \ll M_2 \ll M_3$, $m_1 \ll m_2 \ll m_3$; $M_1 = 5 \times 10^{11}$ GeV;
 real R_{12} , R_{13} , $\text{sign}(R_{12}R_{13}) = +1$, $R_{12}^2 + R_{13}^2 = 1$, $s_{13} = 0.20$;
 a) Majorana CP-violation (blue line), $\delta = 0$ and $\alpha_{32} = \pi/2$ ($\kappa = +1$);
 b) Dirac CP-violation (red line), $\delta = \pi/2$ and $\alpha_{32} = 0$ ($\kappa' = +1$);
 Δm_{\odot}^2 , $\sin^2 \theta_{12}$, Δm_{31}^2 , $\sin^2 2\theta_{23}$ - fixed at their best fit values.



$M_1 \ll M_2 \ll M_3$, $m_3 \ll m_1 < m_2$; $M_1 = 2 \times 10^{11}$ GeV;
 Majorana CP-violation, $\delta = 0$;
 purely imaginary $R_{11}R_{12} = i\kappa|R_{11}R_{12}|$, $\kappa = -1$, $|R_{11}|^2 - |R_{12}|^2 = 1$, $|R_{11}| = 1.2$;
 $s_{13} = 0$ (blue line) and 0.2 (red line).



$M_1 \ll M_2 \ll M_3$, $m_3 \ll m_1 < m_2$; $M_1 = 2 \times 10^{11}$ GeV;
 Majorana CP-violation, $\delta = 0$;
 purely imaginary $R_{11}R_{12} = i\kappa|R_{11}R_{12}|$, $\kappa = +1$, $|R_{11}|^2 - |R_{12}|^2 = 1$, $|R_{11}| = 1.05$;
 $s_{13} = 0$ (blue line) and 0.2 (red line).



$M_1 \ll M_2 \ll M_3$, $m_3 \ll m_1 < m_2$; $M_1 = 2 \times 10^{11}$ GeV;
 Majorana CP-violation, $\delta = 0$, $s_{13} = 0$;
 purely imaginary $R_{11}R_{12} = i\kappa|R_{11}R_{12}|$, $\kappa = +1$ $|R_{11}|^2 - |R_{12}|^2 = 1$, $|R_{11}| = 1.05$.
 The Majorana phase α_{21} is varied in the interval $[-\pi/2, \pi/2]$.

S. Pascoli, S.T.P., A. Riotto, 2006.

Low Energy Leptonic CPV and Leptogenesis: Summary

Leptogenesis: see-saw mechanism; N_j - heavy RH ν 's;

N_j, ν_k - Majorana particles

$$N_j: M_1 \ll M_2 \ll M_3$$

The observed value of the baryon asymmetry of the Universe can be generated

A. CP-violation due to the Dirac phase δ in U_{PMNS} , no other sources of CPV (Majorana phases in U_{PMNS} equal to 0, etc.)

$m_1 \ll m_2 \ll m_3$ (NH):

$$|\sin \theta_{13} \sin \delta| \gtrsim 0.09, \quad \sin \theta_{13} \gtrsim 0.09; \quad |J_{\text{CP}}| \gtrsim 2.0 \times 10^{-2}$$

$m_3 \ll m_1 < m_2$ (IH):

$$|\sin \theta_{13} \sin \delta| \gtrsim 0.02, \quad \sin \theta_{13} \gtrsim 0.02; \quad |J_{\text{CP}}| \gtrsim 4.6 \times 10^{-3}$$

B. CP-violation due to the Majorana phases in U_{PMNS} , no other sources of CPV (Dirac phase in U_{PMNS} equal to 0, etc.)

C. CP-violation due to both Dirac and Majorana phases in U_{PMNS} , no other source of CPV.

Conclusions

The see-saw mechanism provides a link between ν -mass generation and BAU.

Determining the nature - Dirac or Majorana, of massive neutrinos is of fundamental importance for understanding the origin of neutrino masses.

CPV phases in U_{PMNS} can be the leptogenesis CPV parameters.

Low energy leptonic CPV can be directly related to the existence of BAU.

Understanding the status of the CP-symmetry in the lepton sector is of fundamental importance.

These results underline further the importance of the experiments aiming to measure the CHOOZ angle θ_{13} and of the experimental searches for Dirac and/or Majorana leptonic CP-violation at low energies.