Leptogenesis Effects of Lightest Neutrino Mass

Recontres de Moriond EW 2008

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Observed Baryon Asymmetry: $Y_B \equiv \frac{n_B - n_{\bar{B}}}{s} \cong 8.6 \times 10^{-11}$

E. M., S. T. Petcov, T. Shindou and Y. Takanishi, "Effects of Lightest Neutrino Mass in Leptogenesis," arXiv:0709.0413 [hep-ph] (to be published in Nucl. Phys. B)

- We work in the context of "flavoured" thermal leptogenesis.
- In this framework CP-violation necessary for the generation of the observed baryon asymmetry (matter-antimatter) of the Universe can be due exclusively to the Dirac and/or Majorana CP-violating phases in the U_{PMNS} neutrino mixing matrix $\Longrightarrow$ connection between leptogenesis and "low energy" CP-violation in the lepton (neutrino) sector (neutrino oscillations, $(\beta\beta)_{0\nu}$-decay, etc.).

Type I See-Saw Scenario

- $$\mathcal{L}^{\rm lep}(x) = \mathcal{L}_{\rm CC}(x) + \mathcal{L}_{\rm Y}(x) + \mathcal{L}_{\rm M}^{\rm N}(x)$$

$$\begin{aligned}
\mathcal{L}_{\rm CC}(x) &= -\frac{g}{\sqrt{2}}\overline{\ell_L}(x)\,\gamma_\alpha\,\nu_{\ell L}(x)\,W^{\alpha\dagger}(x) + \text{h.c.} \\
\mathcal{L}_{\rm Y}(x) &= \lambda_{i\ell}\,\overline{N_i}(x)\,H^\dagger(x)\,\psi_{\ell L}(x) + h_\ell\,H^c(x)\,\overline{\ell_R}(x)\,\psi_{\ell L}(x) + \text{h.c.} \\
\mathcal{L}_{\rm M}^{\rm N}(x) &= -\frac{1}{2}\,M_i\,\overline{N_i}(x)\,N_i(x)\,, \qquad i = 1,2,3
\end{aligned}$$

- Hierarchical spectrum of heavy Majorana neutrinos: $M_1 \ll M_{2,3}$.
- Lepton flavour effects significant for $M_1 \lesssim 10^{12}\,{\rm GeV}$.
- Orthogonal parametrization: $RR^T = R^T R = 1$

$$\lambda = \frac{1}{v}\sqrt{M}\,R\,\sqrt{m}\,U^\dagger_{\rm PMNS} \qquad v = 174\,{\rm GeV}$$

- "High energy" CP-violation due to $R-$phases

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CP-violating phases

- R CP-conserving: ${R_{jk}}^* = \rho_{jk} R_{jk}$ $\rho_{jk} = \pm 1$
- The violation of CP-symmetry necessary for leptogenesis is due exclusively to the CP-violating phases in $U_{\rm PMNS}$

PMNS Neutrino Mixing Matrix

$$U_{\rm PMNS} = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix} {\rm diag}(1, e^{i\frac{\alpha_{21}}{2}}, e^{i\frac{\alpha_{31}}{2}})$$

- We consider the two possible spectra allowed by data:
  - normal ordering: $m_1 < m_2 < m_3$
  - inverted ordering: $m_3 < m_2 < m_1$
- Analysis performed under the condition of negligible RG running from M_Z to M_1 of m_j and of the parameters in $U_{\rm PMNS} \Longrightarrow \min(m_j) \lesssim 0.10\,{\rm eV}$

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Inverted ordering $(m_3 < m_2 < m_1)$ with $10^{-10}\,\mathrm{eV} \leq m_3 \leq 0.05\,\mathrm{eV}$:

- IH mass spectrum ($10^{-6}\mathrm{eV} \lesssim m_3 \lesssim 5 \times 10^{-3}\mathrm{eV}$, $m_3 \ll m_1 < m_2$, $m_{1,2} \cong \sqrt{|\Delta m^2_{\mathrm{A}}|}$) and real elements R_{1j}. The effects are particularly large for $R_{11} \cong 0$ or $R_{12} \cong 0 \implies$ enhancement by a factor ~ 100 of Y_B with respect to the case $m_3 \cong 0$.

  S. Pascoli, S.T. Petcov, A. Riotto, Nucl. Phys. B 739 (2006) 208

- Baryon asymmetry for CP-violation due to effective Majorana phase $\alpha_{32} \equiv \alpha_{31} - \alpha_{21} \implies M_1 \gtrsim 3.0 \times 10^{10}\,\mathrm{GeV}$.
- Baryon asymmetry for CP-violation due to Dirac phase δ is obtained fo $M_1 \gtrsim 10^{11}\,\mathrm{GeV}$.
- Successful "flavoured" leptogenesis for Dirac CP-violation gives the following bounds: $\sin\theta_{13} \gtrsim (0.04 - 0.09)$, $|J_{\mathrm{CP}}| \equiv |\mathrm{Im}\{U_{e1}U_{\mu 2}U^*_{e2}U^*_{\mu 1}\}| \gtrsim (0.009 - 0.020)$.

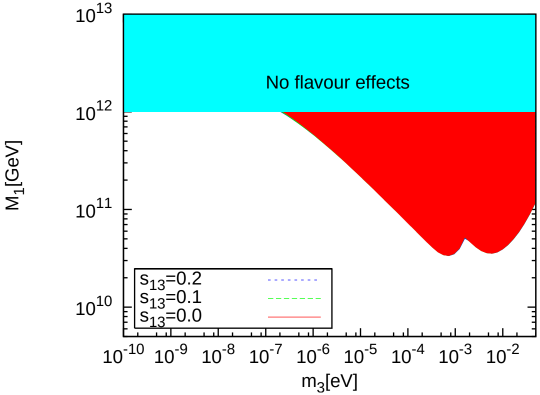
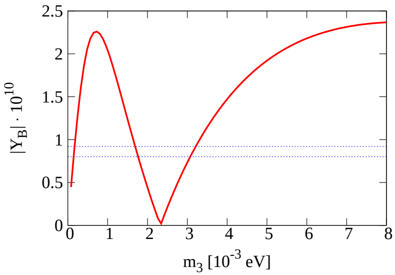


Figure: Values of m_3 and M_1 for which the "flavoured" leptogenesis is successful, generating baryon asymmetry $|Y_B| = 8.6 \times 10^{-11}$ (red/dark shaded area). Light neutrino mass spectrum with inverted ordering (hierarchy), $m_3 < m_1 < m_2$, and real elements R_{1j} of the matrix R. CP-violation due to the Majorana phases in the PMNS matrix. The results shown are obtained using the best fit values of neutrino oscillation parameters: $\Delta m^2_{\odot} = 8.0 \times 10^{-5}\ \mathrm{eV}^2$, $\Delta m^2_{\mathrm{A}} = 2.5 \times 10^{-3}\ \mathrm{eV}^2$, $\sin^2\theta_{12} = 0.30$ and $\sin^2 2\theta_{23} = 1$.



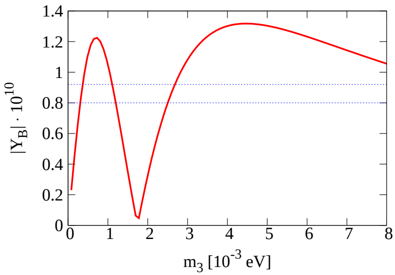


Figure: The dependence of $|Y_B|$ on m_3 in the case of IH spectrum, real $R_{1j}R_{1k}$, Majorana CP-violation, $R_{11} = 0$, $\alpha_{32} = \pi/2$, $s_{13} = 0$, $M_1 = 10^{11}$ GeV, and for i) $\mathrm{sgn}(R_{12}R_{13}) = +1$ (left panel), and ii) $\mathrm{sgn}(R_{12}R_{13}) = -1$ (right panel). The baryon asymmetry $|Y_B|$ was calculated for a given m_3, using the value of $|R_{12}|$, for which the CP-asymmetry $|\epsilon_\tau|$ is maximal. The horizontal dotted lines indicate the allowed range of $|Y_B|$, $|Y_B| = (8.0 - 9.2) \times 10^{-11}$.

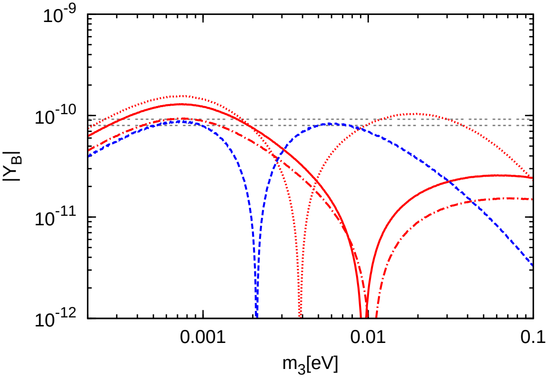


Figure: The dependence of $|Y_B|$ on m_3 in the case of spectrum with inverted ordering (hierarchy), real $R_{1j}R_{1k}$ and Dirac CP-violation, for $R_{11} = 0$, $\delta = \pi/2$, $s_{13} = 0.2$, $\alpha_{32} = 0$, $M_1 = 2.5 \times 10^{11}$ GeV and $\mathrm{sgn}(R_{12}R_{13}) = +1$ (-1) (red lines (blue dashed line)). The baryon asymmetry $|Y_B|$ was calculated for a given m_3, using the value of $|R_{12}|$, for which the CP-asymmetry $|\epsilon_\tau|$ is maximal. The results shown for $\mathrm{sgn}(R_{12}R_{13}) = +1$ are obtained for $\sin^2\theta_{23} = 0.50;\ 0.36;\ 0.64$ (red solid, dotted and dash-dotted lines), while those for $\mathrm{sgn}(R_{12}R_{13}) = -1$ correspond to $\sin^2\theta_{23} = 0.5$.

Normal ordering $(m_1 < m_2 < m_3)$ with $10^{-10}\,\mathrm{eV} \leq m_1 \leq 0.05\,\mathrm{eV}$:

- For $m_1 \lesssim 7.5 \times 10^{-3}\,\mathrm{eV}$, Y_B is the same as in the case $m_1 = 0$.
- For $m_1 \gtrsim 10^{-2}\,\mathrm{eV}$, the lightest neutrino mass has a suppressing effect on the asymmetry Y_B.
- If $R_{12} \cong 0$, Y_B has qualitatively the same depedence on the lightest neutrino mass as in the IH spectrum. It is possible to produce the observed baryon asymmetry for CP-violation due to Majorana phases in U_{PMNS} and $M_1 \gtrsim 5.3 \times 10^{10}\,\mathrm{GeV}$.

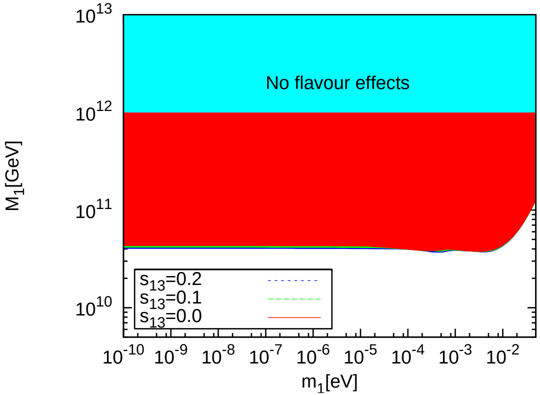


Figure: Values of m_1 and M_1 for which the "flavoured" leptogenesis is successful and baryon asymmetry $Y_B = 8.6 \times 10^{-11}$ can be generated (red shaded area).Light neutrino mass spectrum with normal ordering. The CP-violation necessary for leptogenesis is due to the Majorana and Dirac phases in the PMNS matrix. The results shown are obtained using the best fit values of neutrino oscillation parameters: $\Delta m^2_{\odot} = 8.0 \times 10^{-5}\ \mathrm{eV}^2$, $\Delta m^2_{\mathrm{A}} = 2.5 \times 10^{-3}\ \mathrm{eV}^2$, $\sin^2\theta_{12} = 0.30$ and $\sin^2 2\theta_{23} = 1$.

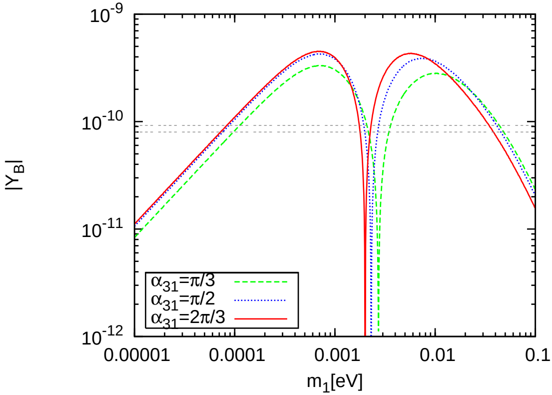


Figure: The dependence of $|Y_B|$ on m_1 in the case of neutrino mass spectrum with normal ordering and real $R_{1j}R_{1k}$, for $R_{12} = 0$, $s_{13} = 0$, $M_1 = 3 \times 10^{11}$ GeV and $\mathrm{sgn}(R_{11}R_{13}) = -1$. The red solid, the blue dotted, and the green dashed lines correspond to $\alpha_{31} = 2\pi/3$, $\pi/2$, and $\pi/3$ respectively. The figure is obtained for $\theta_{23} = \pi/4$.

- CP-asymmetry:

$$\epsilon_\ell = -\frac{3M_1}{16\pi v^2}\frac{\mathrm{Im}\left(\sum_{jk} m_j^{1/2}\, m_k^{3/2}\, U^*_{\ell j}\, U_{\ell k}\, R_{1j}\, R_{1k}\right)}{\sum_i m_i\, |R_{1i}|^2}$$

- Baryon asymmetry in the two flavour regime
$(10^9\,\mathrm{GeV} \lesssim T \sim M_1 \lesssim 10^{12}\,\mathrm{GeV})$:

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

- Wash-out mass parameter:

$$\widetilde{m}_\ell = \left|\sum_k R_{1k}\, m_k^{1/2}\, U^*_{\ell k}\right|^2 , \quad l = e, \mu, \tau\,,$$

- efficiency factor:

$$\eta\,(X) \cong \left(\frac{8.25\times 10^{-3}\,\mathrm{eV}}{X} + \left(\frac{X}{2\times 10^{-4}\,\mathrm{eV}}\right)^{1.16}\right)^{-1}$$