Neutrino CPV phase and Leptogenesis

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The Question

How can the CP-violating phase in the neutrino mixing matrix, delta, possibly be related to leptogenesis?

Can you make a model where this is transparent and has testable predictions?

What is it?

- Experiments have observed an asymmetry in the number of baryons versus anti-baryons in the universe
- Leptogenesis - The process of generating baryogenesis through lepton asymmetry
- This lepton asymmetry is converted into a baryon asymmetry by the sphaleron process
- Leptogenesis is a mechanism that attempts to explain the observed asymmetry
  - Many different models of Leptogenesis exist
  - We only consider Leptogenesis with Type I Seesaw

Sakharov Conditions

Three conditions for dynamically generated baryon asymmetry:

I. Baryon (and lepton) Number Violation

II. C and CP Symmetry Violation

$$\Gamma(A \to B) \neq \Gamma(\overline{A} \to \overline{B})$$

III. Interactions out of Thermal Equilibrium

$$\Gamma(A \to B) \neq \Gamma(B \to A)$$

Seesaw Mechanism

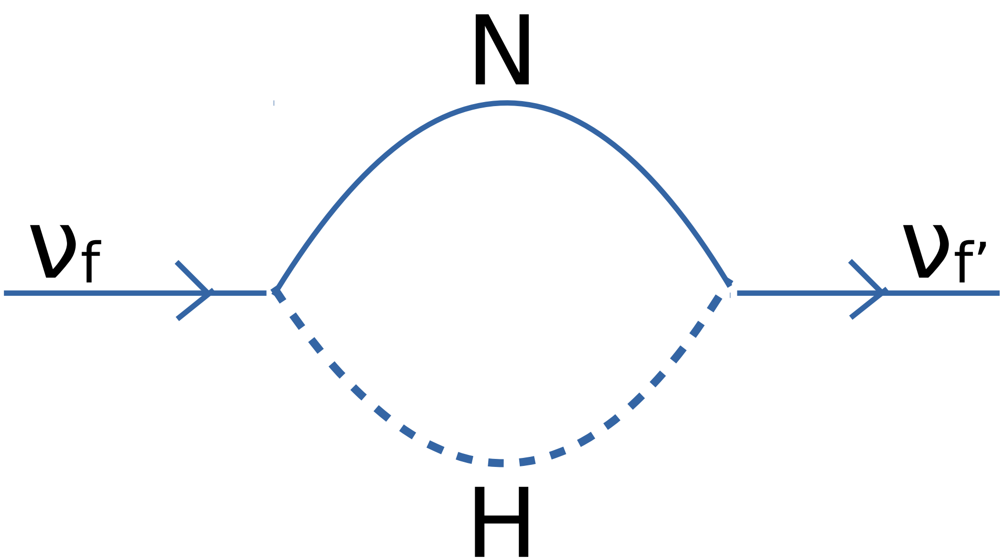
- Introduce three right-handed heavy neutrinos, N_{Ri} with the following Lagrangian:

$$\mathcal{L} = \mathcal{L}_{SM} + \underline{(1/2) N_R^T M N_R} + \left(\underline{\nu_{Lf}^T H^0} - \ell_{Lf} H^- \right) \underline{\lambda_{fi} N_{Ri}} + \text{h.c.}$$

- The Majorana mass matrix M is diagonal, the Yukawa matrix may be complex, and the Higgs will give a Majorana mass term to the neutrinos after symmetry breaking
- This gives a mass to the light neutrinos: $$\boxed{m \sim \frac{v^2 \lambda^2}{M}}$$
- For 0.1 eV light neutrinos and taking λ at the GeV scale, that gives a heavy mass scale of 10^{10} GeV

Seesaw Mechanism

- Self energy diagram showing flavor change at high energy



- The interaction can be described by:

$$\lambda_{fi} M_{ii}^{-1} \lambda_{if'}^{T}$$

- Self energy diagram at low energy with the heavy fields integrated out

- Creates an effective point interaction that can be described by:

$$U_{fa} m_{aa} U_{af'}^{T}$$

Seesaw Mechanism

- Relating the high and low energy interactions, we can write the following:

$$\boxed{v^2\lambda^T M^{-1}\lambda} = v^2\lambda^T M^{-1/2} R R^T M^{-1/2}\lambda = \boxed{U^* m^{1/2} m^{1/2} U^\dagger}$$

- Where R is orthogonal but may be complex (Casas-Ibarra parametrization); it reshuffles and re-phases the flavors. Then we get:

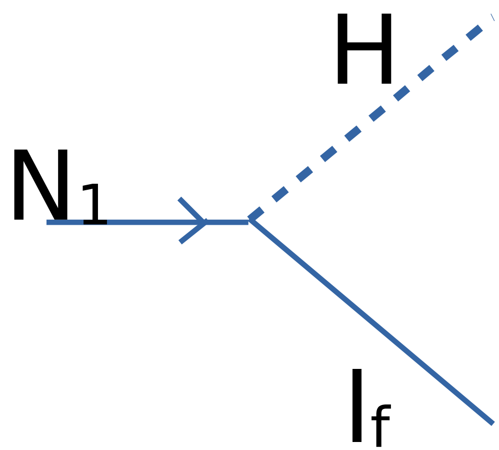
$$\lambda = \frac{1}{v}\sqrt{M} R \sqrt{m} U^\dagger$$

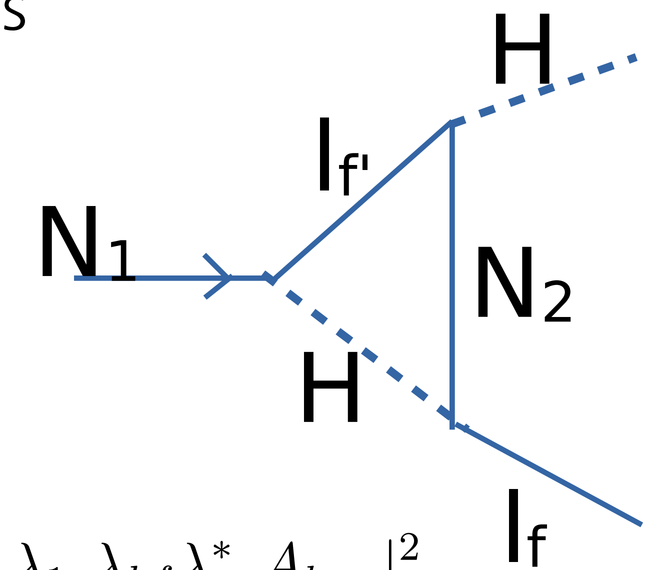
- If we see phases in U, then we are generically likely to see phases in λ. This is the connection between the high and low energy scales.

Casas - Ibarra parametrization: arXiv:hep-ph/0103065

Leptogenesis at High Energy

- The lepton asymmetry is generated by decays of the heavy neutrinos in to Higgs and leptons





$$\Gamma(N_1 \to H + \ell_f) \sim |\lambda_{1f} A_{tree} + \sum_{gk} \lambda_{1g}\lambda_{kf}\lambda^*_{kg} A_{loop}|^2$$

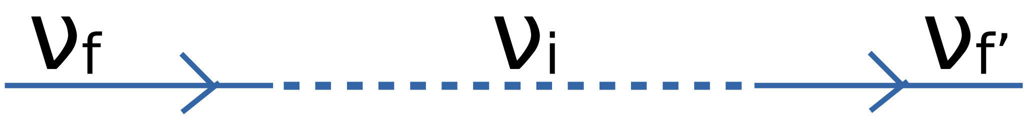
- To get CP violation, higher order diagrams must be included
- For the CP conjugate process, the cross terms will usually be different giving a different rate due to the phases in λ

Define asymmetry that drives leptogenesis:

$$\epsilon_f = \frac{\Gamma(N_1 \to H + \ell_f) - \Gamma(N_1 \to \overline{H} + \overline{\ell_f})}{\Gamma(N_1 \to H + \ell_f) + \Gamma(N_1 \to \overline{H} + \overline{\ell_f})}$$

CP Violation at Low Energy

- The following interaction allows for low energy CP violation:



$$\Gamma(\nu_e \to \nu_\mu) - \Gamma(\overline{\nu_e} \to \overline{\nu_\mu}) \sim \sum_{ij} Im\left(U^*_{ei} U_{\mu i} U_{ej} U^*_{\mu j}\right)$$

- Thus CP violation requires at least one matrix element in U to be complex
- The “Dirac” phase, δ_{CP}, is enough to produce CP violation
- There also exist two “Majorana” phases that also can produce CP violation

The Connection

- If the Yukawa matrix has the appropriate phases it can generate leptogenesis in the early universe
- If the PMNS matrix has non-zero CP violating phases, then the required CP violation will occur at low energy

$$\lambda = \frac{1}{v}\sqrt{M}R\sqrt{m}U^\dagger$$

- Since phases in one matrix generically imply phases in the other, we can conclude that in this model CP violation at low energy can imply leptogenesis at high energy
- For each flavor, the asymmetry can be written as follows:

$$\epsilon_\alpha = -\frac{3M_1}{16\pi v^2}\frac{Im\left(\sum_{\beta\rho} m_\beta^{1/2} m_\rho^{3/2} U^*_{\alpha\beta} U_{\alpha\rho} R_{1\beta} R_{1\rho}\right)}{\sum_\beta m_\beta |R_{1\beta}|^2}$$

http://arxiv.org/pdf/hep-ph/0609125v3.pdf

Baryon Asymmetry Plots

$$J_{CP} = Im(U_{\mu 3} U_{e3}^* U_{e2} U_{\mu 2}^*)$$

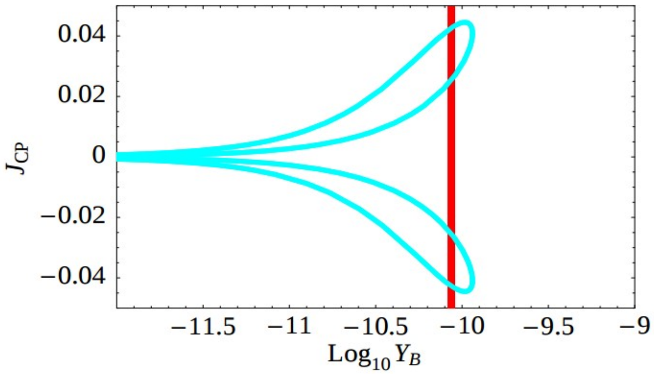


FIG. 1. The invariant J_{CP} versus the baryon asymmetry varying (in blue) $\delta = [0, 2\pi]$ in the case of hierarchical RH neutrinos and NH light neutrino mass spectrum for $s_{13} = 0.2$, $\alpha_{32} = 0$, $R_{12} = 0.86$, $R_{13} = 0.5$ and $M_1 = 5 \times 10^{11}$ GeV . The red region denotes the 2σ range for the baryon asymmetry.

$$\langle m_\nu \rangle$$

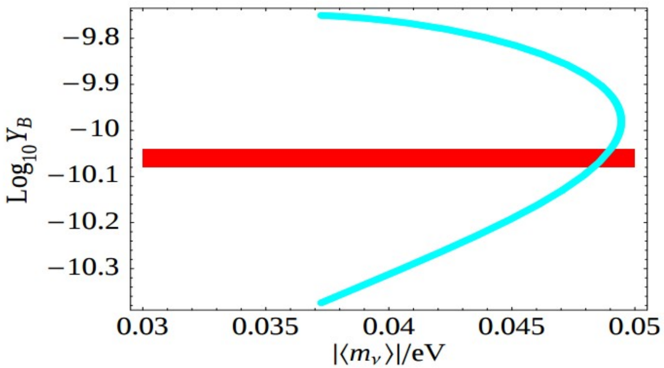


FIG. 2. The baryon asymmetry $|Y_B|$ versus the effective Majorana mass in neutrinoless double beta decay, $\langle m_\nu \rangle$, in the case of Majorana CP-violation, hierarchical RH neutrinos and IH light neutrino mass spectrum, for $\delta = 0$, $s_{13} = 0$, purely imaginary $R_{11} R_{12}$, $|R_{11}| = 1.05$ and $M_1 = 2 \times 10^{11}$ GeV. The Majorana phase α_{21} is varied in the interval $[-\pi/2, \pi/2]$.

- Plots showing the possible variation of CP violation in the PMNS matrix versus the produced baryon asymmetry from the model

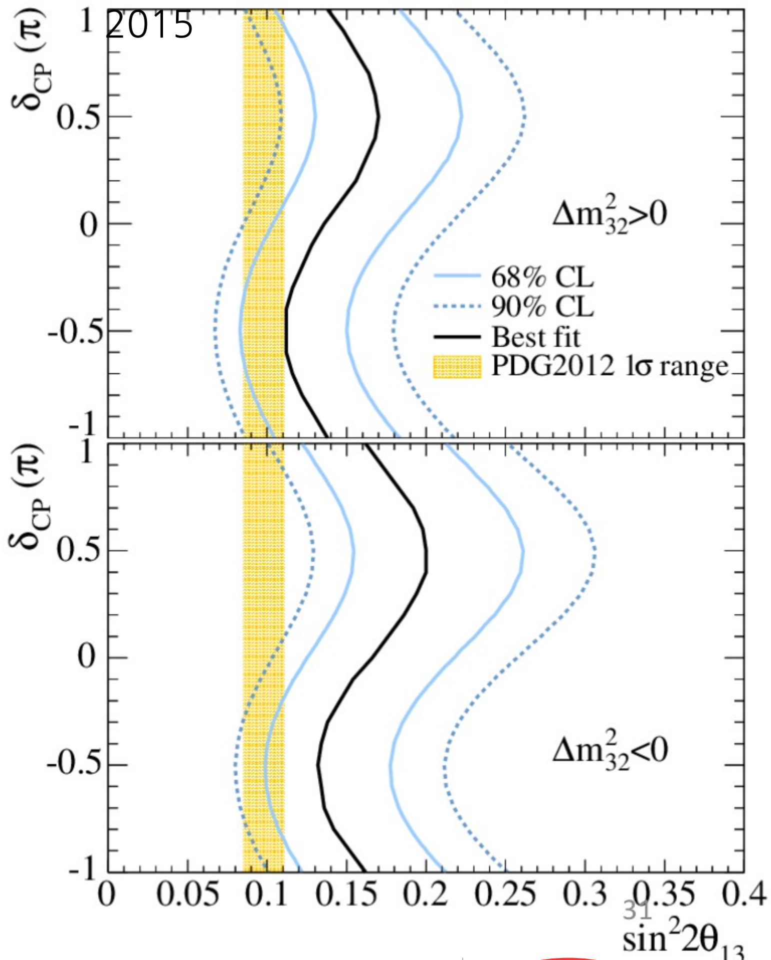
- Red band denotes the two sigma range for the observed baryon asymmetry

http://arxiv.org/pdf/hep-ph/0609125v3.pdf

Experimental Tests – Long Baseline

- Long Baseline Neutrino Oscillation experiments have the potential to measure δ_{CP}
- Experiments measure δ_{CP} through the difference in ν_μ to ν_e versus $\overline{\nu}_\mu$ to $\overline{\nu}_e$ oscillations

T2K Results from Y. Hayato SSI 2015



$$P(\nu_\mu \to \nu_e) \simeq \sin^2(\theta_{23})\sin^2(2\theta_{13})\sin^2\left(\frac{\Delta m^2_{31}L}{4E}\right)$$
$$- \frac{\sin(2\theta_{13})\sin(2\theta_{23})}{2\sin(\theta_{23})}\sin\left(\frac{\Delta m^2_{21}L}{4E}\right)\sin^2\left(\frac{\Delta m^2_{31}L}{4E}\right)\sin^2(2\theta_{13})\sin(\delta_{CP})$$

Plus higher order terms including a CP even term, matter effects, etc.

Experimental Tests – 0νββ

- Neutrino-less double beta decay can determine if neutrinos are Majorana fermions
- If neutrinos are Majorana:
  - There exists two more CP violating phases in the PMNS matrix which could contribute to leptogenesis
  - Strengthens the case for the Seesaw mechanism for neutrino masses and leptogenesis
- Direct information on the Majorana phases, α, may come from the effective Majorana mass:

$$\sin^2(\alpha_{21}/2) \simeq \left(1 - \frac{|\langle m_\nu \rangle|^2}{m^2}\right) \frac{1}{\sin^2(2\theta_{12})}$$

Conclusions

- This is one model to drive leptogenesis and thus baryogenesis
- We have shown one possible connection between the high energy decays of heavy neutrinos with the low energy PMNS matrix
- Some caveats:
  - The CP violation in the PMNS matrix might not be enough to generate the observed amount by experiment
  - CP violation at low energy does not require leptogenesis to occur
  - Conclusions are model dependent, for example the model presented here requires all three lepton flavors to be correctly accounted for in the Boltzmann equations
- Measurements of oscillation parameters and neutrino-less double beta decay could exclude or strengthen the model of leptogenesis

References

- Connecting Low Energy Leptonic CP-violation to Leptogenesis: http://arxiv.org/pdf/hep-ph/0609125v3.pdf
- Leptogenesis and Low Energy CP Violation in Neutrino Physics : http://arxiv.org/pdf/hep-ph/0611338v2.pdf
- Leptonic CP Violation and Leptogenesis: http://arxiv.org/pdf/1405.2263v1.pdf

Back Up Slides

Neutrino Oscillations and CP violation

- We know from neutrino oscillation experiments that neutrinos can change flavor states while propagating.
- We can search for CP violation in the leptonic sector by observing the asymmetry of probabilities for flavor oscillation.

$$A_{\mathrm{CP}}^{(l'l)} \equiv P(\nu_l \to \nu_{l'}) - P(\bar{\nu}_l \to \bar{\nu}_{l'}), \quad A_{\mathrm{T}}^{(l'l)} \equiv P(\nu_l \to \nu_{l'}) - P(\nu_{l'} \to \nu_l).$$

- These probabilities can be measured from current neutrino oscillation experiments.

Leptogenesis and CP violation

- The heavy neutrino N_R can interact to produce leptons. $N \rightarrow \ell^{\mp} + H^{\pm}$ and $N \rightarrow \overset{(-)}{\nu} + \overset{(-)}{H^0}$

SM Higgs particle

- In order to violate CP, we expect to see an asymmetry in these processes. This would lead to an observed asymmetry in lepton number

$$Y_{\mathcal{L}} \simeq (\epsilon_1/g_*)\eta(\widetilde{m_1})$$

Where η is the effective reversal of total lepton asymmetry due to inverse decays, g_* is our relativistic relativistic degrees of freedom, $\widetilde{m_1} = (\lambda\lambda^\dagger)_{11}v^2/M_1$, $\lambda_{i\alpha}$ is our Yukawa couplings to N_R, and

$$\epsilon_1 \equiv \frac{\sum_\alpha[\Gamma(N_1 \rightarrow H\ell_\alpha) - \Gamma(N_1 \rightarrow \overline{H\ell_\alpha})]}{\sum_\alpha[\Gamma(N_1 \rightarrow H\ell_\alpha) + \Gamma(N_1 \rightarrow \overline{H\ell_\alpha})]}$$

Leptogenesis + flavor effects

- Analysis presented in the previous slide corresponds to "one-flavor" leptogenesis, which is valid for
  M1≥10e12 GeV

- As the universe cooled, lepton flavors become distinguishable at different times. The total lepton asymmetry will have contributions from each flavor independently; only interactions of the same flavor can reverse the flavor's contribution to total lepton asymmetry.

- Summing over one flavor with some redefined parameters rela

$$\epsilon_\alpha = -\frac{3M_1}{16\pi v^2}\,\frac{\mathrm{Im}\left(\sum_{\beta\rho} m_\beta^{1/2} m_\rho^{3/2} U^*_{\alpha\beta} U_{\alpha\rho} R_{1\beta} R_{1\rho}\right)}{\sum_\beta m_\beta \left|R_{1\beta}\right|^2}$$

Assumptions

- The matrix R has real or purely imaginary elements
- Heavy Majorana neutrinos possess a hierarchical mas spectrum

  M1 << M2 << M3
- M1 has a value in the interval

  10e9 GeV ≤ M1 ≤ 10e12 GeV ,

  where (in the charged-lepton sector of the SM) only the interaction mediated by the τ Yukawa coupling is in equilibrium

Leptogenesis + flavor effects ctd.

- Final baryon asymmetry is well approximated by

$$Y_B \simeq -\frac{12}{37 g_*}\left(\epsilon_2\,\eta\left(\frac{417}{589}\,\widetilde{m_2}\right)+\epsilon_\tau\,\eta\left(\frac{390}{589}\,\widetilde{m_\tau}\right)\right),$$

where $\epsilon_2 = \epsilon_e + \epsilon_\mu$, $\widetilde{m_2} = \widetilde{m_e} + \widetilde{m_\mu}$ and

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

- Wash-out mass parameter:

$$\left(\frac{\widetilde{m_l}}{3\times 10^{-3}\,\mathrm{eV}}\right) \equiv \frac{\Gamma(N_1\to H\,l)}{H(M_1)},$$

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

Example: Normal ordering

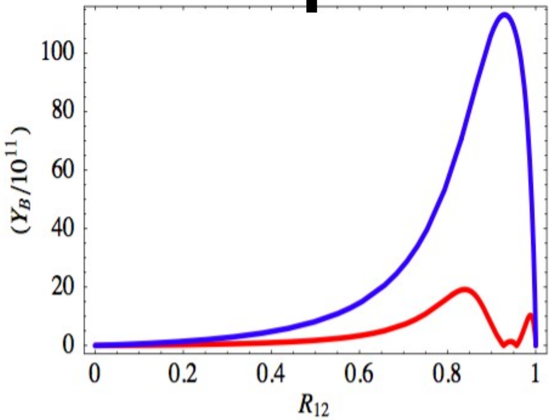


Figure 1: The baryon asymmetry Y_B as a function of R_{12} in the case of real R_{12} and R_{13}, sign $(R_{12}R_{13}) = +1$ $(\beta_{23} = 0)$, $R_{12}^2 + R_{13}^2 = 1$, $s_{13} = 0.20$, hierarchical RH neutrinos and NH light neutrino mass spectrum and a) Majorana CP-violation (blue line), $\delta = 0$ and $\alpha_{32} = \pi/2$ $(\kappa = +1)$, and b) Dirac CP-violation (red line), $\delta = \pi/2$ and $\alpha_{32} = 0$ $(\kappa' = +1)$, for $M_1 = 5 \times 10^{11}$ GeV. The neutrino oscillation parameters $\Delta m^2_{\odot}$, $\sin^2\theta_{12}$, $\Delta m^2_{\rm A}$ and $\sin^2 2\theta_{23}$ are fixed at their best fit values.

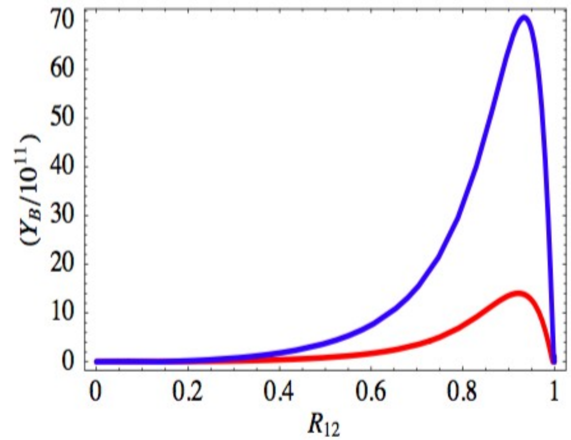


Figure 2: The same as in Fig. 1 but for sign $(R_{12}R_{13}) = -1$ $(\beta_{23} = \pi)$ and a) Majorana CP-violation (blue line), $\delta = 0$ and $\alpha_{32} = \pi/2$ $(\kappa = -1)$, and b) Dirac CP-violation (red

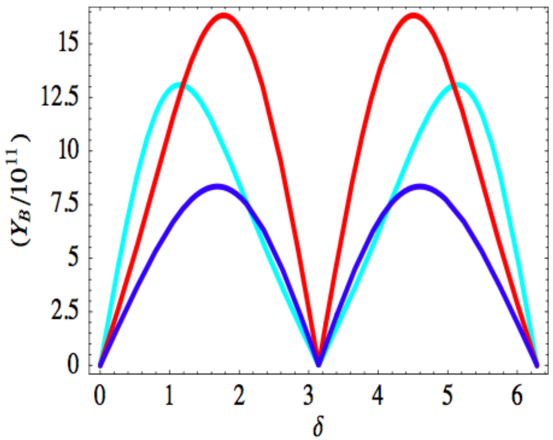


Figure 5: The baryon asymmetry $|Y_B|$ as a function of the Dirac phase δ varying in the interval $\delta = [0, 2\pi]$ in the case of Dirac CP-violation, $\alpha_{32} = 0$; 2π, hierarchical RH neutrinos and NH light neutrino mass spectrum, for $M_1 = 5 \times 10^{11}$ GeV, real R_{12} and R_{13} satisfying $|R_{12}|^2 + |R_{13}|^2 = 1$, $|R_{12}| = 0.86$, $|R_{13}| = 0.51$, sign $(R_{12}R_{13}) = +1$, and for 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).

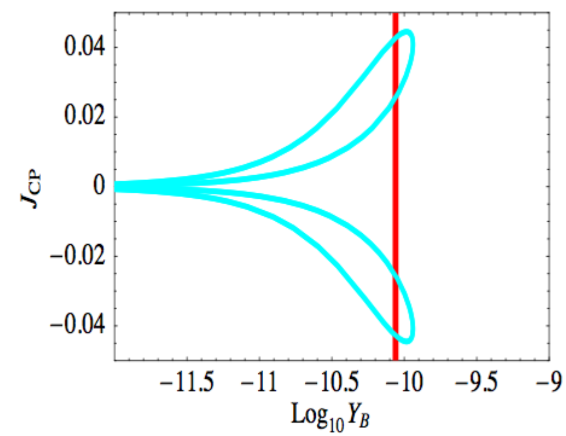


Figure 6: The correlation between the rephasing invariant $J_{\rm CP}$ (in blue) and the baryon asymmetry $Y_{\rm B}$ when varying the Dirac phase $\delta = [0, 2\pi]$, in the case of hierarchical RH neutrinos and NH light neutrino mass spectrum and for $s_{13} = 0.2$, $\alpha_{32} = 0$ (2π), $|R_{12}| = 0.86$, $|R_{13}| = 0.51$, sign $(R_{12}R_{13}) = +1$ (-1) $(\beta_{23} = 0$ (π), $\kappa' = +1)$, $M_1 = 5 \times 10^{11}$ GeV . The red region denotes the 2σ allowed range of $Y_{\rm B}$.

Example: Inverted ordering

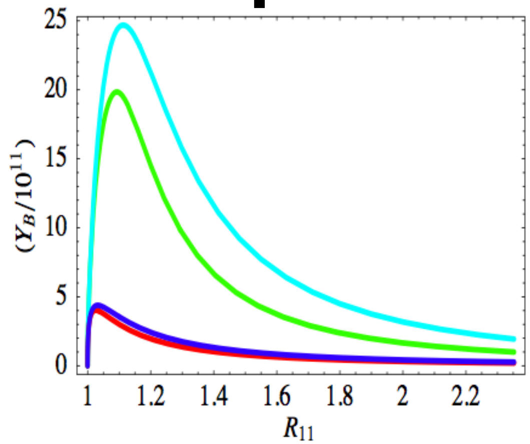


Figure 7: The baryon asymmetry Y_B as a function of $|R_{11}|$ in the case of hierarchical RH neutrinos and IH light neutrino mass spectrum, Majorana CP-violation, $\delta = 0$ and $\alpha_{32} = \pi/2$, $M_1 = 2 \times 10^{11}$ GeV, purely imaginary $R_{11}R_{12} = i\kappa|R_{11}R_{12}|$ and $\kappa = +1$ (dark blue and red lines), $\kappa = -1$ (light blue and green lines), $|R_{12}|^2 - |R_{13}|^2 = 1$, and for $s_{13} = 0.2$ (green and red lines) and $s_{13} = 0$ (light and dark blue lines).

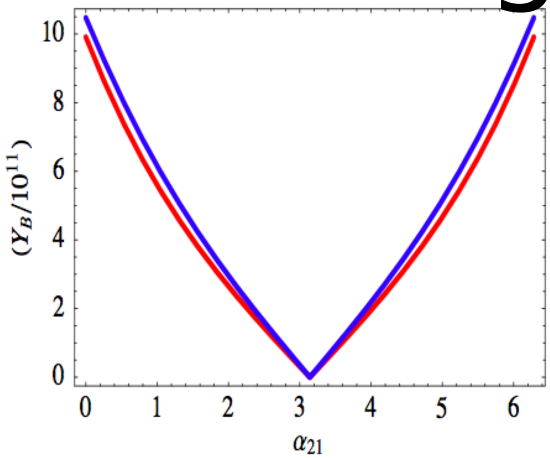


Figure 8: The baryon asymmetry as a function of the Majorana phase α_{32} varying in the interval $\alpha_{32} = [0, 2\pi]$ in the case of hierarchical RH neutrinos and IH light neutrino mass spectrum, Majorana CP-violation, $\delta = 0$, purely imaginary $R_{11}R_{12} = i\kappa|R_{11}R_{12}|$, $\kappa = +1$ $(\beta_{12} = \pi/2)$, $|R_{11}|^2 - |R_{12}|^2 = 1$, $|R_{11}| = 1.05$, and for $M_1 = 2 \times 10^{11}$ GeV, and two values of s_{13}: $s_{13} = 0$ (blue line) and 0.2 (red line).

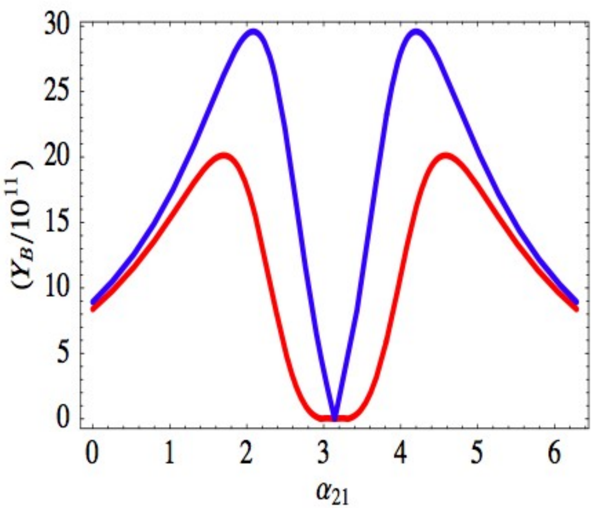


Figure 9: The same as in Fig. 8, but for $\kappa = -1$ $(\beta_{12} = 3\pi/2)$ and $|R_{11}| = 1.2$.

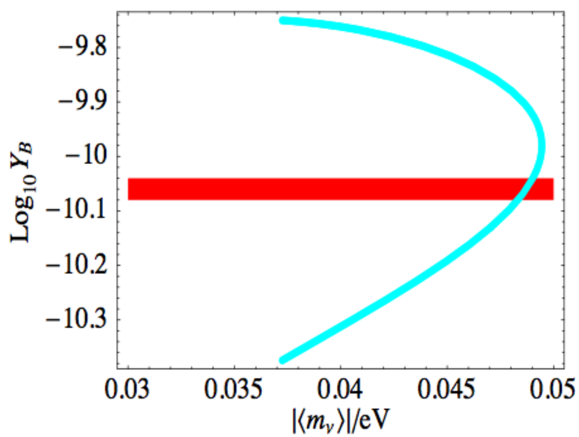


Figure 10: The baryon asymmetry $|Y_B|$ versus the effective Majorana mass in neutrinoless double beta decay, $|\langle m \rangle|$, in the case of Majorana CP-violation, hierarchical RH neutrinos and IH light neutrino mass spectrum, for $\delta = 0$, $s_{13} = 0$, purely imaginary $R_{11}R_{12} = i\kappa|R_{11}R_{12}|$, $\kappa = +1$ $(\beta_{12} = \pi/2)$, $|R_{11}|^2 - |R_{12}|^2 = 1$, $|R_{11}| = 1.05$ and $M_1 = 2 \times 10^{11}$ GeV. The Majorana phase α_{21} is varied in the interval $[-\pi/2, \pi/2]$.