CP violation in leptogenesis and at low energy

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Introduction

The problem :

Relation between low energy CP violation and CP violation in flavoured leptogenesis

Summary :

- Leptogenesis and flavours
- CP-odd observables at low and high energy
- Sensitivity of flavoured leptogenesis from low energy CP-odd observables
- Conclusions

Thermal leptogenesis

$$\mathscr{L}_{seesaw} = (\overline{\ell}^i_L H^*_d)\mathbf{Y}^*_{\mathbf{e}ij} e^j_R + (\overline{\ell}^i_L H^*_u)\lambda^*{}_{iJ} N^J + \overline{N^c}^J \frac{\mathbf{M}^*{}_{JK}}{2} N^K + h.c.$$

- Hierarchical N masses : $M_1 \sim 10^9$ GeV $\ll M_2, M_3$
- Thermal production of the N_1 (and negligible production of N_2)

The process :

- N_1 produced by scattering processes at $T \sim M_1$
- CP violation in $N_1 \to \phi\ell \neq N_1 \to \overline{\phi}\,\overline{\ell} \Rightarrow$ lepton asymmetry ϵ
- If inverse decays are out of equilibrium the asymmetries may survive
- The lepton asymmetry is *converted* into baryon asymmetry by sphalerons, for $\Gamma > H$:

$$Y_B \sim \frac{1}{3} Y_L \sim \frac{H}{3g_*} \frac{\epsilon}{\Gamma_{decay}}$$

Flavour in leptogenesis

- Rates for interactions involving charged lepton yukawas :

$$\Gamma_\alpha \sim 5 \times 10^{-3} h_\alpha^2 T$$

If these rates are in equilibrium $\Rightarrow$ flavours become distinguishable[1 2 3]

- $\Gamma_\tau > H$ at $T < 10^{12}$ GeV and $\Gamma_\mu > H$ at $T < 10^9$ GeV

$\Rightarrow$ Between 10^9 GeV and 10^{12} GeV we can distinguish the τ flavour (which is in equilibrium) from the others

- The lepton asymmetries ϵ_τ and ϵ_0 evolve separately :

$$Y_B \sim \frac{1}{3} \sum_\alpha \frac{n_l - n_{\bar{l}}}{n_N} \frac{n_N}{n_\gamma} \sim \frac{H}{3g_*} \sum_\alpha \frac{\epsilon_{\alpha\alpha}}{\Gamma_{\alpha\alpha}} \neq \frac{H}{3g_*} \frac{\sum_\alpha \epsilon_{\alpha\alpha}}{\sum_\beta \Gamma_{\beta\beta}}$$

[1] R. Barbieri, P. Creminelli, A. Strumia and N. Tetradis, hep-ph/9911315

[2] A. Abada, S. Davidson, F. X. Josse-Michaux, M. Losada and A. Riotto, hep-ph/0601083

[3] E. Nardi, Y. Nir, E. Roulet and J. Racker, hep-ph/0601084

CP violating phases at low energy

$$\mathscr{L}_{seesaw} = (\overline{\ell}^i_L H^*_d)\mathbf{Y}^*_{\mathbf{e}ij} e^j_R + (\overline{\ell}^i_L H^*_u)\lambda^*{}_{iJ} N^J + \overline{N^c}^J \frac{\mathbf{M}^*{}_{JK}}{2} N^K + h.c.$$

At low energy ($\ll M \sim 10^{14}\mathrm{GeV}$) :

- Heavy degrees of freedom are integrated out
- Effective light neutrino mass matrix :

$$[m_\nu] \simeq \lambda M^{-1}\lambda^T v_u^2 = U_{MNS} D_\nu U^T_{MNS} \sim \mathrm{eV}$$

CP violation from "low energy" U_{MNS} phases :

- δ Dirac phase (measurable in ν oscillations)

$$P(\nu_a \to \nu_b) - P(\overline{\nu}_a \to \overline{\nu}_b) = 4\sum_{i>j} \Im(U^*_{ai} U_{bi} U_{aj} U^*_{bj}) \sin(\Delta m^2_{ij} \frac{L}{2E})$$

- α and β Majorana phases (not easily evaluated)

CP violating phases at high energy

$$\mathscr{L}_{seesaw} = (\overline{\ell}^i_L H^*_d)\mathbf{Y}^*_{\mathbf{e}ij} e^j_R + (\overline{\ell}^i_L H^*_u)\lambda^*{}_{iJ} N^J + \overline{N^c}^J \frac{\mathbf{M}^*{}_{JK}}{2} N^K + h.c.$$

Bottom-up parametrisation :

- U_{MNS} : Dirac phase δ, Majorana phases α and β
- $\lambda\lambda^\dagger = V_L^\dagger D_\lambda^2 V_L$, $(\lambda = V_L^\dagger D_\lambda V_R)$:
  - V_L unitary matrix $\Rightarrow$ 3 phases

$\Rightarrow$ 6 phases have a role in the high-energy theory

Unflavoured lepton asymmetry :

$$\epsilon = \frac{\Gamma(N_1 \to \phi\ell) - \Gamma(N_1 \to \overline{\phi}\,\overline{\ell})}{\Gamma(N_1 \to \phi\ell) + \Gamma(N_1 \to \overline{\phi}\,\overline{\ell})} = \frac{1}{8\pi[\lambda^\dagger\lambda]_{11}} \sum_{J\neq 1} \Im[\lambda^\dagger\lambda]^2_{1J} f\left(\frac{M_J^2}{M_1^2}\right)$$

CP violating phases at high energy

$$\mathscr{L}_{seesaw} = (\overline{\ell}^i_L H^*_d)\mathbf{Y}^*_{\mathbf{e}ij} e^j_R + (\overline{\ell}^i_L H^*_u)\lambda^*{}_{iJ} N^J + \overline{N^c}^J \frac{\mathbf{M}^*{}_{JK}}{2} N^K + h.c.$$

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Flavoured lepton asymmetry :

$$\epsilon_{\alpha\alpha} = \frac{\Gamma(N_1 \to \phi\ell_\alpha) - \Gamma(N_1 \to \overline{\phi}\,\overline{\ell}_\alpha)}{\Gamma(N_1 \to \phi\ell_\alpha) + \Gamma(N_1 \to \overline{\phi}\,\overline{\ell}_\alpha)} = \frac{1}{8\pi[\lambda^\dagger\lambda]_{11}} \sum_J \Im[\lambda_{\alpha 1}(\lambda^\dagger\lambda)_{J1}\lambda^*_{\alpha J}] f\left(\frac{M_J^2}{M_1^2}\right)$$

The question

- The relation between :
  - CP violation at low energy (measurable in neutrino oscillations)
  - and CP violation at high energy ⇒ baryon asymmetry

Given the measured value of the baryon asymmetry, can an allowed range for the U_{MNS} phases be predicted ?

- Negative answer in Branco et al.[4] in leptogenesis without flavour

[4] C. Branco, T. Morozumi, B. M. Nobre and M. N. Rebelo, Nucl. Phys. B **617** (2001) 475 [arXiv :hep-ph/0107164].

Simple parametrisation

- Unflavoured lepton asymmetry :

$$\epsilon = \frac{1}{8\pi[\lambda^\dagger\lambda]_{11}} \sum_{J\neq 1} \Im[\lambda^\dagger\lambda]^2_{1J} f\left(\frac{M_J^2}{M_1^2}\right)$$

- In *Casas-Ibarra parametrisation* and hierarchical RH neutrinos :

$$\lambda = U D_k^{1/2} R D_M^{1/2} \qquad \Rightarrow \qquad \epsilon = -\frac{3M_1}{16\pi v^2} \frac{\Im(\sum_\rho m_\rho^2 R_{\rho 1}^2)}{\sum_\beta m_\beta |R_{1\beta}|^2}$$

$\Rightarrow$ ϵ is independent of U_{MNS} phases

- We want to address the same problem in flavoured leptogenesis, where :

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

Analytical proof in flavoured leptogenesis

We look for an area of the parameter space where :

- We have enough baryon asymmetry
- Y_B is independent from low energy phases

[5] S. Davidson, J. Garayoa, F. Palorini and N. Rius, arXiv :0705.1503 [hep-ph]

Analytical proof in flavoured leptogenesis

We look for an area of the parameter space where :

- We have enough baryon asymmetry
- Y_B is independent from low energy phases

It is found :

- In strong wash-out regime
- Using a simple form for R :

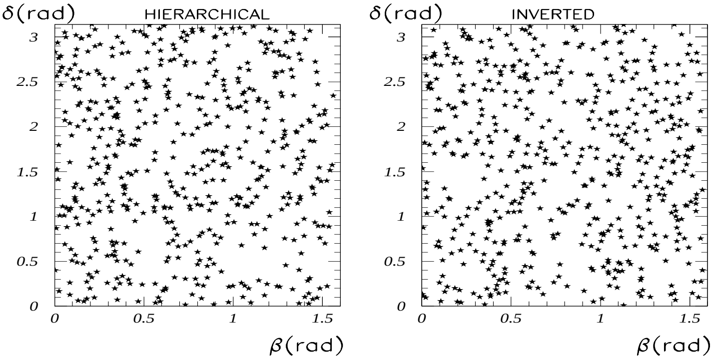
$$R = \begin{bmatrix} \cos\phi & 0 & -\sin\phi \\ 0 & 1 & 0 \\ \sin\phi & 0 & \cos\phi \end{bmatrix}$$

We can write Y_B independentely from the low energy phases (with $\phi = \rho + i\omega$) [5] :

$$Y_B \simeq 10^{-10} \left(\frac{M_1}{10^{11}\mathrm{GeV}} \right) \frac{\sin\rho\cos\rho\sinh\omega\cosh\omega}{\sin^2\rho\cosh^2\omega + \cos^2\rho\sinh^2\omega}$$

[5] S. Davidson, J. Garayoa, F. Palorini and N. Rius, arXiv :0705.1503 [hep-ph]

Numerical proof



A large enough baryon asymmetry can be obtained

for any values of the U_{MNS} phases

Leptogenesis in minimal supergravity

Supersymmetric leptogenesis with universality conditions :

- Enhanced flavour violating processes due to RGE equations of the sneutrino mass matrix

$\Rightarrow$ "Measurable" observables : $\lambda\lambda^\dagger = V_L^\dagger D_\lambda^2 V_L$

- Effects on electric dipole moments

- Parameter scan with Markov Chain Monte Carlo

Work in progress

Conclusions

- The relevant question in discussing "relation" between CP violation in the U_{MNS} matrix :

Is the baryon asymmetry *sensitive* to the U_{MNS} phases ?

- The answer was *NO* for unflavoured leptogenesis in the SM seesaw (Branco et al.)

- We argue that the answer does not change also with the inclusion of flavour effects in leptogenesis :

For any value of the U_{MNS} phases it is possible to find a point in the space of unmeasurable seesaw parameters such that leptogenesis works

- Soon results in Minimal Supergravity