Developments in Leptogenesis

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Abstract

Latest developments in leptogenesis are reviewed with a particular emphasis on the proposals to test leptogenesis. We discuss in particular the important role played by light and heavy flavour effects in the determination of the final asymmetry and the attractive features of the $N_2$ dominated scenario.

Keywords: leptogenesis, cosmology, BSM physics, early Universe, neutrino physics

1. The double side of leptogenesis

Leptogenesis [1] realizes a highly non trivial link between two completely independent experimental observations: a global property of the Universe, the absence of primordial anti-matter in the observable Universe and the observation that neutrinos mix and (therefore) have masses. In this way leptogenesis has a naturally built-in double sided nature. On one hand it describes a very early stage in the history of the Universe characterized by temperatures ($T_{\text{Lep}} \gtrsim 100$ GeV) much higher than those probed by Big Bang Nucleosynthesis ($T_{\text{BBN}} \sim 1$ MeV). On the other hand leptogenesis complements low energy neutrino experiments providing a completely independent phenomenological tool for testing the high energy parameters in the seesaw mechanism [2]. In these proceedings we will mainly focus on this second side of leptogenesis, where the early Universe history is basically exploited as a neutrino physics experiment.

2. Vanilla leptogenesis and beyond

2.1. Vanilla leptogenesis

Leptogenesis is a (cosmo)logical consequence of the the seesaw mechanism that elegantly explains not only why neutrinos mix and have masses but also why they are so much lighter than all the other massive fermions. In a minimal type I seesaw mechanism right-handed neutrinos with neutrino Yukawa coupling $h$ and a right-right Majorana mass term are added to the Standard Model Lagrangian,

$$L = L_{\text{SM}} + iN_R^\dagger Y_\alpha \tau \Phi N_R - h_\alpha L_{eL} N_R \Phi - \frac{1}{2} M_R N_R^\dagger N_R + h.c. \quad (1)$$

($i = 1, 2, 3, \quad \alpha = e, \mu, \tau$). For definiteness we consider the case of three RH neutrinos species. This is also the most attractive option with one RH neutrino for each family, as nicely predicted by $SO(10)$ grand unified models. Notice however that all current data from low energy neutrino experiments are consistent with a more minimal two RH neutrino model.

After spontaneous symmetry breaking, a Dirac mass term $m_D = v h$ is generated by the Higgs vev $v$. In the seesaw limit, $M \gg m_D$, the spectrum of neutrino masses splits into a light set given by the eigenvalues $m_1 < m_2 < m_3$ of the neutrino mass matrix

$$m_\nu = -m_D \frac{1}{M} m_D' \quad (2)$$

and into a heavy set $M_1 < M_2 < M_3$ coinciding with the eigenvalues of the Majorana mass matrix. The symmetric neutrino mass

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\[\text{Talk at Neutrino 2010. Dedicated to the memory of Alexey Anisimov (http://www2.physik.uni-bielefeld.de/714.html).}\]
matrix \( m_r \) is diagonalized by a unitary matrix \( U \), \( D_m \equiv \text{diag}(m_1, m_2, m_3) = -U^* m_r U^* \) that in a basis where the charged lepton mass matrix is diagonal coincides with the leptonic mixing matrix \( U_{PMNS} \).

In this way the lightness of ordinary neutrinos is explained just as an algebraic by-product. If the largest eigenvalue in the Dirac neutrino mass matrix is assumed to be of the order of the electroweak scale, as for the other massive fermions, then the atmospheric neutrino mass scale \( m_{atm} \equiv \sqrt{m_2^2 - m_1^2} \approx 0.05 \text{ eV} \) can be naturally reproduced for \( M_2 \approx 10^{14-15} \text{ GeV} \), very close to the grand-unified scale.

In general, the decays of the right-handed neutrinos violate \( CP \) so that the decay rate \( \Gamma_i \) for \( N_i \rightarrow l_i + \phi^i \) can be different from the decay rate \( \bar{\Gamma}_i \) for \( N_i \rightarrow l_i + \phi \). In this way each \( N_i \)-decay will produce, on average, a \( B-L \) number given by the total \( CP \) asymmetry defined as \( \varepsilon_i \equiv - (\Gamma_i - \bar{\Gamma}_i)/(\Gamma_i + \bar{\Gamma}_i) \). If the \( N_i \)’s decay at temperatures \( T \gtrsim 100 \text{ GeV} \), then non-perturbative \( (B-L \text{ conserving}) \) sphaleron processes are in equilibrium \( (T_{\text{ sph}} \gtrsim H) \) so that lepton and baryon numbers are not separately conserved and \( N_B \approx N_{B-L}/3 \). The final baryon-to-photon number ratio can then be calculated from the final \( B-L \) asymmetry as \( \eta_B \approx 0.01 N_{B-L} \) where we indicate with \( N_X \) the value of any quantity \( X \) in a portion of comoving volume that contains one RH neutrino in ultra-relativistic thermal equilibrium. The result has to be compared with the measured value from CMB anisotropies observations \([3]\):

\[
\eta_B^{\text{CMB}} = (6.2 \pm 0.15) \times 10^{-10}. \tag{3}
\]

In a minimal version of leptogenesis a type I seesaw mechanism is assumed together with a thermal production of the RH neutrinos from the scatterings of particles in the thermal bath (thermal leptogenesis). In this way a non negligible RH neutrino \( N_i \) abundance requires \( T > O(M_i) \).

The final asymmetry has been traditionally calculated in a very simple way neglecting both the flavour composition of the lepton quantum states produced by \( N_i \)-decays (light flavour effects) and the production of the asymmetry from the heavier RH neutrino decays (heavy flavour effects). In this oversimplified picture, that we call \textit{vanilla leptogenesis}, the final asymmetry is then simply given by \( N_{B-L}^i \equiv \varepsilon_1 k^i(K_1) \), where \( K_1 \equiv (\Gamma + \bar{\Gamma})/H(T = M_i) \) is the lightest RH neutrino decay parameter and \( k^i(K_1) \) is the final efficiency factor giving approximately the number of \( N_i \)’s decaying out-of-equilibrium.

Barring fine tuned cancelations among the terms giving the RH neutrino masses in the see-saw formula, the total \( CP \) asymmetry is upper bounded by \([4]\):

\[
\varepsilon_1 \leq \varepsilon_1^{\text{max}} \approx 10^{-6} \frac{M_1}{10^{10} \text{ GeV}} \frac{m_{atm}}{m_1 + m_3}. \tag{4}
\]

and, imposing \( \eta_B^{\text{max}} \approx 0.01 \varepsilon_1^{\text{max}} k^i > \eta_B^{MB} \), one obtains, in the plane \((m_1, M_1)\), the allowed region shown in Fig. 1. One can notice the existence of an upper bound on the light neutrino masses \( m_1 \lesssim 0.12 \text{ eV} \), incompatible with quasi-degenerate neutrino mass models, and a lower bound on \( M_1 \gtrsim 2 \times 10^9 \text{ GeV} \) implying a lower bound on the reheat temperature \( T_{RH} \gtrsim 10^9 \text{ GeV} \) \([5]\). These bounds are valid under the following set of assumptions and approximations \([6]\): i) the flavour composition of the leptons in the final states is neglected; ii) the heavy RH neutrino mass spectrum is assumed to be strongly hierarchical with \( M_2 \gtrsim 10 M_1 \); iii) there is no interference between the heaviest RH neutrino and the next-to-lightest RH neutrino, i.e. \((m_{\nu^2} m_{\nu^3})_{23} = 0\). The last two conditions guarantee that \( \varepsilon_1^{\text{max}} k(K_{2,3}) \ll \varepsilon_1^{\text{max}} k(K_1) \). In particular, the last condition is always verified for \( M_3 \gg 10^{14} \text{ GeV} \), when an effective two RH neutrino model is recovered.

An important feature of vanilla leptogenesis is that the final asymmetry does not directly depend on the parameters of the leptonic mixing matrix and therefore one cannot establish any kind of direct connection. In particular a discovery of \( CP \) violation in neutrino mixing would not be a smoking gun for leptogenesis but on the other hand a non discovery would not rule out leptogenesis. However, within more restricted scenarios, where for example some conditions on the neutrino Dirac mass matrix are imposed, links can emerge. We will discuss in detail the case of \( SO(10) \)-inspired models.

Many different directions have been explored in order to go beyond the assumptions and the approximations of...
Let us briefly discuss the main results.

### 2.2. Beyond a hierarchical RH mass spectrum

If \( (M_2 - M_1)/M_1 \approx \delta_2 \ll 1 \), the CP asymmetries get resonantly enhanced as \( \varepsilon_{12} \propto 1/\delta_2 \). If, more stringently, \( \delta_2 \lesssim 10^{-2} \), then \( \eta_\nu \propto 1/\delta_2 \) and the degenerate limit is obtained. In this limit the lower bounds on \( M_1 \) and on \( T_{\text{RH}} \) get relaxed \( \propto \delta_2 \) and at the resonance they completely disappear \([7]\). However, there are not many models able to justify in a reasonable way such a degenerate limit. Examples are provided by radiative leptogenesis and by models with extra-dimensions where all RH neutrinos masses squeeze together to a common TeV scale \([8]\).

### 2.3. Non minimal leptogenesis

Other proposals to relax the lower bounds on \( M_1 \) and on \( T_{\text{RH}} \) rely on extensions beyond minimal leptogenesis. For example on the addition of a right-right Majorana mass term yielding a type II seesaw mechanism \([9]\) or on a non thermal production of the RH neutrinos whose decays produce the asymmetry \([10]\). However, these non minimal models spoil somehow a remarkable coincidence between the measured values of the atmospheric and solar neutrino mass scales and the possibility to have successful leptogenesis even independently of the initial conditions \([5,6]\). Non minimal models have been also extensively explored in order to get a low scale leptogenesis testable at colliders \([11]\).

### 2.4. Improved kinetic description

Within vanilla leptogenesis the asymmetry is calculated solving simple rate equations, classical Boltzmann equations integrated over the RH neutrino momenta. Different kinds of extensions have been studied, for example accounting for a full momentum dependence \([12]\), for quantum kinetic effects \([13]\) or for thermal effects \([14]\). All these analyses find significant changes in the weak wash-out regime but within \(~50\%\) in the strong wash-out regime. This result has quite a straightforward general explanation. In the strong wash-out regime the final asymmetry is produced by the decays of RH neutrinos in a non relativistic regime \([5]\) when a simple classical momentum independent kinetic description provides quite a good approximation. It should therefore be borne in mind that the use of a simple kinetic description in leptogenesis is not just a simplistic approach but is justified in terms of the neutrino oscillations experimental results on the neutrino masses that support a strong wash-out regime.

### 3. Flavour effects

In the last years, flavour effects proved to be the most relevant modification of the vanilla scenario and for this reason we discuss them in a separate section. There are two kinds of flavour effects that are neglected in the vanilla scenario: heavy flavour effects \([15]\), how heavier RH neutrinos influence the final asymmetry, and light flavour effects \([15]\), how the flavour composition of the leptons quantum states produced in the RH neutrino decays influence the final asymmetry. We first discuss the two effects separately and then we show how their interplay has a very interesting application \([17]\).

#### 3.1. Light flavour effects

Let us first start by continuing to assume that the final asymmetry is dominantly produced by the decays of the lightest RH neutrinos, neglecting the contribution from the decays of the heavier RH neutrinos. If \( M_1 \gtrsim 5 \times 10^{11} \text{ GeV} \), the flavour composition of the quantum states of the leptons produced in \( N_1 \) decays has no influence on the final asymmetry and the unflavoured regime holds. This is because the lepton quantum states evolve coherently between the production of a lepton from an \( N_1 \)-decay and a subsequent inverse decay with an Higgs boson. In this way the lepton flavour composition does not play any role.

However, if \( 5 \times 10^{11} \text{ GeV} \gtrsim M_1 \gtrsim 10^9 \text{ GeV} \), then between one decay and the subsequent inverse decay, the produced lepton quantum states, on average, interact with tauons in a way that the coherent evolution breaks down. Therefore, at the inverse decays, the leptons quantum states are an incoherent mixture of a tauon component and of a (still coherent) superposition of an electron and of a muon component that we will indicate with \( \gamma \). The fraction of asymmetry stored in each flavour component is not proportional in general to the branching ratio of that component. This implies that the dynamics of the two flavour asymmetries, the tauon and the \( \gamma \) asymmetries, are different and have to be separately calculated. In this way the resulting final asymmetry can considerably differ from the result in the unflavoured regime. If \( M_1 \lesssim 10^9 \text{ GeV} \), then even the coherence of the \( \gamma \) component is broken by the muon interactions between decays and inverse decays and a full three flavour regime applies. In the intermediate regimes a density matrix formalism is necessary to describe the transition \([16,18]\).

There are three kinds of major modifications induced by flavour effects. First, the wash-out can be considerably lower than in the unflavoured regime \([16]\). Second,
the low energy phases affect directly the final asymmetry since they contribute to a second source of CP violation in the flavoured CP asymmetries [19, 20, 21]. As a consequence the same source of CP violation that could take place in neutrino oscillations, could be also responsible for the observed matter-antimatter asymmetry of the Universe, though under quite stringent conditions on the RH neutrino mass spectrum [22]. A third modification is that the flavored CP asymmetries contain extra-terms that evade the upper bound eq. (4) if some mild cancelations in the seesaw formula among the light neutrino mass terms and just a mild RH neutrino mass hierarchy \( (M_2/M_1 \lesssim 10) \) are allowed. In this way the lower bound on the reheat temperature can be relaxed by about one order of magnitude, down to \( 10^8 \) GeV [6] (see Fig. 2).

3.2. Heavy flavour effects

In the vanilla scenario the contribution to the final asymmetry from the heavier RH neutrinos is negligible for two reasons: the CP asymmetries of \( N_2 \) and \( N_3 \) are suppressed in the hierarchical limit with respect to \( \epsilon_1^{\text{max}} \) and even assuming that a sizeable asymmetry is produced around \( T \sim M_{2,3} \), this is later on washed out by the lightest RH neutrino inverse processes. However, it has been realized that the assumptions for the validity of the vanilla scenario are quite restrictive and there are a few reasons why heavy flavour effects have to be taken into account in general.

First, in the quasi-degenerate limit when \( \delta_{2,3} \ll 1 \), the CP asymmetries are not suppressed and the wash-out from the lightest RH neutrinos is only partial [7]. Second, even assuming a strong RH neutrino mass hierarchy, there is always a choice of the parameters such that \( N_1 \) decouples and its wash-out vanishes. For the same choice of the parameters, the \( N_2 \) total CP asymmetry is unsuppressed if \( M_3 \lesssim 10^{15} \) GeV. In this case a \( N_2 \)-dominated scenario is realized [15]. Notice that the existence of a third heaviest RH neutrino species is crucial. Third, even assuming a strong mass hierarchy, a coupled \( N_1 \) and \( M_1 \gtrsim 10^{12} \) GeV, the asymmetry produced by the heavier RH neutrino decays, in particular by the \( N_1 \)'s decays, with unsuppressed total CP asymmetry can be sizeable and in general is not completely washed-out by the lightest RH neutrino processes. This is because there is in general a component that escapes the \( N_1 \) wash-out [23, 24]. Notice that for a mild mass hierarchy, \( \delta_1 \lesssim 10 \), even the asymmetry produced by the \( N_1 \)'s decays can be sizeable and circumvent the \( N_1 \) and \( N_2 \) wash-out.

3.3. Flavoured \( N_2 \) dominated scenario

There is another interesting scenario where the asymmetry from the \( N_2 \) decays dominates the final asymmetry. This scenario relies on the interplay between light and heavy flavour effects [17]. Even assuming a strong mass hierarchy, a coupled \( N_1 \) and \( M_1 \gtrsim 10^{12} \) GeV, the \( N_1 \) wash-out can be circumvented. Suppose for example that the lightest RH neutrino wash-out occurs in the three-flavour regime (\( M_1 \ll 10^9 \) GeV). In this case the asymmetry produced by the heavier RH neutrinos, at the \( N_1 \) wash-out, distributes into an incoherent mixture of light flavour quantum eigenstates. It turns out that the \( N_1 \) wash-out in one of the three flavours is negligible in quite a wide region of the parameter space. In this way, accounting for flavour effects, the region of applicability of the \( N_2 \)-dominated scenario enlarges considerably, since it is not necessary that \( N_1 \) fully decouples but it is sufficient that it decouples just in one particular light flavor. Recently, it has been realized that, accounting for the Higgs and for the quark asymmetries, the dynamics of the flavour asymmetries couple and the lightest RH neutrino wash-out in a particular flavour can be circumvented even when \( N_1 \) is strongly coupled in that flavour [25]. Another interesting effect arising in the \( N_2 \)-dominated scenario is phantom leptogenesis. This is a pure quantum-mechanical effect that for example allows parts of the electron and of the muon asymmetries, the phantom terms, to escape completely the wash-out at the production when \( T \sim M_2 \gg 10^9 \) GeV.
4. Testing new physics with leptogenesis

The seesaw mechanism extends the Standard Model introducing eighteen new parameters when three RH neutrinos are considered. On the other hand, low energy neutrino experiments can only potentially test nine parameters in the neutrino mass matrix $m_i$. Nine high energy parameters, those characterizing the properties of the three RH neutrinos (three life times, three masses and three total CP asymmetries) and encoded in the orthogonal matrix $R$ \cite{26}, are not tested by low energy neutrino experiments. Quite interestingly, leptogenesis gives an additional constraint on a combination of both low energy neutrino parameters and high energy neutrino parameters, $\eta_B(m_\nu, R) = \eta_B^{\text{MB}}$. However, just one additional constraint does not seem to be still sufficient to over-constraint the parameter space leading to testable predictions. Despite this, as we have seen, in the vanilla leptogenesis scenario there is an upper bound on the neutrino masses. The reason is that in this case $\eta_B$ does not depend on the 6 parameters related to the properties of the two heavier RH neutrinos and therefore the asymmetry depends on a reduced number of high energy parameters. At the same time, the final asymmetry is strongly suppressed by the absolute neutrino mass scale when this is larger than the atmospheric neutrino mass scale. This is why the leptogenesis bound yields an upper bound on the neutrino masses.

When flavour effects are considered, the vanilla leptogenesis scenario holds only under very special conditions. More generally the parameters in the leptonic mixing matrix also directly affect the final asymmetry and, accounting for flavour effects, one could hope to derive definite predictions on the leptonic mixing matrix. However, when flavour effects are taken into account, the 6 parameters associated to the two heavier RH neutrinos contribute in general to the final asymmetry at the expenses of predictability. For this reason, in a generic scenario with three RH neutrinos, it is not possible to derive any prediction on low energy neutrino parameters.

In order to gain predictive power, two possibilities have been largely explored in the last years. In a first case one considers non minimal scenarios giving rise to additional phenomenological constraints. We have already mentioned how with a non minimal seesaw mechanism it is possible to lower the leptogenesis scale and have signatures at colliders. It has also been noticed that in supersymmetric models one can enhance the branching ratios of lepton flavour violating processes or electric dipole moments and in this way the existing experimental bounds further constrain the seesaw parameter space \cite{27}.

A second possibility is to search again, as within vanilla leptogenesis, for a reasonable scenario where the final asymmetry depends on a reduced number of free parameters in a way that the parameter space gets over-constrained by the leptogenesis bound. Let us briefly discuss some of the ideas that have been proposed.

4.1. Two RH neutrino model

A well motivated scenario that attracted great attention is a two RH neutrino scenario \cite{28}, where the third RH neutrino is either absent or effectively decoupled. This necessarily happens when $M_3 \gg 10^{14}$ GeV, implying that the lightest LH neutrino mass $m_1$ has to vanish. It can be shown that the number of parameters gets reduced from 18 to 11. It has been shown that in this case inverted hierarchical models with $\sin \theta_{13} \cos \delta \gtrsim -0.15$ are viable only if there is CP violation from Majorana phases \cite{29}. However this prediction would be very difficult to test and in any case would be quite unlikely to provide a smoking gun.

4.2. SO(10) inspired models

The only way to gain a strong predictive power is by adding some additional conditions within some model of new physics embedding the seesaw mechanism. In this respect quite an interesting example is represented by the ‘SO(10)-inspired scenario’ \cite{30}, where SO(10)-inspired conditions are over-imposed onto the neutrino Dirac mass matrix. In the basis where the charged leptons mass matrix and the Majorana mass matrix are diagonal, this is expressed in the bi-unitary parametrization as $m_D = V_L^T D_{m_\nu} U_R$, where $D_{m_\nu} \equiv \text{diag}(\lambda_1, \lambda_2, \lambda_3)$ is the diagonalized neutrino Dirac mass matrix and mixing angles in the unitary matrix $V_L$ are of the order of the mixing angles in the CKM matrix. The matrix $U_R$ can then be calculated from $V_L$, $U$ and $m_\nu$, considering that, as it can be seen from the seesaw formula (2), it provides a Takagi factorization of $M^{-1} \equiv D_{m_\nu} V_L U_D U^T V_L^T D_{m_\nu}^{-1}$, or explicitly $M^{-1} \equiv U_R D_M^{-1} U_R^T$. In this way the RH neutrino masses and the matrix $U_R$ are expressed in terms of the low energy neutrino parameters, of the eigenvalues $\lambda_i$ and of the parameters in $V_L$. Since one typically obtains $M_1 \sim 10^5$ GeV and $M_2 \sim 10^{11}$ GeV, the asymmetry produced from the lightest RH neutrino decays is negligible and the $N_2$-dominated scenario is realized \cite{31,32}.

Imposing the leptogenesis bound and considering that the final asymmetry does not depend on $\lambda_1$ and on $\lambda_3$, one obtains constraints on all low energy neutrino parameters and some examples are shown in the Fig. 3.
for a scan over the $2\sigma$ ranges of the allowed values of the low energy parameters and over the parameters in $V_L$ assumed to be $I < V_L < V_{CKM}$, where $V_{CKM}$ is the Cabibbo-Kobayashi-Maskawa matrix [32]. This scenario has been also studied in a more general context including a type II contribution to the seesaw mechanism from a triplet Higgs [33].

4.3. Discrete flavour symmetries

Heavy flavour effects are quite important when leptogenesis is embedded within theories that try to explain the emerging tribimaximal mixing structure in the leptonic mixing matrix via flavour symmetries. It has been shown in particular that if the symmetry is unbroken then the $CP$ asymmetries of the RH neutrinos would exactly vanish. On the other hand when the symmetry is broken, for the naturally expected values of the symmetry breaking parameters, then the observed matter-antimatter asymmetry can be successfully reproduced [34]. It is interesting that in a minimal picture based on $A_4$ symmetry, one has a RH neutrino mass spectrum with $10^{15}$ GeV $\gtrsim M_3 \gtrsim M_2 \gtrsim M_1 \gg 10^{12}$ GeV. One has therefore that all the asymmetry is produced in the unflavoured regime and that the mass spectrum is only mildly hierarchical (it has actually the same kind of hierarchy of light neutrinos). At the same time the small symmetry breaking imposes a quasi-orthogonality of the three lepton quantum states produced in the RH neutrino decays. Under these conditions the wash-out of the asymmetry produced by one RH neutrino species from the inverse decays of a lighter RH neutrino species is essentially negligible. The final asymmetry then receives a non negligible contribution from the decays of all three RH neutrinos species.

4.4. Supersymmetric models

Within a supersymmetric framework the final asymmetry within the vanilla leptogenesis scenario undergoes small changes [35]. However, supersymmetry introduces a conceptual important issue: the stringent lower bound on the reheat temperature, $T_{RH} \gtrsim 10^9$ GeV, is typically marginally compatible with an upper bound from the avoidance of the gravitino problem $T_{RH} \lesssim 10^{6-10}$ GeV, with the exact number depending on the parameters of the model [36]. It is quite remarkable that the solution of such a issue inspired an intense research activity on supersymmetric models able to reconcile minimal leptogenesis and the gravitino problem. Of course on the leptogenesis side, some of the discussed extensions beyond the vanilla scenario that relax the neutrino mass bounds also relax the $T_{RH}$
lower bound. However, notice that in the $N_2$ dominated scenario, while the lower bound on $M_1$ is completely evaded, there is still a lower bound on $T_{RH}$ that is even more stringent, $T_{RH} \gtrsim 6 \times 10^9$ GeV [15].

As we mentioned already, with flavour effects one has the possibility to relax the lower bound on $T_{RH}$ if a mild hierarchy in the RH neutrino masses is allowed together with a mild cancelation in the seesaw formula [6]. However for most models, such as sequential dominated models [37], this solution does not work. A major modification introduced by supersymmetry is that the critical value of the mass of the decaying RH neutrinos setting the transition from an unflavoured regime to a two-flavour regime and from a two-flavour regime to a three flavour regime is enhanced by a factor $\tan^2 \beta$ [38]. This has a practical relevance in the calculation of the asymmetry within supersymmetric models and it is quite interesting that leptogenesis becomes sensitive to such a relevant supersymmetric parameter. Recently, a detailed analysis mainly discussing how asymmetry is distributed among all particle species, has shown different subtle effects in the calculation of the final asymmetry within supersymmetric models but it just found $O(1)$ corrections to the final asymmetry [39].

5. Future prospects

In recent years, there have been important developments in leptogenesis first of all involving a full account of (light and heavy) flavour effects and also a deeper kinetic description accounting for quantum kinetic effects. Many efforts are currently devoted to explore possible ways to test the seesaw mechanism and leptogenesis. The possibility to have models with a seesaw scale down to the TeV scale, are gaining a lot of attention, especially in the light of the LHC and with the prospect of solving the hierarchy problem [11, 40]. This possibility seems necessarily to involve non minimal leptogenesis models based on a seesaw mechanism beyond the minimal type I [41].

Even within traditional high energy scale leptogenesis, flavour effects have opened new opportunities, or re-opened old ones, to test leptogenesis. In a minimal leptogenesis scenario, among the many possible mass patterns, a genuine $N_2$-dominated scenario with $M_1 \ll 10^9$ GeV and $M_2 \gtrsim 10^9$ GeV, presents some attractive features: i) the presence of a double stage, production from $N_2$ decays and wash-out from $N_1$ inverse processes, seems to enhance the predictive power yielding constraints on the low energy parameters; ii) it provides a solution to the problem of the independence of the initial conditions if the final asymmetry is tauon dominated (in this case the constraints on the low energy parameters become even more meaningful) [42]; iii) it rescues the interesting class of $SO(10)$-inspired models leading to testable constraints on the low energy neutrino parameters.

We can fairly conclude saying that leptogenesis is experiencing a mature stage with various interesting ideas about the possibility to test it. Low and high energy scale models lead to quite different phenomenological scenarios. In the first case they necessarily predict some novel phenomenology. In the case of more conventional high energy scale models, the naturally expected experimental progress in low energy neutrino experiments could uncover some non trivial correlations among parameters. These correlations would be a trace of the dynamical processes that led to the generation of observed matter-antimatter asymmetry during a very early stage in the Universe history and would specifically depend on the model of new physics embedding the seesaw mechanism.

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