Leptogenesis with small violation of $B - L$

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Outline of the talk:

- Introduction to leptogenesis.
- Motivation for models with small violation of L.
- Leptogenesis with small violation of L.
- Conclusions.

The mystery of the matter-antimatter asymmetry

Observations:

(a) The Universe is globally asymmetric: the amount of antimatter is negligible with respect to the amount of matter.

- Cosmic rays from the sun.
- Planetary probes.
- Galactic cosmic rays.
- BESS-Polar experiment $\longrightarrow \quad \frac{\overline{He}}{He} < 1 \times 10^{-7}$.
- Absence of strong $\gamma-$ray flux from nucleon-antinucleon annihilations in clusters of Galaxies (like Virgo cluster).

$\Longrightarrow$ Matter and antimatter domains should be larger than 20 Mpc. [Steigman 1976]

Actually they must be larger than $\sim$ the visible Universe (cosmic diffuse γ-ray background) . [Cohen, De Rújula, Glashow 1998]

(b) Baryon density

- Big Bang Nucleosynthesis.
  The abundances of the light elements D, ^{3}He, ^{4}He, and ^{7}Li depend mainly on one parameter, n_B/n_γ.
- CMB anisotropies.

$$Y_B \equiv \frac{n_B - n_{\bar{B}}}{s} = \frac{n_B}{s} \simeq 9 \times 10^{-11}$$

The annihilation catastrophe

Nucleons and antinucleons remain in chemical equilibrium until $\Gamma_{ann} < H$, which occurs at

$$T_{fo} \sim 22\ \text{M}eV$$

If the Universe was locally-baryon-symmetric, then

$$Y_{B\,fo} \sim 7 \times 10^{-20} \quad !!!$$

Conclusion: There was a baryon asymmetry at $T \sim O\left(10^2\right)$ MeV.

Origin?

$\downarrow$

~~initial conditions~~ or dynamic generation

Sakharov's conditions

In 1967 Sakharov showed which are the basic conditions to dynamically generate a baryon asymmetry:

- **Baryonic number (**B**) violation**
- C **and** CP **Violation**
- **Departure from thermal equilibrium**

Is baryogenesis possible in the SM?

- B **violation:** Yes $\longrightarrow$ *sphalerons* (violate $B + L$ but conserve $B - L$).
- C **violation:** Yes
- CP **Violation:** Not enough $\longrightarrow$ $J_{CP}/T_c^{12} \sim 10^{-18}$
- **Departure from thermal equilibrium:** No $\longrightarrow$ $m_H > 114 GeV$ implies that the EW phase transition is not strongly first order.

Conclusion: physics beyond the SM is needed to explain the origin of the cosmic asymmetry.

Leptogenesis

The connection between two mysteries

- Why is there more matter than antimatter?
- Neutrino masses: In the SM neutrinos don't have mass but observations indicate that:

$$\Delta m^2_{21} \equiv m^2_{\text{sol}} \simeq 8 \times 10^{-5}\ \text{eV}^2 \ ,$$
$$\left|\Delta m^2_{32}\right| \equiv m^2_{\text{atm}} \simeq 2{,}5 \times 10^{-3}\ \text{eV}^2 \ ,$$
$$m_i \lesssim 2\ \text{eV}\ (\text{tritium decay}) \ ,$$
$$m_i \lesssim 0{,}5 - 1\ \text{eV}\ (\text{cosmology}) \ .$$

Why are neutrino masses so tiny?

There's a simple and natural extension of the SM that can solve both mysteries:

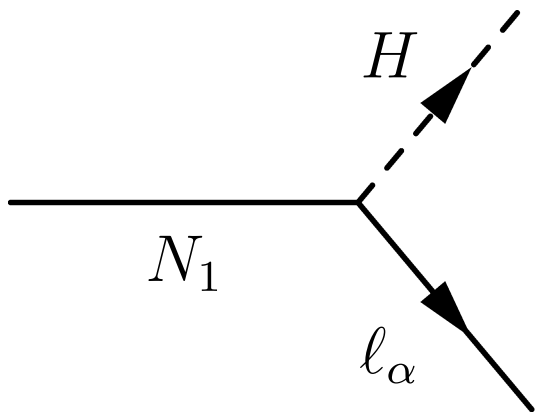
$$\mathcal{L} = \mathcal{L}_{\text{ME}} + i\overline{N}_i \partial\!\!\!/ N_i - \frac{1}{2} M_i \overline{N}_i N_i - \lambda_{\alpha i} \widetilde{H}^\dagger \, \overline{N}_i \ell_\alpha - \lambda^*_{\alpha i} \overline{\ell}_\alpha N_i \widetilde{H} \ ,$$

with $H = (H^+, H^0)^T$ and $\widetilde{H} = i\tau_2 H^*$.

Some heavy Majorana singlet neutrinos N_i are added to the particle content of the SM. The Lagrangian is that of the SM minimally extended to include the (type I) seesaw mechanism.

Baryogenesis through Leptogenesis:

- $\not{B}$: Sphalerons + L violation due to the Majorana nature of the heavy neutrinos.
- $\not{C}$ and $\not{CP}$: The relevant CP violation comes from the complex Yukawa couplings $\lambda_{\alpha i}$.
- Departure from thermal equilibrium: The source of the equilibrium departure is the expansion of the Universe.



$$\Gamma_{N_1} = \frac{1}{8\pi}(\lambda^\dagger\lambda)_{11}M_1$$

The N_1 decay out of equilibrium when $\Gamma_{N_1} \lesssim H(T = M_1)$.

The main parameters

- M_1 $\longrightarrow$ Determines the leptogenesis epoch $(T \sim M_1)$.
- ϵ $\longrightarrow$ CP violation.

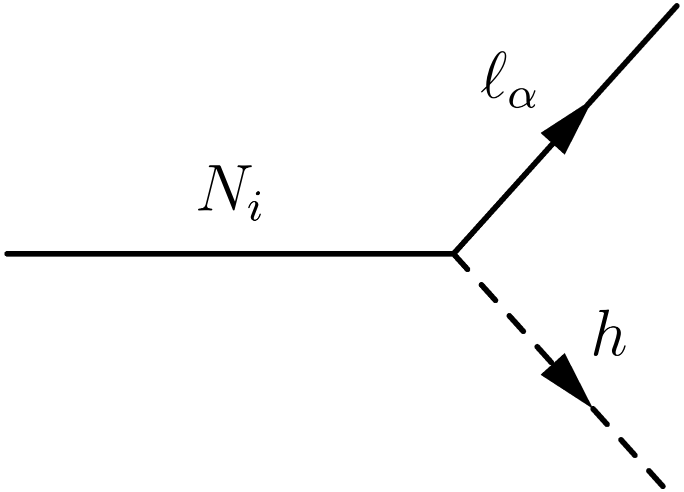
$$\epsilon^i_f \equiv \frac{\gamma(i \to f) - \gamma(\bar{i} \to \bar{f})}{\gamma(i \to f) + \gamma(\bar{i} \to \bar{f})} \quad \xrightarrow{\text{for decays}}$$

$$\epsilon = \sum_\alpha \epsilon_\alpha = \sum_\alpha \quad \frac{\gamma(N_1 \to H\ell_\alpha) - \gamma(N_1 \to \bar{H}\bar{\ell}_\alpha)}{\sum_\beta \gamma(N_1 \to H\ell_\beta) + \gamma(N_1 \to \bar{H}\bar{\ell}_\beta)}$$

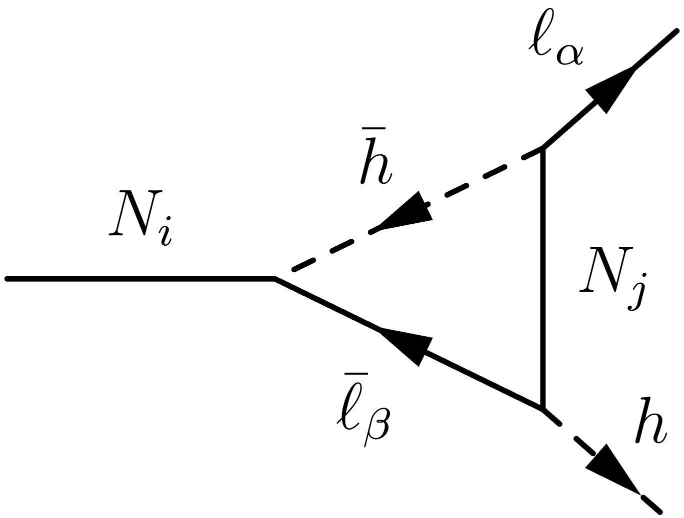
- $\tilde{m}_1$ (effective mass) $\longrightarrow$ Departure from equilibrium.

It is the decay width conveniently normalized: $\tilde{m}_1 \equiv \dfrac{(\lambda^\dagger\lambda)_{11} v^2}{M_1}$.

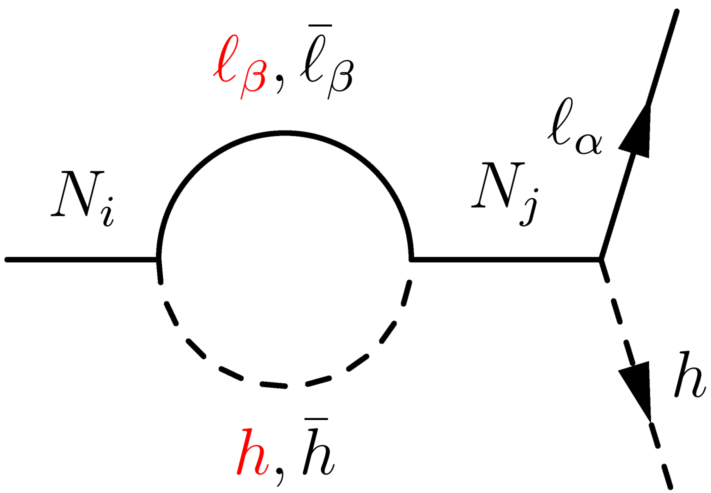
CP violation in decays



(a) Tree



(b) Vertex



(c) Wave

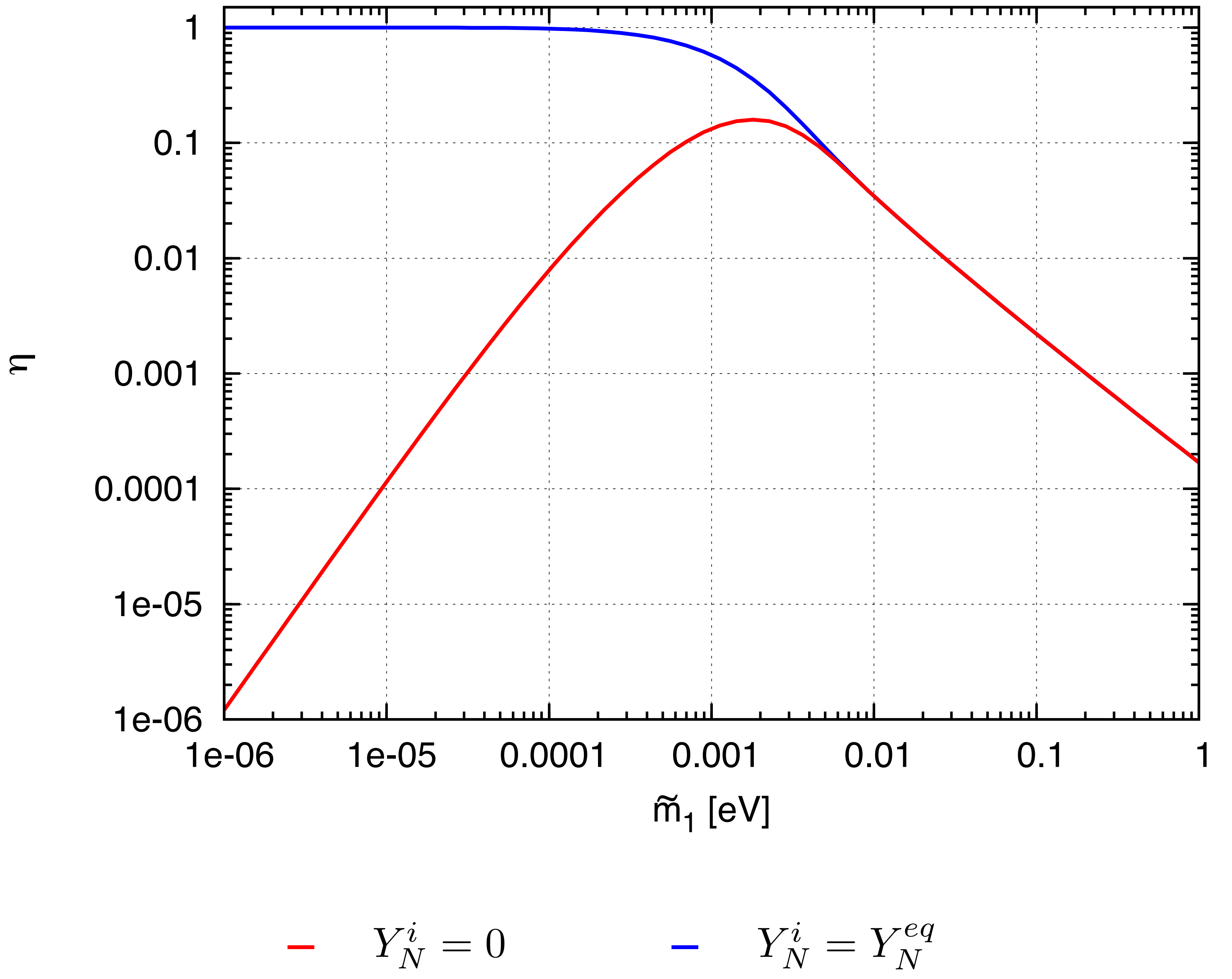
The evolution of Y_B can be obtained with an appropriate set of Boltzmann equations.

For a constant ϵ (usually a good approximation),

$$\boxed{Y_B^f = -\kappa \, \epsilon \, \eta}$$

with $\quad \eta = \textit{efficiency}, \quad \kappa = \frac{28}{79} Y_N^{eq}(T \gg M_1) \sim 10^{-3}$.

η is mainly a function of $\tilde{m}_1$.


η
1
0.1
0.01
0.001
0.0001
1e-05
1e-06
1e-06
1e-05
0.0001
0.001
0.01
0.1
1
m̃1 [eV]
$Y_N^i = 0$
$Y_N^i = Y_N^{eq}$

Connection with low energy observables

$Y_B^f = -\kappa\,\epsilon\,\eta,$ main parameters $M_1, \epsilon, \tilde{m}_1$

- $\epsilon \overset{\text{(hierarchical)}}{\sim} \frac{3}{16\pi}\lambda^2_{\Box 2} M_1/M_2 \overset{\text{(type I seesaw)}}{\sim} \frac{3}{16\pi} m_i M_1/v^2$

  $$|\epsilon| \leq \epsilon^{\text{DI}}_{\text{max}} = \frac{3}{16\pi}\frac{M_1}{v^2}(m_3 - m_1)$$

  (see also [T. Hambye, Y. Lin, A. Notari, M. Papucci, A. Strumia 2003])

  $\eta \leq 1 \implies M_1 \gtrsim 10^9$ GeV (gravitino problem $\rightarrow T_{rh} \lesssim 10^7$ TeV)

- $\tilde{m}_1 \geq m_1,$
  neglecting phases $\tilde{m}_1 \sim \sum_i m_i \gtrsim \sqrt{m^2_{\text{atm}}} \simeq 0{,}05$ eV $\sim m_*!$

- $m_1 \lesssim$ few eV (0,15 eV) flavored (unflavored)

The simplest models will be very difficult to test.

Current research on:

- Falsifying Leptogenesis at LHC

  [J. M. Frère, T. Hambye, G. Vertongen 2008]

  [D. Aristizabal Sierra, J. F. Kamenik, M. Nemevsek 2010]

  [A. Ibarra, C. Simonetto 2009]

- Low energy leptogenesis

  If there is a pair of very degenerate neutrinos the CP asymmetry is resonantly enhanced,

$$\text{when} \quad M_2 - M_1 \sim \frac{\Gamma_{N_2}}{2}, \quad |\epsilon| \sim \frac{1}{2} \frac{\mathrm{Im}\left[(\lambda^\dagger \lambda)^2_{21}\right]}{(\lambda^\dagger \lambda)_{11} (\lambda^\dagger \lambda)_{22}} \leq \frac{1}{2}$$

  The energy scale can be lowered up to the TeV range.

  Even so ...

Type I Seesaw

The mass matrix of the neutral sector in the basis ν_L, N_R^c is

$$\mathcal{M} = \begin{pmatrix} 0 & m_D \\ m_D^T & M \end{pmatrix} ,$$

with $m_D = v\lambda$.

The mass matrix for the light neutrinos is

$$m_\nu = m_D M^{-1} m_D^T \sim m_D \left(\frac{m_D}{M}\right)$$

and the mixing between light and heavy neutrinos is

$$\text{mixing} \sim \frac{m_D}{M} \sim \sqrt{\frac{m_\nu}{M}} \ll 1$$

Models with small violation of $B - L$

Models with $\approx L$ conservation are an interesting alternative.

Inverse seesaw

Particle content: SM + ν_{R_i}, s_{L_i} (singlet fermions).

The mass matrix of the neutral sector in the basis ν_L, ν_R^c, s_L is

$$\mathcal{M} = \begin{pmatrix} 0 & m_D & 0 \\ m_D^T & 0 & M \\ 0 & M^T & \mu \end{pmatrix}$$

$$m_\nu = m_D {M^T}^{-1} \mu M^{-1} m_D^T \sim m_D \left(\frac{\mu}{M}\right) \left(\frac{m_D}{M}\right) \quad (m_D, \mu \ll M)$$

ν_{R_i}, s_{L_i} combine to form quasi-Dirac fermions with mass $\sim M$.

$$\text{mixing} \sim \frac{m_D}{M} \sim \sqrt{\frac{m_\nu}{\mu}}$$

More generally, if $B-L$ is only slightly violated, then each singlet N_i satisfies (i) or (ii):

(i) N_i is a Majorana neutrino with $\lambda_{\alpha i} \ll 1$.

(ii) The N_i is a Dirac or quasi Dirac neutrino, $\lambda_{\alpha i}$ can be large. This means that there are two Majorana neutrinos N_{ih} and N_{il} with masses $M_i + \mu_i$ and $M_i - \mu_i$, such that the Yukawa couplings are given by

$$\mathcal{L}_{Y_{Ni}} = -\lambda_{\alpha i}\, \widetilde{H}^\dagger\, \overline{P_R \frac{N_{ih} + iN_{il}}{\sqrt{2}}} \ell_\alpha + h.c.$$

$$-\lambda'_{\alpha i}\, \widetilde{H}^\dagger\, \overline{P_R \frac{N_{ih} - iN_{il}}{\sqrt{2}}} \ell_\alpha + h.c. \quad \text{with} \quad \lambda'_{\alpha i} \ll 1$$

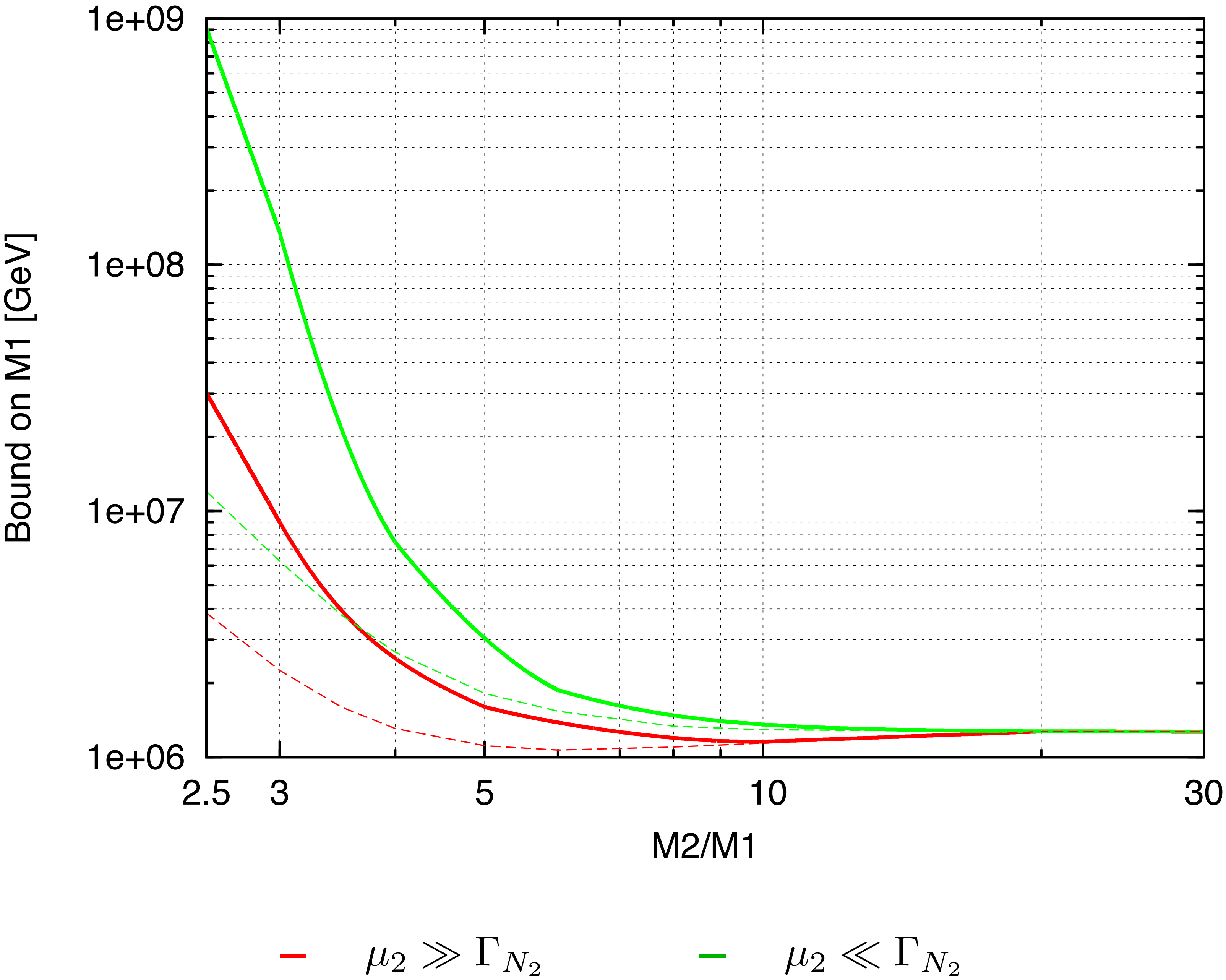
Leptogenesis with small violation of $B - L$

$N_1 \equiv$ The one that generates the largest lepton asymmetry.
$N_2 \equiv$ The one that makes the most important contribution to ϵ_α.
Our analysis includes:

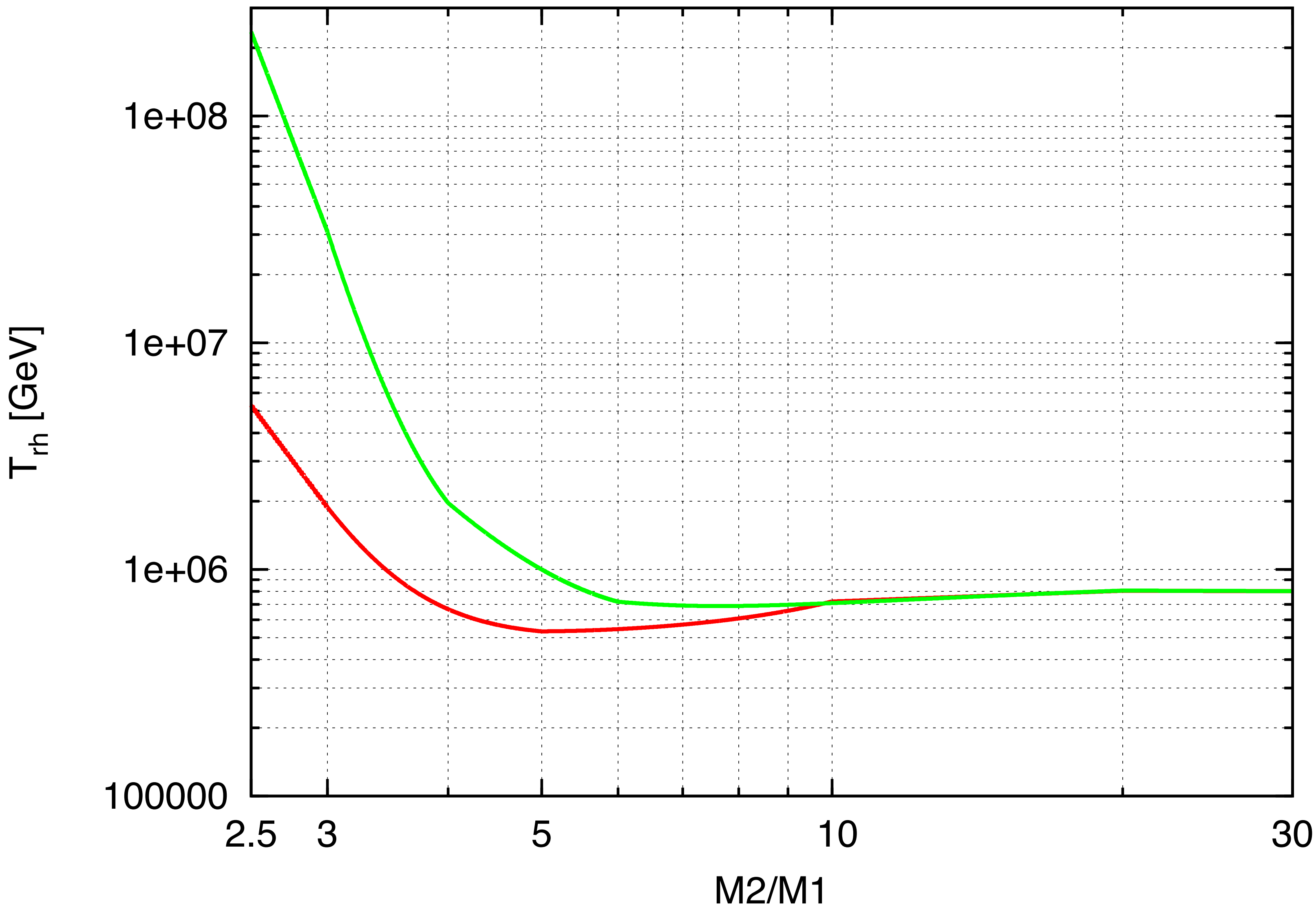
- Different combinations of possibilities, (i) or (ii), for N_1 and N_2.
- Full scan of the parameter space, with 2 cases for quasi Dirac N_i:
  - $\mu_i \ll \Gamma_{N_i}$ (Dirac limit),
  - $\mu_i \gg \Gamma_{N_i}$ (Majorana limit).
- $\epsilon_\alpha = \epsilon_\alpha^{\not{L}} + \epsilon_\alpha^L = O(\mu_2) + \epsilon_\alpha^L \implies \epsilon = \sum_\alpha \epsilon_\alpha = O(\mu_2)$. However, Y_B is generally not suppressed by μ_2 (flavor effects). It's crucial to:
  - Take into account flavor changing interactions.
  - Find the regions of param. space for 2 and 3-flavor regimes.

Also [T. Asaka, S. Blanchet 2008],[S. Antusch, S. Blanchet, M. Blennow, E. Fernandez-Martinez 2009],

[M. C. Gonzalez-Garcia, J. R., N. Rius 2009],[S. Blanchet, T. Hambye, and F.-X. Josse-Michaux 2009].



1e+09
1e+08
1e+07
1e+06
Bound on M1 [GeV]
2.5
3
5
10
30
M2/M1
$\mu_2 \gg \Gamma_{N_2}$
$\mu_2 \ll \Gamma_{N_2}$



$\mu_2 \gg \Gamma_{N_2}$ $\mu_2 \ll \Gamma_{N_2}$

Light neutrino masses:

$$m_i \sim \frac{\lambda_{\Box 1}^2 v^2}{M_1} + \mu \frac{\lambda_{\Box 2}^2 v^2}{M_2^2} + \lambda'_{\Box 2} \lambda_{\Box 2} v^2 / M_2 \ .$$

Taking $m_i \sim m_{atm} \sim 0{,}05$ eV, we get

$$\lambda_{\alpha 1} \sim 10^{-5} - 10^{-4}, \quad \mu_2 / M_2 \sim 10^{-8} - 10^{-6}, \quad \lambda'_{\alpha 2} \sim 10^{-8} - 10^{-7} \ .$$

Moreover,

$$\Gamma_{N_2} / M_2 \sim 5 \times (10^{-4} - 10^{-2}) \quad \Rightarrow \quad (\text{typically}) \quad \mu_2 \ll \Gamma_{N_2}$$

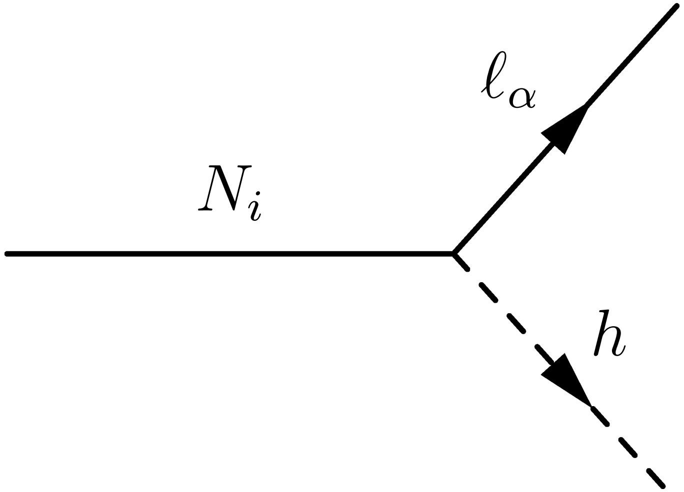
Note: For $M_1 \gtrsim 5 \times 10^6$ GeV, and still not considering large fine tunings related to phase cancellations, it is also possible to have $\mu_2 \gtrsim \Gamma_{N_2}$.

Conclusions

Models with small violation of $B - L$ can:

- Explain naturally the smallness of neutrino masses without a big suppression of the light-heavy neutrino mixing.
- Generate the baryon asymmetry at $T \sim 10^6$ GeV without a resonant enhancement of ϵ_α and independently of the initial conditions (Y_N, Y_{Δ_α}).
- . . . But not both!

CP violation in decays



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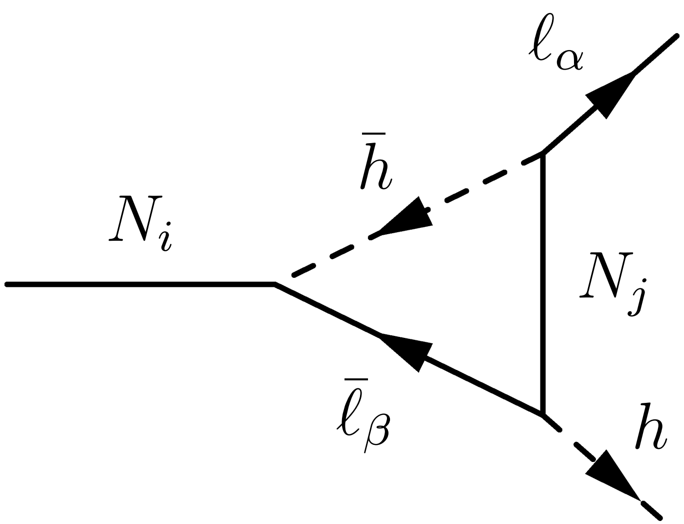
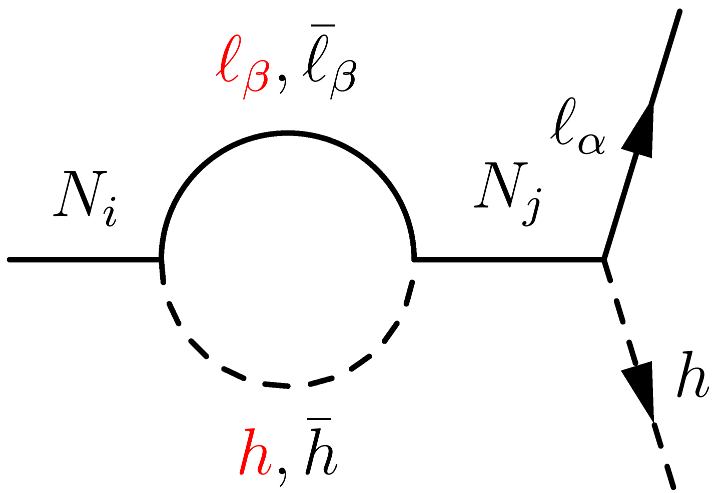


(b) Vertex



(c) Wave

$$\epsilon_{\ell_\alpha}^{N_i} = \epsilon_{\ell_\alpha}^{N_i}(\text{vertex}) + \epsilon_{\ell_\alpha}^{N_i}(\text{wave})$$

$$\epsilon_{\ell_\alpha}^{N_i}(\text{vertex}) = \frac{1}{8\pi}\sum_j f(y_j)\frac{\mathrm{Im}\left[\lambda^*_{\alpha j}\lambda_{\alpha i}(\lambda^\dagger\lambda)_{ji}\right]}{(\lambda^\dagger\lambda)_{ii}}$$

$$\epsilon_{\ell_\alpha}^{N_i}(\text{wave}) = -\frac{1}{8\pi}\sum_{j\neq i}\frac{M_i}{M_j^2 - M_i^2}\frac{\mathrm{Im}\left[\left(M_j(\lambda^\dagger\lambda)_{ji} + M_i(\lambda^\dagger\lambda)_{ij}\right)\lambda^*_{\alpha j}\lambda_{\alpha i}\right]}{(\lambda^\dagger\lambda)_{ii}}$$

with $y_j \equiv M_j^2/M_i^2$ and $f(x) = \sqrt{x}(1 - (1+x)\ln[(1+x)/x])$.

[Covi, Roulet, Vissani 1996]

Boltzmann equations

Simple unflavored version:

$$\frac{\mathrm{d}Y_N}{\mathrm{d}z} = -\frac{1}{zHs}\left(\frac{Y_N}{Y_N^{eq}} - 1\right)\gamma_D$$

$$\frac{\mathrm{d}Y_L}{\mathrm{d}z} = \frac{1}{zHs}\left\{\epsilon\left(\frac{Y_N}{Y_N^{eq}} - 1\right)\gamma_D - \frac{Y_L}{Y_L^{eq}}\frac{\gamma_D}{2}\right\}$$

with $Y_x \equiv \frac{n_x}{s}$ and $z \equiv \frac{M_1}{T}$.

- $\frac{\mathrm{d}Y_N}{\mathrm{d}z} = -\frac{K(z)}{z}(Y_N - Y_N^{eq})$ with $K(z) \sim \frac{\text{rates}}{H}$.
- $\frac{\mathrm{d}Y_L}{\mathrm{d}z}$ = source - washouts

Source = CP violation × L violation × departure from eq.

Washouts = asymmetries (Y_L) × rates (γ).

The role of $\tilde{m}_1$

It determines the amount of departure from eq. and the intensity of the washouts.

Reference value given by the *equilibrium mass* m_* :

$$\frac{\Gamma_{N1}}{H(T=M_1)} = \frac{\tilde{m}_1}{m_*} \ ,$$

with $m_* \simeq 1{,}08 \times 10^{-3}$ eV .

- $\tilde{m}_1 \gg m_* \ \rightarrow$ *strong washout* regime:
  - Independence from initial conditions.
  - $\eta \propto \tilde{m}_1^{-1}$ $\quad (Y_L \sim$ source/wo $\sim (\,\epsilon\, \mathrm{d}Y_N^{eq}/\mathrm{d}z)/$wo $)$.
- $\tilde{m}_1 \ll m_* \ \rightarrow$ *weak washout* regime:
  - Very dependent on initial conditions.
  - If $Y_N^i = 0 \ \rightarrow \ \eta \propto \cancel{\tilde{m}_1^1} \ \ \tilde{m}_1^2$.

Is leptogenesis possible with $\epsilon = 0$?

Flavor effects

$N_1 \longrightarrow \ell_d \; H$

- $T \gtrsim 10^{12}$ GeV: The Yukawa interactions of the charged leptons are out of equilibrium
  $\longrightarrow \ell_d$ is the only relevant "direction" in flavor space.
- $T \lesssim 10^{12}$ GeV: The Yukawa interactions of the τ (and eventually the μ) are in equilibrium
  $\longrightarrow$ they project ℓ_d into the flavor eigenstates $(\ell_\tau, \ell_\mu, \ell_e) \longrightarrow$ *decoherence*

Note: similarly for the antileptons, with $N_1 \longrightarrow \bar{\ell}'_d \; \bar{H}$

Boltzmann equations

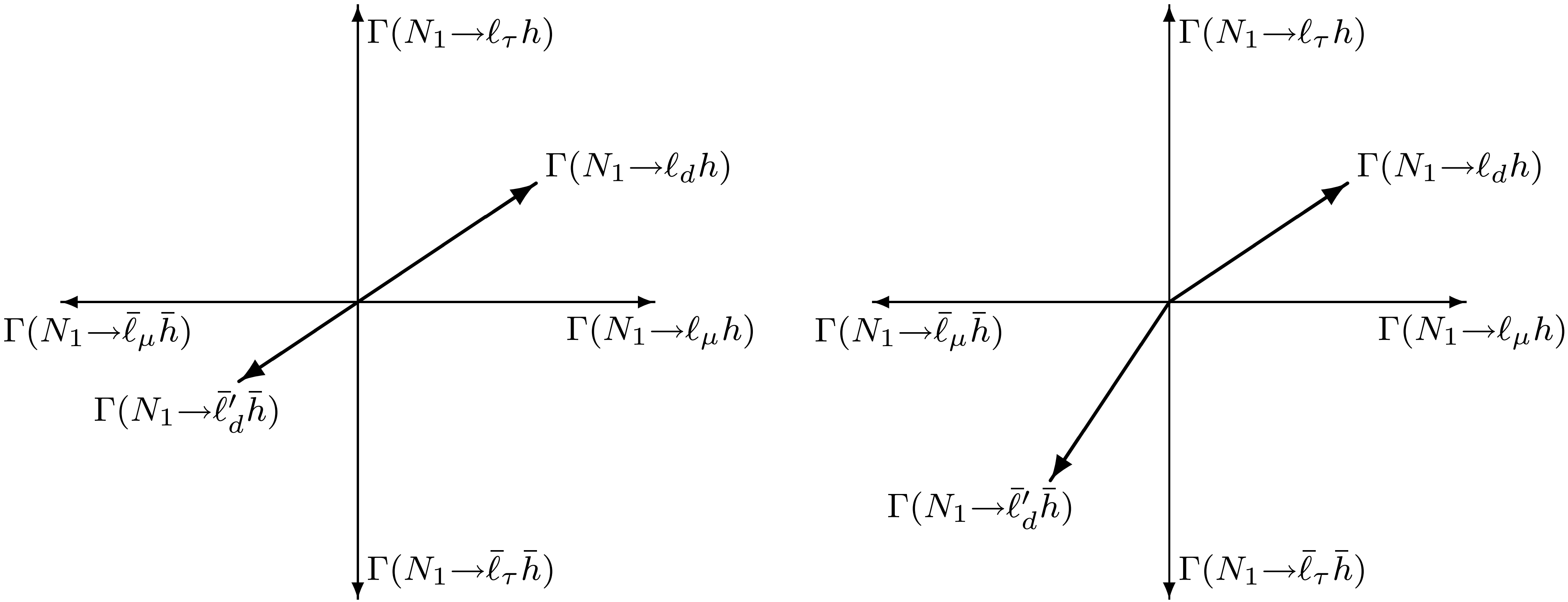
Define $Y_{\Delta_\alpha} \equiv \frac{1}{3}Y_B - Y_{L_\alpha}$ $(B/3 - L_\alpha$ is conserved by sphalerons)

$$\frac{\mathrm{d}Y_{\Delta_\alpha}}{\mathrm{d}z} \approx f(z)\epsilon_\alpha - Y_{\Delta_\alpha} K_\alpha w(z) \qquad (\alpha = e, \mu, \tau),$$

with $z \equiv M_1/T$, $\quad K_\alpha \equiv |\langle \ell_\alpha | \ell_d \rangle|^2$

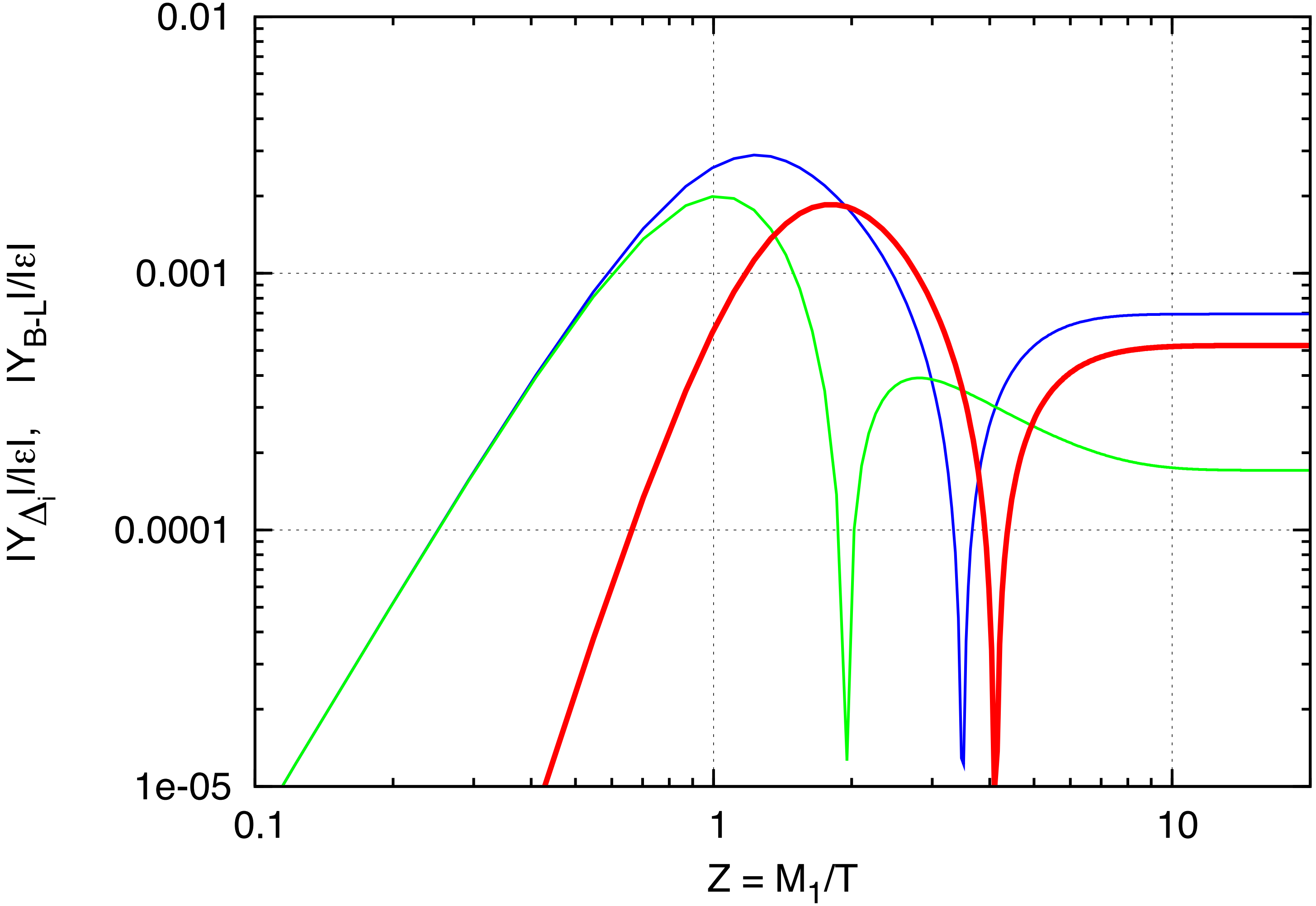
The asymmetries Y_{Δ_α} evolve (approximately) independently.

Two types of CP violation



(a) $\ell'_d = \ell_d, \epsilon \neq 0$

(b) $\epsilon = 0, \ell'_d \neq \ell_d, \epsilon_\alpha \neq 0$



$|Y_{\Delta_\tau}/\epsilon_\tau|$ $\quad$ $\left|Y_{\Delta_\mu}/\epsilon_\mu\right|$ $\quad$ $|Y_{B-L}/\epsilon_\mu|$

$\epsilon_\tau = -\epsilon_\mu \quad K_\tau = 0{,}1 \quad K_\mu = 0{,}9 \quad \tilde{m}_1 = 0{,}01$ eV

The relevant set of BE for the case $\mu_2 \gg \Gamma_{N_2}$ is

$$\frac{\mathrm{d}Y_{N_1}}{\mathrm{d}z} = \frac{-1}{sHz}\left(\frac{Y_{N_1}}{Y_{N_1}^{eq}} - 1\right)\gamma_{D_1} \ ,$$

$$\frac{\mathrm{d}Y_{\Delta_\alpha}}{\mathrm{d}z} = \frac{-1}{sHz}\left\{\left(\frac{Y_{N_1}}{Y_{N_1}^{eq}} - 1\right)\epsilon_{\alpha 1}\,\gamma_{D_1} - \sum_i \gamma_{\ell_\alpha h}^{N_i} y_{\ell_\alpha} - \sum_{\beta\neq\alpha}\left(\gamma_{\ell_\alpha h}^{\ell_\beta h\,\prime} + \gamma_{\ell_\alpha \bar{h}}^{\ell_\beta \bar{h}} + \gamma_{\ell_\alpha \bar{\ell}_\beta}^{h\bar{h}}\right)\left[y_{\ell_\alpha} - y_{\ell_\beta}\right]\right\} \ ,$$

where $z \equiv M_1/T$, $Y_X \equiv n_X/s$, $y_X \equiv (Y_X - Y_{\bar{X}})/Y_X^{eq}$, and $Y_{\Delta_\alpha} \equiv Y_B/3 - Y_{L_\alpha}$.

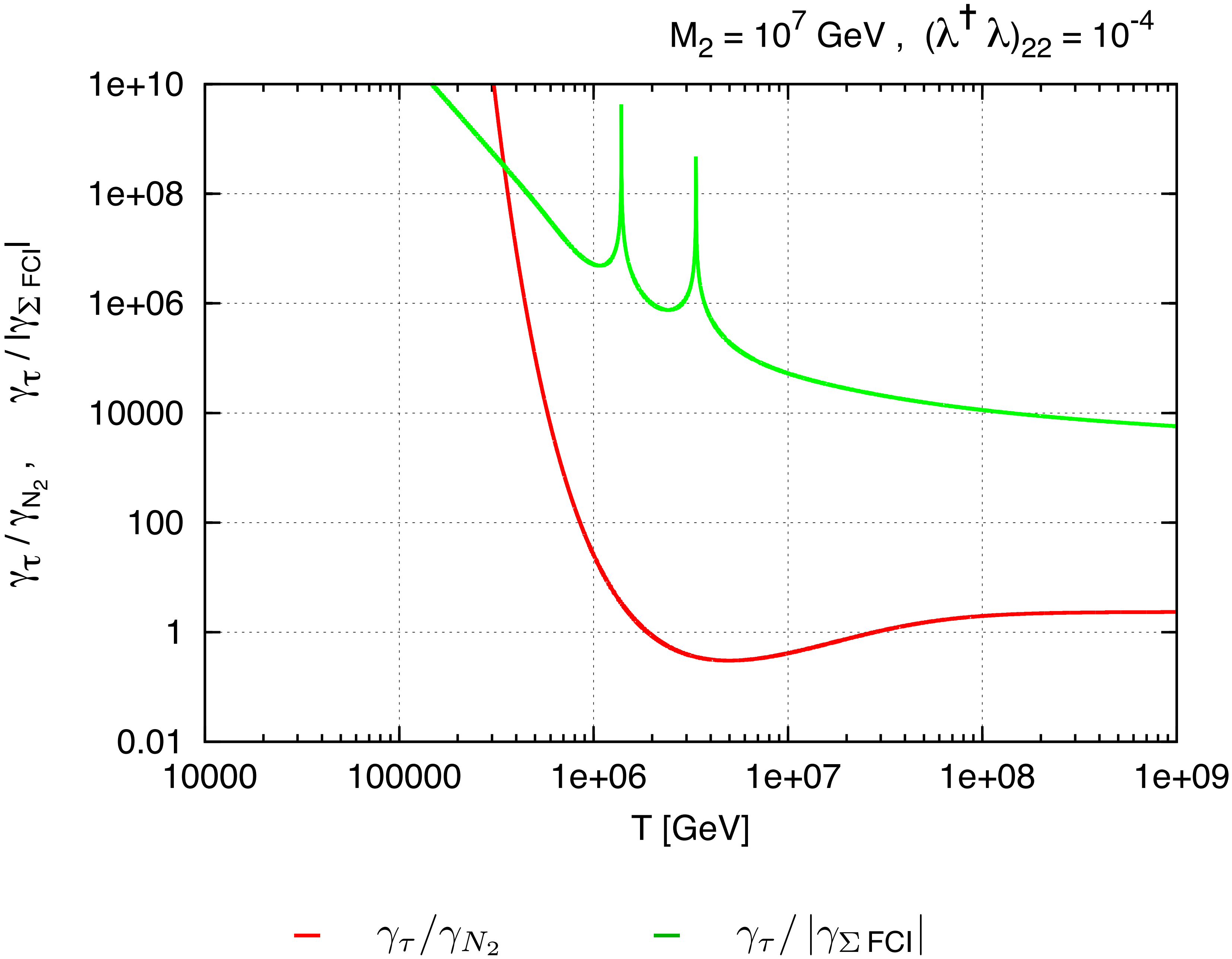
Instead, for $\mu_2 \ll \Gamma_{N_2}$

$$\frac{\mathrm{d}Y_{N_1}}{\mathrm{d}z} = \frac{-1}{sHz}\left(\frac{Y_{N_1}}{Y_{N_1}^{eq}} - 1\right)\gamma_{D_1} \; ,$$

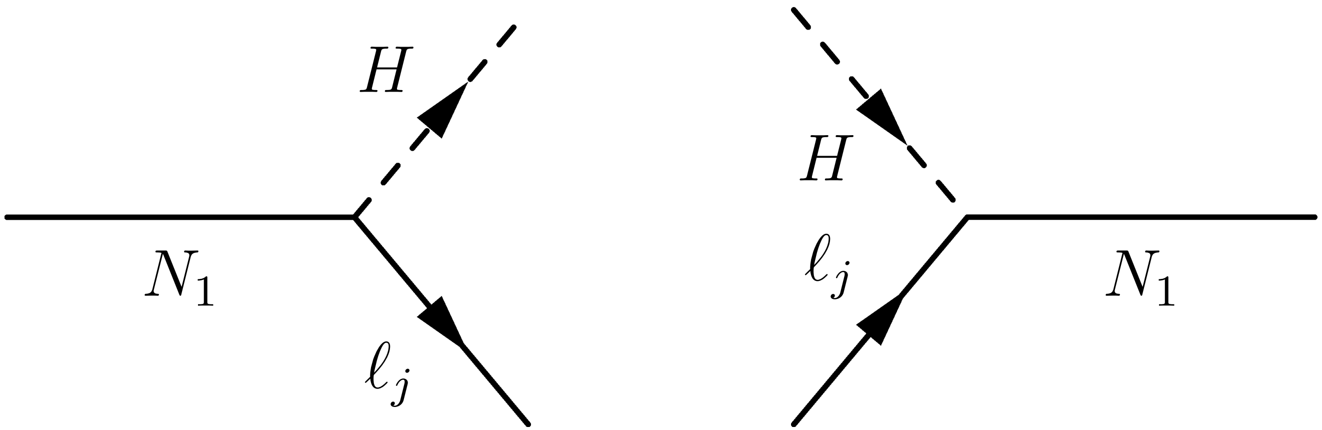
$$\frac{\mathrm{d}Y_{N_2-\bar{N}_2}}{\mathrm{d}z} = \frac{-1}{sHz}\sum_\alpha \gamma_{\ell_\alpha h}^{N_2}\left[y_{N_2} - y_{\ell_\alpha}\right] \; ,$$

$$\frac{\mathrm{d}Y_{\Delta_\alpha}}{\mathrm{d}z} = \frac{-1}{sHz}\left\{\left(\frac{Y_{N_1}}{Y_{N_1}^{eq}} - 1\right)\epsilon_{\alpha 1}\,\gamma_{D_1} - \gamma_{\ell_\alpha h}^{N_1} y_{\ell_\alpha} + \gamma_{\ell_\alpha h}^{N_2}\left[y_{N_2} - y_{\ell_\alpha}\right]\right.$$

$$\left. - \sum_{\beta\neq\alpha}\left(\gamma_{\ell_\alpha h}^{\ell_\beta h\,\prime} + \gamma_{\ell_\alpha \bar{h}}^{\ell_\beta \bar{h}} + \gamma_{\ell_\alpha \bar{\ell}_\beta}^{h\bar{h}}\right)\left[y_{\ell_\alpha} - y_{\ell_\beta}\right]\right\} \; .$$

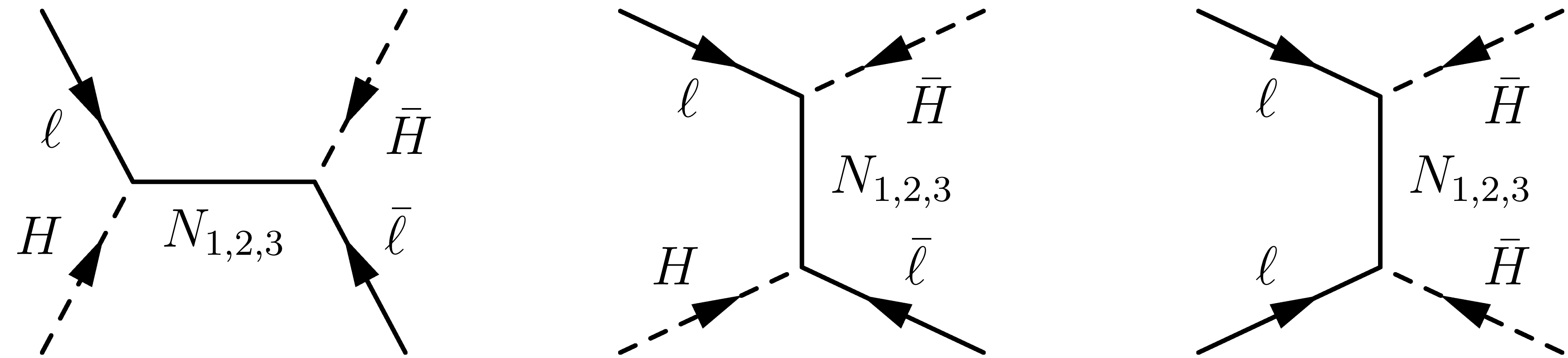

M2 = 10^7 GeV , (λ† λ)22 = 10^-4
γτ / γN2 , γτ / |γΣ FCI|
T [GeV]
1e+10
1e+08
1e+06
10000
100
1
0.01
10000
100000
1e+06
1e+07
1e+08
1e+09
γτ / γN2
γτ / |γΣ FCI|

Relevant processes for N_1–Leptogenesis

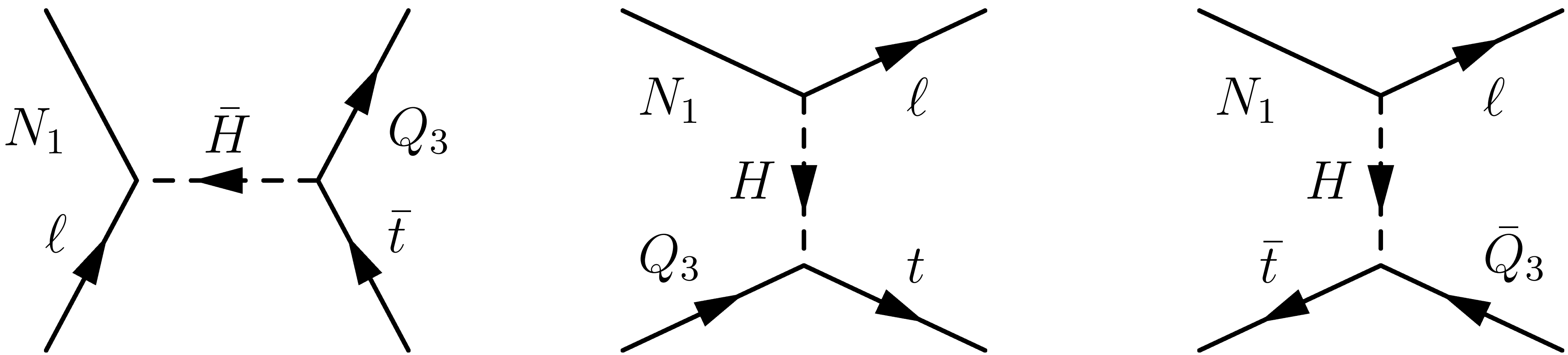


(c) Decay and inverse decay (production) of N_1.

$$\Gamma_{N_1} = \frac{1}{8\pi}(h^\dagger h)_{11} M_1 \ .$$



(d) $\Delta L = 2$ scatterings mediated by $N_{1,2,3}$.



(e) $\Delta L = 1$ scatterings mediated by the Higgs.