Flavour and Thermal Effects on Leptogenesis

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Recent paper (108 pages):

P. S. B. Dev, P. Millington, A.P., D. Teresi, arXiv:1404.1003

Outline:

- Matter–AntiMatter Asymmetry
- Models of Leptogenesis
- Resonant Leptogenesis
- Flavour Covariant Transport Equations
- Numerical Examples
- Conclusions

• Matter–AntiMatter Asymmetry

[P. A. R. Ade *et al.* [PLANCK Collaboration], arXiv:1303.5076.]

$$\eta_B^{\rm CMB} = \frac{n_B}{n_\gamma} = (6.04 \pm 0.08) \times 10^{-10} \qquad (\eta_B^{\rm BBN} = 3.4\text{–}6.9 \times 10^{-10}, \text{ at } 95\% \text{ CL})$$

Sakharov's conditions for generating the BAU
(from an *initially* B-symmetric Universe):

[A.D. Sakharov, JETP Lett. 5 (1967) 24.]

- B-violating interactions
- C and CP violation
- Out-of-equilibrium dynamics

Popular Scenarios for Baryogenesis:

- **Baryogenesis through the decay of a heavy particle**
  Out-of-equilibrium, B-violating decay of a heavy GUT particle, e.g. in SO(10).
  [M. Yoshimura, PRL**41** (1978) 281; S. Dimopoulos and L. Susskind, PR**D18** (1978) 4500; . . .
  K. S. Babu and R. N. Mohapatra, PRL**109** (2012) 091803.]

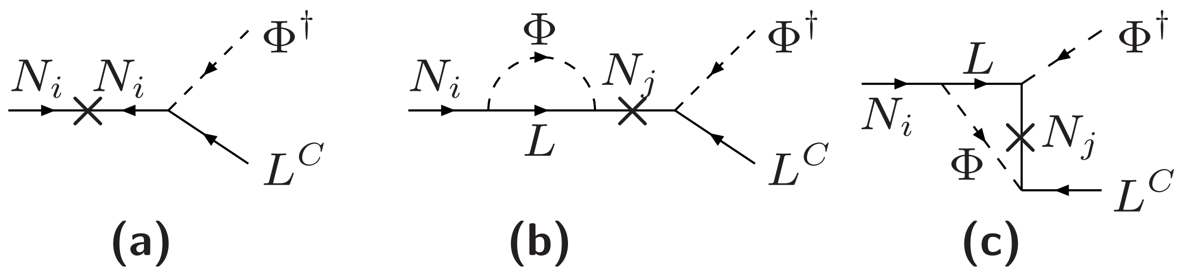
- **Baryogenesis at the electroweak phase transition**
  BAU generated by $(B+L)$-violating sphaleron interactions at $T \sim T_c \approx 140$ GeV, through a 1st order phase transition.
  [V.A. Kuzmin, V.A. Rubakov, M.E. Shaposhnikov, PLB155 (1985) 36;
  MSSM: M. Carena, M. Quirós, C. Wagner '96; K. Rummukainen, M. Laine '98 . . .]

  MSSM parameter space squeezed by EDMs and direct LHC searches:
  [T. Cohen, D. E. Morrissey and A. Pierce, PRD86 (2012) 013009;
  M. Carena, G. Nardini, M. Quiros and C. E. M. Wagner, arXiv:1207.6330;
  M. Laine, G. Nardini and K. Rummukainen, arXiv:1211.7344.]

$\Longrightarrow$ Baryogenesis through Leptogenesis

Out-of-equilibrium L-violating decays of heavy Majorana neutrinos produce a net lepton asymmetry, converted into the BAU through $(B+L)$-violating sphaleron interactions.

[M. Fukugita, T. Yanagida, PLB174 (1986) 45.]



$$\partial_\mu j^\mu_{\rm B} = \partial_\mu j^\mu_{\rm L} = i \frac{N_F}{8\pi} \left(- W_{\mu\nu} \widetilde{W}^{\mu\nu} + B_{\mu\nu} \widetilde{B}^{\mu\nu} \right) .$$

In-equilibrium sphaleron rates:

$$120 \text{ GeV} \lesssim T \lesssim 10^{12} \text{ GeV}$$

• Models of Leptogenesis

- **Hierarchical Leptogenesis** [M. Fukugita, T. Yanagida, PLB174 (1986) 45.]

  Lower mass bound on $m_{N_1} \gtrsim 10^9 - 10^6$ GeV

  [S. Davidson, A. Ibarra, PLB535 (2002) 25;
  W. Buchmüller, P. Di Bari, M. Plümacher, Annals Phys. **315** (2005) 305;
  J. Racker, M. Pena and N. Rius, JCAP **1207** (2012) 030.]

- **Resonant Leptogenesis** [A.P. and T. Underwood, NPB692 (2004) 303, and references therein]

- **Dirac Leptogenesis** [K. Dick, M. Lindner, M. Ratz, D. Wright, PRL84 (2000) 4039.]

- **Other scenarios:** Non-thermal leptogenesis, Affleck–Dine, spontaneous leptogenesis, CPT-Violating Leptogenesis . . .

  [For a review, see, M. Dine and A. Kusenko, Rev. Mod. Phys. **76** (2004) 1;
  N. Mavromatos and S. Sarkar, Eur. Phys. J. C **73** (2013) 2359.]

- **The Flavourdynamics of Leptogenesis**

BAU can be generated from and protected in a single lepton flavour:

$$\frac{1}{3}B - L_{e,\mu,\tau}\,.$$

[e.g. J.A. Harvey, M.S. Turner, PRD42 (1990) 3344;
H. Dreiner, G.G. Ross, NPB410 (1993) 188;
J.M. Cline, K. Kainulainen, K.A. Olive, PRD49 (1994) 6394.]

Two sources of flavour effects:

- Charged-lepton Yukawa couplings $h_{e,\mu,\tau}$

[R. Barbieri, P. Creminelli, A. Strumia, N. Tetradis, NPB575 (2000) 61;
A. Pilaftsis, T.E.J. Underwood, PRD72 (2005) 113001;
E. Nardi, Y. Nir, J. Racker, E. Roulet, JHEP0601 (2006) 068;
A. Abada, S. Davidson, F. X. Josse-Michaux, M. Losada, A. Riotto, JCAP0604 (2006) 004.]

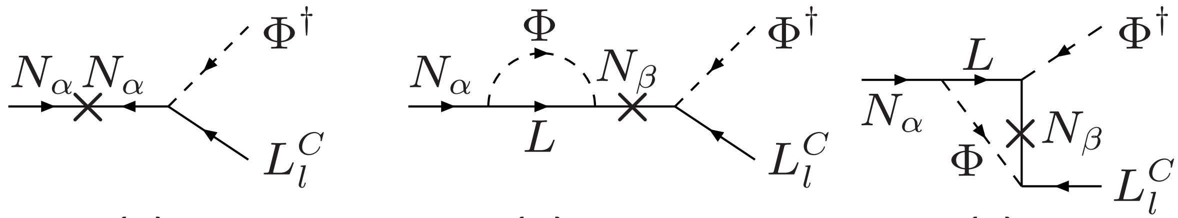
Modify BAU by up to 1-order of magnitude at $T \sim m_N \sim 10^9$ GeV.

- Heavy-neutrino Yukawa couplings $h^{\nu}_{l\alpha}$

[A. Pilaftsis, PRL95 (2005) 081602 [hep-ph/0408103];
T. Endoh, T. Morozumi and Z. h. Xiong, PTP111 (2004) 123;
A. Pilaftsis, T.E.J. Underwood, PRD72 (2005) 113001; O. Vives, PRD73 (2006) 073006.]

Modify BAU by many orders of magnitude, e.g. $> \ 10^6$, in RL models.

• Resonant Leptogenesis



(a) **(b)** **(c)**

Importance of self-energy effects (when $|m_{N_1} - m_{N_2}| \ll m_{N_{1,2}}$)

[J. Liu, G. Segré, PRD48 (1993) 4609;
M. Flanz, E. Paschos, U. Sarkar, PLB345 (1995) 248;
L. Covi, E. Roulet, F. Vissani, PLB384 (1996) 169;
⋮
J. R. Ellis, M. Raidal, T. Yanagida, PLB546 (2002) 228.]

Importance of the heavy-neutrino width effects: Γ_{N_α}

[A.P., PRD56 (1997) 5431; A.P. and T. Underwood, NPB692 (2004) 303.]

Variants of Resonant Leptogenesis:

- **Soft RL** [Y. Grossman, T. Kashti, Y. Nir, E. Roulet, PRL91 (2003) 251801; G. D'Ambrosio, G. F. Giudice, M. Raidal, PLB575 (2003) 75.]

- **Radiative RL** [R. Gonzalez Felipe, F. R. Joaquim and B. M. Nobre, PRD70 (2004) 085009; G. C. Branco, A. J. Buras, S. Jager, S. Uhlig, A. Weiler, JHEP0709 (2007) 004; G. C. Branco, R. Gonzalez Felipe, M. N. Rebelo and H. Serodio, PRD79 (2009) 093008.]

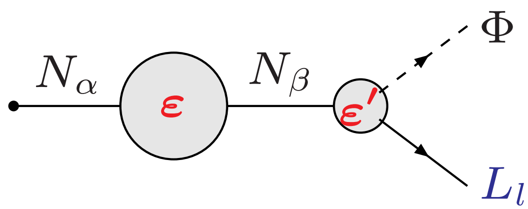
- **Coherent RL** (via sterile neutrino oscillations)

  [E. K. Akhmedov, V. A. Rubakov, A. Y. Smirnov, PRL81 (1998) 1359; T. Asaka, M. Shaposhnikov, PLB620 (2005) 17; M. E. Shaposhnikov, JHEP0808 (2008) 008.]

• The Field-Theory of Resonant Leptogenesis:

[A.P., PRD56 (1997) 5431; NPB504 (1997) 61.]

LSZ-type formalism for mixing and decay of heavy Majorana neutrinos



$$\times\, [S_{\alpha\alpha}(\not{p})]^{-1}\, u_{N_\alpha}(p) \;\equiv\; \mathcal{T}^{\rm eff}(N_\alpha \to L_l \Phi)$$

2-N Mixing Model:

$$S_{\alpha\beta}(\not{p}) \;=\; \begin{pmatrix} \not{p} - m_{N_1} + \Sigma_{11}(\not{p}) & \Sigma_{12}(\not{p}) \\ \Sigma_{21}(\not{p}) & \not{p} - m_{N_2} + \Sigma_{22}(\not{p}) \end{pmatrix}^{-1}$$

[For 3-N mixing, see, A.P., T. Underwood, NPB692 (2004) 303.]

Effective (Resummed) Neutrino Yukawa Couplings:

$$\mathcal{T}^{\text{eff}}(N_\alpha \to L_l \Phi) \; = \; \mathbf{h}_{l\alpha}\, \bar{u}_l\, P_R\, u_{N_\alpha}$$

For 2-N mixing:

$$\mathbf{h}_{l\alpha} \;=\; h^\nu_{l\alpha} + iB_{l\alpha} - \frac{ih^\nu_{l\beta}\, m_{N_\alpha} (m_{N_\alpha} A_{\alpha\beta} + m_{N_\beta} A_{\beta\alpha})}{m^2_{N_\alpha} - m^2_{N_\beta} + 2i\, A_{\beta\beta}\, m^2_{N_\alpha}}$$

$$\mathbf{h}^c_{l\alpha} \;=\; h^{\nu *}_{l\alpha} + iB^*_{l\alpha} - \frac{ih^{\nu *}_{l\beta}\, m_{N_\alpha} (m_{N_\alpha} A^*_{\alpha\beta} + m_{N_\beta} A^*_{\beta\alpha})}{m^2_{N_\alpha} - m^2_{N_\beta} + 2i\, A_{\beta\beta}\, m^2_{N_\alpha}}$$

Lepton Flavour Asymmetries

[A.P., T. Underwood, PRD72 (2005) 113001.]

$$\delta_{\alpha l} \;\equiv\; \frac{\Gamma_{\alpha l} - \Gamma^C_{\alpha l}}{\sum\limits_{l=e,\mu,\tau} \left(\Gamma_{\alpha l} + \Gamma^C_{\alpha l}\right)} \;=\; \frac{\left|\mathbf{h}_{l\alpha}\right|^2 - \left|\mathbf{h}^c_{l\alpha}\right|^2}{\left(\mathbf{h}^\dagger\, \mathbf{h}\right)_{\alpha\alpha} + \left(\mathbf{h}^{c\dagger}\, \mathbf{h}^c\right)_{\alpha\alpha}}$$

ε'-type CP violation :

$$\varepsilon'_{N_\alpha} \; = \; \frac{\mathrm{Im}\,(h^{\nu\dagger}\,h^{\nu})^2_{\alpha\beta}}{(h^{\nu\dagger}\,h^{\nu})_{\alpha\alpha}\,(h^{\nu\dagger}\,h^{\nu})_{\beta\beta}} \left(\frac{\Gamma_{N_\beta}}{m_{N_\beta}}\right)\; f\left(\frac{m^2_{N_\beta}}{m^2_{N_\alpha}}\right)\,,$$

where

$$\Gamma_{N_\beta} \; = \; \frac{(h^{\nu\dagger}\,h^{\nu})_{\beta\beta}}{8\pi}\, m_{N_\beta}$$

ε-type CP violation :

$$\varepsilon_{N_\alpha} \; = \; \frac{\mathrm{Im}\,(h^{\nu\dagger}\,h^{\nu})^2_{\alpha\beta}}{(h^{\nu\dagger}\,h^{\nu})_{\alpha\alpha}\,(h^{\nu\dagger}\,h^{\nu})_{\beta\beta}}\, \frac{(m^2_{N_\alpha}-m^2_{N_\beta})\, m_{N_\alpha}\,\Gamma_{N_\beta}}{(m^2_{N_\alpha}-m^2_{N_\beta})^2 \,+\, m^2_{N_\alpha}\Gamma^2_{N_\beta}}$$

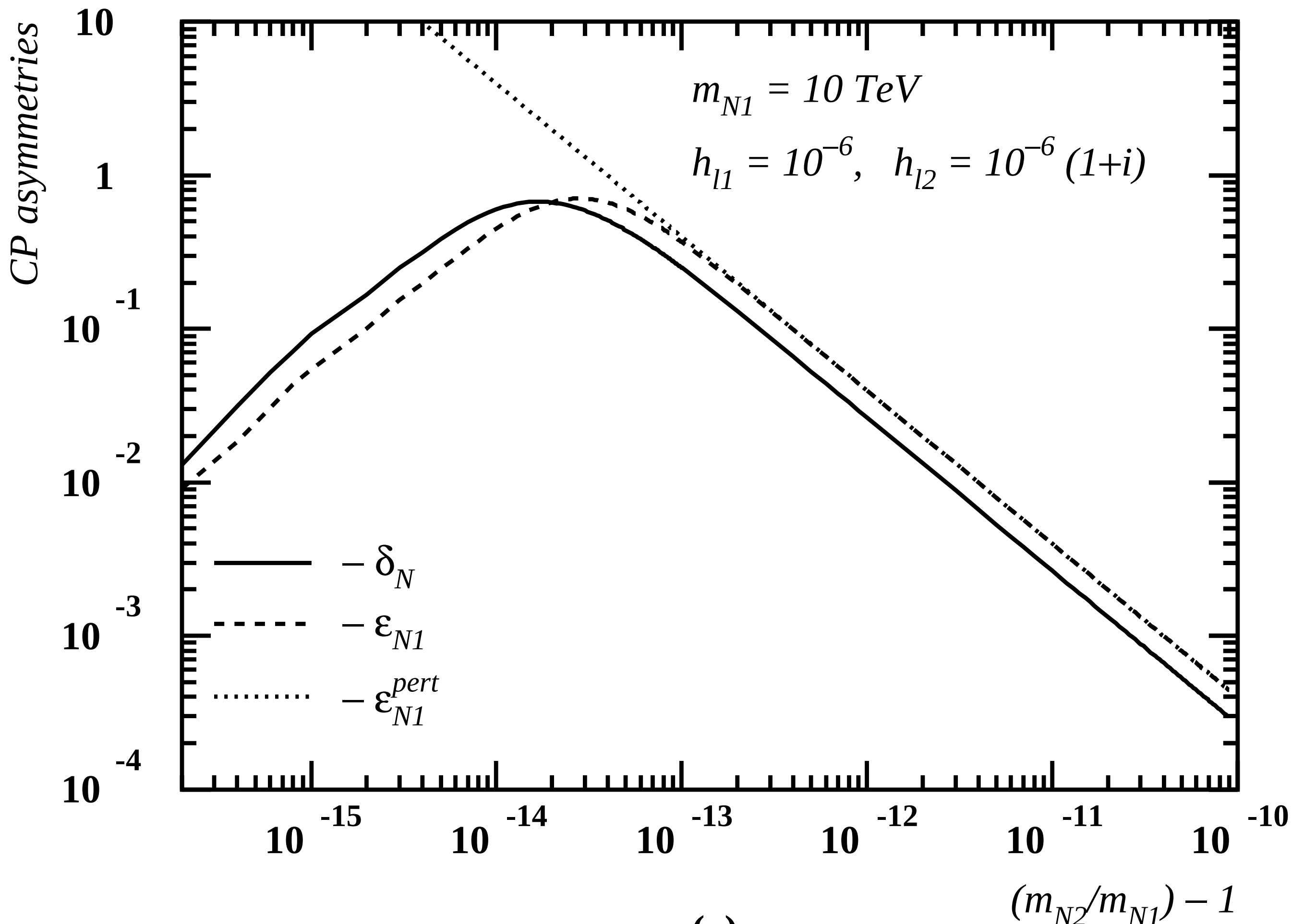
Note that $\varepsilon_{N_{1,2}}$ have the same sign!

Resonant conditions for $O(1)$ leptonic asymmetries:

[A.P., PRD56 (1997) 5431.]

$$\Rightarrow \qquad m_{N_2} - m_{N_1} \sim \frac{1}{2}\,\Gamma_{N_{1,2}}$$

$$\Rightarrow \qquad \frac{\mathrm{Im}\,(h^{\nu\dagger}\,h^{\nu})^2_{\alpha\beta}}{(h^{\nu\dagger}\,h^{\nu})_{\alpha\alpha}\,(h^{\nu\dagger}\,h^{\nu})_{\beta\beta}} \sim 1$$



(a)

• Comparison with Other Methods: ε_{N_1} [F. Deppisch, A.P., PRD83 (2011) 076007.]

Consider a simple Inverse Seesaw-like Model $(1L + 2\nu_R)$:

[R. N. Mohapatra, PRL56 (1986) 561;
R. N. Mohapatra, J. W. F. Valle, PRD34 (1986) 1642;
P. S. B. Dev and A.P., PRD86 (2012) 113001.]

$$M_\nu \;=\; \begin{pmatrix} 0 & vy & 0 \\ vy & \mu_1 & M \\ 0 & M & \mu_2 e^{i\alpha} \end{pmatrix}$$

Heavy neutrino masses:

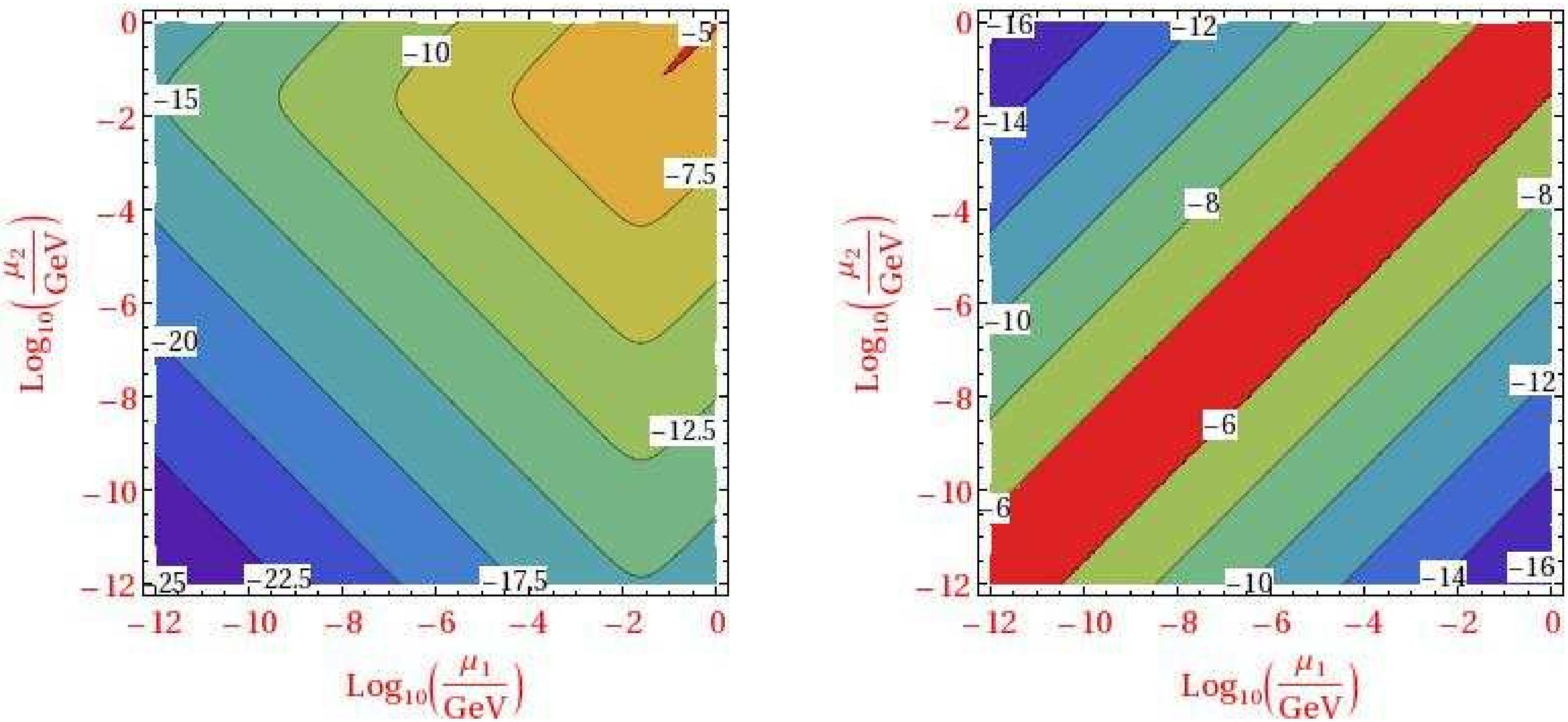
$$M_{1,2} \;\approx\; M \;\mp\; \frac{\mu}{2}\,, \quad \text{with } \mu \;=\; |\mu_1 + \mu_2 e^{i\alpha}|$$

Lepton asymmetry ε_{N_1}:

$$\varepsilon_{N_1} \;=\; \frac{\mathrm{Im}\,(h^{\nu\dagger}\,h^{\nu})^2_{12}}{(h^{\nu\dagger}\,h^{\nu})_{11}\,(h^{\nu\dagger}\,h^{\nu})_{22}}\; f_{\rm reg}$$

$\Longrightarrow \quad \varepsilon_{N_1} \to 0,$ when $\mu_{1,2} \to 0$.

L-conserving limits of ε_{N_1} [P.S.B. Dev, P. Millington, A.P., D. Teresi, arXiv:1404.1003.]



Singular regulator: [W. Buchmüller and M. Plümacher, PLB431 (1998) 354.]

$$f_{\rm reg}^{\rm BP} = \frac{\left|m_{N_1}^2 - m_{N_2}^2\right| m_{N_1}\,\Gamma_{N_2}}{\left(m_{N_1}^2 - m_{N_2}^2\right)^2 + \left(m_{N_1}\Gamma_{N_1} - m_{N_2}\Gamma_{N_2}\right)^2}$$

Thermal QFT Effects

G. F. Giudice, A. Notari, M. Raidal, A. Riotto and A. Strumia,
Towards a complete theory of thermal leptogenesis in the SM and MSSM,
Nucl. Phys. B685 (2004) 89.

A. De Simone and A. Riotto,
Quantum Boltzmann equations and leptogenesis, JCAP 0708 (2007) 002.

M. Garny, A. Hohenegger, A. Kartavtsev and M. Lindner,
Systematic approach to leptogenesis in nonequilibrium QFT: self-energy contribution to the CP-violating parameter, Phys. Rev. D81 (2010) 085027.

M. Beneke, B. Garbrecht, C. Fidler, M. Herranen and P. Schwaller,
Flavoured leptogenesis in the CTP formalism, Nucl. Phys. B843 (2011) 177.

A. Anisimov, W. Buchmüller, M. Drewes and S. Mendizabal,
Quantum leptogenesis I, Annals Phys. 326 (2011) 1998.

Perturbative Non-Equilibrium Thermal Field Theory,
P. Millington and A.P., Phys. Rev. D88 (2013) 085009 (102 pages).

• Flavour Covariant Transport Equations

[E. W. Kolb and S. Wolfram, NP**B172** (1980) 224.]

– Flavour Diagonal Boltzmann Equations

$$\frac{dn_a}{dt} + 3Hn_a \;=\; \sum_{aX'\leftrightarrow Y} \left(-\frac{n_a n_{X'}}{n_a^{\rm eq} n_{X'}^{\rm eq}}\, \gamma(aX' \to Y) \;+\; \frac{n_Y}{n_Y^{\rm eq}}\, \gamma(Y \to aX') \right) \;,$$

where n_a is the **number density**:

$$\begin{aligned} n_a(T) &= g_a \int \frac{d^3\mathbf{p}}{(2\pi)^3}\; \exp\left[-\left(\sqrt{\mathbf{p}^2 + m_a^2} - \mu_a(T) \right)/T \right] \\ &= \frac{g_a\, m_a^2\, T\; e^{\mu_a(T)/T}}{2\pi^2}\; K_2\!\left(\frac{m_a}{T}\right) \end{aligned}$$

and $\gamma(X \to Y)$ is the **collision term**:

$$\gamma(X \to Y) \;=\; \int d\pi_X\, d\pi_Y\, (2\pi)^4\, \delta^{(4)}(p_X - p_Y)\; e^{-p_X^0/T}\, |\mathcal{M}(X \to Y)|^2 \,.$$

– Flavour Diagonal BEs for Leptogenesis

[A.P., T.E. Underwood, NP**B692** (2004) 303; PR**D72** (2005) 113001.]

Define first

$$\eta^X \equiv n_X/n_\gamma\,, \quad z \equiv m_{N_1}/T\,, \quad H \equiv H(T=m_N) \approx 17\, m_N^2/M_{\rm Planck}$$

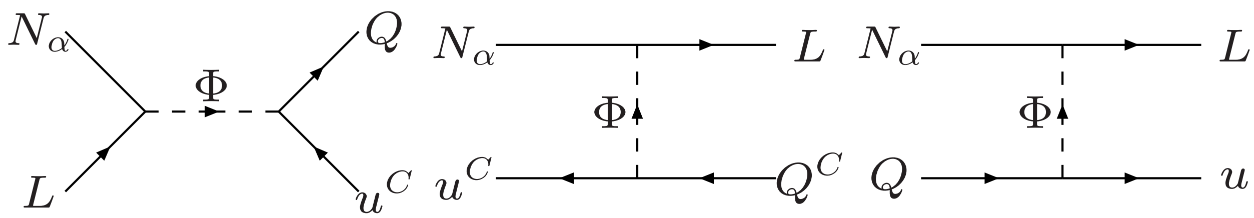
and the short-hands:

$$\begin{aligned} \gamma^X_Y &\equiv \gamma(X\to Y) + \gamma(\overline{X}\to\overline{Y}) \overset{\rm CPT}{=} \gamma^Y_X\,, \\ \delta\gamma^X_Y &\equiv \gamma(X\to Y) - \gamma(\overline{X}\to\overline{Y}) \overset{\rm CPT}{=} -\delta\gamma^Y_X\,. \end{aligned}$$

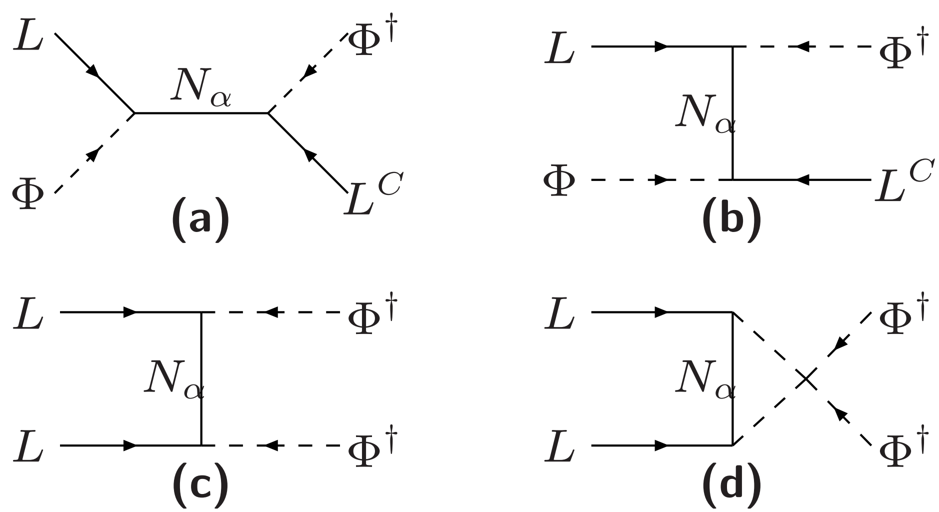
Write down the **Boltzmann equations**:

$$\begin{aligned} \frac{H\,n_\gamma}{z}\frac{d\eta^N_\alpha}{dz} &= \left(1-\frac{\eta^N_\alpha}{\eta^N_{\rm eq}}\right)\sum_k \gamma^{N_\alpha}_{L_k\Phi} + \cdots \\ \frac{H\,n_\gamma}{z}\frac{d\delta\eta^L_l}{dz} &= \sum_\alpha\left(\frac{\eta^N_\alpha}{\eta^N_{\rm eq}}-1\right)\delta\gamma^{N_\alpha}_{L_l\Phi} - \frac{2}{3}\delta\eta^L_l\sum_k\left(\gamma^{L_l\Phi}_{L_k^c\Phi^c}+\gamma^{L_l\Phi}_{L_k\Phi}\right) \\ &\quad -\frac{2}{3}\sum_k\delta\eta^L_k\left(\gamma^{L_k\Phi}_{L_l^c\Phi^c}-\gamma^{L_k\Phi}_{L_l\Phi}\right) + \cdots \end{aligned}$$

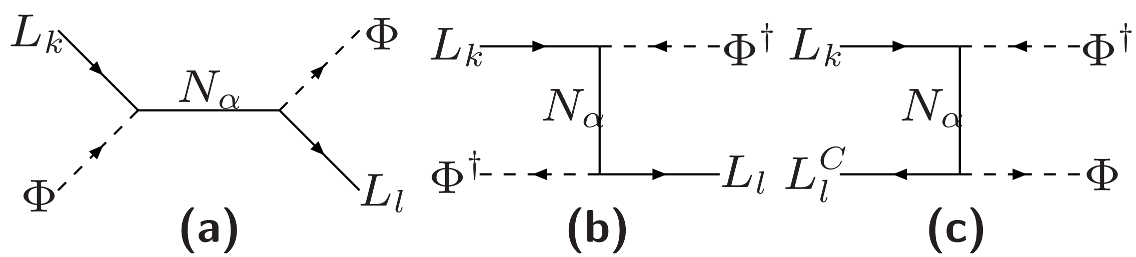
$\Delta L = 1$ scatterings involving L, N_α and quarks



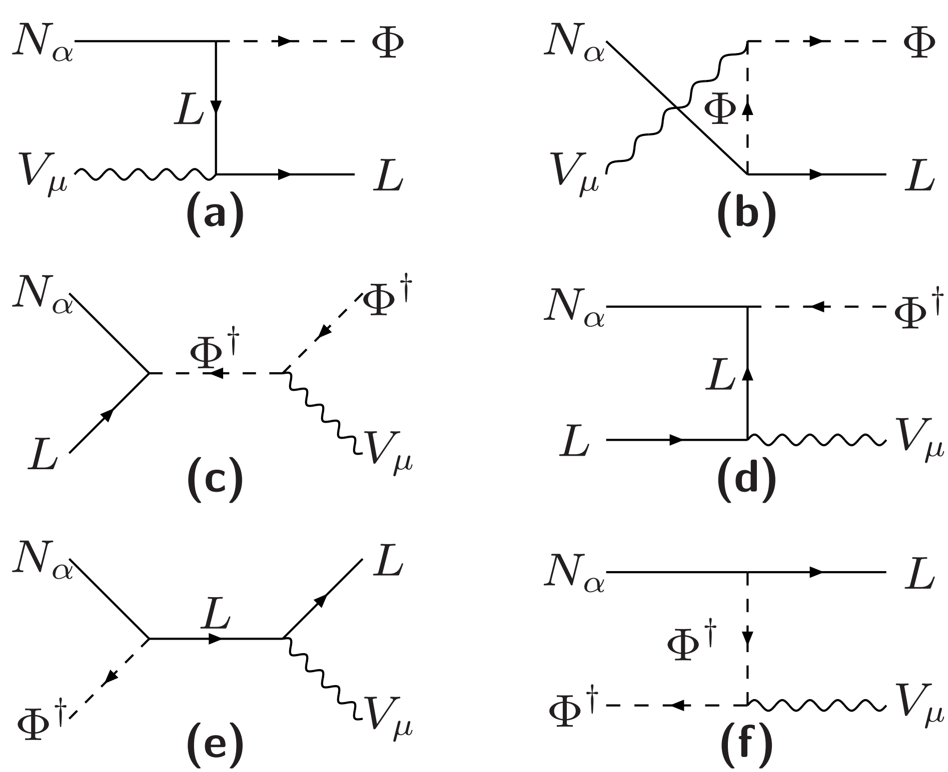
$\Delta L = 2$ scatterings involving L, Φ and N_α



$\Delta L = 0$ scatterings involving L, Φ and N_α



Gauge-mediated $\Delta L = 1$ scatterings



– Order-of-magnitude estimate of the BAU

[F. Deppisch, A.P., PRD83 (2011) 076007.]

Flavour-dependent decay width of heavy Majorana neutrino N_α:

$$\Gamma_{N_\alpha \to l} \;\equiv\; \Gamma(N_\alpha \to L_l \Phi) \;=\; (h^{\nu\dagger})_{il}\, h^{\nu}_{li}\, \frac{m_{N_\alpha}}{8\pi}$$

Define the effective wash-out K-factors:

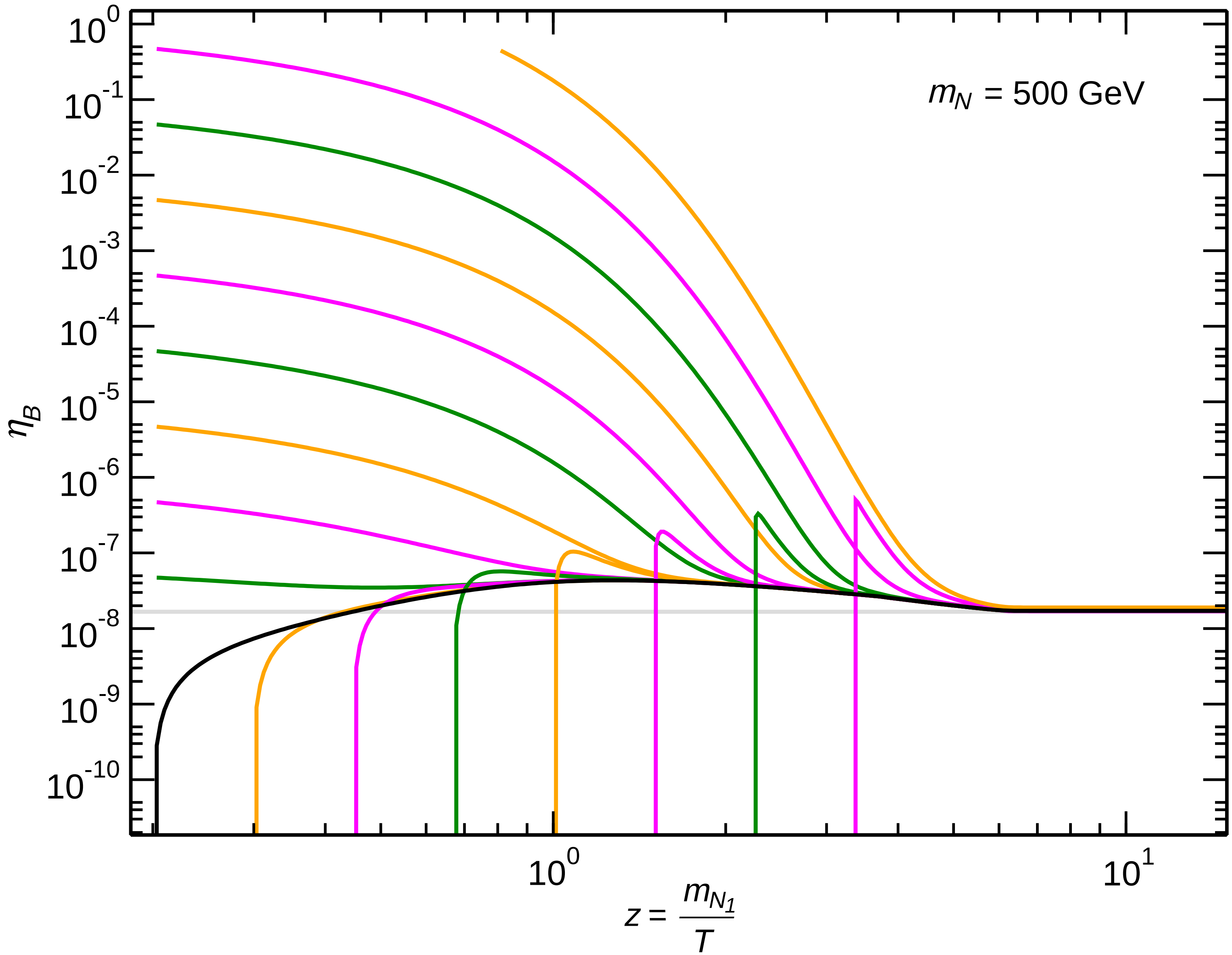
$$K_l^{\rm eff} \;\equiv\; \frac{\sum_{N_\alpha} \Gamma_{N_\alpha \to l}}{H}$$

Estimate of the BAU:

$$\eta_B \;\sim\; -\, 3 \cdot 10^{-2} \sum_{l=e,\mu,\tau} \frac{\delta_l}{K_l^{\rm eff}\, \min\Big[m_N/T_c\,,\; 1.25\, \ln(25 K_l^{\rm eff}) \Big]}\;.$$

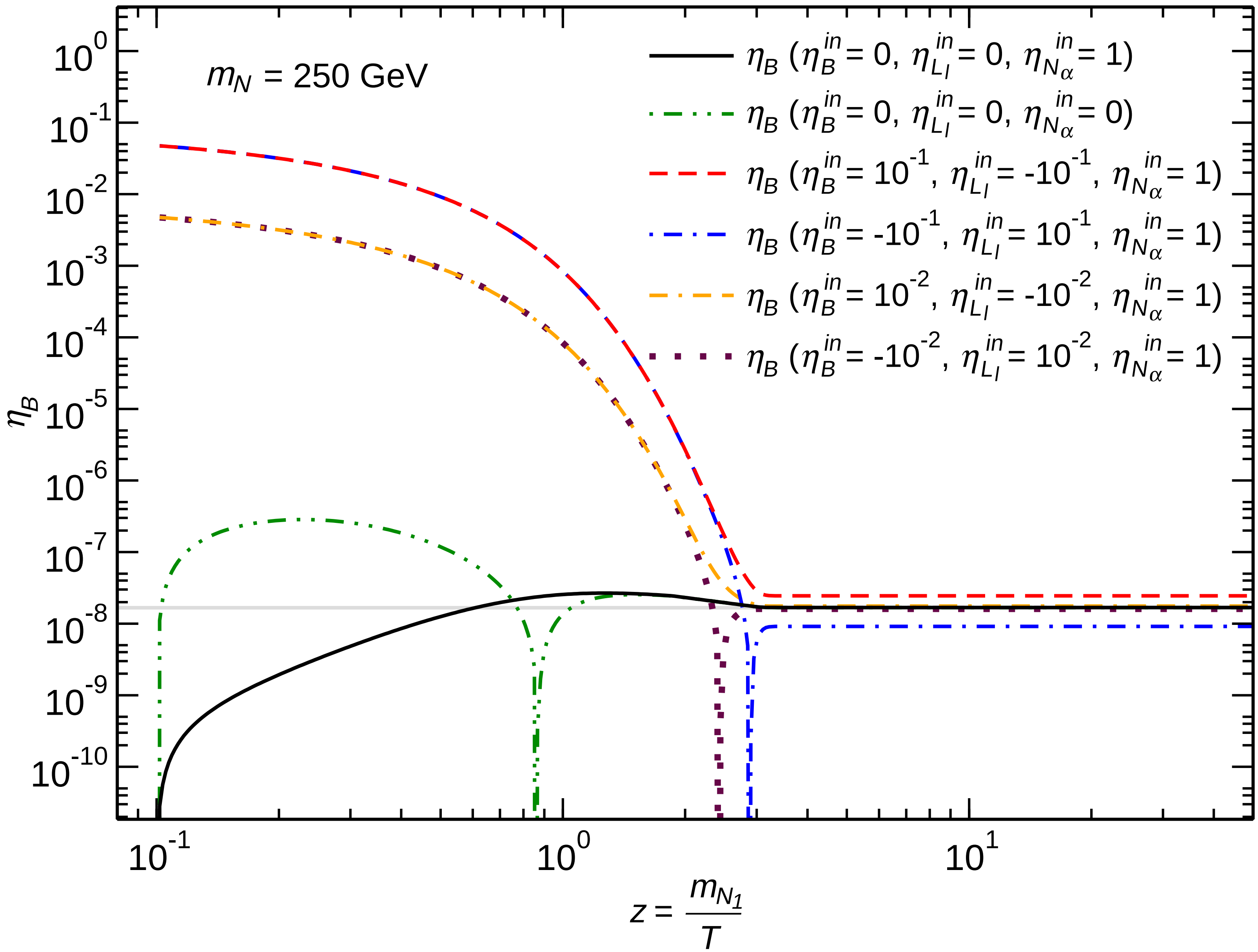
Resonant τ-Genesis

[A.P., T. Underwood, PRD72 (2005) 113001.]



Resonant τ-Genesis

[A.P., T. Underwood, PRD72 (2005) 113001.]



– Flavour Covariant Quantization

[P.S.B. Dev, P. Millington, A.P., D. Teresi, arXiv:1404.1003.]

$U(\mathcal{N}_L) \otimes U(\mathcal{N}_N)$ flavour-invariant Lagrangian:

$$-\mathcal{L}_N \;=\; h_l{}^{\alpha}\,\overline{L}^{l}\,\widetilde{\Phi}\,N_{\mathrm{R},\alpha} \;+\; \overline{N}^{C}_{\mathrm{R},\alpha}\,[M_N]^{\alpha\beta}\,N_{\mathrm{R},\beta} \;+\; \mathrm{H.c.}$$

Under $U(\mathcal{N}_L) \otimes U(\mathcal{N}_N)$ flavour transformations:

$$L_l \;\to\; L'_l \;=\; V_l{}^{m}\,L_m\,, \qquad L^l \;\equiv\; (L_l)^\dagger \;\to\; L'^{\,l} \;=\; V^{l}_{\;m}\,L^m\,,$$

$$N_{\mathrm{R},\alpha} \;\to\; N'_{\mathrm{R},\alpha} \;=\; U_\alpha{}^{\beta}\,N_{\mathrm{R},\beta}\,, \qquad N_{\mathrm{R}}{}^{\alpha} \;\equiv\; (N_{\mathrm{R},\alpha})^\dagger \;\to\; N'^{\,\alpha}_{\mathrm{R}} \;=\; U^{\alpha}{}_{\beta}\,N_{\mathrm{R}}{}^{\beta}\,,$$

$\mathcal{L}_N$ is invariant provided:

$$h_l{}^{\alpha} \;\to\; h'_l{}^{\alpha} \;=\; V_l{}^{m}\,U^{\alpha}{}_{\beta}\,h_m{}^{\beta}\,, \qquad [M_N]^{\alpha\beta} \;\to\; [M'_N]^{\alpha\beta} \;=\; U^{\alpha}{}_{\gamma}\,U^{\beta}{}_{\delta}\,[M_N]^{\gamma\delta}\,.$$

Quantization rules:

$$\big\{b_l(\mathbf{p},s),\, b^m(\mathbf{p}',s')\big\} \;=\; \big\{d^{\dagger,m}(\mathbf{p},s),\, d_l^{\dagger}(\mathbf{p}',s')\big\} \;=\; (2\pi)^3\delta^{(3)}(\mathbf{p}-\mathbf{p}')\,\delta_{ss'}\,\delta_l{}^{m}$$

$$\big\{a_\alpha(\mathbf{k},r),\, a^\beta(\mathbf{k}',r')\big\} \;=\; (2\pi)^3\delta^{(3)}(\mathbf{p}-\mathbf{p}')\,\delta_{rr'}\,\delta_\alpha{}^{\beta}$$

– Flavour Covariant Number Densities and Collision Rates

Flavour-covariant number densities:

$$[n^L_{s_1 s_2}(\mathbf{p})]_l{}^m \equiv \frac{1}{\mathcal{V}} \langle b^m(\mathbf{p}, s_2)\, b_l(\mathbf{p}, s_1)\rangle \ ,$$

$$[\bar{n}^L_{s_1 s_2}(\mathbf{p})]_l{}^m \equiv \frac{1}{\mathcal{V}} \langle d_l^\dagger(\mathbf{p}, s_1)\, d^{\dagger,m}(\mathbf{p}, s_2)\rangle \ ,$$

$$[n^N_{r_1 r_2}(\mathbf{k})]_\alpha{}^\beta \equiv \frac{1}{\mathcal{V}} \langle a^\beta(\mathbf{k}, r_2)\, a_\alpha(\mathbf{k}, r_1)\rangle \ .$$

Flavour-covariant generalization of the collision rates:

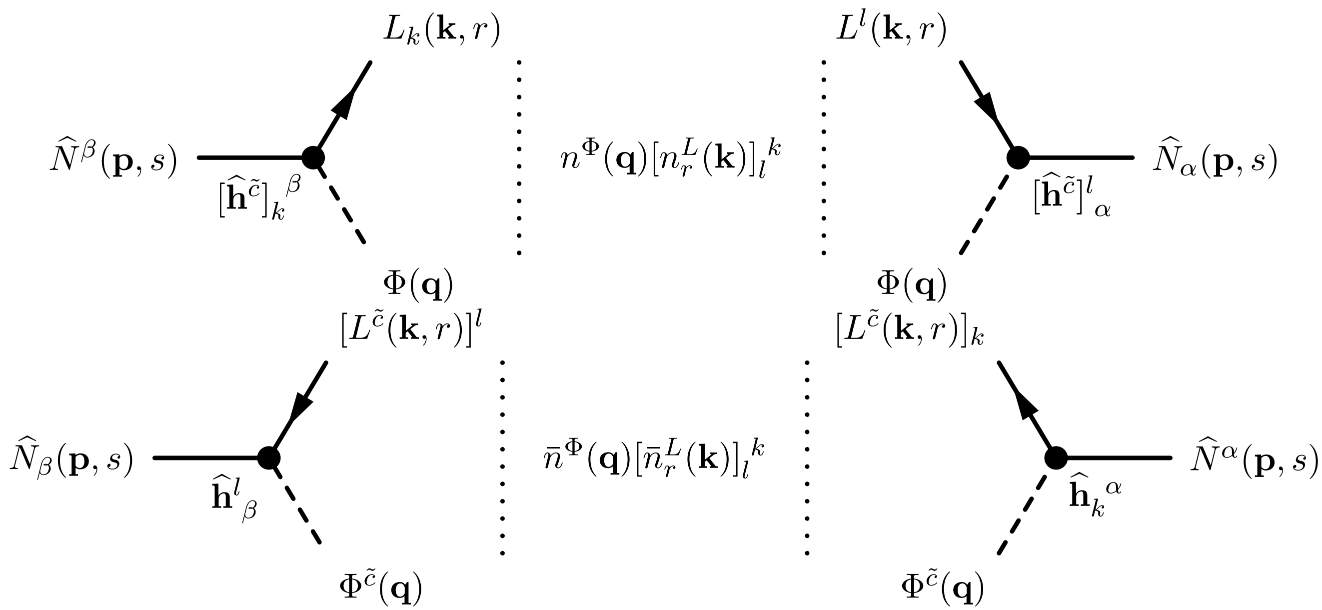
$$[\gamma(N \to L\Phi)]_l{}^m{}_\alpha{}^\beta = \frac{m_N^4}{\pi^2 z}\, \frac{K_1(z)}{16\pi}\, \mathbf{h}^m{}_\alpha\, \mathbf{h}_l{}^\beta \ ,$$

$$[\gamma(N \to L^{\tilde{c}}\Phi^{\tilde{c}})]_l{}^m{}_\alpha{}^\beta = \frac{m_N^4}{\pi^2 z}\, \frac{K_1(z)}{16\pi}\, [\mathbf{h}^{\tilde{c}}]^m{}_\alpha\, [\mathbf{h}^{\tilde{c}}]_l{}^\beta \ ,$$

$$[\gamma^N_{L\Phi}]_l{}^m{}_\alpha{}^\beta \equiv [\gamma(N \to L\Phi)]_l{}^m{}_\alpha{}^\beta + [\gamma(N \to L^{\tilde{c}}\Phi^{\tilde{c}})]_l{}^m{}_\alpha{}^\beta \ ,$$

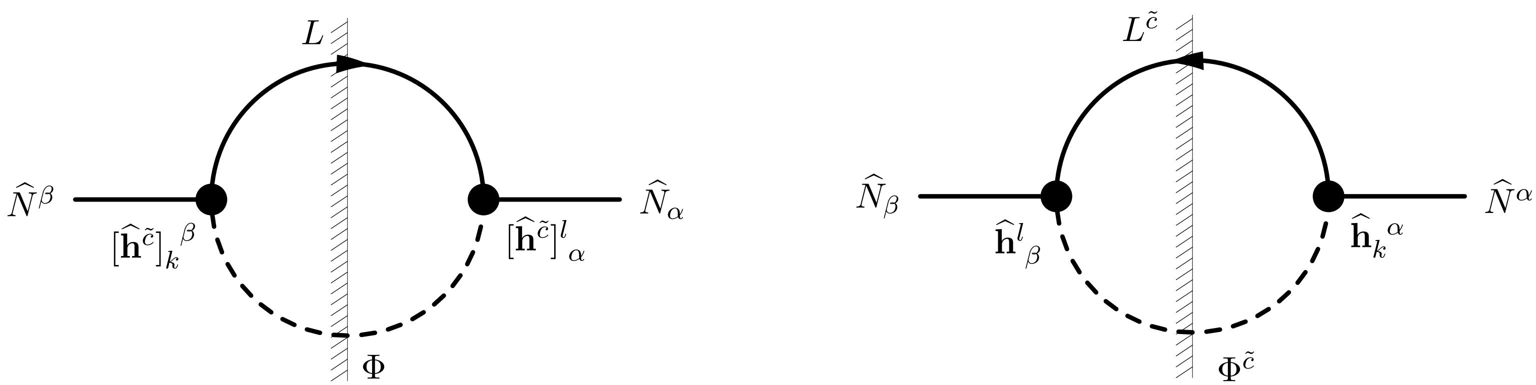
$$[\delta\gamma^N_{L\Phi}]_l{}^m{}_\alpha{}^\beta \equiv [\gamma(N \to L\Phi)]_l{}^m{}_\alpha{}^\beta - [\gamma(N \to L^{\tilde{c}}\Phi^{\tilde{c}})]_l{}^m{}_\alpha{}^\beta \ .$$

– Feynman Diagrammatic Representation



– Closed Time Path (CTP) Representation

[e.g., P. Millington and A.P., PRD88 (2013) 085009.]



– Flavour Covariant Markovian Equations

[P.S.B. Dev, P. Millington, A.P., D. Teresi, arXiv:1404.1003.]

$$\frac{H\,n_\gamma}{z}\,\frac{d[\underline{\eta}^N]_\alpha^{\ \beta}}{dz} = -i\frac{n_\gamma}{2}\Big[\mathcal{E}_N,\,\delta\eta^N\Big]_\alpha^{\ \beta} + [\mathrm{Re}(\gamma^N_{L\Phi})]_\alpha^{\ \beta} - \frac{1}{2\,\eta^N_{\mathrm{eq}}}\Big\{\underline{\eta}^N,\,\mathrm{Re}(\gamma^N_{L\Phi})\Big\}_\alpha^{\ \beta}$$

$$\frac{H\,n_\gamma}{z}\,\frac{d[\delta\eta^N]_\alpha^{\ \beta}}{dz} = -2i\,n_\gamma\Big[\mathcal{E}_N,\,\underline{\eta}^N\Big]_\alpha^{\ \beta} + 2\,i\,[\mathrm{Im}(\delta\gamma^N_{L\Phi})]_\alpha^{\ \beta}$$
$$- \frac{i}{\eta^N_{\mathrm{eq}}}\Big\{\underline{\eta}^N,\,\mathrm{Im}(\delta\gamma^N_{L\Phi})\Big\}_\alpha^{\ \beta} - \frac{1}{2\,\eta^N_{\mathrm{eq}}}\Big\{\delta\eta^N,\,\mathrm{Re}(\gamma^N_{L\Phi})\Big\}_\alpha^{\ \beta}$$

$$\frac{H\,n_\gamma}{z}\,\frac{d\,[\delta\eta^L]_l^{\ m}}{dz} = -[\delta\gamma^N_{L\Phi}]_l^{\ m} + \frac{[\underline{\eta}^N]_\beta^{\ \alpha}}{\widetilde{\eta}^N_{\mathrm{eq}}}\,[\delta\gamma^N_{L\Phi}]_l^{\ m\ \ \beta}_{\ \ \alpha} + \frac{[\delta\eta^N]_\beta^{\ \alpha}}{2\,\widetilde{\eta}^N_{\mathrm{eq}}}\,[\gamma^N_{L\Phi}]_l^{\ m\ \ \beta}_{\ \ \alpha}$$
$$-\frac{1}{3}\Big\{\delta\eta^L,\,\gamma^{L\Phi}_{L^{\tilde{c}}\Phi^{\tilde{c}}} + \gamma^{L\Phi}_{L\Phi}\Big\}_l^{\ m} - \frac{2}{3}\,[\delta\eta^L]_k^{\ n}\,\Big([\gamma^{L\Phi}_{L^{\tilde{c}}\Phi^{\tilde{c}}}]_n^{\ k}{}_l^{\ m} - [\gamma^{L\Phi}_{L\Phi}]_n^{\ k}{}_l^{\ m}\Big)$$
$$-\frac{2}{3}\Big\{\delta\eta^L,\,\gamma_{\mathrm{dec}}\Big\}_l^{\ m} + [\delta\gamma^{\mathrm{back}}_{\mathrm{dec}}]_l^{\ m}$$

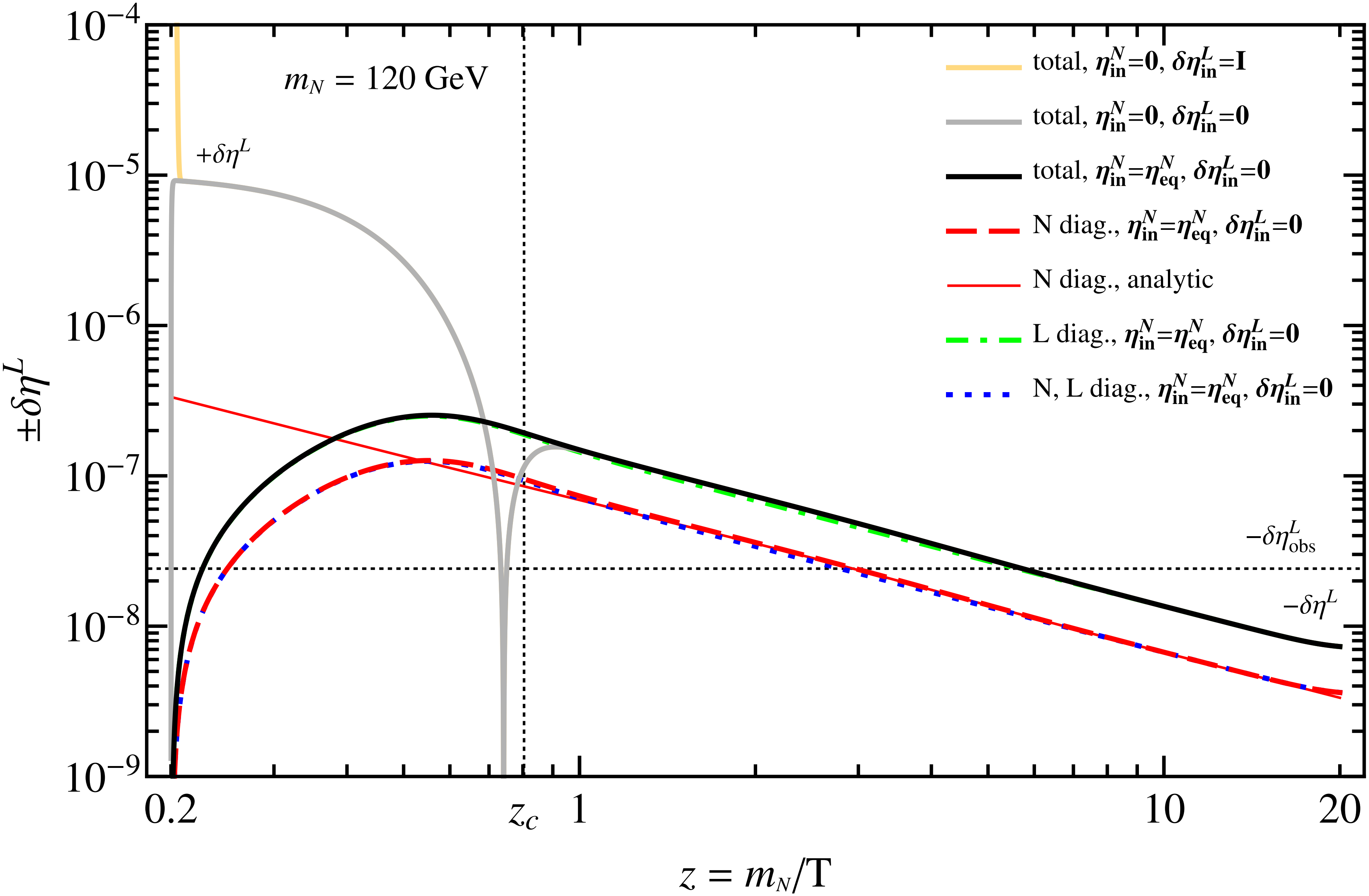
• Numerical Examples

Minimal Resonant Leptogenesis Models: [F. Deppisch, A.P., PRD83 (2011) 076007.]

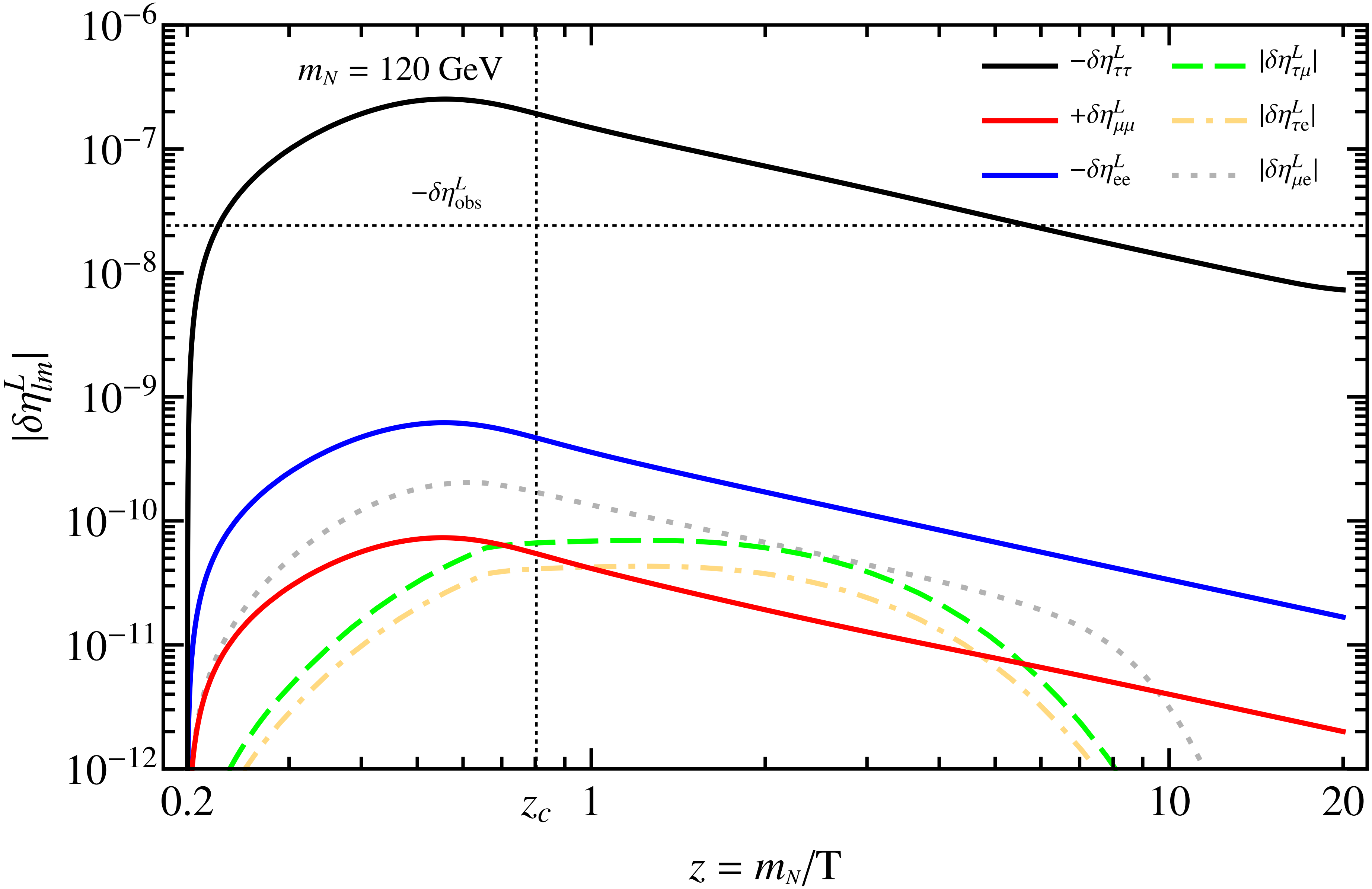
$$\mathbf{m}_M = m_N \mathbf{1}_3 \quad \text{and} \quad \mathbf{m}_D = \frac{v_{\rm SM}}{\sqrt{2}} \begin{pmatrix} \epsilon_e & a\,e^{-i\pi/4} & a\,e^{i\pi/4} \\ \epsilon_\mu & b\,e^{-i\pi/4} & b\,e^{i\pi/4} \\ \epsilon_\tau & \kappa_1\,e^{-i(\pi/4-\gamma_1)} & \kappa_2\,e^{i(\pi/4-\gamma_2)} \end{pmatrix}$$

Parameters	BP1	BP2	BP3
m_N (GeV)	120	400	5000
γ_1	$\pi/4$	$\pi/3$	$3\pi/8$
γ_2	0	0	$\pi/2$
κ_1	4×10^{-5}	2.4×10^{-5}	2×10^{-4}
κ_2	2×10^{-4}	6×10^{-5}	2×10^{-5}
a	$(7.41 - 5.54\,i) \times 10^{-4}$	$(4.93 - 2.32\,i) \times 10^{-3}$	$(4.67 + 4.33\,i) \times 10^{-3}$
b	$(1.19 - 0.89\,i) \times 10^{-3}$	$(8.04 - 3.79\,i) \times 10^{-3}$	$(7.53 + 6.97\,i) \times 10^{-3}$
ϵ_e	3.31×10^{-8}	5.73×10^{-8}	2.14×10^{-7}
ϵ_μ	2.33×10^{-7}	4.3×10^{-7}	1.5×10^{-6}
ϵ_τ	3.5×10^{-7}	6.39×10^{-7}	2.26×10^{-6}

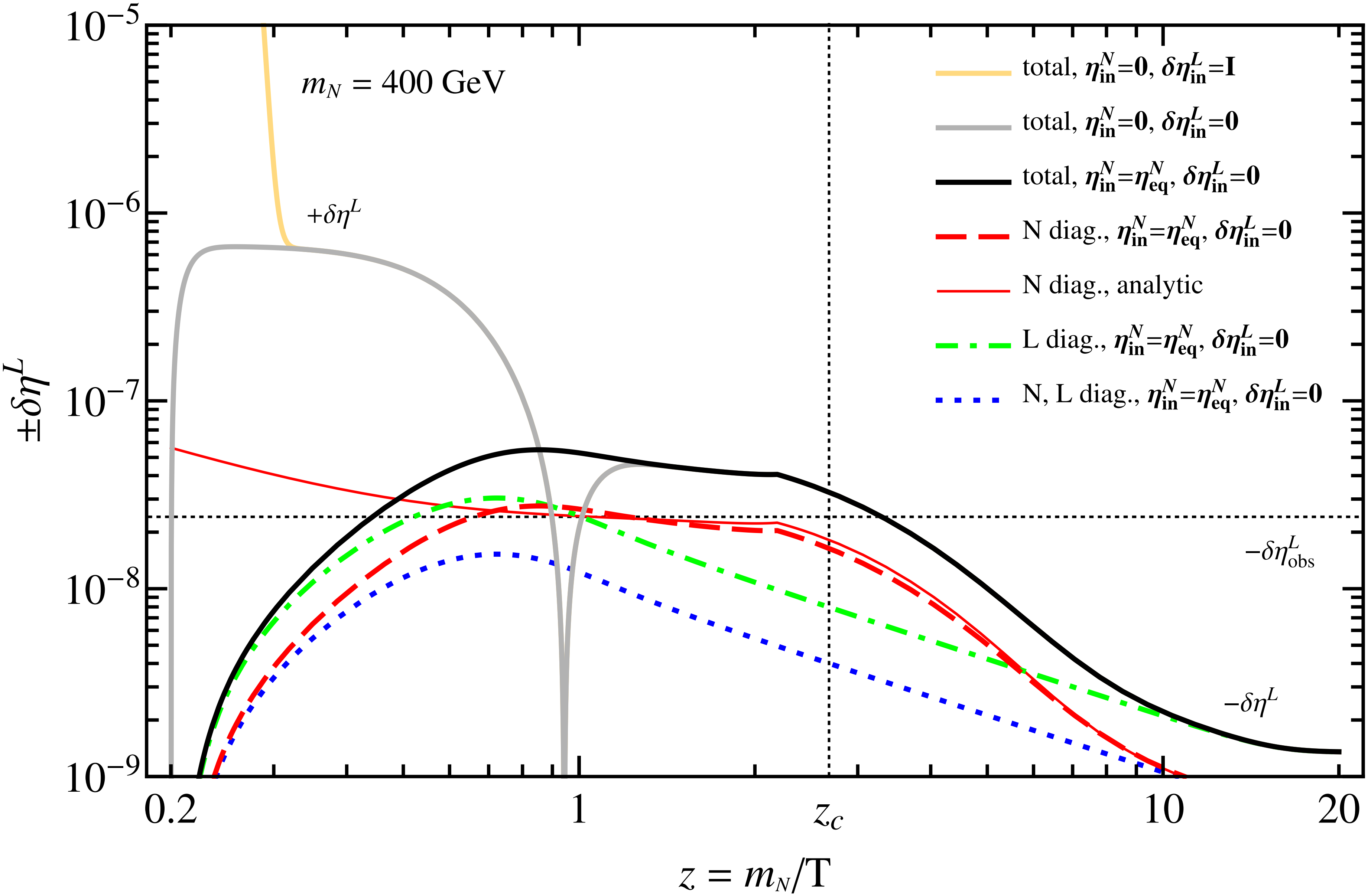
[P.S.B. Dev, P. Millington, A.P., D. Teresi, arXiv:1404.1003.]



[P.S.B. Dev, P. Millington, A.P., D. Teresi, arXiv:1404.1003.]



[P.S.B. Dev, P. Millington, A.P., D. Teresi, arXiv:1404.1003.]



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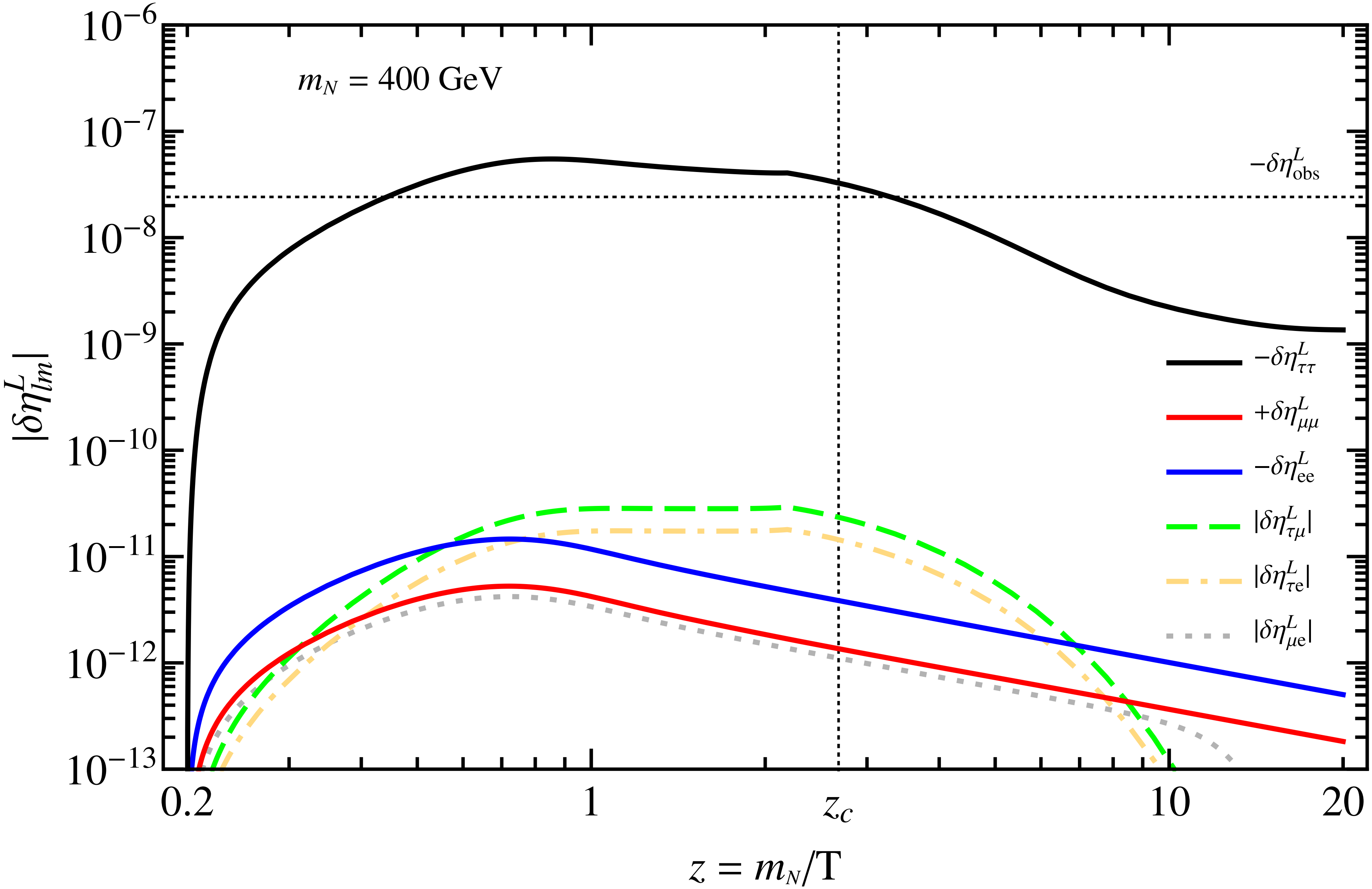
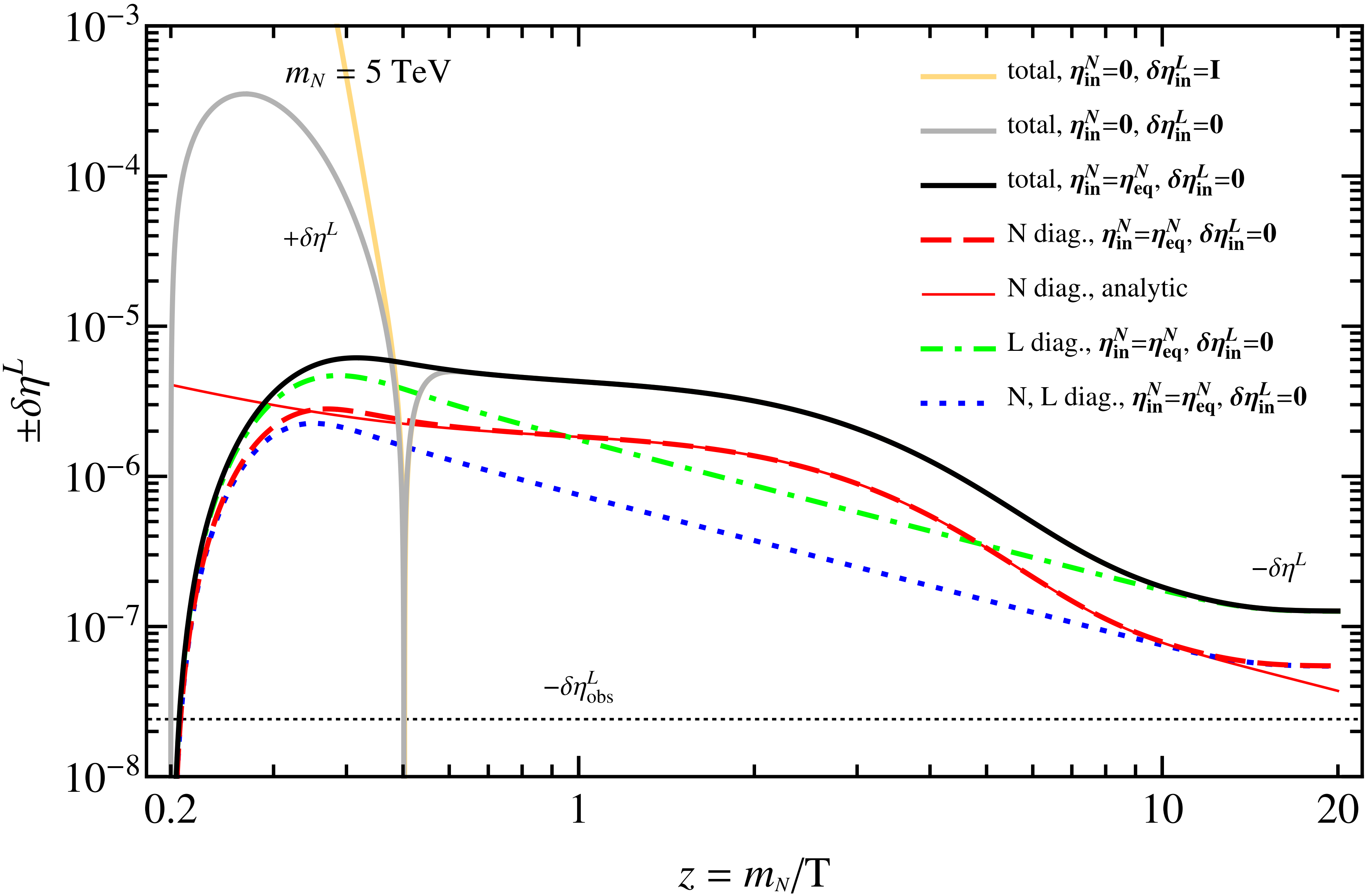
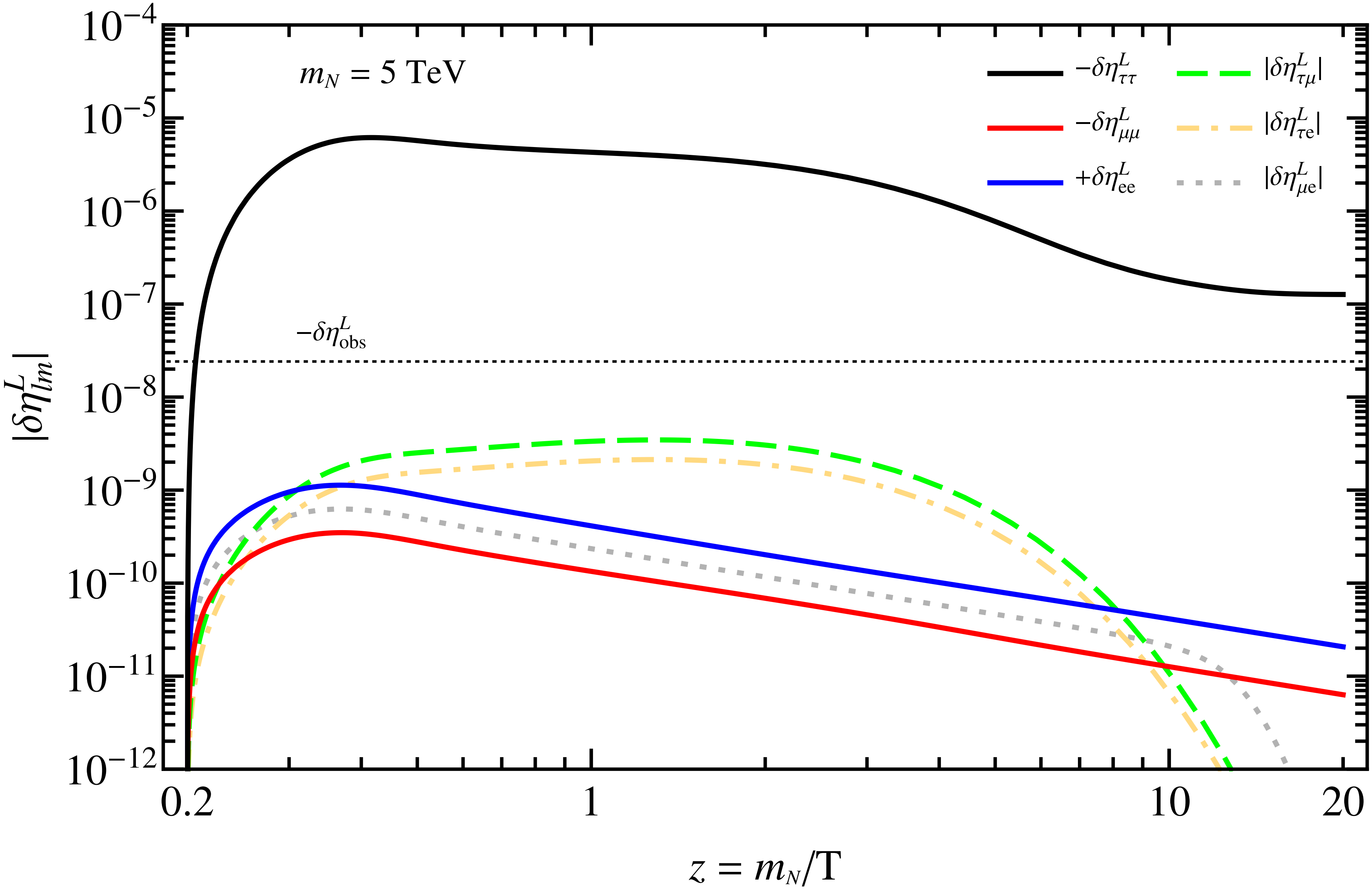


[P.S.B. Dev, P. Millington, A.P., D. Teresi, arXiv:1404.1003.]



[P.S.B. Dev, P. Millington, A.P., D. Teresi, arXiv:1404.1003.]



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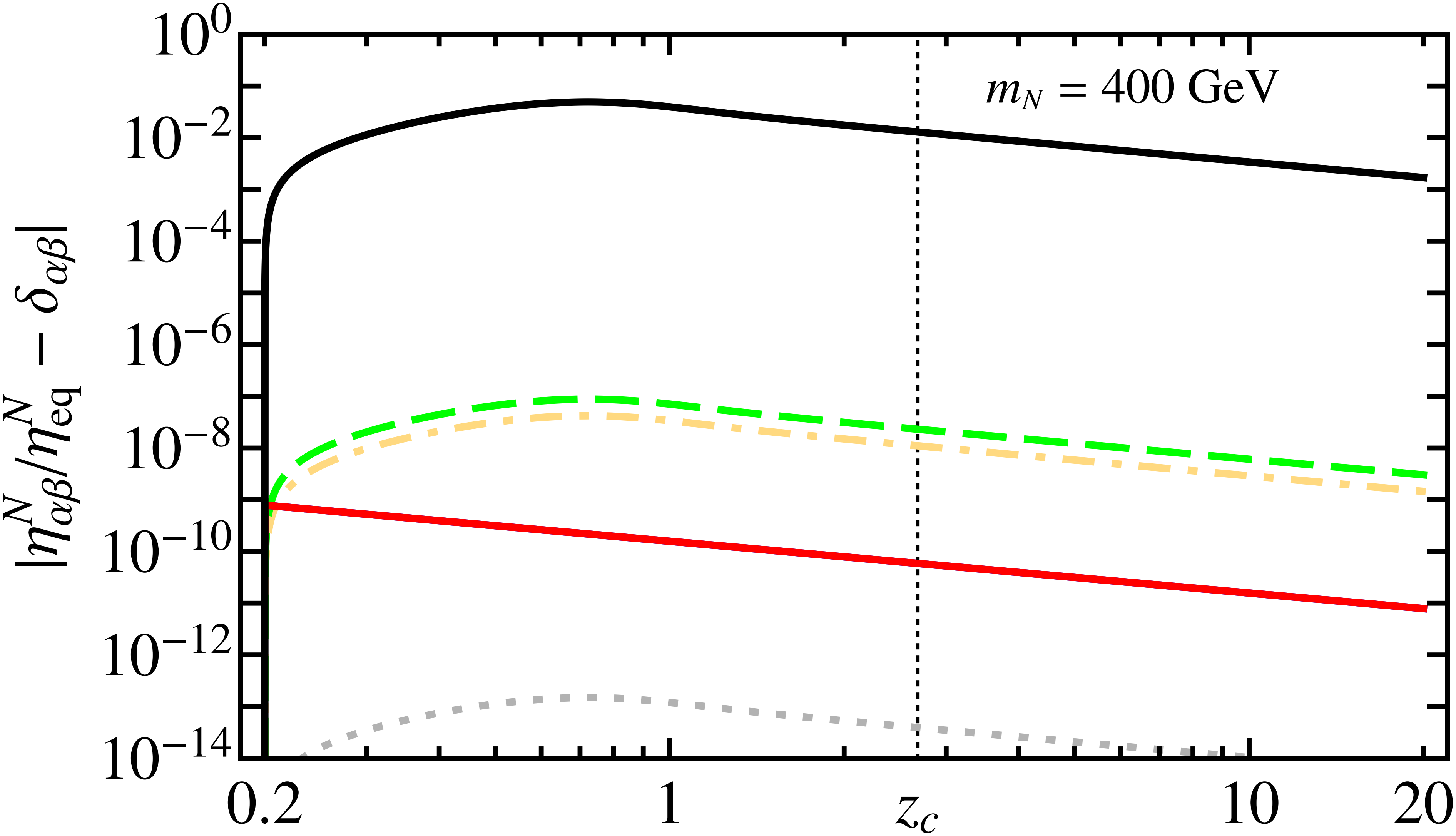

– Phenomenological Implications

[P.S.B. Dev, P. Millington, A.P., D. Teresi, arXiv:1404.1003.]

Low-energy observables	BP1 m_N 120 GeV	BP2 m_N 400 GeV	BP3 m_N 5 TeV	Experimental Limit
BR($\mu \to e\gamma$)	4.5×10^{-15}	1.9×10^{-13}	2.3×10^{-17}	$< 5.7 \times 10^{-13}$
BR($\tau \to \mu\gamma$)	1.2×10^{-17}	1.6×10^{-18}	8.1×10^{-22}	$< 4.4 \times 10^{-8}$
BR($\tau \to e\gamma$)	4.6×10^{-18}	5.9×10^{-19}	3.1×10^{-22}	$< 3.3 \times 10^{-8}$
BR($\mu \to 3e$)	1.5×10^{-16}	9.3×10^{-15}	4.9×10^{-18}	$< 1.0 \times 10^{-12}$
$\mathrm{R}^{\mathrm{Ti}}_{\mu\to e}$	2.4×10^{-14}	2.9×10^{-13}	2.3×10^{-20}	$< 6.1 \times 10^{-13}$
$\mathrm{R}^{\mathrm{Au}}_{\mu\to e}$	3.1×10^{-14}	3.2×10^{-13}	5.0×10^{-18}	$< 7.0 \times 10^{-13}$
$\mathrm{R}^{\mathrm{Pb}}_{\mu\to e}$	2.3×10^{-14}	2.2×10^{-13}	4.3×10^{-18}	$< 4.6 \times 10^{-11}$
$\langle m \rangle (\mathrm{eV})$	3.8×10^{-3}	3.8×10^{-3}	3.8×10^{-3}	$< 0.11 - 0.25$

• Conclusions

- *Fully* Flavour Covariant Formalism for Transport Phenomena, which includes Mixing, Oscillation and Quantum Decoherence of particle species in a thermal bath with *arbitrary* flavour content.

- Flavour Covariance $\Longrightarrow$ *New* Rank-4 Rate Tensors

- Application to Matter–AntiMatter Asymmetry through Resonant Leptogenesis $\Longrightarrow$ Predictions enhanced by 1-order of magnitude.

- $B(\mu \to e\gamma) \sim 10^{-13}$ + successful leptogenesis
  $\Longrightarrow$ ≥ 3 RHNs + Non-trivial Flavour Effects.

- Electroweak-Scale Heavy Majorana Neutrinos can give rise to observable signatures of LNV and CPV at the LHC.

[e.g. P.S.B. Dev, A.P., U.-k. Yang, PRL112 (2014) 081801.]

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