Leptogenesis and CP violation in scatterings with gauge bosons

Juan Diego Racker

In collaboration with C. S. Fong and M. C. Gonzalez-Garcia

Outline of the talk:

- Introduction to leptogenesis.
- The CP asymmetry in top quark scatterings.
- The CP asymmetry in gauge boson scatterings.
- Conclusions.

Introduction

The mystery of the matter-antimatter asymmetry

Observations:

- The Universe is asymmetric: the amount of antimatter is negligible with respect to the amount of matter.
- Baryon density (determined independently from Big Bang Nucleosynthesis and from the CMB anisotropies):

$$\left.\frac{n_B - n_{\bar{B}}}{s}\right|_0 = \left.\frac{n_B}{s}\right|_0 = (8{,}82 \pm 0{,}23) \times 10^{-11} \; .$$

How can the annihilation catastrophe be avoided?

↓

~~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 → *sphalerons* (violate $B+L$ but conserve $B-L$).
- C **violation:** Yes
- CP **Violation:** Not enough
- **Departure from thermal equilibrium:** No → $m_H > 114GeV$ 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:

$$\begin{aligned} \Delta m_{21}^2 \equiv m_{\text{sol}}^2 &= (7{,}9 \pm 0{,}3) \times 10^{-5}\ \text{eV}^2\ , \\ \left|\Delta m_{32}^2\right| \equiv m_{\text{atm}}^2 &= (2{,}6 \pm 0{,}2) \times 10^{-3}\ \text{eV}^2\ , \\ m_i &\lesssim 1\ \text{eV}\ . \end{aligned}$$

Why are neutrino masses so tiny?

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

$$\mathcal{L} = \mathcal{L}_{\mathrm{ME}} + i\overline{N}_\alpha \partial\!\!\!/ N_\alpha - \frac{1}{2} M_\alpha \overline{N}_\alpha N_\alpha - h_{i\alpha}\, \widetilde{H}^\dagger\, \overline{N}_\alpha \ell_i - h^*_{i\alpha} \overline{\ell}_i N_\alpha \widetilde{H}\ ,$$

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

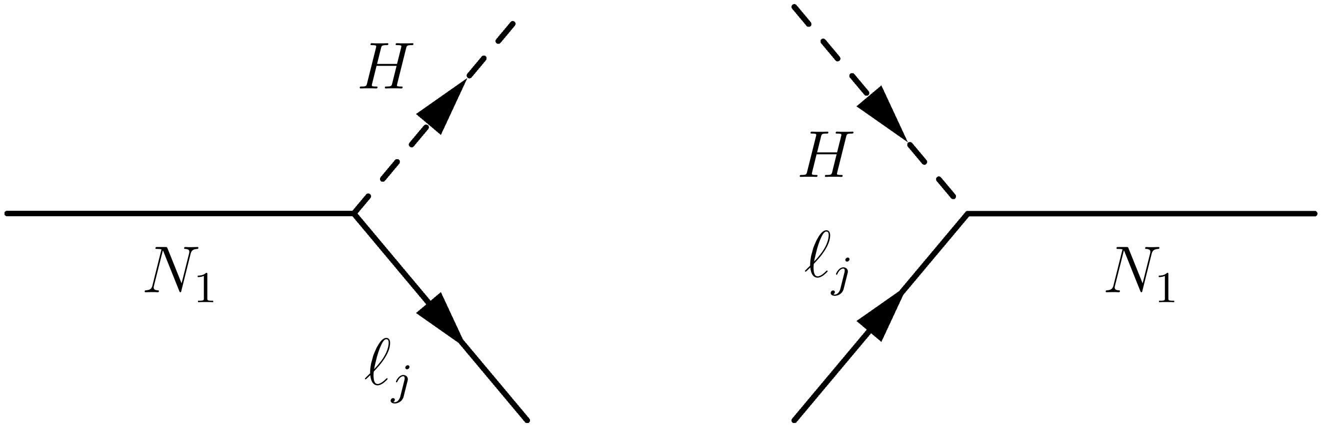
Some heavy Majorana Neutrinos N_α are added to the particle content of the SM. The Lagrangian is that of the SM minimally extended to include the seesaw mechanism.

Baryogenesis through Leptogenesis:

- $\not{B}$: Sphalerons + L violation due to the Majorana nature of the heavy neutrinos.
- $\not{C}$ and $\not{C}\not{P}$: The relevant CP violation comes from the complex Yukawa couplings $h_{i\alpha}$.
- Departure from thermal equilibrium: The source of the equilibrium departure is the expansion of the Universe.
  The N_1 decay out of equilibrium when

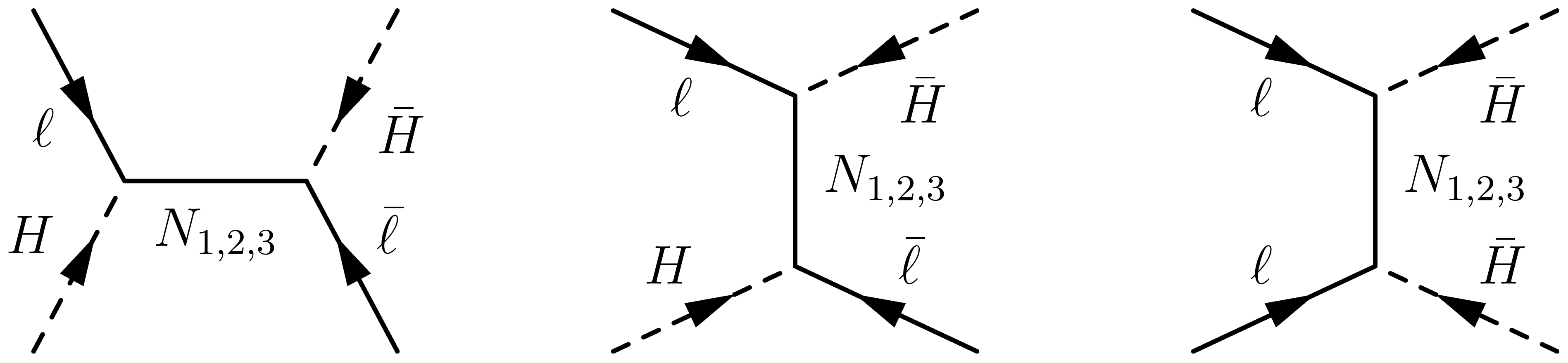
$$\Gamma_{N_1} \lesssim H(T = M_1) \, ,$$

Relevant processes for N_1–Leptogenesis

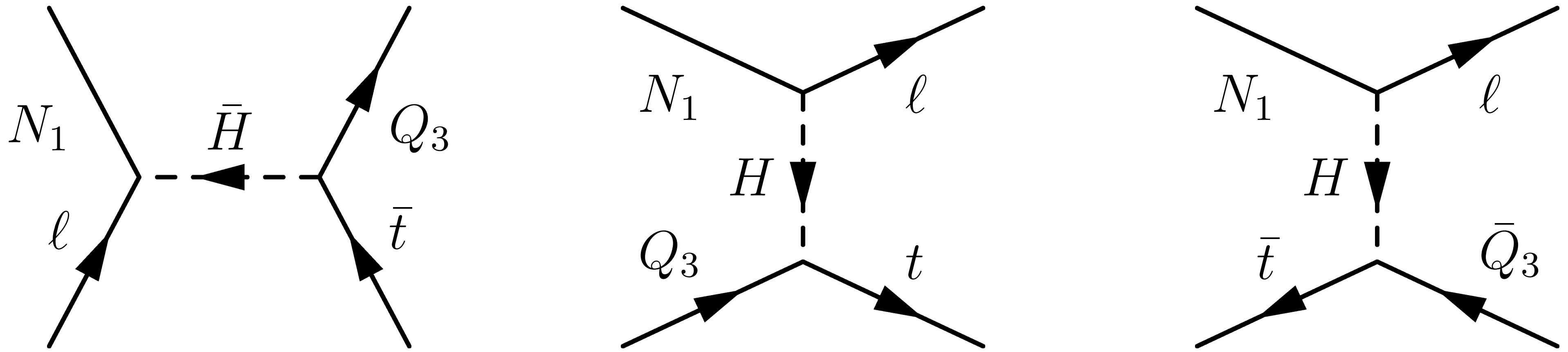


(a) Decay and inverse decay (production) of N_1.

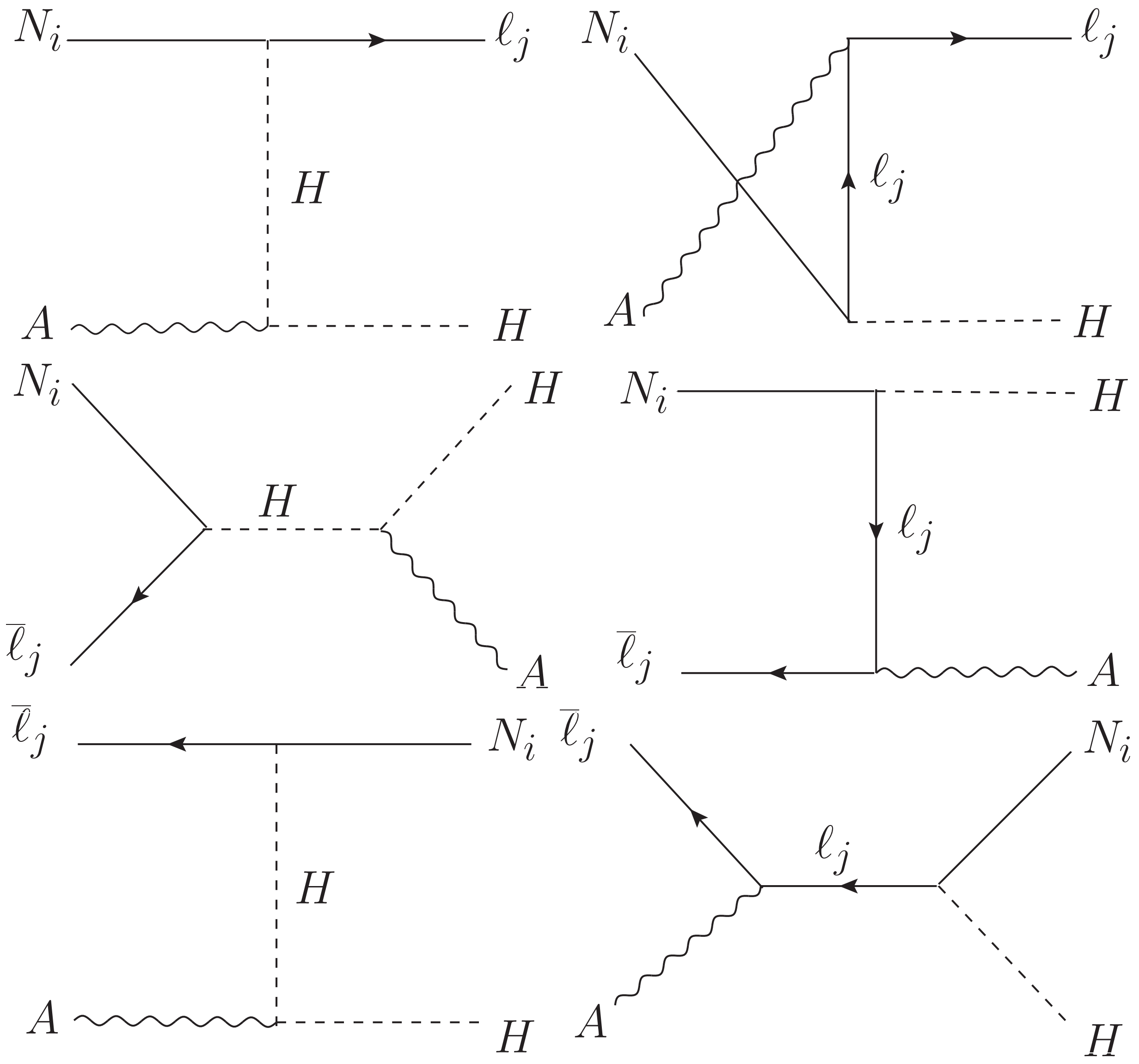
$$\Gamma_{N_1} = \frac{1}{8\pi}(h^\dagger h)_{11} M_1 \ .$$



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



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



Scatterings with gauge bosons

The main parameters

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

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

$$\epsilon = \sum_j \epsilon_j = \sum_j \frac{\gamma(N_1 \to H\ell_j) - \gamma(N_1 \to \bar{H}\bar{\ell}_j)}{\sum_k \gamma(N_1 \to H\ell_k) + \gamma(N_1 \to \bar{H}\bar{\ell}_k)}$$

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

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

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).

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

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

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

The role of $\tilde{m}_1$

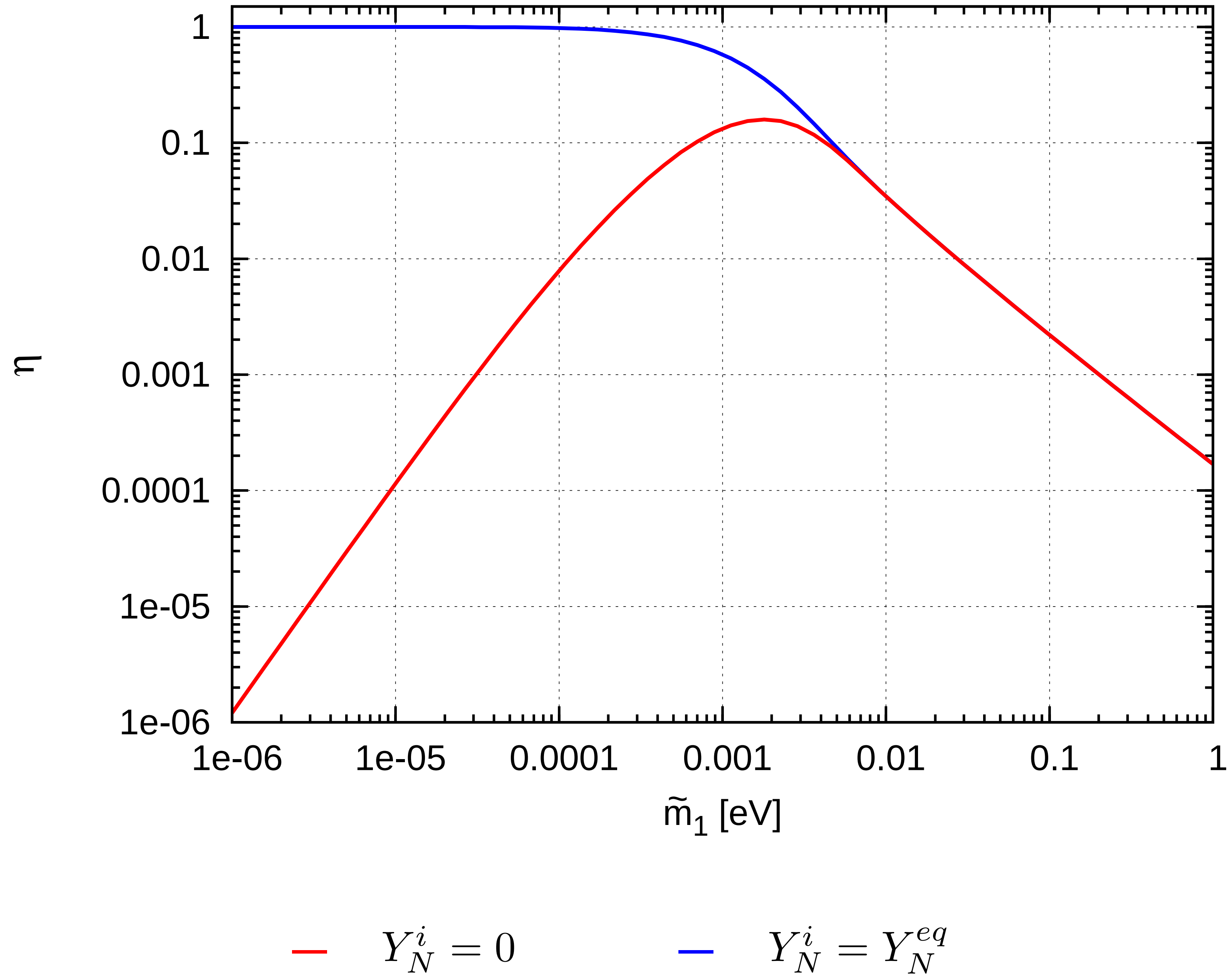
It determines the amount of departure from eq. and the intensity of the washouts.

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 .

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


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
$\tilde{m}_1$ [eV]
$Y_N^i = 0$
$Y_N^i = Y_N^{eq}$

Connection with low energy observables

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

- $|\epsilon| \leq \epsilon^{\text{DI}}_{\text{max}} = \frac{3}{16\pi}\frac{M_1}{v^2}(m_3 - m_1)$ (see also [Hambye et al. 2003])
  $\eta \leq 1 \implies M_1 \gtrsim 10^9$ GeV (conflict with some SUSY scenarios)
- $\tilde{m}_1 \geq m_1,$ neglecting phases $\tilde{m}_1 \sim \sum_i m_i,$
  note that $\sqrt{m^2_{\text{atm}}} \simeq 0{,}05$ eV $\sim m_*!$
- $\boxed{m_1 \lesssim 0{,}15\ \text{eV}}$ (open issue)

The simplest model 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]
- Low energy leptogenesis (resonant leptogenesis, models with small L violation, ...)

CP violation

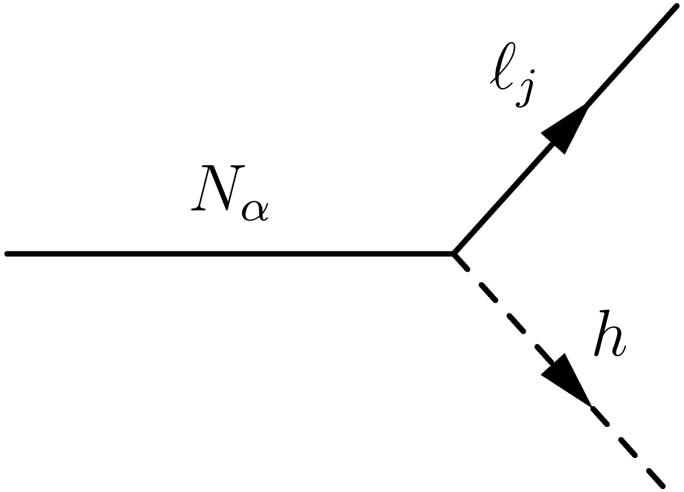
$$A = \lambda_0 I_0 + \lambda_1 I_1$$

$$\epsilon_A = \frac{|\lambda_0 I_0 + \lambda_1 I_1|^2 - |\lambda_0^* I_0 + \lambda_1^* I_1|^2}{|\lambda_0 I_0 + \lambda_1 I_1|^2 + |\lambda_0^* I_0 + \lambda_1^* I_1|^2} \simeq -2 \frac{\text{Im}[\lambda_0^* \lambda_1]}{|\lambda_0|^2} \frac{\text{Im}[I_0^* I_1]}{|I_0|^2}$$

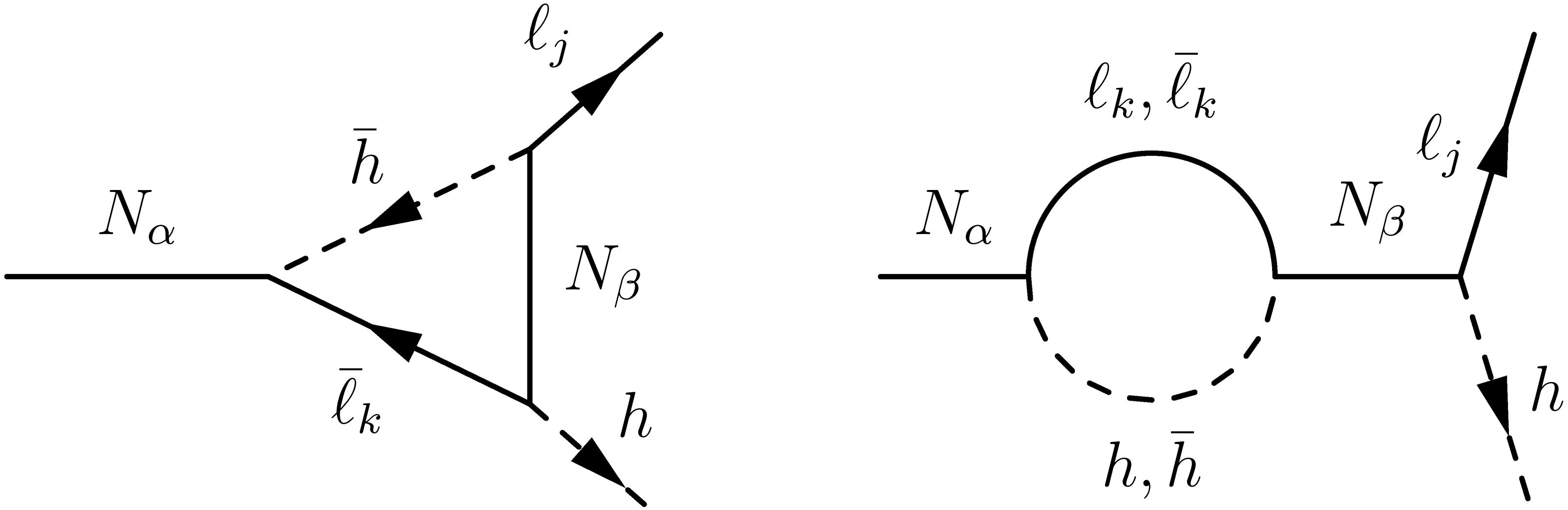
There must be kinematic and coupling phases.

$$\text{Im}[I_0^* I_1] = \frac{1}{2i} I_0 \sum_{\text{cuttings}} I_1$$

CP violation in decays



(a) Tree



(b) Vertex

(c) Wave

$$\epsilon_{\ell_j}^{N_\alpha} = \epsilon_{\ell_j}^{N_\alpha}(\text{vertex}) + \epsilon_{\ell_j}^{N_\alpha}(\text{wave})$$

$$\epsilon_{\ell_j}^{N_\alpha}(\text{vertex}) = \frac{1}{8\pi}\sum_\beta f(y_\beta)\frac{\mathrm{Im}\left[h_{j\beta}^* h_{j\alpha}(h^\dagger h)_{\beta\alpha}\right]}{(h^\dagger h)_{\alpha\alpha}}$$

$$\epsilon_{\ell_j}^{N_\alpha}(\text{wave}) = -\frac{1}{8\pi}\sum_{\beta\neq\alpha}\frac{M_\alpha}{M_\beta^2 - M_\alpha^2}\frac{\mathrm{Im}\left[\left(M_\beta(h^\dagger h)_{\beta\alpha} + M_\alpha(h^\dagger h)_{\alpha\beta}\right) h_{j\beta}^* h_{j\alpha}\right]}{(h^\dagger h)_{\alpha\alpha}}$$

with $y_\beta \equiv M_\beta^2/M_\alpha^2$ and $f(x) = \sqrt{x}(1-(1+x)\ln[(1+x)/x])$.

[Covi, Roulet, Vissani 1996]

CP violation in scatterings

CP is violated not only in decays and inverse decays, but also in scatterings involving the heavy neutrinos.

How much is CP violated in scatterings?

Which are the effects?

The CP asymmetry in top quark scatterings

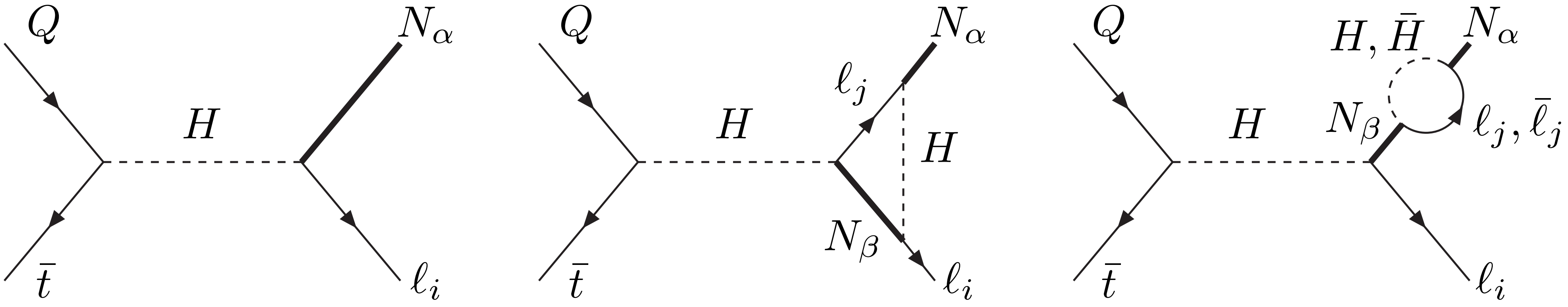
$Q_3\bar{t} \to N\ell$, $Q_3 N \to t\ell$ and $N\bar{t} \to \bar{Q}_3\ell$.

Approximation for the case $M_{\beta\neq 1} \gg M_1$ (*factorized expression*):

$$\frac{\Delta\gamma(Q\bar{t} \to N\ell_i)}{\gamma(Q\bar{t} \to N\ell_i)} \simeq \frac{\Delta\gamma(N \to \ell_i h)}{\gamma(N \to \ell_i h)} \qquad (Q \equiv Q_3)\ .$$

[Pilaftsis & Underwood 2004, 2005], [Abada et al 2006]

Exact (one loop) calculation:



$$\left[|\mathcal{M}(Q\bar{t} \to N_\alpha \ell_i)|^2 - |\bar{\mathcal{M}}|^2\right] (\text{vertex}) = -\frac{6}{\pi}\frac{p_1 \cdot p_2\, p_1' \cdot p_2'}{s^2}|h_t|^2 \times$$

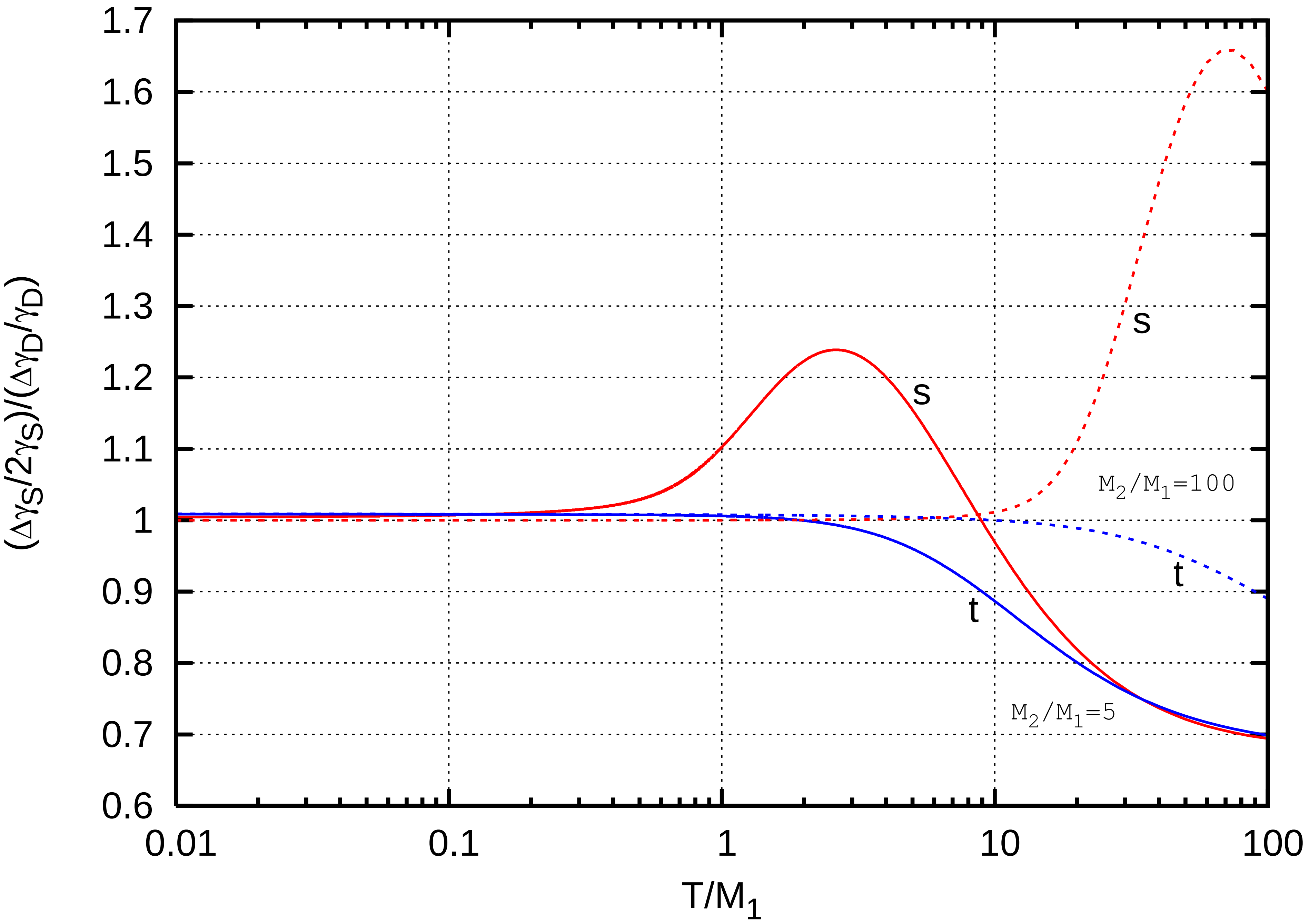
$$\sum_\beta \mathrm{Im}[h_{i\alpha} h^*_{i\beta}(h^\dagger h)_{\beta\alpha}] \frac{M_\alpha M_\beta}{s - M_\alpha^2} \left\{ \left[1 - \frac{M_\alpha^2 + M_\beta^2 - s}{M_\alpha^2 - s} \ln \left(\frac{|M_\alpha^2 + M_\beta^2 - s|}{M_\beta^2} \right) \right] - \right.$$

$$\left. \theta(s - M_\beta^2) \left[\frac{s - M_\beta^2}{s} + \frac{M_\alpha^2 + M_\beta^2 - s}{s - M_\alpha^2} \ln \left(\frac{s|M_\alpha^2 + M_\beta^2 - s|}{M_\beta^2 M_\alpha^2} \right) \right] \right\} .$$

For $N_\alpha \bar{t} \to \bar{Q} \ell_i$ and $N_\alpha Q \to t \ell_i$ replace s by t (*crossing symmetry*).

$$\frac{\Delta\gamma(Q\bar{t} \to N_\alpha \ell_i)\ (\text{wave})}{\sum_j [\gamma(Q\bar{t} \to N_\alpha \ell_j) + \gamma(\bar{Q}t \to N_\alpha \bar{\ell}_j)]} = \frac{\Delta\gamma(N_\alpha \to \ell_i h)\ (\text{wave})}{\sum_j [\gamma(N_\alpha \to \ell_j h) + \gamma(N_\alpha \to \bar{\ell}_j \bar{h})]} .$$

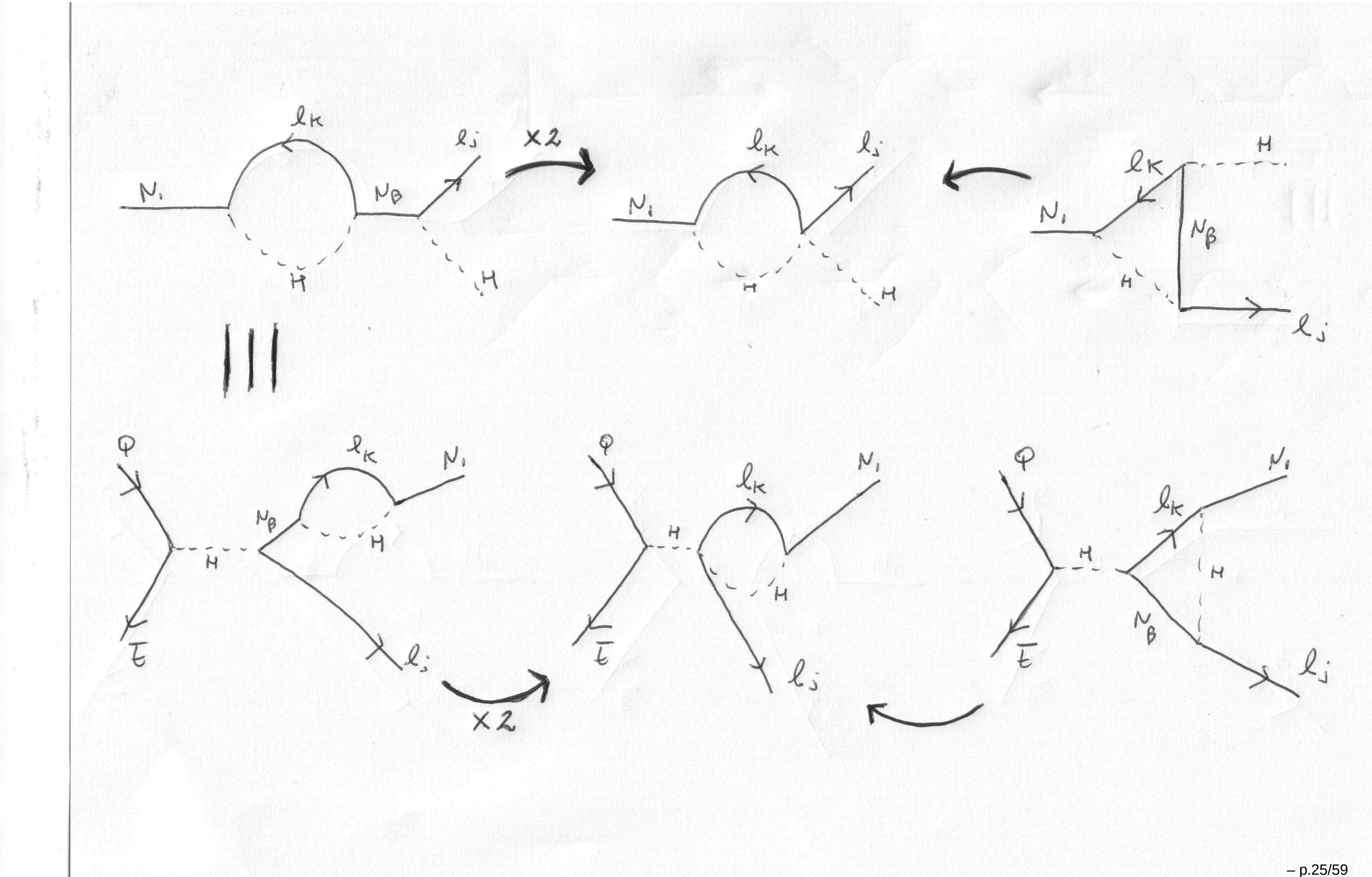
[E. Nardi, J. R., and E. Roulet 2007]



$(\Delta\gamma_S/2\gamma_S)/(\Delta\gamma_D/\gamma_D)$
1.7
1.6
1.5
1.4
1.3
1.2
1.1
1
0.9
0.8
0.7
0.6
0.01
0.1
1
10
100
T/M_1
s
s
t
t
$M_2/M_1=100$
$M_2/M_1=5$

Hierarchical limit $(M_\beta \gg T, M_1)$ → effective field theory approach

[Abada, Davidson, Ibarra, Josse-Michaux, Losada, Riotto 2006].



The effects

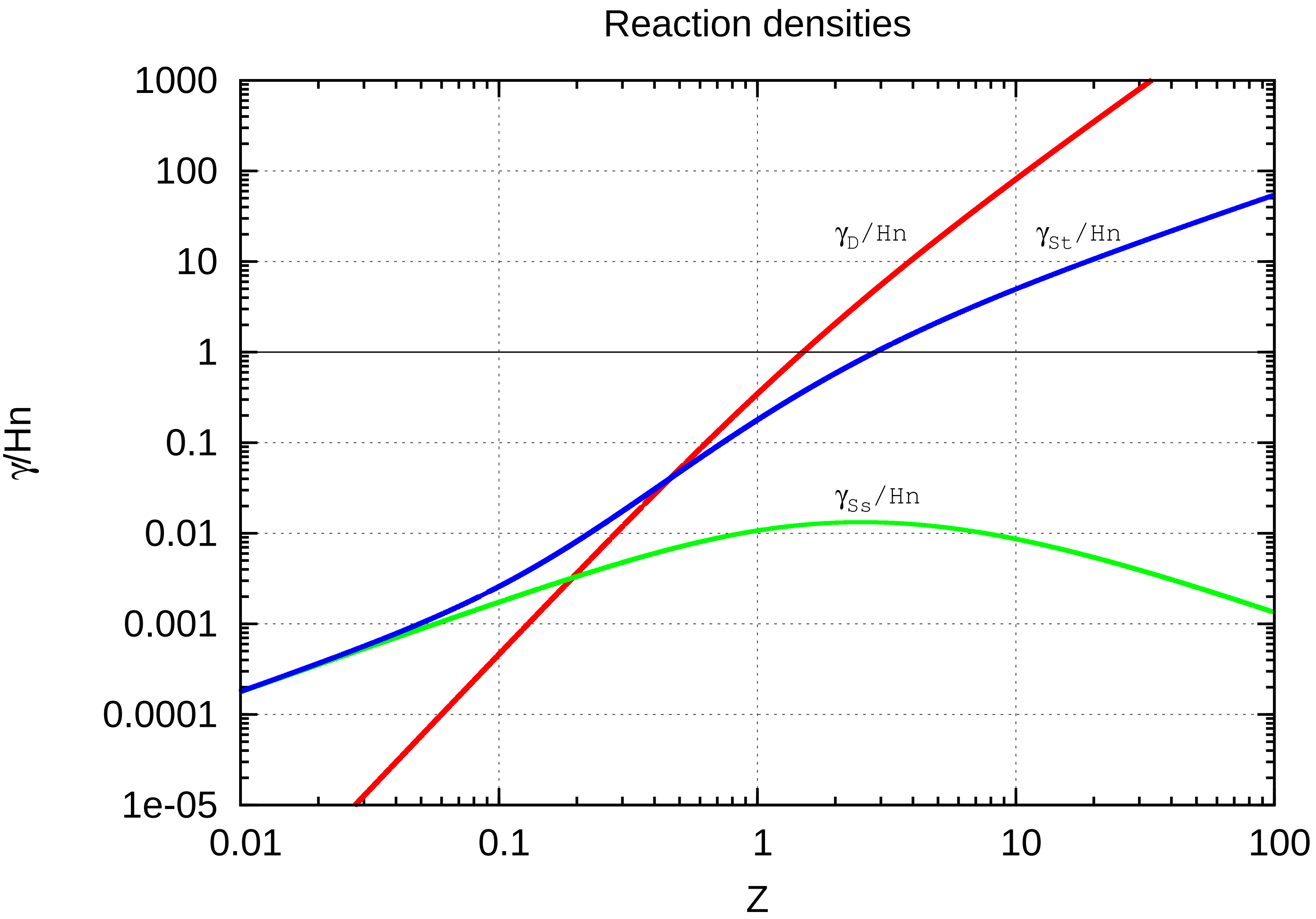
$$\frac{\mathrm{d}Y_N}{\mathrm{d}z} = -\frac{1}{zHs}\left(\frac{Y_N}{Y_N^{eq}} - 1\right)\left[\gamma_D + \sum_{\text{scatt}} \gamma(i \to f)\right]$$

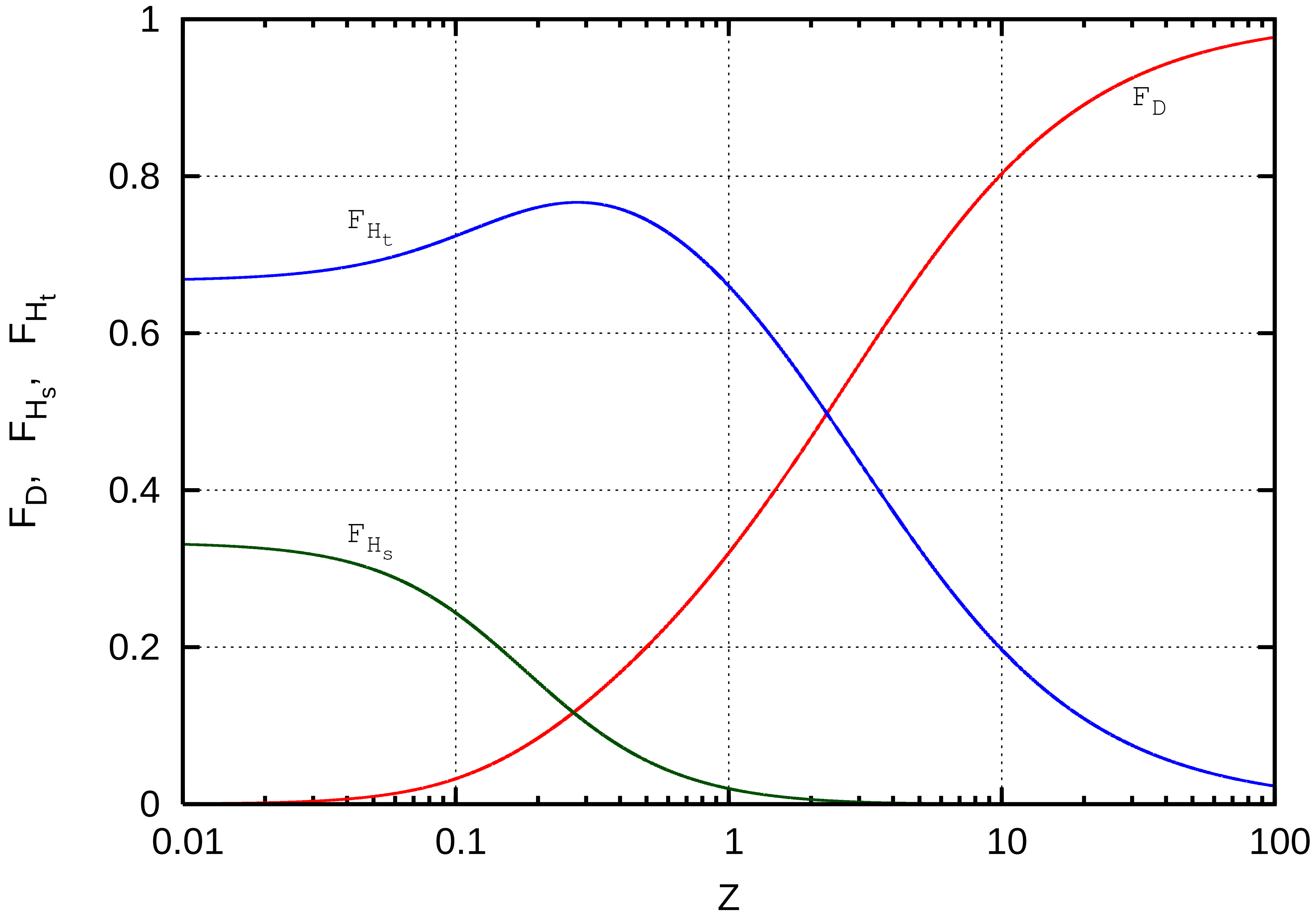
$$\frac{\mathrm{d}Y_L}{\mathrm{d}z} = \frac{1}{zHs}\left\{\left(\frac{Y_N}{Y_N^{eq}} - 1\right)\left[\Delta\gamma_D + \sum_{\text{scatt}} \Delta\gamma(i \to f)\right] - \text{wo}(\gamma_D, \gamma_{\text{scatt}})\right\}$$

with $\Delta\gamma(i \to f) \equiv \gamma(i \to f) - \gamma(\bar{i} \to \bar{f})$.

The relative effects between scatterings and decays depend on

$$\frac{\gamma_{\text{scatt}}}{\gamma_D}, \qquad \frac{\Delta\gamma_{\text{scatt}}}{\Delta\gamma_D} = (0{,}5 - 2) \times \frac{\gamma_{\text{scatt}}}{\gamma_D}$$

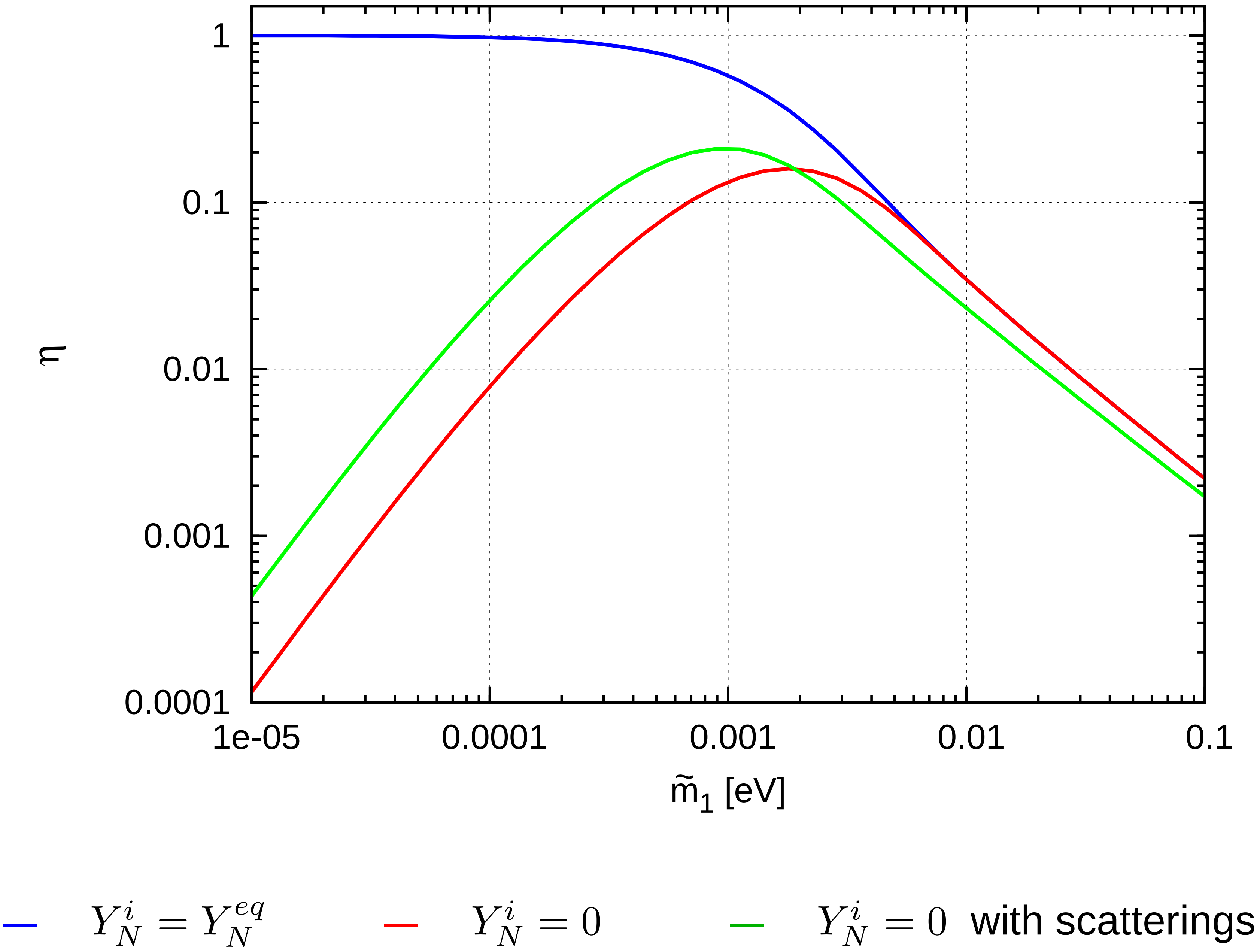

Reaction densities
γ/Hn
Z
1000
100
10
1
0.1
0.01
0.001
0.0001
1e-05
0.01
0.1
1
10
100
γ_D/Hn
γ_{St}/Hn
γ_{Ss}/Hn


1
0.8
0.6
0.4
0.2
0
0.01
0.1
1
10
100
Z
F_D, F_{H_s}, F_{H_t}
F_{H_t}
F_{H_s}
F_D

The scatterings are important in models for leptogenesis that are sensible to the high temperature regime:

- Leptogenesis in the weak washout regime
- Low energy models in which the sphalerons freeze out before the N have decayed

  $\big[$Pilaftsis 2008$\big]$, $\big[$M. C. Gonzalez-Garcia, J. R., N. Rius 2009$\big]$


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

CP violation in scatterings with gauge bosons

$$N_i A \to \ell_j H \quad N_i \bar{\ell}_j \to H A \quad \bar{\ell}_j A \to N_i H$$

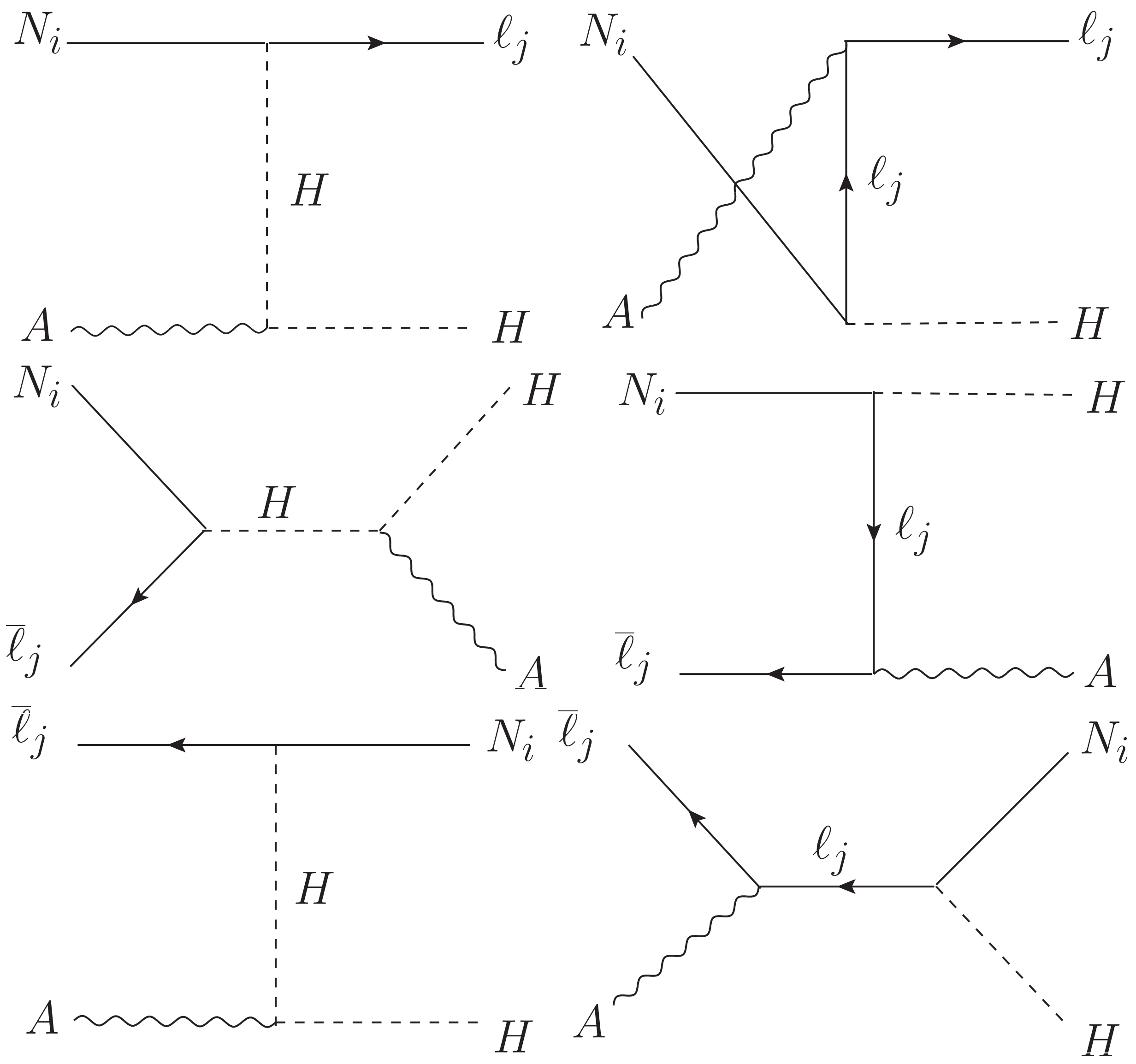
A can be a SU(2)$_L$ or U(1)$_\mathrm{Y}$ gauge boson.

There are new type of contributions to the CP asymmetries:

$$\epsilon_{34}^{12} = \left[\epsilon_{34}^{12\,(w)}\right] + \left[\epsilon_{34}^{12\,(v1)} + \epsilon_{34}^{12\,(b)}\right] + \left[\epsilon_{34}^{12\,(v2)}\right] + \left[\Delta\epsilon_{N_i H}^{\bar{\ell}_j A}\right]$$

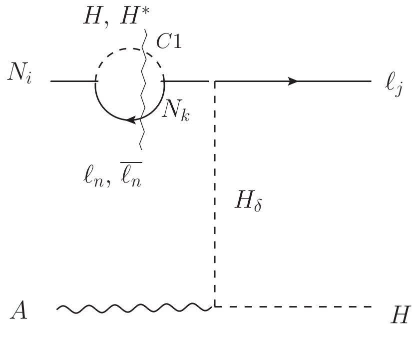
with $\epsilon_{34}^{12} \equiv \dfrac{\gamma(12 \to 34) - \gamma(\bar{1}\bar{2} \to \bar{3}\bar{4})}{\gamma(12 \to 34) + \gamma(\bar{1}\bar{2} \to \bar{3}\bar{4})}$

- The quantities inside each bracket are gauge invariant.
- The $v2$–vertices are not null only for U(1)$_\mathrm{Y}$ gauge bosons.
- There are new contributions to the L– conserving CP asymmetry.

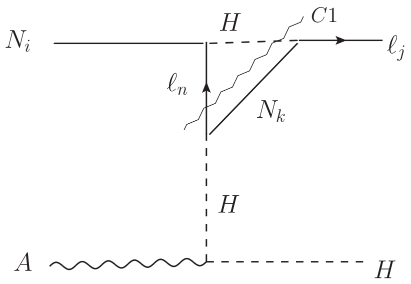


Scatterings with gauge bosons

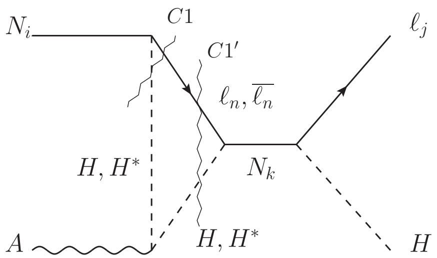
$NA \to \ell H$



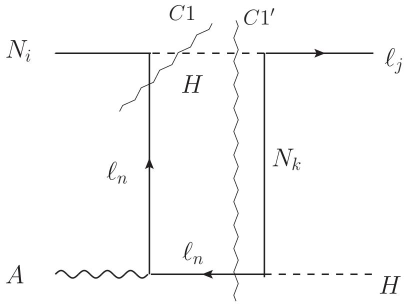
1.(a)



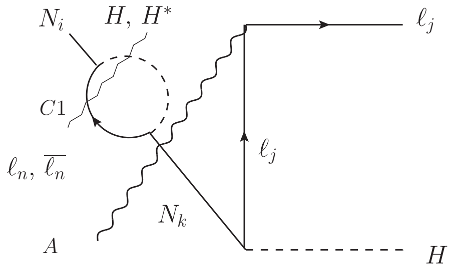
1.(c)



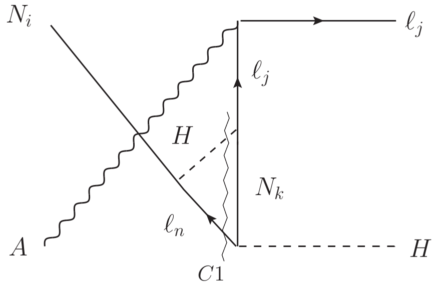
1.(e)



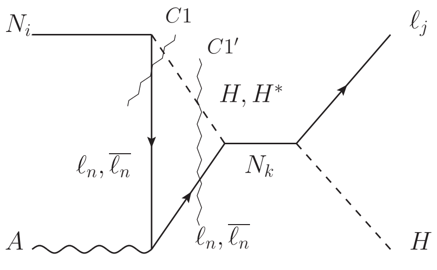
1.(g)



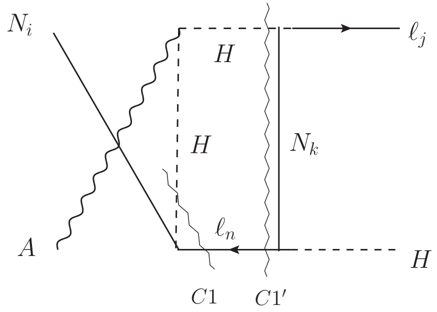
1.(b)



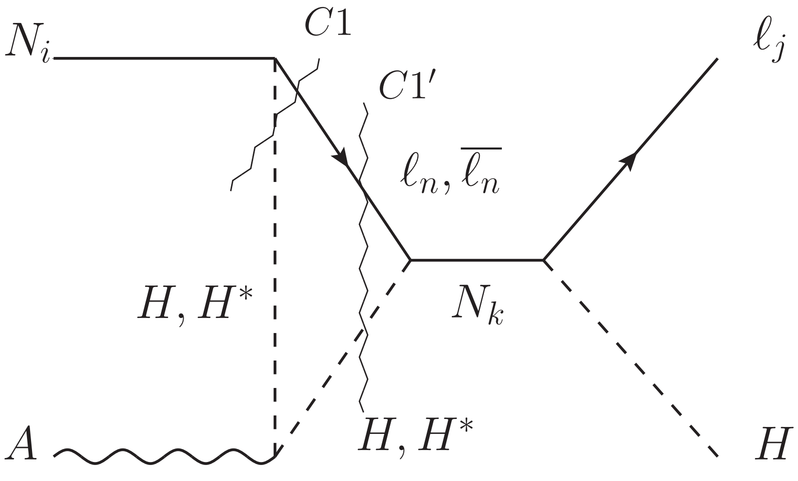
1.(d)



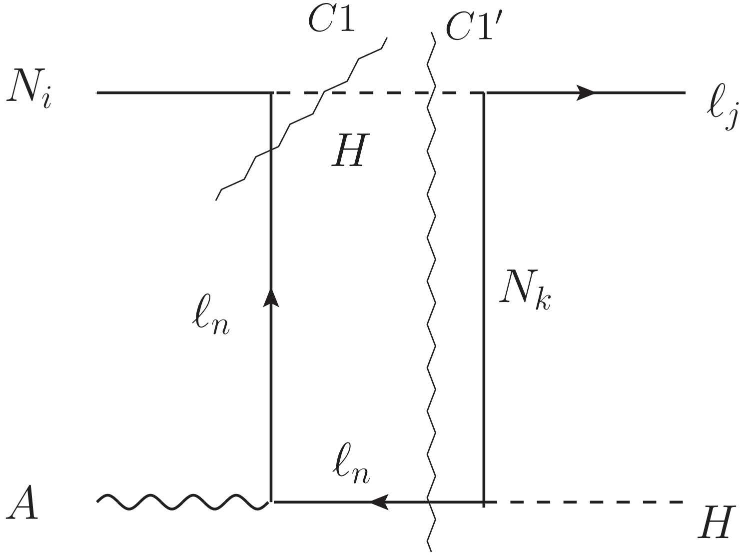
1.(f)



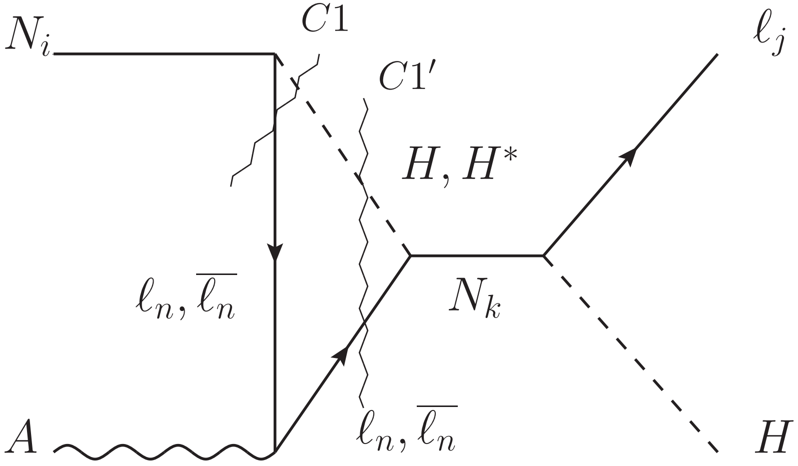
1.(h)


N_i
$C1$
$C1'$
ℓ_j
$\ell_n, \overline{\ell_n}$
H, H^*
N_k
A
H, H^*
H

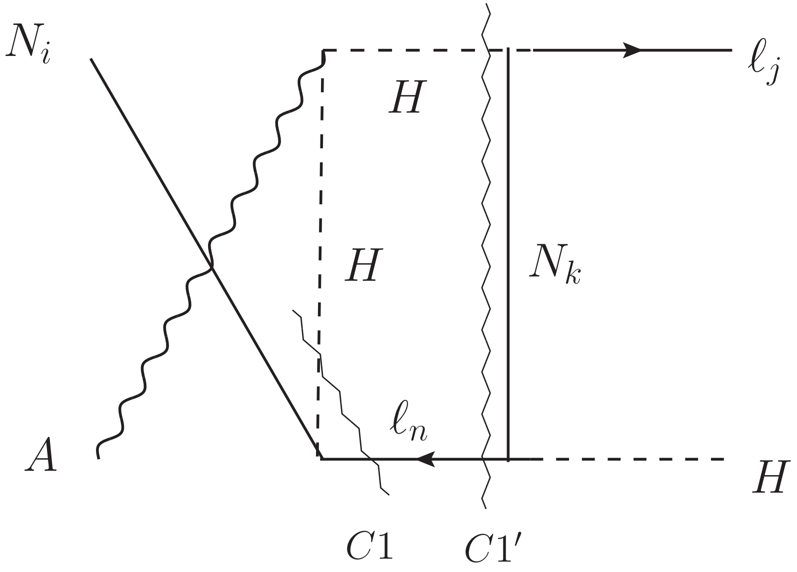
1.(e)


$C1$
$C1'$
N_i
ℓ_j
H
N_k
ℓ_n
ℓ_n
A
H

1.(g)

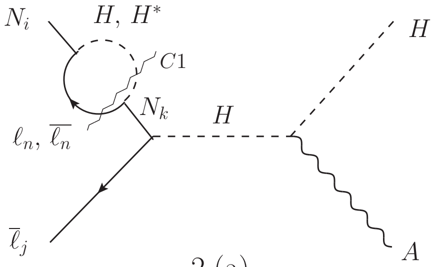

N_i
$C1$
$C1'$
ℓ_j
H, H^*
$\ell_n, \overline{\ell_n}$
N_k
A
$\ell_n, \overline{\ell_n}$
H

1.(f)

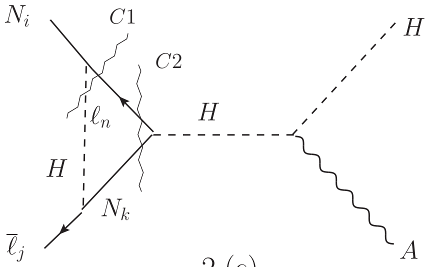

N_i
ℓ_j
H
H
N_k
ℓ_n
A
H
$C1$
$C1'$

1.(h)

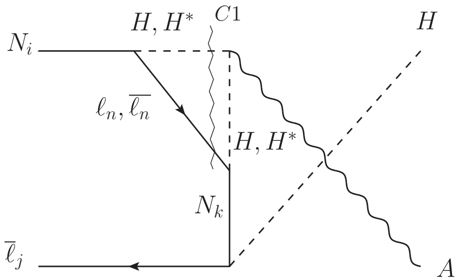
$N\bar{\ell} \to H A$



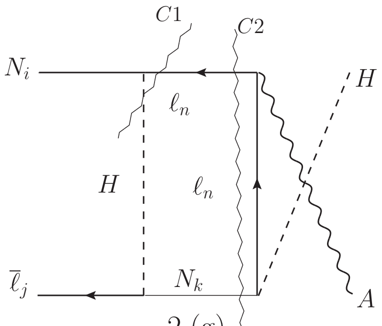
2.(a)



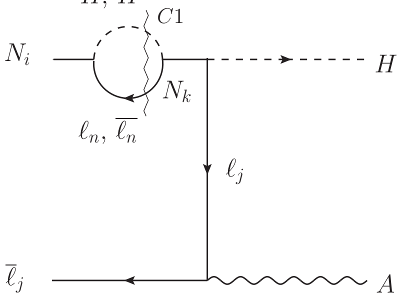
2.(c)



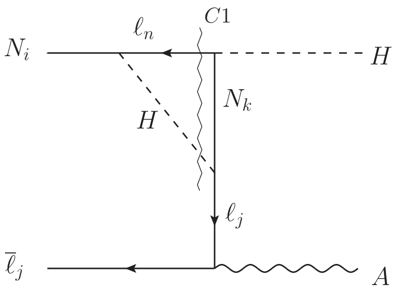
2.(e)



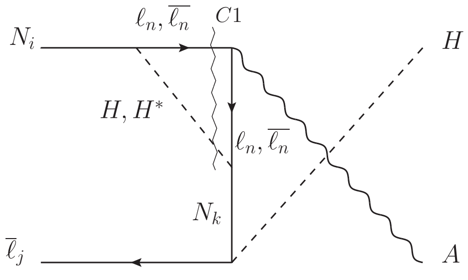
2.(g)



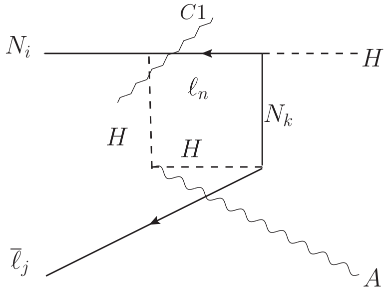
2.(b)



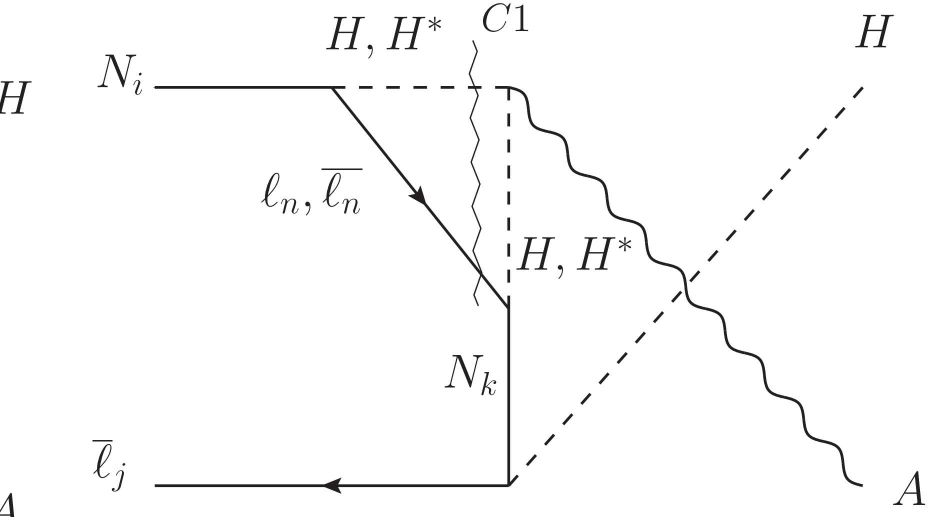
2.(d)



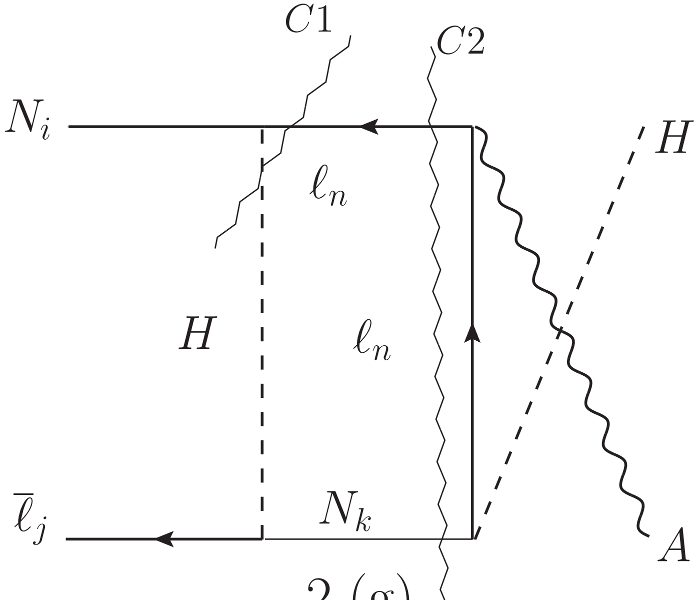
2.(f)



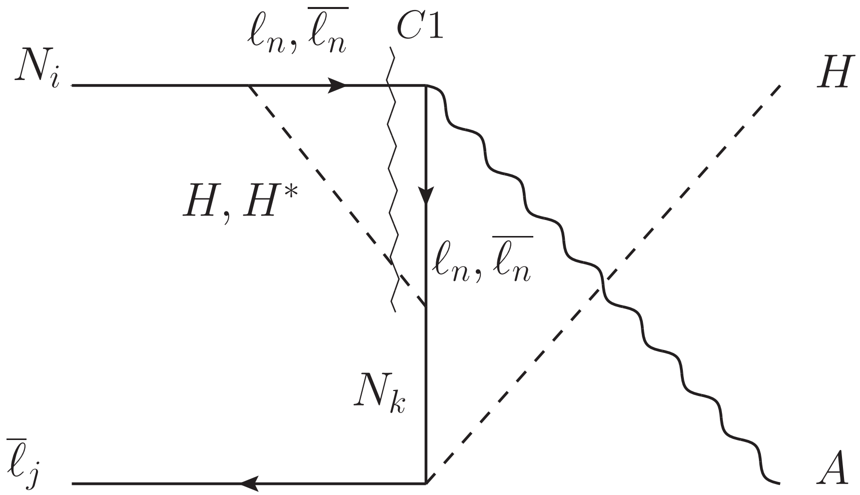
2.(h)


H
A
N_i
H, H^*
$C1$
H
$\ell_n, \overline{\ell_n}$
H, H^*
N_k
$\overline{\ell}_j$
A

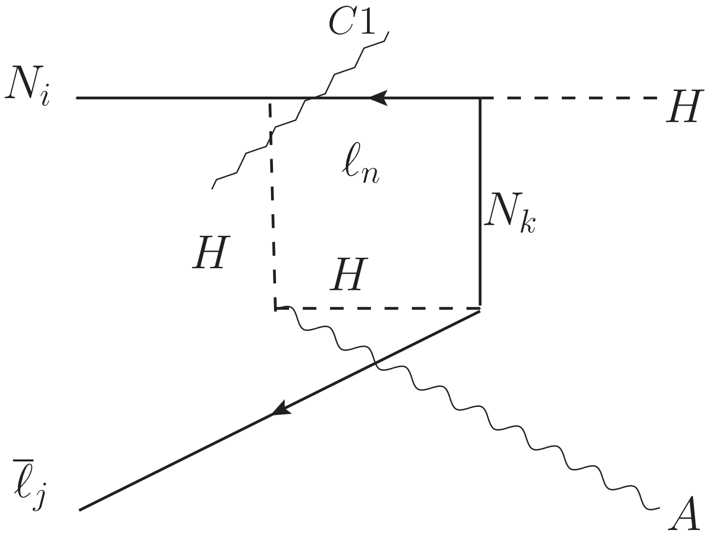
2.(e)


$C1$
$C2$
N_i
H
ℓ_n
H
ℓ_n
N_k
$\overline{\ell}_j$
A

2.(g)

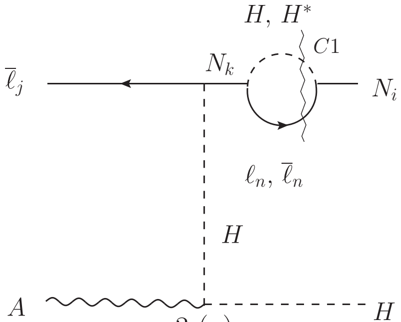

$\ell_n, \overline{\ell_n}$
$C1$
N_i
H
H, H^*
$\ell_n, \overline{\ell_n}$
N_k
$\overline{\ell}_j$
A

2.(f)

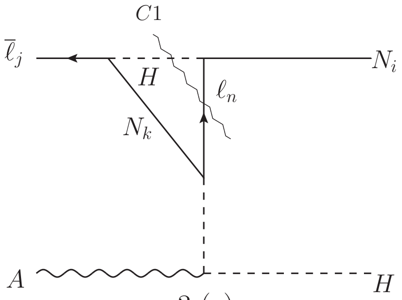

$C1$
N_i
H
ℓ_n
N_k
H
H
$\overline{\ell}_j$
A

2.(h)

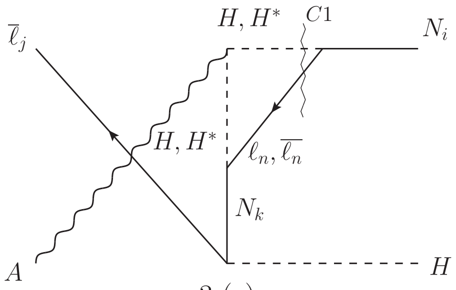
$\bar{\ell} A \to N H$



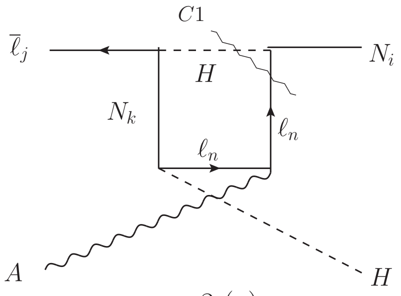
3.(a)



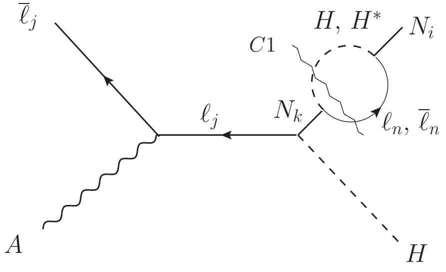
3.(c)



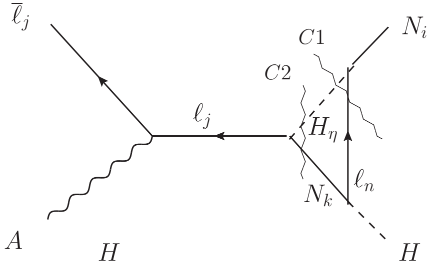
3.(e)



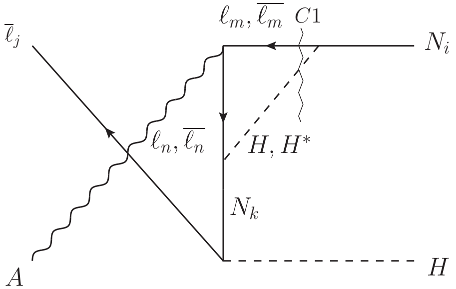
3.(g)



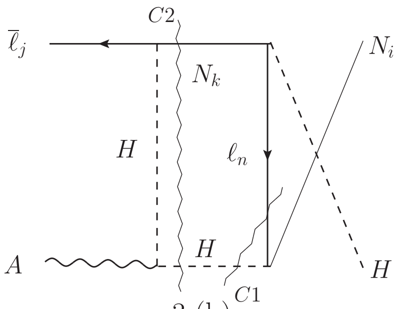
3.(b)



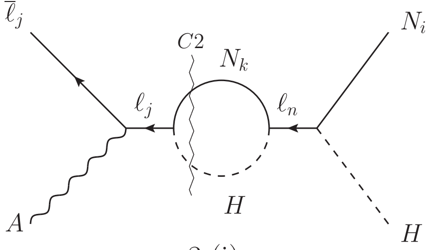
3.(d)



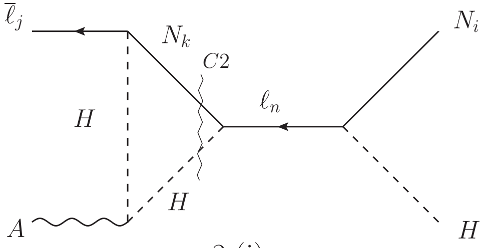
3.(f)



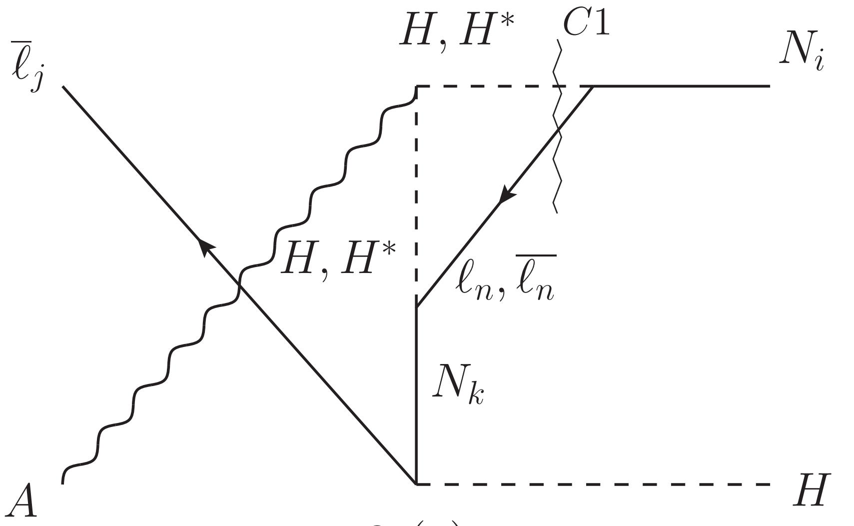
3.(h)



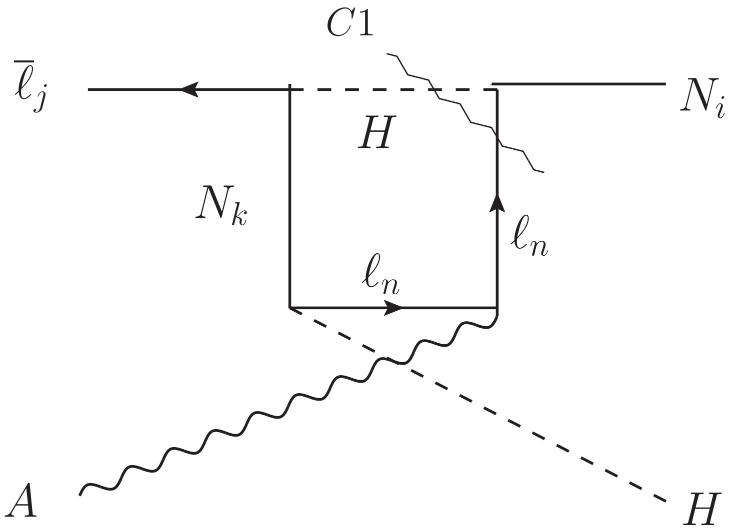
3.(i)



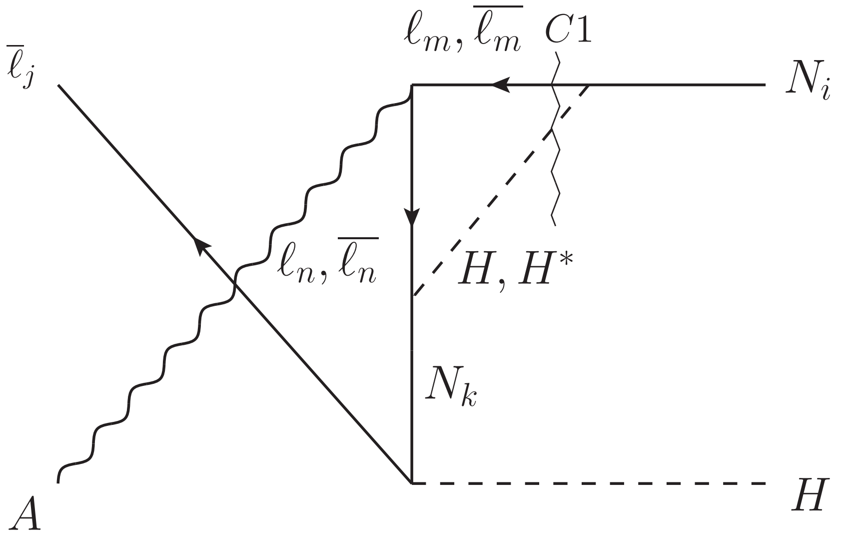
3.(j)


$\overline{\ell}_j$
H, H^*
$C1$
N_i
H, H^*
$\ell_n, \overline{\ell_n}$
N_k
A
H

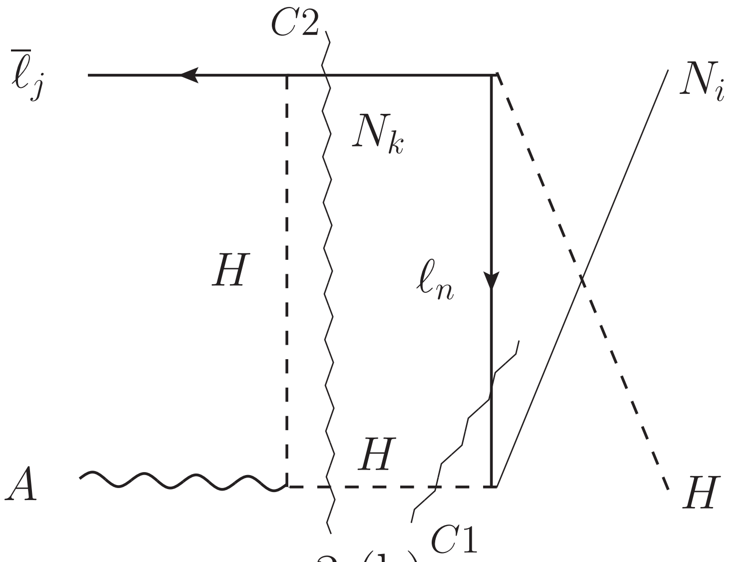
3.(e)


$C1$
$\overline{\ell}_j$
N_i
H
N_k
ℓ_n
ℓ_n
A
H

3.(g)

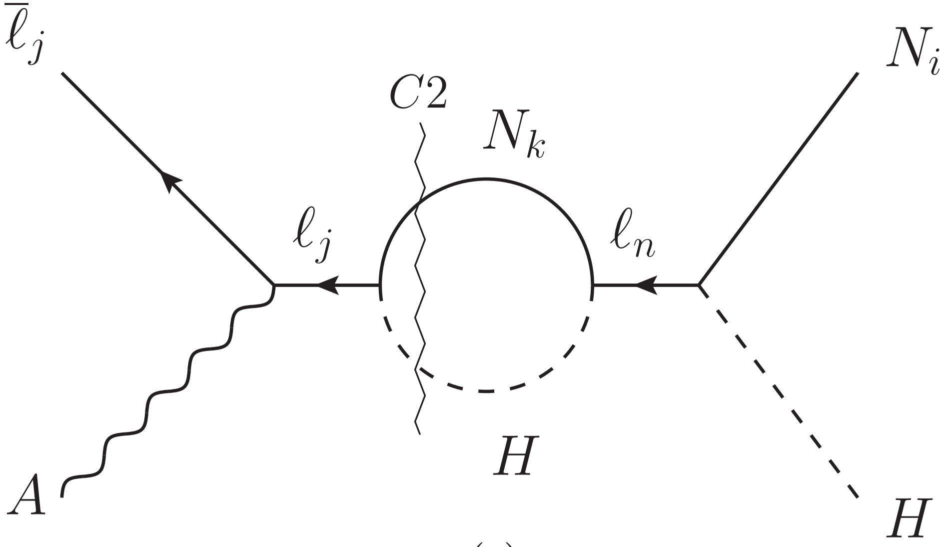

$\overline{\ell}_j$
$\ell_m, \overline{\ell_m}$
$C1$
N_i
$\ell_n, \overline{\ell_n}$
H, H^*
N_k
A
H

3.(f)

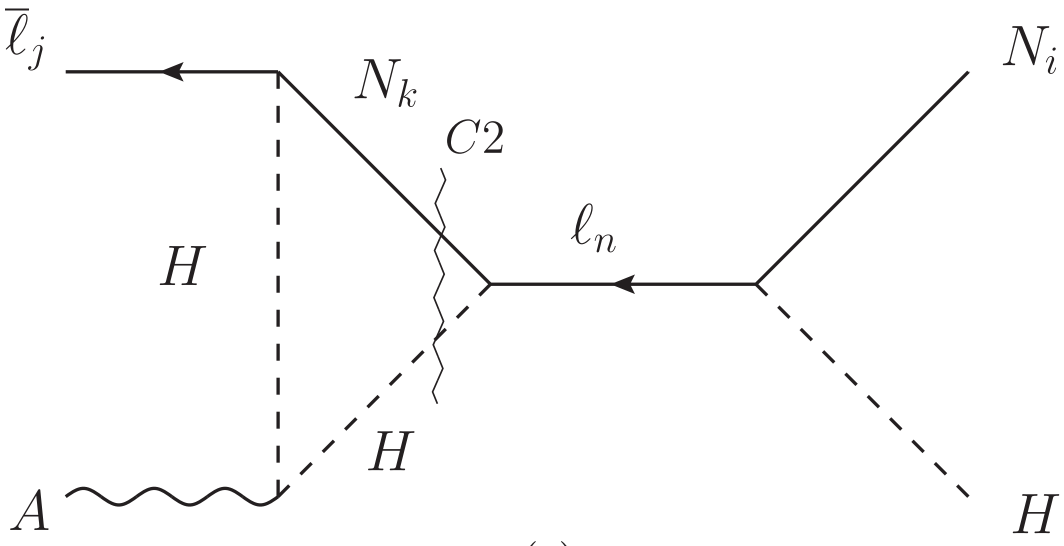

$C2$
$\overline{\ell}_j$
N_k
N_i
H
ℓ_n
H
A
H
$C1$

3.(h)

3.(b) 3.(d)


$\overline{\ell}_j$
$C2$
N_k
N_i
ℓ_j
ℓ_n
A
H
H

3.(i)


$\overline{\ell}_j$
N_k
N_i
$C2$
H
ℓ_n
A
H
H

3.(j)

Hierarchical limit $\longrightarrow$ $M_2 \gg M_1, T$

L–violating contribution

- $\epsilon^{(w)}_{\text{scatt}} = \epsilon^{(w)}_{\text{D}}$
- $\epsilon^{(v1)}_{\text{scatt}} \rightarrow \epsilon^{(v1)}_{\text{D}}$
- Note: at leading order in M_1/M_2 the $(v1)$ and (b) contributions are separately gauge invariant.

Therefore

$$\frac{\epsilon_{\text{scatt}}}{\epsilon_{\text{D}}} \rightarrow 1 + \frac{\epsilon^{(b)}_{\text{scatt}} + \epsilon^{(v2)}_{\text{scatt}}}{\epsilon_{\text{D}}}$$

- $N_i A \rightarrow \ell_j H$: $(\epsilon^{(b)}_{\text{scatt}} + \epsilon^{(v2)}_{\text{scatt}})/\epsilon_{\text{D}} \rightarrow 0$ ($C1$ and $C1'$ cancellation)
- $N_i \bar{\ell}_j \rightarrow H A,\ \bar{\ell}_j A \rightarrow N_i H$: $(\epsilon^{(b)}_{\text{scatt}} + \epsilon^{(v2)}_{\text{scatt}})/\epsilon_{\text{D}} \not\rightarrow 0$

L– conserving contribution

- They are suppressed by a higher power of M_1/M_2 compared to the L–violating contributions.
- Only source of CP violation in models with conservation of L.

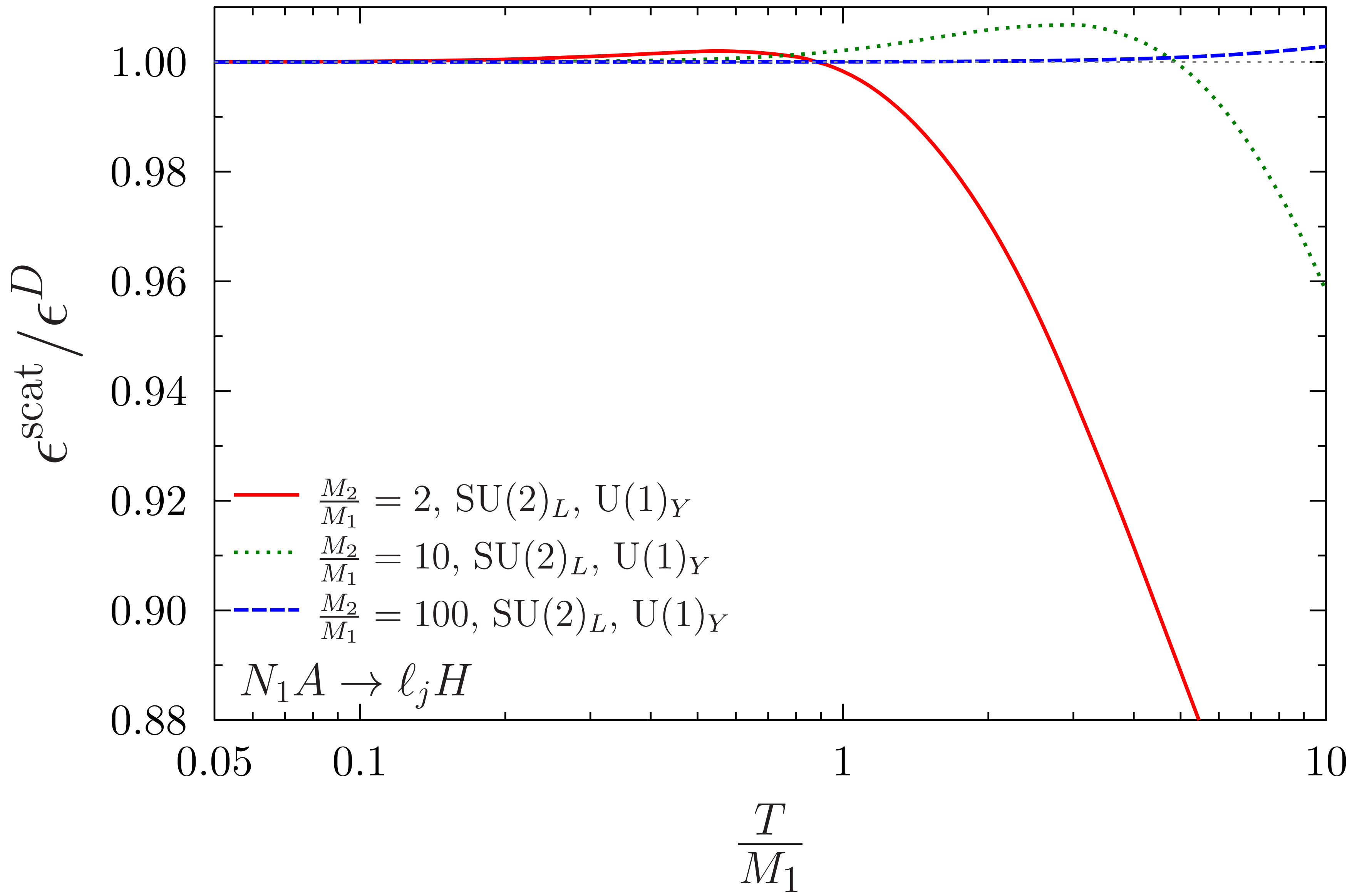
🟩 $\epsilon^{(w)}_{\text{scatt}} \;=\; \epsilon^{(w)}_{\text{D}}$

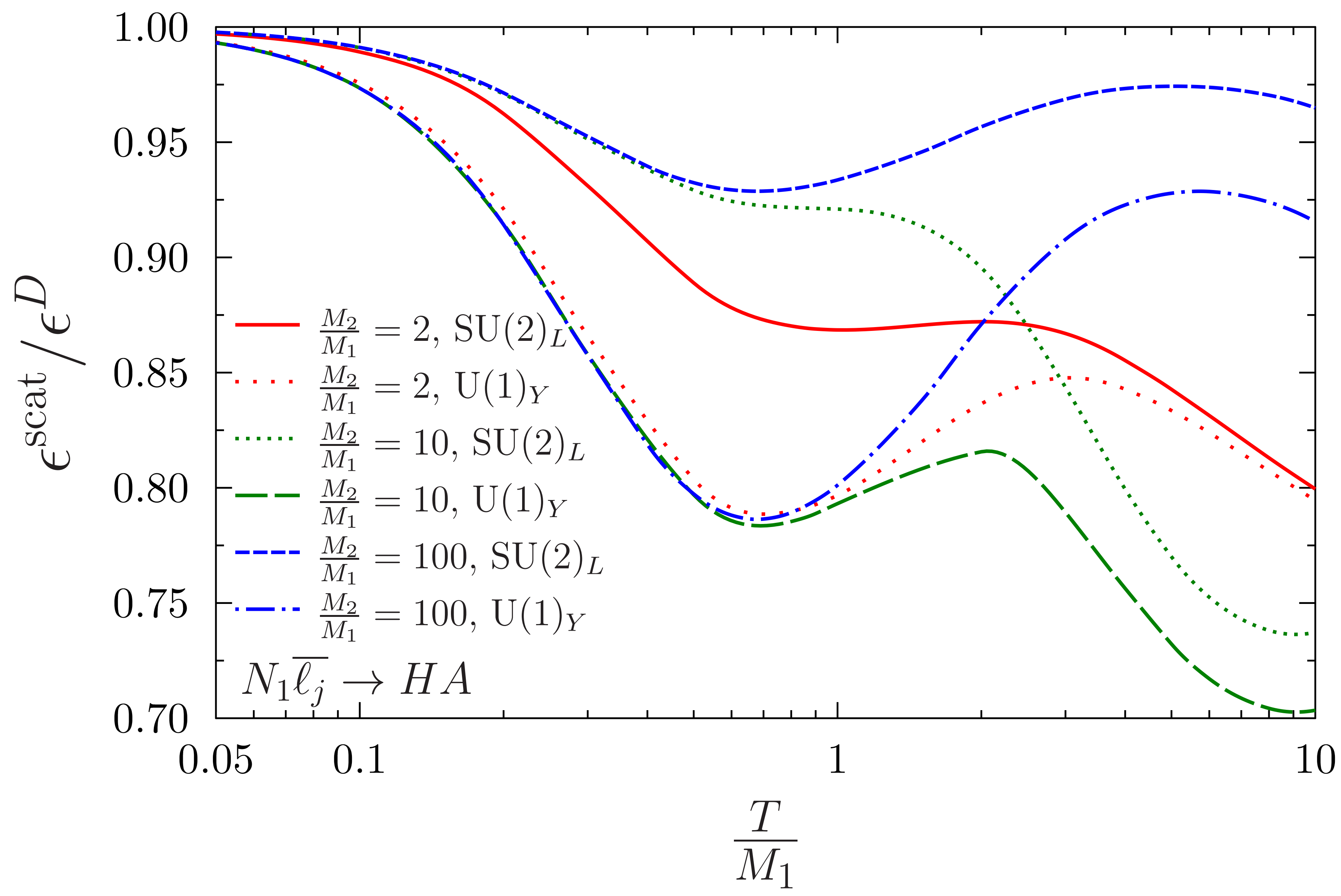
Therefore for scatterings with U(1)$_\text{Y}$ gauge bosons

$$\frac{\epsilon_{\text{scatt}}}{\epsilon_{\text{D}}} \quad\longrightarrow\quad 1 \,+\, \frac{\epsilon^{(v2)}_{\text{scatt}}}{\epsilon_{\text{D}}}$$

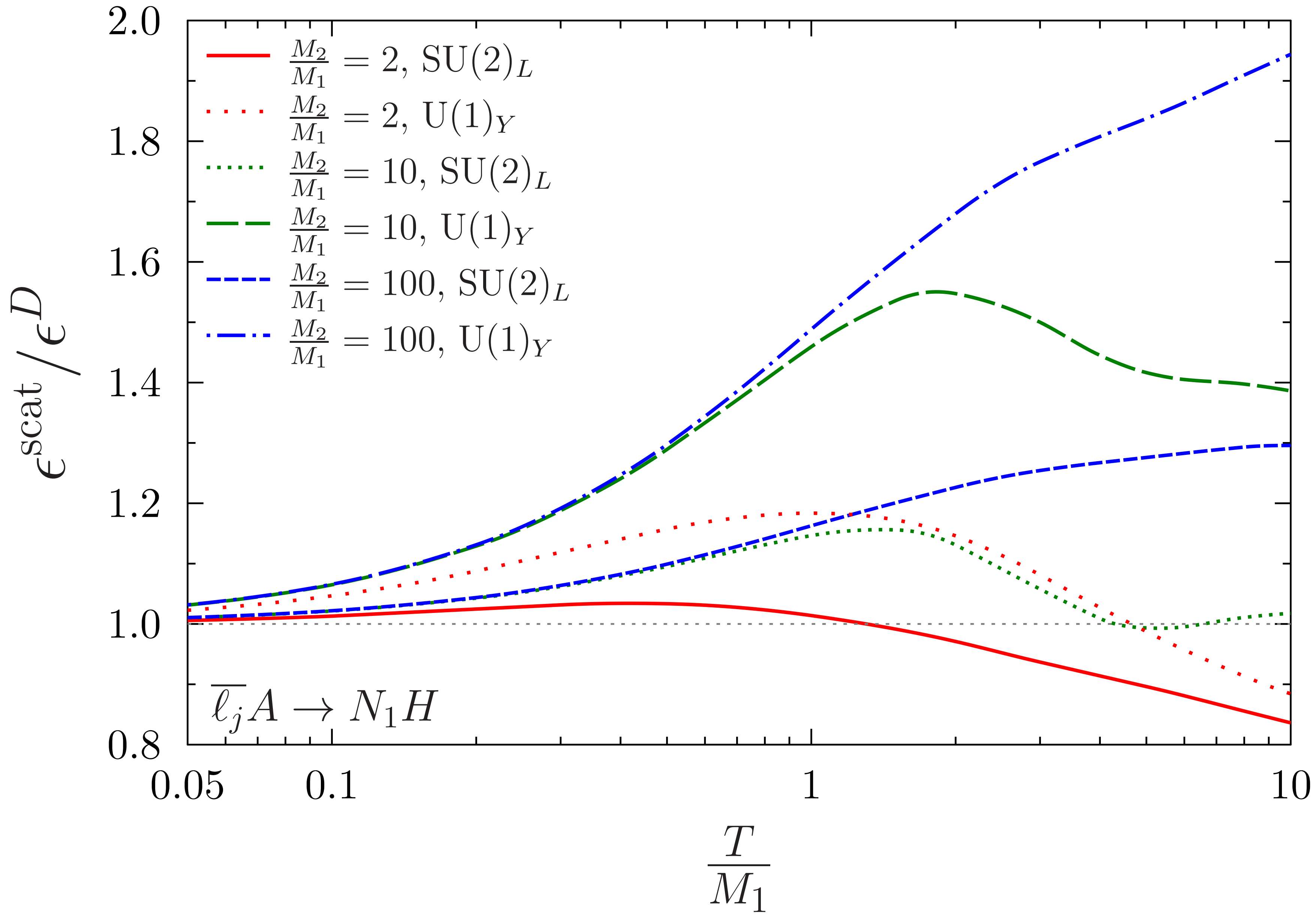
🟩 $N_i A \to \ell_j H : \epsilon^{(v2)}_{\text{scatt}}/\epsilon_{\text{D}} \;\longrightarrow\; 0$ $\quad$ ($C1$ and $C1'$ cancellation)

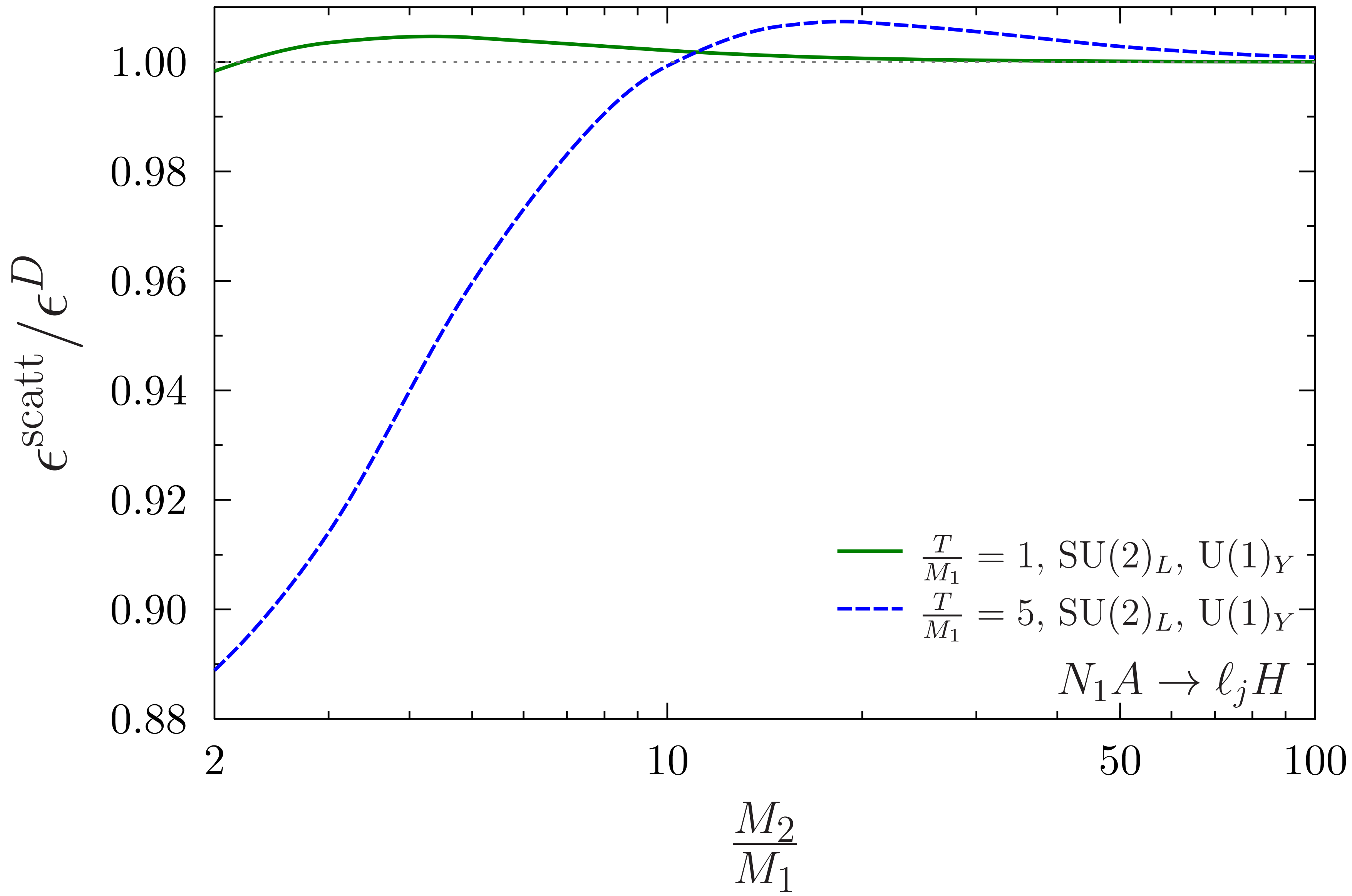
🟩 $N_i \bar{\ell}_j \to HA,\; \bar{\ell}_j A \to N_i H : \epsilon^{(v2)}_{\text{scatt}}/\epsilon_{\text{D}} \;\not\to\; 0$

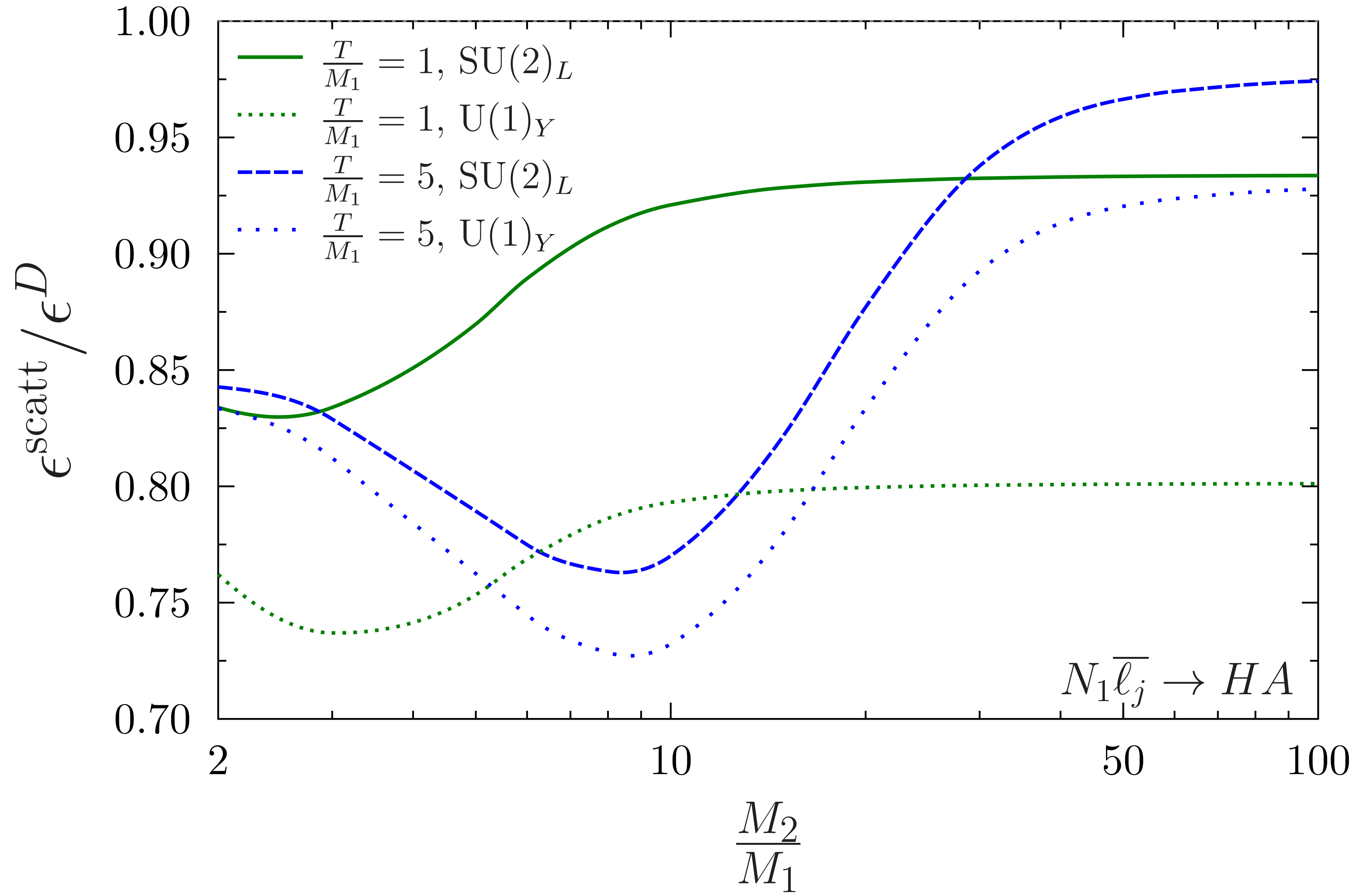

$\epsilon^{\mathrm{scat}}/\epsilon^{D}$
1.00
0.98
0.96
0.94
0.92
0.90
0.88
0.05
0.1
1
10
$\frac{T}{M_1}$
$\frac{M_2}{M_1} = 2$, SU$(2)_L$, U$(1)_Y$
$\frac{M_2}{M_1} = 10$, SU$(2)_L$, U$(1)_Y$
$\frac{M_2}{M_1} = 100$, SU$(2)_L$, U$(1)_Y$
$N_1 A \to \ell_j H$



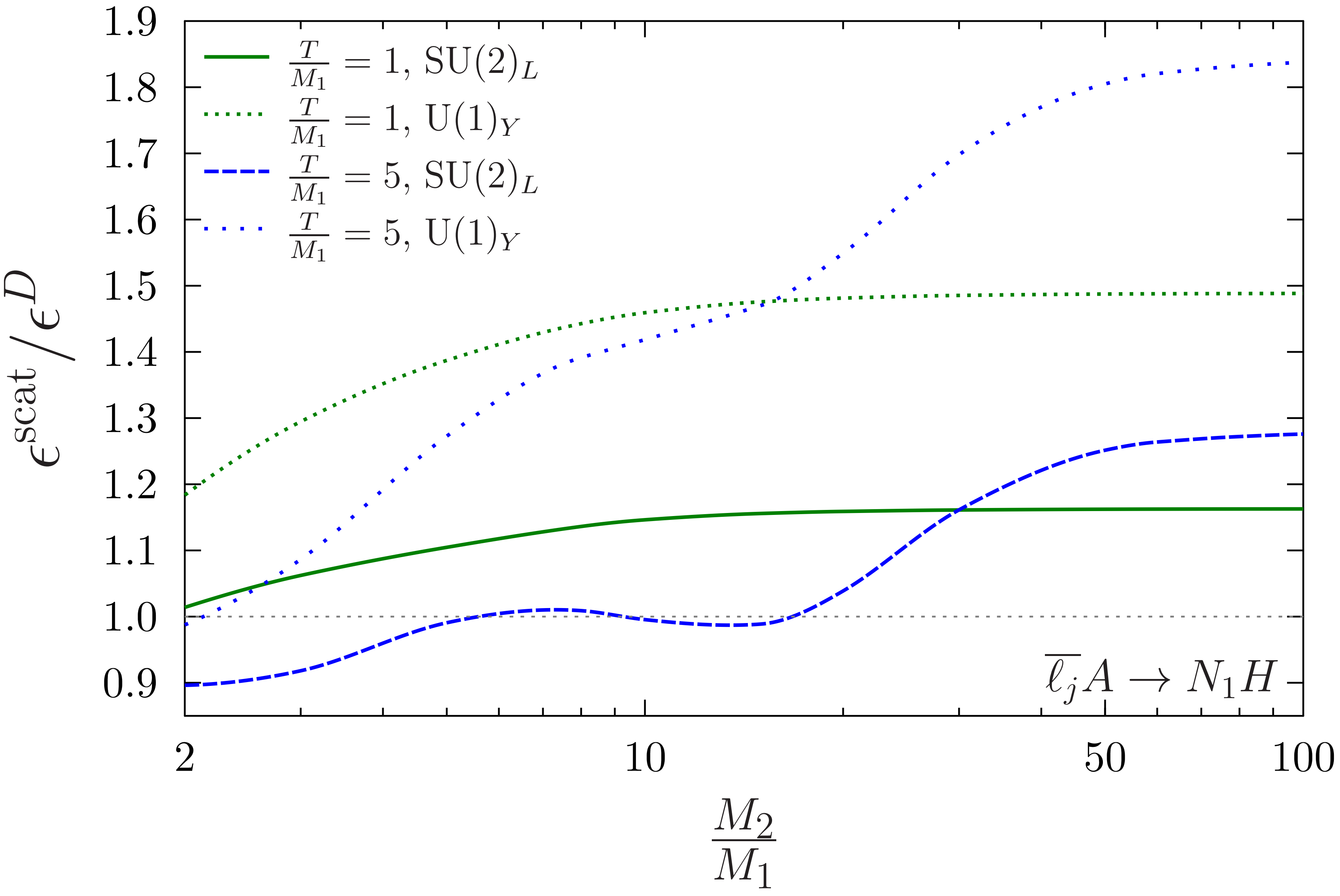
$\epsilon^{\text{scat}} / \epsilon^{D}$
1.00
0.95
0.90
0.85
0.80
0.75
0.70
0.05
0.1
1
10
$\frac{T}{M_1}$
$\frac{M_2}{M_1} = 2$, SU(2)$_L$
$\frac{M_2}{M_1} = 2$, U(1)$_Y$
$\frac{M_2}{M_1} = 10$, SU(2)$_L$
$\frac{M_2}{M_1} = 10$, U(1)$_Y$
$\frac{M_2}{M_1} = 100$, SU(2)$_L$
$\frac{M_2}{M_1} = 100$, U(1)$_Y$
$N_1 \overline{\ell_j} \to H A$


$\frac{M_2}{M_1} = 2$, SU$(2)_L$
$\frac{M_2}{M_1} = 2$, U$(1)_Y$
$\frac{M_2}{M_1} = 10$, SU$(2)_L$
$\frac{M_2}{M_1} = 10$, U$(1)_Y$
$\frac{M_2}{M_1} = 100$, SU$(2)_L$
$\frac{M_2}{M_1} = 100$, U$(1)_Y$
$\overline{\ell_j} A \to N_1 H$
$\epsilon^{\rm scat} / \epsilon^D$
$\frac{T}{M_1}$
2.0
1.8
1.6
1.4
1.2
1.0
0.8
0.05
0.1
1
10


$\epsilon^{\rm scatt}/\epsilon^{D}$
1.00
0.98
0.96
0.94
0.92
0.90
0.88
2
10
50
100
$\frac{M_2}{M_1}$
$\frac{T}{M_1} = 1$, $\mathrm{SU}(2)_L$, $\mathrm{U}(1)_Y$
$\frac{T}{M_1} = 5$, $\mathrm{SU}(2)_L$, $\mathrm{U}(1)_Y$
$N_1 A \to \ell_j H$



1.00
0.95
0.90
0.85
0.80
0.75
0.70
2
10
50
100
$\epsilon^{\text{scatt}}/\epsilon^{D}$
$\frac{M_2}{M_1}$
$\frac{T}{M_1} = 1$, $\text{SU}(2)_L$
$\frac{T}{M_1} = 1$, $\text{U}(1)_Y$
$\frac{T}{M_1} = 5$, $\text{SU}(2)_L$
$\frac{T}{M_1} = 5$, $\text{U}(1)_Y$
$N_1\overline{\ell_j} \to HA$


$\frac{T}{M_1} = 1$, SU(2)$_L$
$\frac{T}{M_1} = 1$, U(1)$_Y$
$\frac{T}{M_1} = 5$, SU(2)$_L$
$\frac{T}{M_1} = 5$, U(1)$_Y$
$\epsilon^{\rm scat}/\epsilon^D$
1.9
1.8
1.7
1.6
1.5
1.4
1.3
1.2
1.1
1.0
0.9
$\overline{\ell_j} A \to N_1 H$
2
10
50
100
$\frac{M_2}{M_1}$

Conclusions

- $\epsilon_{\text{scatt}} \; = \; (0{,}5 - 2) \; \times \; \epsilon_{\text{D}}$
- Even for very hierarchical heavy neutrinos

$$\epsilon^{N_i A}_{\ell_j H} = \epsilon^{N_i}_{\ell_j H} \neq \epsilon^{N_i \bar{\ell}_j}_{AH} \neq \epsilon^{\bar{\ell}_j A}_{N_i H}$$

Initial conditions

We will consider two cases:

a) The heavy neutrinos are thermally produced only by inverse decays and scatterings involving the Yukawa couplings:

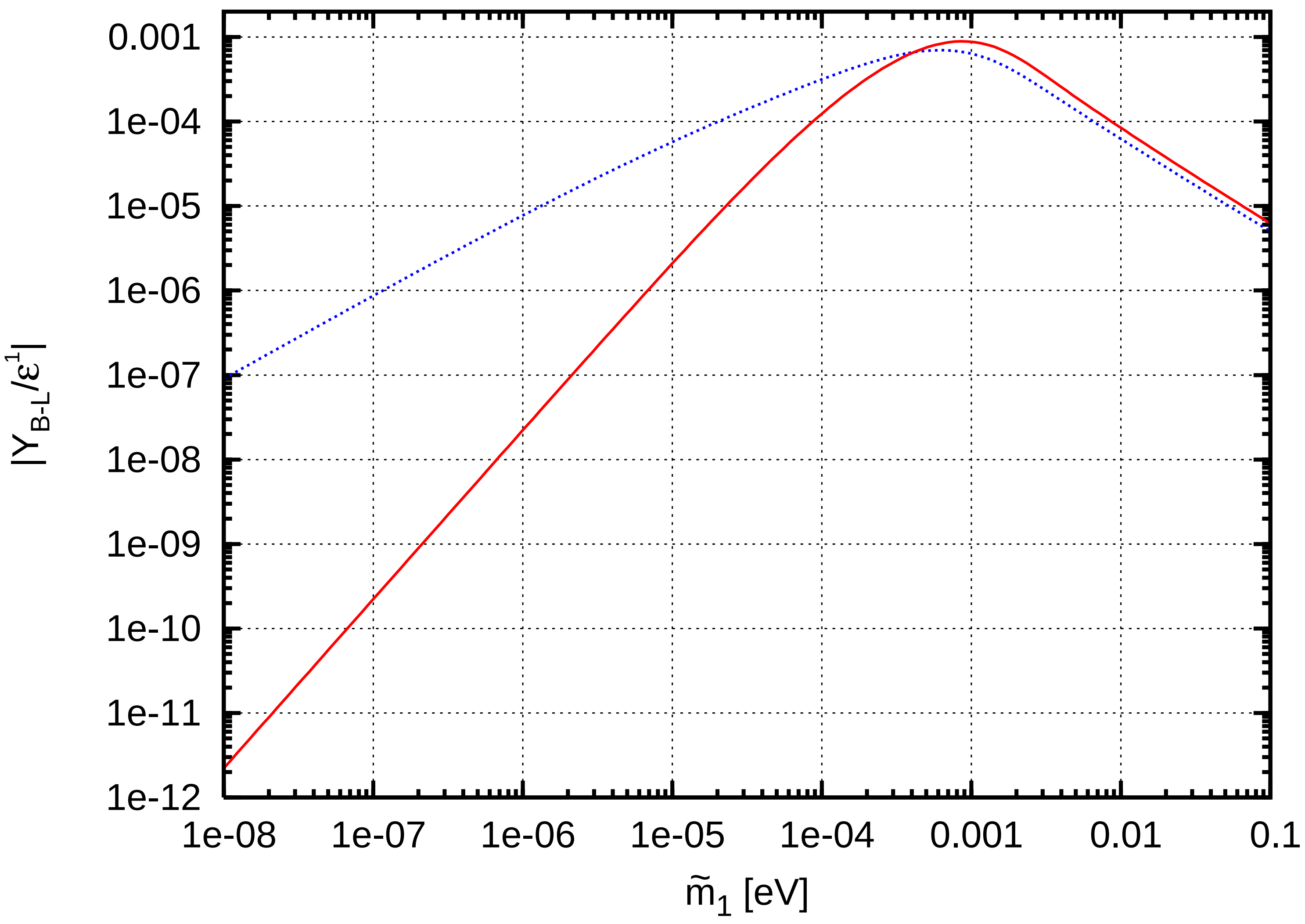
$$Y_N(T \gg M_1) = 0 \ .$$

b) Some process which was active at $T \gg M_1$ but not at $T \sim M_1$, produced an equilibrium population of heavy neutrinos:

$$Y_N(T \gg M_1) = Y_N^{eq}(T \gg M_1) \ .$$

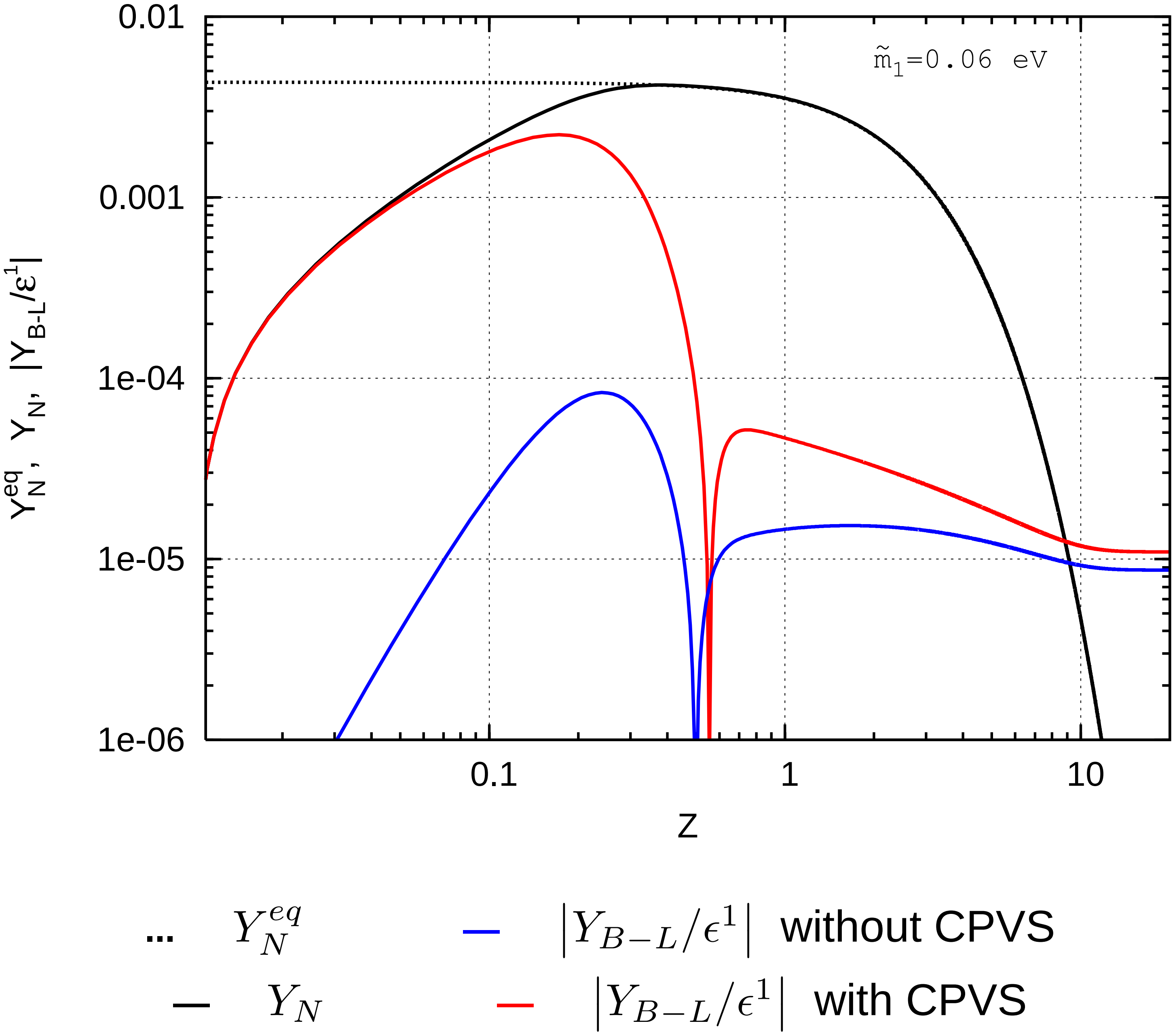
E.g. heavy Z' bosons, [M. Plümacher 1997] , [J. R. & E. Roulet 2009] .

The effects



... without CPVS — with CPVS

Strong washout regime



Weak washout regime

- without CPVS: $Y_{B-L} \propto \tilde{m}_1$.
- with CPVS: $Y_{B-L} \propto \tilde{m}_1^2$.

Why?

cancellation effect :

$$\frac{\mathrm{d}Y_{B-L}}{\mathrm{d}z} = \epsilon \frac{\mathrm{d}Y_N}{\mathrm{d}z} - w(z) Y_{B-L} \ .$$

Then:

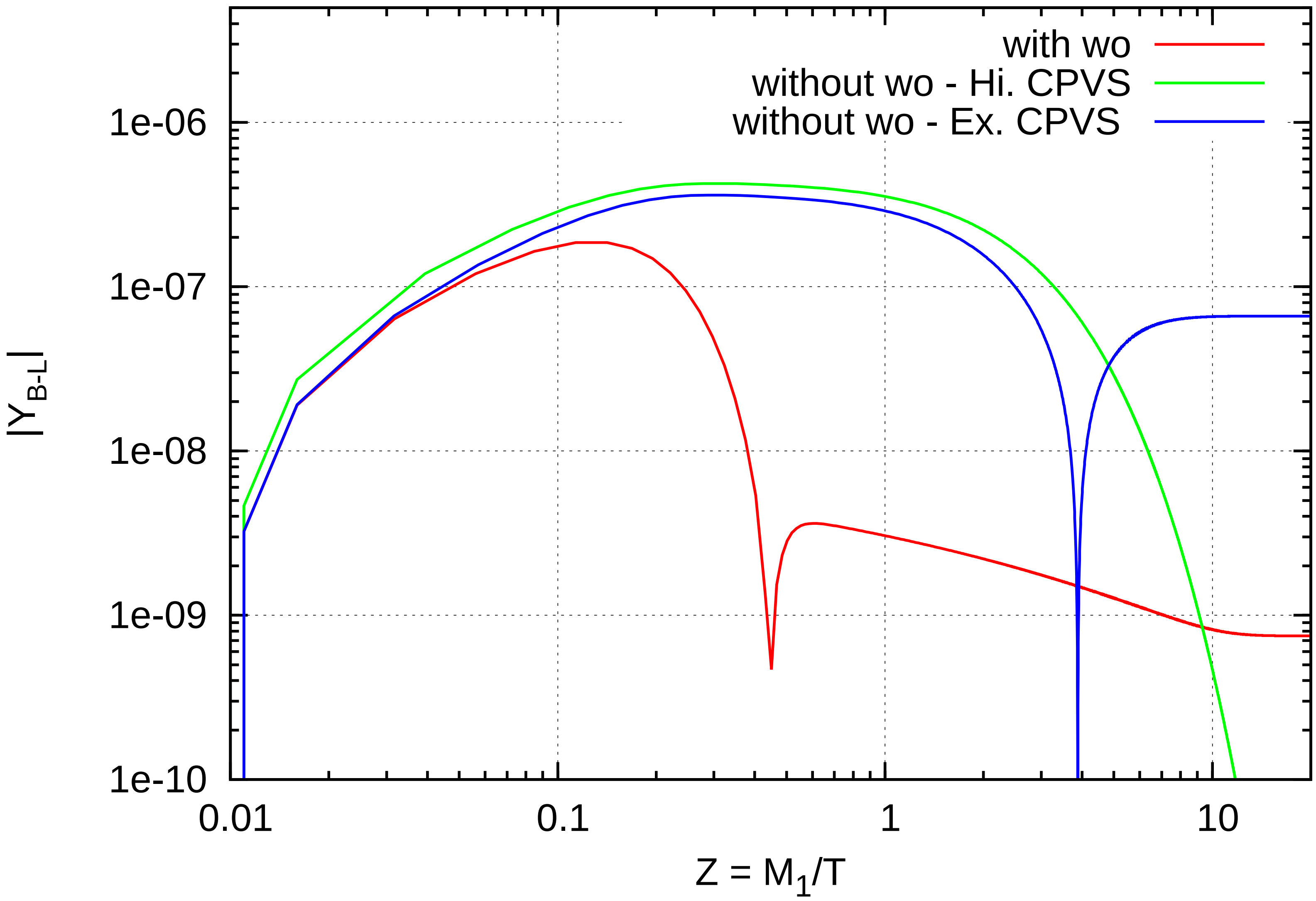
$$Y_{B-L}^{f} = \epsilon (Y_N^f - Y_N^i) + (\Delta Y_{B-L}^{wo})^- - (\Delta Y_{B-L}^{wo})^+ \ .$$

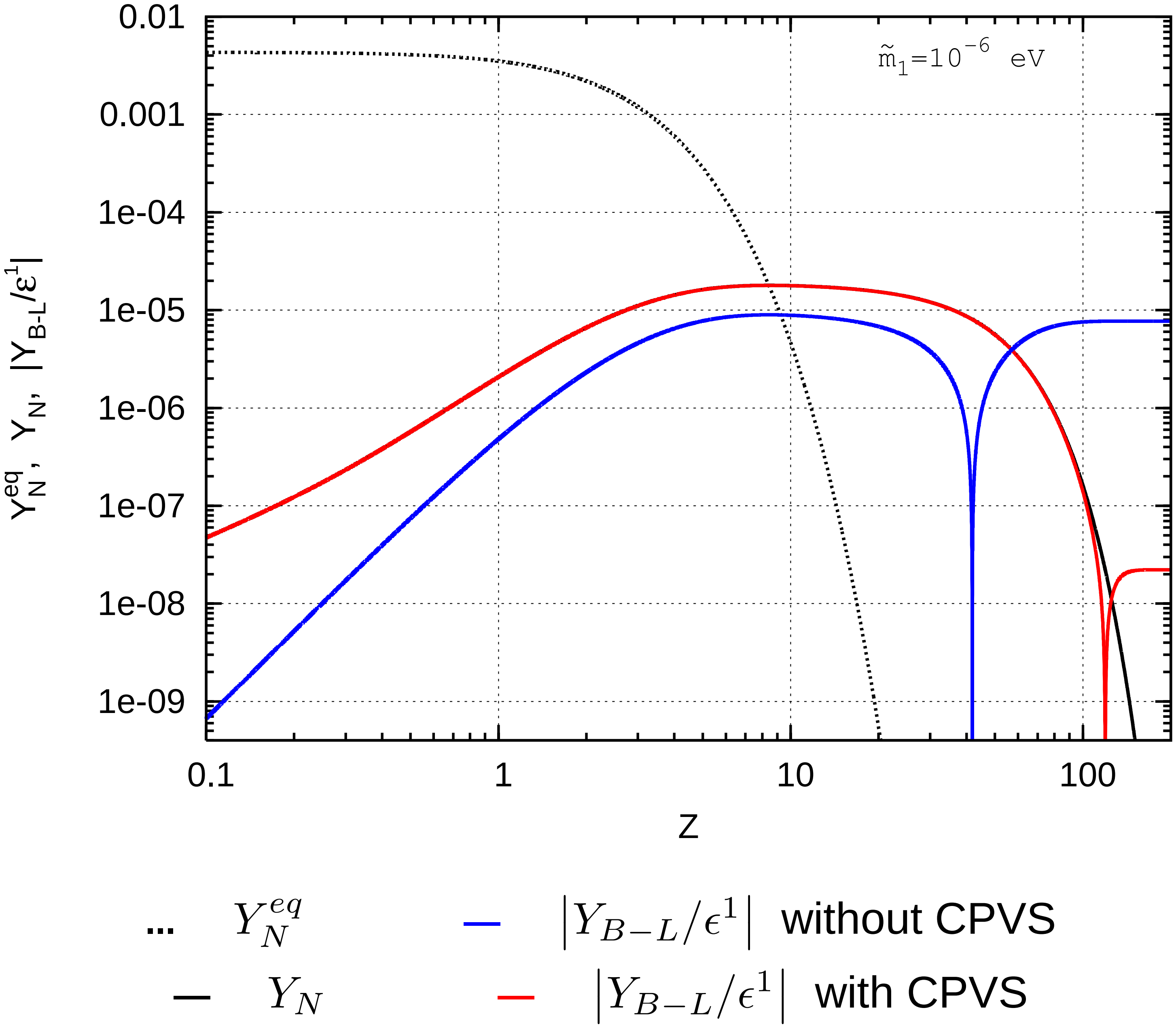
The final asymmetry is null if there are no washouts!

This is a consequence of unitarity and CPT.

But what happens if the exact expression for the CPVS is used?

(Note that in this case source $\neq \epsilon \frac{\mathrm{d}Y_N}{\mathrm{d}z}$)




$\tilde{m}_1=10^{-6}$ eV
Y_N^{eq}, Y_N, $|Y_{B-L}/\varepsilon^1|$
0.01
0.001
1e-04
1e-05
1e-06
1e-07
1e-08
1e-09
0.1
1
10
100
z
... Y_N^{eq}
— Y_N
— $\left|Y_{B-L}/\epsilon^1\right|$ without CPVS
— $\left|Y_{B-L}/\epsilon^1\right|$ with CPVS

Regions of the $\tilde{m}_1 - M_1$ plane allowed by observations

$$Y_B^f = -\kappa \epsilon^1 \eta \ ,$$

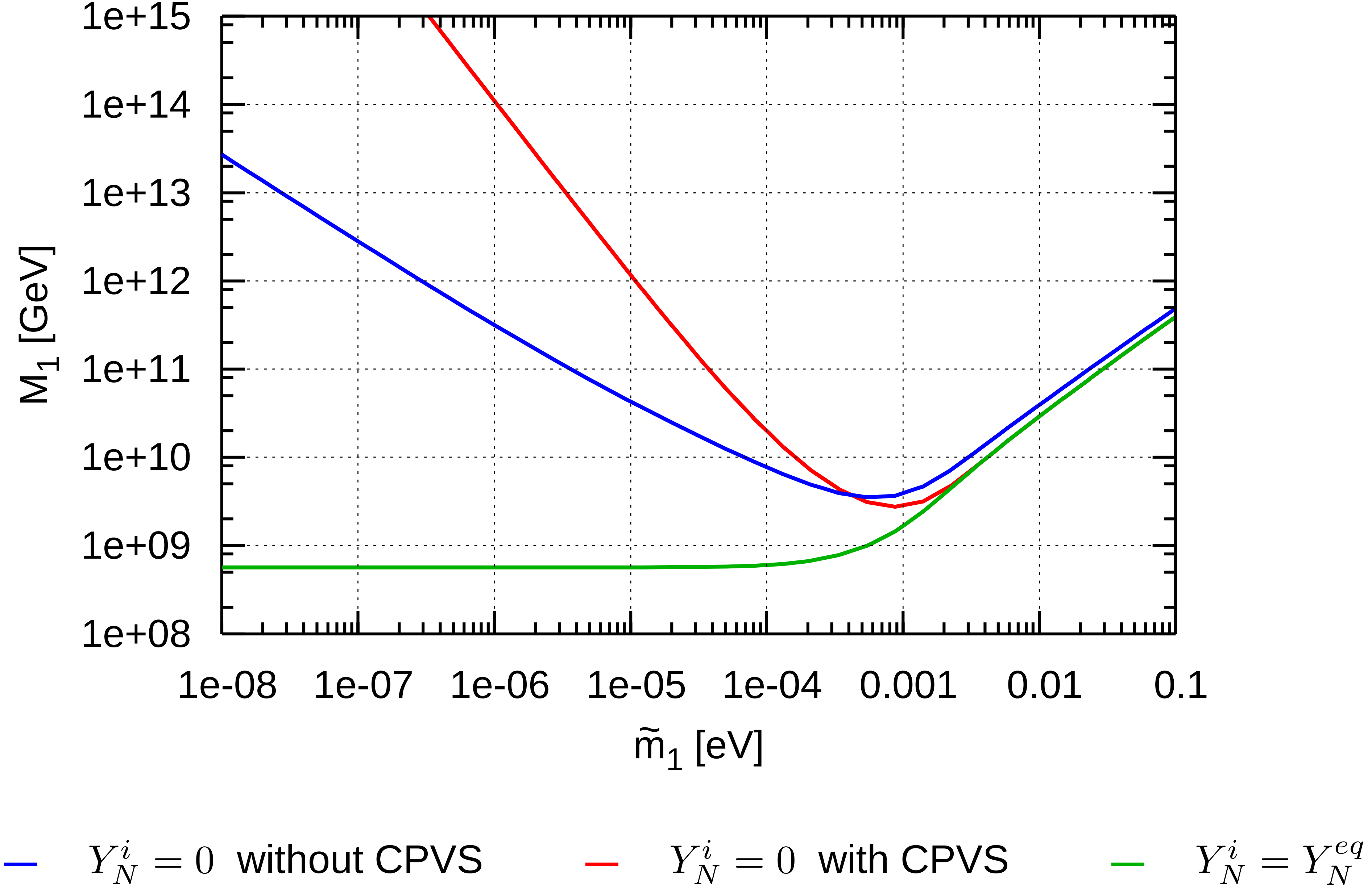
with $\kappa \simeq 1/724$ and $\eta = \eta(\tilde{m}_1, M_1)$.

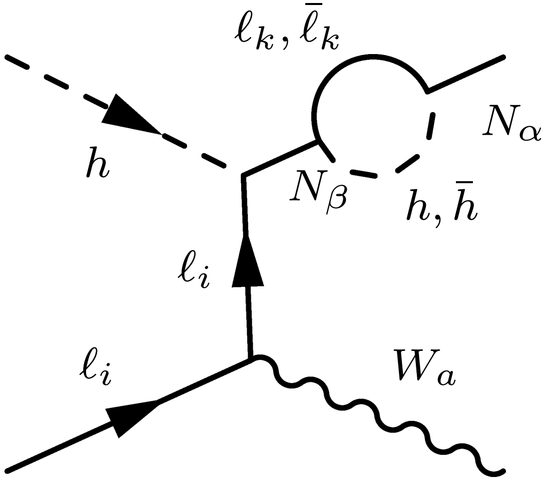
$$\left|\epsilon^1\right| \leq \epsilon^{\mathrm{DI}}_{\mathrm{max}} = \frac{3}{16\pi} \frac{M_1}{v^2} (m_3 - m_1) \ .$$

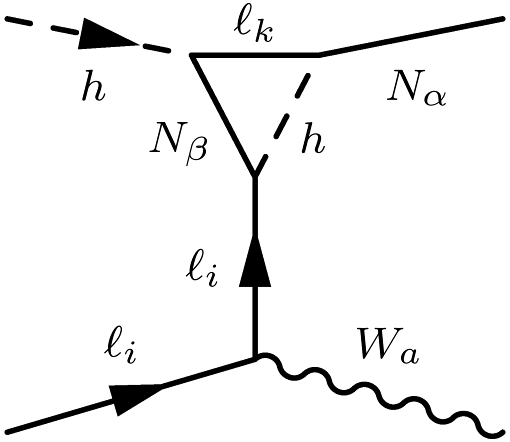
$$\Downarrow$$

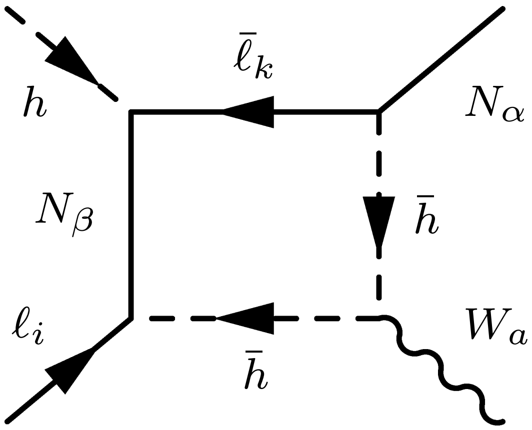
$$\frac{3}{16\pi} \frac{M_1}{v^2} (m_3 - m_1) \, \kappa \, \eta \left(\tilde{m}_1, M_1\right) > Y_B^{obs} \ , \tag{1}$$

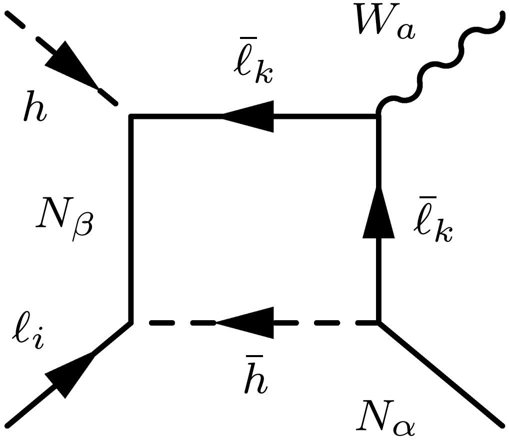
with $Y_B^{obs} \simeq 8{,}7 \times 10^{-11}$.


1e+15
1e+14
1e+13
1e+12
1e+11
1e+10
1e+09
1e+08
M_1 [GeV]
1e-08
1e-07
1e-06
1e-05
1e-04
0.001
0.01
0.1
$\tilde{m}_1$ [eV]
$Y_N^i = 0$ without CPVS
$Y_N^i = 0$ with CPVS
$Y_N^i = Y_N^{eq}$


$\ell_k, \bar{\ell}_k$
h
N_α
N_β
$h, \bar{h}$
ℓ_i
ℓ_i
W_a


ℓ_k
h
N_α
N_β
h
ℓ_i
ℓ_i
W_a


$\bar{\ell}_k$
h
N_α
N_β
$\bar{h}$
ℓ_i
W_a
$\bar{h}$


W_a
$\bar{\ell}_k$
h
N_β
$\bar{\ell}_k$
ℓ_i
$\bar{h}$
N_α