A New Mechanism for Leptogenesis in three Higgs doublet model

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Based on K. Mukaida, HW, M. Yamada, JCAP 09 (2024) 063 [arXiv:2405.14332].

Introduction

From Cosmic Microwave Background and Big Bang Nucleosynthesis

$$\frac{q_B}{s} := \frac{n_B - n_{\bar{B}}}{s} = 8.6\times10^{-11}$$

n_B : baryon number density
$n_{\bar{B}}$: anti-baryon number density
s : entropy density

We need this baryon asymmetry.

↓ Is there possibility that baryon asymmetry existed in the beginning?

Because of inflation and reheating, pre-existing baryon asymmetry is diluted.

↓

The problem of baryon asymmetry is inevitable
Beyond Standard Model is necessary.

Leptogenesis

Vanilla leptogenesis(Thermal leptogenesis)

M. Fukugita, T. Yanagida Phys.Lett.B 174 (1986) 45-47

mass > 10^9GeV

N

Majorana neutrino

L violation
CP violation
Nonthermal equilibrium

Weak wash-out

$$\frac{1}{2}MNN + y\bar{\ell}H_{SM}N$$

B-L
(Lepton number)

Chemical transport

$$B = \frac{28}{79}(B-L)$$

Sphaleron
thermal process

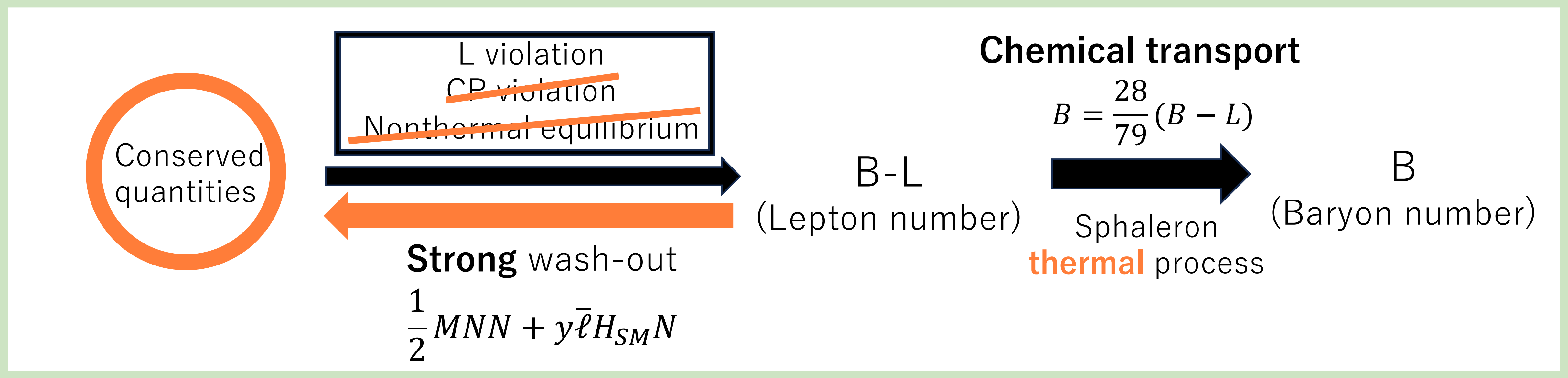
B
(Baryon number)

Conditions to produce the enough baryon asymmetry

- Weak wash-out and nonthermal equilibrium
- CP violation in the neutrino sector
- Large Majorana mass
- L violation when non-equilibrium decay

Our work

Wash-in leptogenesis + Three Higgs doublet model



Conditions to produce the enough baryon asymmetry

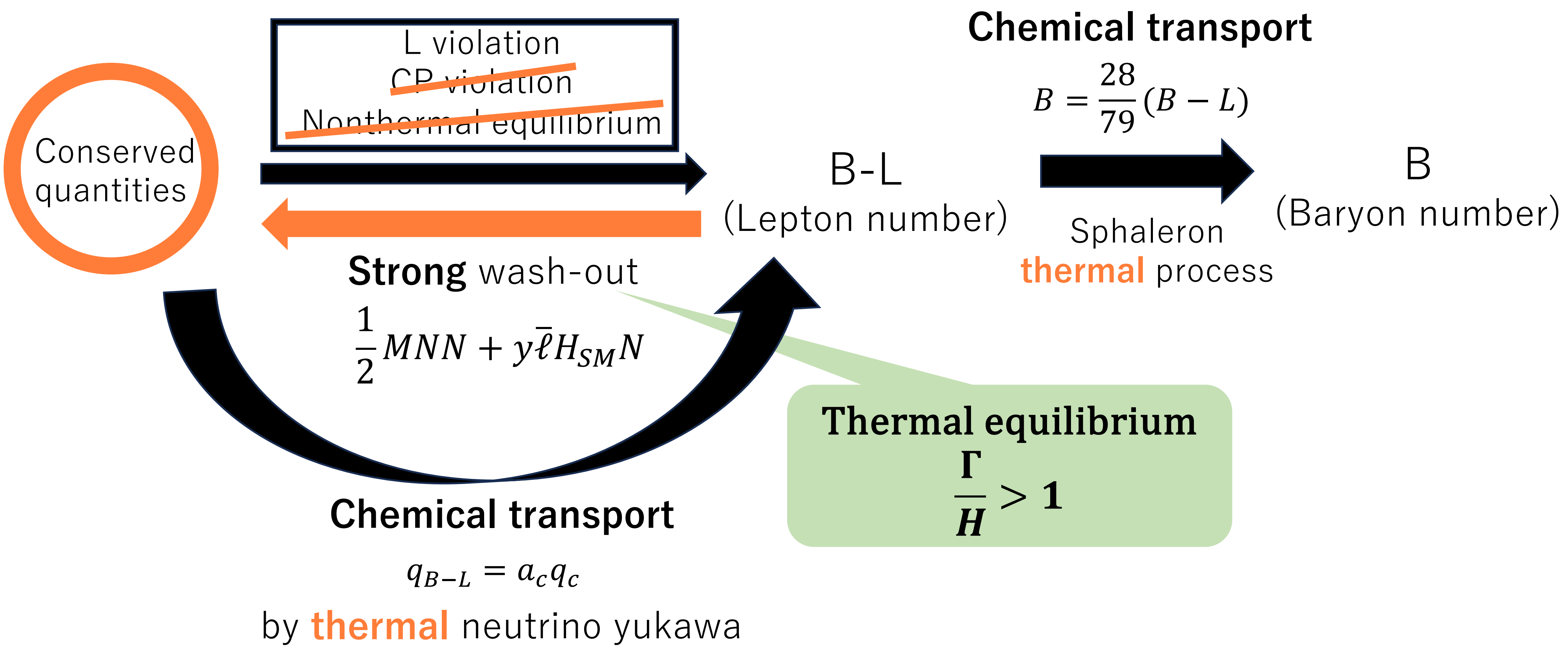
- ~~Weak wash-out and nonthermal equilibrium~~
- ~~CP violation in the neutrino sector~~
- ~~Large Majorana mass~~
- ~~L violation when non-equilibrium decay~~

These conditions are not necessary.

Wash-in Leptogenesis

V. Domcke *et al.*, Phys. Lev. Lett. 126 (2021) 201802.

Wash-in leptogenesis



Decoupling and Conserved Quantities

Interaction rate Γ
and Hubble parameter H

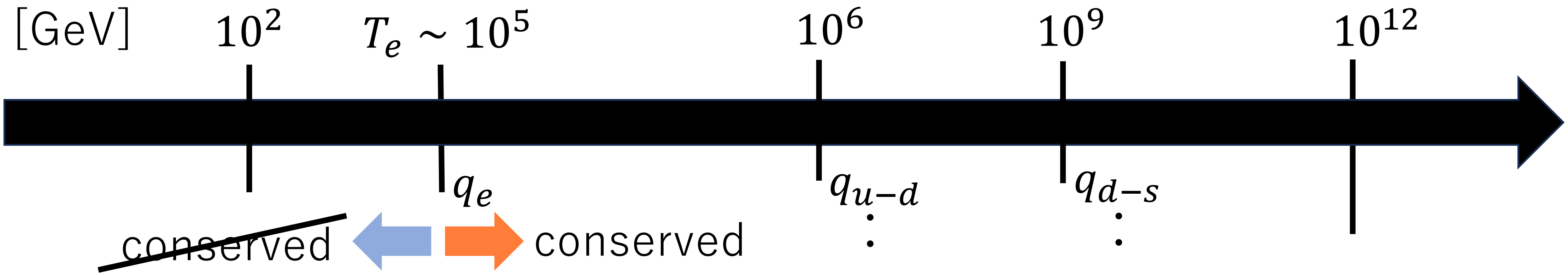
$\frac{\Gamma}{H} < 1$ → Conserved quantities

decoupling

Γ and H when all particles are relativistic

$\Gamma \propto g^2 T \qquad H \propto T^2 \qquad$ g: coupling constant

$\frac{\Gamma}{H} \propto \frac{g^2}{T}$ → weaker coupling / higher temperature } easier decoupling



The right-handed electron asymmetry q_e is conserved until lowest temperature.

q_e can be a source of $B - L$ $\quad q_{B-L} = -\frac{3}{10} q_e$ → The rest problem is how to produce q_e

UV model to realize Wash-in Leptogenesis

- GUT baryogenesis [V. Domcke *et al.*, Phys. Lev. Lett. 126 (2021) 201802.]
- Axion Inflation [V. Domcke, *et al.*, 2210.06412]
- Evaporation of PBH [K. Schmitz, *et al.,* 2311.01089]

etc

These models can violate charges other than the required conserved quantities.

➡ These violations are **not** necessary. ➡ **3HDM**

Three-Higgs doublet model

V. Keus, S. F. King, and S. Moretti, *JHEP* **01** (2014) 052,arXiv:1310.8253 [hep-ph].

$$\mathscr{L} = \mathscr{L}_{\rm SM} + \mathscr{L}_{{\rm RH}\nu} + \mathscr{L}_{HH}$$

$$\mathscr{L}_{{\rm RH}\nu} = \bar{N}_i i \partial\!\!\!/ N_i - \underline{\frac{1}{2} M_i \bar{N}_i N_i - \left(\bar{\ell}_f \tilde{H}_{\rm SM} \lambda^{\rm SM}_{fi} N_i + {\rm H.c.} \right)}$$

The thermal equilibrium process which produces q_{B-L}

$$\mathscr{L}_{HH} = |DH_\alpha|^2 - M^2_{H_\alpha} |H_\alpha|^2 - \left(\underline{\bar{\ell}_f H_\alpha Y^\alpha_{ff'} e_{f'}} + \bar{\ell}_f \tilde{H}_\alpha \lambda^\alpha_{fi} N_i + {\rm H.c.} \right)$$

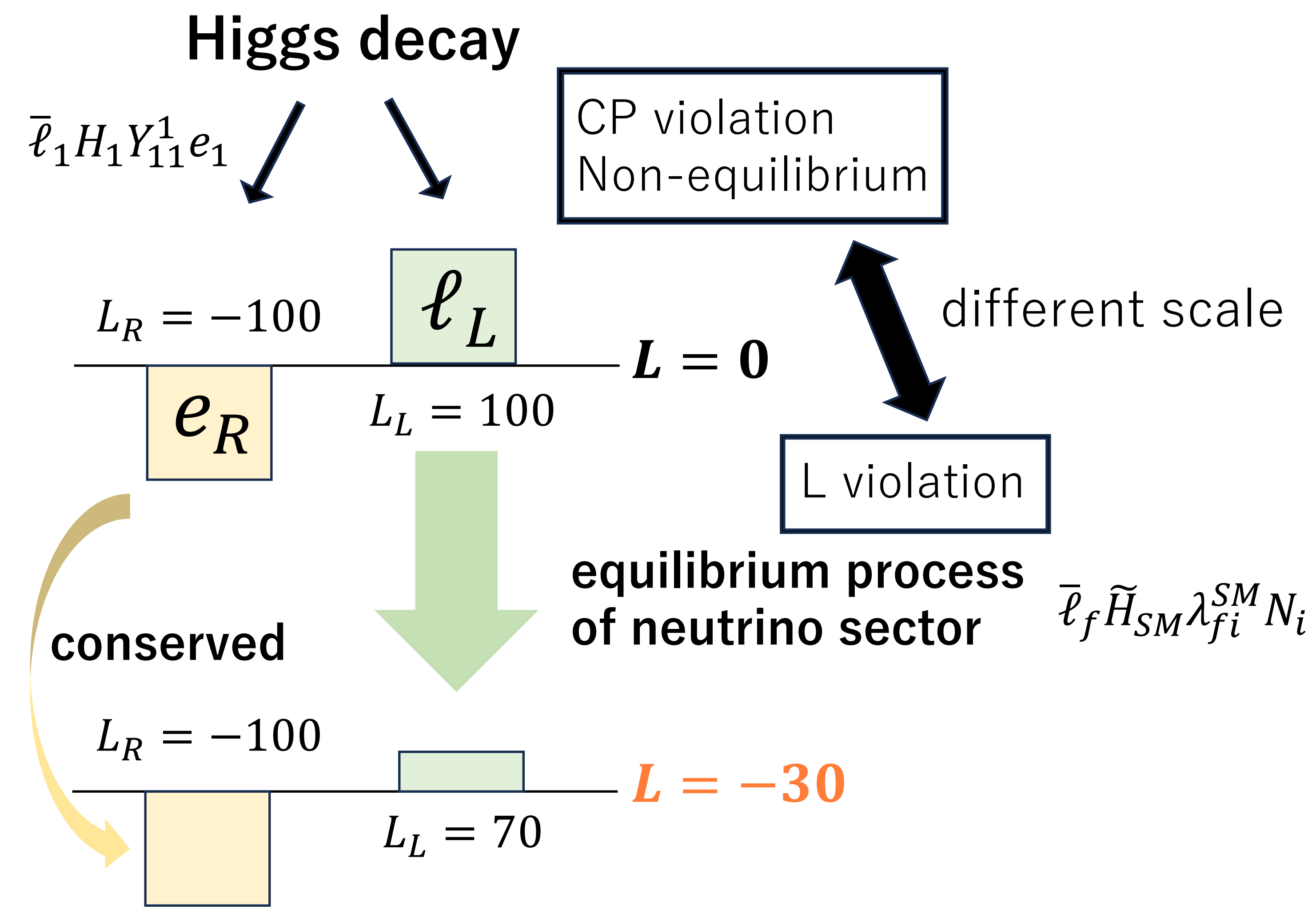
decay of Higgs to produce q_e

- violate CP
- not violate L

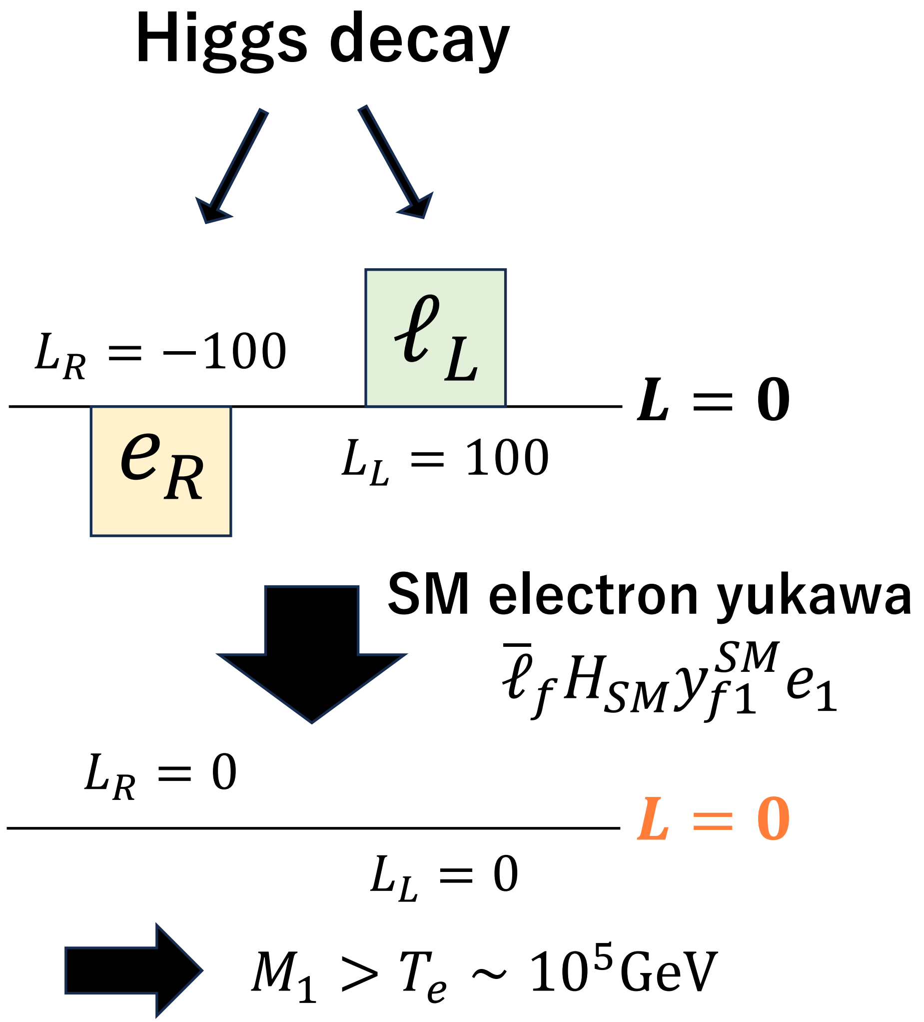
N_i	: Majorana neutrinos
M_i	: Mass of Majorana
ℓ_f	: lepton doublet
H_{SM}	: SM Higgs doublet
$H_\alpha (\alpha = 1,2)$	: new Higgs doublet
M_{H_α}	: Mass of H_α
λ^{SM}, Y, λ	: coupling constant

The flow of this model to produce B

If q_e is conserved,



If q_e is not conserved,



result

Mass of each particle in this scenario

Non-thermal equilibrium condition of Higgs decay

Majorana Mass

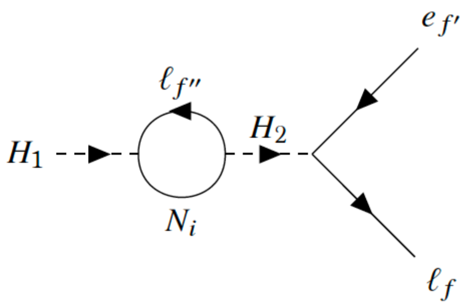
$M_1 \sim 10^5 \mathrm{GeV}$

Higgs Mass

$M_{H_1} \sim 10^{12} \mathrm{GeV}$

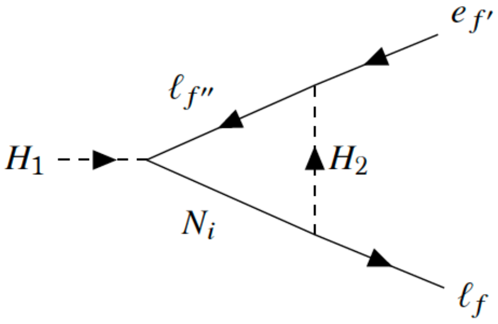
Final baryon asymmetry

observation : $\frac{q_B}{s} \sim 8.6 \times 10^{-11}$



$$\frac{q_B}{s} \sim 8 \times 10^{-11} \delta_{CP} \left(\frac{Y}{0.01} \right)^2$$

δ_{CP} : CP phase
Y : yukawa coupling



➡ **We probe baryon asymmetry in 3HDM**

Summary and Future Work

Summary

- In vanilla leptogenesis, some conditions such as “weak wash-out” are needed to produce enough amount of baryon asymmetry. However, we probe it **without** such conditions by using wash-in leptogenesis and three Higgs doublet model.
- In our scenario, Majorana mass and Higgs mass are 10^5GeV and 10^{12}GeV to produce enough baryon asymmetry.

According to the recent research [K. Schmitz, *et al.,* (2501.07634)], M_1 can be as small as $7\mathrm{TeV}$

Future Work

- How about the cases of other conserved quantities?(Higgs can be coupled to quarks.)
- Quantitative analysis by using Boltzmann equation

Back up

The condition to determine M_{H_1}

Suppose weak wash-out to produce enough q_e

⇔ $$1 \geq \frac{\Gamma}{H}\bigg|_{T=M_{H1}}$$

⇔ $$M_{H_1} \geq 10^{12}\,\mathrm{GeV}\left(\frac{Y}{0.01}\right)^2$$

Decay rate

$$\Gamma \sim \frac{1}{16\pi}\mathrm{tr}\left(Y^{1\dagger}Y^1\right)M_{H_1}$$

Hubble parameter

$$H = \sqrt{\frac{\pi^2}{90}g_*}\frac{T^2}{M_{pl}} \quad \text{(RD)}$$

Relation between B and B-L

Conserved quantities

$q_Y = 0$ ⟺ $\sum(\mu_{qi} + 2\mu_{ui} - \mu_{di} - \mu_{li} - \mu_{ei}) + 2\mu_H = 0$

$\frac{B}{3} - L_f \quad f = e, \mu, \tau$ ⟺ $\frac{1}{3}\sum(2\mu_{qi} + \mu_{ui} + \mu_{di}) - 2\mu_{lf} - \mu_f$

Equilibrium process

strong sphaleron ⟺ $\sum(2\mu_{qi} - \mu_{ui} - \mu_{di}) = 0$

Weak sphaleron ⟺ $\sum(3\mu_{qi} + \mu_{li}) = 0$

Up yukawa ⟺ $\mu_{qi} + \mu_H - \mu_{uj} = 0$

Down yukawa ⟺ $\mu_{qi} - \mu_H - \mu_{dj} = 0$

Charged lepton yukawa ⟺ $\mu_{li} - \mu_H - \mu_{ej} = 0$

⇒ $\boldsymbol{q_B = \frac{28}{79} q_{B-L}}$

$$q_X = \frac{g}{6} T^2 \begin{cases} \mu_X/T & \text{fermions} \\ 2\mu_X/T & \text{bosons} \end{cases}$$

Relation between B-L and q_e

10^5 GeV $< T <$ 10^6 GeV

Conserved quantity

$q_Y = 0$ ⟺ $\sum(\mu_{qi} + 2\mu_{ui} - \mu_{di} - \mu_{li} - \mu_{ei}) + 2\mu_H = 0$

q_{e1} ⟺ μ_{e1}

Equilibrium process

strong sphaleron ⟺ $\sum(2\mu_{qi} - \mu_{ui} - \mu_{di}) = 0$

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Charged yukawa ⟺ $\mu_{li} - \mu_H - \mu_{ej} = 0$

Nuetrino yukawa ⟺ $\boldsymbol{\mu_{li} - \mu_H = 0}$ $\mu_N = 0$

⟹ $\boldsymbol{q_{B-L} = -\frac{3}{10} q_{e1}}$

The amount of right-handed electron asymmetry

$$\frac{q_B}{s} = \frac{28}{79}\frac{q_{B-L}}{s} = -\frac{42}{395}\frac{q_e}{s}$$

Sphaleron equilibrium

$$q_B = \frac{28}{79} q_{B-L}$$

Neutrino yukawa equilibrium

$$q_{B-L} = -\frac{3}{10} q_e$$

$$\frac{q_B}{s} \sim 8.6\times 10^{-11}$$

$$\Rightarrow \quad \frac{q_e}{s} \simeq -8.1\times 10^{-10}$$

This is the value to explain today's baryon asymmetry！！

The production of q_e in 3HDM

$$\frac{q_e}{s} := \frac{n_e}{s} - \frac{n_{\bar{e}}}{s} = \frac{\Gamma_{\bar{H}_1 \to e\bar{\ell}}}{\Gamma_{H_1}}\frac{n_{\bar{H}_1}}{s} - \frac{\Gamma_{H_1 \to \bar{e}\ell}}{\Gamma_{H_1}}\frac{n_{H_1}}{s}$$

$$= -\frac{\Gamma_{H_1 \to \bar{e}\ell} - \Gamma_{\bar{H}_1 \to e\bar{\ell}}}{\Gamma_{H_1}}\frac{n_{H_1}}{s}$$

$$\simeq -\epsilon_{\bar{e}\ell} \times \frac{45\zeta(3)}{\pi^4}\frac{1}{g_*}$$

Assumption : Thermal production of H_1

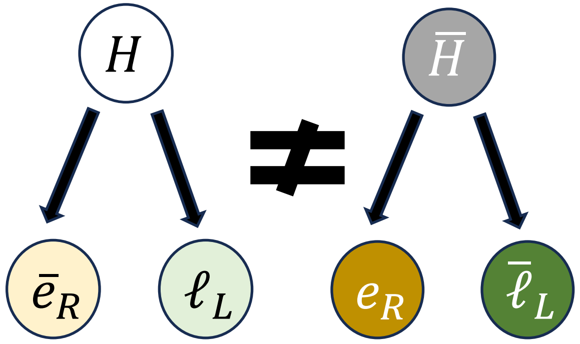
$$\frac{n_{H_1}}{s} = \frac{n_{\bar{H}_1}}{s} = \frac{45\zeta(3)}{\pi^4}\frac{1}{g_*} \qquad (T_{rh} > M_{H_1})$$

g_*: effective degrees of freedom

$$\Gamma_{H_1} := \Gamma_{H_1 \to \bar{e}\ell} + \Gamma_{H_1 \to \ell N}$$

$\epsilon_{\bar{e}\ell}$: asymmetry parameter (CP violation)

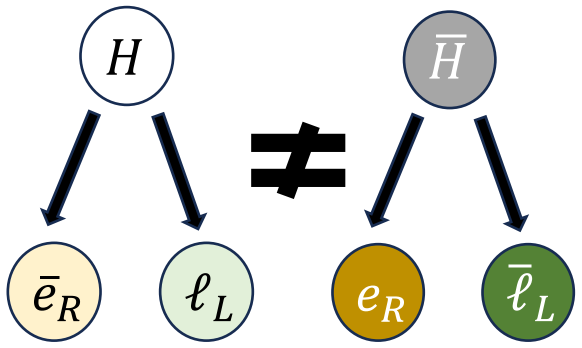
$$\epsilon_{\bar{e}\ell} := \frac{\Gamma_{H_1 \to \bar{e}\ell} - \Gamma_{\bar{H}_1 \to e\bar{\ell}}}{\Gamma_{H_1 \to \bar{e}\ell} + \Gamma_{\bar{H}_1 \to e\bar{\ell}}}$$

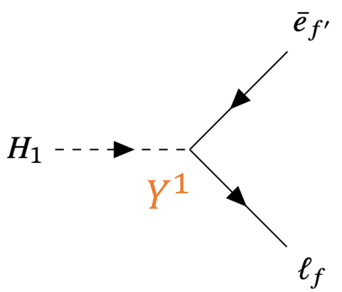


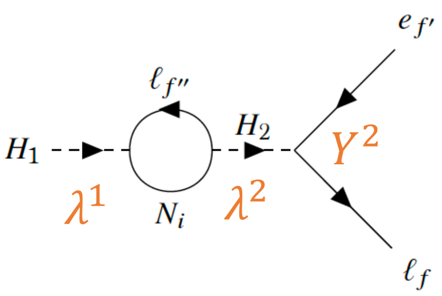
Asymmetry parameter

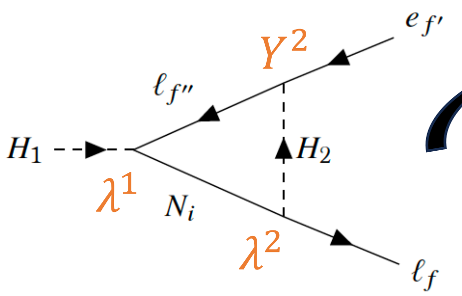
$\epsilon_{\bar{e}\ell}$: asymmetry parameter (CP violation)

$$\epsilon_{\bar{e}\ell} := \frac{\Gamma_{H_1\to\bar{e}\ell} - \Gamma_{\bar{H}_1\to e\bar{\ell}}}{\Gamma_{H_1\to\bar{e}\ell} + \Gamma_{\bar{H}_1\to e\bar{\ell}}}$$









We need to calculate one-loop to get ϵ

$$\Gamma^{(0)}_{H_1\to\bar{e}\ell} \sim \left|\boldsymbol{Y}^{\boldsymbol{1}}\right|^{\boldsymbol{2}} M_{H_1}$$

CP transformation

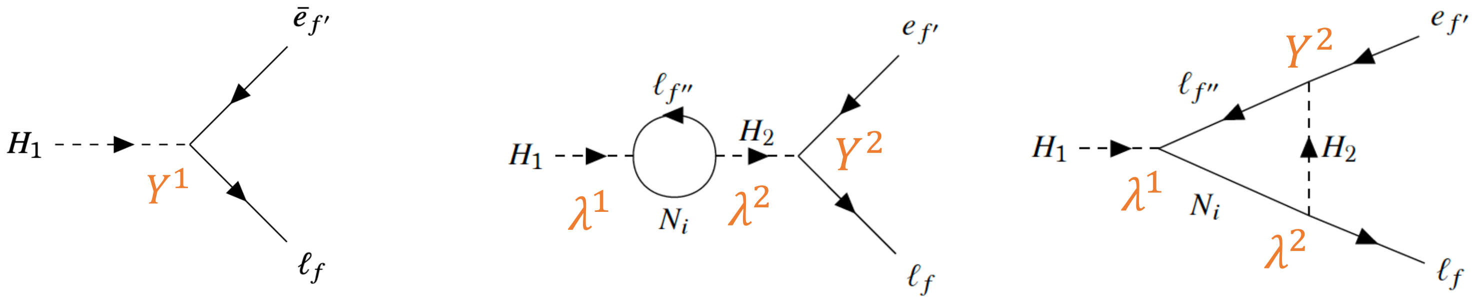
$$\Gamma^{(0)}_{\bar{H}_1\to e\bar{\ell}} \sim \left|\boldsymbol{Y}^{\boldsymbol{1}*}\right|^{\boldsymbol{2}} M_{H_1}$$

Asymmetry parameter comes from interference between tree and one-loop

$$\epsilon_{\bar{e}\ell} \propto \frac{\mathrm{Im}\left(Y^1_{11}Y^{2\dagger}_{11}\lambda^1_{11}\lambda^{2\dagger}_{11}\right)}{|\mathrm{Y}^1|^2}$$

$\mathrm{Im}(\cdots)$ ⟺ CP violation

Asymmetry parameter



$$\epsilon_{\bar{e}\ell} = \frac{1}{8\pi}\frac{\mathrm{Im}\left(Y^1_{11}Y^{2\dagger}_{11}\lambda^1_{11}\lambda^{2\dagger}_{11}\right)}{\mathrm{tr}\left(Y^{1\dagger}Y^1\right)}\left(\underbrace{\frac{1}{x^2-1}}_{\text{self}}+\underbrace{1-x^2\log\left(1+\frac{1}{x^2}\right)}_{\text{vertex}}\right)$$

self

vertex

$x = M_{H_2}/M_{H_1}$