Leptogenesis in gauged $U(1)_{L_\mu - L_\tau}$ model

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[Work in progress; arXiv:2212.*****]

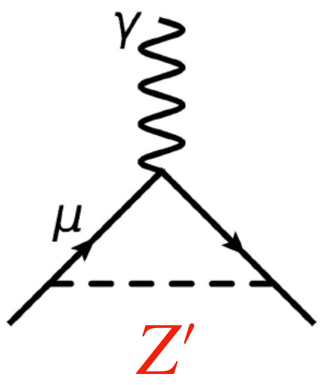
The Dark Side of the Universe DSU2022, Dec. 6, 2022
@ The University of New South Wales, Sydney, Australia

Muon g-2 and gauged $U(1)_{L_\mu - L_\tau}$ symmetry

Muon g-2 anomaly can be explained by an additional neutral gauge boson Z' in gauged $U(1)_{L_\mu - L_\tau}$ model

Deviation from the SM; 4.2σ

[The Muon g-2 Collaboration ('21)]



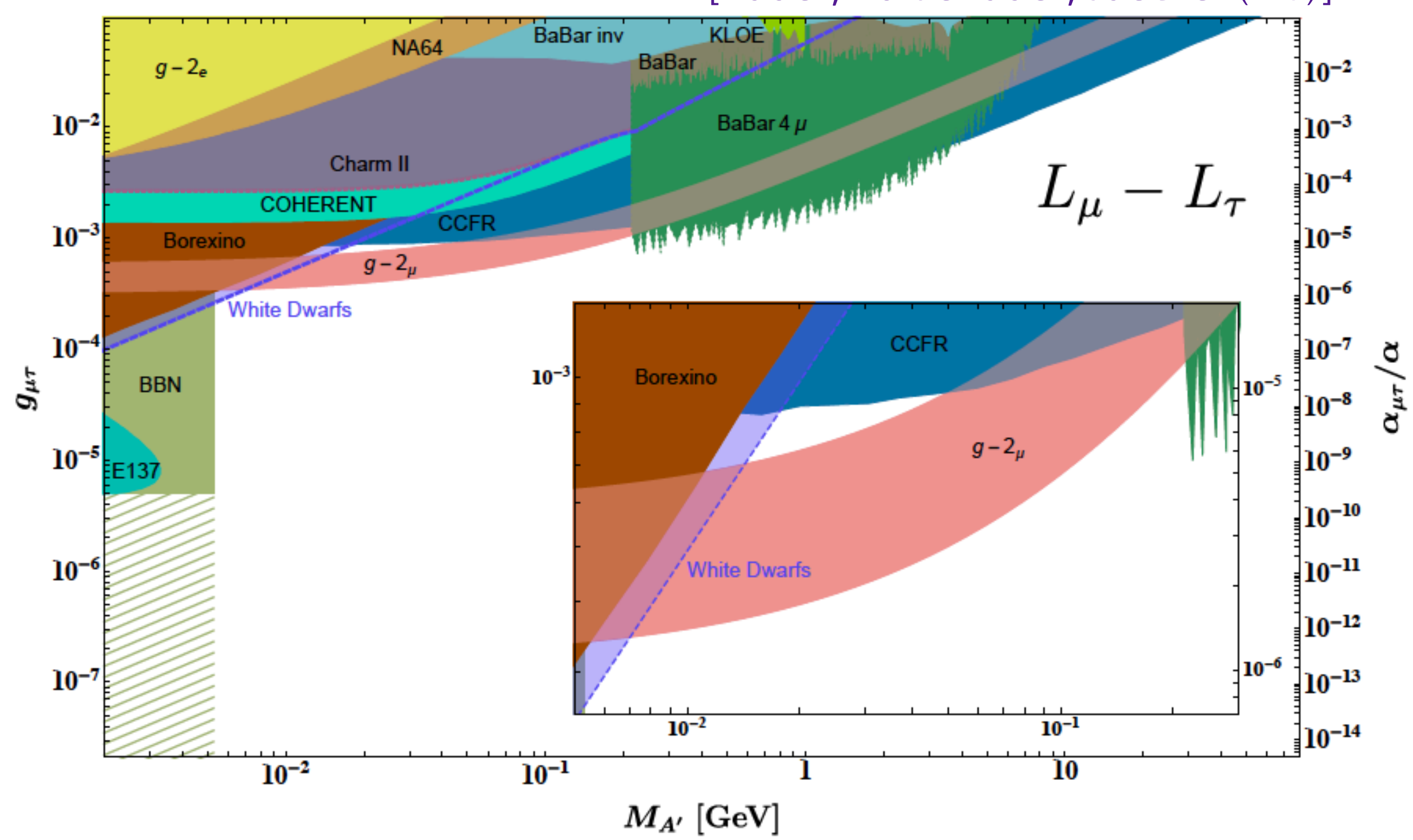
$$g_{Z'} \approx 10^{-3}$$

$$M_{Z'} \approx 10 - 100\,\mathrm{MeV}$$

Breaking scale

$$= \mathcal{O}(10)\,\mathrm{GeV}$$

[Bauer, Foldenauer, Jaeckel ('18)]



Charge assignment;

SM:	L_μ, μ_R	+1
	L_τ, τ_R	-1
	Others $(L_e, e_R, \cdots)$	0

3 Right-handed neutrinos (RHν's):

N_μ	+1
N_τ	-1
N_e	0

It is non-trivial if seesaw mechanism work under such a symmetry

Seesaw mechanism in gauged $U(1)_{L_\mu - L_\tau}$ model

Introducing $U(1)_{L_\mu - L_\tau}$ breaking scalar(s), the model can reproduce observed neutrino oscillations [Harigaya, Igari, Nojiri, Takeuchi, Tobe ('13)] [Asai, Hamaguchi, Nagata ('17)] [Asai, Hamaguchi, Nagata, Tseng, Tsumura ('18)]

Lagrangian for neutrino sector;

$$\mathscr{L}_\nu = -\lambda_\nu L_\alpha \tilde{\Phi} \bar{N}_\beta - \frac{M_R}{2} \bar{N}_\alpha \bar{N}_\beta - h_{e\mu}\sigma_1 \bar{N}_e \bar{N}_\mu - h_{e\tau}\sigma_1^* \bar{N}_e \bar{N}_\tau - \frac{1}{2} h_{\mu\mu}\sigma_2 \bar{N}_\mu \bar{N}_\mu - \frac{1}{2} h_{\tau\tau}\sigma_2^* \bar{N}_\tau \bar{N}_\tau \qquad (\alpha = e, \mu, \tau)$$

Scalars (Charge);

Φ (0)
σ_1 (+1)
σ_2 (+2)

Dirac Yukawa;

$$\lambda_\nu = \mathrm{diag}(\lambda_e, \lambda_\mu, \lambda_\tau)$$

Majorana mass;

$$M_R = \begin{pmatrix} M_{ee} & 0 & 0 \\ 0 & 0 & M_{\mu\tau} \\ 0 & M_{\mu\tau} & 0 \end{pmatrix} \xrightarrow{\text{SSB of } U(1)_{L_\mu - L_\tau}} \begin{pmatrix} M_{ee} & h_{e\mu}\langle\sigma_1\rangle & h_{e\tau}\langle\sigma_1\rangle \\ h_{e\mu}\langle\sigma_1\rangle & h_{\mu\mu}\langle\sigma_2\rangle & M_{\mu\tau} \\ h_{e\tau}\langle\sigma_1\rangle & M_{\mu\tau} & h_{\tau\tau}\langle\sigma_2\rangle \end{pmatrix}$$

ν mass matrix from seesaw: $m_\nu = -\langle\Phi\rangle^2 [\lambda_\nu M_R^{-1} \lambda_\nu^T]$

$$U_{\text{PMNS}}\, m_\nu\, U_{\text{PMNS}}^T = m_\nu^d = \mathrm{diag}(m_1, m_2, m_3)$$

Leptogenesis in gauged $U(1)_{L_\mu - L_\tau}$ model

It is natural to wonder if leptogenesis can work under the $U(1)_{L_\mu - L_\tau}$ in which neutrino masses and muon g-2 can be explained

In this work, we clarify

1) Which scale of Majorana mass parameters of RHν's $M_{ee}, M_{\mu\tau}$ are allowed from observed neutrino oscillations

$$\begin{pmatrix} \frac{M_{ee}}{\lambda_e^2} & \frac{h_{e\mu}\langle\sigma_1\rangle}{\lambda_e\lambda_\mu} & \frac{h_{e\tau}\langle\sigma_1\rangle}{\lambda_e\lambda_\tau} \\ \frac{h_{e\mu}\langle\sigma_1\rangle}{\lambda_e\lambda_\mu} & \frac{h_{\mu\mu}\langle\sigma_2\rangle}{\lambda_\mu^2} & \frac{M_{\mu\tau}}{\lambda_\mu\lambda_\tau} \\ \frac{h_{e\tau}\langle\sigma_1\rangle}{\lambda_e\lambda_\tau} & \frac{M_{\mu\tau}}{\lambda_\mu\lambda_\tau} & \frac{h_{\tau\tau}\langle\sigma_2\rangle}{\lambda_\tau^2} \end{pmatrix} = \langle\Phi\rangle^2 U_{\mathrm{PMNS}}\,[m_\nu^d]^{-1}\, U_{\mathrm{PMNS}}^T$$

$\longrightarrow$ Possible dynamics of leptogenesis

2) If the $U(1)_{L_\mu - L_\tau}$ symmetry is preserved or broken in early universe

For mass basis of RHν's, Yukawa couplings and masses in the exact and broken phases of $U(1)_{L_\mu - L_\tau}$ are completely different

1) Mass scale of right-handed neutrinos

M_{ee} and $M_{\mu\tau}$ are restricted from parameters of active neutrinos

$$\begin{pmatrix} \frac{M_{ee}}{\lambda_e^2} & \frac{h_{e\mu}\langle\sigma_1\rangle}{\lambda_e\lambda_\mu} & \frac{h_{e\tau}\langle\sigma_1\rangle}{\lambda_e\lambda_\tau} \\ \frac{h_{e\mu}\langle\sigma_1\rangle}{\lambda_e\lambda_\mu} & \frac{h_{\mu\mu}\langle\sigma_2\rangle}{\lambda_\mu^2} & \frac{M_{\mu\tau}}{\lambda_\mu\lambda_\tau} \\ \frac{h_{e\tau}\langle\sigma_1\rangle}{\lambda_e\lambda_\tau} & \frac{M_{\mu\tau}}{\lambda_\mu\lambda_\tau} & \frac{h_{\tau\tau}\langle\sigma_2\rangle}{\lambda_\tau^2} \end{pmatrix} = \langle\Phi\rangle^2 \underline{U_{\mathrm{PMNS}}\,[m_\nu^d]^{-1}\,U_{\mathrm{PMNS}}^T}$$

from oscillation parameters and Majorana phases

Non-zero entries give conditions for theoretical parameters

i) All non-zero;

$$\begin{cases} M_{ee}M_{\mu\tau} \simeq h_{e\mu}h_{e\tau}\langle\sigma_1\rangle^2 \\ M_{\mu\tau}^2 \simeq h_{\mu\mu}h_{\tau\tau}\langle\sigma_2\rangle^2 \end{cases} \longrightarrow \begin{cases} M_{ee} \simeq M_{\mu\tau} \lesssim 10^2\,\mathrm{GeV} \\ M_{ee} \gg 10^2\,\mathrm{GeV}\ \&\ M_{\mu\tau} \ll 10^2\,\mathrm{GeV} \end{cases}$$

$$\langle\sigma_{1,2}\rangle|_{\max} \simeq 100\,\mathrm{GeV}$$

ii) LHS(1,2),(2,2)=0;

(Normal ordering: NO)

$$M_{\mu\tau} \sim \lambda_\mu h_{e\tau}\langle\sigma_1\rangle\left(\frac{5\times10^{14}\,\mathrm{GeV}}{M_{ee}}\right)^{1/2} \lesssim 10^6\,\mathrm{GeV}\left(\frac{5\times10^{6}\,\mathrm{GeV}}{M_{ee}}\right)^{1/2}$$

2) Symmetry breaking of $U(1)_{L_\mu - L_\tau}$ in early universe

Sign of $\lambda_{\Phi\sigma}$ is important to decide the phase of $U(1)_{L_\mu - L_\tau}$ in early universe

Potential; $V(\sigma, \Phi) = -\mu_\sigma^2 |\sigma|^2 - \mu_\Phi^2 \Phi^\dagger \Phi + \lambda_\sigma |\sigma|^4 + \lambda_\Phi \left(\Phi^\dagger \Phi\right)^2 + \lambda_{\Phi\sigma} |\sigma|^2 (\Phi^\dagger \Phi)$

$(\mu_\sigma, \mu_\Phi, \lambda_\sigma, \lambda_\Phi) > 0$

Thermal and finite density effects $m_{\text{eff}}^2(T)$;

$$V(\sigma) = (-\mu_\sigma^2 + m_{\text{eff}}^2(T))\,|\sigma|^2 + \lambda_\sigma |\sigma|^4$$

$\begin{cases} \geq 0; \text{ Symmetric} \\ < 0; \text{ Broken} \end{cases}$

a) $T \leq T_{\text{th}} = 6 \times 10^4\,\text{GeV}(g_{Z'}/10^{-3})^4$;

$$m_{\text{eff}}^2(T) = \left(\frac{\lambda_\sigma}{6} + \frac{\lambda_{\Phi\sigma}}{24} + \frac{g_{Z'}^2}{8} + \cdots \right) T^2$$

b) $T > T_{\text{th}}$; $m_{\text{eff}}^2(T) = \sum_X C_X n_X \langle p_{X,0}{}^{-1} \rangle$

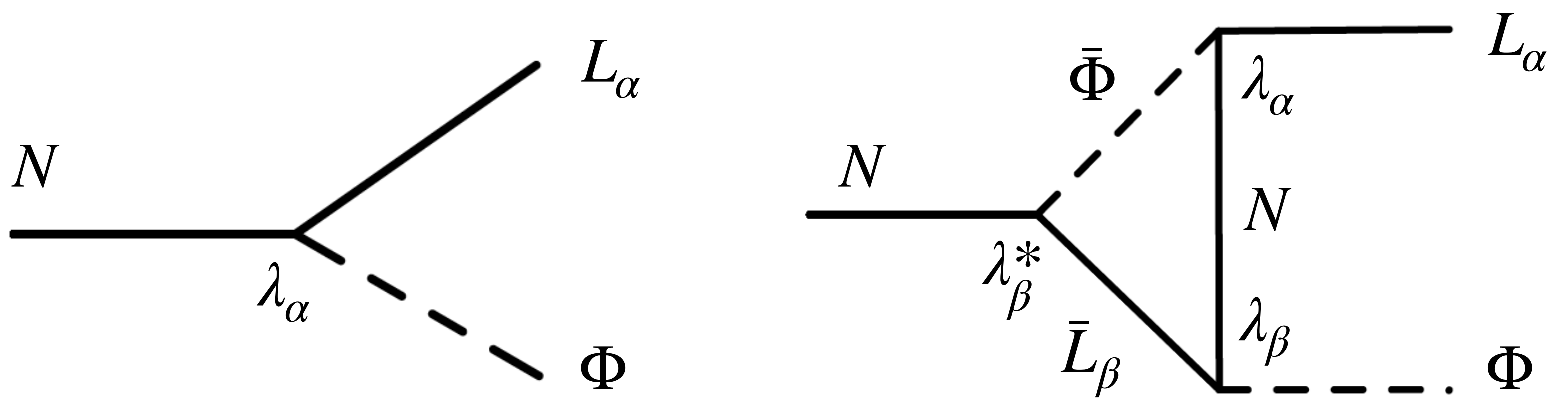
e.g. $m_{\text{eff}}^2(T)|_{\lambda_\sigma} \simeq c \dfrac{\lambda_\sigma g_{Z'}^4}{4\pi} M_P T$

$\longrightarrow \begin{cases} \lambda_{\Phi\sigma} > 0 & \text{; Symmetric at } T > \langle\sigma\rangle = \mathcal{O}(10)\ \text{GeV} \\ \lambda_{\Phi\sigma} < 0 \text{ \& dominant; Broken at } T > T_{\text{EW}} & \text{\& } \langle\sigma\rangle(T) \simeq \sqrt{\lambda_{\Phi\sigma}/\lambda_\sigma}\,T \end{cases}$

Leptogenesis in symmetric phase of $U(1)_{L_\mu - L_\tau}$

Due to the flavor charge, any leptogenesis cannot work in the symmetric phase of $U(1)_{L_\mu - L_\tau}$

Decaying leptogenesis [Fukugita, Yanagida ('86)]



$Y_{B-L} = \epsilon Y_N$; Asymmetric parameter $\epsilon = \dfrac{\Gamma(N \to L\Phi) - \Gamma(N \to \bar{L}\bar{\Phi})}{\Gamma(N \to L\Phi) + \Gamma(N \to \bar{L}\bar{\Phi})}$

$(Y_X = n_X / s)$

$$\epsilon \propto \mathrm{Im}[\,|\lambda_e|^4\,] \text{ or } \mathrm{Im}[\,|\lambda_\mu|^2 |\lambda_\tau|^2\,] = 0$$

Oscillating leptogenesis [Akhmedov, Rubakov, Smirnov ('98)] [Asaka, Shaposhnikov ('05)]

RHν's cannot oscillate because they are states with different charges under $U(1)_{L_\mu - L_\tau}$

Leptogenesis in broken phase of $U(1)_{L_\mu - L_\tau}$

In broken phase of $U(1)_{L_\mu - L_\tau}$ in early universe from the negative $\lambda_{\Phi\sigma}$, physical mass and couplings of RHν's are T-dependent

$$M_R = \begin{pmatrix} M_{ee} & h_{e\mu}\langle\sigma_1\rangle(T) & h_{e\tau}\langle\sigma_1\rangle(T) \\ h_{e\mu}\langle\sigma_1\rangle(T) & h_{\mu\mu}\langle\sigma_2\rangle(T) & M_{\mu\tau} \\ h_{e\tau}\langle\sigma_1\rangle(T) & M_{\mu\tau} & h_{\tau\tau}\langle\sigma_2\rangle(T) \end{pmatrix} \longrightarrow \begin{cases} \tilde{M}_R(T) = \Omega(T)\, M_R\, \Omega^T(T) \\ \qquad = \mathrm{diag}(M_1(T), M_2(T), M_3(T)) \\ [\tilde{\lambda}_\nu]_{\alpha I}(T) = \lambda_\nu\, \Omega^*(T) \\ [\tilde{h}]_{IJ}(T) = \Omega(T)\, h_{\alpha\beta}\, \Omega^*(T) \end{cases}$$

Non-thermal leptogenesis; [Kumekawa, Moroi, Yanagida ('94)] [Asaka, Hamaguchi, Kawasaki, Yanagida ('99)]

Inflaton φ decay $\longrightarrow$ thermal plasma with SM particles & RHν's

↓ Cosmic temperature; T

↓ If $M_I \gg T_R$, Decay @ $T = T_R$

$$Y_{B-L} = \sum_I 2\, Br(\varphi \to 2N_I) Br(N_I \to L\Phi)\, \epsilon_I \frac{T_R}{m_\varphi}$$

Setup of numerical analysis

We evaluate leptogenesis numerically with the following parameter set

Benchmark; (NO)

Case ii) for $M_{ee}, M_{\mu\tau}$ $(M_{ee} \sim M_{\mu\tau} \sim 10^6$ GeV)

$$m_l = 0.06 \text{ eV}\,, \quad \Delta m^2_{\rm sol} = 7.42 \times 10^{-5} \text{ eV}^2\,, \quad \Delta m^2_{\rm atm} = 2.510 \times 10^{-3} \text{ eV}^2\,,$$

$$\sin^2\theta_{12} = 0.304\,, \quad \sin^2\theta_{13} = 0.02246\,, \quad \sin^2\theta_{23} \simeq 0.565$$

$$\delta \simeq 268^\circ\,, \quad \eta_1 \simeq 355^\circ\,, \quad \eta_2 \simeq 177^\circ \quad \langle\sigma_{1,2}\rangle = 100\,\text{GeV}$$

(orange) ; Center

(green) ; 2σ

(magenta) ; CP phases

[Esteban, Gonzalez-Garcia, Maltoni, Schwetz, Zhou ('20)]

$\longrightarrow$ $h_{e\mu} \approx 0, h_{\mu\mu} \approx 0$

For $\lambda_\mu \approx 1$,

$$\begin{cases} M_{ee} \simeq (5 - 0.1i) \times 10^6\,\text{GeV} \\ M_{\mu\tau} \simeq (-1 + 0.1i) \times 10^7\,\text{GeV} \end{cases}$$

$\lambda_e, \lambda_\tau \ll \lambda_\mu$ and $h_{\tau\tau} \ll h_{e\tau} \sim \mathcal{O}(1)$

At high temperature $T = T_R = 10^5\,\text{GeV}$, for $\langle\sigma_{1,2}\rangle(T_R) = 10^5\,\text{GeV}$,

$$(M_1(T_R), M_2(T_R), M_3(T_R)) \simeq (5 \times 10^6, 10^7, 10^7)\,\text{GeV}$$

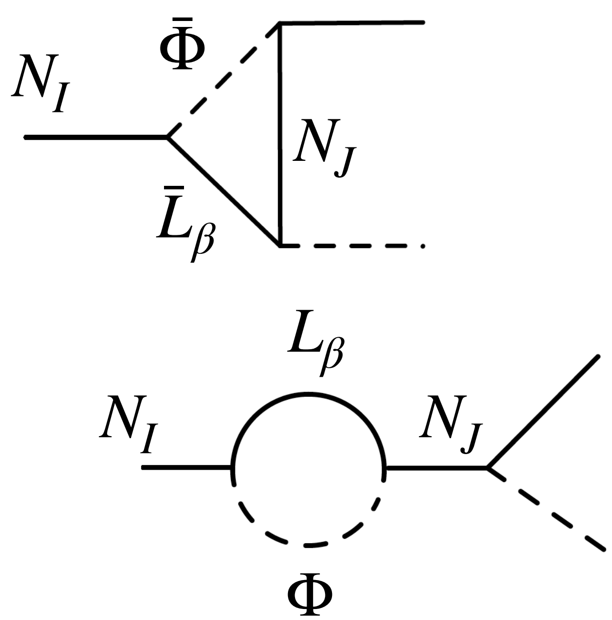
Results

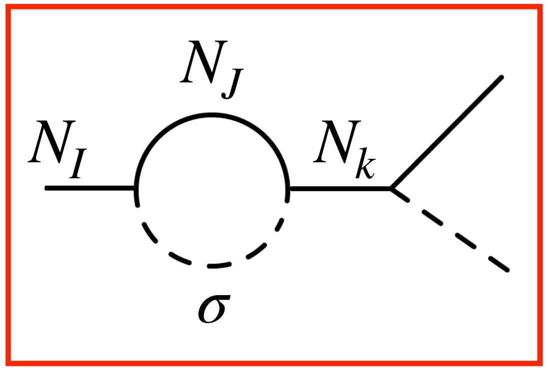
Large enough lepton asymmetry can be generated by non-thermal leptogenesis in broken phase of $U(1)_{L_\mu - L_\tau}$

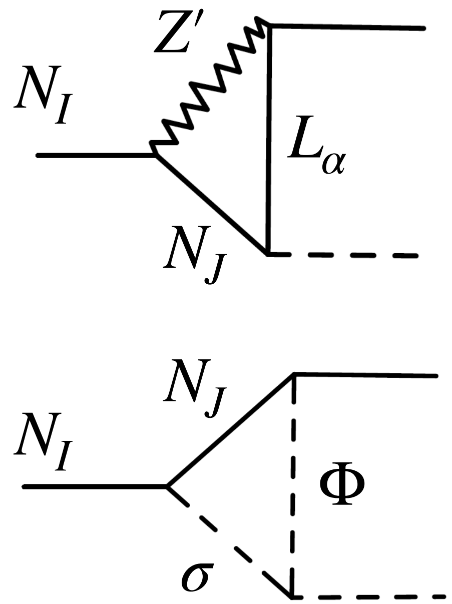
$N_I \to L_\alpha \Phi$;

(NO)

$$\begin{cases} Y_B \simeq -\dfrac{28}{79} Y_{B-L} \\ Y_B^{\rm obs} \simeq 10^{-10} \end{cases}$$







N_1	$\epsilon \simeq +6 \times 10^{-7}$	—
N_2	$\epsilon \simeq -6 \times 10^{-8}$	$\epsilon \simeq -3 \times 10^{-6}$
N_3	$\epsilon \simeq +6 \times 10^{-8}$	$\epsilon \simeq -7 \times 10^{-6}$

Observed baryon asymmetry of the universe can be explained

Summary

We show that non-thermal leptogenesis in gauged $U(1)_{L_\mu - L_\tau}$ model can work, and thus neutrino oscillation, baryon asymmetry of the universe, and muon g-2 can be explained at the same time

In near future, this scenario will be proved with

i) NA64 experiment will prove Z'

ii) CMB constraint on Σm_i;

$$m_{\rm lightest} = 0.06 \text{ eV} \longrightarrow \Sigma m_i = 0.2 \text{ eV} \longleftrightarrow \Sigma m_i < 0.24 \text{ eV}$$

[Planck Collaboration ('18)]

iii) $m_{\beta\beta}$ in neutrioless double beta decay;

$$m_{\beta\beta} \approx 61 \text{ meV} \longleftrightarrow m_{\beta\beta} < 36 \text{ - } 156 \text{ meV}$$

[KamLAND-Zen Collaboration ('22)]

Backup

Global fit of neutrino oscillation parameters

NuFIT 5.1 (2021)

		Normal Ordering (best fit)		Inverted Ordering ($\Delta\chi^2 = 2.6$)	
		bfp $\pm 1\sigma$	3σ range	bfp $\pm 1\sigma$	3σ range
without SK atmospheric data	$\sin^2\theta_{12}$	$0.304^{+0.013}_{-0.012}$	$0.269 \to 0.343$	$0.304^{+0.012}_{-0.012}$	$0.269 \to 0.343$
	$\theta_{12}/^\circ$	$33.44^{+0.77}_{-0.74}$	$31.27 \to 35.86$	$33.45^{+0.77}_{-0.74}$	$31.27 \to 35.87$
	$\sin^2\theta_{23}$	$0.573^{+0.018}_{-0.023}$	$0.405 \to 0.620$	$0.578^{+0.017}_{-0.021}$	$0.410 \to 0.623$
	$\theta_{23}/^\circ$	$49.2^{+1.0}_{-1.3}$	$39.5 \to 52.0$	$49.5^{+1.0}_{-1.2}$	$39.8 \to 52.1$
	$\sin^2\theta_{13}$	$0.02220^{+0.00068}_{-0.00062}$	$0.02034 \to 0.02430$	$0.02238^{+0.00064}_{-0.00062}$	$0.02053 \to 0.02434$
	$\theta_{13}/^\circ$	$8.57^{+0.13}_{-0.12}$	$8.20 \to 8.97$	$8.60^{+0.12}_{-0.12}$	$8.24 \to 8.98$
	$\delta_{CP}/^\circ$	194^{+52}_{-25}	$105 \to 405$	287^{+27}_{-32}	$192 \to 361$
	$\frac{\Delta m^2_{21}}{10^{-5}\ \mathrm{eV}^2}$	$7.42^{+0.21}_{-0.20}$	$6.82 \to 8.04$	$7.42^{+0.21}_{-0.20}$	$6.82 \to 8.04$
	$\frac{\Delta m^2_{3\ell}}{10^{-3}\ \mathrm{eV}^2}$	$+2.515^{+0.028}_{-0.028}$	$+2.431 \to +2.599$	$-2.498^{+0.028}_{-0.029}$	$-2.584 \to -2.413$
		Normal Ordering (best fit)		Inverted Ordering ($\Delta\chi^2 = 7.0$)	
		bfp $\pm 1\sigma$	3σ range	bfp $\pm 1\sigma$	3σ range
with SK atmospheric data	$\sin^2\theta_{12}$	$0.304^{+0.012}_{-0.012}$	$0.269 \to 0.343$	$0.304^{+0.013}_{-0.012}$	$0.269 \to 0.343$
	$\theta_{12}/^\circ$	$33.45^{+0.77}_{-0.75}$	$31.27 \to 35.87$	$33.45^{+0.78}_{-0.75}$	$31.27 \to 35.87$
	$\sin^2\theta_{23}$	$0.450^{+0.019}_{-0.016}$	$0.408 \to 0.603$	$0.570^{+0.016}_{-0.022}$	$0.410 \to 0.613$
	$\theta_{23}/^\circ$	$42.1^{+1.1}_{-0.9}$	$39.7 \to 50.9$	$49.0^{+0.9}_{-1.3}$	$39.8 \to 51.6$
	$\sin^2\theta_{13}$	$0.02246^{+0.00062}_{-0.00062}$	$0.02060 \to 0.02435$	$0.02241^{+0.00074}_{-0.00062}$	$0.02055 \to 0.02457$
	$\theta_{13}/^\circ$	$8.62^{+0.12}_{-0.12}$	$8.25 \to 8.98$	$8.61^{+0.14}_{-0.12}$	$8.24 \to 9.02$
	$\delta_{CP}/^\circ$	230^{+36}_{-25}	$144 \to 350$	278^{+22}_{-30}	$194 \to 345$
	$\frac{\Delta m^2_{21}}{10^{-5}\ \mathrm{eV}^2}$	$7.42^{+0.21}_{-0.20}$	$6.82 \to 8.04$	$7.42^{+0.21}_{-0.20}$	$6.82 \to 8.04$
	$\frac{\Delta m^2_{3\ell}}{10^{-3}\ \mathrm{eV}^2}$	$+2.510^{+0.027}_{-0.027}$	$+2.430 \to +2.593$	$-2.490^{+0.026}_{-0.028}$	$-2.574 \to -2.410$

[Esteban, Gonzalez-Garcia, Maltoni, Schwetz, Zhou ('20); NuFIT 5.1 (2021), www.nu-fit.org]