New Constraints on Gaguged $U(1)_{L_\mu - L_\tau}$ Model via Z-Z' Mixing

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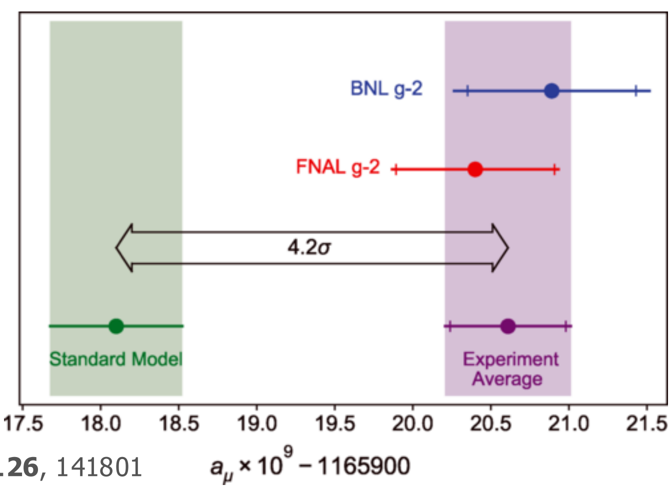
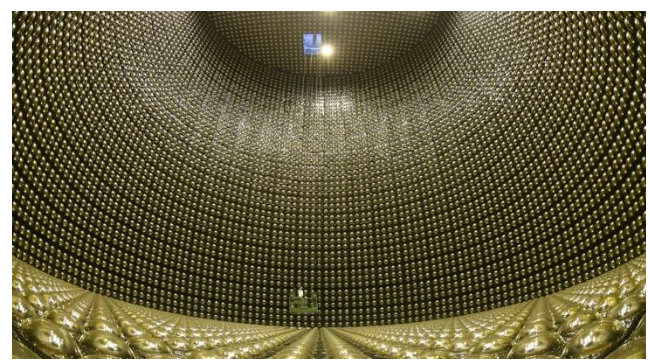
Background

- The recent experiments of the neutrino oscillation become more precise.
  → The simple $\mathrm{U}(1)_{L_\mu - L_\tau}$ gauge models seem hard to describe the neutrino physics.
- The discrepancy of muon g-2 between the SM and experimental results exist.
  → $\mathrm{U}(1)_{L_\mu - L_\tau}$ gauge models can explain.



Cited from
Phys. Rev. Lett. **126**, 141801



Cited from https://www-sk.icrr.u-tokyo.ac.jp/sk/

Purpose

- To find what is the minimum $\mathrm{U(1)}_{L_\mu - L_\tau}$ gauge model based on the latest experimental results.
- To study details of the model.

		Normal Ordering (best fit)		Inverted Ordering ($\Delta\chi^2 = 6.4$)	
		bfp $\pm 1\sigma$	3σ range	bfp $\pm 1\sigma$	3σ range
with SK atmospheric data	$\sin^2\theta_{12}$	$0.303^{+0.012}_{-0.012}$	$0.270 \to 0.341$	$0.303^{+0.012}_{-0.011}$	$0.270 \to 0.341$
	$\theta_{12}/^\circ$	$33.41^{+0.75}_{-0.72}$	$31.31 \to 35.74$	$33.41^{+0.75}_{-0.72}$	$31.31 \to 35.74$
	$\sin^2\theta_{23}$	$0.451^{+0.019}_{-0.016}$	$0.408 \to 0.603$	$0.569^{+0.016}_{-0.021}$	$0.412 \to 0.613$
	$\theta_{23}/^\circ$	$42.2^{+1.1}_{-0.9}$	$39.7 \to 51.0$	$49.0^{+1.0}_{-1.2}$	$39.9 \to 51.5$
	$\sin^2\theta_{13}$	$0.02225^{+0.00056}_{-0.00059}$	$0.02052 \to 0.02398$	$0.02223^{+0.00058}_{-0.00058}$	$0.02048 \to 0.02416$
	$\theta_{13}/^\circ$	$8.58^{+0.11}_{-0.11}$	$8.23 \to 8.91$	$8.57^{+0.11}_{-0.11}$	$8.23 \to 8.94$
	$\delta_{\mathrm{CP}}/^\circ$	232^{+36}_{-26}	$144 \to 350$	276^{+22}_{-29}	$194 \to 344$
	$\frac{\Delta m^2_{21}}{10^{-5}\ \mathrm{eV}^2}$	$7.41^{+0.21}_{-0.20}$	$6.82 \to 8.03$	$7.41^{+0.21}_{-0.20}$	$6.82 \to 8.03$
	$\frac{\Delta m^2_{3\ell}}{10^{-3}\ \mathrm{eV}^2}$	$+2.507^{+0.026}_{-0.027}$	$+2.427 \to +2.590$	$-2.486^{+0.025}_{-0.028}$	$-2.570 \to -2.406$

From NuFIT v5.2

The Simplest Model

- Fields：SM + Right-handed Neutrinos N_i + Scalar
- Symmetry：SM gauge × $\mathrm{U}(1)_{L_\mu - L_\tau}$ gauge

Leptons	$(\mathrm{L}_e\ \mathrm{L}_\mu\ \mathrm{L}_\tau)$	$(e_R\ \mu_R\ \tau_R)$	$(N_e\ N_\mu\ N_\tau)$
$\mathrm{U}(1)_{L_\mu - L_\tau}$charge	(0 +1 -1)	(0 +1 -1)	(0 +1 -1)

Scalar	Φ_{+1} SU(2) doublet	Φ_{-1} SU(2) doublet
$\mathrm{U}(1)_{L_\mu - L_\tau}$charge	+1	-1

Neutrino Mass Matrix

- Neutrino mass matrix through Seesaw Mech;

Model with Φ_{+1})

$$\mathcal{M}_\nu \simeq -\mathcal{M}_D \mathcal{M}_R^{-1} \mathcal{M}_D^T = \begin{pmatrix} * & 0 & * \\ 0 & 0 & * \\ * & * & * \end{pmatrix}$$

$$\mathcal{M}_D = \frac{1}{\sqrt{2}} \begin{pmatrix} \lambda_e v_1 & \lambda_{e\mu} v_2 & 0 \\ 0 & \lambda_\mu v_1 & 0 \\ \lambda_{\tau e} v_2 & 0 & \lambda_\tau v_1 \end{pmatrix}, \quad \mathcal{M}_R = \begin{pmatrix} M_{ee} & 0 & 0 \\ 0 & 0 & M_{\mu\tau} \\ 0 & M_{\mu\tau} & 0 \end{pmatrix}$$

- General form by PMNS matrix.

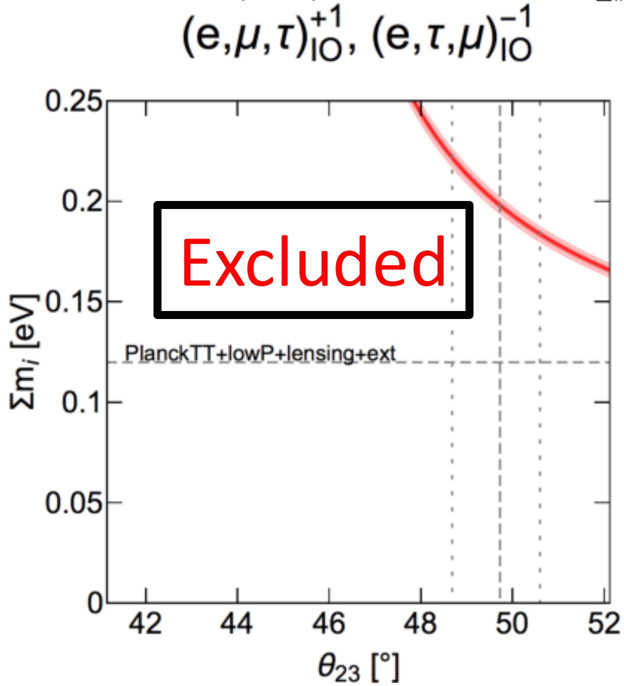
$$\mathcal{M}_\nu = U^* \mathrm{diag}(m_1, m_2, m_3) U^\dagger$$ (3×3 components)

➡ **Analysis using an equation obtained by comparing the component that is zero by symmetry with the corresponding component.**

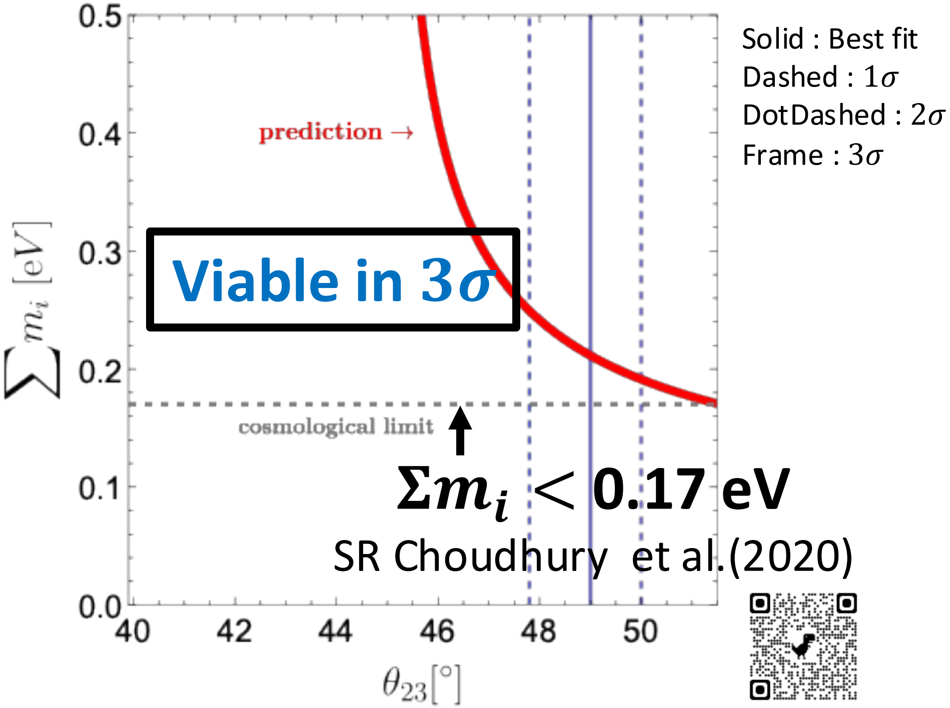
One of Results
(Model with Φ_{+1}, Inverted Ordering)

- Previous Work

From K.Asai et al. (2018) based on NuFIT4.0



- Our Results



- The range of θ_{23} moves to the left in NuFITv5.2.
- The limit on the sum of masses for the mass hierarchy is relaxed compared to the previous limit.
- The model survives in the 3 σ range in our analysis.

Summary of analysis results

- Results of analysis assuming forward and inverse hierarchies for each model.

Model	Normal Ordering	Inverted Ordering
SM $+ \mathrm{N}_i + \Phi_{+1}$	Excluded (Excluded)	Viable in 3σ (Excluded)
SM $+ \mathrm{N}_i + \Phi_{-1}$	Excluded (Excluded)	Excluded (Excluded)

Our Results
(K.Asai et al. (2018))

- The model have survived in the latest analysis.

→ Other Constraints?

Z-Z' Mixing

- Z-Z' mixing is induced by additional $\mathrm{U}(1)_{L_\mu - L_\tau}$ gauge symmetry.

$$\mathcal{L}_{\text{gauge}} = -\frac{1}{4}B_{\mu\nu}B^{\mu\nu} - \frac{1}{4}Z'_{\mu\nu}Z'^{\mu\nu} + \frac{1}{2}\frac{\varepsilon}{\cos\theta_W}B_{\mu\nu}Z'^{\mu\nu}$$

$$\mathcal{L}_{\varepsilon_Z} = \frac{m_Z^2}{2}\begin{pmatrix} Z_\mu & Z'_\mu \end{pmatrix}\begin{pmatrix} 1 & -\varepsilon_Z \\ -\varepsilon_Z & m_{Z'}^2/m_Z^2 \end{pmatrix}\begin{pmatrix} Z^\mu \\ Z'^\mu \end{pmatrix}$$

$$\mathcal{L} \supset Z'_\mu \left(g_{Z'} J^\mu_{L_\mu - L_\tau} + \varepsilon e J^\mu_{\text{em}} + \varepsilon_Z g_Z J^\mu_{\text{NC}} \right)$$

G_F and $\sin^2\theta_W$ are changed.

(In our works, the kinetic mixing $\varepsilon \sim g_{Z'}/70$ is negligible because it is much smaller than mass mixing ε_Z in our parameter region.)

Atomic Parity Violation (APV)

- The weak charge of Cs from APV experiment:

$$Q_{\mathrm{W}}^{\mathrm{exp}}({}^{133}_{55}\mathrm{Cs}) = -72.94(43)$$

M. Cadeddu et al. (2021)

- Changing of the Cs weak charge induces by Z-Z' mixing is characterized by $\delta \equiv \frac{\mathrm{m_Z}}{m_{Z'}} \varepsilon_Z$:

$$Q_W({}^{133}_{55}\mathrm{Cs}) \simeq Q_W^{\mathrm{SM}}({}^{133}_{55}\mathrm{Cs}) \left(1 + \delta^2\right)$$

$$|\delta|^2 \lesssim 5.7 \times 10^{-3}$$

(90% CL)

Flavor Changing Meson Decay (FCMD)

- Flavor changing meson decay is the good probe of Z' boson.

- Branching ratio of $K^+ \to \pi^+ Z'$ is characterized by $\delta \equiv \frac{\mathrm{m_Z}}{m_{Z'}} \varepsilon_Z$:

$$\mathrm{Br}(K^+ \to \pi^+ Z') = 6.2 \times 10^{-4} \times \underline{\delta^2} \times \left[X1(m_{H^+}) + \frac{X2(m_{H^+})}{\tan^2\beta} \right] \sqrt{\lambda(m_K^2, m_\pi^2, m_{Z'}^2)}$$

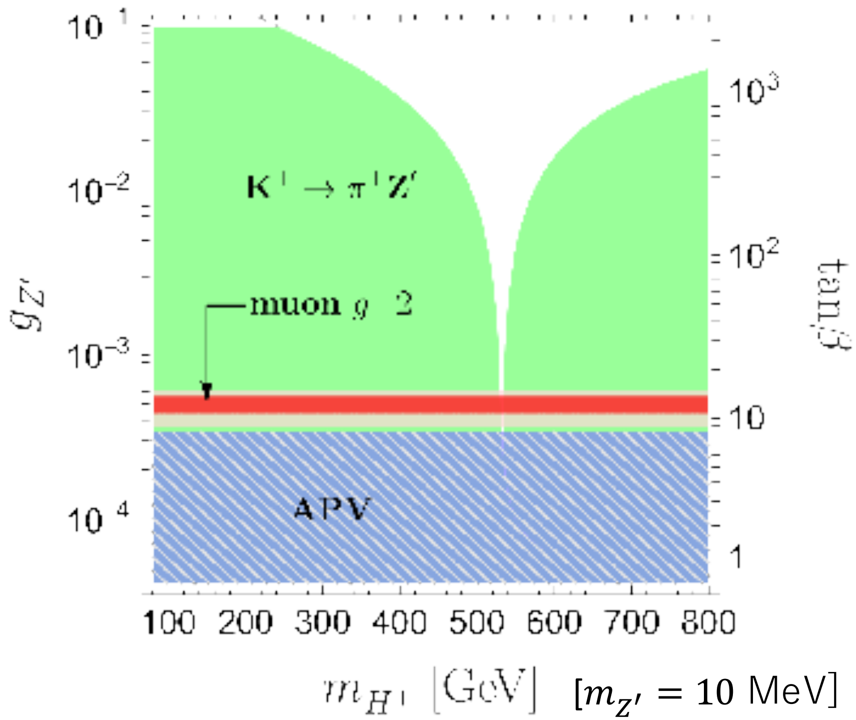
$X1, X2$: loop function $\quad \tan\beta = v_1/v_2 \quad \lambda(a,b,c) \equiv a^2 + b^2 + c^2 - 2ab - 2bc - 2ca$

- The experimental limit :

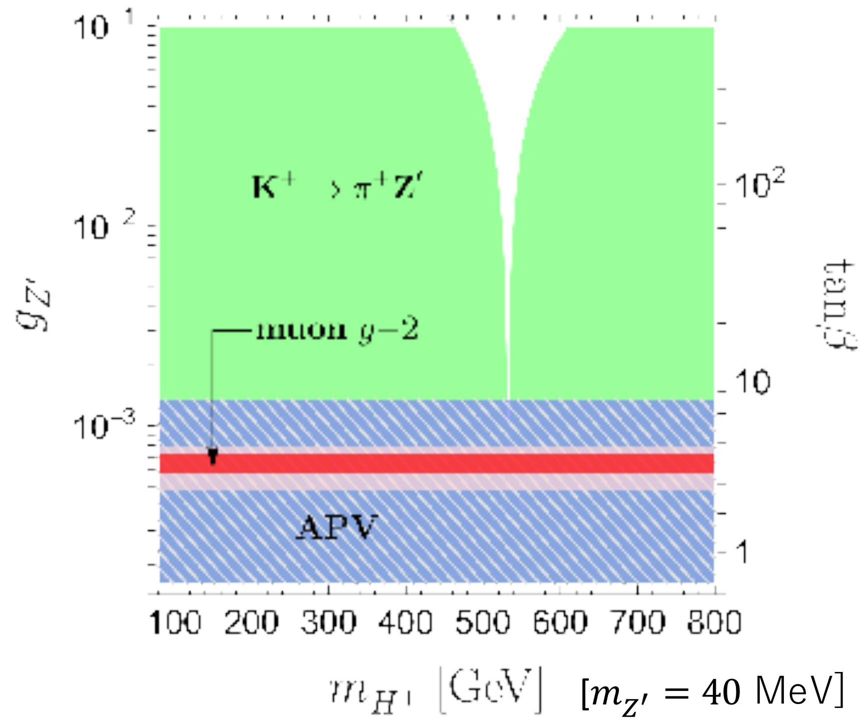
$$\mathrm{Br}(K^+ \to \pi^+ Z') \leq (1-6) \times 10^{-11} \quad \text{(90\% CL)}$$

The NA62 collaboration(2021)

Constraints on the simplest model (with Φ_{+1})



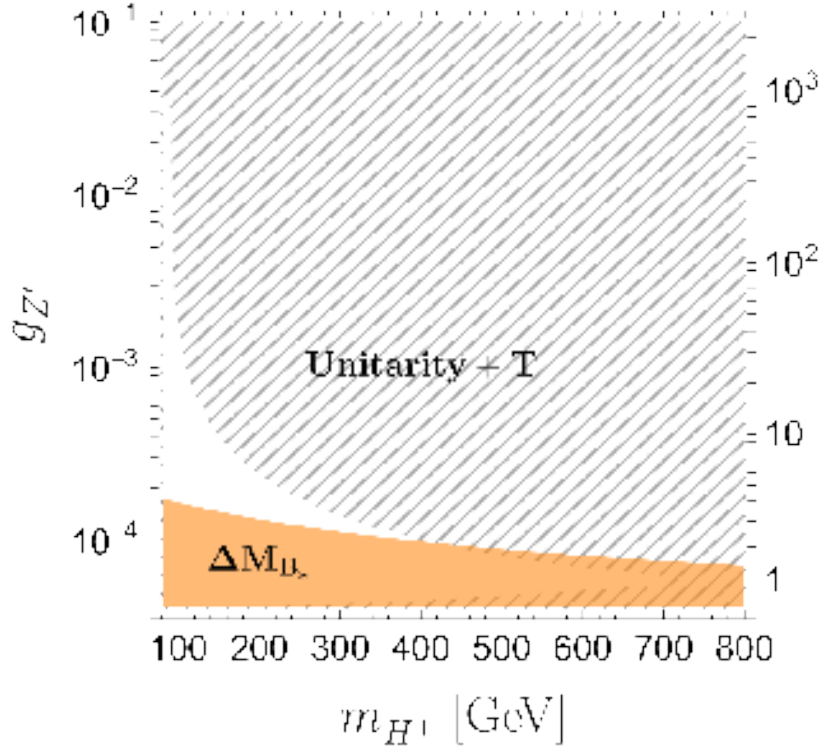
[$m_{Z'}$ = 10 MeV]



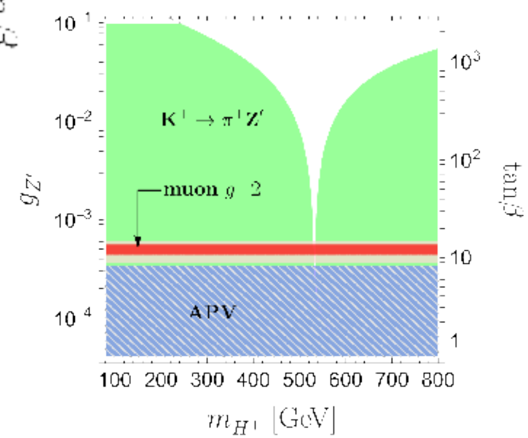
[$m_{Z'}$ = 40 MeV]

- Mixing parameter is $\delta = \frac{1}{v}\frac{m_{Z'}}{g_{Z'}}$.
- Green region(FCMD) and blue hatched region(APV) are excluded.
- At $m_{Z'} = 10$ MeV, there seems to exist the viable region.

Constraints from the Higgs Sector



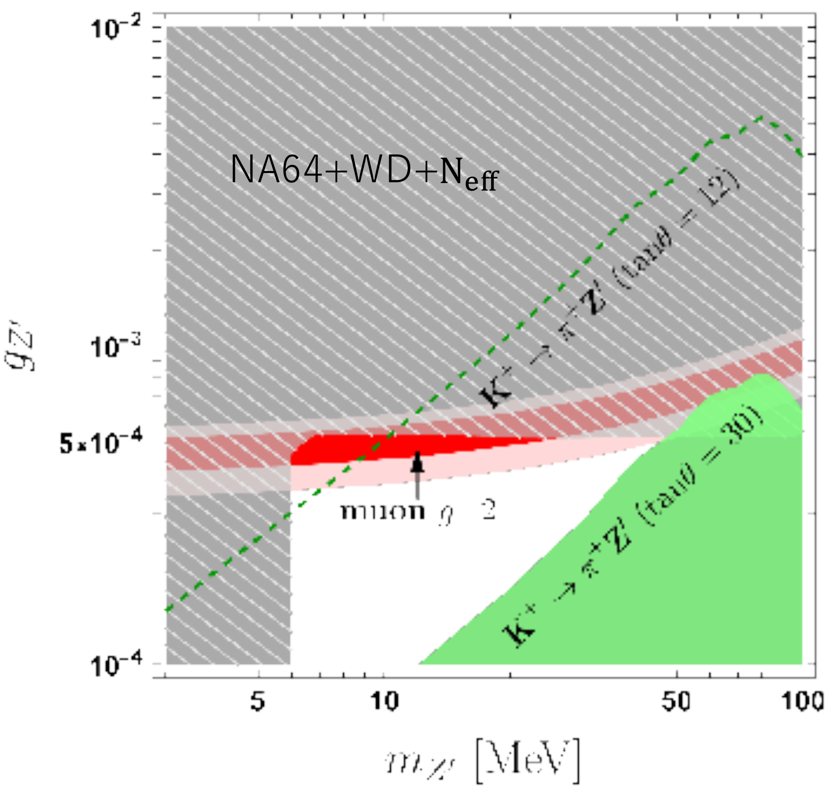
$[m_{Z'} = 10 \text{ MeV}]$



- The hatced region(Unitarity, T parameter) and the orange region(B meson oscillation[A.Giorgi et al. (2023)]) are excluded.
- **The simplest model is completely excluded.**

Constraint on the extended model (with Φ_{+1}, σ_{+1})

$[m_{H^+} = 300\ \text{GeV}]$



Φ_{+1}: SU(2) doublet scalar
σ_{+1}: SU(2) singlet scalar
(The subscription means $\mathrm{U}(1)_{L_\mu - L_\tau}$ charge.)

In this model, $\delta = \dfrac{\text{sign}(Q_\Phi)}{1+\tan^2\theta}\dfrac{1}{v}\dfrac{m_{Z'}}{g_{Z'}}$

$\tan\theta \equiv \dfrac{v_\sigma}{v_\Phi}$ ($v_{\Phi(\sigma)}$ is vev of $\Phi(\sigma)$).

Cs APV : Much smaller than FCMD.

$$g_{Z'} \gtrsim \frac{5.4\times10^{-4}}{1+\tan^2\theta}\left(\frac{m_{Z'}}{10\,\text{MeV}}\right)$$

$K^+ \to \pi^+ Z'$:

$$g_{Z'} \gtrsim \frac{1.6\times10^{-1}}{1+\tan^2\theta}\sqrt{\frac{1\times10^{-11}}{\text{Br}(K^+\to\pi^+Z')_{\text{exp}}}}\left(\frac{m_{Z'}}{10\,\text{MeV}}\right)$$

- At $m_{Z'} = 10$ MeV, muon g-2 can be explained when $\tan\theta \gtrsim 12$.

2401.17613

Conclusion

- From the analysis of neutrino mass matrix structure based on NuFITv5.2, the simplest $\mathrm{U(1)}_{L_\mu - L_\tau}$ gauge model with $\boldsymbol{\Phi_{+1}}$ is viable in 3σ in case of inverted ordering although the model was excluded in the previous work based on NuFITv4.0.
- With considering Z-Z' mixing, the simplest model is excluded completely by constraints from APV, FCMD, and Higgs sector.
- When $\tan\theta \gtrsim 12$, the extended model with SU(2) singlet scalar $\boldsymbol{\sigma}$ and $\boldsymbol{\Phi_{+1}}$ is viable in the region which give the proper correction to muon g-2 at $m_{Z'} = 10\ \mathrm{MeV}$.