Symmetry and Cosmology Probed by Neutrinos

[C01 Group Report in Grant-in-Aid for Scientific Research on Innovation Areas
“Exploration of Particle Physics and Cosmology with Neutrinos”]

Masahiro Ibe (ICRR University of Tokyo)

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Symmetry and Cosmology Probed by Neutrinos (C01 Theory Group)

- The Standard Model (SM) has become established as the most successful theory that explains almost all experimental results.
- The important questions that the SM does not answer…
  - What is the origin of neutrino masses ?
  - How the matter-antimatter asymmetry in the Universe is generated ?
  - What is the nature of dark matter ?
  - What is the nature of dark energy ?
  - What about further unification of forces?
- To tackle to those problems, it is important to explore physics far beyond the TeV scale !
- Understanding symmetry provides a very powerful tool to access theories that are difficult to directly verify experimentally.

The goal of the C01 group is to propose new ideas for models that solve unsolved problems of the Standard Model and Cosmology with particular attention to symmetry.

PI : Masahiro Ibe (ICRR, University of Tokyo)

Members :

- Ryuichiro Kitano (KEK)
- Koji Ishiwata (Kanazawa University)
- Natsumi Nagata (Sci. Dept., University of Tokyo)
- Taizan Watari (IPMU, University of Tokyo)

Postdoctroal Researchers :

- Shintaro Eijima (2018-2023 KEK→ICRR)
- Ryo Nagai (2018-2019, ICRR)
- Hiromasa Takaur (2020-2023, KEK)

By utilizing symmetry in relation to neutrino physics as a keyword, we come together to pursue new physics.

Research Highlight

Probing L_μ - L_τ Gauge Boson at MUonE

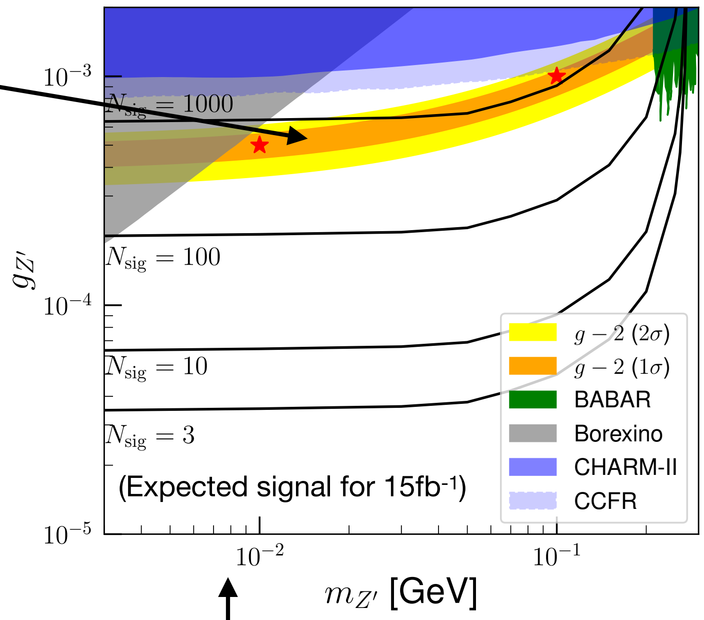
K. Asai, K. Hamaguchi, N. Nagata, S. Tseng, J. Wada, Phys. Rev. D**106**, L051702 (2022).

- ✓ $L_\mu - L_\tau$ gauge theory can explain muon *g-2* *evading all other constraints :*

$$\mathcal{L}_{Z'} \supset -g_{Z'} Q_\alpha Z'_\kappa \left(L_\alpha^\dagger \bar{\sigma}^\kappa L_\alpha - \bar{l}_{R\alpha}^\dagger \bar{\sigma}^\kappa \bar{l}_{R\alpha} \right)$$

U(1) gauge charge $\mu : +1, \tau : -1$

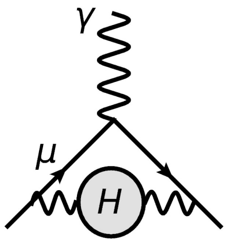
- ✓ This work demonstrated that this experiment can also be used to probe the $L_\mu - L_\tau$ gauge boson.



- ✓ The MUonE experiment is planned to measure the Standard Model contribution to the hadronic vacuum polarization.

Elastic scattering

$\mu e \to \mu e$



150 GeV

Fixed

$\mu e \to \mu e Z' \to \mu e \nu \bar{\nu}$ @ MUonE

Selection Criteria

- $\theta_\mu > 1.5$ mrad
- $1\ {\rm GeV} < E_e < 25\ {\rm GeV}$
- Photon veto

(Electroweak process is negligibly small)

Muon *g*–2 and non-thermal Leptogenesis in L_μ - L_τ theory

Shintaro Eijima, MI, Kai Murai, arXiv:2303.0975

✓ $L_\mu - L_\tau$ gauge theory can explain muon *g-2.*

✓ $L_\mu - L_\tau$ model can be consistent with the neutrino oscillation data via the seesaw mechanism by appropriate spontaneous breaking.

> This itself is non-trivial as the Yukawa interaction and the Majorana Right-handed (N_R) neutrino masses are highly limited by $L_\mu - L_\tau$ symmetry…

Can we simultaneously explain the baryon asymmetry by Leptogenesis ?

Mass matrix of N_R : we need $L_\mu - L_\tau$ breaking $\langle\sigma_{1,2}\rangle$ to explain ν oscillation.

$$M_{R,\text{eff}} = \begin{pmatrix} M_{ee} & h_{e\mu}\langle\sigma_1\rangle & h_{e\tau}\langle\sigma_1\rangle \\ h_{e\mu}\langle\sigma_1\rangle & h_{\mu\mu}\langle\sigma_2\rangle & M_{\mu\tau} \\ h_{e\tau}\langle\sigma_1\rangle & M_{\mu\tau} & h_{\tau\tau}\langle\sigma_2\rangle \end{pmatrix}$$

Muon g-2 requires breaking scale is O(10-100) GeV to explain O(1) mixing angles in U$_{\text{PMNS}}$

→ Majorana masses $M_{ee} \sim M_{\mu\tau} \sim$ O(10-100) GeV ?

Leptogenesis seems difficult… ?

✓ $M_{ee} \sim M_{\mu\tau} \sim$ O(10^6) GeV is possible for a very specific texture : $h_{\mu\mu} = h_{e\mu} = 0$

→ Non-thermal Leptogenesis is possible !

Strict prediction on the neutrino parameters :

$$\sin\theta_{23} \simeq 0.57 \ , \quad \delta_{\text{CP}} \simeq 270^\circ \ , \quad \Sigma m_\nu \simeq 0.23\,\text{eV} \ , \quad m_{\beta\beta} \simeq 60\,\text{meV}$$

Testable from ν-experiments, CMB, ν-less double beta decay !

μTRISTAN [Hamada, Kitano, Matsudo, Takaura, Yoshida '22]

μ^+ beam

- Production of large amount of μ^+ is easier
- There is an established method to make small μ^+ beam (ultra-cold muon)

μ^- beam

- Production of large amount of μ^- is difficult
- Method to make small μ^- beam is still under investigation

Proton acceleration (Proton LINAC & RCS) ⟶ Pion production (Pion production ring)

$p(3\,\mathrm{GeV})$

$p(3\,\mathrm{GeV}) + C \to \pi^+ + X$

⟶ Ultra-cold muon production ⟶ Muon acceleration (Booster ring) ⟶ Collide (Main ring)

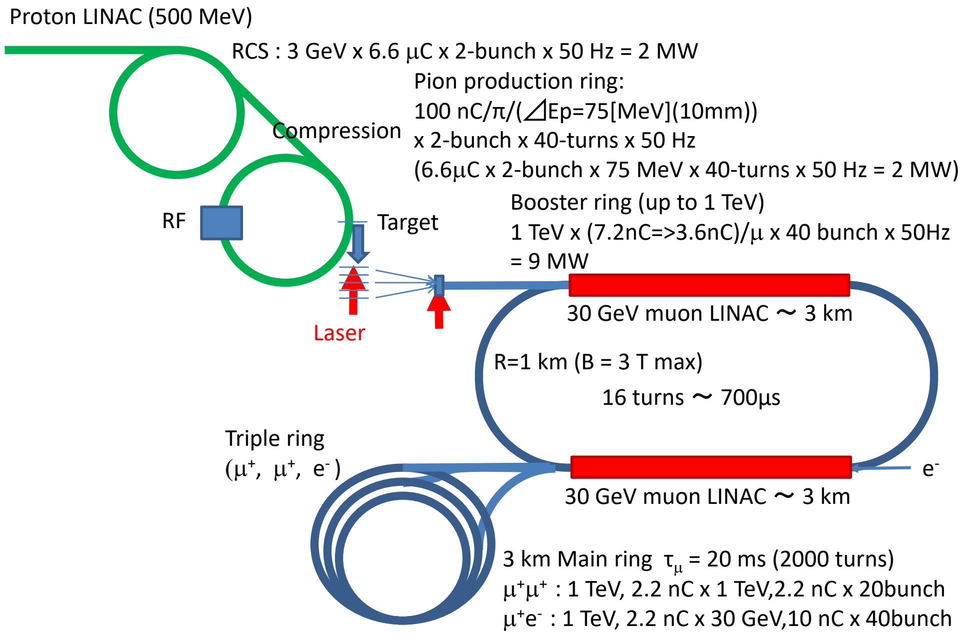
$\pi^+ \to \mu^+ + \nu_\mu$ ↘ Muonium $(\mu^+ e^-)$ formation in silica aerogel ↗ Ionized by laser ↗ Ultra-cold muon

$\mu^+(1\,\mathrm{TeV})$

$[\mu^+(1\,\mathrm{TeV}), e^-(30\,\mathrm{GeV})]$

or

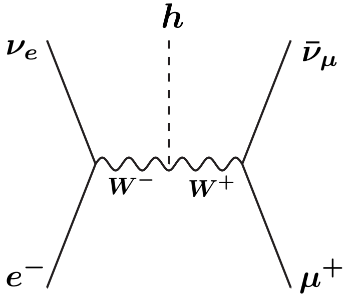
$[\mu^+(1\,\mathrm{TeV}), \mu^+(1\,\mathrm{TeV})]$



Proposal of new collider experiments

We propose collider experiments using high-quality μ^+ beam and accelerating it to TeV scale!

Using the 3 km ring, we can realize



- μ^+e^- collider Higgs factory

$E_{\mu^+} = 1\ \mathrm{TeV},\ E_{e^-} = 30\ \mathrm{GeV}$ (TRISTAN energy)

$\longrightarrow \sqrt{s} = 346\ \mathrm{GeV}$ (Luminosity ~ 100 fb^{-1} /yr)

- $\mu^+\mu^+$ collider New physics search

$E_{\mu^+} = 1\ \mathrm{TeV},\ E_{\mu^+} = 1\ \mathrm{TeV}$

$\longrightarrow \sqrt{s} = 2\ \mathrm{TeV}$ (Luminosity ~ 10 fb^{-1} /yr)

μTRISTAN!

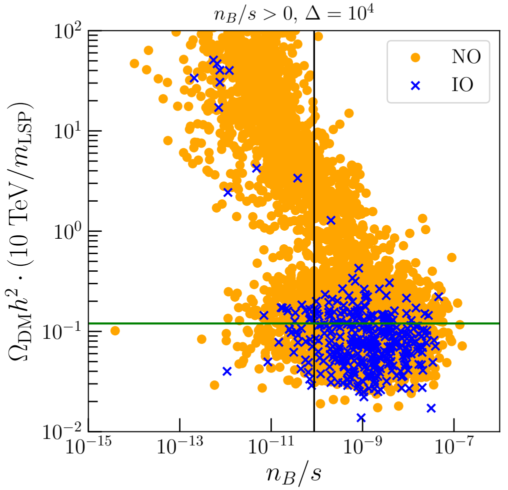
We can explore new physics through Higgs precision (μ^+e^- collier) and high energy frontier ($\mu^+\mu^+$ collider) !

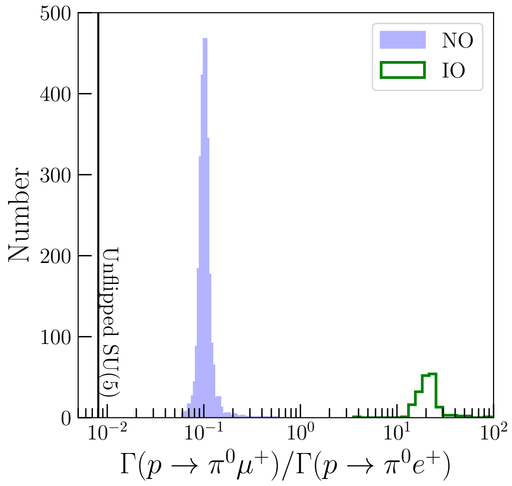
A no-scale flipped SU(5) GUT model

J. Ellis, M. A. Garcia, N. Nagata, D. V. Nanopoulos, K. A. Olive, JCAP **1904**, 009 (2019);
Phys. Lett. **B797**, 134864 (2019); JCAP **2001**, 035 (2020).

This paper studied an inflation model based on the no-scale flipped SU(5) Grand Unified Theory.

- ✓ Flipped SU(5) (~ SU(5)x U(1)) is free from the doublet-triplet splitting problem of the Higgs multiplet.
- ✓ In flipped SU(5), right-handed neutrinos are inevitable : $\mathbf{10} = (Q, \bar{D}, \bar{N}_R)$, $\mathbf{5} = (\bar{U}, L)$,





We found that in this scenario

- A singlet field to generate $\bar{N}_R$ mass plays a role of inflation

and

- Neutrino masses and mixing
- (Thermal + diluted non-thermal) Dark matter abundance
- Baryon asymmetry

can be explained simultaneously.

Distinct prediction on the branching fractions on the proton decay from the minimal SU(5) !

Inflation model with modular A_4 symmetry

Gunji, Koji Ishiwata, Yoshida '22

Modular symmetry
= symmetry associated with the compactification of the extra dimensions

The flavor structure of the coupling constant is highly restricted —> precise predictions !
['17 Feruglio]

✓ A scenario where the right-handed "s"neutrino plays a role of inflaton:

$$W_\lambda = \lambda S_+ S_- (N^c Y)_{\mathbf{1}}$$ Inflation

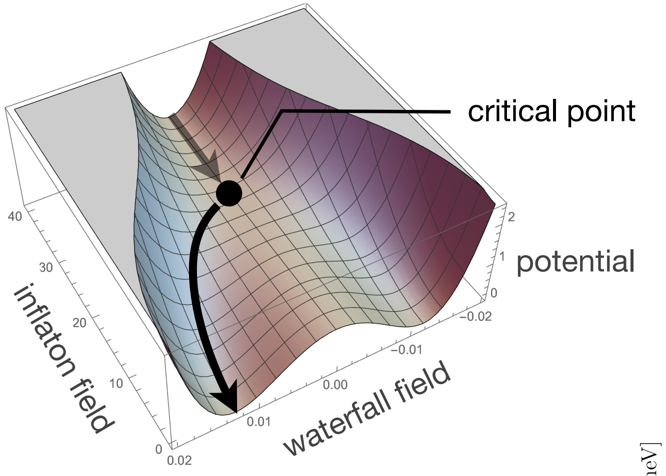
$$W_N = \Lambda (N^c N^c Y)_{\mathbf{1}}$$

$$W_D = g_1 (N^c H_u (LY)_{\mathbf{3s}})_{\mathbf{1}} + g_2 (N^c H_u (LY)_{\mathbf{3a}})_{\mathbf{1}}$$

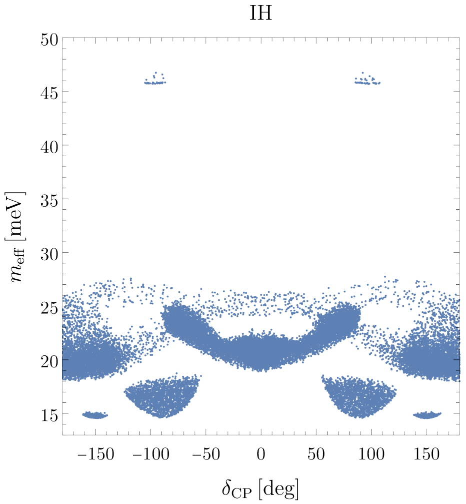
Neutrino masses & mixing

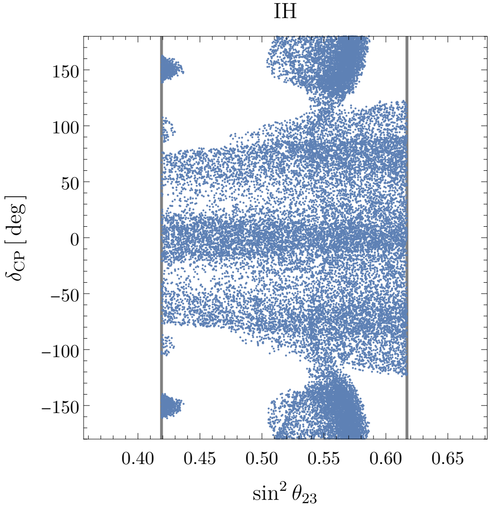
	L	N^c	H_u	S_+	S_-
A_4	$\mathbf{3}$	$\mathbf{3}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$
U(1)	0	0	0	$+q$	$-q$

g_i, λ: Yukawa coupling
Λ: Mass scale of N^c



- The lightest neutrino is massless
- Only the inverted hierarchy is allowed
- Predict rather large $m_{\beta\beta}$





Constructing F-theory flux vacua with massive moduli and small gravitino mass

Keita Kanno, Taizan Watari Commun.Math.Phys. 398 (2023) 2, 703

✓ Compactification of string theory

$\ni$ Moduli fields ~ massless field
(Degrees of freedom of deformation to the structure of compact space)

✓ For successful low energy theory, the moduli fields should be stabilized !

✓ Flux compactification = to give resistance to the deformation by giving
non-vanishing value of the flux in string theory

✓ Flux compactification usually leads to the vacuum expectation value of the superpotential of $\langle W \rangle = M_{\rm pl}^3$ → gravitino mass of $O(M_{\rm pl})$.

→ **No low-energy supersymmetry ?**

✓ In this work, arithmetic conditions of $\langle W \rangle = 0$ are worked out.

The important step connecting string theory and realistic low energy supersymmetry phenomenology.

- ✓ Through this research area, we have received various stimuli from the experimental side.

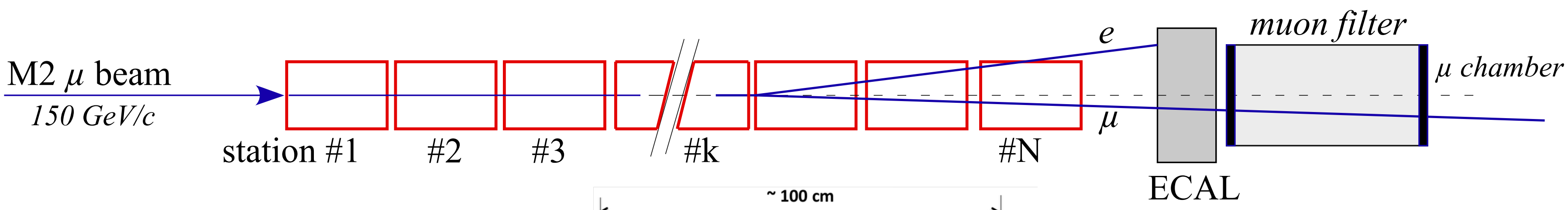
- ✓ We have published more than 100 publications in the past five years.

- ✓ We hope that our works have also provided new inputs to encourage experimental efforts on neutrino physics, Grand Unification and early Universe.

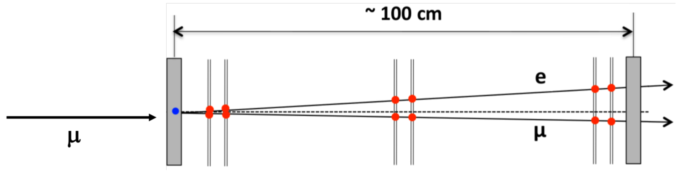
Backup

MUonE Experiment

https://arxiv.org/pdf/2201.13177.pdf



Each station



15 mm thick Be target

https://arxiv.org/pdf/2109.10093.pdf

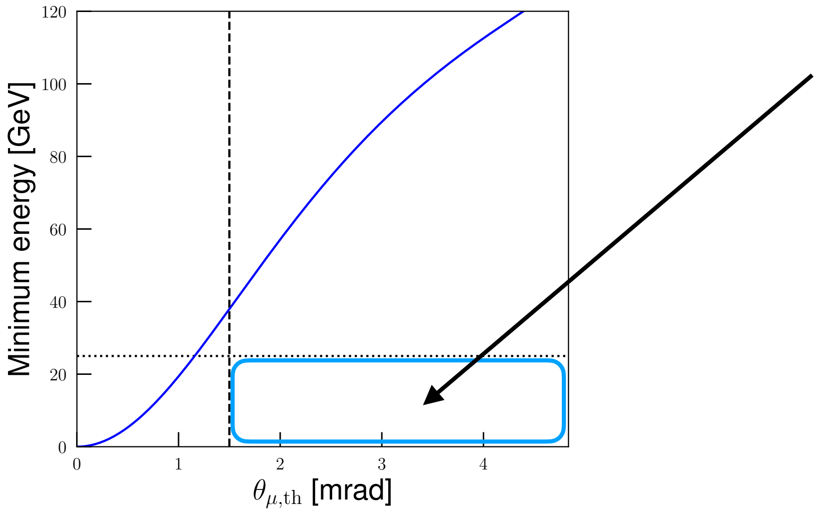


FIG. 1. Minimum value of E_e ($E_{e\gamma}$) under the condition $\theta_\mu > \theta_{\mu,\mathrm{th}}$ as a function of $\theta_{\mu,\mathrm{th}}$ for $\mu e \to \mu e$ ($\mu e \to \mu e \gamma$). The vertical dashed and horizontal dotted lines correspond to the threshold values of θ_μ and E_e we require for our selection criteria, respectively.

Signal Region of

$$\mu e \to \mu e Z' \to \mu e \nu \bar{\nu}$$

Electroweak process is negligibly small

$$\mu e \to \mu e \nu \bar{\nu}$$ $N_{\mathrm{electroweak}} \sim 10^{-4}$ (15 fb^{-1})

Inflation model with modular A4 symmetry

$$W_{\mathrm{neu}} = W_D + W_N + W_\lambda$$

Seesaw mechanism: $M_\nu = -\tilde{M}_D^T \tilde{M}^{-1} \tilde{M}_D$ (← rank 2)

$$\tilde{M}_D = \langle H_u \rangle \begin{pmatrix} 2g_1Y_1 & (-g_1+g_2)Y_3 & (-g_1-g_2)Y_2 \\ (-g_1-g_2)Y_3 & 2g_1Y_2 & (-g_1+g_2)Y_1 \\ (-g_1+g_2)Y_2 & (-g_1-g_2)Y_1 & 2g_1Y_3 \\ 0 & 0 & 0 \end{pmatrix}$$

4 × 3 matrix

$$\tilde{M} = \Lambda \begin{pmatrix} 2Y_1 & -Y_3 & -Y_2 & rY1 \\ -Y_3 & 2Y_2 & -Y_1 & rY_3 \\ -Y_2 & -Y_1 & 2Y_3 & rY_2 \\ rY_1 & rY_3 & rY_2 & 0 \end{pmatrix}$$

4 × 4 matrix

$r = \lambda \langle S_+ \rangle / \Lambda$
$\langle S_+ \rangle$: VEV of S_+
$\langle H_u \rangle$: VEV of H_u

The mass matrix is different from a conventional one