Presentation by

Yoshio Koide

at Kuno Lab, Osaka U

26 June, 2018

My English is very poor.
So, I will often use Japanese
in my talk.

I am sorry for your inconvenience.

To foreigners:
This talk is a good chance
to lean Japanese language .
Listen my talk, and then, read my slide.

Plan of My Talks

Part I Review of my Research

What physics does

the charged lepton mass spectrum

tell us ?

Part II Journal Reading

Y. Sumino, Phys. Lett. B 677, 477 (2009)

Another purpose of the Part I is to give

a background knowledge of Sumino's paper.

Another "I am sorry"

Today, my talk (Part I and Part II) is
pure theoretical topic.
Therefore, you will be forced into hard patience.
But your nightmare will finish within only 60
minutes. Please endure pain!

Jun 26, 2018

Part I　Review of my Research

What Physics does the Charged Lepton Mass Spectrum Tell Us?

I-1 Why I direct my attention to the charged leptons?

The success of the Bohr theory is owing to his attention to the most simple (clear) atom of atoms known at that times, i.e. hydrogen.

How about in the elementary particles?
What is the most simple and clear particles?

I think This is the Charged Lepton Family!

My major research subject is
to investigate the origin of "families",
not "flavors".

（余談）　*How to use the scientific terms "Flavor" and "Family"*

Examples

SU(3) flavor symmetry for (u, d, s)

SU(4) flavor symmetry for (u, d, s, c)

Citation: C. Patrignani *et al.* (Particle Data Group), Chin. Phys. C, **40**, 100001 (2016)

TESTS OF NUMBER CONSERVATION LAWS

LEPTON FAMILY NUMBER

Lepton family number conservation means separate conservation of each of L_e, L_μ, L_τ.

$\Gamma(Z \to e^\pm \mu^\mp)/\Gamma_{total}$	[n]	$<7.5 \times 10^{-7}$, CL = 95%
$\Gamma(Z \to e^\pm \tau^\mp)/\Gamma_{total}$	[n]	$<9.8 \times 10^{-6}$, CL = 95%
$\Gamma(Z \to \mu^\pm \tau^\mp)/\Gamma_{total}$	[n]	$<1.2 \times 10^{-5}$, CL = 95%
$\sigma(e^+ e^- \to e^\pm \tau^\mp)$ / $\sigma(e^+ e^- \to \mu^+ \mu^-)$		$<8.9 \times 10^{-6}$, CL = 95%
$\sigma(e^+ e^- \to \mu^\pm \tau^\mp)$ / $\sigma(e^+ e^- \to \mu^+ \mu^-)$		$<4.0 \times 10^{-6}$, CL = 95%
limit on $\mu^- \to e^-$ conversion		
$\sigma(\mu^- \, {}^{32}S \to e^- \, {}^{32}S)$ /		$<7 \times 10^{-11}$, CL = 90%

However, nowadays, we cannot stop the misuse of "flavor"

[24] A. A. Petrov and D. V. Zhuridov, *Lepton flavor-violating transitions in effective field theory and gluonic operators*, *Phys. Rev.* **D89** (2014) 033005, [1308.6561].

[42] CMS collaboration, C. Collaboration, *Search for lepton flavour violating decays of heavy resonances and quantum black holes to eμ pairs in proton-proton collisions at* $\sqrt{s} = 13$ TeV, *CMS-PAS-EXO-16-058* (2017) .

[15] SINDRUM II collaboration, C. Dohmen et. al., *Test of lepton flavor conservation in mu → e conversion on titanium*, *Phys.Lett.* **B317** (1993) 631–636.

[50] R. Kitano, M. Koike and Y. Okada, *Detailed calculation of lepton flavor violating muon electron conversion rate for various nuclei*, *Phys. Rev.* **D66** (2002) 096002, [hep-ph/0203110].

[54] V. Cirigliano, S. Davidson and Y. Kuno, *Spin-dependent* $\mu \to e$ *conversion*, *Phys. Lett.* **B771** (2017) 242–246, [1703.02057].

[55] S. Davidson, Y. Kuno and A. Saporta, *"Spin-dependent"* $\mu \to e$ *conversion on light nuclei*, *Eur. Phys. J.* **C78** (2018) 109, [1710.06787].

"What happens if an unbroken flavor symmetry exists?",
Yoshio Koide, Phys. Rev. **D 71**, 016010-1 - 016010-06 (2005).

"Color" versus "Flavor"

1964: SU(3) color vs SU(3) (u,d,s)

[no nickname]

perception

by eyes --> by tongue

19??: SU(3) color vs SU(3) flavor

Hint from a signboard of ice-cream shop

(主題)　1-2　Do you know a mysterious mass formula?

Charged lepton mass relation

$$K \equiv \frac{m_e + m_\mu + m_\tau}{(\sqrt{m_e} + \sqrt{m_\mu} + \sqrt{m_\tau})^2} = \frac{2}{3}$$

The observed masses:

$$K^{obs} = (2/3) \times (0.999989 \pm 0.000014)$$

This is a miracle coincidence! Are you happy?

No! This is a serious problem!

What is the problem?

Comment on "mass"

There are two kind of "mass"

pole mass and running mass

Pole mass: **the observed mass in the experiments**

energy-scale independent

Running mass: **masses in a field theoretical model**

energy-scale dependent

This formula has been derived on the basis of a field theoretical model!

Y.K. Mod. Phys. Lett. A, 2319 (1990)

We must use the running masses for the K-relation.

However, if we use the running masses, we obtain

$$K(\mu) = (2/3) \times (1.00189 \pm 0.000002) \quad \text{at } \mu = m_Z$$

The coincidence is not so excellent.

On the other hand, for the pole masses, we have

$$K^{pole} = (2/3) \times (0.999989 \pm 0.000014)$$

Why the K-relation is so excellently satisfied by the pole masses?

This problem is solved by Sumino (2009).

Wait until my journal review in Part II

1-3 Another Formula

We have three charged leptons, and
we know the values of those mass values,
in other words, we have two mass ratios.

Therefore, it is possible that there is another charged lepton mass relation in addition to

$$K \equiv \frac{m_e + m_\mu + m_\tau}{(\sqrt{m_e} + \sqrt{m_\mu} + \sqrt{m_\tau})^2} = \frac{2}{3}$$

Recently, I found another mass relation

$$\kappa \equiv \frac{\sqrt{m_e m_\mu m_\tau}}{(\sqrt{m_e} + \sqrt{m_\mu} + \sqrt{m_\tau})^3} = \frac{1}{2 \cdot 3^5} = \frac{1}{486}$$

Y. Koide, Phys.Lett. B 777, 131 (2018)

$$K \equiv \frac{m_e + m_\mu + m_\tau}{(\sqrt{m_e} + \sqrt{m_\mu} + \sqrt{m_\tau})^2} = \frac{2}{3}$$

$$\kappa \equiv \frac{\sqrt{m_e m_\mu m_\tau}}{(\sqrt{m_e} + \sqrt{m_\mu} + \sqrt{m_\tau})^3} = \frac{1}{2 \cdot 3^5} = \frac{1}{486}$$

Note that those relation are invariant under a transformation

$$(m_e, m_\mu, m_\tau) \to (\lambda m_e, \lambda m_\mu, \lambda m_\tau)$$

I-4 Brief Review of the History

$$m_e + m_\mu + m_\tau = \frac{2}{3}(\sqrt{m_e} + \sqrt{m_\mu} + \sqrt{m_\tau})^2$$

This formula was first proposed in 1982:

Y.K, Lett.Nuvo Cim. 34, 201 (1982); Phys. Lett. B 120, 161, (1983)

This formula predicts a tau lepton mass

$$m_\tau = 1776.97 \text{ MeV}$$

by inputting m_e & m_μ

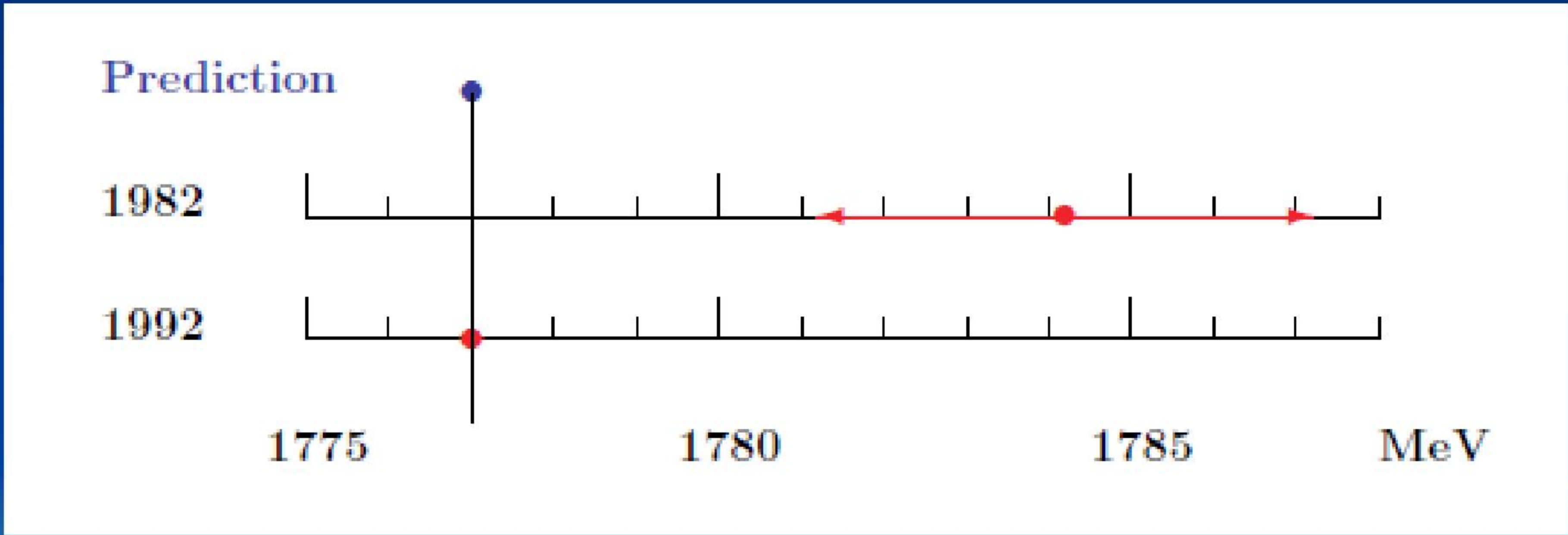
The observed mass at 1982:

$$(m_\tau^{exp})_{old} = 1784.2 \pm 3.2 \quad \text{MeV}$$

Ten years after, an accurate value was reported by ARGUS, BES, CLEO (1992)

$$(m_\tau^{exp})_{new} = 1776.99^{+0.29}_{-0.26} \quad \text{MeV}$$

Experimental value of the tau lepton mass



Thus, since 1992, the formula has attracted a wide attention.

（余談）

Percept

I frequently say for young theoretical physicists:

"Prior to investigate a new theory or to building a theoretical model, never see the experimental data!."

If you see the experimental data, your theory will be affected by the experimental values, so that you will lose your way in physics.

（余談）

Digression:

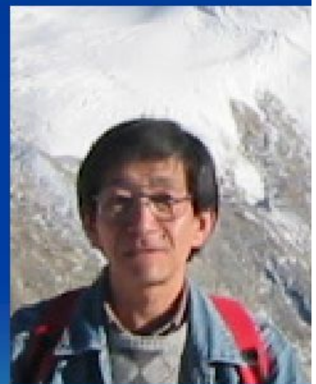
When the formula has attracted a wide attention, Sumirnov said me:

Your formula is wonderful!

Thank you. But, the QED correction destroys the excellent coincidence

Smirnov (No picture)

Don't worry about.
Even taking such a deviation, your formula is still wonderful.



So, hereafter, I understood that this formula is only approximate one.

I-5 Mass generation originated by a Higgs-like mechanism

We introduce U(3)-family nonet scalar $(\Phi)_i^{\ j}$ $(i, j = 1, 2, 3)$

and the charged lepton mass matrix is given by

$$M_e \propto \langle \Phi \rangle \langle \Phi \rangle$$

Then the vacuum expectation values (VEVs) are given by

$$\langle \Phi \rangle \propto \mathrm{diag}(\sqrt{m_e}, \sqrt{m_\mu}, \sqrt{m_\tau}),$$

In such the model, our relations are expressed as

$$K \equiv \frac{[\Phi\Phi]}{[\Phi]^2} = \frac{m_e + m_\mu + m_\tau}{(\sqrt{m_e} + \sqrt{m_\mu} + \sqrt{m_\tau})^2} = \frac{2}{3}$$

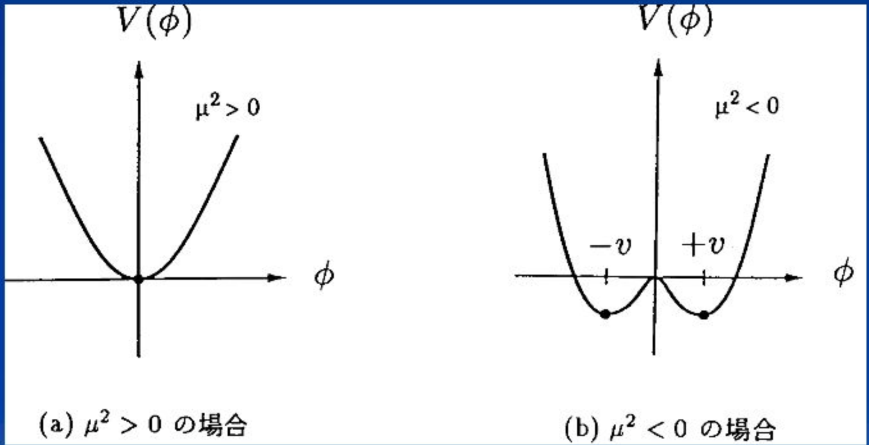
$$\kappa \equiv \frac{\det\Phi}{[\Phi]^3} = \frac{\sqrt{m_e m_\mu m_\tau}}{(\sqrt{m_e} + \sqrt{m_\mu} + \sqrt{m_\tau})^3} = \frac{1}{2 \cdot 3^5} = \frac{1}{486}$$

where, for convenience, we denote Tr[A] as [A] simply.

Backup slide

K- and κ-relations from Higgs mechanism-like model

- Mass generated from
  Vacuum Expectation Value (VEV)



vacuum	$\phi = 0$	$\phi = V$
scalar	ϕ	$\phi' = \phi - V$
Interaction	$\bar{\psi}\phi\psi$ →	$\bar{\psi}\phi'\phi + v\bar{\psi}\psi$

How to derive the K -relation

Y.K. Mod. Phys. Lett. A, 2319 (1990)

We assume a simple form of the scalar potential

$$V = \mu^2 \mathrm{Tr}[\Phi\Phi] + \lambda \mathrm{Tr}[\Phi\Phi\Phi\Phi] + \lambda' \mathrm{Tr}[\Phi_8\Phi_8]\mathrm{Tr}[\Phi]^2,$$

where

$$\Phi_8 \equiv \Phi - \frac{1}{3}[\Phi].$$

Then we can obtain

$$\frac{\partial V}{\partial \Phi} = \left(\mu^2 + \lambda[\Phi\Phi] + \lambda'[\Phi]^2\right)\Phi + 2\lambda'\left([\Phi\Phi] - \frac{2}{3}[\Phi]^2\right)1.$$

Ⅰ-6 Concluding Remarks

What does the K-relation leave to physics
apart from the phenomenological success?
Let us see the phenomenological law by Kepler.
The law is a typical phenomenology.
The true understanding had to wait
until the establishment of the Newton dynamics.
However, note that the Kepler law established
the Copernics theory instead of Ptolematic theory.
How about the K-relation.
Many people's eyes were dazzled
by the phenomenological success.
However, we should pay attention to the fact that
we must consider U(3) family symmetry, not SU(3).

Part II Journal Reading

Classic paper series III Journal Club

26 June 2018

Y. Sumino, Phys. Lett. B 677, 477 (2009)

Physics Letters B 677 (2009) 477–480

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Family gauge symmetry and Koide's mass formula

Yukinari Sumino

Department of Physics, Tohoku University, Sendai 980-8578, Japan

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ABSTRACT

Koide's mass formula is an empirical relation among the charged lepton masses which holds with a striking precision. We propose a mechanism for cancelling the QED correction to Koide's formula. This is discussed in an effective theory with $U(3)$ family gauge symmetry and a scenario in which this symmetry is unified with $SU(2)_L$ symmetry at 10^2–10^3 TeV scale.

Ⅱ-1 What is new in his paper

First, I would like to show

What is new in his paper?

He brought realistic family gauge bosons to us!

There are many works on the family symmetry in 1980's. Nevertheless, why it is new?

Family symmetries in 1980's were nothing but ideological one.

The scale is extremely high, and we cannot observe the symmetry effects directly.

On the other hand,

Sumino's FGB mass scale is of the order 1000 TeV,

so that we can observe its effects at terrestrial experiments.

Recall

What is the problem?

The K-relation was derived on the basis

of a field theoretical potential model:

Y.K. Mod. Phys. Lett. A, 2319 (1990)

On the other hand, the miracle coincidence

$$K^{pole} = (2/3) \times (0.999989 \pm 0.000014)$$

was obtained for pole (observed) masses.

If you adopt the running masses, we obtain

$$K(\mu) = (2/3) \times (1.00189 \pm 0.000002) \quad \text{at } \mu = m_Z$$

The coincidence is not so excellent.

This problem is solved by Sumino (2009)

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Ⅱ-2 Sumino Mechanism

$$K \equiv \frac{m_e + m_\mu + m_\tau}{(\sqrt{m_e} + \sqrt{m_\mu} + \sqrt{m_\tau})^2} = \frac{2}{3}$$

The deviation of $K(m_{ei}^{running})$ **form** $K(m_{ei}^{pole})$

is caused by the logarithmic term of the QED correction

$$m_i(\mu) = m_i \left\{ 1 - \frac{\alpha(\mu)}{\pi} \left(1 + \frac{3}{4} \boxed{\log \frac{\mu^2}{m_i^2}} \right) \right\}$$

The origin of the pollution

$$(m_1, m_2, m_3) = (m_e, m_\mu, m_\tau)$$

In 2009, Sumino proposed an attractive mechanism:

(a) Assume U(3) family gauge bosons

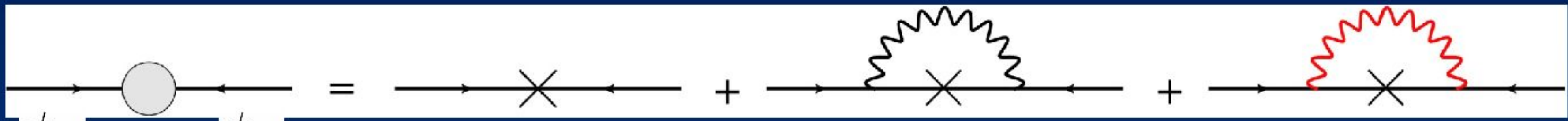
(b) with their masses M $_{ij}$ are given by $M_{ii}^2 \propto m_{ei}$

Then, the unwelcome term $\log(m_{ei}/\mu)$ **is canceled**

by the new additional term $\log(M_{ii}/\mu)$

Note: $M_{ii}^2 = \lambda m_{ei}$ then $2 \log M_{ii} = \log m_{ei} + \log \lambda$

$$\frac{1}{2} g_F = e = g_w \sin^2 \theta_W$$



ψ_L ψ_R

$m_i(\mu)$ $\qquad m_i^{pole} \qquad$ ***e*** $e^2 \log m_i^2$ ***e*** $\qquad$ ***g*** $-g^2 \log M_{ii}^2$ ***-g***

Note that, in order to guarantee the cancellation,
we must take the coupling constant *g* as
+*g* for *e*$_L$ but -*g* for *e*$_R$,
in other word, we must assign the U(3) family as
3 for *e*$_L$, but 3* for *e*$_R$: $(\psi_L, \psi_R) = (\mathbf{3}, \mathbf{3}^*)$

（Exactly speaking, his model is based on, O(3)x U(3).)

Note: Since the factor $\alpha(\mu)$ in the QED also depends on the energy scale μ, the scale of the family gauge bosons must be the order of 1000 TeV.

II-3 Problem in the Sumino Model

(i) An anomaly non-free model can not be renormalizable model.
The Sumino model is not anomaly free model because of the assignment $(\psi_L, \psi_R) = (\mathbf{3}, \mathbf{3}^*)$

(ii) The K -relation cannot be derived simply in his model.
The relation is derived from a family symmetry U(9), not U(3). The symmetry breaking is very complicated.

(iii) In his model, unwelcome decay modes $\Delta N_{fam} = 2$ inevitably appear.

(iv) Against his hope, his FGB masses are still heavy because of the severe constraint from the observed K^0-$\bar{K}^0$ mixing data.

II-4 Modified Sumino model

Such defects in the original Sumino model are due to the family number assignment $(\psi_L, \psi_R) = (\mathbf{3}, \mathbf{3}^*)$

In order to this defect, Yamashita and YK proposed a modified Sumino model with $(\psi_L, \psi_R) = (\mathbf{3}, \mathbf{3})$

YK and T.Yamashita, PLB 711, 384 (2012)

In this model, the minus sign comes from the following idea:

The family gauge bosons have an inverted mass hierarchy.

i.e.

$$M_{ij}^2 = k\left(\frac{1}{m_{ei}} + \frac{1}{m_{ej}}\right) + \cdots$$

Then, we can obtain the minus sign from

$$2\log M_{ii} = \log(k/m_{ei}) = \log k - \log m_{ei}$$

Lepton-Quark Correspondence

Conventional L-Q correspondence is based on the order of masses.

$$(\nu_1, \nu_2, \nu_3) = (\nu_e, \nu_\mu, \nu_\tau)$$
$$(e_1, e_2, e_3) = (e^-, \mu^-, \tau^-)$$

$$(u_1, u_2, u_3) = (u, c, t)$$
$$(d_1, d_2, d_3) = (d, s, b)$$

We call them "generations"

On the other hand, in the Koide-Yamashita model,

Lepton-Quark Correspondence **was changed as**

$$(\nu_1, \nu_2, \nu_3) = (\nu_e, \nu_\mu, \nu_\tau)$$
$$(e_1, e_2, e_3) = (e^-, \mu^-, \tau^-)$$

$$(u_1, u_2, u_3) = (t, c, u)$$
$$(d_1, d_2, d_3) = (b, s, d)$$

However, note that the conventional one is based on neither theoretical nor experimental grounds, because photon and weak bosons interact with quarks and leptons family-independently. We may adopt favorite assignments.

Merit of the modified Sumino model

The family gauge boson with lightest mass is A_{11}, which only couples with b quark.

(i) The inverted family number assignment for quarks weakens the severe constraint from K^0-$\bar{K}^0$ mixing data, so that we can obtain considerably low FGB masses.

YK, Phys.Lett. B 763, 499 (2014)

(ii) Possibility of observations of FGB effects

μ - e conversion

YK and M. Yamanaka, PLB 762, 41 (2016)

A_{11} production at LHC

YK, M. Yamanaka, H. Yokoya, PLB 750, 384 (2015)

If FGB mass relation is given as

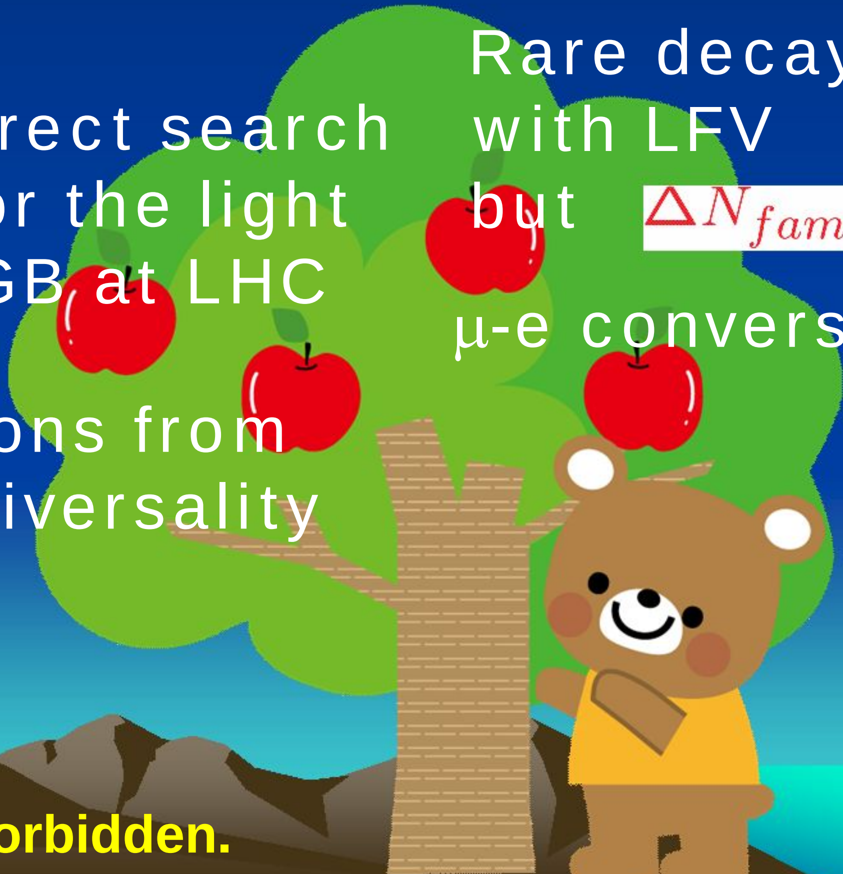
$$\frac{M_{11}}{M_{33}} = \left(\frac{m_e}{m_\tau}\right)^{n/2} = (2.87564 \times 10^{-4})^{n/2}$$

We can expect

$$M_{11} \sim \frac{m_e}{m_\tau}\Lambda_{fam} \sim 3 \times 10^4 \sim \text{a few TeV}$$

for n=2.

We can expect fruitful and rich new events.



Direct search for the light FGB at LHC

Rare decays with LFV but $\Delta N_{family} = 0$

μ-e conversion

Deviations from e-μ-τ universality

However， μ - > e + γ is forbidden.

II-5 Another Approach to the "$m_i^{model} = m_i^{pole}$" Problem

There is an effect which disturb K -relation:

$\Phi_8 \leftrightarrow \Phi_0 \equiv [\Phi]/3$ **mixing due to renormalization effect**

(T. Yamashita, private communication)

The K and κ relations were derived from potential model. However, note that there is no vertex correction in a SUSY model. Therefore, if we derive the relations on the basis of SUSY scenario, then the problem will disappear.

Very recently, we succeeded to re-derive K and k relations on the basis of SUSY scenario.

(YK and T. Yamashita, arXiv:1805.09533 (hep-ph))

Final page

I believe that
the charged lepton
mass relations will
bring fruitful clues
to new physics.
However, of course,
it is possible that
this is nothing but
a daydream.

Thank you for your patience