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Spectroscopy of Family Gauge Bosons

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Based on Y.K., Phys.Lett. B736 (2014) 499

Abstract

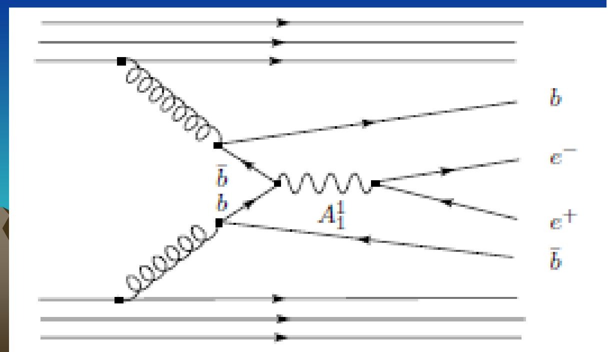
In this talk, I will conclude the following result:

If we take Sumino's model of family gauge bosons (FGBs) seriously, and we want to observe the lowest FGB A_1^1 by terrestrial experiments, a possible case has to be only the following case:

The mass is $M_{11} \simeq 0.54$ TeV;

A_1^1 interacts with the first generation for leptons, while it does with the third generation for quarks, so that we can expect a direct production of A_1^1 at the LHC as

$$p + p \to A_1^1 + b + \bar{b} + X \to e^+ e^- + X$$



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5. Summary

1. Introduction

What is the aim of our investigation

We investigate a family gauge boson model in which the family gauge bosons (FGBs) can be observed by terrestrial experiments.

My work is deeply related to Sumino's FGB model. Let us start my talk from the Sumino FGB model.

Why we consider that FGBs exist in a lower mass scale?

Sumino's basic idea: Y.Sumino, PLB671, 477 (2009)

Sumino paid attention to the mass relation

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

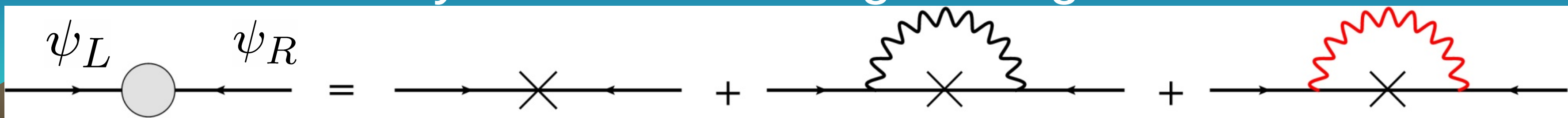
Y.K. LNC34,201(1982)
PLB120, 161(1983)

This relation is beautifully satisfied with pole masses to $\Delta K \sim 10^{-5}$, but, it is not so with running masses ($\Delta K \sim 10^{-3}$). Why?

The deviation comes from log m_{ei} term in the QED correction.

$$\delta m_{ei}(\mu)^{photon} = m_{ei}\left[\frac{\alpha_{em}(\mu)}{\pi}\left(\frac{3}{4}\log\frac{m_{ei}^2(\mu)}{\mu^2} - 1\right)\right]$$

(i) Sumino mechanism: the log m_{ei} term is cancelled by FGB exchange diagram.



$m_{ei}(\mu)$ $\quad m_{ei}^{pole}$ $\quad e^2 \log m_{ei}^2$ $\quad -g^2 \log M_{ii}^2$

Note:

(a) Sumino's cancellation mechanism holds only at one-loop level. In the next order diagram, the cancellation does not hold any more.

(b) Therefore, if FGBs have a large mass scale, we would see a sizable deviation form K=2/3 due to the next order diagram. However, the observed fact is not so.

(ii) He has speculated that the above relation is generated at a scale of an order of 10^4 TeV

(iii) On the other hand, we may consider that

$$\frac{M_{33}}{M_{11}} \sim 10^3 \quad \text{because of} \quad \frac{m_\tau}{m_e} \sim 10^3$$

(iv) Therefore, we have a possibility that the lightest FGB mass is an order of TeV.

Major obstacle to light FGBs is still in K^0-$\bar{K}^0$ mixing

The most severe constraint on the FGB masses comes from the observed K^0-$\bar{K}^0$ mixing .

The FGBs concerned have to be, at least, larger than 10^3 TeV.

Usually, even if FGBs exist, the scale is understood as $10^{14\text{-}16}$ GeV.

Nevertheless, **Why such a low scale FGB model is possible?**

[1] We adopt Sumino's FGB model and/or its extended model.
In this model, family number violation is caused only through the quark mixing. In the limit of small quark mixing, flavor-changing modes such as K^0-$\bar{K}^0$ mixing are forbidden.

[2] The conventional "Q-L correspondence" is taken as
(d, s, b) ⟺ (e, μ, τ) based on the "generation" picture.

However, in the family symmetry, differently from the "generation" picture, we can adopt another Q-L correspondence,
e.g. (b, s, d) ⟺ (e, μ, τ) , and so on.

Therefore, we have the following scenario:
Only FGBs which contribute to K^0-$\bar{K}^0$ mixing have masses of the order of 10^2 - 10^4 TeV,
but the others may have masses of an order of TeV.

2. Sumino's FGB model Y.Sumino, PLB671, 477 (2009)

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

(i) Family symmetries: $U(3) \times U(3)' \xrightarrow[\Lambda']{} U(3) \xrightarrow[\Lambda]{}$ broken

The symmetry U(3) is dominantly broken by a scalar $\Phi =$ (3, 3) of $U(3) \times U(3)'$ with VEV $\langle (3,3) \rangle \sim \Lambda$

(ii) In the flavor basis in the Sumino model:

Charged lepton and FGB mass matrices are simultaneously diagonal, but quark mass matrices are, in general, not diagonal.

$$(u_i^0, d_i^0) = (U_{ij}^u u_j, U_{ij}^d d_j)$$

(iii) so that

$$\mathcal{H}_{fam} = \frac{g_F}{\sqrt{2}} \left[(\bar{e}_i \gamma_\mu e_j) + (\bar{\nu}_i \gamma_\mu \nu_j) + U_{ik}^{*u} U_{jl}^u (\bar{u}_k \gamma_\mu u_l) + U_{ik}^{*d} U_{jl}^d (\bar{d}_k \gamma_\mu d_l) \right] (A_i^{\ j})^\mu$$

(iv) Coupling constant g_F is not a free parameter because of Sumino's cancellation condition between photon and FGB diagrams

Note:

Conventional FGB models with single U(3) [or SU(3)] cannot lead to above results (ii) and (iii).

Why K^0-$\bar{K}^0$ mixing can comparatively be suppressed in the Sumino model?

Effective quark interactions with $\Delta N_{family} = 2$ can appear only through the quark mixing U_u and U_d:

$$H^{eff} = \frac{1}{2} g_F^2 \left[\sum_i \frac{(\lambda_i)^2}{M_{ii}^2} + 2 \sum_{i<j} \frac{\lambda_i \lambda_j}{M_{ij}^2} \right] (\bar{q}_k \gamma_\mu q_l)(\bar{q}_k \gamma^\mu q_l)$$

$$\lambda_1 = U_{1k}^{q*} U_{1l}^{q}, \quad \lambda_2 = U_{2k}^{q*} U_{2l}^{q}, \quad \lambda_3 = U_{3k}^{q*} U_{3l}^{q}.$$

$\lambda_1 + \lambda_2 + \lambda_3 = 0$ from "unitary triangle"

Note that if all FGB masses M_{ij} are degenerated, the effective FCNC interactions become harmless.

For a simplicity, we assume that $U^d \simeq V_{CKM}$ and $U^u \simeq 1$

$$\lambda_1 \simeq 0.220, \quad \lambda_2 \simeq -0.219, \quad \lambda_3 \simeq -0.00035$$

so that only FGB A_1^1, A_2^1, A_1^2, A_2^2 contribute to K^0-$\bar{K}^0$ mixing

$$\Delta m_K^{obs} = (3.484 \pm 0.006) \times 10^{-18} \text{ TeV}$$
$$\Delta m_K^{SM} \sim 2 \times 10^{-18} \text{ TeV}$$

⇒ $$\frac{M_{11}}{g_F/\sqrt{2}} \geq 340 \text{ TeV}$$

However, this value is still large to me.

Note: i=1,2,3 in this page mean the quark generation numbers.

3. Which case is the best for our aim?

3.1 We have 12 options in the Sumino model

3.2 Which option can give the lightest FGB?

?

FGB: normal M_{ij}
quark: inverted family

FGB: inverted M_{ij}
quark: normal family

3.1 We have 12 options in the Sumino model

(i) 2 options for FGB mass hierarchy:

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

YK and T.Yamashita, PLB (2012) Y.Sumino, PLB (2009)

∗We investigate not only the case with n=1 (original Sumino model) but also cases with n=2, 3, … .

∗ (For case (B), in order to avoid "non anomaly free", we assume $(e_{Li}, e_{Ri}) = (\mathbf{3}, \mathbf{3})$ of U(3) in quark sector.)

(ii) 6 options for assignments of quark family numbers.

We investigate physics of the above 12 options.

with n=2

Quark family number assignment		FGB masses (A) Inverted	FGB masses (B) Normal
Normal	(d, s, b)	$\tilde{M}_{33} \sim 20$ TeV	No light FGBs
twisted	(s, d, b)		
Inverted	(b, s, d)	No light FGBs	$\tilde{M}_{11} \sim 1.8$ TeV
twisted	(b, d, s)		

$\tilde{M}_{ij} \equiv \frac{M_{ij}}{g_F/\sqrt{2}}$

3.2 Which case can give a TeV scale mass?

Y.K., Phys.Lett. B736 (2014) 499

Interesting cases are only ones with n=2

(Although the original Sumino model has been given with n=1, a model with n=2 is also given easily.)

Case	M_{11}	M_{22}	M_{33}	M_{12}	M_{23}	M_{31}
(A_1)	$\tilde{M}_{dd}$	$\tilde{M}_{ss}$	$\tilde{M}_{bb}$	$\tilde{M}_{ds}$	$\tilde{M}_{sb}$	$\tilde{M}_{bd}$
$n=2$	7×10^4	355	21	5×10^4	251	5×10^4
(A_2)	$\tilde{M}_{ss}$	$\tilde{M}_{dd}$	$\tilde{M}_{bb}$	$\tilde{M}_{sd}$	$\tilde{M}_{db}$	$\tilde{M}_{bs}$
$n=2$	7×10^4	353	21	5×10^4	250	5×10^4
(B_1)	$\tilde{M}_{bb}$	$\tilde{M}_{ss}$	$\tilde{M}_{dd}$	$\tilde{M}_{bs}$	$\tilde{M}_{sd}$	$\tilde{M}_{db}$
$n=2$	1.77	365	6×10^3	258	4352	365
(B_2)	$\tilde{M}_{bb}$	$\tilde{M}_{dd}$	$\tilde{M}_{ss}$	$\tilde{M}_{bd}$	$\tilde{M}_{ds}$	$\tilde{M}_{sb}$
$n=2$	1.76	364	6×10^3	257	4334	364

$$\tilde{M}_{ij} \equiv \frac{M_{ij}}{g_F/\sqrt{2}}$$

in unit of TeV

For convenience of numerical estimates,
we have used an approximation $U_d \simeq V_{CKM}$ and $U_u \simeq 1$

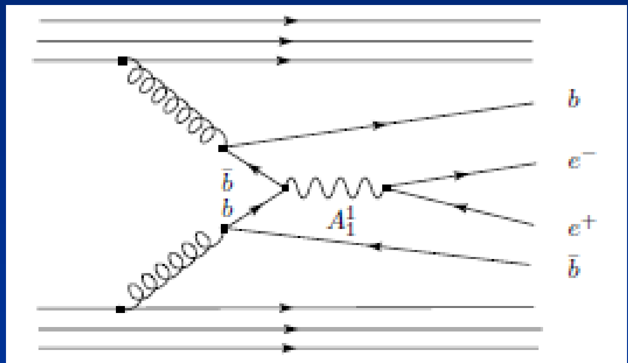
In the obtaining in the numerical results, not only data on K^0-$\bar{K}^0$ mixing but also data on B^0-$\bar{B}^0$ mixing , B^0_s-$\bar{B}^0_s$ mixing, $K^+ \to \pi^+ \nu\bar{\nu}$ and so on have been taken into consideration.

4. Where do we can find the FGB?

4.1 Direct production of $A_1{}^1$ at the LHC

(B1) , (B2) with n=2

$$p + p \to A_1^1 + b + \bar{b} + X \to e^+ e^- + X$$



$$\tilde{M}_{11} = 1.77 \text{ TeV } (1.76 \text{ TeV})$$

$$\left.\frac{g_F}{\sqrt{2}}\right|_{n=2} = e = 0.30684$$

$$M_{11} \simeq 0.543 \text{ TeV } \quad (0.540 \text{ TeV})$$

No peak in $(\mu^+\mu^-)$

$$Br(A_1{}^1 \to e^- e^+) = \frac{2}{15} = 13.3\%$$

$$Br(A_1{}^1 \to \nu_e \bar{\nu}_e) = \frac{1}{15} = 6.7\%$$

$$\Gamma_{full} = 102 \ (101) \text{ GeV}$$

If neutrinos are Dirac, $Br(A_1{}^1 \to \nu_e \bar{\nu}_e) = \frac{2}{16} = 12.5\%$

We can determine

whether neutrinos are Dirac or Majorana

4.2 Rare decays

Example: Skip

$$Br(K^+ \to \pi^+ \nu\bar{\nu})_{obs} = (1.7 \pm 1.1) \times 10^{-10}$$

$$Br(K^+ \to \pi^+ \nu\bar{\nu})_{SM} = (0.80 \pm 0.11) \times 10^{-10}$$

Ishidori et al (2005)

$$Br(K^+ \to \pi^+ \nu_e \bar{\nu}_e)_{fam} = 1.1\times 10^{-10} \ (0.91\times 10^{-10})$$

for $\tilde{M}_{11} \equiv \frac{M_{11}}{g_f/\sqrt{2}} = 1.8 \ (1.9) \ \text{TeV}$

4.3 Deviations from the e-μ-τ universality

An observation in τ-decays cannot be observed because of $\tilde{M}_{23} \simeq \tilde{M}_{31}$.

In future, a deviation in Υ decays

$$1 - \frac{Br(\Upsilon \to e^+e^-)}{Br(\Upsilon \to \mu^+\mu^-)} \simeq 2 \frac{g_F^2/2}{(e/3)^2} \frac{M_\Upsilon^2}{M_{11}^2 - M_\Upsilon^2} = 0.0053$$

may be observed.

4.4 μ-e conversion

$$\mu^- + N(A,Z) \to e^- + N(A,Z)$$

The reaction is caused by $A_1{}^2$ exchange $\tilde{M}_{12} = 260$ TeV

The present experimental limit is

$A_1{}^2 = A_b{}^s$ in (B1)
$A_1{}^2 = A_b{}^d$ in (B2)

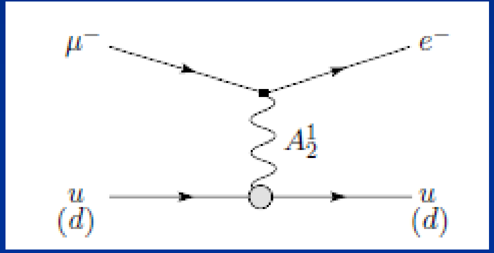
$$R(Au) \equiv \frac{\sigma(\mu^- + Au \to e^- + Au)}{\sigma(\mu \text{ capture})} < 7 \times 10^{-13}$$

SINDRUM (2006)

The COMET experiment will reach a sensitivity 2.6×10^{-17}

Rough estimate:

$$R_q \equiv \frac{\sigma(\mu^- + q \to e^- + q)}{\sigma(\mu^- + u \to \nu_\mu + d)} \simeq \left(\xi \frac{g_F^2/2}{\tilde{M}_{12}^2} \frac{M_W^2}{g_w^2/8} \right)^2$$

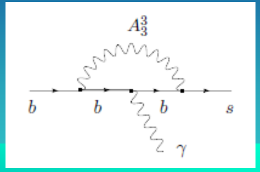


$$R_q \simeq R_d \sim 1.32 \times 10^{-17} \ (2.52 \times 10^{-16})$$

Case (B2) can be visible in COMET, but (B1) is critical.

If we observe $\mu^- + N(A,Z) \to e^- + N(A,Z)$

without observation of $\mu^- \to e^- + \gamma$



then it will strongly support our FGB scenario.

COMET Experiment

(Coherent Muon to Electron Transition)

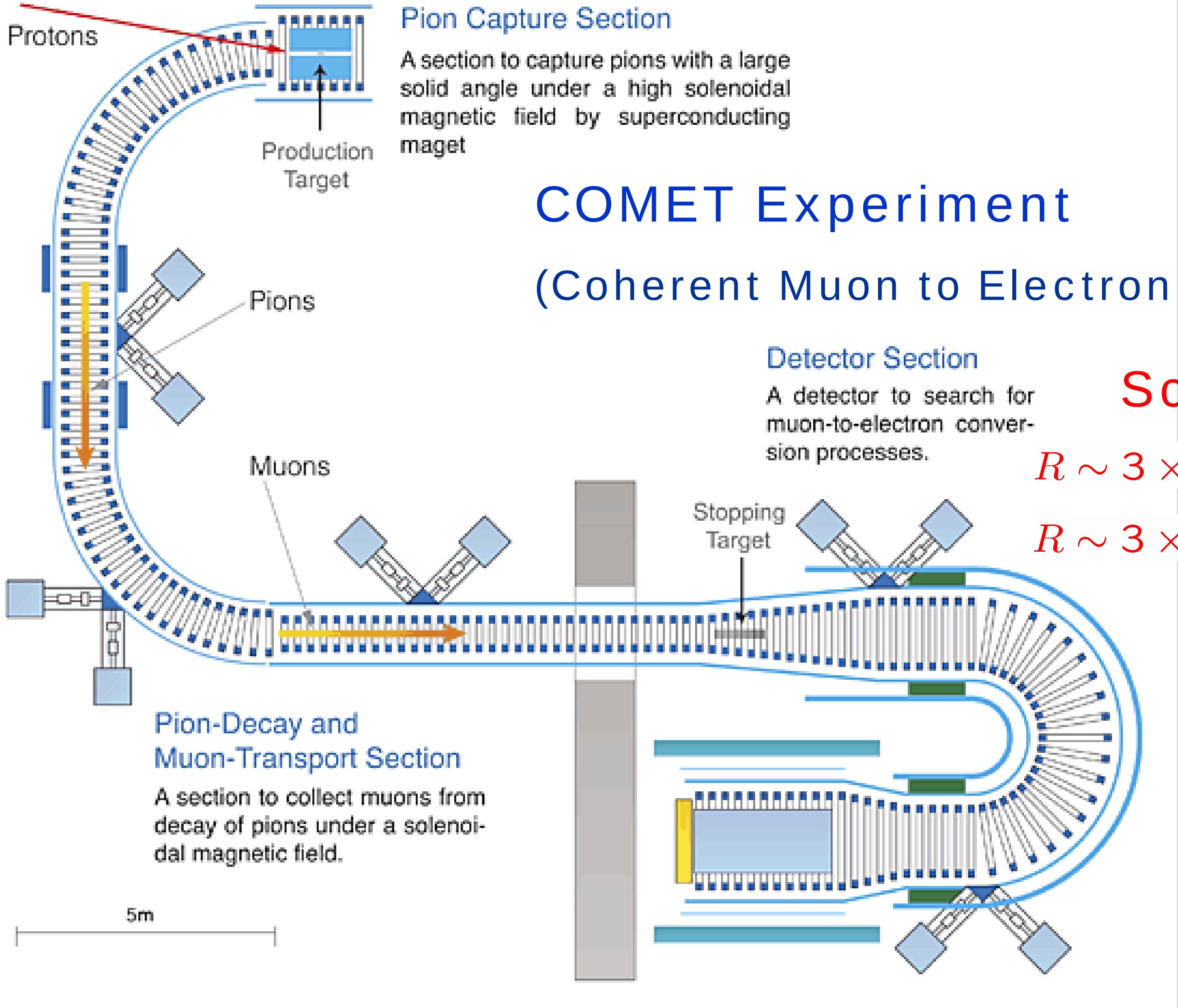


図1 COMET全体図

quoted from http://www-kuno.phys.sci.osaka-u.ac.jp/research/index.html

Schedule

$R \sim 3 \times 10^{-15}$ (2017)

$R \sim 3 \times 10^{-17}$ (2021)

5. Summary

- According to Sumino' FGB scenario (and its extended version), we have investigated a model of FGBs which can be observed by terrestrial experiments.
 As a result, in the quark family assignments
 $(d_1,d_2,d_3)=(b, d, s)$ and $(d_1,d_2,d_3)=(b, s, d)$
 corresponding to the definition $(e_1,e_2, e_3)=(e, \mu, \tau)$,
 we have found that the FGB A_1^1 can have $M_{11}=0.54$ TeV.
 In the cases, FGBs have normal mass hierarchy
 and with n=2 in the mass relation between M_{ij} and m_{ei}.

- We expect direct production of A_1^1

$$p + p \to A_1^1 + b + \bar{b} + X \to e^+ e^- + X$$

at the LHC (peak in e^+e^-, but no peak in $\mu^+\mu^-$).
- We will observe μ-e conversion in μ N reaction in future, but without observation of $\mu^- \to e^- + \gamma$.
- Since the case (B) has anomaly in the lepton sector, we are forced to introduce heavy leptons (N, E).
Although our FGB are highly unstable, the new leptons N may be stable, so that N may can join to candidates of DM.

We are very happy

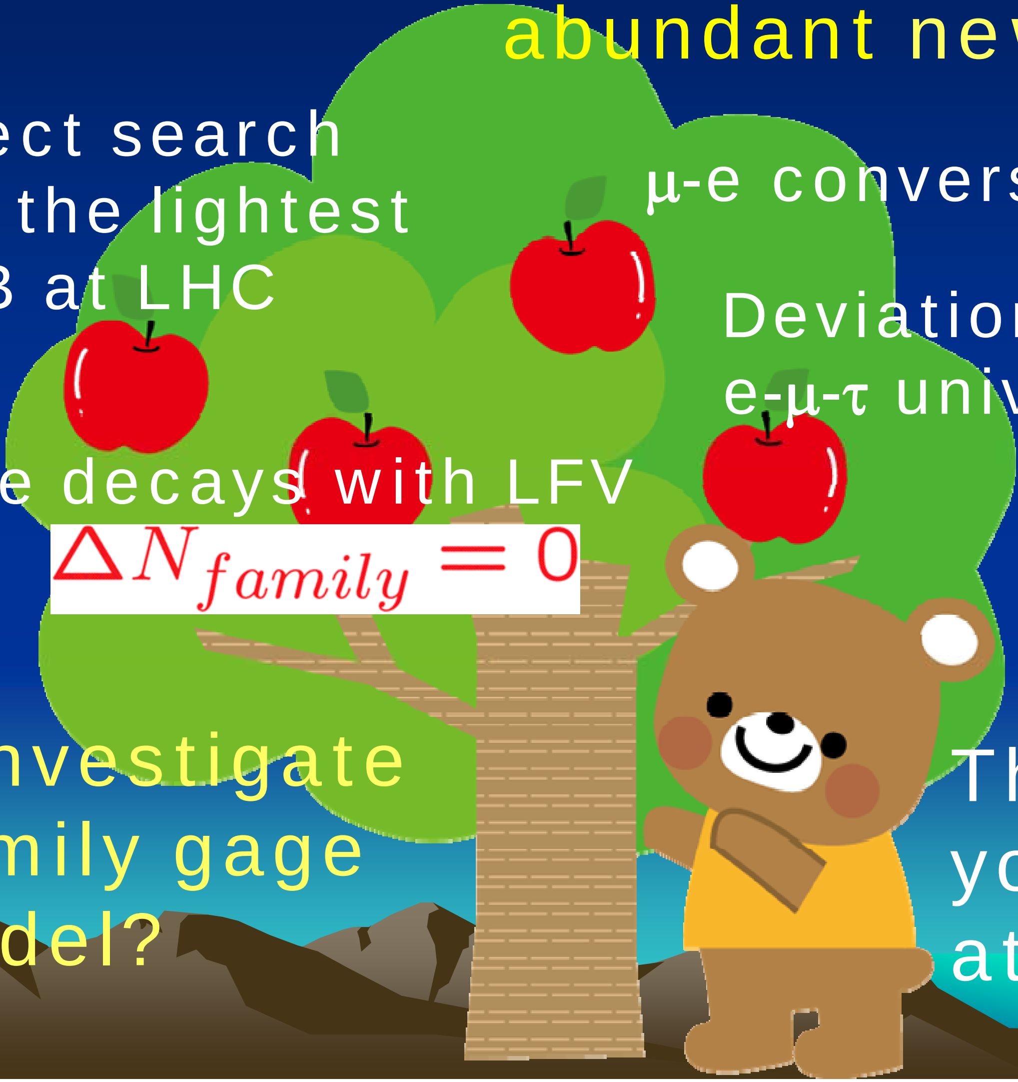
because we can expect
abundant new physics

Direct search
for the lightest
FGB at LHC

μ-e conversion

Deviations from
e-μ-τ universality

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



Why not investigate
such a family gage
boson model?

Thank for
your kind
attention

Backup Slides

- Why family gauge bosons?
- Sumino's cancellation mechanism
- Sumino model vs. Koide-Yamashita model
- FGB masses in the Sumino model
- Classification of cases investigated

Why family gauge bosons?

Why do we consider family gauge bosons ?

(i) If the family gauge bosons (FGBs) are absent, the CKM mixing $V_{CKM} = U_{Lu}^{\dagger} U_{Ld}$ is observable in SM, while the quark mixing matrices U_u and U_d are not observable!

I think that a theory which includes such unobservable quantities is incomplete.

(ii) FGBs are only gauge bosons which can interact not only to ν_L but also ν_R, so that we can easily see whether ν is Majorana or Dirac.

The idea of family symmetry is most natural and minimal extension of the SM.

Sumino's cancellation mechanism

His motivation

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

Why the formula is satisfied by pole masses but, it is not so by running masses?

Origin of the deviation

$$\delta m_{ei}(\mu)^{photon} = m_{ei} \left[\frac{\alpha_{em}(\mu)}{\pi} \left(\frac{3}{4} \log \frac{m_{ei}^2(\mu)}{\mu^2} - 1 \right) \right]$$

The deviation comes from this part

Sumino's idea: If there are FGBs whose masses are proportional to m_{ei}, then we can remove the term $\log m_{ei}^2$ by the additional new contribution

$$\log M_{ii}^2 = c_1 \log m_{ei}^2 + c_0$$

Note: $m_{ei}(\mu)$ itself still evolutes.
The cancellation is satisfied only at one-loop level.

Sumino model vs. Koide-Yamashita model

Y.Sumino, PLB671, 477 (2009) vs. YK and T.Yamashita, PLB 711, 384 (2012)

	Sumino Model	K-Y model
$(e_{Li}, e_{Ri}) =$	$(\mathbf{3}, \mathbf{3}^*)$ of U(3)	$(\mathbf{3}, \mathbf{3})$ of U(3)
	not anomaly free	anomaly free
Currents:	$J_\mu = \bar{f}_L^i \gamma_\mu f_{Lj} - \bar{f}_{Rj} \gamma_\mu f_R^i$	$J_\mu = \bar{f}^i \gamma_\mu f_j$
FGB mass:	$M_{ij}^2 \equiv m^2(A_i^j) = k(m_{ei} + m_{ej})$	$M_{ij}^2 \equiv m^2(A_i^j) = k\left(\frac{1}{m_{ei}} + \frac{1}{m_{ej}}\right)$
	$-\log M_{ii}^2 = -\frac{1}{2}\log m_{ei}^2 - \log k$	$+\log M_{ii}^2 = -\frac{1}{2}\log m_{ei}^2 + \log k$
	Normal **mass hierarchy**	Inverted **mass hierarch**
Scalars:	**A scalar** Φ contributes to M_{ij} and m_{ei} simultaneously	Φ contributes to m_{ei}, but M_{ij} are dominantly contributed by another scalar Ψ $|\langle\Psi\rangle| \gg |\langle\Phi\rangle|$.

FGB masses in the Sumino model

- Family symmetry: $U(3) \times U(3)$ scales Λ and Λ'

$\Lambda \ll \Lambda'$

Scalars: $\Psi = (3, 3)$ of $U(3) \times U(3)$

$\Phi = (3, 3)$ of $U(3) \times U(3)$

In the limit of $\Lambda' \gg \Lambda$

$$M_{ij}^2 = \frac{1}{2}\left(\frac{g_F}{\sqrt{2}}\right)^2 \left(|\langle\Psi_{i\alpha}\rangle| \left|\langle\Psi^{\dagger\alpha i}\rangle\right| + \left|\langle\Psi_{j\alpha}\rangle\right| \left|\langle\Psi^{\dagger\alpha j}\rangle\right| + (\Psi \to \bar{\Psi})\right) + \cdots$$

$$m_{ei} = y_i \delta_i^j \langle\Phi_{i\alpha}\rangle\langle\bar{\Phi}^{\alpha j}\rangle$$

$|\langle\Psi\rangle| \gg |\langle\Phi\rangle|.$

If we assume $\langle\Psi\rangle \propto \langle\Phi\rangle$ → $M_{ij}^2 = k\left(m_{ei} + m_{ej}\right)$

$\langle\Psi\rangle\langle\bar{\Phi}\rangle \propto 1$ → $M_{ij}^2 = k\left(\frac{1}{m_{ei}} + \frac{1}{m_{ej}}\right)$

Both cases satisfy

$$2M_{ij}^2 = M_{ii}^2 + M_{jj}^2$$

Classification of cases investigated

(i) FGB mass hierarchy: (A) Inverted? or (B) Normal?

(ii) Quark family number assignments: Possible 6 cases

Which of these 12 cases are desirable ones with TeV scale FGB?

$$2M_{ij}^2 = M_{ii}^2 + M_{jj}^2$$

(A) $$M_{33} : M_{32} : M_{22} : M_{31} : M_{21} : M_{11} = 1 : \sqrt{\frac{a^2+1}{2}} : a : \sqrt{\frac{b^2+1}{2}} : \sqrt{\frac{b^2+a^2}{2}} : b$$

$$a \equiv \frac{M_{22}}{M_{33}} = \left(\frac{m_\tau}{m_\mu}\right)^{n/2}, \quad b \equiv \frac{M_{11}}{M_{33}} = \left(\frac{m_\tau}{m_e}\right)^{n/2}$$

(B) $$M_{11} : M_{12} : M_{22} : M_{13} : M_{23} : M_{33} = 1 : \sqrt{\frac{a^2+1}{2}} : a : \sqrt{\frac{b^2+1}{2}} : \sqrt{\frac{b^2+a^2}{2}} : b$$

$$a \equiv \frac{M_{22}}{M_{11}} = \left(\frac{m_\mu}{m_e}\right)^{n/2}, \quad b \equiv \frac{M_{33}}{M_{11}} = \left(\frac{m_\tau}{m_e}\right)^{n/2}$$

Note: For the cases (B), we have changed the original Sumino currents into those in the K-Y model

$(e_{Li}, e_{Ri}) = (\mathbf{3}, \mathbf{3}^*)$ of U(3) $\quad (q_{Li}, q_{Ri}) = (\mathbf{3}, \mathbf{3})$ of U(3)