0.

ニュートリノとゲージーノ混合にもとづくニュートリノ質量

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1. Introduction
2. Model = extra U(1) =
3. Various issues ← 省略？
4. Summary

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1. Introduction

solar neutrino
atmospheric neutrino } ⇒ large mixing

large mixing の起源？ ⟵ quark sector small mixing

$V^{(MNS)} = L_l^{\dagger} U_\nu$

- charged lepton に起源　(ex) SU(5), Froggatt-Nielsen

or

- neutrino に起源

可能性 ⇒ いずれかの sector の mass metrix

⇒ almost democratic form

$$M \sim m \begin{pmatrix} 1 & 1 & 1 \\ 1 & 1 & 1 \\ 1 & 1 & 1 \end{pmatrix}$$

rank of $M > 1$ の起源？
order one coefficients の重要性 } ⟶ 物理的背景？

⇓

Supersymmetry ⊕ extra U(1) sym.

gauge hierarchy problem　　string の low energy effective model によく現れ.

neutrino sector に large mixing の起源.

* R-parity violation

R-parity $\quad R_p = (-1)^{3B+L+2S}$

$$\left\{ \begin{array}{ll} \cdot \text{ superparticles} & -1 \\ \cdot \text{ ordinary particles} & +1 \end{array} \right.$$

$\not{R}_p$ があると mixing が起こる

neutral fermion $\qquad \qquad$ gaugino $\quad$ Higgsino

neutrino (ν_α) — neutralino ($\lambda_W, \lambda_Y, \tilde{H}_1^0, \tilde{H}_2^0$)

relevant int. to mixing

$\cdot \; W_{R^0} \supset \epsilon_\alpha L_\alpha H_2 \quad$: explicit $\not{R}_p$ ~ $\epsilon_\alpha \tilde{\nu}_\alpha \tilde{H}_2^0$

$\cdot \; i\sqrt{2} g_a (\tilde{\nu}_\alpha^* \lambda^a T^a \nu_\alpha - \bar{\lambda}^a \bar{\nu}_\alpha T^a \tilde{\nu}_\alpha)$

$\langle \tilde{\nu}_\alpha \rangle \neq 0 \quad$ spontaneous $\not{R}_p$

$\Downarrow$

$$(\nu_e \; \nu_\mu \; \nu_\tau) \begin{pmatrix} \sqrt{2} g_2 \langle \tilde{\nu}_e \rangle & \sqrt{2} g_1 \langle \tilde{\nu}_e \rangle & \epsilon_e \\ \sqrt{2} g_2 \langle \tilde{\nu}_\mu \rangle & \sqrt{2} g_1 \langle \tilde{\nu}_\mu \rangle & \epsilon_\mu \\ \sqrt{2} g_2 \langle \tilde{\nu}_\tau \rangle & \sqrt{2} g_1 \langle \tilde{\nu}_\tau \rangle & \epsilon_\tau \end{pmatrix} \begin{pmatrix} -i\lambda_{W_3} \\ i\lambda_Y \\ \tilde{H}_2^0 \end{pmatrix}$$

ここが[illegible]

pot. study $\quad \langle \tilde{\nu}_\alpha \rangle \sim \epsilon_\alpha$

gaugino mass $\gg \langle \tilde{\nu}_i \rangle \qquad$ mixing に関しては 大きいほうが支配的

seesaw ⟶ $\quad M_{ij}^\nu \propto \langle \tilde{\nu}_i \rangle \langle \tilde{\nu}_j \rangle$

nonzero mass eigenvalue ~ 1個

mass perturbation の[illegible] ⇒ one-loop effect

tree level 2つ mixing & mass eigenvalues ?

2. A model

extra U(1) model （TeV 領域）

- string model ⇝ additional U(1)'s
- μ-problem の解

model としておもしろい.

= constraints =

- precision measurement

$\rightsquigarrow \; m_{Z'} \gtrsim 600\,\mathrm{GeV}, \quad Z\text{-}Z' \text{ mixing} \lesssim 10^{-3}$

[· precision measurement, atomic parity violation) ⟶ extra U(1) favor ? Langacker et al.]

generation dependent U(1) flavor diagonal

neutrino - gaugino mixing $\sqrt{2}\, g_X \underline{b_\alpha} \langle \tilde{\nu}_\alpha \rangle$

⇝ at tree level nonzero mass eigenvalues : 2個 !!

- neutrino oscillation phenomena ?
- other features ?

《発想の転換》

- ◎ neutrino mass — TeV 領域の物理
- · quark mass, charged lepton — Froggatt - Nielsen mechanism

extra $U(1)_x$ （TeV領域）　（<u>lepton sectorのみ考える</u>）— Toy model

$$\begin{cases} l_L(q_I,\ q_I,\ q_{III}),\quad \bar{l}_R(-q_I,\ -q_I,\ -q_{III}) \\ H_1,\ H_2\ :\ \text{zero charge.} \end{cases}$$

flavor identificationはまだ.

• charged lepton

$$m_e = \begin{pmatrix} * & * & 0 \\ * & * & 0 \\ 0 & 0 & * \end{pmatrix}$$

以下簡単のため. diagonal と仮定

• neutrino $\quad \langle\tilde{\nu}_e\rangle = \langle\tilde{\nu}_\mu\rangle = \langle\tilde{\nu}_\tau\rangle \equiv u$

$$\mathcal{M} = \begin{pmatrix} 0 & m^T \\ m & M \end{pmatrix} \qquad m = \begin{pmatrix} a_2 & a_1 & b \\ a_2 & a_1 & b \\ a_2 & a_1 & c \end{pmatrix} \qquad M = \begin{pmatrix} M_2 & & 0 \\ & M_1 & \\ 0 & & M_x \end{pmatrix}$$

$$a_i \equiv \frac{g_i}{\sqrt{2}}u,\quad b \equiv \sqrt{2}g_x q_I u,\quad c \equiv \sqrt{2}g_x q_{III} u$$

$$M^\nu = m^T M^{-1} m = \begin{pmatrix} m_0+\epsilon^2 & m_0+\epsilon^2 & m_0+\epsilon\delta \\ m_0+\epsilon^2 & m_0+\epsilon^2 & m_0+\epsilon\delta \\ m_0+\epsilon\delta & m_0+\epsilon\delta & m_0+\delta^2 \end{pmatrix}$$

$$m_0 = \frac{g_2^2u^2}{2M_2}+\frac{g_1^2u^2}{2M_1},\quad \epsilon = \frac{g_x q_I u}{\sqrt{M_x}},\quad \delta = \frac{g_x q_{III} u}{\sqrt{M_x}}$$

diagonalization matrix U $\qquad \nu_\alpha = U_{\alpha i}\tilde{\nu}_i$

mass eigenstate

$$U = \begin{pmatrix} \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}}\cos\theta & \frac{1}{\sqrt{2}}\sin\theta \\ -\frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}}\cos\theta & \frac{1}{\sqrt{2}}\sin\theta \\ 0 & -\sin\theta & \cos\theta \end{pmatrix}$$

charged lepton diagonal

$$\sin^2 2\theta = \frac{8(m_0+\epsilon\delta)^2}{(m_0+2\epsilon^2-\delta^2)^2+8(m_0+\epsilon\delta)^2}$$

$$\begin{cases} m_{2,3} = \frac{1}{2}\left\{(3m_0+2\epsilon^2+\delta^2)\mp\sqrt{(m_0+2\epsilon^2-\delta^2)^2+8(m_0+\epsilon\delta)^2}\right\} \\ m_1 = 0 \end{cases}$$

$$P_{\nu_\alpha \to \nu_\beta}(L) = \delta_{\alpha\beta} - 4 \sum_{i>j} U_{\alpha i} U_{\beta i} U_{\alpha j} U_{\beta j} \sin^2\left(\frac{\Delta m_{ij}^2}{4E} L\right)$$

(α, β)	(i, j)	$-4 U_{\alpha i} U_{\beta i} U_{\alpha j} U_{\beta j}$ $(\equiv A)$	
(I, II)	(1, 2)	$\cos^2\theta$	(A)
	(1, 3)	$\sin^2\theta$	(B)
	(2, 3)	$-\sin^2\theta \cos^2\theta$	(C)
(I, III)	(2, 3)	$2\sin^2\theta\cos^2\theta$	(D)
(II, III)	(2, 3)	$2\sin^2\theta\cos^2\theta$	(E)

inverse hierarchy

ν_2 と ν_3 : almost degenerate case

m_3, m_2

$m_1 = 0$

atm $\quad 2 \times 10^{-3}\ \mathrm{eV}^2 \lesssim \Delta m_{12}^2 \simeq \Delta m_{13}^2 \lesssim 6 \times 10^{-3}\ \mathrm{eV}^2$

solar $\quad 10^{-10}\ \mathrm{eV}^2 \lesssim \Delta m_{23}^2 \lesssim 1.5 \times 10^{-4}\ \mathrm{eV}^2$

2つ solution dep. に 依存

$$(\mathrm{I}, \mathrm{II}, \mathrm{III}) \Longrightarrow (\tau, \mu, e)$$

$$U^{MNS} = \begin{array}{c} \begin{pmatrix} 0 & -\sin\theta & \cos\theta \\ -\frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}}\cos\theta & \frac{1}{\sqrt{2}}\sin\theta \\ \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}}\cos\theta & \frac{1}{\sqrt{2}}\sin\theta \end{pmatrix} \\ \begin{array}{lll} m_1 = 0 & & \end{array} \end{array}$$

atm $\quad \nu_\mu \to \nu_\tau \qquad (A) + (B)$

$\Delta m_{12}^2 \simeq \Delta m_{13}^2$

solar $\quad \nu_e \to \nu_\mu \ (E)$

$\nu_e \to \nu_\tau \ (D)$

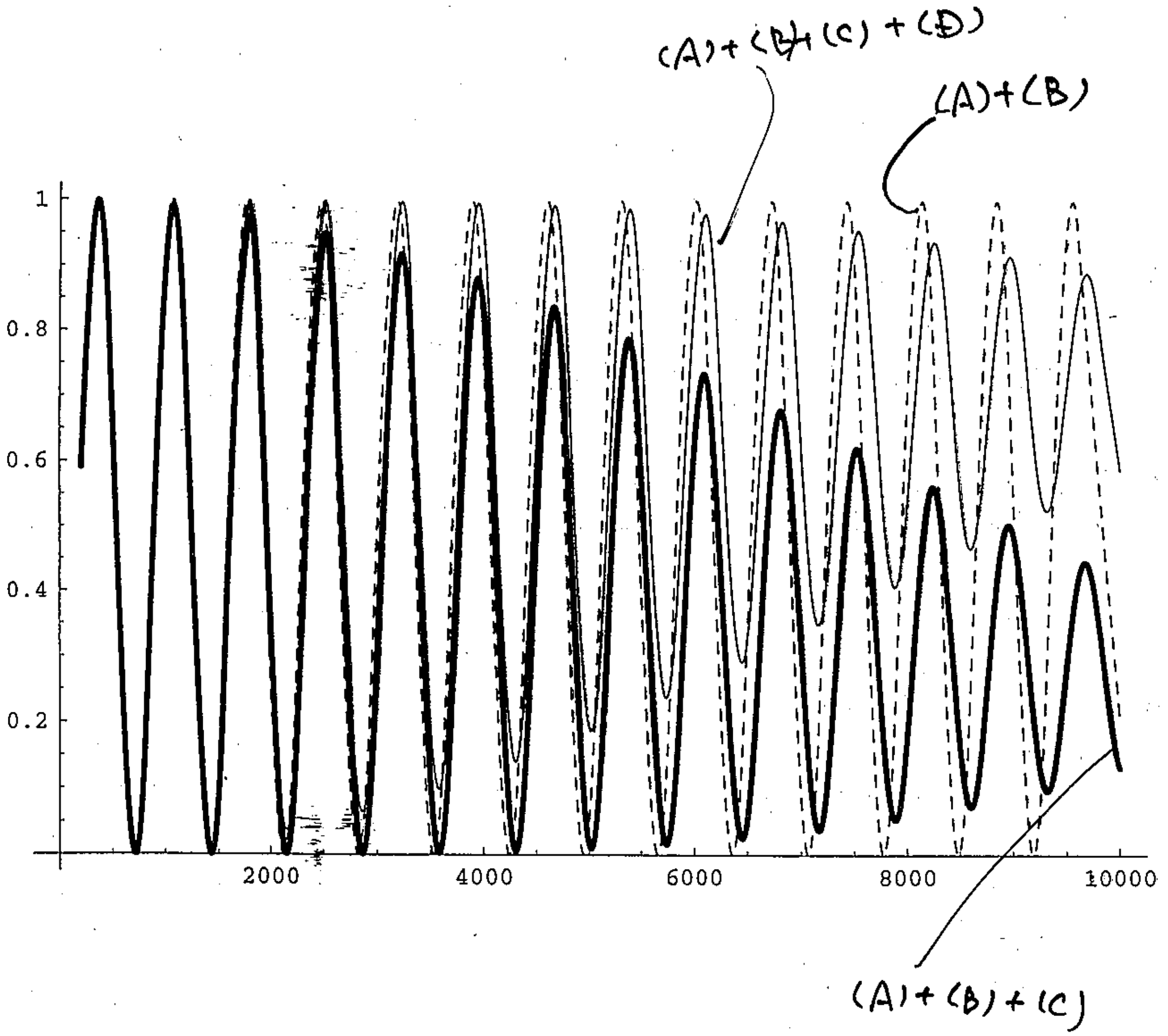
Δm_{23}^2

$\sin^2 2\theta$

$\sin^2 2\theta \sim 10^{-2}$ SMA

$\sin^2 2\theta \sim 1$: LMA, LOW, VO

Δm_{23}^2 dep.


(A)+(B)+(C)+(D)
(A)+(B)
(A)+(B)+(C)
1
0.8
0.6
0.4
0.2
2000
4000
6000
8000
10000

- CHOOZ constraint (power station, long base line $L \sim 1\,\mathrm{km}$, $E \sim 3\,\mathrm{MeV}$)

  $\nu_e \to \nu_x$ with Δm_{12}^2 or Δm_{13}^2

  $\phi \propto U_{e1}$ ~ これに敏感 $U_{e1} = 0$ O.K

- mode (c) $\nu_\mu \to \nu_\tau$ if $\sin^2 2\theta \simeq 1$

  irrelevant to short baseline exp.

  but $\Delta m_{23}^2 \sim 10^{-4}\,\mathrm{eV}$ (LMA) Fig

  $L \gtrsim 2000\,\mathrm{km}$ long baseline exp.

- neutrinoless double β-decay $\phi_j = 0$ とし $m_2 \sim m_3$

$$|m_{ee}| = \left| \sum_j |U_{ej}|^2 e^{2\phi_j} m_j \right| = \left(m_2 \sin^2\theta + m_3 \cos^2\theta \right) \sim m_3$$

$\Downarrow$

$|m_{ee}| \sim 0.04 - 0.08\,\mathrm{eV}$ <u>indep. of $\sin\theta$</u>

◎ realization of oscillation parameters

M_A, g_A, g_α, n : parameters

universal gaugino mass M_0

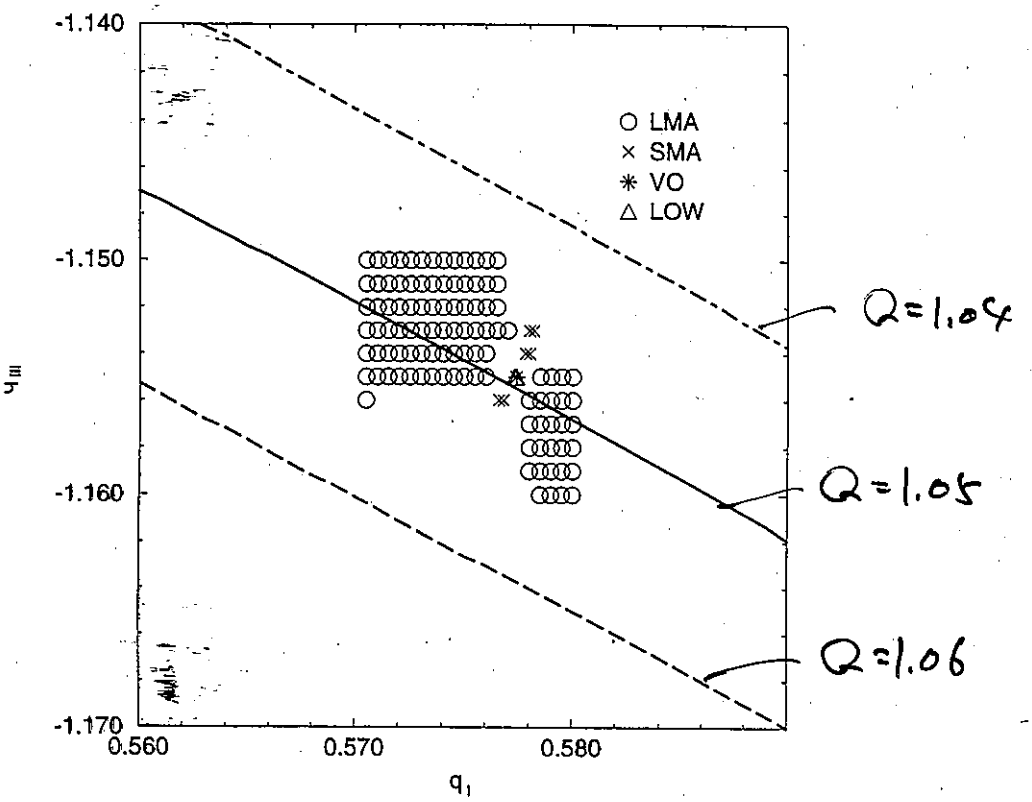
one-loop RGE

$$M_2(\mu) = \frac{M_0}{g_U^2} g_2^2(\mu), \quad M_1(\mu) = \frac{5}{3} \frac{M_0}{g_U^2} g_1^2(\mu)$$

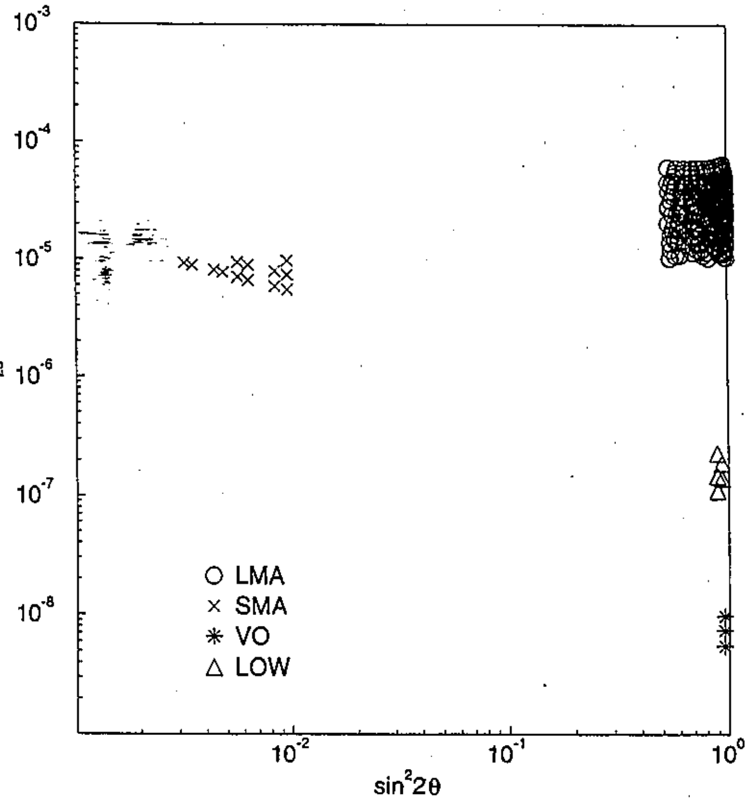
M_X, g_X : M_1, g_1 と同様となる

(U(1)$_X$ Kac-Moody level の自由度)

(a)


LMA
SMA
VO
LOW
Q=1.04
Q=1.05
Q=1.06
-1.140
-1.150
-1.160
-1.170
0.560
0.570
0.580
q_{III}
q_1

(b)


LMA
SMA
VO
LOW
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-2}
10^{-1}
10^{0}
m^2_{23}
$\sin^2 2\theta$

$$\left\{\begin{aligned} m_{2,3} &= \frac{3}{5}\left(2+2g_I^2+g_{III}^2 \mp \sqrt{(2+2g_I^2+g_{III}^2)^2-\frac{16}{3}(g_I-g_{III})^2}\right)\underbrace{\frac{g_U^2 u^2}{M_0}}_{\text{overall factor}} \\ \sin^2 2\theta &= \frac{8(2+3g_I g_{III})^2}{(2+6g_I^2-3g_{III}^2)^2+8(2+3g_I g_{III})^2} \end{aligned}\right.$$

atmospheric neutrino $\sim$ $0.017\,\mathrm{eV} \lesssim \frac{g_U^2}{M_0}u^2 \lesssim 0.023\,\mathrm{eV}$

Ex $\left.\begin{aligned} M_0 &\sim 100\,\mathrm{GeV} \\ g_U &\sim 0.72 \end{aligned}\right\} \Rightarrow u \sim 60\text{-}70\,\mathrm{GeV}$

$\Delta m^2,\ \sin^2 2\theta \Rightarrow g_I,\ g_{III}$ Fig.

$$\left\{\begin{aligned} &\Delta m_{23}^2 \propto \sqrt{(2+2g_I^2+g_{III}^2)^2-\frac{16}{3}(g_I-g_{III})^2} \\ &m_{2,3}\text{の完全縮退}\left(\underbrace{g_I = 1/\sqrt{3},\ g_{III} = -2/\sqrt{3}}_{\text{これからのずれ}}\quad \left(\sum_\alpha g_\alpha = 0\right)\right) \end{aligned}\right.$$

LMA: $U(1)_X$ chargeのtuningは他にくらべてmildでO.K.

注 parameter数が少ない (gauge coupling)

$\sim$ factorの議論まで含め

$U(1)_X$ charge $\sim$ massの大きさ

mixingに反映

$\underbrace{\text{Froggatt-Nielsen}}_{\text{chargeは1つのcontrolに限られる}}$と異なる low energy $U(1)_X$

$\frac{\langle\Theta\rangle}{M_{pl}} \sim \lambda$

3. Various issues

(1°) anomaly free $U(1)_X$?

anomaly free condition $\multimap$ consistent with (g_{I}, g_{II}) ?

additional fields $SU(2)_L \times U(1)_Y$

2_0, $1_{\pm 1}$, $4(1_0)$

$$\left\{ \begin{array}{l} \circ \text{ anomaly free conditions} \\ \circ\ 2_0,\ 1_{\pm 1} \text{ massive at TeV 領域} \end{array} \right.$$

$\Downarrow$

$f(g_{I}, g_{II}, Q) = 0$ $\quad$ Q : charge of $\underset{(ひとつの)}{1_0}$

consistent になる領域

(2°) Z' nonuniversal coupling $\longrightarrow$ FCNC ?

$U(1)_X$: flavor diagonal but generation dep.

$\hookrightarrow$ in general FCNC dangerous

coherent μ-e conversion, $\tau \to 3e, 3\mu$, $\mu \to e\gamma, \cdots$

Z' interaction in mass eigenstates

$$\left\{ \begin{array}{l} \mathcal{L}_{Z'} = -g_1 \left[\frac{g_X}{g_1} \cos\xi\, J^{\mu}_{(X)} - \sin\xi\, J^{\mu}_{(1)} \right] Z'_{\mu} \\ J^{\mu}_{(X)} = \sum_{ij} \left[\bar{\nu}_{Li} B^{\nu_L}_{ij} \nu_{Lj} + \bar{\ell}_{Li} B^{\ell_L}_{ij} \ell_{Lj} + \bar{\ell}_{Ri} B^{\ell_R}_{ij} \ell_{Rj} \right] \\ B^{\psi}_{ij} = V^{\psi\dagger} \operatorname{diag}(g_{II}, g_{I}, g_{I}) V^{\psi} \end{array} \right.$$

$V^{\psi\dagger} m_D^{\psi} V^{\psi} = \text{diag.}$ $\qquad$ $m_e = \begin{pmatrix} * & 0 & 0 \\ 0 & * & * \\ 0 & * & * \end{pmatrix}$

$$\begin{cases} m_{e\mu} = m_{e\tau} = 0 & \Rightarrow B_{12}^{\ell_{L,R}} = B_{13}^{\ell_{L,R}} = 0 \\ g_\mu = g_\tau & \Rightarrow B_{23}^{\ell_{L,R}} = 0 \end{cases}$$

nonuniversal coupling $\Rightarrow$ FCNC : O.K

extended neutralino sector $\rightsquigarrow$ FCNC

MSSM 2" bound 与えられる soft ~~supersym~~ parameters

$\rightsquigarrow$ O.K.

$m_{Z'} \gtrsim 600$ GeV. Z-Z' mixing $\leq 10^{-3}$

no phenomenological problem

(3°) sneutrino VEV $\sim O(10^2$ keV$)$?

e.g. bilinear R-parity violating terms $\epsilon L_\alpha H_2$

potential minimization

$$u \sim \frac{6\epsilon(\mu\langle H_1\rangle + B_\epsilon\langle H_2\rangle)}{3(g_1^2+g_2^2)(\langle H_1\rangle^2 - \langle H_2\rangle^2) + 2g_x^2(\sum_\alpha g_\alpha)(g_1\langle H_1\rangle^2 + g_2\langle H_2\rangle^2) + 6m^2}$$

$\epsilon \ll \mu,\ m^2,\ B_\epsilon \sim M_W$

$\hookrightarrow$ small u は可能 stability ?

detailed study が必要.

4. Summary

1°) supersym. と neutrino mass の関連づけは可能.
R-parity violation & generation dep. low-energy U(1)
parameter の少ない model　LMA 可能

2°) sneutrino VEV の起源??

3°) quark sector も含む model への拡張　$U(1)_{F_1} \times U(1)_{F_2}$ (anomalous)

- quark sector / charged lepton　Froggatt-Nielsen　high energy breaking
〜 charge は小さくなる
- neutrino　R-parity　low energy breaking
〜 charge は mass に直接反映

LMA を許す model ができそう

hep-ph/0104187

4°) mass matrix form
〜 scale up
- ordinary seesaw
- Froggatt-Nielsen

O(1) coefficient の重要性.
model は作れる

hep-ph/0105223

sterile neutrino の導入
LSND を説明する 〜 LMA が favor