Neutrino mass normal ordering with a partial degeneracy in high scale supersymmetry

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The 3rd Neutrino Theories and Phenos in JUNO, September 25-26, 2023, CCAST, Beijing

Basic idea: Supersymmetry is for fermion mass hierarchies (not for the gauge hierarchy)

CL, A supersymmetry model of leptons, phys. Lett. B609 (2005) 111.

Flavor puzzle:

fermion masses, mixing & $\not{C}P$

Observation of the masses:

$$3rd \gg 2nd \gg 1st$$

$$\Downarrow$$

family symmetry: Z_{3L} of the $SU(2)_L$ doublets

$$L_1, Q_1 \rightarrow L_2, Q_2 \rightarrow L_3, Q_3 \rightarrow L_1, Q_1$$

$$\Downarrow$$

$$m_\tau \neq 0,\ m_t \neq 0,\ m_b \neq 0 \text{ only}$$

flavor symmetry: The^c

gauge

$$\Downarrow \langle h \rangle \swarrow$$

lepton mass matrix: $\begin{pmatrix} 1 & 1 & 1 \\ 1 & 1 & 1 \\ 1 & 1 & 1 \end{pmatrix}$

$$\Downarrow$$

$m_e = 0 \quad m_\mu = 0 \quad m_\tau = 3$

How to break this flavor symmetry?

SUSY !

$$\langle \text{Sneutrino} \rangle \neq 0$$

gauge ⊗ flavor ✗

LLE^c

$m_e = 0 \quad m_\mu \neq 0 \quad m_\tau \neq 0$

SUSY breaking

$\Downarrow$

$m_e \neq 0$

a resalt of

gauge $\otimes$ flavor $\otimes$ SUSY $\times$

electron mass

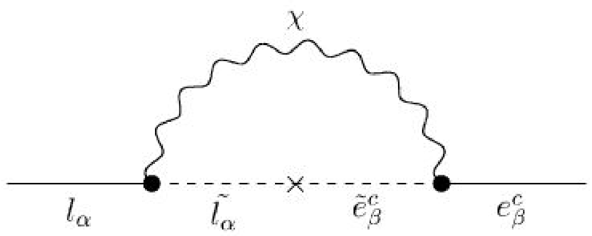


Fig. 2 SUSY loop generation of the charged lepton masses. χ and l, e^c denote the neutral gauginos and charged leptons.

$$\delta M^l_{\alpha\beta} = \sum_\chi \frac{g_\chi^2}{16\pi^2} \frac{m_\chi}{m_\chi^2 - m^2_{\tilde{l}^c_\beta}} \left(\frac{m_\chi^2}{m_\chi^2 - m^2_{\tilde{l}_\alpha}} \ln \frac{m^2_{\tilde{l}_\alpha}}{m_\chi^2} + \frac{m^2_{\tilde{l}^c_\beta}}{m^2_{\tilde{l}_\alpha} - m^2_{\tilde{l}^c_\beta}} \ln \frac{m^2_{\tilde{l}_\alpha}}{m^2_{\tilde{l}^c_\beta}} \right) y_\tau \tilde{m}_S v_d \,. \qquad (21)$$

Approximately it is

$$\delta M^l_{\alpha\beta} \simeq \frac{\alpha}{\pi} \frac{y_\tau \tilde{m}_S v_d}{m_S} \,. \qquad (22)$$

Taking $\tilde{m}_S/m_S \simeq 0.1$, $\delta M^l_{\alpha\beta} \sim \mathcal{O}$ (MeV), which determines the electron mass. Note that the loop induced

of the soft Z_{3L} violating terms. However, the roles of the sneutrino VEVs and the loop effects are switched.[20] The sneutrino VEVs contribute to the first generation quark masses, and the loop effects to the charm and strange quark masses. Under the family symmetry Z_{3L}, the three

The analytical expressions of m_τ and m_μ are obtained as,

$$m_\tau \simeq \sqrt{y_\tau^2 v_d^2 + \lambda_\tau^2 (v_{l_e}^2 + v_{l_\mu}^2)}\,,$$
$$m_\mu \simeq \lambda_\mu \sqrt{v_{l_e}^2 + v_{l_\mu}^2}\,.$$

How Z_{3L} breaks? For the leptons, we have noted:

sneutrino VEV $v_i \neq 0$**,** $LLE^c \Longrightarrow$ **charged lepton masses.** (D.-S. Du and C L , 1993)

But, $m_\nu \sim \dfrac{(g_2 v_i)^2}{M_{\tilde{Z}}} \sim 100$ MeV – too large!

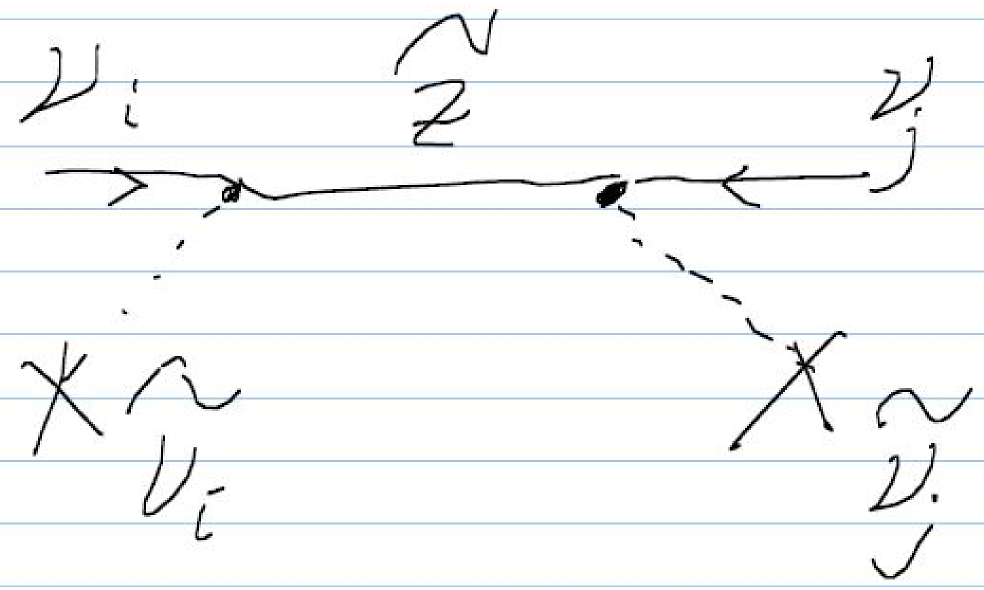
We will make $M_{\tilde{Z}}$ large.

Look at neutrinos,

$$m_\nu = \frac{g_2^2}{M_Z^2} \begin{pmatrix} v_1 v_1 & v_1 v_2 & v_1 v_3 \\ v_2 v_1 & v_2 v_2 & v_2 v_3 \\ v_3 v_1 & v_3 v_2 & v_3 v_3 \end{pmatrix}$$

(rank 1)

Understanding:



see-saw

Low energy effective theory:

(below $m_{\tilde{t}}$)

exact Standard Model

$$h = a_u h_u + a_d h_d + a_e \tilde{l}_e^* + a_\mu \tilde{l}_\mu^* + a_\tau \tilde{l}_\tau^*$$

w/ $\lambda_h \simeq \frac{1}{2}\left[g_2^2(m_{\tilde{t}}) + g_1^2(m_{\tilde{t}})\right]\cos^2 2\beta$

After 2012， Higgs mass = 125 GeV, instead of 140 GeV.

CL and Z.-h. Zhao, *θ13 and the Higgs mass from high scale supersymmetry*, Commun. Theor. Phys. 59 (2013) 467

Try:

1. singlets

   neutrino masses are o.k.

   $\lambda_h \supset \lambda^2 \sin^2 2\beta$ too small!

2. triplets ! $\lambda_h \supset \lambda^2 \sin^4 \beta$

   (Giudice & Strumia 2011)

We introduce a vector-like triplet,

$$\lambda_h = \frac{g_2^2 + g_1^2}{8} \cos^2 2\beta + \Delta\lambda$$

$$\Delta\lambda = \frac{\lambda_4'^2 \sin^4\beta}{M_T^2} \left[m_T^2 - (B_T - A)^2 \right]$$

no $\sin^2 2\beta$ dependence

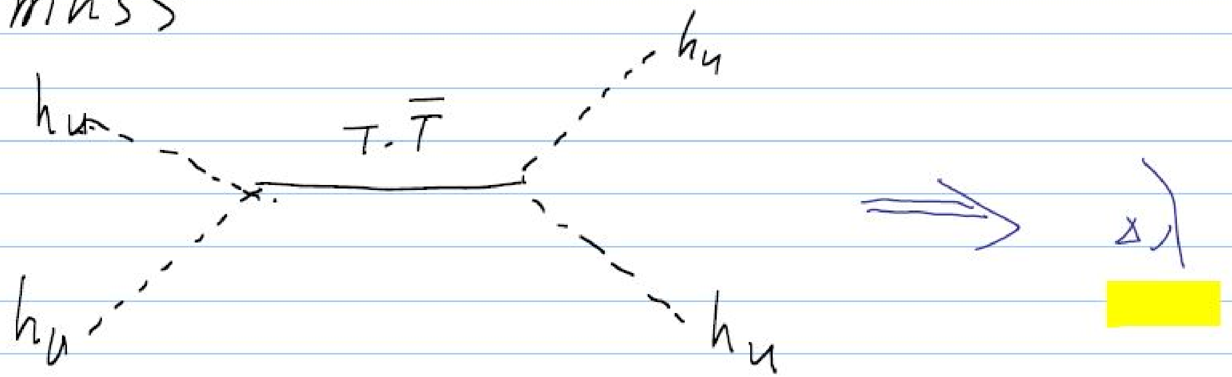
where $M_T \simeq 10^{13}$ GeV, m_T, B_T, A are soft parameters,

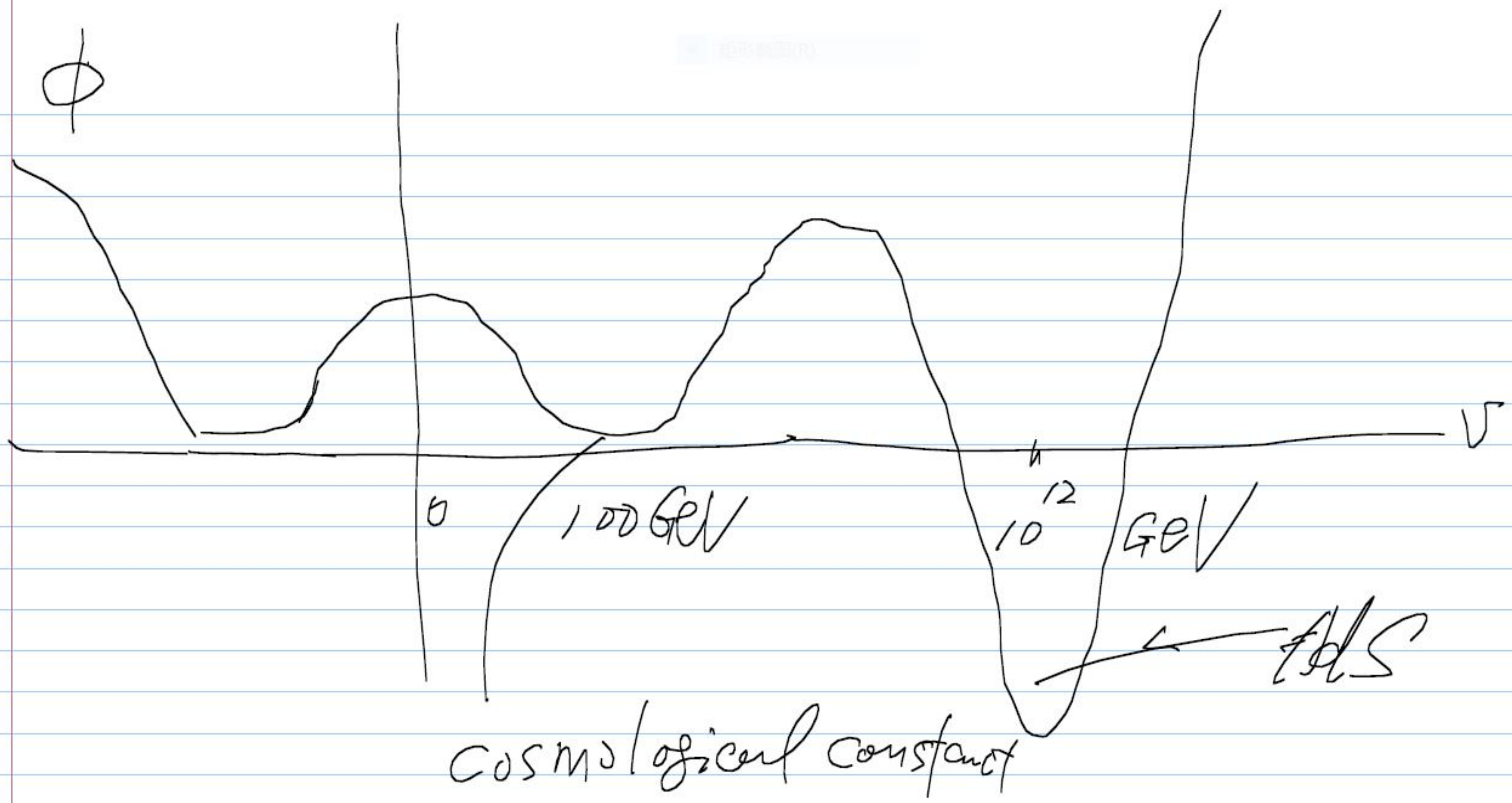
126 Higgs mass can be obtained

Our electroweak vacuum is metastable !

w/ a safe lifetime

For Higgs mass





Phenomenology

CL and Z.-h. Zhao, *θ13 and the Higgs mass from high scale supersymmetry*,
Commun. Theor. Phys. 59 (2013) 467 (arXiv:1205.3849 [hep-ph]);

Y.-K. Lei and CL, *Neutrino phenomenology of a high scale supersymmetry model*,
Commun. Theor. Phys. 71 (2019) 287 (arXiv:1808.10599 [hep-ph]).

Model construction

We proposed that supersymmetry (SUSY) can be the theory underlying the fermion masses. It assumes a flavor symmetry. The flavor symmetry is broken after the sneutrinos obtain nonvanishing vacuum expectation values (VEVs). The flavor symmetry is Z_3 cyclic among the three generation $SU(2)_L$ lepton doublets L_1, L_2 and L_3.

The Z_3 invariant : $\sum_{i=1}^{3} L_i$ and $(L_1L_2 + L_2L_3 + L_3L_1)$

Redefine lepton superfields:

$$L_e = \frac{1}{\sqrt{2}}(L_1 - L_2),$$

$$L_\mu = \frac{1}{\sqrt{6}}(L_1 + L_2 - 2L_3),$$

$$L_\tau = \frac{1}{\sqrt{3}}(\sum_i L_i),$$

The superpotential is then

$$\mathcal{W} \supset y_\tau L_\tau H_d E_\tau^c + L_e L_\mu(\lambda_\tau E_\tau^c + \lambda_\mu E_\mu^c) + \bar{\mu} H_u H_d \,, \qquad (1)$$

Model construction

A heavy vector-like $SU(2)_L$ triplet field $T(\bar{T})$ needs to be introduced so as to make the Higgs mass realistic.
This triplet field also contributes to neutrino masses.
In terms of the redefined fields, the flavor symmetric superpotential relevant to the triplet T and $\bar{T}$ fields is

$$\begin{aligned} \mathcal{W} \supset\ & y^{\nu}\{L_{\tau}H_d\}T + \lambda_1^{\nu}\{L_e L_e + L_{\mu}L_{\mu}\}T + \lambda_2^{\nu}\{L_{\tau}L_{\tau}\}T \\ & + \lambda_3^{\nu}\{H_d H_d\}T + \lambda_4^{\nu}\{H_u H_u\}\bar{T} + M_T T\bar{T} \end{aligned} \qquad (2)$$

For Eq. (2) The mass parameters $\bar{\mu}$ and M_T are taken real, thus H_u and H_d always have opposite phases, and so do T and $\bar{T}$. λ_2^{ν} is real via rotating the phase of L_{τ}, λ_4^{ν} is real via rotating H_u (or $\bar{T}$), y_{τ} is real via E_{τ}^c, λ_{τ} real via $L_e L_{\mu}$ rotating, and λ_{μ} real via E_{μ}^c. In such a phase convention, only y^{ν}, λ_1^{ν} and λ_3^{ν} can be complex.

Sneutrino VEVs

The scalar potential relevant to the electroweak symmetry breaking is

$$\begin{aligned} V =&(|\bar{\mu}|^2 + m_{h_u}^2)|h_u|^2 + (|\bar{\mu}|^2 + m_{h_d}^2)|h_d|^2 + \\ &\frac{g^2+g'^2}{8}(|h_u|^2 - |h_d|^2 - \tilde{l}_\alpha^\dagger \tilde{l}_\alpha)^2 \\ &+ \frac{g^2}{4}[2|h_u^\dagger h_d|^2 + 2(h_u^\dagger \tilde{l}_\alpha)(\tilde{l}_\alpha^\dagger h_u) + 2(h_d^\dagger \tilde{l}_\alpha)(\tilde{l}_\alpha^\dagger h_d) \\ &- 2|h_d|^2(\tilde{l}_\alpha^\dagger \tilde{l}_\alpha) + (\tilde{l}_\alpha^\dagger \tilde{l}_\beta)(\tilde{l}_\beta^\dagger \tilde{l}_\alpha) - (\tilde{l}_\alpha^\dagger \tilde{l}_\alpha)(\tilde{l}_\beta^\dagger \tilde{l}_\beta)] \\ &+ (\frac{1}{2} m_{d\alpha}^2 h_d^\dagger \tilde{l}_\alpha + \frac{1}{2} m_{\alpha\beta}^2 \tilde{l}_\alpha^\dagger \tilde{l}_\beta + B_\mu h_u h_d + B_{\mu\alpha} h_u \tilde{l}_\alpha + \text{h.c.}) \end{aligned} \tag{3}$$

- Field redefinition of h_d and $\tilde{l}_\alpha$ may remove phases of B_μ and $B_{\mu\alpha}$ respectively.
- the phases of $m_{d\alpha}^2$ and off-diagonal terms of $m_{\alpha\beta}^2$ are still there
- VEVs of the Higgs and the sneutrino fields are denoted as v_u, $v_d e^{i\delta_{v_d}}$, $v_{l_e} e^{i\delta_{l_e}}$, $v_{l_\mu} e^{i\delta_{l_\mu}}$, $v_{l_\tau} e^{i\delta_{l_\tau}}$

Neutrino masses

The sneutrino VEVs result in a nonvanishing neutrino mass,

$$M_0^\nu = \frac{a^2}{M_{\tilde{Z}}} \begin{pmatrix} v_{l_e} v_{l_e} e^{2i\delta_{l_e}} & v_{l_e} v_{l_\mu} e^{i(\delta_{l_e}+\delta_{l_\mu})} & v_{l_e} v_{l_\tau} e^{i(\delta_{l_e}+\delta_{l_\tau})} \\ v_{l_\mu} v_{l_e} e^{i(\delta_{l_e}+\delta_{l_\mu})} & v_{l_\mu} v_{l_\mu} e^{2i\delta_{l_\mu}} & v_{l_\mu} v_{l_\tau} e^{i(\delta_{l_\mu}+\delta_{l_\tau})} \\ v_{l_\tau} v_{l_e} e^{i(\delta_{l_e}+\delta_{l_\tau})} & v_{l_\mu} v_{l_\tau} e^{i(\delta_{l_\mu}+\delta_{l_\tau})} & v_{l_\tau} v_{l_\tau} e^{2i\delta_\tau} \end{pmatrix}, \tag{4}$$

the superpotential (2) contributes following neutrino masses ,

$$M_1^\nu = -\frac{\lambda_4^\nu v_u^2}{M_T} \begin{pmatrix} \lambda_1^\nu e^{\delta_{\lambda_1}} & 0 & 0 \\ 0 & \lambda_1^\nu e^{\delta_{\lambda_1}} & 0 \\ 0 & 0 & \lambda_2^\nu \end{pmatrix}, \tag{5}$$

The full neutrino mass matrix is

$$M^\nu = M_0^\nu + M_1^\nu \,. \tag{6}$$

Neutrino mass

the neutrino masses in our model are

$$\begin{aligned} m_{\nu_1} &= \frac{a^2}{M_{\tilde{Z}}}\lambda'_1\,, \\ m_{\nu_2} &\simeq \frac{a^2}{M_{\tilde{Z}}}[\lambda'_1 + (v_{l_e}^2 + v_{l_\mu}^2)\frac{\Delta\lambda}{v_{l_\tau}^2 + \Delta\lambda}\cos(\delta_{\lambda_1} + \delta_Z)]\,, \\ m_{\nu_3} &= \frac{a^2}{M_{\tilde{Z}}}\sqrt{\lambda_2'^2 + v_{l_\tau}^4 + 2\lambda'_2 v_{l_\tau}^2 \cos\delta_Z}\,. \end{aligned} \qquad (7)$$

Finally, we obtain the unitary matrix U_ν which diagonalizes M^ν,

$$U_\nu^T M^\nu U_\nu = -\frac{a^2}{M_{\tilde{Z}}}\begin{pmatrix} m_{\nu_1} & 0 & 0 \\ 0 & m_{\nu_2} & 0 \\ 0 & 0 & m_{\nu_3} \end{pmatrix}, \qquad (8)$$

$$U_\nu = O_\nu P^\dagger \qquad (9)$$

with P being the pure phase matrix appearing in Eq.

Charged lepton masses

- $$M^l = \begin{pmatrix} 0 & \lambda_\mu v_{l_\mu} e^{i\delta_{l_\mu}} & \lambda_\tau v_{l_\mu} e^{i\delta_{l_\mu}} \\ 0 & \lambda_\mu v_{l_e} e^{i\delta_{l_e}} & \lambda_\tau v_{l_e} e^{i\delta_{l_e}} \\ 0 & 0 & y_\tau v_d e^{i\delta_{v_d}} \end{pmatrix} . \tag{10}$$

  It is standard to find the unitary matrix U_l which diagonalizes $M^l M^{l\dagger}$,
- It can be expressed as

  $$U_l = P_l O_l \,,$$

  where

  $$P_l = \begin{pmatrix} e^{i\delta_{l_\mu}} & 0 & 0 \\ 0 & e^{i\delta_{l_e}} & 0 \\ 0 & 0 & e^{i\delta_{v_d}} \end{pmatrix} , \tag{11}$$

  $$O_l \simeq \begin{pmatrix} \frac{-v_{l_e}}{\sqrt{v_{l_e}^2+v_{l_\mu}^2}} & \frac{v_{l_\mu}}{\sqrt{v_{l_e}^2+v_{l_\mu}^2}} & \frac{y_\tau v_d}{\sqrt{y_\tau^2 v_d^2+|\lambda_\tau|^2(v_{l_e}^2+v_{l_\mu}^2)}} & \frac{\lambda_\tau v_{l_\mu}}{\sqrt{y_\tau^2 v_d^2+|\lambda_\tau|^2(v_{l_e}^2+v_{l_\mu}^2)}} \\ \frac{v_{l_\mu}}{\sqrt{v_{l_e}^2+v_{l_\mu}^2}} & \frac{v_{l_e}}{\sqrt{v_{l_e}^2+v_{l_\mu}^2}} & \frac{y_\tau v_d}{\sqrt{y_\tau^2 v_d^2+|\lambda_\tau|^2(v_{l_e}^2+v_{l_\mu}^2)}} & \frac{\lambda_\tau v_{l_e}}{\sqrt{y_\tau^2 v_d^2+|\lambda_\tau|^2(v_{l_e}^2+v_{l_\mu}^2)}} \\ 0 & \frac{-\lambda_\tau \sqrt{v_{l_e}^2+v_{l_\mu}^2}}{\sqrt{y_\tau^2 v_d^2+|\lambda_\tau|^2(v_{l_e}^2+v_{l_\mu}^2)}} & & \frac{y_\tau v_d}{\sqrt{y_\tau{}^2 v_d^2+|\lambda_\tau|^2(v_{l_e}^2+v_{l_\mu}^2)}} \end{pmatrix} . \tag{12}$$

Lepton mixing matrix

$\nu_e - \nu_\mu$ mixing is

$$V_{e2} = \frac{v_{l_\mu}^2 - v_{l_e}^2}{v_{l_e}^2 + v_{l_\mu}^2} e^{-i\frac{\beta_1}{2}} \ . \tag{13}$$

$\nu_\mu - \nu_\tau$ mixing is

$$\begin{aligned} V_{\mu 3} =& \frac{2 v_{l_e} v_{l_\mu} v_{l_\tau}}{\sqrt{v_{l_e}^2 + v_{l_\mu}^2}\,(v_{l_\tau}^2 + \Delta\lambda)} \frac{y_\tau v_d}{\sqrt{y_\tau^2 v_d^2 + \lambda_\tau^2 (v_{l_e}^2 + v_{l_\mu}^2)}} e^{-i\frac{\beta_2}{2}} \\ & - \frac{\lambda_\tau \sqrt{v_{l_e}^2 + v_{l_\mu}^2}}{\sqrt{y_\tau^2 v_d^2 + \lambda_\tau^2 (v_{l_e}^2 + v_{l_\mu}^2)}} e^{-i\delta_{v_d} - i\frac{\beta_2}{2}} \ . \end{aligned} \tag{14}$$

Lepton mixing matrix

$\nu_e - \nu_\tau$ mixing is

$$V_{e3} \simeq \frac{v_{l_\mu}^2 - v_{l_e}^2}{\sqrt{v_{l_e}^2 + v_{l_\mu}^2}} \frac{v_{l_\tau}}{v_{l_\tau}^2 + \Delta\lambda} e^{-i\frac{\beta_2}{2}} \qquad (13)$$

Obviously, taking $v_{l_\mu} \sim 2v_{l_e}$, $|V_{e2}|$ is in agreement with data.

Then $|V_{e3}| \simeq |V_{e_2}| \frac{\sqrt{v_{l_e}^2 + v_{l_\nu}^2}\, v_{l_\tau}}{r}$. Choosing $r \sim 3v_{l_\tau}^2$, it is easy to get $|V_{e3}| \sim 0.3|V_{e_2}|$.

Lepton mixing matrix

- Obviously, taking $v_{l_\mu} \simeq 2v_{l_e}$, $|V_{e2}|$ is in agreement with data
- The value of v_{l_τ} is taken to be larger and still in the natural range, $v_{l_\tau} \simeq 3v_{l_\mu}$
- Choosing $\Delta\lambda \simeq 0.3v_{l_\tau}^2$
- $\lambda_\tau\sqrt{{v_{l_\mu}}^2 + {v_{l_e}}^2} = y_\tau v_d$, a smaller λ_τ is more natural.

The important CP violation in neutrino oscillations is given through the invariant parameter J [13],

$$J \simeq \frac{2 v_{l_e} v_{l_\mu} v_{l_\tau} (v_{l_e}^2 - v_{l_\mu}^2)^2 \lambda_\tau y_\tau v_d}{(y_\tau^2 v_d^2 + \lambda_\tau^2 (v_{l_e}^2 + v_{l_\mu}^2))(v_{l_e}^2 + v_{l_\mu}^2)^2 (v_{l_\tau}^2 + \Delta\lambda)} \sin\delta \simeq 0.04 \sin\delta, \tag{28}$$

$$\delta = - \delta_{v_d} .$$

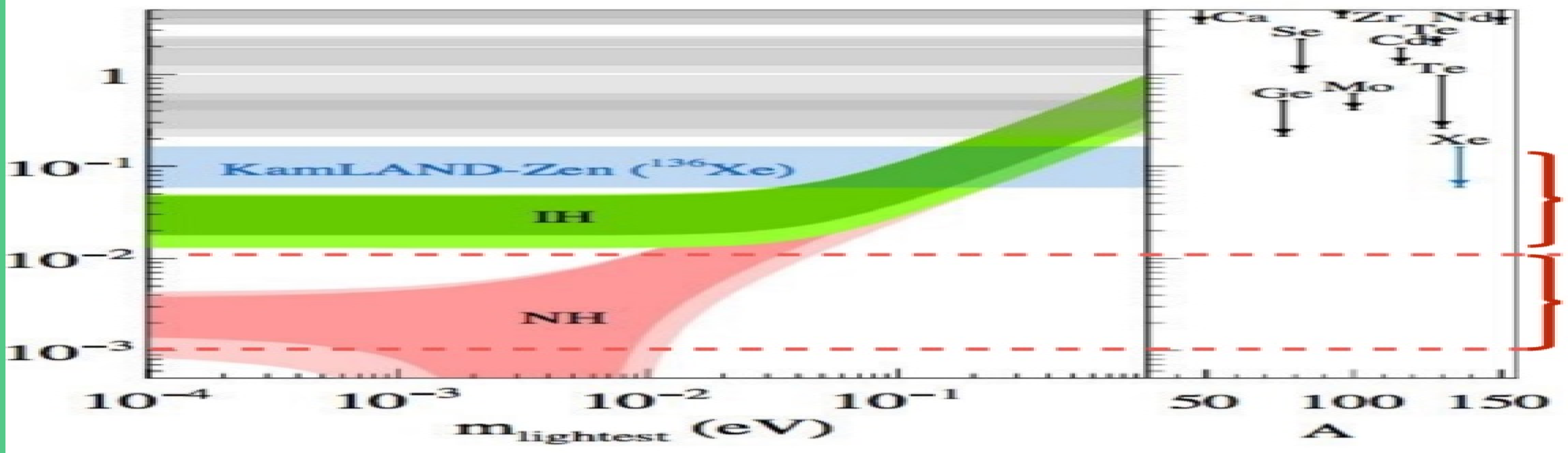
δ_{v_d} is expected to be large, namely $|\sin\delta| \sim 0.1 - 1$. This agrees with current preliminary experimental results [15].

Further discussions

- the model is quite natural:
  sneutrino VEVs results in a massive neutrino;
  triplet field is originally for the realistic Higgs mass;
  it also contributes to neutrino masses through a type-II seesaw mechanism.
  especially it gives a degeneracy of m_{ν_1} and m_{ν_2}.
- In terms of parameters in the superpotential, we have $M_{\tilde{Z}} \simeq 3 \times 10^{11}$ GeV. $M_T \simeq (1 - 10)M_{\tilde{Z}}$, and $\lambda' s \simeq (0.01 - 0.1)$.
- there is a possibility of inverted neutrino mass hierarchy, namely a very small m_{ν_3}.

from Langacker’s summary talk in ICHEP2018（Seoul）,

ernova, atmospheric, high energy, rel



. Right: ‘‘Lobster-claw’’ diagram of the e

Summary

- CP violation in neutrino oscillation is large .
- The effective Majorana neutrino mass in the neutrinoless double beta decay is about 0.02 eV, it is within the detection ability of future measurements.
- θ_{23} is in the first octant.
- The neutrino masses are in normal ordering.
- The electron neutrino mass is about 0.02 eV.
- The sum of three neutrino masses is close to $\sum m_\nu \simeq 0.1$ eV.

Thank you　!

Commun. Theor. Phys. (Beijing, China) **47** (2007) pp. 1088–1098
© International Academic Publishers Vol. 47, No. 6, June 15, 2007

Supersymmetry for Fermion Masses*

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(Received December 14, 2006)

Abstract *It is proposed that supersymmetry (SUSY) may be used to understand fermion mass hierarchies. A family symmetry Z_{3L} is introduced, which is the cyclic symmetry among the three generation SU(2) doublets. SUSY breaks at a high energy scale $\sim 10^{11}$ GeV. The electroweak energy scale ~ 100 GeV is unnaturally small. No additional global symmetry, like the R-parity, is imposed. The Yukawa couplings and R-parity violating couplings all take their natural values, which are $\mathcal{O}(10^0 \sim 10^{-2})$. Under the family symmetry, only the third generation charged fermions get their masses. This family symmetry is broken in the soft SUSY breaking terms, which result in a hierarchical pattern of the fermion masses. It turns out that for the charged leptons, the τ mass is from the Higgs vacuum expectation value (VEV) and the sneutrino VEVs, the muon mass is due to the sneutrino VEVs, and the electron gains its mass due to both Z_{3L} and SUSY breaking. The large neutrino mixing are produced with neutralinos playing the partial role of right-handed neutrinos. $|V_{e3}|$, which is for ν_e-ν_τ mixing, is expected to be about 0.1. For the quarks, the third generation masses are from the Higgs VEVs, the second generation masses are from quantum corrections, and the down quark mass due to the sneutrino VEVs. It explains m_c/m_s, m_s/m_e, $m_d > m_u$, and so on. Other aspects of the model are discussed.*

PACS numbers: 12.15.Ff, 11.30.Pb, 11.30.Hv
Key words: fermion mass, family symmetry, supersymmetry

1 Introduction

In elementary particle physics, SUSY[1] was proposed

symmetry breaks. Naively the symmetry breaking can be achieved by introducing family-dependent Higgs fields.

7 Summary

If SUSY is not for stabilizing the EW energy scale, what is it used for in particle physics? In this paper, motivated by our previous works,[16,19,20] we have proposed that SUSY is for flavor problems. A family symmetry Z_{3L}, which is the cyclic symmetry among the three generation $SU(2)_L$ doublets, is introduced. No additional global symmetry, like the R-parity is imposed. SUSY breaks at a high scale $\sim 10^{11}$ GeV. The EW energy scale ~ 100 GeV is unnaturally small from the point of view of the field theory. Under the family symmetry, only the third generation fermions get to be massive after EW symmetry breaking. This family symmetry is broken by soft SUSY breaking terms. These terms contribute masses via loops to the second generation quarks and the electron. Furthermore they induce sneutrino VEVs which result in the masses of the muon and the down quark. The neutrino large mixing can be obtained. The KM mechanism of CP violation is realized at low energies. A hierarchical pattern of the lepton and quark masses are obtained. The Higgs mass of this model is about 145 GeV. This point can be tested in the future experiments at Tevatron and LHC. It is expected that ν_e-ν_τ mixing is near to its experimental limit.

Acknowledgments

We would like to thank Yue-Liang Wu, Jin-Min Yang, Zhi-Zhong Xing, and Pyungwon Ko for helpful discussions.

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being valid, $m_{\tilde{q}^c}^2/m_{\tilde{q}}^2$ should be smaller than 10^{-3}.

CP violation originates from the SUSY soft breaking part. In general, there are several possible origins of CP violation within the framework of SUSY. The first one is the complex Yukawa couplings y_t and y_b in Eq. (27), from which, it is seen explicitly that their phases can be absorbed by the redefinition of the quark fields. The second possible origin is from the R-parity-violating couplings λ''s. Their CP violation effect is suppressed by the heavy squarks. As for the small down quark mass terms $(\lambda' v_{l_\alpha})_{c\beta}$ and $(\lambda' v_{l_\alpha})_{u\beta}$, not only can most of their phases be rotated away, but also they themselves are very

4 Effective Theory and Higgs Mass

The light Higgs is the following combination,

$$h = a_u h_u + a_d h_d^* + a_e \tilde{l}_e^* + a_\mu \tilde{l}_\mu^* + a_\tau \tilde{l}_\tau^* \,, \tag{37}$$

where

$$a_u = \frac{v_u}{v}\,, \quad a_d = \frac{v_d}{v}\,, \quad a_\alpha = \frac{v_{l_\alpha}}{v}\,, \tag{38}$$

and $v \equiv \sqrt{v_u^2 + v_d^2 + \sum_\alpha v_{l_\alpha}^2}$. The low-energy effective theory is written as

$$\mathcal{L}_{\rm eff} = y_{\tau\tau} l_\tau h^\dagger e_\tau^c + y_{\mu\mu} l_\mu h^\dagger e_\mu^c + y_{\mu\tau} l_\mu h^\dagger e_\tau^c + y_{e\tau} l_e h^\dagger e_\tau^c + y_{e\mu} l_e h^\dagger e_\mu^c + y_e^{\alpha\beta} l_\alpha h^\dagger e_\beta^c$$

$$+ \frac{a^2 v_{l_\alpha} v_{l_\beta}}{M_{\tilde{Z}}} \nu_\alpha^{Tc} \nu_\beta + y_{tt} q_t h t^c + y_{tb} q_t h^\dagger b^c + y_{cc}^{\alpha\beta} q_{c_\alpha} h c_\beta^c + y_{cs}^{\alpha\beta} q_{c_\alpha} h^\dagger s_\beta^c + m^2 h^\dagger h - \frac{\lambda}{2}(h^\dagger h)^2 + \text{h.c.}\,, \tag{39}$$

where the effective Yukawa couplings are

$$y_{\tau\tau} = y_\tau a_d\,, \quad y_{\mu\mu} = \lambda_\mu a_e\,, \quad y_{\mu\tau} = \lambda_\tau a_e\,,$$

δM^l

significant. We put such a systematic analysis for future works. Nevertheless, the Higgs mass should be discussed. As far as this point is concerned, our model is the same as that given in Ref. [13]. By taking $\tan\beta \sim m_t/m_b$, it was shown[13] that

$$m_h \simeq 145 \pm 7 \;\; \text{GeV}\,, \tag{42}$$

where the uncertainty includes that of both m_t and α_s.