新しい multi-Higgs model と TeV-scale seesaw

EXTRADIMENSION 20100 大阪大学研究会, 24,25 Jan., 2011

based on collaboration with K. Tsumura and M. Hirotsu.
(Eur.Phys.J.C69 (2010) 481, N. Haba and M. Hirotsu)

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Contents

1. introduction

- ν mass means beyond SM

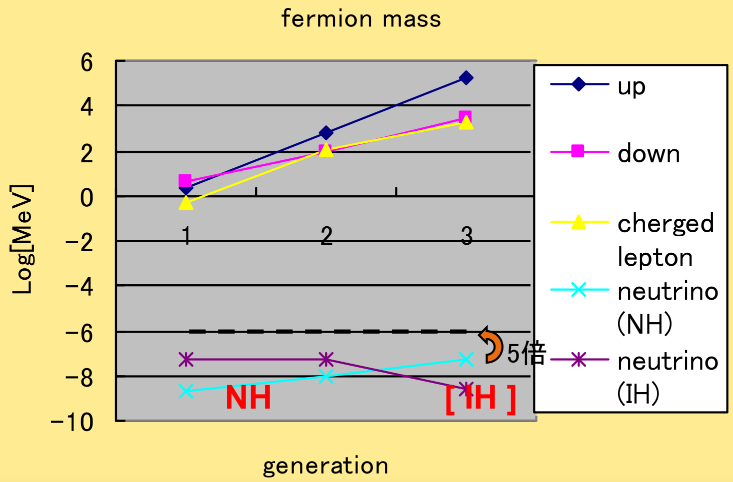
  → key of beyond SM

- existence of ν mass is probed by ν-oscillation exps.

- $m_\nu \leqq 0.1$ eV (with cosmologies)

- Why so tiny, $m_\nu \ll m_{q,l}$? → key of beyond SM

Why $m_\nu \ll m_{q/l}$?



low energy effective theory:

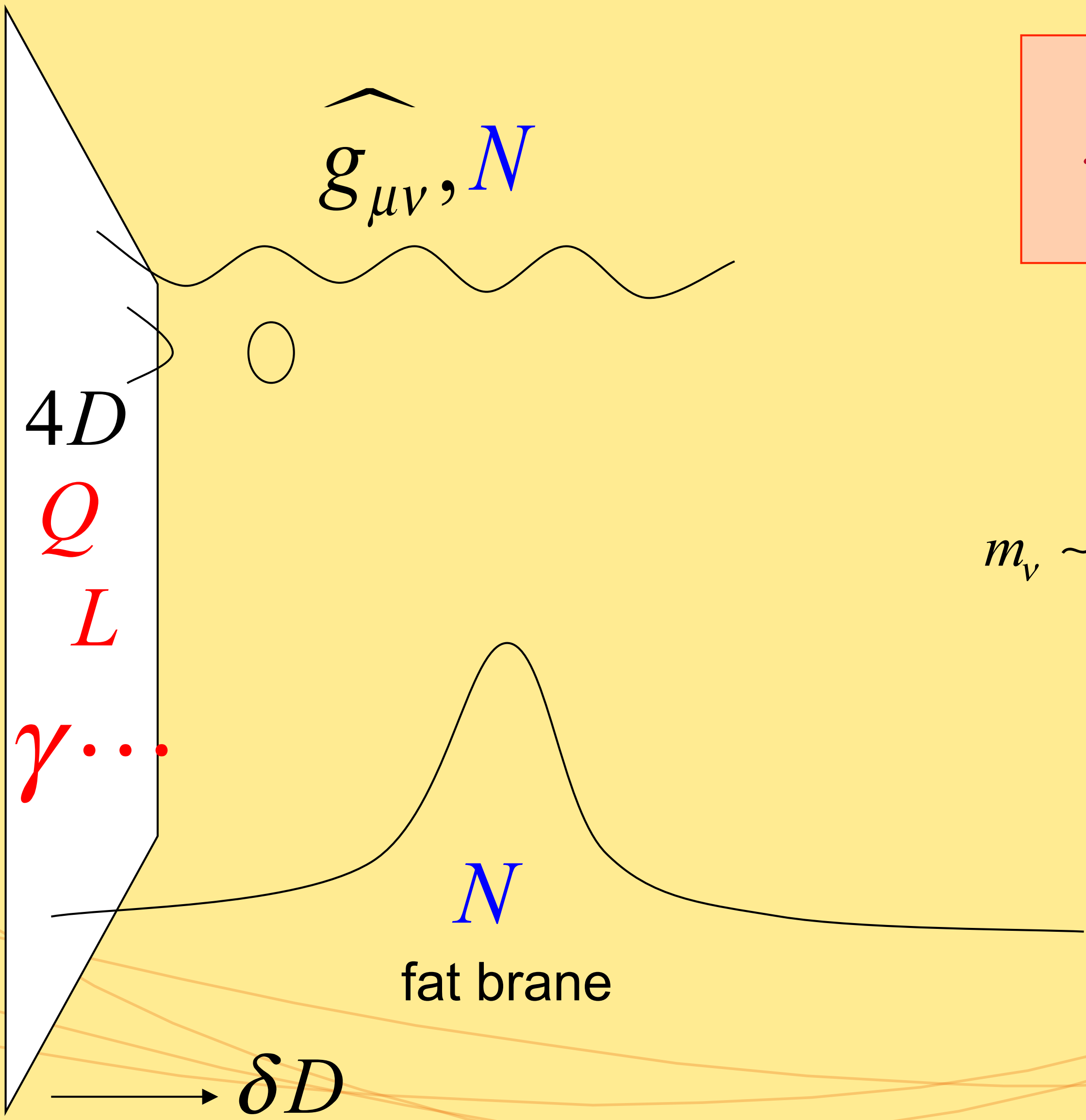
① effective ν-Yukawa is tiny (dim 4 OP)

$$\boxed{m_\nu \sim y_\nu^{(eff)} \langle H \rangle}$$

What is the UV theory ?

new physics in UV theory which generate tiny $y_\nu^{(eff)}$

(ex): large extra dimensional theory



volume suppression

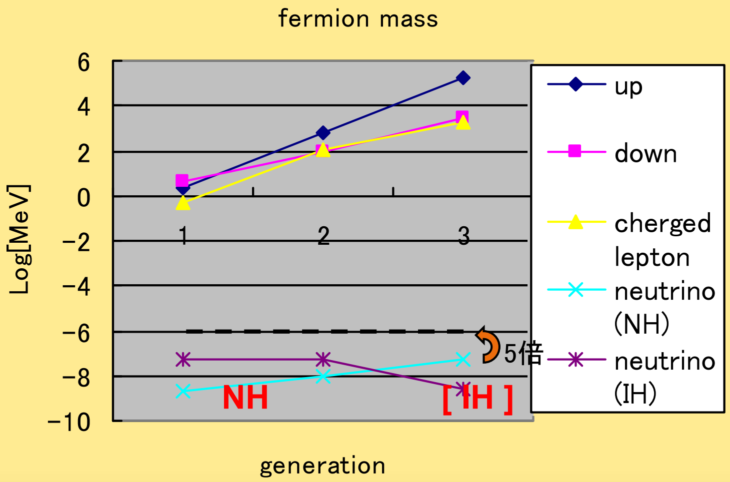
$$y_\nu^{(eff)} \sim \frac{1}{(M_* R)^{\delta/2}} Y_\nu$$

$$m_\nu \sim \begin{array}{cc} \begin{array}{cccc} \nu_{N_R}^{(0)} & \nu_{N_R}^{(1)} & \nu_{N_R}^{(2)} & \end{array} & \\ \begin{pmatrix} m_D & m_D & m_D & \cdots \\ 0 & 1/R & 0 & \\ 0 & 0 & 2/R & \\ \vdots & & & \ddots \end{pmatrix} & \begin{array}{c} \nu_L^{(0)} \\ \nu_{N_L}^{(1)} \\ \nu_{N_L}^{(2)} \\ \end{array} \end{array}$$

distant suppression

$$y_\nu^{(eff)} \propto e^{-(y-y_0)^2}$$

Why $m_\nu \ll m_{q/l}$?



effective OPs in SM fields:

② dim5 OP (lowest in SM)

$$m_\nu \sim \gamma \frac{LL\langle H\rangle\langle H\rangle}{M}$$

ΔL=2 (lepton # is violated)

SM renormalizability is consistent with exps.

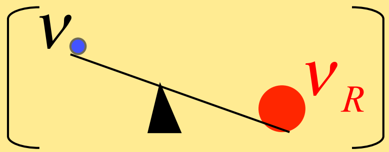
⇕

$M \gg M_Z$ and/or $\gamma \ll 1$

What is the UV theory of dim5 OP?

new physics in UV theory which generate dim5 OP

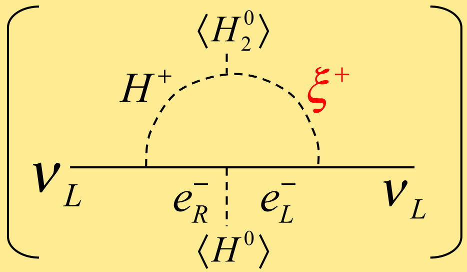
(ex1): seesaw mechanism



(Minkowski, Yanagida, Gell-Mann-Ramond, Slansky)

M $=\nu_R$ *mass*, γ $=\nu$*-Yukawa*

(ex2): radiative inducing models



(Zee, Ma, NH, Matsuda, Tanimoto, Kanemura, Aoki, ･････)

M $=\xi$ *mass*, γ $=1/(4\pi^2)$

⋮

Why $m_\nu \ll m_{q/l}$?

effective OPs in SM fields:

③ dim7 OP

$$m_\nu \sim \frac{LL\langle H\rangle\langle H\rangle}{M}\left|\frac{\langle H\rangle}{M}\right|^2$$

ΔL=2 (lepton # is violated)

☆ dim5 OP is forbidden by discrete symmetry

☆ M (dim7 OP) can be naturally smaller than M (dim5 OP)

→ can be TeV scale!

What is the UV theory of dim7 OP?

(ex) model with double & triple charged Higgs ($SU(2)_L$ 4-rep. Higgs) in type III seesaw
K.S.Babu, S.Nandi and Z.Tavartkiladze, PRD80 (2009) 071702.

As we see, there are a lot of attempts ･･･, but,

･always use the same SM-like Higgs doublet, $\langle H \rangle \sim 100$ GeV ･･･, and

then must try to make tiny effective ν-“Yukawa”･･･

This is the essence of difficulty for reproducing 0.1 eV ν-mass ･･･

Here let me look at the difficulty from a different angle

How about introducing extra Higgs $\langle H_\nu \rangle \ll 100$ GeV

instead of effective tiny ν-“Yukawa”?

This is an essence of our suggesting model today

But, maybe, you may worry about appearing light Higgs・・・

(ex): SM, $V = -m^2 H^2 + \lambda H^4 \to m \sim \langle H \rangle$

tiny VEV ⇔ light physical Higgs・・・?

However, situation is drastically changed in multi-Higgs model with an *effective linear term* as,

$V \ni H^3 H_\nu + \text{h.c.} \to \langle H_\nu \rangle \sim \langle H \rangle^3 / M_{H\nu}^2$

tiny VEV ⇔ HEAVY physical Higgs!

like a "seesaw" between VEV & Higgs mass

Therefore, even evidences of "type I seesaw" is expected to be discovered at TeV-scale and so LHC exps.

type I seesaw

$$L_\nu = m_D(\bar{\nu}_L \nu_R + \bar{\nu}_R \nu_L) + M \bar{\nu^c}_R \nu_R$$

$$\xrightarrow[m_D \ll M]{} \quad m_\nu \sim \frac{m_D^2}{M}$$

conventional model: $m_D = y_\nu \langle H \rangle \sim 100$ GeV

For $m_\nu \sim 0.1$ eV, we need $M \sim 10^{14}$ GeV , and it is impossible to find in experiments such as LHC, ILC, etc.

⇕

our model: $m_D = y_\nu \langle H_\nu \rangle \sim 0.1$ MeV

For $m_\nu \sim 0.1$ eV, $M \sim 1$ TeV & and also H_ν mass ~ 1 TeV, and they are detectable in LHC experiment.

2. model

2. model

setup of our model

In order to obtain $V \ni H^3 H_\nu$ + h.c. ($\rightarrow \langle H_\nu \rangle \sim \langle H \rangle^3 / M_{H\nu}^2$),

we introduce singlet Higgs, S, and construct the similar structure as

$$\rightarrow V \ni \mu S H H_\nu + \text{h.c.} \rightarrow \langle H_\nu \rangle \sim \mu \langle H \rangle / \langle S \rangle$$

☆Introducing Z_3 sym. (which distinguish H_ν from H)

fields	Z_3 charge	**Lepton #**
SM fields (SM Higgs: H)	1 1	1 for leptons (others, 0) 0
Right-handed ν : N	ω	1
Singlet Higgs : S	ω	-2
New Doublet Higgs: H_ν	ω^2	0

setup of our model

- Yukawa interactions:

$$L_{yukawa} = y_u \bar{Q}_L H U_R + y_d \bar{Q}_L \tilde{H} D_R + y_e \bar{L} \tilde{H} E_R$$
$$+ \boxed{y_\nu \bar{L} H_\nu N} + y_N S \bar{N}^c N + h.c$$

seesaw $\rightarrow$

$$m_\nu = \frac{y_\nu^2 \langle H_\nu \rangle^2}{y_N \langle S \rangle}$$

Wanted vacuum is
$$\begin{cases} \langle S \rangle \sim \text{TeV} \\ \langle H \rangle \sim 100\ \text{GeV} \\ \langle H_\nu \rangle \sim 0.1\ \text{MeV} \end{cases}$$

Then, $\rightarrow m_\nu \sim 0.1\ eV$

setup of our model

under Z_3 sym. & softly broken $U(1)_L$

- Higgs potential:

$$
\begin{aligned}
V =& m^2|H|^2 + m_1^2|H_\nu|^2 - M^2|S|^2 - \lambda S^3 - \mu S H^\dagger H_\nu \\
&+ \lambda_1|H|^4 + \lambda_2|H_\nu|^4 + \lambda_3|H|^2|H_\nu|^2 + \lambda_4|H^\dagger H_\nu|^2 \\
&+ \lambda_S|S|^4 + \lambda_H|S|^2|H|^2 + \lambda_{H_\nu}|S|^2|H_\nu|^2 + h.c
\end{aligned}
$$

terms forbidden by Z_3: $(H^\dagger H_\nu)^2,\ S^4,\ S^2|H_\nu|^2,\ \cdots$

terms forbidden by lepton #: $H_\nu^\dagger H S^2$

☆ lepton # is softly broken by μ & λ ,

(and also Majorana mass of ν_R)

thus, mass hierarchy of $\mu \ll M_W$ is preserved against from quantum correction.

Vacuum

vacuum @ $\langle H_\nu \rangle \ll \langle H \rangle \ll \langle S \rangle$

- stationary conditions:

$$\langle S \rangle = s,\ \langle H \rangle = h,\ \langle H_\nu \rangle = h_\nu$$

$$\frac{\partial V}{\partial s} = -2M^2 s + 4\lambda_S s^3 = 0 \quad \Rightarrow \quad \langle S \rangle = \frac{M}{\sqrt{2\lambda_S}} \quad (\sim\text{TeV})$$

$$\frac{\partial V}{\partial h} = -2(\lambda_H s^2 - m^2)h + 2\lambda_1 h^3 = 0 \quad \Rightarrow \quad \langle H \rangle = \sqrt{\frac{\boxed{\lambda_H s^2 - m^2}}{\lambda_1}} \quad (\sim 100\text{ GeV})$$

☆When λ_H is negative, we do not need "wine-bottle" potential at initial setup

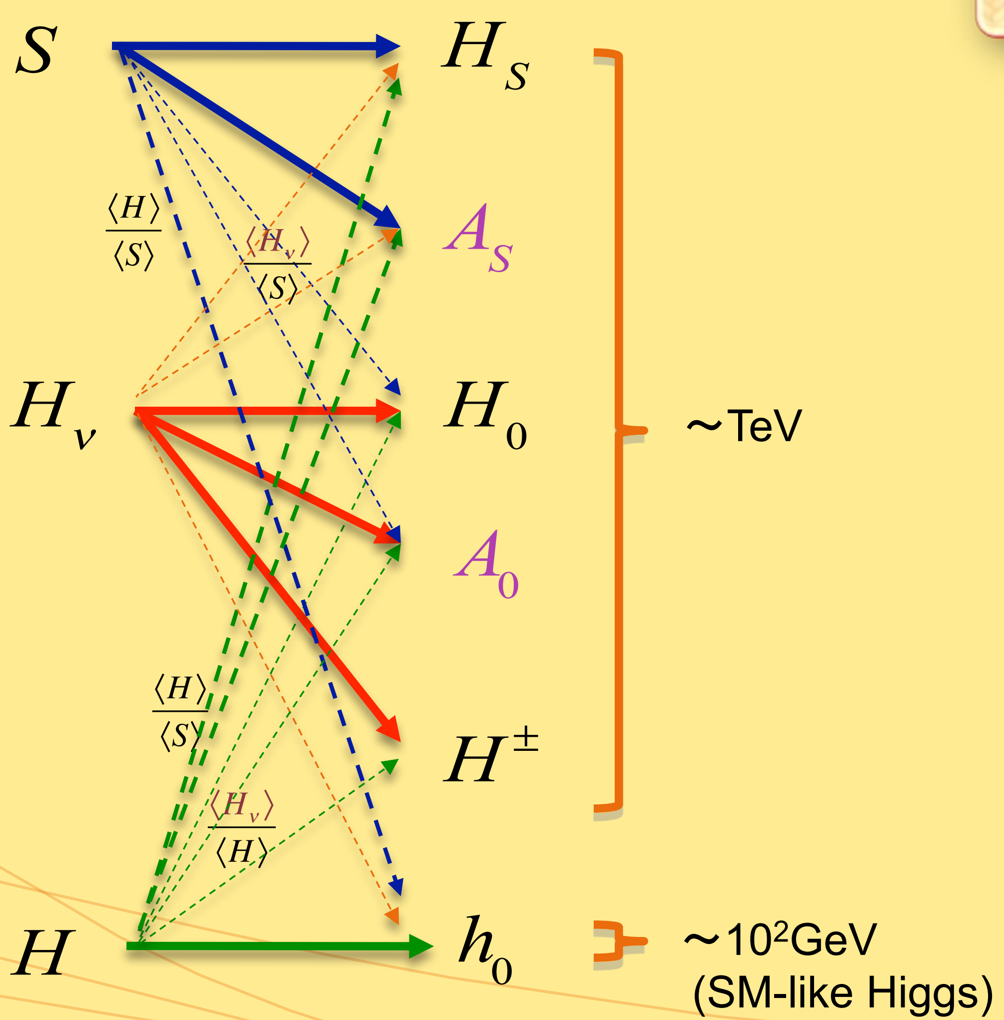
$$\frac{\partial V}{\partial h_\nu} = -2\mu s h + 2\lambda_{H_\nu} h_\nu s^2 = 0 \quad \Rightarrow \quad \langle H_\nu \rangle = \frac{\boxed{\mu} h}{\lambda_{H_\nu} s} \quad (\sim 0.1\text{ MeV})$$

1 MeV

(consistency condition: $\mu s h_\nu \ll \lambda_1 h^3$)

Higgs mass spectra

- physical Higgs particles:



Mixings ∝ rations of VEVs

H_v ⇒ heavy although tiny VEV!!

$$M^2_{H_0,A_0} = \frac{2\mu s}{\sin\beta}$$

$$M^2_{H^\pm} = -\lambda_4 h^2 + M^2_{H_0,A_0}$$

$$M^2_{H_s} = 2M^2$$

$$M^2_{A_s} = \frac{9\lambda s}{2}$$

$$M^2_{h_0} = 2\lambda_1 h^2$$

A_s is massless, when λ =0, since accidental global U(1)

$$H \to e^{-i\theta_1} H, \quad H_\nu \to e^{i\theta_1} H_\nu, \quad S \to e^{-i2\theta_1} S.$$

exists. Thus, A_s is pNG.

Similarly A_0 is massless, when μ =0, since there appear global U(1) of $H \to e^{i\theta_2} H, \quad H_\nu \to e^{-i\theta_2} H_\nu,$

3. phenomenology

3. phenomenology

3-1. charged Higgs decay

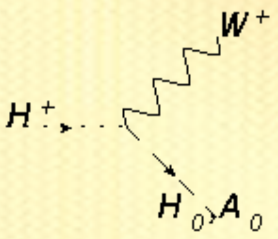
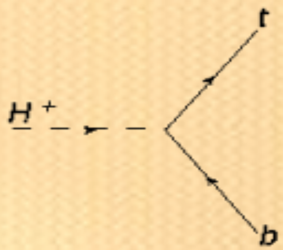
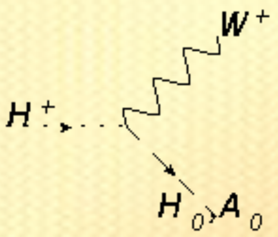
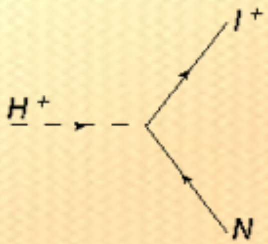
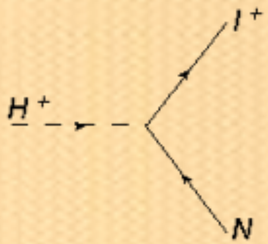
3-2. ρ parameter

3-3. LFV

…

3-1. charged Higgs decay

decay channel strongly depends on $M_{H^+} \lessgtr M_{H_0,A_0}$, $M_{H^+} \lessgtr M_N$

	$M_{H^+} > M_{A^0,H^0}$	$M_{H^+} < M_{A^0,H^0}$
$M_{H^+} < M_N$	 $\Gamma \approx \frac{M_{H^+}^2}{16\pi P_0} g^2 \left(1 - \frac{M_{H_0,A_0}^2}{M_{H^+}^2}\right)^2$	 $\Gamma \approx \frac{3M_{H^+}^2}{16\pi P_0}\left(\frac{h_1}{h}\right)^2 y_t^2$ $\tau \sim 10^{-11}\ m$
$M_{H^+} > M_N$	 	 $\Gamma \approx \frac{M_{H^+}^2}{32\pi P_0} y_\nu^2$ $\tau \sim 10^{-12}\ m$

lepton signals (also L# violation) are expected to be detected in LHC

3-2. ρ parameter

- tiny contribution to ρ parameter as,

$$\delta\rho = \frac{2\sqrt{2}G_F}{(4\pi)^2} F_\Delta(m_A^2, m_{H^\pm}^2) \sim 10^{-5}$$

$$F_\Delta(x, y) = \frac{1}{2}(x+y) - \frac{xy}{x-y}\ln\frac{x}{y}.$$

- it is because tiny breaking of custordial symmetry as,

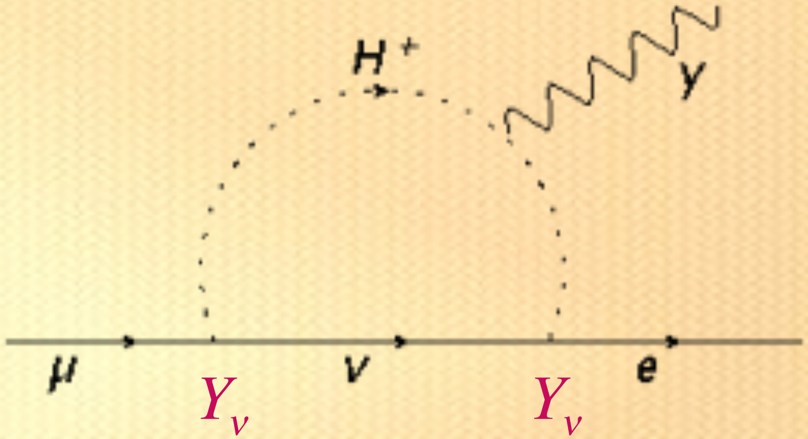
$$M_{H^\pm}^2 = M_{H_0}^2 - \lambda_4 h^2$$

TeV 100 GeV

3-3. LFV

- LFV processes from charged Higgs loop diagram

  (assuming $M_{Rij}=M\delta_{ij}$, R=1, and using ν-oscillation data)



$$Br(\mu \to e\gamma) \to \frac{\pi\alpha}{1536 G_F^2}\left(\frac{\alpha_{\nu_i}}{m_{h^-}^2}\right)^2 \frac{\cos^2\theta}{m_\nu^4}\left(\sqrt{3}\Delta m_{12}^2 + \sin\theta(3\Delta m_{12}^2 + 4\Delta m_{23}^2)\right)^2.$$

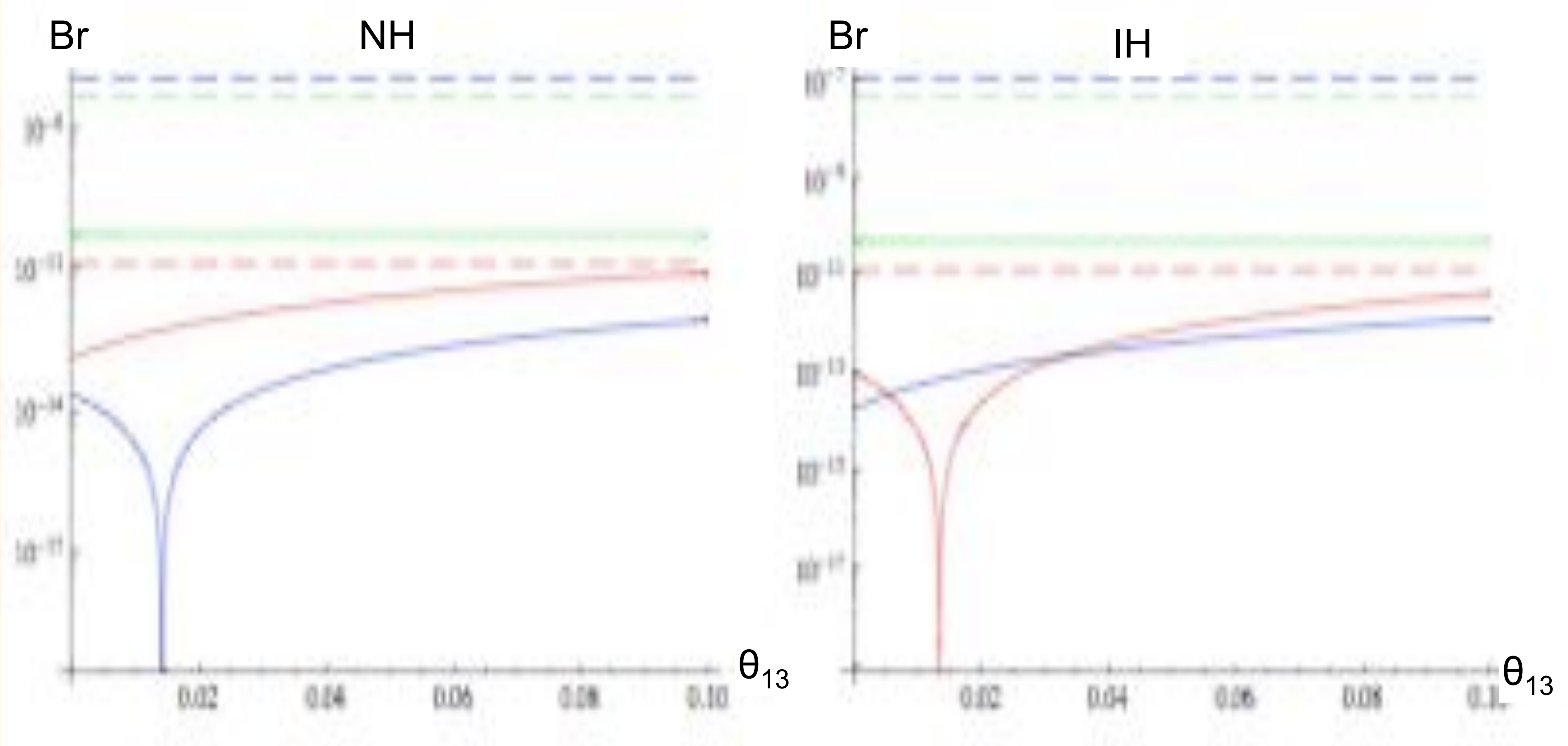
$$Br(\tau \to \mu\gamma) = Br(\tau \to \mu\nu\bar{\nu})\frac{\pi\alpha}{768 G_F^2}\left(\frac{\alpha_{\nu_i}}{m_{h^+}^2}\right)^2\left(\frac{(\delta m_{12} + 4\delta m_{23}) - \sin^2\theta(3\delta m_{12} + 4\delta m_{23})}{m_{\nu_i}}\right)^2,$$

$$Br(\tau \to e\gamma) = Br(\tau \to e\nu\bar{\nu})\frac{\pi\alpha}{384 G_F^2}\left(\frac{\alpha_{\nu_i}}{m_{h^+}^2}\right)^2\frac{\cos^2\theta}{m_{\nu_i}^2}\left(\sqrt{3}\delta m_{12} - \sin\theta(3\delta m_{12} + 4\delta m_{23})\right)^2$$

$$\theta_{12} = \frac{\pi}{6}, \theta_{23} = \frac{\pi}{4}, \theta_{13} = \theta,$$

3-3. LFV

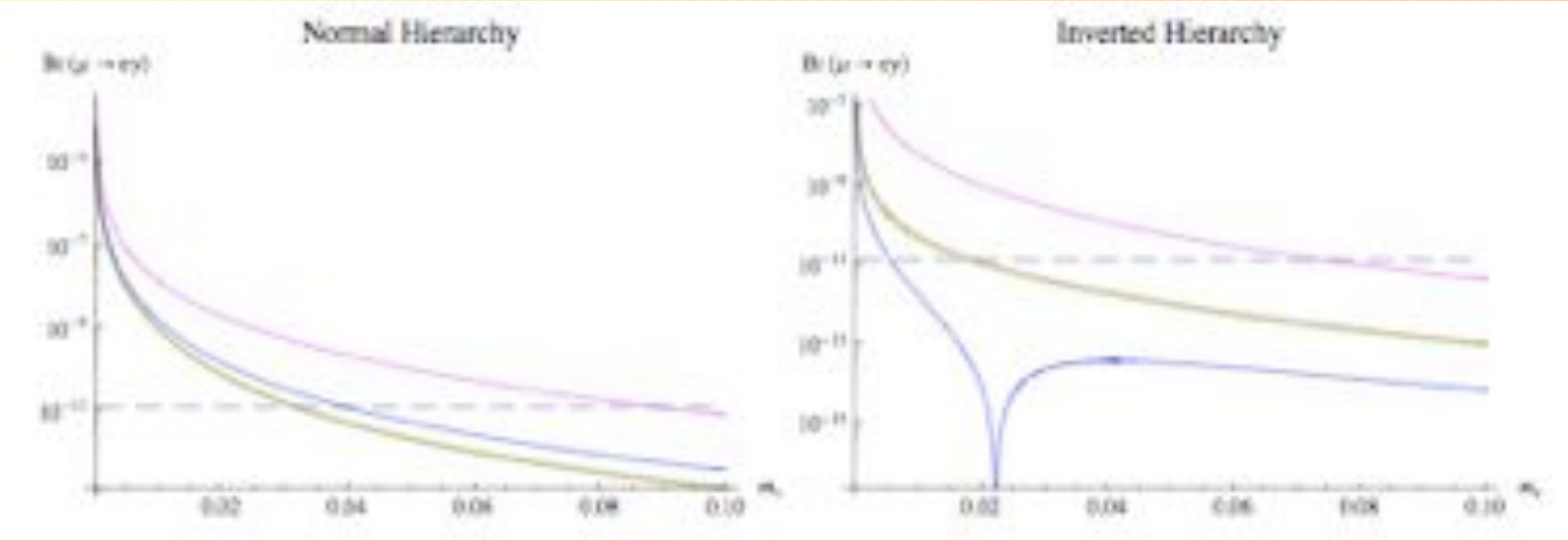
- Θ_{13} dependence:



(μ→eγ τ→eγ τ→μγ、dashed lines are their experimental bounds, m_{H+}=1TeV)

3-3. LFV

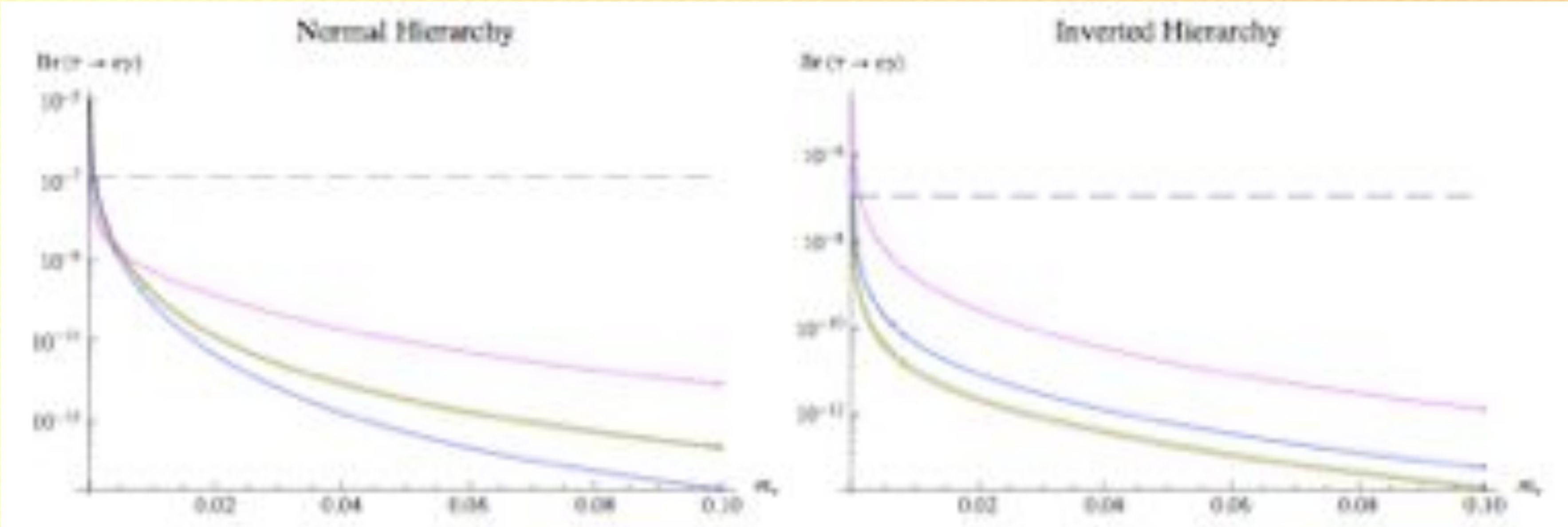
- m_ν (lightest mass) dependence: ($\mu \to e\gamma$)



($\theta=0$, $\theta=0.1$, $\theta=0.01$, $\theta=0.001$、dashed lines are their experimental bounds, $m_{H+}=1\text{TeV}$)

3-3. LFV

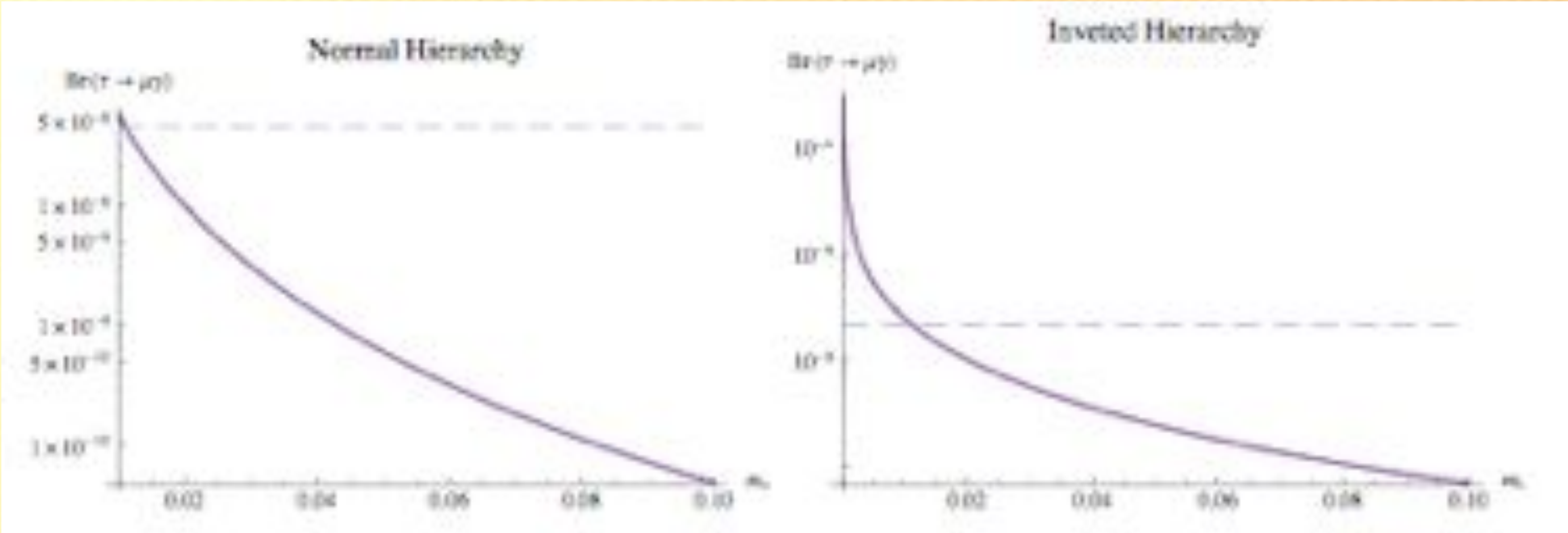
- m_ν (lightest mass) dependence: ($\tau \to e\gamma$)



(θ=0, θ=0.1, θ=0.01, θ=0.001、dashed lines are their experimental bounds, m_{H+}=1TeV)

3-3. LFV

- m_ν (lightest mass) dependence: ($\tau \rightarrow \mu\gamma$)



(θ=0, θ=0.1, θ=0.01, θ=0.001、dashed lines are their experimental bounds, m_{H+}=1TeV)

4. summary & discussions

4. summary

・We suggest new (2D+1S) Higgs model.

☆ 0.1 MeV Dirac ν mass is produced by extra Higgs Doublet, **H_ν**

☆ **H_ν** only couple lepton doublet and ν_R

☆ **H_ν** is heavy (～TeV) but taking tiny VEV (～0.1 MeV) !

☆ TeV-scale type I seesaw → detectable phenomenology at LHC

・5 physical Higgs particles, charged Higgs decay, LFV, ・・・

4. discussions

☆ about a role of S,

In fact, 2HD with extremely large tanβ is also consistent model.
models by Ma (PRL86 (2001) 2502) and Davidson and Logan (PRD 80 (2009) 095008) are the model with heavy *p*-scalar & tiny VEV.

・ In a model by Davidson and Logan, ν IS DIRAC.

⇔ In our model ν IS MAJORANA.

→ 0νββ,

→ L# violating process @LHC
(same sign di-lepton events through N-decay. (wi[illegible], K. Tsumura))

preliminary

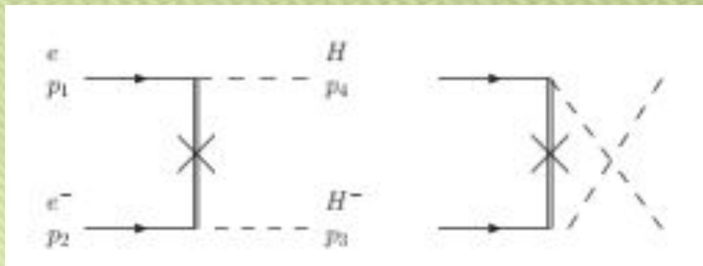
→ TeV-scale Leptogenesis (with M. Hirotsu, O. Seto)

→ L# violation processes in electron collider. (with M. Hirotsu, K. Tsumura)

4. discussions

preliminary

☆ L# violation processes in electron collider. (with M. Hirotsu, K. Tsumura)



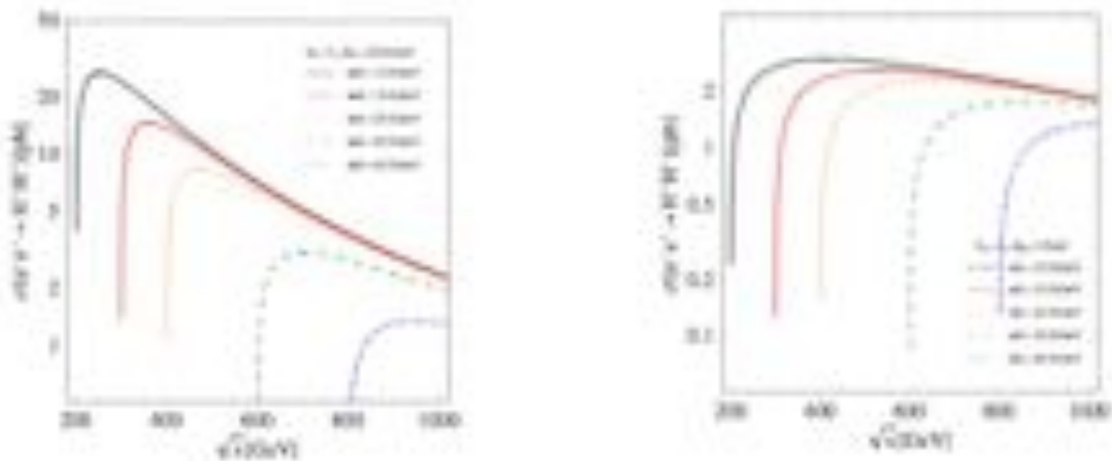


Figure 4: Total cross sections of $e^+e^- \to H^+H^-$ in νTHDM with N_R. Mass of right-handed neutrinos is set as $M_N = 200$ GeV(left) and 1 TeV(right).

4. discussions

preliminary

☆ comparing to model by Ma (ν is MAJORANA in both models), we have singlet Higgs, S.

by modification of discrete symmetry and taking zero-VEV of it, S can be a stable DM.

by a pair annihilation, this model can explain PAMERA anomaly through a similar way of
"The Leptonic Higgs as a Messenger of Dark Matter", L. Hall et al, JHEP 0905 (2009) 097

$$SS \rightarrow H_\nu H_\nu \rightarrow \text{leptons}$$