Neutrinophilic Higgs doublet model and its phenomenology

Scalars 2011, 28. Aug. 2011

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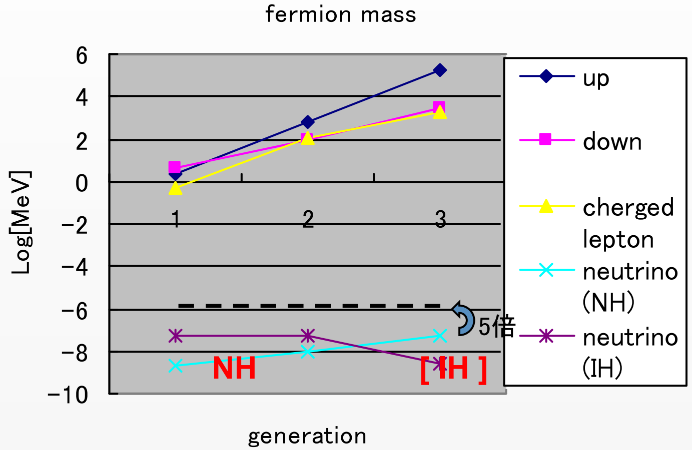
based on collaborations with O. Seto, K. Tsumura, M. Hirotsu and T. Horita.

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



- existence of ν mass is probed by ν-oscillation exps.
- $m_\nu \leqq 0.1$ eV (with cosmologies)

  → key of searching new physics beyond SM

- A lot of its explanations have been suggested

  2 options of tiny ν mass:

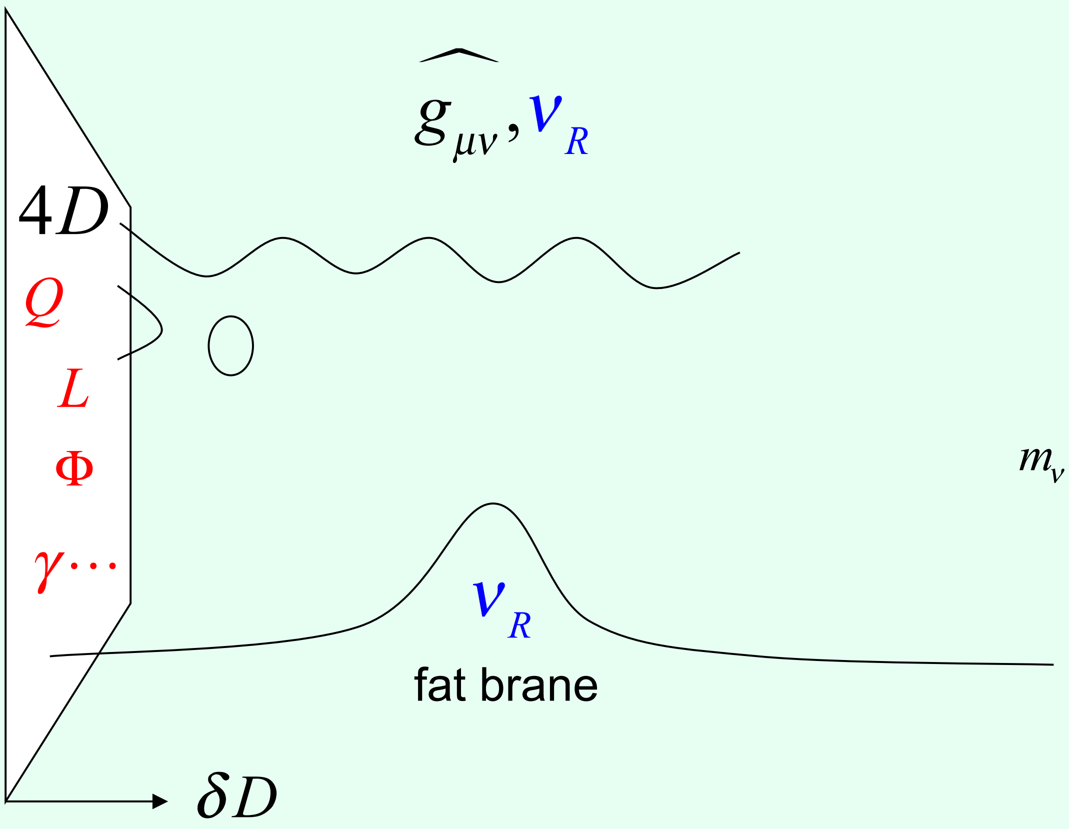
  (1): Dirac or (2): Majorana

(1): Dirac case:

$$\boxed{m_\nu \sim y_\nu \langle \Phi \rangle}$$

effective ν-Yukawa is tiny

(ex): large extra dimensional theory



volume suppression

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

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

distant suppression

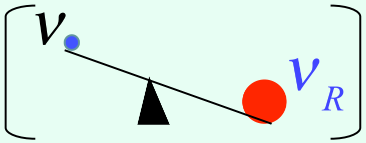
$$\boxed{y_\nu \propto e^{-(y-y_0)^2}}$$

(2): Majorana case:

$$m_\nu \sim y_\nu^2 \frac{\langle \Phi \rangle \langle \Phi \rangle}{M}$$

M (scale of L# violation) is very large
$\Delta L=2$

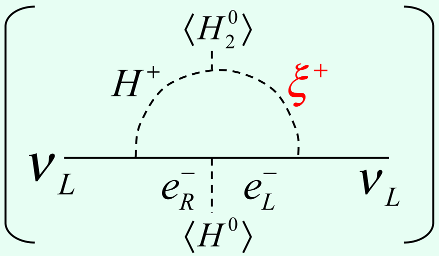
(ex1): type-I seesaw mechanism



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

$M = \nu_R$ *mass*

(ex2): radiative inducing models



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

$M = \xi$ *mass* × $(4\pi^2)$

⋮

there have been a lot of attempts ･･･, but, always use the same SM-Higgs doublet, $\langle\Phi\rangle \sim 100$ GeV ･･･, and thus, must try to make

“tiny y_ν” and/or “large M ”

This is the essence of difficulty for reproducing 0.1 eV ν-mass, and let us look at the difficulty from a different angle.

“How about introducing another Higgs doublet $\langle\Phi_\nu\rangle \ll 100$ GeV ?”

neutrinophilic Higgs doublet model (νHDM)

$$m_D = y_\nu \langle\Phi_\nu\rangle \sim 0.1\ \mathrm{eV}\ \text{(Dirac case)},\ 0.1\ \mathrm{MeV}\ \text{(Majorana case)}$$

$L_{yukawa} \supset y_\nu L \langle\Phi_\nu\rangle \mathrm{N}$

E. Ma (2001), E. Ma and M. Raidal (2001), F. Wang, W. Wang and J. M. Yang (2006),
E. Ma (2006), S. Gabriel and S. Nandi (2007), S. M. Davidson and H. E. Logan (2009, 2010),
G. Marshall, M. McCaskey and M. Sher (2010), N. H. and M. Hirotsu (2010),
N. H. and K. Tsumura (2010), N. H. and O. Seto (2010)

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

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

tiny VEV ⇔ light physical Higgs・・・?

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

$V \ni m_3^2 \langle\Phi\rangle\Phi_v + \text{h.c.} \rightarrow \langle\Phi_v\rangle \sim m_3^2\langle\Phi\rangle / M_{\Phi v}^2$

tiny VEV ⇔ small $\boldsymbol{m_3^2}$ and/or heavy $M_{\Phi v}^2$!

(1): Dirac case:

νHDM: $\boldsymbol{m_D = y_\nu \langle \Phi_\nu \rangle \sim 0.1\ \mathrm{eV}}$

☆ $\boldsymbol{y}_\nu$ can be non-small!

☆ Φ_ν mass ~ 100 GeV → detectable in LHC experiment.

↕

conventional model: $m_D = y_\nu \langle \Phi \rangle \sim 0.1$ eV

$\boldsymbol{y}_\nu$ must be very tiny ($\sim 10^{-12}$) for $m_\nu \sim 0.1$ eV, and it is impossible to find in experiments such as LHC, ILC.

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(2): Majorana case:

νHDM: $m_D = y_\nu \langle \Phi_\nu \rangle \sim 0.1$ MeV

☆ y_ν can be non-small with $M \sim 100$ GeV for $m_\nu \sim 0.1$ eV. (type-I seesaw)

☆ Φ_ν mass ~ 100 GeV → detectable in LHC experiment.

☆ low energy thermal leptogenesis with $M \sim 5$ TeV

↕

conventional model: $m_D = y_\nu \langle \Phi \rangle \sim 100$ 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.

Contents

2. νHDM

2. ν HDM

☆ Z_2 sym. (which distinguishes Φ_ν from Φ)

fields	Z_2-charge
SM fields (SM Higgs: Φ)	$+$
ν_R: N	$-$
ν Higgs doublet: Φ_ν	$-$

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☆ Z_2 sym. (which distinguishes Φ_ν from Φ)

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SM fields (SM Higgs: Φ)	$+$
ν_R: N	$-$
ν Higgs doublet: Φ_ν	$-$

- Yukawa interactions:

$$L_{yukawa} = y_u Q\Phi U + y_d Q\Phi D + y_e L\Phi E + y_\nu L\Phi_\nu N$$

Dirac case

F. Wang, W. Wang and J. M. Yang (2006), S. Gabriel and S. Nandi (2007), G. Marshall, M. McCaskey, M. Sher (2010), S. M. Davidson and H. E. Logan (2009, 2010),

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$$+M\,\overline{N^c}N$$

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wanted vacuum is

$\langle\Phi\rangle \sim 100$ GeV $\gg \langle\Phi_\nu\rangle \sim 0.1$ eV/y_ν (Dirac) or 0.1 MeV/y_ν (Majorana)

- Higgs potential:

$$V=-m_{\Phi}^{2}|\Phi|^{2}+m_{\Phi_\nu}^{2}|\Phi_\nu|^{2}+m_{3}^{2}(\Phi^{\dagger}\Phi_\nu+\Phi_\nu^{\dagger}\Phi)+\frac{\lambda_1}{2}|\Phi|^{4}+\frac{\lambda_2}{2}|\Phi_\nu|^{4}$$

$$+\lambda_3|\Phi|^{2}|\Phi_\nu|^{2}+\lambda_4(\Phi^{\dagger}\Phi_\nu)(\Phi_\nu^{\dagger}\Phi)+\frac{\lambda_5}{2}[(\Phi^{\dagger}\Phi_\nu)^{2}+(\Phi_\nu^{\dagger}\Phi)^{2}]$$

$$|m_3^2|\ll m_{\Phi}^{2},m_{\Phi_\nu}^{2}$$

- Higgs potential:

soft Z_2 breaking mass parameter

$$V = -m_\Phi^2 |\Phi|^2 + m_{\Phi_\nu}^2 |\Phi_\nu|^2 + \boxed{m_3^2}(\Phi^\dagger \Phi_\nu + \Phi_\nu^\dagger \Phi) + \frac{\lambda_1}{2} |\Phi|^4 + \frac{\lambda_2}{2} |\Phi_\nu|^4$$

$$+ \lambda_3 |\Phi|^2 |\Phi_\nu|^2 + \lambda_4 (\Phi^\dagger \Phi_\nu)(\Phi_\nu^\dagger \Phi) + \frac{\lambda_5}{2} [(\Phi^\dagger \Phi_\nu)^2 + (\Phi_\nu^\dagger \Phi)^2]$$

$$|m_3^2| \ll m_\Phi^2, m_{\Phi_\nu}^2$$

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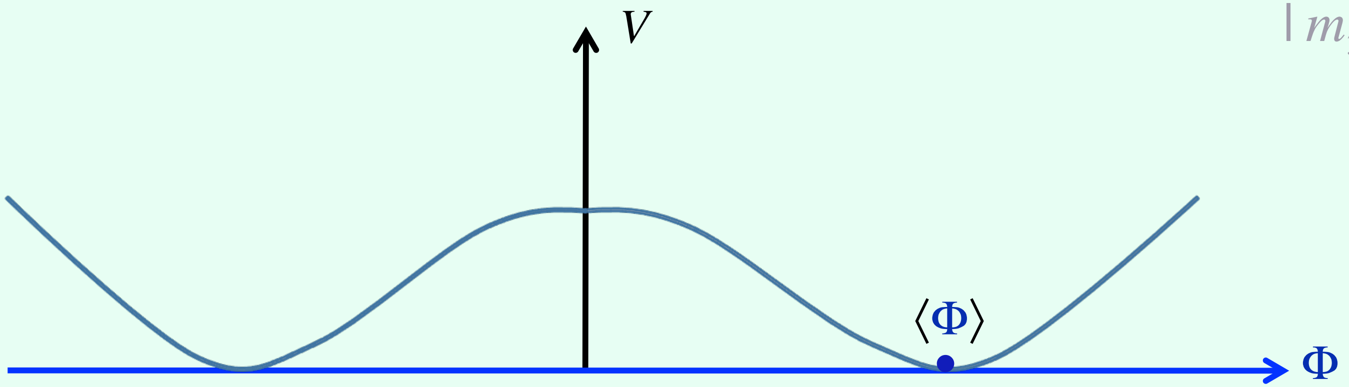

$$\frac{dV}{d\Phi} = 0 \rightarrow \langle \Phi \rangle = \sqrt{\frac{2m_{\Phi}^2}{\lambda_1}}$$

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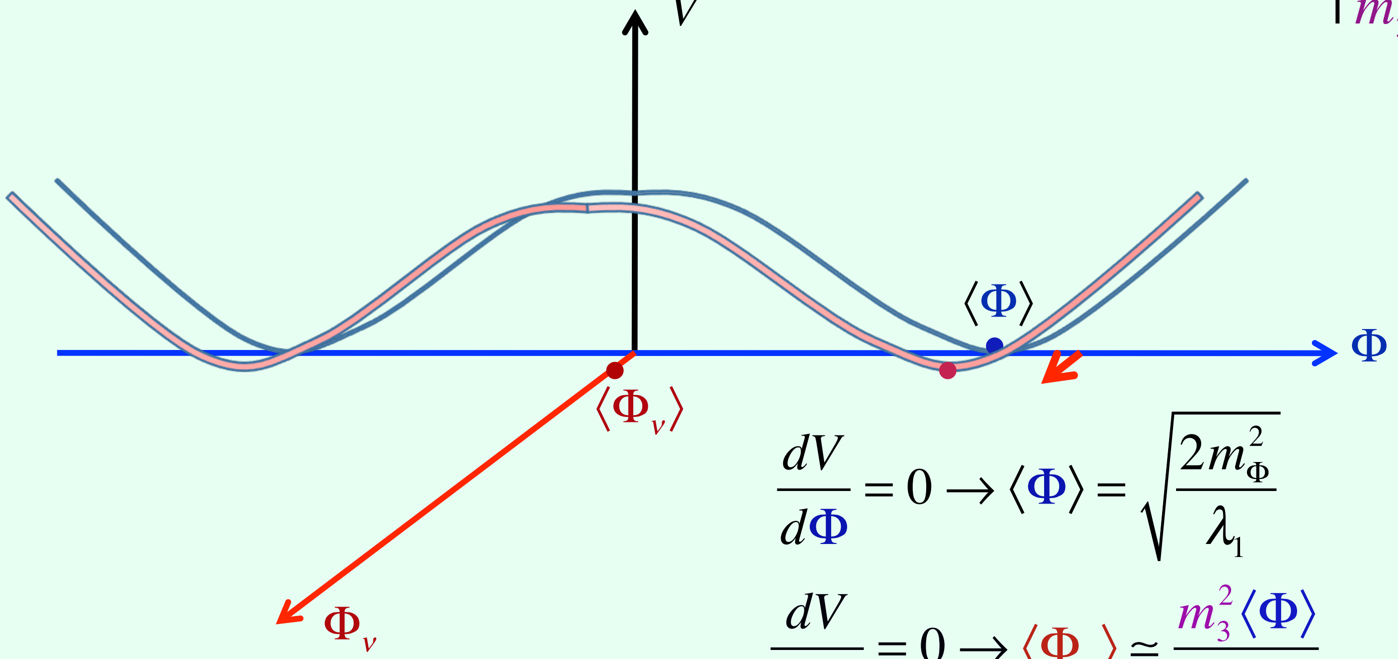

$$\frac{dV}{d\Phi} = 0 \to \langle \Phi \rangle = \sqrt{\frac{2m_\Phi^2}{\lambda_1}}$$

$$\frac{dV}{d\Phi_\nu} = 0 \to \langle \Phi_\nu \rangle \simeq \frac{m_3^2 \langle \Phi \rangle}{m_{\Phi_\nu}^2}$$

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$$|m_3^2| \ll m_\Phi^2, m_{\Phi_\nu}^2$$

$$\left(\frac{dV}{d\Phi} = 0 \rightarrow\right) \langle \Phi \rangle = \sqrt{\frac{2m_\Phi^2}{\lambda_1}} \qquad \left(\frac{dV}{d\Phi_\nu} = 0 \rightarrow\right) \langle \Phi_\nu \rangle \simeq \frac{m_3^2 \langle \Phi \rangle}{m_{\Phi_\nu}^2}$$

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①: **tiny** m_3^2 and/or ②: **large** $m_{\Phi\nu}^2 \Rightarrow \langle\Phi\rangle \gg \langle\Phi_\nu\rangle$

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①: **tiny m_3^2** $\xrightarrow{(m_{\Phi\nu}^2\sim 100\text{GeV})}$
- (1): Dirac case: $m_3^2 \sim 1$ MeV^2
- (2): Majorana case: $m_3^2 \sim 10^{0.5}(10^2)$ GeV^2
  ($y_\nu \sim 0.01$ ($10^{-3.5}$))

→ §3 (§4)

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②: **large $m_{\Phi\nu}^2$** → Interesting option!→ §6

like a “seesaw” between VEV & Higgs mass

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$\left(\frac{dV}{d\Phi}=0\rightarrow\right)$ $\langle\Phi\rangle = \sqrt{\frac{2m_\Phi^2}{\lambda_1}}$ $\left(\frac{dV}{d\Phi_\nu}=0\rightarrow\right)$ $\langle\Phi_\nu\rangle \simeq \frac{m_3^2\langle\Phi\rangle}{m_{\Phi_\nu}^2}$

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like a "seesaw" between VEV & Higgs mass

tiny Z2-breaking mass is an origin of small ν mass

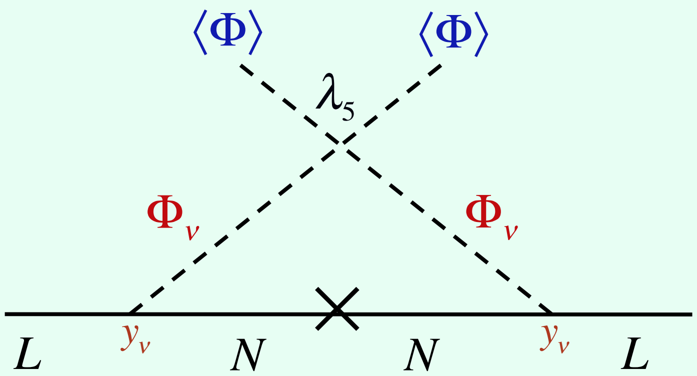
(m_3^2 (λ_5)→0 limit has a global U(1), but, $\langle\Phi_\nu\rangle$=0,so no NG boson)

- ①: **tiny m_3^2, ②: large $m_{\Phi v}^2$**

- ⓪: $m_3^2 = 0$

☆ exact Z_2 sym.→ ν_R is DM & $\langle\Phi_\nu\rangle$=0

☆ ν mass induced radiatively



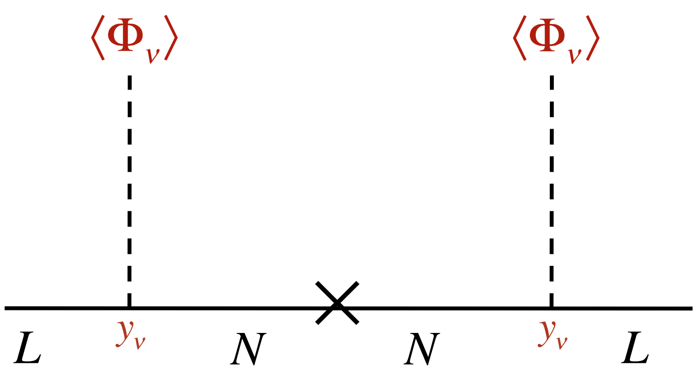
E. Ma, PRD 73, 077301 (2006).

☆ m_3^2 =0 induces $\langle\Phi_\nu\rangle$=0, so Z2 is not broken.
☆ no global U(1) due to $\lambda_5 \neq 0$, so no NG boson.

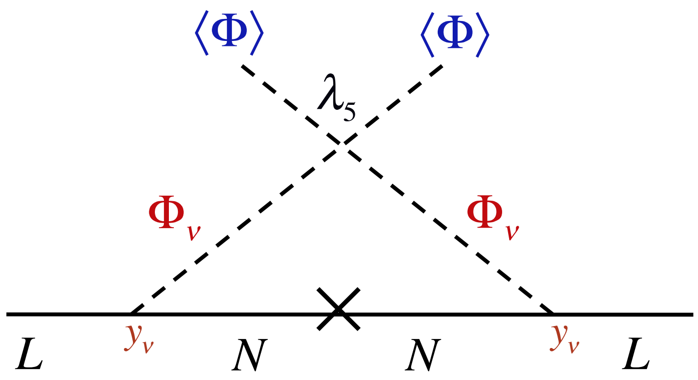
- Majorana case with $\langle \Phi_\nu \rangle \neq 0$ ($m_3^2 \neq 0$)

there are two sources of ν mass as,

☆ ν mass from seesaw



☆ ν mass induced radiatively



$$m_\nu^{tree} : m_\nu^{loop} \sim \langle\Phi_\nu\rangle^2 : \lambda_5 \langle\Phi\rangle^2/(4\pi)^2$$

for example,

①: tiny m_3^2 with (2): Majorana case in §3,4, we see parameter space of $m_\nu^{tree} > m_\nu^{loop}$

Higgs mass spectra

- physical Higgs particles:

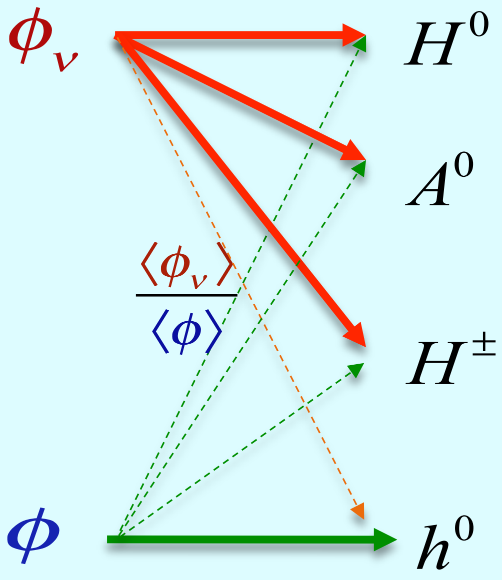
$$\underset{\begin{pmatrix}\bullet\bullet\\ \bullet\bullet\end{pmatrix}}{\phi_\nu} \longrightarrow \underset{(\bullet)}{H^0},\quad \underset{(\bullet)}{A^0},\quad \underset{(\bullet\bullet)}{H^\pm}$$

$$\underset{\begin{pmatrix}\bullet\bullet\\ \bullet\bullet\end{pmatrix}}{\phi} \longrightarrow \underset{(\bullet)}{h^0}$$

Higgs mass spectra

- physical Higgs particles:

Mixings ∝ rations of VEVs

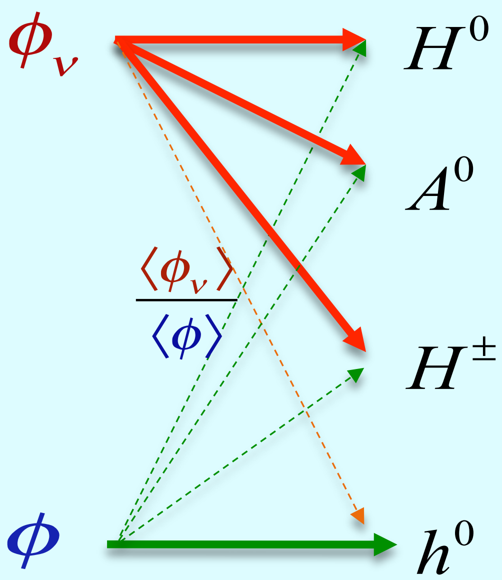


Higgs mass spectra

- physical Higgs particles:

Mixings ∝ rations of VEVs

$\Phi_\nu \Rightarrow$ heavy although tiny VEV!!



$$m_H^2 \simeq m_{\Phi_\nu}^2 + \frac{\lambda_3+\lambda_4+\lambda_5}{2}\langle\phi\rangle^2$$

$$m_A^2 \simeq m_{\Phi_\nu}^2 + \frac{\lambda_3+\lambda_4-\lambda_5}{2}\langle\phi\rangle^2$$

$$m_{H^\pm}^2 \simeq m_{\Phi_\nu}^2 + \frac{\lambda_3}{2}\langle\phi\rangle^2$$

$\sim 10^2$GeV ($\boldsymbol{m_{\Phi\nu}^2}$)

$$m_{h^0}^2 \simeq 2\lambda_1\langle\phi\rangle^2$$

$\sim 10^2$GeV (SM-like Higgs)

(A is not pseudo-NG boson ($\propto m_3$), since no global U(1) due to $\lambda_5 \neq 0$ and mass spectrum drastically changes whether $\langle\Phi_\nu\rangle=0$ ($m_3=0$) or $\langle\Phi_\nu\rangle\neq 0$ ($m_3\neq 0$))

stability of $\langle \Phi_\nu \rangle \ll \langle \Phi \rangle$

T. Morozumi, H. Takata, K. Tamai (2011),
N. H. and T. Horita (2011)

- $\langle \Phi_\nu \rangle \ll \langle \Phi \rangle$ is global minimum?

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  $\rightarrow$ yes, under condition of $(\lambda_3+\lambda_4+\lambda_5)^2>\lambda_1\lambda_2$ with $\lambda_2 m_\Phi{}^4 > \lambda_1 m_{\Phi\nu}{}^4$

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- $\langle \Phi_\nu \rangle \ll \langle \Phi \rangle$ is preserved against radiative corrections?

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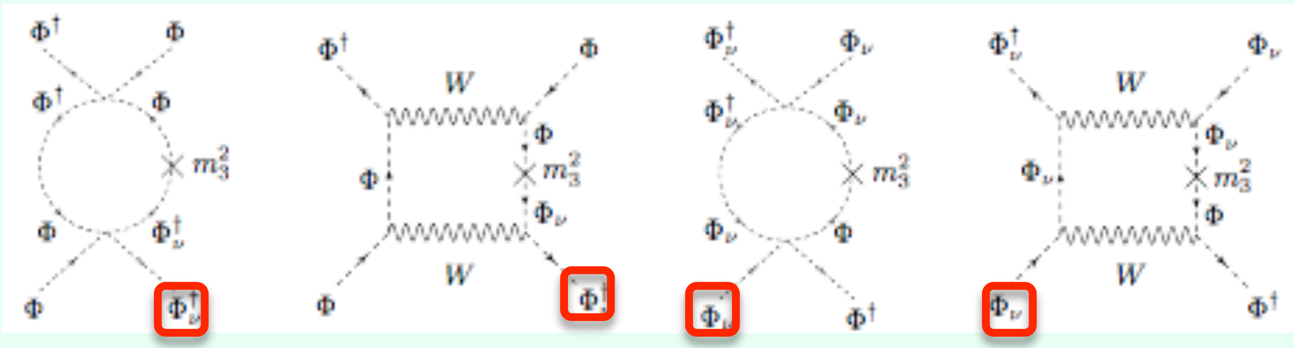
- $\langle \Phi_\nu \rangle \ll \langle \Phi \rangle$ is preserved against radiative corrections?

  $\rightarrow$ yes, νHDM satisfies $\frac{\alpha}{16\pi^2}\langle\Phi\rangle^3 / m_3^2 \le \frac{3}{4\pi^2}\log\frac{\langle\Phi\rangle}{\langle\Phi_\nu\rangle}$



(most dangerous diagrams with 4-external lines in Coleman-Weinberg 1-loop effective potential)

$$V^{1-loop} \sim \frac{\alpha}{16\pi^2}\langle\Phi_\nu\rangle\langle\Phi\rangle^3 \rightarrow \frac{dV^{1-loop}}{d\langle\Phi_\nu\rangle} \sim \frac{\alpha}{16\pi^2}\langle\Phi\rangle^3 \quad \Rightarrow V \sim \left(m_3^2 + \frac{\alpha}{16\pi^2}\langle\Phi\rangle^3\right)\langle\Phi_\nu\rangle + \cdots$$

All 6-, 8-, 10-, ・・・external lines diagrams are summed, and the above condition is obtained.

☆Z_2 is softly broken by m_3^2 → $m_3^2 \ll m_\Phi^2, m_{\Phi\nu}^2$ is preserved against from quantum correction.

phenomenology

- Majorana case with tiny $\langle \Phi_\nu \rangle$ from tiny m_3^2

①: tiny m_3^2 $\xrightarrow{(m_{\Phi_\nu}^2 \sim 100\text{GeV})}$ { (2): Majorana case

phenomenology

- Majorana case with tiny $\langle \Phi_\nu \rangle$ from tiny m_3^2

$$\boxed{①\text{: tiny } m_3^2} \xrightarrow{(m_{\Phi\nu}^2 \sim 100\text{GeV})} \{ \text{(2): Majorana case}$$

non-small y_ν

phenomenology

- Majorana case with tiny $\langle \Phi_\nu \rangle$ from tiny m_3^2

①: tiny m_3^2 $\xrightarrow{(m_{\Phi\nu}^2 \sim 100\text{GeV})}$ (2): Majorana case

non-small y_ν

§3: LHC, ILC phenomenology

☆$H^\pm$ is originated from Φ_ν, which has only y_ν coupling!

$m_3^2 \sim 10^{0.5}\ \text{GeV}^2$

$M \sim 10^2\ \text{GeV} \sim 1\text{TeV}$

($y_\nu \sim 0.01$, $\langle \Phi_\nu \rangle \sim 10^{-1.5}$ GeV)

phenomenology

- Majorana case with tiny $\langle\Phi_\nu\rangle$ from tiny m_3^2

①: tiny m_3^2 $\xrightarrow{(m_{\Phi\nu}^2 \sim 100\text{GeV})}$ (2): Majorana case

non-small y_ν

§3: LHC, ILC phenomenology

☆$H^\pm$ is originated from Φ_ν, which has only y_ν coupling!

$m_3^2 \sim 10^{0.5}$ GeV^2

$M \sim 10^2$ GeV~1TeV

($y_\nu \sim 0.01$, $\langle\Phi_\nu\rangle \sim 10^{-1.5}$ GeV)

§4: low energy thermal leptogenesis

☆ no fine-tuning, no gravitino problem (SUSY)

$m_3^2 \sim 10^2$ GeV^2

$M_1 \sim 5$ TeV ($y_\nu \sim 10^{-3.5}$, $\langle\Phi_\nu\rangle \sim 1$ GeV)