Loop Suppression of Dirac Neutrino Mass in the Neutrinophilic Two Higgs Doublet Model

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Based on arXiv: 1305.4521, in collaboration with

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In this talk,

- We consider the neutrinophilic two Higgs doublet model, where the second doublet has a small VEV.
- We discuss a natural scenario in which the VEV is generated by the one loop diagram.
- In addition, this scenario contains a DM candidate.
- We also discuss a possible signature at the LHC in this scenario.

How do neutrino masses generate?

- The standard model is successful.
- But! Neutrino oscillation suggests that neutrinos have tiny masses.

$m_\nu \simeq 0.1\mathrm{eV}$ →There are large mass hierarchy.

- Type of neutrino masses:

Dirac or Majorana

-For the case of Dirac neutrino,

$$v \simeq \mathcal{O}(100\mathrm{GeV}) \Rightarrow \boxed{y_\nu \simeq \frac{m_\nu}{v} \simeq 10^{-12}}$$

Small Yukawa!!

⇒It is unnatural that m_ν are generated by the SM VEV.

Neutrinophilic Two Higgs Doublet Model (νTHDM)

S.M.Davidson & H.E.Logan, Phys. Rev. D **80** (2009) 095008

	Φ	ν_{iR}	Φ_ν
$SU(2)_L$	**2**	**1**	**2**
$U(1)_Y$	$\frac{1}{2}$	0	$\frac{1}{2}$
Global $U(1)_X$	0	1	1

- The origin of m_ν are explained by the neutrinophilic doublet Φ_ν.
- Particle contents & scalar potential:

$$V^{(\nu\mathrm{THDM})} = -\mu_{\Phi 1}^2 \Phi^\dagger \Phi + \mu_{\Phi 2}^2 \Phi_\nu^\dagger \Phi_\nu - \left(\mu_{\Phi 12}^2 \Phi_\nu^\dagger \Phi + \mathrm{h.c.}\right) + \lambda_{\Phi 1}(\Phi^\dagger\Phi)^2 + \lambda_{\Phi 2}(\Phi_\nu^\dagger \Phi_\nu)^2 + \lambda_{\Phi 12}(\Phi^\dagger\Phi)(\Phi_\nu^\dagger\Phi_\nu) + \lambda'_{\Phi 12}(\Phi^\dagger\Phi_\nu)(\Phi_\nu^\dagger\Phi)$$

- $U(1)_X$ is softly broken by $\mu_{\Phi 12}^2 \Phi_\nu^\dagger \Phi$.

$$v_\nu \equiv \langle \Phi_\nu \rangle$$

$$\langle \Phi_\nu \rangle \simeq \frac{2v\,\mu_{\Phi 12}^2}{2\mu_{\Phi 2}^2 + (\lambda_{\Phi 12} + \lambda'_{\Phi 12})v^2} \longrightarrow m_\nu \simeq y_\nu \langle \Phi_\nu \rangle$$

$$y_\nu \simeq \mathcal{O}(1) \Rightarrow \boxed{\frac{v_\nu}{v} \simeq \left(\frac{\mu_{\Phi 12}}{v}\right)^2 \simeq \frac{m_\nu}{y_\nu v} \simeq 10^{-12}}$$

Small VEV!!

⇒But, v_ν requires the fine-tuning of the parameter $\mu_{\Phi 12}^2$.

Our Model: Loop suppressed νTHDM

	ν_{iR}	$\Phi_\nu = \begin{pmatrix}\phi_\nu^+ \\ \phi_\nu^0\end{pmatrix}$	$\boxed{s_1^0}$	$\eta = \begin{pmatrix}\eta^+ \\ \eta^0\end{pmatrix}$	s_2^0
$SU(2)_L$	$\underline{\mathbf{1}}$	$\underline{\mathbf{2}}$	$\underline{\mathbf{1}}$	$\underline{\mathbf{2}}$	$\underline{\mathbf{1}}$
$U(1)_Y$	0	1/2	0	1/2	0
Global $U(1)_X$	3	3	1	3/2	1/2

νTHDM

No VEV

$$v_s \equiv \langle s_1^0 \rangle$$

$$V = -\mu_{s1}^2|s_1^0|^2 + \mu_{s2}^2|s_2^0|^2 - \mu_{\Phi1}^2\Phi^\dagger\Phi + \mu_{\Phi2}^2\Phi_\nu^\dagger\Phi_\nu + \mu_\eta^2\eta^\dagger\eta$$
$$-\left(\mu\, s_1^{0*}(s_2^0)^2 + \text{h.c.}\right) + \left(\lambda_{s\Phi1\eta}\, s_1^{0*}(s_2^0)^*\Phi^\dagger\eta + \text{h.c.}\right) + \left(\lambda_{s\Phi2\eta}\, s_1^0 s_2^0\Phi_\nu^\dagger\eta + \text{h.c.}\right) + \cdots$$

- The soft-term $\mu_{\Phi12}^2\Phi_\nu^\dagger\Phi$ is forbidden.

$$v_\nu|_{\text{tree}} = 0$$

- But, $\frac{1}{16\pi^2\Lambda^2}(s_1^0)^3\Phi_\nu^\dagger\Phi$ is allowed at the loop level.

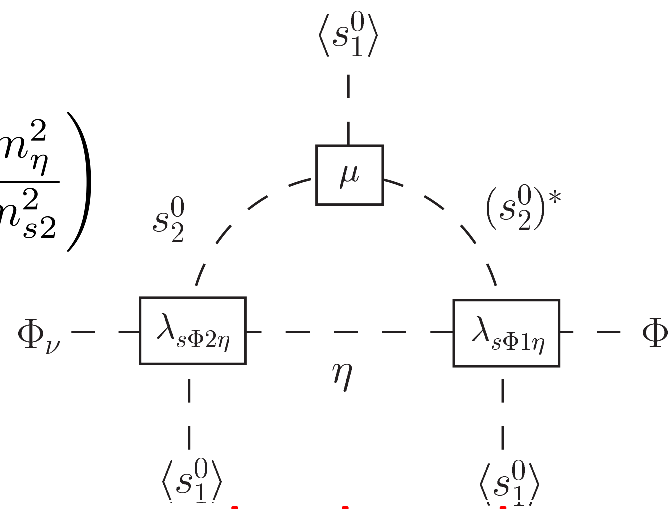
$\Rightarrow$ By the spontaneous breaking of $U(1)_X$, we can get the suppressed VEV of Φ_ν:

$$\boxed{\frac{v_\nu|_{\text{loop}}}{v} \simeq \left(\frac{(\mu_{\Phi12})_{\text{eff}}}{v}\right)^2}$$

Dark Matter

- Z_2-sym. remains unbroken after $U(1)_X$ breaking.
- $(\mu^2_{\Phi 12})_{\rm eff}\,[\Phi^\dagger_\nu \Phi]$ is generated by the loop effect of Z_2-odd particles (η & s_2^0) whose lightest one is a DM candidate.

$$(\mu^2_{\Phi 12})_{\rm eff} = \frac{\mu\,\lambda_{s\Phi 1\eta}\,\lambda_{s\Phi 2\eta}\,v_s^3}{32\sqrt{2}\,\pi^2(m_\eta^2 - m_{s2}^2)}\left(1 - \frac{m_\eta^2}{m_\eta^2 - m_{s2}^2}\ln\frac{m_\eta^2}{m_{s2}^2}\right)$$



⇒We can explain m_ν without large fine-tuning by this relation.

$$\left(\frac{(\mu_{\Phi 12})_{\rm eff}}{v}\right)^2 \simeq \frac{m_\nu}{y_\nu v} \quad \Rightarrow \quad \boxed{\frac{\mu\,\lambda_{s\Phi 1\eta}\,\lambda_{s\Phi 2\eta}\,y_\nu\,v_s^3}{m_\eta^2 - m_{s2}^2} \simeq (10^{-3}\mathrm{GeV})^2}$$

Collider Phenomenology

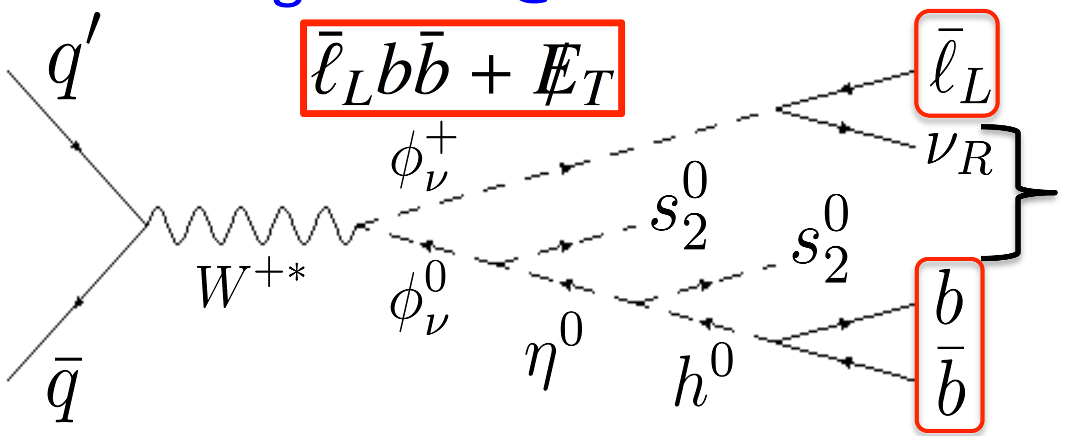
- Allowed parameter set (the singlet DM case):

$$\boxed{\begin{array}{l}(y_\nu)_{\ell i} \sim 10^{-4}, \quad \lambda_{s\Phi 1\eta} = \lambda_{s\Phi 2\eta} = 10^{-2}, \quad \mu = 1\,\text{GeV}, \quad v_s = 300\,\text{GeV}, \\ m_{\phi_\nu} = m_{\phi_\nu^\pm} = 300\,\text{GeV}, \quad m_\eta = 230\,\text{GeV}, \quad m_{s_2} = 65\,\text{GeV}\end{array}}$$

satisfying ρ parameter, lepton flavor violating processes, the relic abundance of DM and direct searches for DM.

Possible signature @LHC

$\boxed{\bar{\ell}_L b\bar{b} + \not{E}_T}$



$\sqrt{s} = 14\text{TeV}$

$pp \to \phi_\nu^+\phi_\nu^0 + \phi_\nu^-\phi_\nu^0$	7 fb
$pp \to t\bar{t}$	833 pb
$pp \to W^+Z + W^-Z$	55.4 pb
$pp \to t\bar{b} + \bar{t}b$	3.91 pb

R.Bonciani et al, 9801375
J.M.Campbell et al, 9905386
N.Kidonakis et al, 1001.5034

⇒We expect that the background can be reduced!

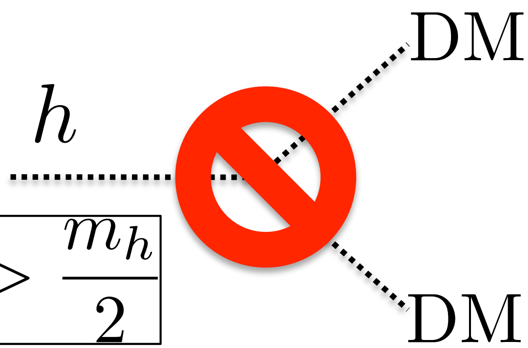
Conclusions

- We investigated the model of νTHDM.
- To explain the smallness of the VEV of Φ_ν, we introduced with a new mechanism that the VEV is suppressed by the loop diagram.
- Then, there was a DM candidate in our model.
- We suggested a possible signature at the LHC in this scenario.

Back Up

Dark Matter

Higgs invisible decay is not allowed.



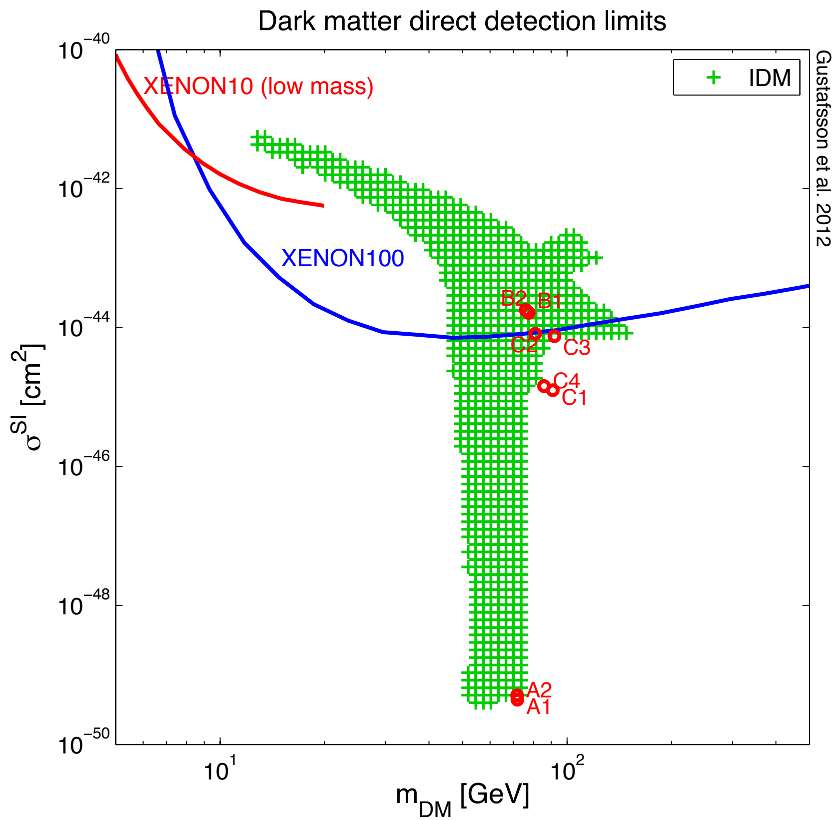
$$\boxed{m_{\mathrm{DM}} > \frac{m_h}{2}}$$

Constraint from DM direct search for inert doublet model.

$$\boxed{|m_{\eta_i} - m_{\eta_r}| \gtrsim 100\,\mathrm{keV}}$$

M.Gustafsson, PoS CHARGED **2010** (2010) 030

$$|\lambda_{s\Phi 1\eta}| \gtrsim 10^{-3}$$

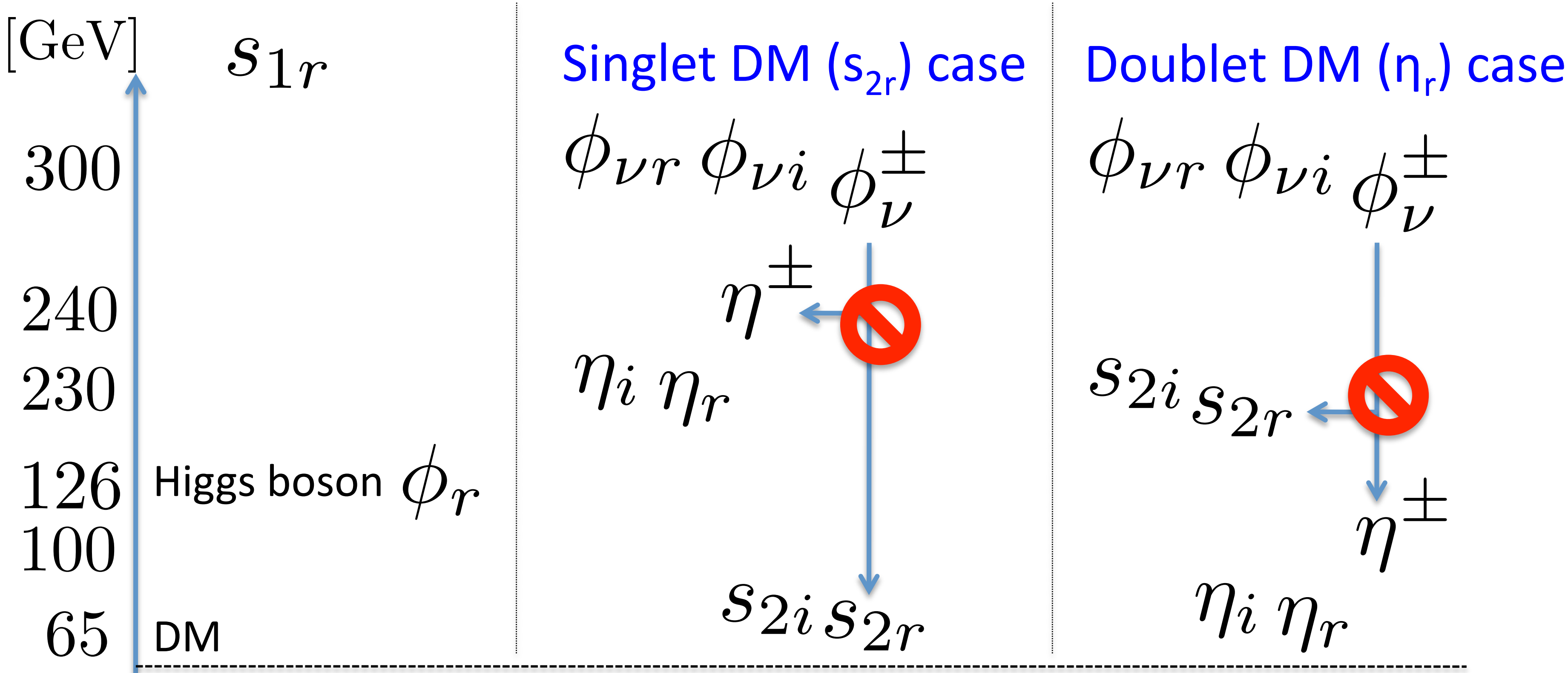


$$\boxed{45\mathrm{GeV} \lesssim m_{DM} \lesssim 80\mathrm{GeV}}$$

M.Gustafsson et al, Phys. Rev. D **86** (2012) 075019

⇒We choose m_{DM} =65GeV.

Mass spectrum

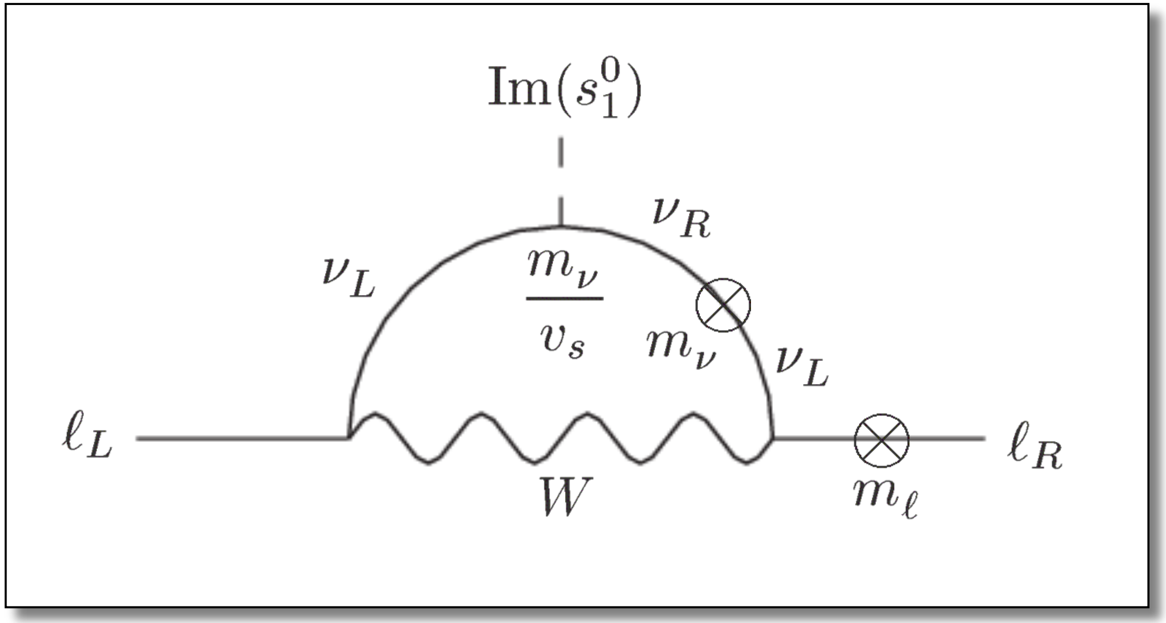


0 NG boson s_{1i}

1. We want to test the process of vTHDM: $\phi_\nu^+ \to \overline{\ell_L} \nu_R$
   we forbid the process: $\phi_\nu^\pm \to s_{2r}\eta^\pm$ & $\phi_\nu^\pm \to W^\pm \phi_\nu$
2. To test the our characteristic process: $\phi_\nu \to s_2\eta$
   we forbid the process: $\phi_\nu \to W^\pm \phi_\nu^\pm$ $\boxed{m_{\phi_\nu} = m_{\phi_\nu^\pm}}$

NG boson Interaction to Matter

Y.Chikashige, R.N.Mohapatra and R.D.Peccei, Phys. Lett. B **98** (1981) 265



$$\frac{m_\nu}{v_s} \simeq 10^{-12}$$

$$\Rightarrow \quad g_{ffJ} \sim \frac{G_F m_\nu^2 m_f}{16\pi^2 v_s} \sim \left(\frac{m_\nu}{0.1\,\mathrm{eV}}\right)^2 \left(\frac{m_f}{1\,\mathrm{MeV}}\right) \left(\frac{100\,\mathrm{GeV}}{v_s}\right) \times 10^{-32}$$

⇒The coupling of this process is very small.

Phenomenology of original vTHDM

S.M.Davidson & H.E.Logan, Phys. Rev. D **82** (2010) 115031

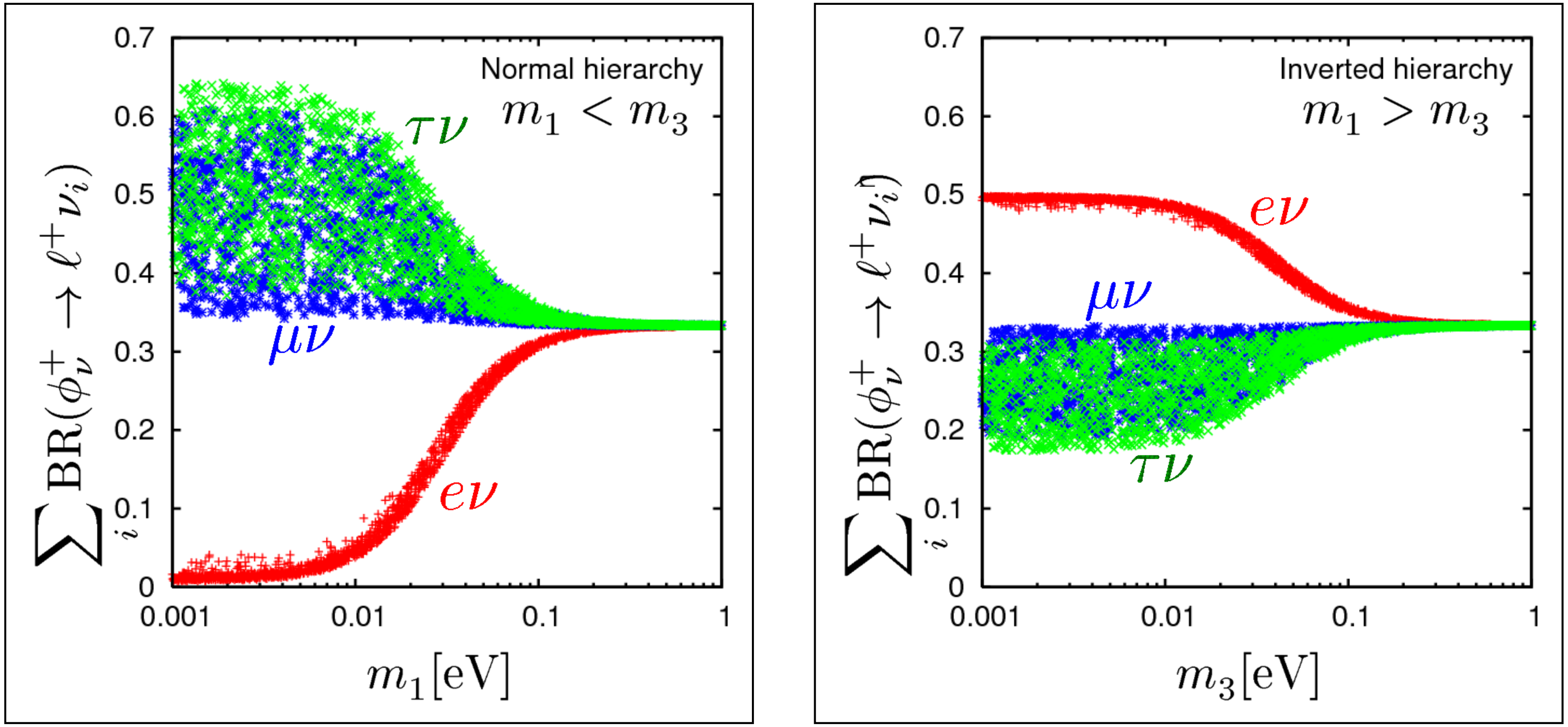
Because $\phi_\nu \to \nu\bar{\nu}$ of vTHDM process is missing, the possible signature of vTHDM is pp→$\phi_\nu^+\phi_\nu^-$

Process	Cross section
$pp \to \phi_\nu^+\phi_\nu^-$ $(M_{\phi_\nu^+} = 100$ GeV$)$	295 fb
$pp \to \phi_\nu^+\phi_\nu^-$ $(M_{\phi_\nu^+} = 300$ GeV$)$	5.32 fb
$pp \to W^+W^-$	127.8 pb
$pp \to ZZ$	17.2 pb
$pp \to t\bar{t}$	833 pb

We can distinguish this model to test $\phi_\nu \to s_2\eta$ of our model.

1.Prediction of vTHDM $\phi_\nu^+ \to \overline{\ell_L}\nu_R$

S.M.Davidson & H.E.Logan, Phys. Rev. D **80** (2009) 095008



⇒When we measure $\dfrac{\mathrm{BR_e}}{\mathrm{BR}_\mu}$,

we can understand neutrino mass hierarchy.

2.The partial decay width

- The partial decay width of our model: $\phi_\nu \to s_2\eta$, in comparison with original vTHDM.

$$\Gamma(\phi_\nu \to \nu\bar{\nu}) = \frac{\mathrm{tr}(y_\nu^\dagger y_\nu) m_{\phi_\nu}}{16\pi} \simeq 60\,\mathrm{eV},$$

$$\Gamma(\phi_\nu \to s_2\eta) = \frac{\lambda_{s\Phi 2\eta}^2 v_s^2}{64\pi m_{\phi_\nu}} \sqrt{1 - \frac{(m_{s_2} + m_\eta)^2}{m_{\phi_\nu}^2}} \sqrt{1 - \frac{(m_{s_2} - m_\eta)^2}{m_{\phi_\nu}^2}} \simeq \underline{\underline{20\,\mathrm{keV}}}$$

$$m_{\phi_\nu} = 300\,\mathrm{GeV}, \quad m_\eta = 230\,\mathrm{GeV}, \quad m_{s_2} = 65\,\mathrm{GeV}$$

The process of our model is dominant in comparison with original vTHDM.