The Model of Neutrino Mass and Its Phenomenology

PPP7

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Outline

- The model
- Structure of Scalars
- Neutrino Mass Generation
- $0\nu\beta\beta$ decays
- LHC signatures
- Conclusion

The Model

- The model is based on the SM gauge symmetry with an extended Higgs sector

Scalars :

$$\phi = \begin{pmatrix} \phi^0 \\ \phi^- \end{pmatrix}_{-1} \quad , \quad T = \begin{pmatrix} T^0 & \frac{T^-}{\sqrt{2}} \\ \frac{T^-}{\sqrt{2}} & T^{--} \end{pmatrix}_{-2} \quad , \quad \psi_4^{++}$$

Fermions :

$$L = \begin{pmatrix} \nu \\ l \end{pmatrix}_L \quad , \quad \begin{pmatrix} u \\ d \end{pmatrix}_L \quad , \quad u_R \quad , \quad d_R$$

Our convention $Q = T_3 + \frac{Y}{2}$

Scalar Potential :

$$
\begin{aligned}
V(\phi,T,\psi) = & -\mu^2\phi^\dagger\phi + \lambda_\phi(\phi^\dagger\phi)^2 - \mu_T^2 Tr(T^\dagger T) \\
& +\lambda_T[Tr(T^\dagger T)]^2 + \lambda_T' Tr(T^\dagger T T^\dagger T) \\
& +m^2\Psi^\dagger\Psi + \lambda_\Psi(\Psi^\dagger\Psi)^2 + \kappa_1 Tr(\phi^\dagger\phi T^\dagger T) \\
& +\kappa_2\phi^\dagger T T^\dagger\phi + \kappa_\Psi\phi^\dagger\phi\Psi^\dagger\Psi \\
& +\rho Tr(T^\dagger T\Psi^\dagger\Psi) \\
& +[\lambda(\tilde{\phi}^T T\tilde{\phi}^*\Psi^\dagger) - M(\phi^T T^\dagger\phi) + h.c.] \,,
\end{aligned}
$$

Yukawa interactions :

$$Y_{ab}\overline{l_{aR}^c} l_{bR}\Psi$$

and “LLT” is not allowed in the model as our assumption.

Structure of Scalars

- VEVs $<\phi^0>=\frac{v}{\sqrt{2}}$ and $<T^0>=\frac{v_T}{\sqrt{2}}$

$$\rightarrow \rho = 1.002^{+.0007}_{-.0009} \quad , \quad v_T < 4.41 GeV$$

- After symmetry breaking we have one SM-like Higgs , one pseudo-scalar , one single-charged scalar ,and two double-charged scalars

doubly charged scalars :

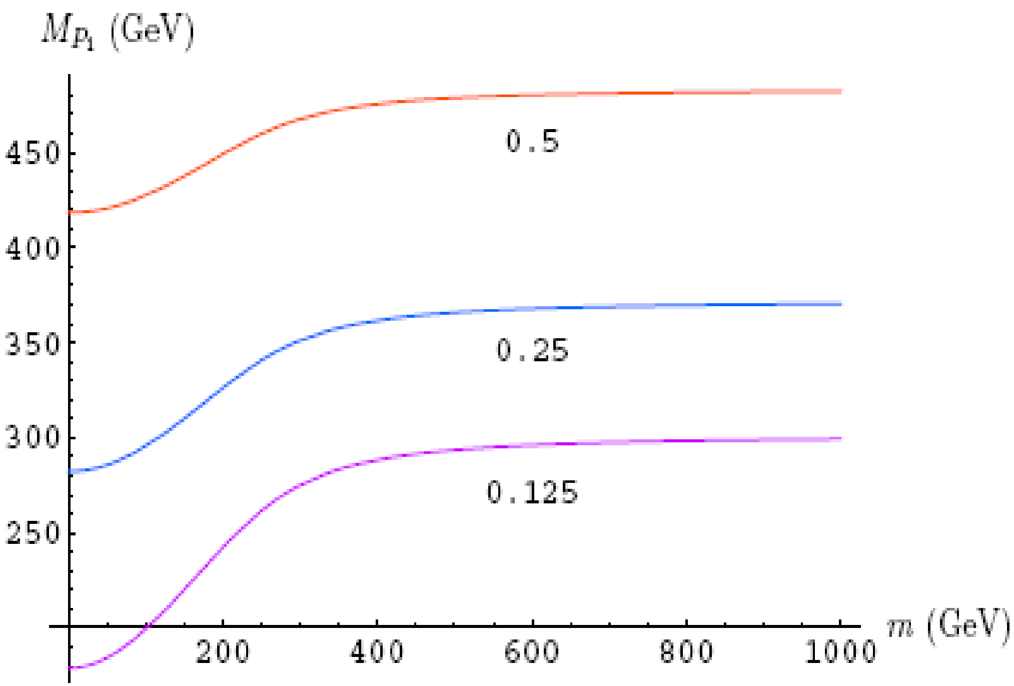
$$\frac{1}{2}\left[(\frac{\rho}{2}-\lambda_T')v_T^2+\frac{1}{2}(\kappa_\Psi-\kappa_2+2\omega)v^2+m^2\pm\sqrt{[m^2+\frac{1}{2}(\kappa_\Psi+\kappa_2+2\omega)v^2+(\frac{\rho}{2}-\lambda_T')v_T^2]^2+\lambda^2v^4}\right].$$

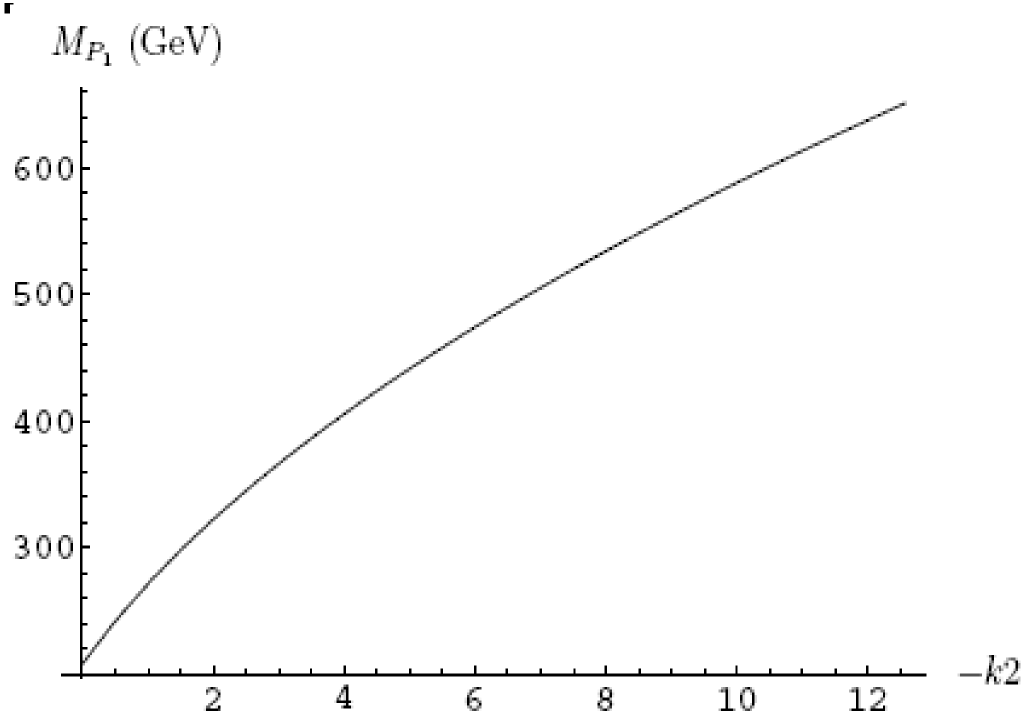
where $\omega=\frac{M}{\sqrt{2}v_T}.$

- Notations :

$$\begin{pmatrix} P_1^{\pm\pm} \\ P_2^{\pm\pm} \end{pmatrix} = \begin{pmatrix} \cos\delta & \sin\delta \\ -\sin\delta & \cos\delta \end{pmatrix} \begin{pmatrix} T^{\pm\pm} \\ \Psi^{\pm\pm} \end{pmatrix} \qquad \sin 2\delta \simeq \frac{1}{\sqrt{1+\left[\frac{m^2}{\lambda v^2}+\frac{\omega}{\lambda}+\frac{(\kappa_\Psi+\kappa_2)}{2\lambda}\right]^2}}.$$

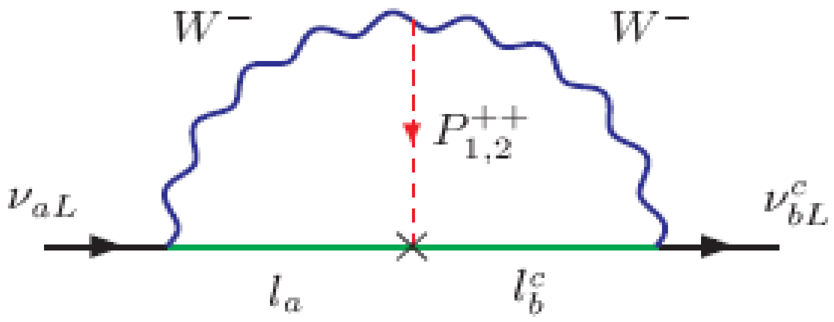
- One of the mass of doubly charged scalar will saturate at 700 GeV. It makes it to be well within reach of the LHC.





Neutrino Mass Generartion

- The neutrino mass will generate in two loop level

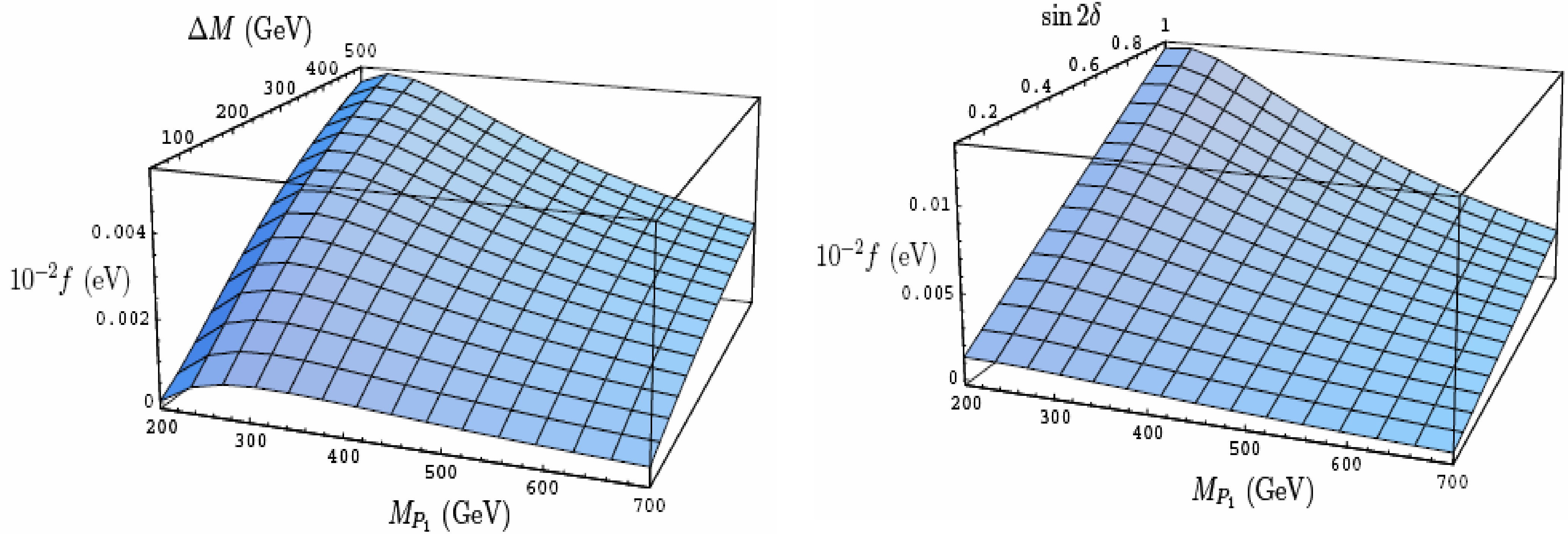


- We find

$$m_\nu = f(M_1, M_2) \times \begin{pmatrix} \frac{m_e^2}{m_\mu^2} Y_{ee} & \frac{m_e}{m_\mu} Y_{e\mu} & \frac{m_e m_\tau}{m_\mu^2} Y_{e\tau} \\ \frac{m_e}{m_\mu} Y_{e\mu} & Y_{\mu\mu} & \frac{m_\tau}{m_\mu} Y_{\mu\tau} \\ \frac{m_e m_\tau}{m_\mu^2} Y_{e\tau} & \frac{m_\tau}{m_\mu} Y_{\mu\tau} & \frac{m_\tau^2}{m_\mu^2} Y_{\tau\tau} \end{pmatrix}$$

$$= f(M_1, M_2) \times \begin{pmatrix} 2.3 \times 10^{-5} Y_{ee} & 4.8 \times 10^{-3} Y_{e\mu} & 0.08 Y_{e\tau} \\ 4.8 \times 10^{-3} Y_{e\mu} & Y_{\mu\mu} & 16.9 Y_{\mu\tau} \\ 0.08 Y_{e\tau} & 16.9 Y_{\mu\tau} & 284.1 Y_{\tau\tau} \end{pmatrix}$$

where $f(M_1, M_2) = \frac{\sqrt{2} g^4 m_\mu^2 v_T \sin 2\delta}{128\pi^4} \left[\frac{1}{M_1^2} \ln^2\left(\frac{M_W}{M_1}\right) - \frac{1}{M_2^2} \ln^2\left(\frac{M_W}{M_2}\right) \right]$



we generically obtain neutrino at O(eV) scale in terms of parameters Y_{ab} , and they are normal heirarchy structure.

Constraints on Y_{ab} :

--- By using μ-e conversion , Bhabha scattering , rare μ , τ decays , radiative flavor violating decays , and neutrino oscillation

Results :

μ-e conversion :

$$Y_{ee}Y_{\mu\mu} < 2.7 \times 10^{-3}(M_{--}/100GeV)^2$$

Bhabha scattering $e^+e^- \rightarrow l^+l^-$

$$Y_{ee}^2 \;<\; 1.8 \times 10^{-3}(M_{--}/100GeV)^2$$
$$Y_{e\mu}^2 \;<\; 2.4 \times 10^{-3}(M_{--}/100GeV)^2$$
$$Y_{e\tau}^2 \;<\; 2.4 \times 10^{-3}(M_{--}/100GeV)^2$$

rare decays

$$Y_{e\mu}Y_{ee} \;<\; 6.6 \times 10^{-7}(M_{--}/100GeV)^2$$
$$Y_{e\tau}Y_{ee} \;<\; 3.0 \times 10^{-4}(M_{--}/100GeV)^2$$
$$Y_{e\tau}Y_{\mu\mu} \;<\; 3.0 \times 10^{-4}(M_{--}/100GeV)^2$$
$$Y_{\mu\tau}Y_{\mu\mu} \;<\; 2.9 \times 10^{-4}(M_{--}/100GeV)^2$$
$$Y_{\mu\tau}Y_{ee} \;<\; 2.9 \times 10^{-4}(M_{--}/100GeV)^2$$

radiative flavor violating decays

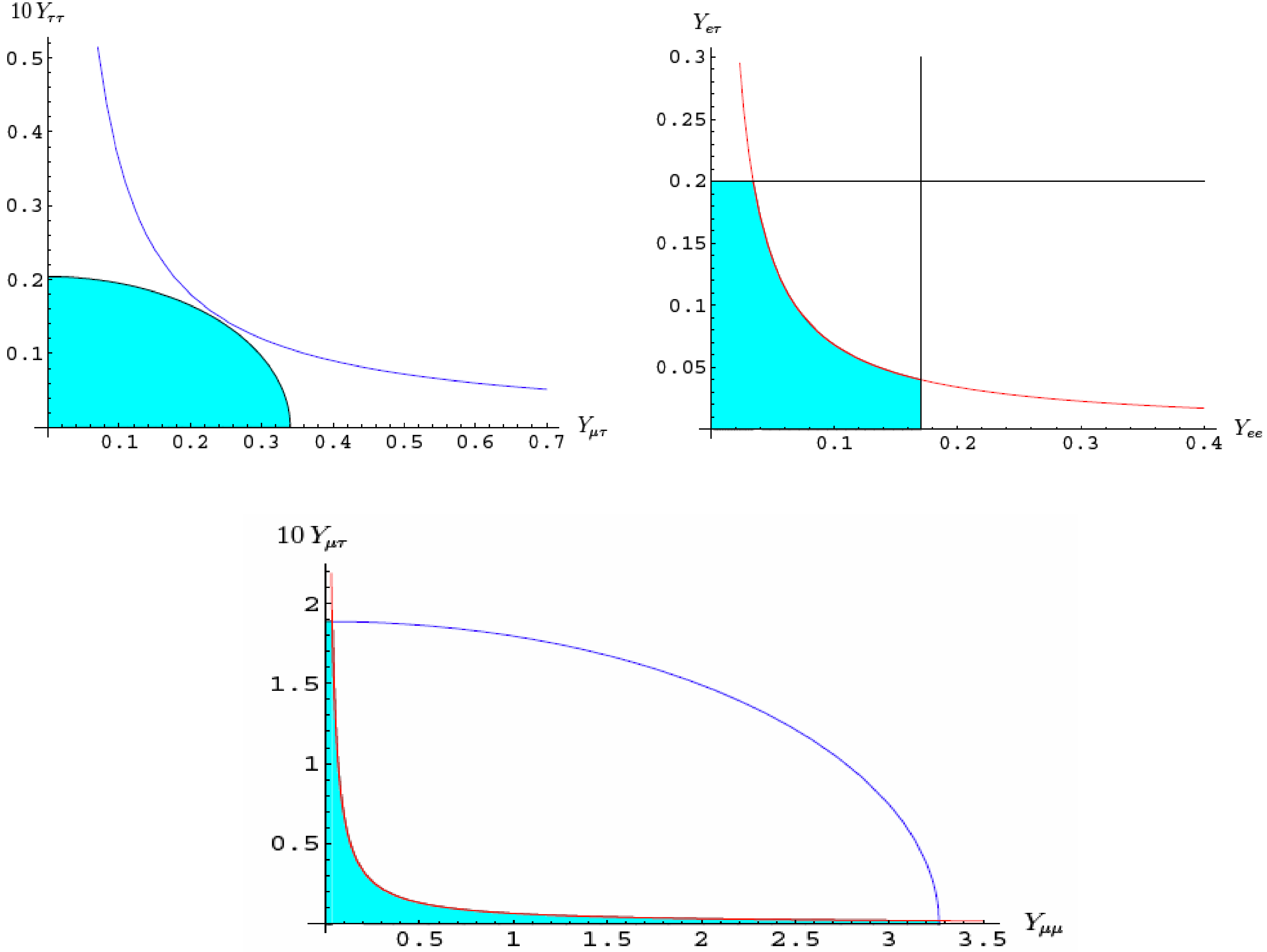
$$\sum_l Y_{l\mu} Y_{le} \; < \; 1.5 \times 10^{-5} (M_{--}/100GeV)^2$$
$$\sum_l Y_{l\tau} Y_{le} \; < \; 1.4 \times 10^{-3} (M_{--}/100GeV)^2$$
$$\sum_l Y_{l\tau} Y_{l\mu} \; < \; 1.1 \times 10^{-3} (M_{--}/100GeV)^2$$

neutrino oscillation

$$f^2 Y_{e\tau}^2 \; \leq \; 1.32 \times 10^2 (M_{--}/100GeV)^2$$
$$f^2 Y_{e\tau} Y_{\mu\tau} \; \leq \; 1 (M_{--}/100GeV)^2$$
$$f^2 Y_{e\tau} Y_{\tau\tau} \; \leq \; 9.0 \times 10^{-2} (M_{--}/100GeV)^2$$
$$f^2 (Y_{\mu\mu}^2 + 300 Y_{\mu\tau}^2) \; \leq \; 2.7 (M_{--}/100GeV)^2$$
$$f^2 (Y_{\mu\mu} + 285 Y_{\tau\tau}) Y_{\mu\tau} \; \leq \; 2.4 \times 10^{-1} (M_{--}/100GeV)^2$$
$$f^2 (Y_{\mu\tau}^2 + 285 Y_{\tau\tau}^2) \; \leq \; 2.9 \times 10^{-2}$$

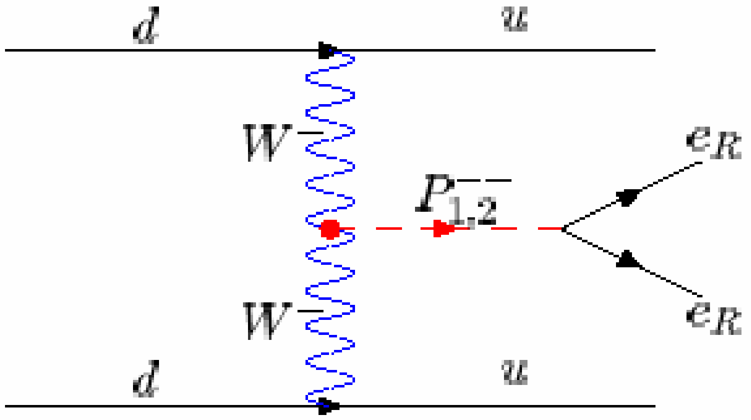
we obtain

$$Y_{ee} < 0.17, \qquad Y_{e\mu} < 0.2, \qquad Y_{e\tau} < 0.2$$
$$Y_{\mu\mu} < 3.5, \qquad Y_{\mu\tau} < 0.2, \qquad Y_{\tau\tau} < 0.02$$


$10\,Y_{\tau\tau}$
0.5
0.4
0.3
0.2
0.1
0.1 0.2 0.3 0.4 0.5 0.6 0.7
$Y_{\mu\tau}$
$Y_{e\tau}$
0.3
0.25
0.2
0.15
0.1
0.05
0.1 0.2 0.3 0.4
Y_{ee}
$10\,Y_{\mu\tau}$
2
1.5
1
0.5
0.5 1 1.5 2 2.5 3 3.5
$Y_{\mu\mu}$

Neutrinoless double-beta decay

- Besides the Majorana induced $0\nu\beta\beta$ decay , we also have extra process



Majorana neutrino :

$$A_\nu \sim \frac{g^4}{M_W^4}\frac{m_{ee}}{<p>^2},$$

Doubly charged scalar :

$$A_{P_{1,2}^{--}} \sim \frac{g^4 Y_{ee} v_T \sin 2\delta}{16\sqrt{2}M_W^4}\left(\frac{1}{M_{P_1}^2}-\frac{1}{M_{P_2}^2}\right),$$

We find

$$A_\nu / A_{P_{1,2}^{--}} \lesssim 10^{-7}$$

- The smallness of this ratio is due to the fact that in our model , m_{ee} is suppressed not only by a two-loop factor , it is also suppressed by the helicity flip factor $(m_e/M_W)^2$.

- If it does the case , $0\nu\beta\beta$ of nuclei will be due to the existence of doubly charged Higgs at the electroweak scale. This can be tested in LHC.

LHC Signature

- As argued before , if not both , at least one of the doubly charged Higgs is well within the reach of the LHC
- The two processes of P^{++} production is looking –

  W-fusion ~ the same diagram as $0\nu\beta\beta$

and

  Drell-Yan annihilation

$$q\bar{q} \to \gamma^*, Z^* \to P_1^{++} P_1^{--} \quad (q = u, d)$$

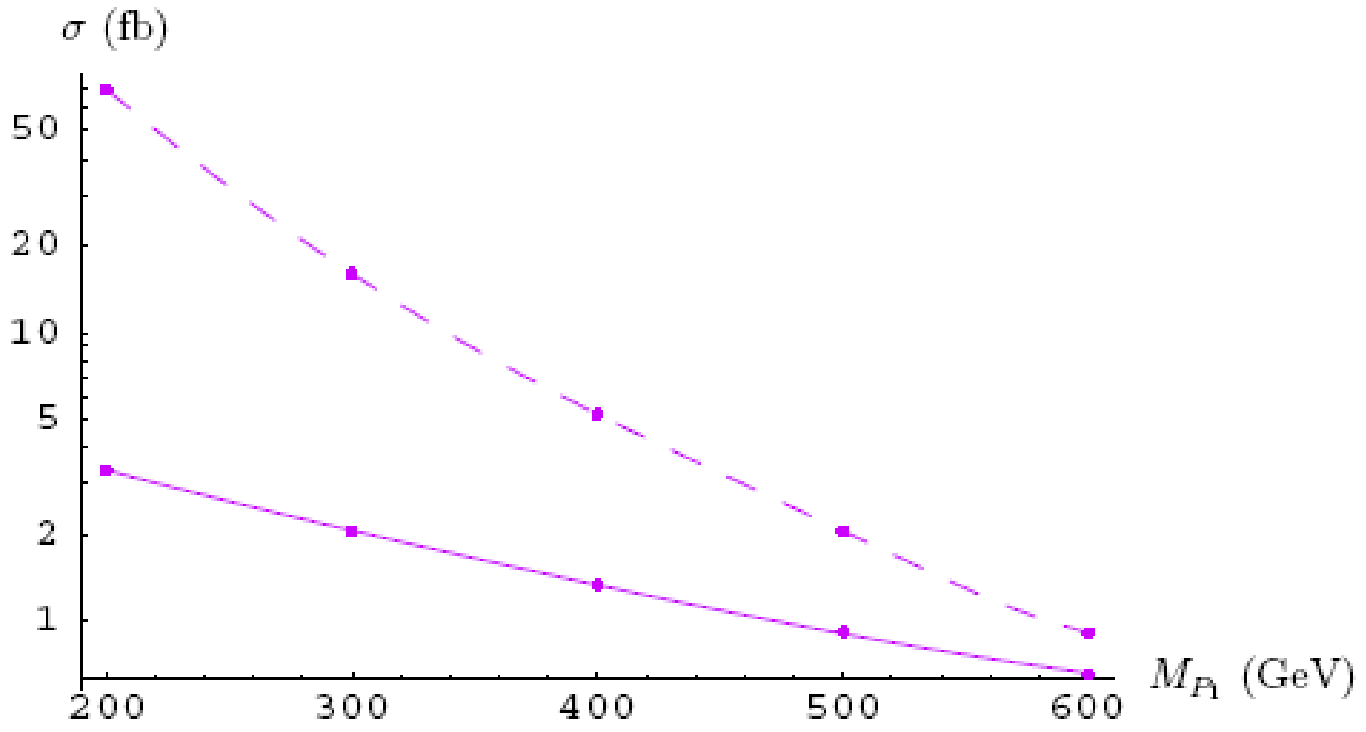
The relevant gauge-Higgs couplings are

$$W_\mu^\mp W^{\mu\mp} P_1^{\pm\pm} : \frac{g^2}{\sqrt{2}} v_T\, c_\delta P_1^{--} W_\mu^+ W^{\mu+} + h.c.$$

$$A_\mu\, P_1^{++} P_1^{--} : i\,2e\, A_\mu\, \partial P_1^{++} P_1^{--} + h.c.$$

$$Z_\mu\, P_1^{++} P_1^{--} : \frac{ig}{c_W} \left[(1 - 2s_W^2)c_\delta^2 - 2s_W^2 s_\delta^2\right] Z_\mu\, \partial P_1^{++} P_1^{--} + h.c.$$

$$W_\mu^\mp P^\mp P_1^{\pm\pm} : ig \cos\delta\; W^{\mu+} [(\partial_\mu P_1^{--}) P^+ - P_1^{--} (\partial_\mu P^+] + h.c.$$



- Decays of doubly charged Higgs

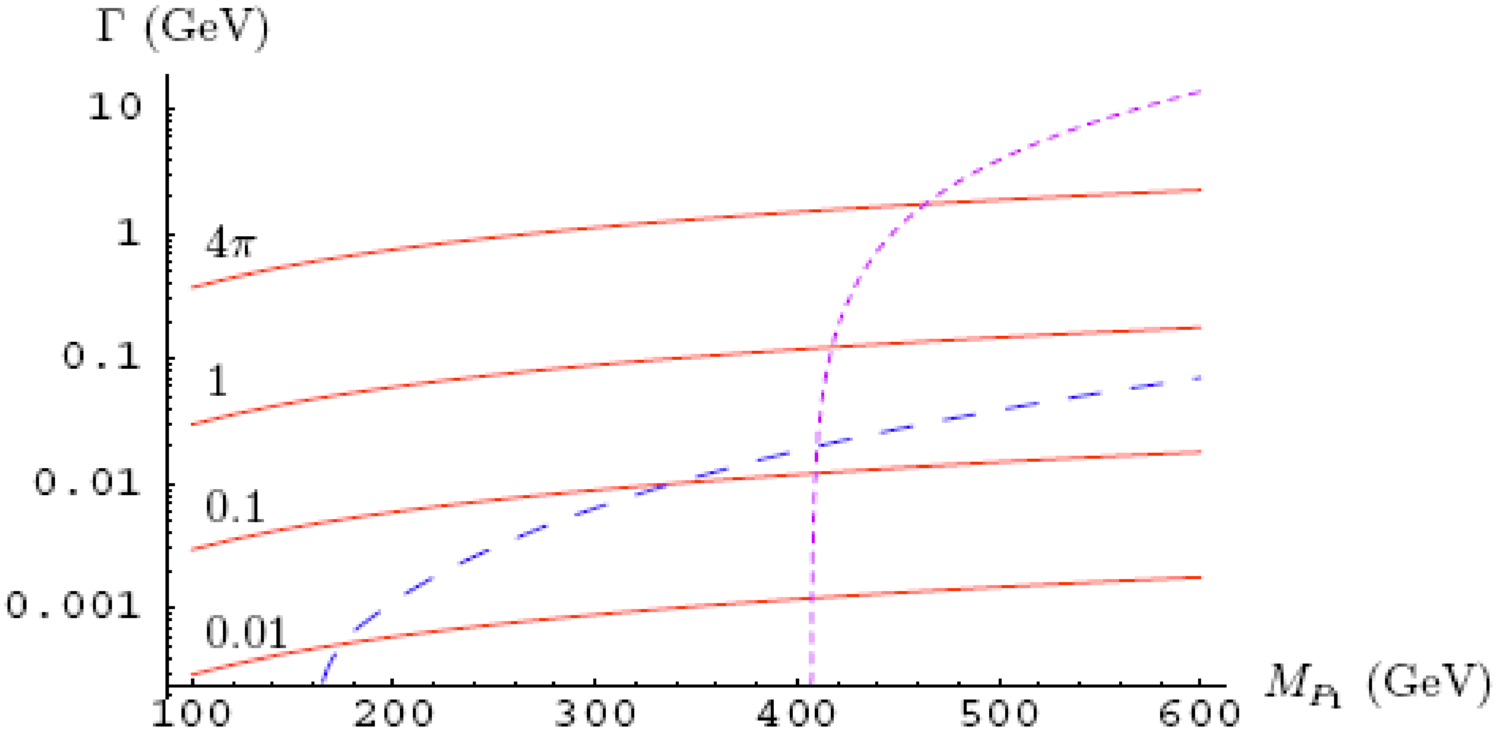
$$P_1^{\pm\pm} \to l_{aR}^{\pm} l_{bR}^{\pm}\,, \quad a,b = e,\mu,\tau$$
$$P_1^{\pm\pm} \to W^{\pm}W^{\pm}$$
$$P_1^{\pm\pm} \to W^{\pm}P^{\pm}$$

correspondingly

$$\Gamma(l_{aR}l_{bR}) = (1+\delta_{ab})\frac{|Y_{ab}|^2}{16\pi}M_{P_1} \quad (\text{no sum})\,.$$

$$\Gamma(WW) = \frac{g^4 v_T^2 c_\delta^2}{16\pi M_1}\left(1-\frac{4M_W^2}{M_{P_1}^2}\right)^{\frac{1}{2}}\left(3-\frac{M_{P_1}^2}{M_W^2}+\frac{M_{P_1}^4}{4M_W^4}\right)\,,$$

$$\Gamma(WP) = \frac{g^2 c_\delta M_{P_1}^3}{16\pi M_W^2}\lambda\left(1,\frac{M_W^2}{M_{P_1}^2},\frac{M_P^2}{M_{P_1}^2}\right)^3\,,$$



Γ (GeV)
10
1
0.1
0.01
0.001
4π
1
0.1
0.01
100
200
300
400
500
600
M_{P_1} (GeV)

Conclusion

- The model of neutrino mass generation is presented , the structure of neutrino mass is hierarchy.
- At least one EW scale doubly charged Higgs exist , the model can be testable.
- The same mechanism of neutrino mass also gives $0\nu\beta\beta$, and it is the dominant over Majorana mass contribution.
- Parameters constraints are studied.
- Doubly charged Higgs search in LHC is studied.