Doubly Charged Higgs, Neutirno Masses and The LHC

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Triumf

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PRD 75,053004 (2007) and hepph 0706.1964

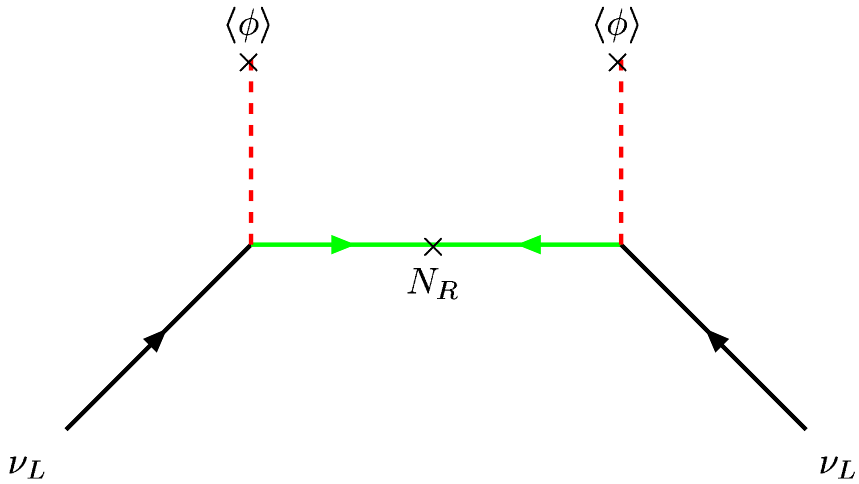
2007

Content

- Motivation
- The model
- Neutrino Mass at 2-loop
- Existence of Charged Higgs is necessary
- Implication for Colliders
- Conclusions

Motivation

- Orthodox view of neutrino mass generation is the seesaw mechanism



- $$m_\nu \sim \frac{y}{M_N} LL\phi\phi \xrightarrow{SSB} \frac{yv^2}{M_N}\nu_L\nu_L$$

  where L, ϕ are the SM the lepton and Higgs doublets. $v = 246$ GeV.
- Require mass of right-handed singlet neutrino N_R to be $M_N > 10^{12}$ GeV
- Elegantly connects to GUT's. Very difficult to test experimentally
- Attempts to lower the scale to TeV requires fine tuning

Alternative to Seesaw

- Without N_R how do neutirnos get masses?
  1. Extend the Higgs sector
     (a) Group theory demands that the new fields be Higgs singlet and/or triplet
     (b) m_ν radiatively induced.
     (c) All new physics is at the the TeV scale.
  2. R-parity violating supersymmetry LLE and LQE terms

Ingredients

- The gauge group is SM $SU(2) \times U(1)$
- Add to the SM the set of Higgs fields . Matter fields remain minimal
  1. One triplet T with SM q.n $(1, 2)$ carries no lepton number

$$T = \begin{pmatrix} T^0 & \frac{T^-}{\sqrt{2}} \\ \frac{T^-}{\sqrt{2}} & T^{--} \end{pmatrix}_{-2}$$

  2. A doubly charged singlet Higgs $\Psi^{++}$with q.n. $(0, 4)$ with lepton number 2
- New Yukawa term $Y_{ab}\overline{e^c_{aR}}e_{bR}\Psi$ is allowed. a, b are family indices.
- No LLT term.
- The rest of the Yukawa terms are same as SM

The Scalar Potential

- Lepton number violation is introduced in the Higgs potential

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

- It is natural in the technical sense $\lambda, M\to 0$ lepton symmtery is restored.
- Majorana neutrino mass must involove λ
- μ_T^2 is positive so that there is SSB for the triplet field.
- Counting physical spin zero field
  1. Neutral scalars h^0 , t^0 from mixing of ϕ^0 T^0.
  2. Pseudoscalar t_a from the imagianary part of T^0
  3. A pair of charge scalar $P^\pm$ originates from $T^\pm$
  4. Two pairs of doubly charged scalars $P_{1,2}^{\pm\pm}$ from the mixing of $T^{\pm\pm}$, $\Psi^{\pm\pm}$

Mass Range for Scalars

- v_T is constrained by $\rho = 1.002^{+.0007}_{-.0009}$ paramater

$$M_W^2 = \frac{g^2}{4}(v^2 + 2v_T^2)\,, \qquad M_Z^2 = \frac{g^2}{4\cos^2\theta_W}(v^2 + 4v_T^2)\,,$$

  We get $v_T < 4GeV$.

- Minimizing V yields

$$\begin{aligned} -\mu^2 + \lambda_\phi v^2 + \frac{1}{2}\kappa_+ v_T^2 - \sqrt{2} M v_T &= 0\,, \\ -\mu_T^2 + \lambda_+ v_T^2 + \frac{1}{2}\kappa_+ v^2 - \frac{v^2}{\sqrt{2}}\left(\frac{M}{v_T}\right) &= 0\,, \end{aligned}$$

  where $\kappa_+ = \kappa_1 + \kappa_2$ and $\lambda_+ = \lambda_T + \lambda'_T$.

- The limiting cases are
  1. $M \sim v_T$ conditions satified by $\mu_T \sim v_T$. Parameters not fine tuned.
  2. $M \sim v_T$ needs $\mu_T^2 \sim v^3/v_T$. Appears not natural
  3. $M > v$. Fine tuning required . Will not consider this case.

Scalar Mass contd

- Keeping all the parameters perturbative $< 4\pi$. Singly charged Higgs between 200 and 600 GeV
- The pair of doubly charged Higgs from a two level system. They mix i.e. mass and weak eigenstates are different

$$\begin{pmatrix} P_1^{\pm\pm} \\ P_2^{\pm\pm} \end{pmatrix} = \begin{pmatrix} \cos\delta & \sin\delta \\ -\sin\delta & \cos\delta \end{pmatrix} \begin{pmatrix} T^{\pm\pm} \\ \Psi^{\pm\pm} \end{pmatrix}$$

- Mixing angle is given by

$$\sin 2\delta = \left[1 + \left(\frac{2m^2 + (2\lambda'_T + \rho) v_T^2}{2\lambda v^2} + \frac{\kappa_2 + \kappa_\Psi}{2\lambda} - \frac{\omega}{\lambda} \right)^2 \right]^{-\frac{1}{2}} ,$$

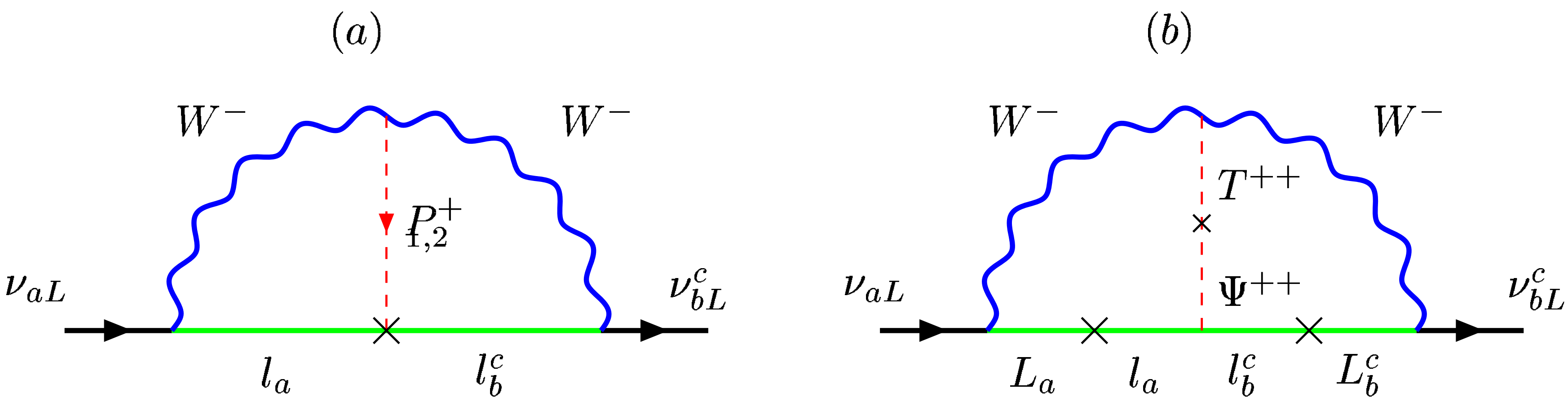
- For Case A, if $m^2 \lesssim v^2$, the mixing can be large and close to maximal. But if $m^2 \gg v^2$, the mixing will be small, which is expected since the two states are widely split
- For case B, large mixing can be achieved only if a cancellation occurs between the various parameter

More Masses

- For the masses
  1. $M \sim v_T$: The mass of $P_{1,2}^{\pm\pm}$ is expected to be in the range $200 - 600$ GeV if $m \lesssim 1$ TeV. Otherwise $P_2^{\pm\pm} > TeV$.
  2. $M \sim v \gg v_T$: Here, only the mass of $P_1^{\pm\pm}$ is expected to be at the weak scale. All others $\gg$ TeV. Out of reach of LHC

Radiative Neutrino Masses

Active neturinos have masses from 2-loop effect



The neutrino mass matrix is

$$(m_\nu)_{ab} = \frac{1}{\sqrt{2}}\, g^4 m_a\, m_b\, v_T Y_{ab} \sin(2\delta) \left[I(M_W^2, M_{P_1}^2, m_a, m_b) - I(M_W^2, M_{P_2}^2, m_a, m_b) \right] ,$$

where $a, b = e, \mu, \tau$. The integral I is

$$I(M_W^2, M_{P_i}^2, m_a^2, m_b^2) = \int \frac{d^4q}{(2\pi)^4} \int \frac{d^4k}{(2\pi)^4} \frac{1}{k^2 - m_a^2} \frac{1}{k^2 - M_W^2} \frac{1}{q^2 - M_W^2} \frac{1}{q^2 - m_b^2} \frac{1}{(k-q)^2 -}$$

Neutrino Mass matrix

- In the limit $M_{P_{1,2}} > M_W$

$$I(M_W^2, M_{P_i}^2, 0, 0) \sim \frac{1}{(4\pi)^4} \frac{1}{M_{P_i}^2} \log^2\left(\frac{M_W^2}{M_{P_i}^2}\right)$$

- Controlling factor of the absolute scale for m_ν is v_T
- There is a G.I.M. cancellation bet $P_1^{\pm\pm}$ and $P_2^{\pm\pm}$
- It is further suppress by two helicity flips of internal charged lepton line
- Suppress by the 2-loop factor
- ${(m_\nu)_e}^e$ element is very small
- Expected to be in the sub-eV range
- If Y_{ab} si not too weird $\rightarrow$ normal hierarchy

Active Neutrino mass matrix

$$
\begin{aligned}
m_\nu &= \widetilde{f}(M_{P_1}, M_{P_2}) \times \begin{pmatrix} m_e^2\, Y_{ee} & m_e m_\mu Y_{e\mu} & m_e m_\tau Y_{e\tau} \\ m_e m_\mu Y_{e\mu} & m_\mu^2\, Y_{\mu\mu} & m_\tau m_\mu Y_{\mu\tau} \\ m_e m_\tau Y_{e\tau} & m_\tau m_\mu Y_{\mu\tau} & m_\tau^2\, Y_{\tau\tau} \end{pmatrix} \\
&= f(M_{P_1}, M_{P_2}) \times \begin{pmatrix} 2.6\times 10^{-7}\, Y_{ee} & 5.4\times 10^{-5}\, Y_{e\mu} & 9.1\times 10^{-4}\, Y_{e\tau} \\ 5.4\times 10^{-5}\, Y_{e\mu} & 1.1\times 10^{-2}\, Y_{\mu\mu} & 0.19\, Y_{\mu\tau} \\ 9.1\times 10^{-4}\, Y_{e\tau} & 0.19\, Y_{\mu\tau} & 3.17\, Y_{\tau\tau} \end{pmatrix},
\end{aligned}
$$

where

$$
\widetilde{f}(M_{P_1}, M_{P_2}) = \frac{\sqrt{2} g^4 v_T \sin(2\delta)}{128\pi^4} \left[\frac{1}{M_{P_1}^2} \log^2\left(\frac{M_W}{M_{P_1}}\right) - \frac{1}{M_{P_2}^2} \log^2\left(\frac{M_W}{M_{P_2}}\right) \right],
$$

and $f = \widetilde{f} \times (1\mathrm{GeV}^2)$ gives a qualitatively estimate of the overall scale of active neutrino masses.

Neutrino Mass contd

- It is the NH

$$\begin{pmatrix} \varepsilon' & \varepsilon & \varepsilon \\ \varepsilon & 1+\eta & 1+\eta \\ \varepsilon & 1+\eta & 1+\eta \end{pmatrix} ,$$

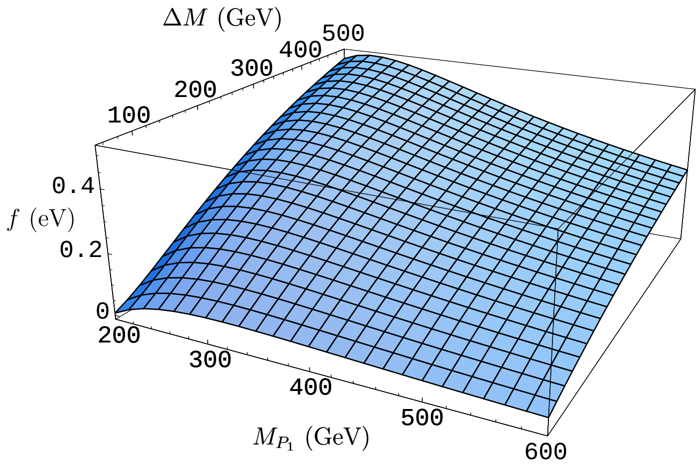
where ε, ε' and $\eta \ll 1$.

- Relate to neutrino oscillation data via

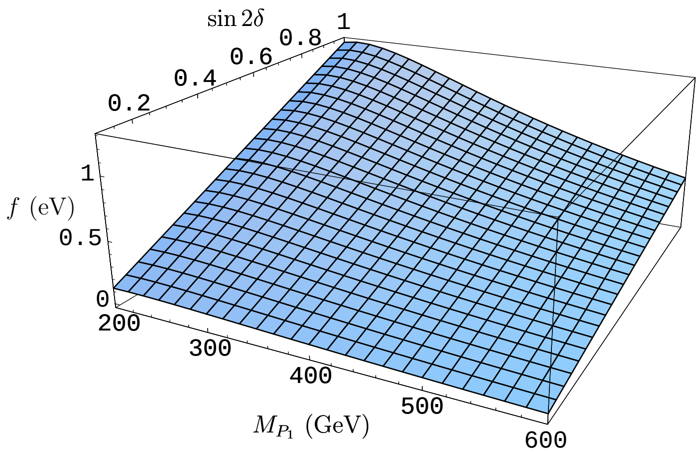
$$m_\nu^2 = V_{PMNS}^T \, U \begin{pmatrix} m_1^2 & 0 & 0 \\ 0 & m_2^2 & 0 \\ 0 & 0 & m_3^2 \end{pmatrix} U \, V_{PMNS} \, , \qquad U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\varphi_1} & 0 \\ 0 & 0 & e^{i(\varphi_2+\alpha)} \end{pmatrix} ,$$

where V_{PMNS} is the usual neutrino mixing matrix.

Scale of neutrino masses



and



Constraints from neutirno data

- The data

$$7.1\times10^{-5}<\Delta m^2_{\odot}<8.9\times10^{-5}\,(\mathrm{eV}^2)\,,\qquad 0.164<\sin^2\theta_{12}<0.494\,,$$
$$1.4\times10^{-3}<|\Delta m^2_{atm}|<3.3\times10^{-3}\,(\mathrm{eV}^2)\,,\qquad 0.22<\sin^2\theta_{23}<0.85\,,$$
$$\sin^2 2\theta_{13}=0\pm0.04\,. \tag{1}$$

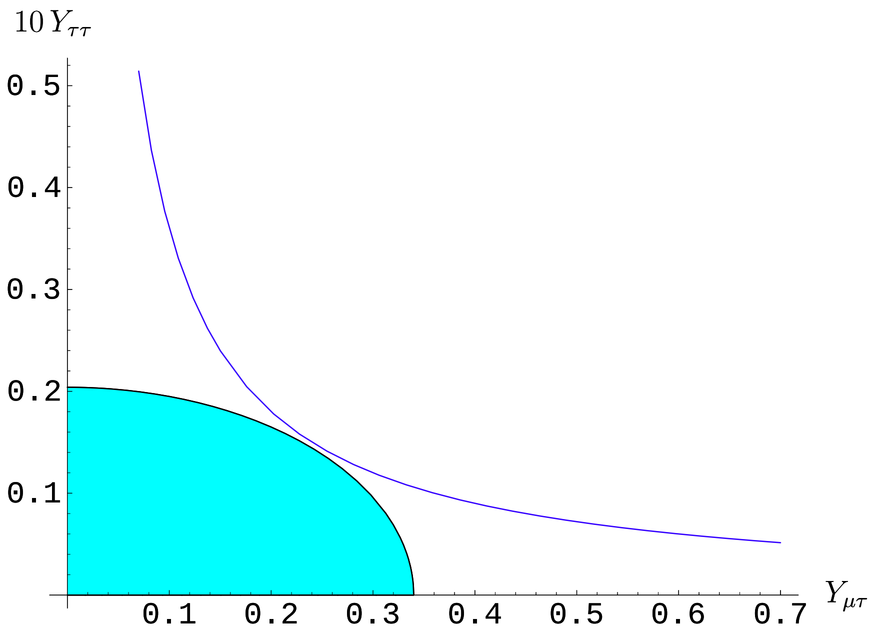
- We get six constraints from m_ν^2
- The fisrt row

$$f^2\,Y^2_{e\tau}\le1.32\times10^2\,\mathrm{eV}^2\,,\qquad f^2\,Y_{e\tau}Y_{\mu\tau}\le1\,\mathrm{eV}^2\,,\qquad f^2\,Y_{e\tau}Y_{\tau\tau}\le9.0\times10^{-2}\,\mathrm{eV}^2\,.$$

- Remaining three

$$\begin{aligned}
f^2(Y^2_{\mu\mu}+300Y^2_{\mu\tau}) &\le 2.7\,\mathrm{eV}^2\,,\\
f^2(Y_{\mu\mu}+285Y_{\tau\tau})Y_{\mu\tau} &\le 2.4\times10^{-1}\,\mathrm{eV}^2\,,\\
f^2(Y^2_{\mu\tau}+278Y^2_{\tau\tau}) &\le 2.9\times10^{-2}\,\mathrm{eV}^2\,.
\end{aligned}$$

A typical graph



for $f = 0.5$ eV

Constraints from lepton rare decays

The tree level exchanges are the most stringent

- muonium anti-muonium conversion. The effective Hamiltonian from both $P_{1,2}^{\pm\pm}$ exchange

$$H_{M\bar{M}} = \frac{Y_{ee}Y_{\mu\mu}}{2M_{--}^2}\,\bar{\mu}\gamma^\mu e_R\,\bar{\mu}\gamma_\mu e_R + h.c.\,,$$

  Always in terms of reduced mass

$$\frac{1}{M_{--}^2} = \frac{\sin^2\delta}{M_{P_1}^2} + \frac{\cos^2\delta}{M_{P_2}^2}$$

  Current limit

$$Y_{ee}Y_{\mu\mu} < 2.0\times 10^{-3}\,(M_{--}/100\,\mathrm{GeV})^2\,.$$

Rare decays II

- Effective $e^+e^- \to l^+l^-$, $l = e, \mu, \tau$, contact interactions;
  The bounds are

$$
\begin{aligned}
Y_{ee}^2 &< 1.8 \times 10^{-3}\,(M_{--}/100\,\mathrm{GeV})^2\,, \\
Y_{e\mu}^2 &< 2.4 \times 10^{-3}\,(M_{--}/100\,\mathrm{GeV})^2\,, \\
Y_{e\tau}^2 &< 2.4 \times 10^{-3}\,(M_{--}/100\,\mathrm{GeV})^2\,.
\end{aligned}
$$

- $\mu \to 3e$ and τ cousins. The BR's give

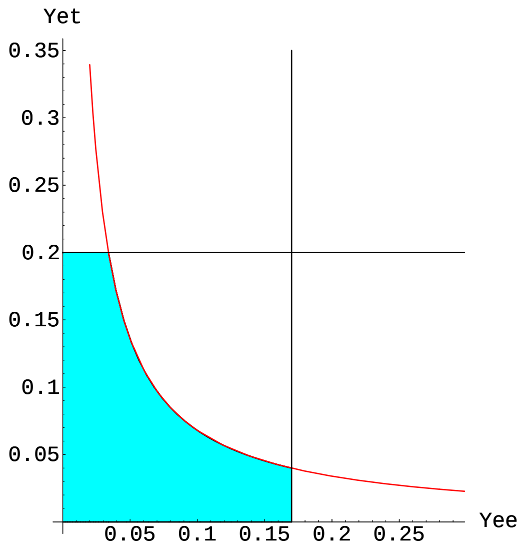
$$
\begin{aligned}
Y_{e\mu}Y_{ee} &< 6.6 \times 10^{-7}\,(M_{--}/100\,\mathrm{GeV})^2\,, \\
Y_{e\tau}Y_{ee} &< 3.0 \times 10^{-4}\,(M_{--}/100\,\mathrm{GeV})^2\,, \\
Y_{e\tau}Y_{\mu\mu} &< 3.0 \times 10^{-4}\,(M_{--}/100\,\mathrm{GeV})^2\,, \\
Y_{\mu\tau}Y_{\mu\mu} &< 2.9 \times 10^{-4}\,(M_{--}/100\,\mathrm{GeV})^2\,, \\
Y_{\mu\tau}Y_{ee} &< 2.9 \times 10^{-4}\,(M_{--}/100\,\mathrm{GeV})^2\,.
\end{aligned}
$$

Rare decays III

- Radiative decays $\mu \to e\gamma, \tau \to \mu(e)\gamma$ are less restrictive. The limits are

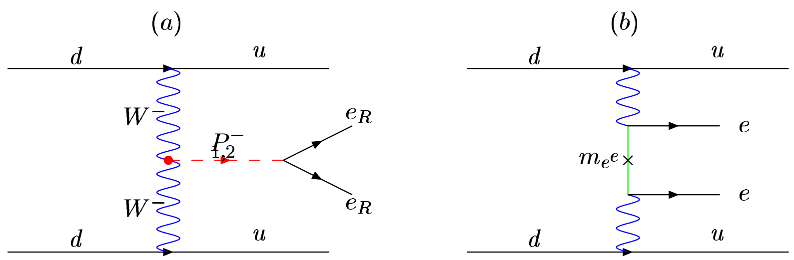
$$\begin{aligned}
Y_{e\mu}Y_{ee} &< 6.6 \times 10^{-7}\,(M_{--}/100\,\mathrm{GeV})^2\,, \\
Y_{e\tau}Y_{ee} &< 3.0 \times 10^{-4}\,(M_{--}/100\,\mathrm{GeV})^2\,, \\
Y_{e\tau}Y_{\mu\mu} &< 3.0 \times 10^{-4}\,(M_{--}/100\,\mathrm{GeV})^2\,, \\
Y_{\mu\tau}Y_{\mu\mu} &< 2.9 \times 10^{-4}\,(M_{--}/100\,\mathrm{GeV})^2\,, \\
Y_{\mu\tau}Y_{ee} &< 2.9 \times 10^{-4}\,(M_{--}/100\,\mathrm{GeV})^2\,.
\end{aligned}$$

- Example with $f = 0.5$ eV and $M_{--} = 400$ GeV. Lines from C.T and curve is $\tau \to 3e$



$0\nu\beta\beta$ *decays of nuclei*

There are two amplitudes for this process



- The amplitude due to Majorana neutrino mass

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

- From doubly charged Higgs exchange

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

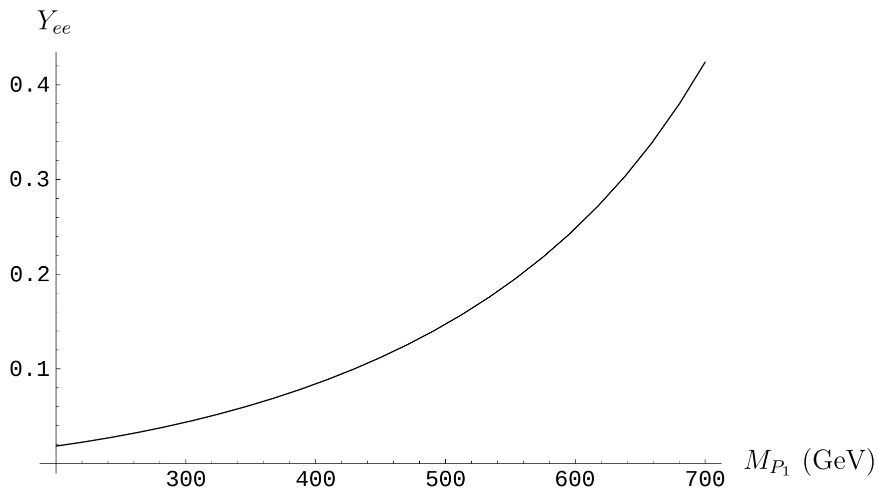
- $A_\nu / A_{P^{--}_{1,2}} \lesssim 10^{-7}$

Implication for LHC

- If $0\nu\beta\beta$ is seen it may **Not** be due to Majorana neutrino mass.

  m_{ee} is vanishingly small

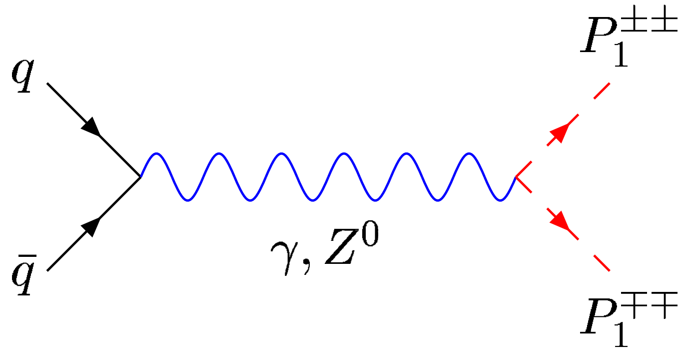
- In our model its due to doubly charged Higgs. Observation give values of Y_{ee} and M_{--}



- LHC must find at least one doubly charged Higgs or rule out the model

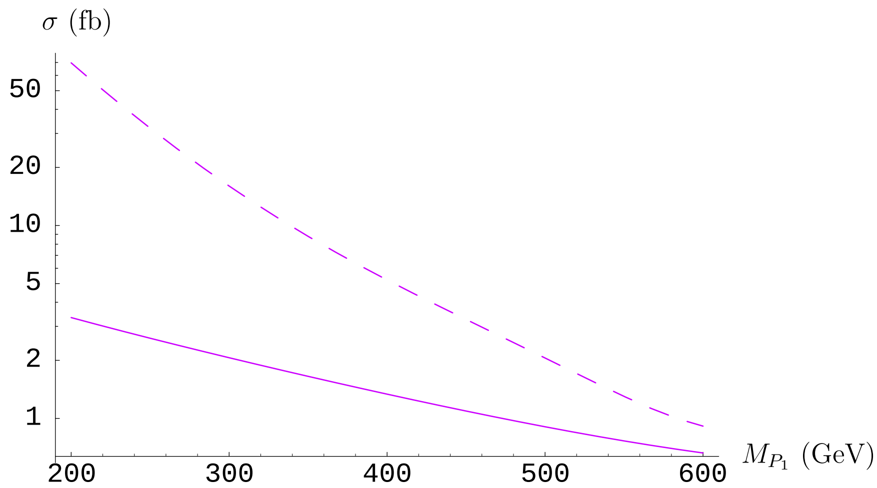
Production of $P^{\pm\pm}$ at the LHC

- Single production via WW fusion same diagram as $0\nu\beta\beta$
- Pair producion via Drell-Yan



- DY production is very robust. Must occur for all models with DCH.
- Model dependence in Z exchange. In our case only on mixing angle of the two DCH.

Production Cross section



- DY dominates over WW fusion although kinematically not as favorable
- WW fusion is suppress because amplitude :
  1. $WWP^{\pm\pm}$ coupling has $\frac{v_t}{v}$
  2. Higher order in gauge coupling g^4
- DY cross section is large enough that LHC can produce them.

Signatures at the LHC

DHC has spectacular decays if Yukawa couplings are large enough

- Two body decays

$$\begin{aligned}
(1)\ P_1^{\pm\pm} &\rightarrow l_{aR}^{\pm} l_{bR}^{\pm} \quad (a, b = e, \mu, \tau)\,, \\
(2)\ P_1^{\pm\pm} &\rightarrow W^{\pm} W^{\pm}\,, \\
(3)\ P_1^{\pm\pm} &\rightarrow P^{\pm} W^{\pm}\,, \\
(4)\ P_1^{\pm\pm} &\rightarrow P^{\pm} P^{\pm}\,,
\end{aligned} \tag{2}$$

  The last one is energetically forbidden is our model

- The same sign leptonic modes can be flavor violating $e\tau, \tau\mu, \ldots$(unmistakable)
- Helicity is always right-handed
- Doable for τ ?

DCH decays II

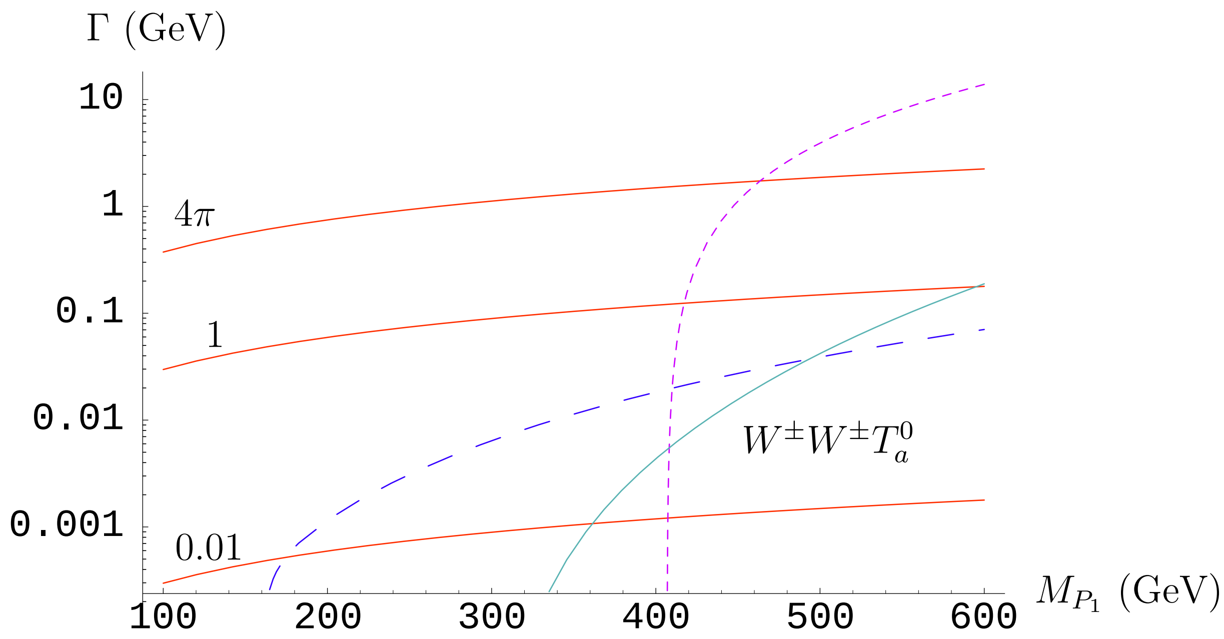
- Only 3-body decay allowed is

$$P_1^{\pm\pm} \to W^{\pm} W^{\pm} X^0 \,, \qquad X^0 = T_a^0, h^0, P^0$$

- The couplings are

$$\begin{aligned}
P_1^{\pm\pm} l_{aR}^{\mp} l_{bR}^{\mp} &\quad : \quad Y_{ab}\, s_\delta P_1^{--}\, \overline{l_{aR}^c}\, l_{bR} + h.c. \\
P_1^{\pm\pm} W_\mu^{\mp} P^{\mp} &\quad : \quad i g\, c_\delta\, W_\mu^- \left[\partial_\nu P_1^{++} P^- - P_1^{++} \partial_\nu P^- \right] + h.c. \\
P_1^{\pm\pm} W_\mu^{\mp} W_\nu^{\mp} X^0 &\quad : \quad \frac{g^2}{\sqrt{2}}\, c_\delta\, c_X\, P_1^{\pm\pm} W_\mu^{\mp} W_\nu^{\mp} X^0 + h.c.
\end{aligned}$$

Different Widths



- Long dash line $W^{\pm}W^{\pm}$.
- Short dash line $W^{\pm}P^{\pm}$
- Solid lines for leptonic modes different Yukawa couplings

Conclusions

- Small Neutrino masses can be generated as a 2-loop process useing DCH
- Agrees with all data.
- It connects origin of m_ν with physics that can be probed at LHC
- Production of DCH should be searched in its own right.
- $0\nu\beta\beta$ decay if observed does not necessary mean that it is due to Majorana neutrino masses.
- It does imply Majorana neutrinos masses at some level.
- LHC and $0\nu\beta\beta$ are strongly connected in this model