Majorana Neutrino Masses and Neutrinoless Double Beta Decays

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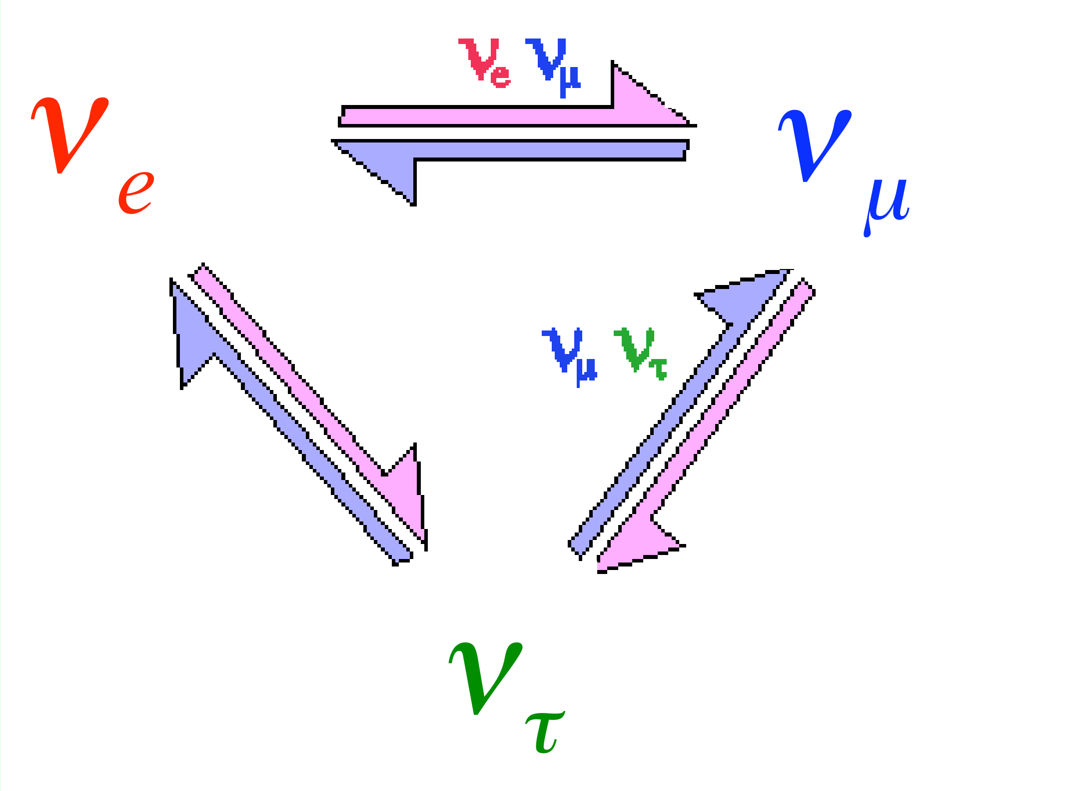
3. Summary

C.S.Chen,CQG,J.N.Ng,PRD75,053004(2007)
C.S.Chen,CQG,J.N.Ng,J.Wu,JHEP0708,22(2007)
C.S.Chen,CQG,D.V.Zhuridov,arXiv:0801.2011[hep-ph]

1. Introduction:

Neutrino Oscillations:

SNO, Super-Kamiokande, KamLAND ...



☞ **This is only possible if neutrinos have masses and mix with each other.**

⇨ ***New Physics beyond the standard model (BSM)***

Experiments on solar neutrinos

$$7.1 \times 10^{-5} < \Delta m^2_{\odot} < 8.9 \times 10^{-5}\,(\mathrm{eV}^2) \quad \longleftarrow \quad |\, m^2_{\nu_1} - m^2_{\nu_2} \,|$$

Neutrinos born in Cosmic ray collisions and on earth

$$1.4 \times 10^{-3} < |\Delta m^2_{atm}| < 3.3 \times 10^{-3}\,(\mathrm{eV}^2) \quad \longleftarrow \quad |\, m^2_{\nu_2} - m^2_{\nu_3} \,|$$

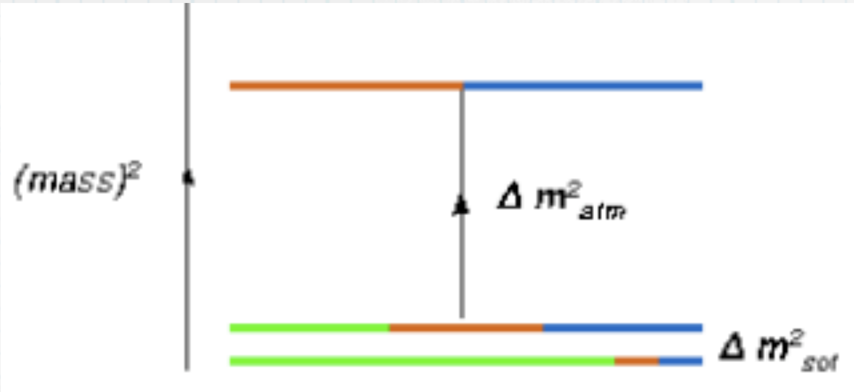
The best bound to their absolute values of the masses comes from the WMAP

$$\sum_i m_{\nu_i} < .71 \text{ eV} \quad \longrightarrow \quad 0.63 \text{ eV} \quad (\text{WMAP-5})$$

Normal hierarchy

$$|m_{\nu_1}| < |m_{\nu_2}| \ll |m_{\nu_3}|$$

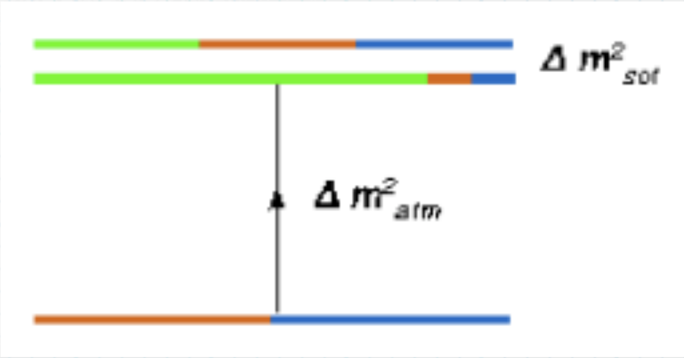
$$m_1 \simeq 0,\ m_2^2 \simeq \Delta m^2_{\odot},\ \text{and}\ m_3^2 \simeq \Delta m^2_{atm}.$$



Inverse hierarchy

$$|m_{\nu_1}| \simeq |m_{\nu_2}| \gg |m_{\nu_3}|$$

$$m_1^2 \simeq m_2^2 \simeq \Delta m^2_{atm} \gg m_3^2$$



$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

In terms of the PMNS mixing matrix

$$V_{PMNS} = \begin{bmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{bmatrix}$$

The various experiments yield

$$0.164 < \sin^2\theta_{12} < 0.494\,,$$
$$0.22 < \sin^2\theta_{23} < 0.85\,,$$
$$\sin^2 2\theta_{13} = 0 \pm 0.04\,.$$

Bimaximal Matrix

$$\begin{pmatrix} \frac{\sqrt{2}}{2} & \frac{\sqrt{2}}{2} & 0 \\ -\frac{1}{2} & \frac{1}{2} & \frac{\sqrt{2}}{2} \\ \frac{1}{2} & -\frac{1}{2} & \frac{\sqrt{2}}{2} \end{pmatrix}$$

Tribimaximal Matrix

$$\begin{pmatrix} \frac{\sqrt{6}}{3} & \frac{\sqrt{3}}{3} & 0 \\ -\frac{\sqrt{6}}{6} & \frac{\sqrt{3}}{3} & \frac{\sqrt{2}}{2} \\ \frac{\sqrt{6}}{6} & -\frac{\sqrt{3}}{3} & \frac{\sqrt{2}}{2} \end{pmatrix}$$

Neutrino oscillations measure m^2 but they do not provide information about the absolute neutrino spectrum and cannot distinguish between pure Dirac and Majorana neutrinos.

What is a Dirac neutrino or Majorana neutrino?

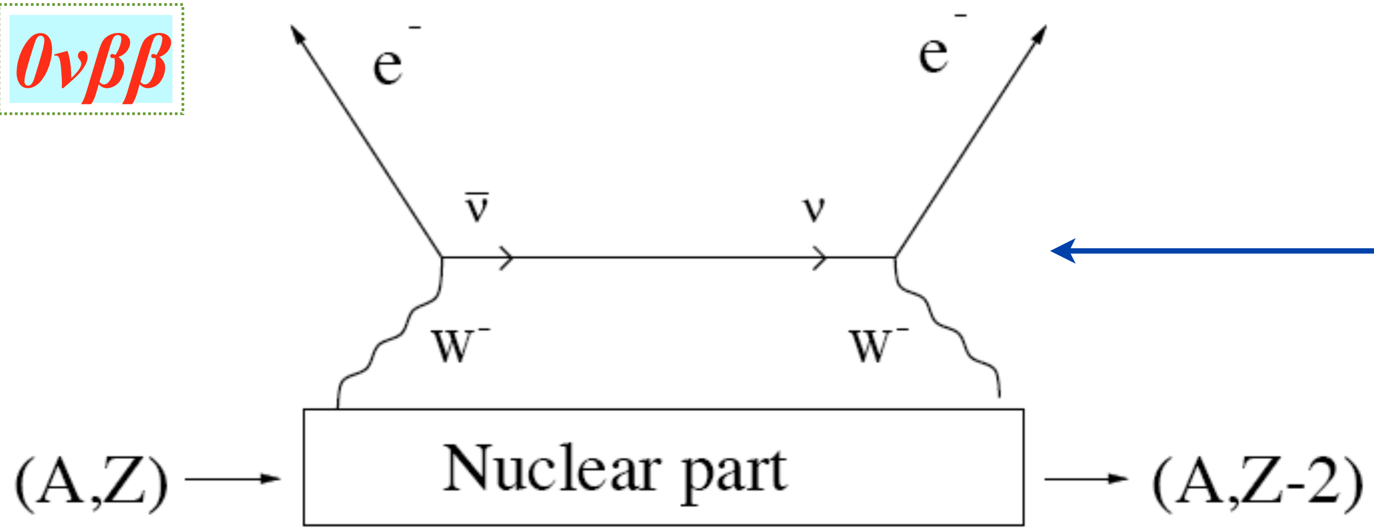
Dirac neutrino mass: $\mathcal{L}_D = -m_D \overline{\nu_L} \nu_R + \text{h.c.}$

☞ the lepton number L is conserved

Majorana neutrino mass: $\mathcal{L}_M = -m_M \overline{\nu_R^c} \nu_R + \text{h.c.}$

☞ $\nu \leftrightarrow \bar{\nu}$ Thus, it clearly does not conserve L

0νββ



Forbidden in the SM.

Fig. 4. Massive Majorana neutrino exchange mechanism describing the neutrinoless double β decay. The antineutrino $\bar{\nu}$ emitted in one vertex must be absorbed as a neutrino ν in other. Such a scenario is possible only if the neutrino is massive (then there is a chance that the emitted antineutrino has negative helicity $\bar{\nu}$ and must be a Majorana particle (then $\bar{\nu} = \nu$).

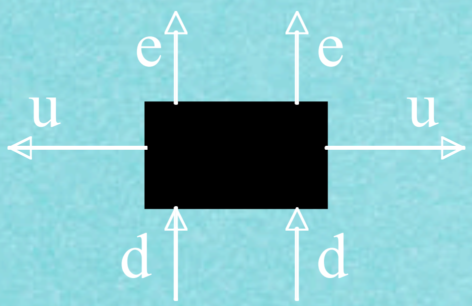
The present limit is given by [H.V.Klapdor-Kleingrothaus]

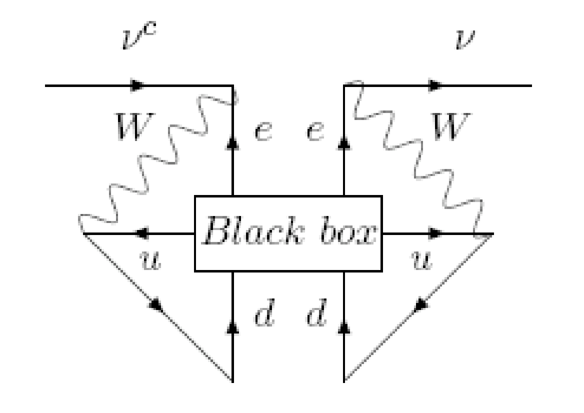
$$|\langle m_\nu \rangle| \equiv \left| \sum U_{ei}^2 m_i \right| < 0.2 \text{ eV}$$

“Black Box” theorem

J. Schechter and J.W.F. Valle, Phys.Rev. D 25, 2951 (1982)

Any mechanism inducing the 0νββ decay produces an effective Majorana neutrino mass term, which must therefore contribute to this decay.





?

the 0νββ decay ⟷ **Majorana neutrino mass**

Note that (1) the theorem does not state which mechanism of 0νββ decay is the dominant one and (2) in some SUSY models with ~~R-parity~~, 0νββ decay can be generated without ν_M :

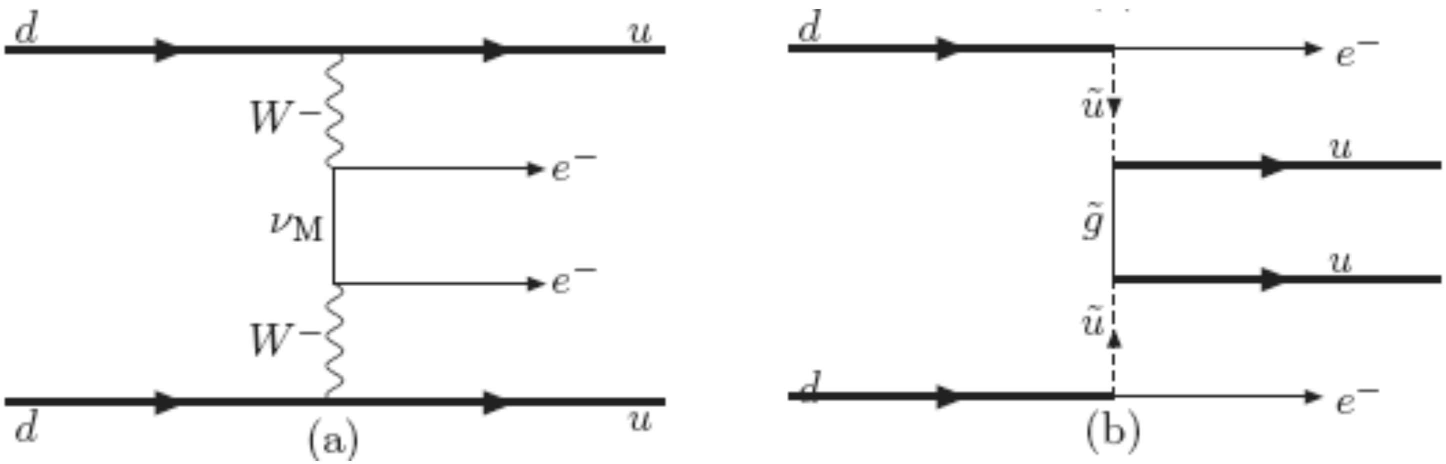


FIG. 1: *a) 0νββ-decay through the exchange of a light Majorana neutrino. b) 0νββ-decay through the exchange of heavy particles, in this case two squarks and a gluino in RPV SUSY.*

- SUSY
- Higgs triplets
- Right–handed interactions
- Majorons

• If the 0νββ decay is observed, how can we tell (a) which mechanism is responsible and (b) what value of mν is?

☺ Three important questions:

1. What are the masses of the neutrino mass eigenstates (ν_i)?

2. Are the neutrino mass eigenstates Dirac or Majorana particles?

3. If $0\nu\beta\beta$ is observed, is ν a Majorana particle?

In the SM:

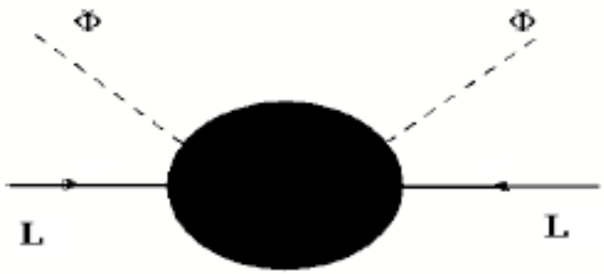
	$SU(3) \otimes SU(2) \otimes U(1)$
$L_a = (\nu_a, l_a)^T$	$(1, 2, -1)$
e^c_a	$(1, 1, 2)$
$Q_a = (u_a, d_a)^T$	$(3, 2, 1/3)$
u^c_a	$(\bar{3}, 1, -4/3)$
d^c_a	$(\bar{3}, 1, 2/3)$
Φ	$(1, 2, 1)$

Table 1: Matter and scalar multiplets of the Standard Model (SM)

- No Dirac mass term (no right-handed neutrino).
- No Majorana mass term either (ν_L is an SU(2) doublet).

In the SM:

S. Weinberg, Phys. Rev. D22, 1694 (1980).



Dimension five operator responsible for neutrino mass

Effective Dim-5 operator:

$$O=(\lambda_0/M_X)L\Phi L\Phi$$

↓ ***SSB***

$$m_\nu = \lambda_0 \frac{\langle\Phi\rangle^2}{M_X}, \quad \text{(Majorana)}$$

For $\lambda_0 \sim 1$, $<\Phi>\sim 100$ GeV, $M_X \sim M_P$ → $m_\nu \sim 10^{-6}$ eV (too small)

BSM: **(a) If the right handed neutrinos ν_R exist:**

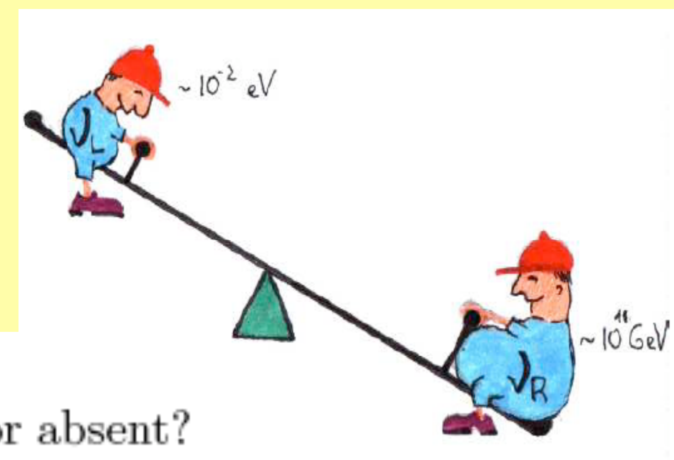
$$\mathcal{L}_Y = Y_\nu \bar{L}\Phi\nu_R + h.c. \quad \Rightarrow \quad m_\nu^D = Y_\nu < \Phi >$$

The observed neutrino masses would require $Y_\nu \leq 10^{-13} - 10^{-12}$ (unnatural)

(b) Majorana mass for ν_R: $M_R \nu_R^T C^{-1} \nu_R + h.c.$

See-saw mechanism: $\mathcal{M}_\nu = -m_D^T M_R^{-1} m_D.$

(naturally small+Majorana)

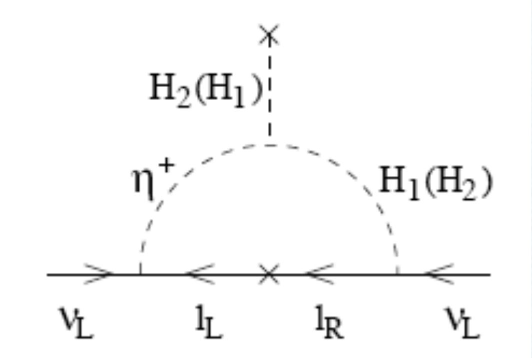


- Where are the RH neutrinos, ν_R?
- If ν_R exist, why the Dirac mass terms effects are small or absent?

Many other possible mechanisms for m_ν without introducing ν_R:

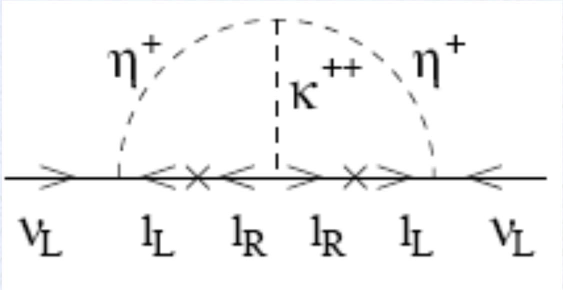
- **Model with scalar triplet:** $\mathcal{L}_T = -g\bar{L}_L T L_L^c + h.c. \Rightarrow m_{\nu L} = g < T >$

- **Zee model (with charged scalar singlet and additional scalar doublets) Majorana neutrino masses arise at one loop level.**



$$l^T \hat{f} i\sigma_2 l \eta^+ + \sum_{i=1,2} \bar{l} \hat{f}_i e H_i$$

- **Babu-Zee model (with doubly charged scalar singlet) Majorana neutrino masses arise at two loop level.**



$$l^T \hat{f} l \eta^+ + l_R^T \hat{h} l_R k^{++}$$

- **Other models ...**

No 0νββ decays in Zee and Babu-Zee models

2. A new model with radiative neutrino mass generation:

C.S.Chen+CQG+J.Ng, PRD75,053004(07); Chen+CQG+Ng+Wu, JHEP0708,22(07).

	$SU(3)_C \otimes SU(2)_L \otimes U(1)_Y$
$L_a = (\nu_a, l_a)^T_L$	$(1, 2, -1)$
e^c_{aL}	$(1, 1, 2)$
$Q_a = (u_a, d_a)^T_L$	$(3, 2, 1/3)$
u^c_{aL}	$(\bar{3}, 1, -4/3)$
d^c_{aL}	$(\bar{3}, 1, 2/3)$
Φ	$(1, 2, 1)$

Table 1: Matter and scalar multiplets of the Standard Model (SM)

No ν_R added

New scalars: a triplet T (1,3,2) + a singlet Ψ (1,1,4)

$$V(\phi, T, \psi) = -\mu^2\phi^\dagger\phi + \lambda_\phi(\phi^\dagger\phi)^2 - \mu_T^2 \mathrm{Tr}(T^\dagger T) + \lambda_T[\mathrm{Tr}(T^\dagger T)]^2 + \lambda'_T \mathrm{Tr}(T^\dagger T T^\dagger T) + m^2\Psi^\dagger\Psi + \lambda_\Psi(\Psi^\dagger\Psi)^2$$
$$+ \kappa_1 \mathrm{Tr}(\phi^\dagger\phi T^\dagger T) + \kappa_2\phi^\dagger T T^\dagger\phi + \kappa_\Psi\phi^\dagger\phi\Psi^\dagger\Psi + \rho\,\mathrm{Tr}(T^\dagger T\Psi^\dagger\Psi)$$
$$+ [\lambda(\phi^T T\phi\Psi^\dagger) - M(\phi^T T^\dagger\phi) + \mathrm{H.c.}],$$

New Yukawa term: $Y_{ab}\bar{l}^c_{aR} l_{bR}\Psi$ ← lepton # for Ψ is 2

No Yukawa coupling for the triplet: ~~LLT~~

Highly suppressed or forbidden by some symmetry*

*For example: two Higgs doublets (Φ_1 and Φ_2) with Z_2 discrete symmetry or T-parity

T-parity: $\Phi_1 \rightarrow - \Phi_1$; $\Phi_2 \rightarrow \Phi_2$; $T \rightarrow -T$; $L \rightarrow -L$

~~*LLT*~~

No effects for other couplings.

Constraints on the model:

VEVs: $\langle \phi^0 \rangle \equiv \frac{v}{\sqrt{2}}$ and $\langle T^0 \rangle \equiv \frac{v_T}{\sqrt{2}}$.

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

$$\rho = 1.0002^{+0.0007}_{-0.0004} \quad \Rightarrow \quad v_T < 4.41\ \mathrm{GeV}$$

Two doubly charged scalars:

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

Mass eigenstates:

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

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

$$M_{P_{1,2}}^2 = \frac{1}{2}\left[a + c \mp \sqrt{4b^2 + (c-a)^2}\right]$$

$$\omega \equiv \frac{M}{\sqrt{2}v_T}$$

$$a = \frac{1}{2}(2\omega - \kappa_2)v^2 - \lambda_T' v_T^2\,, \qquad b = \frac{1}{2}\lambda v^2\,, \qquad c = m^2 + \frac{1}{2}(\kappa_\Psi v^2 + \rho v_T^2)\,.$$

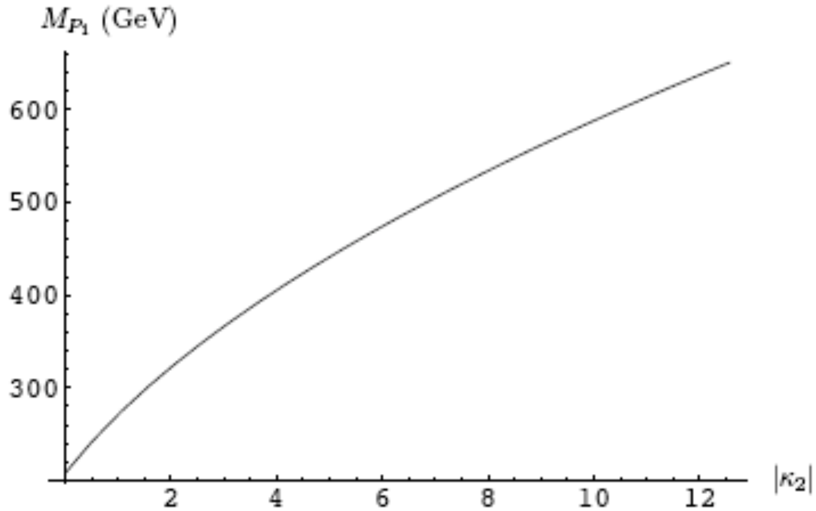


Figure 1: Maximum value of M_{P_1} for $v_T = M = 4\,\text{GeV}$, and $|\lambda'_T|$ set to 4π.

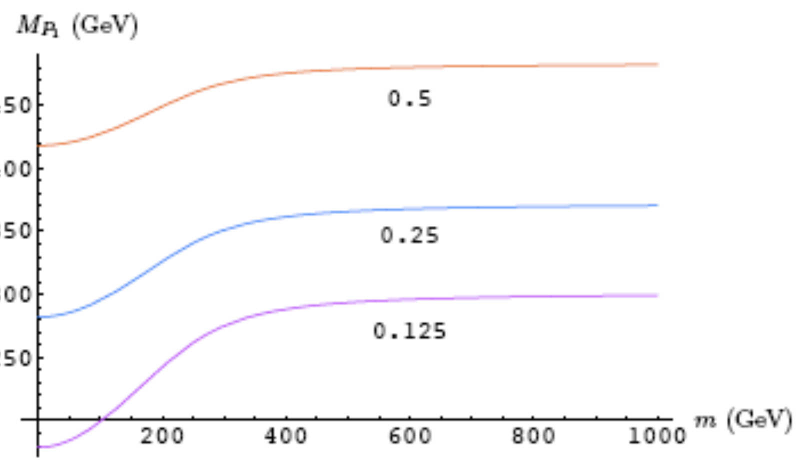
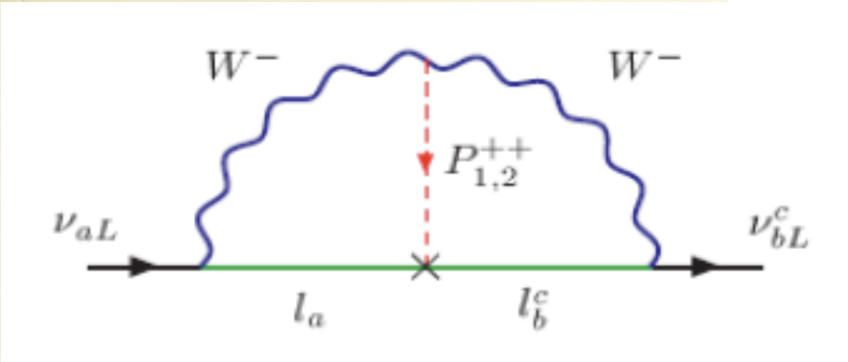


Figure 2: M_{P_1} as a function of m for $|\kappa_2| = 0.5, 0.25, 0.125$ in units of 4π, with $v_T = M = 4\,\text{GeV}$ and $\lambda = -\lambda'_T = 1$.

The P_1 state is well within the reach of the LHC;
P_2 will be too heavy to be of interest to the LHC.

(i) Neutrino masses:

The neutrino masses are generated radiatively at two-loop level



$a, b = e, \mu, \tau.$

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

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

$M_{P_{1,2}} > M_W$

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

$$m_\nu = \tilde{f}(M_{P_1}, M_{P_2}) \times \begin{pmatrix} m_e^2 Y_{ee} & m_e m_\mu Y_{e\mu} & m_e m_\tau Y_{e\tau} \\ m_e m_\mu Y_{e\mu} & m_\mu^2 Y_{\mu\mu} & m_\tau m_\mu Y_{\mu\tau} \\ m_e m_\tau Y_{e\tau} & m_\tau m_\mu Y_{\mu\tau} & m_\tau^2 Y_{\tau\tau} \end{pmatrix}$$

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

normal hierarchy:

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

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

$f = \tilde{f} \times (1\mathrm{GeV}^2)$

$Y_{ee} < 0.17,\quad Y_{e\mu} < 0.2,\quad Y_{e\tau} < 0.2$

$Y_{\mu\mu} < 3.5,\quad Y_{\mu\tau} < 0.2,\quad Y_{\tau\tau} < 0.02$

(ii) 0νββ decays:

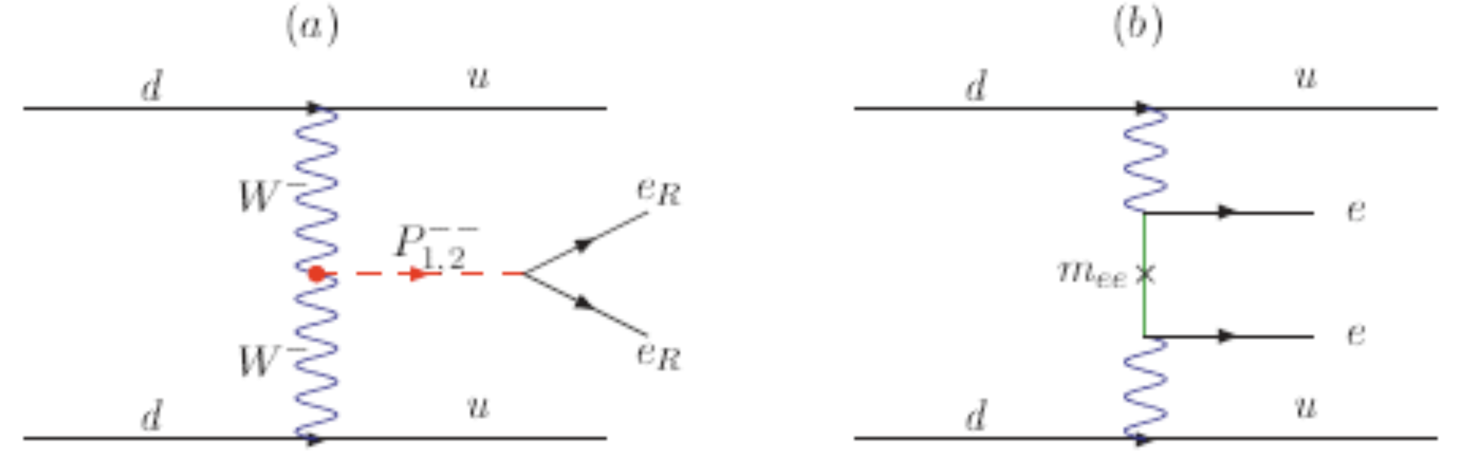


Figure 9: $0\nu\beta\beta$ decays via exchange of: (a) doubly charged Higgs and (b) light Majorana neutrinos.

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

››

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

$<p> \sim 0.1$ GeV

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

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 electron mass factor $(m_e/M_W)^2$ coming from the doubly charged scalar coupling.

No **Black box** theorem, 0νββ is from P^{--} tree diagram without ν_M.

(iii) Other phenomenology:

Doubly Charged Scalars

a. Lepton flavor physics:

1. *Muonium anti-muonium conversion* $\mu^+ e^- - \mu^- e^+$

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

experimental limit →

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

$$M \equiv \mu^+ e^-$$

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

2. *Effective* $e^+e^- \to l^+l^-$, $l = e, \mu, \tau$, *contact interactions*

Bhabha scattering

$$\frac{Y_{ee}^2}{M_{--}^2} \bar{e}_R \gamma^\mu e_R \bar{e}_R \gamma_\mu e_R$$

⇒

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

3. *Rare* $\mu \to 3e$ *decays and its* τ *counterparts*

$$Br(\mu \to 3e)_{expt} < 1.0 \times 10^{-12}\,,$$
$$Br(\tau \to 3e)_{expt} < 2.0 \times 10^{-7}\,,$$
$$Br(\tau \to e\mu\mu)_{expt} < 2.0 \times 10^{-7}\,,$$
$$Br(\tau \to 3\mu)_{expt} < 1.9 \times 10^{-7}\,,$$
$$Br(\tau \to \mu ee)_{expt} < 1.9 \times 10^{-7}\,.$$

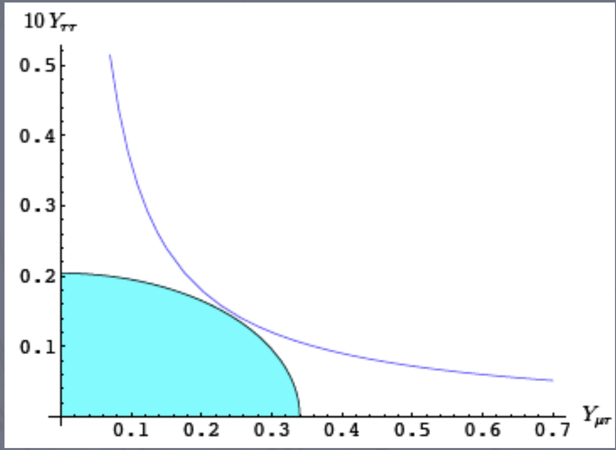
→

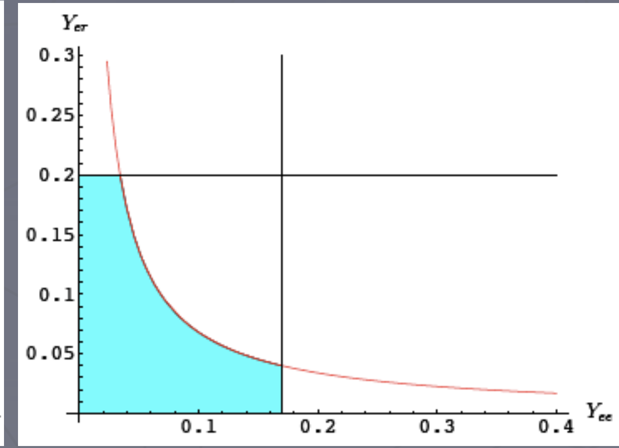
$$Y_{e\mu} Y_{ee} < 6.6 \times 10^{-11}\,(M_{--}/100\,GeV)^2\,,$$
$$Y_{e\tau} Y_{ee} < 3.0 \times 10^{-8}\,(M_{--}/100\,GeV)^2\,,$$
$$Y_{e\tau} Y_{\mu\mu} < 3.0 \times 10^{-8}\,(M_{--}/100\,GeV)^2\,,$$
$$Y_{\tau\mu} Y_{\mu\mu} < 2.9 \times 10^{-8}\,(M_{--}/100\,GeV)^2\,,$$
$$Y_{\tau\mu} Y_{ee} < 2.9 \times 10^{-8}\,(M_{--}/100\,GeV)^2\,.$$

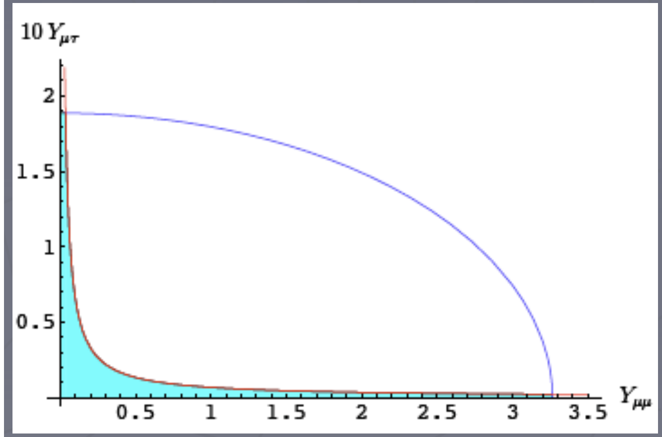
4. *Radiative flavor violating charged leptonic decays* $\mu \to e\gamma$ and $\tau \to \mu(e)\gamma$.

$$Br(\mu \to e\gamma) = \frac{\alpha}{3\pi G_F^2} \sum_{l=e,\mu,\tau} \left(\frac{Y_{l\mu} Y_{le}}{M_{--}^2}\right)^2$$

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







In summary, we have from contact interactions the upper limits

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

and from neutrino data

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

b. Doubly charged Higgs at the LHC:

1 Production of the doubly charged Higgs

- **There are no direct couplings between P^{++} and quarks.**

The WW fusion processes similar to $0\nu\beta\beta$ decays

+

the Drell-Yan annihilation processes:

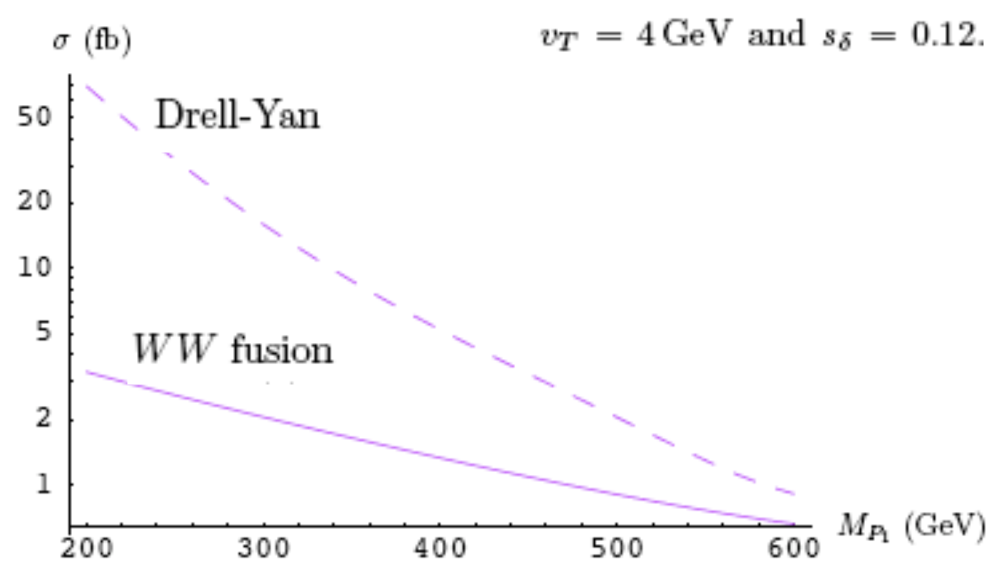
$$q\bar{q} \to \gamma^*, Z^* \to P_1^{++} P_1^{--} \quad (q = u, d)$$

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

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

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

C.S.Chen+CQG+J.Ng+ J.Wu, JHEP0708, 22 (07)



2 The decay of $P_1^{\pm\pm}$

(1) $P_1^{\pm\pm} \to l_{aR}^{\pm} l_{bR}^{\pm} \quad (a, b = e, \mu, \tau)$,

(2) $P_1^{\pm\pm} \to W^{\pm} W^{\pm}$,

(3) $P_1^{\pm\pm} \to P^{\pm} W^{\pm}$,

(4) $P_1^{\pm\pm} \to P^{\pm} P^{\pm}$,

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

(6) $P_1^{\pm\pm} \to P^{\pm} P^{\pm} X^0$.

$P_1^{\pm\pm} l_{aR}^{\mp} l_{bR}^{\mp} : Y_{ab}\, s_\delta P_1^{--}\, \overline{l_{aR}^c}\, l_{bR} + h.c.$

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

$P_1^{\pm\pm} W_\mu^{\mp} P^{\mp} : ig\, c_\delta\, W_\mu^{-} \left[\partial_\nu P_1^{++} P^{-} - P_1^{++} \partial_\nu P^{-}\right] + h.c.$

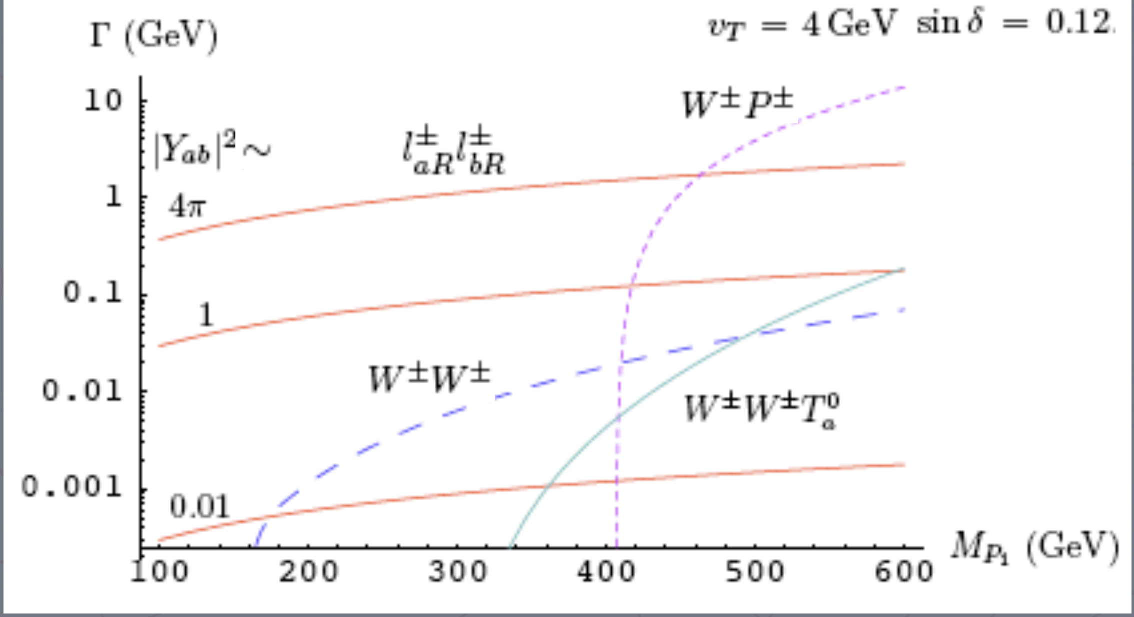
$P_1^{\pm\pm} W_\mu^{\mp} W_\nu^{\mp} X^0 : \frac{g^2}{\sqrt{2}} c_\delta\, c_X\, P_1^{\pm\pm} W_\mu^{\mp} W_\nu^{\mp} X^0 + h.c.$

(4) and (6) are not allowed in our model

$$\Gamma(l_{aR}^{\pm} l_{bR}^{\pm}) = (1 + \delta_{ab}) \frac{|Y_{ab}|^2}{16\pi} s_\delta^2\, M_{P_1}$$

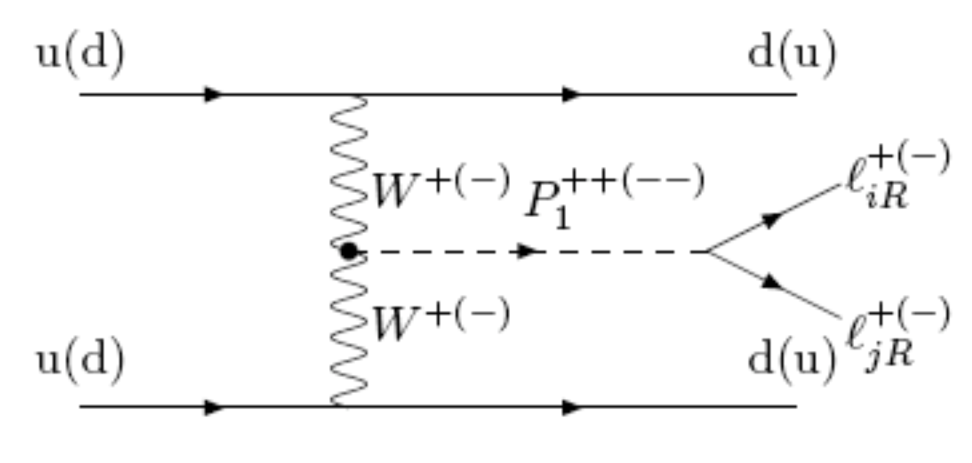
$$\Gamma(W^{\pm}W^{\pm}) = \frac{g^4 v_T^2 c_\delta^2}{16\pi M_{P_1}} \sqrt{1 - \frac{4M_W^2}{M_{P_1}^2}} \left(3 - \frac{M_{P_1}^2}{M_W^2} + \frac{M_{P_1}^4}{4M_W^4}\right)$$

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



3 Same-sign single dilepton signatures: $pp \to \ell_i^\pm \ell_j^\pm \underline{X}$ ← JJ

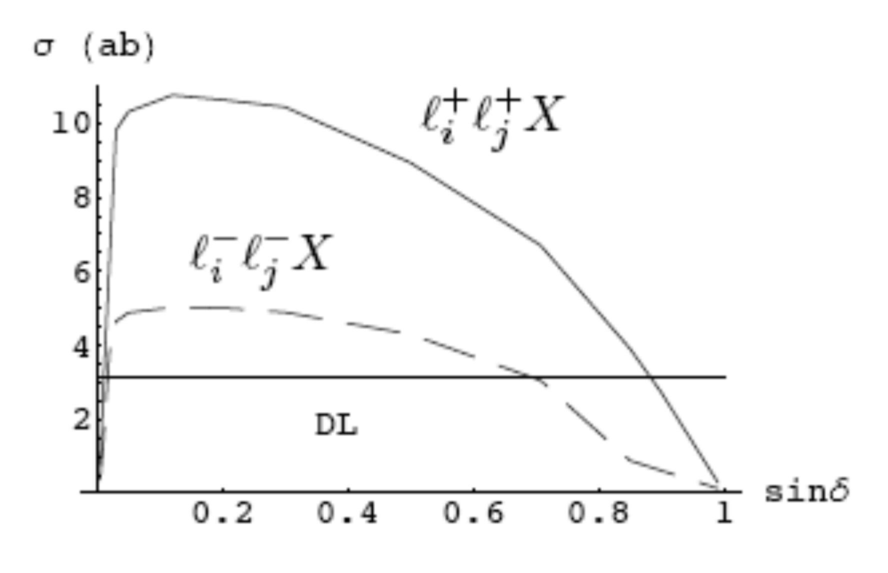
C.S.Chen,CQG,D.V.Zhuridov,
arXiv:0801.2011 [hep-ph]

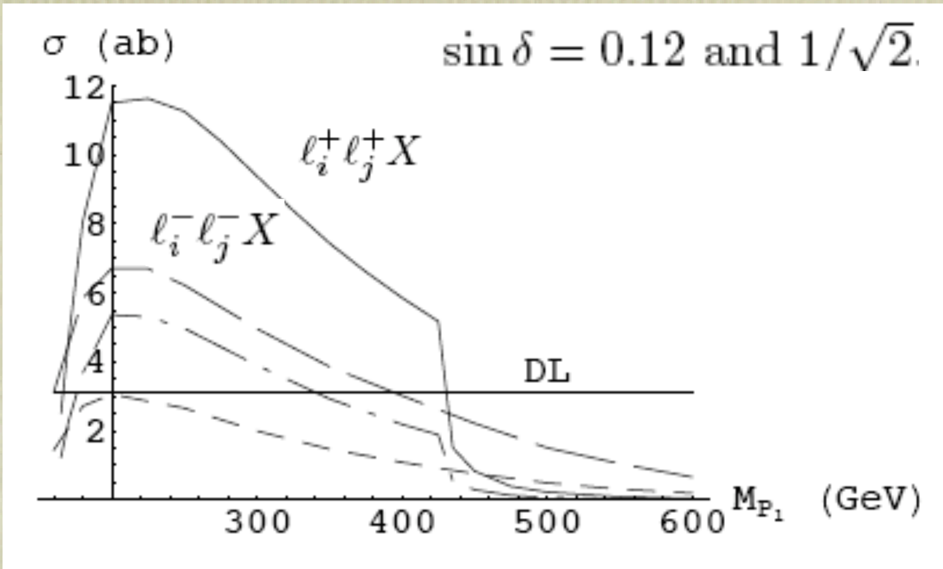


$$\frac{d\sigma_\pm^{pp}}{d\cos\theta} = A\left(\lambda_1^{ij}\right)^2 H_\pm^{pp}$$

$$A = \frac{G_F^4 M_W^6}{2^7\pi^5} = 50\ \text{ab},\ \lambda_1^{ij} = \sqrt{2-\delta_{ij}}\,|Y_{ij}|\,c_\delta s_\delta,$$

$$H_\pm^{pp} = \left(\frac{v_T}{M_W}\right)^2 \int_{z_0}^1 \frac{dz}{z}\int_z^1 \frac{dy}{y}\int_y^1 \frac{dx}{x} p_\pm(x, xs)\, p_\pm\left(\frac{y}{x}, \frac{y}{x}s\right) l\left(\frac{z}{y}\right) h\left(\frac{s}{M_{P_1}^2} z\right)$$





DL: $\sigma L \geq n$ ← n events of the observation criteria

LHC: $\sqrt{s}$=14 TeV and L=320 fb^{-1}

Remarks:

(a) In our model, the final state charged leptons are right-handed. Hence in principle, helicity measurements can be used to distinguish between our model and those whose doubly charged Higgs coupling only to left-handed leptons.

(b) $P_1^{\pm\pm}$ will directly produce spectacular lepton # violating signals from like-sign dileptons such as eμ, eτ and μτ.

3. Summary:

♥ A new neutrino mass generation model is proposed with an SU(2) triplet and a doubly charged SU(2) singlet.

♠ Majorana neutrino masses are generated radiatively at two-loop level with a normal neutrino mass hierachy.

♦ The neutrinoless double beta ($0\nu\beta\beta$) decays predominantly arise from exchange processes involving the doubly charged Higgs, *whereas the long range contributions due to Majorana neutrinos are negligible.*

The **Black box** theorem is irrelevant here, i.e., $0\nu\beta\beta$ decays are not originated from the Majorana neutrino mass term.

♥ Rich physics for lepton flavor processes and unique signatures at the LHC due to the doubly charged Higgs.

☞ Future data on $0\nu\beta\beta$ decays and the LHC searches would distinguish our model from other neutrino models.

Thank you!

謝謝！

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