Majorana Neutrinos
&
TeV Phenomenology

Chao-Qiang Geng
耿朝強
清華大學（台灣新竹）

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Outline

- Introduction
- Models with Majorana neutrinos
- TeV Phenomenology: (i) ν mass generations, (ii) $0\nu\beta\beta$ decays, and (iii) other physics
- Summary

Introduction

Experiments on solar neutrinos

$$\Delta m^2_{21} = 7.59^{+0.20}_{-0.18} \times 10^{-5}\ \mathrm{eV}^2$$

$$\Delta m^2_{sun} = |m_2|^2 - |m_1|^2 > 0$$

Neutrinos born in Cosmic ray collisions and on earth

$$|\Delta m^2_{31}| = \begin{cases} 2.45 \pm 0.09 \times 10^{-3}\ \mathrm{eV}^2 & \text{normal hierarchy,} \\ 2.34^{+0.10}_{-0.09} \times 10^{-3}\ \mathrm{eV}^2 & \text{inverted hierarchy,} \end{cases}$$

$$\Delta m^2_{atm} = |\Delta m^2_{31}|$$

$$\Delta m^2_{31} = |m_3|^2 - |m_1|^2$$

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

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

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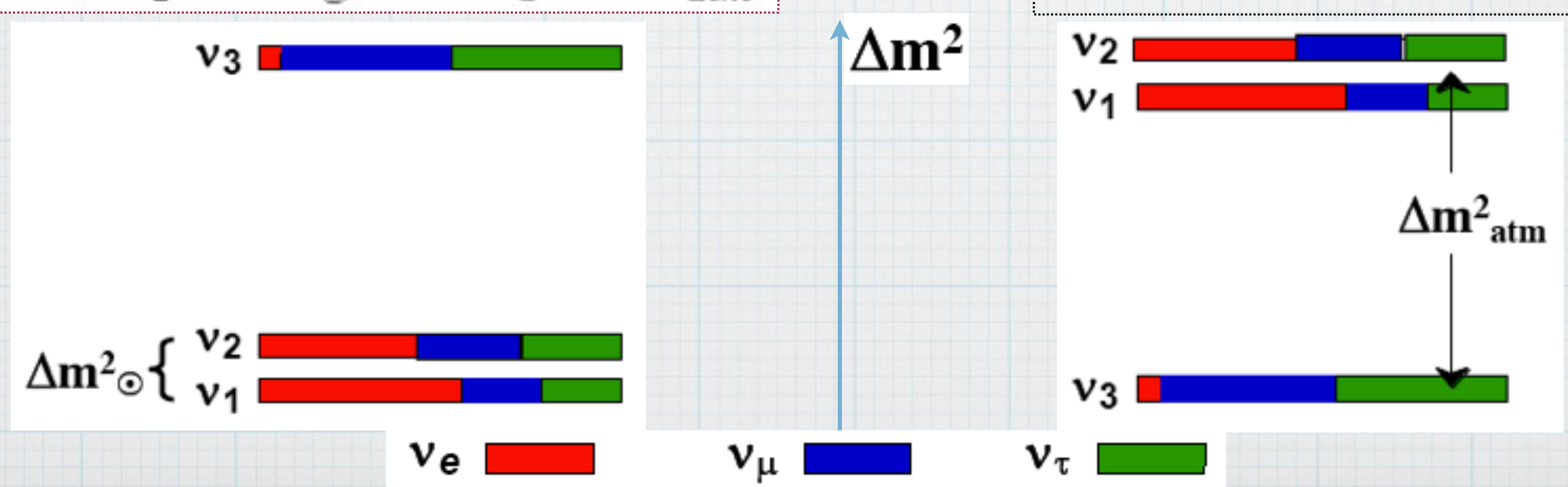

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The Troitzk and Mainz ^{3}H β-decay experiments

$m_{\nu_e} < 2.3$ eV (95% C.L.)

KATRIN → **0.2 eV**

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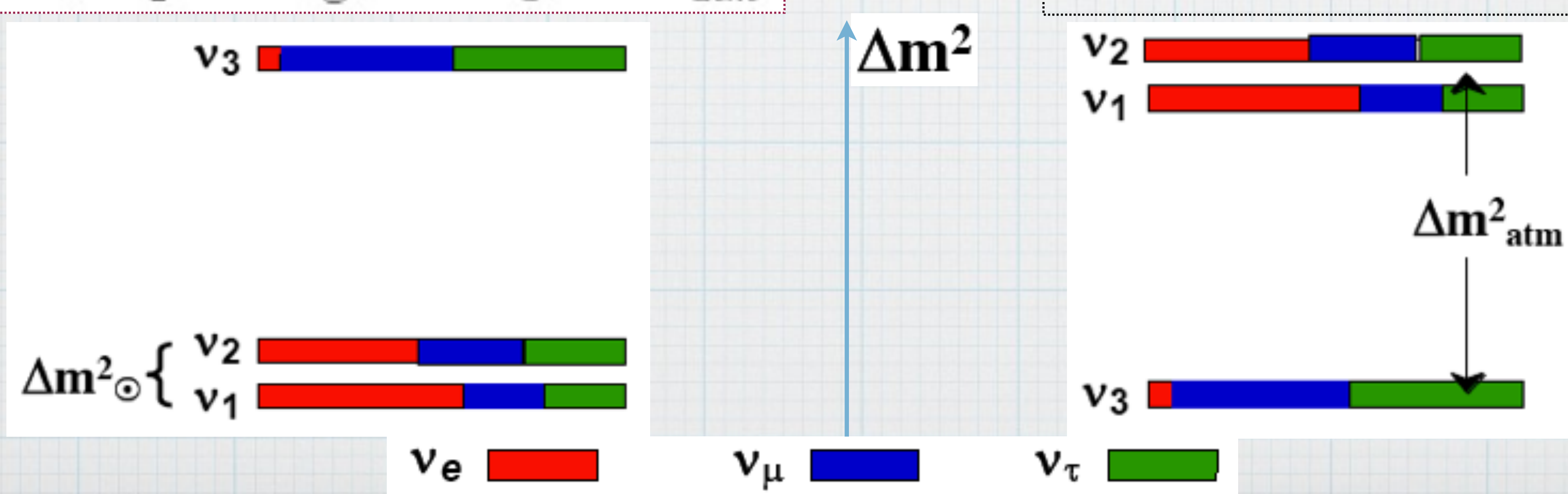

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The Troitzk and Mainz ^{3}H β-decay experiments $m_{\nu_e} < 2.3$ eV (95% C.L.) → KATRIN 0.2 eV

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

$$\sum_i m_{\nu_i} < 0.25\ \mathrm{eV}\quad 95\%\mathrm{CL}\ (\text{Planck+other data})$$

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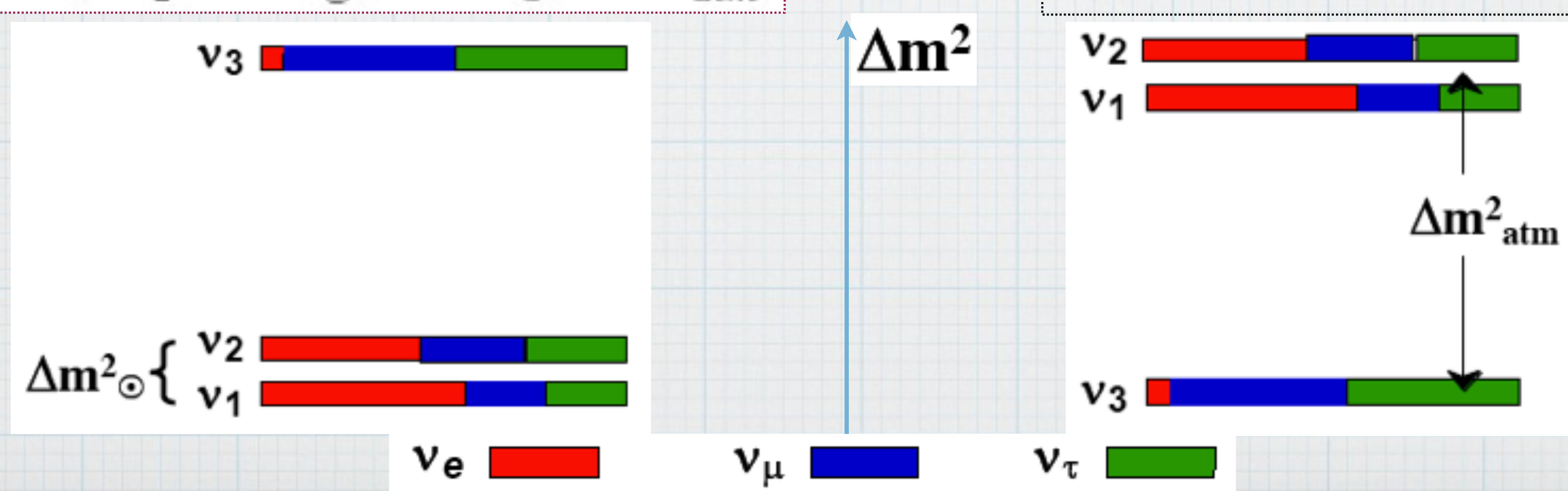

$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = \begin{pmatrix}U_{e1} & U_{e2} & U_{e3}\\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3}\\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3}\end{pmatrix}\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$

In terms of the PMNS mixing matrix

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

A global fit yields

$$\sin^2\theta_{12} = 3.07^{+0.18}_{-0.16}\times 10^{-1}\,,(16\%) \qquad \sin^2\theta_{23} = 3.86^{+0.24}_{-0.21}\times 10^{-1}\,,(21\%)$$
$$\sin^2\theta_{13} = 2.41\pm 0.25\times 10^{-2}\,,(10\%) \qquad \delta/\pi = 1.08^{+0.28}_{-0.31}\,\mathrm{rad}\,,$$

BF

$\theta_{12}\approx 33.7^o$
$\theta_{23}\approx 38.4^o$
$\theta_{13}\approx 8.93^o$
$\delta\approx\pi$

Bimaximal Matrix

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

$\theta_{12}=45^o$, $\theta_{23}=45^o$, $\theta_{13}=0$

Tribimaximal Matrix

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

Daya-Bay

$\theta_{12}=35.3^o$, $\theta_{23}=45^o$, $\theta_{13}=0$

$$|U_{\mathrm{PMNS}}| \sim \begin{pmatrix}0.8 & 0.5 & 0.2\\ 0.4 & 0.6 & 0.7\\ 0.4 & 0.6 & 0.7\end{pmatrix}$$

$$|V_{\mathrm{CKM}}| \sim \begin{pmatrix}1 & 0.2 & 0.004\\ 0.2 & 1 & 0.04\\ 0.008 & 0.04 & 1\end{pmatrix}$$

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

Origin of the neutrino masses: Dirac or Majorana?

Dirac neutrino mass:

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

Majorana neutrino mass:

$$\mathcal{L}_M = -m_M \overline{\nu^c} \nu \quad + \text{h.c.}$$

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☺the lepton number L is conserved

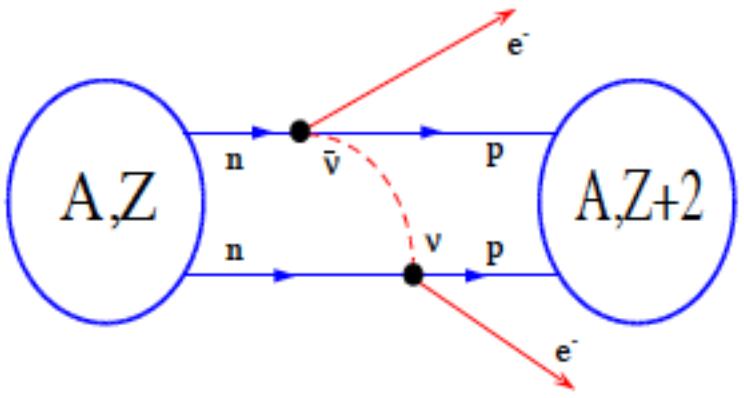
Majorana neutrino mass:

$$\mathcal{L}_M = -m_M \overline{\nu^c} \nu \quad + \text{h.c.}$$

$\nu \leftrightarrow \bar{\nu}$

• the lepton number L is violated

Nuclear $0\nu\beta\beta$-decay



FORBIDDEN IN THE SM.

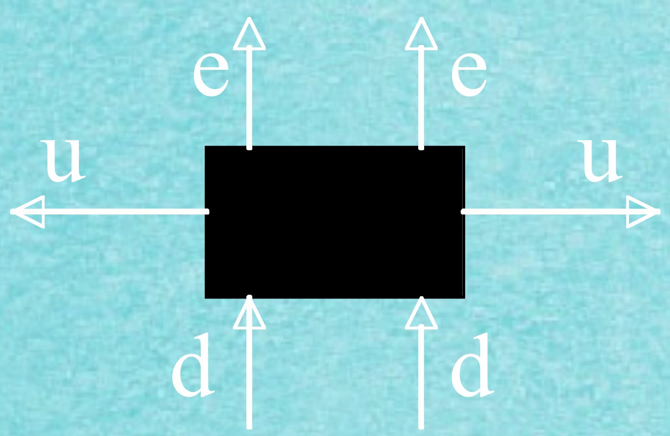
The present limit is given by [H.V.Klapdor-Kleingrothaus]

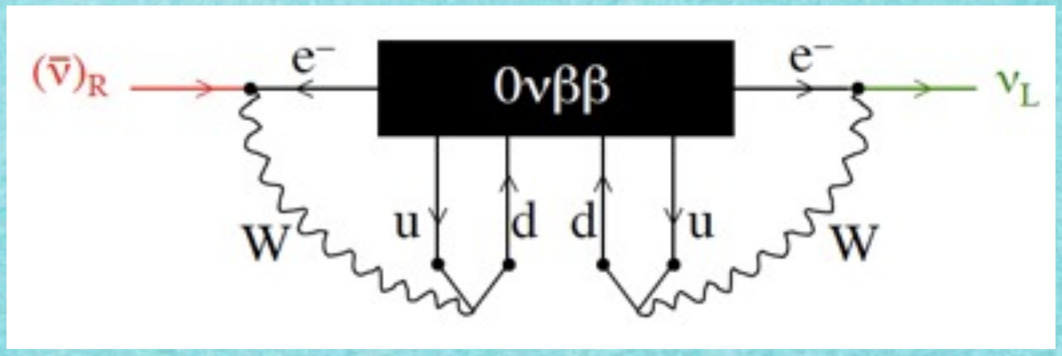
$$|\langle m_\nu \rangle| \equiv \left| \sum U_{ei}^2 m_i \right| < 0.2 \text{ eV}$$

“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.”





0νββ decay ⟷ **Majorana neutrino mass**

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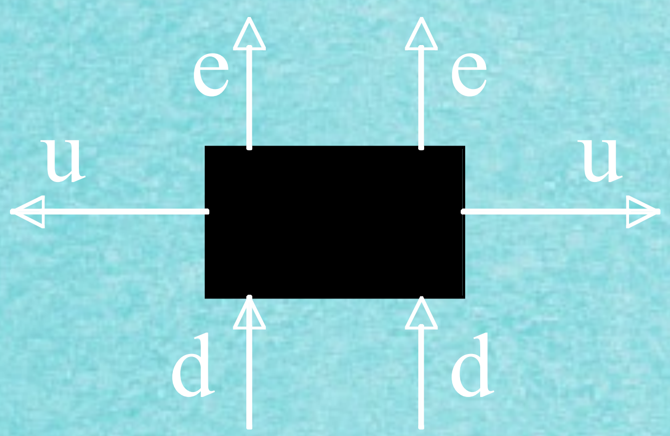

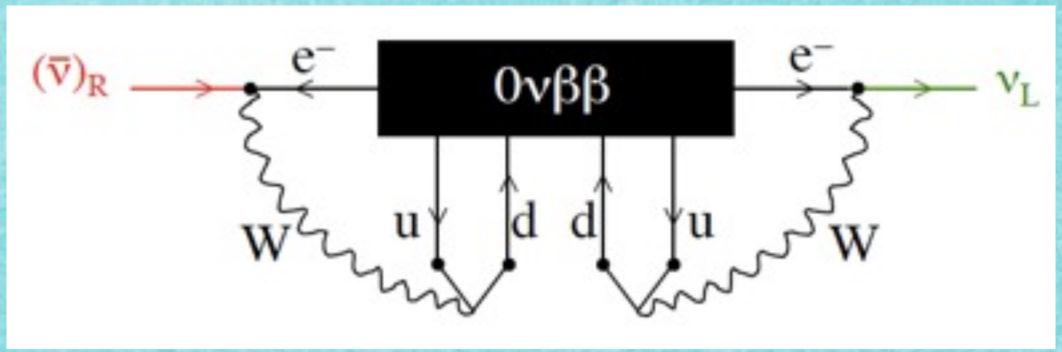

0νββ decay ? ⟷ **Majorana neutrino mass**

☞ **The theorem does not state if the mechanism for 0νββ from m_ν is the dominant one.**

In some models, the dominant contributions to 0νββ are generated without directly involving ν_M.

In the SM:

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

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

- A $SU(2)$ doublet fundamental scalar Higgs field is employed to give masses to BOTH the $SU(2)\times U(1)$ gauge bosons and fermions.

$$H=\begin{pmatrix}0\\ \frac{v+h^0}{\sqrt{2}}\end{pmatrix},\quad v=247\text{GeV}$$

- Higgs fermion interaction

$$y_e\,(\overline{\nu_{eL}}\quad \overline{e_L})\begin{pmatrix}0\\ \frac{v+h^0}{\sqrt{2}}\end{pmatrix} e_R + h.c. \to \frac{y_e\,v}{\sqrt{2}}\bar{e}e+\frac{y_e v}{\sqrt{2}}\bar{e}\,eh^0$$

- Fermion mass $m_f=\frac{y_f v}{\sqrt{2}}$ and $\bar{f}fH$ coupling is proportional to fermion mass

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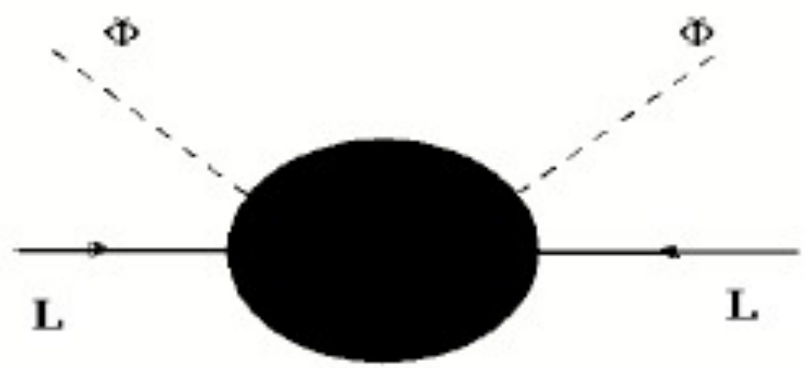

Dimension five operator responsible for neutrino mass

Effective Dim-5 operator:

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

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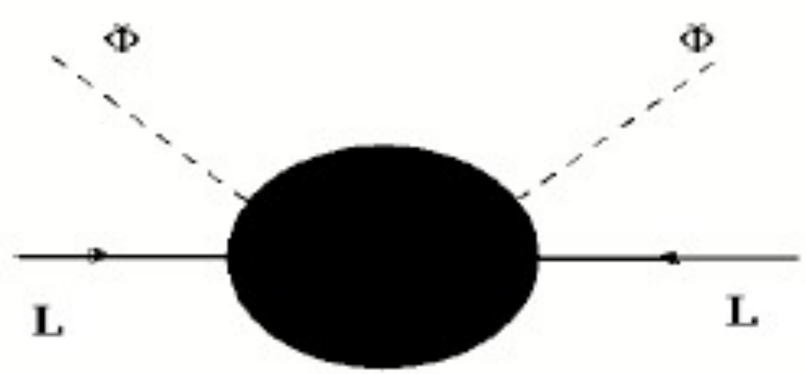

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↓ ***SSB***

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

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

BSM: (a) If the right handed neutrinos ν_R exist: ν_R=(1,1,0)

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

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

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

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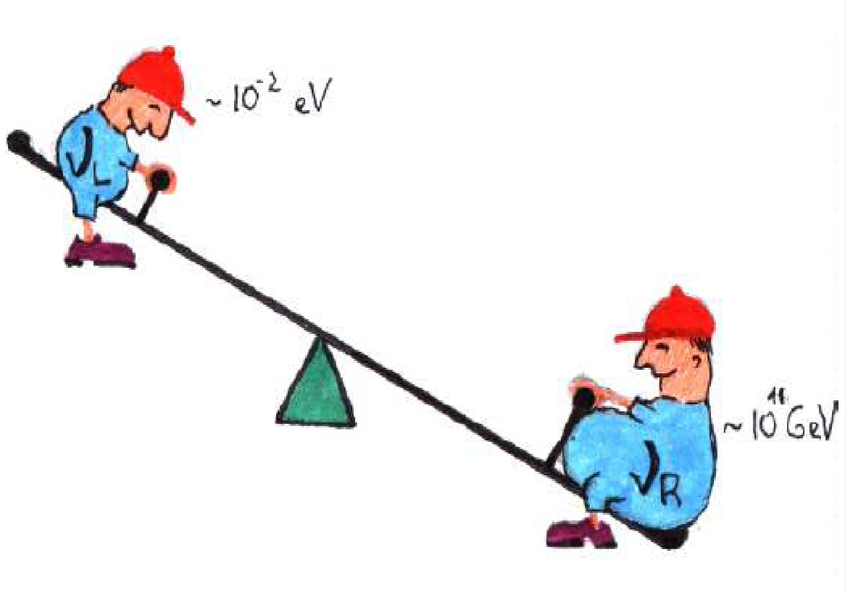
$$\mathcal{M}_\nu = -m_D^T M_R^{-1} m_D.$$

(naturally small?+Majorana)



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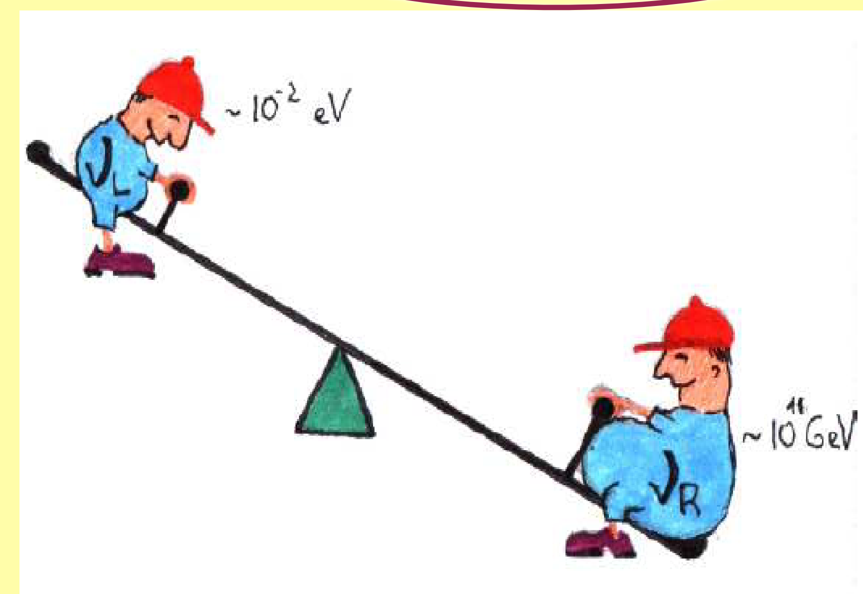
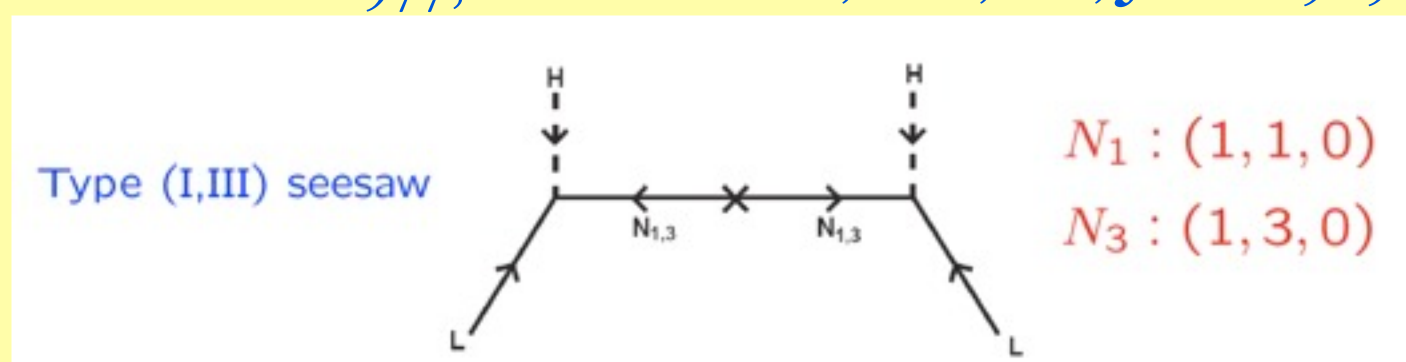


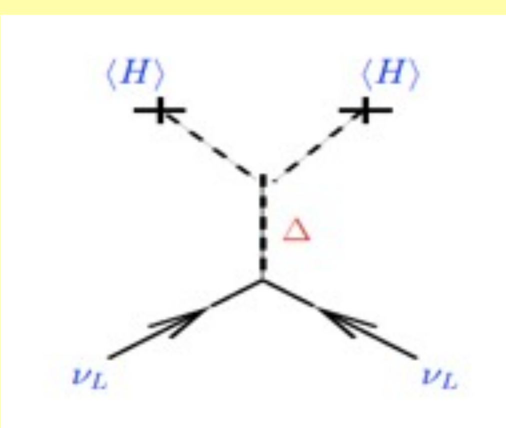
(c) Without ν_R:

- **Majorana : tree level**

Minkowski 1977; ...

Foot, Lew, He, Joshi 1989





Type II seesaw

Schechter & Valle, 1980, 1982
Cheng & Li, 1980
Mohapatra, Senjanovic, 1981
...

$$\Delta \equiv \begin{pmatrix} H^- & -\sqrt{2}\,H^0 \\ \sqrt{2}\,H^{--} & -H^- \end{pmatrix} = (1, 3, 2)$$ **scalar triplet**

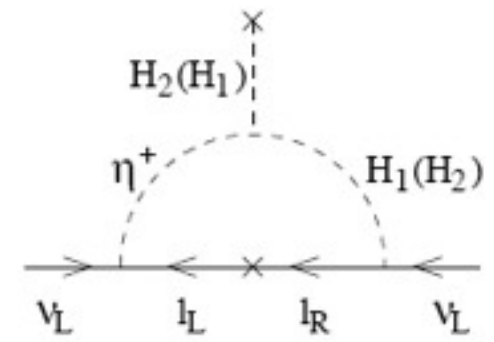
$$M_\nu = \sqrt{2} Y_\Delta \langle\Delta\rangle = Y_\Delta \frac{\mu_\Delta v^2}{M_\Delta^2}$$

Majorana : loop level

1980

- **Zee model (with charged scalar singlet and additional scalar doublets).**

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



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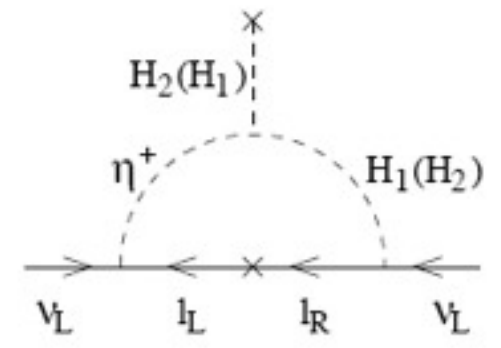

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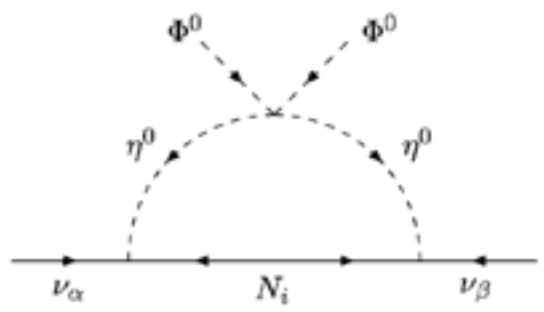

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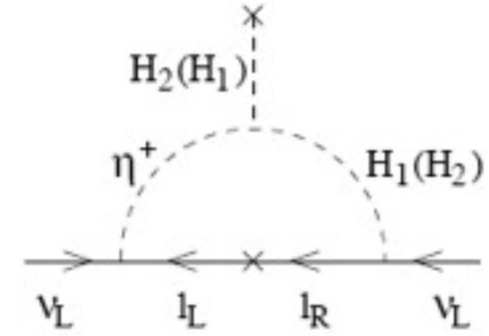

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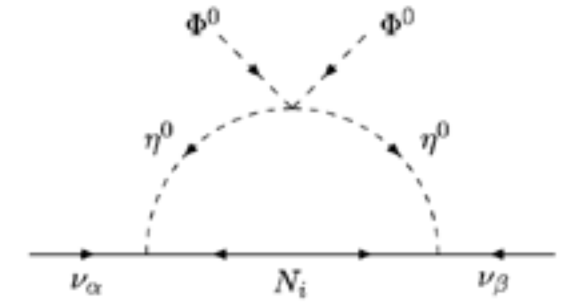

1986 1988

- **Zee-Babu model (with doubly and singly charged scalars).**

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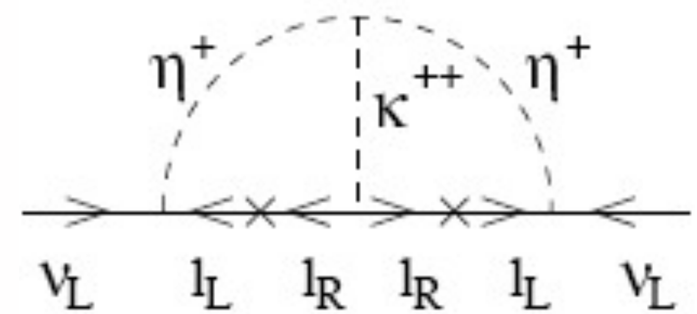

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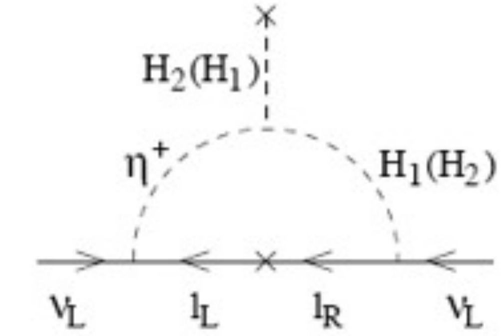

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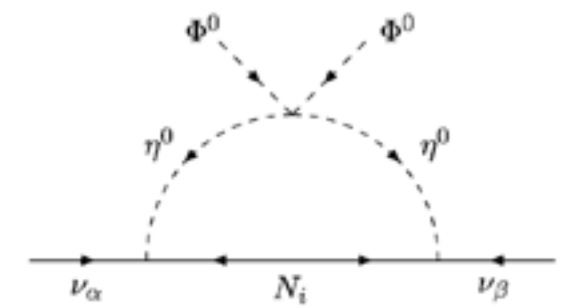

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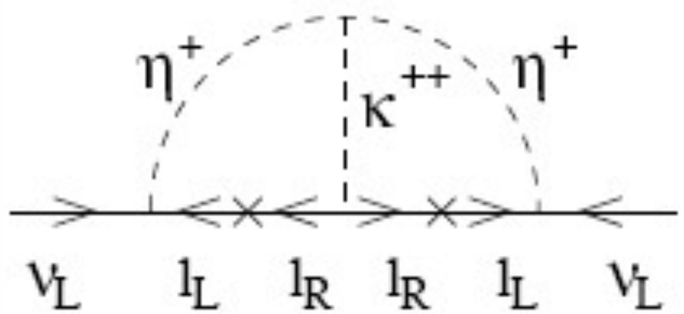
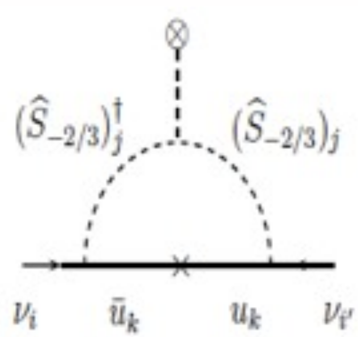
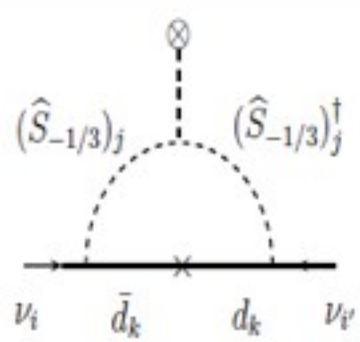


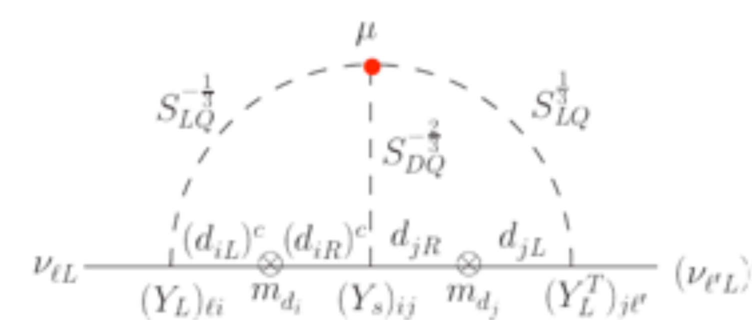
- **Other models:**

Hirsch et al. 1996, Aristizabal et al. 2008

Leptoquarks







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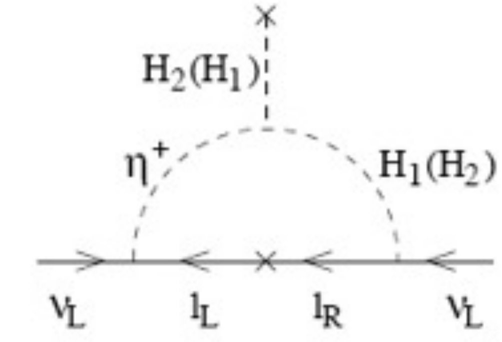

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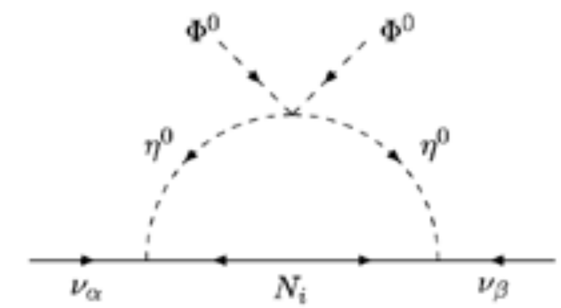

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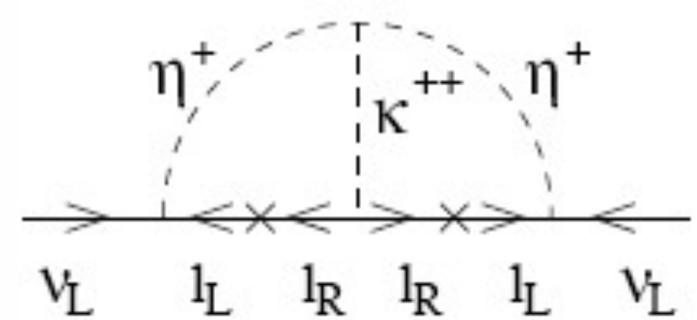

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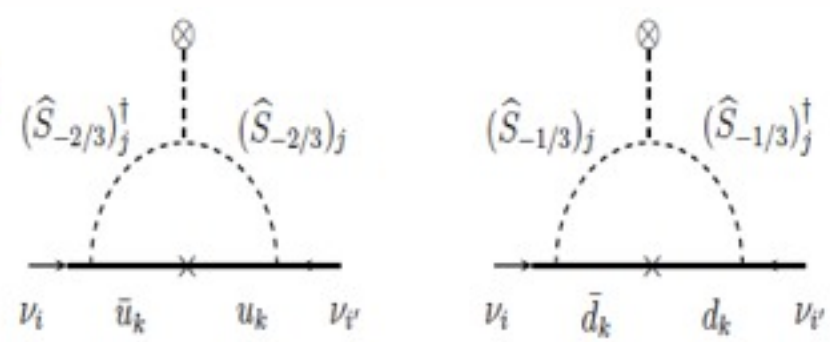

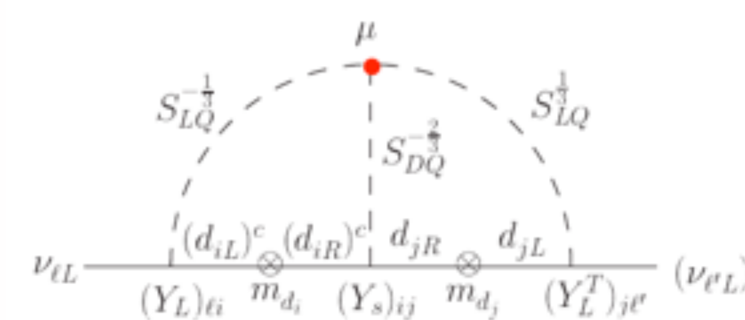

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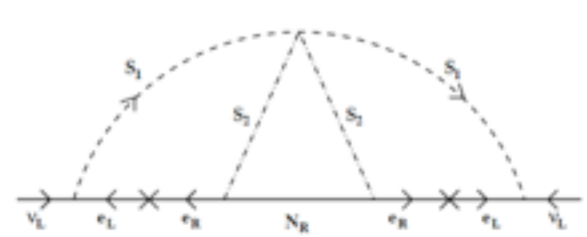

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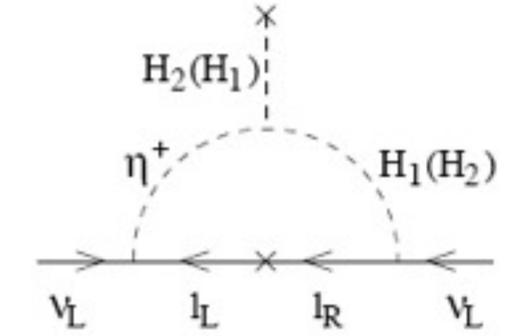

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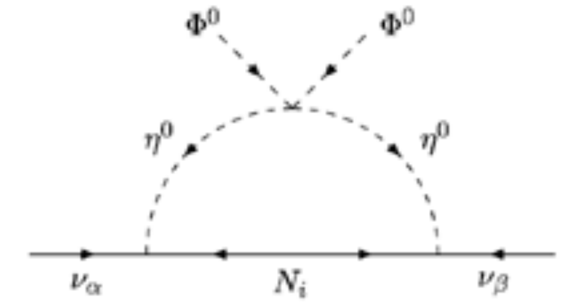

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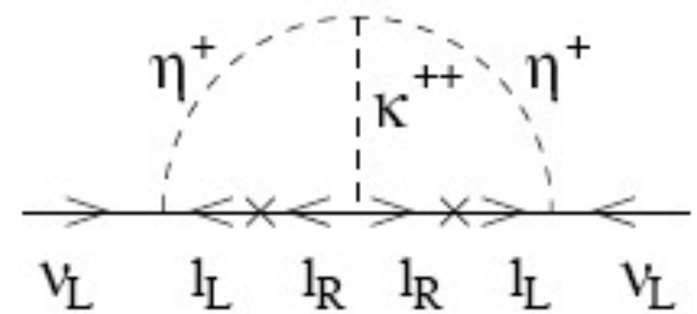

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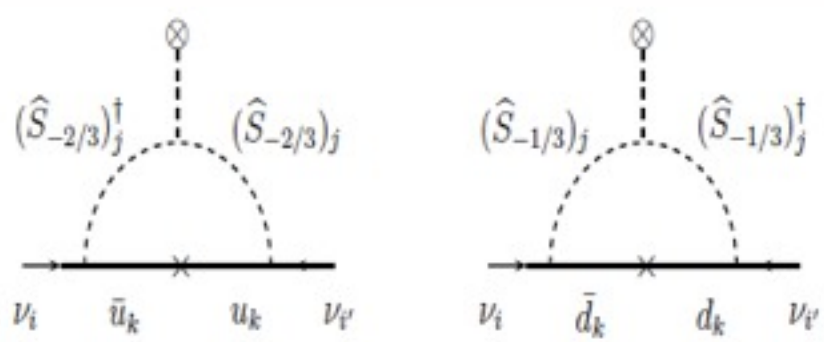

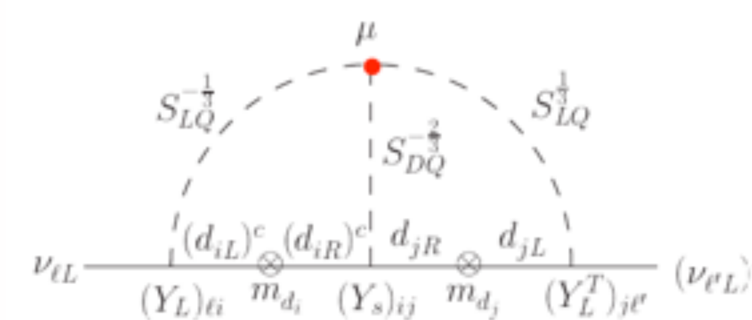

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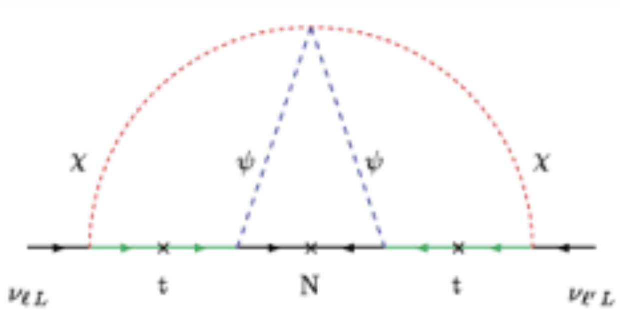

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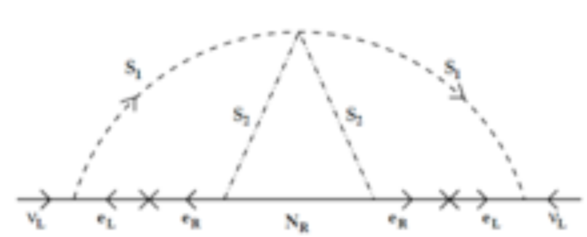

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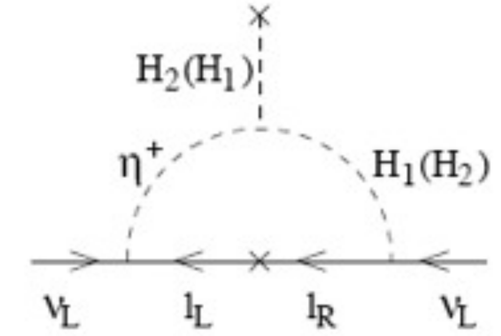

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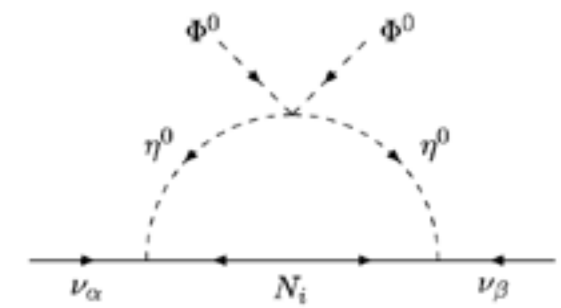

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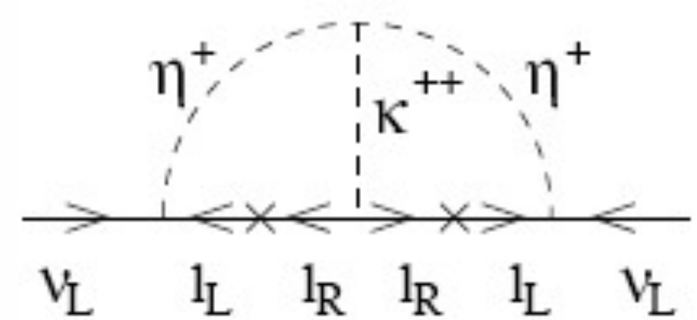

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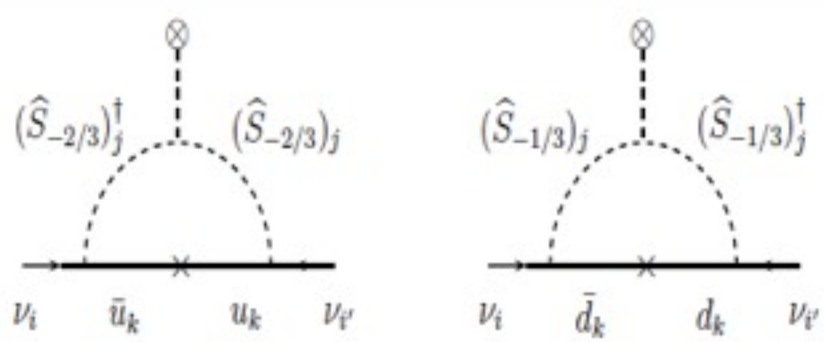

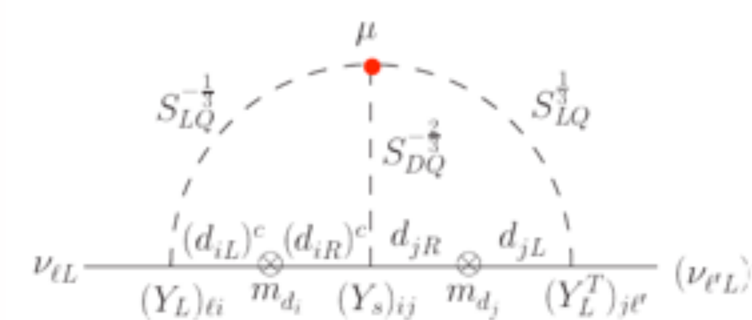

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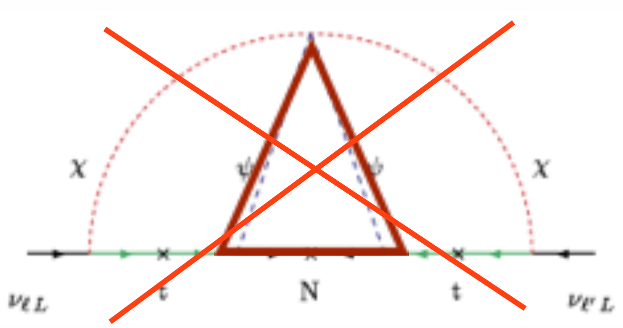

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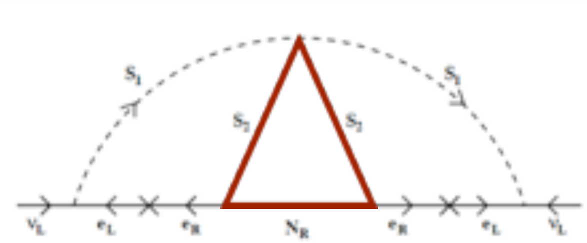

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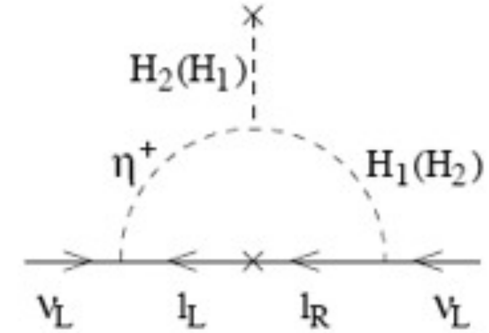

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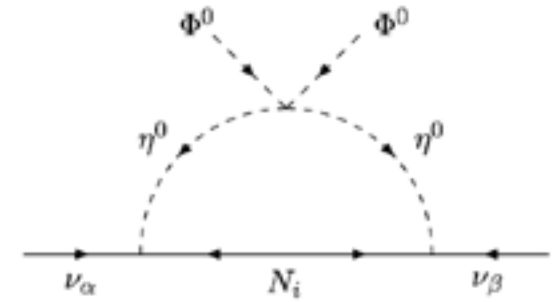

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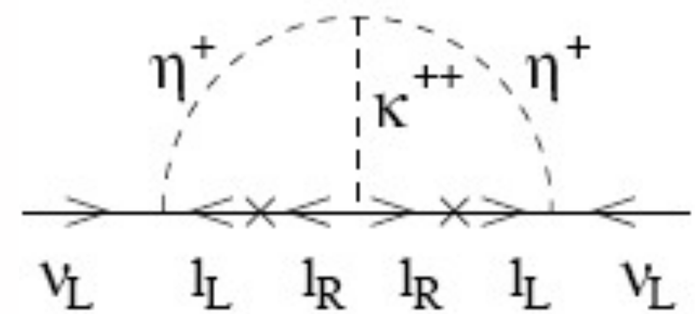

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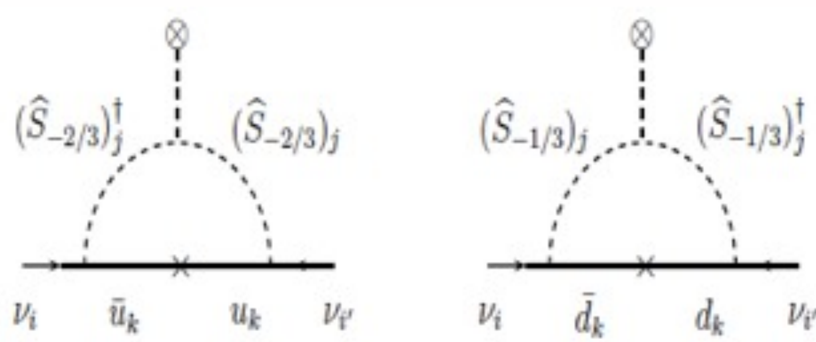

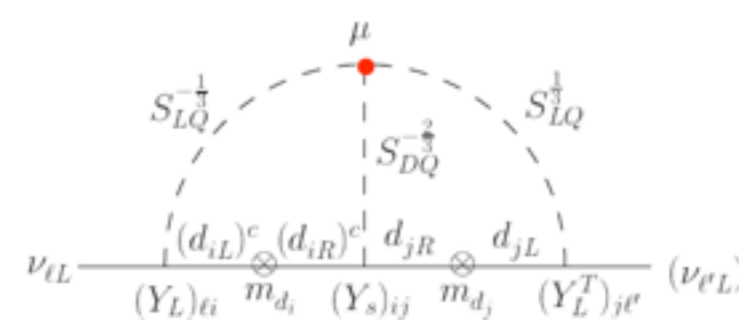

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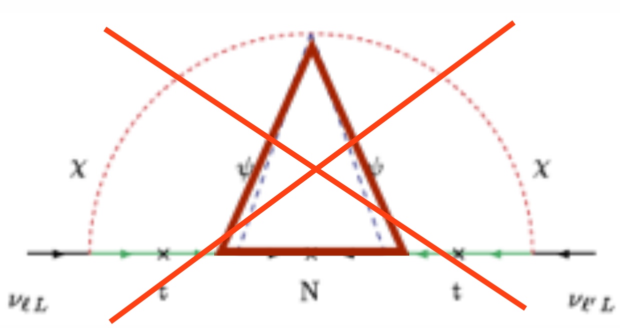

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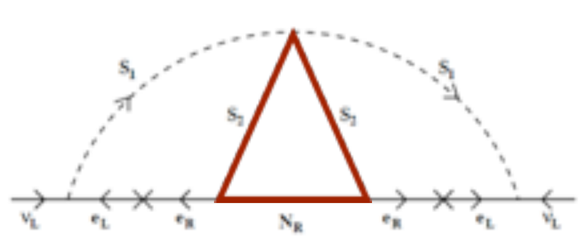

C.S.Chen,K.L.McDonald,S.Nasri, 2014

Suppressed $0\nu\beta\beta$ in these models!

- Models with Majorana Neutrinos:

C.S.Chen+CQG+J.N.Ng, PRD75,053004(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}	$(1, 1, 2)$
$Q_a = (u_a, d_a)^T_L$	$(3, 2, 1/3)$
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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)

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$$+ \kappa_1 \,\mathrm{Tr}(\phi^\dagger \phi T^\dagger T) + \kappa_2 \phi^\dagger T T^\dagger \phi + \kappa_\Psi \phi^\dagger \phi \Psi^\dagger \Psi + \rho \,\mathrm{Tr}(T^\dagger T \Psi^\dagger \Psi)$$
$$+ [\lambda (\phi^T T \phi \Psi^\dagger) - M(\phi^T T^\dagger \phi) + \mathrm{H.c.}]$$

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

Forbidden by some symmetry*

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

CS.Chen,CQG,PRD82,105004(2010)

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

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Chen, CQG, Huang, Tsai, PRD87, 077702 (2013)

Without Symmetry: $\xi(1,N,2) + \Psi(1,1,4)$ ➡ ~~$LL\xi$~~ *if N>3*

We will consider higher dimensional multiplets so that NO LL-like term is allowed in the Yukawa interactions.

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enhance

Higgs → 2 photon

1.6 times of excess at the LHC

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The scalar potential reads

$$V(\Phi,\xi,\Psi) = -\mu_\Phi^2|\Phi|^2 + \lambda_\Phi|\Phi|^4 + \mu_\xi^2|\xi|^2 + \lambda_\xi^\alpha|\xi|_\alpha^4 + \mu_\Psi^2|\Psi|^2 + \lambda_\Psi|\Psi|^4$$
$$+\lambda_{\Phi\xi}^\beta(|\Phi|^2|\xi|^2)_\beta + \lambda_{\Phi\Psi}|\Phi|^2|\Psi|^2 + \lambda_{\xi\Psi}|\xi|^2|\Psi|^2$$
$$+[\mu\xi\xi\Psi + \mathrm{h.c.}]$$

No N=4, 6, 8, 10,…, even dimensions due to their antisymmetric products

→ N=5, 7, …, odd dimensions

Constraints on the models:

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

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

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

Two doubly charged scalars:

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

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Mass eigenstates:

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

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

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

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

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

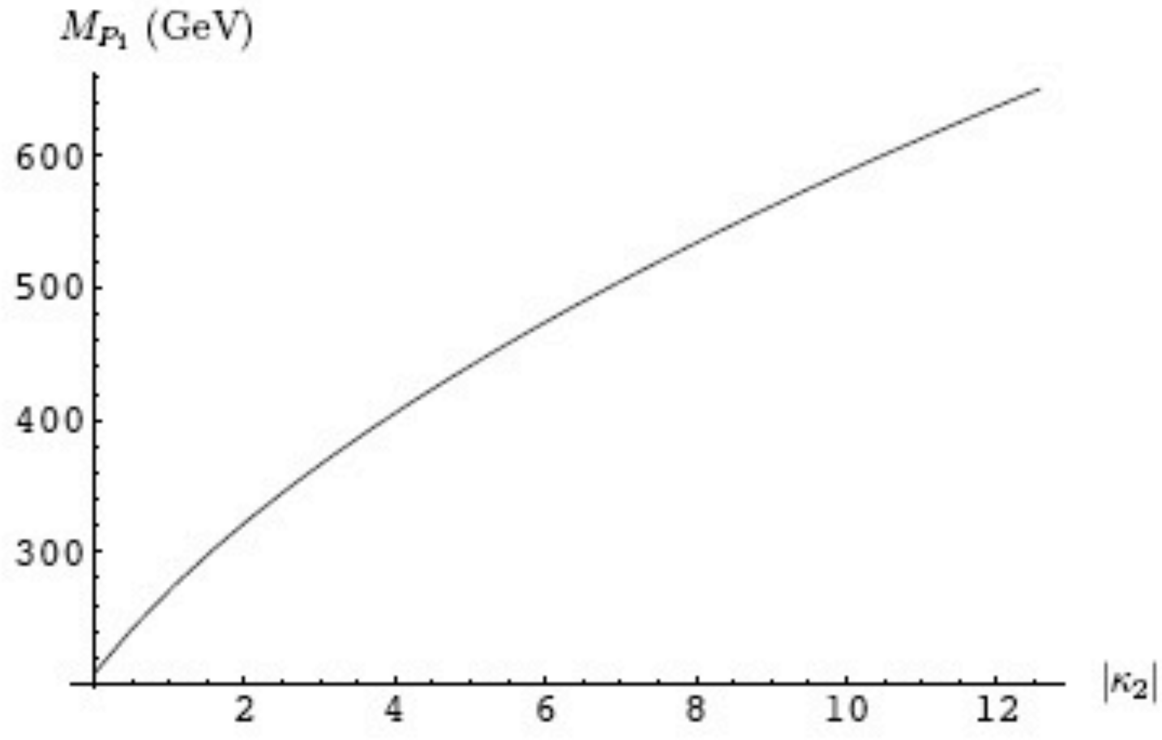


Figure 1: Maximum value of M_{P_1} for $v_T = M = 4\,\mathrm{GeV}$, and $|\lambda'_T|$ set to 4π.

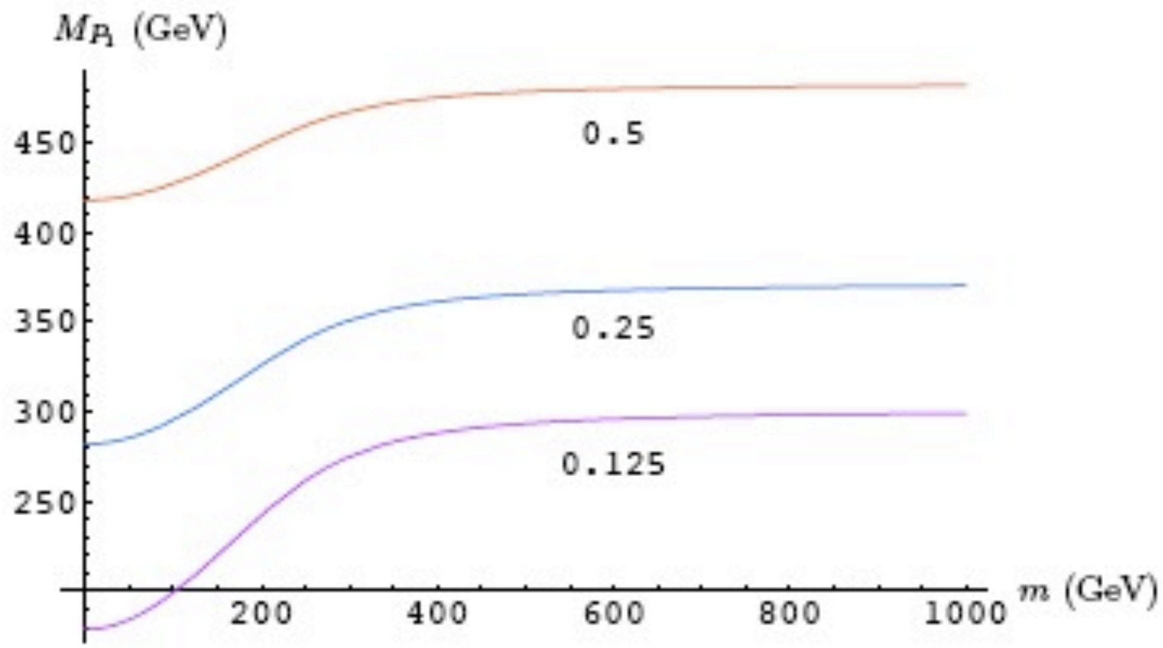


Figure 2: M_{P_1} as a function of m for $|\kappa_2| = 0.5, 0.25, 0.125$ in units of 4π, with $v_T = M = 4\,\mathrm{GeV}$ and $\lambda = -\lambda'_T = 1$.

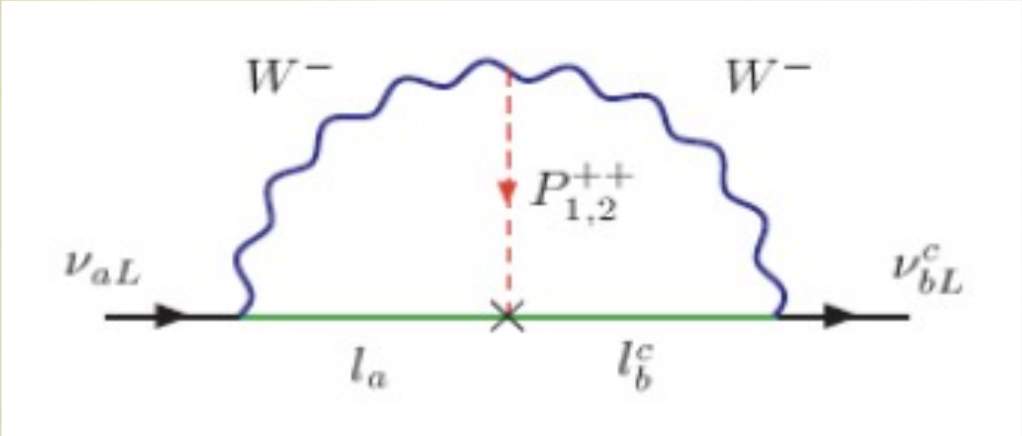
The P_1 state is well within the reach of the LHC; P_2 will be too heavy to be of interest to the LHC.

Current LHC limit: 200-400 GeV

- TeV Phenomenology:

(i) ν mass generations:

The neutrino masses are generated radiatively at two-loop level



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

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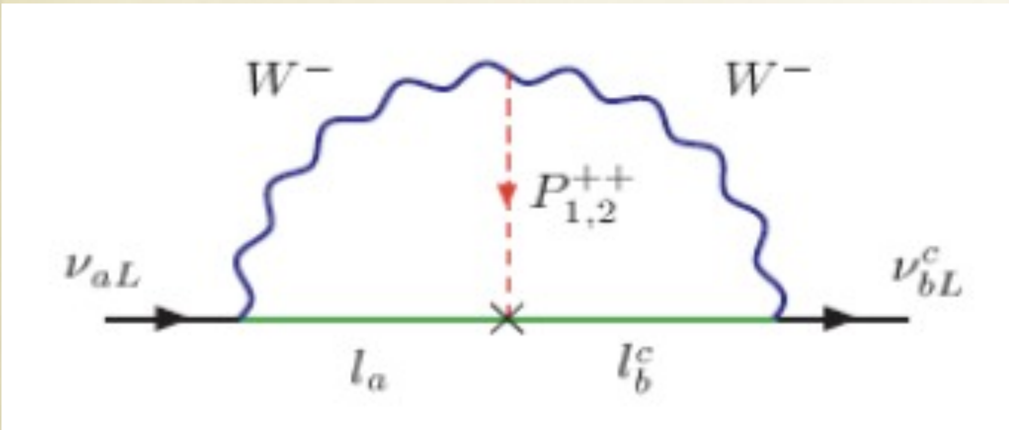

$a, b = e, \mu, \tau.$

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

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

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

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

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

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

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

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

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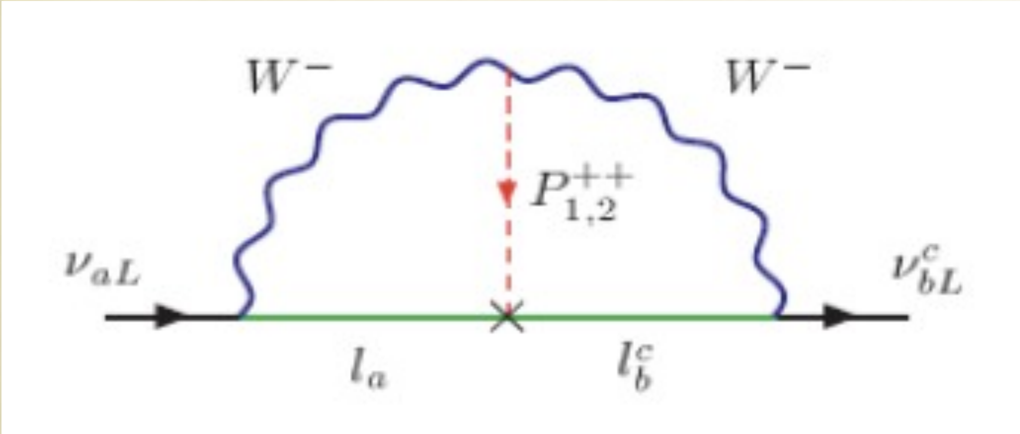

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normal hierarchy:

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

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

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

(ii) 0νββ decays:

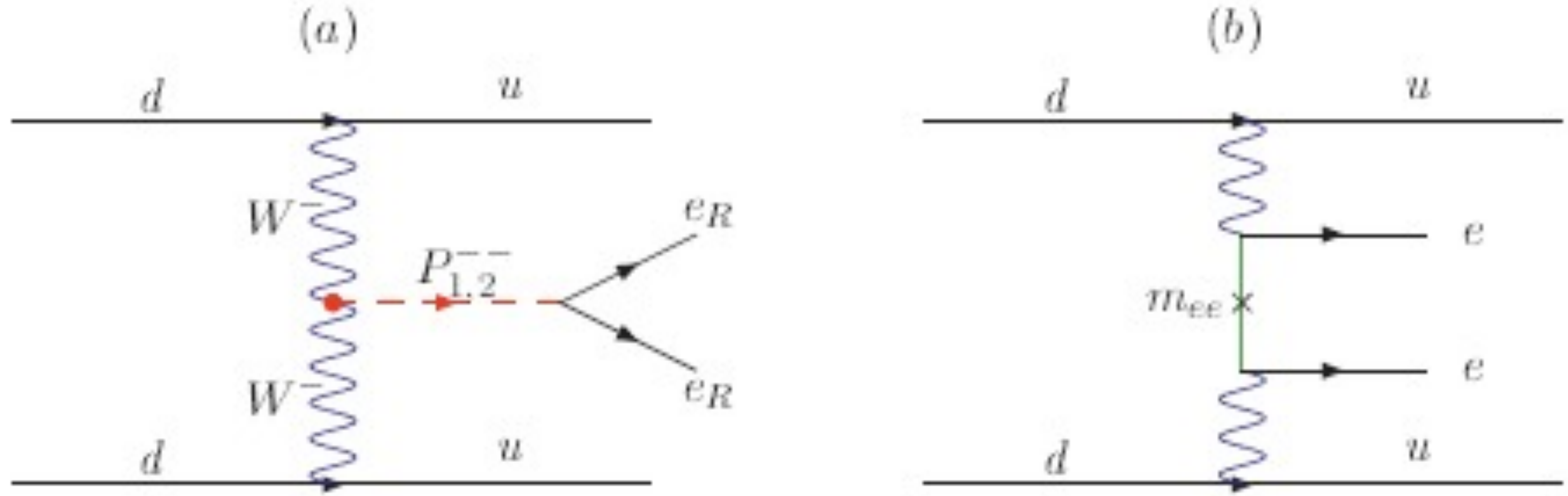

Figure 9: $0\nu\beta\beta$ decays via exchange of: (a) doubly charged Higgs and (b) light Majorana neutrinos.

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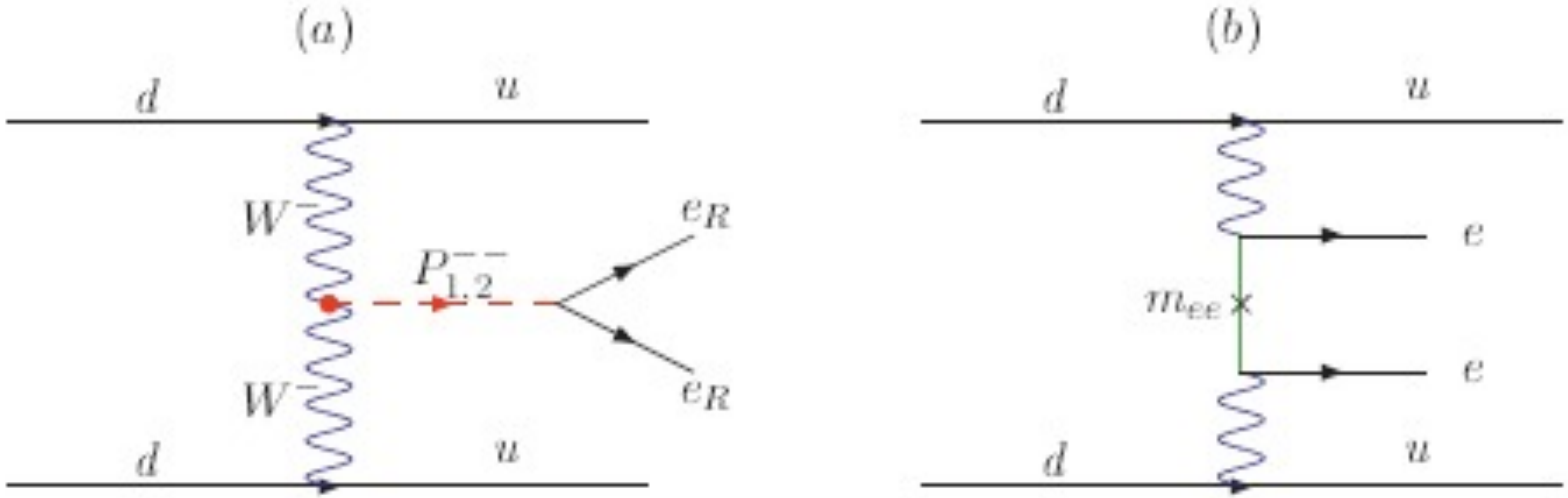

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$$A_{P^{--}_{1,2}} \sim \frac{g^4\, Y_{ee} v_T \sin 2\delta}{16\sqrt{2} M_W^4}\left(\frac{1}{M^2_{P_1}} - \frac{1}{M^2_{P_2}}\right)$$

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

$$<p>\sim 0.1\,\text{GeV}$$

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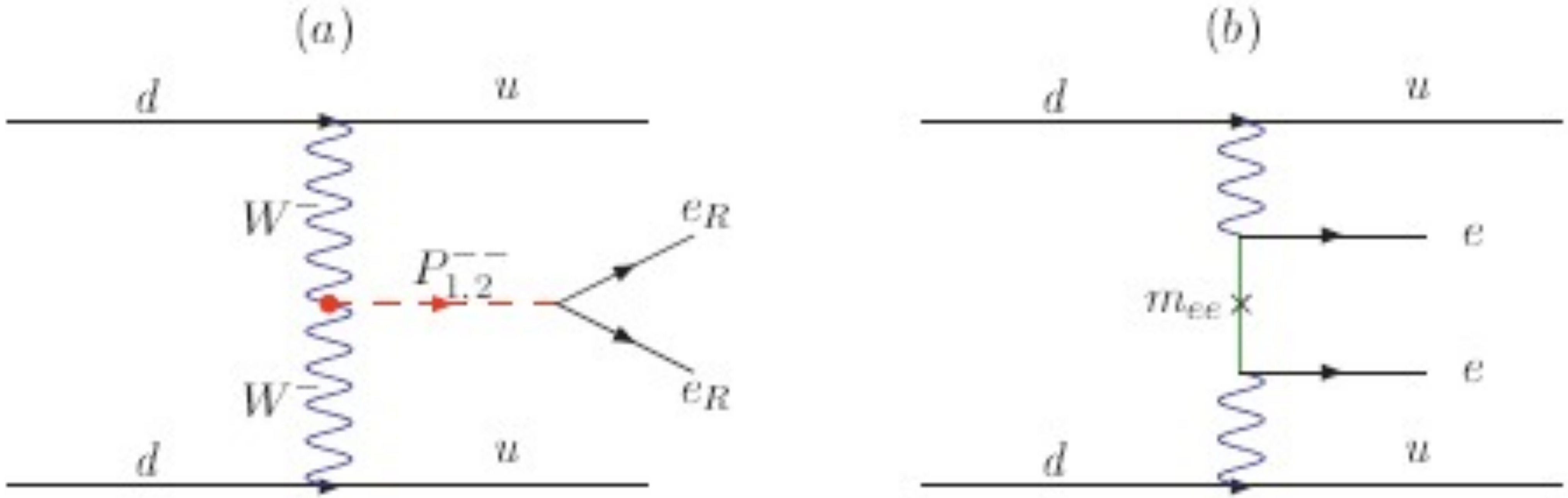

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»

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$<p> \sim 0.1\,\text{GeV}$

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

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.

☞ **Black box** theorem is irrelevant as 0νββ dominantly arises from the SD contribution

M.Gustafsson,J.M.No,M.A.Rivera,
arXiv:1402.0515 [hep-ph]

$$\frac{C^{(9)}_{ab}}{\tilde{\Lambda}} \overline{\ell^c}_{R_a} \ell_{R_b} W^+_\mu W^{+\mu}$$

←

$$\mathcal{O}^9 \equiv C^{(9)}_{ab} \overline{\ell^c}_{R_a} \ell_{R_b} \left[(D_\mu H)^T \, i\sigma_2 H \right]^2$$

dimension-9
L violating O

M.Gustafsson,J.M.No,M.A.Rivera, arXiv:1402.0515 [hep-ph]

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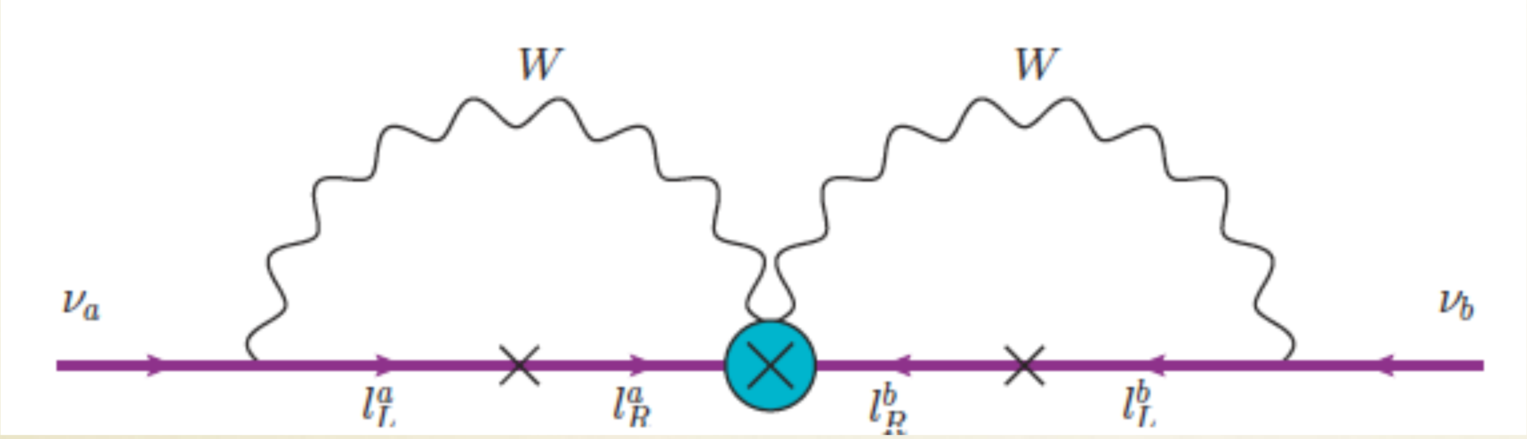
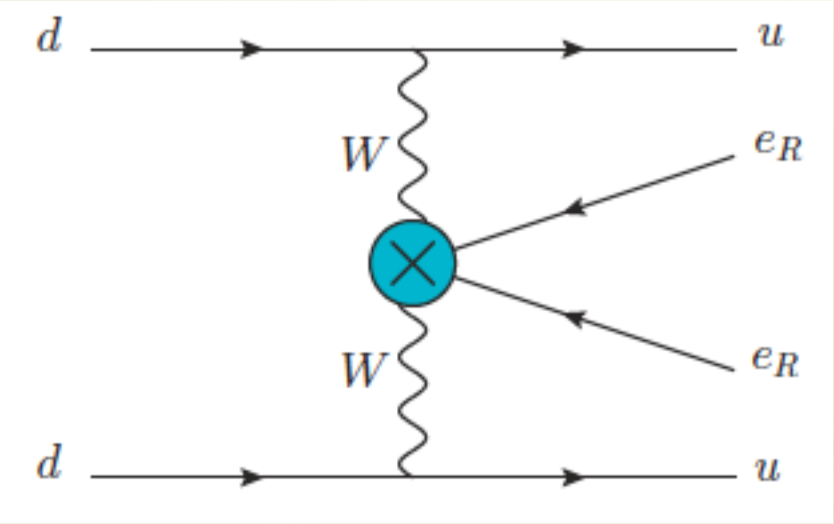


$$m_{ab}^\nu \sim \left(\frac{1}{16\,\pi^2} \right)^n C_{ab}^{(9)} \frac{m_{l_a}\, m_{l_b}}{\Lambda}$$

n=# of loops



$$\mathcal{L}_{0\nu\beta\beta} = \frac{G_F^2}{2\,m_p} \epsilon_3\, J^\mu\, J_\mu\, \bar{e}(1-\gamma_5)e^c$$

$$J^\mu = \bar{u}\gamma^\mu(1-\gamma_5)d$$

$$\epsilon_3 = -2\, m_p\, \mathcal{A}_{0\nu\beta\beta}^{\rm SD}$$

(iii) Other physics:

Multi Charged Scalars

a. Lepton flavor physics:

1. *Muonium anti-muonium conversion* $\mu^+e^- - \mu^-e^+$ $\quad H_{M\bar{M}} = \frac{Y_{ee}Y_{\mu\mu}}{2M_{--}^2}\bar{\mu}\gamma^\mu e_R\bar{\mu}\gamma_\mu e_R + h.c.,$

2. *Effective* $e^+e^- \to l^+l^-$, $l = e, \mu, \tau$, *contact interactions* $\quad \frac{Y_{ee}^2}{M_{--}^2}\bar{e}_R\gamma^\mu e_R\bar{e}_R\gamma_\mu e_R$

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

4. *Radiative flavor violating charged leptonic decays* $\quad Br(\mu \to e\gamma) = \frac{\alpha}{3\pi G_F^2}\sum_{l=e,\mu,\tau}\left(\frac{Y_{l\mu}Y_{le}}{M_{--}^2}\right)^2$

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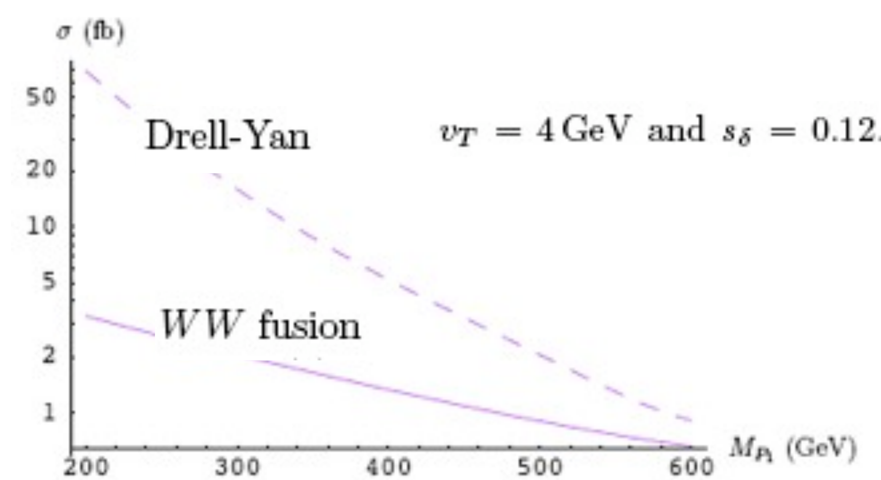
b. Doubly charged scalars at the LHC:



1 Production of the doubly charged Higgs

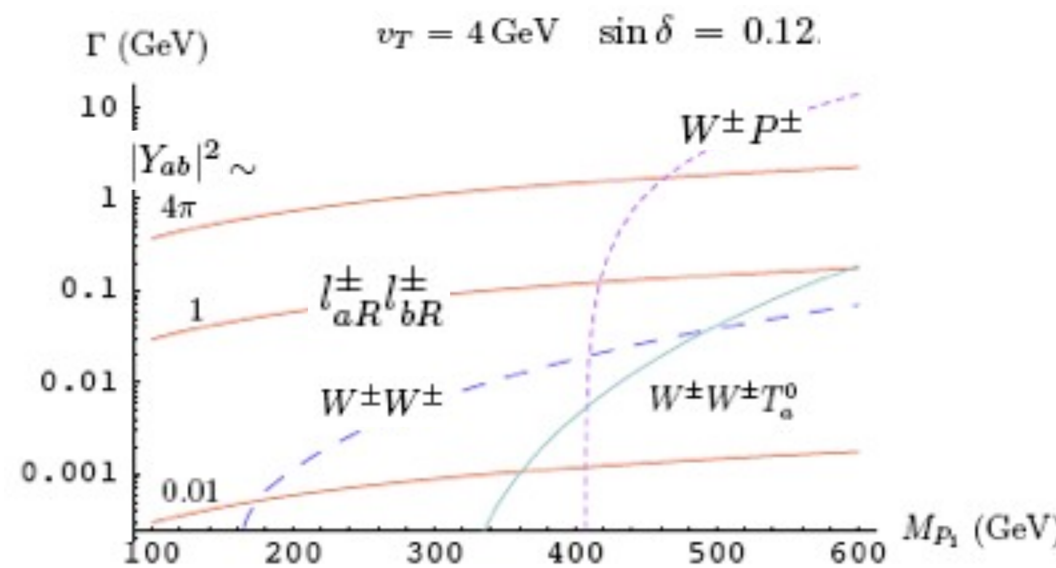
WW fusion processes similar to 0νββ decays
+Drell-Yan Annihilation processes

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

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

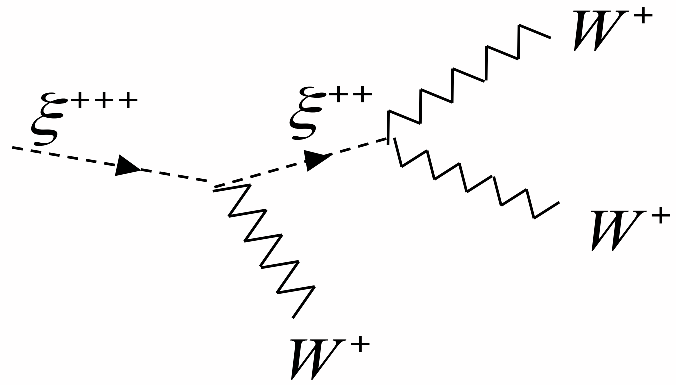
(1) $P_1^{\pm\pm} \to l_{aR}^{\pm}l_{bR}^{\pm}$ $\quad (a, b = e, \mu, \tau)$,
(2) $P_1^{\pm\pm} \to W^{\pm}W^{\pm}$,
(3) $P_1^{\pm\pm} \to P^{\pm}W^{\pm}$,
(4) $P_1^{\pm\pm} \to P^{\pm}P^{\pm}$,
(5) $P_1^{\pm\pm} \to W^{\pm}W^{\pm}X^0$, $\quad X^0 = T_a^0, h^0, P^0$
(6) $P_1^{\pm\pm} \to P^{\pm}P^{\pm}X^0$.

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

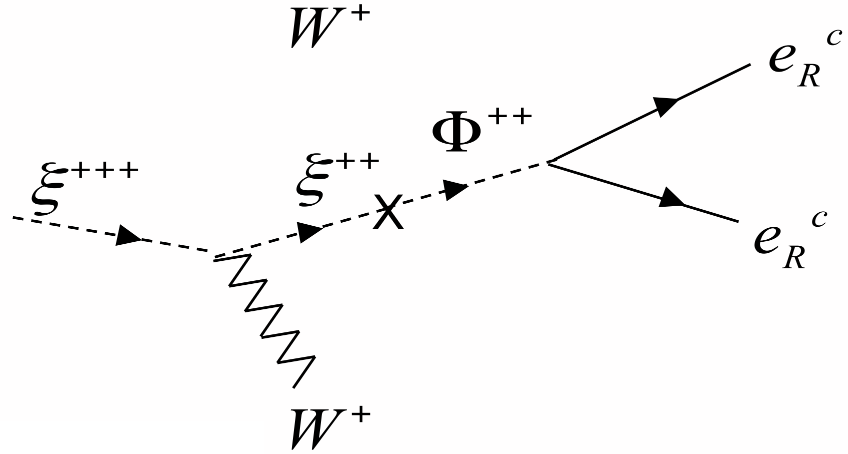


C.S.Chen+CQG+J.Ng+ J.Wu, JHEP0708, 22 (07)

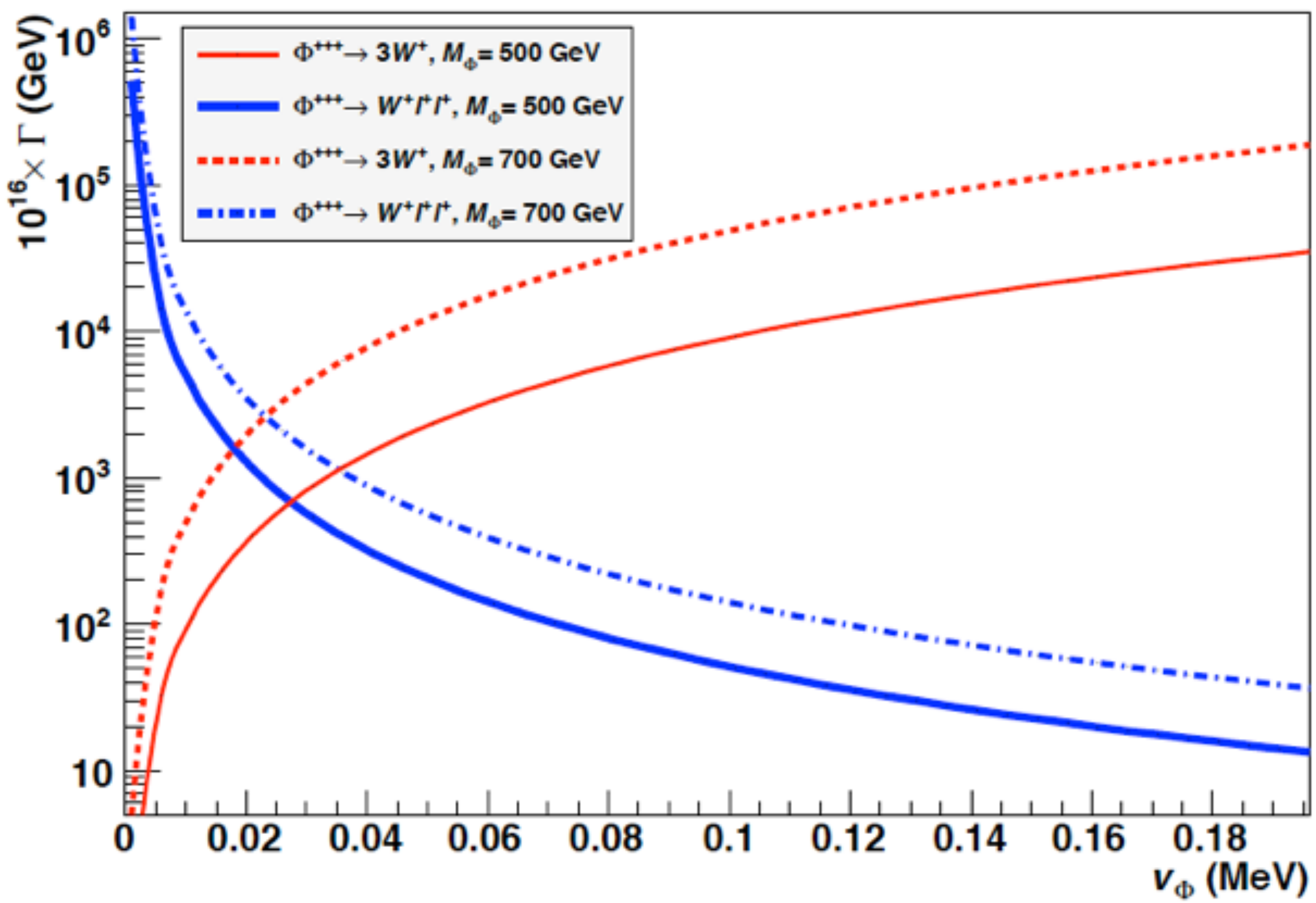
c. Triply charged scalar decays:



$$\Gamma(\Phi^{+++} \to 3W) = \frac{3g^6}{2048\pi^3}\frac{v_\Phi^2 M_\Phi^5}{m_W^6}$$

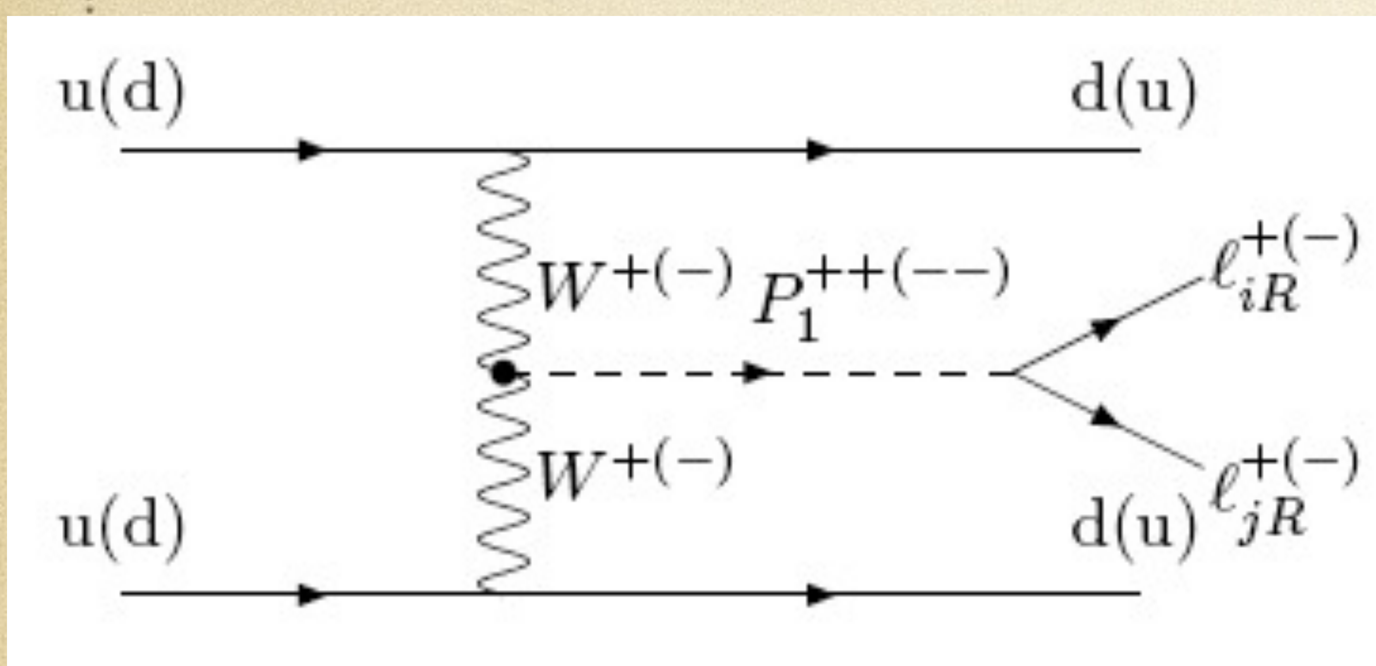


$$\Gamma(\Phi^{+++} \to W^+\ell^+\ell^+) = \frac{g^2}{6144\pi^3}\frac{M_\Phi \sum_i m_i^2}{v_\Phi^2}$$



d. Same-sign single dilepton signatures:

$$pp \to \ell_i^{\pm} \ell_j^{\pm} X \quad (X = JJ)$$



Chen, CQG, Zhuridov, Eur.Phys.J.C60,119(2009)

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

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

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

Remarks:

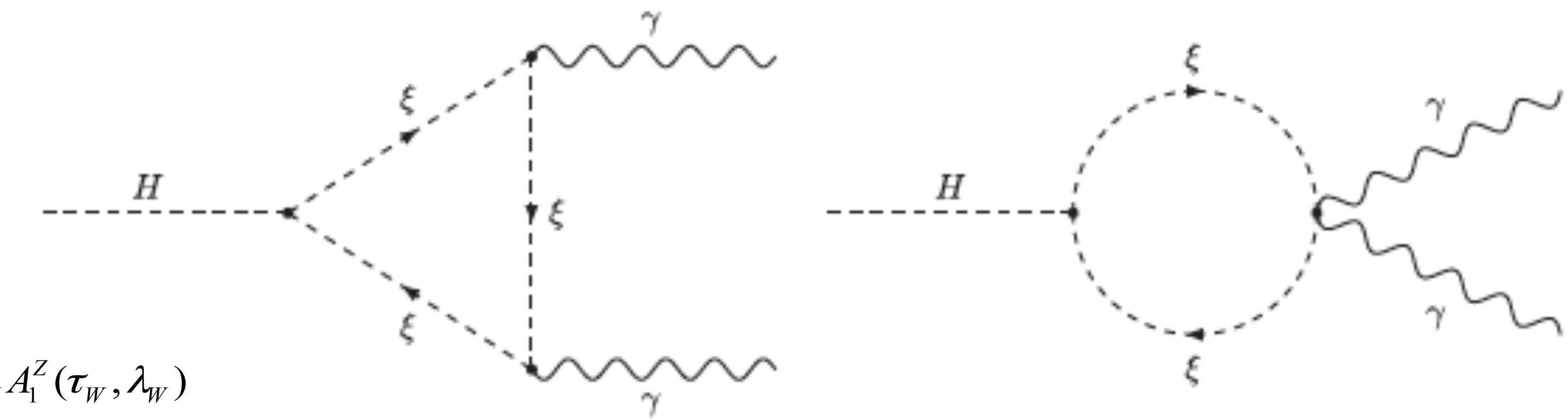
(a) In our model, the final state charged leptons are right-handed. Hence, in principle, helicity measurements can be used to distinguish between our model and those whose doubly charged Higgs coupling only to left-handed leptons.

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

e. Multi charged scalar contributions to H→ γγ and H→ Zγ :

$$\Gamma(H\to\gamma\gamma)=\frac{G_F\alpha^2 m_H^3}{128\sqrt{2}\pi^3}\left|\sum_f N_f^c Q_f^2 A_{\frac{1}{2}}(\tau_f)+A_1(\tau_W)+\sum_{I_3}(I_3+1)^2\frac{v}{2}\frac{\mu_s}{m_s^2}A_0(\tau_s)\right|^2,$$

$$\Gamma(H\to Z\gamma)=\frac{G_F\alpha\alpha_Z m_H^3}{64\sqrt{2}\pi^3}\left|\sum_f N_f^c Q_f^Z Q_f A_{1/2}^Z(\tau_f,\lambda_f)+Q_W^Z A_1^Z(\tau_W,\lambda_W)+\sum_{I_3} Q_s^Z Q_s\frac{v}{2}\frac{\mu_s}{m_s^2}A_0^Z(\tau_s,\lambda_s)\right|^2,\quad -\frac{(\mathbf{n}-1)}{2}\le I_3\le\frac{\mathbf{n}-1}{2}$$



ξ=(1, N, 2) with N=3, 5, ...

e.g. $\xi=(\xi^{+++},\xi^{++},\xi^{+},\xi^{0},\xi^{-})^T$ **for N=5**

I_3=(-N+3)/2 to (N+1)/2

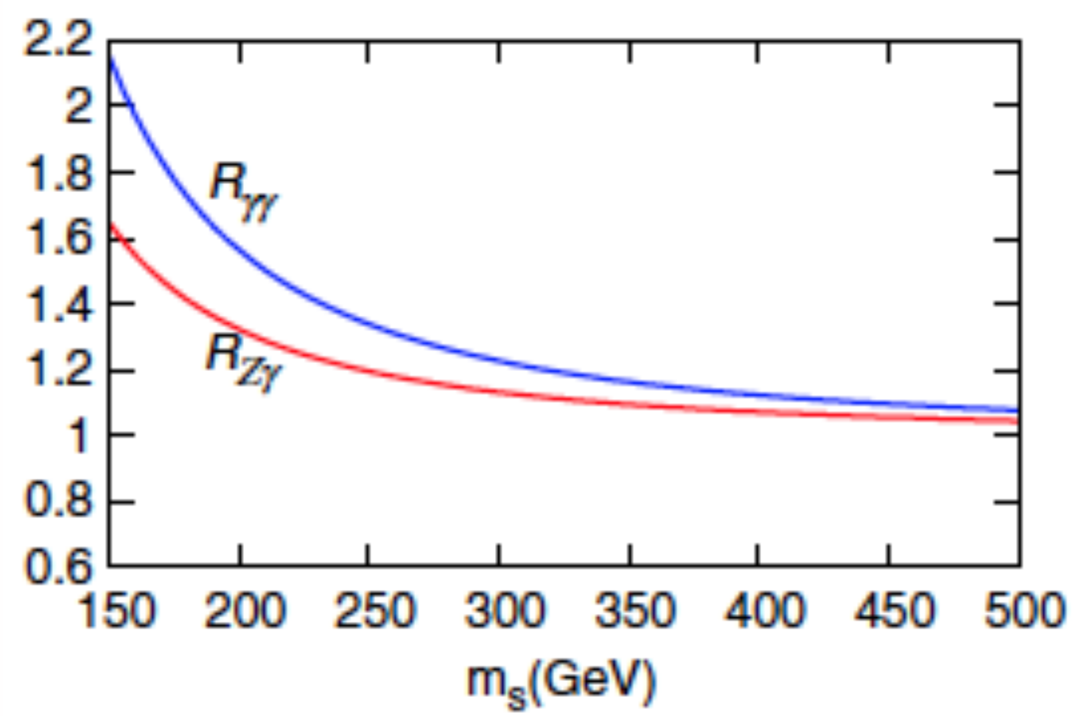


FIG. 4 (color online). $R_{\gamma\gamma}\equiv\Gamma(H\to\gamma\gamma)/\Gamma(H\to\gamma\gamma)_{SM}$ and $R_{Z\gamma}\equiv\Gamma(H\to Z\gamma)/\Gamma(H\to Z\gamma)_{SM}$ as functions of the degenerate mass factor m_s of the multicharged scalar states with $\mathbf{n}=5$ and the universal trilinear coupling to Higgs, $\mu_s=-100$ GeV.

Chen, CQG, Huang, Tsai, PRD87, 077702 (2013); PRD87, 075019 (2013)

The correlation among H→γγ and H→Zγ strongly depends on the Gauge representation of charged scalars

● Summary

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

2nd International Workshop on

Particle Physics and Cosmology after Higgs and Planck

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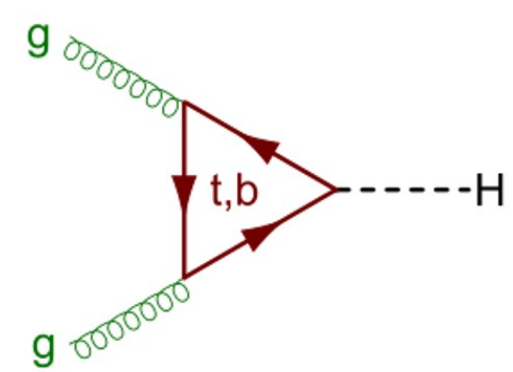

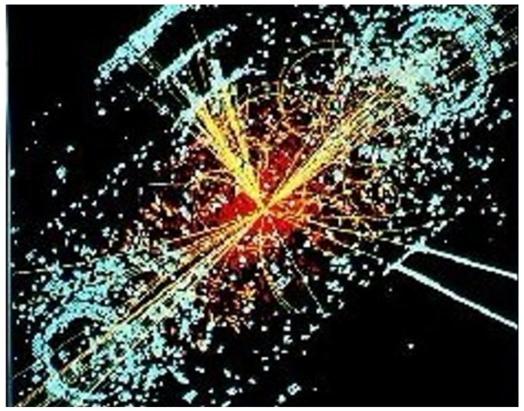

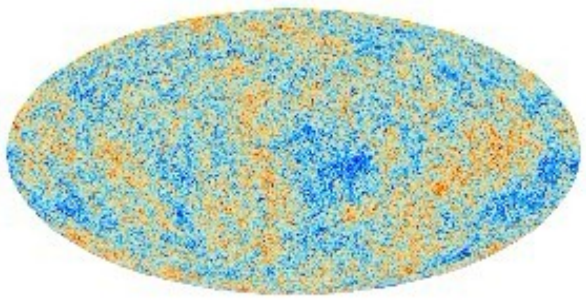

Thank you!

謝謝！