Multi High Charged Scalars & Majorana Neutrino Mass Generations

Chao-Qiang Geng
National Tsing Hua University
Hsinchu, Taiwan

CosPA 2013
November 12-15, 2013 Honolulu, Hawaii

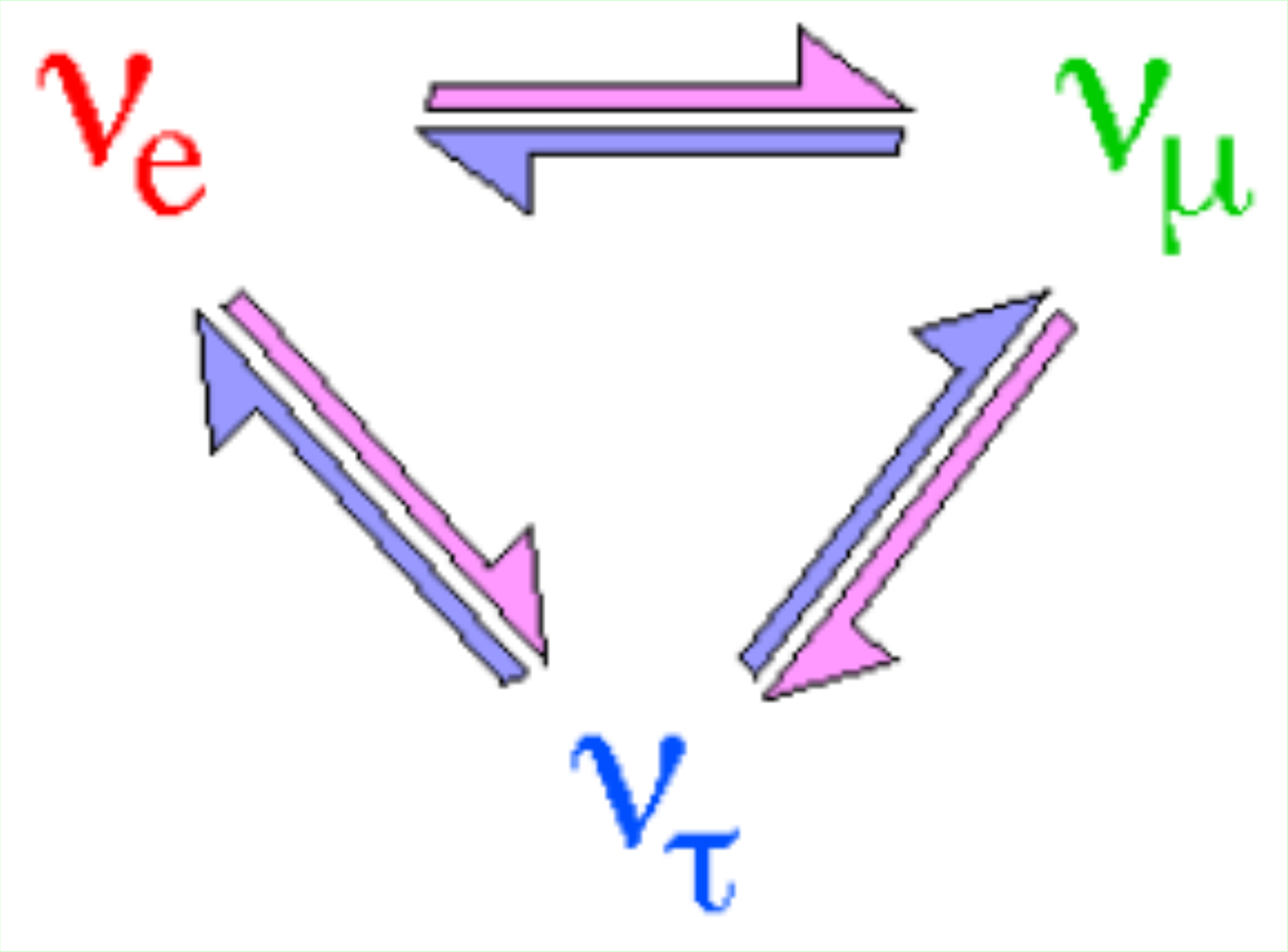
Outline

- Introduction
- Models with multi high charged scalars
- Majorana neutrino mass generations
- Summary

- Introduction

Neutrino Oscillations:

SNO, Super-Kamiokande, KamLAND ...



☞ **These are possible only if neutrinos have masses and mix with each other.**

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

Experiments on solar neutrinos

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

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

Neutrinos born in Cosmic ray collisions and on earth

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

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

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

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

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

Normal hierarchy

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

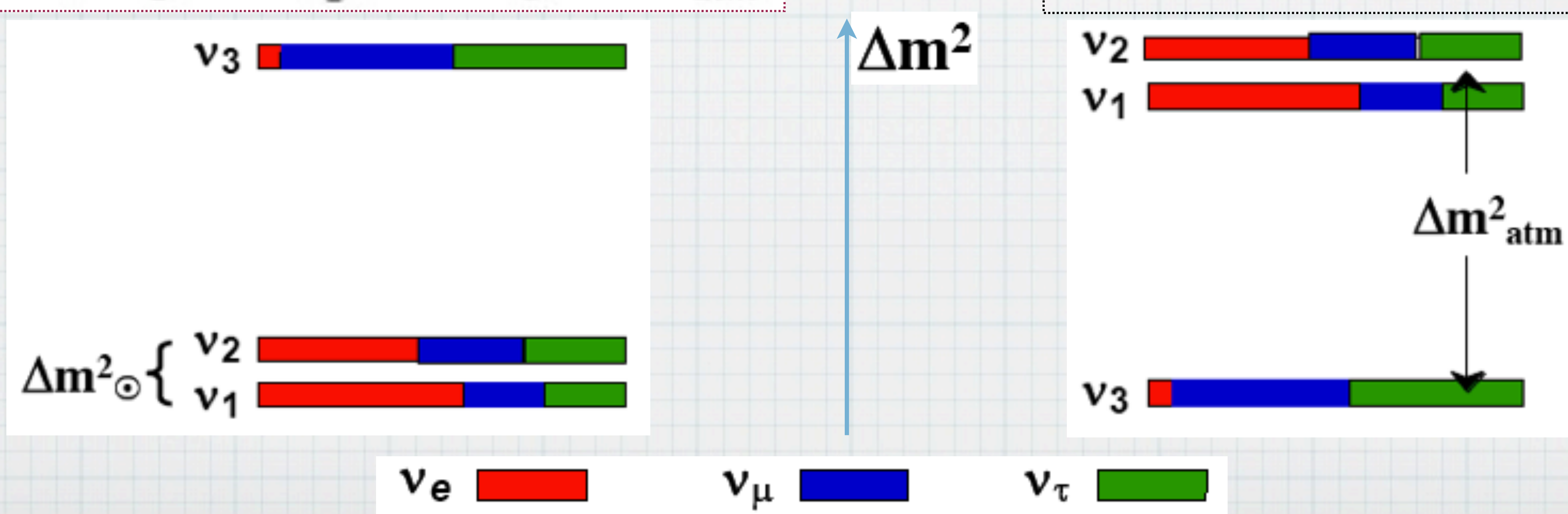
$$m_1 \simeq 0,\ m_2^2 \simeq \Delta m^2_{\odot},\ \text{and}\ m_3^2 \simeq \Delta m^2_{atm}.$$

Inverse hierarchy

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

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

Abnormal



Origin of the neutrino masses: Dirac or Majorana?

Dirac neutrino mass:

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

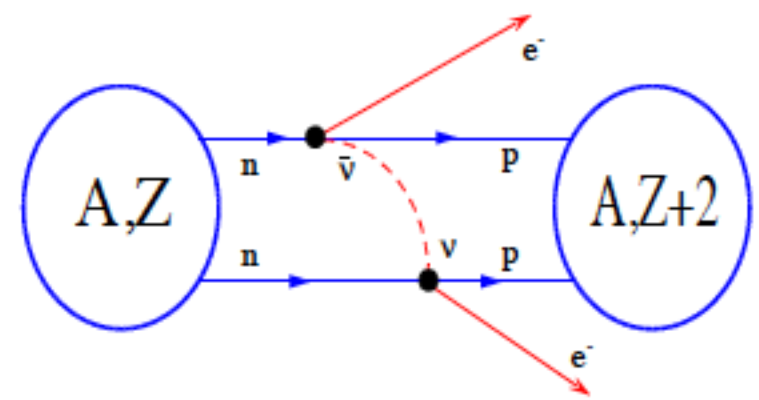
☺ the lepton number L is conserved

Majorana neutrino mass:

$$\mathcal{L}_M = -m_M \overline{\nu^c} \nu \; + \text{h.c.}$$ ☞ $\nu \leftrightarrow \bar{\nu}$

Thus, it clearly does not conserve L

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



FORBIDDEN IN THE SM.

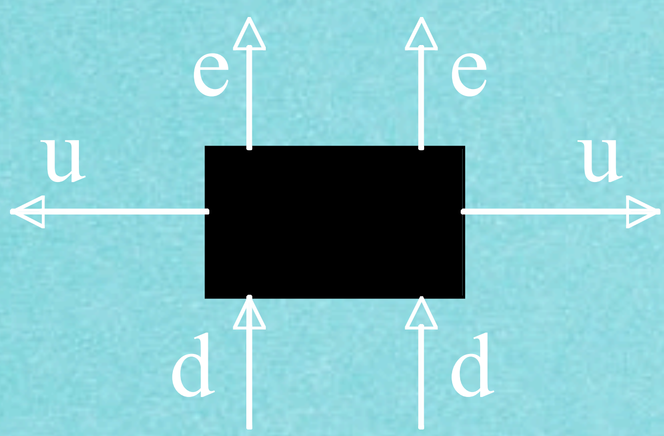
The present limit is given by [H.V.Klapdor-Kleingrothaus]

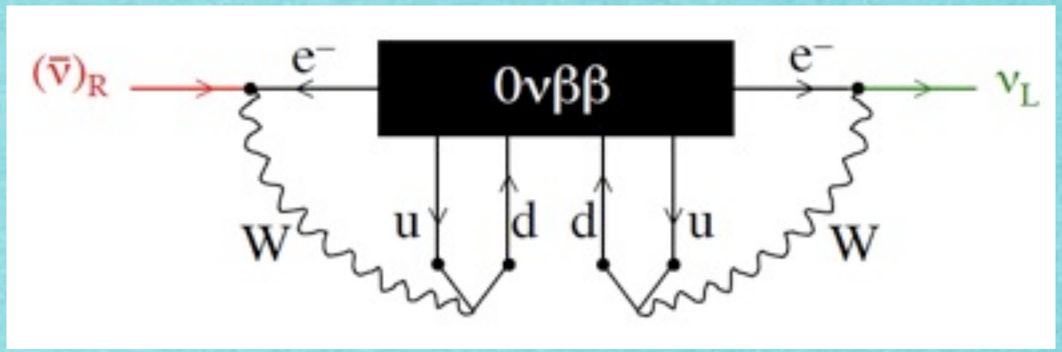
$$|\langle m_\nu \rangle| \equiv \left| \sum U_{ei}^2 m_i \right| < 0.2 \text{ eV}$$

"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.





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

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

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

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

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

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

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

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

$$|U_{\rm PMNS}| \sim \begin{pmatrix}0.8 & 0.5 & 0.2\\ 0.4 & 0.6 & 0.7\\ 0.4 & 0.6 & 0.7\end{pmatrix} \qquad |V_{\rm CKM}| \sim \begin{pmatrix}1 & 0.2 & 0.004\\ 0.2 & 1 & 0.04\\ 0.008 & 0.04 & 1\end{pmatrix}$$

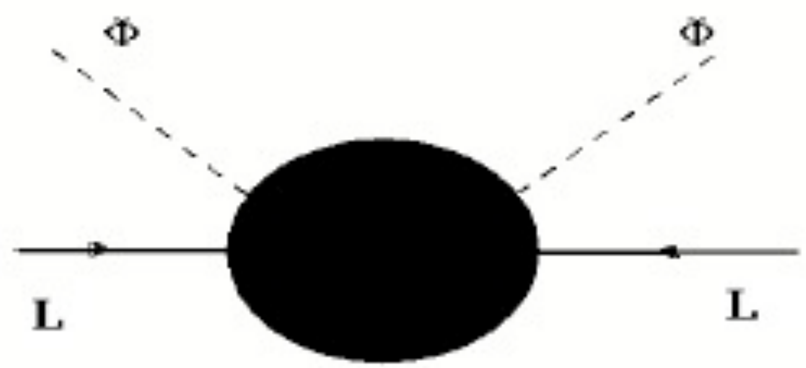
In the SM:

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

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

$$m_\nu = \lambda_0 \frac{\langle \Phi \rangle^2}{M_X},$$

(Majorana)

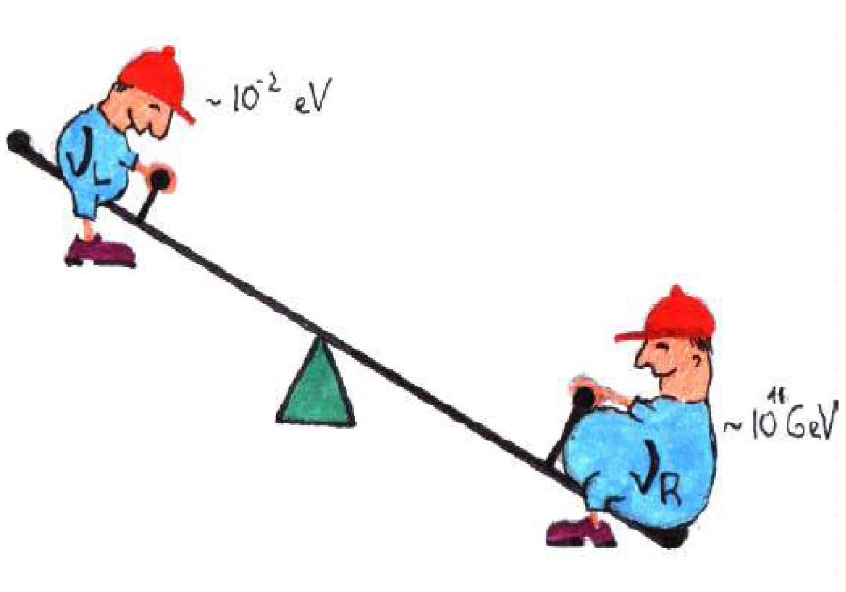
For $\lambda_0 \sim 1$, $\langle\Phi\rangle \sim 100$ GeV, $M_X \sim M_P$ $\rightarrow$ $m_\nu \sim 10^{-6}$ eV (too small)

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) ?

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



Type-I see-saw mechanism:

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

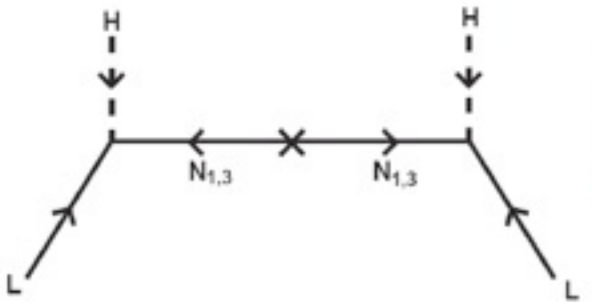
(naturally small?+Majorana)

(c) Without ν_R:

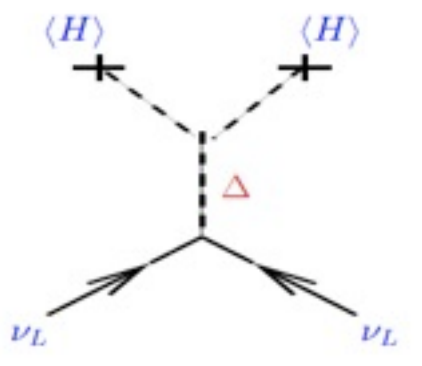
- **Majorana : tree level**

Minkowski 1977 Foot, Lew, He, Joshi 1989

Type (I,III) seesaw



$N_1 : (1,1,0)$
$N_3 : (1,3,0)$



Type II seesaw

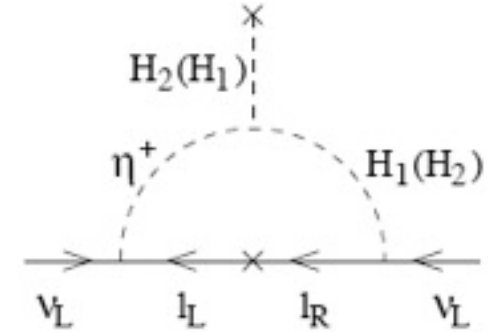
Schechter & Valle, 1980, 1982
Cheng & Li, 1980
Mohapatra, Senjanovic, 1981
...

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

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

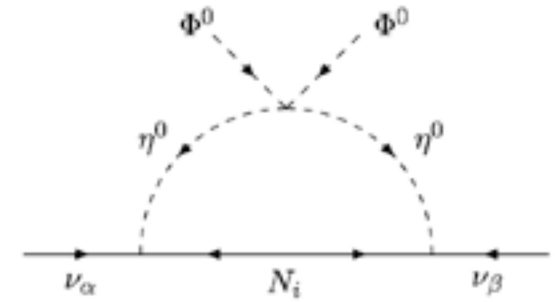
Majorana : loop level

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



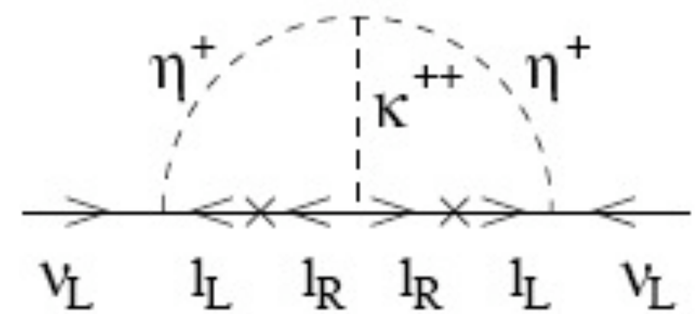
$$l^T \hat{f} i\sigma_2 l\eta^+ + \sum_{i=1,2} \bar{l}\hat{f}_i e H_i$$

- **Ma model (with fermion singlet and additional scalar doublet).**



- **Zee-Babu model (with doubly charged scalar singlet).**

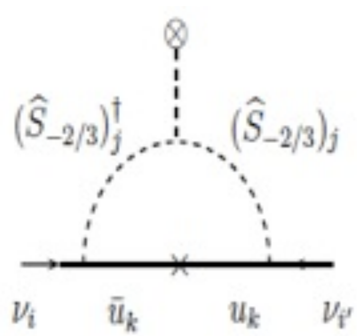
$$l^T \hat{f} l\eta^+ + l_R^T \hat{h} l_R k^{++}$$

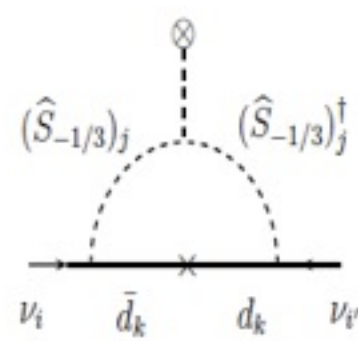


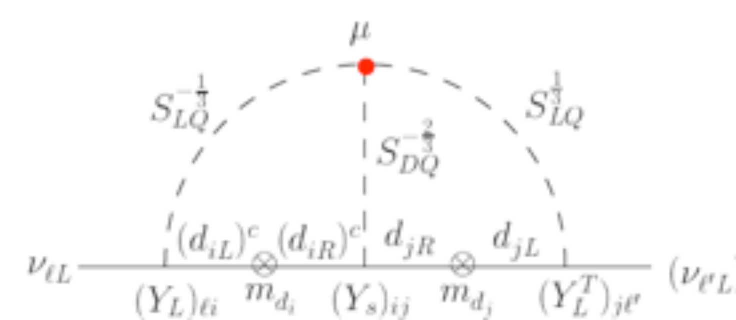
- **Other models:**

Hirsch et al. 1996, Aristizabal et al. 2008

Leptoquarks

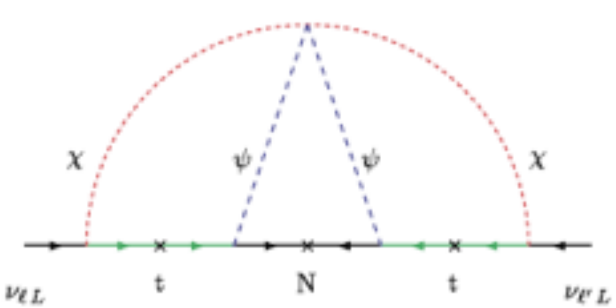






Top quark as a dark portal

John N. Ng, Alejandro de la Puente 2013



3-loop generation of a Majorana mass for active neutrinos from the t-quark.

See also the talk by Seto (3-loop?)

No 0νββ in these models

- Models with multi high charged scalars:

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}	$(1, 1, 2)$
$Q_a = (u_a, d_a)^T_L$	$(3, 2, 1/3)$
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)

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

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: $\Phi_1 \to \Phi_1$; $\Phi_2 \to -\Phi_2$; $T \to -T$; $L \to L$

~~LLT~~

C.S.Chen,CQG,PRD82,105004(2010)

$$
\begin{aligned}
V = & -\mu_1^2 \phi_1^\dagger \phi_1 + \lambda_1(\phi_1^\dagger\phi_1)^2 - \mu_2^2\phi_2^\dagger\phi_2 + \lambda_2(\phi_2^\dagger\phi_2)^2 \\
& - \mu_T^2 \mathrm{Tr}(T^\dagger T) + \lambda_T[\mathrm{Tr}(T^\dagger T)]^2 + \lambda_T' \mathrm{Tr}(T^\dagger T T^\dagger T) \\
& + m^2 \Psi^\dagger\Psi + \lambda_\Psi(\Psi^\dagger\Psi)^2 + \kappa_{\phi_1}\mathrm{Tr}(\phi_1^\dagger\phi_1 T^\dagger T) \\
& + \kappa_{\phi_1}'\phi_1^\dagger T T^\dagger \phi_1 + \kappa_{\Psi_1}\phi_1^\dagger\phi_1\Psi^\dagger\Psi \\
& + \kappa_{\phi_2}\mathrm{Tr}(\phi_2^\dagger\phi_2 T^\dagger T) + \kappa_{\phi_2}'\phi_2^\dagger T T^\dagger\phi_2 \\
& + \kappa_{\Psi_2}\phi_2^\dagger\phi_2\Psi^\dagger\Psi + \lambda_3\phi_1^\dagger\phi_1\phi_2^\dagger\phi_2 \\
& + \lambda_4\phi_1^\dagger\phi_2\phi_2^\dagger\phi_1 + \rho\,\mathrm{Tr}(T^\dagger T\Psi^\dagger\Psi) + (M\phi_1^T T^\dagger\phi_2 \\
& + \lambda_5\phi_1^\dagger\phi_2\phi_1^\dagger\phi_2 + \lambda\tilde{\phi}_1^\dagger T\tilde{\phi}_2^*\Psi + \mathrm{H.c.}),
\end{aligned}
$$

No effects for other couplings

For all non-Higgs like scalars with non-trivial $SU(2)_L \times U(1)_Y$ quantum #s, there are only three possible renormalizable Yukawa interactions:

~~$f_{ab}\bar{L}_a^c L_b s$~~ , $y_{ab}\bar{\ell}_{R_a}^c \ell_{R_b}\Psi$, ~~$g_{ab}\bar{L}_a^c L_b T$~~

(Colorless scalars)

Zee model — Zee-Babu model — Type-II seesaw

We will consider higher dimension multiplets so that no LL-like term is allowed in the Yukawa interaction

- **We replace s(T)=(1,1(3),2) by ξ=(1,N,2)**

C.S.Chen, CQG, D.Huang, H.H.Tsai, PRD87, 077702 (2013)

N>3 (=4, 5, 6, 7,…) is the quantum # under $SU(2)_L$ and Y=2 is the hypercharge with $Q_{em}=I_3+Y/2$

→ **Multi High Charged Scalars** **e.g. for N=5** ☞ $\xi=(\xi^{+++},\xi^{++},\xi^{+},\xi^{0},\xi^{-})^T$

enhance

Higgs → 2 photon

1.6 times of excess at the LHC

- **The scalar potential reads**

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

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 $\langle T^0\rangle \equiv \frac{v_T}{\sqrt{2}}$.

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

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

Two doubly charged scalars:

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

or for N=5 $\xi = (\xi^{+++}, \xi^{++}, \xi^{+}, \xi^{0}, \xi^{-})^T$

Mass eigenstates:

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

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

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

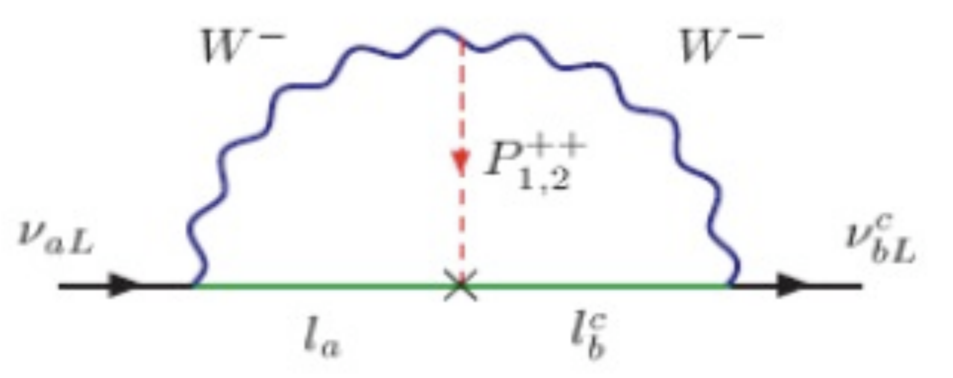
$$\omega \equiv \frac{M}{\sqrt{2}v_T}$$

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

- Majorana neutrino mass generations:

(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:

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

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

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

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

(ii) 0νββ decays:

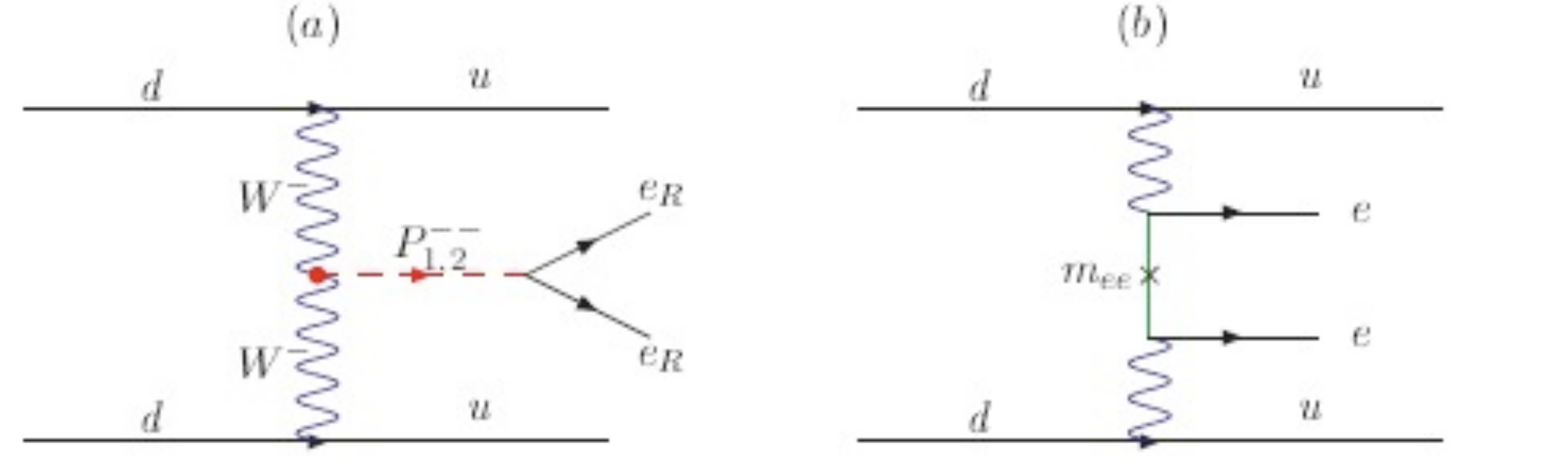


Figure 9: $0\nu\beta\beta$ decays via exchange of: (a) doubly charged Higgs and (b) light Majorana neutrinos.

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

»

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

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

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

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) Phenomenology:

Multi Charged Scalars

a. Lepton flavor physics:

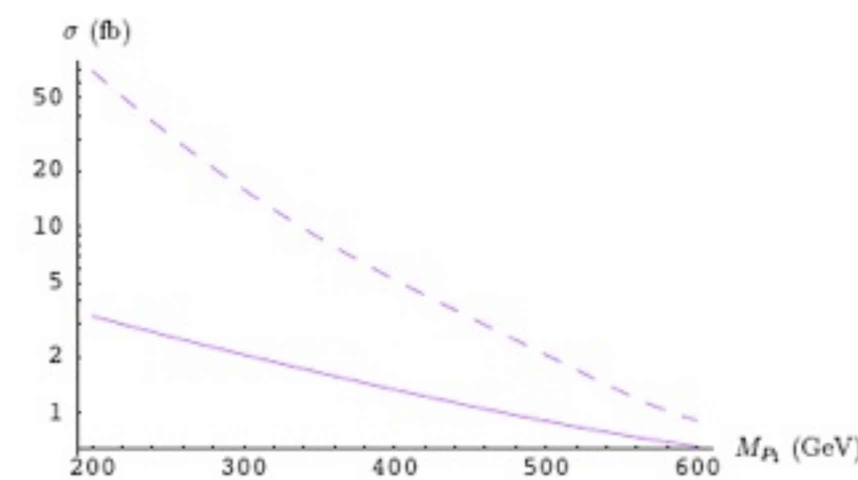
1. *Muonium anti-muonium conversion* $\mu^+e^- - \mu^-e^+$ $\quad H_{M\bar{M}} = \frac{Y_{ee}Y_{\mu\mu}}{2M^2_{--}}\bar{\mu}\gamma^\mu e_R \bar{\mu}\gamma_\mu e_R + h.c.,$

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

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

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

b. Doubly charged scalars at the LHC:



1 Production of the doubly charged Higgs

The WW fusion processes similar to 0νββ decays + the 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) $P_1^{\pm\pm} \to l^\pm_{aR}l^\pm_{bR} \quad (a, b = e, \mu, \tau)$,

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

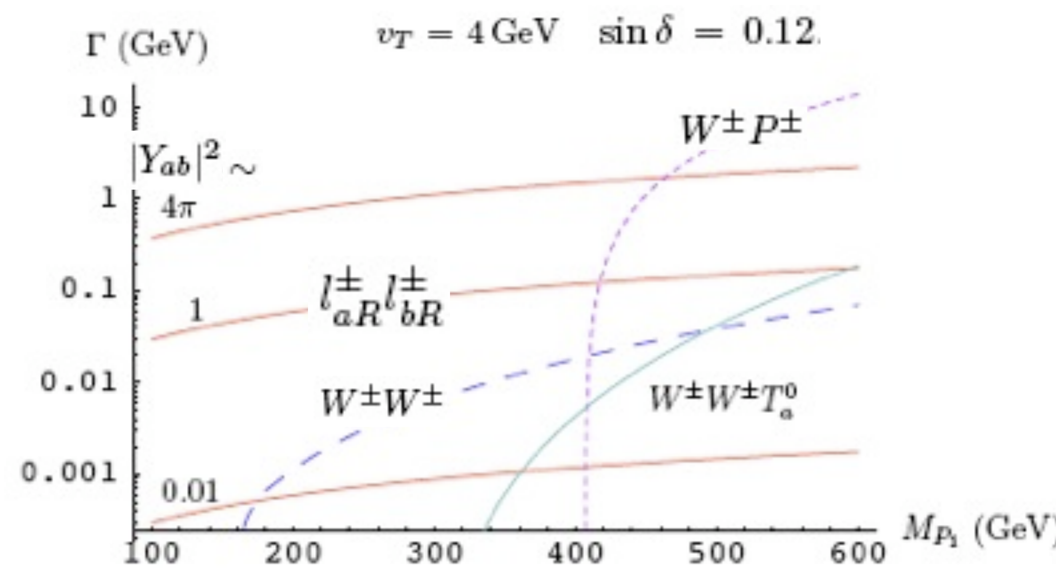
(3) $P_1^{\pm\pm} \to P^\pm W^\pm$,

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

(5) $P_1^{\pm\pm} \to W^\pm W^\pm X^0$, $\quad X^0 = T^0_a, h^0, P^0$

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

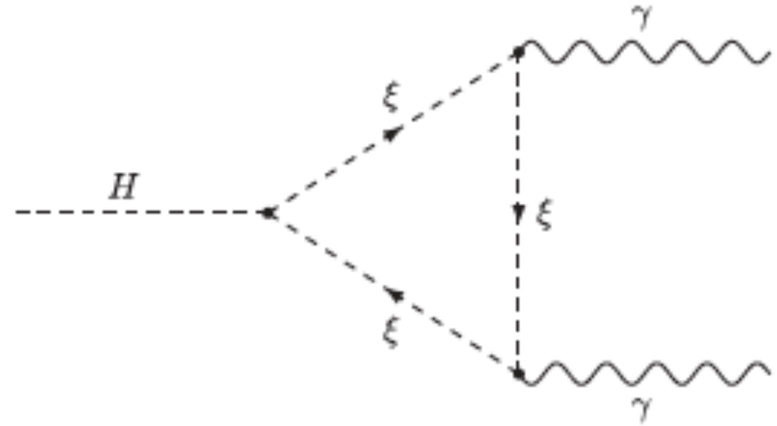
(4) and (6) are not allowed in our model.

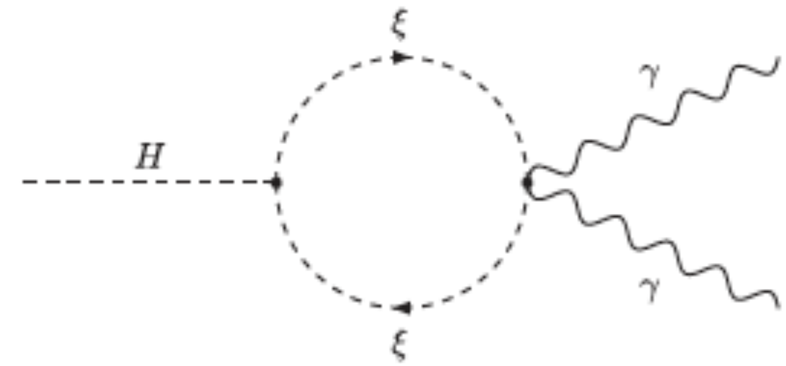


C.S.Chen+CQG+J.Ng+ J.Wu, JHEP0708, 22 (07)

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

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





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

C.S.Chen,CQG,D.Huang,H.H.Tsai, PRD87,077702 (2013)

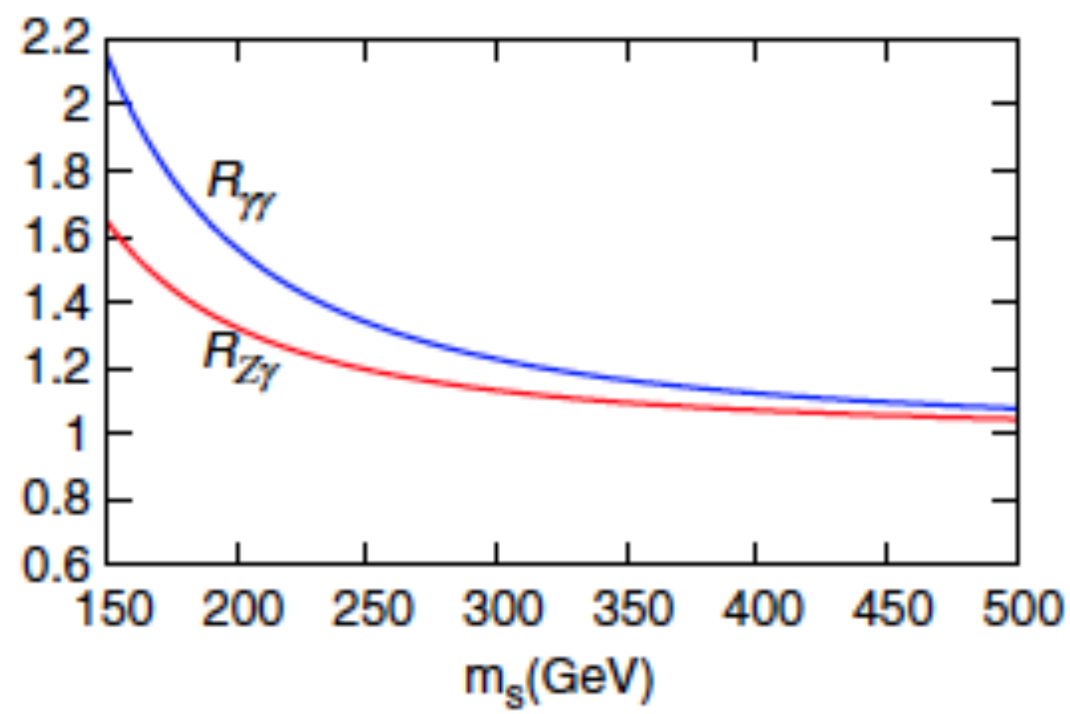


FIG. 4 (color online). $R_{\gamma\gamma}\equiv\Gamma(H\to\gamma\gamma)/\Gamma(H\to\gamma\gamma)_{\rm SM}$ and $R_{Z\gamma}\equiv\Gamma(H\to Z\gamma)/\Gamma(H\to Z\gamma)_{\rm SM}$ as functions of the degenerate mass factor m_s of the multicharged scalar states with $\mathbf{n}=\mathbf{5}$ and the universal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

● Summary

♥ **Models with multi high charged scalars are proposed with an $SU(2)_L$ multiplet and a doubly charged $SU(2)_L$ singlet.**

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

♦ **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 originated from the Majorana neutrino mass term can be ignored.

♥ **Rich physics for lepton flavor processes and unique signatures at the LHC due to the multi high charged scalars.**

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

Thank you!

謝謝！