Dark Matter and Radiatively Generated Neutrino Masses – A Model for Neutrino Masses and Dark Matter with a Discrete Gauge Symmetry.

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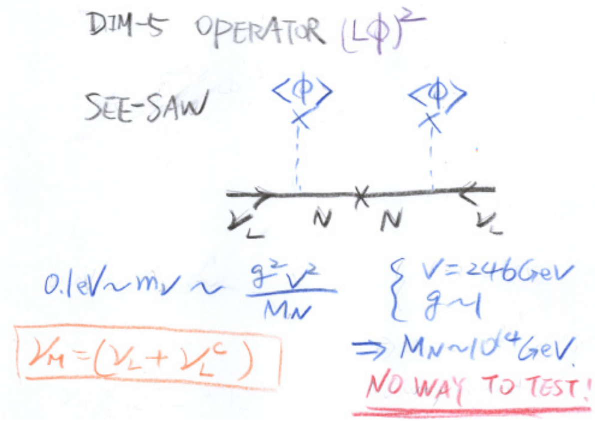
Outlines

- Model for neutrino mass and dark matter
- Our proposal and how it works
- Consequences
- Conclusion

Pressing Questions

- There is no RH neutrino in SM ⇒ No Yukawa (mass) for SM neutrino.
- Due to the accidental $U(1)_{B-L}$, the effective operator $(L\Phi)^2$ can NOT be generated by any quantum correction within SM.
- To generate nonzero neutrino masses, we need to go beyond SM.
  - How many extra degrees of freedom BSM?
  - Are they fermionic or bosonic?
  - Can the mechanism be tested?

Traditional See-Saw



DIM-5 OPERATOR $(L\phi)^2$

SEE-SAW

$0.1\,\mathrm{eV} \sim m_\nu \sim \frac{g^2 v^2}{M_N}$ $\left\{ \begin{array}{l} v = 246\,\mathrm{GeV} \\ g \sim 1 \end{array} \right.$

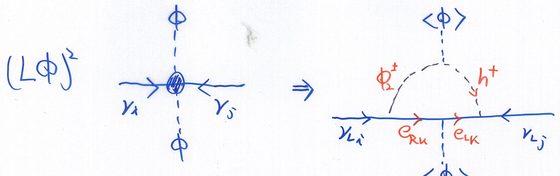
$\boxed{\nu_M = (\nu_L + \nu_L^c)}$ $\Rightarrow M_N \sim 10^{14}\,\mathrm{GeV}$

NO WAY TO TEST!

- Majarana mass of RH, M_N, breaks $B - L$.
- More than 2 fermionic DOFs.
- Direct test impossible.

Radiative generation

One way to lower the scale of new DOF: Radiative Mass Generation, Zee (1985), Zee, Babu (1988),...
How the representative "Wolfenstein-Zee-model" works:



New D.O.F : Φ_2 , $h^\pm$

$\cancel{(B-L)}$: $h\,\bar{L}^c L$ $\qquad 2\otimes 2 = \underbrace{1}_{\text{anti-sym}} \oplus 3$

* $m_{ij} \sim \left(\frac{1}{16\pi^2}\right) y^2 \frac{V^2}{M^2}\mu \sim \frac{1}{16\pi^2}\mu\frac{m_e^2}{M^2}$

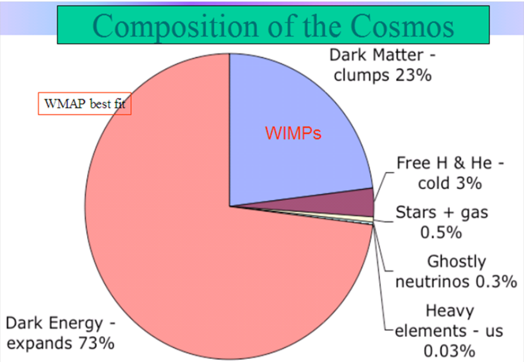
$\sim (10^{-2})_{\text{loop}} \cdot (\underline{100\,\text{GeV}}) \left(\frac{10^6\,\text{eV}}{\underline{100\,\text{GeV}}}\right)^2$

* Anti-Sym $\Rightarrow m_{ij} = \begin{pmatrix} 0 & \times & \times \\ \times & 0 & \times \\ \times & \times & 0 \end{pmatrix} \Rightarrow$ bi-maximal mixing

Radiative generation 2

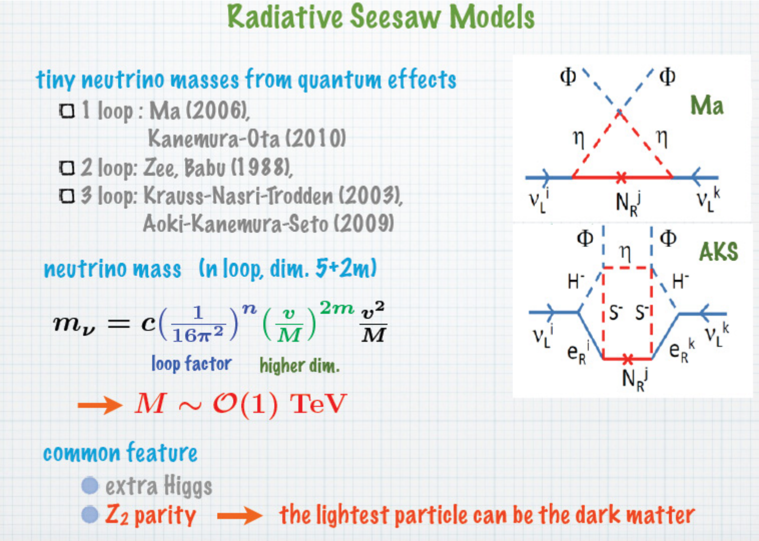
- The masses of new DOF are totally arbitrary. But more likely to be tested in some parameter space.
- There are many other proposals to generate neutrino masses with possible accessible parameter configuration.
- A unified mechanism such that the mass scale of new DOF is not totally arbitrary?

Dark universe



- What are the DM and DE?
- DM must be electrically neutral and long lived.
- DM = One of the new DOF for M_ν?

From the talk given by Takashi Shimomura at KEKPH2011.



Radiative Seesaw Models

tiny neutrino masses from quantum effects

- ☐ 1 loop : Ma (2006),
  Kanemura-Ota (2010)
- ☐ 2 loop: Zee, Babu (1988),
- ☐ 3 loop: Krauss-Nasri-Trodden (2003),
  Aoki-Kanemura-Seto (2009)

neutrino mass (n loop, dim. 5+2m)

$$m_\nu = c\underbrace{\left(\frac{1}{16\pi^2}\right)^n}_{\text{loop factor}}\underbrace{\left(\frac{v}{M}\right)^{2m}}_{\text{higher dim.}}\frac{v^2}{M}$$

→ $M \sim \mathcal{O}(1)$ TeV

common feature

- extra Higgs
- Z_2 parity → the lightest particle can be the dark matter

Common origin of the TeV Majorana mass and Z_2?

- Where comes the Z_2?
- It is not respected by the gravity anyway!
  e.g.: throw a Z2 odd particle into a black hole and comes out Z2 even Hawking radiation.
- Can we cook up a model which has a unified origin for the TeV Majorana mass and the Z_2 to stabilize the Dark Matter?
- The answer is confirmative. By using the Krauss-Wilczek Mechanism, PRL62,1221 (1989).

Krauss-Wilczek Mechanism

U(1) local transformation

$\psi_Q \to \exp[-i\, Q\, \alpha(x,t)]\, \psi_Q$

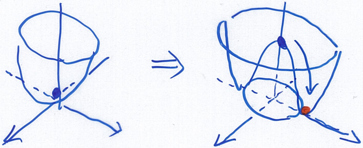
α is universal

$Q \sim$ diff ω

$D_\mu \psi = [\partial_\mu - i Q A_\mu]\, \psi$

$A_\mu \to A_\mu + \partial_\mu \alpha$

SSB by a scalar S. with $Q_S = 2$



VEV is inv. under a 2π rotation $\langle S \rangle = e^{2\pi i} \langle S \rangle$

But $\psi_{Q=1} \to e^{i\pi} \psi_{Q=1} = (-1)\, \psi_{Q=1} \Rightarrow Z_2$-parity

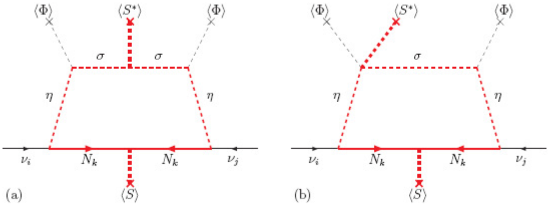
Charge assignment

	Q_L	u_R	d_R	L	e_R	N_{Ra}	n_{Lb}	Φ	η	σ	S
$SU(2)_L$	2	1	1	2	1	1	1	2	2	1	1
$U(1)_Y$	$\frac{1}{6}$	$\frac{2}{3}$	$-\frac{1}{3}$	$-\frac{1}{2}$	-1	0	0	$\frac{1}{2}$	$\frac{1}{2}$	0	0
$U(1)_\nu$	0	0	0	0	0	-1	-1	0	-1	-1	2
$Z_{2\nu}$	$+$	$+$	$+$	$+$	$+$	$-$	$-$	$+$	$-$	$-$	$\times$

- Charge assignment and the remaining discrete $Z_{2\nu}$ parity for the fields, where Q_L, u_R, d_R, L, e_R are the standard notation for SM quark and lepton.
- No tree-level Majorana mass before SSB of $U(1)_\nu$.
- As always, there is price to pay to simplify things.

Active neutrino mass

- Active neutrino masses arise from the 1-loop diagrams



- dim-7 operator $(\Phi L)^2 S^\dagger S$ (dominated by diag-(b))

$$\mathcal{M}^{\nu}_{ij} \sim \frac{1}{16\pi^2}\frac{\kappa\mu_2 v_\Phi^2 v_S^2}{\Lambda^4}\sum_a y_a^N g^*_{ia} g^*_{ja} \sim 0.001 \times \frac{|g|^2}{16\pi^2}\mu_2$$

for $\Lambda \sim v_S \sim$TeV, $\kappa y \sim 0.1$, and $\mu_2 \sim 0.1$TeV,
$g \sim 10^{-4} \sim 10 m_e/v$

Masses of new fermionic DOF

- The $U(1)_\nu$ allowed Yukawa and the Dirac mass

$$\frac{y_a^N}{2}\overline{N_a^C}SN_a + \frac{y_a^n}{2}\overline{n_a^C}Sn_a + g_{ia}\overline{L_i}\tilde{\eta}N_a + m^D_{ab}\bar{n}_a N_b + h.c.$$

- What value should m^D take? (Traditional see-saw does not have this term.)
- In principle, any will do!
- If the first two terms were absent (or $y^N = y^n = 0$), the $U(1)_A$ symmetry

$$N_R \to e^{i\theta} N_R\,,\ e_L \to e^{-i\theta} n_L$$

  forbids the Dirac mass!
- SSB of $U(1)_\nu$ suggests a 'NATURAL' values of $m^D \sim y\langle S\rangle$. Or, simply because it is phenomenologically interesting.

Singlet fermion masses

- Let's consider only one pair of vector fermion N_R and n_L.
- After SSB, the fermionic DOF take the following mass matrix:

$$\mathcal{L} \supset \frac{1}{2} \left(\overline{n_L^{\mathbf{c}}}, \overline{N_R} \right) \begin{pmatrix} g^n v_S & m^D \\ m^D & g^N v_S \end{pmatrix} \begin{pmatrix} n_L \\ N_R^{\mathbf{c}} \end{pmatrix} + h.c.$$

Two eigenvalues:
$\frac{1}{4} \left[v_S (g^N + g^n) \pm \sqrt{v_S^2 (g^N - g^n)^2 + (m^D)^2} \right]$

- Two mass eigenstate Majorana fermions:

$$\begin{aligned} \chi_1 &= \cos\theta (n_L + n_L^{\mathbf{c}}) - \sin\theta (N_R + N_R^{\mathbf{c}}) = \chi_1^{\mathbf{c}} \\ \chi_2 &= \sin\theta (n_L + n_L^{\mathbf{c}}) + \cos\theta (N_R + N_R^{\mathbf{c}}) = \chi_2^{\mathbf{c}} \\ \tan 2\theta &= \frac{m^D}{v_S (g^n - g^N)} \end{aligned}$$

Is one pair of vector fermion enough?

- If there is only one pair of $N - n$, the resulting active neutrino mass matrix is proportional to

$$\mathcal{M}^{\nu}_{ij} \propto \begin{pmatrix} g_1^2 & g_1 g_2 & g_1 g_3 \\ g_2 g_1 & g_2^2 & g_2 g_3 \\ g_3 g_1 & g_3 g_2 & g_3^2 \end{pmatrix}$$

- The eigenvalues are $\{0, 0, g_1^2 + g_2^2 + g_3^2\}$
- Need at least two pairs of $N - n$.
- 4 massive Majorana fermions, χ_{1-4}, large mixing between the N_R and n_L sectors.

Effective potential

- After the S get a VEV, we integrate out the heavy degree of freedom.
- The potential becomes

$$\begin{aligned} V_{eff} &= \mu_\Phi^2|\Phi|^2 + \mu_\eta^2|\eta|^2 + \mu_\sigma^2|\sigma|^2 + \lambda_1|\Phi|^4 + \lambda_2|\eta|^4 + \lambda_3|\sigma|^4 \\ &+ \lambda_5|\Phi|^2|\eta|^2 + \lambda_6|\Phi^\dagger\eta|^2 + \lambda_7|\Phi|^2|\sigma|^2 + \lambda_9|\eta|^2|\sigma|^2 \\ &+ \kappa v_S(\Phi^\dagger\eta\sigma) + \mu_1 v_S(\sigma\sigma) + \mu_2(\eta^\dagger\Phi\sigma) + h.c. \end{aligned}$$

- It's easy to have the solution that $\langle\Phi\rangle = 246$GeV, $\langle\eta\rangle = \langle\sigma\rangle = 0$.
- Due to the Z_2, SM Higgs does NOT mix with the η and σ
  - 3 out of 4 D.O.F. are the would be Goldstone bosons.
  - One Z2-even SM Higgs.
  - Z2-odd: 2 Charged, 2 Scalars, 2 Pseudoscalars.

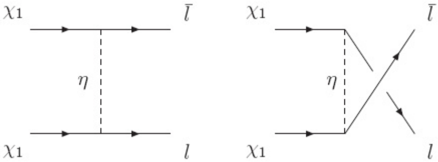
Majorana Dark Matter

- Which DOF is the DM?
- Equations

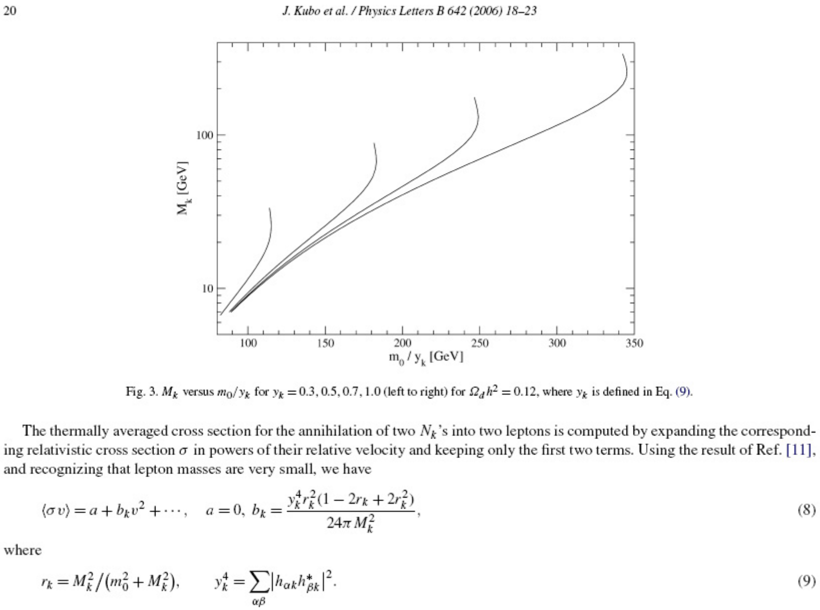
$$\left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G}{3}\rho$$

$$\frac{dn}{dt} + 3Hn = -\langle\sigma_{ann} v_{rel}\rangle(n - n_{eq})$$

- Roughly speaking, the relic density $\Omega_{DM} h^2 \propto 1/\langle\sigma_{ann} v_{rel}\rangle$.
- annihilation for Majorana fermion



Majorana Dark Matter relic density



20 J. Kubo et al. / Physics Letters B 642 (2006) 18–23

Fig. 3. M_k versus m_0/y_k for $y_k = 0.3, 0.5, 0.7, 1.0$ (left to right) for $\Omega_d h^2 = 0.12$, where y_k is defined in Eq. (9).

The thermally averaged cross section for the annihilation of two N_k's into two leptons is computed by expanding the corresponding relativistic cross section σ in powers of their relative velocity and keeping only the first two terms. Using the result of Ref. [11], and recognizing that lepton masses are very small, we have

$$\langle \sigma v \rangle = a + b_k v^2 + \cdots, \quad a = 0, \; b_k = \frac{y_k^4 r_k^2 (1 - 2r_k + 2r_k^2)}{24\pi M_k^2}, \tag{8}$$

where

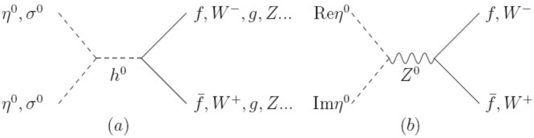
$$r_k = M_k^2 / (m_0^2 + M_k^2), \qquad y_k^4 = \sum_{\alpha\beta} |h_{\alpha k} h_{\beta k}^*|^2. \tag{9}$$

Not χ_1

- Given that $g \sim 10^{-4}$, $M_\eta \ll M_\chi$ is required to yield $\Omega_{\chi_1} h^2 \sim 0.11$
- $M_{\chi_{1-4}} > M_\eta$
- All the four Majorana decay into η and SM leptons (through Yukawa and the n_L and N_R mixing).
- Either H_1 or A_1 is the viable dark matter candidate.
- All the heavier $Z_{2\nu}$-odd scalars decay into SM $W^\pm/Z^0$ plus H_1 or A_1.

Scalar Dark Matter

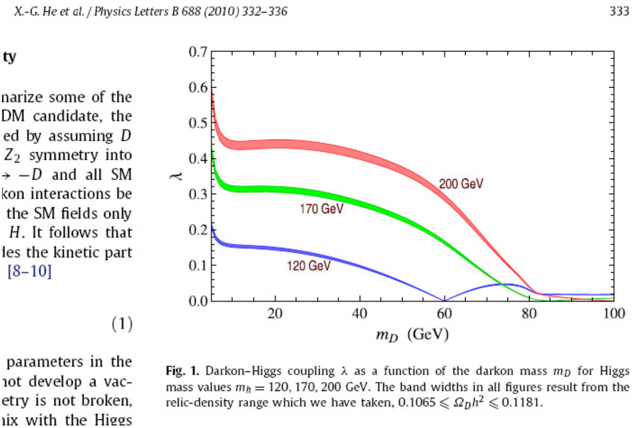
- diagrams for (co)-annihilation cross section



$$\sigma_{ann} v_{rel} = \frac{8\lambda^2 v_\Phi^2 \sum_i \Gamma(h^0 \to X_i)}{(4M_S^2 - m_{h^0}^2)^2 + \Gamma_{h^0}^2 m_{h^0}^2} \frac{1}{2M_S} ,$$

- $\Gamma(h^0 \to X_i)$ is the rate for the virtual Higgs decays into X_i.
- $M_S \gg m_h$, the hh, WW, ZZ channels open up.
- Almost everything about the scalar DM has been studied in the past 25 years.

Scalar Dark Matter relic density



X.-G. He et al. / Physics Letters B 688 (2010) 332–336 333

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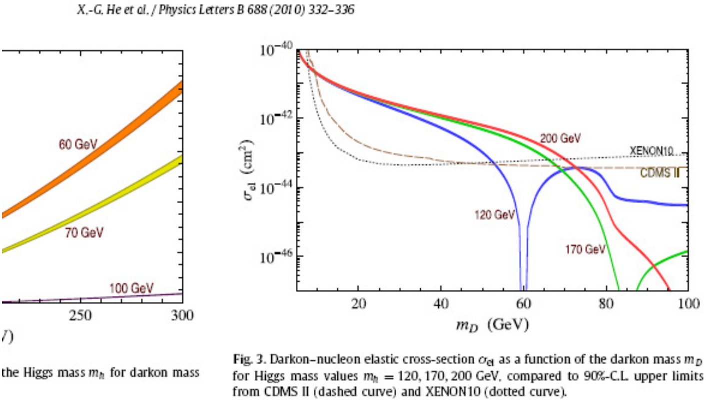
Fig. 1. Darkon–Higgs coupling λ as a function of the darkon mass m_D for Higgs mass values $m_h = 120, 170, 200$ GeV. The band widths in all figures result from the relic-density range which we have taken, $0.1065 \leqslant \Omega_D h^2 \leqslant 0.1181$.

Scalar Dark Matter direct detection-1



X.-G. He et al. / Physics Letters B 688 (2010) 332–336

the Higgs mass m_h for darkon mass

Fig. 3. Darkon–nucleon elastic cross-section σ_{el} as a function of the darkon mass m_D for Higgs mass values $m_h = 120, 170, 200$ GeV, compared to 90%-C.L. upper limits from CDMS II (dashed curve) and XENON10 (dotted curve).

Scalar Dark Matter direct detection-2

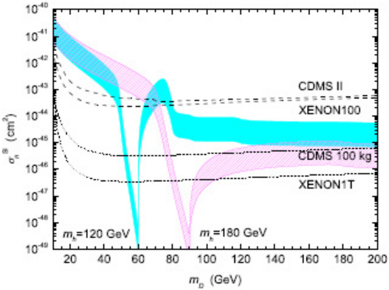


FIG. 2: The predicted DM-nucleon elastic scattering cross section $\sigma_n^{\rm SI}$ for 10 GeV $\leq m_D \leq$ 200 GeV in the SSDM-SM. The dashed lines indicate the current experimental upper bounds from the CDMS II [25] and XENON100 [29]. The short dotted lines denote the future experimental upper bounds from the CDMS 100 kg [30] and XENON1T [31].

Scalar Dark Matter

- Plenty of parameter space to make the scalar dark matter viable and could be directly detected at the underground laboratories in the near future.
- mass M_S and λ are strongly correlated, and such tight relation unexplained in the general scalar dark matter models. (Neither in ours)

Conclusions

- Singlet fermions acquire Majorana masses via $U(1)_\nu$ breaking at TeV scale.
- Active neutrino masses arise from 1-loop diagrams, equivalent to a dim-7 operator, without much fine tuning.
- Z_2 discrete gauge symmetry a la Krauss-Wilczek stabilize the dark matter candidate
- Thermal relic density of the lightest Z_2-odd scalar can explain the observed dark matter abundance.
- New degrees of freedom can be probed at TeV scale.
- Neutrino flavor problem not addressed in this model.

Backup-1: Side Remarks

- The usual leptogenesis mechanism does not work. The Yukawa coupling too large to be out of equilibrium,

$$\sum |g|^2 \leq 8\pi\sqrt{4\pi^3 g_*/45}(M_\chi/M_{Planck}) \sim 10^{-14}$$

- To utilize the TeV scale singlet fermions for leptogenesis requires extra arrangement such as the resonance leptogenesis (Pilaftsis, 03) or via the 3 body decay mechanism (Hambye, 01). But fine tuning is then unavoidable.
- The $Z_{2\nu}$-odd scalar sector still helps to get a stronger first order EW phase transition which is crucial for EWBAU.

Backup-2: Z' at the LHC

- A new term can be added (PRD74:095005,2006.)

$$-\frac{\epsilon}{2}B^{\mu\nu}X_{\mu\nu}$$

- Drell-Yan Production at LHC, $q(p)+\bar{q}(p)\rightarrow Z'^{*}\rightarrow X$
- Definite relative decay BRs :

$$B(Z'_\nu\rightarrow u\bar{u}):B(Z'_\nu\rightarrow d\bar{d}):B(Z'_\nu\rightarrow e\bar{e}):B(Z'_\nu\rightarrow \nu\bar{\nu}) \\ =5.63:1.66:4.99:1\ \ (\epsilon=0.07)$$

- When χ_1 and H_1, A_1 are much lighter than Z'_ν, $Z'_\nu\rightarrow\chi_1\chi_1, H_1H_1, A_1A_1$ will become the dominate decay channels.

Backup-3: Lepton Flavor violation

- When neutrino are massive, lepton flavor is no longer conserved.
- For example, $\mu \rightarrow e\gamma$, $\mu \rightarrow 3e$ could happen.
- However, $Br(\mu \rightarrow e\gamma) < 10^{-12}$
- $\mu \rightarrow e\gamma$ arises from the dim-6 operator, active neutrinos play no role(GIM).

$$\bar{L}\Phi\sigma^{\mu\nu} e_R F_{\mu\nu}$$

- The branching ratio can be estimated

$$\frac{Br(\mu \rightarrow e\gamma)}{Br(\mu \rightarrow e\bar{\nu}_e\nu_\mu)} \sim \left(\frac{e|g_{\mu k}g_{ke}|}{(16\pi^2)G_F\Lambda^2}\right)^2 \sim 10^{-8} \times |g_{\mu k}g_{ke}|^2 \times \left(\frac{1\mathrm{TeV}}{\Lambda}\right)^4$$

No problem with $g \sim 10^{-4}$.

Backup-4: Searches

- The lightest scalar and pseudoscalar can be pair produced associated with the SM Higgs through the $h^0 H_1 H_1, h^0 A_1 A_1$ vertices, or $H_1 A_1$ can be produced via the $Z^0 H_1 A_1$ coupling.
- For the charged Higgs, it can be produced at the LHC via $pp \to W^{\pm *} \to H_1 H^{\pm}, A_1 H^{\pm}$ or $pp \to \gamma^* / Z^{0*} \to H^{\mp} H^{\pm}$.
- The lightest Majorana fermion χ_1 is most likely to be studied via the $U(1)_\nu$ gauge boson decay.