Connection between Proton Decay and Neutrino Mass

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Outline

- Introduction
- Concept of connection between neutrino mass and proton decay
- Three models for three scenarios
- Constraints and Remarks
- Conclusion

Introduction

- SM has been established by numerous experimental tests, yet evidences on neutrino mass via neutrino oscillation, the mystery of dark matter, and baryon asymmetry of the universe call for BSM.

- While the proton is considered a stable particle in the renormalizable SM due to the conservation of baryon number, numerous BSM models predict proton decay mediated by new particles.
  - GUTs serve as representative examples, suggesting proton decay with a lifetime closely tied to the grand unification scale.

- The experiments dictate the proton lifetime to be more than 10^{30} -10^{34} yrs.

Introduction

- Massive neutrinos demand BSM physics.
  - we need to explore mechanisms for tiny neutrino masses, distinct from the conventional approach to other fermions.
- The scale of BSM physics may be the origin of smallness of neutrino masses.
- The most popular mechanism to generate tiny neutrino masses is seesaw mechanism at tree level.
- The scotogenic scenario is a good alternative to the seesaw mechanism, where tiny neutrino masses can be obtained by radiative 1-loop corrections and a dark matter candidate is naturally accommodated.

Connection between Neutrino Mass and Proton Decay

- Usually, generation of neutrino mass and proton decay have been considered as separate problems.

- Our proposal is that the origin of neutrino masses is connected with the life time of the proton.

  → Smallness of the neutrino masses and Longevity of the proton are connected or stem from the same source.

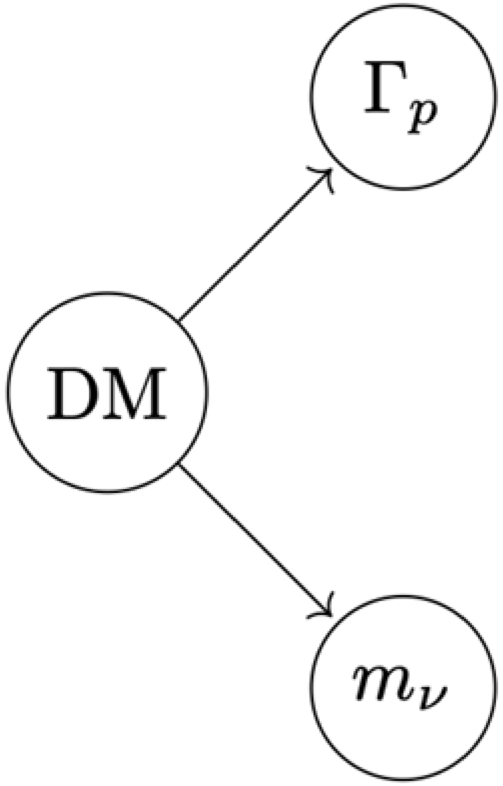
Connection between Neutrino Mass and Proton Decay

Three possible scenarios

- One source generates two effects:
  tiny neutrino masses and long proton lifetime,
  which are correlated.

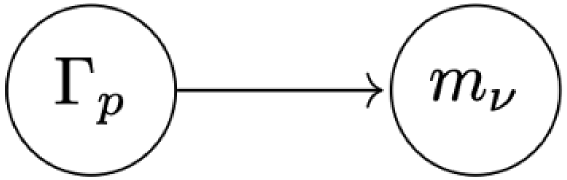
  - the source is dark matter that leads to
    both radiative neutrino mass origin
    and radiative proton decay operator.

  - If the source vanishes, both the neutrino mass
    and the proton decay width approach zero.

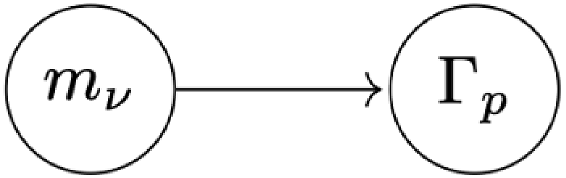


Connection between Neutrino mass and Proton Decay

- Proton decay serves as the source and
  the neutrino mass is induced.
  - As a consequence, radiative neutrino mass is generated from the proton decay operator, giving rise to a correlation between the two.



- The source is the neutrino mass and
  the proton decay is induced, which vanishes in the limit of massless neutrino.



Models for Each Scenario

- First Scenario

- Both the longevity of the proton and the smallness of the neutrino mass are naturally achieved through the dark matter.

- Field content of the model with symmetries

Fields	$SU(3)_c$	$SU(2)_L$	$U(1)_Y$	$\mathbb{Z}_2$
Q	$\mathbf{3}$	$\mathbf{2}$	$\frac{1}{6}$	$+$
$\bar{u}$	$\bar{\mathbf{3}}$	$\mathbf{1}$	$-\frac{2}{3}$	$+$
$\bar{d}$	$\bar{\mathbf{3}}$	$\mathbf{1}$	$\frac{1}{3}$	$+$
L	$\mathbf{1}$	$\mathbf{2}$	$-\frac{1}{2}$	$+$
$\bar{e}$	$\mathbf{1}$	$\mathbf{1}$	1	$+$
N	$\mathbf{1}$	$\mathbf{1}$	0	$-$
$D, \bar{D}^\dagger$	$\mathbf{3}$	$\mathbf{1}$	$-\frac{1}{3}$	$-$
H	$\mathbf{1}$	$\mathbf{2}$	$\frac{1}{2}$	$+$
$\tilde{R}_{2D}$	$\mathbf{3}$	$\mathbf{2}$	$\frac{1}{6}$	$-$
η	$\mathbf{1}$	$\mathbf{2}$	$-\frac{1}{2}$	$-$

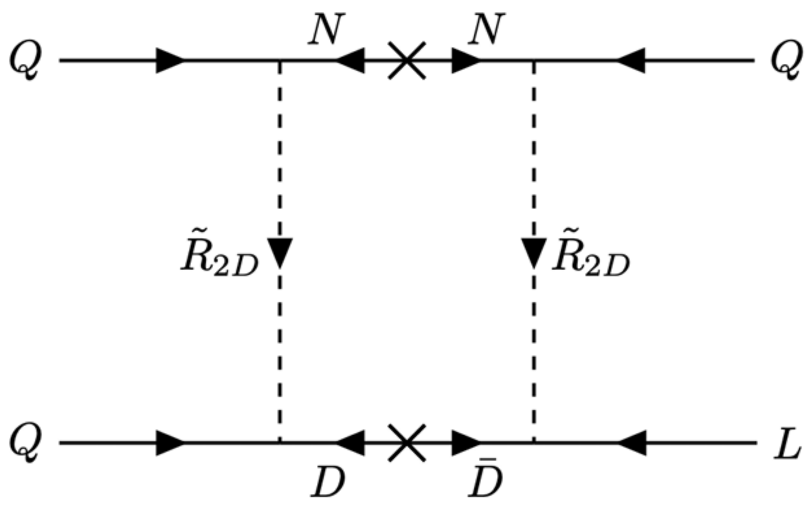
N : dark matter (heavy singlet Neutrino)
$D, \bar{D}^\dagger$: VL EW singlet quarks
$\tilde{R}_{2D}$: scalar leptoquark

-First Scenario

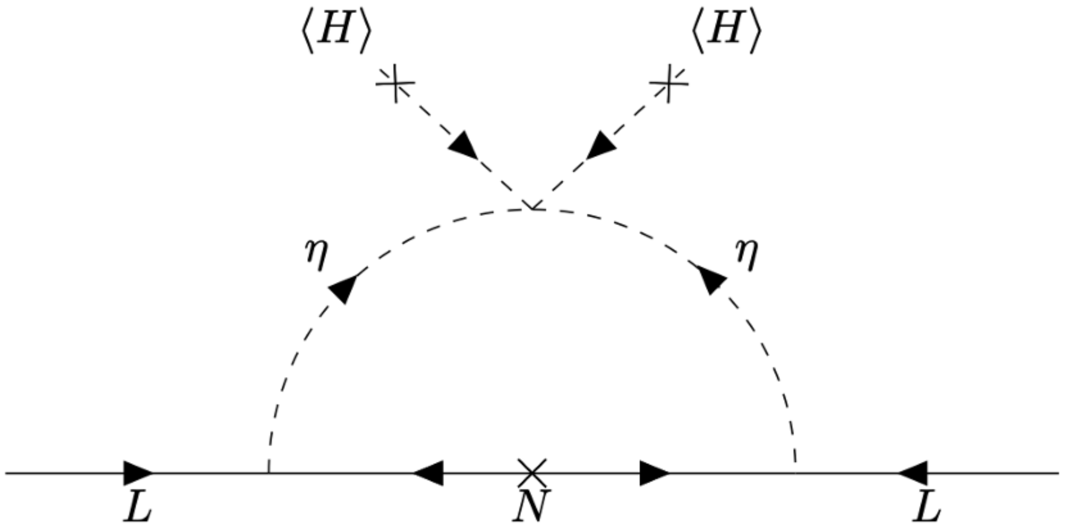
$$
\begin{aligned}
-\mathcal{L}_{\rm BSM}^{\rm Yuk} &= Y_1 \bar{D} L \tilde{R}_{2D} + Y_2 Q N \tilde{R}_{2D}^{\dagger} + Y_3 Q D \tilde{R}_{2D} \\
&+ Y_4 L N \eta^{\dagger} + Y_5 Q \bar{D} \eta \\
&+ M_N N N + M_D D \bar{D} + \text{h.c.}, \\
V &= m_H^2 \left(H^{\dagger} H\right) + m_{\eta}^2 \left(\eta^{\dagger} \eta\right) + m_R^2 \left(\tilde{R}_{2D}^{\dagger} \tilde{R}_{2D}\right) \\
&+ \lambda_H \left(H^{\dagger} H\right)^2 + \lambda_{\eta} \left(\eta^{\dagger} \eta\right)^2 + \lambda_R \left(\tilde{R}_{2D}^{\dagger} \tilde{R}_{2D}\right)^2 \\
&+ \lambda_R' \left(\tilde{R}_{2D}^{\dagger} \tilde{R}_{2D} \tilde{R}_{2D}^{\dagger} \tilde{R}_{2D}\right) + \lambda_{H\eta} \left(H^{\dagger} H\right) \left(\eta^{\dagger} \eta\right) \\
&+ \lambda_{H\eta}' \left(H^{\dagger} \eta\right) \left(\eta^{\dagger} H\right) + \lambda_{HR} \left(H^{\dagger} H\right) \left(\tilde{R}_{2D}^{\dagger} \tilde{R}_{2D}\right) \\
&+ \lambda_{HR}' \left(H^{\dagger} \tilde{R}_{2D}\right) \left(\tilde{R}_{2D}^{\dagger} H\right) \\
&+ \lambda_{\eta R} \left(\eta^{\dagger} \eta\right) \left(\tilde{R}_{2D}^{\dagger} \tilde{R}_{2D}\right) + \lambda_{\eta R}' \left(\eta^{\dagger} \tilde{R}_{2D}\right) \left(\tilde{R}_{2D}^{\dagger} \eta\right) \\
&+ \left(\lambda H H \eta \eta + \lambda_{3R} \tilde{R}_{2D} \tilde{R}_{2D} \tilde{R}_{2D} \eta + \text{h.c.}\right)
\end{aligned}
$$

-First Scenario

- Feynman diagram of Proton Decay



- Feynman diagram of Neutrino Mass



$$\Gamma\left(p \to e^+\pi^0, \nu_\alpha^\dagger \pi^+\right) = \frac{m_p}{512\pi^3}\left(1 - \frac{m_\pi^2}{m_p^2}\right)^2 \Bigg| Y_2^{1a}\frac{M_N^{ab}}{m_R} Y_2^{b1} Y_3^{1c} \frac{M_D^{cd}}{m_R} Y_1^{d\alpha} \frac{W_0^l\left(p \to e^+\pi^0, \nu^\dagger\pi^+\right)}{m_R^2}$$
$$\times \left[F_0(x_N, x_D, y) + F_1(x_N, x_D, y)\frac{q^2}{m_R^2}\right]\Bigg|^2,$$

- Proton decay matrix elements and exchanged momentum between the proton's quarks during decay process are obtained from the lattice calculations (PRD96 (2017)014506)

$$W_0^e(p \to e^+\pi^0) = \langle \pi^0 | (ud)_L u_L |p\rangle = 0.134(5)(16)\ \mathrm{GeV}^2$$

$$q^2 = 0.2\ \mathrm{GeV}^2$$

$$W_0^\nu(p \to \nu^\dagger\pi^+) = \langle \pi^+ | (du)_L d_L |p\rangle = 0.189(6)(22)\ \mathrm{GeV}^2$$

- Neutrino Masses:

$$m_\nu^{ij} = \frac{1}{32\pi^2} Y_4^{ik} M_{N_k} Y_4^{kj} \left[f\left(\frac{m_{\eta_R}^2}{M_{N_k}^2}\right) - f\left(\frac{m_{\eta_I}^2}{M_{N_k}^2}\right) \right]$$

$$\approx -\frac{1}{16\pi^2}\frac{\lambda v^2}{M_\eta^2} Y_4^{ik} M_{N_k} Y_4^{kj},$$

$$f(x) = \tfrac{x}{1-x}\ln x \text{ and } M_\eta^2 = \tfrac{m_{\eta_R}^2 + m_{\eta_I}^2}{2}.$$

-Second Scenario

- The proton decay operators induce neutrino masses at loop level.

- If the proton's lifetime is large, as a consequence, the neutrino masses become tiny.

- Field content of the model with symmetries ($F = 3B - L$)

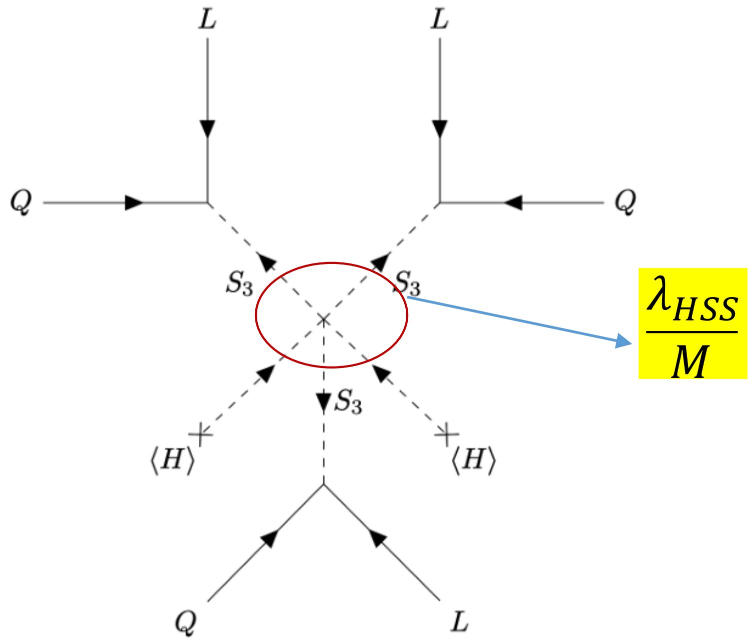
Fields	$SU(3)_c$	$SU(2)_L$	$U(1)_Y$	$U(1)_F$
Q	$\mathbf{3}$	$\mathbf{2}$	$\frac{1}{6}$	1
$\bar{u}$	$\bar{\mathbf{3}}$	$\mathbf{1}$	$-\frac{2}{3}$	-1
$\bar{d}$	$\bar{\mathbf{3}}$	$\mathbf{1}$	$\frac{1}{3}$	-1
L	$\mathbf{1}$	$\mathbf{2}$	$-\frac{1}{2}$	-1
$\bar{e}$	$\mathbf{1}$	$\mathbf{1}$	1	1
H	$\mathbf{1}$	$\mathbf{2}$	$\frac{1}{2}$	0
S_3, S_3'	$\bar{\mathbf{3}}$	$\mathbf{3}$	$\frac{1}{3}$	$0, 2$

-Second Scenario

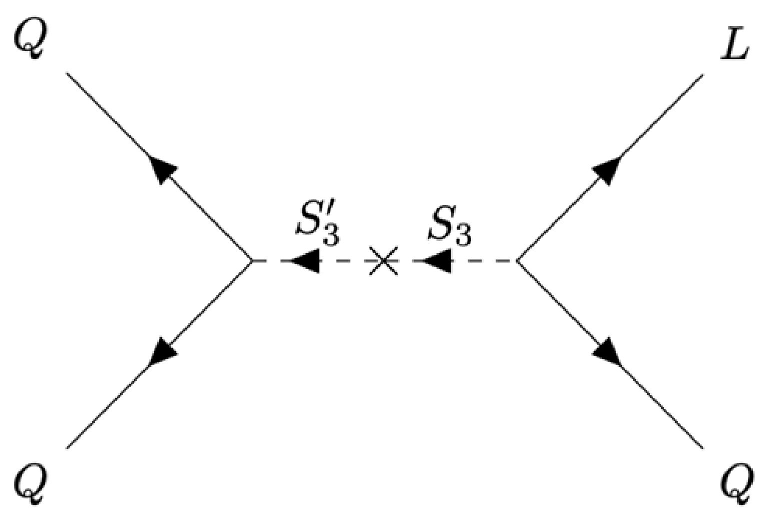
$$
\begin{aligned}
-\mathcal{L}_{\mathrm{BSM}}^{\mathrm{Yuk}} &= Y_1' Q L S_3 + Y_2' Q Q S_3'^{\dagger} + \mathrm{h.c.} \\
V &= m_H^2 \left(H^\dagger H\right) + m_{S_3}^2 \left(S_3^\dagger S_3\right) + m_{S_3'}^2 \left(S_3'^\dagger S_3'\right) \quad + m_3^2 \left(S_3'^\dagger S_3\right) + \mathrm{H.c.} \\
&+ \lambda_H \left(H^\dagger H\right)^2 + \lambda_{S_3} \left(S_3^\dagger S_3\right)^2 + \lambda_{S_3'} \left(S_3'^\dagger S_3'\right)^2 \\
&+ \lambda_{HS_3} \left(H^\dagger H\right) \left(S_3^\dagger S_3\right) + \lambda_{HS_3} \left(H^\dagger H\right) \left(S_3'^\dagger S_3'\right) \\
&+ \lambda_{S_3 S_3'} \left(S_3^\dagger S_3\right) \left(S_3'^\dagger S_3'\right) + \lambda'_{HS_3} \left(H^\dagger S_3\right) \left(S_3^\dagger H\right) \\
&+ \lambda'_{HS_3'} \left(H^\dagger S_3'\right) \left(S_3'^\dagger H\right) + \lambda'_{S_3 S_3'} \left(S_3^\dagger S_3'\right) \left(S_3'^\dagger S_3\right) \\
&+ \left(\frac{\lambda_{HSS}}{M} \left(H^\dagger H^\dagger S_3 S_3 S_3\right) + \mathrm{H.c.}\right).
\end{aligned}
$$

-Second Scenario

- Operator contributing to proton decay $(p \to e^+ \nu\nu)$ with $\Delta F = 0$



- Operator contributing to proton decay $(p \to \pi^+ \nu, \pi^+ \pi^+ e^-)$ with $\Delta F \neq 0$

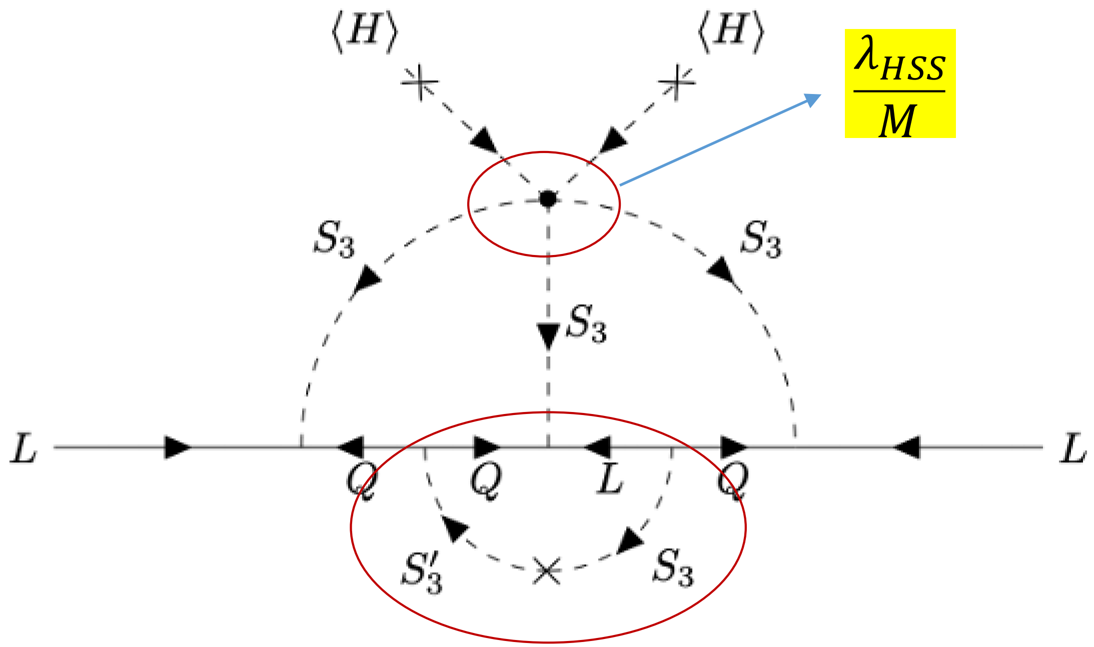


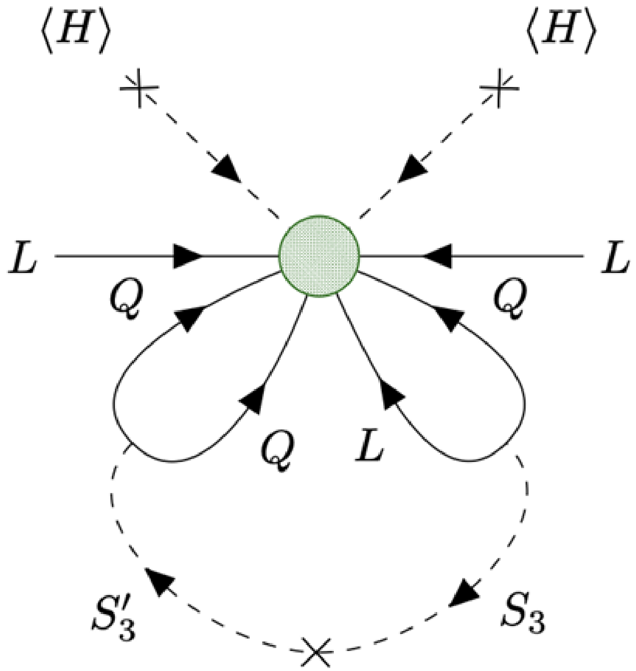
$$\Gamma\left(p \to e^+ \nu^\dagger \nu^\dagger\right) = \frac{m_p}{(8\pi)^3} \left| \frac{\lambda_{HSS} v^2}{M m_S} \frac{(Y_1')^{1\alpha} (Y_1')^{1\beta} (Y_1')^{11}}{\left[1 - q^2/m_S^2\right]^3} \times \frac{W_0^l\left(p \to e^+ \nu^\dagger \nu^\dagger\right)}{m_S^2} \right|^2$$

$$\Gamma(p \to \pi^+ \nu) = \frac{m_p}{32\pi} \left(1 - \frac{m_p^2}{m_\pi^2}\right)^2 \left| \frac{Y_1' Y_2'}{m_3^2} W_0^l \right|^2$$

-Second Scenario

- Feynman diagram of Neutrino Mass





$$m_\nu \sim \frac{\lambda_{HSS} Y_1'^2 Y_2'^2 < H >^2}{(16\pi^2)^3 M} \mathcal{F}(m_3^2, m_{S_3}^2, m_Q^2)$$

$$\mathcal{F}(m_3^2, m_{S_3}^2, m_Q^2) = \frac{1}{m_{S_3}^2} \int_0^1 dx \int_0^1 dy \int_0^1 dz \frac{xyz}{(1-x)(1-y)(1-z) + \frac{x m_3^2}{m_{S_3}^2} + \frac{y m_Q^2}{m_{S_3}^2}}$$

- In this scenario, neutrino masses arise from the proton decay operator constructed by S_3, S'_3, and $U(1)_F$ global symmetry.

- In the limit of the stable proton, i.e. the limit $m_3 \to 0$ and $\lambda_{HSS} \to 0$, the neutrino masses vanish identically.

- As a result of this construction, naturally tiny neutrino masses are connected with the proton's longevity

-Third Scenario

- Proton stability is achieved via smallness of neutrino mass. (i.e proton decay is proportional to neutrino mass.)

- The model proposed is minimal in the sense that no BSM symmetry and no DM are required.

- Field content of the model

Fields	$SU(3)_c$	$SU(2)_L$	$U(1)_Y$
Q	$\mathbf{3}$	$\mathbf{2}$	$\frac{1}{6}$
$\bar{u}$	$\bar{\mathbf{3}}$	$\mathbf{1}$	$-\frac{2}{3}$
$\bar{d}$	$\bar{\mathbf{3}}$	$\mathbf{1}$	$\frac{1}{3}$
L	$\mathbf{1}$	$\mathbf{2}$	$-\frac{1}{2}$
$\bar{e}$	$\mathbf{1}$	$\mathbf{1}$	1
$\bar{\nu}$	$\mathbf{1}$	$\mathbf{1}$	0
H	$\mathbf{1}$	$\mathbf{2}$	$\frac{1}{2}$
R_2	$\mathbf{3}$	$\mathbf{2}$	$\frac{7}{6}$
$\bar{S}_1$	$\bar{\mathbf{3}}$	$\mathbf{1}$	$-\frac{2}{3}$

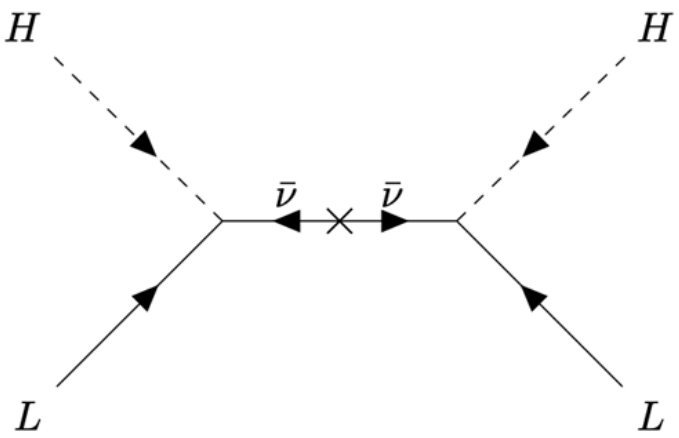
R_2: SU(2) doublet leptoquark
$\bar{S}_1$: EW singlet leptoquark

-Third Scenario

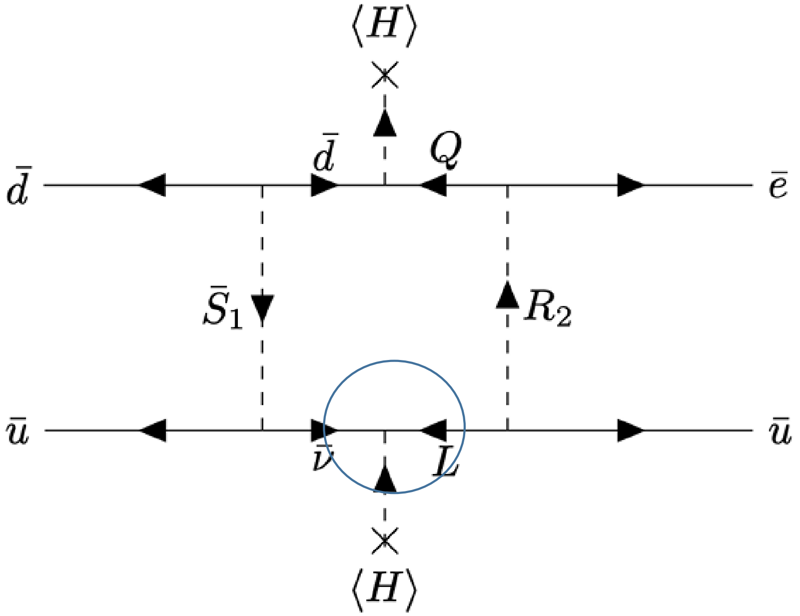
$$
\begin{aligned}
-\mathcal{L}_{\mathrm{BSM}}^{\mathrm{Yuk}} &= Y_1'' \bar{d}\bar{d}\bar{S}_1 + Y_2'' \bar{u}\bar{\nu}\bar{S}_1^\dagger + Y_3'' Q\bar{e}R_2^\dagger \\
&+ Y_4'' L\bar{u}R_2 + Y_5'' L\bar{\nu}H + M_\nu \bar{\nu}\bar{\nu} + \text{h.c.} \\
V &= m_H^2 \left(H^\dagger H\right) + m_{S_1}^2 \left(\bar{S}_1^\dagger \bar{S}_1\right) + \mu_R^2 \left(\tilde{R}_2^\dagger \tilde{R}_2\right) \\
&+ \lambda_H \left(H^\dagger H\right)^2 + \lambda_S \left(\bar{S}_1^\dagger \bar{S}_1\right)^2 + \lambda_R \left(\tilde{R}_2^\dagger \tilde{R}_2\right)^2 \\
&+ \lambda_{HS} \left(H^\dagger H\right)\left(\bar{S}_1^\dagger \bar{S}_1\right) + \lambda_{HR} \left(H^\dagger H\right)\left(R_2^\dagger R_2\right) \\
&+ \lambda_{RS} \left(R_2^\dagger R_2\right)\left(\bar{S}_1^\dagger \bar{S}_1\right) + \lambda'_{HR} \left(H^\dagger R_2\right)\left(R_2^\dagger H\right) \\
&+ \lambda'_{HS} \left(H^\dagger \bar{S}_1\right)\left(\bar{S}_1^\dagger H\right) + \lambda'_{RS} \left(R_2^\dagger \bar{S}_1\right)\left(\bar{S}_1^\dagger R_2\right) \\
&+ \mu_{HRS} \left(H R_2 \bar{S}_1\right) + \text{h.c.}
\end{aligned}
$$

-Third Scenario

- Dim.5 operator leading to neutrino mass (a kind of type I seesaw)



- Feynman diagram contributing to proton decay

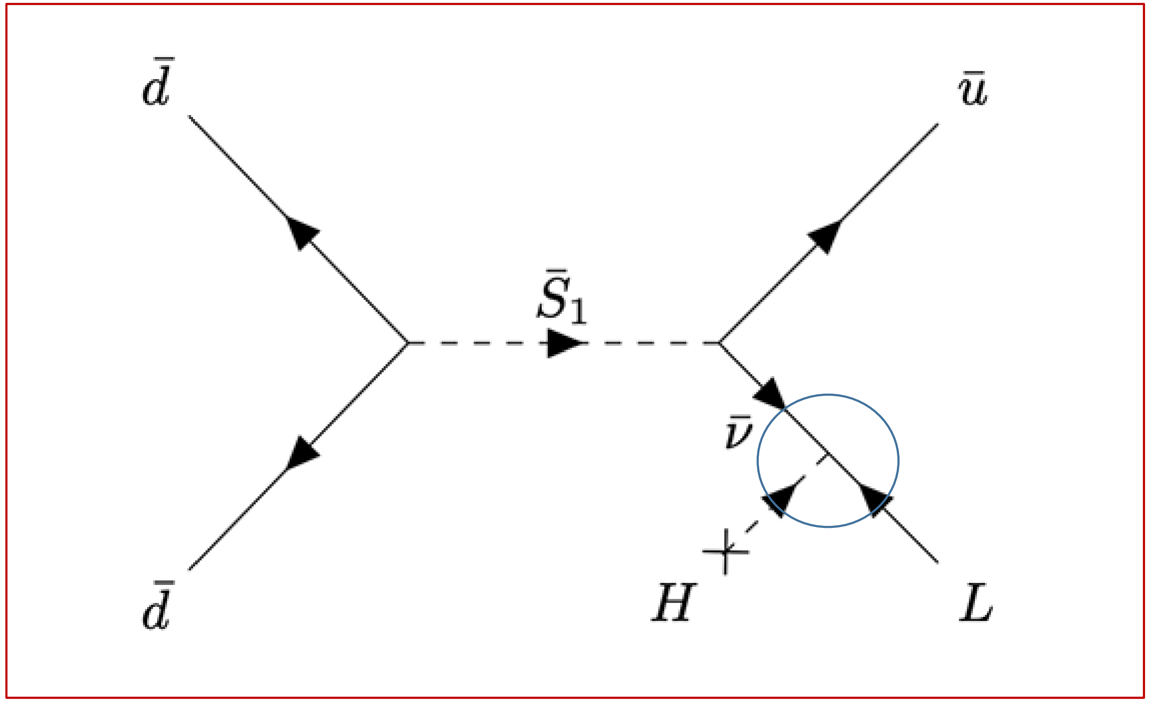


$$\Gamma\left(p \to e^+\pi^0\right) = \frac{m_p}{512\pi^3}\left(1-\frac{m_\pi^2}{m_p^2}\right)^2 \left|(Y_1'')^{1a}\,\frac{m_d^{ab}}{m_R}\,(Y_3'')^{b1}\,(Y_2'')^{1c}\,\frac{m_\nu^{cd}}{m_R}\,(Y_4'')^{d1}\,\frac{W_0^l\left(p \to e^+\pi^0\right)}{m_R^2}\right.$$

$$\left.\times\left[H_0(x_d, x_\nu, x_S, y) + H_1(x_d, x_\nu, x_S, y)\frac{q^2}{m_R^2}\right]\right|^2,$$

$$
\begin{aligned}
y\left(x_S-1\right) H_0\left(x_d, x_\nu, y\right) &= \left[\left\{f_-(x_d-x_S)-f_-(x_d-x_S-y)+f_+(x_d-x_S)-f_+(x_d-x_S-y)\right.\right. \\
&\quad \left.\left.-g(x_d-x_S)+g(x_d-x_S-y)\right\}-(x_S\to 1)\right], \\
f_\pm(x) &= \operatorname{DiLog}\left[\frac{2x}{x_d-2x_S+x_\nu-y\pm\sqrt{\lambda\left(x_d,x_S,y\right)}}, \mp yx\right], \\
g(x) &= \operatorname{PolyLog}\left[2, \frac{x\left(x_\nu-x_S\right)}{\left(x_d-x_S\right)\left(x_\nu-x_S\right)+yx_S}\right], \\
y^2\left(x_S-1\right)^3 H_1\left(x_d, x_\nu, y\right) &= \left[\vphantom{\frac{1}{2}}\right.(x_S-1)y+\frac{\left(x_S-x_d\right)y\ln x_d}{x_d-1}+\frac{\left(x_d-1\right)x_S\ln\left(\frac{x_d}{x_S}\right)}{x_d-x_S} \\
&\quad -\frac{1}{2}\left(x_S-1\right)\left(x_d-x_\nu\right)\ln\left(\frac{x_d}{x_\nu}\right)-\left(x_S-1\right)\lambda^{1/2}\left(x_d,x_\nu,y\right)\left\{\ln\left(2x_d\right)\right. \\
&\quad \left.-\ln\left[x_d+x_\nu-y+\lambda^{1/2}\left(x_d,x_\nu,y\right)\right]\right\}+\left\{x_d\left(1+x_S-x_\nu\right)-x_S-\frac{y}{2}\left(x_S+1\right)\right\} \\
&\quad \times yH_0\left(x_d,x_\nu,y\right)\left(x_S-1\right)+\left(x_d\longleftrightarrow x_\nu\right)\left.\vphantom{\frac{1}{2}}\right], \\
\text{where } \lambda\left(a,b,c\right) &= a^2+b^2+c^2-2ab-2ac-2bc, \\
\text{and } x_d &= \frac{m_d^2}{m_R^2}, \quad x_\nu=\frac{m_\nu^2}{m_R^2}, \quad x_S=\frac{m_S^2}{m_R^2}, \quad y=\frac{m_p^2}{m_R^2}.
\end{aligned}
$$

$\bar{S}_1$ mediated, proportional to Dirac neutrino mass, proton decay Feynman diagram in the framework of neutrino mass mediated proton decay model



Constraints

1. Lepton flavor violation

- For the 1st Scenario, the Yukawa interaction $Y_4 L N \eta^\dagger$ generates charged lepton flavor violating processes, $l_i \to l_j \gamma$
- The most stringent constraint comes from non-observation of $\mu \to e\gamma$

$Y_4^{e,\mu} \leq 0.04 \sim 1$ for mediators with masses of around 1-2 TeV

- For the 2rd Scenario, those CLFV processes are occurred at three loop level, which are suppressed enough to satisfy the constraints.

- For the 3rd Scenario, those CLFV processes are proportional to small neutrino masses, and thus suppressed.

Constraints

2. Constraints on Leptoquarks

- The models we proposed contain scalar LQs as heavy new particles.
- Direct bounds are derived from their production cross sections at colliders, while indirect bounds are obtained from bounds on LQ-induced jjll final states, which are observables from experiments.
- The recent analysis for the searches of jjll final states at the LHC produced via pair production of scalar leptoquarks shows that their masses below around 1.7 TeV are excluded by the LHC data.

Remarks

- As mentioned before, the 1st scenario has a DM candidate, the lightest N, which was thermally produced and frozen out in the early Universe.

- Annihilation $NN \rightarrow LL$ mediated by η, can contribute to the relic density of DM. For those processes to be efficient enough, Y_4 should be rather large.

- There exist another contributions to the relic density of DM, which stem from the annihilation processes, $NN \rightarrow QQ$ mediated by R_{2D}. Not so small values of Y_2 is required to satisfy the right amount of the relic density.

- Unifying the proton decay and neutrino mass origins within the GUT framework is not so easy, nevertheless a very charming, path which requires gluing the proton decay mechanism to the neutrino mass generation in the context of a larger symmetries.

Conclusions

- We have presented three possible scenarios for realizing the correlation between proton lifetime longevity and smallness of the neutrino mass, and brief discussion of the idea and future prospective directions was given.

- This framework gives opportunity to link the open questions of neutrino mass and proton decay to each other, and possibly to the existence of dark matter as the common source.

- This framework also complements the proton decay experimental searches with the neutrino search data and possibly new physics search data.