Triple-leptoquark interactions for tree- and loop-level proton decays

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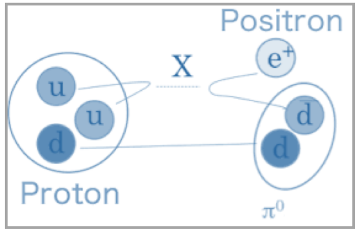

ICHEP 2022 BOLOGNA
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International Conference
on High Energy Physics
Bologna (Italy)
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Motivation

theories: GUTs,…
experiments

Effective lagrangian describing baryon number violation

Lattice QCD for the hadronic part

Scalar Leptoquarks

Triple leptoquark interactions

Proton decay at tree-level

Proton decay at loop-level

Motivation

Theoretical side

- Wigner suggested proton decay in1949 and 1952

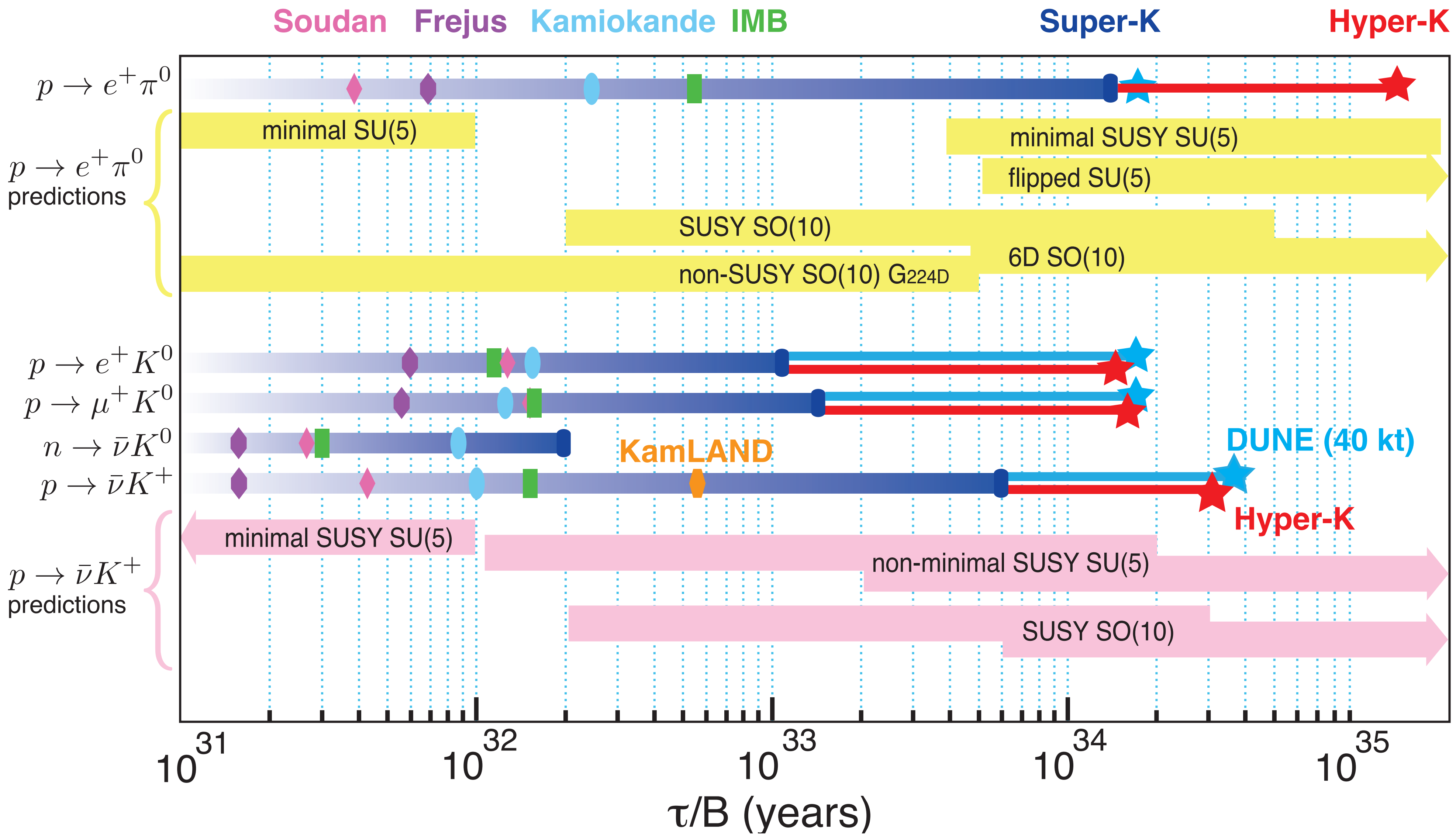
Wigner “It is conceivable, for instance, that a conservation law for the number of heavy particles (protons and neutrons) is responsible for the stability of the protons in the same way as the conservation law for charges is responsible for the stability of the electron. Without the conservation law in question, the proton could disintegrate, under emission of a light quantum, into a positron, just as the electron could disintegrate, were it not for the conservation law for the electric charge, into a light quantum and a neutrino."

- 1965 Sakharov

After 1965 Sakharov returned to fundamental science and began working on particle physics and particle cosmology.
He tried to explain the baryon asymmetry of the universe; in that regard, he was the first to give a theoretical motivation for proton decay.

- 1974: Grand unified theories, Georgi & Glashow SU(5)

Future experiments



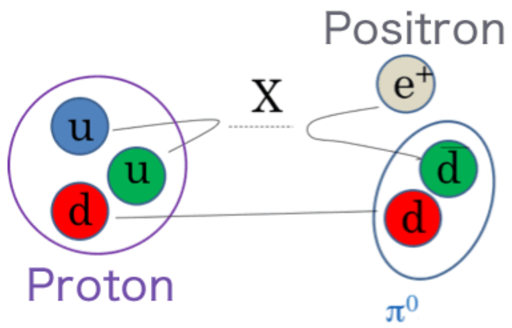
Proton decays in effective Lagrangian approach

dimension 6

$$\mathcal{L}_{d=6} = y^1_{abcd}\epsilon^{\alpha\beta\gamma}(\overline{d}^C_{a,\alpha}u_{b,\beta})(\overline{Q}^C_{i,c,\gamma}\epsilon_{ij}L_{j,d})$$
$$+ y^2_{abcd}\epsilon^{\alpha\beta\gamma}(\overline{Q}^C_{i,a,\alpha}\epsilon_{ij}Q_{j,b,\beta})(\overline{u}^C_{c,\gamma}\ell_d)$$
$$+ y^3_{abcd}\epsilon^{\alpha\beta\gamma}\epsilon_{il}\epsilon_{jk}(\overline{Q}^C_{i,a,\alpha}Q_{j,b,\beta})(\overline{Q}^C_{k,c,\gamma}L_{l,d})$$
$$+ y^4_{abcd}\epsilon^{\alpha\beta\gamma}(\overline{d}^C_{a,\alpha}u_{b,\beta})(\overline{u}^C_{c,\gamma}\ell_d) + \text{h.c.}\,,$$

Q, L → $SU(2)_L$ quark, lepton doublets
u ,d, l → $SU(2)_L$ u, d, charged lepton singlets
C → charge conjugation

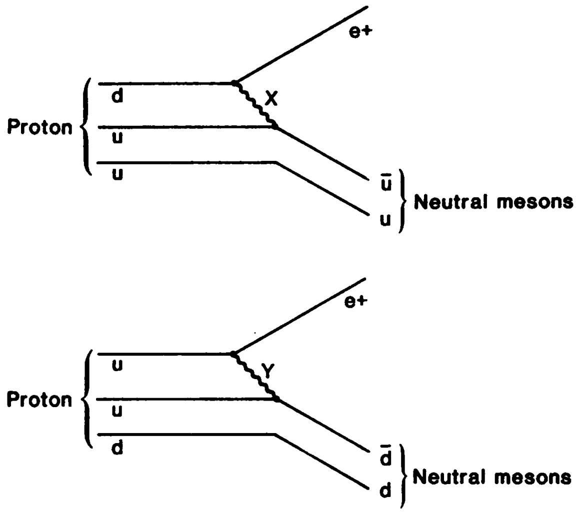
$$y^i_{abcd} \sim \frac{1}{\Lambda^2}$$



$$\Gamma(p \to e^+\pi^0) \simeq \frac{1}{2\times 10^{34}\,\text{yr}}\left|\frac{y^j_{1111}}{(3\times 10^{15}\,\text{GeV})^{-2}}\right|^2.$$

$$\Gamma(n \to \bar{\nu}_\tau\pi^0) \simeq \frac{1}{10^{33}\,\text{yr}}\left|\frac{y^4_{3333}}{(5\times 10^{8}\,\text{GeV})^{-2}}\right|^2.$$

Vector LQ

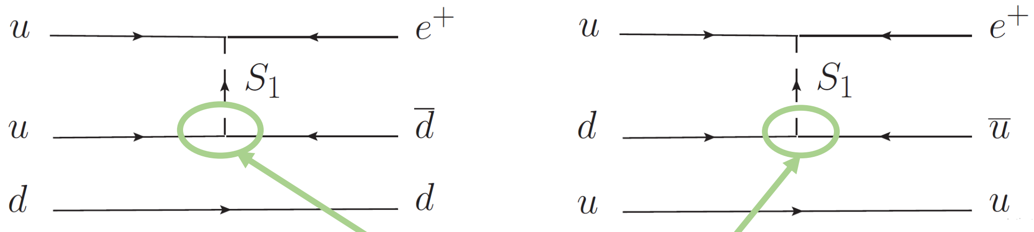


X,Y gauge bosons within GUT

Instead of X,Y **scalar leptoquarks** can mediate this process

Scalar LQ

dim-6



e.g. Doršner, SF & Košnik, 1204.0674

Important: scalar LQ should have di-quark couplings that proton decays at the tree level (dim-6, dim-9,…)

$(SU(3), SU(2), U(1))$	Spin	Symbol	Type	F
$(\bar{\mathbf{3}}, \mathbf{3}, 1/3)$	0	S_3	$LL\,(S_1^L)$	-2
$(\mathbf{3}, \mathbf{2}, 7/6)$	0	R_2	$RL\,(S_{1/2}^L),\ LR\,(S_{1/2}^R)$	0
$(\mathbf{3}, \mathbf{2}, 1/6)$	0	$\tilde{R}_2$	$RL\,(\tilde{S}_{1/2}^L),\ \overline{LR}\,(\tilde{S}_{1/2}^L)$	0
$(\bar{\mathbf{3}}, \mathbf{1}, 4/3)$	0	$\tilde{S}_1$	$RR\,(\tilde{S}_0^R)$	-2
$(\bar{\mathbf{3}}, \mathbf{1}, 1/3)$	0	S_1	$LL\,(S_0^L),\ RR\,(S_0^R),\ \overline{RR}\,(S_0^R)$	-2
$(\bar{\mathbf{3}}, \mathbf{1}, -2/3)$	0	$\bar{S}_1$	$\overline{RR}\,(\bar{S}_0^R)$	-2
$(\mathbf{3}, \mathbf{3}, 2/3)$	1	U_3	$LL\,(V_1^L)$	0
$(\bar{\mathbf{3}}, \mathbf{2}, 5/6)$	1	V_2	$RL\,(V_{1/2}^L),\ LR\,(V_{1/2}^R)$	-2
$(\bar{\mathbf{3}}, \mathbf{2}, -1/6)$	1	$\tilde{V}_2$	$RL\,(\tilde{V}_{1/2}^L),\ \overline{LR}\,(\tilde{V}_{1/2}^R)$	-2
$(\mathbf{3}, \mathbf{1}, 5/3)$	1	$\tilde{U}_1$	$RR\,(\tilde{V}_0^R)$	0
$(\mathbf{3}, \mathbf{1}, 2/3)$	1	U_1	$LL\,(V_0^L),\ RR\,(V_0^R),\ \overline{RR}\,(V_0^R)$	0
$(\mathbf{3}, \mathbf{1}, -1/3)$	1	$\bar{U}_1$	$\overline{RR}\,(\bar{V}_0^R)$	0

I. Dorsner, SF, A. Greljo, J.F. Kamenik and Košnik, 1603.04993

F- fermion number $F = 3B + L$

F=0 proton stable

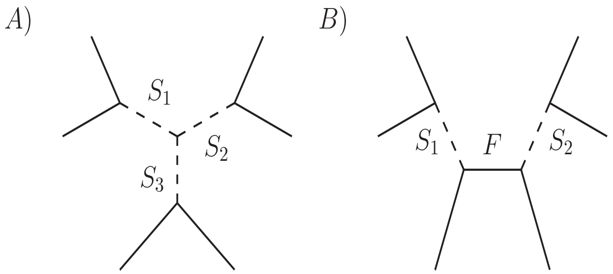
Tree-level renormalizable interactions are not the only possible source of baryon number violation. It might also occur through higher-dimensional operators.

Proton decay to charged leptons

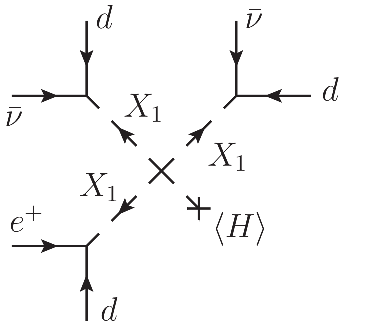
channel	$(\Delta L_e, \Delta L_\mu)$	limit/years
$p \to e^+ e^+ e^-$	$(1, 0)$	793×10^{30}
$p \to e^+ \mu^+ \mu^-$	$(1, 0)$	359×10^{30}
$p \to \mu^+ e^+ e^-$	$(0, 1)$	529×10^{30}
$p \to \mu^+ \mu^+ \mu^-$	$(0, 1)$	675×10^{30}
$p \to \mu^+ \mu^+ e^-$	$(-1, 2)$	359×10^{30}
$p \to e^+ e^+ \mu^-$	$(2, -1)$	529×10^{30}

Hambye & Heeck 1712.04871

16 dimension-nine operators

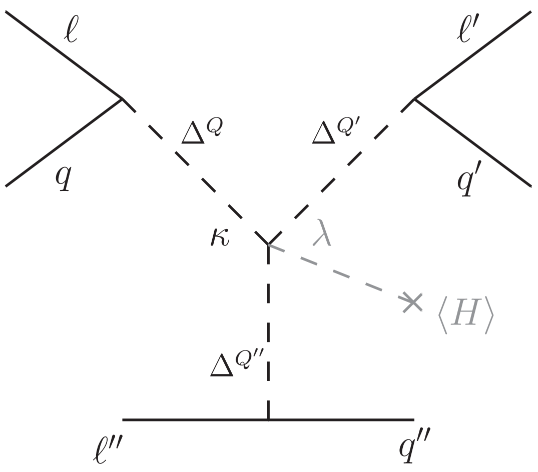


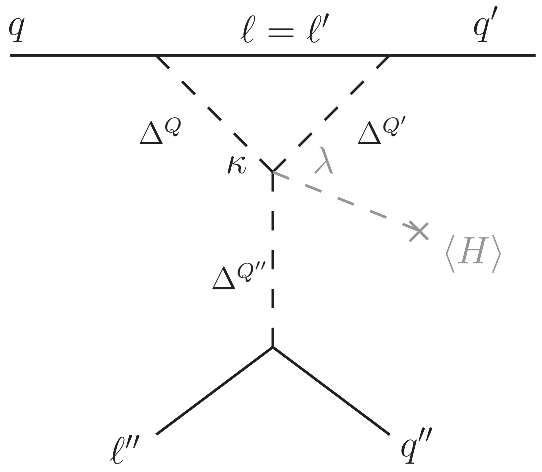
F - new fermion



Arnold et al., 1212.455, Murgui &Wise, 2105.14029 found if three LQ X_1 are in the same representation that this amplitude vanishes.

Triple-leptoquark interactions for tree- and loop-level proton decays





I. Doršner, SF & O. Sumensari, 2202.08287

Triple-LQs - scalars only!

Two different proton decay topologies

- with or without a Higgs vacuum expectation value

-Δ_Q, $\Delta_{Q'}$, and $\Delta_{Q''}$ are scalar leptoquark mass eigenstates with electric charges Q, Q', and Q'', respectively.

Classification

scalars

Leptoquark multiplets	Yukawa interactions
$R_2 = (\mathbf{3}, \mathbf{2}, 7/6)$	$-(y^L_{R_2})_{ij}\, \bar{u}_{R\,i} R_2 i\tau_2 L_j + (y^R_{R_2})_{ij}\, \bar{Q}_i R_2 e_{R\,j} + \text{h.c.}$
$\tilde{R}_2 = (\mathbf{3}, \mathbf{2}, 1/6)$	$-(y^L_{\tilde{R}_2})_{ij}\, \bar{d}_{R\,i} \tilde{R}_2 i\tau_2 L_j + \text{h.c.}$
$S_1 = (\bar{\mathbf{3}}, \mathbf{1}, 1/3)$	$(y^L_{S_1})_{ij}\, \bar{Q}^C_i i\tau_2 S_1 L_j + (y^R_{S_1})_{ij}\, \bar{u}^C_{R\,i} S_1 e_{R\,j} + \text{h.c.}$
$S_3 = (\bar{\mathbf{3}}, \mathbf{3}, 1/3)$	$(y^L_{S_3})_{ij}\, \bar{Q}^C_i i\tau_2 (\vec{\tau} \cdot \vec{S}_3) L_j + \text{h.c.}$
$\tilde{S}_1 = (\bar{\mathbf{3}}, \mathbf{1}, 4/3)$	$(y^R_{\tilde{S}_1})_{ij}\, \bar{d}^C_{R\,i} \tilde{S}_1 e_{R\,j} + \text{h.c.}$

Scalar leptoquark multiplets and their interactions with the SM quark-lepton pairs.

The SM extended with up to three different scalar leptoquark multiplets, denoted with Δ, Δ′, and Δ′′ and study all possible cubic and quartic contractions Δ-Δ′-Δ′′ and Δ-Δ′-Δ′′-H, yield to 3-LQ interactions and 3-LQ ⟨H⟩.

	$SU(3)\times SU(2)\times U(1)$ level	$SU(3)\times U(1)_{\rm em}$ level
(a)	$\kappa \tilde{R}_2^T i\tau_2 \tilde{R}_2 S_1^*$	$-2\kappa\epsilon_{abc}\tilde{R}_{2a}^{-1/3}\,\tilde{R}_{2b}^{2/3}\,S_{1c}^{-1/3}$
(b)	$\kappa R_2^T i\tau_2 \tilde{R}_2 \tilde{S}_1^*$	$\kappa\epsilon_{abc}\left(R_{2a}^{5/3}\,\tilde{R}_{2b}^{-1/3}\,\tilde{S}_{1c}^{-4/3} - R_{2a}^{2/3}\,\tilde{R}_{2b}^{2/3}\,\tilde{S}_{1c}^{-4/3}\right)$
(c)	$\lambda H^\dagger i\tau_2(\vec{\tau}\cdot\vec{S}_3)^* i\tau_2 R_2 S_1^*$	$\lambda\frac{v}{\sqrt{2}}\epsilon_{abc}\left(-S_{3a}^{-1/3}\,R_{2b}^{2/3}\,S_{1c}^{-1/3}+\sqrt{2}S_{3a}^{-4/3}\,R_{2b}^{5/3}\,S_{1c}^{-1/3}\right)$
(d)	$\lambda H^\dagger i\tau_2(\vec{\tau}\cdot\vec{S}_3)^*(\vec{\tau}\cdot\vec{S}_3)^* i\tau_2 R_2$	$\lambda v\sqrt{2}\epsilon_{abc}\left(\sqrt{2}S_{3a}^{-1/3}\,S_{3b}^{-4/3}\,R_{2c}^{5/3} - S_{3a}^{-4/3}\,S_{3b}^{2/3}\,R_{2c}^{2/3}\right)$
(e)	$\lambda H^T i\tau_2 R_2 S_1^* \tilde{S}_1^*$	$-\lambda\frac{v}{\sqrt{2}}\epsilon_{abc}R_{2a}^{5/3}\,S_{1b}^{-1/3}\,\tilde{S}_{1c}^{-4/3}$
(f)	$\lambda H^T(\vec{\tau}\cdot\vec{S}_3)^* i\tau_2 R_2 \tilde{S}_1^*$	$\lambda\frac{v}{\sqrt{2}}\epsilon_{abc}\left(\sqrt{2}S_{3a}^{2/3}\,R_{2b}^{2/3}\,\tilde{S}_{1c}^{-4/3}+S_{3a}^{-1/3}\,R_{2b}^{5/3}\,\tilde{S}_{1c}^{-4/3}\right)$
(g)	$\lambda H^T(\vec{\tau}\cdot\vec{S}_3)^* i\tau_2 \tilde{R}_2 S_1^*$	$\lambda\frac{v}{\sqrt{2}}\epsilon_{abc}\left(\sqrt{2}S_{3a}^{2/3}\,\tilde{R}_{2b}^{-1/3}\,S_{1c}^{-1/3}+S_{3a}^{-1/3}\,\tilde{R}_{2b}^{2/3}\,S_{1c}^{-1/3}\right)$
(h)	$\lambda H^\dagger(\vec{\tau}\cdot\vec{S}_3)^*(\vec{\tau}\cdot\vec{S}_3)^* i\tau_2 \tilde{R}_2$	$\lambda v\sqrt{2}\epsilon_{abc}\left(\sqrt{2}S_{3a}^{2/3}\,S_{3b}^{-1/3}\,\tilde{R}_{2c}^{-1/3}+S_{3a}^{-4/3}\,S_{3b}^{2/3}\,\tilde{R}_{2c}^{2/3}\right)$

Mentioned in
Kovalenko and Schmidt, hep-ph/0210187
Crivellin and Schnell, 2105.04844

$$S_3^{1/3}=S_3^3,\; S_3^{4/3}=(S_3^1-iS_3^2)/\sqrt{2},\; S_3^{-2/3}=(S_3^1+iS_3^2)/\sqrt{2}$$

Cubic and quartic leptoquark multiplet contractions at the SU(3)×SU(2)× U(1) level and the associated triple-leptoquark interactions at the SU(3) × U(1)$_{\rm em}$ level

$\tilde{R}_2$-$\tilde{R}_2$-$\tilde{R}_2$-H^*, S_1-S_1-R_2^*-H,
$\tilde{R}_2$-$\tilde{R}_2$-S_3^*, S_1-S_1-$\tilde{R}_2^*$-H^*

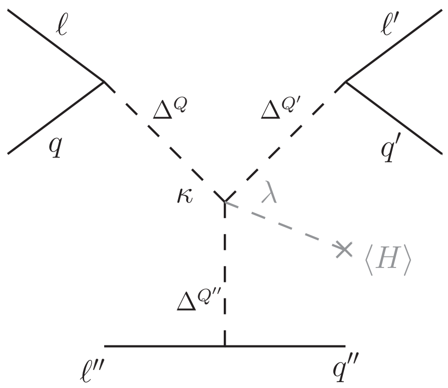
vanish

symmetric under the exchange of two identical electric charge eigenstates in direct conflict with the antisymmetric nature in the colour SU(3) space.

Way out: to accommodate them in different representations.

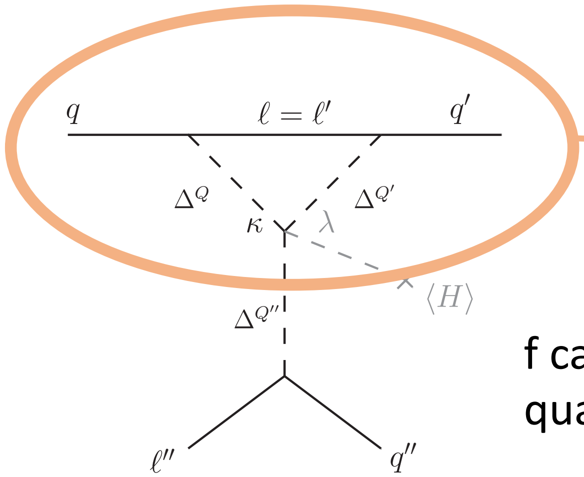
Phenomenological analysis

Tree level proton decays



$$\Gamma(p \to e^+ e^+ e^-) \simeq \frac{m_p}{(16\pi)^3} \left(\frac{m_p^5 v}{\Lambda^6} \right)^2 |\lambda\, y_{ue}^2\, y_{de}|^2$$

Loop-level proton decay



Effective di-quark coupling

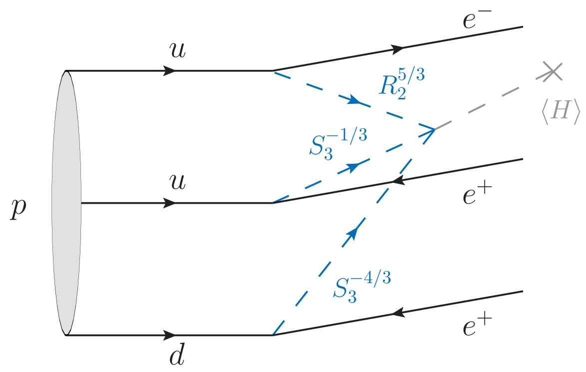
$$y_{ud} \simeq \frac{1}{16\pi^2} \frac{m_f v}{\Lambda^2} \lambda\, y_{ue} y_{de}^*$$

f can be either the valence quark q, or the lepton running in the loop

$$\Gamma(p \to \pi^0 e^+) \simeq \frac{m_p}{16\pi} \left(\frac{m_p^2}{\Lambda^2} \right)^2 |y_{ud}\, y_{ue}|^2$$

Comparison tree and loop level proton decay width

an example



$$\frac{\Gamma(p \to e^+ e^+ e^-)}{\Gamma(p \to \pi^0 e^+)} \simeq \frac{1}{\pi^2}\left(\frac{m_p^3}{m_f\,\Lambda^2}\right)^2 \simeq 10^{-7}\left(\frac{m_e}{m_f}\right)^2\left(\frac{1\,\mathrm{TeV}}{\Lambda}\right)^4 ,$$

The loop-induced processes are more sensitive probes of the triple-leptoquark interactions than the tree-level ones

comparison of the existing data

$$\left\{\begin{array}{l} p \to e^- e^+ e^+ \\ p \to \pi^0 e^+ \end{array}\right.$$

$$\Gamma(p \to \pi^0 \ell^+) \sim \frac{1}{10}\Gamma(p \to \ell^+ \ell^- \ell^+)$$

	Contractions	Operators	Proton decay (tree)	Proton decay (one-loop)
(a)	$\tilde{R}_2$-$\tilde{R}_2$-S_1^*	$ddd\bar{e}\nu\bar{\nu}$	$p \to \pi^+\pi^+e^-\nu\bar{\nu}$	–
		$ddue\bar{e}\bar{\nu}$	$p \to \pi^+e^+e^-\nu$	$p \to \pi^+\nu$
(b)	R_2-$\tilde{R}_2$-$\tilde{S}_1^*$	$dddee\bar{e}$	$p \to \pi^+\pi^+e^-e^+e^-$	–
		$ddue\bar{e}\bar{\nu}$	$p \to \pi^+e^+e^-\nu$	$p \to \pi^+\nu$
(c)	S_1-S_3-R_2^*-H	$ddue\bar{e}\nu$	$p \to \pi^+e^+e^-\bar{\nu}$	$p \to \pi^+\bar{\nu}$
		$duue\nu\bar{\nu}$	$p \to e^+\nu\bar{\nu}$	$p \to \pi^0e^+$
		$duuee\bar{e}$	$p \to e^+e^+e^-$	$p \to \pi^0e^+$
		$uuuee\bar{\nu}$	$p \to \pi^-e^+e^+\nu$	–
(d)	S_3-S_3-R_2^*-H	$ddue\bar{e}\nu$	$p \to \pi^+e^+e^-\bar{\nu}$	$p \to \pi^+\bar{\nu}$
		$duue\nu\bar{\nu}$	$p \to e^+\nu\bar{\nu}$	–
		$duuee\bar{e}$	$p \to e^+e^+e^-$	$p \to \pi^0e^+$
(e)	S_1-$\tilde{S}_1$-R_2^*-H^*	$ddue\bar{e}\nu$	$p \to \pi^+e^+e^-\bar{\nu}$	$p \to \pi^+\bar{\nu}$
		$duuee\bar{e}$	$p \to e^+e^+e^-$	$p \to \pi^0e^+$
(f)	S_3-$\tilde{S}_1$-R_2^*-H^*	$ddue\bar{e}\nu$	$p \to \pi^+e^+e^-\bar{\nu}$	$p \to \pi^+\bar{\nu}$
		$duue\nu\bar{\nu}$	$p \to e^+\nu\bar{\nu}$	$p \to \pi^0e^+$
		$duuee\bar{e}$	$p \to e^+e^+e^-$	$p \to \pi^0e^+$
(g)	S_1-S_3-$\tilde{R}_2^*$-H^*	$ddu\nu\bar{\nu}\nu$	$p \to \pi^+\nu\bar{\nu}\bar{\nu}$	$p \to \pi^+\bar{\nu}$
		$ddue\bar{e}\nu$	$p \to \pi^+e^+e^-\bar{\nu}$	$p \to \pi^+\bar{\nu}$
		$duue\nu\bar{\nu}$	$p \to e^+\nu\bar{\nu}$	$p \to \pi^0e^+$
		$duuee\bar{e}$	$p \to e^+e^+e^-$	$p \to \pi^0e^+$
(h)	S_3-S_3-$\tilde{R}_2^*$-H^*	$ddu\nu\bar{\nu}\nu$	$p \to \pi^+\nu\bar{\nu}\bar{\nu}$	$p \to \pi^+\bar{\nu}$
		$ddue\bar{e}\nu$	$p \to \pi^+e^+e^-\bar{\nu}$	–
		$duue\nu\bar{\nu}$	$p \to e^+\nu\bar{\nu}$	$p \to \pi^0e^+$

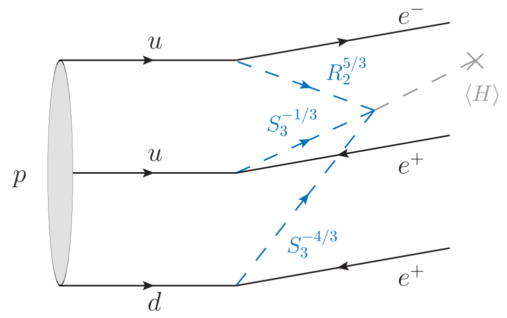
non-trivial Δ-Δ'-Δ'' and Δ-Δ'-Δ''-H contractions,

d = 9 effective operators, and corresponding proton decay

The effective operators in scenarios (a) and (b) conserve B + L, while the ones appearing in the remaining scenarios conserve B − L, where B and L are baryon and lepton numbers, respectively.

Tree-level leptoquark mediation of $p \to e^- e^+ e^+$

$$\mathcal{L}_{\text{eff}}^{(d=9)} \supset \sum_{X=L,R} \epsilon_{abc}\, C_X\, (\bar{u}_a^C P_L e)(\bar{d}_b^C P_L e)(\bar{e} P_X u_c) + \text{h.c.}\,,$$



S_3-S_3-R_2^*-H

$$C_L = \frac{2\sqrt{2}\lambda v}{m_{S_3}^4 m_{R_2}^2} (V^* y_{S_3}^L) y_{S_3}^L (V y_{R_2}^R)^*\,,$$

$$C_R = -\frac{2\sqrt{2}\lambda v}{m_{S_3}^4 m_{R_2}^2} (V^* y_{S_3}^L) y_{S_3}^L (y_{R_2}^L)^*\,.$$

$$\epsilon_{abc}\langle 0|(\bar{u}_a^C P_R d_b) P_L u_c|p\rangle = \alpha_p P_R u_p \qquad \alpha_p = -0.0144(3)(21)\,\text{GeV}^3$$

$$\epsilon_{abc}\langle 0|(\bar{u}_a^C P_L d_b) P_L u_c|p\rangle = \beta_p P_L u_p \qquad \beta_p = +0.0144(3)(21)\,\text{GeV}^3$$

Lattice QCD   Aoki et al. 1705.01338

Decay width

$$\Gamma(p \to e^+ e^+ e^-) = \frac{m_p^5}{6(16\pi)^3} \left(\beta_p^2 |C_L|^2 + \alpha_p^2 |C_R|^2\right)$$

$\tau(p \to e^+ e^+ e^-) > 3.4 \times 10^{34}$ years   experiment SuperKamiokande
Takenaka et al., 2010.16098

assumptions $y_{S_3}^L = y_{R_2}^R = y_{R_2}^L = \lambda = 1$

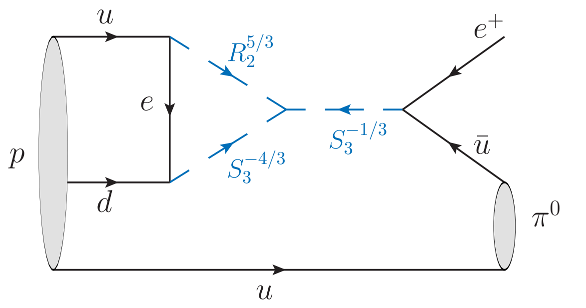
$m_{S_3} = m_{R_2} = \Lambda$

$$p \to e^+ e^+ e^- : \qquad \Lambda \geq 1.6 \times 10^2\,\text{TeV}$$

Loop-level leptoquark mediation of $p \to \pi^0 e^+$

$$\mathcal{L}_{\rm eff}^{(d=6)} \supset C_{LL}^{udeu}\ \left(\overline{u}^{\rm C} P_L d\right) \left(\overline{e}^{\rm C} P_L u\right) + C_{LR}^{udeu}\ \left(\overline{u}^{\rm C} P_L d\right) \left(\overline{e}^{\rm C} P_R u\right) + \text{h.c.}\,,$$

Explicit loop computation



General scenario $\quad \mathcal{L}_{\rm scalar} \supset \lambda\, v\, \varepsilon_{abc}\, \Delta_a^{Q}\, \Delta_b^{Q'}\, \Delta_c^{Q''} + \text{h.c.}$

LQ interactions with quarks and leptons

$$\mathcal{L}_{\rm yuk.} \supset \overline{q}\,(y_R P_R + y_L P_L)\,\ell\,\Delta^{Q} + \overline{q'^{C}}\,(y'_R P_R + y'_L P_L)\,\ell\,\Delta^{Q'*} + \text{h.c.}$$

The loop diagram corresponds to a loop-induced diquark coupling of the $\Delta_{Q''}$ leptoquark

$$\mathcal{L}_{\rm qq'} = \varepsilon_{abc}\,\overline{q_a^C}\,\left(y_{qq'}^L P_L + y_{qq'}^L P_R\right) q'_b\,\Delta_c^{Q''} + \text{h.c.}$$

$$y_{qq'}^L = \frac{\lambda v}{16\pi^2 m_\Delta^2}\left(m_\ell\, y'_L y_R^* - \frac{m_q}{4} y'_R y_R^* - \frac{m_{q'}}{4} y'_L y_L^*\right)$$

$$y_{qq'}^R = \frac{\lambda v}{16\pi^2 m_\Delta^2}\left(m_\ell\, y'_R y_L^* - \frac{m_q}{4} y'_L y_L^* - \frac{m_{q'}}{4} y'_R y_R^*\right)$$

Chirality flip in the internal lepton and external quark lines

Ingredients

$$C_{LL}^{udeu} = \frac{\sqrt{2}\lambda}{8\pi^2}\frac{v m_e}{\Lambda^4}(V^* y_{S_3}^L)\left[y_{S_3}^L (V y_{R_2}^R)^* + \frac{m_d}{4m_e} y_{S_3}^L (y_{R_2}^L)^*\right],$$

$$C_{LR}^{udeu} = \frac{\lambda}{32\pi^2}\frac{v m_u}{\Lambda^4}(V^* y_{S_3}^L)^2 (y_{R_2}^L)^*.$$

$$\left\langle \pi^0 \middle| \mathcal{O}^{\Gamma\Gamma'} \middle| p \right\rangle = \left[W_0^{\Gamma\Gamma'}(q^2) - \frac{i\not{q}}{m_p} W_1^{\Gamma\Gamma'}(q^2)\right] P_{\Gamma'} u_p$$

Form factors

$$\mathcal{O}^{\Gamma\Gamma'} = \left(\overline{u}^{\mathrm{C}} P_\Gamma d\right) P_{\Gamma'} u$$

$\Gamma, \Gamma' = R, L.$ $\langle \pi^+ | \left(\overline{u}^{\mathrm{C}} P_\Gamma d\right) P_{\Gamma'} d | p\rangle = \sqrt{2}\langle \pi^0 | \left(\overline{u}^{\mathrm{C}} P_\Gamma d\right) P_{\Gamma'} u | p\rangle$

$$\Gamma(p \to \pi^0 e^+) = \frac{m_p}{32\pi}\left(1 - \frac{m_\pi^2}{m_p^2}\right)^2 \left[(W_0^{LL})^2 |C_{LL}^{udeu}|^2 + (W_0^{RL})^2 |C_{LR}^{udeu}|^2\right]$$

$W_0^{LL} = 0.134(5)\,\mathrm{GeV}^2$ $W_0^{LR} = -0.131(4)\,\mathrm{GeV}^2$ Lattice QCD, Aoki et al., 1705.01338

assuming $y_{S_3}^L = y_{R_2}^L = y_{R_2}^R = \lambda = 1$ and $m_{S_3} = m_{R_2} = \Lambda$

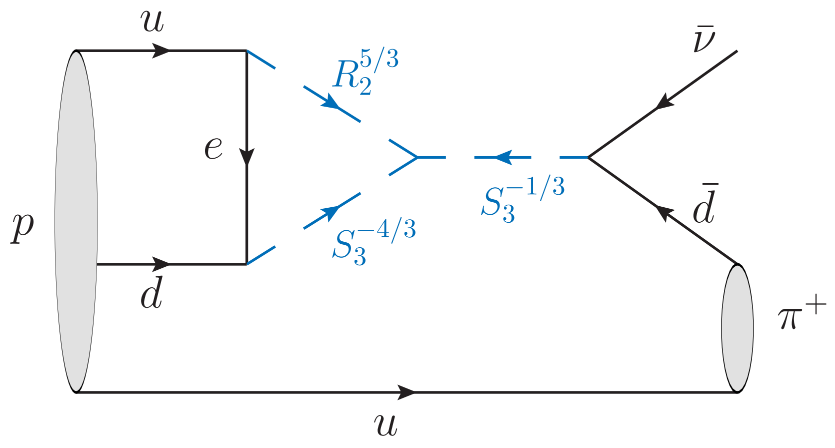
$$p \to \pi^0 e^+ : \quad \Lambda \geq 1.8 \times 10^4\ \mathrm{TeV}$$

$p \to \pi^+ \bar{\nu}$

$$\mathcal{L}_{\text{eff}}^{(d=6)} \supset C_{LL}^{ud\nu d}\ \left(\overline{u}^{\text{C}} P_L d\right) \left(\overline{\nu}^{\text{C}} P_L d\right) + C_{RL}^{ud\nu d}\ \left(\overline{u}^{\text{C}} P_R d\right) \left(\overline{\nu}^{\text{C}} P_L d\right) + \text{h.c.}$$

$$C_{LL}^{ud\nu d} = -\frac{\sqrt{2}\lambda}{8\pi^2}\frac{v m_e}{\Lambda^4}(y_{S_3}^L)^2\left[(V y_{R_2}^R)^* + \frac{m_d}{4m_e}(y_{R_2}^L)^*\right]$$

$$C_{RL}^{ud\nu d} = -\frac{\lambda}{32\pi^2}\frac{v m_u}{\Lambda^4}(V^* y_{S_3}^L)^2 (y_{R_2}^L)^* \,.$$



$$\Gamma(p \to \pi^+ \nu) = \frac{m_p}{16\pi}\left(1 - \frac{m_\pi^2}{m_p^2}\right)^2 \left[(W_0^{LL})^2 |C_{LL}^{ud\nu d}|^2 + (W_0^{RL})^2 |C_{RL}^{ud\nu d}|^2\right]$$

assuming $\quad y_{S_3}^L = y_{R_2}^L = y_{R_2}^R = \lambda = 1$ and $\quad m_{S_3} = m_{R_2} = \Lambda$

$$p \to \pi^+ \bar{\nu}\ : \qquad \Lambda \geq 1.2 \times 10^4\ \text{TeV}$$

Conclusions

- we study a phenomenological impact of triple-leptoquark interactions on proton stability;

- there are two different decay topologies under the assumption that scalar leptoquarks of interest couple solely to the quark-lepton pairs;

- the tree - level topology has been analysed in the literature before in the context of baryon number violation while the one-loop level one has not been featured in any scientific study to date;

- we demonstrate that it is the one-loop level topology that is producing more stringent bounds on the scalar leptoquark masses of the two, if and when they coexist;

$$p \to e^+ e^+ e^- : \qquad \Lambda \geq 1.6 \times 10^2 \, \text{TeV}$$

$$p \to \pi^0 e^+ : \quad \Lambda \geq 1.8 \times 10^4 \, \text{TeV}$$

- we also specify the most prominent proton decay signatures due to the presence of all non-trivial cubic and quartic contractions involving three scalar leptoquark multiplets, where in the latter case one of the scalar multiplets is the SM Higgs doublet

Thanks

Grazie

dimension-nine operators

Hambye & Heeck 1712.04871

$$\begin{aligned}
\mathcal{O}_1^9 &= (QQ)_1(\bar{L}\bar{L})_1(\ell d)\,, & \mathcal{O}_2^9 &= (QQ)_1(\bar{L}\ell)(\bar{L}d)\,,\\
\mathcal{O}_3^9 &= (QL)_1(\bar{L}d)(\bar{L}d)\,, & \mathcal{O}_4^9 &= (\bar{\ell}Q)(\bar{L}d)(\ell d)\,,\\
\mathcal{O}_5^9 &= (\bar{L}\bar{L})(ud)(\ell d)\,, & \mathcal{O}_6^9 &= (\bar{L}u)(\bar{L}d)(\ell d)\,,\\
\mathcal{O}_7^9 &= (\bar{L}d)(\bar{L}\ell)(ud)\,, & \mathcal{O}_8^9 &= (\bar{L}d)(\bar{L}d)(\ell u)\,,\\
\mathcal{O}_9^9 &= (QL)_3((\bar{L}d)(\bar{L}d))_3\,, & \mathcal{O}_{10}^9 &= (QL)_1(\bar{L}\bar{L})_1(dd)\,,\\
\mathcal{O}_{11}^9 &= (QL)_3(\bar{L}\bar{L})_3(dd)\,, & \mathcal{O}_{12}^9 &= (\bar{\ell}Q)(\bar{L}\ell)(dd)\,,\\
\mathcal{O}_{13}^9 &= (\bar{L}\bar{L})(u\ell)(dd)\,, & \mathcal{O}_{14}^9 &= (\bar{L}u)(\bar{L}\ell)(dd)\,,\\
\mathcal{O}_{15}^9 &= (\bar{\ell}L)(\bar{L}d)(dd)\,, & \mathcal{O}_{16}^9 &= (\bar{\ell}\bar{\ell})(\ell d)(dd)\,.
\end{aligned}$$

$$\Gamma(p \to \ell_\alpha^+ \ell_\beta^+ \ell_\gamma^-) \sim \frac{\langle H\rangle^2 \beta_{\rm h}^2 m_p^5}{6144\pi^3\Lambda^{12}} \simeq \frac{(100\,\mathrm{TeV}/\Lambda)^{12}}{10^{33}\,\mathrm{yrs}}$$

d = 9 effective operators

$$\mathcal{L}_{(a)} \supset \frac{2\kappa\epsilon_{abc}}{m_{\tilde{R}_2}^4 m_{S_1}^2} (y_{\tilde{R}_2}^L)_{1j}^* (\bar{\nu}_L^j d_{R\,a})\, (y_{\tilde{R}_2}^L)_{1k}^* (\bar{e}_L^k d_{R\,b})$$

$$\times \Big[(V^* y_{S_1}^L)_{1i} (\bar{u}_{L\,c}^C e_L^i) - (y_{S_1}^L)_{1i} (\bar{d}_{L\,c}^C \nu_L^i) + (y_{S_1}^R)_{1i} (\bar{u}_{R\,c}^C e_R^i) \Big] + \text{h.c.}\,,$$

$$\mathcal{L}_{(b)} \supset \frac{\kappa\epsilon_{abc}}{m_{\tilde{S}_1}^2 m_{R_2}^2 m_{\tilde{R}_2}^2} \Bigg\{ \Big[(V y_{R_2}^R)_{1j}^* (\bar{e}_R^j u_{L\,a}) - (y_{R_2}^L)_{1j}^* (\bar{e}_L^j u_{R\,a}) \Big] (y_{\tilde{R}_2}^L)_{1k}^* (\bar{\nu}_L^k d_{R\,b})$$

$$+ \Big[(y_{R_2}^L)_{1j}^* (\bar{\nu}_L^j u_{R\,a}) + (y_{R_2}^R)_{1j}^* (\bar{e}_R^j d_{L\,a}) \Big] (y_{\tilde{R}_2}^L)_{1k}^* (\bar{e}_L^k d_{R\,b}) \Bigg\} (y_{\tilde{S}_1}^R)_{1i} (\bar{d}_{L\,c}^C e_R^i) + \text{h.c.}\,,$$

$$\mathcal{L}_{(c)} \supset \frac{\lambda\epsilon_{abc} v}{\sqrt{2} m_{S_3}^2 m_{R_2}^2 m_{S_1}^2} \Big[(V^* y_{S_1}^L)_{1i} (\bar{u}_{L\,c}^C e_L^i) - (y_{S_1}^L)_{1i} (\bar{d}_{L\,c}^C \nu_L^i) + (y_{S_1}^R)_{1i} (\bar{u}_{R\,c}^C e_R^i) \Big]$$

$$\times \Bigg\{ \Big[(V^* y_{S_3}^L)_{1j} (\bar{u}_{L\,a}^C e_L^j) + (y_{S_3}^L)_{1j} (\bar{d}_{L\,a}^C \nu_L^j) \Big] \Big[(y_{R_2}^L)_{1k}^* (\bar{\nu}_L^k u_{R\,b}) + (y_{R_2}^R)_{1k}^* (\bar{e}_R^k d_{L\,b}) \Big]$$

$$- \sqrt{2} (y_{S_3}^L)_{1j} (\bar{d}_{L\,a}^C e_L^j) \Big[(V y_{R_2}^R)_{1k}^* (\bar{e}_R^k u_{L\,b}) - (y_{R_2}^L)_{1k}^* (\bar{e}_L^k u_{R\,b}) \Big] \Bigg\} + \text{h.c.}\,,$$

$$\mathcal{L}_{(d)} \supset \frac{2\sqrt{2}\lambda\epsilon_{abc} v}{m_{S_3}^4 m_{R_2}^2} (y_{S_3}^L)_{1j} (\bar{d}_{L\,a}^C e_L^j)$$

$$\times \Bigg\{ (V^* y_{S_3}^L)_{1k} (\bar{u}_{L\,b}^C \nu_L^k) \Big[(y_{R_2}^L)_{1i}^* (\bar{\nu}_L^i u_{R\,c}) + (y_{R_2}^R)_{1i}^* (\bar{e}_R^i d_{L\,c}) \Big]$$

$$+ \Big[(y_{S_3}^L)_{1k} (\bar{d}_{L\,b}^C \nu_L^k) + (V^* y_{S_3}^L)_{1k} (\bar{u}_{L\,b}^C e_L^k) \Big] \Big[(y_{R_2}^L)_{1i}^* (\bar{e}_L^i u_{R\,c}) - (V y_{R_2}^R)_{1i}^* (\bar{e}_R^i u_{L\,c}) \Big] \Bigg\}$$

$$+ \text{h.c.}$$

$$\mathcal{L}_{(e)} \supset \frac{-\lambda\epsilon_{abc}v}{\sqrt{2}m_{\tilde{S}_1}^2 m_{R_2}^2 m_{S_1}^2}(y_{\tilde{S}_1}^R)_{1i}(\bar{d}_{R\,c}^C e_R^i)\Big[(y_{R_2}^L)_{1j}^*(\bar{e}_L^j u_{R\,a}) - (V y_{R_2}^R)_{1j}^*(\bar{e}_R^j u_{L\,a})\Big]$$
$$\times\Big[(V^* y_{S_1}^L)_{1k}(\bar{u}_{L\,b}^C e_L^k) + (y_{S_1}^R)_{1k}(\bar{u}_{R\,b}^C e_R^k) - (y_{S_1}^L)_{1k}(\bar{d}_{L\,b}^C \nu_L^k)\Big] + \text{h.c.}\,,$$

$$\mathcal{L}_{(f)} \supset \frac{\lambda\epsilon_{abc}v}{\sqrt{2}m_{R_2}^2 m_{S_3}^2 m_{\tilde{S}_1}^2}(y_{\tilde{S}_1}^R)_{1i}(\bar{d}_c^C P_R e^i)$$
$$\times\Big\{2(V^* y_{S_3}^L)_{1j}(\bar{u}_{L\,a}^C \nu_L^j)\Big[(y_{R_2}^L)_{1k}^*(\bar{\nu}_L^k u_{R\,b}) + (y_{R_2}^R)_{1k}^*(\bar{e}_R^k d_{L\,b})\Big]$$
$$+\Big[(y_{S_3}^L)_{1j}(\bar{d}_{L\,a}^C \nu_L^j) + (V^* y_{S_3}^L)_{1j}(\bar{u}_{L\,a}^C e_L^j)\Big]\Big[(y_{R_2}^L)_{1k}^*(\bar{e}_L^k u_{R\,b}) - (V y_{R_2}^R)_{1k}^*(\bar{e}_R^k u_{L\,b})\Big]\Big\}$$

$$\mathcal{L}_{(g)} \supset \frac{\lambda\epsilon_{abc}v}{\sqrt{2}m_{S_3}^2 m_{\tilde{R}_2}^2 m_{S_1}^2}\Big[(V^* y_{S_1}^L)_{1i}(\bar{u}_{L\,c}^C e_L^i) - (y_{S_1}^L)_{1i}(\bar{d}_{L\,c}^C \nu_L^i) + (y_{S_1}^R)_{1i}(\bar{u}_{R\,c}^C e_R^i)\Big]$$
$$\times\Big\{\Big[(y_{S_3}^L)_{1j}(\bar{d}_{L\,a}^C \nu_L^j) + (V^* y_{S_3}^L)_{1j}(\bar{u}_{L\,a}^C e_L^j)\Big](y_{\tilde{R}_2}^L)_{1k}^*(\bar{e}_L^k d_{R\,b})$$
$$+\, 2(V^* y_{S_3}^L)_{1j}(\bar{u}_{L\,a}^C \nu_L^j)\,(y_{\tilde{R}_2}^L)_{1k}^*(\bar{\nu}_L^k d_{R\,b})\Big\} + \text{h.c.}\,,$$

$$\mathcal{L}_{(h)} \supset \frac{2\sqrt{2}\lambda\epsilon_{abc}v}{m_{S_3}^4 m_{\tilde{R}_2}^2}\Big\{(y_{S_3}^L)_{1j}(\bar{d}_{L\,a}^C e_L^j)\,(V^* y_{S_3}^L)_{1k}(\bar{u}_{L\,b}^C \nu_L^k)\,(y_{\tilde{R}_2}^L)_{1i}^*(\bar{e}_L^i d_{R\,c})$$
$$-\,(y_{\tilde{R}_2}^L)_{1i}^*(\bar{\nu}_L^i d_{R\,c})\,(V^* y_{S_3}^L)_{1j}(\bar{u}_{L\,a}^C \nu_L^j)\Big[(y_{S_3})_{1k}^L(\bar{d}_{L\,b}^C \nu_L^k) + (V^* y_{S_3}^L)_{1k}(\bar{u}_{L\,b}^C e_L^k)\Big]\Big\} + \text{h.c.}$$

Channel	$\lvert\Delta(B-L)\rvert$	$\frac{\Gamma^{-1}}{10^{30}\ \mathrm{yr}}$
$p \to e^+ + \gamma$	0	41000 [72]
$p \to e^+ + \pi^0$	0	16000 [24]
$p \to e^+ + \eta$	0	10000 [73]
$p \to e^+ + \rho^0$	0	720 [73]
$p \to e^+ + \omega$	0	1600 [73]
$p \to e^+ + K^0$	0	1000 [74]
$p \to e^+ + K^{*,0}$	0	84 [65]
$p \to \mu^+ + \gamma$	0	21000 [72]
$p \to \mu^+ + \pi^0$	0	7700 [24]
$p \to \mu^+ + \eta$	0	4700 [73]
$p \to \mu^+ + \rho^0$	0	570 [73]
$p \to \mu^+ + \omega$	0	2800 [73]
$p \to \mu^+ + K^0$	0	1600 [75]
$p \to \nu + \pi^+$	0,2	390 [76]
$p \to \nu + \rho^+$	0,2	162 [65]
$p \to \nu + K^+$	0,2	5900 [77]
$p \to \nu + K^{*,+}$	0,2	130 [78]

Super-Kamiokande Collaboration, 1610.03597
1811.12430 …