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

Ilja Doršner

University of Split & Institute Jožef Stefan

Workshop on the Standard Model and Beyond
Corfu, Greece

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*I.D., Svjetlana Fajfer, and Olcyr Sumensari, JHEP 05 (2022) 183, arXiv:2202.08287.

OUTLINE

- **INTRODUCTION OF RELEVANT TOPOLOGIES**
- **TRIPLE-LEPTOQUARK INTERACTION CLASSIFICATION**
- **CASE STUDY: TREE- VS. LOOP-LEVEL PROTON DECAYS**
- **CONCLUSIONS**

"CONVENTIONAL" TWO-BODY PROTON DECAY

$p \to \pi^0 e^+$

$p \to \pi^0 \mu^+$

$p \to \eta^0 e^+$

$p \to \eta^0 \mu^+$

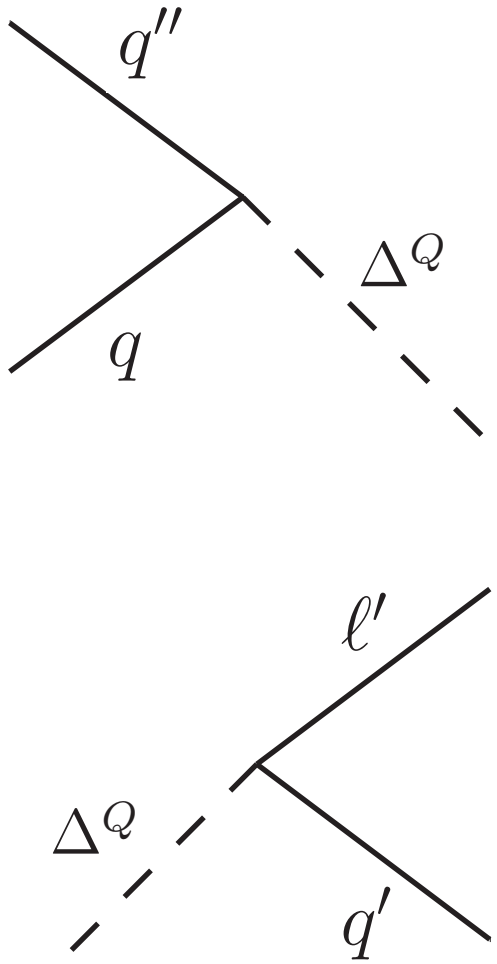
$p \to K^0 e^+$

$p \to K^0 \mu^+$

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

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

$\Delta^Q \equiv$ LEPTOQUARK OF ELECTRIC CHARGE Q [@]



[@]I.D., Svjetlana Fajfer, and Nejc Košnik, Phys. Rev. D 86 (2012) 015013, arXiv:1204.0674.

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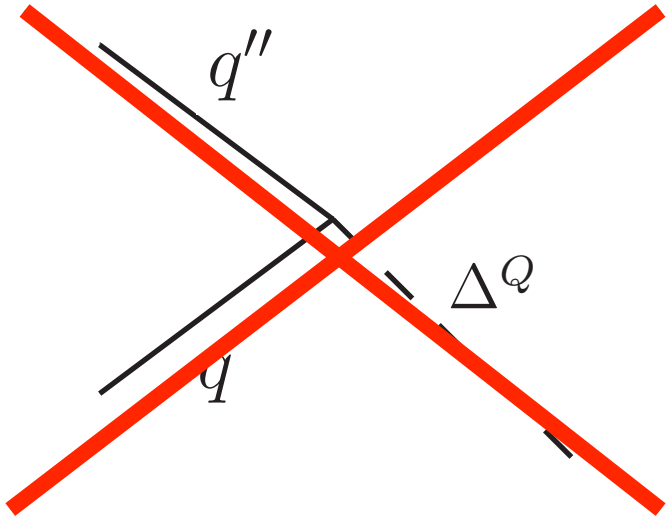
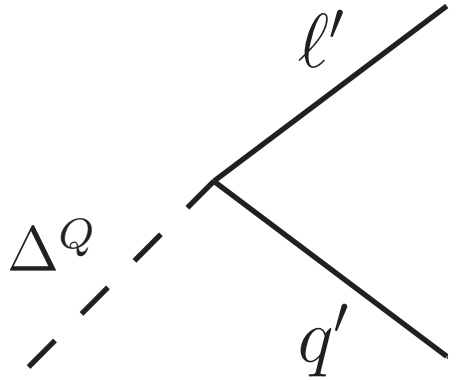
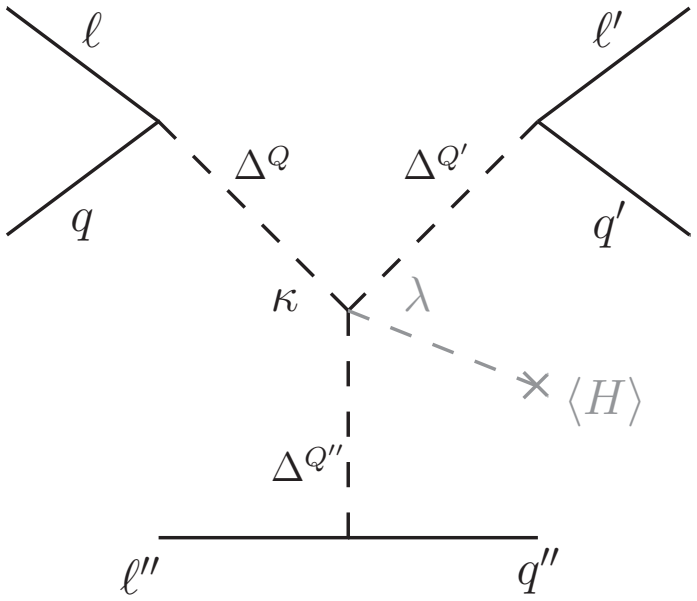




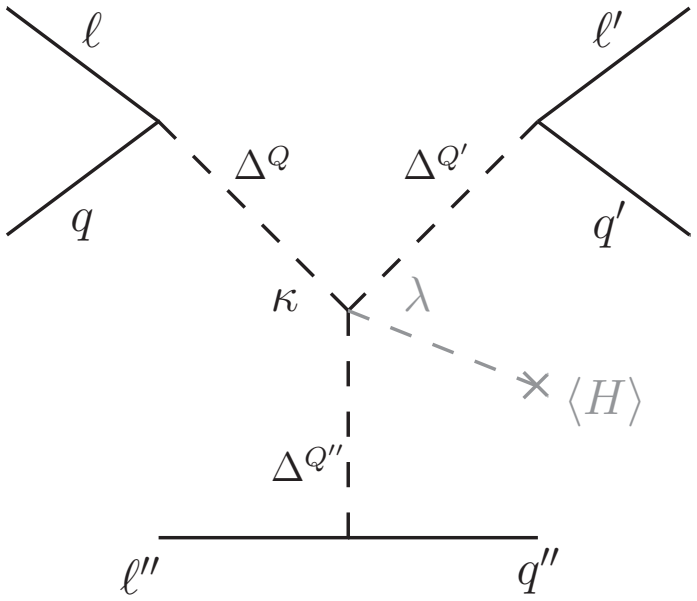
"UNCONVENTIONAL" PROTON DECAY



$$p \to e^+ e^+ e^- \quad @$$

@T. Hambye and J. Heeck, Phys. Rev. Lett. 120, no.17, 171801 (2018).

TREE- AND LOOP-LEVEL TOPOLOGIES



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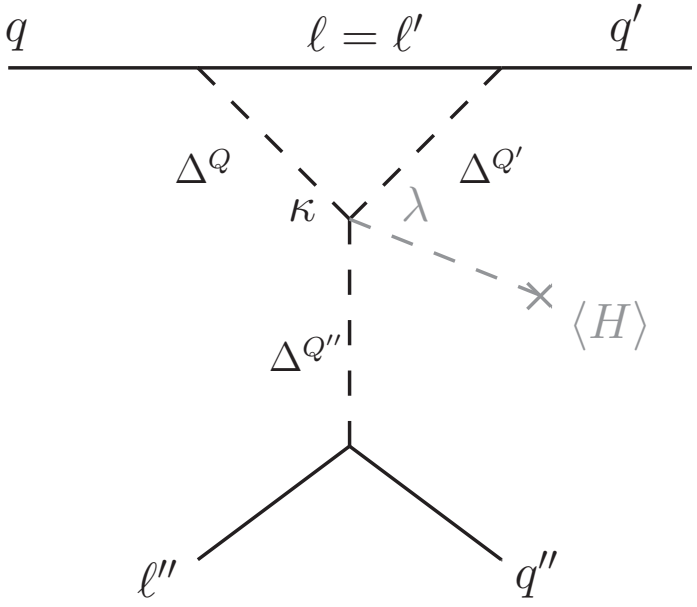

$p \to \pi^0 e^+$ •

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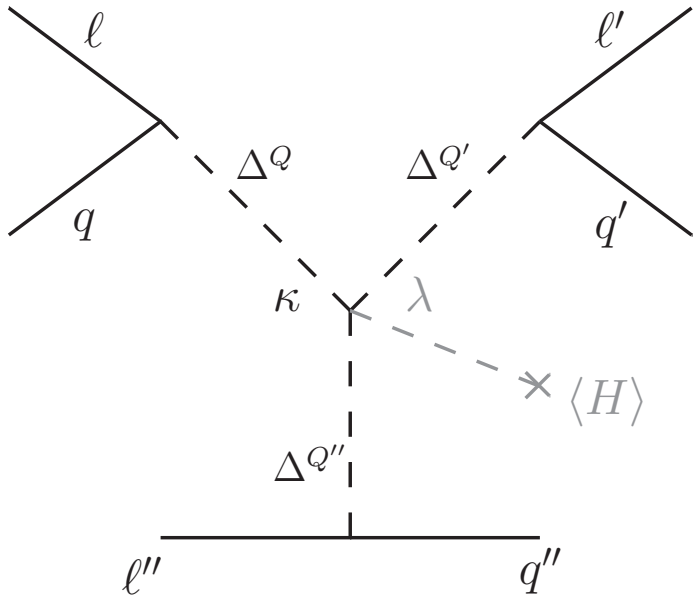
•I.D., Svjetlana Fajfer, and Olcyr Sumensari, JHEP 05 (2022) 183, arXiv:2202.08287.

PROTON DECAY VIA TREE-LEVEL TOPOLOGY



Cyrus Faroughy, Siddharth Prabhu, Bob Zheng, JHEP 06 (2015) 073.

Sergey Kovalenko, Ivan Schmidt, Phys. Lett. B 562 (2003) 104-108.

H.V. Klapdor-Kleingrothaus, Ernest Ma, Utpal Sarkar, Mod. Phys. Lett. A 17 (2002) 2221.

Jonathan M. Arnold, Bartosz Fornal, Mark B. Wise, Phys. Rev. D 87 (2013) 075004.

T. Hambye and J. Heeck, Phys. Rev. Lett. 120, no.17, 171801 (2018).

Julian Heeck, Volodymyr Takhistov, Phys. Rev. D 101 (2020) 1, 015005.

Renato M. Fonseca, Martin Hirsch, Rahul Srivastava, Phys. Rev. D 97 (2018) 7, 075026.

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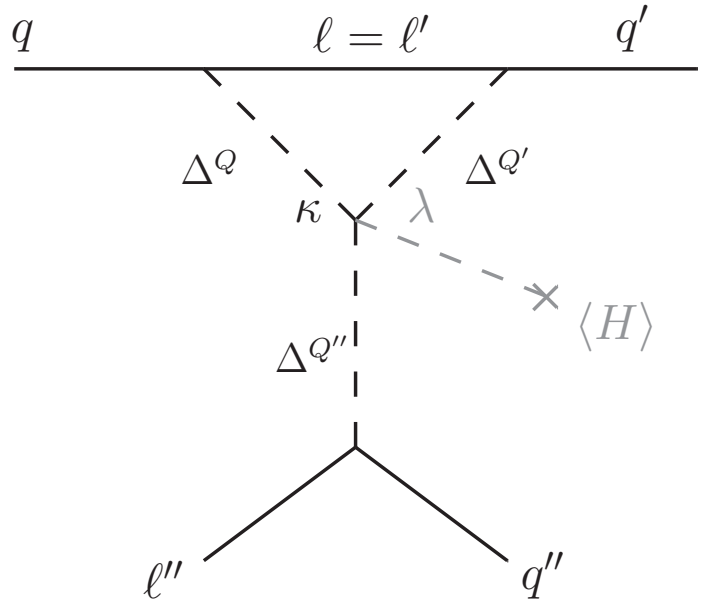
PROTON DECAY VIA LOOP-LEVEL TOPOLOGY



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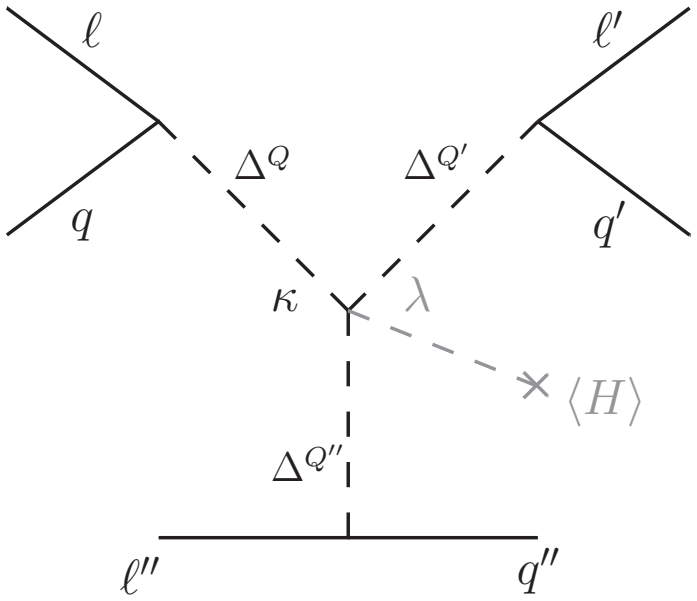
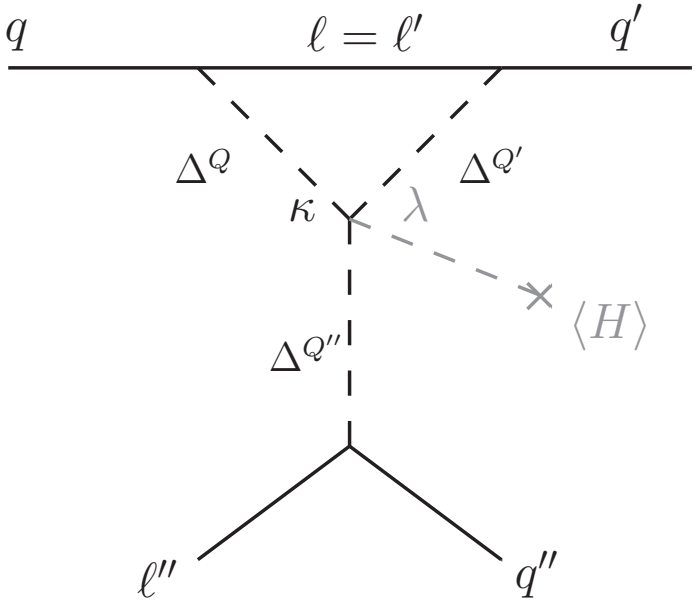
WHICH ONE IS MORE RELEVANT?•



$p \to e^+ e^+ e^-$



$p \to \pi^0 e^+$

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SCALAR LEPTOQUARK PRIMER

LQ multiplets (Δ)	q-ℓ-LQ interactions	$F = 3B + L$
$R_2 = (\mathbf{3}, \mathbf{2}, 7/6)$	$-(y^L_{R_2})_{ij}\, \bar{u}_{R\,i} R_2 i\tau_2 L_j + (y^R_{R_2})_{ij}\, \bar{Q}_i R_2 e_{R\,j}$	0
$\tilde{R}_2 = (\mathbf{3}, \mathbf{2}, 1/6)$	$-(y^L_{\tilde{R}_2})_{ij}\, \bar{d}_{R\,i} \tilde{R}_2 i\tau_2 L_j$	0
$S_1 = (\bar{\mathbf{3}}, \mathbf{1}, 1/3)$	$(y^L_{S_1})_{ij}\, \bar{Q}^C_i i\tau_2 S_1 L_j + (y^R_{S_1})_{ij}\, \bar{u}^C_{R\,i} S_1 e_{R\,j}$	-2
$S_3 = (\bar{\mathbf{3}}, \mathbf{3}, 1/3)$	$(y^L_{S_3})_{ij}\, \bar{Q}^C_i i\tau_2 (\vec{\tau}\cdot\vec{S}_3) L_j$	-2
$\tilde{S}_1 = (\bar{\mathbf{3}}, \mathbf{1}, 4/3)$	$(y^R_{\tilde{S}_1})_{ij}\, \bar{d}^C_{R\,i} \tilde{S}_1 e_{R\,j}$	-2

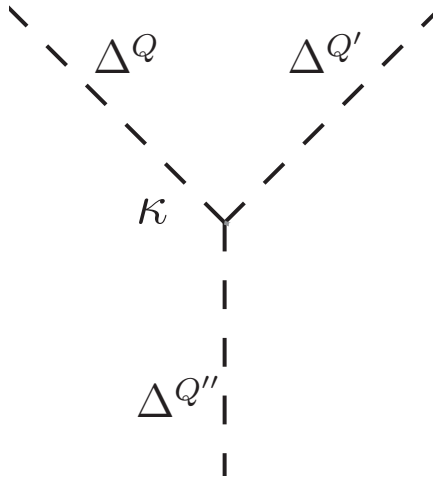
$$|F| = 2: \quad \mathrm{LQ} \to q\,\ell \qquad \overline{\mathrm{LQ}} \to \bar{q}\,\bar{\ell}$$

$$F = 0: \quad \mathrm{LQ} \to q\,\bar{\ell} \qquad \overline{\mathrm{LQ}} \to \bar{q}\,\ell$$

I. D., Svjetlana Fajfer, Admir Greljo, Jernej F. Kamenik, and Nejc Košnik, arXiv:1603.04993.

TRIPLE-LEPTOQUARK INTERACTIONS

κ-Δ-Δ'-Δ''

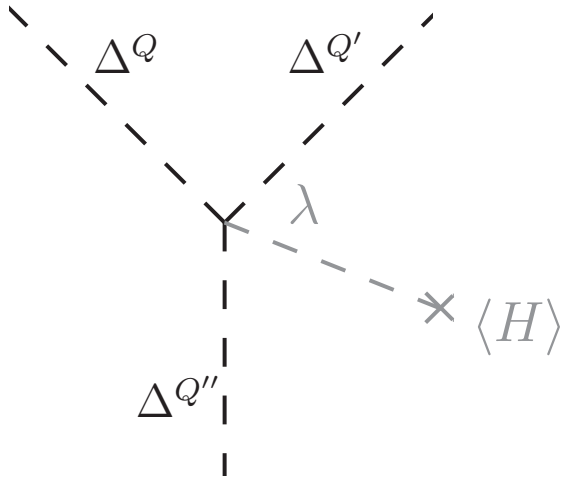


$\Delta : S_3, R_2, \tilde{R}_2, \tilde{S}_1, S_1$

$\Delta^Q : S_3^{+4/3}, S_3^{+1/3}, S_3^{-2/3}, R_2^{+5/3}, R_2^{+2/3}, \tilde{R}_2^{+2/3}, \tilde{R}_2^{-1/3}, \tilde{S}_1^{+4/3}, S_1^{+1/3}$

TRIPLE-LEPTOQUARK INTERACTIONS

λ-Δ-Δ'-Δ''-H



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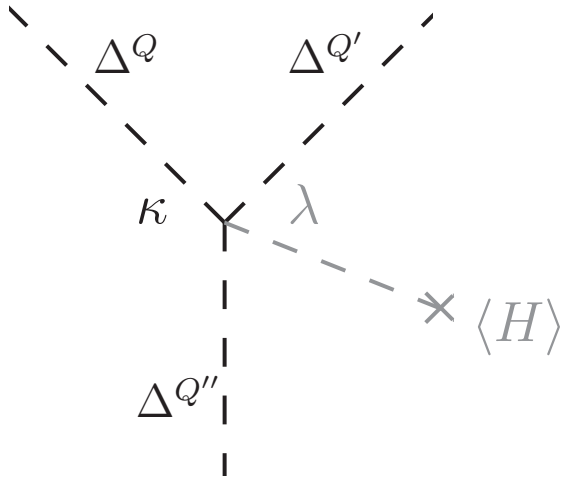
TRIPLE-LEPTOQUARK INTERACTIONS



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κ-Δ-Δ'-Δ''	λ-Δ-Δ'-Δ''-H
$\tilde{R}_2$-$\tilde{R}_2$-S_1^* •	$\tilde{R}_2$-$\tilde{R}_2$-$\tilde{R}_2$-H^* □
$\tilde{R}_2$-$\tilde{R}_2$-S_3^* •	S_1-S_1-R_2^*-H ◎
R_2-$\tilde{R}_2$-$\tilde{S}_1^*$ •	S_1-S_3-R_2^*-H &
	S_3-S_3-R_2^*-H @
	S_1-$\tilde{S}_1$-R_2^*-H^* &
	S_3-$\tilde{S}_1$-R_2^*-H^* &
	S_1-S_1-$\tilde{R}_2^*$-H^* ◎
	S_1-S_3-$\tilde{R}_2^*$-H^* &
	S_3-S_3-$\tilde{R}_2^*$-H^* &

•S. Kovalenko and I. Schmidt, Phys. Lett. B 562, 104-108 (2003).

□H.V. Klapdor-Kleingrothaus, Ernest Ma, Utpal Sarkar, Mod. Phys. Lett. A 17 (2002) 2221.

&A. Crivellin and L. Schnell, Comput. Phys. Commun. 271 (2022), 108188.

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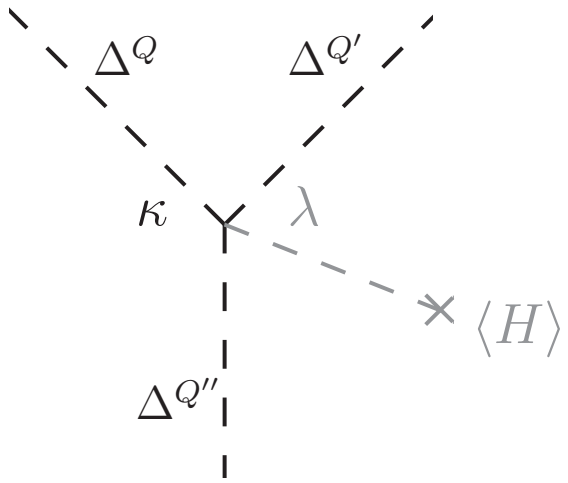
TRIPLE-LEPTOQUARK INTERACTIONS



κ-Δ-Δ'-Δ''	λ-Δ-Δ'-Δ''-H
$\tilde{R}_2$-$\tilde{R}_2$-S_1^* •	$\tilde{R}_2$-$\tilde{R}_2$-$\tilde{R}_2$-H^* □
$\tilde{R}_2$-$\tilde{R}_2$-S_3^* •	S_1-S_1-R_2^*-H ◎
R_2-$\tilde{R}_2$-$\tilde{S}_1^*$ •	S_1-S_3-R_2^*-H &
	S_3-S_3-R_2^*-H @
	S_1-$\tilde{S}_1$-R_2^*-H^* &
	S_3-$\tilde{S}_1$-R_2^*-H^* &
	S_1-S_1-$\tilde{R}_2^*$-H^* ◎
	S_1-S_3-$\tilde{R}_2^*$-H^* &
	S_3-S_3-$\tilde{R}_2^*$-H^* &

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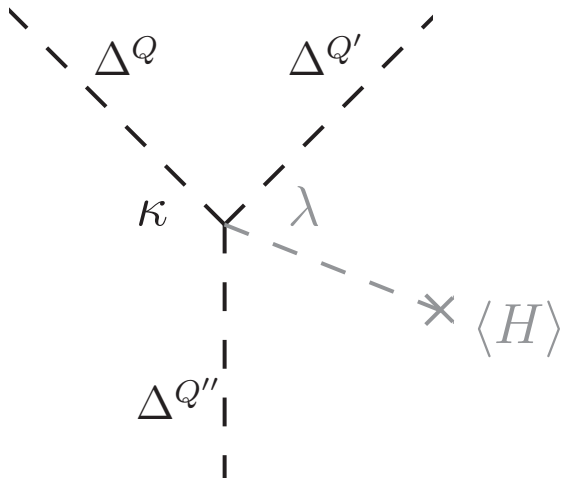

κ-Δ-Δ'-Δ''

κ-Δ^Q-$\Delta^{Q'}$-$\Delta^{Q''}$

λ-Δ-Δ'-Δ''-H

λ-Δ^Q-$\Delta^{Q'}$-$\Delta^{Q''}$-$\langle H \rangle$

$$\langle H \rangle = (0 \;\; v/\sqrt{2})^T$$

$$H = (\mathbf{1}, \mathbf{2}, 1/2)$$

$$\Delta : S_3, R_2, \tilde{R}_2, \tilde{S}_1, S_1$$

$$\Delta^Q : S_3^{+4/3}, S_3^{+1/3}, S_3^{-2/3}, R_2^{+5/3}, R_2^{+2/3}, \tilde{R}_2^{+2/3}, \tilde{R}_2^{-1/3}, \tilde{S}_1^{+4/3}, S_1^{+1/3}$$

TRIPLE-LEPTOQUARK INTERACTIONS •

	$SU(3) \times SU(2) \times U(1)$ 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)	$\lambda H^\dagger (\vec{\tau}\cdot\vec{S}_3)^* (\vec{\tau}\cdot\vec{S}_3)^* i\tau_2 \tilde{R}_2$	$\lambda v\sqrt{2}\epsilon_{abc}\left(\sqrt{2} S_{3a}^{2/3}\, S_{3b}^{-1/3}\, \tilde{R}_{2c}^{-1/3} + S_{3a}^{-4/3}\, S_{3b}^{2/3}\, \tilde{R}_{2c}^{2/3}\right)$	&

•I.D., Svjetlana Fajfer, and Olcyr Sumensari, JHEP 05 (2022) 183, arXiv:2202.08287.

*S. Kovalenko and I. Schmidt, Phys. Lett. B 562, 104-108 (2003).

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CASE STUDY

- I.D., Svjetlana Fajfer, and Olcyr Sumensari, JHEP 05 (2022) 183, arXiv:2202.08287.

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-$\tilde{R}_2$-$\tilde{S}_1^*$	$ddde\bar{e}\bar{e}$	$p \to \pi^+\pi^+e^-e^+e^-$	–
	$ddue\bar{e}\bar{\nu}$	$p \to \pi^+e^+e^-\nu$	$p \to \pi^+\nu$
(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^*	$ddu\nu\bar{\nu}\nu$	$p \to \pi^+\nu\bar{\nu}\bar{\nu}$	$p \to \pi^+\bar{\nu}$
	$ddue\bar{e}\nu$	$p \to \pi^+e^+e^-\bar{\nu}$	–
	$duue\nu\bar{\nu}$	$p \to e^+\nu\bar{\nu}$	$p \to \pi^0e^+$

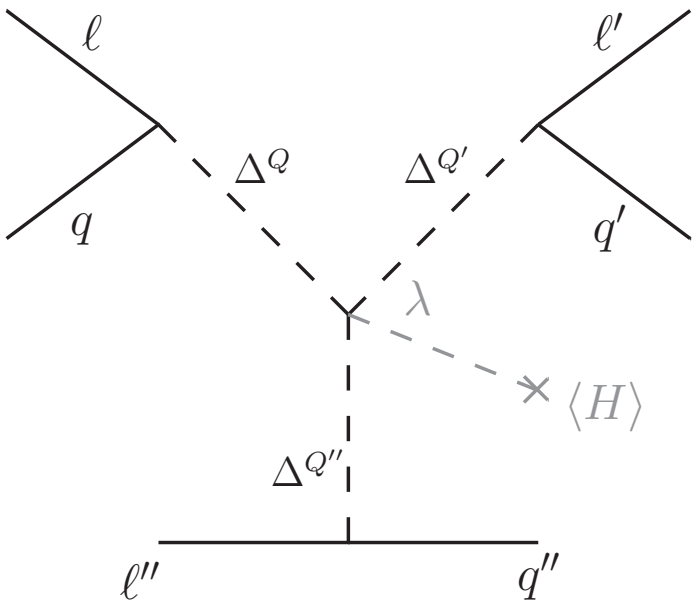
Contractions	Operators	Proton decay (tree)	Proton decay (one-loop)
(a) $\tilde{R}_2$-$\tilde{R}_2$-S_1^*	$ddd\bar{e}\nu\bar{\nu}$	$p \to \pi^+\pi^+e^-\nu\bar{\nu}$	–
	$ddue\bar{e}\bar{\nu}$	$p \to \pi^+e^+e^-\nu$	$p \to \pi^+\nu$
(b) R_2-$\tilde{R}_2$-$\tilde{S}_1^*$	$ddde\bar{e}\bar{e}$	$p \to \pi^+\pi^+e^-e^+e^-$	–
	$ddue\bar{e}\bar{\nu}$	$p \to \pi^+e^+e^-\nu$	$p \to \pi^+\nu$
(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^*	$ddu\nu\bar{\nu}\nu$	$p \to \pi^+\nu\bar{\nu}\bar{\nu}$	$p \to \pi^+\bar{\nu}$
	$ddue\bar{e}\nu$	$p \to \pi^+e^+e^-\bar{\nu}$	–
	$duue\nu\bar{\nu}$	$p \to e^+\nu\bar{\nu}$	$p \to \pi^0e^+$

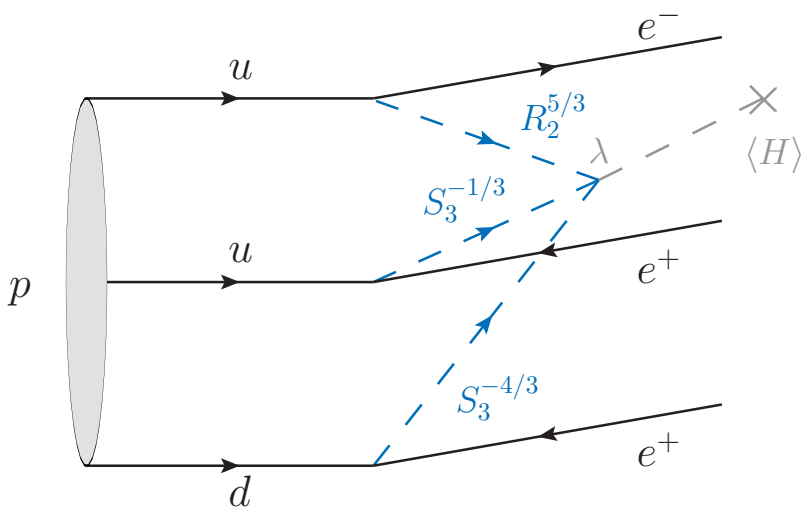
CASE STUDY•

Contractions	Operators	Proton decay (tree)	Proton decay (one-loop)
(d) S_3-S_3-R_2^*-H	$ddue\bar{e}\nu$	$p \to \pi^+ e^+ e^- \bar{\nu}$	$p \to \pi^+ \bar{\nu}$
	$duue\nu\bar{\nu}$	$p \to e^+ \nu \bar{\nu}$	–
	$duuee\bar{e}$	$p \to e^+ e^+ e^-$	$p \to \pi^0 e^+$

•I.D., Svjetlana Fajfer, and Olcyr Sumensari, JHEP 05 (2022) 183, arXiv:2202.08287.

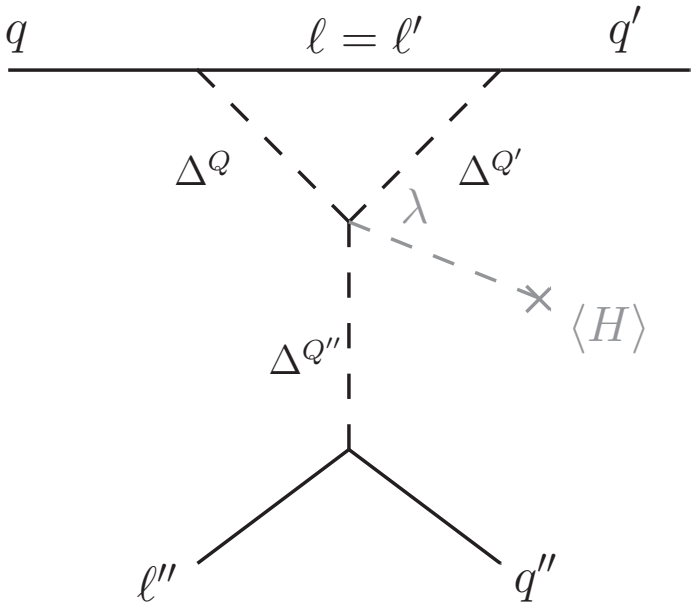
TREE-LEVEL TOPOLOGY

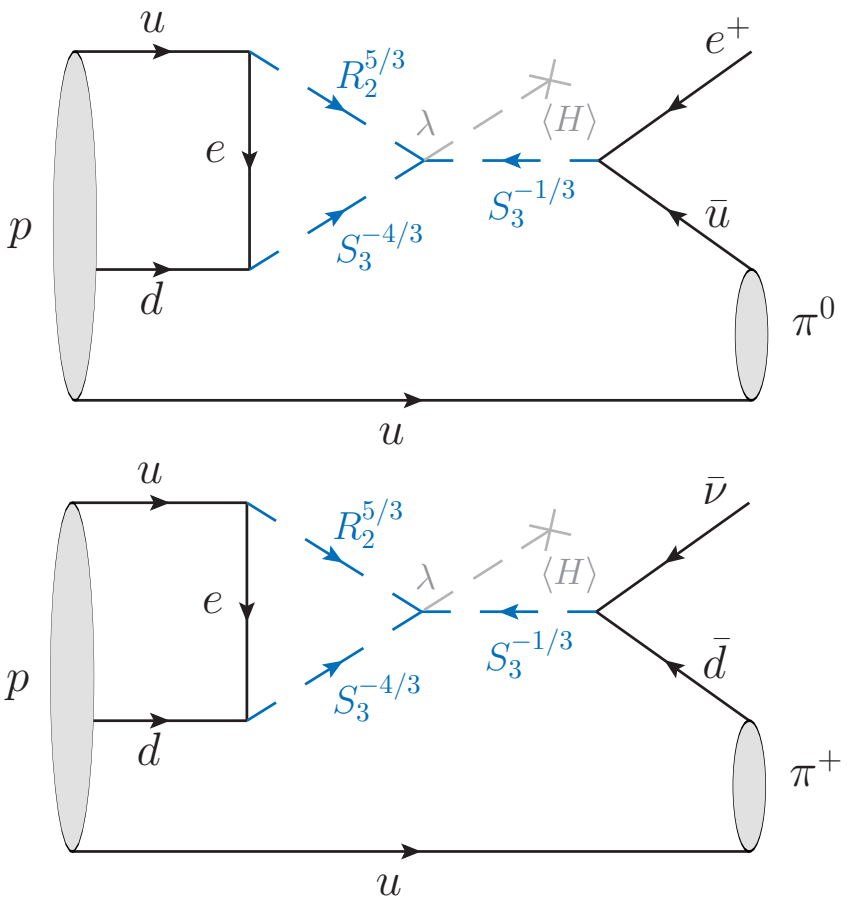




•I.D., Svjetlana Fajfer, and Olcyr Sumensari, JHEP 05 (2022) 183, arXiv:2202.08287.

LOOP-LEVEL TOPOLOGY•





•I.D., Svjetlana Fajfer, and Olcyr Sumensari, JHEP 05 (2022) 183, arXiv:2202.08287.

CASE STUDY•

$$p \to e^+ e^+ e^-$$

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

$$p \to \pi^0 e^+$$

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

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

•I.D., Svjetlana Fajfer, and Olcyr Sumensari, JHEP 05 (2022) 183, arXiv:2202.08287.

CASE STUDY•

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

$\tau(p \to e^+e^+e^-)^{\text{exp}} > 7.93 \times 10^{32}\,\text{years}$

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

tree-level topology

$\tau(p \to \pi^0 e^+)^{\text{exp}} > 2.4 \times 10^{34}\,\text{years}$

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

loop-level topology

$\tau(p \to \pi^+ \bar{\nu})^{\text{exp}} > 3.9 \times 10^{32}\,\text{years}$

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

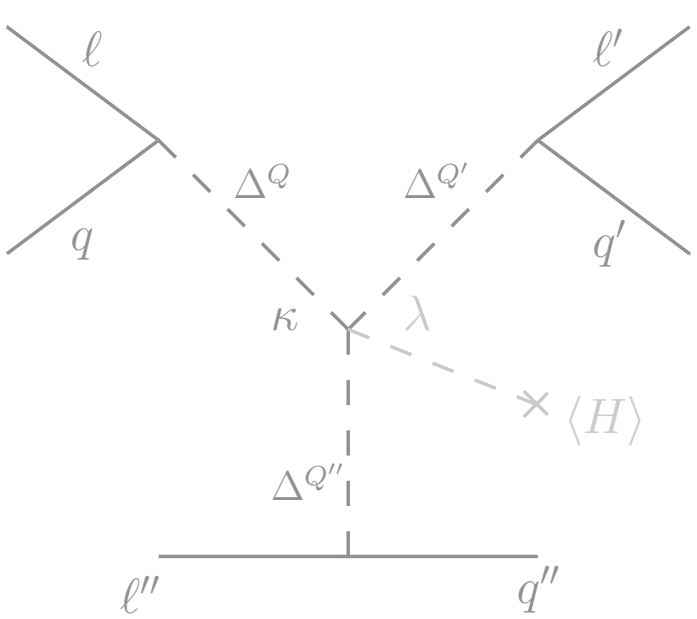
loop-level topology

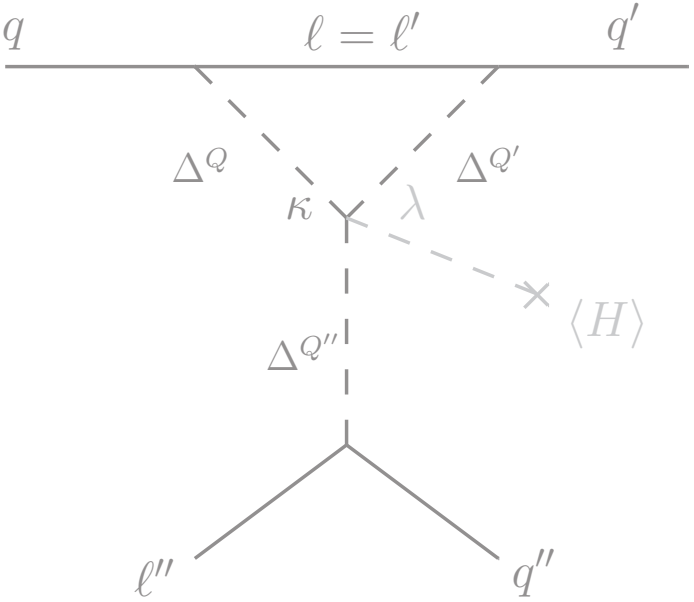
•I.D., Svjetlana Fajfer, and Olcyr Sumensari, JHEP 05 (2022) 183, arXiv:2202.08287.

CONCLUSIONS

The one-loop level topology that yields two-body proton decays via triple-leptoquark interactions is always more relevant than the tree-level topology if and when these two coexist.

This study also provides complete classification of triple-leptoquark interactions.





THANK YOU

dorsner@fesb.hr