

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

Ilja Doršner

University of Split & Institute Jožef Stefan

Portorož 2023: Particle Physics from Early Universe to Future Colliders
Portorož, Slovenija

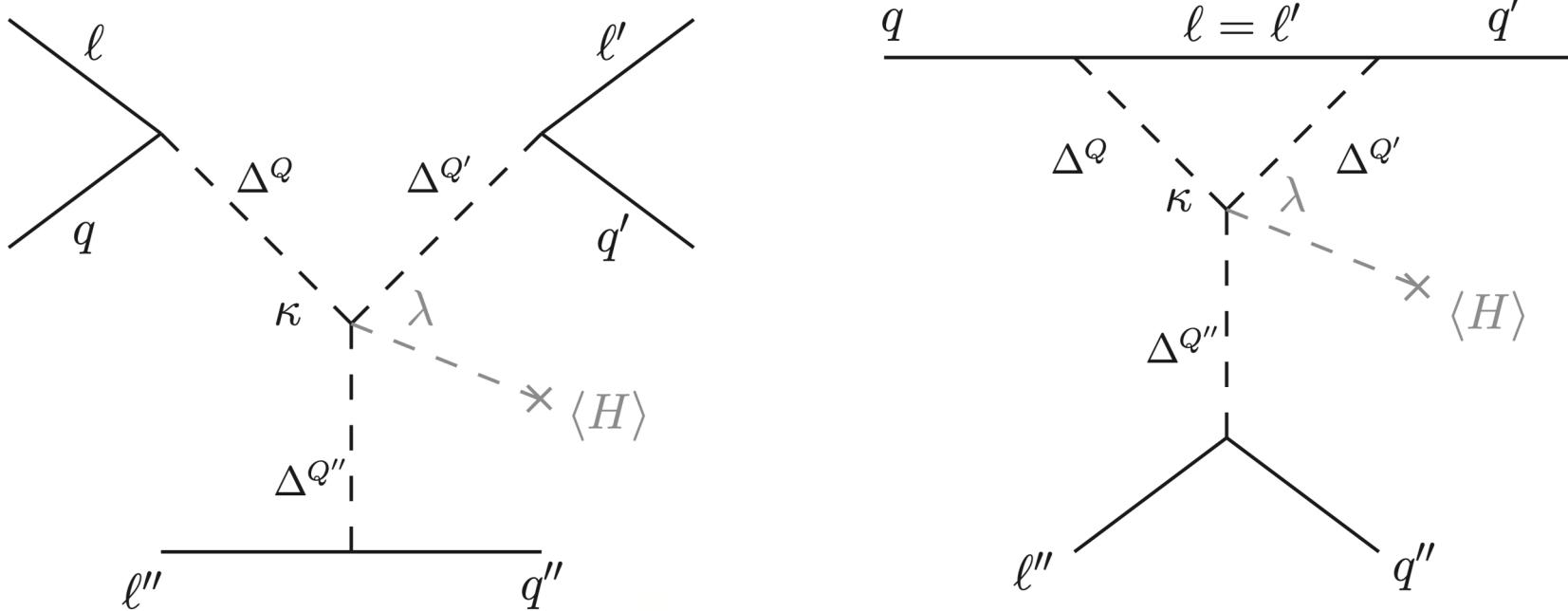
April 12th, 2023

*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

TREE- AND LOOP-LEVEL TOPOLOGIES



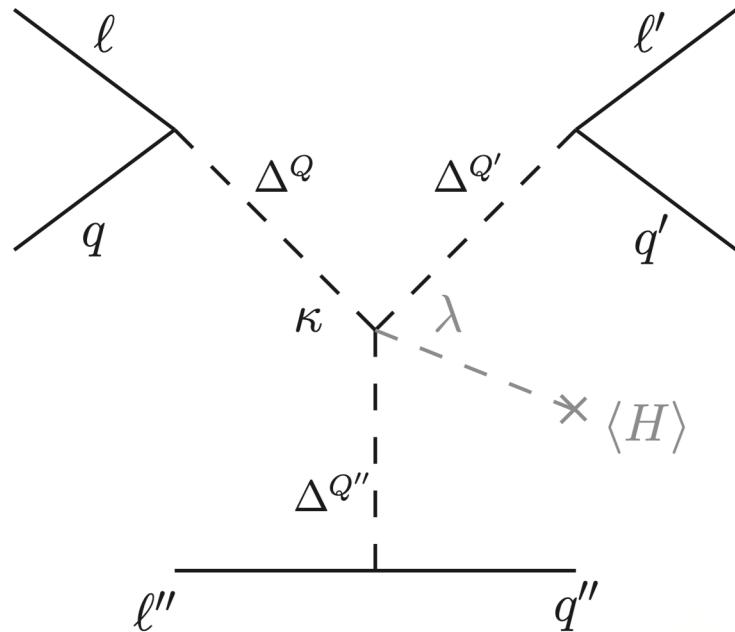
$$p \rightarrow e^+ e^+ e^- \quad @$$

$$p \rightarrow \pi^0 e^+ \quad \bullet$$

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

• 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.

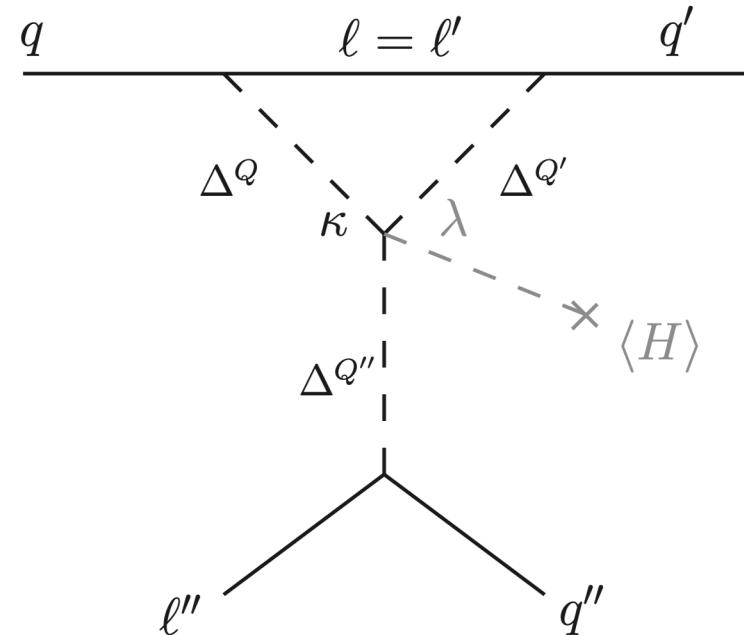
T. Hambye and J. Heeck, Phys. Rev. Lett. 120, no.17, 171801 (2018).

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

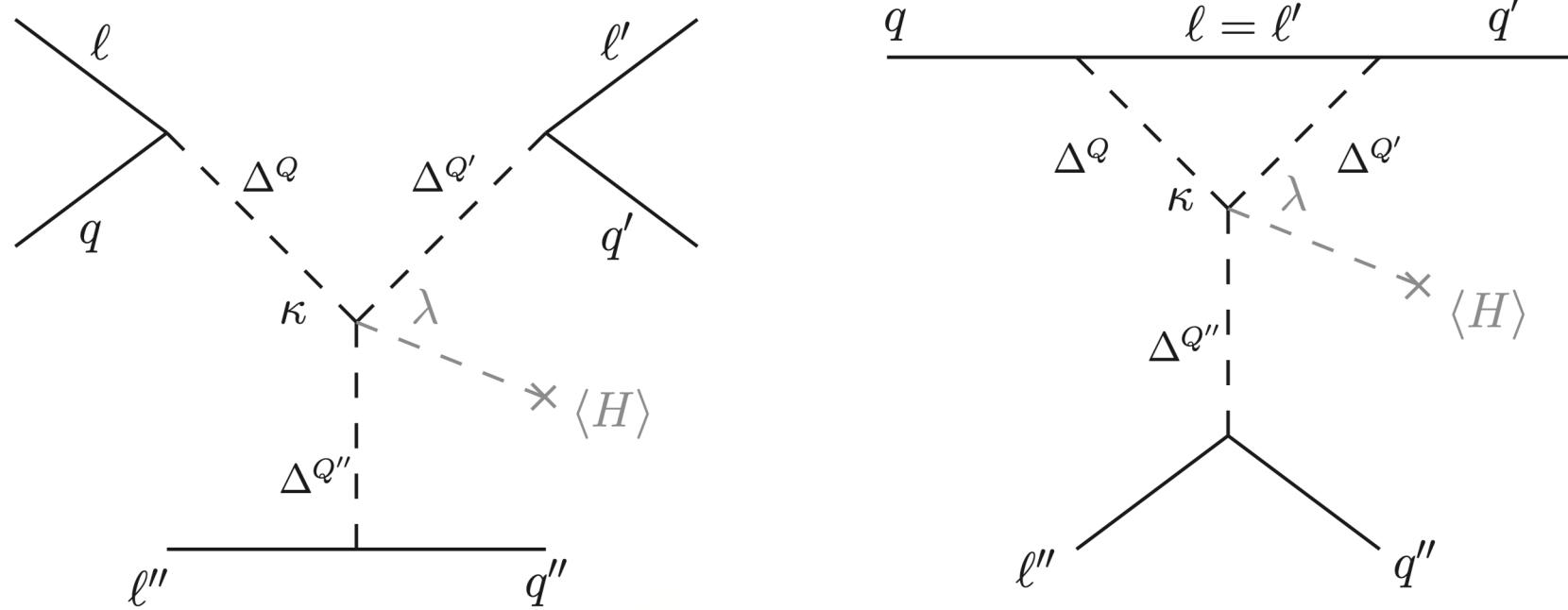
Renato M. Fonseca, Martin Hirsch, Rahul Srivastava, Phys. Rev. D 97 (2018) 7, 075026.

Clara Murgui, Mark B. Wise, Phys. Rev. D 104 (2021) 3, 035017.

PROTON DECAY VIA LOOP-LEVEL TOPOLOGY



WHICH ONE IS MORE RELEVANT?•



$$p \rightarrow e^+ e^+ e^-$$

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

SCALAR LEPTOQUARK PRIMER

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

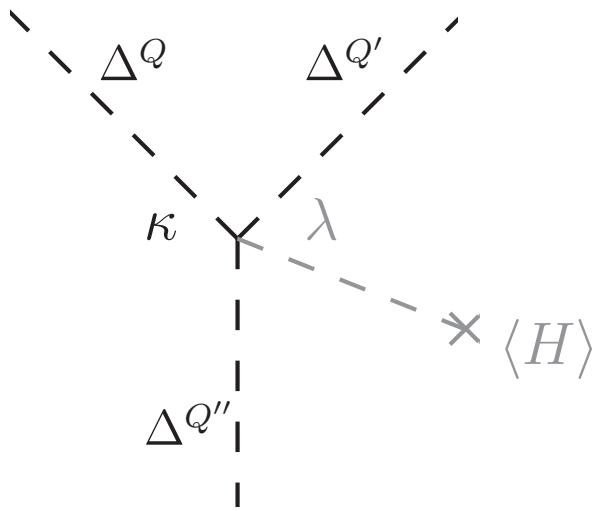
$$|F| = 2: \quad \text{LQ} \rightarrow q \ell \quad \overline{\text{LQ}} \rightarrow \bar{q} \bar{\ell}$$

$$F = 0: \quad \text{LQ} \rightarrow q \bar{\ell} \quad \overline{\text{LQ}} \rightarrow \bar{q} \ell$$

TRIPLE-LEPTOQUARK INTERACTIONS

κ - Δ - Δ' - Δ''

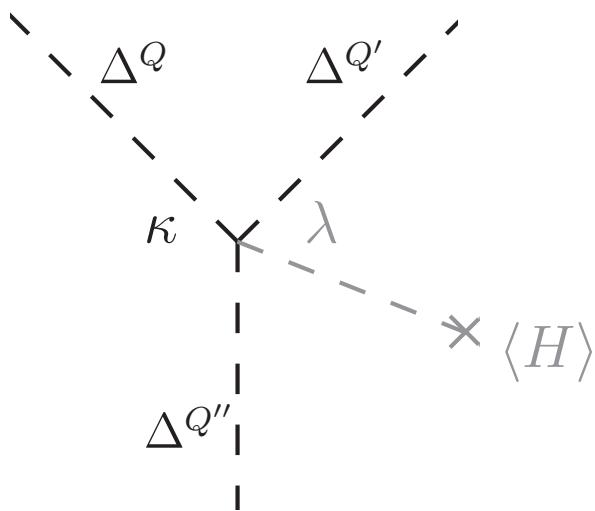
λ - Δ - Δ' - Δ'' - H



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

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

TRIPLE-LEPTOQUARK INTERACTIONS



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

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

● 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.

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

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

$\kappa\text{-}\Delta\text{-}\Delta'\text{-}\Delta''$

$\lambda\text{-}\Delta\text{-}\Delta'\text{-}\Delta''\text{-}H$

$\tilde{R}_2\text{-}\tilde{R}_2\text{-}S_1^*$ ●

$\tilde{R}_2\text{-}\tilde{R}_2\text{-}S_3^*$ ●

$R_2\text{-}\tilde{R}_2\text{-}\tilde{S}_1^*$ ●

$\tilde{R}_2\text{-}\tilde{R}_2\text{-}\tilde{R}_2\text{-}H^*$ □

$S_1\text{-}S_1\text{-}R_2^*\text{-}H$ ◎

$S_1\text{-}S_3\text{-}R_2^*\text{-}H$ &

$S_3\text{-}S_3\text{-}R_2^*\text{-}H$ @

$S_1\text{-}\tilde{S}_1\text{-}R_2^*\text{-}H^*$ &

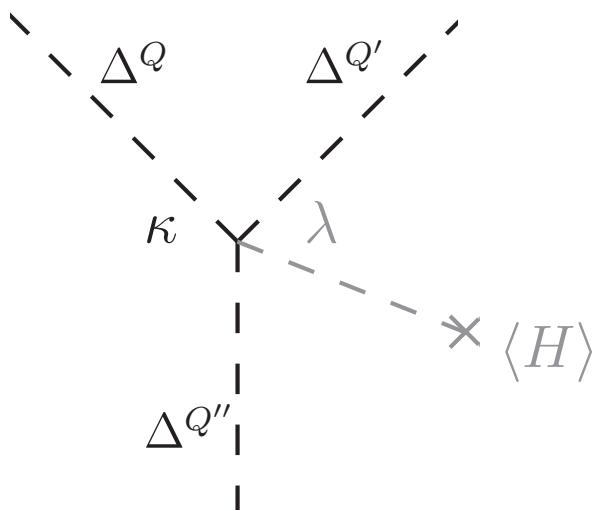
$S_3\text{-}\tilde{S}_1\text{-}R_2^*\text{-}H^*$ &

$S_1\text{-}S_1\text{-}\tilde{R}_2^*\text{-}H^*$ ◎

$S_1\text{-}S_3\text{-}\tilde{R}_2^*\text{-}H^*$ &

$S_3\text{-}S_3\text{-}\tilde{R}_2^*\text{-}H^*$ &

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^* &

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

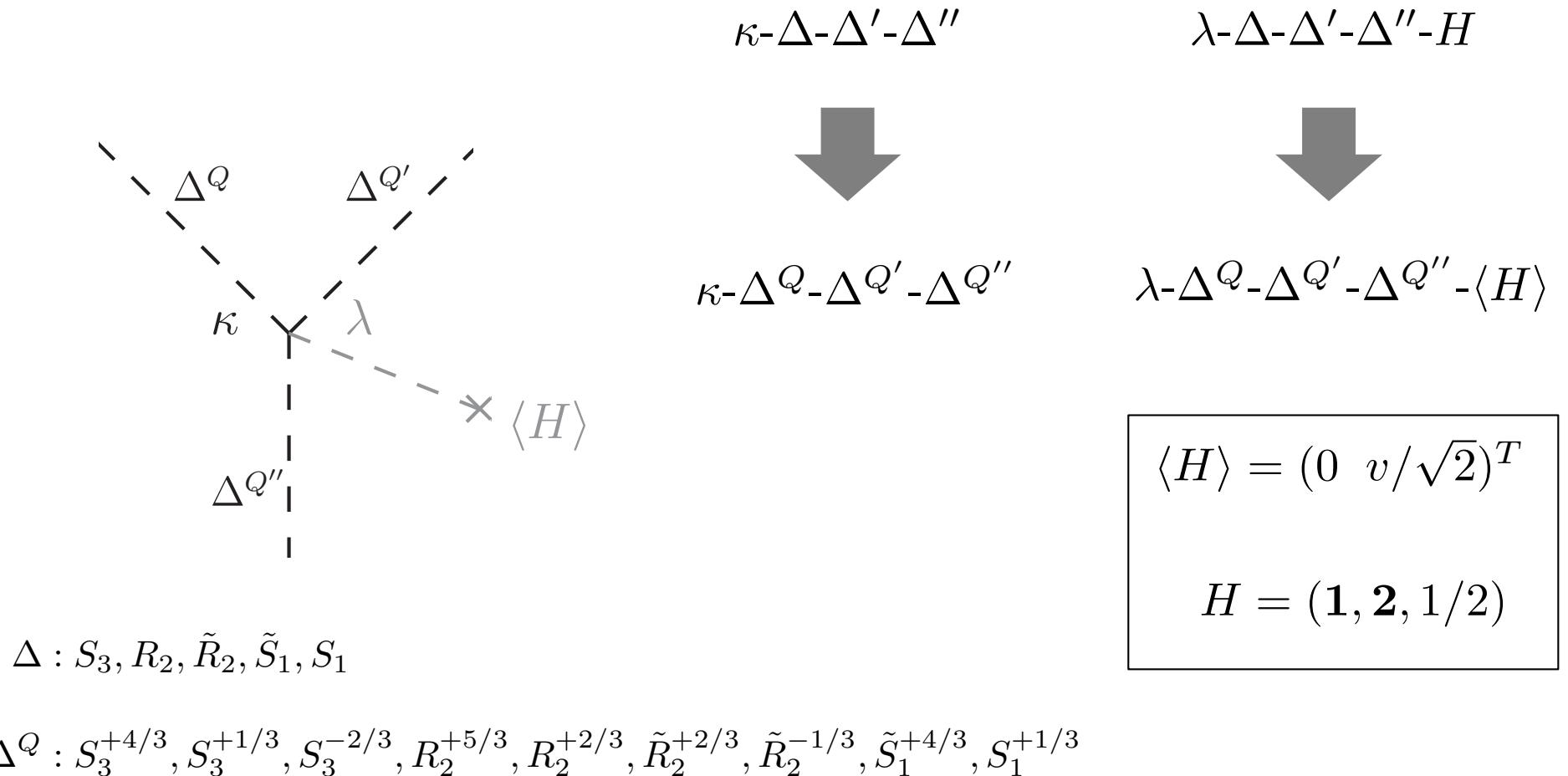
□ H.V. Klapdor-Kleingrothaus, Ernest Ma, Utpal Sarkar, Mod. Phys. Lett. A 17 (2002) 2221.

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

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

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

TRIPLE-LEPTOQUARK INTERACTIONS



TRIPLE-LEPTOQUARK INTERACTIONS

$SU(3) \times SU(2) \times U(1)$ level	$SU(3) \times U(1)_{\text{em}}$ 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).

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

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

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) $\tilde{R}_2\text{-}\tilde{R}_2\text{-}S_1^*$	$ddd\bar{e}\nu\bar{\nu}$	$p \rightarrow \pi^+ \pi^+ e^- \nu\bar{\nu}$	–
	$ddue\bar{e}\bar{\nu}$	$p \rightarrow \pi^+ e^+ e^- \nu$	$p \rightarrow \pi^+ \nu$
(b) $R_2\text{-}\tilde{R}_2\text{-}\tilde{S}_1^*$	$ddde\bar{e}\bar{e}$	$p \rightarrow \pi^+ \pi^+ e^- e^+ e^-$	–
	$ddue\bar{e}\bar{\nu}$	$p \rightarrow \pi^+ e^+ e^- \nu$	$p \rightarrow \pi^+ \nu$
(c) $S_1\text{-}S_3\text{-}R_2^*\text{-}H$	$ddue\bar{e}\nu$	$p \rightarrow \pi^+ e^+ e^- \bar{\nu}$	$p \rightarrow \pi^+ \bar{\nu}$
	$duue\nu\bar{\nu}$	$p \rightarrow e^+ \nu\bar{\nu}$	$p \rightarrow \pi^0 e^+$
	$duuee\bar{e}$	$p \rightarrow e^+ e^+ e^-$	$p \rightarrow \pi^0 e^+$
	$uuuee\bar{\nu}$	$p \rightarrow \pi^- e^+ e^+ \nu$	–
(d) $S_3\text{-}S_3\text{-}R_2^*\text{-}H$	$ddue\bar{e}\nu$	$p \rightarrow \pi^+ e^+ e^- \bar{\nu}$	$p \rightarrow \pi^+ \bar{\nu}$
	$duue\nu\bar{\nu}$	$p \rightarrow e^+ \nu\bar{\nu}$	–
	$duuee\bar{e}$	$p \rightarrow e^+ e^+ e^-$	$p \rightarrow \pi^0 e^+$
(e) $S_1\text{-}\tilde{S}_1\text{-}R_2^*\text{-}H^*$	$ddue\bar{e}\nu$	$p \rightarrow \pi^+ e^+ e^- \bar{\nu}$	$p \rightarrow \pi^+ \bar{\nu}$
	$duuee\bar{e}$	$p \rightarrow e^+ e^+ e^-$	$p \rightarrow \pi^0 e^+$
(f) $S_3\text{-}\tilde{S}_1\text{-}R_2^*\text{-}H^*$	$ddue\bar{e}\nu$	$p \rightarrow \pi^+ e^+ e^- \bar{\nu}$	$p \rightarrow \pi^+ \bar{\nu}$
	$duue\nu\bar{\nu}$	$p \rightarrow e^+ \nu\bar{\nu}$	$p \rightarrow \pi^0 e^+$
	$duuee\bar{e}$	$p \rightarrow e^+ e^+ e^-$	$p \rightarrow \pi^0 e^+$
(g) $S_1\text{-}S_3\text{-}\tilde{R}_2^*\text{-}H^*$	$ddu\nu\bar{\nu}\nu$	$p \rightarrow \pi^+ \nu\bar{\nu}\bar{\nu}$	$p \rightarrow \pi^+ \bar{\nu}$
	$ddue\bar{e}\nu$	$p \rightarrow \pi^+ e^+ e^- \bar{\nu}$	$p \rightarrow \pi^+ \bar{\nu}$
	$duue\nu\bar{\nu}$	$p \rightarrow e^+ \nu\bar{\nu}$	$p \rightarrow \pi^0 e^+$
	$duuee\bar{e}$	$p \rightarrow e^+ e^+ e^-$	$p \rightarrow \pi^0 e^+$
(h) $S_3\text{-}S_3\text{-}\tilde{R}_2^*\text{-}H^*$	$ddu\nu\bar{\nu}\nu$	$p \rightarrow \pi^+ \nu\bar{\nu}\bar{\nu}$	$p \rightarrow \pi^+ \bar{\nu}$
	$ddue\bar{e}\nu$	$p \rightarrow \pi^+ e^+ e^- \bar{\nu}$	–
	$duue\nu\bar{\nu}$	$p \rightarrow e^+ \nu\bar{\nu}$	$p \rightarrow \pi^0 e^+$

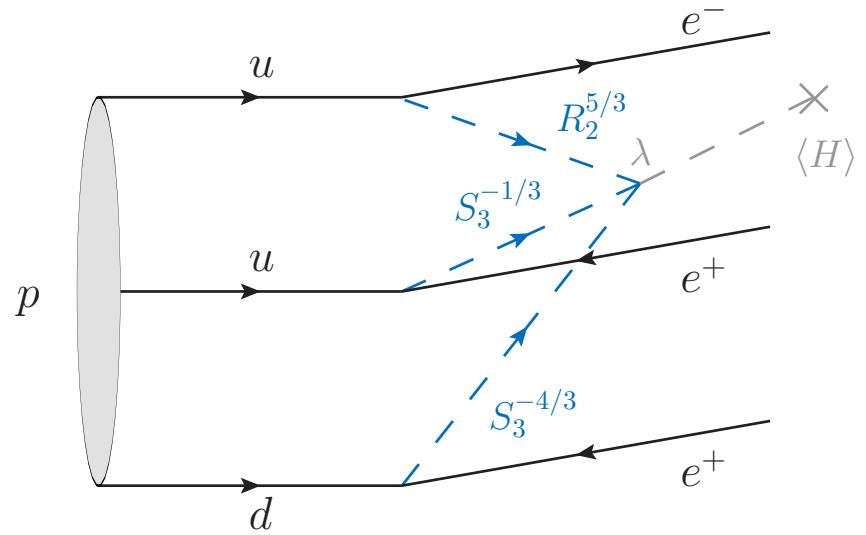
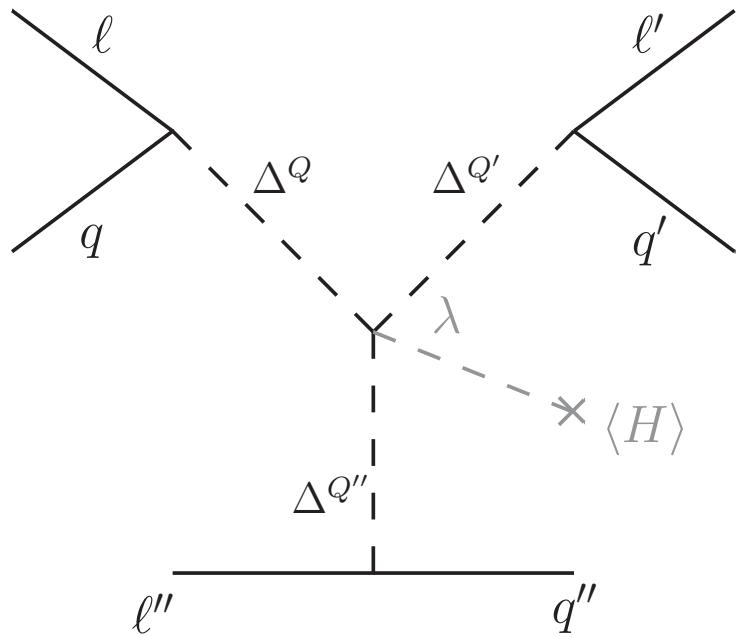
Contractions	Operators	Proton decay (tree)	Proton decay (one-loop)
(a) $\tilde{R}_2\text{-}\tilde{R}_2\text{-}S_1^*$	$ddd\bar{e}\nu\bar{\nu}$	$p \rightarrow \pi^+ \pi^+ e^- \nu\bar{\nu}$	–
	$ddue\bar{e}\bar{\nu}$	$p \rightarrow \pi^+ e^+ e^- \nu$	$p \rightarrow \pi^+ \nu$
(b) $R_2\text{-}\tilde{R}_2\text{-}\tilde{S}_1^*$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

CASE STUDY

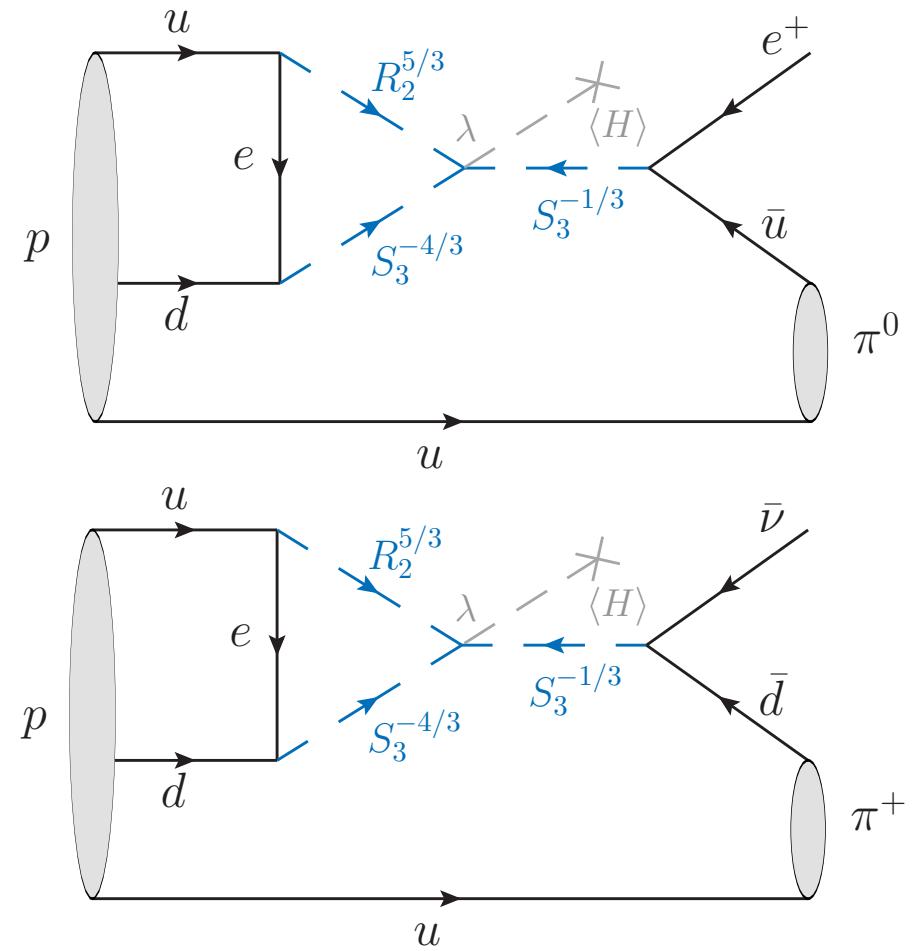
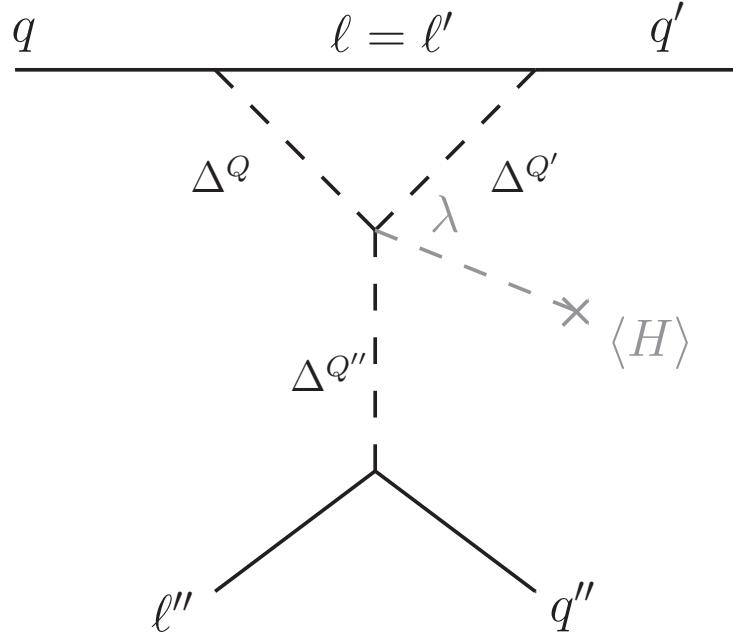
Contractions	Operators	Proton decay (tree)	Proton decay (one-loop)
(d) S_3 - S_3 - R_2^* - H	$ddue\bar{e}\nu$ $duue\nu\bar{\nu}$ $duueee\bar{e}$	$p \rightarrow \pi^+ e^+ e^- \bar{\nu}$ $p \rightarrow e^+ \nu\bar{\nu}$ $p \rightarrow e^+ e^+ e^-$	$p \rightarrow \pi^+ \bar{\nu}$ $-$ $p \rightarrow \pi^0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

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

TREE-LEVEL TOPOLOGY



LOOP-LEVEL TOPOLOGY



CASE STUDY •

$$p \rightarrow e^+ e^+ e^-$$

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

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

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

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

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

CASE STUDY

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

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

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

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

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

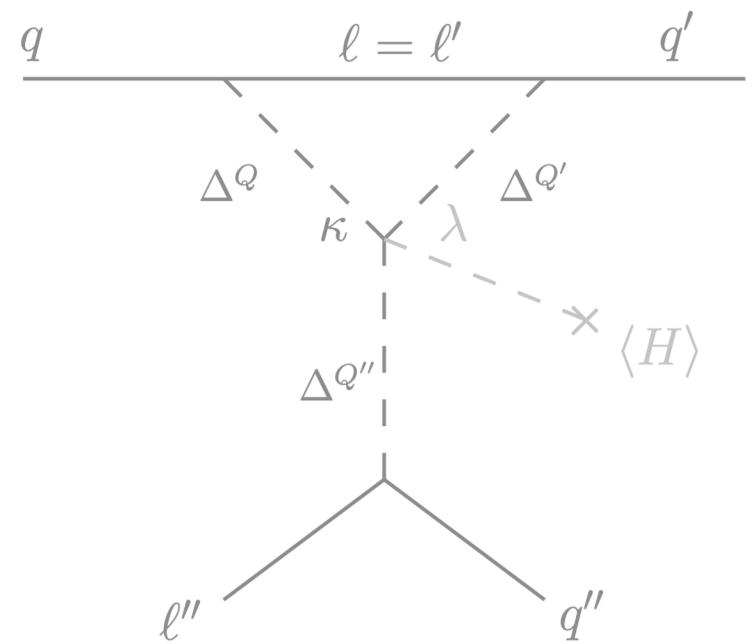
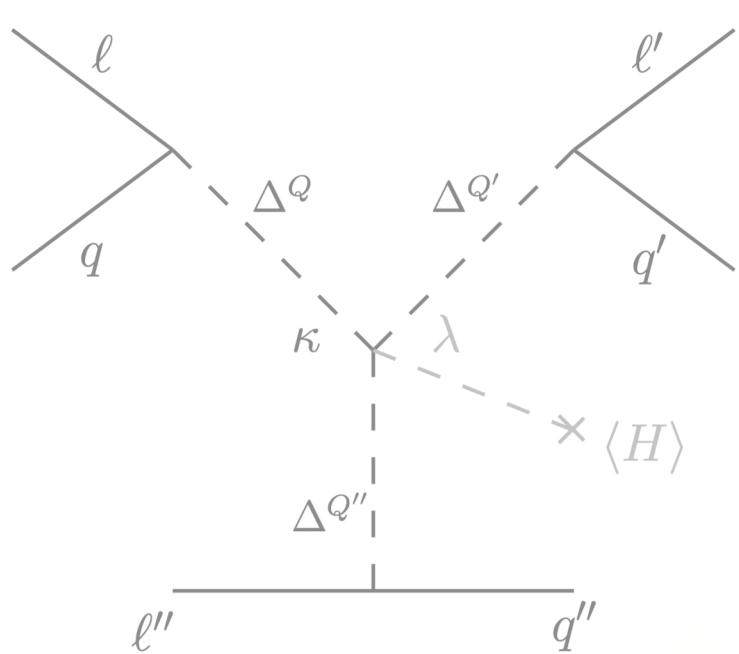
$$\tau(p \rightarrow \pi^+ \bar{\nu})_{\text{exp}} > 3.9 \times 10^{32} \text{ years}$$

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

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 coexist.

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



THANK YOU

dorsner@fesb.hr