BNV nucleon decays in the landscape of effective field theory

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Outline

- Introduction
- General BNV nucleon decay interactions in low-energy EFT (LEFT)
- Hadronic counterparts in chiral perturbation theory (ChPT)
- Applications to various decay modes
- Summary

Baryon number violation (BNV) is related to many BIG questions

- Baryogenesis

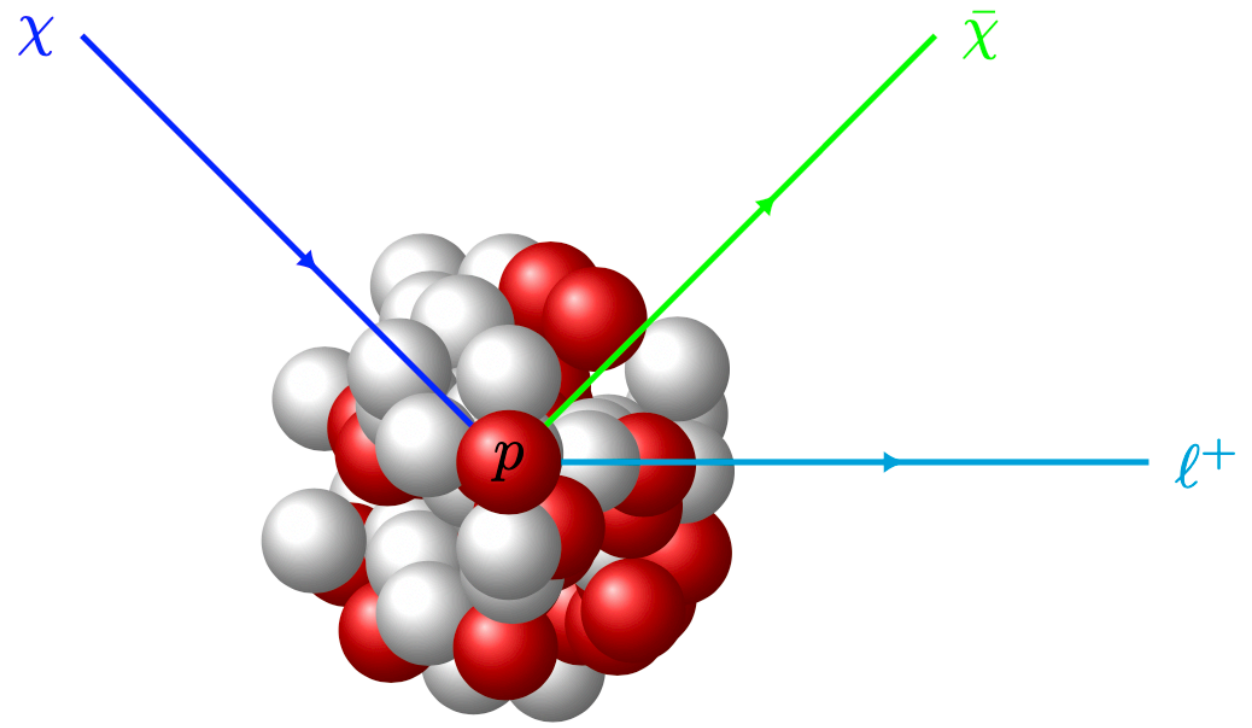
Sakharov's conditions: BNV; C, CP violation; Out of thermal equilibrium

$$\eta = \frac{n_B - n_{\bar{B}}}{n_\gamma} \sim 6 \times 10^{-10}$$

Sakharov, 1967

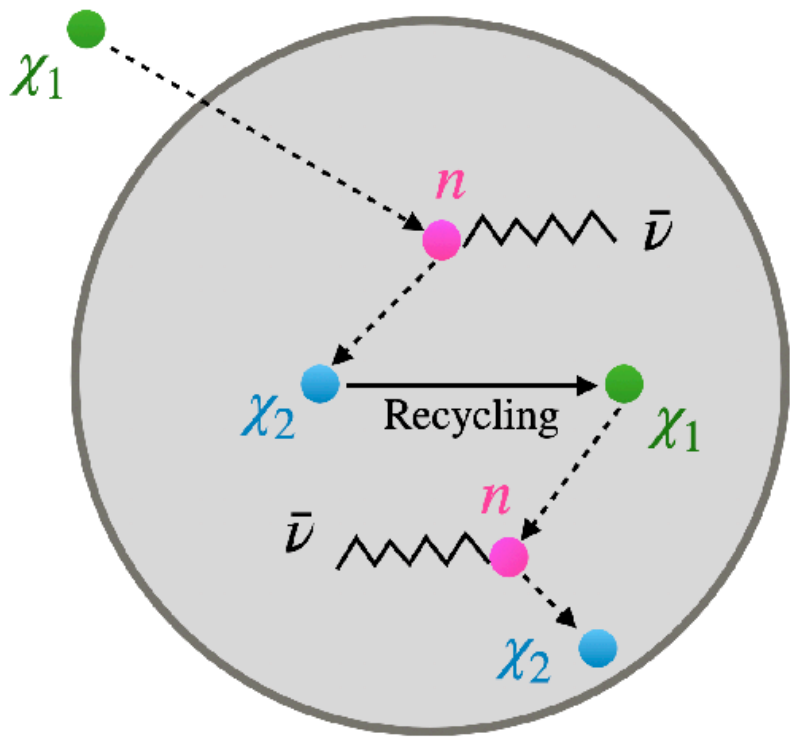
- Dark matter

Nucleon consumption induced by DM



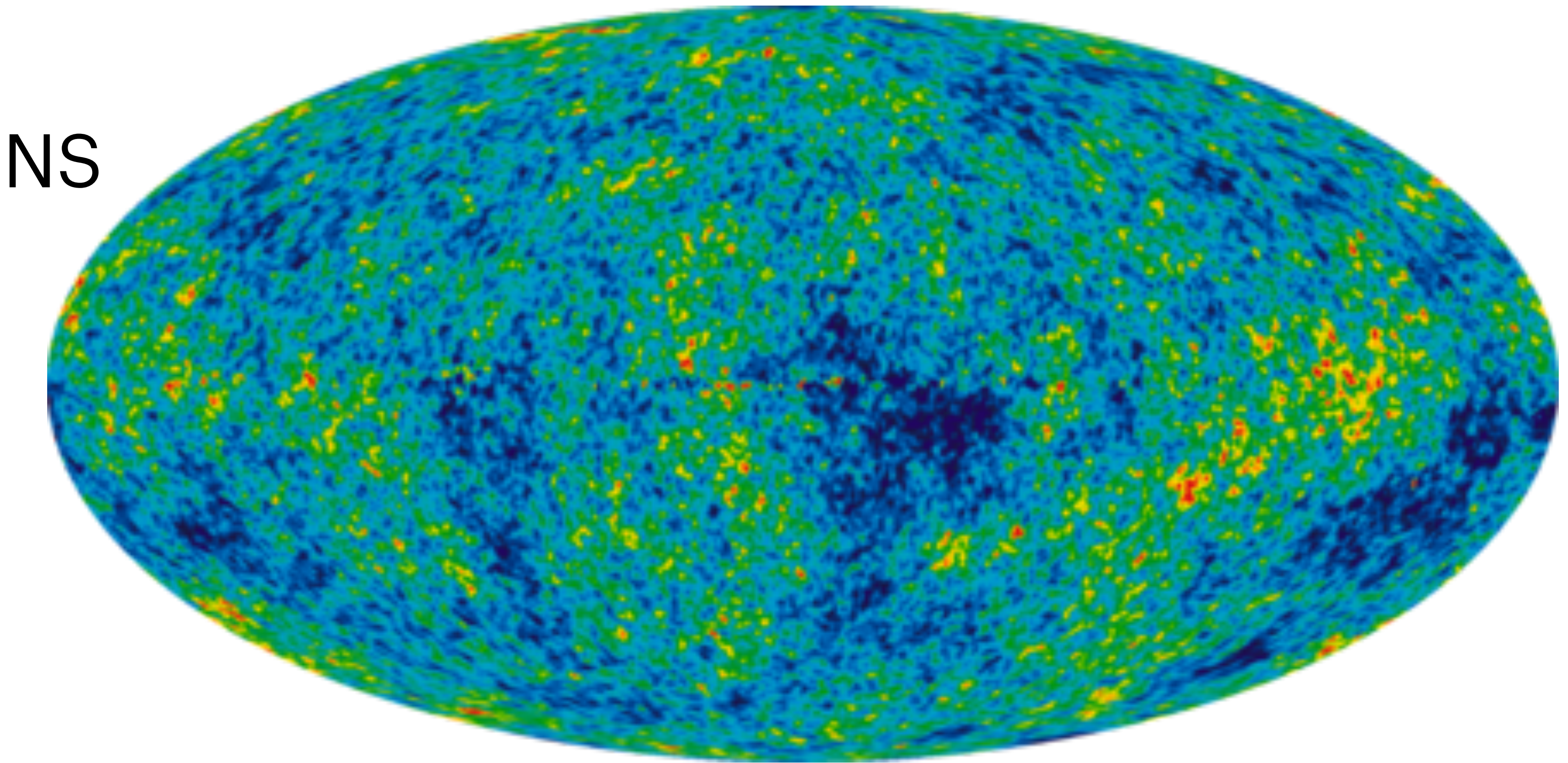
Shao-Feng Ge, XDM, 2406.00445, PRD

DM-catalyzed baryon destruction inside a NS



Y. Ema, R. McGehee, M. Pospelov, and A. Ray, 2405.18472

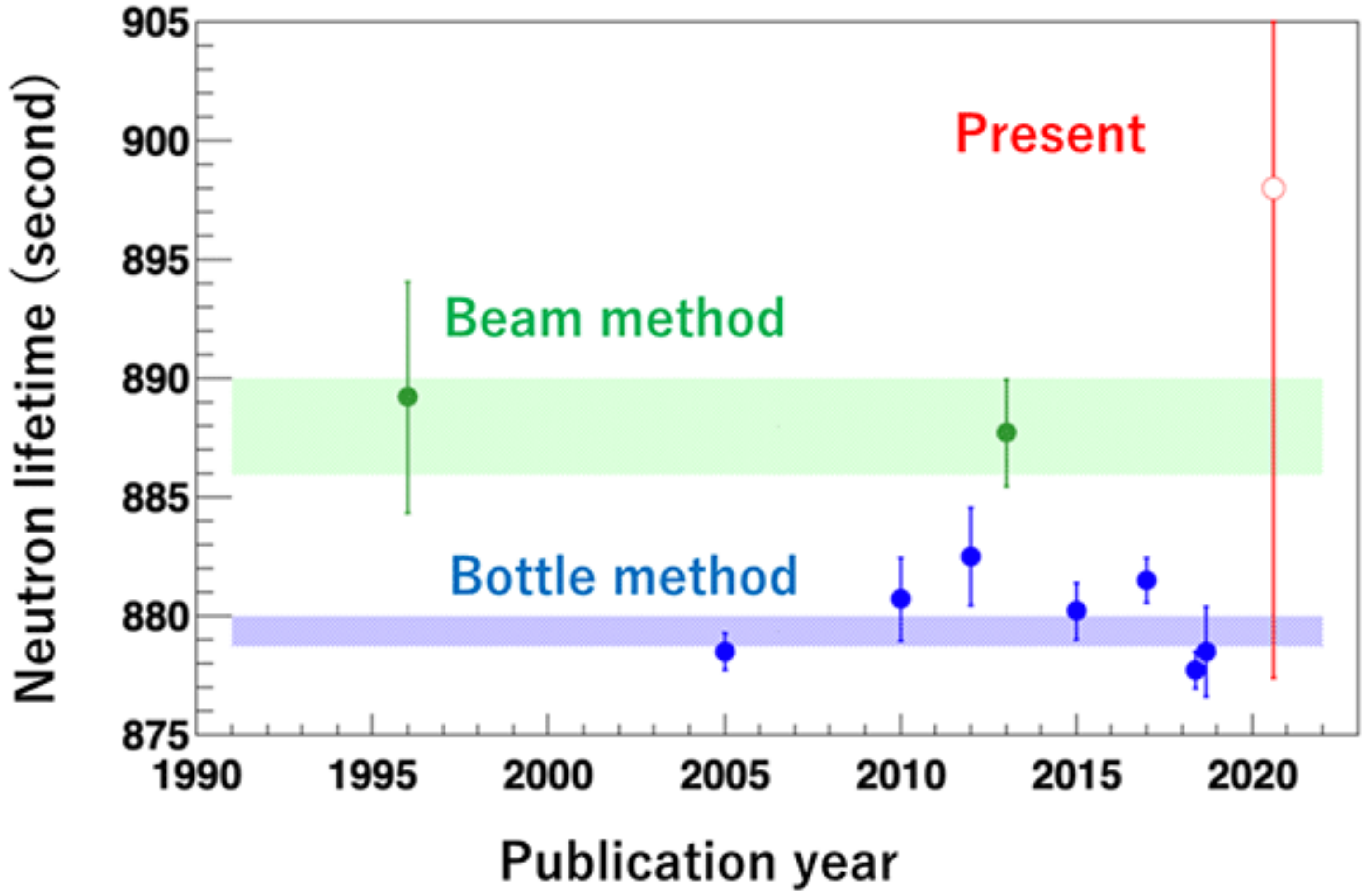
+ many many works along this direction



https://en.wikipedia.org/wiki/Baryogenesis

- Mesogenesis G. Elor, M. Escudero, and A. Nelson, 1810.00880
- Grand unification
- Neutron lifetime anomaly: Neutron dark decay

B. Fornal and B. Grinstein: 1801.01124; 1810.00862

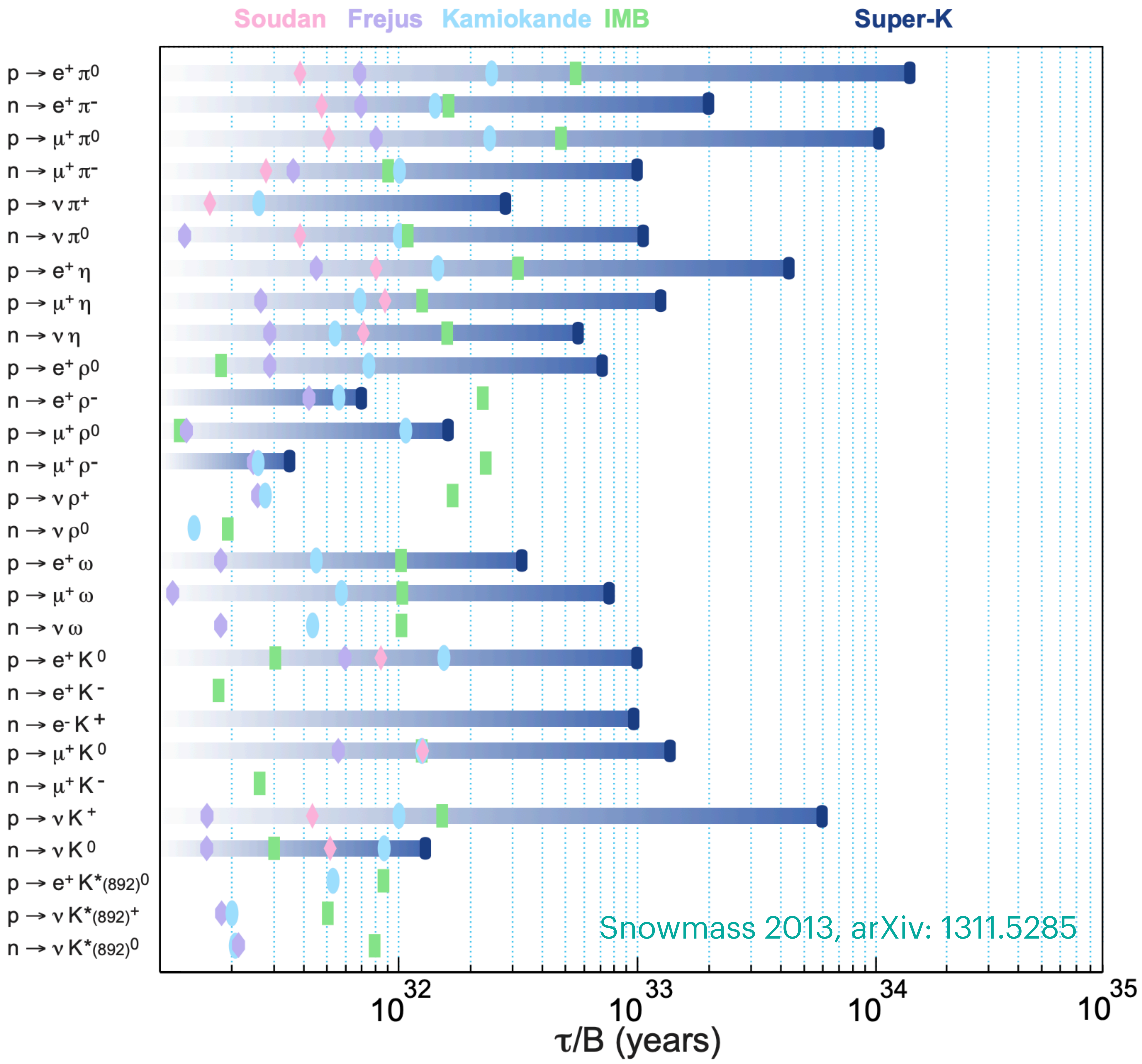


Low energy probes of BNV signals

$\Delta B = 1$ ✔

- The most sensitive probe of BNV is through nucleon decay
- Experimental efforts in the past: IMB, SNO+, KamLAND, Super-Kamiokande, …

  → Null result but stringent bound



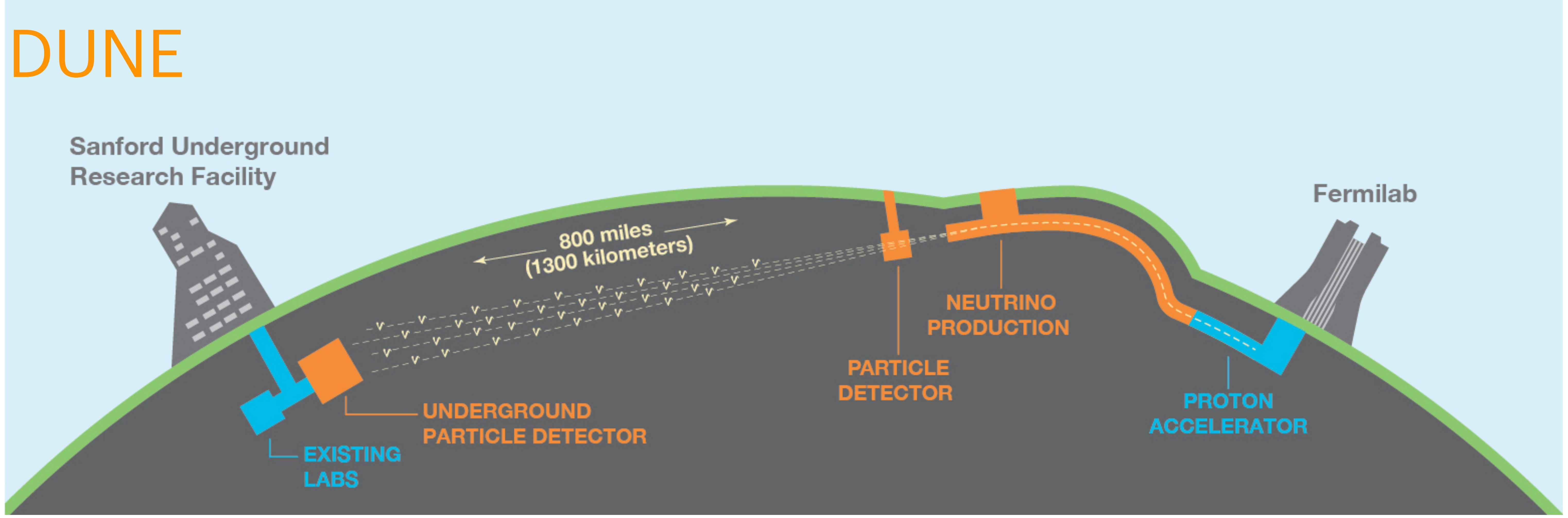
Snowmass 2013, arXiv: 1311.5285

$\Delta B = 2$

- $n - \bar{n}$ oscillation D. G. Phillips et al, 1410.1100
- $H - \bar{H}$ oscillation Feinberg, Goldhaber and Steigman, 1978
- Dinucleon decays: $NN' \to MM', \ell\ell', \ell\nu', \nu\nu'$ Xiao-Gang He, XDM, 2102.02562, JHEP

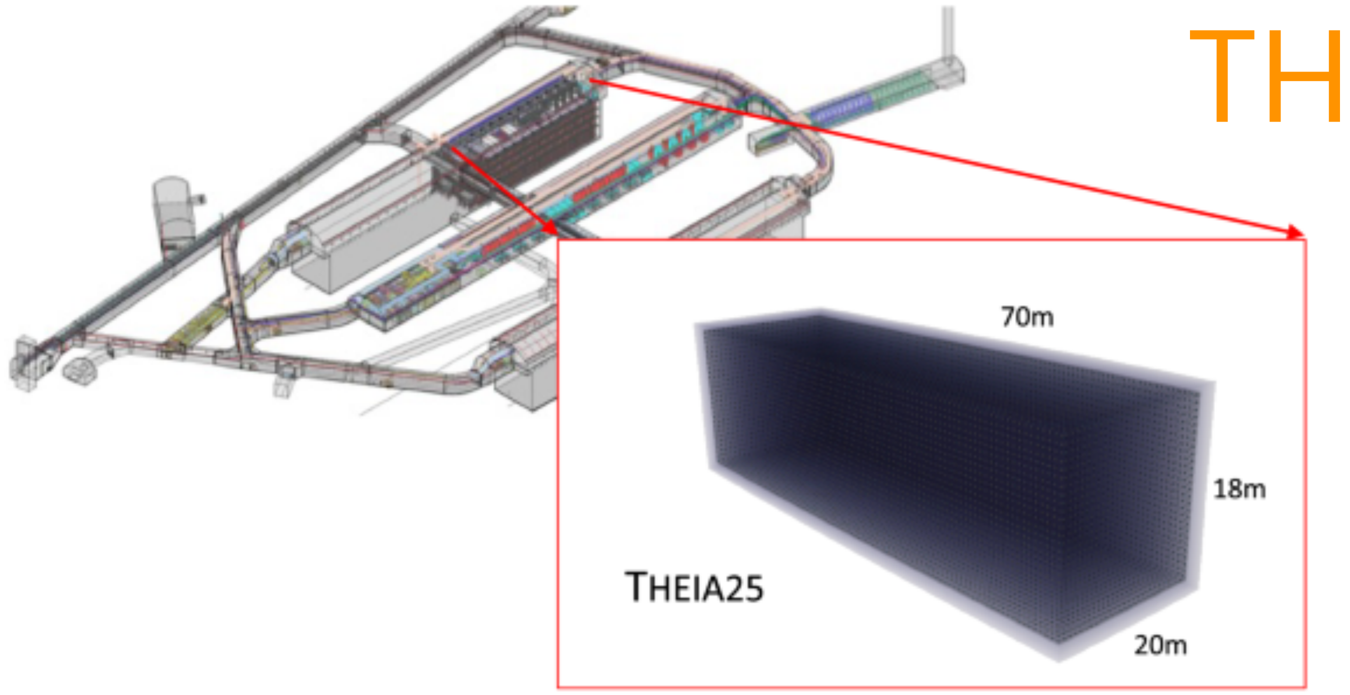
Nucleon decay searches as experimental frontiers

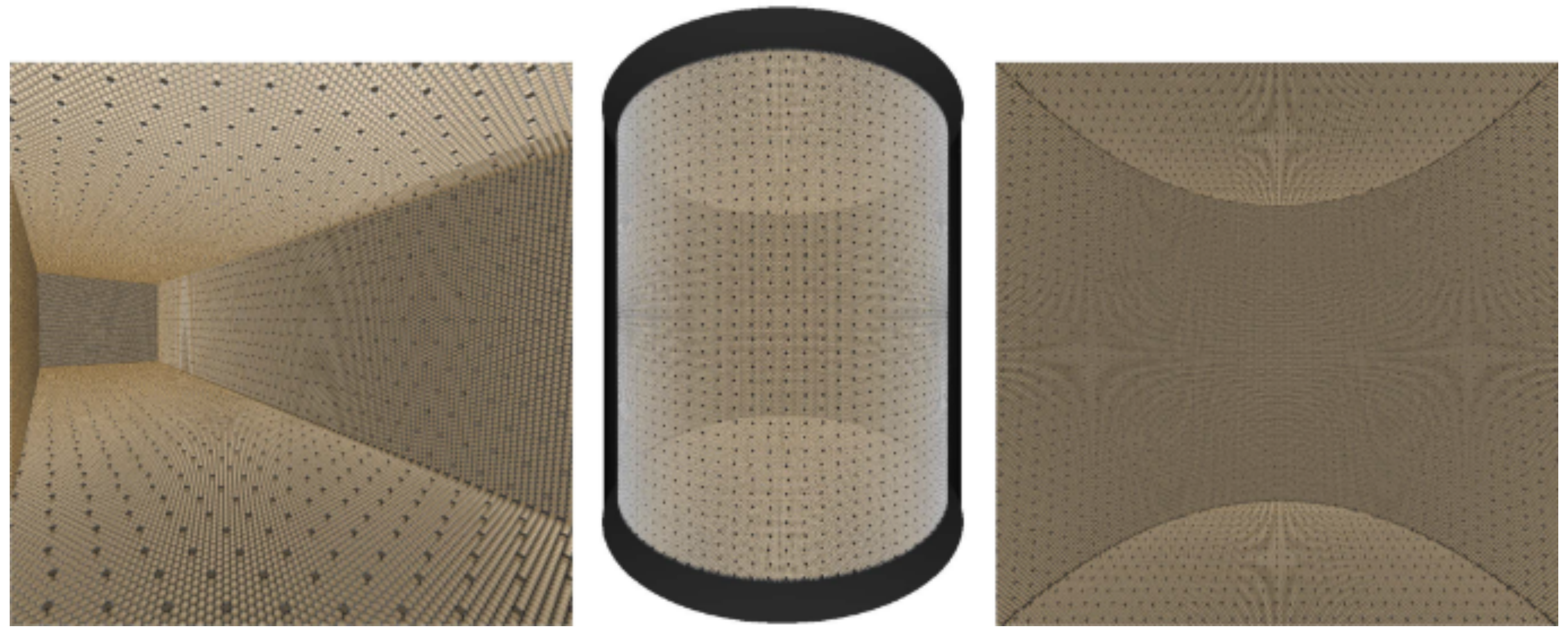
DUNE



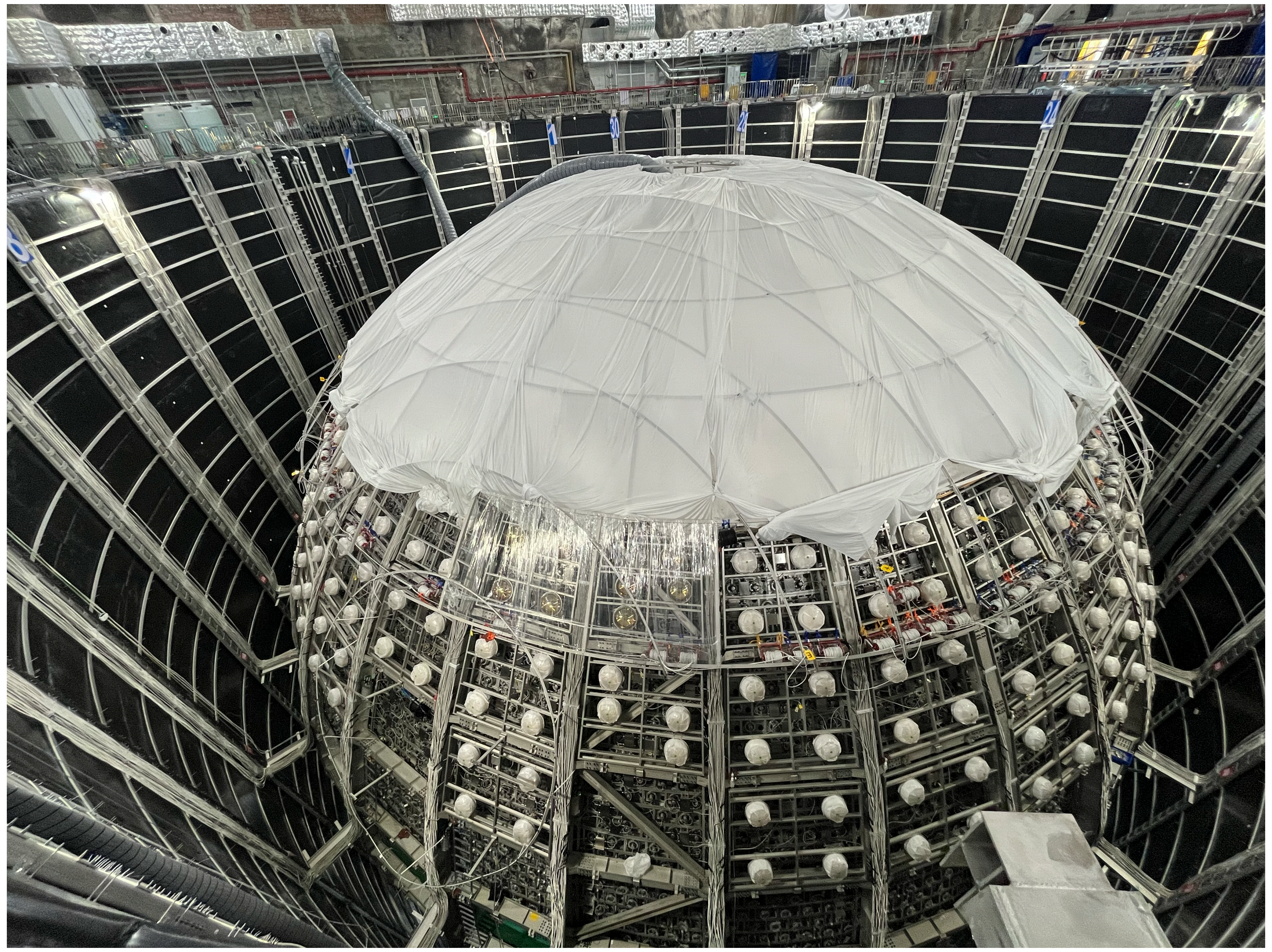
https://www.dunescience.org/

THEIA

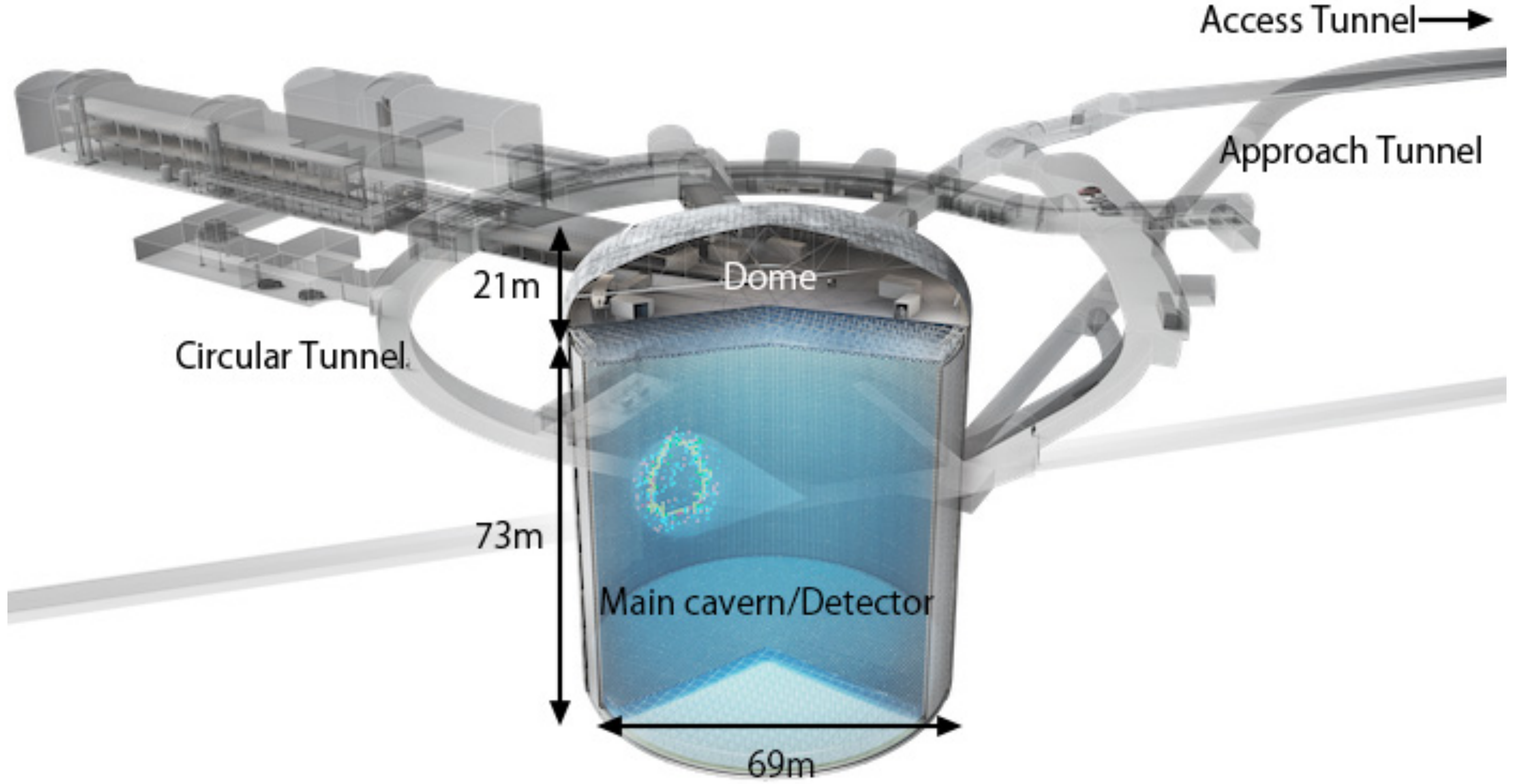




JUNO



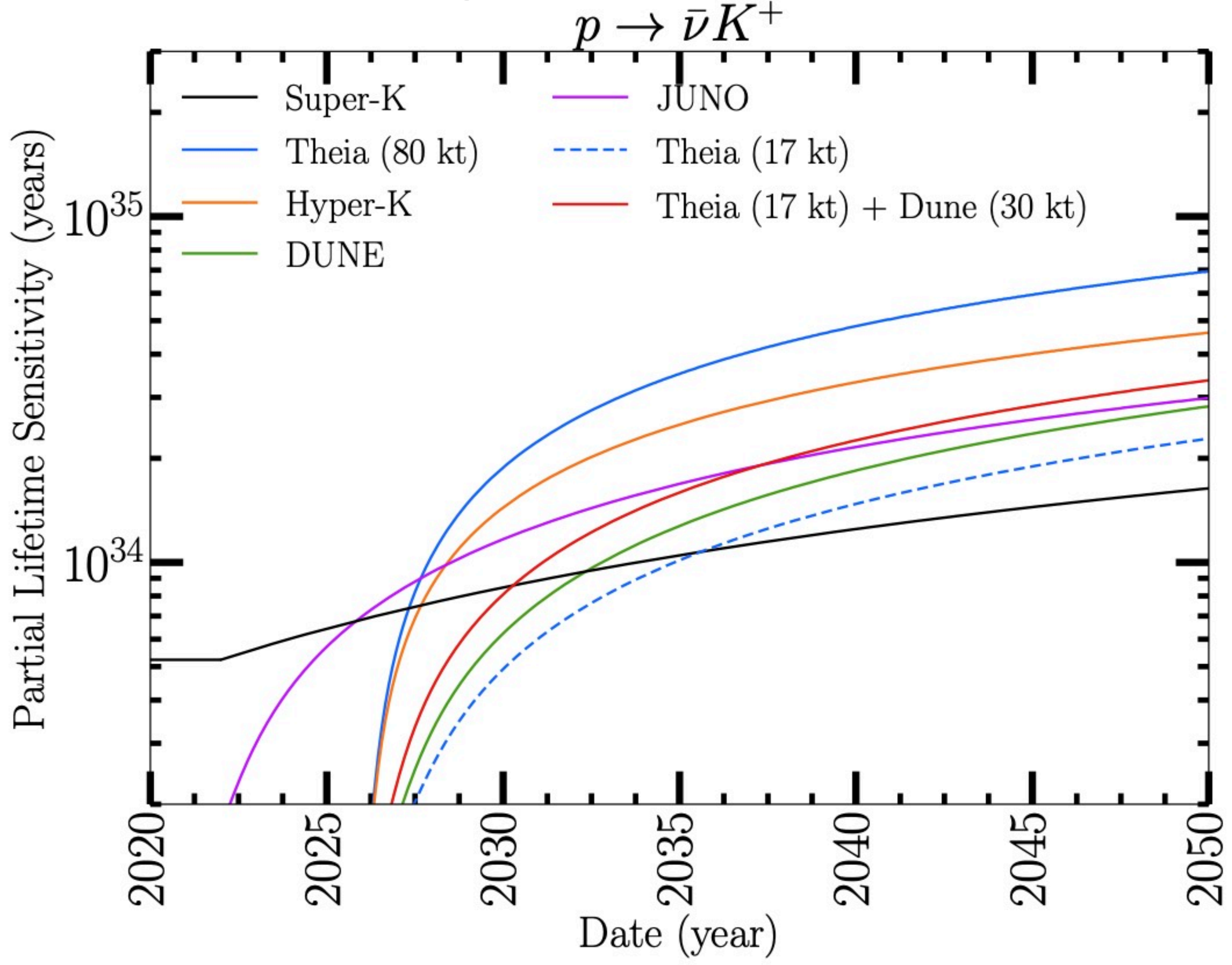
Hyper-K



https://www-sk.icrr.u-tokyo.ac.jp/en/news/detail/684

Expanding the scope of experimental searches

- Improving sensitivity to conventional modes



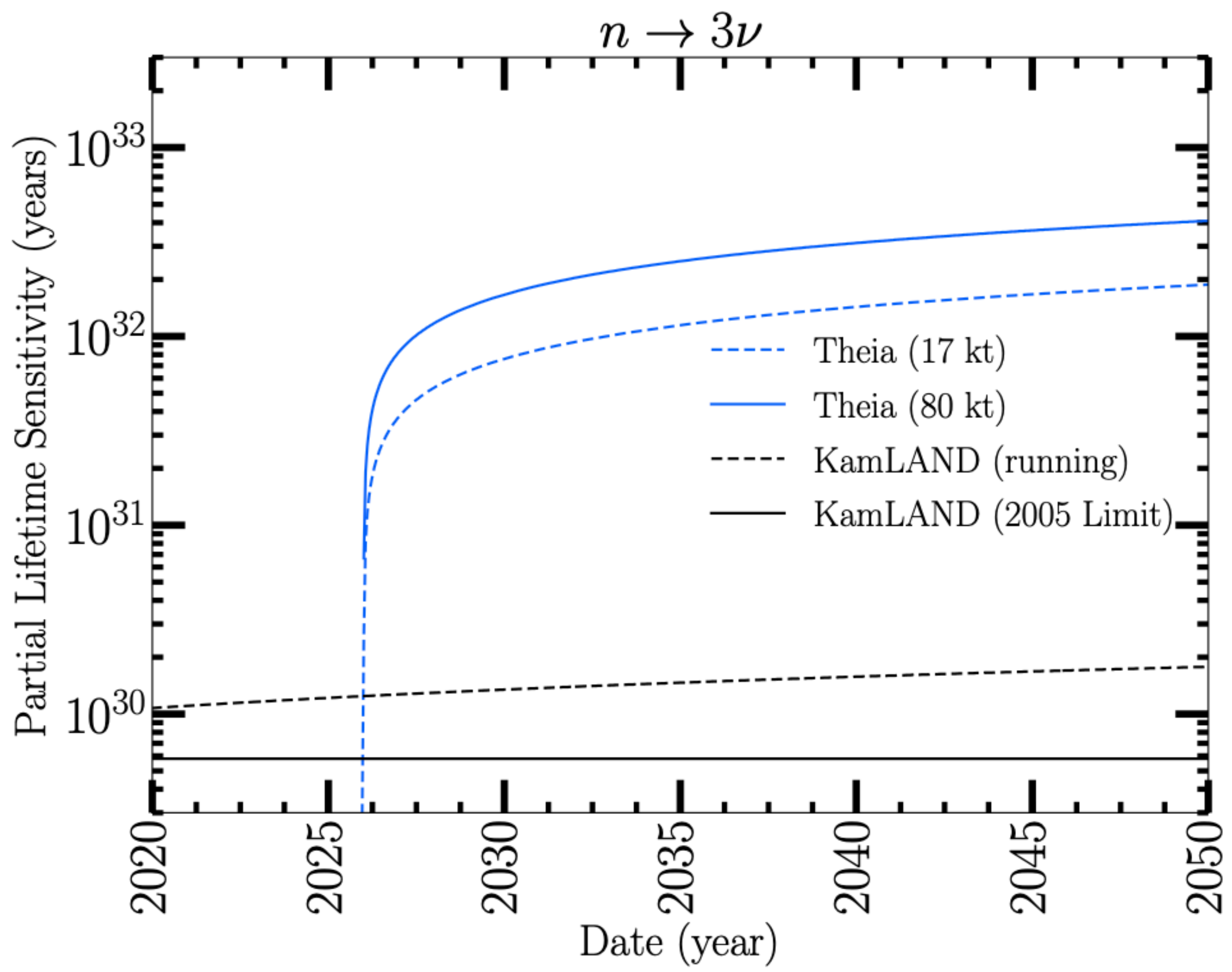
All possible decay channels should be attempted

Conventional and exotic

- 2-body vs 3-body modes
- Pseudoscalar vs vector meson modes
- SM particles vs new light particles
- ……

Needing a complete theoretical framework

- Searching for exotic modes



THEIA, 2202.12839

Classification of nucleon decay channels

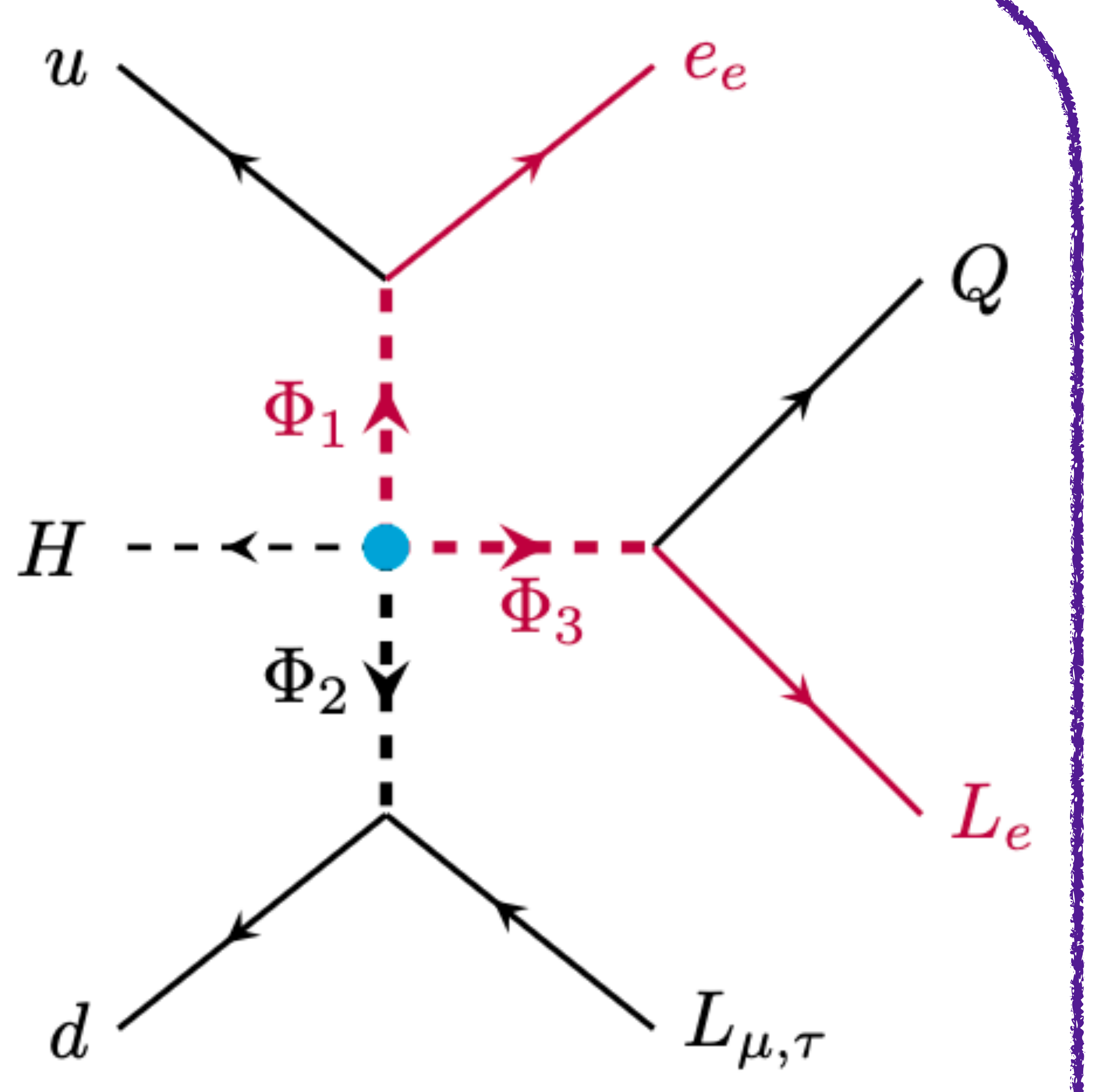
	SM particles	**SM+ a new particle**
2-body	$\mathrm{N} \to M + l$ **Widely studied**	$\mathrm{N} \to l + a/\varphi/X$
	$\mathrm{N} \to V + l$	$\mathrm{N} \to M + N$
3-body	$\mathrm{N} \to l_1 + l_2 + l_3$	$\mathrm{N} \to l + M + a/\varphi/X$
	$\mathrm{N} \to l + M_1 + M_2$	

- N — nucleon (p, n)
- M — octet pseudoscalar meson (π, η, K)
- V — octet vector meson (ρ, ω, K^*)
- l — lepton $(e, \mu, \hat{\nu})$

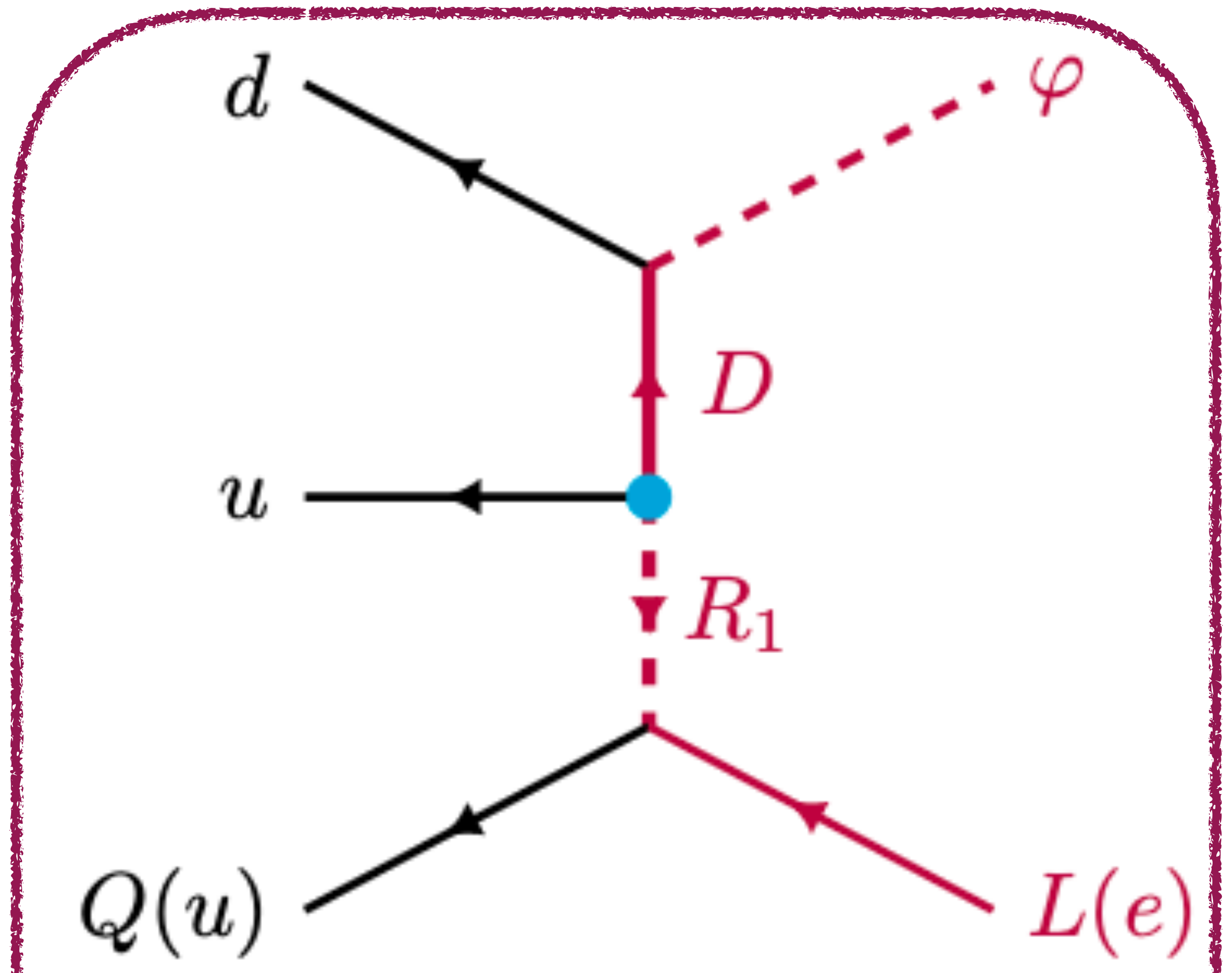
- a — ALP
- φ — a general scalar
- N — sterile neutrino
- X — dark photon

New physics scenarios

- Various GUT models
- Leptoquark models
- Models involving DM
- ……



Nucleon decays into three leptons



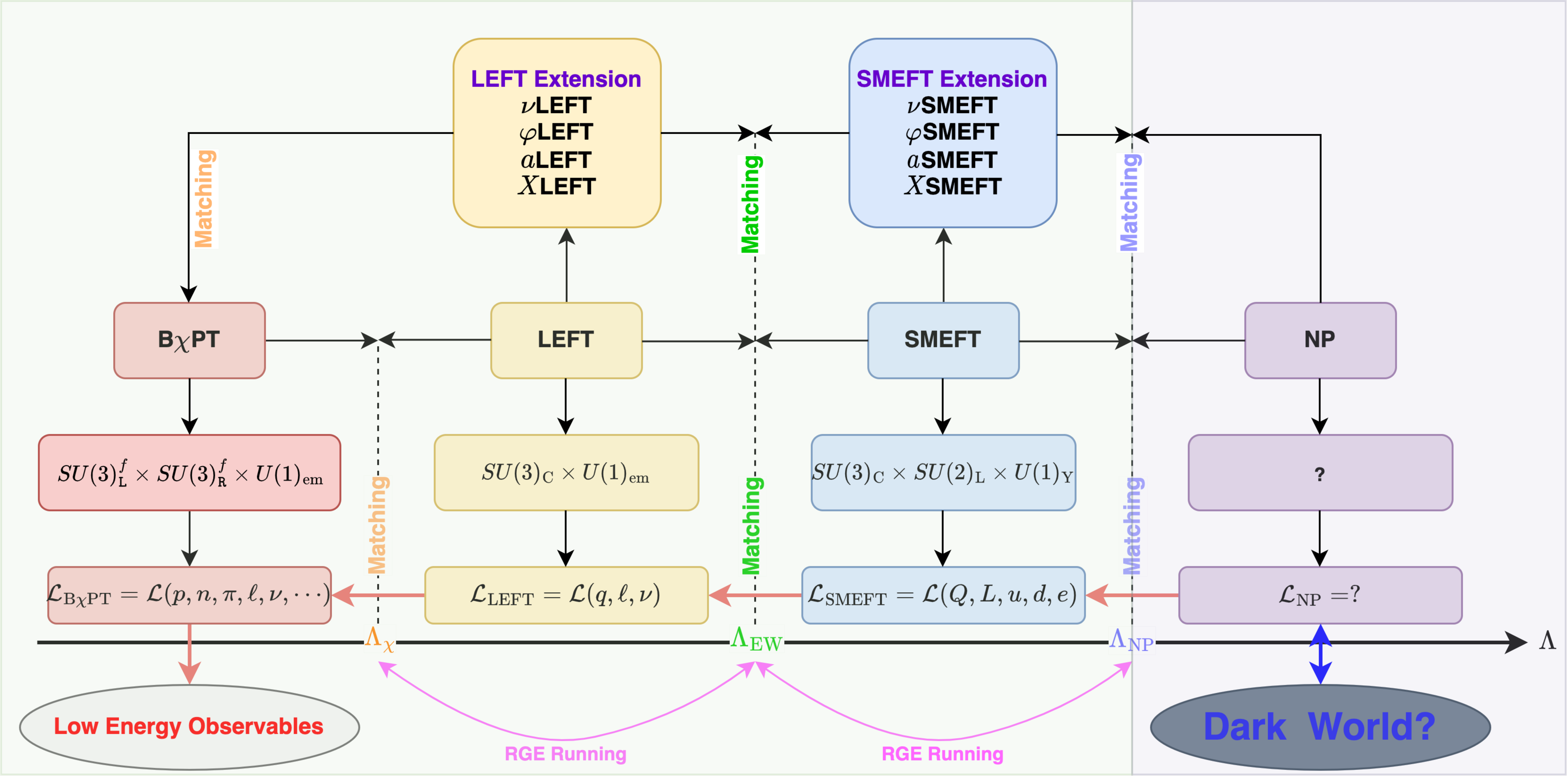
Nucleon decays involving a light scalar φ

Snowmass 2021: 2203.08771

Model	Decay modes	τ_N $(N = p, n)$ [years]	Ref.
Non-SUSY minimal $SU(5)$	$p \to e^+\pi^0$	$10^{30} - 10^{32}$	Georgi, Glashow [16]
Non-SUSY minimally extended $SU(5)$ (neutrino mass: 1-loop)	$p \to e^+\pi^0$	$\lesssim 2.3 \times 10^{36}$	Doršner, Saad [82]
Non-SUSY minimally extended $SU(5)$ (neutrino mass: 1-loop)	$p \to e^+\pi^0$ $p \to \overline{\nu} K^+$	$10^{32} - 10^{36}$ $10^{34} - 10^{37}$	Perez, Murgui [74]
Non-SUSY Minimal $SU(5)$ [NR] (neutrino mass: type-II seesaw)	$p \to \nu + (K^+, \pi^+, \rho^+)$ $n \to \nu + (\pi^0, \rho^0, \eta^0, \omega^0, K^0)$	$10^{31} - 10^{38}$	Doršner, Perez [64]
Non-SUSY Minimal $SU(5)$ [NR] (neutrino mass: type-III+I seesaw)	$p \to e^+\pi^0$	$\lesssim 10^{36}$	Bajc, Senjanović [65]
Non-SUSY Extended $SU(5)$ (neutrino mass: 2-loop)	$p \to e^+\pi^0$	$10^{34} - 10^{40}$	Saad [80]
Minimal flipped non-SUSY $SU(5)$	$p \to e/\mu^+\pi^0$	$10^{38} - 10^{42}$	Arbeláez, Kolešová, Malinský [175]
Non-SUSY Minimal $SO(10)$	$p \to e^+\pi^0$	$\lesssim 5 \times 10^{35}$	Babu, Khan [165]
Minimal $SO(10)$ with 45 Higgs	$p \to e^+\pi^0$	$\lesssim 10^{36}$	Bertolini, Di Luzio, Malinský [176]
Minimal non-Renormalizable $SO(10)$	$p \to e^+\pi^0$	$\lesssim 10^{35}$	Preda, Senjanović, Zantedeschi [173]
Non-SUSY Generic $SO(10)$ $M_{\text{int}} : G_{422}$ $M_{\text{int}} : G_{422D}$ $M_{\text{int}} : G_{3221}$ $M_{\text{int}} : G_{3221D}$	$p \to e^+\pi^0$	 $10^{34} - 10^{46}$ $10^{31} - 10^{34}$ $10^{36} - 10^{46}$ $10^{33} - 10^{43}$	Chakrabortty, King, Maji [164]
Non-SUSY Generic E_6 $M_{\text{int}} : G_{4221}$ $M_{\text{int}} : G_{4221D}$ $M_{\text{int}} : G_{333} \to G_{3221}$ $M_{\text{int}} : G_{4221D} \to G_{421}$ $M_{\text{int}} : G_{4221} \to G_{421}$	$p \to e^+\pi^0$	 $10^{27} - 10^{36}$ $10^{27} - 10^{36}$ $10^{32} - 10^{36}$ $10^{26} - 10^{48}$ $10^{25} - 10^{48}$	Chakrabortty, King, Maji [164]
Minimal SUSY $SU(5)$	$p \to \bar{\nu} K^+$ $n \to \bar{\nu} K^0$	 $10^{28} - 10^{32}$	Dimopoulos, Georgi [42], Sakai [100] Hisano, Murayama, Yanagida [99]
Minimal SUSY $SU(5)$ (cMSSM)	$p \to \bar{\nu} K^+$ $p \to e^+\pi^0$	$\lesssim (2-6) \times 10^{34}$ $10^{35} - 10^{40}$	Ellis et. al. [107]
Minimal SUSY $SU(5)$ ($\mathbf{5} + \overline{\mathbf{5}}$ matter fields)	$p \to \bar{\nu} K^+$ $p \to \mu^+\pi^0/K^0, n \to \overline{\nu}\pi^0/K^0$	$\lesssim 4 \times 10^{33}$ $10^{33} - 10^{34}$	Babu, Bajc, Tavartkiladze [177]
SUGRA $SU(5)$	$p \to \bar{\nu} K^+$	$10^{32} - 10^{34}$	Nath, Arnowitt [103, 178]
mSUGRA $SU(5)$ (Higgs mass constraint) NUSUGRA $SU(5)$ (Higgs mass constraint)	$p \to \bar{\nu} K^+$ $p \to \bar{\nu} K^+$	$3 \times 10^{34} - 2 \times 10^{35}$ $3 \times 10^{34} - 10^{36}$	Liu, Nath [111]
SUSY $SU(5)$ or $SO(10)$ MSSM ($d = 6$)	$p \to e^+\pi^0$	$\sim 10^{34.9 \pm 1}$	Pati [179]
Flipped SUSY $SU(5)$ (cMSSM)	$p \to e/\mu^+\pi^0$	$10^{35} - 10^{37}$	Ellis et. al. [180–182]
Split SUSY $SU(5)$	$p \to e^+\pi^0$	$10^{35} - 10^{37}$	Arkani-Hamed, et. al. [183]
SUSY $SU(5)$ in 5D	$p \to \mu^+ K^0$ $p \to e^+\pi^0$	$10^{34} - 10^{35}$	Hebecker, March-Russell[184]
SUSY $SU(5)$ in 5D variant II	$p \to \bar{\nu} K^+$	$10^{36} - 10^{39}$	Alciati et.al.[185]
Mini-split SUSY $SO(10)$	$p \to \bar{\nu} K^+$	$\lesssim 6 \times 10^{34}$	Babu, Bajc, Saad [146]
SUSY $SO(10) \times U(1)_{\text{PQ}}$	$p \to \bar{\nu} K^+$	$10^{33} - 10^{35}$	Babu, Bajc, Saad [147]
Extended SUSY $SO(10)$ Type-I seesaw Type-II seesaw Inverse seesaw	$p \to \bar{\nu} K^+$	 $10^{30} - 10^{37}$ $\lesssim 6.6 \times 10^{33}$ $\lesssim 10^{34}$	 Mohapatra, Severson [186] Mohapatra, Severson [186] Dev, Mohapatra [187]
SUSY $SO(10)$ with anomalous flavor $U(1)$	$p \to \bar{\nu} K^+$ $n \to \bar{\nu} K^0$ $p \to \mu^+ K^0$	$10^{32} - 10^{35}$	Shafi, Tavartkiladze [188]
SUSY $SO(10)$ MSSM	$p \to \bar{\nu} K^+$ $n \to \bar{\nu} K^0$	$10^{33} - 10^{34}$ $10^{32} - 10^{33}$	Lucas, Raby [189], Pati [179]
SUSY $SO(10)$ ESSM	$p \to \bar{\nu} K^+$	$10^{33} - 10^{34}$ $\lesssim 10^{35}$	Pati [179]
SUSY $SO(10)/G(224)$ MSSM or ESSM (new $d = 5$)	$p \to \bar{\nu} K^+$ $p \to \mu^+ K^0$	$\lesssim 2 \cdot 10^{34}$ $B \sim (1-50)\%$	Babu, Pati, Wilczek [190–192], Pati [179]
SUSY $SO(10) \times S_4$	$p \to \bar{\nu} K^+$	$\lesssim 7 \times 10^{33}$	Dev, Mohapatra, Dutta, Severson [193]
SUSY $SO(10)$ in 6D	$p \to e^+\pi^0$	$10^{34} - 10^{35}$	Buchmuller, Covi, Wiesenfeldt [194]
GUT-like models from Type IIA string with D6-branes	$p \to e^+\pi^0$	$\sim 10^{36}$	Klebanov, Witten [195]

EFT as a powerful tool to study all kinds of decay modes in a model-independent and systematic way.

Nucleon decay in the effective field theory (EFT) landscape



Working framework: low energy effective field theory (LEFT)

- Fields: u, d, s, ~~c, b~~; e, μ, τ; ν_e, ν_μ, ν_τ
- Symmetry: $\mathrm{SU}(3)_{\mathrm{c}} \times \mathrm{U}(1)_{\mathrm{em}}$
- Power counting: canonical dimension d
- Range: $\ll \Lambda_{\mathrm{EW}}$

$\boldsymbol{\Delta(B-L)=0}$		$\boldsymbol{\Delta(B+L)=0}$	
$\mathcal{O}^{\mathrm{LL}}_{\nu dud}$	$(\overline{\nu^{\mathrm{C}}_{\mathrm{L}}} d^{\alpha}_{\mathrm{L}})(\overline{u^{\beta\mathrm{C}}_{\mathrm{L}}} d^{\gamma}_{\mathrm{L}})\epsilon_{\alpha\beta\gamma}$	$\mathcal{O}^{\mathrm{LL}}_{\bar{\ell}ddd}$	$(\overline{\ell_{\mathrm{R}}} d^{\alpha}_{\mathrm{L}})(\overline{d^{\beta\mathrm{C}}_{\mathrm{L}}} d^{\gamma}_{\mathrm{L}})\epsilon_{\alpha\beta\gamma}$
$\mathcal{O}^{\mathrm{LL}}_{\ell udu}$	$(\overline{\ell^{\mathrm{C}}_{\mathrm{L}}} u^{\alpha}_{\mathrm{L}})(\overline{d^{\beta\mathrm{C}}_{\mathrm{L}}} u^{\gamma}_{\mathrm{L}})\epsilon_{\alpha\beta\gamma}$	$\mathcal{O}^{\mathrm{RL}}_{\bar{\nu}dud}$	$(\overline{\nu_{\mathrm{L}}} d^{\alpha}_{\mathrm{R}})(\overline{u^{\beta\mathrm{C}}_{\mathrm{L}}} d^{\gamma}_{\mathrm{L}})\epsilon_{\alpha\beta\gamma}$
$\mathcal{O}^{\mathrm{RL}}_{\ell duu}$	$(\overline{\ell^{\mathrm{C}}_{\mathrm{R}}} d^{\alpha}_{\mathrm{R}})(\overline{u^{\beta\mathrm{C}}_{\mathrm{L}}} u^{\gamma}_{\mathrm{L}})\epsilon_{\alpha\beta\gamma}$	$\mathcal{O}^{\mathrm{RL}}_{\bar{\nu}udd}$	$(\overline{\nu_{\mathrm{L}}} u^{\alpha}_{\mathrm{R}})(\overline{d^{\beta\mathrm{C}}_{\mathrm{L}}} d^{\gamma}_{\mathrm{L}})\epsilon_{\alpha\beta\gamma}$
$\mathcal{O}^{\mathrm{RL}}_{\ell udu}$	$(\overline{\ell^{\mathrm{C}}_{\mathrm{R}}} u^{\alpha}_{\mathrm{R}})(\overline{d^{\beta\mathrm{C}}_{\mathrm{L}}} u^{\gamma}_{\mathrm{L}})\epsilon_{\alpha\beta\gamma}$	$\mathcal{O}^{\mathrm{RL}}_{\bar{\ell}ddd}$	$(\overline{\ell_{\mathrm{L}}} d^{\alpha}_{\mathrm{R}})(\overline{d^{\beta\mathrm{C}}_{\mathrm{L}}} d^{\gamma}_{\mathrm{L}})\epsilon_{\alpha\beta\gamma}$
$\mathcal{O}^{\mathrm{LR}}_{\ell duu}$	$(\overline{\ell^{\mathrm{C}}_{\mathrm{L}}} d^{\alpha}_{\mathrm{L}})(\overline{u^{\beta\mathrm{C}}_{\mathrm{R}}} u^{\gamma}_{\mathrm{R}})\epsilon_{\alpha\beta\gamma}$	$\mathcal{O}^{\mathrm{LR}}_{\bar{\ell}ddd}$	$(\overline{\ell_{\mathrm{R}}} d^{\alpha}_{\mathrm{L}})(\overline{d^{\beta\mathrm{C}}_{\mathrm{R}}} d^{\gamma}_{\mathrm{R}})\epsilon_{\alpha\beta\gamma}$
$\mathcal{O}^{\mathrm{LR}}_{\ell udu}$	$(\overline{\ell^{\mathrm{C}}_{\mathrm{L}}} u^{\alpha}_{\mathrm{L}})(\overline{d^{\beta\mathrm{C}}_{\mathrm{R}}} u^{\gamma}_{\mathrm{R}})\epsilon_{\alpha\beta\gamma}$	$\mathcal{O}^{\mathrm{RR}}_{\bar{\nu}dud}$	$(\overline{\nu_{\mathrm{L}}} d^{\alpha}_{\mathrm{R}})(\overline{u^{\beta\mathrm{C}}_{\mathrm{R}}} d^{\gamma}_{\mathrm{R}})\epsilon_{\alpha\beta\gamma}$
$\mathcal{O}^{\mathrm{LR}}_{\nu ddu}$	$(\overline{\nu^{\mathrm{C}}_{\mathrm{L}}} d^{\alpha}_{\mathrm{L}})(\overline{d^{\beta\mathrm{C}}_{\mathrm{R}}} u^{\gamma}_{\mathrm{R}})\epsilon_{\alpha\beta\gamma}$	$\mathcal{O}^{\mathrm{RR}}_{\bar{\ell}ddd}$	$(\overline{\ell_{\mathrm{L}}} d^{\alpha}_{\mathrm{R}})(\overline{d^{\beta\mathrm{C}}_{\mathrm{R}}} d^{\gamma}_{\mathrm{R}})\epsilon_{\alpha\beta\gamma}$
$\mathcal{O}^{\mathrm{LR}}_{\nu udd}$	$(\overline{\nu^{\mathrm{C}}_{\mathrm{L}}} u^{\alpha}_{\mathrm{L}})(\overline{d^{\beta\mathrm{C}}_{\mathrm{R}}} d^{\gamma}_{\mathrm{R}})\epsilon_{\alpha\beta\gamma}$		
$\mathcal{O}^{\mathrm{RR}}_{\ell udu}$	$(\overline{\ell^{\mathrm{C}}_{\mathrm{R}}} u^{\alpha}_{\mathrm{R}})(\overline{d^{\beta\mathrm{C}}_{\mathrm{R}}} u^{\gamma}_{\mathrm{R}})\epsilon_{\alpha\beta\gamma}$		

Jenkins, Manohar, Stoffer, 2018

Jenkins, Manohar, Stoffer, 2018

Li, Ren, Xiao, Yu, Zheng, 2020

$$\mathscr{L}_{\mathrm{LEFT}} = \mathscr{L}_{\dim\leq4} + \sum_{\dim 5,i}\frac{\hat{C}_{5,i}}{\Lambda}\mathscr{Q}^{i}_{\dim-5} + \sum_{\dim 6,i}\frac{\hat{C}_{6,i}}{\Lambda^2}\mathscr{Q}^{i}_{\dim-6} + \sum_{\dim 7,i}\frac{\hat{C}_{7,i}}{\Lambda^3}\mathscr{Q}^{i}_{\dim-7} + \sum_{\dim 8,i}\frac{\hat{C}_{8,i}}{\Lambda^4}\mathscr{Q}^{i}_{\dim-8} + \sum_{\dim 9,i}\frac{\hat{C}_{9,i}}{\Lambda^5}\mathscr{Q}^{i}_{\dim-9} + \cdots$$

Yi Liao, XDM, Quan-Yu Wang, 2020 Murphy, 2020 Yi Liao, XDM, Hao-Lin Wang, 2019

F. Wilczek, A. Zee, PRL 43 (1979)
J. R. Ellis, M. k. Gaillard, D. V. Nanopoulos, PLB 88 (1979)
S. Weinberg, PRL 43 (1979) & PRD 22 (1980)
L. F. Abbott and M. B. Wise, PRD 22 (1980)

Easily to bridge with the SMEFT framework

SMEFT examples

Dim-6 operators

$\Delta(B-L)=0$

$$\mathcal{O}_{duQL}=\epsilon_{\alpha\beta\gamma}\epsilon_{ij}(\overline{d^{\alpha C}}u^{\beta})(\overline{Q^{\gamma iC}}L^{j}),\qquad \mathcal{O}_{QQue}=\epsilon_{\alpha\beta\gamma}\epsilon_{ij}(\overline{Q^{\alpha iC}}Q^{\beta j})(\overline{u^{\gamma C}}e),$$

$$\mathcal{O}_{QQQL}=\epsilon_{\alpha\beta\gamma}\epsilon_{il}\epsilon_{jk}(\overline{Q^{\alpha iC}}Q^{\beta j})(\overline{Q^{\gamma kC}}L^{l}),\qquad \mathcal{O}_{duue}=\epsilon_{\alpha\beta\gamma}(\overline{d^{\alpha C}}u^{\beta})(\overline{u^{\gamma C}}e),$$

L. F. Abbott, M. B. Wise, PRD, 1980

Dim-7 operators

$\Delta(B+L)=0$

$$\mathcal{O}_{\bar{L}dud\tilde{H}}=\epsilon_{\alpha\beta\gamma}(\bar{L}d^{\alpha})(\overline{u^{\beta C}}d^{\gamma})\tilde{H},\qquad \mathcal{O}_{\bar{L}dddH}=\epsilon_{\alpha\beta\gamma}(\bar{L}d^{\alpha})(\overline{d^{\beta C}}d^{\gamma})H,$$

$$\mathcal{O}_{\bar{e}Qdd\tilde{H}}=\epsilon_{\alpha\beta\gamma}\epsilon_{ij}(\bar{e}Q^{\alpha i})(\overline{d^{\beta C}}d^{\gamma})\tilde{H}^{j},\qquad \mathcal{O}_{\bar{L}dQ\tilde{H}}=\epsilon_{\alpha\beta\gamma}\epsilon_{ij}(\bar{L}d^{\alpha})(\overline{Q^{\beta C}}Q^{\gamma i})\tilde{H}^{j},$$

$$\mathcal{O}_{\bar{L}QdDd}=\epsilon_{\alpha\beta\gamma}(\bar{L}\gamma^{\mu}Q^{\alpha})(\overline{d^{\beta C}}i\overleftrightarrow{D}_{\mu}d^{\gamma}),\qquad \mathcal{O}_{\bar{e}dddD}=\epsilon_{\alpha\beta\gamma}(\bar{e}\gamma^{\mu}d^{\alpha})(\overline{d^{\beta C}}i\overleftrightarrow{D}_{\mu}d^{\gamma}).$$

L. Lehman, 1410.4193
Yi Liao, XDM, 1607.07309

Exotic nucleon decay involving new light particles

LEFT + new light particles ⇒ LEFT-like framework ⇒ SMEFT-like framework

- νLEFT = LEFT + sterile neutrino (N): $p \to N\pi^+,\ n \to N\pi^0, \cdots$

  $(\overline{N_R} d_L^\alpha)(\overline{u_L^{\beta C}} d_L^\gamma)\epsilon_{\alpha\beta\gamma},\ \cdots$

- aLEFT = LEFT + ALP (a): $p \to e^+a,\ n \to e^+\pi^-a, \cdots$

  $(\partial_\mu a)(\overline{e_L^C} u_L^\alpha)(\overline{u_L^{\beta C}} \gamma^\mu d_R^\gamma)\epsilon_{\alpha\beta\gamma},\ \cdots$

- φLEFT = LEFT + scalar (φ): $p \to e^+\varphi,\ n \to e^+\pi^-\varphi, \cdots$

  $\varphi(\overline{\nu_L^C} d_L^\alpha)(\overline{u_L^{\beta C}} d_L^\gamma)\epsilon_{\alpha\beta\gamma},\ \cdots$

- XLEFT = LEFT + dark photon (X): $p \to e^+X,\ n \to e^+\pi^-X, \cdots$

  $X_{\mu\nu}(\overline{\ell_R} d_L^\alpha)(\overline{d_L^{\beta C}} \sigma^{\mu\nu} d_L^\gamma)\epsilon_{\alpha\beta\sigma},\ \cdots$

Sandbox Studio, Chicago

General $\Delta B = 1$ nucleon decay operator structures

- Must involve an odd number of light quarks: $qqq,\ qqqG,\ qqqq\bar{q}, \cdots$
- Leading-order interactions: involve only three light quarks
- Only four general triple-quark (without a derivative) structures

$$\mathcal{O}_a^{yzw} = (\overline{\Psi}_a q^{\alpha}_{\mathtt{L},y})(\overline{q^{\beta\mathtt{C}}_{\mathtt{L},z}} q^{\gamma}_{\mathtt{L},w})\epsilon_{\alpha\beta\gamma}$$

$$\mathcal{O}_b^{yzw} = (\overline{\Psi}_b q^{\alpha}_{\mathtt{R},y})(\overline{q^{\beta\mathtt{C}}_{\mathtt{L},z}} q^{\gamma}_{\mathtt{L},w})\epsilon_{\alpha\beta\gamma}$$

$$\mathcal{O}_c^{yzw} = (\overline{\Psi}_{c,\mu} q^{\alpha}_{\mathtt{L},\{y})(\overline{q^{\beta\mathtt{C}}_{\mathtt{L},z\}}} \gamma^{\mu} q^{\gamma}_{\mathtt{R},\mathtt{w}})\epsilon_{\alpha\beta\gamma}$$

$$\mathcal{O}_d^{yzw} = (\overline{\Psi}_{d,\mu\nu} q^{\alpha}_{\mathtt{L},\{y})(\overline{q^{\beta\mathtt{C}}_{\mathtt{L},z}} \sigma^{\mu\nu} q^{\gamma}_{\mathtt{L},\mathtt{w}\}})\epsilon_{\alpha\beta\gamma}$$

Newly identified structures

+ their chiral partners with $\mathtt{L} \leftrightarrow \mathtt{R}$

- ❖ $\overline{\Psi}_a, \overline{\Psi}_b, \overline{\Psi}_{c,\mu}, \overline{\Psi}_{d,\mu\nu}$: combinations of non-QCD fields
- ❖ $y, z, w = 1,2,3$: quark flavor indices with $q_{1,2,3} = u, d, s$
- ❖ $\{y, z\}$ and $\{y, z, w\}$: total symmetrization of flavor indices

- Form a basis for any triple-quark operators

Yi Liao, XDM, Hao-Lin Wang, 2504.14855, PRL

Chiral structures

- 3-flavor ($u,\ d,\ s$) QCD has a global chiral symmetry: $\mathrm{SU(3)_L} \otimes \mathrm{SU(3)_R}$

in the massless limit

- Restrict to triple-quark sector

$$\mathcal{N}^{\rm LL}_{yzw} \equiv q^{\alpha}_{\rm L,y}(\overline{q^{\beta C}_{\rm L,z}} q^{\gamma}_{\rm L,w})\epsilon_{\alpha\beta\gamma} \in \mathbf{8}_{\rm L} \otimes \mathbf{1}_{\rm R}$$

$$\mathcal{N}^{\rm RL}_{yzw} \equiv q^{\alpha}_{\rm R,y}(\overline{q^{\beta C}_{\rm L,z}} q^{\gamma}_{\rm L,w})\epsilon_{\alpha\beta\gamma} \in \bar{\mathbf{3}}_{\rm L} \otimes \mathbf{3}_{\rm R}$$

$$+\mathrm{L} \leftrightarrow \mathrm{R}$$

$$\boxed{\begin{aligned} \mathcal{N}^{\mathrm{LR},\mu}_{yzw} &\equiv q^{\alpha}_{\rm L,\{y}(\overline{q^{\beta C}_{\rm L,z\}}}\gamma^{\mu} q^{\gamma}_{\rm R,w})\epsilon_{\alpha\beta\gamma} \in \mathbf{6}_{\rm L} \otimes \mathbf{3}_{\rm R} \\ \mathcal{N}^{\mathrm{LL},\mu\nu}_{yzw} &\equiv q^{\alpha}_{\rm L,\{y}(\overline{q^{\beta C}_{\rm L,z}}\sigma^{\mu\nu} q^{\gamma}_{\rm L,w\}})\epsilon_{\alpha\beta\gamma} \in \mathbf{10}_{\rm L} \otimes \mathbf{1}_{\rm R} \end{aligned}}$$

New chiral structures

- Different isospin property

$$\mathcal{N}^{\rm LL}_{yzw} \text{ and } \mathcal{N}^{\rm RL}_{yzw} \Rightarrow \Delta I = 0,\ 1/2,\ 1$$

$$\mathcal{N}^{\mathrm{LR},\mu}_{yzw} \text{ and } \mathcal{N}^{\mathrm{LL},\mu\nu}_{yzw} \Rightarrow \Delta I = 0,\ 1/2,\ 1,\ 3/2 \Rightarrow n \to e^{-}\pi^{+},\ n \to \mu^{-}\pi^{+}$$

Non-trivial Lorentz structures

- Usual structures—spin-1/2 objects:

$$\mathcal{N}_{\mathbf{8}_{\mathrm{L}}\otimes\mathbf{1}_{\mathrm{R}}},\ \mathcal{N}_{\mathbf{3}_{\mathrm{L}}\otimes\bar{\mathbf{3}}_{\mathrm{R}}} \in (1/2,\ 0), \qquad \mathcal{N}_{\mathbf{1}_{\mathrm{L}}\otimes\mathbf{8}_{\mathrm{R}}},\ \mathcal{N}_{\bar{\mathbf{3}}_{\mathrm{L}}\otimes\mathbf{3}_{\mathrm{R}}} \in (0,\ 1/2)$$

- New structures—spin-3/2 objects:

Vector-spinor object: $\mathcal{N}^{\mathrm{LR},\mu}_{yzw} \in (1,\ 1/2)$, $\mathcal{N}^{\mathrm{RL},\mu}_{yzw} \in (1/2,\ 1)$ $\gamma_\mu \mathcal{N}^{\mathrm{LR},\mu}_{yzw} = \gamma_\mu \mathcal{N}^{\mathrm{RL},\mu}_{yzw} = 0$

Tensor-spinor object: $\mathcal{N}^{\mathrm{LL},\mu\nu}_{yzw} \in (3/2,0)$, $\mathcal{N}^{\mathrm{RR},\mu\nu}_{yzw} \in (0,\ 3/2)$ $\gamma_\mu \mathcal{N}^{\mathrm{LL},\mu\nu}_{yzw} = \gamma_\mu \mathcal{N}^{\mathrm{RR},\mu\nu}_{yzw} = 0$

Complicating the chiral matching → Needing proper Lorentz projectors

$$\Gamma^{\mathrm{L,R}}_{\mu\nu} \equiv \left(g_{\mu\nu} - \frac{1}{4}\gamma_\mu\gamma_\nu\right)P_{\mathrm{L,R}}$$

$$\Gamma^{\mathrm{L,R}}_{\mu\rho}\Gamma^{\mathrm{L,R}\,\rho}_{\nu} = \Gamma^{\mathrm{L,R}}_{\mu\nu} \qquad \gamma^\mu\Gamma^{\mathrm{L,R}}_{\mu\nu} = 0$$

$$\hat{\Gamma}^{\mathrm{L,R}}_{\mu\nu\alpha\beta} \equiv \frac{1}{24}\left(2\{\sigma_{\mu\nu},\sigma_{\alpha\beta}\} - [\sigma_{\mu\nu},\sigma_{\alpha\beta}]\right)P_{\mathrm{L,R}}$$

$$\hat{\Gamma}^{\mathrm{L,R}}_{\mu\nu\rho\sigma}\hat{\Gamma}^{\mathrm{L,R}\,\rho\sigma}_{\alpha\beta} = \hat{\Gamma}^{\mathrm{L,R}}_{\mu\nu\alpha\beta} \qquad \gamma^\mu\hat{\Gamma}^{\mathrm{L,R}}_{\mu\nu\alpha\beta} = 0$$

E. Delgado et al., EPJA 51 (2015)

The general LEFT Lagrangian involving triple quarks

Non-quark factor as spurion fields

$$\mathscr{L}_{q^3}^{\not{B}} = \sum_i C_i^{yzw}\mathcal{O}_i^{yzw} = \sum_i \boxed{C_i^{yzw}\overline{\psi}}\,\Gamma_1 q(\overline{q^{\mathrm{C}}}\Gamma_2 q)$$

Quark factor

$$\equiv \mathscr{P}^i_{yzw} \qquad \equiv \mathscr{N}^i_{yzw}$$

$$\begin{aligned}\mathscr{L}_{q^3}^{\not{B}} = {} & \mathrm{Tr}\left[\mathscr{P}_{\mathbf{8}_{\rm L}\otimes\mathbf{1}_{\rm R}}\mathscr{N}_{\mathbf{8}_{\rm L}\otimes\mathbf{1}_{\rm R}} + \mathscr{P}_{\mathbf{1}_{\rm L}\otimes\mathbf{8}_{\rm R}}\mathscr{N}_{\mathbf{1}_{\rm L}\otimes\mathbf{8}_{\rm R}}\right] \\ & + \mathrm{Tr}\left[\mathscr{P}_{\mathbf{3}_{\rm L}\otimes\bar{\mathbf{3}}_{\rm R}}\mathscr{N}_{\bar{\mathbf{3}}_{\rm L}\otimes\mathbf{3}_{\rm R}} + \mathscr{P}_{\bar{\mathbf{3}}_{\rm L}\otimes\mathbf{3}_{\rm R}}\mathscr{N}_{\mathbf{3}_{\rm L}\otimes\bar{\mathbf{3}}_{\rm R}}\right] \\ & + \left[\mathscr{P}^{\{yz\}w,\mu}_{\bar{\mathbf{6}}_{\rm L}\otimes\bar{\mathbf{3}}_{\rm R}}\mathscr{N}^{\{yz\}w}_{\mathbf{6}_{\rm L}\otimes\mathbf{3}_{\rm R},\mu} + \mathscr{P}^{\{yz\}w,\mu}_{\bar{\mathbf{3}}_{\rm L}\otimes\bar{\mathbf{6}}_{\rm R}}\mathscr{N}^{\{yz\}w}_{\mathbf{3}_{\rm L}\otimes\mathbf{6}_{\rm R},\mu}\right] \\ & + \left[\mathscr{P}^{\{yzw\},\mu\nu}_{\overline{\mathbf{10}}_{\rm L}\otimes\mathbf{1}_{\rm R}}\mathscr{N}^{\{yzw\}}_{\mathbf{10}_{\rm L}\otimes\mathbf{1}_{\rm R},\mu\nu} + \mathscr{P}^{\{yzw\},\mu\nu}_{\mathbf{1}_{\rm L}\otimes\overline{\mathbf{10}}_{\rm R}}\mathscr{N}^{\{yzw\}}_{\mathbf{1}_{\rm L}\otimes\mathbf{10}_{\rm R},\mu\nu}\right] \\ & + \mathrm{h.c.}\end{aligned}$$

Matrix form for easy chiral realization

$$\mathscr{N}_{\mathbf{8}_{\rm L}\otimes\mathbf{1}_{\rm R}} = \begin{pmatrix} \mathscr{N}^{\rm LL}_{uds} & \mathscr{N}^{\rm LL}_{usu} & \mathscr{N}^{\rm LL}_{uud} \\ \mathscr{N}^{\rm LL}_{dds} & \mathscr{N}^{\rm LL}_{dsu} & \mathscr{N}^{\rm LL}_{dud} \\ \mathscr{N}^{\rm LL}_{sds} & \mathscr{N}^{\rm LL}_{ssu} & \mathscr{N}^{\rm LL}_{sud} \end{pmatrix} \qquad \mathscr{N}_{\bar{\mathbf{3}}_{\rm L}\otimes\mathbf{3}_{\rm R}} = \begin{pmatrix} \mathscr{N}^{\rm RL}_{uds} & \mathscr{N}^{\rm RL}_{usu} & \mathscr{N}^{\rm RL}_{uud} \\ \mathscr{N}^{\rm RL}_{dds} & \mathscr{N}^{\rm RL}_{dsu} & \mathscr{N}^{\rm RL}_{dud} \\ \mathscr{N}^{\rm RL}_{sds} & \mathscr{N}^{\rm RL}_{ssu} & \mathscr{N}^{\rm RL}_{sud} \end{pmatrix}$$

Chiral building blocks

$$\mathscr{P}_{\mathbf{8}_{\rm L}\otimes\mathbf{1}_{\rm R}} = \begin{pmatrix} 0 & \mathscr{P}^{\rm LL}_{dds} & \mathscr{P}^{\rm LL}_{sds} \\ \mathscr{P}^{\rm LL}_{usu} & \mathscr{P}^{\rm LL}_{dsu} & \mathscr{P}^{\rm LL}_{ssu} \\ \mathscr{P}^{\rm LL}_{uud} & \mathscr{P}^{\rm LL}_{dud} & \mathscr{P}^{\rm LL}_{sud} \end{pmatrix} \qquad \mathscr{P}_{\mathbf{3}_{\rm L}\otimes\bar{\mathbf{3}}_{\rm R}} = \begin{pmatrix} \mathscr{P}^{\rm RL}_{uds} & \mathscr{P}^{\rm RL}_{dds} & \mathscr{P}^{\rm RL}_{sds} \\ \mathscr{P}^{\rm RL}_{usu} & \mathscr{P}^{\rm RL}_{dsu} & \mathscr{P}^{\rm RL}_{ssu} \\ \mathscr{P}^{\rm RL}_{uud} & \mathscr{P}^{\rm RL}_{dud} & \mathscr{P}^{\rm RL}_{sud} \end{pmatrix} \qquad \mathscr{P}^{\rm LR,\mu}_{yzw} \qquad \mathscr{P}^{\rm LL,\mu\nu}_{yzw}$$

Wei-Qi Fan, Yi Liao, XDM, Hao-Lin Wang, 2412.20774, PLB

Chiral matching procedures

- Building blocks in ChPT: Octet baryons, pseudoscalars, vector mesons + spurions

$$\Sigma(x) = \xi^2(x) = \exp\left(\frac{i\sqrt{2}\Pi(x)}{F_0}\right) \quad \Pi(x) = \begin{pmatrix} \frac{\pi^0}{\sqrt{2}} + \frac{\eta}{\sqrt{6}} & \pi^+ & K^+ \\ \pi^- & -\frac{\pi^0}{\sqrt{2}} + \frac{\eta}{\sqrt{6}} & K^0 \\ K^- & \bar{K}^0 & -\sqrt{\frac{2}{3}}\eta \end{pmatrix}, \quad B(x) = \begin{pmatrix} \frac{\Sigma^0}{\sqrt{2}} + \frac{\Lambda^0}{\sqrt{6}} & \Sigma^+ & p \\ \Sigma^- & -\frac{\Sigma^0}{\sqrt{2}} + \frac{\Lambda^0}{\sqrt{6}} & n \\ \Xi^- & \Xi^0 & -\sqrt{\frac{2}{3}}\Lambda^0 \end{pmatrix}, \quad V_\mu(x) = \begin{pmatrix} \frac{\rho_\mu^0}{\sqrt{2}} + \frac{\phi_\mu^{(8)}}{\sqrt{6}} & \rho_\mu^+ & K_\mu^{*+} \\ \rho_\mu^- & -\frac{\rho_\mu^0}{\sqrt{2}} + \frac{\phi_\mu^{(8)}}{\sqrt{6}} & K_\mu^{*0} \\ K_\mu^{*-} & \bar{K}_\mu^{*0} & -\sqrt{\frac{2}{3}}\phi_\mu^{(8)} \end{pmatrix}$$

+ Spurion fields

$$\mathscr{P}_{\mathbf{8}_\mathrm{L}\otimes\mathbf{1}_\mathrm{R}} = \begin{pmatrix} 0 & \mathscr{P}_{dds}^{\mathrm{LL}} & \mathscr{P}_{sds}^{\mathrm{LL}} \\ \mathscr{P}_{usu}^{\mathrm{LL}} & \mathscr{P}_{dsu}^{\mathrm{LL}} & \mathscr{P}_{ssu}^{\mathrm{LL}} \\ \mathscr{P}_{uud}^{\mathrm{LL}} & \mathscr{P}_{dud}^{\mathrm{LL}} & \mathscr{P}_{sud}^{\mathrm{LL}} \end{pmatrix} \qquad \mathscr{P}_{\mathbf{3}_\mathrm{L}\otimes\bar{\mathbf{3}}_\mathrm{R}} = \begin{pmatrix} \mathscr{P}_{uds}^{\mathrm{RL}} & \mathscr{P}_{dds}^{\mathrm{RL}} & \mathscr{P}_{sds}^{\mathrm{RL}} \\ \mathscr{P}_{usu}^{\mathrm{RL}} & \mathscr{P}_{dsu}^{\mathrm{RL}} & \mathscr{P}_{ssu}^{\mathrm{RL}} \\ \mathscr{P}_{uud}^{\mathrm{RL}} & \mathscr{P}_{dud}^{\mathrm{RL}} & \mathscr{P}_{sud}^{\mathrm{RL}} \end{pmatrix} \qquad \mathscr{P}_{yzw}^{\mathrm{LR},\mu} \qquad \mathscr{P}_{yzw}^{\mathrm{LL},\mu\nu}$$

- Chiral symmetry: $SU(3)_\mathrm{L} \otimes SU(3)_\mathrm{R}$

- Chiral power counting: momentum p: $\{\Sigma, \xi, B, D_\mu B, V, D_\mu V\} \sim \mathcal{O}(p^0) \quad D_\mu\Sigma \sim \mathcal{O}(p^1)$

- Low energy constant (LEC): associate an unknown LEC for each indep. operator

Leading-order chiral Lagrangian for nucleon decay

$$\mathcal{L}_B^{\not{B},0} = c_1 \mathrm{Tr}\left[\mathscr{P}_{\bar{\mathbf{3}}_{\mathrm{L}}\otimes\mathbf{3}_{\mathrm{R}}}\xi B_{\mathrm{L}}\xi - \mathscr{P}_{\mathbf{3}_{\mathrm{L}}\otimes\bar{\mathbf{3}}_{\mathrm{R}}}\xi^\dagger B_{\mathrm{R}}\xi^\dagger\right]$$
$$+c_2 \mathrm{Tr}\left[\mathscr{P}_{\mathbf{8}_{\mathrm{L}}\otimes\mathbf{1}_{\mathrm{R}}}\xi B_{\mathrm{L}}\xi^\dagger - \mathscr{P}_{\mathbf{1}_{\mathrm{L}}\otimes\mathbf{8}_{\mathrm{R}}}\xi^\dagger B_{\mathrm{R}}\xi\right]$$

M. Claudson, M. B. Wise, PRD, 1981

Related to new structures

$$+\frac{c_3}{\Lambda_\chi}\left[\mathscr{P}^{\mathrm{LR},\mu}_{yzi}\Gamma^{\mathrm{L}}_{\mu\nu}(\xi i D^\nu B_{\mathrm{L}}\xi)_{yj}\Sigma_{zk}\epsilon_{ijk} - \mathscr{P}^{\mathrm{RL},\mu}_{yzi}\Gamma^{\mathrm{R}}_{\mu\nu}(\xi^\dagger i D^\nu B_{\mathrm{R}}\xi^\dagger)_{yj}\Sigma^*_{kz}\epsilon_{ijk}\right]$$
$$+\mathrm{h.c.},$$

$$\mathcal{L}_B^{\not{B},1} = \frac{c_4}{\Lambda_\chi^2}\left[\mathscr{P}^{\mathrm{LL},\mu\nu}_{yzw}\hat{\Gamma}^{\mathrm{L}}_{\mu\nu\alpha\beta}(\xi D^\alpha B_{\mathrm{L}}\xi)_{yi}\Sigma_{zj}(D^\beta\Sigma)_{wk}\epsilon_{ijk} - \mathscr{P}^{\mathrm{RR},\mu\nu}_{yzw}\hat{\Gamma}^{\mathrm{R}}_{\mu\nu\alpha\beta}(\xi^\dagger D^\alpha B_{\mathrm{R}}\xi^\dagger)_{iy}\Sigma^*_{jz}(D^\beta\Sigma)^*_{kw}\epsilon_{ijk}\right]$$
$$+\mathrm{h.c.}\,.$$

$$\Gamma^{\mathrm{L,R}}_{\mu\nu} \equiv \left(g_{\mu\nu} - \frac{1}{4}\gamma_\mu\gamma_\nu\right)P_{\mathrm{L,R}} \qquad \hat{\Gamma}^{\mathrm{L,R}}_{\mu\nu\alpha\beta} \equiv \frac{1}{24}\left(2\{\sigma_{\mu\nu},\sigma_{\alpha\beta}\} - [\sigma_{\mu\nu},\sigma_{\alpha\beta}]\right)P_{\mathrm{L,R}}$$

LECs can be determined by data, LQCD, or estimated by NDA.

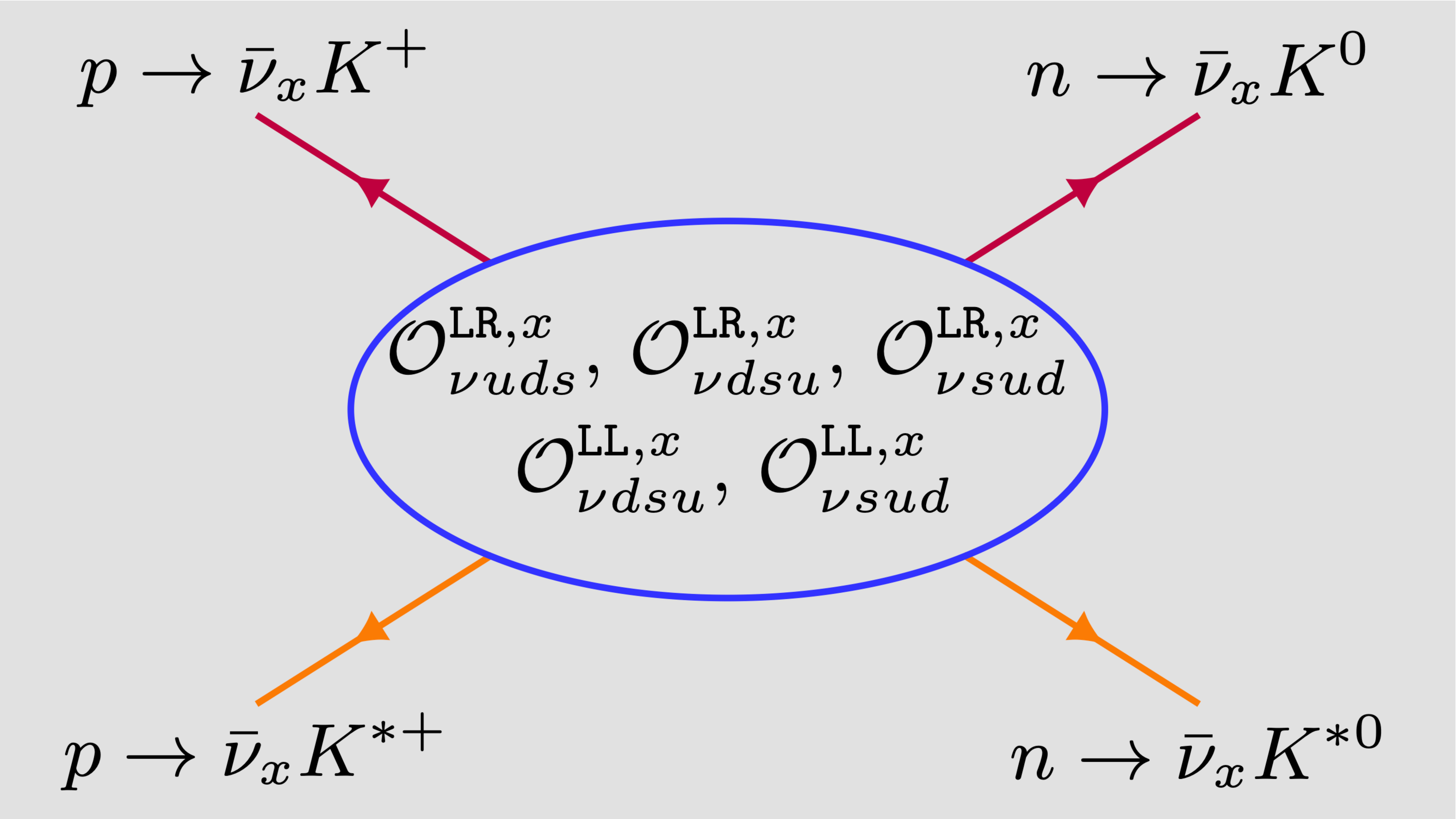
$c_1 = -0.01257(111)\,\mathrm{GeV}^3, c_2 = 0.01269(107)\,\mathrm{GeV}^3$ J.-S. Yoo et al., 2111.01608

Yi Liao, XDM, Hao-Lin Wang, 2504.14855, PRL

Chiral Lagrangian involving octet vector mesons

$$\begin{aligned}
\mathcal{L}_{BV}^{\not{B}} = {} & d_1 \mathrm{Tr}\left[\mathcal{P}_{\bar{\mathbf{3}}_{\mathrm{L}}\otimes\mathbf{3}_{\mathrm{R}}} \xi \gamma_\mu V^\mu B_{\mathrm{R}} \xi - \mathcal{P}_{\mathbf{3}_{\mathrm{L}}\otimes\bar{\mathbf{3}}_{\mathrm{R}}} \xi^\dagger \gamma_\mu V^\mu B_{\mathrm{L}} \xi^\dagger\right] \\
& + d_1' \mathrm{Tr}\left[\mathcal{P}_{\bar{\mathbf{3}}_{\mathrm{L}}\otimes\mathbf{3}_{\mathrm{R}}} \xi \gamma_\mu B_{\mathrm{R}} V^\mu \xi - \mathcal{P}_{\mathbf{3}_{\mathrm{L}}\otimes\bar{\mathbf{3}}_{\mathrm{R}}} \xi^\dagger \gamma_\mu B_{\mathrm{L}} V^\mu \xi^\dagger\right] \\
& + d_2 \mathrm{Tr}\left[\mathcal{P}_{\mathbf{8}_{\mathrm{L}}\otimes\mathbf{1}_{\mathrm{R}}} \xi \gamma_\mu V^\mu B_{\mathrm{R}} \xi^\dagger - \mathcal{P}_{\mathbf{1}_{\mathrm{L}}\otimes\mathbf{8}_{\mathrm{R}}} \xi^\dagger \gamma_\mu V^\mu B_{\mathrm{L}} \xi\right] \\
& + d_2' \mathrm{Tr}\left[\mathcal{P}_{\mathbf{8}_{\mathrm{L}}\otimes\mathbf{1}_{\mathrm{R}}} \xi \gamma_\mu B_{\mathrm{R}} V^\mu \xi^\dagger - \mathcal{P}_{\mathbf{1}_{\mathrm{L}}\otimes\mathbf{8}_{\mathrm{R}}} \xi^\dagger \gamma_\mu B_{\mathrm{L}} V^\mu \xi\right] \\
& + d_3 \left[\mathcal{P}_{yzi}^{\mathrm{LR},\mu} \Gamma_{\mu\nu}^{\mathrm{L}} (\xi B_{\mathrm{L}} \xi)_{yj} (\xi V^\nu \xi)_{zk} \epsilon_{ijk}\right. \\
& \left. - \mathcal{P}_{yzi}^{\mathrm{RL},\mu} \Gamma_{\mu\nu}^{\mathrm{R}} (\xi^\dagger B_{\mathrm{R}} \xi^\dagger)_{yj} (\xi^\dagger V^\nu \xi^\dagger)_{kz} \epsilon_{ijk}\right] \\
& + d_3' \left[\mathcal{P}_{yzi}^{\mathrm{LR},\mu} \Gamma_{\mu\nu}^{\mathrm{L}} (\xi V^\nu B_{\mathrm{L}} \xi)_{yj} \Sigma_{zk} \epsilon_{ijk}\right. \\
& \left. - \mathcal{P}_{yzi}^{\mathrm{RL},\mu} \Gamma_{\mu\nu}^{\mathrm{R}} (\xi^\dagger V^\nu B_{\mathrm{R}} \xi^\dagger)_{yj} \Sigma_{kz}^* \epsilon_{ijk}\right] \\
& + d_3'' \left[\mathcal{P}_{yzi}^{\mathrm{LR},\mu} \Gamma_{\mu\nu}^{\mathrm{L}} (\xi B_{\mathrm{L}} V^\nu \xi)_{yj} \Sigma_{zk} \epsilon_{ijk}\right. \\
& \left. - \mathcal{P}_{yzi}^{\mathrm{RL},\mu} \Gamma_{\mu\nu}^{\mathrm{R}} (\xi^\dagger B_{\mathrm{R}} V^\nu \xi^\dagger)_{yj} \Sigma_{kz}^* \epsilon_{ijk}\right] \\
& + \frac{d_4}{\Lambda_\chi} \left[\mathcal{P}_{yzw}^{\mathrm{LL},\mu\nu} \hat{\Gamma}_{\mu\nu\alpha\beta}^{\mathrm{L}} (\xi D^\alpha B_{\mathrm{L}} \xi)_{yi} \Sigma_{zj} (\xi V^\beta \xi)_{wk} \epsilon_{ijk}\right. \\
& \left. - \mathcal{P}_{yzw}^{\mathrm{RR},\mu\nu} \hat{\Gamma}_{\mu\nu\alpha\beta}^{\mathrm{R}} (\xi^\dagger D^\alpha B_{\mathrm{R}} \xi^\dagger)_{yi} \Sigma_{jz}^* (\xi V^\beta \xi)_{kw}^* \epsilon_{ijk}\right] \\
& + \mathrm{h.c.},
\end{aligned}$$

Complementarity between pseudoscalar and vector meson



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

$n \to \bar{\nu}_x K^0$

$\mathcal{O}_{\nu uds}^{\mathrm{LR},x}$, $\mathcal{O}_{\nu dsu}^{\mathrm{LR},x}$, $\mathcal{O}_{\nu sud}^{\mathrm{LR},x}$

$\mathcal{O}_{\nu dsu}^{\mathrm{LL},x}$, $\mathcal{O}_{\nu sud}^{\mathrm{LL},x}$

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

$n \to \bar{\nu}_x K^{*0}$

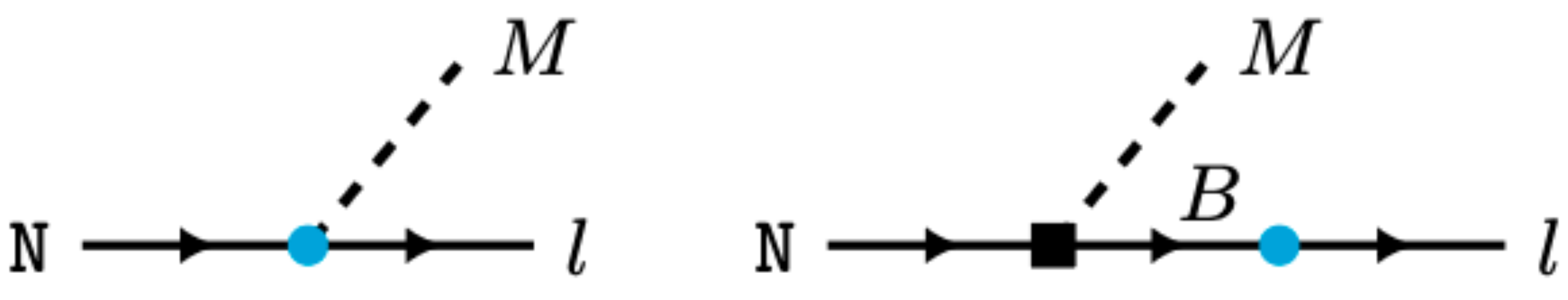
Yi Liao, XDM, Hao-Lin Wang, 2506.05052, PRDL

Applications to various decay modes

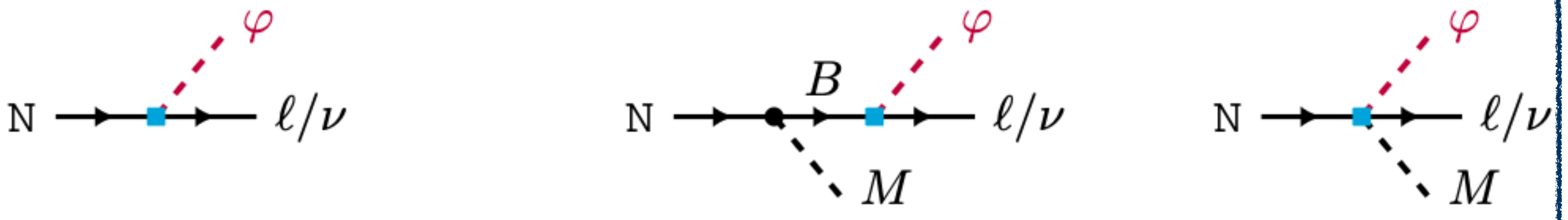
$\mathscr{L}_{\not B}$ + standard ChPT interactions + $\mathscr{L}_{\rm SM,EW}$

$$\mathcal{L}^{B,0}_{\texttt{ChPT}} \supset \frac{D}{2}\mathrm{Tr}(\bar{B}\gamma^{\mu}\gamma_5\{u_\mu, B\}) + \frac{F}{2}\mathrm{Tr}(\bar{B}\gamma^{\mu}\gamma_5[u_\mu, B]) + \mathrm{G_D}\mathrm{Tr}(\bar{B}\gamma_\mu\{V^\mu, B\}) + \mathrm{G_F}\mathrm{Tr}(\bar{B}\gamma_\mu[V^\mu, B]), \quad (11)$$

Expanding the chiral Lagrangian → $\mathscr{L} \supset M^n(\mathscr{P}B)$ → Draw diagram and calculate



$\mathtt{N} \to l + M$



$\mathtt{N} \to l + \varphi$

$\mathtt{N} \to l + M + \varphi$

Status of nucleon decays in the EFT

SM particles	**SM+ a new particle**
$\mathrm{N} \to M + l$ A. B. Beneito *et al*, 2312.13361	$\mathrm{N} \to l + a, \mathrm{N} \to l + M + a$ T. Li, M. A. Schmidt, C.-Y. Yao, 2406.11382 Wei-Qi Fan, Yi Liao, XDM, Hao-Lin Wang, 2507.11844
$\mathrm{N} \to V + l$ Yi Liao, XDM, Hao-Lin Wang, 2506.05052	$\mathrm{N} \to l + \varphi, \mathrm{N} \to l + M + \varphi$ XDM, Michael Schmidt, Wei-Hang Zhang, 2511.02169
$\mathrm{N} \to l_1 + l_2 + l_3$ Jing Chen, Yi Liao, XDM, Hao-Lin Wang, 2512.02692 Yi Liao, XDM, Xiang Zhao, 2512.09287	$\mathrm{N} \to M + N$ T. Li, M. A. Schmidt, C.-Y. Yao, 2502.14303
$\mathrm{N} \to l + M_1 + M_2$ Wei-Qi Fan, Yi Liao, XDM, in preparation	$\mathrm{N} \to l + X, \mathrm{N} \to l + M + X$ Jin-Han Liang, Yi Liao, XDM, Xiang Zhao, in preparation

NP? ⇒ SMEFT? ⇒ LEFT ⇒ ChPT ⇒ $\Gamma^{-1}(\mathrm{N} \to \cdots) = \sum a_{ij} C_i C_j^*$

To be done | Done

Nucleon decay with a light scalar: $\mathrm{N} \to l+\varphi, \mathrm{N} \to l + M+\varphi$

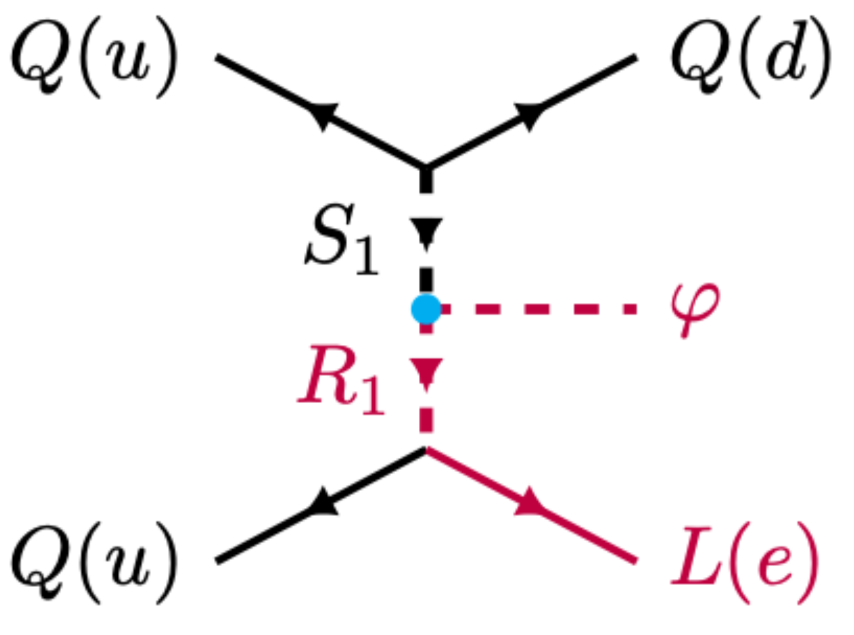
$$\mathscr{L} \supset \left[R_1^\dagger(y_{Lpr}\overline{Q_p^{i\mathrm{C}}}\epsilon_{ij}L_r^j + y_{Rpr}\overline{u_p^{\mathrm{C}}}e_r) + S_1^\alpha(z_{Lpr}\overline{Q_p^{i\beta\mathrm{C}}}\epsilon_{ij}Q_r^{j\gamma} + z_{Rpr}\overline{u_p^{\beta\mathrm{C}}}d_r^\gamma)\epsilon_{\alpha\beta\gamma} - \kappa R_1^\dagger S_1\varphi + \mathrm{h.c.}\right],$$

Leptoquark model

Dim-7 in φSMEFT

$$C_{LQdu\varphi}^{prst} = -\frac{\kappa^*[y_L]_{rp}[z_R]_{ts}}{m_S^2 m_R^2}, \qquad C_{euQQ\varphi}^{prst} = -\frac{\kappa^*[y_R]_{rp}[z_L]_{st}}{m_S^2 m_R^2},$$

$$C_{LQQQ\varphi}^{prst} = \frac{2\kappa^*[y_L]_{rp}[z_L]_{st}}{m_S^2 m_R^2}, \qquad C_{eudu\varphi}^{prst} = \frac{\kappa^*[y_R]_{rp}[z_R]_{ts}}{m_S^2 m_R^2}.$$



$\mathbb{Z}_2$ symmetry

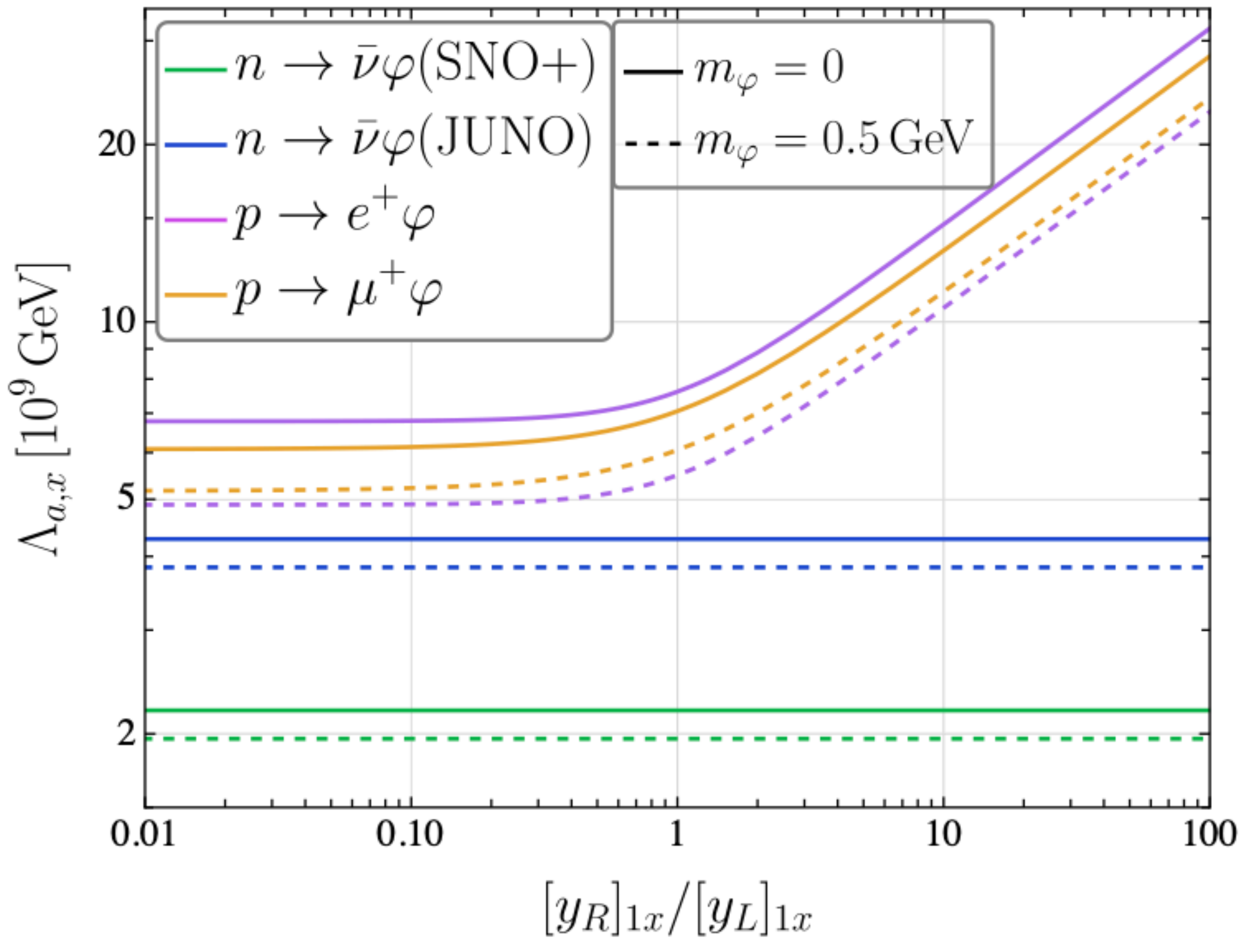
↓

No dim-6 SMEFT

Dim-7 in φLEFT

$$C_{\varphi\nu dud}^{\mathrm{LR},x} = 1.32\frac{\kappa^*[y_L]_{1x}[z_R]_{11}}{m_S^2 m_R^2}, C_{\varphi\ell uud}^{\mathrm{LR},x} = -C_{\varphi\nu dud}^{\mathrm{LR},x}, C_{\varphi\ell uud}^{\mathrm{RL},x} = -1.32\frac{2\kappa^*[y_R]_{1x}[z_L]_{11}}{m_S^2 m_R^2},$$

$$C_{\varphi\nu dud}^{\mathrm{LL},x} = 1.32\frac{2\kappa^*[y_L]_{1x}[z_L]_{11}}{m_S^2 m_R^2}, C_{\varphi\ell uud}^{\mathrm{LL},x} = -C_{\varphi\nu dud}^{\mathrm{LL},x}, C_{\varphi\ell uud}^{\mathrm{RR},x} = -1.32\frac{\kappa^*[y_R]_{1x}[z_R]_{11}}{m_S^2 m_R^2},$$



Spurion fields

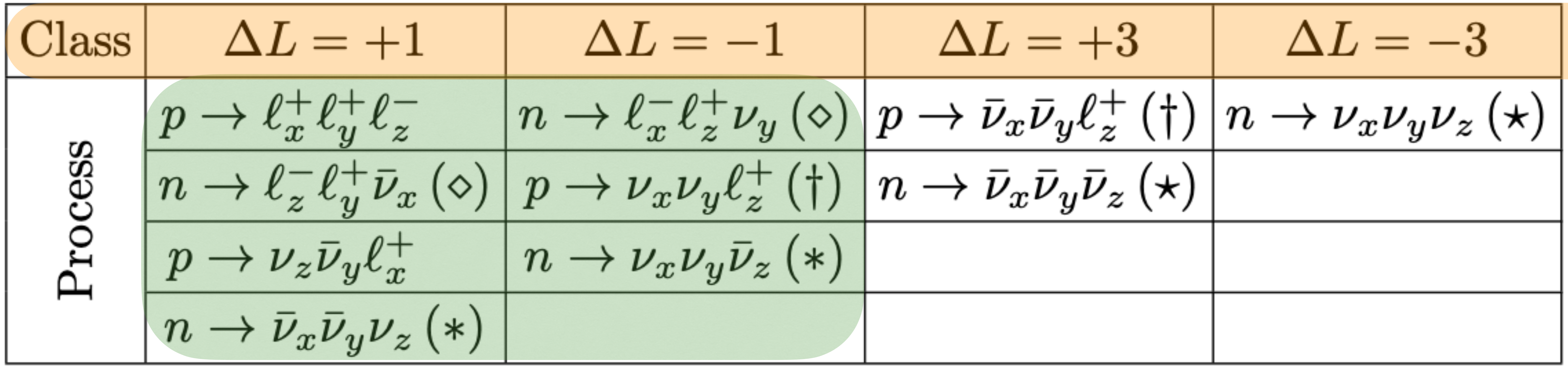
$$\mathcal{N}_{yzw}^{\mathrm{LL}} \text{ and } \mathcal{N}_{yzw}^{\mathrm{RL}} + \mathrm{L} \leftrightarrow \mathrm{R}$$

XDM, Michael Schmidt, Wei-Hang Zhang, 2511.02169, JHEP

$$\Lambda_{a,x} \equiv (m_S^2 m_R^2/|\kappa^*[y_L]_{1x}([z_R]_{11} - 2[z_L]_{11})|)^{1/3}$$

Nucleon decay into triple leptons

Generalized lepton flavor number: $\Delta F_L \equiv |\Delta F_e| + |\Delta F_\mu| + |\Delta F_\tau|$



Class	$\Delta L = +1$	$\Delta L = -1$	$\Delta L = +3$	$\Delta L = -3$
Process	$p \to \ell_x^+ \ell_y^+ \ell_z^-$	$n \to \ell_x^- \ell_z^+ \nu_y$ $(\diamond)$	$p \to \bar{\nu}_x \bar{\nu}_y \ell_z^+$ $(\dagger)$	$n \to \nu_x \nu_y \nu_z$ $(\star)$
	$n \to \ell_z^- \ell_y^+ \bar{\nu}_x$ $(\diamond)$	$p \to \nu_x \nu_y \ell_z^+$ $(\dagger)$	$n \to \bar{\nu}_x \bar{\nu}_y \bar{\nu}_z$ $(\star)$	
	$p \to \nu_z \bar{\nu}_y \ell_x^+$	$n \to \nu_x \nu_y \bar{\nu}_z$ $(*)$		
	$n \to \bar{\nu}_x \bar{\nu}_y \nu_z$ $(*)$			

Lepton number

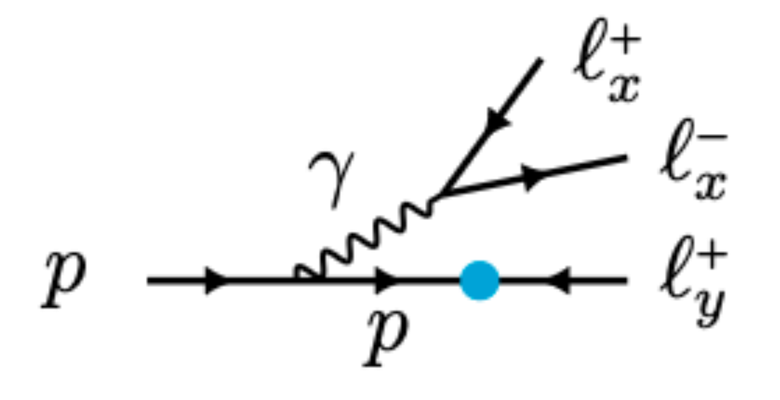
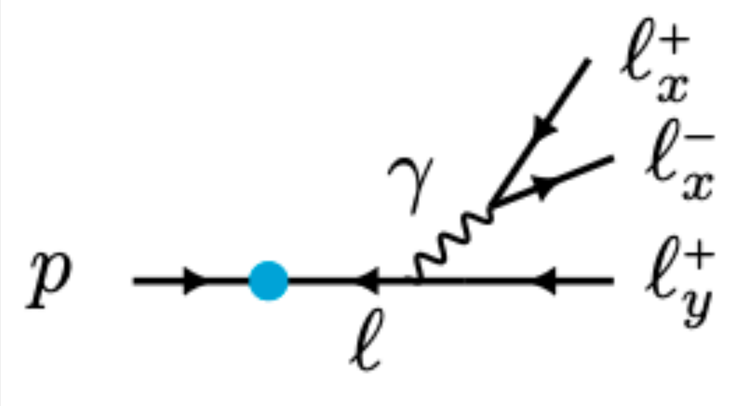
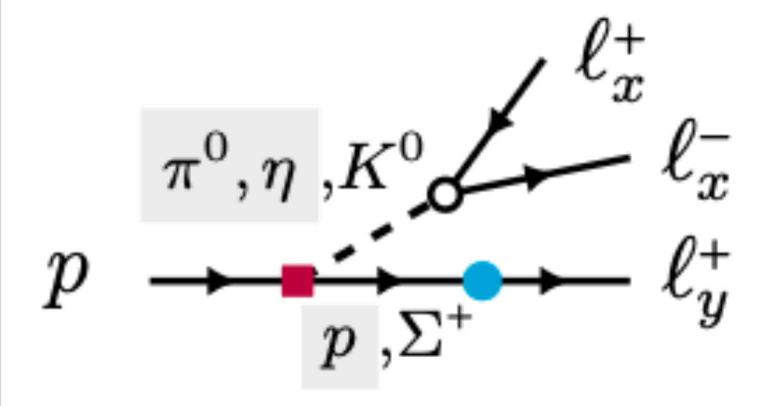
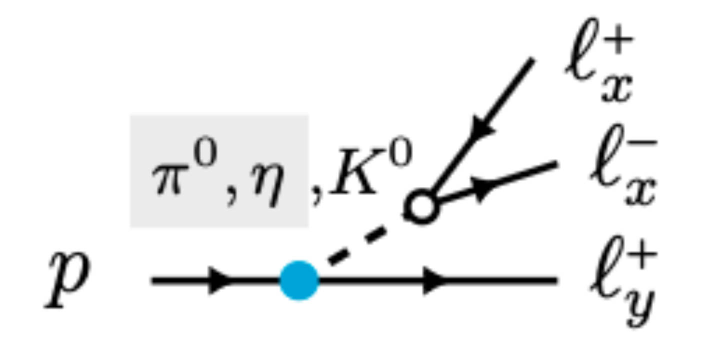
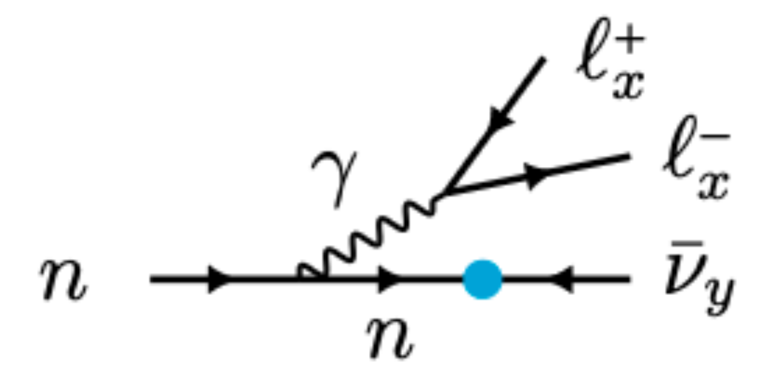
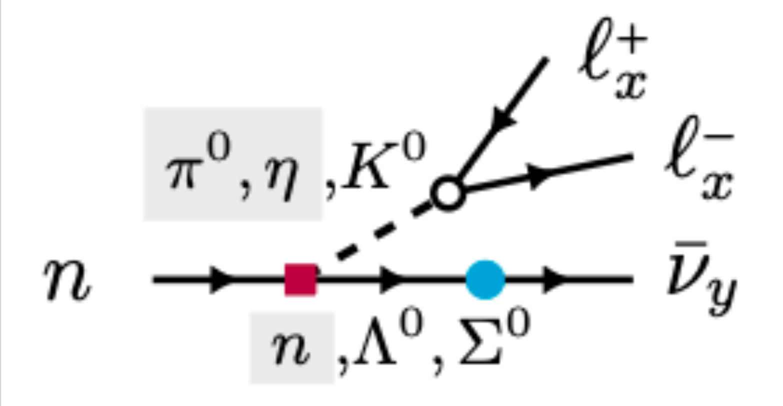
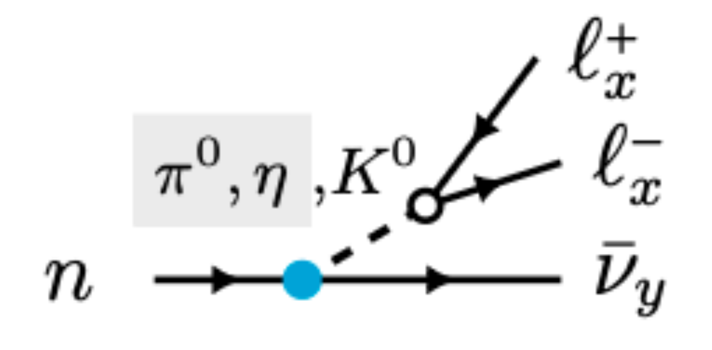
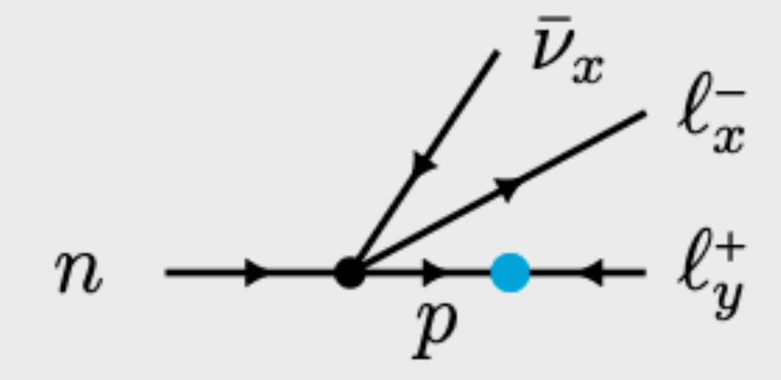
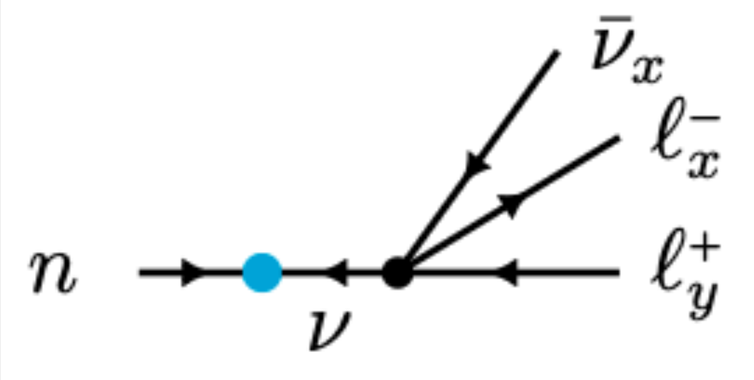
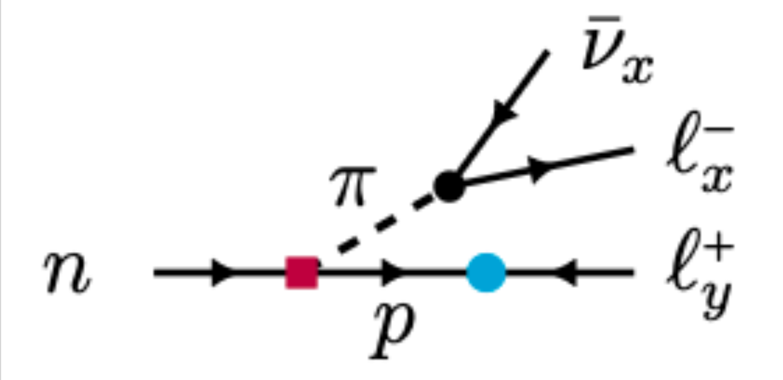
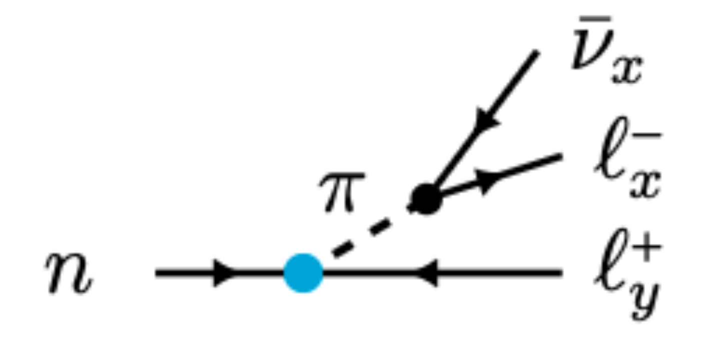
$z = x$ or $y \Rightarrow \Delta F_L = 1$

Remaining ones: $\Delta F_L = 3$

- LO contribution: dim-6 operators | dim-9 operators
- Mechanism: Noncontact diagrams | Contact diagrams

Nucleon decay into triple leptons: Noncontact contributions

Dim-6 LEFT operators + SM vertices

Mode		Feynman diagrams			
$p \to \ell_x^-\ell_x^+\ell_y^+$ $(xy = ee, \mu\mu, e\mu, \mu e)$					
$n \to \ell_x^-\ell_x^+\bar{\nu}_x$ $(x = e, \mu)$	$n \to \ell_x^-\ell_x^+\bar{\nu}_y$ $(xy = e\mu, e\tau,$ $\mu e, \mu\tau)$		—		
	$n \to \ell_x^-\ell_y^+\bar{\nu}_x$ $(xy = e\mu, \mu e)$				

Process	Exp. bound Γ^{-1}[yr]
$p \to e^+e^+e^-$	3.4×10^{34} [29]
$p \to e^+e^+\mu^-$	1.9×10^{34} [29]
$p \to e^+\mu^+e^-$	2.3×10^{34} [29]
$p \to e^+\mu^+\mu^-$	9.2×10^{33} [29]
$p \to \mu^+\mu^+e^-$	1.1×10^{34} [29]
$p \to \mu^+\mu^+\mu^-$	1.0×10^{34} [29]

Electromagnetic

Weak interactions

Hadron-lepton vetices,…

- Resonance enhancement for final states involving $\mu^+\nu_\mu/\mu^-\bar{\nu}_\mu$ pair
- Generally, the noncontact contributions yield bounds on Γ^{-1} that suprpass experimental constraints by a factor $\mathcal{O}(10^{4--17})$

⇩

Making contact dim-9 contributions relevant

Jing Chen, Yi Liao, XDM and Hao-Lin Wang, 2512.02692, PLB

Nucleon decay into triple leptons: Contact contributions

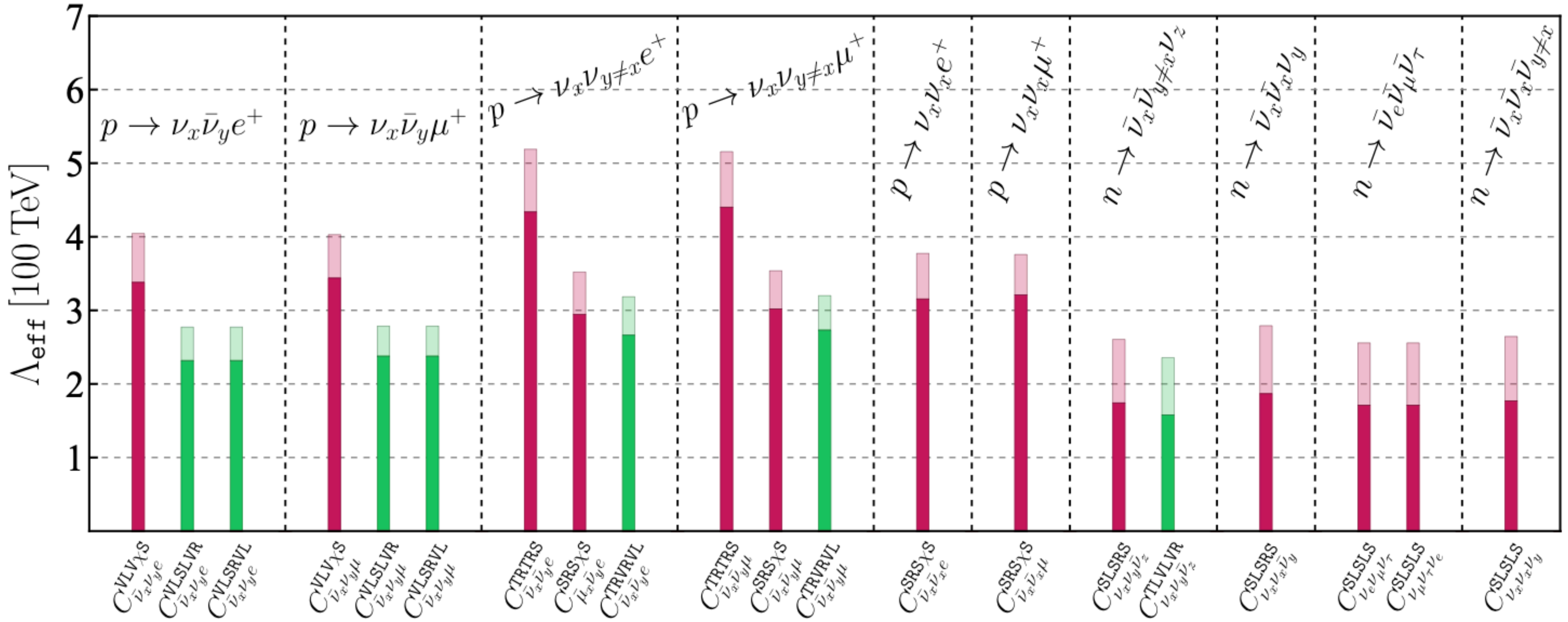
Yi Liao, XDM, Xiang Zhao, 2512.09287, JHEP

	Notation	Operator	Chiral Irrep.	# of operators	Process
$\Delta L = +3$	$\mathcal{O}^{\mathtt{SLSRSR}}_{\nu\nu\ell,xyz}$	$(\overline{\nu^{\mathrm{C}}_{\mathrm{L}x}}\nu_{\mathrm{L}y})(\overline{\ell^{\mathrm{C}}_{\mathrm{R}z}}\mathcal{N}^{\mathrm{RR}}_{uud})$	$\mathbf{1}_{\mathrm{L}}\otimes\mathbf{8}_{\mathrm{R}}$	$\frac{1}{2}n_\ell n_\nu(n_\nu+1)\,\langle 18\rangle$	$p\to\bar{\nu}_x\bar{\nu}_y\ell^+_z$
	$\mathcal{O}^{\mathtt{SLSLSL}}_{\nu\nu\ell,xyz}$	$(\overline{\nu^{\mathrm{C}}_{\mathrm{L}x}}\nu_{\mathrm{L}y})(\overline{\ell^{\mathrm{C}}_{\mathrm{L}z}}\mathcal{N}^{\mathrm{LL}}_{uud})$	$\mathbf{8}_{\mathrm{L}}\otimes\mathbf{1}_{\mathrm{R}}$	$\frac{1}{2}n_\ell n_\nu(n_\nu+1)\,\langle 18\rangle$	
	$\mathcal{O}^{\mathtt{TLTLSL}}_{\nu\nu\ell,xyz}$	$(\overline{\nu^{\mathrm{C}}_{\mathrm{L}x}}\sigma_{\mu\nu}\nu_{\mathrm{L}y})(\overline{\ell^{\mathrm{C}}_{\mathrm{L}z}}\sigma^{\mu\nu}\mathcal{N}^{\mathrm{LL}}_{uud})$	$\mathbf{8}_{\mathrm{L}}\otimes\mathbf{1}_{\mathrm{R}}$	$\frac{1}{2}n_\ell n_\nu(n_\nu-1)\,\langle 9\rangle$	
	$\mathcal{O}^{\mathtt{TLSLTL}}_{\nu\nu\ell,xyz}$	$(\overline{\nu^{\mathrm{C}}_{\mathrm{L}x}}\sigma_{\mu\nu}\nu_{\mathrm{L}y})(\overline{\ell^{\mathrm{C}}_{\mathrm{L}z}}\mathcal{N}^{\mathrm{LL},\mu\nu}_{uud})$	$\mathbf{10}_{\mathrm{L}}\otimes\mathbf{1}_{\mathrm{R}}$	$\frac{1}{2}n_\ell n_\nu(n_\nu-1)\,\langle 9\rangle$	
	$\mathcal{O}^{\mathtt{SLSRSL}}_{\nu\nu\ell,xyz}$	$(\overline{\nu^{\mathrm{C}}_{\mathrm{L}x}}\nu_{\mathrm{L}y})(\overline{\ell^{\mathrm{C}}_{\mathrm{R}z}}\mathcal{N}^{\mathrm{RL}}_{uud})$	$\bar{\mathbf{3}}_{\mathrm{L}}\otimes\mathbf{3}_{\mathrm{R}}$	$\frac{1}{2}n_\ell n_\nu(n_\nu+1)\,\langle 18\rangle$	
	$\mathcal{O}^{\mathtt{TLVLVR1}}_{\nu\nu\ell,xyz}$	$(\overline{\nu^{\mathrm{C}}_{\mathrm{L}x}}\sigma_{\mu\nu}\nu_{\mathrm{L}y})(\overline{\ell^{\mathrm{C}}_{\mathrm{R}z}}\gamma^{\mu}\mathcal{N}^{\mathrm{LR},\nu}_{udu})$	$\mathbf{6}_{\mathrm{L}}\otimes\mathbf{3}_{\mathrm{R}}$	$\frac{1}{2}n_\ell n_\nu(n_\nu-1)\,\langle 9\rangle$	
	$\mathcal{O}^{\mathtt{TLVLVR2}}_{\nu\nu\ell,xyz}$	$(\overline{\nu^{\mathrm{C}}_{\mathrm{L}x}}\sigma_{\mu\nu}\nu_{\mathrm{L}y})(\overline{\ell^{\mathrm{C}}_{\mathrm{R}z}}\gamma^{\mu}\mathcal{N}^{\mathrm{LR},\nu}_{uud})$	$\mathbf{6}_{\mathrm{L}}\otimes\mathbf{3}_{\mathrm{R}}$	$\frac{1}{2}n_\ell n_\nu(n_\nu-1)\,\langle 9\rangle$	
	$\mathcal{O}^{\mathtt{SLSLSR}}_{\nu\nu\ell,xyz}$	$(\overline{\nu^{\mathrm{C}}_{\mathrm{L}x}}\nu_{\mathrm{L}y})(\overline{\ell^{\mathrm{C}}_{\mathrm{L}z}}\mathcal{N}^{\mathrm{LR}}_{uud})$	$\mathbf{3}_{\mathrm{L}}\otimes\bar{\mathbf{3}}_{\mathrm{R}}$	$\frac{1}{2}n_\ell n_\nu(n_\nu+1)\,\langle 18\rangle$	
	$\mathcal{O}^{\mathtt{TLTLSR}}_{\nu\nu\ell,xyz}$	$(\overline{\nu^{\mathrm{C}}_{\mathrm{L}x}}\sigma_{\mu\nu}\nu_{\mathrm{L}y})(\overline{\ell^{\mathrm{C}}_{\mathrm{L}z}}\sigma^{\mu\nu}\mathcal{N}^{\mathrm{LR}}_{uud})$	$\mathbf{3}_{\mathrm{L}}\otimes\bar{\mathbf{3}}_{\mathrm{R}}$	$\frac{1}{2}n_\ell n_\nu(n_\nu-1)\,\langle 9\rangle$	
	$\mathcal{O}^{\mathtt{SLSLSL}}_{\nu\nu\nu,xyz}$	$(\overline{\nu^{\mathrm{C}}_{\mathrm{L}x}}\nu_{\mathrm{L}[y})(\overline{\nu^{\mathrm{C}}_{\mathrm{L}z]}}\mathcal{N}^{\mathrm{LL}}_{dud})$	$\mathbf{8}_{\mathrm{L}}\otimes\mathbf{1}_{\mathrm{R}}$	$\frac{1}{3}n_\nu(n_\nu^2-1)\,\langle 8\rangle$	$n\to\bar{\nu}\bar{\nu}\bar{\nu}$
	$\mathcal{O}^{\mathtt{TLSLTL}}_{\nu\nu\nu,xyz}$	$(\overline{\nu^{\mathrm{C}}_{\mathrm{L}[x}}\sigma_{\mu\nu}\nu_{\mathrm{L}y})(\overline{\nu^{\mathrm{C}}_{\mathrm{L}z]}}\mathcal{N}^{\mathrm{LL},\mu\nu}_{udd})$	$\mathbf{10}_{\mathrm{L}}\otimes\mathbf{1}_{\mathrm{R}}$	$\frac{1}{6}n_\nu(n_\nu-2)(n_\nu-1)\,\langle 1\rangle$	
	$\mathcal{O}^{\mathtt{SLSLSR}}_{\nu\nu\nu,xyz}$	$(\overline{\nu^{\mathrm{C}}_{\mathrm{L}x}}\nu_{\mathrm{L}[y})(\overline{\nu^{\mathrm{C}}_{\mathrm{L}z]}}\mathcal{N}^{\mathrm{LR}}_{dud})$	$\mathbf{3}_{\mathrm{L}}\otimes\bar{\mathbf{3}}_{\mathrm{R}}$	$\frac{1}{3}n_\nu(n_\nu^2-1)\,\langle 8\rangle$	
$\Delta L = -3$	$\mathcal{O}^{\mathtt{SRSRSR}}_{\bar{\nu}\bar{\nu}\bar{\nu},xyz}$	$(\overline{\nu_{\mathrm{L}x}}\nu^{\mathrm{C}}_{\mathrm{L}[y})(\overline{\nu_{\mathrm{L}z]}}\mathcal{N}^{\mathrm{RR}}_{dud})$	$\mathbf{1}_{\mathrm{L}}\otimes\mathbf{8}_{\mathrm{R}}$	$\frac{1}{3}n_\nu(n_\nu^2-1)\,\langle 8\rangle$	$n\to\nu\nu\nu$
	$\mathcal{O}^{\mathtt{TRSRTR}}_{\bar{\nu}\bar{\nu}\bar{\nu},xyz}$	$(\overline{\nu_{\mathrm{L}[x}}\sigma_{\mu\nu}\nu^{\mathrm{C}}_{\mathrm{L}y})(\overline{\nu_{\mathrm{L}z]}}\mathcal{N}^{\mathrm{RR},\mu\nu}_{udd})$	$\mathbf{1}_{\mathrm{L}}\otimes\mathbf{10}_{\mathrm{R}}$	$\frac{1}{6}n_\nu(n_\nu-2)(n_\nu-1)\,\langle 1\rangle$	
	$\mathcal{O}^{\mathtt{SRSRSL}}_{\bar{\nu}\bar{\nu}\bar{\nu},xyz}$	$(\overline{\nu_{\mathrm{L}x}}\nu^{\mathrm{C}}_{\mathrm{L}[y})(\overline{\nu_{\mathrm{L}z]}}\mathcal{N}^{\mathrm{RL}}_{dud})$	$\bar{\mathbf{3}}_{\mathrm{L}}\otimes\mathbf{3}_{\mathrm{R}}$	$\frac{1}{3}n_\nu(n_\nu^2-1)\,\langle 8\rangle$	

- All LO operators fit into the four general chiral structure
- Γ^{-1}s can be formulated as functions of WCs

$$\frac{\Gamma_{n\to\bar{\nu}_x\bar{\nu}_{y\neq x}\nu_z}}{10^{-9}\mathrm{GeV}^{11}} = 0.6|C^{\mathtt{SLSRS}}_{\nu\nu\bar{\nu},xyz}|^2 + 0.2|C^{\mathtt{TLVLVR}}_{\nu\nu\bar{\nu},xyz}|^2,$$

$$\frac{\Gamma_{n\to\bar{\nu}_x\bar{\nu}_x\nu_z}}{10^{-9}\mathrm{GeV}^{11}} = 1.2|C^{\mathtt{SLSRS}}_{\nu\nu\bar{\nu},xxz}|^2.$$



Corresponding UV models can be tested at colliders

RG-improved constraints on dim-7 SMEFT BNV operators

Yi Liao, XDM, Xiang Zhao, 2604.00952

$$\mathcal{O}^{prst}_{\bar{L}dud\tilde{H}} = \epsilon_{\alpha\beta\gamma}(\overline{L_p} d_r^{\alpha})(\overline{u_s^{\beta\mathtt{C}}} d_t^{\gamma})\tilde{H},$$

$$\mathcal{O}^{prst}_{\bar{L}dddH} = \epsilon_{\alpha\beta\gamma}(\overline{L_p} d_r^{\alpha})(\overline{d_s^{\beta\mathtt{C}}} d_t^{\gamma})H,$$

$$\mathcal{O}^{prst}_{\bar{e}Qdd\tilde{H}} = \epsilon_{ij}\epsilon_{\alpha\beta\gamma}(\overline{e_p} Q_r^{i\alpha})(\overline{d_s^{\beta\mathtt{C}}} d_t^{\gamma})\tilde{H}^j,$$

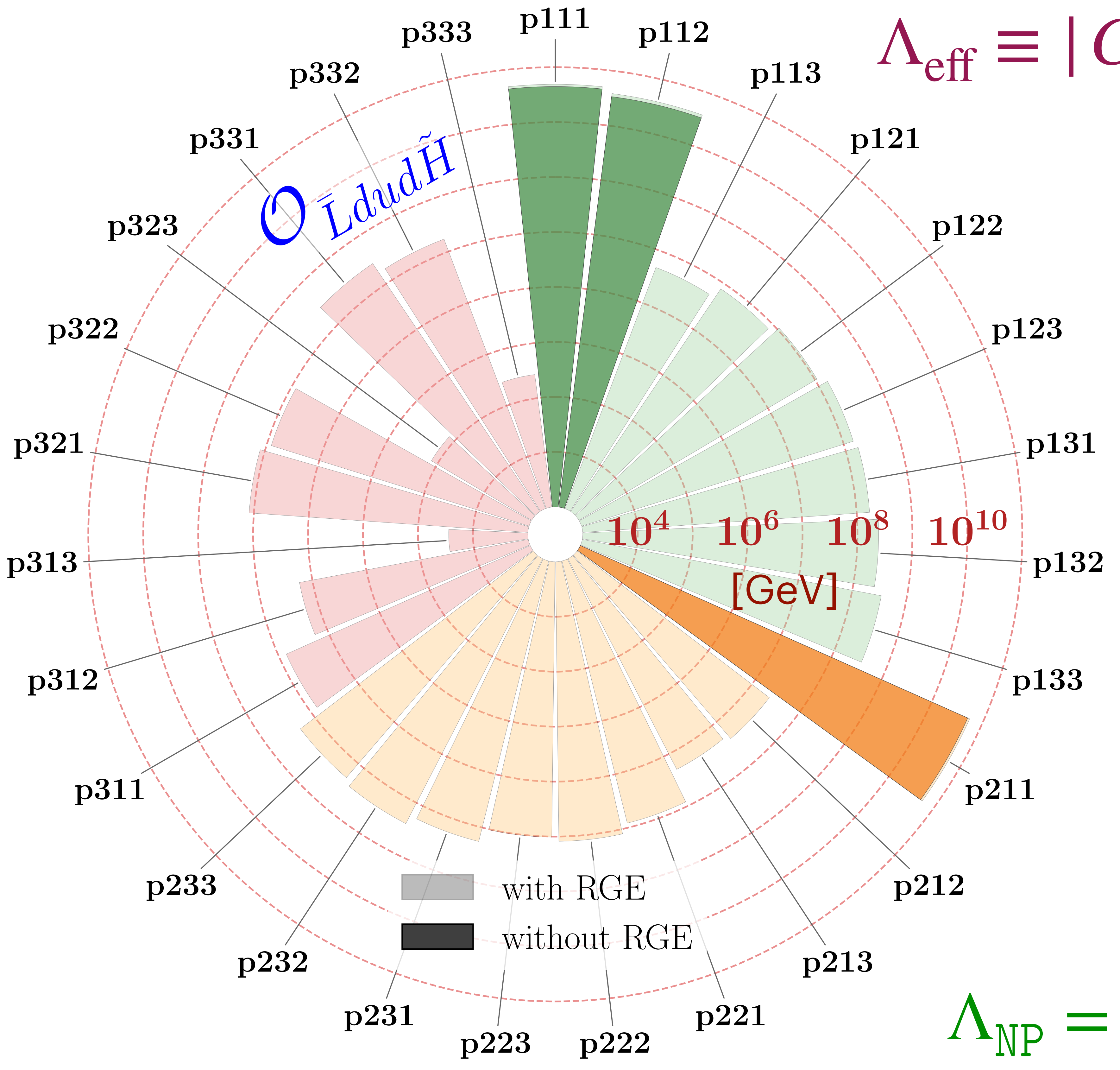
$$\mathcal{O}^{prst}_{\bar{L}dQQ\tilde{H}} = \epsilon_{ij}\epsilon_{\alpha\beta\gamma}(\overline{L_p} d_r^{\alpha})(\overline{Q_s^{\beta\mathtt{C}}} Q_t^{i\gamma})\tilde{H}^j,$$

$$\mathcal{O}^{prst}_{\bar{L}QdDd} = \epsilon_{\alpha\beta\gamma}(\overline{L_p}\gamma_{\mu} Q_r^{\alpha})(\overline{d_{\{s}^{\beta\mathtt{C}}} iD^{\mu} d_{t\}}^{\gamma}),$$

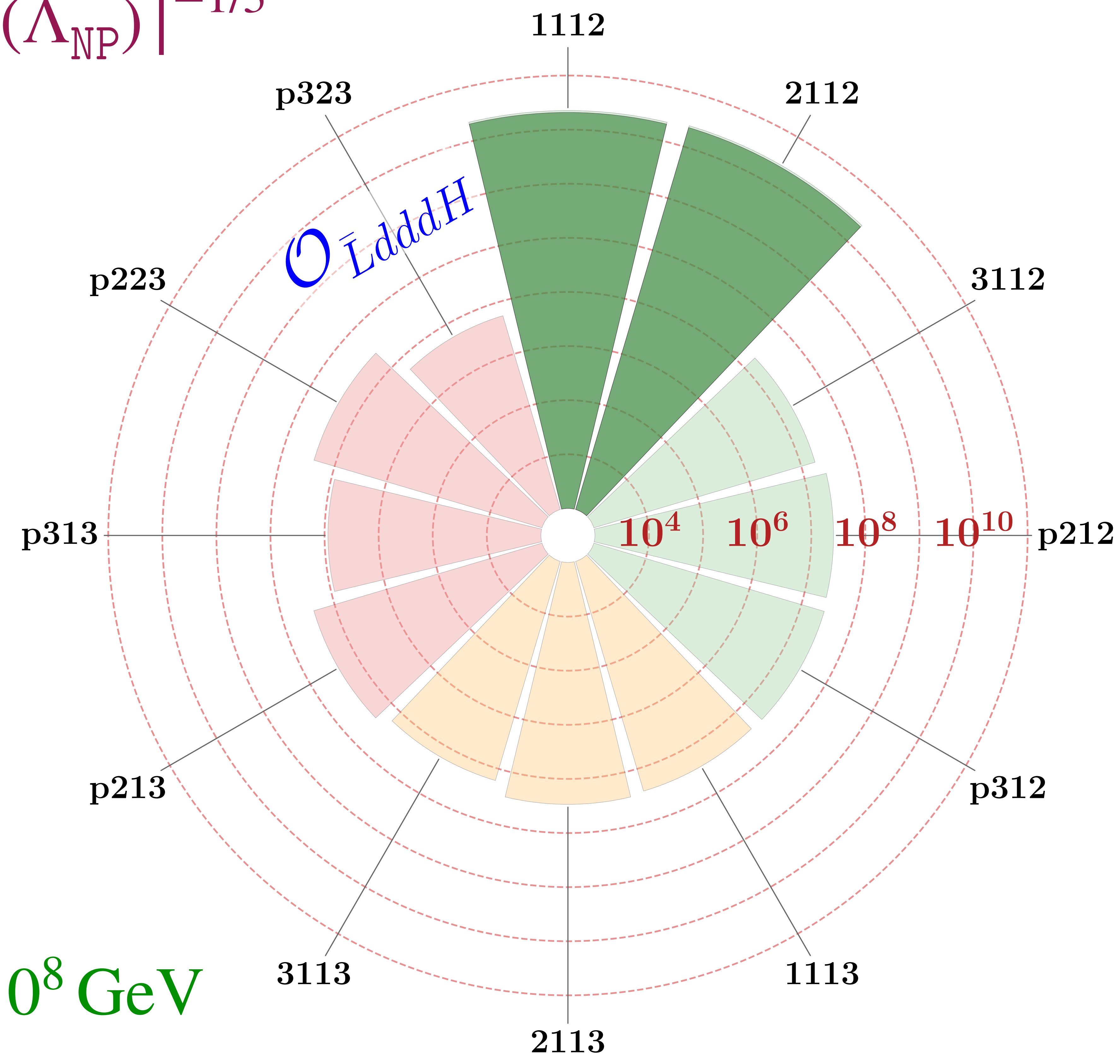
$$\mathcal{O}^{prst}_{\bar{e}ddDd} = \epsilon_{\alpha\beta\gamma}(\overline{e_p}\gamma_{\mu} d_{\{r}^{\alpha})(\overline{d_s^{\beta\mathtt{C}}} iD^{\mu} d_{t\}}^{\gamma}),$$

Lepton generation

$p = 1,\ 2,\ 3$



$\Lambda_{\rm eff} \equiv |\,C_7^i(\Lambda_{\rm NP})\,|^{-1/3}$



$\Lambda_{\rm NP} = 10^8\,{\rm GeV}$

Rotations from flavor (SMEFT) to mass (nucleon decay) eigenstates + Yukawa mixing

Constraints on 297 operators with RGE vs tens of few from a tree-level analysis

Summary

- General nucleon decay triple-quark interactions without a ∂ are identified: $\bar{\mathbf{3}}_{\mathrm{L(R)}} \otimes \mathbf{3}_{\mathrm{R(L)}}$, $\mathbf{8}_{\mathrm{L(R)}} \otimes \mathbf{1}_{\mathrm{R(L)}}$, $\mathbf{6}_{\mathrm{L(R)}} \otimes \mathbf{3}_{\mathrm{R(L)}}$ and $\mathbf{10}_{\mathrm{L(R)}} \otimes \mathbf{1}_{\mathrm{R(L)}}$ (new);
- Their LO chiral matching are realized, and new LECs are estimated by the NDA;
- A consistent chiral framework is established for nucleon decays involving vector mesons;
- Within the LEFT+ChPT, the most important 2- and 3-body nucleon decay modes are formulated;
- The theoretical framework can facilitate both theoretical and experimental studies for various nucleon decays.

Thank you for your time!