



Baryon-number-violating nucleon decays into dark particles

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W.-Q. Fan, Y. Liao, XDM, H.-L. Wang, 2507.11844, CPC, editor sugg.

XDM, M. A. Schmidt, W.-H. Zhang, 2511.02169, JHEP

J.-H. Liang, Y. Liao, XDM, X. Zhao, 2607.22452, JHEP (accepted)

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

- Baryogenesis

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

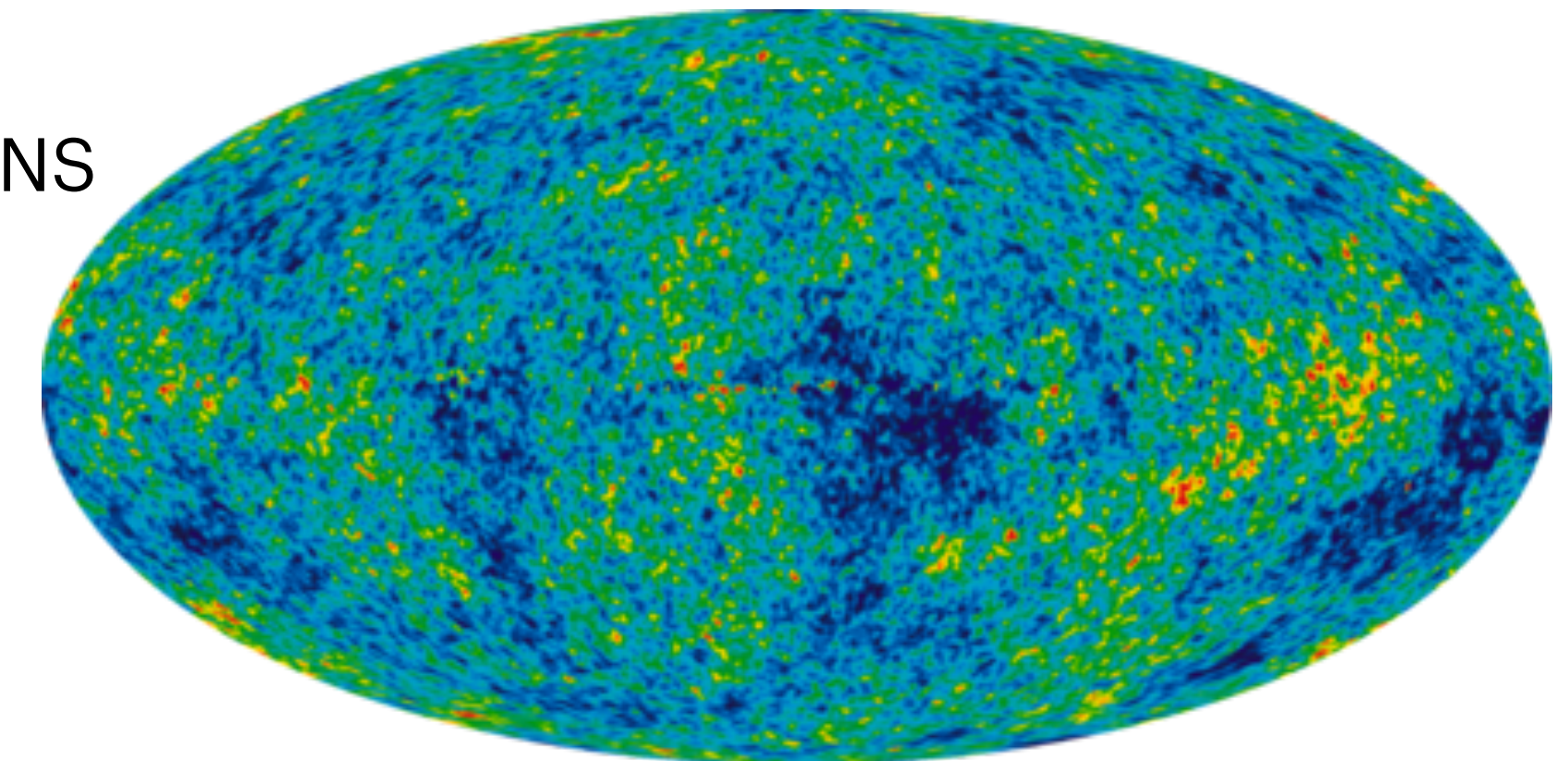
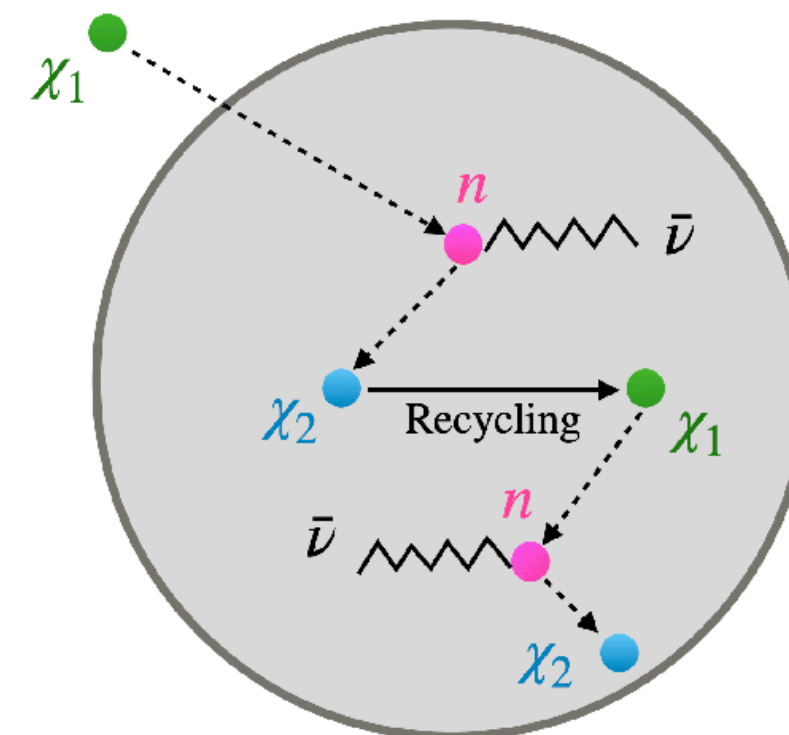
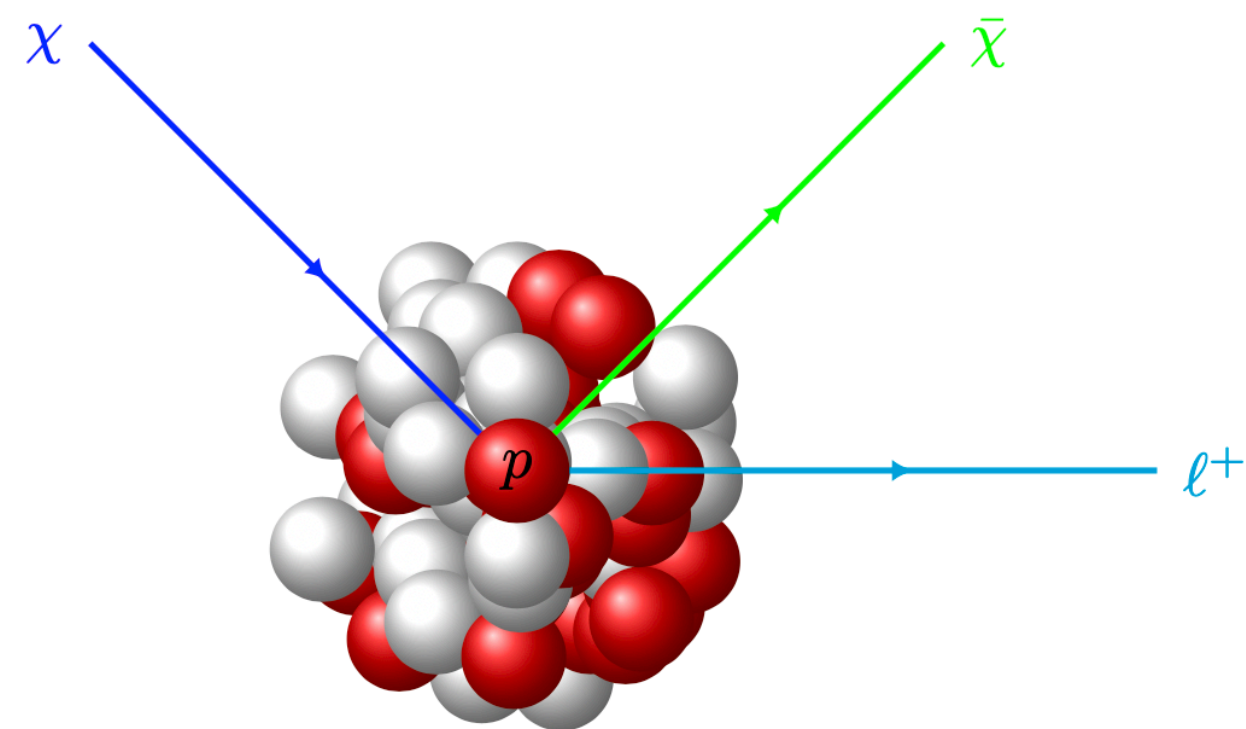
$$\eta = \frac{n_B - n_{\bar{B}}}{n_\gamma} \sim 6 \times 10^{-10}$$

Sakharov, 1967

- Dark matter

Nucleon consumption induced by DM

DM-catalyzed baryon destruction inside a NS



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

Shao-Feng Ge, XDM, 2406.00445, PRD

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

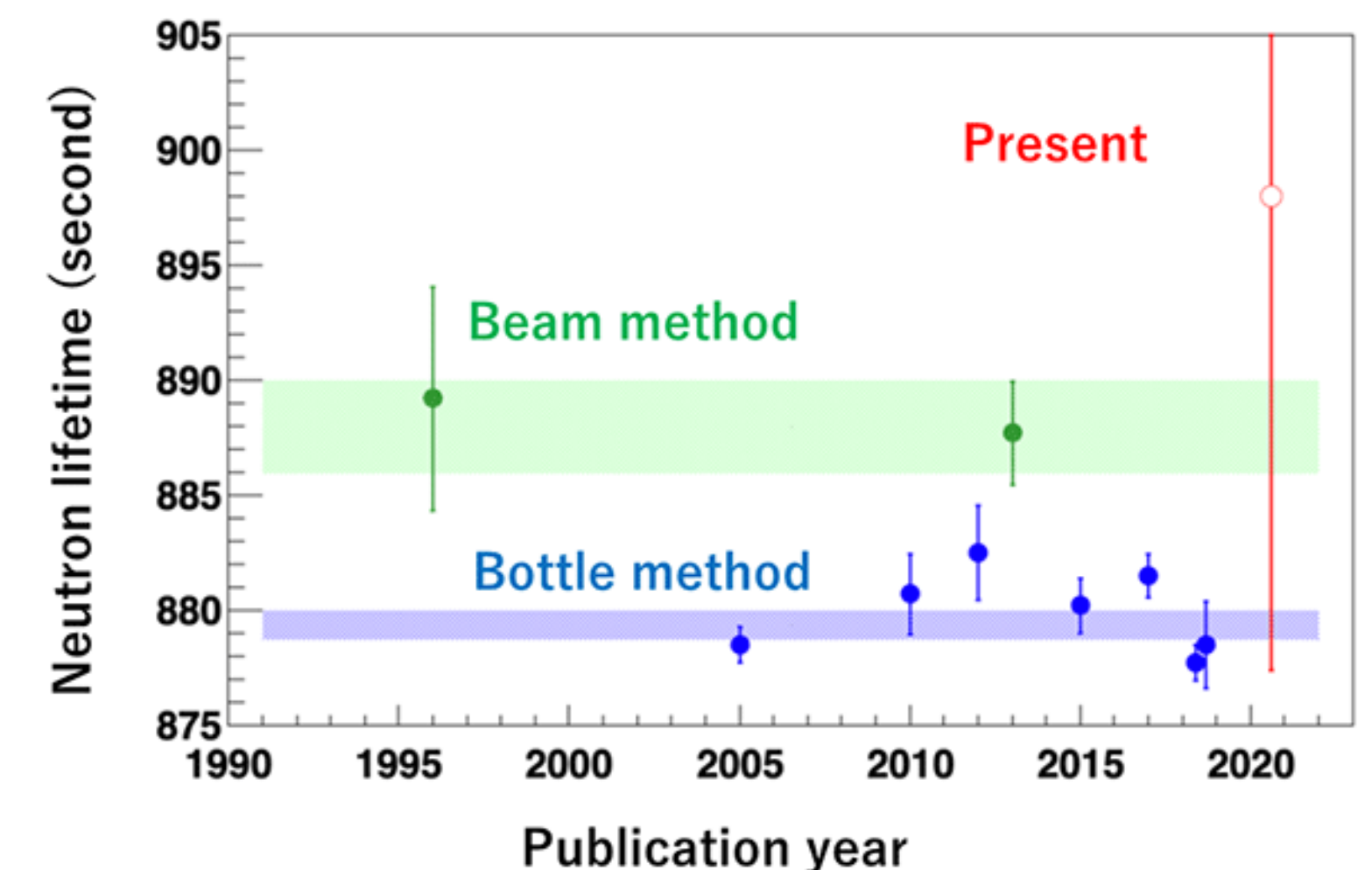
+ many works along this direction

- 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



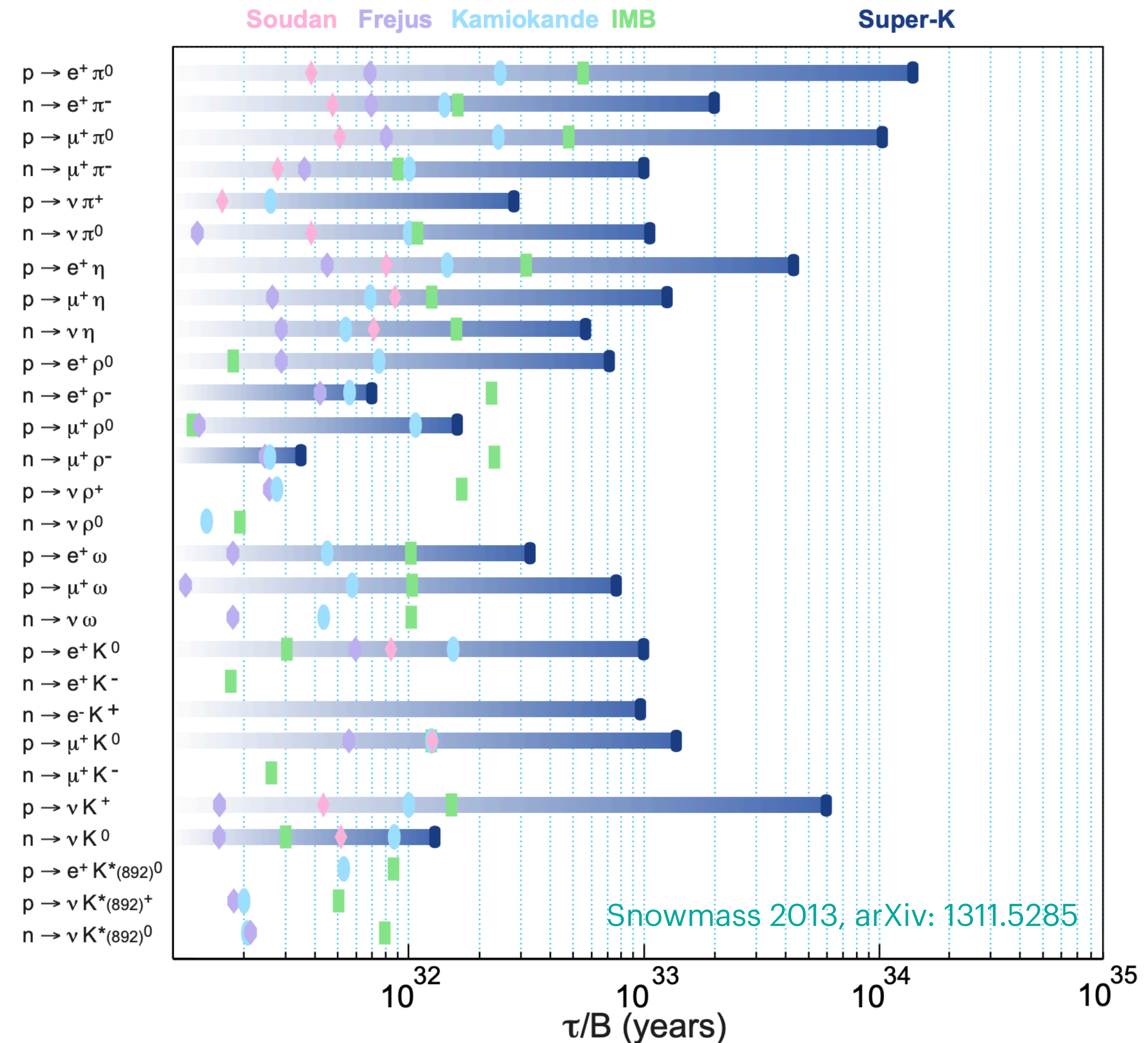
Low energy probes of BNV signals

$$\Delta B = 1 \quad \checkmark$$

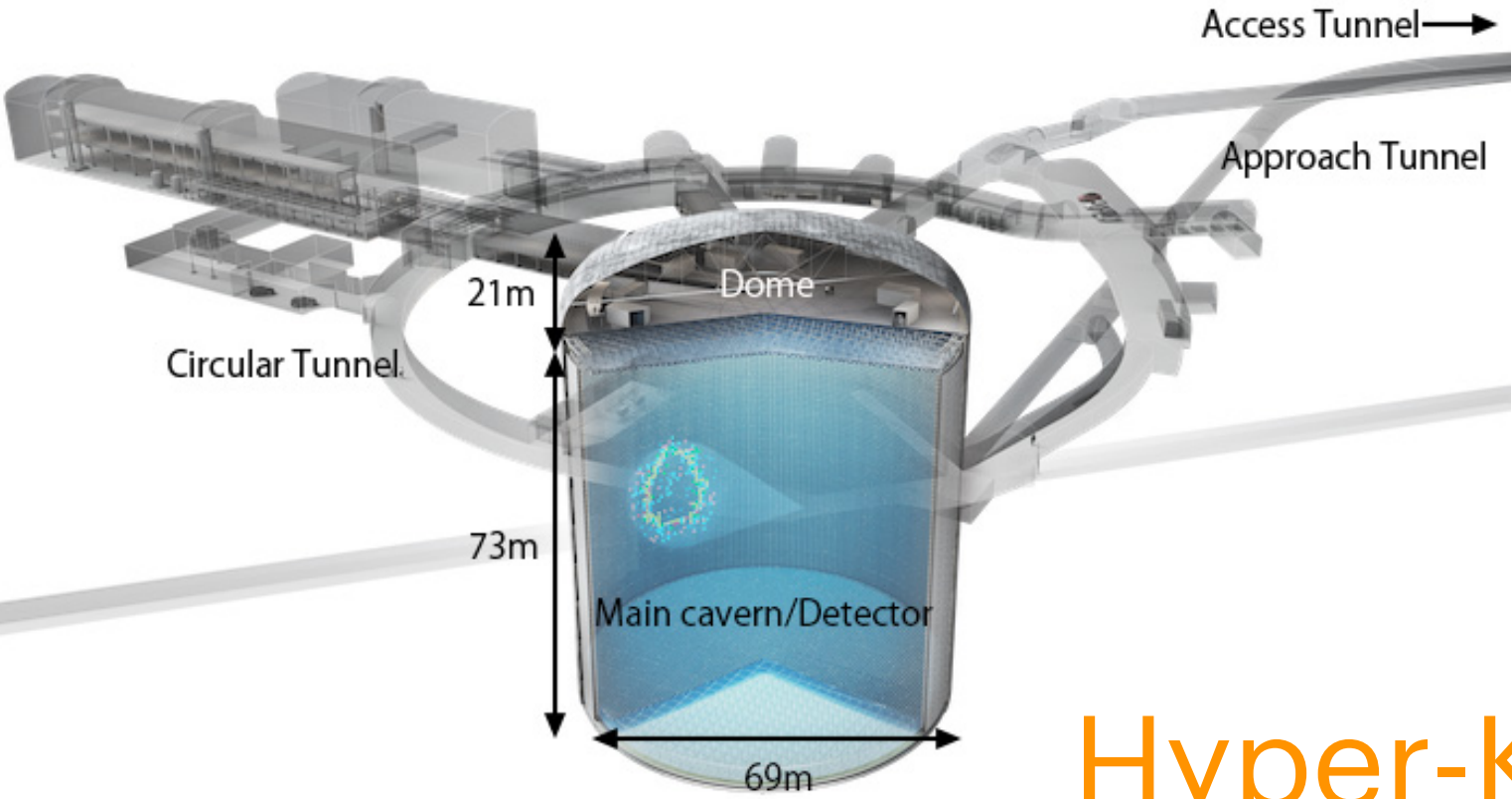
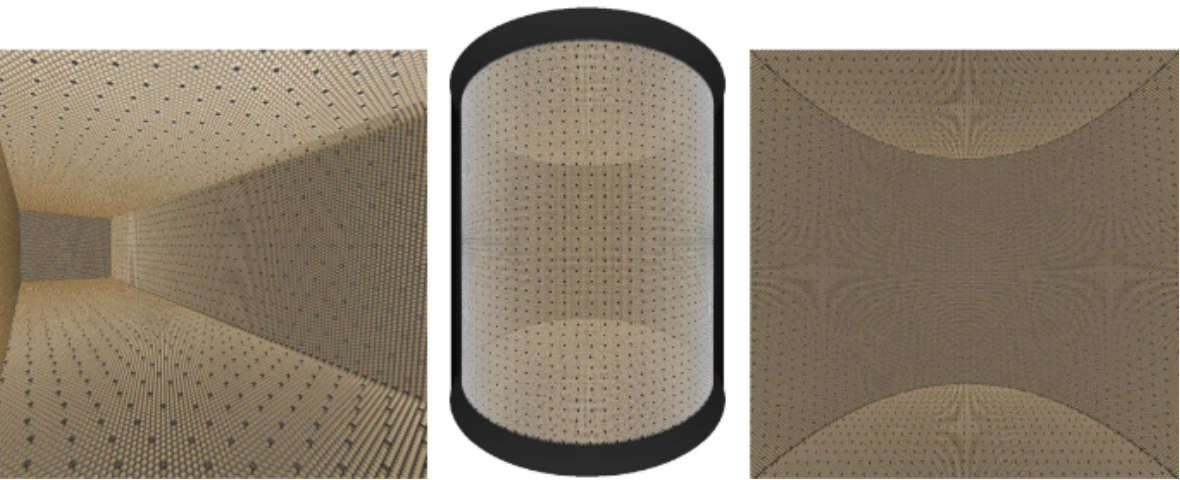
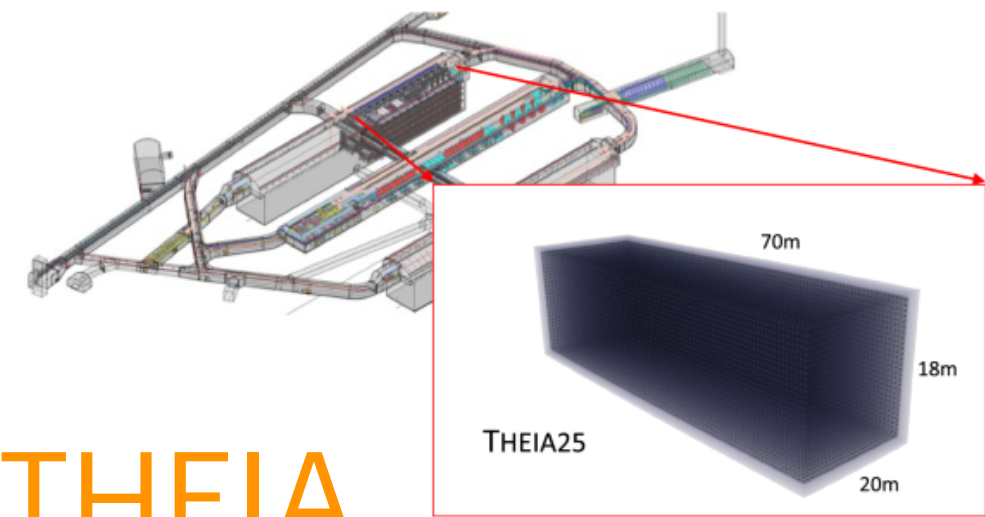
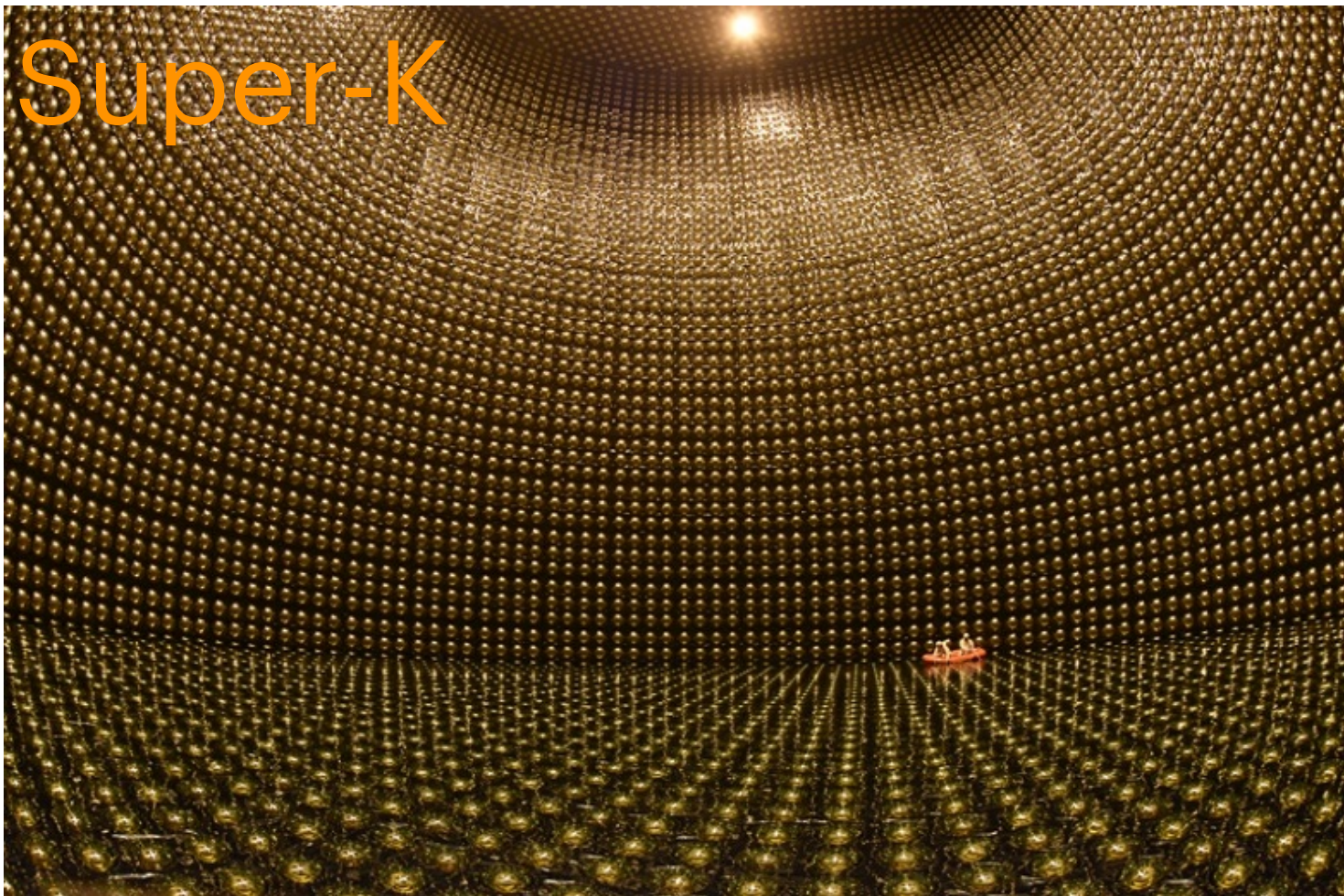
- The most sensitive probe of BNV is through **nucleon decay**
- Experimental efforts in the past: **IMB**, **SNO+**, **KamLAND**, **Super-Kamiokande**, ...
- Null result but stringent bound

$$\Delta B = 2$$

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

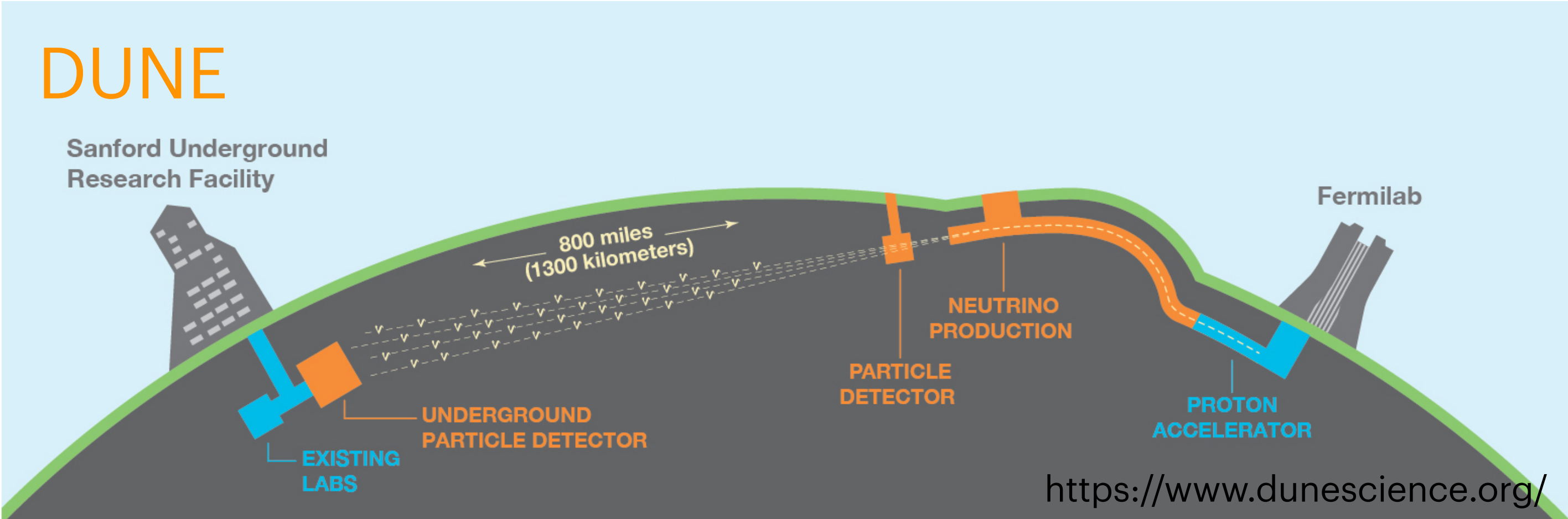


Nucleon decay searches as experimental frontiers



Hyper-K

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



<https://www.dunescience.org/>

Expanding the scope of experimental searches

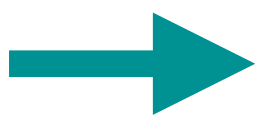
	SM particles	SM+ a new particle
2-body	$N \rightarrow M + l$ Widely studied	$N \rightarrow l + a/\varphi/X$
	$N \rightarrow V + l$	$N \rightarrow M + N$
3-body	$N \rightarrow l_1 + l_2 + l_3$	$N \rightarrow l + M + a/\varphi/X$
	$N \rightarrow l + M_1 + M_2$	
• N — nucleon (p, n) • M — octet pseudoscalar 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

This talk

- * Nucleon decays into a light scalar
 $p \rightarrow e^+ \varphi, n \rightarrow e^+ \pi^- \varphi, \dots$
- * Nucleon decays into an ALP
 $p \rightarrow e^+ \varphi, n \rightarrow e^+ \pi^- \varphi, \dots$
- * Nucleon decays into a dark photon
 $p \rightarrow e^+ \varphi, n \rightarrow e^+ \pi^- \varphi, \dots$



- Light new particles are motivated by DM, neutrino mass, etc
- Nucleon decays with invisible particles provide a unique opportunity to explore BNV and light new physics.



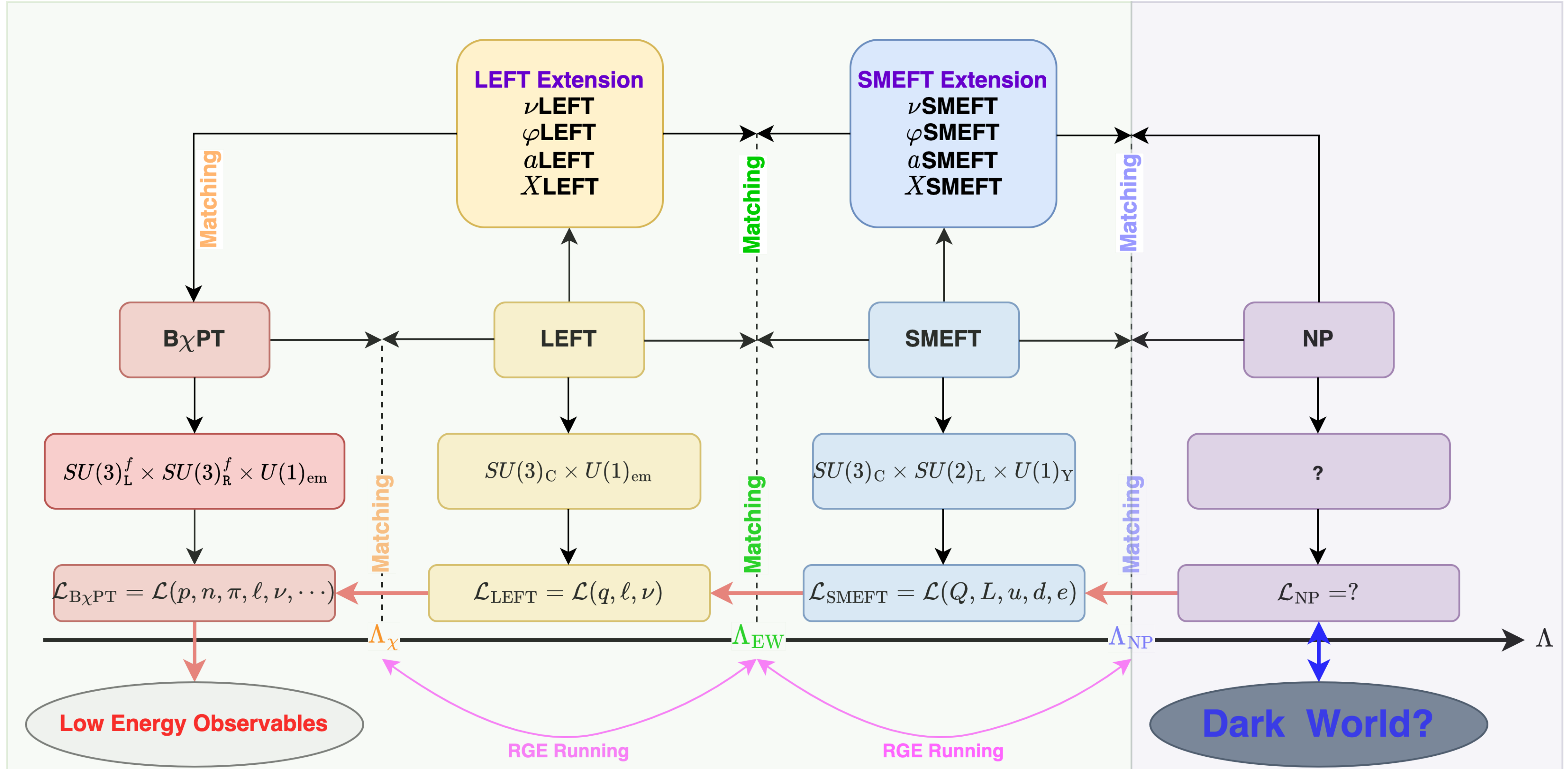
Construct a complete theoretical description for these decays

Effective field theory approach

- BNV interactions mediated by heavy new particles with $M \gg \Lambda_{EW}$
- Energy scale for nucleon decays is below GeV
- Focus on only the relevant degrees of freedom at low energy $\Rightarrow$ EFT

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

Nucleon decays in the effective field theory (EFT) landscape



Working framework: low energy effective field theory (LEFT)

- Fields: $u, d, s, \cancel{c, b}; e, \mu, \tau; \nu_e, \nu_\mu, \nu_\tau$
- Symmetry: $SU(3)_c \times U(1)_{em}$
- Power counting: canonical dimension d
- Range: $\ll \Lambda_{EW}$

$\Delta(B - L) = 0$		$\Delta(B + L) = 0$	
$\mathcal{O}_{\nu dud}^{LL}$	$(\bar{\nu}_L^c d_L^\alpha)(\bar{u}_L^{\beta c} d_L^\gamma) \epsilon_{\alpha\beta\gamma}$	$\mathcal{O}_{\bar{\ell} ddd}^{LL}$	$(\bar{\ell}_R d_L^\alpha)(\bar{d}_L^{\beta c} d_L^\gamma) \epsilon_{\alpha\beta\gamma}$
$\mathcal{O}_{\ell udu}^{LL}$	$(\bar{\ell}_L^c u_L^\alpha)(\bar{d}_L^{\beta c} u_L^\gamma) \epsilon_{\alpha\beta\gamma}$	$\mathcal{O}_{\bar{\nu} dud}^{RL}$	$(\bar{\nu}_L d_R^\alpha)(\bar{u}_L^{\beta c} d_L^\gamma) \epsilon_{\alpha\beta\gamma}$
$\mathcal{O}_{\ell duu}^{RL}$	$(\bar{\ell}_R^c d_R^\alpha)(\bar{u}_L^{\beta c} u_L^\gamma) \epsilon_{\alpha\beta\gamma}$	$\mathcal{O}_{\bar{\nu} udd}^{RL}$	$(\bar{\nu}_L u_R^\alpha)(\bar{d}_L^{\beta c} d_L^\gamma) \epsilon_{\alpha\beta\gamma}$
$\mathcal{O}_{\ell udu}^{RL}$	$(\bar{\ell}_R^c u_R^\alpha)(\bar{d}_L^{\beta c} u_L^\gamma) \epsilon_{\alpha\beta\gamma}$	$\mathcal{O}_{\bar{\ell} ddd}^{RL}$	$(\bar{\ell}_L d_R^\alpha)(\bar{d}_L^{\beta c} d_L^\gamma) \epsilon_{\alpha\beta\gamma}$
$\mathcal{O}_{\ell duu}^{LR}$	$(\bar{\ell}_L^c d_L^\alpha)(\bar{u}_R^{\beta c} u_R^\gamma) \epsilon_{\alpha\beta\gamma}$	$\mathcal{O}_{\bar{\ell} ddd}^{LR}$	$(\bar{\ell}_R d_L^\alpha)(\bar{d}_R^{\beta c} d_R^\gamma) \epsilon_{\alpha\beta\gamma}$
$\mathcal{O}_{\ell udu}^{LR}$	$(\bar{\ell}_L^c u_L^\alpha)(\bar{d}_R^{\beta c} u_R^\gamma) \epsilon_{\alpha\beta\gamma}$	$\mathcal{O}_{\bar{\nu} dud}^{RR}$	$(\bar{\nu}_L d_R^\alpha)(\bar{u}_R^{\beta c} d_R^\gamma) \epsilon_{\alpha\beta\gamma}$
$\mathcal{O}_{\nu ddu}^{LR}$	$(\bar{\nu}_L^c d_L^\alpha)(\bar{d}_R^{\beta c} u_R^\gamma) \epsilon_{\alpha\beta\gamma}$	$\mathcal{O}_{\bar{\ell} ddd}^{RR}$	$(\bar{\ell}_L d_R^\alpha)(\bar{d}_R^{\beta c} d_R^\gamma) \epsilon_{\alpha\beta\gamma}$
$\mathcal{O}_{\nu udd}^{LR}$	$(\bar{\nu}_L^c u_L^\alpha)(\bar{d}_R^{\beta c} d_R^\gamma) \epsilon_{\alpha\beta\gamma}$	Jenkins, Manohar, Stoffer, 2018	
$\mathcal{O}_{\ell udu}^{RR}$	$(\bar{\ell}_R^c u_R^\alpha)(\bar{d}_R^{\beta c} u_R^\gamma) \epsilon_{\alpha\beta\gamma}$		

Jenkins, Manohar, Stoffer, 2018

Li, Ren, Xiao, Yu, Zheng, 2020

$$\mathcal{L}_{LEFT} = \mathcal{L}_{\dim \leq 4} + \sum_{\dim 5, i} \frac{\hat{C}_{5,i}}{\Lambda} Q_{\dim-5}^i + \sum_{\dim 6, i} \frac{\hat{C}_{6,i}}{\Lambda^2} Q_{\dim-6}^i + \sum_{\dim 7, i} \frac{\hat{C}_{7,i}}{\Lambda^3} Q_{\dim-7}^i + \sum_{\dim 8, i} \frac{\hat{C}_{8,i}}{\Lambda^4} Q_{\dim-8}^i + \sum_{\dim 9, i} \frac{C_{9,i}}{\Lambda^5} Q_{\dim-9}^i + \dots$$

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(-like) framework

Exotic nucleon decays involving new light particles

LEFT + new light particles $\Rightarrow$ LEFT-like framework $\Rightarrow$ SMEFT-like framework

- ν LEFT = LEFT + sterile neutrino (N): $p \rightarrow N\pi^+$, $n \rightarrow N\pi^0$, $\dots$

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

T. Li, M. A. Schmidt and C.-Y. Yao, 2502.14303, JHEP

- a LEFT = LEFT + ALP (a): $p \rightarrow e^+ a$, $n \rightarrow e^+ \pi^- a$, $\dots$

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

T. Li, M. A. Schmidt and C.-Y. Yao, 2406.11382, JHEP

W.-Q. Fan, Y. Liao, XDM, H.-L. Wang, 2507.11844, CPC, editor sugg.

- φ LEFT = LEFT + scalar (φ): $p \rightarrow e^+ \varphi$, $n \rightarrow e^+ \pi^- \varphi$, $\dots$

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

XDM, M. A. Schmidt, W.-H. Zhang, 2511.02169, JHEP

- X LEFT = LEFT + dark photon (X): $p \rightarrow e^+ X$, $n \rightarrow e^+ \pi^- X$, $\dots$

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

J.-H. Liang, Y. Liao, XDM, X. Zhao, 2607.22452, JHEP (accepted)



BNV φ LEFT basis—nucleon decay into a light scalar

$\Delta(B - L) = 0$			$\Delta(B + L) = 0$		
Operators		Matching (up vs down basis)	Operators		Matching (up vs down basis)
$\mathcal{O}_{\varphi\nu\text{dud}}^{\text{LL}}$	$\varphi(\bar{\nu}_L^c d_L^\alpha)(\bar{u}_L^{\beta\text{c}} d_L^\gamma)\epsilon_{\alpha\beta\gamma}$	$C_{\varphi\nu\text{dud}}^{\text{LL},xyzw} = V_{ay}V_{bw}(C_{LQQQ\varphi}^{xabz} + C_{LQQQ\varphi}^{xzab} - C_{LQQQ\varphi}^{xzba})$ $C_{\varphi\nu\text{dud}}^{\text{LL},xyzw} = V_{za}^*(C_{LQQQ\varphi}^{xywa} + C_{LQQQ\varphi}^{xayw} - C_{LQQQ\varphi}^{xawy})$	$\mathcal{O}_{\varphi\bar{\ell}\text{ddd}}^{\text{RL}}$	$\varphi(\bar{\ell}_L d_R^\alpha)(\bar{d}_L^{\beta\text{c}} d_L^\gamma)\epsilon_{\alpha\beta\gamma}$	$C_{\varphi\bar{\ell}\text{ddd}}^{\text{RL},xyzw} = \frac{v}{2\sqrt{2}}(V_{az}V_{bw} - V_{aw}V_{bz})C_{LdQQH\varphi}^{xyab}$ $C_{\varphi\bar{\ell}\text{ddd}}^{\text{RL},xyzw} = \frac{v}{2\sqrt{2}}(C_{LdQQH\varphi}^{xyzw} - C_{LdQQH\varphi}^{xywz})$
$\mathcal{O}_{\varphi\ell\text{udu}}^{\text{LL}}$	$\varphi(\bar{\ell}_L^c u_L^\alpha)(\bar{d}_L^{\beta\text{c}} u_L^\gamma)\epsilon_{\alpha\beta\gamma}$	$C_{\varphi\ell\text{udu}}^{\text{LL},xyzw} = V_{az}(C_{LQQQ\varphi}^{xywa} + C_{LQQQ\varphi}^{xayw} - C_{LQQQ\varphi}^{xawy})$ $C_{\varphi\ell\text{udu}}^{\text{LL},xyzw} = V_{ya}^*V_{wb}^*(C_{LQQQ\varphi}^{xabz} + C_{LQQQ\varphi}^{xzab} - C_{LQQQ\varphi}^{xzba})$	$\mathcal{O}_{\varphi\bar{\nu}\text{dud}}^{\text{RL}}$	$\varphi(\bar{\nu}_L d_R^\alpha)(\bar{u}_L^{\beta\text{c}} d_L^\gamma)\epsilon_{\alpha\beta\gamma}$	$C_{\varphi\bar{\nu}\text{dud}}^{\text{RL},xyzw} = \frac{v}{\sqrt{2}}V_{aw}C_{LdQQH\varphi}^{xyza}$ $C_{\varphi\bar{\nu}\text{dud}}^{\text{RL},xyzw} = \frac{v}{\sqrt{2}}V_{za}^*C_{LdQQH\varphi}^{xyaw}$
$\mathcal{O}_{\varphi\ell\text{duu}}^{\text{RL}}$	$\varphi(\bar{\ell}_R^c d_R^\alpha)(\bar{u}_L^{\beta\text{c}} u_L^\gamma)\epsilon_{\alpha\beta\gamma}$	—	$\mathcal{O}_{\varphi\bar{\nu}\text{udd}}^{\text{RL}}$	$\varphi(\bar{\nu}_L u_R^\alpha)(\bar{d}_L^{\beta\text{c}} d_L^\gamma)\epsilon_{\alpha\beta\gamma}$	—
$\mathcal{O}_{\varphi\ell\text{udu}}^{\text{RL}}$	$\varphi(\bar{\ell}_R^c u_R^\alpha)(\bar{d}_L^{\beta\text{c}} u_L^\gamma)\epsilon_{\alpha\beta\gamma}$	$C_{\varphi\ell\text{udu}}^{\text{RL},xyzw} = -2V_{az}C_{euQQ\varphi}^{xyaw}$	$\mathcal{O}_{\varphi\bar{\ell}\text{ddd}}^{\text{LR}}$	$\varphi(\bar{\ell}_R d_L^\alpha)(\bar{d}_R^{\beta\text{c}} d_R^\gamma)\epsilon_{\alpha\beta\gamma}$	$C_{\varphi\bar{\ell}\text{ddd}}^{\text{LR},xyzw} = \frac{v}{\sqrt{2}}V_{ay}C_{eQddH\varphi}^{xazw}$
		$C_{\varphi\ell\text{udu}}^{\text{RL},xyzw} = -2V_{wa}^*C_{euQQ\varphi}^{xyza}$			$C_{\varphi\bar{\ell}\text{ddd}}^{\text{LR},xyzw} = \frac{v}{\sqrt{2}}C_{eQddH\varphi}^{xyzw}$
$\mathcal{O}_{\varphi\ell\text{duu}}^{\text{LR}}$	$\varphi(\bar{\ell}_L^c d_L^\alpha)(\bar{u}_R^{\beta\text{c}} u_R^\gamma)\epsilon_{\alpha\beta\gamma}$	—	$\mathcal{O}_{\varphi\bar{\ell}\text{ddd}}^{\text{LL}}$	$\varphi(\bar{\ell}_R d_L^\alpha)(\bar{d}_L^{\beta\text{c}} d_L^\gamma)\epsilon_{\alpha\beta\gamma}$	—
$\mathcal{O}_{\varphi\ell\text{udu}}^{\text{LR}}$	$\varphi(\bar{\ell}_L^c u_L^\alpha)(\bar{d}_R^{\beta\text{c}} u_R^\gamma)\epsilon_{\alpha\beta\gamma}$	$C_{\varphi\ell\text{udu}}^{\text{LR},xyzw} = -C_{LQdu\varphi}^{xyzw}$	$\mathcal{O}_{\varphi\bar{\nu}\text{dud}}^{\text{RR}}$	$\varphi(\bar{\nu}_L d_R^\alpha)(\bar{u}_R^{\beta\text{c}} d_R^\gamma)\epsilon_{\alpha\beta\gamma}$	$C_{\varphi\bar{\nu}\text{dud}}^{\text{RR},xyzw} = \frac{v}{\sqrt{2}}C_{LdudH\varphi}^{xyzw}$
		$C_{\varphi\ell\text{udu}}^{\text{LR},xyzw} = -V_{ya}^*C_{LQdu\varphi}^{xazw}$	$\mathcal{O}_{\varphi\bar{\ell}\text{ddd}}^{\text{RR}}$	$\varphi(\bar{\ell}_L d_R^\alpha)(\bar{d}_R^{\beta\text{c}} d_R^\gamma)\epsilon_{\alpha\beta\gamma}$	$C_{\varphi\bar{\ell}\text{ddd}}^{\text{RR},xyzw} = \frac{v}{\sqrt{2}}C_{LdddH\varphi}^{xyzw}$
$\mathcal{O}_{\varphi\nu\text{ddu}}^{\text{LR}}$	$\varphi(\bar{\nu}_L^c d_L^\alpha)(\bar{d}_R^{\beta\text{c}} u_R^\gamma)\epsilon_{\alpha\beta\gamma}$	$C_{\varphi\nu\text{ddu}}^{\text{LR},xyzw} = V_{ay}C_{LQdu\varphi}^{xazw}$			
		$C_{\varphi\nu\text{ddu}}^{\text{LR},xyzw} = C_{LQdu\varphi}^{xyzw}$			
$\mathcal{O}_{\varphi\nu\text{udd}}^{\text{LR}}$	$\varphi(\bar{\nu}_L^c u_L^\alpha)(\bar{d}_R^{\beta\text{c}} d_R^\gamma)\epsilon_{\alpha\beta\gamma}$	—			
$\mathcal{O}_{\varphi\ell\text{udu}}^{\text{RR}}$	$\varphi(\bar{\ell}_R^c u_R^\alpha)(\bar{d}_R^{\beta\text{c}} u_R^\gamma)\epsilon_{\alpha\beta\gamma}$	$\mathcal{O}_{\varphi\ell\text{udu}}^{\text{RR},xyzw} = C_{eu\text{du}\varphi}^{xyzw}$			

Leading-order φ SMEFT operators

Dim 7: $\Delta(B - L) = 0$	
$\mathcal{O}_{LQdu\varphi}$	$\epsilon_{\alpha\beta\gamma}\epsilon_{ij}(\bar{L}^{i\text{c}}Q^{\alpha j})(\bar{d}^{\beta\text{c}}u^\gamma)\varphi$
$\mathcal{O}_{euQQ\varphi}$	$\epsilon_{\alpha\beta\gamma}\epsilon_{ij}(\bar{e}^cu^\alpha)(\bar{Q}^{\beta i\text{c}}Q^{\gamma j})\varphi$
$\mathcal{O}_{LQQQ\varphi}$	$\epsilon_{\alpha\beta\gamma}\epsilon_{ik}\epsilon_{jl}(\bar{L}^{i\text{c}}Q^{\alpha j})(\bar{Q}^{\beta k\text{c}}Q^{\gamma l})\varphi$
$\mathcal{O}_{eudu\varphi}$	$\epsilon_{\alpha\beta\gamma}(\bar{e}^cu^\alpha)(\bar{d}^{\beta\text{c}}u^\gamma)\varphi$

Dim 8: $\Delta(B + L) = 0$	
$\mathcal{O}_{LdudH\varphi}$	$\epsilon_{\alpha\beta\gamma}(\bar{L}d^\alpha\tilde{H})(\bar{u}^{\beta\text{c}}d^\gamma)\varphi$
$\mathcal{O}_{LdddH\varphi}$	$\epsilon_{\alpha\beta\gamma}(\bar{L}d^\alpha H)(\bar{d}^{\beta\text{c}}d^\gamma)\varphi$
$\mathcal{O}_{eQddH\varphi}$	$\epsilon_{\alpha\beta\gamma}(H^\dagger\bar{e}Q^\alpha)(\bar{d}^{\beta\text{c}}d^\gamma)\varphi$
$\mathcal{O}_{LdQQH\varphi}$	$\delta_{ij}\epsilon_{\alpha\beta\gamma}(\bar{L}^id^\alpha)(H^\dagger\bar{Q}^{\beta j\text{c}}Q^\gamma)\varphi$

The leading-order operators appear at dimension 7 and there exist various UV—models that generate them.

BNV a LEFT basis—nucleon decay into an ALP

	Notation	Operator	Chiral Irrep.	# of operators
$\Delta(B-L)=0$	$\mathcal{O}_{\partial a e u u d}^{\text{VL,SL}}$	$\partial_\mu a (\bar{e}_R^c \gamma^\mu u_L^\alpha) (\bar{u}_L^{\beta c} d_L^\gamma) \epsilon_{\alpha\beta\gamma}$	$\mathbf{8}_L \otimes \mathbf{1}_R$	$n_e n_u^2 n_d [2n_e]$
	$\mathcal{O}_{\partial a e u u d}^{\text{SL,VR}}$	$\partial_\mu a (\bar{e}_L^c u_L^\alpha) (\bar{u}_L^{\beta c} \gamma^\mu d_R^\gamma) \epsilon_{\alpha\beta\gamma}$	$\mathbf{6}_L \otimes \mathbf{3}_R$	$n_e n_u^2 n_d [2n_e]$
	$\mathcal{O}_{\partial a e u d u}^{\text{SL,VR}}$	$\partial_\mu a (\bar{e}_L^c u_L^\alpha) (\bar{d}_L^{\beta c} \gamma^\mu u_R^\gamma) \epsilon_{\alpha\beta\gamma}$	$\mathbf{6}_L \otimes \mathbf{3}_R \oplus \bar{\mathbf{3}}_L \otimes \mathbf{3}_R$	$n_e n_u^2 n_d [2n_e]$
	$\mathcal{O}_{\partial a e d u u}^{\text{SL,VR}}$	$\partial_\mu a (\bar{e}_L^c d_L^\alpha) (\bar{u}_L^{\beta c} \gamma^\mu u_R^\gamma) \epsilon_{\alpha\beta\gamma}$	$\mathbf{6}_L \otimes \mathbf{3}_R \oplus \bar{\mathbf{3}}_L \otimes \mathbf{3}_R$	$n_e n_u^2 n_d [2n_e]$
	$\mathcal{O}_{\partial a e u u d}^{\text{VR,SR}}$	$\partial_\mu a (\bar{e}_L^c \gamma^\mu u_R^\alpha) (\bar{u}_R^{\beta c} d_R^\gamma) \epsilon_{\alpha\beta\gamma}$	$\mathbf{1}_L \otimes \mathbf{8}_R$	$n_e n_u^2 n_d [2n_e]$
	$\mathcal{O}_{\partial a e u u d}^{\text{SR,VL}}$	$\partial_\mu a (\bar{e}_R^c u_R^\alpha) (\bar{u}_R^{\beta c} \gamma^\mu d_L^\gamma) \epsilon_{\alpha\beta\gamma}$	$\mathbf{3}_L \otimes \mathbf{6}_R$	$n_e n_u^2 n_d [2n_e]$
	$\mathcal{O}_{\partial a e u d u}^{\text{SR,VL}}$	$\partial_\mu a (\bar{e}_R^c u_R^\alpha) (\bar{d}_R^{\beta c} \gamma^\mu u_L^\gamma) \epsilon_{\alpha\beta\gamma}$	$\mathbf{3}_L \otimes \mathbf{6}_R \oplus \mathbf{3}_L \otimes \bar{\mathbf{3}}_R$	$n_e n_u^2 n_d [2n_e]$
	$\mathcal{O}_{\partial a e d u u}^{\text{SR,VL}}$	$\partial_\mu a (\bar{e}_R^c d_R^\alpha) (\bar{u}_R^{\beta c} \gamma^\mu u_L^\gamma) \epsilon_{\alpha\beta\gamma}$	$\mathbf{3}_L \otimes \mathbf{6}_R \oplus \mathbf{3}_L \otimes \bar{\mathbf{3}}_R$	$n_e n_u^2 n_d [2n_e]$
	$\mathcal{O}_{\partial a \nu d d u}^{\text{VR,SR}}$	$\partial_\mu a (\bar{\nu}_L^c \gamma^\mu d_R^\alpha) (\bar{d}_R^{\beta c} u_R^\gamma) \epsilon_{\alpha\beta\gamma}$	$\mathbf{1}_L \otimes \mathbf{8}_R$	$n_\nu n_u n_d^2 [4n_\nu]$
	$\mathcal{O}_{\partial a \nu d d u}^{\text{SL,VR}}$	$\partial_\mu a (\bar{\nu}_L^c d_L^\alpha) (\bar{d}_L^{\beta c} \gamma^\mu u_R^\gamma) \epsilon_{\alpha\beta\gamma}$	$\mathbf{6}_L \otimes \mathbf{3}_R \oplus \bar{\mathbf{3}}_L \otimes \mathbf{3}_R$	$n_\nu n_u n_d^2 [4n_\nu]$
	$\mathcal{O}_{\partial a \nu d u d}^{\text{SL,VR}}$	$\partial_\mu a (\bar{\nu}_L^c d_L^\alpha) (\bar{u}_L^{\beta c} \gamma^\mu d_R^\gamma) \epsilon_{\alpha\beta\gamma}$	$\mathbf{6}_L \otimes \mathbf{3}_R \oplus \bar{\mathbf{3}}_L \otimes \mathbf{3}_R$	$n_\nu n_u n_d^2 [4n_\nu]$
	$\mathcal{O}_{\partial a \nu u d d}^{\text{SL,VR}}$	$\partial_\mu a (\bar{\nu}_L^c u_L^\alpha) (\bar{d}_L^{\beta c} \gamma^\mu d_R^\gamma) \epsilon_{\alpha\beta\gamma}$	$\mathbf{6}_L \otimes \mathbf{3}_R \oplus \bar{\mathbf{3}}_L \otimes \mathbf{3}_R$	$n_\nu n_u n_d^2 [4n_\nu]$

$\Delta(B+L)=0$	$\mathcal{O}_{\partial a \nu d d u}^{\text{VL,SL}}$	$\partial_\mu a (\bar{\nu}_L \gamma^\mu d_L^\alpha) (\bar{d}_L^{\beta c} u_L^\gamma) \epsilon_{\alpha\beta\gamma}$	$\mathbf{8}_L \otimes \mathbf{1}_R$	$n_\nu n_u n_d^2 [4n_\nu]$
	$\mathcal{O}_{\partial a \nu d d u}^{\text{SR,VL}}$	$\partial_\mu a (\bar{\nu}_L d_R^\alpha) (\bar{d}_R^{\beta c} \gamma^\mu u_L^\gamma) \epsilon_{\alpha\beta\gamma}$	$\mathbf{3}_L \otimes \mathbf{6}_R \oplus \mathbf{3}_L \otimes \bar{\mathbf{3}}_R$	$n_\nu n_u n_d^2 [4n_\nu]$
	$\mathcal{O}_{\partial a \nu d u d}^{\text{SR,VL}}$	$\partial_\mu a (\bar{\nu}_L d_R^\alpha) (\bar{u}_R^{\beta c} \gamma^\mu d_L^\gamma) \epsilon_{\alpha\beta\gamma}$	$\mathbf{3}_L \otimes \mathbf{6}_R \oplus \mathbf{3}_L \otimes \bar{\mathbf{3}}_R$	$n_\nu n_u n_d^2 [4n_\nu]$
	$\mathcal{O}_{\partial a \nu u d d}^{\text{SR,VL}}$	$\partial_\mu a (\bar{\nu}_L u_R^\alpha) (\bar{d}_R^{\beta c} \gamma^\mu d_L^\gamma) \epsilon_{\alpha\beta\gamma}$	$\mathbf{3}_L \otimes \mathbf{6}_R \oplus \mathbf{3}_L \otimes \bar{\mathbf{3}}_R$	$n_\nu n_u n_d^2 [4n_\nu]$
	$\mathcal{O}_{\partial a e d d d}^{\text{VR,SR}}$	$\partial_\mu a (\bar{e}_R \gamma^\mu d_R^\alpha) (\bar{d}_R^{\beta c} d_R^\gamma) \epsilon_{\alpha\beta\gamma}$	$\mathbf{1}_L \otimes \mathbf{8}_R$	$\frac{1}{3} n_e n_d (n_d^2 - 1) [2n_e]$
	$\mathcal{O}_{\partial a e d d d}^{\text{SR,VL}}$	$\partial_\mu a (\bar{e}_L d_R^\alpha) (\bar{d}_R^{\beta c} \gamma^\mu d_L^\gamma) \epsilon_{\alpha\beta\gamma}$	$\mathbf{3}_L \otimes \mathbf{6}_R \oplus \mathbf{3}_L \otimes \bar{\mathbf{3}}_R$	$n_e n_d^3 [8n_e]$
	$\mathcal{O}_{\partial a e d d d}^{\text{VL,SL}}$	$\partial_\mu a (\bar{e}_L \gamma^\mu d_L^\alpha) (\bar{d}_L^{\beta c} d_L^\gamma) \epsilon_{\alpha\beta\gamma}$	$\mathbf{8}_L \otimes \mathbf{1}_R$	$\frac{1}{3} n_e n_d (n_d^2 - 1) [2n_e]$
	$\mathcal{O}_{\partial a e d d d}^{\text{SL,VR}}$	$\partial_\mu a (\bar{e}_R d_L^\alpha) (\bar{d}_L^{\beta c} \gamma^\mu d_R^\gamma) \epsilon_{\alpha\beta\gamma}$	$\mathbf{6}_L \otimes \mathbf{3}_R \oplus \bar{\mathbf{3}}_L \otimes \mathbf{3}_R$	$n_e n_d^3 [8n_e]$

Assuming that the interactions preserve the shift symmetry in the axion field: ∂a

The SMEFT extension: C. Grojean, J. Kley and C.-Y. Yao, 2307.08563, JHEP

BNV X_{LEFT} basis—nucleon decay into a dark photon

Parametrized by a four-potential X_μ

Parametrized by a field strength $X_{\mu\nu}$

Case A				
	Notation	Operator	Chiral Irrep.	# of operators
$\Delta(B-L)=0$	$\mathcal{O}_{X\ell u u d}^{\text{VL,SL}}$	$X_\mu(\bar{\ell}_R^C \gamma^\mu u_L^\alpha)(\bar{u}_L^{\beta C} d_L^\gamma) \epsilon_{\alpha\beta\gamma}$	$\mathbf{8}_L \otimes \mathbf{1}_R$	$n_\ell n_u^2 n_d [2n_\ell]$
	$\mathcal{O}_{X\ell u u d}^{\text{SL,VR}}$	$X_\mu(\bar{\ell}_L^C u_L^\alpha)(\bar{u}_L^{\beta C} \gamma^\mu d_R^\gamma) \epsilon_{\alpha\beta\gamma}$	$\mathbf{6}_L \otimes \mathbf{3}_R$	$n_\ell n_u^2 n_d [2n_\ell]$
	$\mathcal{O}_{X\ell u d u}^{\text{SL,VR}}$	$X_\mu(\bar{\ell}_L^C u_L^\alpha)(\bar{d}_L^{\beta C} \gamma^\mu u_R^\gamma) \epsilon_{\alpha\beta\gamma}$	$\mathbf{6}_L \otimes \mathbf{3}_R \oplus \bar{\mathbf{3}}_L \otimes \mathbf{3}_R$	$n_\ell n_u^2 n_d [2n_\ell]$
	$\mathcal{O}_{X\ell d u u}^{\text{SL,VR}}$	$X_\mu(\bar{\ell}_L^C d_L^\alpha)(\bar{u}_L^{\beta C} \gamma^\mu u_R^\gamma) \epsilon_{\alpha\beta\gamma}$	$\mathbf{6}_L \otimes \mathbf{3}_R \oplus \bar{\mathbf{3}}_L \otimes \mathbf{3}_R$	$n_\ell n_u^2 n_d [2n_\ell]$
	$\mathcal{O}_{X\ell u u d}^{\text{VR,SR}}$	$X_\mu(\bar{\ell}_L^C \gamma^\mu u_R^\alpha)(\bar{u}_R^{\beta C} d_R^\gamma) \epsilon_{\alpha\beta\gamma}$	$\mathbf{1}_L \otimes \mathbf{8}_R$	$n_\ell n_u^2 n_d [2n_\ell]$
	$\mathcal{O}_{X\ell u u d}^{\text{SR,VL}}$	$X_\mu(\bar{\ell}_R^C u_R^\alpha)(\bar{u}_R^{\beta C} \gamma^\mu d_L^\gamma) \epsilon_{\alpha\beta\gamma}$	$\mathbf{3}_L \otimes \mathbf{6}_R$	$n_\ell n_u^2 n_d [2n_\ell]$
	$\mathcal{O}_{X\ell u d u}^{\text{SR,VL}}$	$X_\mu(\bar{\ell}_R^C u_R^\alpha)(\bar{d}_R^{\beta C} \gamma^\mu u_L^\gamma) \epsilon_{\alpha\beta\gamma}$	$\mathbf{3}_L \otimes \mathbf{6}_R \oplus \mathbf{3}_L \otimes \bar{\mathbf{3}}_R$	$n_\ell n_u^2 n_d [2n_\ell]$
	$\mathcal{O}_{X\ell d u u}^{\text{SR,VL}}$	$X_\mu(\bar{\ell}_R^C d_R^\alpha)(\bar{u}_R^{\beta C} \gamma^\mu u_L^\gamma) \epsilon_{\alpha\beta\gamma}$	$\mathbf{3}_L \otimes \mathbf{6}_R \oplus \mathbf{3}_L \otimes \bar{\mathbf{3}}_R$	$n_\ell n_u^2 n_d [2n_\ell]$
$\Delta(B-L)=0$	$\mathcal{O}_{X\nu d d u}^{\text{VR,SR}}$	$X_\mu(\bar{\nu}_L^C \gamma^\mu d_R^\alpha)(\bar{d}_R^{\beta C} u_R^\gamma) \epsilon_{\alpha\beta\gamma}$	$\mathbf{1}_L \otimes \mathbf{8}_R$	$n_\nu n_u n_d^2 [4n_\nu]$
	$\mathcal{O}_{X\nu d d u}^{\text{SL,VR}}$	$X_\mu(\bar{\nu}_L^C d_L^\alpha)(\bar{d}_L^{\beta C} \gamma^\mu u_R^\gamma) \epsilon_{\alpha\beta\gamma}$	$\mathbf{6}_L \otimes \mathbf{3}_R \oplus \bar{\mathbf{3}}_L \otimes \mathbf{3}_R$	$n_\nu n_u n_d^2 [4n_\nu]$
	$\mathcal{O}_{X\nu d u d}^{\text{SL,VR}}$	$X_\mu(\bar{\nu}_L^C d_L^\alpha)(\bar{u}_L^{\beta C} \gamma^\mu d_R^\gamma) \epsilon_{\alpha\beta\gamma}$	$\mathbf{6}_L \otimes \mathbf{3}_R \oplus \bar{\mathbf{3}}_L \otimes \mathbf{3}_R$	$n_\nu n_u n_d^2 [4n_\nu]$
	$\mathcal{O}_{X\nu u d d}^{\text{SL,VR}}$	$X_\mu(\bar{\nu}_L^C u_L^\alpha)(\bar{d}_L^{\beta C} \gamma^\mu d_R^\gamma) \epsilon_{\alpha\beta\gamma}$	$\mathbf{6}_L \otimes \mathbf{3}_R \oplus \bar{\mathbf{3}}_L \otimes \mathbf{3}_R$	$n_\nu n_u n_d^2 [4n_\nu]$
$\Delta(B+L)=0$	$\mathcal{O}_{X\bar{\nu} d d u}^{\text{VL,SL}}$	$X_\mu(\bar{\nu}_L \gamma^\mu d_L^\alpha)(\bar{d}_L^{\beta C} u_L^\gamma) \epsilon_{\alpha\beta\gamma}$	$\mathbf{8}_L \otimes \mathbf{1}_R$	$n_\nu n_u n_d^2 [4n_\nu]$
	$\mathcal{O}_{X\bar{\nu} d d u}^{\text{SR,VL}}$	$X_\mu(\bar{\nu}_L d_R^\alpha)(\bar{d}_R^{\beta C} \gamma^\mu u_L^\gamma) \epsilon_{\alpha\beta\gamma}$	$\mathbf{3}_L \otimes \mathbf{6}_R \oplus \mathbf{3}_L \otimes \bar{\mathbf{3}}_R$	$n_\nu n_u n_d^2 [4n_\nu]$
	$\mathcal{O}_{X\bar{\nu} d u d}^{\text{SR,VL}}$	$X_\mu(\bar{\nu}_L d_R^\alpha)(\bar{u}_R^{\beta C} \gamma^\mu d_L^\gamma) \epsilon_{\alpha\beta\gamma}$	$\mathbf{3}_L \otimes \mathbf{6}_R \oplus \mathbf{3}_L \otimes \bar{\mathbf{3}}_R$	$n_\nu n_u n_d^2 [4n_\nu]$
	$\mathcal{O}_{X\bar{\nu} u d d}^{\text{SR,VL}}$	$X_\mu(\bar{\nu}_L u_R^\alpha)(\bar{d}_R^{\beta C} \gamma^\mu d_L^\gamma) \epsilon_{\alpha\beta\gamma}$	$\mathbf{3}_L \otimes \mathbf{6}_R \oplus \mathbf{3}_L \otimes \bar{\mathbf{3}}_R$	$n_\nu n_u n_d^2 [4n_\nu]$
	$\mathcal{O}_{X\bar{\ell} d d d}^{\text{VR,SR}}$	$X_\mu(\bar{\ell}_R \gamma^\mu d_R^\alpha)(\bar{d}_R^{\beta C} d_R^\gamma) \epsilon_{\alpha\beta\gamma}$	$\mathbf{1}_L \otimes \mathbf{8}_R$	$\frac{1}{3} n_\ell n_d (n_d^2 - 1) [2n_\ell]$
	$\mathcal{O}_{X\bar{\ell} d d d}^{\text{SR,VL}}$	$X_\mu(\bar{\ell}_L d_R^\alpha)(\bar{d}_R^{\beta C} \gamma^\mu d_L^\gamma) \epsilon_{\alpha\beta\gamma}$	$\mathbf{3}_L \otimes \mathbf{6}_R \oplus \mathbf{3}_L \otimes \bar{\mathbf{3}}_R$	$n_\ell n_d^3 [8n_\ell]$
	$\mathcal{O}_{X\bar{\ell} d d d}^{\text{VL,SL}}$	$X_\mu(\bar{\ell}_L \gamma^\mu d_L^\alpha)(\bar{d}_L^{\beta C} d_L^\gamma) \epsilon_{\alpha\beta\gamma}$	$\mathbf{8}_L \otimes \mathbf{1}_R$	$\frac{1}{3} n_\ell n_d (n_d^2 - 1) [2n_\ell]$
	$\mathcal{O}_{X\bar{\ell} d d d}^{\text{SL,VR}}$	$X_\mu(\bar{\ell}_R d_L^\alpha)(\bar{d}_L^{\beta C} \gamma^\mu d_R^\gamma) \epsilon_{\alpha\beta\gamma}$	$\mathbf{6}_L \otimes \mathbf{3}_R \oplus \bar{\mathbf{3}}_L \otimes \mathbf{3}_R$	$n_\ell n_d^3 [8n_\ell]$

Case B				
	Notation	Operator	Chiral Irrep.	# of operators
$\Delta(B-L)=0$	$\tilde{\mathcal{O}}_{X\ell u d}^{\text{TL,SL}}$	$X_{\mu\nu}(\overline{\ell_L^c}\sigma^{\mu\nu}u_L^\alpha)(u_L^{\beta C}d_L^\gamma)\epsilon_{\alpha\beta\gamma}$	$\mathbf{8}_L \otimes \mathbf{1}_R$	$n_\ell n_u^2 n_d [2n_\ell]$
	$\tilde{\mathcal{O}}_{X\ell d u u}^{\text{SL,TL}}$	$X_{\mu\nu}(\overline{\ell_L^c}\{d_L^\alpha\})(u_L^{\beta C}\sigma^{\mu\nu}u_L^\gamma)\epsilon_{\alpha\beta\gamma}$	$\mathbf{10}_L \otimes \mathbf{1}_R$	$\frac{1}{2}n_\ell n_u(n_u+1)n_d [2n_\ell]$
	$\tilde{\mathcal{O}}_{X\ell d u u}^{\text{VR,VL}}$	$X_{\mu\nu}(\overline{\ell_L^c}\gamma^\mu d_R^\alpha)(u_R^{\beta C}\gamma^\nu u_L^\gamma)\epsilon_{\alpha\beta\gamma}$	$\mathbf{3}_L \otimes \mathbf{6}_R \oplus \mathbf{3}_L \otimes \mathbf{\bar{3}}_R$	$n_\ell n_u^2 n_d [2n_\ell]$
	$\tilde{\mathcal{O}}_{X\ell u d u}^{\text{VR,VL}}$	$X_{\mu\nu}(\overline{\ell_L^c}\gamma^\mu u_R^\alpha)(d_R^{\beta C}\gamma^\nu u_L^\gamma)\epsilon_{\alpha\beta\gamma}$	$\mathbf{3}_L \otimes \mathbf{6}_R \oplus \mathbf{3}_L \otimes \mathbf{\bar{3}}_R$	$n_\ell n_u^2 n_d [2n_\ell]$
	$\tilde{\mathcal{O}}_{X\ell u u d}^{\text{VR,VL}}$	$X_{\mu\nu}(\overline{\ell_L^c}\gamma^\mu u_R^\alpha)(u_R^{\beta C}\gamma^\nu d_L^\gamma)\epsilon_{\alpha\beta\gamma}$	$\mathbf{3}_L \otimes \mathbf{6}_R$	$n_\ell n_u^2 n_d [2n_\ell]$
	$\tilde{\mathcal{O}}_{X\ell u u d}^{\text{TR,SR}}$	$X_{\mu\nu}(\overline{\ell_R^c}\sigma^{\mu\nu}u_R^\alpha)(u_R^{\beta C}d_R^\gamma)\epsilon_{\alpha\beta\gamma}$	$\mathbf{1}_L \otimes \mathbf{8}_R$	$n_\ell n_u^2 n_d [2n_\ell]$
	$\tilde{\mathcal{O}}_{X\ell d u u}^{\text{SR,TR}}$	$X_{\mu\nu}(\overline{\ell_R^c}\{d_R^\alpha\})(u_R^{\beta C}\sigma^{\mu\nu}u_R^\gamma)\epsilon_{\alpha\beta\gamma}$	$\mathbf{1}_L \otimes \mathbf{10}_R$	$\frac{1}{2}n_\ell n_u(n_u+1)n_d [2n_\ell]$
	$\tilde{\mathcal{O}}_{X\ell d u u}^{\text{VL,VR}}$	$X_{\mu\nu}(\overline{\ell_R^c}\gamma^\mu d_L^\alpha)(u_L^{\beta C}\gamma^\nu u_R^\gamma)\epsilon_{\alpha\beta\gamma}$	$\mathbf{6}_L \otimes \mathbf{3}_R \oplus \mathbf{\bar{3}}_L \otimes \mathbf{3}_R$	$n_\ell n_u^2 n_d [2n_\ell]$
	$\tilde{\mathcal{O}}_{X\ell u d u}^{\text{VL,VR}}$	$X_{\mu\nu}(\overline{\ell_R^c}\gamma^\mu u_L^\alpha)(d_L^{\beta C}\gamma^\nu u_R^\gamma)\epsilon_{\alpha\beta\gamma}$	$\mathbf{6}_L \otimes \mathbf{3}_R \oplus \mathbf{\bar{3}}_L \otimes \mathbf{3}_R$	$n_\ell n_u^2 n_d [2n_\ell]$
	$\tilde{\mathcal{O}}_{X\ell u u d}^{\text{VL,VR}}$	$X_{\mu\nu}(\overline{\ell_R^c}\gamma^\mu u_L^\alpha)(u_L^{\beta C}\gamma^\nu d_R^\gamma)\epsilon_{\alpha\beta\gamma}$	$\mathbf{6}_L \otimes \mathbf{3}_R$	$n_\ell n_u^2 n_d [2n_\ell]$
$\Delta(B-L)=0$	$\tilde{\mathcal{O}}_{X\nu d d u}^{\text{TL,SL}}$	$X_{\mu\nu}(\overline{\nu_L^c}\sigma^{\mu\nu}d_L^\alpha)(d_L^{\beta C}u_L^\gamma)\epsilon_{\alpha\beta\gamma}$	$\mathbf{8}_L \otimes \mathbf{1}_R$	$n_\nu n_u n_d^2 [4n_\nu]$
	$\tilde{\mathcal{O}}_{X\nu u d d}^{\text{SL,TL}}$	$X_{\mu\nu}(\overline{\nu_L^c}\{u_L^\alpha\})(d_L^{\beta C}\sigma^{\mu\nu}d_L^\gamma)\epsilon_{\alpha\beta\gamma}$	$\mathbf{10}_L \otimes \mathbf{1}_R$	$\frac{1}{2}n_\nu n_u n_d(n_d+1) [3n_\nu]$
	$\tilde{\mathcal{O}}_{X\nu d u d}^{\text{VR,VL}}$	$X_{\mu\nu}(\overline{\nu_L^c}\gamma^\mu d_R^\alpha)(u_R^{\beta C}\gamma^\nu d_L^\gamma)\epsilon_{\alpha\beta\gamma}$	$\mathbf{3}_L \otimes \mathbf{6}_R \oplus \mathbf{3}_L \otimes \mathbf{\bar{3}}_R$	$n_\nu n_u n_d^2 [4n_\nu]$
	$\tilde{\mathcal{O}}_{X\nu u d d}^{\text{VR,VL}}$	$X_{\mu\nu}(\overline{\nu_L^c}\gamma^\mu u_R^\alpha)(d_R^{\beta C}\gamma^\nu d_L^\gamma)\epsilon_{\alpha\beta\gamma}$	$\mathbf{3}_L \otimes \mathbf{6}_R \oplus \mathbf{3}_L \otimes \mathbf{\bar{3}}_R$	$n_\nu n_u n_d^2 [4n_\nu]$
	$\tilde{\mathcal{O}}_{X\nu d d u}^{\text{VR,VL}}$	$X_{\mu\nu}(\overline{\nu_L^c}\gamma^\mu d_R^\alpha)(d_R^{\beta C}\gamma^\nu u_L^\gamma)\epsilon_{\alpha\beta\gamma}$	$\mathbf{3}_L \otimes \mathbf{6}_R \oplus \mathbf{3}_L \otimes \mathbf{\bar{3}}_R$	$n_\nu n_u n_d^2 [4n_\nu]$
$\Delta(B+L)=0$	$\tilde{\mathcal{O}}_{X\bar{\nu} d d u}^{\text{TR,SR}}$	$X_{\mu\nu}(\overline{\nu_L}\sigma^{\mu\nu}d_R^\alpha)(d_R^{\beta C}u_R^\gamma)\epsilon_{\alpha\beta\gamma}$	$\mathbf{1}_L \otimes \mathbf{8}_R$	$n_\nu n_u n_d^2 [4n_\nu]$
	$\tilde{\mathcal{O}}_{X\bar{\nu} u d d}^{\text{SR,TR}}$	$X_{\mu\nu}(\overline{\nu_L}\{u_R^\alpha\})(d_R^{\beta C}\sigma^{\mu\nu}d_R^\gamma)\epsilon_{\alpha\beta\gamma}$	$\mathbf{1}_L \otimes \mathbf{10}_R$	$\frac{1}{2}n_\nu n_u n_d(n_d+1) [3n_\nu]$
	$\tilde{\mathcal{O}}_{X\bar{\nu} d u d}^{\text{VL,VR}}$	$X_{\mu\nu}(\overline{\nu_L}\gamma^\mu d_L^\alpha)(u_L^{\beta C}\gamma^\nu d_R^\gamma)\epsilon_{\alpha\beta\gamma}$	$\mathbf{6}_L \otimes \mathbf{3}_R \oplus \mathbf{\bar{3}}_L \otimes \mathbf{3}_R$	$n_\nu n_u n_d^2 [4n_\nu]$
	$\tilde{\mathcal{O}}_{X\bar{\nu} u d d}^{\text{VL,VR}}$	$X_{\mu\nu}(\overline{\nu_L}\gamma^\mu u_L^\alpha)(d_L^{\beta C}\gamma^\nu d_R^\gamma)\epsilon_{\alpha\beta\gamma}$	$\mathbf{6}_L \otimes \mathbf{3}_R \oplus \mathbf{\bar{3}}_L \otimes \mathbf{3}_R$	$n_\nu n_u n_d^2 [4n_\nu]$
	$\tilde{\mathcal{O}}_{X\bar{\nu} d d u}^{\text{VL,VR}}$	$X_{\mu\nu}(\overline{\nu_L}\gamma^\mu d_L^\alpha)(d_L^{\beta C}\gamma^\nu u_R^\gamma)\epsilon_{\alpha\beta\gamma}$	$\mathbf{6}_L \otimes \mathbf{3}_R \oplus \mathbf{\bar{3}}_L \otimes \mathbf{3}_R$	$n_\nu n_u n_d^2 [4n_\nu]$
	$\tilde{\mathcal{O}}_{X\ell d d d}^{\text{TL,SL}}$	$X_{\mu\nu}(\overline{\ell_R}\sigma^{\mu\nu}d_L^\alpha)(d_L^{\beta C}d_L^\gamma)\epsilon_{\alpha\beta\gamma}$	$\mathbf{8}_L \otimes \mathbf{1}_R$	$\frac{1}{3}n_\ell n_d(n_d^2-1) [2n_\ell]$
	$\tilde{\mathcal{O}}_{X\ell d d d}^{\text{SL,TL}}$	$X_{\mu\nu}(\overline{\ell_R}\{d_L^\alpha\})(d_L^{\beta C}\sigma^{\mu\nu}d_L^\gamma)\epsilon_{\alpha\beta\gamma}$	$\mathbf{10}_L \otimes \mathbf{1}_R$	$\frac{1}{6}n_\ell n_d(n_d^2+3n_d+2) [4n_\ell]$
	$\tilde{\mathcal{O}}_{X\ell d d d}^{\text{VR,VL}}$	$X_{\mu\nu}(\overline{\ell_R}\gamma^\mu d_R^\alpha)(d_R^{\beta C}\gamma^\nu d_L^\gamma)\epsilon_{\alpha\beta\gamma}$	$\mathbf{3}_L \otimes \mathbf{6}_R \oplus \mathbf{3}_L \otimes \mathbf{\bar{3}}_R$	$n_\ell n_d^3 [8n_\ell]$
	$\tilde{\mathcal{O}}_{X\ell d d d}^{\text{TR,SR}}$	$X_{\mu\nu}(\overline{\ell_L}\sigma^{\mu\nu}d_R^\alpha)(d_R^{\beta C}d_R^\gamma)\epsilon_{\alpha\beta\gamma}$	$\mathbf{1}_L \otimes \mathbf{8}_R$	$\frac{1}{3}n_\ell n_d(n_d^2-1) [2n_\ell]$
$\tilde{\mathcal{O}}_{X\ell d d d}^{\text{SR,TR}}$	$X_{\mu\nu}(\overline{\ell_L}\{d_R^\alpha\})(d_R^{\beta C}\sigma^{\mu\nu}d_R^\gamma)\epsilon_{\alpha\beta\gamma}$	$\mathbf{1}_L \otimes \mathbf{10}_R$	$\frac{1}{6}n_\ell n_d(n_d^2+3n_d+2) [4n_\ell]$	
$\tilde{\mathcal{O}}_{X\ell d d d}^{\text{VL,VR}}$	$X_{\mu\nu}(\overline{\ell_L}\gamma^\mu d_L^\alpha)(d_L^{\beta C}\gamma^\nu d_R^\gamma)\epsilon_{\alpha\beta\gamma}$	$\mathbf{6}_L \otimes \mathbf{3}_R \oplus \mathbf{\bar{3}}_L \otimes \mathbf{3}_R$	$n_\ell n_d^3 [8n_\ell]$	

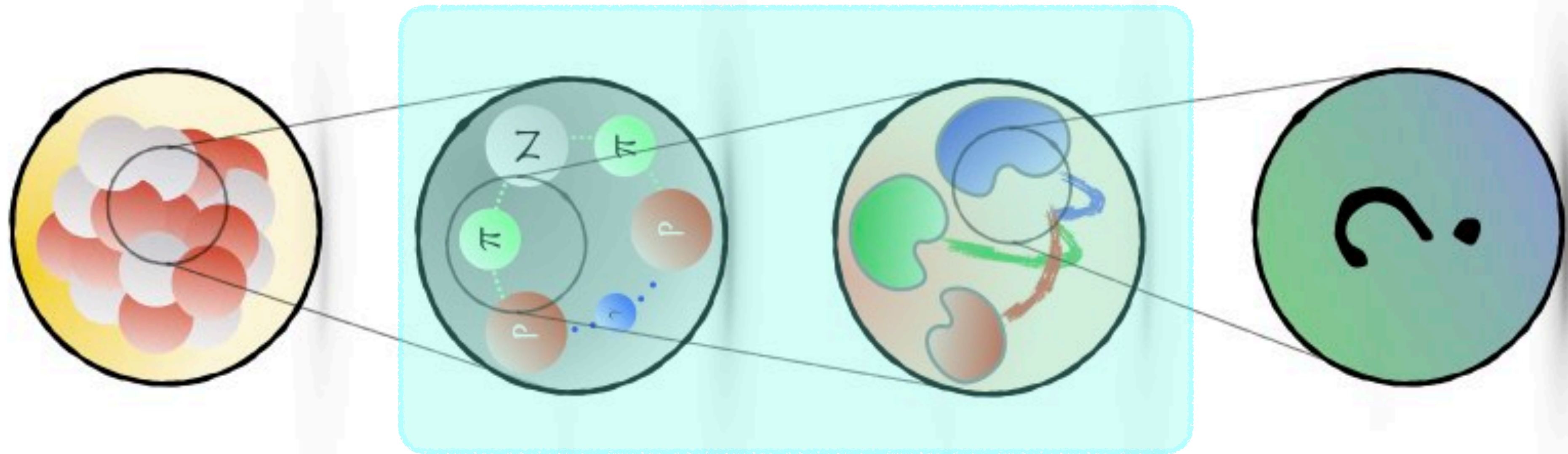
Chiral Perturbation Theory

Nucleon level operators

$$SU(3)_L \otimes SU(3)_R$$

u, d, s

Quark level operators



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

Y. Liao, XDM, H.-L. Wang, 2504.14855, PRL

- Nucleon decays: focus on operators involving light quarks u, d, s
- Operators in the exotic decays can be described by four general triple-quark structures

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

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

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

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

+ their chirality partners with $L \leftrightarrow R$

- ❖ $\overline{\Psi}_a, \overline{\Psi}_b, \overline{\Psi}_{c,\mu}, \overline{\Psi}_{d,\mu\nu}$: 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 without being acted upon by a derivative
- For operators involving derivatives on quark fields, see

XDM, 2609.08785
C.-Q. Song, J.-H. Yu, 2603.11158

Chiral structures

- 3-flavor (u, d, s) QCD has a global chiral symmetry: $SU(3)_L \otimes SU(3)_R$
in the massless limit
- Restrict to triple-quark sector

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

$$\mathcal{N}_{yzw}^{RL} \equiv q_{R,y}^\alpha (\overline{q_{L,z}^{\beta\bar{C}}} q_{L,w}^\gamma) \epsilon_{\alpha\beta\gamma} \in \bar{\mathbf{3}}_L \otimes \mathbf{3}_R \quad +L \leftrightarrow R$$

$$\mathcal{N}_{yzw}^{LR,\mu} \equiv q_{L,\{y}^\alpha (\overline{q_{L,z}^{\beta\bar{C}}} \gamma^\mu q_{R,w}^\gamma) \epsilon_{\alpha\beta\gamma} \in \mathbf{6}_L \otimes \mathbf{3}_R$$

$$\mathcal{N}_{yzw}^{LL,\mu\nu} \equiv q_{L,\{y}^\alpha (\overline{q_{L,z}^{\beta\bar{C}}} \sigma^{\mu\nu} q_{L,w}^\gamma) \epsilon_{\alpha\beta\gamma} \in \mathbf{10}_L \otimes \mathbf{1}_R$$

The general LEFT Lagrangian involving triple quarks

Non-quark factor as spurion fields

$$\mathcal{L}_{q^3}^{\mathcal{B}} = \sum_i C_i^{yzw} \mathcal{O}_i^{yzw} = \sum_i \boxed{C_i^{yzw} \bar{\psi}} \Gamma_1 q (\bar{q}^c \Gamma_2 q) \quad \text{Quark factor}$$

$$\equiv \mathcal{P}_{yzw}^i \quad \equiv \mathcal{N}_{yzw}^i$$

$$\begin{aligned} \mathcal{L}_{q^3}^{\mathcal{B}} = & \text{Tr}[\mathcal{P}_{\mathbf{8}_L \otimes \mathbf{1}_R} \mathcal{N}_{\mathbf{8}_L \otimes \mathbf{1}_R} + \mathcal{P}_{\mathbf{1}_L \otimes \mathbf{8}_R} \mathcal{N}_{\mathbf{1}_L \otimes \mathbf{8}_R}] \\ & + \text{Tr}[\mathcal{P}_{\mathbf{3}_L \otimes \bar{\mathbf{3}}_R} \mathcal{N}_{\bar{\mathbf{3}}_L \otimes \mathbf{3}_R} + \mathcal{P}_{\bar{\mathbf{3}}_L \otimes \mathbf{3}_R} \mathcal{N}_{\mathbf{3}_L \otimes \bar{\mathbf{3}}_R}] \\ & + [\mathcal{P}_{\bar{\mathbf{6}}_L \otimes \bar{\mathbf{3}}_R}^{\{yz\}w, \mu} \mathcal{N}_{\mathbf{6}_L \otimes \mathbf{3}_R, \mu}^{\{yz\}w} + \mathcal{P}_{\bar{\mathbf{3}}_L \otimes \bar{\mathbf{6}}_R}^{\{yz\}w, \mu} \mathcal{N}_{\mathbf{3}_L \otimes \mathbf{6}_R, \mu}^{\{yz\}w}] \\ & + [\mathcal{P}_{\mathbf{10}_L \otimes \mathbf{1}_R}^{\{yzw\}, \mu\nu} \mathcal{N}_{\mathbf{10}_L \otimes \mathbf{1}_R, \mu\nu}^{\{yzw\}} + \mathcal{P}_{\mathbf{1}_L \otimes \mathbf{10}_R}^{\{yzw\}, \mu\nu} \mathcal{N}_{\mathbf{1}_L \otimes \mathbf{10}_R, \mu\nu}^{\{yzw\}}] \\ & + \text{h.c.} \end{aligned}$$

Matrix form for easy chiral realization

$$\mathcal{N}_{\mathbf{8}_L \otimes \mathbf{1}_R} = \begin{pmatrix} \mathcal{N}_{uds}^{\text{LL}} \mathcal{N}_{usu}^{\text{LL}} \mathcal{N}_{uud}^{\text{LL}} \\ \mathcal{N}_{dds}^{\text{LL}} \mathcal{N}_{dsu}^{\text{LL}} \mathcal{N}_{dud}^{\text{LL}} \\ \mathcal{N}_{sds}^{\text{LL}} \mathcal{N}_{ssu}^{\text{LL}} \mathcal{N}_{sud}^{\text{LL}} \end{pmatrix} \quad \mathcal{N}_{\bar{\mathbf{3}}_L \otimes \mathbf{3}_R} = \begin{pmatrix} \mathcal{N}_{uds}^{\text{RL}} \mathcal{N}_{usu}^{\text{RL}} \mathcal{N}_{uud}^{\text{RL}} \\ \mathcal{N}_{dds}^{\text{RL}} \mathcal{N}_{dsu}^{\text{RL}} \mathcal{N}_{dud}^{\text{RL}} \\ \mathcal{N}_{sds}^{\text{RL}} \mathcal{N}_{ssu}^{\text{RL}} \mathcal{N}_{sud}^{\text{RL}} \end{pmatrix}$$

Chiral building blocks

$$\mathcal{P}_{\mathbf{8}_L \otimes \mathbf{1}_R} = \begin{pmatrix} 0 & \mathcal{P}_{dds}^{\text{LL}} & \mathcal{P}_{sds}^{\text{LL}} \\ \mathcal{P}_{usu}^{\text{LL}} & \mathcal{P}_{dsu}^{\text{LL}} & \mathcal{P}_{ssu}^{\text{LL}} \\ \mathcal{P}_{uud}^{\text{LL}} & \mathcal{P}_{dud}^{\text{LL}} & \mathcal{P}_{sud}^{\text{LL}} \end{pmatrix} \quad \mathcal{P}_{\mathbf{3}_L \otimes \bar{\mathbf{3}}_R} = \begin{pmatrix} \mathcal{P}_{uds}^{\text{RL}} & \mathcal{P}_{dds}^{\text{RL}} & \mathcal{P}_{sds}^{\text{RL}} \\ \mathcal{P}_{usu}^{\text{RL}} & \mathcal{P}_{dsu}^{\text{RL}} & \mathcal{P}_{ssu}^{\text{RL}} \\ \mathcal{P}_{uud}^{\text{RL}} & \mathcal{P}_{dud}^{\text{RL}} & \mathcal{P}_{sud}^{\text{RL}} \end{pmatrix} \quad \mathcal{P}_{yzw}^{\text{LR}, \mu} \quad \mathcal{P}_{yzw}^{\text{LL}, \mu\nu}$$

Chiral matching procedures

- Building blocks in ChPT: Octet baryons, pseudoscalars + 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

(Non-quark components in $\mathcal{L}_{\text{EFT}}$)

$$\mathcal{P}_{\mathbf{8}_L \otimes \mathbf{1}_R} = \begin{pmatrix} 0 & \mathcal{P}_{dds}^{\text{LL}} & \mathcal{P}_{sds}^{\text{LL}} \\ \mathcal{P}_{usu}^{\text{LL}} & \mathcal{P}_{dsu}^{\text{LL}} & \mathcal{P}_{ssu}^{\text{LL}} \\ \mathcal{P}_{uud}^{\text{LL}} & \mathcal{P}_{dud}^{\text{LL}} & \mathcal{P}_{sud}^{\text{LL}} \end{pmatrix} \quad \mathcal{P}_{\mathbf{3}_L \otimes \bar{\mathbf{3}}_R} = \begin{pmatrix} \mathcal{P}_{uds}^{\text{RL}} & \mathcal{P}_{dds}^{\text{RL}} & \mathcal{P}_{sds}^{\text{RL}} \\ \mathcal{P}_{usu}^{\text{RL}} & \mathcal{P}_{dsu}^{\text{RL}} & \mathcal{P}_{ssu}^{\text{RL}} \\ \mathcal{P}_{uud}^{\text{RL}} & \mathcal{P}_{dud}^{\text{RL}} & \mathcal{P}_{sud}^{\text{RL}} \end{pmatrix} \quad \mathcal{P}_{yzw}^{\text{LR},\mu} \quad \mathcal{P}_{yzw}^{\text{LL},\mu\nu}$$

- Chiral symmetry: $SU(3)_L \otimes SU(3)_R$
- Chiral power counting: momentum p : $\{\Sigma, \xi, B, D_\mu B\} \sim \mathcal{O}(p^0) \quad D_\mu \Sigma \sim \mathcal{O}(p^1)$
- Low energy constant (LEC): associate an unknown LEC for each indep. operator

Leading-order chiral Lagrangian for nucleon decay

Y. Liao, XDM, H.-L. Wang, 2504.14855, PRL

$$\mathcal{L}_B^{\mathcal{B},0} = c_1 \text{Tr} \left[\mathcal{P}_{\bar{3}_L \otimes 3_R} \xi B_L \xi - \mathcal{P}_{3_L \otimes \bar{3}_R} \xi^\dagger B_R \xi^\dagger \right] \\ + c_2 \text{Tr} \left[\mathcal{P}_{8_L \otimes 1_R} \xi B_L \xi^\dagger - \mathcal{P}_{1_L \otimes 8_R} \xi^\dagger B_R \xi \right]$$

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

Related to new structures

$$+ \frac{c_3}{\Lambda_\chi} \left[\mathcal{P}_{yzi}^{\text{LR},\mu} \Gamma_{\mu\nu}^L (\xi i D^\nu B_L \xi)_{yj} \Sigma_{zk} \epsilon_{ijk} - \mathcal{P}_{yzi}^{\text{RL},\mu} \Gamma_{\mu\nu}^R (\xi^\dagger i D^\nu B_R \xi^\dagger)_{yj} \Sigma_{kz}^* \epsilon_{ijk} \right] \\ + \text{h.c.}, \\ \mathcal{L}_B^{\mathcal{B},1} = \frac{c_4}{\Lambda_\chi^2} \left[\mathcal{P}_{yzw}^{\text{LL},\mu\nu} \hat{\Gamma}_{\mu\nu\alpha\beta}^L (\xi D^\alpha B_L \xi)_{yi} \Sigma_{zj} (D^\beta \Sigma)_{wk} \epsilon_{ijk} - \mathcal{P}_{yzw}^{\text{RR},\mu\nu} \hat{\Gamma}_{\mu\nu\alpha\beta}^R (\xi^\dagger D^\alpha B_R \xi^\dagger)_{iy} \Sigma_{jz}^* (D^\beta \Sigma)_{kw}^* \epsilon_{ijk} \right] \\ + \text{h.c.}.$$

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

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

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

$$c_1 = -0.01257(111) \text{ GeV}^3, c_2 = 0.01269(107) \text{ GeV}^3$$

J.-S. Yoo et al., 2111.01608

Spurion fields — examples

φ LEFT

$$\begin{aligned}\mathcal{P}_{\bar{3}_L \otimes 3_R} &= \varphi \begin{pmatrix} C_{\varphi vuds}^{\text{LR},x} \overline{\nu_{Lx}^C} & C_{\varphi \bar{l}dds}^{\text{LR},x} \overline{\ell_{Rx}} & C_{\varphi \bar{l}sds}^{\text{LR},x} \overline{\ell_{Rx}} \\ C_{\varphi lusu}^{\text{LR},x} \overline{\ell_{Lx}^C} & C_{\varphi vdsu}^{\text{LR},x} \overline{\nu_{Lx}^C} & C_{\varphi \nu ssu}^{\text{LR},x} \overline{\nu_{Lx}^C} \\ C_{\varphi lvud}^{\text{LR},x} \overline{\ell_{Lx}^C} & C_{\varphi \nu dud}^{\text{LR},x} \overline{\nu_{Lx}^C} & C_{\varphi \nu sud}^{\text{LR},x} \overline{\nu_{Lx}^C} \end{pmatrix}, \\ \mathcal{P}_{3_L \otimes \bar{3}_R} &= \varphi \begin{pmatrix} C_{\varphi \bar{v}uds}^{\text{RL},x} \overline{\nu_{Lx}} & C_{\varphi \bar{l}dds}^{\text{RL},x} \overline{\ell_{Lx}} & C_{\varphi \bar{l}sds}^{\text{RL},x} \overline{\ell_{Lx}} \\ C_{\varphi lusu}^{\text{RL},x} \overline{\ell_{Rx}^C} & C_{\varphi \bar{v}dsu}^{\text{RL},x} \overline{\nu_{Lx}} & C_{\varphi \bar{\nu}ssu}^{\text{RL},x} \overline{\nu_{Lx}} \\ C_{\varphi lvud}^{\text{RL},x} \overline{\ell_{Rx}^C} & C_{\varphi \bar{\nu}dud}^{\text{RL},x} \overline{\nu_{Lx}} & C_{\varphi \bar{\nu}sud}^{\text{RL},x} \overline{\nu_{Lx}} \end{pmatrix}, \\ \mathcal{P}_{8_L \otimes 1_R} &= \varphi \begin{pmatrix} 0 & C_{\varphi \bar{l}dds}^{\text{LL},x} \overline{\ell_{Rx}} & C_{\varphi \bar{l}sds}^{\text{LL},x} \overline{\ell_{Rx}} \\ C_{\varphi lusu}^{\text{LL},x} \overline{\ell_{Lx}^C} & C_{\varphi vdsu}^{\text{LL},x} \overline{\nu_{Lx}^C} & C_{\varphi \nu ssu}^{\text{LL},x} \overline{\nu_{Lx}^C} \\ C_{\varphi lvud}^{\text{LL},x} \overline{\ell_{Lx}^C} & C_{\varphi \nu dud}^{\text{LL},x} \overline{\nu_{Lx}^C} & C_{\varphi \nu sud}^{\text{LL},x} \overline{\nu_{Lx}^C} \end{pmatrix}, \\ \mathcal{P}_{1_L \otimes 8_R} &= \varphi \begin{pmatrix} 0 & C_{\varphi \bar{l}dds}^{\text{RR},x} \overline{\ell_{Lx}} & C_{\varphi \bar{l}sds}^{\text{RR},x} \overline{\ell_{Lx}} \\ C_{\varphi lusu}^{\text{RR},x} \overline{\ell_{Rx}^C} & C_{\varphi \bar{v}dsu}^{\text{RR},x} \overline{\nu_{Lx}} & C_{\varphi \bar{\nu}ssu}^{\text{RR},x} \overline{\nu_{Lx}} \\ C_{\varphi lvud}^{\text{RR},x} \overline{\ell_{Rx}^C} & C_{\varphi \bar{\nu}dud}^{\text{RR},x} \overline{\nu_{Lx}} & C_{\varphi \bar{\nu}sud}^{\text{RR},x} \overline{\nu_{Lx}} \end{pmatrix}.\end{aligned}$$

a LEFT

$6_{\text{L(R)}} \otimes 3_{\text{R(L)}}$	$\mathcal{P}_{uuu}^{\text{LR},\mu}$	—
	$\mathcal{P}_{uud}^{\text{LR},\mu}$	$[C_{\partial a e u u d}^{\text{SL,VR}}]_{x112} (\partial^\mu a) \overline{e_{L,x}^C}$
	$\mathcal{P}_{uus}^{\text{LR},\mu}$	$[C_{\partial a e u u d}^{\text{SL,VR}}]_{x113} (\partial^\mu a) \overline{e_{L,x}^C}$
	$\mathcal{P}_{udu}^{\text{LR},\mu}$	$[C_{\partial a e u d u}^{\text{SL,VR}}]_{x121}^+ (\partial^\mu a) \overline{e_{L,x}^C}$
	$\mathcal{P}_{udd}^{\text{LR},\mu}$	$[C_{\partial a v u d d}^{\text{SL,VR}}]_{x122}^+ (\partial^\mu a) \overline{\nu_{L,x}^C}$
	$\mathcal{P}_{uds}^{\text{LR},\mu}$	$[C_{\partial a v u d d}^{\text{SL,VR}}]_{x123}^+ (\partial^\mu a) \overline{\nu_{L,x}^C}$
	$\mathcal{P}_{usu}^{\text{LR},\mu}$	$[C_{\partial a e u d u}^{\text{SL,VR}}]_{x131}^+ (\partial^\mu a) \overline{e_{L,x}^C}$
	$\mathcal{P}_{usd}^{\text{LR},\mu}$	$[C_{\partial a v u d d}^{\text{SL,VR}}]_{x132}^+ (\partial^\mu a) \overline{\nu_{L,x}^C}$
	$\mathcal{P}_{uss}^{\text{LR},\mu}$	$[C_{\partial a v u d d}^{\text{SL,VR}}]_{x133}^+ (\partial^\mu a) \overline{\nu_{L,x}^C}$
	$\mathcal{P}_{ddu}^{\text{LR},\mu}$	$[C_{\partial a v d d u}^{\text{SL,VR}}]_{x221} (\partial^\mu a) \overline{\nu_{L,x}^C}$
	$\mathcal{P}_{ddd}^{\text{LR},\mu}$	$[C_{\partial a e d d d}^{\text{SL,VR}}]_{x222} (\partial^\mu a) \overline{e_{R,x}}$
	$\mathcal{P}_{dds}^{\text{LR},\mu}$	$[C_{\partial a e d d d}^{\text{SL,VR}}]_{x223} (\partial^\mu a) \overline{e_{R,x}}$
	$\mathcal{P}_{dsu}^{\text{LR},\mu}$	$[C_{\partial a v d d u}^{\text{SL,VR}}]_{x231}^+ (\partial^\mu a) \overline{\nu_{L,x}^C}$
	$\mathcal{P}_{dsd}^{\text{LR},\mu}$	$[C_{\partial a e d d d}^{\text{SL,VR}}]_{x232}^+ (\partial^\mu a) \overline{e_{R,x}}$
	$\mathcal{P}_{dss}^{\text{LR},\mu}$	$[C_{\partial a e d d d}^{\text{SL,VR}}]_{x233}^+ (\partial^\mu a) \overline{e_{R,x}}$
	$\mathcal{P}_{ssu}^{\text{LR},\mu}$	$[C_{\partial a v d d u}^{\text{SL,VR}}]_{x331} (\partial^\mu a) \overline{\nu_{L,x}^C}$
	$\mathcal{P}_{ssd}^{\text{LR},\mu}$	$[C_{\partial a e d d d}^{\text{SL,VR}}]_{x332} (\partial^\mu a) \overline{e_{R,x}}$
	$\mathcal{P}_{sss}^{\text{LR},\mu}$	$[C_{\partial a e d d d}^{\text{SL,VR}}]_{x333} (\partial^\mu a) \overline{e_{R,x}}$

X LEFT

Irrep.	Spurions	Expressions	Spurions	Expressions
		case B		case B
$10_{\text{L(R)}} \otimes 1_{\text{R(L)}}$	$\mathcal{P}_{uuu}^{\text{LL},\mu\nu}$	—	$\mathcal{P}_{uuu}^{\text{RR},\mu\nu}$	—
	$\mathcal{P}_{uud}^{\text{LL},\mu\nu}$	$\frac{1}{3} \tilde{C}_{X l u u d}^{\text{SL,TL},x} X^{\mu\nu} \overline{\ell_{L,x}^C}$	$\mathcal{P}_{uud}^{\text{RR},\mu\nu}$	$\frac{1}{3} \tilde{C}_{X l u u d}^{\text{SR,TR},x} X^{\mu\nu} \overline{\ell_{R,x}^C}$
	$\mathcal{P}_{uus}^{\text{LL},\mu\nu}$	$\frac{1}{3} \tilde{C}_{X l u u s}^{\text{SL,TL},x} X^{\mu\nu} \overline{\ell_{L,x}^C}$	$\mathcal{P}_{uus}^{\text{RR},\mu\nu}$	$\frac{1}{3} \tilde{C}_{X l u u s}^{\text{SR,TR},x} X^{\mu\nu} \overline{\ell_{R,x}^C}$
	$\mathcal{P}_{ddd}^{\text{LL},\mu\nu}$	$\tilde{C}_{X \bar{l} d d d}^{\text{SL,TL},x} X^{\mu\nu} \overline{\ell_{R,x}} (\dagger)$	$\mathcal{P}_{ddd}^{\text{RR},\mu\nu}$	$\tilde{C}_{X \bar{l} d d d}^{\text{SR,TR},x} X^{\mu\nu} \overline{\ell_{L,x}} (\dagger)$
	$\mathcal{P}_{dds}^{\text{LL},\mu\nu}$	$\frac{1}{3} \tilde{C}_{X \bar{l} d d s}^{\text{SL,TL},x} X^{\mu\nu} \overline{\ell_{R,x}} (\dagger)$	$\mathcal{P}_{dds}^{\text{RR},\mu\nu}$	$\frac{1}{3} \tilde{C}_{X \bar{l} d d s}^{\text{SR,TR},x} X^{\mu\nu} \overline{\ell_{L,x}} (\dagger)$
	$\mathcal{P}_{udd}^{\text{LL},\mu\nu}$	$\frac{1}{3} \tilde{C}_{X \nu u d d}^{\text{SL,TL},x} X^{\mu\nu} \overline{\nu_{L,x}^C}$	$\mathcal{P}_{udd}^{\text{RR},\mu\nu}$	$\frac{1}{3} \tilde{C}_{X \bar{\nu} u d d}^{\text{SR,TR},x} X^{\mu\nu} \overline{\nu_{L,x}} (\dagger)$
	$\mathcal{P}_{uds}^{\text{LL},\mu\nu}$	$\frac{1}{6} \tilde{C}_{X \nu u d s}^{\text{SL,TL},x} X^{\mu\nu} \overline{\nu_{L,x}^C}$	$\mathcal{P}_{uds}^{\text{RR},\mu\nu}$	$\frac{1}{6} \tilde{C}_{X \bar{\nu} u d s}^{\text{SR,TR},x} X^{\mu\nu} \overline{\nu_{L,x}} (\dagger)$
	$\mathcal{P}_{uss}^{\text{LL},\mu\nu} (\times)$	$\frac{1}{3} \tilde{C}_{X \nu u s s}^{\text{SL,TL},x} X^{\mu\nu} \overline{\nu_{L,x}^C}$	$\mathcal{P}_{uss}^{\text{RR},\mu\nu} (\times)$	$\frac{1}{3} \tilde{C}_{X \bar{\nu} u s s}^{\text{SR,TR},x} X^{\mu\nu} \overline{\nu_{L,x}} (\dagger)$
	$\mathcal{P}_{dss}^{\text{LL},\mu\nu} (\times)$	$\frac{1}{3} \tilde{C}_{X \bar{l} d s s}^{\text{SL,TL},x} X^{\mu\nu} \overline{\ell_{R,x}} (\dagger)$	$\mathcal{P}_{dss}^{\text{RR},\mu\nu} (\times)$	$\frac{1}{3} \tilde{C}_{X \bar{l} d s s}^{\text{SR,TR},x} X^{\mu\nu} \overline{\ell_{L,x}} (\dagger)$
	$\mathcal{P}_{sss}^{\text{LL},\mu\nu} (\times)$	$\tilde{C}_{X \bar{l} s s s}^{\text{SL,TL},x} X^{\mu\nu} \overline{\ell_{R,x}} (\dagger)$	$\mathcal{P}_{sss}^{\text{RR},\mu\nu} (\times)$	$\tilde{C}_{X \bar{l} s s s}^{\text{SR,TR},x} X^{\mu\nu} \overline{\ell_{L,x}} (\dagger)$

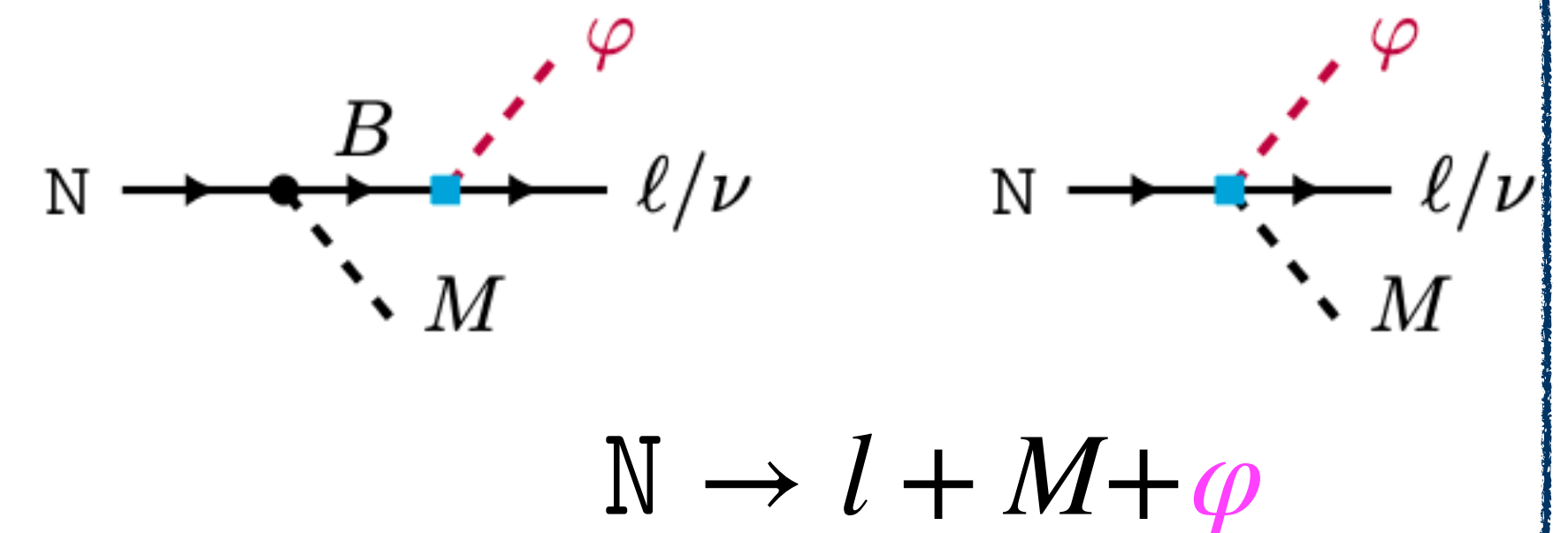
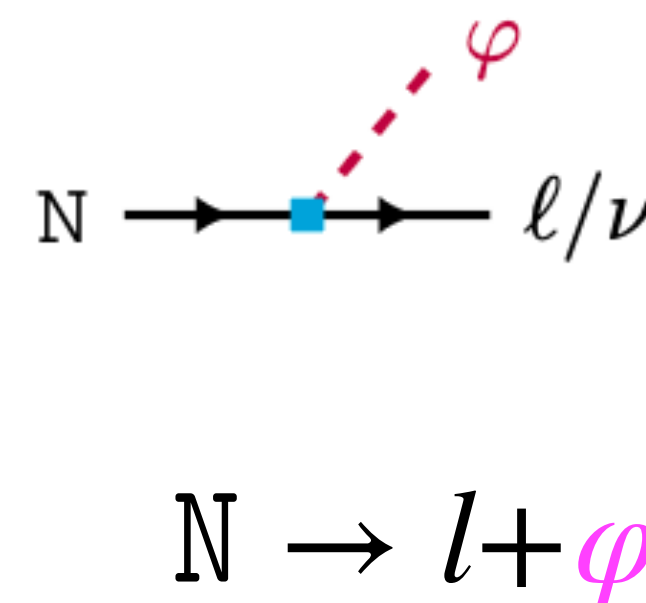
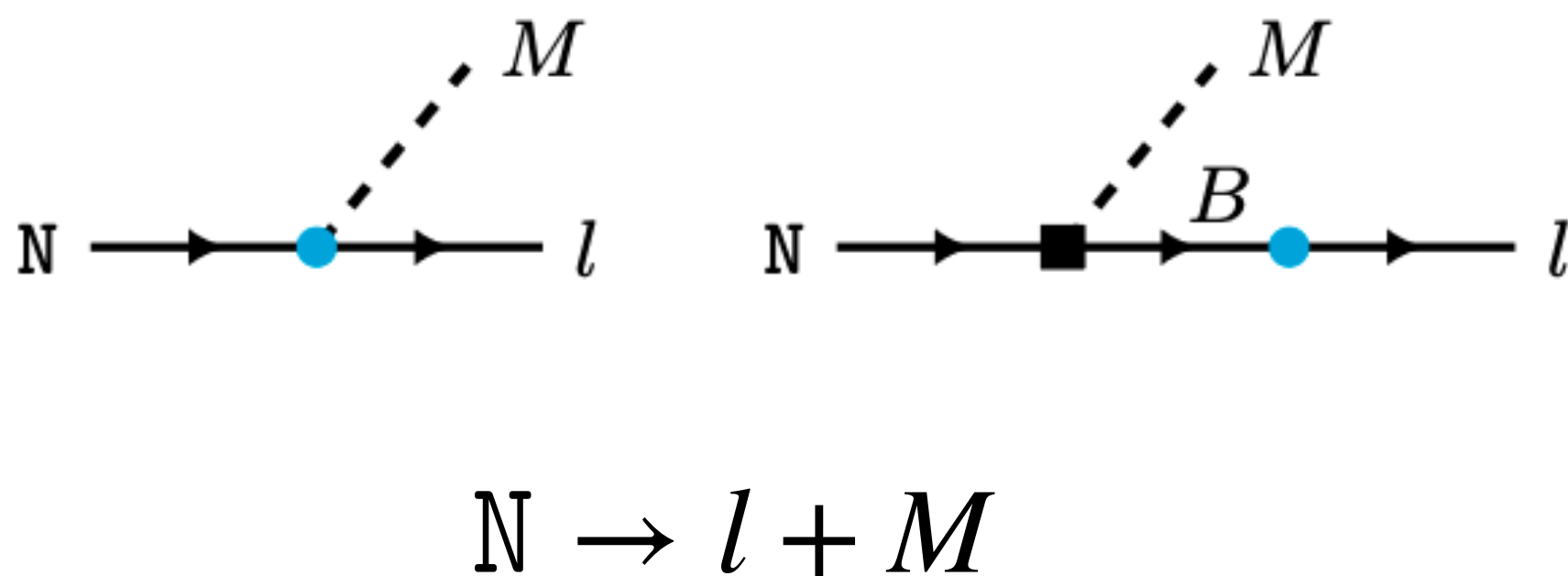
Taking these spurion fields into the BNV chiral Lagrangian and expanding to proper order in meson fields to obtain various desired interaction vertices.

Applications to various decay modes

$\mathcal{L}_B$ + standard ChPT interactions + $\mathcal{L}_{\text{SM,EW}}$

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

Expanding the chiral Lagrangian $\longrightarrow \mathcal{L} \supset M^n(\mathcal{P}B) \longrightarrow$ Draw diagrams and calculate



General decay width expressions

Based on the LEFT plus ChPT formalism, we formulate general decay width expressions for $N \rightarrow l + \varphi/a/X$ and $N \rightarrow l + M + \varphi/a/X$ in terms of EFT WCs

$$\frac{\Gamma_{p \rightarrow e^+ \varphi}}{10^{-8} \text{ GeV}^7} = 147|C_{\varphi l u d}^{\text{LR},e}|^2 + 150|C_{\varphi l u d}^{\text{LL},e}|^2 - 298\Re(C_{\varphi l u d}^{\text{LR},e} C_{\varphi l u d}^{\text{LL},e*}) - 0.161C_{\varphi l u d}^{\text{LR},e} C_{\varphi l u d}^{\text{RL},e*} + 0.162(C_{\varphi l u d}^{\text{LR},e} C_{\varphi l u d}^{\text{RR},e*} + C_{\varphi l u d}^{\text{LL},e} C_{\varphi l u d}^{\text{RL},e*}) - 0.164C_{\varphi l u d}^{\text{LL},e} C_{\varphi l u d}^{\text{RR},e*} + L \leftrightarrow R,$$

$$\frac{\Gamma_{p \rightarrow \mu^+ \varphi}}{10^{-8} \text{ GeV}^7} = 147|C_{\varphi l u d}^{\text{LR},\mu}|^2 + 150|C_{\varphi l u d}^{\text{LL},\mu}|^2 - 298\Re(C_{\varphi l u d}^{\text{LR},\mu} C_{\varphi l u d}^{\text{LL},\mu*}) - 32.8C_{\varphi l u d}^{\text{LR},\mu} C_{\varphi l u d}^{\text{RL},\mu*} + 33.1(C_{\varphi l u d}^{\text{LR},\mu} C_{\varphi l u d}^{\text{RR},\mu*} + C_{\varphi l u d}^{\text{LL},\mu} C_{\varphi l u d}^{\text{RL},\mu*}) - 33.4C_{\varphi l u d}^{\text{LL},\mu} C_{\varphi l u d}^{\text{RR},\mu*} + L \leftrightarrow R,$$

$$\frac{\Gamma_{p \rightarrow e^+ \pi^0 \varphi}}{10^{-8} \text{ GeV}^7} = 27.2|C_{\varphi l u d}^{\text{LR},e}|^2 + 27.7|C_{\varphi l u d}^{\text{LL},e}|^2 - 55\Re(C_{\varphi l u d}^{\text{LR},e} C_{\varphi l u d}^{\text{LL},e*}) - 0.0035C_{\varphi l u d}^{\text{LR},e} C_{\varphi l u d}^{\text{RL},e*} + 0.0035(C_{\varphi l u d}^{\text{LR},e} C_{\varphi l u d}^{\text{RR},e*} + C_{\varphi l u d}^{\text{LL},e} C_{\varphi l u d}^{\text{RL},e*}) - 0.0036C_{\varphi l u d}^{\text{LL},e} C_{\varphi l u d}^{\text{RR},e*} + L \leftrightarrow R,$$

$$\frac{\Gamma_{p \rightarrow \mu^+ \pi^0 \varphi}}{10^{-8} \text{ GeV}^7} = 25.6|C_{\varphi l u d}^{\text{LR},\mu}|^2 + 26.1|C_{\varphi l u d}^{\text{LL},\mu}|^2 - 51.6\Re(C_{\varphi l u d}^{\text{LR},\mu} C_{\varphi l u d}^{\text{LL},\mu*}) - 0.58C_{\varphi l u d}^{\text{LR},\mu} C_{\varphi l u d}^{\text{RL},\mu*} + 0.59(C_{\varphi l u d}^{\text{LR},\mu} C_{\varphi l u d}^{\text{RR},\mu*} + C_{\varphi l u d}^{\text{LL},\mu} C_{\varphi l u d}^{\text{RL},\mu*}) - 0.60C_{\varphi l u d}^{\text{LL},\mu} C_{\varphi l u d}^{\text{RR},\mu*} + L \leftrightarrow R,$$

+ ...

$$\frac{\Gamma_{p \rightarrow e^+ X}}{(0.1 \text{ GeV})^9} = 1300|C_{X l u d}^{\text{VL},\text{SL},e}|^2 + 1300|C_{X l u d}^{\text{SL},\text{VR},e}|^2 + 50\kappa_3^2(|C_{X l u d}^{\text{SL},\text{VR},e}|^2 + |C_{X l u d}^{\text{SL},\text{VR},e}|^2) + 2600\Re(C_{X l u d}^{\text{SL},\text{VR},e} C_{X l u d}^{\text{VR},\text{SR},e*}) + 510\kappa_3\Re((C_{X l u d}^{\text{SL},\text{VR},e} - C_{X l u d}^{\text{SL},\text{VR},e}) C_{X l u d}^{\text{VR},\text{SR},e*}) + 510\kappa_3\Re((C_{X l u d}^{\text{SL},\text{VR},e} - C_{X l u d}^{\text{SL},\text{VR},e}) C_{X l u d}^{\text{SL},\text{VR},e*}) - 99\kappa_3^2\Re(C_{X l u d}^{\text{SL},\text{VR},e} C_{X l u d}^{\text{SL},\text{VR},e*}) + 0.6\kappa_3\Re((C_{X l u d}^{\text{SL},\text{VR},e} - C_{X l u d}^{\text{SL},\text{VR},e}) C_{X l u d}^{\text{VL},\text{SL},e*}) + 0.2\kappa_3^2\Re(C_{X l u d}^{\text{SL},\text{VR},e} C_{X l u d}^{\text{SR},\text{VL},e*}) - 0.5\kappa_3\Re((C_{X l u d}^{\text{SL},\text{VR},e} - C_{X l u d}^{\text{SL},\text{VR},e}) C_{X l u d}^{\text{SR},\text{VL},e*}) - 0.1\kappa_3^2\Re(C_{X l u d}^{\text{SL},\text{VR},e} C_{X l u d}^{\text{SR},\text{VL},e*}) - 0.1\kappa_3^2\Re(C_{X l u d}^{\text{SL},\text{VR},e} C_{X l u d}^{\text{SR},\text{VL},e*}) + L \leftrightarrow R,$$

$$\frac{\Gamma_{p \rightarrow \mu^+ X}}{(0.1 \text{ GeV})^9} = 1300|C_{X l u d}^{\text{VL},\text{SL},\mu}|^2 + 1200|C_{X l u d}^{\text{SL},\text{VR},\mu}|^2 + 50\kappa_3^2(|C_{X l u d}^{\text{SL},\text{VR},\mu}|^2 + |C_{X l u d}^{\text{SL},\text{VR},\mu}|^2) + 2500\Re(C_{X l u d}^{\text{SL},\text{VR},\mu} C_{X l u d}^{\text{VR},\text{SR},\mu*}) - 490\kappa_3\Re((C_{X l u d}^{\text{SL},\text{VR},\mu} - C_{X l u d}^{\text{SL},\text{VR},\mu}) C_{X l u d}^{\text{VR},\text{SR},\mu*}) - 490\kappa_3\Re((C_{X l u d}^{\text{SL},\text{VR},\mu} - C_{X l u d}^{\text{SL},\text{VR},\mu}) C_{X l u d}^{\text{SL},\text{VR},\mu*}) - 100\kappa_3^2\Re(C_{X l u d}^{\text{SL},\text{VR},\mu} C_{X l u d}^{\text{SL},\text{VR},\mu*}) - 110\kappa_3\Re((C_{X l u d}^{\text{SL},\text{VR},\mu} - C_{X l u d}^{\text{SL},\text{VR},\mu}) C_{X l u d}^{\text{VL},\text{SL},\mu*}) + 43\kappa_3^2\Re(C_{X l u d}^{\text{SL},\text{VR},\mu} C_{X l u d}^{\text{SR},\text{VL},\mu*}) - 110\kappa_3\Re((C_{X l u d}^{\text{SL},\text{VR},\mu} - C_{X l u d}^{\text{SL},\text{VR},\mu}) C_{X l u d}^{\text{SR},\text{VL},\mu*}) - 22\kappa_3^2\Re(C_{X l u d}^{\text{SL},\text{VR},\mu} C_{X l u d}^{\text{SR},\text{VL},\mu*}) - 22\kappa_3^2\Re(C_{X l u d}^{\text{SL},\text{VR},\mu} C_{X l u d}^{\text{SR},\text{VL},\mu*}) + L \leftrightarrow R,$$

+ ...

NP? $\Rightarrow$ SMEFT? $\Rightarrow$
To be done

LEFT $\Rightarrow$ ChPT $\Rightarrow$ $\Gamma(N \rightarrow \dots) = \sum a_{ij} C_i C_j^*$
Done

Nucleon decay with a light scalar: $N \rightarrow l + \varphi, N \rightarrow l + M + \varphi$

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

Dim-7 in φ SMEFT

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

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

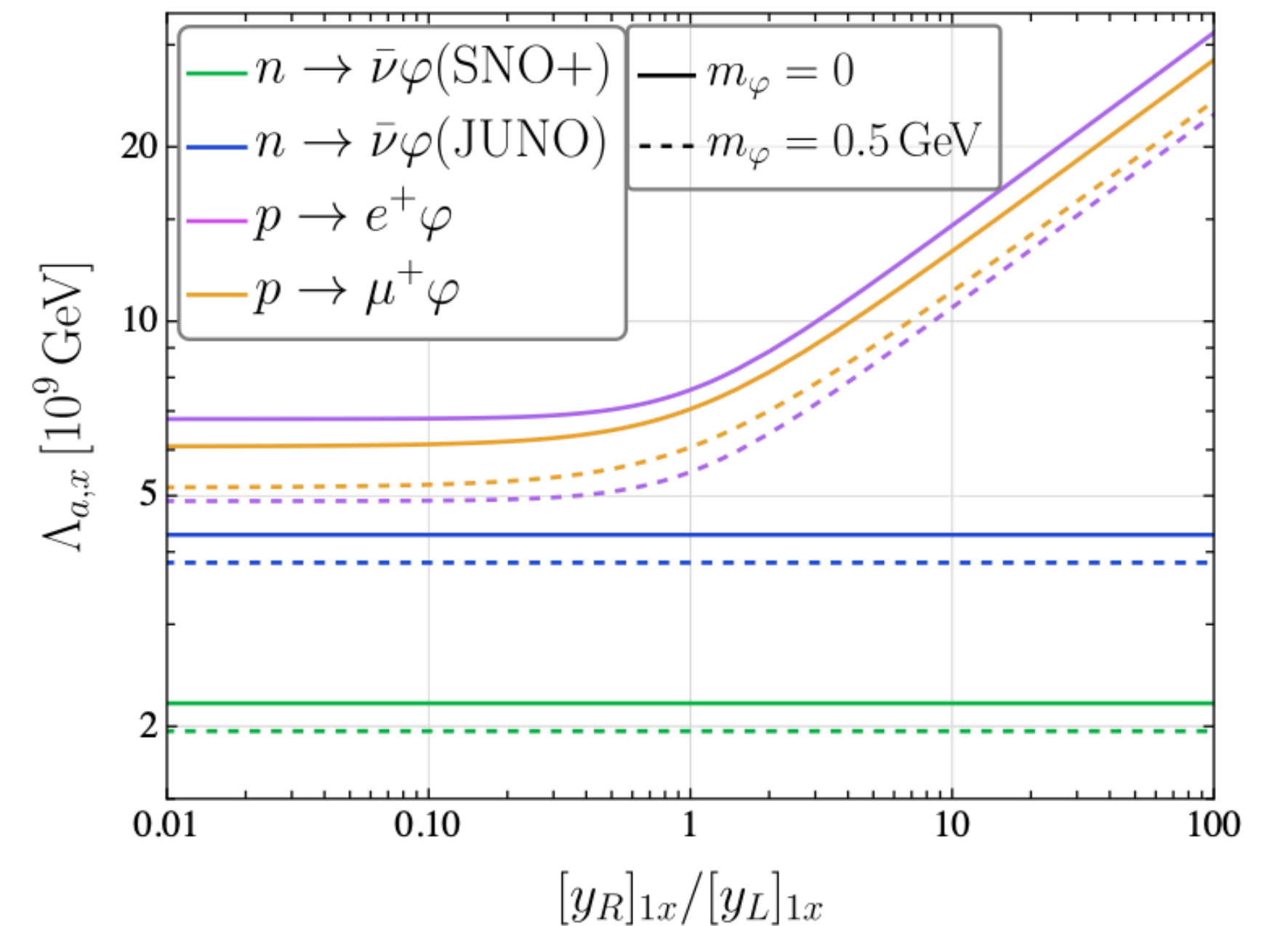
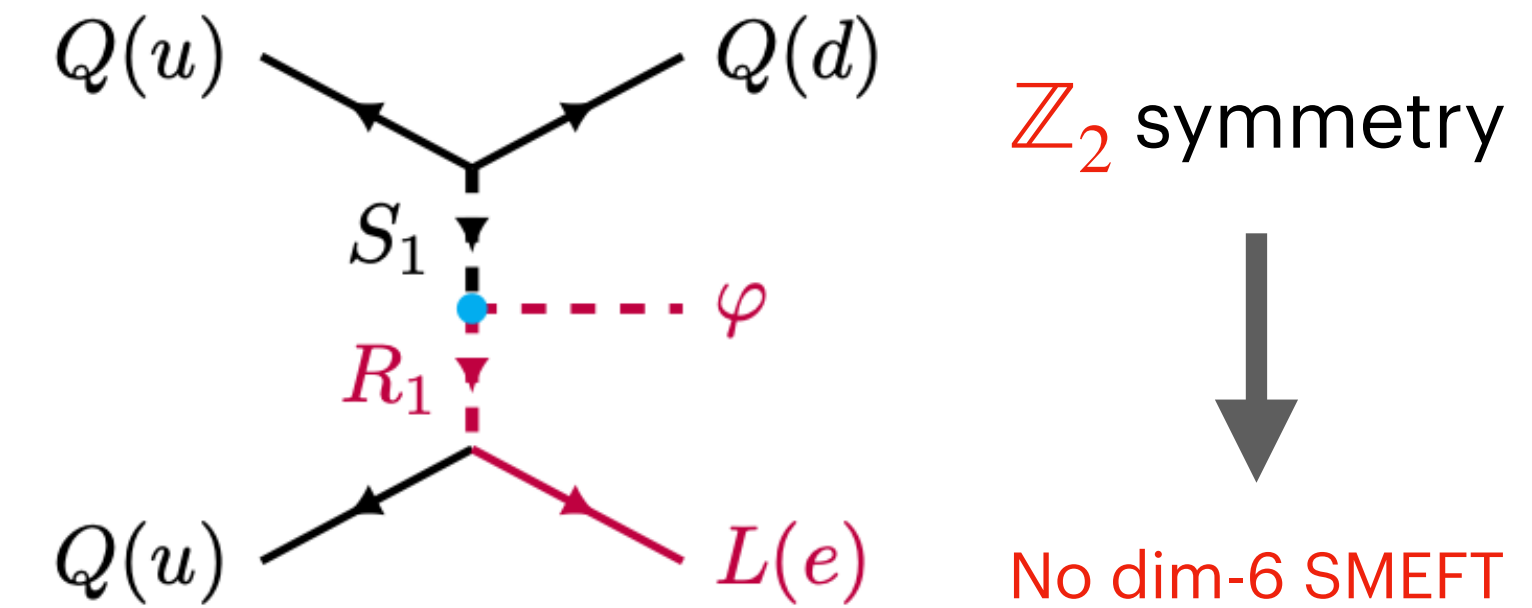
$$C_{euQQ\varphi}^{prst} = -\frac{\kappa^* [y_R]_{rp} [z_L]_{st}}{m_S^2 m_R^2},$$

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

Dim-7 in φ LEFT

$$C_{\varphi\nu dud}^{\text{LR},x} = 1.32 \frac{\kappa^* [y_L]_{1x} [z_R]_{11}}{m_S^2 m_R^2}, \quad C_{\varphi l u u d}^{\text{LR},x} = -C_{\varphi\nu dud}^{\text{LR},x}, \quad C_{\varphi l u u d}^{\text{RL},x} = -1.32 \frac{2\kappa^* [y_R]_{1x} [z_L]_{11}}{m_S^2 m_R^2},$$

$$C_{\varphi\nu dud}^{\text{LL},x} = 1.32 \frac{2\kappa^* [y_L]_{1x} [z_L]_{11}}{m_S^2 m_R^2}, \quad C_{\varphi l u u d}^{\text{LL},x} = -C_{\varphi\nu dud}^{\text{LL},x}, \quad C_{\varphi l u u d}^{\text{RR},x} = -1.32 \frac{\kappa^* [y_R]_{1x} [z_R]_{11}}{m_S^2 m_R^2},$$



Nucleon decays with a dark photon: $N \rightarrow l + X, N \rightarrow l + M + X$

Case A	$\mathcal{O}_{Xl\bar{u}ud}^{VL,SL}$ $\mathcal{O}_{Xl\bar{u}d}^{SL,VR-}$ $\mathcal{O}_{Xl\bar{u}d}^{SL,VR+}$ $\mathcal{O}_{Xl\bar{u}d}^{SL,VR}$	$\mathcal{O}_{Xl\bar{u}ud}^{VR,SR,x}$ $\mathcal{O}_{Xl\bar{u}d}^{SR,VL-}$ $\mathcal{O}_{Xl\bar{u}d}^{SR,VL+}$ $\mathcal{O}_{Xl\bar{u}d}^{SR,VL}$	$\mathcal{O}_{Xl\bar{u}s}^{VL,SL}$ $\mathcal{O}_{Xl\bar{u}s}^{SL,VR-}$ $\mathcal{O}_{Xl\bar{u}s}^{SL,VR+}$ $\mathcal{O}_{Xl\bar{u}s}^{SL,VR}$	$\mathcal{O}_{Xl\bar{u}s}^{VR,SR}$ $\mathcal{O}_{Xl\bar{u}s}^{SR,VL-}$ $\mathcal{O}_{Xl\bar{u}s}^{SR,VL+}$ $\mathcal{O}_{Xl\bar{u}s}^{SR,VL}$	$\mathcal{O}_{Xl\bar{d}dd}^{SL,VR}$ $\mathcal{O}_{Xl\bar{d}dd}^{SR,VL}$	$\mathcal{O}_{Xl\bar{d}ds}^{VL,SL}$ $\mathcal{O}_{Xl\bar{d}s}^{SL,VR-}$ $\mathcal{O}_{Xl\bar{d}s}^{SL,VR+}$ $\mathcal{O}_{Xl\bar{d}s}^{SL,VR}$	$\mathcal{O}_{Xl\bar{d}ds}^{VR,SR}$ $\mathcal{O}_{Xl\bar{d}s}^{SR,VL-}$ $\mathcal{O}_{Xl\bar{d}s}^{SR,VL+}$ $\mathcal{O}_{Xl\bar{d}s}^{SR,VL}$	$\mathcal{O}_{Xl\bar{v}ddu}^{VL,SL}$ $\mathcal{O}_{Xl\bar{v}udd}^{SR,VL-}$ $\mathcal{O}_{Xl\bar{v}udd}^{SR,VL+}$ $\mathcal{O}_{Xl\bar{v}ddu}^{SR,VL}$	$\mathcal{O}_{Xl\bar{v}ddu}^{VR,SR}$ $\mathcal{O}_{Xl\bar{v}udd}^{SL,VR-}$ $\mathcal{O}_{Xl\bar{v}udd}^{SL,VR+}$ $\mathcal{O}_{Xl\bar{v}ddu}^{SL,VR}$	$\mathcal{O}_{Xl\bar{v}dsu}^{VL,SL}$ $\mathcal{O}_{Xl\bar{v}uds}^{SR,VL-}$ $\mathcal{O}_{Xl\bar{v}dsu}^{SR,VL-}$ $\mathcal{O}_{Xl\bar{v}uds}^{SR,VL+}$	$\mathcal{O}_{Xl\bar{v}dsu}^{VR,SR}$ $\mathcal{O}_{Xl\bar{v}sdu}^{SL,VR-}$ $\mathcal{O}_{Xl\bar{v}dsu}^{SL,VR-}$ $\mathcal{O}_{Xl\bar{v}sdu}^{SL,VR+}$	$\mathcal{O}_{Xl\bar{v}dsu}^{VR,SR}$ $\mathcal{O}_{Xl\bar{v}sdu}^{SL,VR-}$ $\mathcal{O}_{Xl\bar{v}dsu}^{SL,VR-}$ $\mathcal{O}_{Xl\bar{v}sdu}^{SL,VR+}$
Case B	$\tilde{\mathcal{O}}_{Xl\bar{u}ud}^{TL,SL}$ $\tilde{\mathcal{O}}_{Xl\bar{u}d}^{VL,VR-}$ $\tilde{\mathcal{O}}_{Xl\bar{u}d}^{VL,VR+}$ $\tilde{\mathcal{O}}_{Xl\bar{u}d}^{VL,VR}$ $\tilde{\mathcal{O}}_{Xl\bar{u}d}^{SL,TL}$	$\tilde{\mathcal{O}}_{Xl\bar{u}ud}^{TR,SR}$ $\tilde{\mathcal{O}}_{Xl\bar{u}d}^{VR,VL-}$ $\tilde{\mathcal{O}}_{Xl\bar{u}d}^{VR,VL+}$ $\tilde{\mathcal{O}}_{Xl\bar{u}d}^{VR,VL}$ $\tilde{\mathcal{O}}_{Xl\bar{u}d}^{SR,TR}$	$\tilde{\mathcal{O}}_{Xl\bar{u}s}^{TL,SL}$ $\tilde{\mathcal{O}}_{Xl\bar{u}s}^{TR,SR}$ $\tilde{\mathcal{O}}_{Xl\bar{u}s}^{VL,VR-}$ $\tilde{\mathcal{O}}_{Xl\bar{u}s}^{VL,VR+}$ $\tilde{\mathcal{O}}_{Xl\bar{u}s}^{VL,VR}$ $\tilde{\mathcal{O}}_{Xl\bar{u}s}^{SL,TL}$	$\tilde{\mathcal{O}}_{Xl\bar{u}s}^{VR,SR}$ $\tilde{\mathcal{O}}_{Xl\bar{u}s}^{SR,VL-}$ $\tilde{\mathcal{O}}_{Xl\bar{u}s}^{SR,VL+}$ $\tilde{\mathcal{O}}_{Xl\bar{u}s}^{SR,VL}$ $\tilde{\mathcal{O}}_{Xl\bar{u}s}^{SR,TR}$	$\tilde{\mathcal{O}}_{Xl\bar{d}dd}^{VL,VR}$ $\tilde{\mathcal{O}}_{Xl\bar{d}dd}^{SR,TR}$	$\tilde{\mathcal{O}}_{Xl\bar{d}ds}^{TL,SL}$ $\tilde{\mathcal{O}}_{Xl\bar{d}s}^{VL,VR-}$ $\tilde{\mathcal{O}}_{Xl\bar{d}s}^{VL,VR+}$ $\tilde{\mathcal{O}}_{Xl\bar{d}s}^{VL,VR}$ $\tilde{\mathcal{O}}_{Xl\bar{d}s}^{SL,TL}$	$\tilde{\mathcal{O}}_{Xl\bar{d}ds}^{TR,SR}$ $\tilde{\mathcal{O}}_{Xl\bar{d}s}^{VR,VL-}$ $\tilde{\mathcal{O}}_{Xl\bar{d}s}^{VR,VL+}$ $\tilde{\mathcal{O}}_{Xl\bar{d}s}^{VR,VL}$ $\tilde{\mathcal{O}}_{Xl\bar{d}s}^{SR,TR}$	$\tilde{\mathcal{O}}_{Xl\bar{v}ddu}^{TR,SR}$ $\tilde{\mathcal{O}}_{Xl\bar{v}udd}^{VL,VR-}$ $\tilde{\mathcal{O}}_{Xl\bar{v}udd}^{VL,VR+}$ $\tilde{\mathcal{O}}_{Xl\bar{v}ddu}^{VL,VR}$ $\tilde{\mathcal{O}}_{Xl\bar{v}udd}^{SR,TR}$	$\tilde{\mathcal{O}}_{Xl\bar{v}ddu}^{TL,SL}$ $\tilde{\mathcal{O}}_{Xl\bar{v}udd}^{VR,VL-}$ $\tilde{\mathcal{O}}_{Xl\bar{v}udd}^{VR,VL+}$ $\tilde{\mathcal{O}}_{Xl\bar{v}ddu}^{VR,VL}$ $\tilde{\mathcal{O}}_{Xl\bar{v}udd}^{SL,TL}$	$\tilde{\mathcal{O}}_{Xl\bar{v}dsu}^{TR,SR}$ $\tilde{\mathcal{O}}_{Xl\bar{v}uds}^{VL,VR-}$ $\tilde{\mathcal{O}}_{Xl\bar{v}dsu}^{VL,VR-}$ $\tilde{\mathcal{O}}_{Xl\bar{v}uds}^{VL,VR+}$ $\tilde{\mathcal{O}}_{Xl\bar{v}dsu}^{VL,VR+}$ $\tilde{\mathcal{O}}_{Xl\bar{v}uds}^{SR,TR}$	$\tilde{\mathcal{O}}_{Xl\bar{v}dsu}^{TR,SR}$ $\tilde{\mathcal{O}}_{Xl\bar{v}sdu}^{VL,VR-}$ $\tilde{\mathcal{O}}_{Xl\bar{v}dsu}^{VL,VR-}$ $\tilde{\mathcal{O}}_{Xl\bar{v}sdu}^{VL,VR+}$ $\tilde{\mathcal{O}}_{Xl\bar{v}dsu}^{VL,VR+}$ $\tilde{\mathcal{O}}_{Xl\bar{v}sdu}^{SR,TR}$	$\tilde{\mathcal{O}}_{Xl\bar{v}dsu}^{TL,SL}$ $\tilde{\mathcal{O}}_{Xl\bar{v}sdu}^{VR,VL-}$ $\tilde{\mathcal{O}}_{Xl\bar{v}dsu}^{VR,VL-}$ $\tilde{\mathcal{O}}_{Xl\bar{v}sdu}^{VR,VL+}$ $\tilde{\mathcal{O}}_{Xl\bar{v}dsu}^{VR,VL+}$ $\tilde{\mathcal{O}}_{Xl\bar{v}sdu}^{SL,TL}$
Nucleon decay modes	$p \rightarrow e^+ X$ (✓) $p \rightarrow \mu^+ X$ (✓) $p \rightarrow e^+ \pi^0 X$ $p \rightarrow \mu^+ \pi^0 X$ $p \rightarrow e^+ \eta X$ $p \rightarrow \mu^+ \eta X$ $n \rightarrow e^+ \pi^- X$ $n \rightarrow \mu^+ \pi^- X$	$p \rightarrow e^+ K^0 X$ (✓) $p \rightarrow \mu^+ K^0 X$ (✓)	$n \rightarrow e^- \pi^+ X$ (✓) $n \rightarrow \mu^- \pi^+ X$ (✓)	$n \rightarrow e^- K^+ X$ (✓) $n \rightarrow \mu^- K^+ X$ (✓)	$n \rightarrow \hat{\nu}_x X$ $p \rightarrow \hat{\nu}_x \pi^+ X$ $n \rightarrow \hat{\nu}_x \pi^0 X$ (✓) $n \rightarrow \hat{\nu}_x \eta X$	$p \rightarrow \hat{\nu}_x K^+ X$ (✓) $n \rightarrow \hat{\nu}_x K^0 X$						

Reinterpretation of existing Super-K data

- Except for $p \rightarrow e^+ + X$ and $p \rightarrow \mu^+ + X$, all other modes have not yet been searched for experimentally

(Dated: September 1, 2026)

The Super-Kamiokande,
arXiv:2608.30361v1

A search for proton decay via $p \rightarrow l^+ + X$, where l^+ is a positively charged lepton and X is an invisible, massless, neutral particle, was performed using a 401 kton-years exposure representing the entire pure water phase of Super-Kamiokande. No significant indication of a proton decay was observed beyond the expected atmospheric neutrino background. Lower limits on the partial lifetime of the proton were set to at 1.72×10^{33} years for $p \rightarrow e^+ + X$ and 0.61×10^{33} years for $p \rightarrow \mu^+ + X$ at the 90% confidence level. These results improve on previous limits by factors of 2 and 1.5, respectively.

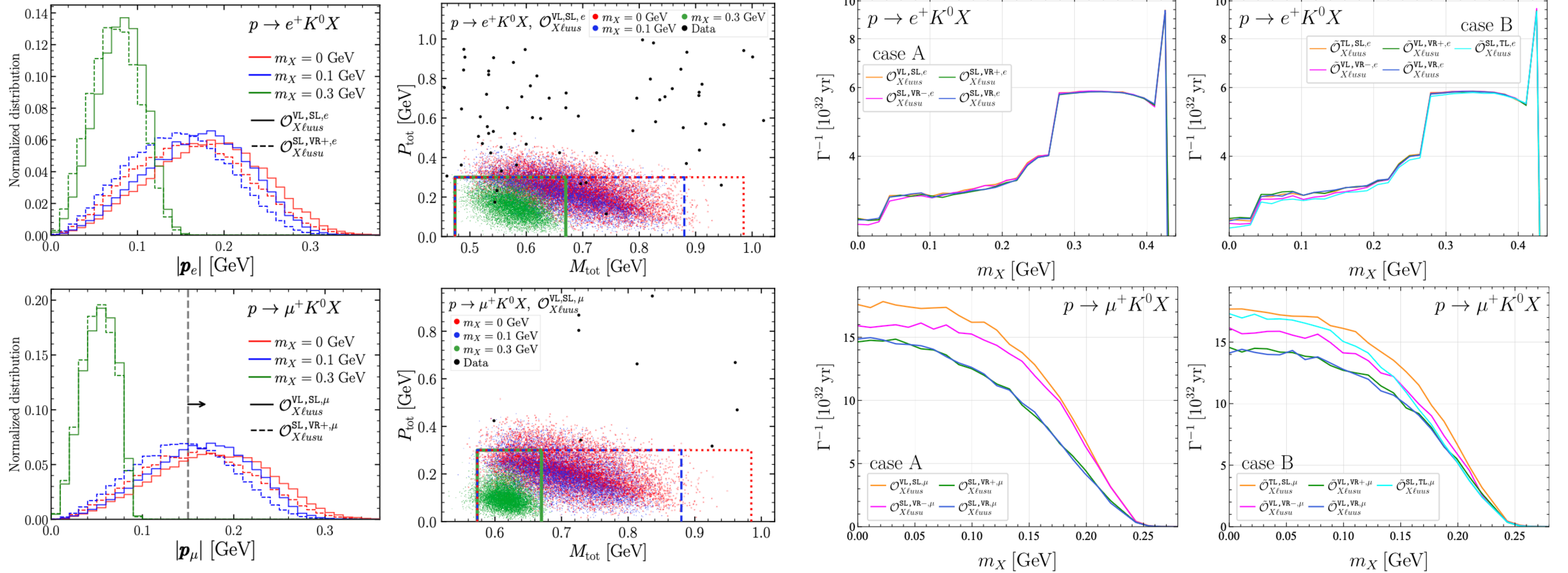
- Similarity in the experimental signatures between conventional modes $N \rightarrow l + M$ and $N \rightarrow l + M + X$



- The existing experimental data from two-body searches can be reinterpreted to constrain the exotic three-body modes
- Use existing Super-K data to set bounds on

$$p \rightarrow \ell^+ K^0 X, n \rightarrow \ell^- \pi^+ X, n \rightarrow \ell^- K^+ X, n \rightarrow \nu \pi^0 X, \text{ and } p \rightarrow \nu K^+ X$$

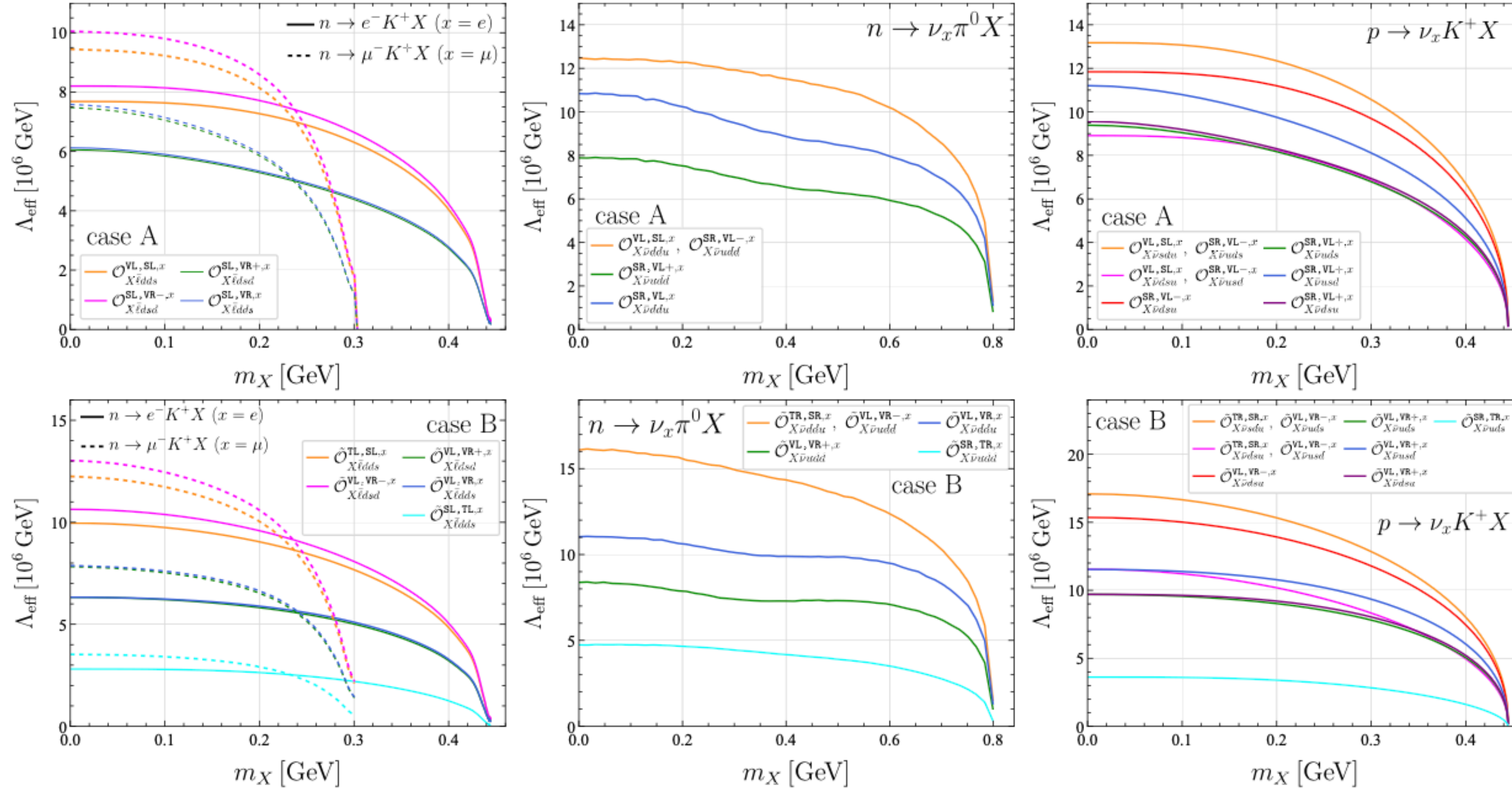
Recasting bounds on their partial lifetimes



Consider initial-state nuclear effects + final-state intranuclear interactions + detector resolutions

Lifetime bounds: $10^{32} - 10^{33}$ yr

Constraints on the WCs associated with various XLEFT operators



$$C_A = \frac{m_X}{\Lambda_{\text{eff}}^4}$$

$$C_B = \frac{1}{\Lambda_{\text{eff}}^4}$$

The energy scales are constrained to be above 1000 TeV, reflecting the high sensitivity of nucleon decays in probing new physics.

Summary

- A systematic EFT framework is established for three types of nucleon decay scenarios: a light scalar, an ALP, and a dark photon;
- General triple-quark chiral structures are identified: $\bar{\mathbf{3}}_{L(R)} \otimes \mathbf{3}_{R(L)}$, $\mathbf{8}_{L(R)} \otimes \mathbf{1}_{R(L)}$, $\mathbf{6}_{L(R)} \otimes \mathbf{3}_{R(L)}$ and $\mathbf{10}_{L(R)} \otimes \mathbf{1}_{R(L)}$;
- Within the LEFT+ChPT, the decay widths for the 2- and 3-body nucleon decay modes into an invisible particle are formulated;
- Existing experimental data are used to set stringent limits on those exotic modes;
- The developed theoretical framework can facilitate both theoretical and experimental studies for the BNV nucleon decays.

Thank you for your time!