BNV nucleon decay in ALP EFTs

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Outline

- Nucleon decay and axion-like particle (ALP)
- ALP EFTs with baryon number violation (BNV)
- BNV nucleon decay to ALP and constraints
- Summary

Nucleon decay and ALP

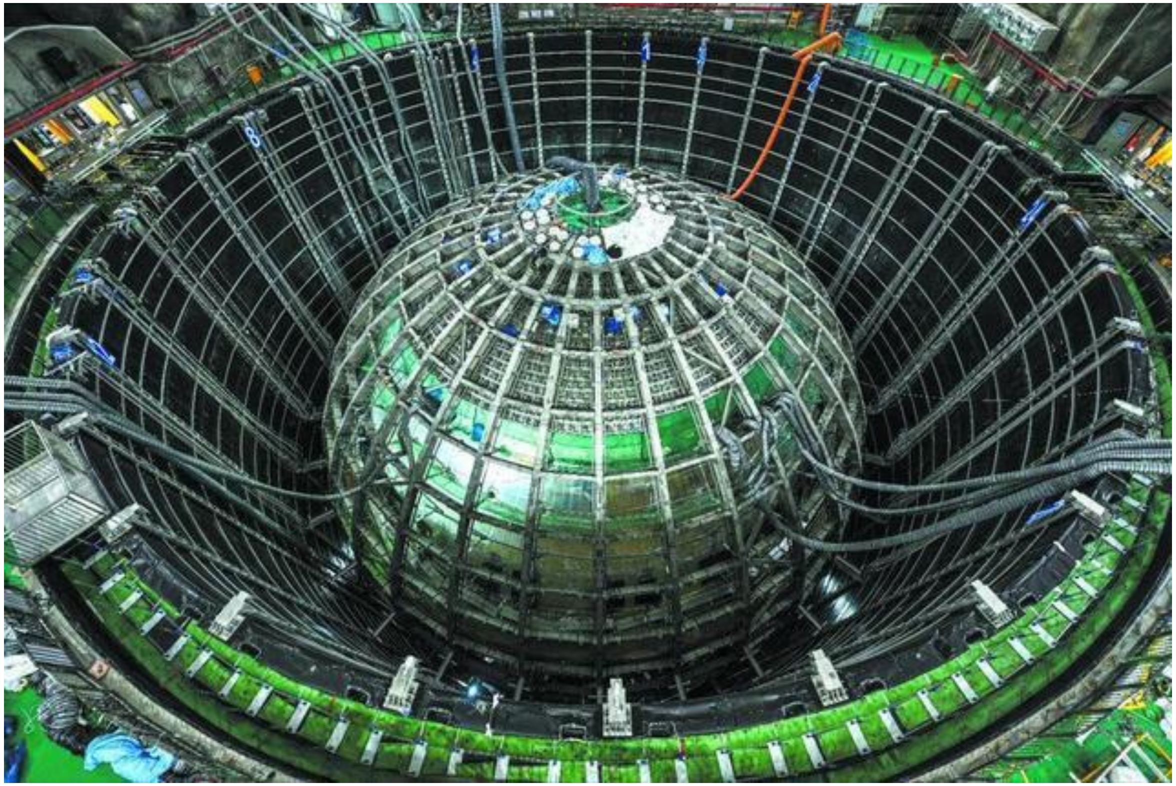
- The baryon number as a conserved global symmetry in the SM and the stability of proton
- Any observation of BNV in proton decay would imply NP beyond the SM and matter-antimatter asymmetry
- BNV predicted in GUTs or SUSY
- Super-K/Hyper-K, DUNE or JUNO probe BNV nucleon decays, e.g. $p \to e^+\pi^0$ Super-K, arXiv: 2010.16098

Process	$\lvert\Delta(B-L)\rvert$	τ (10^{33} years)
$p \to \pi^0 \ell^+$	0	24 [16]
$p \to \eta^0 \ell^+$	0	10 [4.7]
$p \to K^+ \nu$	0, 2	6.61
$n \to \pi^- \ell^+$	0	5.3 [3.5]
$n \to \pi^0 \nu$	0, 2	1.1
$p \to K^0 \ell^+$	0	1 [1.6]
$p \to \pi^+ \nu$	0, 2	0.39
$n \to \eta^0 \nu$	0, 2	0.158
$n \to K^0 \nu$	0, 2	0.13
$n \to K^+ \ell^-$	2	0.032 [0.057]

- Sensitivity of neutrino experiments (e.g. JUNO)

large numbers of proton $N_p \sim 10^{33}$

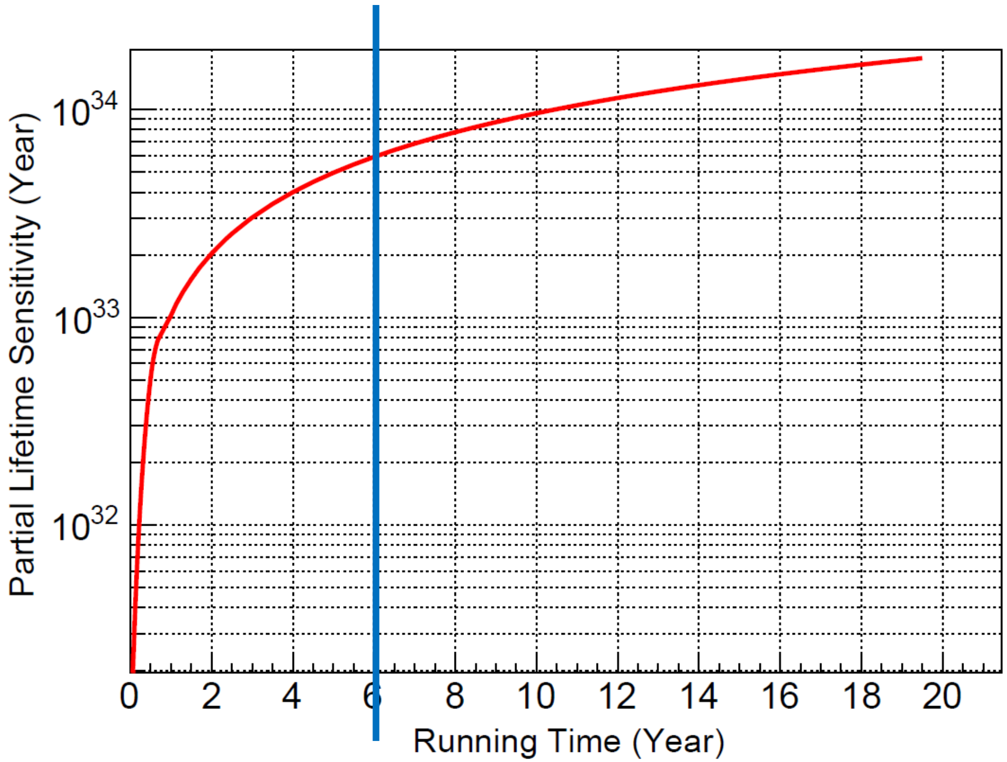
arXiv: 2212.08502



$$\tau/B(p \to \bar{\nu}K^+) = \frac{N_p T \epsilon}{n_{90}} > 9.6 \times 10^{33} \text{ years}$$

arXiv: 2212.08502

$$\epsilon = 36.9\%$$



- Lower limits on NP scale for SMEFT BNV operators:

$\sim 10^{15}$ GeV for dim-6

$$\mathcal{O}_{qqql,pqrs} = (Q_p^i Q_q^j)(Q_r^l L_s^k)\epsilon_{ik}\epsilon_{jl} \,, \quad \mathcal{O}_{qque,pqrs} = (Q_p^i Q_q^j)(\bar{u}_r^\dagger \bar{e}_s^\dagger)\epsilon_{ij} \,,$$
$$\mathcal{O}_{duue,pqrs} = (\bar{d}_p^\dagger \bar{u}_q^\dagger)(\bar{u}_r^\dagger \bar{e}_s^\dagger) \,, \quad \mathcal{O}_{duql,pqrs} = (\bar{d}_p^\dagger \bar{u}_q^\dagger)(Q_r^i L_s^j)\epsilon_{ij} \,.$$

$\sim 10^{11}$ GeV for dim-7

$$\mathcal{O}_{\bar{l}dddH,pqrs} = (L_p^\dagger \bar{d}_q^\dagger)(\bar{d}_r^\dagger \bar{d}_s^\dagger)H \,, \quad \mathcal{O}_{\bar{l}dqq\tilde{H},pqrs} = (L_p^\dagger \bar{d}_q^\dagger)(Q_r Q_s^i)\tilde{H}^j \epsilon_{ij} \,,$$
$$\mathcal{O}_{\bar{e}qdd\tilde{H},pqrs} = (\bar{e}_p Q_q^i)(\bar{d}_r^\dagger \bar{d}_s^\dagger)\tilde{H}^j \epsilon_{ij} \,, \quad \mathcal{O}_{\bar{l}dud\tilde{H},pqrs} = (L_p^\dagger \bar{d}_q^\dagger)(\bar{u}_r^\dagger \bar{d}_s^\dagger)\tilde{H} \,,$$

2312.13361

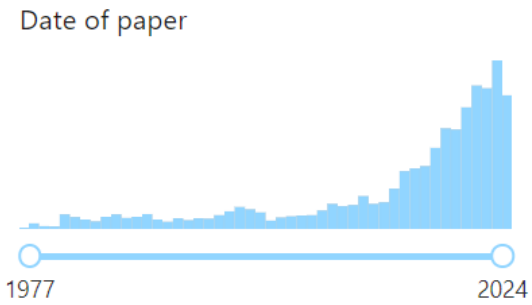
- BNV nucleon decay may offer a novel probe of dark sector particles:

$$\frac{(X u d d)_R}{M^2} \quad \Rightarrow \quad N \to X + \text{meson}$$ e.g. 1409.4823

$$\frac{\phi\,(u u d\,\ell)_R}{\Lambda^3} \quad \Rightarrow \quad N \to \phi + \ell$$ e.g. 2304.06071

- The new dark states may mimic the standard BNV decays with neutrinos ($N \to \nu + \text{meson}$) and provide distinct kinematics

A brief introduction to axion



- strong CP problem

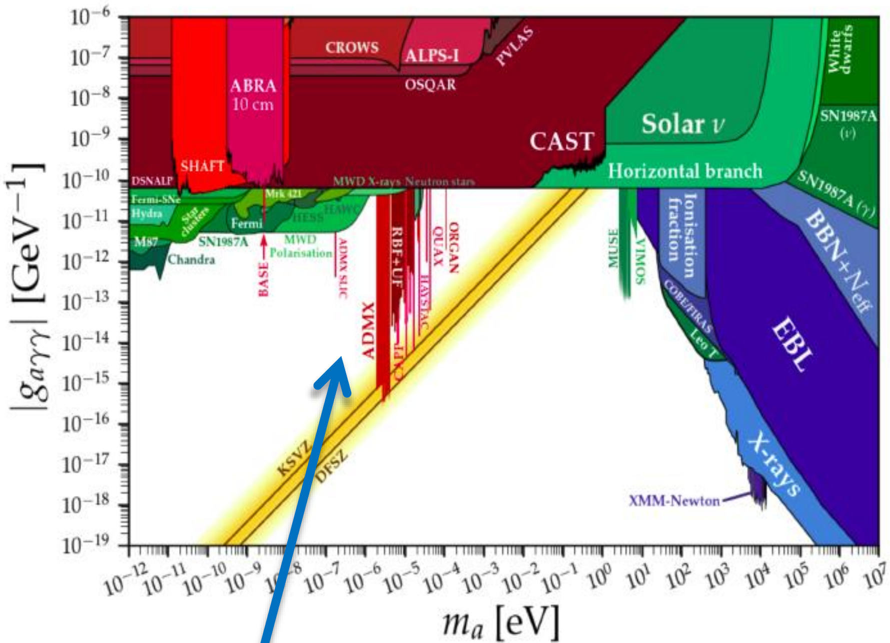
$$\theta \frac{g_s^2}{32\pi^2} G^{a\,\mu\nu} \tilde{G}^a_{\mu\nu} \xrightarrow{\text{nEDM}} \bar{\theta} \lesssim 10^{-10}$$

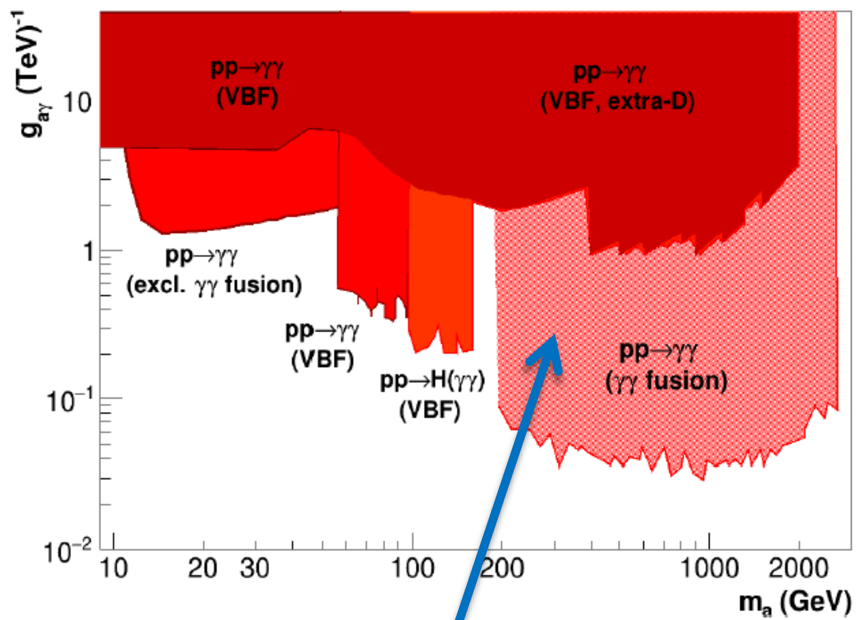
- Peccei-Quinn mechanism： $U(1)_{PQ}$

$$\frac{a}{f_a} \frac{g_s^2}{32\pi^2} G\tilde{G} \longrightarrow \bar{\theta} \to \bar{\theta} + \frac{a}{f_a} \qquad m_a \simeq 6 \cdot 10^{-6}\ \text{eV}\ \frac{10^{12}\ \text{GeV}}{f_a}$$

- candidate of cold dark matter
- a portal to topology, symmetry, QFT, DM, astro/cosmo, detection and etc.

abundant phenomenology





≲ μeV
2406.11382
2401.14195
2312.01355
2304.12525
2305.01344
2211.06847

~keV-MeV
2410.17591
2208.02696

~TeV
2406.13234
2402.14232
2203.05484

BNV nucleon decay to invisible ALP

ALP EFTs with BNV

- EFTs with a light degree of freedom (ALP)

H. Song, H. Sun, J.-H. Yu, 2305.16770, 2306.05999
C. Grojean, J. Kley, C.-Y. Yao, 2307.08563

➢ aSMEFT: extended SMEFT with a light ALP respecting shift symmetry between NP scale Λ and EW scale

dimension-8 BNV operators with $|\Delta(B-L)| = 2$:

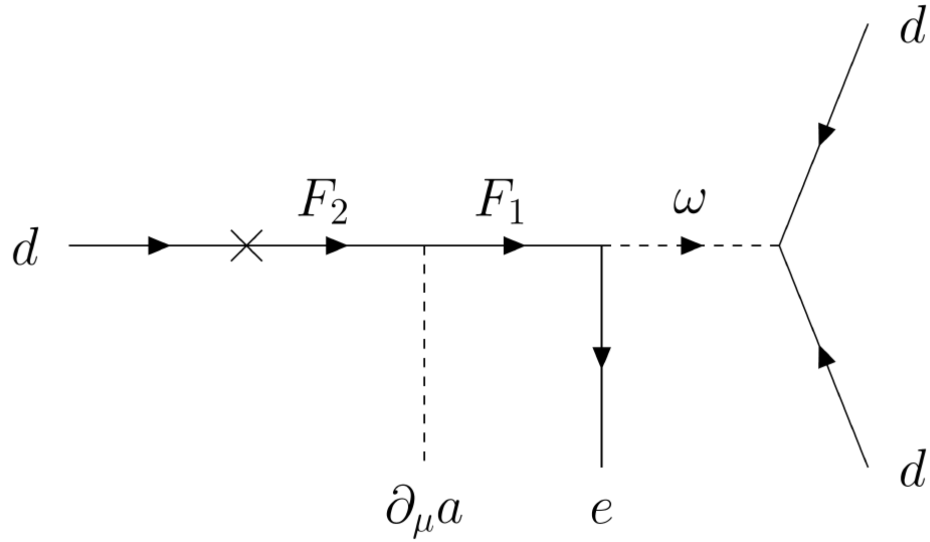
$$\mathcal{O}_{\partial aLQd} = \epsilon^{\alpha\beta\gamma}\partial_\mu a(\bar{L}d_\alpha)(\bar{Q}^c_\beta\gamma^\mu d_\gamma)\ , \quad \mathcal{O}_{\partial aed} = \epsilon^{\alpha\beta\gamma}\partial_\mu a(\bar{d}^c_\alpha d_\beta)(\bar{e}\gamma^\mu d_\gamma)$$

only exists for $N_f \neq 1$

An ad-hoc model for $\mathcal{O}_{\partial aed} = \epsilon^{\alpha\beta\gamma}\partial_\mu a(\bar{d}^c_\alpha d_\beta)(\bar{e}\gamma^\mu d_\gamma)$

- scalar diquark $\omega \sim (3,1,2/3)$
- two vector-like fermions $F_i \sim (3,1,-1/3), i = 1,2$

$$\mathcal{L} = y_{1,ij}\omega\bar{d}^c_i d_j + m_{Fd,k}\overline{F_{2L}}d_k + y_{2,l}\omega^\dagger\bar{e}_l F_{1L} + \frac{\partial_\mu a}{\Lambda}\overline{F_{1L}}C_{12}\gamma^\mu F_{2L} + \text{h.c.}\ .$$



➢ aLEFT: extended LEFT with a derivatively coupled $\partial_\mu a$

dimension-8 BNV operators:

Name	Operator with $\lvert\Delta(B-L)\rvert = 2$	
$\tilde{\mathcal{O}}^{VR,SR}_{\partial aeddd}$	$\partial_\mu a \epsilon^{\alpha\beta\gamma}(\bar{e}_L d_{R,\alpha})(\bar{d}^c_{L,\beta}\gamma^\mu d_{R,\gamma})$	
$\mathcal{O}^{VL,SR}_{\partial addde}$	$\partial_\mu a \epsilon^{\alpha\beta\gamma}(\bar{d}_{L,\alpha}\gamma^\mu d^c_{R,\beta})(\bar{d}_{L,\gamma} e_R)$	
$\mathcal{O}^{VL,SL}_{\partial a\nu ddu}$	$\partial_\mu a \epsilon^{\alpha\beta\gamma}(\bar{\nu}_L\gamma^\mu d_{L,\alpha})(\bar{d}^c_{L,\beta} u_{L,\gamma})$	✓
$\mathcal{O}^{VR,SR}_{\partial aud\nu d}$	$\partial_\mu a \epsilon^{\alpha\beta\gamma}(\bar{u}^c_{L,\alpha}\gamma^\mu d_{R,\beta})(\bar{\nu}_L d_{R,\gamma})$	
$\mathcal{O}^{VR,SR}_{\partial add\nu u}$	$\partial_\mu a \epsilon^{\alpha\beta\gamma}(\bar{d}^c_{L,\alpha}\gamma^\mu d_{R,\beta})(\bar{\nu}_L u_{R,\gamma})$	
$\mathcal{O}^{VR,SR}_{\partial adu\nu d}$	$\partial_\mu a \epsilon^{\alpha\beta\gamma}(\bar{d}^c_{L,\alpha}\gamma^\mu u_{R,\beta})(\bar{\nu}_L d_{R,\gamma})$	
$\mathcal{O}^{VL,SL}_{\partial aeddd}$	$\partial_\mu a \epsilon^{\alpha\beta\gamma}(\bar{e}_L\gamma^\mu d_{L,\alpha})(\bar{d}^c_{L,\beta} d_{L,\gamma})$	✓⋆
$\mathcal{O}^{VR,SR}_{\partial aeddd}$	$\partial_\mu a \epsilon^{\alpha\beta\gamma}(\bar{e}_R\gamma^\mu d_{R,\alpha})(\bar{d}^c_{R,\beta} d_{R,\gamma})$	✓⋆

$\mathcal{O}_{\partial aLQd}$

$\mathcal{O}_{\partial aed}$

Name	Operator with $\lvert\Delta(B-L)\rvert = 0$	
$\mathcal{O}^{VR,SR}_{\partial aeuud}$	$\partial_\mu a \epsilon^{\alpha\beta\gamma}(\bar{e}^c_L\gamma^\mu u_{R,\alpha})(\bar{u}^c_{R,\beta} d_{R,\gamma})$	✓
$\mathcal{O}^{VR,SR}_{\partial aduue}$	$\partial_\mu a \epsilon^{\alpha\beta\gamma}(\bar{d}^c_{L,\alpha}\gamma^\mu u_{R,\beta})(\bar{u}^c_{R,\gamma} e_R)$	
$\mathcal{O}^{VL,SR}_{\partial aeudu}$	$\partial_\mu a \epsilon^{\alpha\beta\gamma}(\bar{e}^c_R\gamma^\mu u_{L,\alpha})(\bar{d}^c_{R,\beta} u_{R,\gamma})$	✓
$\mathcal{O}^{VL,SR}_{\partial adueu}$	$\partial_\mu a \epsilon^{\alpha\beta\gamma}(\bar{d}^c_{R,\alpha}\gamma^\mu u_{L,\beta})(\bar{e}^c_R u_{R,\gamma})$	
$\mathcal{O}^{VL,SR}_{\partial auude}$	$\partial_\mu a \epsilon^{\alpha\beta\gamma}(\bar{u}_{L,\alpha}\gamma^\mu u^c_{R,\beta})(\bar{d}_{L,\gamma} e^c_L)$	
$\mathcal{O}^{VL,SR}_{\partial aduue}$	$\partial_\mu a \epsilon^{\alpha\beta\gamma}(\bar{d}_{L,\alpha}\gamma^\mu u^c_{R,\beta})(\bar{u}_{L,\gamma} e^c_L)$	
$\mathcal{O}^{VL,SL}_{\partial aeudu}$	$\partial_\mu a \epsilon^{\alpha\beta\gamma}(\bar{e}^c_R\gamma^\mu u_{L,\alpha})(\bar{d}^c_{L,\beta} u_{L,\gamma})$	✓
$\mathcal{O}^{VL,SR}_{\partial audue}$	$\partial_\mu a \epsilon^{\alpha\beta\gamma}(\bar{u}_{L,\alpha}\gamma^\mu d^c_{R,\beta})(\bar{u}_{L,\gamma} e^c_L)$	
$\mathcal{O}^{VL,SL}_{\partial ad\nu ud}$	$\partial_\mu a \epsilon^{\alpha\beta\gamma}(\bar{d}^c_{R,\alpha}\gamma^\mu \nu_L)(\bar{u}^c_{L,\beta} d_{L,\gamma})$	✓
$\mathcal{O}^{VL,SR}_{\partial add\nu u}$	$\partial_\mu a \epsilon^{\alpha\beta\gamma}(\bar{d}_{L,\alpha}\gamma^\mu d^c_{R,\beta})(\bar{\nu}_L u^c_{L,\gamma})$	
$\mathcal{O}^{VL,SR}_{\partial ad\nu du}$	$\partial_\mu a \epsilon^{\alpha\beta\gamma}(\bar{d}^c_{R,\alpha}\gamma^\mu \nu_L)(\bar{d}^c_{R,\beta} u_{R,\gamma})$	✓
$\mathcal{O}^{VL,SR}_{\partial adud\nu}$	$\partial_\mu a \epsilon^{\alpha\beta\gamma}(\bar{d}_{L,\alpha}\gamma^\mu u^c_{R,\beta})(\bar{d}_{L,\gamma} \nu^c_L)$	

The operators with "✓" can be matched to baryon chiral perturbation theory at leading order

- representations under quark flavor group $SU(3)_L \times SU(3)_R$

Name	Operator with $\|\Delta(B-L)\| = 2$		$SU(3)_L \times SU(3)_R$
$\mathcal{O}_{\partial a\nu ddu}^{VL,SL}$	$\partial_\mu a \epsilon^{\alpha\beta\gamma}(\bar{\nu}_L \gamma^\mu d_{L,\alpha})(\bar{d}^c_{L,\beta} u_{L,\gamma})$	✓	$(1+8, 1)$
$\mathcal{O}_{\partial aeddd}^{VL,SL}$	$\partial_\mu a \epsilon^{\alpha\beta\gamma}(\bar{e}_L \gamma^\mu d_{L,\alpha})(\bar{d}^c_{L,\beta} d_{L,\gamma})$	✓⋆	$(8, 1)$
$\mathcal{O}_{\partial aeddd}^{VR,SR}$	$\partial_\mu a \epsilon^{\alpha\beta\gamma}(\bar{e}_R \gamma^\mu d_{R,\alpha})(\bar{d}^c_{R,\beta} d_{R,\gamma})$	✓⋆	$(1, 8)$

Name	Operator with $\|\Delta(B-L)\| = 0$		$SU(3)_L \times SU(3)_R$
$\mathcal{O}_{\partial aeuud}^{VR,SR}$	$\partial_\mu a \epsilon^{\alpha\beta\gamma}(\bar{e}^c_L \gamma^\mu u_{R,\alpha})(\bar{u}^c_{R,\beta} d_{R,\gamma})$	✓	$(1, 8)$
$\mathcal{O}_{\partial aeudu}^{VL,SR}$	$\partial_\mu a \epsilon^{\alpha\beta\gamma}(\bar{e}^c_R \gamma^\mu u_{L,\alpha})(\bar{d}^c_{R,\beta} u_{R,\gamma})$	✓	$(3, \bar{3})$
$\mathcal{O}_{\partial aeudu}^{VL,SL}$	$\partial_\mu a \epsilon^{\alpha\beta\gamma}(\bar{e}^c_R \gamma^\mu u_{L,\alpha})(\bar{d}^c_{L,\beta} u_{L,\gamma})$	✓	$(8, 1)$
$\mathcal{O}_{\partial ad\nu ud}^{VL,SL}$	$\partial_\mu a \epsilon^{\alpha\beta\gamma}(\bar{d}^c_{R,\alpha} \gamma^\mu \nu_L)(\bar{u}^c_{L,\beta} d_{L,\gamma})$	✓	$(\bar{3}, 3)$
$\mathcal{O}_{\partial ad\nu du}^{VL,SR}$	$\partial_\mu a \epsilon^{\alpha\beta\gamma}(\bar{d}^c_{R,\alpha} \gamma^\mu \nu_L)(\bar{d}^c_{R,\beta} u_{R,\gamma})$	✓	$(1, 1+8)$

- Matching to Baryon Chiral Perturbation Theory (all ingredients for nucleon decay)

➢ The leading order chiral Lagrangian for baryons and mesons

$$\mathcal{L} = \frac{1}{8} f_\pi^2 \mathrm{tr}(\partial_\mu \Sigma \partial^\mu \Sigma^\dagger) + \mathrm{tr}(\overline{B}(i\not{D} - M_B)B) - \frac{D}{2}\mathrm{tr}(\overline{B}\gamma^\mu\gamma_5\{\xi_\mu, B\}) - \frac{F}{2}\mathrm{tr}(\overline{B}\gamma^\mu\gamma_5[\xi_\mu, B])$$

$$B = \begin{pmatrix} \frac{\Sigma^0}{\sqrt{2}} + \frac{\Lambda^0}{\sqrt{6}} & \Sigma^+ & p \\ \Sigma^- & -\frac{\Sigma^0}{\sqrt{2}} + \frac{\Lambda^0}{\sqrt{6}} & n \\ \Xi^- & \Xi^0 & -\sqrt{\frac{2}{3}}\Lambda^0 \end{pmatrix}, \quad \overline{B} = \begin{pmatrix} \frac{\overline{\Sigma^0}}{\sqrt{2}} + \frac{\overline{\Lambda^0}}{\sqrt{6}} & \overline{\Sigma^-} & \overline{\Xi^-} \\ \overline{\Sigma^+} & -\frac{\overline{\Sigma^0}}{\sqrt{2}} + \frac{\overline{\Lambda^0}}{\sqrt{6}} & \overline{\Xi^0} \\ \overline{p} & \overline{n} & -\sqrt{\frac{2}{3}}\overline{\Lambda^0} \end{pmatrix}$$

Nucl. Phys. B 195 (1982) 297-307

$$M = \begin{pmatrix} \frac{\pi^0}{\sqrt{2}} + \frac{\eta^0}{\sqrt{6}} & \pi^+ & K^+ \\ \pi^- & -\frac{\pi^0}{\sqrt{2}} + \frac{\eta^0}{\sqrt{6}} & K^0 \\ K^- & \bar{K}^0 & -\sqrt{\frac{2}{3}}\eta^0 \end{pmatrix}, \quad M^\dagger = M, \quad \Sigma \equiv e^{2iM/f_\pi}, \quad \xi \equiv e^{iM/f_\pi}$$

$$\Rightarrow \quad \mathcal{L}_0 \supset \left(\frac{D-F}{f_\pi} \overline{\Sigma^+}\gamma^\mu\gamma_5 p - \frac{D+3F}{\sqrt{6}f_\pi}\overline{\Lambda^0}\gamma^\mu\gamma_5 n - \frac{D-F}{\sqrt{2}f_\pi}\overline{\Sigma^0}\gamma^\mu\gamma_5 n \right) \partial_\mu \bar{K}^0$$
$$+ \left(\frac{D-F}{\sqrt{2}f_\pi}\overline{\Sigma^0}\gamma^\mu\gamma_5 p - \frac{D+3F}{\sqrt{6}f_\pi}\overline{\Lambda^0}\gamma^\mu\gamma_5 p + \frac{D-F}{f_\pi}\overline{\Sigma^-}\gamma^\mu\gamma_5 n \right) \partial_\mu K^-$$
$$+ \frac{3F-D}{2\sqrt{6}f_\pi} \left(\overline{p}\gamma^\mu\gamma_5 p + \overline{n}\gamma^\mu\gamma_5 n \right) \partial_\mu \eta$$
$$+ \frac{D+F}{f_\pi} \overline{p}\gamma^\mu\gamma_5 n\, \partial_\mu \pi^+$$
$$+ \frac{D+F}{2\sqrt{2}f_\pi} \left(\overline{p}\gamma^\mu\gamma_5 p - \overline{n}\gamma^\mu\gamma_5 n \right) \partial_\mu \pi^0 + \mathrm{h.c.}\,.$$

Phys. Rept. 441 (2007) 191-317

- The leading nuclear matrix elements of nucleons

$$\langle 0|\epsilon^{\alpha\beta\gamma}(\bar{u}^c_{R,\alpha}d_{R,\beta})u_{L,\gamma}|p^{(s)}\rangle = \alpha u^{(s)}_{pL}\ , \quad \langle 0|\epsilon^{\alpha\beta\gamma}(\bar{u}^c_{L,\alpha}d_{L,\beta})u_{L,\gamma}|p^{(s)}\rangle = \beta u^{(s)}_{pL}$$

$$\langle 0|\epsilon^{\alpha\beta\gamma}(\bar{d}^c_{R,\alpha}u_{R,\beta})d_{L,\gamma}|n^{(s)}\rangle = \alpha u^{(s)}_{nL}\ , \quad \langle 0|\epsilon^{\alpha\beta\gamma}(\bar{d}^c_{L,\alpha}u_{L,\beta})d_{L,\gamma}|n^{(s)}\rangle = \beta u^{(s)}_{nL}$$

9911026, 2111.01608

- transformation properties

$$\xi B \xi \sim (3,\bar{3}) \to L\xi B \xi R^\dagger\ ,$$

$$\xi^\dagger B \xi^\dagger \sim (\bar{3},3) \to R\xi^\dagger B \xi^\dagger L^\dagger\ ,$$

$$\xi B \xi^\dagger \sim (8,1) \to L\xi B \xi^\dagger L^\dagger\ ,$$

$$\xi^\dagger B \xi \sim (1,8) \to R\xi^\dagger B \xi R^\dagger\ ,$$

Nucl. Phys. B 195 (1982) 297-307

- Matching results: e.g. $|\Delta(B-L)|=2$

$$[\mathcal{O}^{VL,SL}_{\partial a\nu ddu}]_{r221} \to \beta\partial_\mu a\bar{\nu}_L\gamma^\mu \mathrm{tr}(\xi B\xi^\dagger \tilde{P}_{32})$$

$$\supset \partial_\mu a\bar{\nu}_L\gamma^\mu[-\beta n + \frac{i\beta}{f_\pi}(-\sqrt{\frac{3}{2}}n\eta + \frac{1}{\sqrt{2}}n\pi^0 - p\pi^-)] \ ,$$

$$[\mathcal{O}^{VL,SL}_{\partial a\nu ddu}]_{r231} \to \beta\partial_\mu a\bar{\nu}_L\gamma^\mu \mathrm{tr}(\xi B\xi^\dagger(\frac{2}{3}P_{22} + \frac{1}{3}\tilde{P}_{11} + \frac{1}{3}\tilde{P}_{33}))$$

$$\supset \partial_\mu a\bar{\nu}_L\gamma^\mu[\beta\frac{1}{\sqrt{6}}\Lambda^0 - \beta\frac{1}{\sqrt{2}}\Sigma^0 - \frac{i\beta}{f_\pi}\bar{K}^0 n] \ ,$$

$$[\mathcal{O}^{VL,SL}_{\partial a\nu ddu}]_{r321} \to \beta\partial_\mu a\bar{\nu}_L\gamma^\mu \mathrm{tr}(\xi B\xi^\dagger(\frac{1}{3}P_{22} + \frac{1}{3}P_{11} + \frac{2}{3}\tilde{P}_{33}))$$

$$\supset \partial_\mu a\bar{\nu}_L\gamma^\mu[\beta\sqrt{\frac{2}{3}}\Lambda^0 - \frac{i\beta}{f_\pi}(\bar{K}^0 n + K^- p)] \ ,$$

$$[\mathcal{O}^{VL,SL}_{\partial a\nu ddu}]_{r331} \to \beta\partial_\mu a\bar{\nu}_L\gamma^\mu \mathrm{tr}(\xi B\xi^\dagger P_{23}) \supset \partial_\mu a\bar{\nu}_L\gamma^\mu[\beta\Xi^0] \ .$$

$$[\mathcal{O}^{VL,SL}_{\partial aeddd}]_{r223} \to \beta\partial_\mu a\bar{e}_L\gamma^\mu \mathrm{tr}(\xi B\xi^\dagger P_{12}) \supset \partial_\mu a\bar{e}_L\gamma^\mu[\beta\Sigma^- - \frac{i\beta}{f_\pi}nK^-] \ ,$$

$$[\mathcal{O}^{VL,SL}_{\partial aeddd}]_{r323} \to \beta\partial_\mu a\bar{e}_L\gamma^\mu \mathrm{tr}(\xi B\xi^\dagger P_{13}) \supset \partial_\mu a\bar{e}_L\gamma^\mu[\beta\Xi^-] \ .$$

$$[\mathcal{O}^{VR,SR}_{\partial aeddd}]_{r223} \to -\beta\partial_\mu a\bar{e}_R\gamma^\mu \mathrm{tr}(\xi^\dagger B\xi P_{12}) \supset \partial_\mu a\bar{e}_R\gamma^\mu[-\beta\Sigma^- - \frac{i\beta}{f_\pi}nK^-] \ ,$$

$$[\mathcal{O}^{VR,SR}_{\partial aeddd}]_{r323} \to -\beta\partial_\mu a\bar{e}_R\gamma^\mu \mathrm{tr}(\xi^\dagger B\xi P_{13}) \supset \partial_\mu a\bar{e}_R\gamma^\mu[-\beta\Xi^-] \ .$$

$|\Delta(B-L)|=0$

$$[\mathcal{O}^{VR,SR}_{\partial aeuud}]_{r112} \to -\beta\partial_\mu a\bar{e}^c_L\gamma^\mu \mathrm{tr}(\xi^\dagger B\xi P_{31}) \supset \partial_\mu a\bar{e}^c_L\gamma^\mu[-\beta p+\frac{i\beta}{f_\pi}(\sqrt{\frac{3}{2}}p\eta+\frac{1}{\sqrt{2}}p\pi^0+n\pi^+)]\,,$$

$$[\mathcal{O}^{VR,SR}_{\partial aeuud}]_{r113} \to -\beta\partial_\mu a\bar{e}^c_L\gamma^\mu \mathrm{tr}(\xi^\dagger B\xi \tilde{P}_{21}) \supset \partial_\mu a\bar{e}^c_L\gamma^\mu[\beta\Sigma^+ +\frac{i\beta}{f_\pi}p\bar{K}^0]\,.$$

$$[\mathcal{O}^{VL,SR}_{\partial aeudu}]_{r121} \to -\alpha\partial_\mu a\bar{e}^c_R\gamma^\mu \mathrm{tr}(\xi B\xi P_{31}) \supset \partial_\mu a\bar{e}^c_R\gamma^\mu[-\alpha p-\frac{i\alpha}{f_\pi}(-\frac{1}{\sqrt{6}}p\eta+\frac{1}{\sqrt{2}}p\pi^0+n\pi^+)]\,,$$

$$[\mathcal{O}^{VL,SR}_{\partial aeudu}]_{r131} \to -\alpha\partial_\mu a\bar{e}^c_R\gamma^\mu \mathrm{tr}(\xi B\xi \tilde{P}_{21}) \supset \partial_\mu a\bar{e}^c_R\gamma^\mu[\alpha\Sigma^+ +\frac{i\alpha}{f_\pi}p\bar{K}^0]\,.$$

$$[\mathcal{O}^{VL,SL}_{\partial aeudu}]_{r121} \to -\beta\partial_\mu a\bar{e}^c_R\gamma^\mu \mathrm{tr}(\xi B\xi^\dagger P_{31}) \supset \partial_\mu a\bar{e}^c_R\gamma^\mu[-\beta p-\frac{i\beta}{f_\pi}(\sqrt{\frac{3}{2}}p\eta+\frac{1}{\sqrt{2}}p\pi^0+n\pi^+)]\,,$$

$$[\mathcal{O}^{VL,SL}_{\partial aeudu}]_{r131} \to -\beta\partial_\mu a\bar{e}^c_R\gamma^\mu \mathrm{tr}(\xi B\xi^\dagger \tilde{P}_{21}) \supset \partial_\mu a\bar{e}^c_R\gamma^\mu[\beta\Sigma^+ -\frac{i\beta}{f_\pi}p\bar{K}^0]\,.$$

$$[\mathcal{O}^{VL,SL}_{\partial ad\nu ud}]_{2r12} \to -\alpha\partial_\mu a\bar{\nu}^c_L\gamma^\mu \mathrm{tr}(\xi^\dagger B\xi^\dagger \tilde{P}_{32}) \supset \partial_\mu a\bar{\nu}^c_L\gamma^\mu[\alpha n+\frac{i\alpha}{f_\pi}(\frac{1}{\sqrt{6}}n\eta+\frac{1}{\sqrt{2}}n\pi^0-p\pi^-)]\,,$$

$$[\mathcal{O}^{VL,SL}_{\partial ad\nu ud}]_{2r13} \to -\alpha\partial_\mu a\bar{\nu}^c_L\gamma^\mu \mathrm{tr}(\xi^\dagger B\xi^\dagger P_{22}) \supset \partial_\mu a\bar{\nu}^c_L\gamma^\mu[\alpha(\frac{1}{\sqrt{2}}\Sigma^0-\frac{1}{\sqrt{6}}\Lambda^0)+\frac{i\alpha}{f_\pi}n\bar{K}^0]\,,$$

$$[\mathcal{O}^{VL,SL}_{\partial ad\nu ud}]_{3r12} \to -\alpha\partial_\mu a\bar{\nu}^c_L\gamma^\mu \mathrm{tr}(\xi^\dagger B\xi^\dagger \tilde{P}_{33}) \supset \partial_\mu a\bar{\nu}^c_L\gamma^\mu[-\alpha\sqrt{\frac{2}{3}}\Lambda^0-\frac{i\alpha}{f_\pi}(n\bar{K}^0+pK^-)]\,,$$

$$[\mathcal{O}^{VL,SL}_{\partial ad\nu ud}]_{3r13} \to -\alpha\partial_\mu a\bar{\nu}^c_L\gamma^\mu \mathrm{tr}(\xi^\dagger B\xi^\dagger P_{23}) \supset \partial_\mu a\bar{\nu}^c_L\gamma^\mu[-\alpha\Xi^0]\,.$$

$$[\mathcal{O}^{VL,SR}_{\partial ad\nu du}]_{2r21} \to \beta\partial_\mu a\bar{\nu}^c_L\gamma^\mu \mathrm{tr}(\xi^\dagger B\xi \tilde{P}_{32}) \supset \partial_\mu a\bar{\nu}^c_L\gamma^\mu[-\beta n+\frac{i\beta}{f_\pi}(\sqrt{\frac{3}{2}}n\eta-\frac{1}{\sqrt{2}}n\pi^0+p\pi^-)]\,,$$

$$[\mathcal{O}^{VL,SR}_{\partial ad\nu du}]_{2r31} \to \beta\partial_\mu a\bar{\nu}^c_L\gamma^\mu \mathrm{tr}(\xi^\dagger B\xi(\frac{2}{3}P_{22}+\frac{1}{3}\tilde{P}_{11}+\frac{1}{3}\tilde{P}_{33})) \supset \partial_\mu a\bar{\nu}^c_L\gamma^\mu[\beta\frac{1}{\sqrt{6}}\Lambda^0-\beta\frac{1}{\sqrt{2}}\Sigma^0+\frac{i\beta}{f_\pi}\bar{K}^0 n]\,,$$

$$[\mathcal{O}^{VL,SR}_{\partial ad\nu du}]_{3r21} \to \beta\partial_\mu a\bar{\nu}^c_L\gamma^\mu \mathrm{tr}(\xi^\dagger B\xi(\frac{1}{3}P_{22}+\frac{1}{3}P_{11}+\frac{2}{3}\tilde{P}_{33})) \supset \partial_\mu a\bar{\nu}^c_L\gamma^\mu[\beta\sqrt{\frac{2}{3}}\Lambda^0+\frac{i\beta}{f_\pi}(\bar{K}^0 n+K^- p)]\,,$$

$$[\mathcal{O}^{VL,SR}_{\partial ad\nu du}]_{3r31} \to \beta\partial_\mu a\bar{\nu}^c_L\gamma^\mu \mathrm{tr}(\xi^\dagger B\xi P_{23}) \supset \partial_\mu a\bar{\nu}^c_L\gamma^\mu[\beta\Xi^0]\,.$$

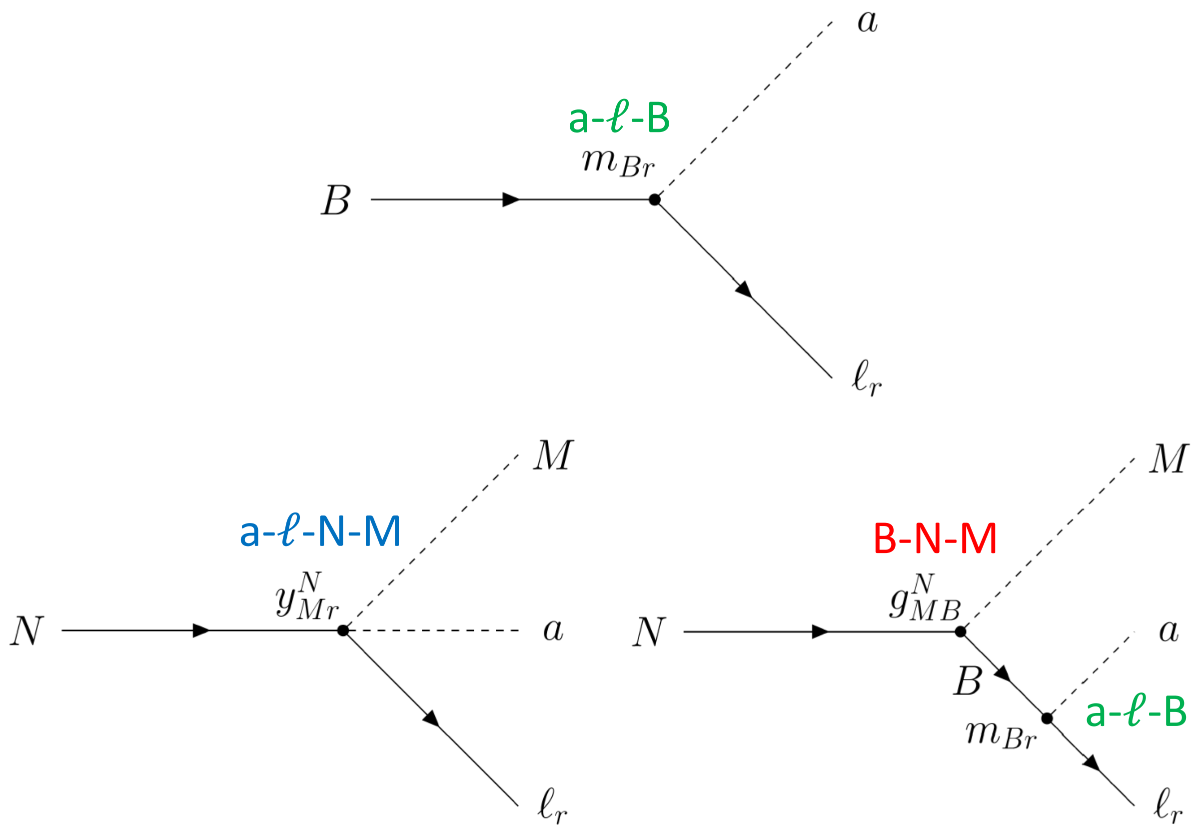
BNV nucleon decay to ALP

B-N-M   a-ℓ-B   a-ℓ-N-M

$$\mathcal{L} = g^N_{MB}\overline{B}\gamma^\mu\gamma_5 N\partial_\mu M + m_{Br,X}\partial_\mu a\overline{\ell_r}P_{\bar{X}}\gamma^\mu B + i y^N_{Mr,X}\partial_\mu a\overline{\ell_r}P_{\bar{X}}\gamma^\mu N M$$

B chiral Lagrangian

BNV aLEFT matching to BChPT



- Two-body baryon decays $B \to \ell(\text{or } \nu) + a$

$|\Delta(B-L)| = 2$

Process	$m_{Br,X}$
$n \to \nu a$	$m_{nr,L} = [C^{VL,SL}_{\partial a\nu ddu}]_{r221}(-\beta)$
$\Lambda^0 \to \nu a$	$m_{\Lambda r,L} = [C^{VL,SL}_{\partial a\nu ddu}]_{r231}(\frac{1}{\sqrt{6}}\beta) + [C^{VL,SL}_{\partial a\nu ddu}]_{r321}(\sqrt{\frac{2}{3}}\beta)$
$\Sigma^0 \to \nu a$	$m_{\Sigma r,L} = [C^{VL,SL}_{\partial a\nu ddu}]_{r231}(-\frac{1}{\sqrt{2}}\beta)$
$\Xi^0 \to \nu a$	$m_{\Xi r,L} = [C^{VL,SL}_{\partial a\nu ddu}]_{r331}(\beta)$
$\Sigma^- \to \ell^- a$	$m_{\Sigma r,L} = [C^{VL,SL}_{\partial aeddd}]_{r223}(\beta)$ $m_{\Sigma r,R} = [C^{VR,SR}_{\partial aeddd}]_{r223}(-\beta)$
$\Xi^- \to \ell^- a$	$m_{\Xi r,L} = [C^{VL,SL}_{\partial aeddd}]_{r323}(\beta)$ $m_{\Xi r,R} = [C^{VR,SR}_{\partial aeddd}]_{r323}(-\beta)$

$|\Delta(B-L)| = 0$

Process	$m_{Br,X}$
$p \to \ell^+ a$	$m_{pr,L} = [C^{VR,SR}_{\partial aeuud}]_{r112}(-\beta)$ $m_{pr,R} = [C^{VL,SR}_{\partial aeudu}]_{r121}(-\alpha) + [C^{VL,SL}_{\partial aeudu}]_{r121}(-\beta)$
$\Sigma^+ \to \ell^+ a$	$m_{\Sigma r,L} = [C^{VR,SR}_{\partial aeuud}]_{r113}(\beta)$ $m_{\Sigma r,R} = [C^{VL,SR}_{\partial aeudu}]_{r131}(\alpha) + [C^{VL,SL}_{\partial aeudu}]_{r131}(\beta)$
$n \to \bar{\nu} a$	$m_{nr,L} = [C^{VL,SL}_{\partial ad\nu ud}]_{2r12}(\alpha) + [C^{VL,SR}_{\partial ad\nu du}]_{2r21}(-\beta)$
$\Lambda^0 \to \bar{\nu} a$	$m_{\Lambda r,L} = [C^{VL,SL}_{\partial ad\nu ud}]_{2r13}(-\frac{1}{\sqrt{6}}\alpha) + [C^{VL,SL}_{\partial ad\nu ud}]_{3r12}(-\sqrt{\frac{2}{3}}\alpha)$ $+[C^{VL,SR}_{\partial ad\nu du}]_{2r31}(\frac{1}{\sqrt{6}}\beta) + [C^{VL,SR}_{\partial ad\nu du}]_{3r21}(\sqrt{\frac{2}{3}}\beta)$
$\Sigma^0 \to \bar{\nu} a$	$m_{\Sigma r,L} = [C^{VL,SL}_{\partial ad\nu ud}]_{2r13}(\frac{1}{\sqrt{2}}\alpha) + [C^{VL,SR}_{\partial ad\nu du}]_{2r31}(-\frac{1}{\sqrt{2}}\beta)$
$\Xi^0 \to \bar{\nu} a$	$m_{\Xi r,L} = [C^{VL,SL}_{\partial ad\nu ud}]_{3r13}(-\alpha) + [C^{VL,SR}_{\partial ad\nu du}]_{3r31}(\beta)$

- Two-body baryon decays $B \to \ell(\text{or } \nu) + a$

$|\Delta(B-L)| = 2$

Process	$m_{Br,X}$
$n \to \nu a$	$m_{nr,L} = [C^{VL,SL}_{\partial a\nu ddu}]_{r221}(-\beta)$
$\Lambda^0 \to \nu a$	$m_{\Lambda r,L} = [C^{VL,SL}_{\partial a\nu ddu}]_{r231}(\frac{1}{\sqrt{6}}\beta) + [C^{VL,SL}_{\partial a\nu ddu}]_{r321}(\sqrt{\frac{2}{3}}\beta)$
$\Sigma^0 \to \nu a$	$m_{\Sigma r,L} = [C^{VL,SL}_{\partial a\nu ddu}]_{r231}(-\frac{1}{\sqrt{2}}\beta)$
$\Xi^0 \to \nu a$	$m_{\Xi r,L} = [C^{VL,SL}_{\partial a\nu ddu}]_{r331}(\beta)$
$\Sigma^- \to \ell^- a$	$m_{\Sigma r,L} = [C^{VL,SL}_{\partial aeddd}]_{r223}(\beta)$ $m_{\Sigma r,R} = [C^{VR,SR}_{\partial aeddd}]_{r223}(-\beta)$
$\Xi^- \to \ell^- a$	$m_{\Xi r,L} = [C^{VL,SL}_{\partial aeddd}]_{r323}(\beta)$ $m_{\Xi r,R} = [C^{VR,SR}_{\partial aeddd}]_{r323}(-\beta)$

$|\Delta(B-L)| = 0$

Process	$m_{Br,X}$
$p \to \ell^+ a$	$m_{pr,L} = [C^{VR,SR}_{\partial aeuud}]_{r112}(-\beta)$ $m_{pr,R} = [C^{VL,SR}_{\partial aeudu}]_{r121}(-\alpha) + [C^{VL,SL}_{\partial aeudu}]_{r121}(-\beta)$
$\Sigma^+ \to \ell^+ a$	$m_{\Sigma r,L} = [C^{VR,SR}_{\partial aeuud}]_{r113}(\beta)$ $m_{\Sigma r,R} = [C^{VL,SR}_{\partial aeudu}]_{r131}(\alpha) + [C^{VL,SL}_{\partial aeudu}]_{r131}(\beta)$
$n \to \bar{\nu} a$	$m_{nr,L} = [C^{VL,SL}_{\partial ad\nu ud}]_{2r12}(\alpha) + [C^{VL,SR}_{\partial ad\nu du}]_{2r21}(-\beta)$
$\Lambda^0 \to \bar{\nu} a$	$m_{\Lambda r,L} = [C^{VL,SL}_{\partial ad\nu ud}]_{2r13}(-\frac{1}{\sqrt{6}}\alpha) + [C^{VL,SL}_{\partial ad\nu ud}]_{3r12}(-\sqrt{\frac{2}{3}}\alpha)$ $+[C^{VL,SR}_{\partial ad\nu du}]_{2r31}(\frac{1}{\sqrt{6}}\beta) + [C^{VL,SR}_{\partial ad\nu du}]_{3r21}(\sqrt{\frac{2}{3}}\beta)$
$\Sigma^0 \to \bar{\nu} a$	$m_{\Sigma r,L} = [C^{VL,SL}_{\partial ad\nu ud}]_{2r13}(\frac{1}{\sqrt{2}}\alpha) + [C^{VL,SR}_{\partial ad\nu du}]_{2r31}(-\frac{1}{\sqrt{2}}\beta)$
$\Xi^0 \to \bar{\nu} a$	$m_{\Xi r,L} = [C^{VL,SL}_{\partial ad\nu ud}]_{3r13}(-\alpha) + [C^{VL,SR}_{\partial ad\nu du}]_{3r31}(\beta)$

Super-K (1508.05530):
$\tau(p \to e^+(\mu^+)X) >$
$0.79(0.41) \times 10^{33}$ years

- Two-body baryon decays $B \to \ell(\text{or } \nu) + a$

$|\Delta(B-L)| = 2$

Process	$m_{Br,X}$
$n \to \nu a$	$m_{nr,L} = [C^{VL,SL}_{\partial a\nu ddu}]_{r221}(-\beta)$
$\Lambda^0 \to \nu a$	$m_{\Lambda r,L} = [C^{VL,SL}_{\partial a\nu ddu}]_{r231}(\frac{1}{\sqrt{6}}\beta) + [C^{VL,SL}_{\partial a\nu ddu}]_{r321}(\sqrt{\frac{2}{3}}\beta)$
$\Sigma^0 \to \nu a$	$m_{\Sigma r,L} = [C^{VL,SL}_{\partial a\nu ddu}]_{r231}(-\frac{1}{\sqrt{2}}\beta)$
$\Xi^0 \to \nu a$	$m_{\Xi r,L} = [C^{VL,SL}_{\partial a\nu ddu}]_{r331}(\beta)$
$\Sigma^- \to \ell^- a$	$m_{\Sigma r,L} = [C^{VL,SL}_{\partial aeddd}]_{r223}(\beta)$
	$m_{\Sigma r,R} = [C^{VR,SR}_{\partial aeddd}]_{r223}(-\beta)$
$\Xi^- \to \ell^- a$	$m_{\Xi r,L} = [C^{VL,SL}_{\partial aeddd}]_{r323}(\beta)$
	$m_{\Xi r,R} = [C^{VR,SR}_{\partial aeddd}]_{r323}(-\beta)$

BESIII (2110.06759): BR($\Lambda^0 \to$ invisible) $< 7.4 \times 10^{-5}$

$|\Delta(B-L)| = 0$

Process	$m_{Br,X}$
$p \to \ell^+ a$	$m_{pr,L} = [C^{VR,SR}_{\partial aeuud}]_{r112}(-\beta)$
	$m_{pr,R} = [C^{VL,SR}_{\partial aeudu}]_{r121}(-\alpha) + [C^{VL,SL}_{\partial aeudu}]_{r121}(-\beta)$
$\Sigma^+ \to \ell^+ a$	$m_{\Sigma r,L} = [C^{VR,SR}_{\partial aeuud}]_{r113}(\beta)$
	$m_{\Sigma r,R} = [C^{VL,SR}_{\partial aeudu}]_{r131}(\alpha) + [C^{VL,SL}_{\partial aeudu}]_{r131}(\beta)$
$n \to \bar{\nu} a$	$m_{nr,L} = [C^{VL,SL}_{\partial ad\nu ud}]_{2r12}(\alpha) + [C^{VL,SR}_{\partial ad\nu du}]_{2r21}(-\beta)$
$\Lambda^0 \to \bar{\nu} a$	$m_{\Lambda r,L} = [C^{VL,SL}_{\partial ad\nu ud}]_{2r13}(-\frac{1}{\sqrt{6}}\alpha) + [C^{VL,SL}_{\partial ad\nu ud}]_{3r12}(-\sqrt{\frac{2}{3}}\alpha)$ $+[C^{VL,SR}_{\partial ad\nu du}]_{2r31}(\frac{1}{\sqrt{6}}\beta) + [C^{VL,SR}_{\partial ad\nu du}]_{3r21}(\sqrt{\frac{2}{3}}\beta)$
$\Sigma^0 \to \bar{\nu} a$	$m_{\Sigma r,L} = [C^{VL,SL}_{\partial ad\nu ud}]_{2r13}(\frac{1}{\sqrt{2}}\alpha) + [C^{VL,SR}_{\partial ad\nu du}]_{2r31}(-\frac{1}{\sqrt{2}}\beta)$
$\Xi^0 \to \bar{\nu} a$	$m_{\Xi r,L} = [C^{VL,SL}_{\partial ad\nu ud}]_{3r13}(-\alpha) + [C^{VL,SR}_{\partial ad\nu du}]_{3r31}(\beta)$

Super-K (1508.05530): $\tau(p \to e^+(\mu^+)X) >$ $0.79(0.41) \times 10^{33}$ years

- Two-body baryon decays $B \to \ell(\text{or } \nu) + a$

$|\Delta(B-L)| = 2$

Process	$m_{Br,X}$
$n \to \nu a$	$m_{nr,L} = [C^{VL,SL}_{\partial a\nu ddu}]_{r221}(-\beta)$
$\Lambda^0 \to \nu a$	$m_{\Lambda r,L} = [C^{VL,SL}_{\partial a\nu ddu}]_{r231}(\frac{1}{\sqrt{6}}\beta) + [C^{VL,SL}_{\partial a\nu ddu}]_{r321}(\sqrt{\frac{2}{3}}\beta)$
$\Sigma^0 \to \nu a$	$m_{\Sigma r,L} = [C^{VL,SL}_{\partial a\nu ddu}]_{r231}(-\frac{1}{\sqrt{2}}\beta)$
$\Xi^0 \to \nu a$	$m_{\Xi r,L} = [C^{VL,SL}_{\partial a\nu ddu}]_{r331}(\beta)$
$\Sigma^- \to \ell^- a$	$m_{\Sigma r,L} = [C^{VL,SL}_{\partial aeddd}]_{r223}(\beta)$ $m_{\Sigma r,R} = [C^{VR,SR}_{\partial aeddd}]_{r223}(-\beta)$
$\Xi^- \to \ell^- a$	$m_{\Xi r,L} = [C^{VL,SL}_{\partial aeddd}]_{r323}(\beta)$ $m_{\Xi r,R} = [C^{VR,SR}_{\partial aeddd}]_{r323}(-\beta)$

BESIII (2110.06759):
BR($\Lambda^0 \to$ invisible)
$< 7.4 \times 10^{-5}$

$|\Delta(B-L)| = 0$

Process	$m_{Br,X}$
$p \to \ell^+ a$	$m_{pr,L} = [C^{VR,SR}_{\partial aeuud}]_{r112}(-\beta)$ $m_{pr,R} = [C^{VL,SR}_{\partial aeudu}]_{r121}(-\alpha) + [C^{VL,SL}_{\partial aeudu}]_{r121}(-\beta)$
$\Sigma^+ \to \ell^+ a$	$m_{\Sigma r,L} = [C^{VR,SR}_{\partial aeuud}]_{r113}(\beta)$ $m_{\Sigma r,R} = [C^{VL,SR}_{\partial aeudu}]_{r131}(\alpha) + [C^{VL,SL}_{\partial aeudu}]_{r131}(\beta)$
$n \to \bar{\nu} a$	$m_{nr,L} = [C^{VL,SL}_{\partial ad\nu ud}]_{2r12}(\alpha) + [C^{VL,SR}_{\partial ad\nu du}]_{2r21}(-\beta)$
$\Lambda^0 \to \bar{\nu} a$	$m_{\Lambda r,L} = [C^{VL,SL}_{\partial ad\nu ud}]_{2r13}(-\frac{1}{\sqrt{6}}\alpha) + [C^{VL,SL}_{\partial ad\nu ud}]_{3r12}(-\sqrt{\frac{2}{3}}\alpha)$ $+[C^{VL,SR}_{\partial ad\nu du}]_{2r31}(\frac{1}{\sqrt{6}}\beta) + [C^{VL,SR}_{\partial ad\nu du}]_{3r21}(\sqrt{\frac{2}{3}}\beta)$
$\Sigma^0 \to \bar{\nu} a$	$m_{\Sigma r,L} = [C^{VL,SL}_{\partial ad\nu ud}]_{2r13}(\frac{1}{\sqrt{2}}\alpha) + [C^{VL,SR}_{\partial ad\nu du}]_{2r31}(-\frac{1}{\sqrt{2}}\beta)$
$\Xi^0 \to \bar{\nu} a$	$m_{\Xi r,L} = [C^{VL,SL}_{\partial ad\nu ud}]_{3r13}(-\alpha) + [C^{VL,SR}_{\partial ad\nu du}]_{3r31}(\beta)$

Super-K (1508.05530):
$\tau(p \to e^+(\mu^+)X) >$
$0.79(0.41) \times 10^{33}$ years

KamLAND (0512059):
$\tau(n \to$ invisible$) >$
5.8×10^{29} years

- Lower limits on energy scale of aLEFT operators

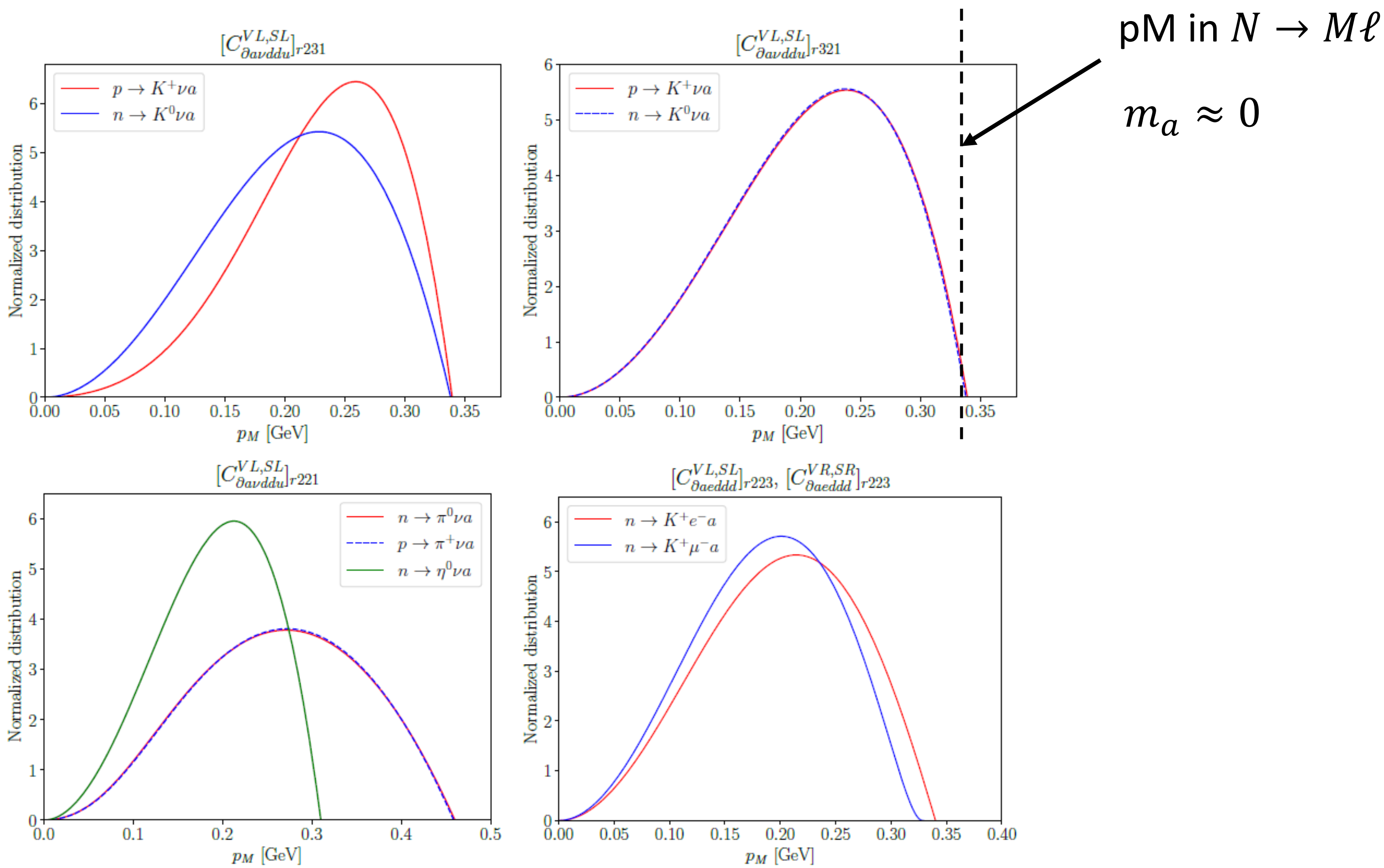
Super-K/KamLAND: $\sim 10^7$ GeV

BESIII: $\sim 30 - 40$ GeV

	Process	aLEFT WC	$1/\sqrt[4]{C}$	Projection
$\lvert\Delta(B-L)\rvert = 2$	$n \to \nu a$	$[C^{VL,SL}_{\partial a\nu ddu}]_{r221}$	8.8×10^6 GeV	$\tau(n \to \pi^0 \nu a) > 1.5 \times 10^{31}$ years
				$\tau(n \to \eta^0 \nu a) > 4.7 \times 10^{32}$ years
				$\tau(p \to \pi^+ \nu a) > 7.6 \times 10^{30}$ years
	$\Lambda^0 \to \nu a$	$[C^{VL,SL}_{\partial a\nu ddu}]_{r231}$	34.5 GeV	$\mathrm{BR}(\Sigma^0 \to \nu a) < 7.4 \times 10^{-14}$
		$[C^{VL,SL}_{\partial a\nu ddu}]_{r321}$	41.0 GeV	
$\lvert\Delta(B-L)\rvert = 0$	$p \to e^+ a$	$[C^{VL,SL}_{\partial aeudu}]_{1121}$, $[C^{VR,SR}_{\partial aeuud}]_{1112}$, $[C^{VL,SR}_{\partial aeudu}]_{1121}$	2.2×10^7 GeV	$\tau(p \to \pi^0 e^+ a) > 2.0 \times 10^{34}$ years
				$\tau(p \to \eta^0 e^+ a) > 1.8 \times 10^{37}$ years
				$\tau(n \to \pi^- e^+ a) > 9.9 \times 10^{33}$ years
	$p \to \mu^+ a$	$[C^{VL,SL}_{\partial aeudu}]_{2121}$, $[C^{VR,SR}_{\partial aeuud}]_{2112}$, $[C^{VL,SR}_{\partial aeudu}]_{2121}$	2.0×10^7 GeV	$\tau(p \to \pi^0 \mu^+ a) > 1.2 \times 10^{34}$ years
				$\tau(p \to \eta^0 \mu^+ a) > 1.4 \times 10^{37}$ years
				$\tau(n \to \pi^- \mu^+ a) > 6.2 \times 10^{33}$ years
	$n \to \bar{\nu} a$	$[C^{VL,SL}_{\partial ad\nu ud}]_{2r12}$, $[C^{VL,SR}_{\partial ad\nu du}]_{2r21}$	8.8×10^6 GeV	$\tau(n \to \pi^0 \bar{\nu} a) > 1.5 \times 10^{31}$ years
				$\tau(n \to \eta^0 \bar{\nu} a) > 1.3 \times 10^{34}$ years
				$\tau(p \to \pi^+ \bar{\nu} a) > 7.6 \times 10^{30}$ years
	$\Lambda^0 \to \bar{\nu} a$	$[C^{VL,SL}_{\partial ad\nu ud}]_{2r13}$, $[C^{VL,SR}_{\partial ad\nu du}]_{2r31}$	34.5 GeV	$\mathrm{BR}(\Sigma^0 \to \bar{\nu} a) < 7.4 \times 10^{-14}$
		$[C^{VL,SL}_{\partial ad\nu ud}]_{3r12}$, $[C^{VL,SR}_{\partial ad\nu du}]_{3r21}$	41.0 GeV	

- Three-body nucleon decays $N \to M + \ell(\text{or}\ \nu) + a$

They exhibit different kinematics (pM) from the conventional nucleon decays $N \to M + \ell(\text{or}\ \nu)$



Summary

- The search for baryon number violation in nucleon decays is an important probe of NP beyond the SM. The future neutrino experiments will improve the search.
- We investigate the ALP EFTs with baryon number violation and the impact of light ALP on BNV nucleon decays.
- We find the constraints on the energy scale from two-body decay $B \to \ell(\mathrm{or}\, \nu) + a$
- We show the projections of other nucleon decays and the distinct distributions of kinematic observable in three-body decay $N \to M + \ell(\mathrm{or}\, \nu) + a$

Summary

- The search for baryon number violation in nucleon decays is an important probe of NP beyond the SM. The future neutrino experiments will improve the search.
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Thank you!