



# Probing baryon number violation via nucleon and hyperon decays

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# Introduction

- The **stability of matter** requires baryon number to be highly conserved
- Baryon number violation (BNV) as one of the three Sahkarov conditions to explain **matter-antimatter asymmetry** in the Universe
- Understanding the fate of baryon number is a fundamental question at the interface of particle physics and cosmology

# Introduction

- The most sensitive probe of BNV is through **nucleon decay**: *Large samples*
  - Past: IMB, KamLAND, SNO+, Super-Kamiokande,... ➔ *Null result but stringent bound*
  - Future: DUNE, Hyper-K, JUNO, THEIA, ...
- All possible decay channels should be attempted, exotic as well as conventional
- If BNV exists → Origin at **a very high energy scale**
  - EFT-based framework for **low energy pheno.**

# General $|\Delta B| = 1$ triple-quark interactions

- In EFT framework, the lowest-dim operators are generally dominant
- Nucleon has  $B = 1 \rightarrow$  at least 3 light quarks  $q$  involved
- We find only **four** triple-quark operators **without** derivative in LEFT or xLEFT

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

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

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

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

+L  $\leftrightarrow$  R

Chiral partners

Combination of non-QCD fields

$$y, z, w = 1, 2, 3$$

$$q_{1,2,3} = u, d, s$$

$$A_{\{y} B_{z\}} \equiv \frac{1}{2}(A_y B_z + A_z B_y)$$

$$A_{\{y} B_z C_w\} \equiv \frac{1}{6}[A_y B_z C_w + 5 \text{ permutations of } (y, z, w)]$$

**Completeness and independence of them can be proved using Fierz identities:**

$$(\overline{\Psi}_{c,\mu} q_{L,[y}^\alpha)(\overline{q_{L,z}^{\beta C}} \gamma^\mu q_{R,w}^\gamma) \epsilon_{\alpha\beta\gamma} = \frac{1}{2}(\overline{\Psi}_{c,\mu} \gamma^\mu q_{R,w}^\alpha)(\overline{q_{L,z}^{\beta C}} q_{L,y}^\gamma) \epsilon_{\alpha\beta\gamma} \sim \mathcal{O}_b^{yzw}$$

$$(\overline{\Psi}_{d,\mu\nu} q_{R,y}^\alpha)(\overline{q_{L,z}^{\beta C}} \sigma^{\mu\nu} q_{L,w}^\gamma) \epsilon_{\alpha\beta\gamma} = -2i(\overline{\Psi}_{d,\mu\nu} \gamma^\mu q_{L,\{z}^\alpha)(\overline{q_{L,w}^{\beta C}} \gamma^\nu q_{R,y}^\gamma) \epsilon_{\alpha\beta\gamma} \sim \mathcal{O}_c^{yzw}$$

$$(\overline{\Psi}_{d,\mu\nu} q_{L,[y}^\alpha)(\overline{q_{L,z}^{\beta C}} \sigma^{\mu\nu} q_{L,w}^\gamma) \epsilon_{\alpha\beta\gamma} = -\frac{1}{2}(\overline{\Psi}_{d,\mu\nu} \sigma^{\mu\nu} q_{L,w}^\alpha)(\overline{q_{L,y}^{\beta C}} q_{L,z}^\gamma) \epsilon_{\alpha\beta\gamma} \sim \mathcal{O}_a^{yzw}$$

$$A_{[y} B_{z]} \equiv \frac{1}{2}(A_y B_z - A_z B_y)$$

Y. Liao, X.-D. Ma, and **HLW**, PRL 135 (2025)

# General $|\Delta B| = 1$ triple-quark interactions

- We find only **four** triple-quark operators **without** derivative in LEFT or xLEFT

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

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

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

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

- The first two were well-known in 1980s in the form of dim-6 LEFT operators:

*F. Wilczek and A. Zee, PRL 43 (1979)*

*J. R. Ellis, M. k. Gaillard, and D. V. Nanopoulos, PLB 88 (1979)*

*S. Weinberg, PRL 43 (1979) & PRD 22 (1980)*

*L. F. Abbott and M. B. Wise, PRD 22 (1980)*

*O. Kaymakalan, C.-H. Lo, and K. C. Wali, PRD 29 (1984)*

*M. Claudson, M. B. Wise, and L. J. Hall, NPB 195 (1982)*

$$\overline{\Psi}_{a.b} = \overline{\ell}, \overline{\nu}$$

## Combination of non-QCD fields

- The operators corresponding to  $\mathcal{O}_{c,d}^{yzw}$  vanish for dim-6 LEFT operators

$$\overline{\Psi}_{c,\mu} = \overline{\ell} \gamma_\mu$$

$$\overline{\Psi}_{d,\mu\nu} = \overline{\ell} \sigma_{\mu\nu}$$

$$\begin{aligned} \gamma^\mu P_\pm \otimes \gamma_\mu P_\mp &= -2P_\mp \odot P_\pm \\ \sigma^{\mu\nu} P_\pm \otimes \sigma_{\mu\nu} P_\pm &= -4P_\pm \otimes P_\pm - 8P_\pm \odot P_\pm \end{aligned}$$

# When $\mathcal{O}_c$ and $\mathcal{O}_d$ enter?

*Y. Liao, X.-D. Ma, and **HLW**, PRL 135 (2025)*

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

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

+L  $\leftrightarrow$  R

- Identified for the first time
- When will they become relevant or even important?

- Important for exotic nucleon decays:
  - *Forbidden processes at dim-6*: e.g.  $\Delta I = 3/2$  BNV nucleon decays,  $n \rightarrow \ell^- \pi^+$
  - BNV nucleon decays through *higher dimensional operators*
  - BNV nucleon decays involving *new light particles*, e.g. aLEFT, DSEFT et al.
- We will show the new structures have nontrivial chiral realizations in ChPT

# Chiral realization

- Explore the chiral realization within ChPT: symmetries (**chiral**, C/P/T, **Lorentz**)
- Decompose each interaction into non-quark and quark factors

$$\begin{aligned}\mathcal{O}_a^{yzw} &= (\overline{\Psi}_a q_{L,y}^\alpha)(\overline{q_{L,z}^{\beta C}} q_{L,w}^\gamma) \epsilon_{\alpha\beta\gamma} \\ \mathcal{O}_b^{yzw} &= (\overline{\Psi}_b q_{R,y}^\alpha)(\overline{q_{L,z}^{\beta C}} q_{L,w}^\gamma) \epsilon_{\alpha\beta\gamma} \\ \mathcal{O}_c^{yzw} &= (\overline{\Psi}_{c,\mu} q_{L,\{y}^\alpha)(\overline{q_{L,z}^{\beta C}} \gamma^\mu q_{R,w}^\gamma) \epsilon_{\alpha\beta\gamma} \\ \mathcal{O}_d^{yzw} &= (\overline{\Psi}_{d,\mu\nu} q_{L,\{y}^\alpha)(\overline{q_{L,z}^{\beta C}} \sigma^{\mu\nu} q_{L,w}^\gamma) \epsilon_{\alpha\beta\gamma}\end{aligned}$$

+ L  $\leftrightarrow$  R

$$\mathcal{L}_{q^3}^B = \sum_i C_i^{yzw} \mathcal{O}_i^{yzw}$$

Non-quark factor

Quark factor

$C_i^{yzw} \overline{\psi}$ 

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

$\Gamma_1 q (\overline{q^C} \Gamma_2 q)$ 

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

$$\mathcal{L}_{q^3}^B = \left\{ \left[ (\mathcal{P}_{yzw}^{LL} q_{L,y}^\alpha)(\overline{q_{L,z}^{\beta C}} q_{L,w}^\gamma) \epsilon_{\alpha\beta\gamma} + (\mathcal{P}_{yzw}^{RL} q_{R,y}^\alpha)(\overline{q_{L,z}^{\beta C}} q_{L,w}^\gamma) \epsilon_{\alpha\beta\gamma} \right. \right. \\ \left. \left. + (\mathcal{P}_{yzw}^{LR,\mu} q_{L,\{y}^\alpha)(\overline{q_{L,z}^{\beta C}} \gamma_\mu q_{R,w}^\gamma) \epsilon_{\alpha\beta\gamma} + (\mathcal{P}_{yzw}^{LL,\mu\nu} q_{L,\{y}^\alpha)(\overline{q_{L,z}^{\beta C}} \sigma_{\mu\nu} q_{L,w}^\gamma) \epsilon_{\alpha\beta\gamma} \right] + L \leftrightarrow R \right\} + \text{h.c.}$$

# Chiral properties

Triple-quark sector:

Chiral group:  $SU(3)_L \otimes SU(3)_R$

- Under the chiral group, each structure belongs an irreducible representation

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

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

Can be organized in the matrix form  $\rightarrow$

$$\mathcal{N}_{\mathbf{8}_L \otimes \mathbf{1}_R} \xrightarrow{G} \hat{L} \mathcal{N}_{\mathbf{8}_L \otimes \mathbf{1}_R} \hat{L}^\dagger \quad \mathcal{N}_{\bar{\mathbf{3}}_L \otimes \mathbf{3}_R} \xrightarrow{G} \hat{R} \mathcal{N}_{\bar{\mathbf{3}}_L \otimes \mathbf{3}_R} \hat{L}^\dagger$$

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

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

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

$$\mathcal{N}_{yzw}^{\text{LR},\mu} \xrightarrow{G} \hat{L}_{yy'} \hat{L}_{zz'} \hat{R}_{ww'} \mathcal{N}_{\mathbf{6}_L \otimes \mathbf{3}_R}^{\{y'z'\}w',\mu}$$

$$\mathcal{N}_{yzw}^{\text{LL},\mu\nu} \xrightarrow{G} \hat{L}_{yy'} \hat{L}_{zz'} \hat{L}_{ww'} \mathcal{N}_{\mathbf{10}_L \otimes \mathbf{1}_R}^{\{y'z'w'\},\mu\nu}$$

# Chiral properties

## Non-quark sector:

Chiral group:  $SU(3)_L \otimes SU(3)_R$

- Treat non-quark factors as a **spurion field**
- Assign transformation rules to the spurion fields so that the **interactions are invariant**

$$\mathcal{P}_{\mathbf{8}_L \otimes \mathbf{1}_R} \rightarrow \hat{L} \mathcal{P}_{\mathbf{8}_L \otimes \mathbf{1}_R} \hat{L}^\dagger \quad \mathcal{P}_{\mathbf{3}_L \otimes \bar{\mathbf{3}}_R} \rightarrow \hat{L} \mathcal{P}_{\mathbf{3}_L \otimes \bar{\mathbf{3}}_R} \hat{R}^\dagger \quad \mathcal{P}_{yzw}^{\text{LR},\mu} \rightarrow \hat{L}_{yy'}^* \hat{L}_{zz'}^* \hat{R}_{ww'}^* \mathcal{P}_{y'z'w'}^{\text{LR},\mu} \quad \mathcal{P}_{yzw}^{\text{LL},\mu\nu} \rightarrow \hat{L}_{yy'}^* \hat{L}_{zz'}^* \hat{L}_{ww'}^* \mathcal{P}_{y'z'w'}^{\text{LL},\mu\nu}$$

- Organize  $\mathcal{P}_{\mathbf{8}_L \otimes \mathbf{1}_R}$  and  $\mathcal{P}_{\mathbf{3}_L \otimes \bar{\mathbf{3}}_R}$  in matrix form similarly

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

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

# Lorentz properties

Triple-quark sector:

Lorentz algebra  $\mathfrak{su}_l(2) \oplus \mathfrak{su}_r(2)$

- It is important to incorporate the correct Lorentz properties for chiral matching

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

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

$$\mathcal{N}_{\mathbf{8}_\text{L} \otimes \mathbf{1}_\text{R}} \in \left(\frac{1}{2}, 0\right) \quad \mathcal{N}_{\bar{\mathbf{3}}_\text{L} \otimes \mathbf{3}_\text{R}} \in \left(0, \frac{1}{2}\right)$$

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

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

$$\mathcal{N}_{yzw}^{\text{LR},\mu} \in \left(1, \frac{1}{2}\right) \quad \mathcal{N}_{yzw}^{\text{LL},\mu\nu} \in \left(\frac{3}{2}, 0\right)$$

These complicate the  
chiral matching

$$\gamma_\mu \mathcal{N}_{yzw}^{\text{LR},\mu} = \gamma_\mu \mathcal{N}_{yzw}^{\text{RL},\mu} = 0 \quad \gamma_\mu \mathcal{N}_{yzw}^{\text{LL},\mu\nu} = \gamma_\mu \mathcal{N}_{yzw}^{\text{RR},\mu\nu} = 0$$

# Chiral matching

- To build the interactions for baryons and pseudoscalars →

*Building blocks in ChPT:*

ChPT is a systematic and consistent approach

$$\Sigma(x) = \xi^2(x) = \exp\left(\frac{i\sqrt{2}\Pi(x)}{F_0}\right) \quad \Pi(x) = \begin{pmatrix} \frac{\pi^0}{\sqrt{2}} + \frac{\eta}{\sqrt{6}} & \pi^+ & K^+ \\ \pi^- & -\frac{\pi^0}{\sqrt{2}} + \frac{\eta}{\sqrt{6}} & K^0 \\ K^- & \bar{K}^0 & -\sqrt{\frac{2}{3}}\eta \end{pmatrix} \quad B(x) = \begin{pmatrix} \frac{\Sigma^0}{\sqrt{2}} + \frac{\Lambda^0}{\sqrt{6}} & \Sigma^+ & p \\ \Sigma^- & -\frac{\Sigma^0}{\sqrt{2}} + \frac{\Lambda^0}{\sqrt{6}} & n \\ \Xi^- & \Xi^0 & -\sqrt{\frac{2}{3}}\Lambda^0 \end{pmatrix} \quad + \text{Spurion fields}$$

Chiral group:  $SU(3)_L \otimes SU(3)_R$

$$\Sigma \rightarrow \hat{L}\Sigma\hat{R}^\dagger, \quad \xi \rightarrow \hat{L}\xi\hat{h}^\dagger = \hat{h}\xi\hat{R}^\dagger, \quad B \rightarrow \hat{h}B\hat{h}^\dagger$$

- Chiral Lagrangian is ordered by the typical momentum transfer  $p$

$$\{\Sigma, \xi, B, D_\mu B\} \sim \mathcal{O}(p^0) \quad D_\mu \Sigma \sim \mathcal{O}(p^1)$$

*The higher the chiral order, more suppressed the term*

$$D_\mu \Sigma = \partial_\mu \Sigma - il_\mu \Sigma + i\Sigma r_\mu \quad D_\mu B = \partial_\mu B + [\Gamma_\mu, B] \quad \Gamma_\mu = \frac{1}{2} \left[ \xi(\partial_\mu - ir_\mu)\xi^\dagger + \xi^\dagger(\partial_\mu - il_\mu)\xi \right]$$

# Chiral matching

- Project the appropriate irreducible Lorentz rep. from **vector-spinor** and **tensor-spinor**:

$$\boxed{\Gamma_{\mu\nu}^{L,R} \equiv (g_{\mu\nu} - \frac{1}{4}\gamma_\mu\gamma_\nu)P_{L,R}} \quad \left(1, \frac{1}{2}\right) \quad \left(\frac{1}{2}, 1\right) \quad \boxed{\hat{\Gamma}_{\mu\nu\alpha\beta}^{L,R} \equiv \frac{1}{24} \left(2[\sigma_{\mu\nu}, \sigma_{\alpha\beta}] - \{\sigma_{\mu\nu}, \sigma_{\alpha\beta}\}\right) P_{L,R}} \quad \left(\frac{3}{2}, 0\right) \quad \left(0, \frac{3}{2}\right)$$

$$\Gamma_{\mu\rho}^{L,R} \Gamma_{\nu}^{L,R} = \Gamma_{\mu\nu}^{L,R} \quad \gamma^\mu \Gamma_{\mu\nu}^{L,R} = 0$$

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

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

- Construct the **LO** chiral-invariant Lagrangian:

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

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

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

Involve at least one pseudoscalar

*Y. Liao, X.-D. Ma, and HLW, PRL 135 (2025)*

# Determination of the LECs

*Y. Liao, X.-D. Ma, and HLW, PRL 135 (2025)*

$$\begin{aligned}\mathcal{L}_B^{\mathcal{B},0} &= c_1 \text{Tr}[\mathcal{P}_{\bar{3}_L \otimes 3_R} \xi B_L \xi - \mathcal{P}_{3_L \otimes \bar{3}_R} \xi^\dagger B_R \xi^\dagger] + c_2 \text{Tr}[\mathcal{P}_{8_L \otimes 1_R} \xi B_L \xi^\dagger - \mathcal{P}_{1_L \otimes 8_R} \xi^\dagger B_R \xi] \\ &\quad + \frac{c_3}{\Lambda_\chi} [\mathcal{P}_{yzi}^{\text{LR},\mu} \Gamma_{\mu\nu}^L (\xi i D^\nu B_L \xi)_{yj} \Sigma_{zk} \epsilon_{ijk} - \mathcal{P}_{yzi}^{\text{RL},\mu} \Gamma_{\mu\nu}^R (\xi^\dagger i D^\nu B_R \xi^\dagger)_{yj} \Sigma_{kz}^* \epsilon_{ijk}] + \text{h.c.}, \\ \mathcal{L}_B^{\mathcal{B},1} &= \frac{c_4}{\Lambda_\chi^2} [\mathcal{P}_{yzw}^{\text{LL},\mu\nu} \hat{\Gamma}_{\mu\nu\alpha\beta}^L (\xi D^\alpha B_L \xi)_{yi} \Sigma_{zj} (D^\beta \Sigma)_{wk} \epsilon_{ijk} - \mathcal{P}_{yzw}^{\text{RR},\mu\nu} \hat{\Gamma}_{\mu\nu\alpha\beta}^R (\xi^\dagger D^\alpha B_R \xi^\dagger)_{iy} \Sigma_{jz}^* (D^\beta \Sigma)_{kw}^* \epsilon_{ijk}] + \text{h.c.}.\end{aligned}$$

- LQCD results for  $c_1$  &  $c_2$ :  
 $c_1 = \alpha = -0.01257(111) \text{ GeV}^3$   
 $c_2 = \beta = 0.01269(107) \text{ GeV}^3$

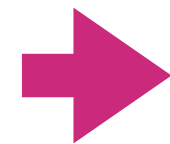
*J.-S. Yoo, et al., PRD 105 (2022)*

- NDA for the unknown LECs:

*S. Weinberg, PRL 63 (1989), A. Manohar and H. Georgi, NPB 234 (1984), B. M. Gavela et al. EPJC 76 (2016)*

$$C_{q,\text{had}} = g(4\pi)^{2-m} \Lambda_\chi^{D-4}$$

Reduced coupling  
 $g$ : coupling constant  
 $m$ : minimal # of physical fields  
 $D$ : dim. of op.



$$\begin{aligned}c_{1,2,3} &\sim \Lambda_\chi^3 / (4\pi)^2 \approx 0.011 \text{ GeV}^3 \\ c_4 &\sim \Lambda_\chi^2 F_0 / (4\pi\sqrt{2}) \approx 0.007 \text{ GeV}^3\end{aligned}$$

*The reliability of NDA can be verified with  $c_{1,2}$*

- **We expect NDA really works, but still we encourage calculations on the two new LECs  $c_3$  and  $c_4$  by LQCD community**

# Phenomenological applications

- Above central results offer a starting point to all *BNV octet baryon decays* into *SM particles* and *new light particles* incorporated through spurions
- They enable systematic analyses of BNV decay channels within ChPT
- The framework allows correlations among different decay modes to be investigated, including:
  - ✓ 2-body versus 3-body decays;
  - ✓ pseudoscalar- versus vector-meson final states;
  - ✓ nucleon versus hyperon decays

$$\mathcal{L} \supset M^n(\mathcal{P}B)$$

# Phenomenological applications

## A. The $\Delta I = 3/2$ processes: $n \rightarrow \ell^- \pi^+$ with $\ell = e, \mu$ :

From the dim-7 SMEFT operator:

leading contribution from  
irreps  $\mathbf{6}_{L(R)} \otimes \mathbf{3}_{R(L)}$

$$\mathcal{L}_{\mathcal{P}\pi n} = \frac{i\sqrt{2}c_3}{(F_0\Lambda_\chi)} \pi^- \mathcal{P}_{ddd}^{\text{LR},\mu} i\tilde{\partial}_\mu n_L + L \leftrightarrow R$$

$$\mathcal{O}_{DLddQ}^{\text{prst}} = (\overline{iD}_\mu L_p d_{\{r\}}^\alpha) (\overline{d}_s^{\beta\text{C}} \gamma^\mu Q_t^\gamma) \epsilon_{\alpha\beta\gamma}$$

$$\tilde{\partial}_\mu = \Gamma_{\mu\nu} \partial^\nu = \partial_\mu - \frac{1}{4} \gamma_\mu \not{\partial}$$

$$\mathcal{P}_{ddd}^{\text{RL},\mu} = -0.91 C_{DLddQ}^{\ell 111} i\partial^\mu \overline{\ell}_L$$

RGE effects  $\sim \Lambda_\ell^{-3}$

$$\Gamma(n \rightarrow \ell^- \pi^+) \sim \left( \frac{7 \times 10^9 \text{ GeV}}{\Lambda_\ell} \right)^6 / (5 \times 10^{31} \text{ yr})$$

## B. The process: $p \rightarrow \ell_\alpha^+ \ell_\alpha^+ \ell_\beta^-$ with $\ell_\alpha = e, \ell_\beta = \mu$ or vice versa

- Among the most experimentally constrained proton decay processes

$$\mathcal{O}_{\ell\ell'} = (\overline{\ell}_L^{\text{C}} \gamma_\mu \ell_R) (\overline{\ell}_R' u_L^\alpha) (\overline{u}_L^{\beta\text{C}} \gamma^\mu d_R^\gamma) \epsilon_{\alpha\beta\gamma} \quad \mathcal{P}_{uud}^{\text{LR},\mu} = \Lambda_{\ell\ell'}^{-5} (\overline{\ell}_L^{\text{C}} \gamma^\mu \ell_R) \overline{\ell}_R'$$

- Can be only mediated by dim-9 and higher LEFT operators

- Associated with irreps  $\mathbf{6}_{L(R)} \otimes \mathbf{3}_{R(L)}$

$$\Gamma(p \rightarrow e^+ e^+ \mu^-) \sim \Gamma(p \rightarrow \mu^+ \mu^+ e^-) \sim \left( \frac{4 \times 10^5 \text{ GeV}}{\Lambda_{\mu e}} \right)^{10} / (10^{34} \text{ yr})$$

Nucleon decay into triple leptons have been systematically studied in:

*J. Chen, Y. Liao, X.-D. Ma, and HLW, PLB 876 (2026)*

*Y. Liao, X.-D. Ma, and X. Zhao, JHEP 05 (2026)*

**Noncontact contributions**

**Contact contributions**

# Phenomenological applications

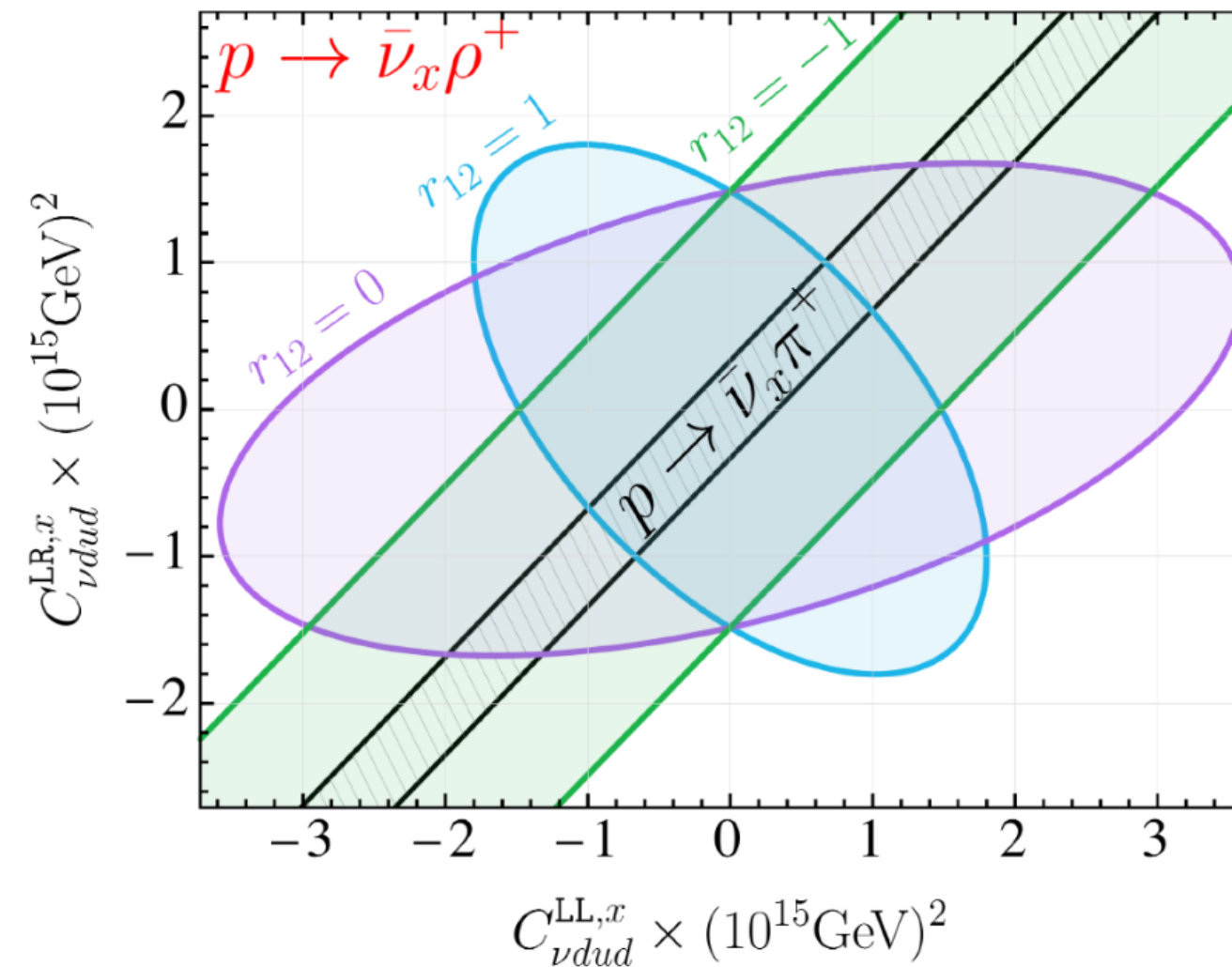
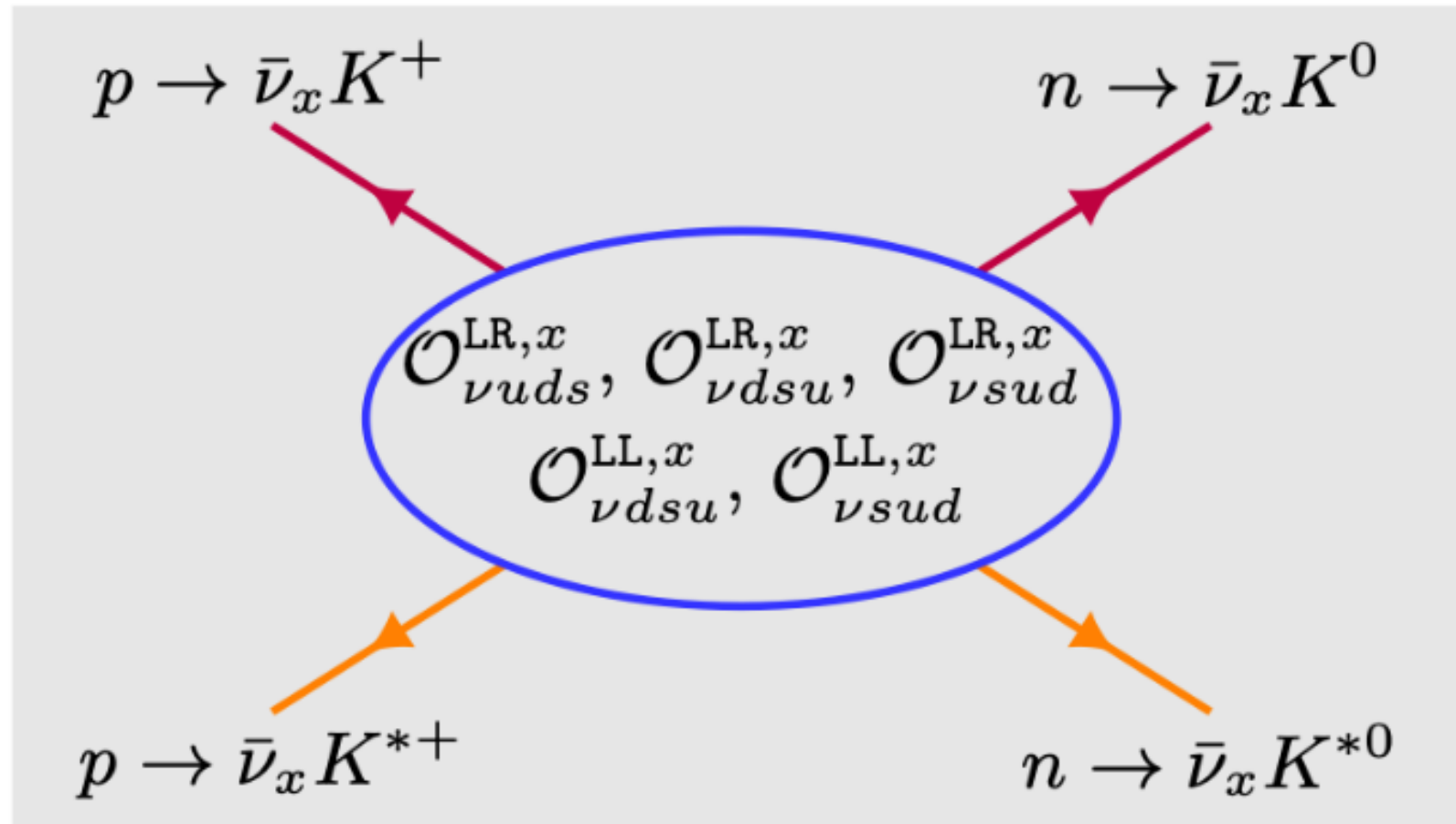
- Chiral Lagrangian involving vector mesons:

*Y. Liao, X.-D. Ma, and **HLW**, PRD Letter 112 (2025)*

$$\begin{aligned} \mathcal{L}_{BV}^B = & d_1 \text{Tr} [\mathcal{P}_{\bar{3}_L \otimes 3_R} \xi \gamma_\mu V^\mu B_R \xi - \mathcal{P}_{3_L \otimes \bar{3}_R} \xi^\dagger \gamma_\mu V^\mu B_L \xi^\dagger] + d'_1 \text{Tr} [\mathcal{P}_{\bar{3}_L \otimes 3_R} \xi \gamma_\mu B_R V^\mu \xi - \mathcal{P}_{3_L \otimes \bar{3}_R} \xi^\dagger \gamma_\mu B_L V^\mu \xi^\dagger] \\ & + d_2 \text{Tr} [\mathcal{P}_{8_L \otimes 1_R} \xi \gamma_\mu V^\mu B_R \xi^\dagger - \mathcal{P}_{1_L \otimes 8_R} \xi^\dagger \gamma_\mu V^\mu B_L \xi] + d'_2 \text{Tr} [\mathcal{P}_{8_L \otimes 1_R} \xi \gamma_\mu B_R V^\mu \xi^\dagger - \mathcal{P}_{1_L \otimes 8_R} \xi^\dagger \gamma_\mu B_L V^\mu \xi] \\ & + d_3 [\mathcal{P}_{yzi}^{\text{LR},\mu} \Gamma_{\mu\nu}^L (\xi B_L \xi)_{yj} (\xi V^\nu \xi)_{zk} \epsilon_{ijk} - \mathcal{P}_{yzi}^{\text{RL},\mu} \Gamma_{\mu\nu}^R (\xi^\dagger B_R \xi^\dagger)_{yj} (\xi^\dagger V^\nu \xi^\dagger)_{zk} \epsilon_{ijk}] \\ & + d'_3 [\mathcal{P}_{yzi}^{\text{LR},\mu} \Gamma_{\mu\nu}^L (\xi V^\nu B_L \xi)_{yj} \Sigma_{zk} \epsilon_{ijk} - \mathcal{P}_{yzi}^{\text{RL},\mu} \Gamma_{\mu\nu}^R (\xi^\dagger V^\nu B_R \xi^\dagger)_{yj} \Sigma_{zk}^* \epsilon_{ijk}] \\ & + d''_3 [\mathcal{P}_{yzi}^{\text{LR},\mu} \Gamma_{\mu\nu}^L (\xi B_L V^\nu \xi)_{yj} \Sigma_{zk} \epsilon_{ijk} - \mathcal{P}_{yzi}^{\text{RL},\mu} \Gamma_{\mu\nu}^R (\xi^\dagger B_R V^\nu \xi^\dagger)_{yj} \Sigma_{zk}^* \epsilon_{ijk}] \\ & + \frac{d_4}{\Lambda_\chi} [\mathcal{P}_{yzw}^{\text{LL},\mu\nu} \hat{\Gamma}_{\mu\nu\alpha\beta}^L (\xi D^\alpha B_L \xi)_{yi} \Sigma_{zj} (\xi V^\beta \xi)_{wk} \epsilon_{ijk} - \mathcal{P}_{yzw}^{\text{RR},\mu\nu} \hat{\Gamma}_{\mu\nu\alpha\beta}^R (\xi^\dagger D^\alpha B_R \xi^\dagger)_{yi} \Sigma_{zj}^* (\xi V^\beta \xi)_{kw}^* \epsilon_{ijk}] + \text{H.c.} \end{aligned}$$

$$V_\mu(x) = \begin{pmatrix} \frac{\rho_\mu^0}{\sqrt{2}} + \frac{\phi_\mu^{(8)}}{\sqrt{6}} & \rho_\mu^+ & K_\mu^{*+} \\ \rho_\mu^- & -\frac{\rho_\mu^0}{\sqrt{2}} + \frac{\phi_\mu^{(8)}}{\sqrt{6}} & K_\mu^{*0} \\ K_\mu^{*-} & \bar{K}_\mu^{*0} & -\sqrt{\frac{2}{3}} \phi_\mu^{(8)} \end{pmatrix} \quad V_\mu \xrightarrow{G} \hat{h} V_\mu \hat{h}^\dagger$$

NDA:  $d_{1,2,3,4}^{('')} \sim \Lambda_\chi^2 / (4\pi) \approx 0.115 \text{ GeV}^2$

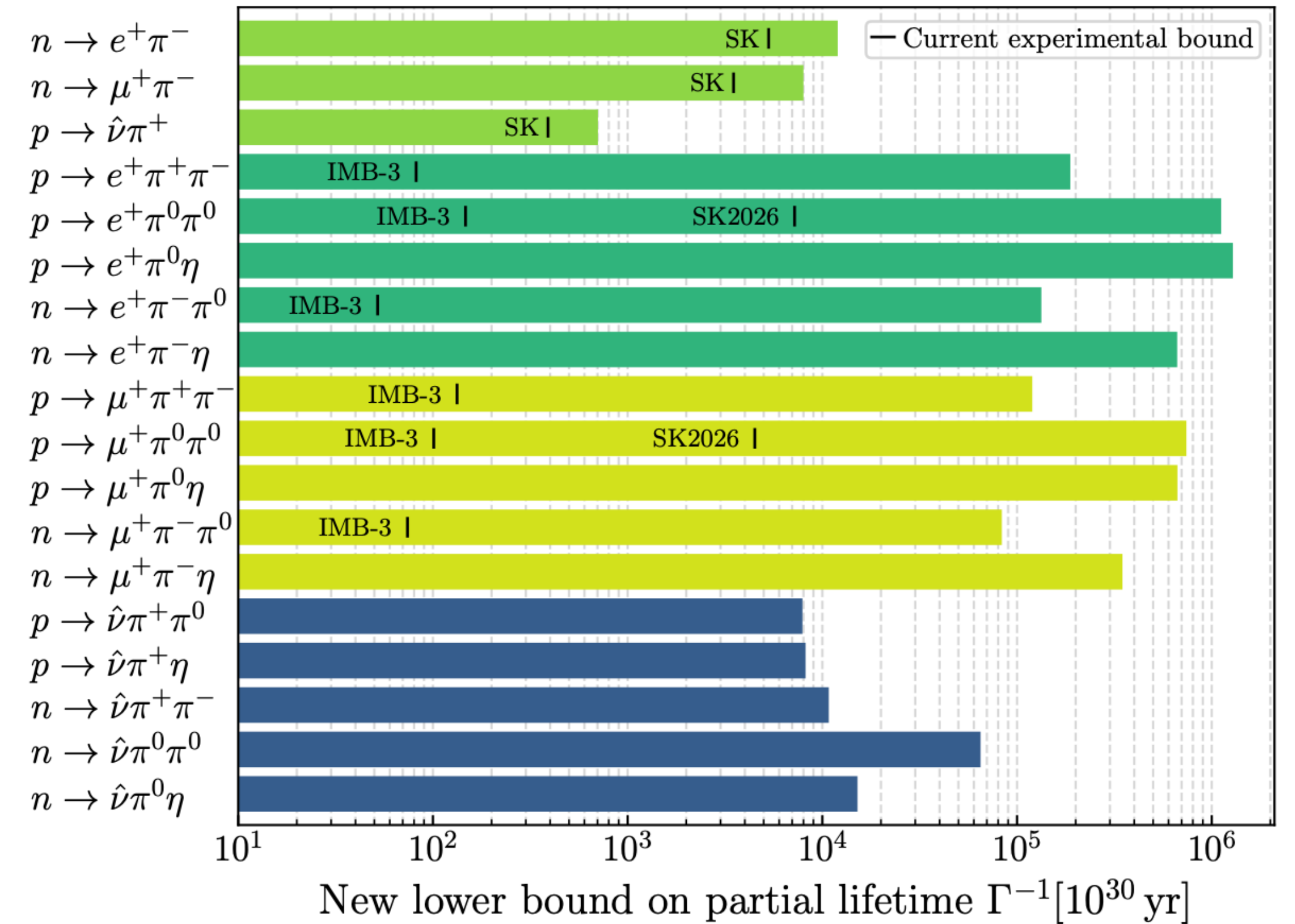
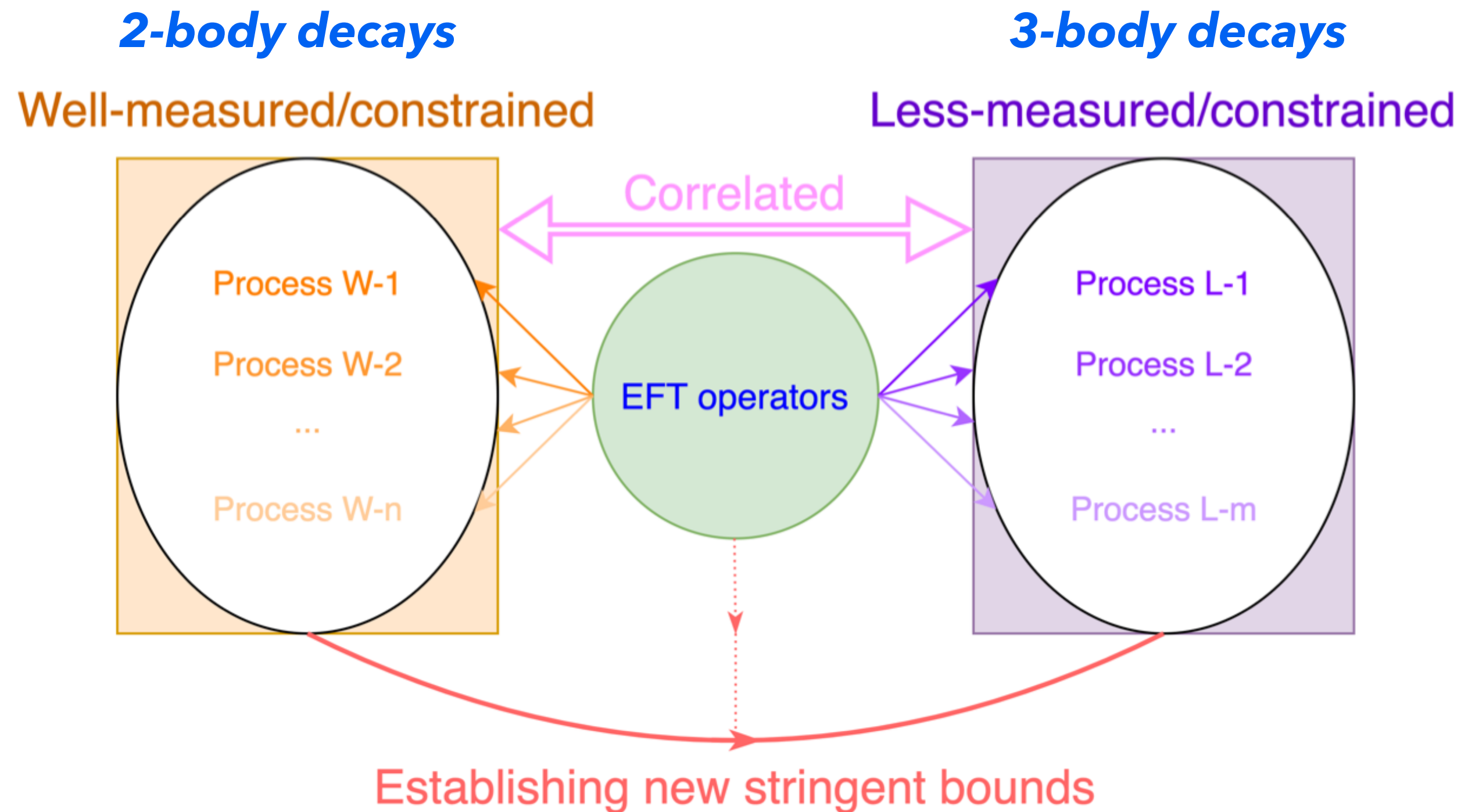


$r_{12} \equiv d_1/d_2$

**Complementarity  
between pseudoscalar  
and vector mesons**

# Phenomenological applications

- Establish new bounds on 3-body modes from experimental limits on 2-body ones



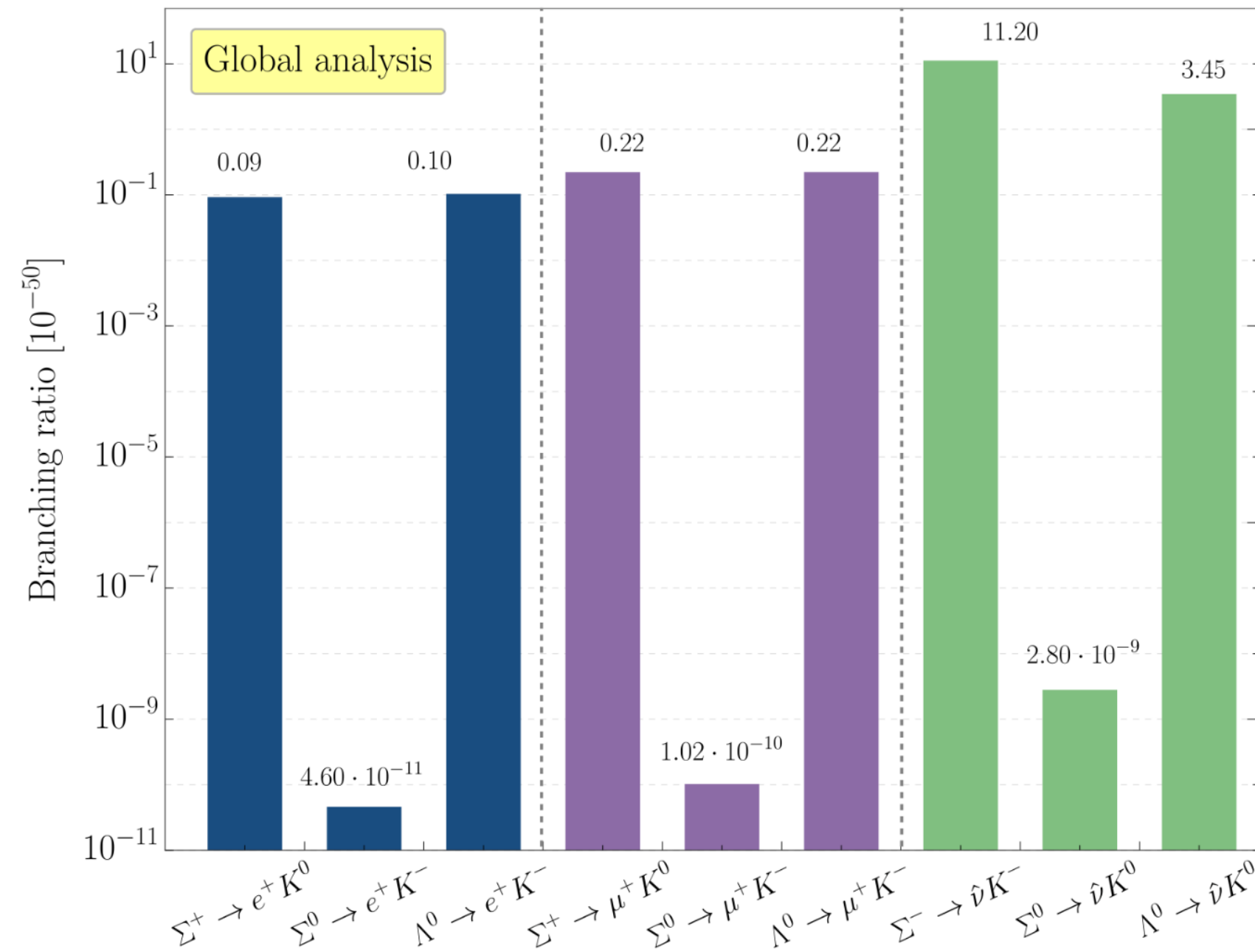
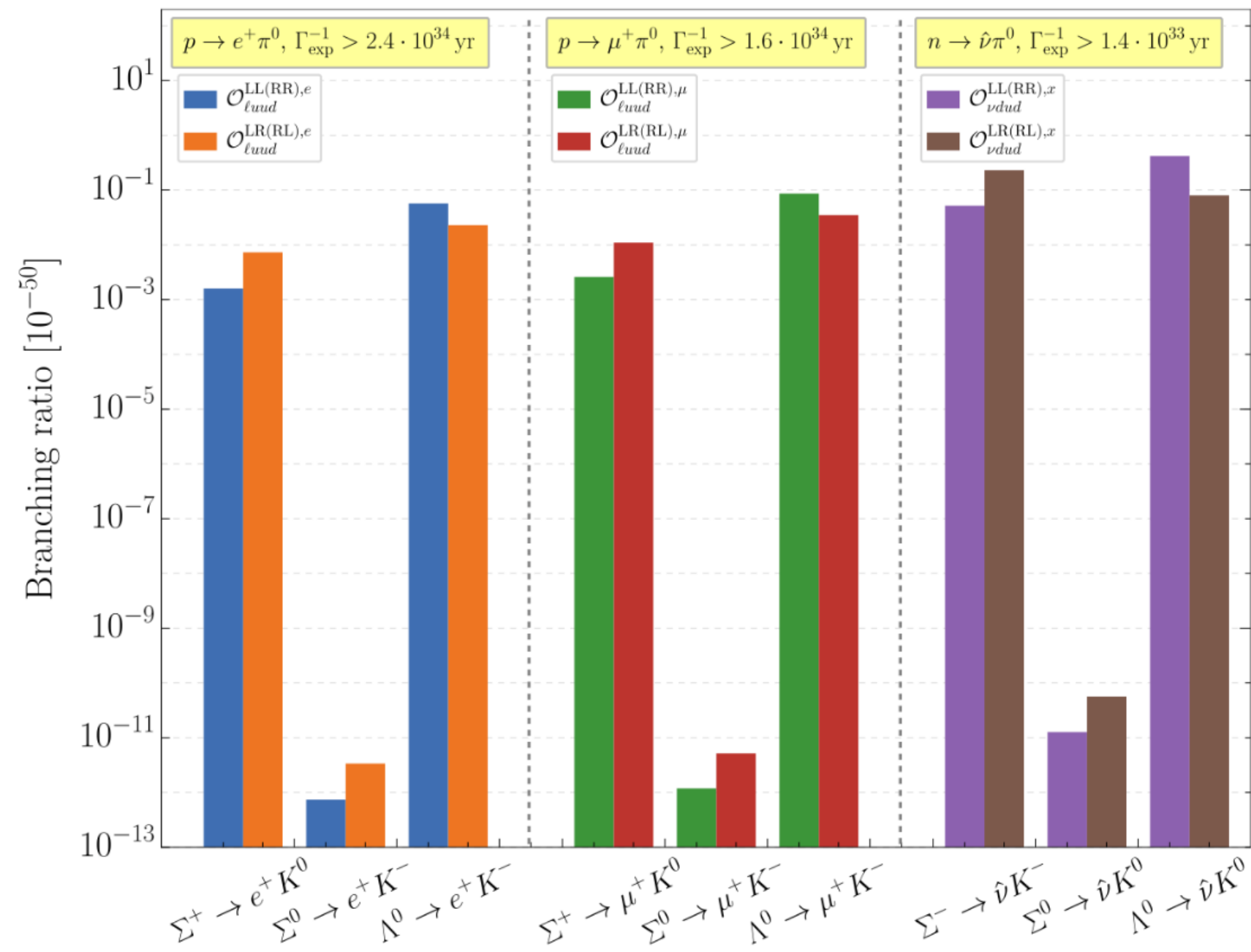
W.-Q. Fan, Y. Liao, and X.-D. Ma, 2604.24613, 2605.17525

# Phenomenological applications

- BNV hyperon decays are automatically formulated in the SU(3) ChPT:

*J. Chen, Y. Liao, X.-D. Ma, HLW, and X. Zhao, in preparation*

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



- ✓ Current constraints from nucleon decay imply  $\text{Br} < 10^{-50}$ , far below present experimental sensitivity ( $\sim 10^{-6}$ )
- ✓ Hyperon decays probe NP scenarios that are not accessible through nucleon decays

# Phenomenological applications

- BNV nucleon decays involving **new light particles**

- ✓ **Sterile neutrino  $N$**

*T. Li, M. A. Schmidt, and C.-Y. Yao, JHEP 08 (2024)*

*W.-Q. Fan, Y. Liao, X.-D. Ma, and HLW, CPC 50 (2026)*

- ✓ **Axion-like particle  $a$**

*T. Li, M. A. Schmidt, and C.-Y. Yao, JHEP 06 (2025)*

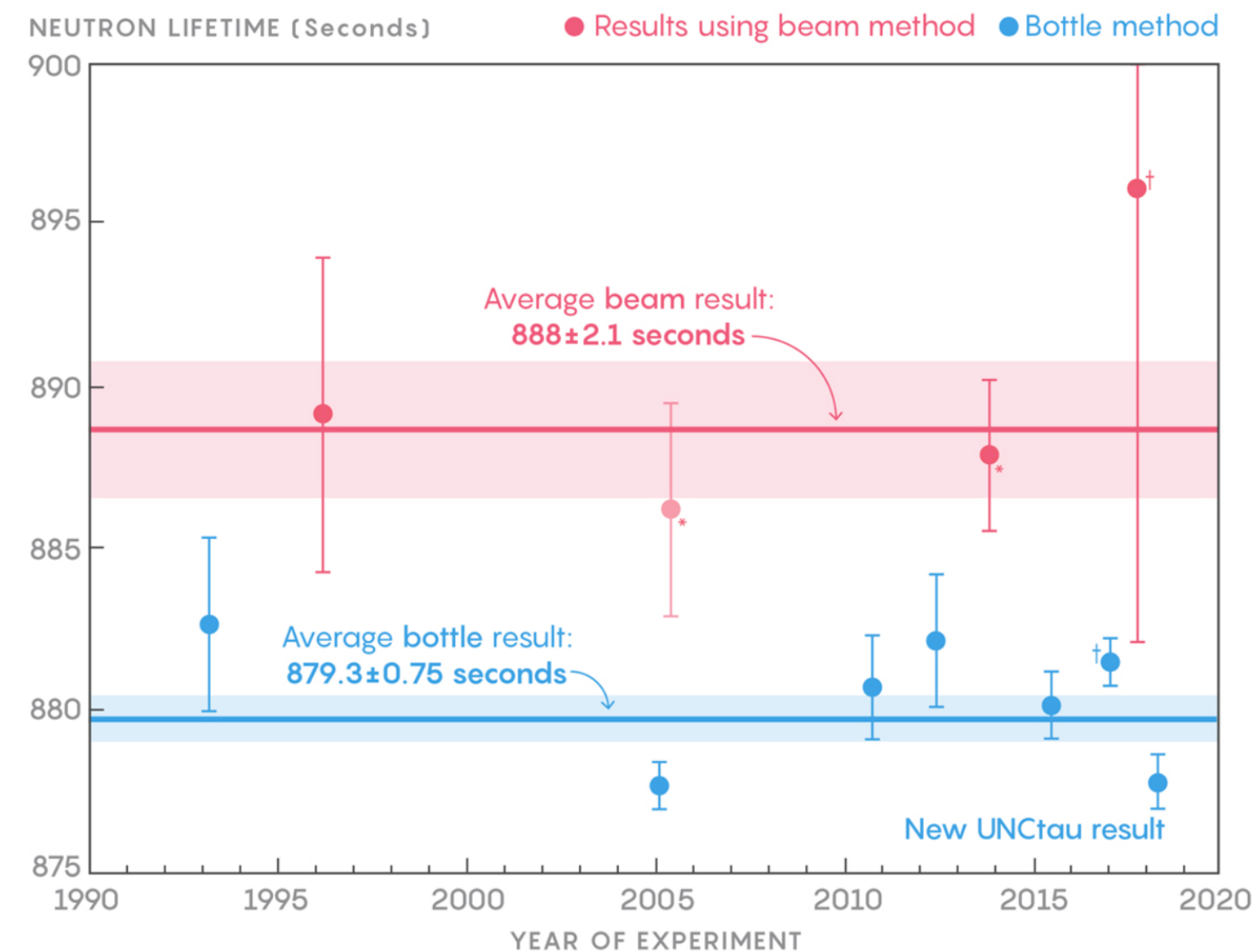
- ✓ **Scalar  $\varphi$**

*X.-D. Ma, M. A. Schmidt, and W. Zhang, JHEP 02 (2026)*

- ✓ **Dark photon  $X$**

*J.-H. Liang, Y. Liao, X.-D. Ma, and X. Zhao, 2607.22452*

- **Connection to the neutron-lifetime anomaly**



- ✓ The beam method: counting the producing  $p$

$$\tau_n^{\text{beam}} \simeq 888.0 \text{ s}$$

- ✓ The bottle method: measuring the total neutron lifetime

$$\tau_n^{\text{bottle}} \simeq 879.6 \text{ s}$$

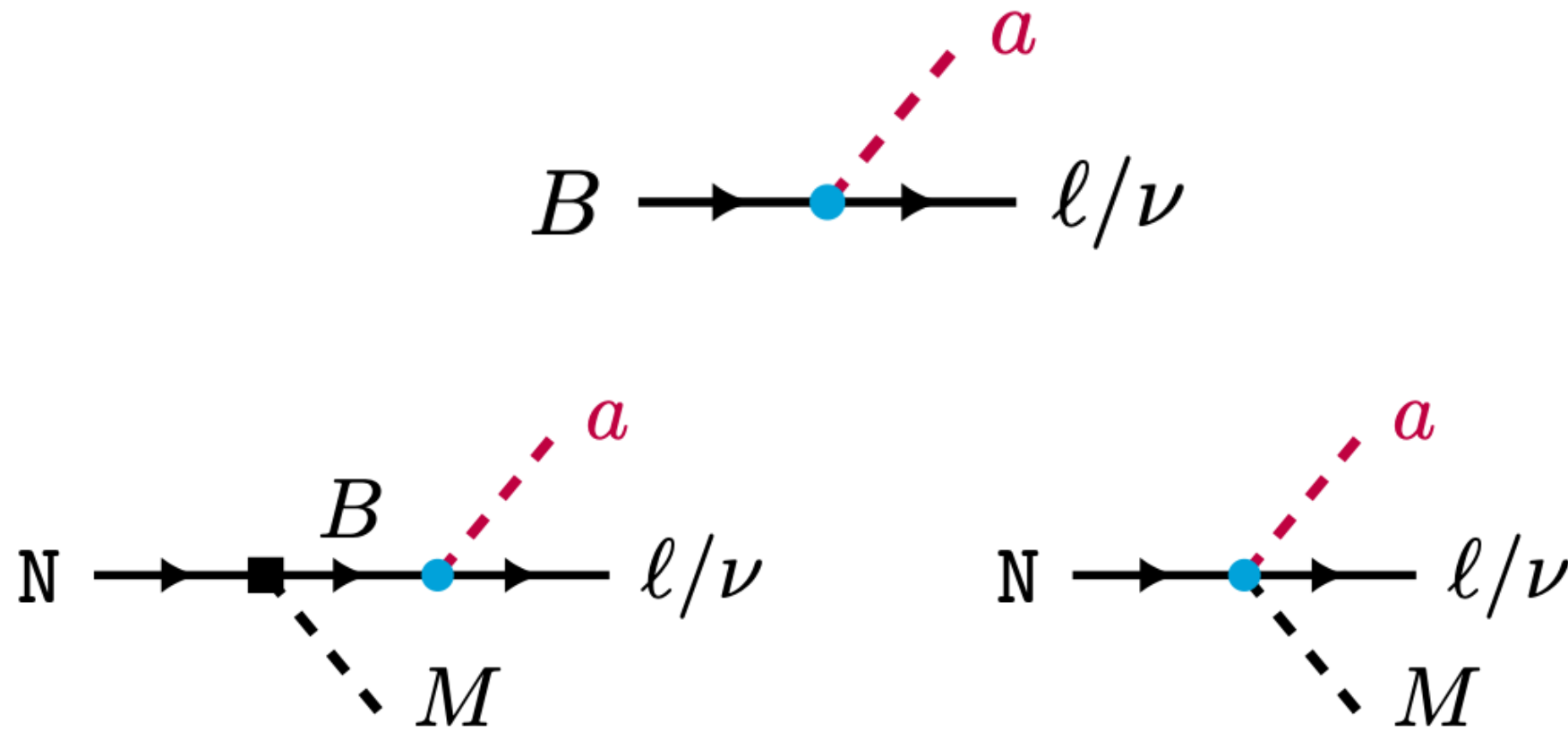
**The ~9s discrepancy motivates searches for exotic nucleon decay channels**

# Phenomenological applications

## ALP as an example

- Shift symmetry is assumed
- The LO operators appear at dim-8,  $lqqq\partial a$
- Operators involved  $\mathbf{6}_L \otimes \mathbf{3}_R$  ( $\mathbf{3}_L \otimes \mathbf{6}_R$ ) are (partially) neglected in the literature, 14 out of 20

*T. Li, M. A. Schmidt, and C.-Y. Yao, JHEP 08 (2024)*



*W.-Q. Fan, Y. Liao, X.-D. Ma, and HLW, CPC 50 (2026)*

|                 | Notation                                          | Operator                                                                                                             | Chiral Irrep.                                                                      | # of operators                           | Comparison with [18]                                                                                             |
|-----------------|---------------------------------------------------|----------------------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------|------------------------------------------|------------------------------------------------------------------------------------------------------------------|
| $\Delta(B-L)=0$ | $\mathcal{O}_{\partial a e u u d}^{\text{VL,SL}}$ | $\partial_\mu a (\bar{e}_R^c \gamma^\mu u_L^\alpha) (\bar{u}_L^{\beta c} d_L^\gamma) \epsilon_{\alpha\beta\gamma}$   | $\mathbf{8}_L \otimes \mathbf{1}_R$                                                | $n_e n_u^2 n_d [2n_e]$                   | $-\mathcal{O}_{\partial a e u d u}^{\text{VL,SL}}$                                                               |
|                 | $\mathcal{O}_{\partial a e u u d}^{\text{SL,VR}}$ | $\partial_\mu a (\bar{e}_L^c u_L^\alpha) (\bar{u}_L^{\beta c} \gamma^\mu d_R^\gamma) \epsilon_{\alpha\beta\gamma}$   | $\mathbf{6}_L \otimes \mathbf{3}_R$                                                | $n_e n_u^2 n_d [2n_e]$                   | $-\mathcal{O}_{\partial a u d u e}^{\text{VL,SR}\dagger}$                                                        |
|                 | $\mathcal{O}_{\partial a e u d u}^{\text{SL,VR}}$ | $\partial_\mu a (\bar{e}_L^c u_L^\alpha) (\bar{d}_L^{\beta c} \gamma^\mu u_R^\gamma) \epsilon_{\alpha\beta\gamma}$   | $\mathbf{6}_L \otimes \mathbf{3}_R \oplus \bar{\mathbf{3}}_L \otimes \mathbf{3}_R$ | $n_e n_u^2 n_d [2n_e]$                   | $-\mathcal{O}_{\partial a d u u e}^{\text{VL,SR}\dagger}$                                                        |
|                 | $\mathcal{O}_{\partial a e d u u}^{\text{SL,VR}}$ | $\partial_\mu a (\bar{e}_L^c d_L^\alpha) (\bar{u}_L^{\beta c} \gamma^\mu u_R^\gamma) \epsilon_{\alpha\beta\gamma}$   | $\mathbf{6}_L \otimes \mathbf{3}_R \oplus \bar{\mathbf{3}}_L \otimes \mathbf{3}_R$ | $n_e n_u^2 n_d [2n_e]$                   | $-\mathcal{O}_{\partial a u u d e}^{\text{VL,SR}\dagger}$                                                        |
|                 | $\mathcal{O}_{\partial a e u u d}^{\text{VR,SR}}$ | $\partial_\mu a (\bar{e}_L^c \gamma^\mu u_R^\alpha) (\bar{u}_R^{\beta c} d_R^\gamma) \epsilon_{\alpha\beta\gamma}$   | $\mathbf{1}_L \otimes \mathbf{8}_R$                                                | $n_e n_u^2 n_d [2n_e]$                   | $\mathcal{O}_{\partial a e u u d}^{\text{VR,SR}}$                                                                |
|                 | $\mathcal{O}_{\partial a e u u d}^{\text{SR,VL}}$ | $\partial_\mu a (\bar{e}_R^c u_R^\alpha) (\bar{u}_R^{\beta c} \gamma^\mu d_L^\gamma) \epsilon_{\alpha\beta\gamma}$   | $\mathbf{3}_L \otimes \mathbf{6}_R$                                                | $n_e n_u^2 n_d [2n_e]$                   | $\mathcal{O}_{\partial a d u u e}^{\text{VR,SR}}$                                                                |
|                 | $\mathcal{O}_{\partial a e u d u}^{\text{SR,VL}}$ | $\partial_\mu a (\bar{e}_R^c u_R^\alpha) (\bar{d}_R^{\beta c} \gamma^\mu u_L^\gamma) \epsilon_{\alpha\beta\gamma}$   | $\mathbf{3}_L \otimes \mathbf{6}_R \oplus \mathbf{3}_L \otimes \bar{\mathbf{3}}_R$ | $n_e n_u^2 n_d [2n_e]$                   | $\mathcal{O}_{\partial a d u e u}^{\text{VL,SR}}$                                                                |
|                 | $\mathcal{O}_{\partial a e d u u}^{\text{SR,VL}}$ | $\partial_\mu a (\bar{e}_R^c d_R^\alpha) (\bar{u}_R^{\beta c} \gamma^\mu u_L^\gamma) \epsilon_{\alpha\beta\gamma}$   | $\mathbf{3}_L \otimes \mathbf{6}_R \oplus \mathbf{3}_L \otimes \bar{\mathbf{3}}_R$ | $n_e n_u^2 n_d [2n_e]$                   | $\mathcal{O}_{\partial a d u e u}^{\text{VL,SR}} - \mathcal{O}_{\partial a e u d u}^{\text{VL,SR}}$              |
|                 | $\mathcal{O}_{\partial a v d d u}^{\text{VR,SR}}$ | $\partial_\mu a (\bar{\nu}_L^c \gamma^\mu d_R^\alpha) (\bar{d}_R^{\beta c} u_R^\gamma) \epsilon_{\alpha\beta\gamma}$ | $\mathbf{1}_L \otimes \mathbf{8}_R$                                                | $n_\nu n_u n_d^2 [4n_\nu]$               | $-\mathcal{O}_{\partial a d v d u}^{\text{VL,SR}}$                                                               |
|                 | $\mathcal{O}_{\partial a v d d u}^{\text{SL,VR}}$ | $\partial_\mu a (\bar{\nu}_L^c d_L^\alpha) (\bar{d}_L^{\beta c} \gamma^\mu u_R^\gamma) \epsilon_{\alpha\beta\gamma}$ | $\mathbf{6}_L \otimes \mathbf{3}_R \oplus \bar{\mathbf{3}}_L \otimes \mathbf{3}_R$ | $n_\nu n_u n_d^2 [4n_\nu]$               | $-\mathcal{O}_{\partial a d u d \nu}^{\text{VL,SR}\dagger}$                                                      |
| $\Delta(B+L)=0$ | $\mathcal{O}_{\partial a v d u d}^{\text{SL,VR}}$ | $\partial_\mu a (\bar{\nu}_L^c d_L^\alpha) (\bar{u}_L^{\beta c} \gamma^\mu d_R^\gamma) \epsilon_{\alpha\beta\gamma}$ | $\mathbf{6}_L \otimes \mathbf{3}_R \oplus \bar{\mathbf{3}}_L \otimes \mathbf{3}_R$ | $n_\nu n_u n_d^2 [4n_\nu]$               | $-(\mathcal{O}_{\partial a d v u d}^{\text{VL,SL}} + [\mathcal{O}_{\partial a d d v u}^{\text{VL,SR}}]^\dagger)$ |
|                 | $\mathcal{O}_{\partial a v u d d}^{\text{SL,VR}}$ | $\partial_\mu a (\bar{\nu}_L^c u_L^\alpha) (\bar{d}_L^{\beta c} \gamma^\mu d_R^\gamma) \epsilon_{\alpha\beta\gamma}$ | $\mathbf{6}_L \otimes \mathbf{3}_R \oplus \bar{\mathbf{3}}_L \otimes \mathbf{3}_R$ | $n_\nu n_u n_d^2 [4n_\nu]$               | $-\mathcal{O}_{\partial a d d v u}^{\text{VL,SR}\dagger}$                                                        |
|                 | $\mathcal{O}_{\partial a v d d u}^{\text{VL,SL}}$ | $\partial_\mu a (\bar{\nu}_L \gamma^\mu d_L^\alpha) (\bar{d}_L^{\beta c} u_L^\gamma) \epsilon_{\alpha\beta\gamma}$   | $\mathbf{8}_L \otimes \mathbf{1}_R$                                                | $n_\nu n_u n_d^2 [4n_\nu]$               | $\mathcal{O}_{\partial a v d d u}^{\text{VL,SL}}$                                                                |
|                 | $\mathcal{O}_{\partial a v d d u}^{\text{SR,VL}}$ | $\partial_\mu a (\bar{\nu}_L d_R^\alpha) (\bar{d}_R^{\beta c} \gamma^\mu u_L^\gamma) \epsilon_{\alpha\beta\gamma}$   | $\mathbf{3}_L \otimes \mathbf{6}_R \oplus \mathbf{3}_L \otimes \bar{\mathbf{3}}_R$ | $n_\nu n_u n_d^2 [4n_\nu]$               | $\mathcal{O}_{\partial a u d v d}^{\text{VR,SR}}$                                                                |
|                 | $\mathcal{O}_{\partial a v d u d}^{\text{SR,VL}}$ | $\partial_\mu a (\bar{\nu}_L d_R^\alpha) (\bar{u}_R^{\beta c} \gamma^\mu d_L^\gamma) \epsilon_{\alpha\beta\gamma}$   | $\mathbf{3}_L \otimes \mathbf{6}_R \oplus \mathbf{3}_L \otimes \bar{\mathbf{3}}_R$ | $n_\nu n_u n_d^2 [4n_\nu]$               | $\mathcal{O}_{\partial a d u v d}^{\text{VR,SR}}$                                                                |
|                 | $\mathcal{O}_{\partial a v u d d}^{\text{SR,VL}}$ | $\partial_\mu a (\bar{\nu}_L u_R^\alpha) (\bar{d}_R^{\beta c} \gamma^\mu d_L^\gamma) \epsilon_{\alpha\beta\gamma}$   | $\mathbf{3}_L \otimes \mathbf{6}_R \oplus \mathbf{3}_L \otimes \bar{\mathbf{3}}_R$ | $n_\nu n_u n_d^2 [4n_\nu]$               | $\mathcal{O}_{\partial a d d v u}^{\text{VR,SR}}$                                                                |
|                 | $\mathcal{O}_{\partial a e d d d}^{\text{VR,SR}}$ | $\partial_\mu a (\bar{e}_R \gamma^\mu d_R^\alpha) (\bar{d}_R^{\beta c} d_R^\gamma) \epsilon_{\alpha\beta\gamma}$     | $\mathbf{1}_L \otimes \mathbf{8}_R$                                                | $\frac{1}{3} n_e n_d (n_d^2 - 1) [2n_e]$ | $\mathcal{O}_{\partial a e d d d}^{\text{VR,SR}}$                                                                |
|                 | $\mathcal{O}_{\partial a e d d d}^{\text{SR,VL}}$ | $\partial_\mu a (\bar{e}_L d_R^\alpha) (\bar{d}_R^{\beta c} \gamma^\mu d_L^\gamma) \epsilon_{\alpha\beta\gamma}$     | $\mathbf{3}_L \otimes \mathbf{6}_R \oplus \mathbf{3}_L \otimes \bar{\mathbf{3}}_R$ | $n_e n_d^3 [8n_e]$                       | $\tilde{\mathcal{O}}_{\partial a e d d d}^{\text{VR,SR}}$                                                        |
|                 | $\mathcal{O}_{\partial a e d d d}^{\text{VL,SL}}$ | $\partial_\mu a (\bar{e}_L \gamma^\mu d_L^\alpha) (\bar{d}_L^{\beta c} d_L^\gamma) \epsilon_{\alpha\beta\gamma}$     | $\mathbf{8}_L \otimes \mathbf{1}_R$                                                | $\frac{1}{3} n_e n_d (n_d^2 - 1) [2n_e]$ | $\mathcal{O}_{\partial a e d d d}^{\text{VL,SL}}$                                                                |
|                 | $\mathcal{O}_{\partial a e d d d}^{\text{SL,VR}}$ | $\partial_\mu a (\bar{e}_R d_L^\alpha) (\bar{d}_L^{\beta c} \gamma^\mu d_R^\gamma) \epsilon_{\alpha\beta\gamma}$     | $\mathbf{6}_L \otimes \mathbf{3}_R \oplus \bar{\mathbf{3}}_L \otimes \mathbf{3}_R$ | $n_e n_d^3 [8n_e]$                       | $-\mathcal{O}_{\partial a d d d e}^{\text{VL,SR}\dagger}$                                                        |

# Phenomenological applications

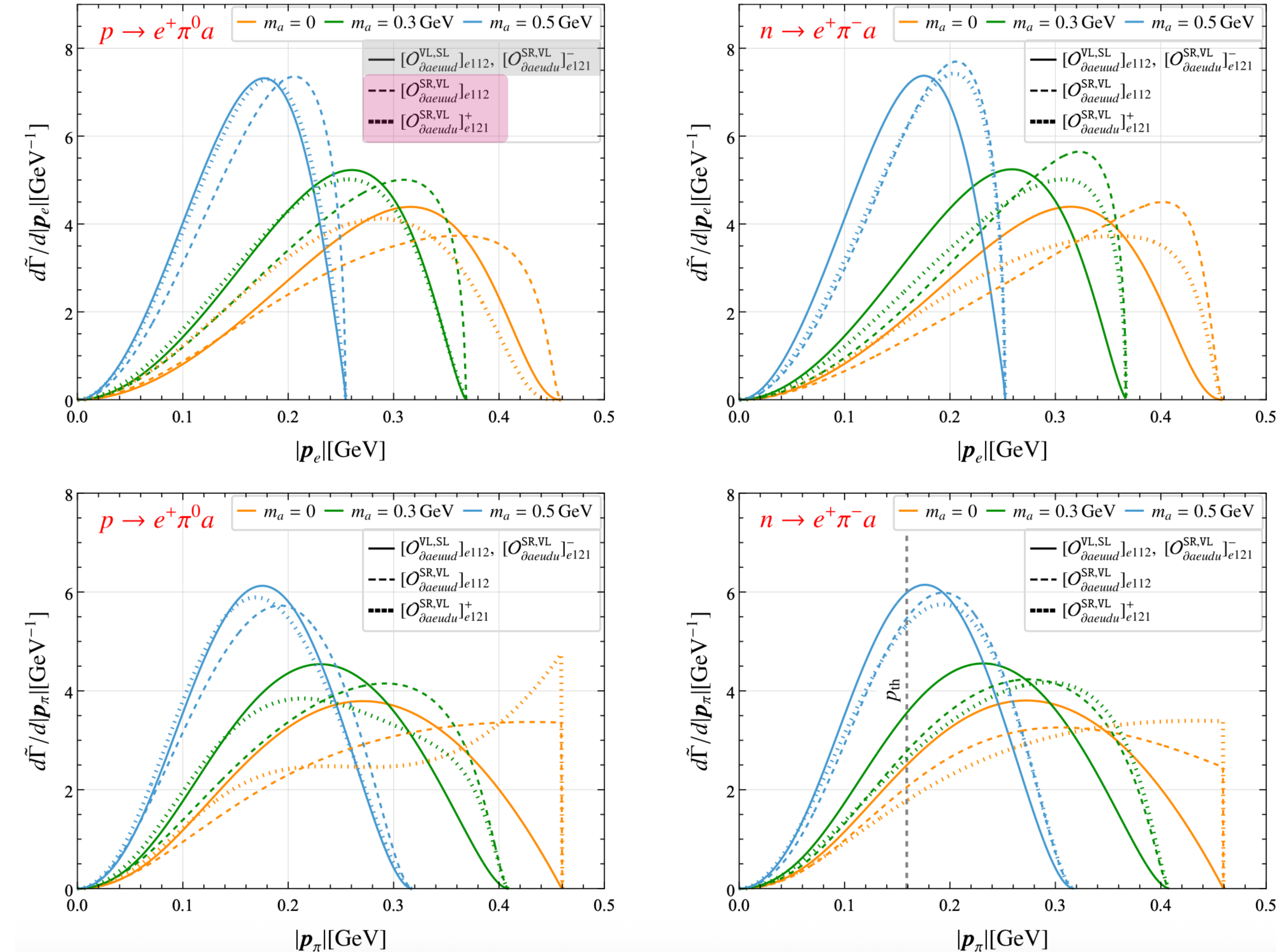
*W.-Q. Fan, Y. Liao, X.-D. Ma, and HLW, CPC 50 (2026)*

- Consider the normalized distributions

$$\frac{d\tilde{\Gamma}}{d|\mathbf{p}_\ell|} = \frac{1}{\Gamma} \frac{d\Gamma}{d|\mathbf{p}_\ell|}, \quad \frac{d\tilde{\Gamma}}{d|\mathbf{p}_M|} = \frac{1}{\Gamma} \frac{d\Gamma}{d|\mathbf{p}_M|}$$

- $[\mathcal{O}_{\partial ae u u d}^{\text{VL,SL}}]_{x112} \in \mathbf{8}_L \otimes \mathbf{1}_R, [\mathcal{O}_{\partial ae u d u}^{\text{SR,VL}}]_{x121}^- \in \mathbf{3}_L \otimes \bar{\mathbf{3}}_R$
- $[\mathcal{O}_{\partial ae u u d}^{\text{SR,VL}}]_{x112}, [\mathcal{O}_{\partial ae u d u}^{\text{SR,VL}}]_{x121}^+ \in \mathbf{3}_L \otimes \mathbf{6}_R$
- Newly identified chiral irreps  $\mathbf{6}_L \otimes \mathbf{3}_R$  ( $\mathbf{3}_L \otimes \mathbf{6}_R$ ) exhibit markedly different behavior:
  - \* Tend to be concentrated at higher  $|\mathbf{p}_\pi|$
  - \* Different isospin components

*ALP as an example*



# Phenomenological applications

- Existing experimental limits

*Super-Kamiokande (2015)*

$$\Gamma^{-1}(p \rightarrow e^+ + X) > 7.9 \times 10^{32} \text{ yr}, \quad \Gamma^{-1}(p \rightarrow \mu^+ + X) > 4.1 \times 10^{32} \text{ yr}$$

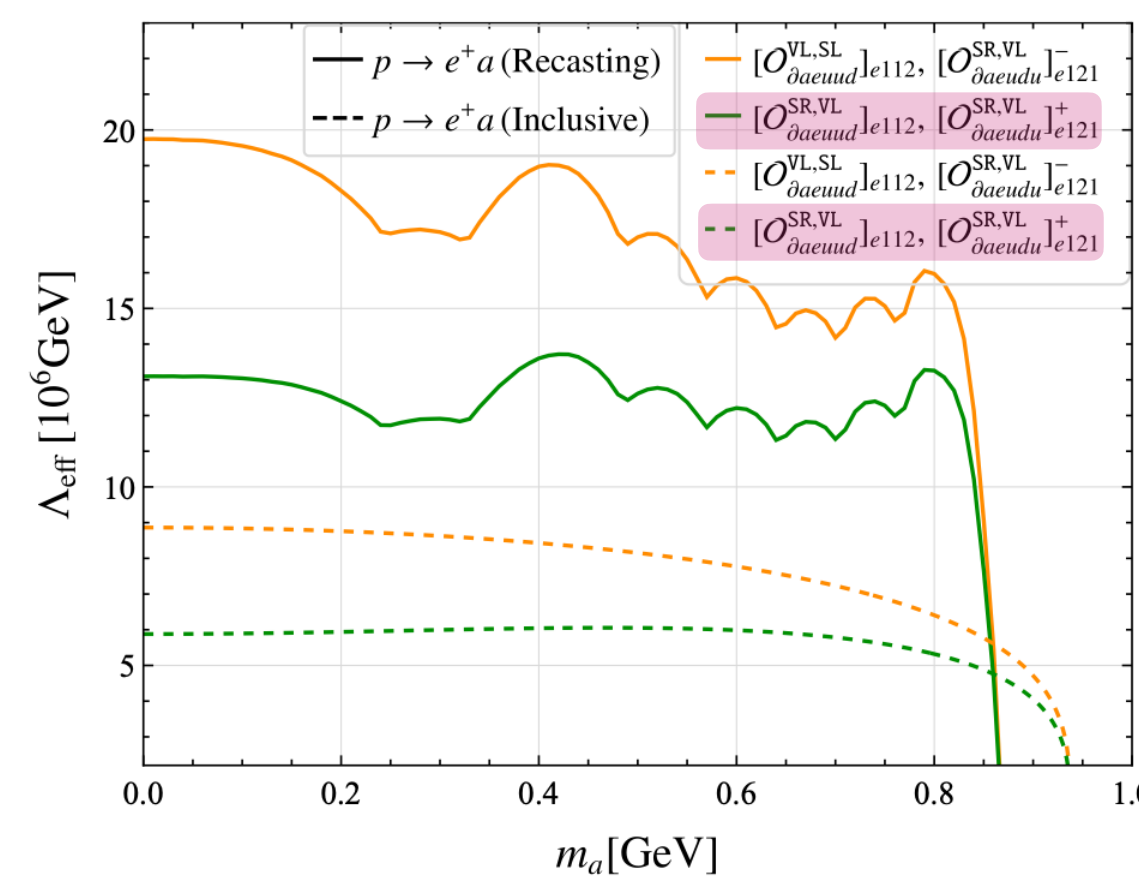
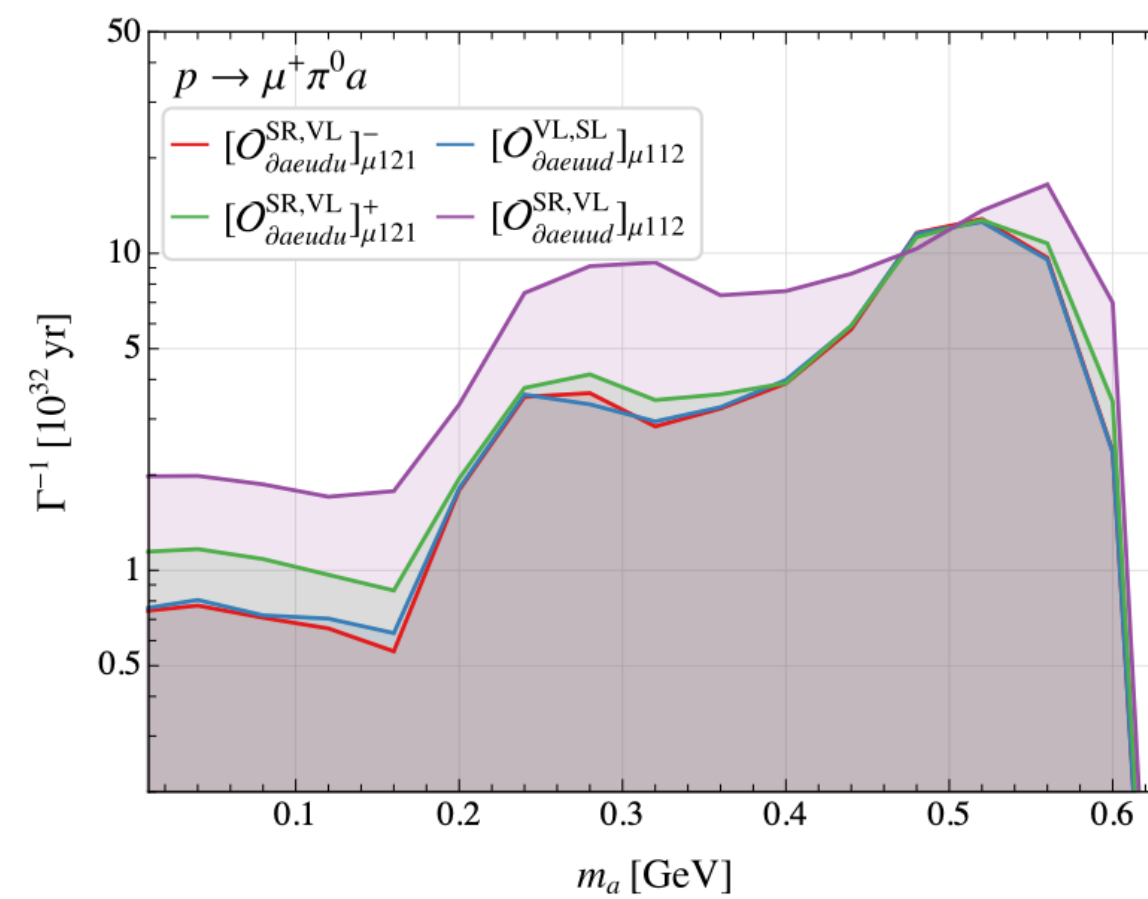
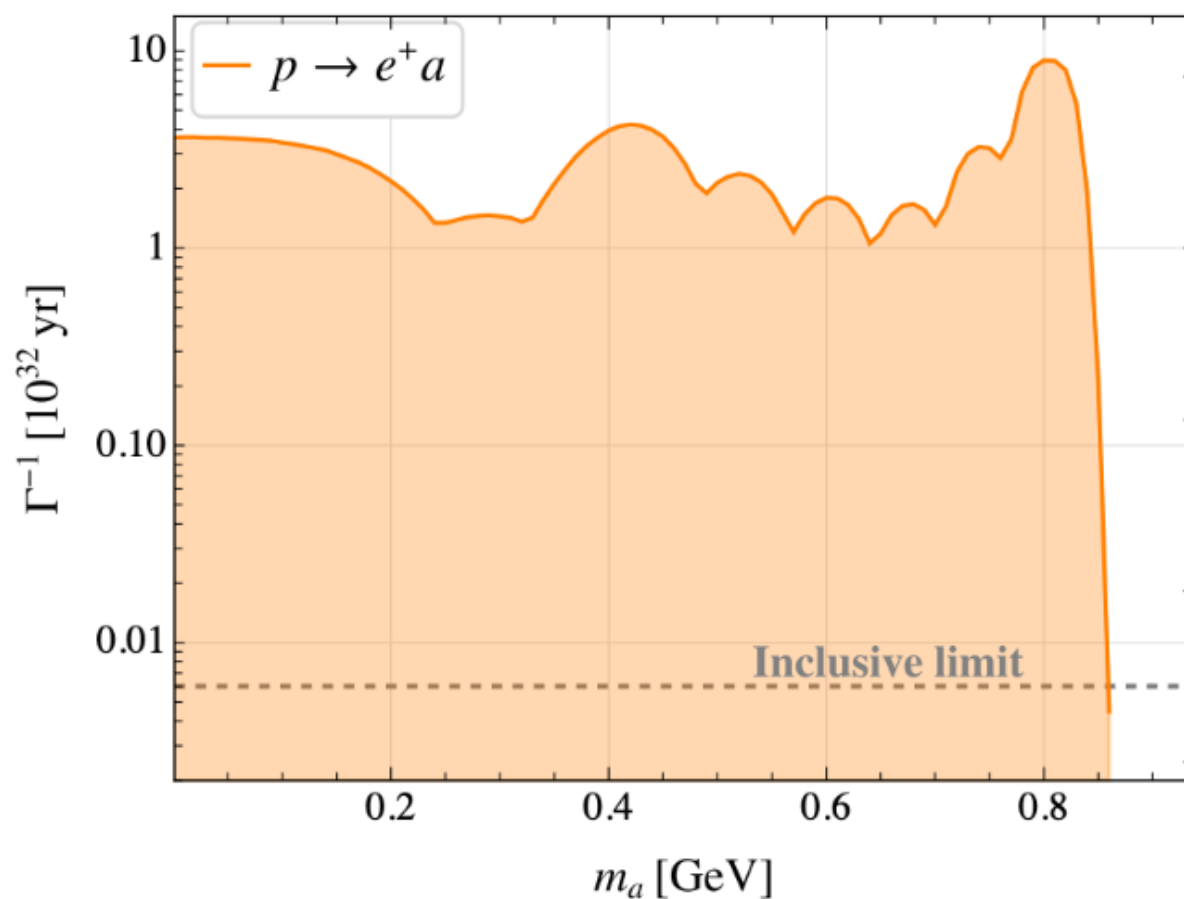
$$m_X = 0$$

*SNO+ (2022)*

$$\Gamma^{-1}(n \rightarrow \text{invisible}) > 9.0 \times 10^{29} \text{ yr}$$

$$\Gamma^{-1}(N \rightarrow e^+ + \text{anything}) > 0.6 \times 10^{30} \text{ yr}, \quad \Gamma^{-1}(N \rightarrow \mu^+ + \text{anything}) > 12 \times 10^{30} \text{ yr}$$

- Searches designed for conventional SM final states can be recast to constrain nucleon decays with an additional light invisible particle



✓ Bounds shown here use the free-proton approximation

✓ The later detailed studies include nuclear effects

*X.-D. Ma, M. A. Schmidt, and W. Zhang, JHEP 02 (2026)*

*J.-H. Liang, Y. Liao, X.-D. Ma, and X. Zhao, 2607.22452*

*W.-Q. Fan, Y. Liao, X.-D. Ma, and HLW, CPC 50 (2026)*

# Summary

- The general triple-quark interactions are identified and the LO chiral matching has been carried out.
- The identified new chiral structures can induce exotic nucleon decays beyond the conventional ones.
- The developed theoretical framework facilitates systematic studies on BNV nucleon and hyperon decays

Thank You!

# Backup: The chiral lagrangian involving decuplet baryons

$$\begin{aligned} \mathcal{L}_T^{\mathcal{B},0} = & \tilde{c}_3 \left[ \mathcal{P}_{yzw}^{\text{LR},\mu} \Gamma_{\mu\nu}^{\text{L}} T_{ijk}^{\nu} \xi_{yi} \xi_{zj} \xi_{kw}^* - \mathcal{P}_{yzw}^{\text{RL},\mu} \Gamma_{\mu\nu}^{\text{R}} T_{ijk}^{\nu} \xi_{iy}^* \xi_{jz}^* \xi_{wk} \right] \\ & + \frac{\tilde{c}_4}{\Lambda_\chi} \left[ \mathcal{P}_{yzw}^{\text{LL},\mu\nu} \hat{\Gamma}_{\mu\nu\alpha\beta}^{\text{L}} iD^\alpha T_{ijk}^\beta \xi_{yi} \xi_{zj} \xi_{wk} - \mathcal{P}_{yzw}^{\text{RR},\mu\nu} \hat{\Gamma}_{\mu\nu\alpha\beta}^{\text{R}} iD^\alpha T_{ijk}^\beta \xi_{iy}^* \xi_{jz}^* \xi_{kw}^* \right] + \text{h.c.} \end{aligned}$$

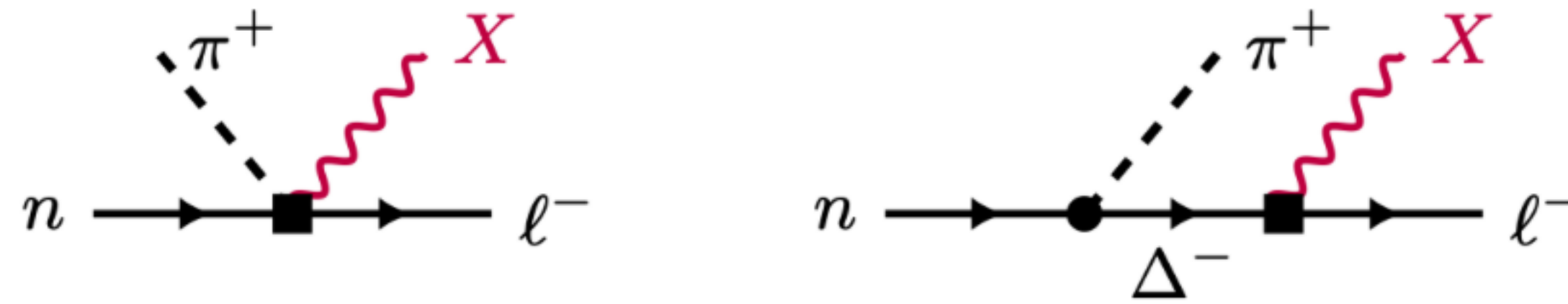
$$\text{NDA: } \tilde{c}_{3,4} \sim \Lambda_\chi^3 / (4\pi)^2 \approx 0.011 \text{ GeV}^3$$

$$\begin{aligned} T_{111} &= \Delta^{++}, \quad T_{112} = \frac{\Delta^+}{\sqrt{3}}, \quad T_{122} = \frac{\Delta^0}{\sqrt{3}}, \quad T_{222} = \Delta^-, \\ T_{113} &= \frac{\Sigma^{*+}}{\sqrt{3}}, \quad T_{123} = \frac{\Sigma^{*0}}{\sqrt{6}}, \quad T_{223} = \frac{\Sigma^{*-}}{\sqrt{3}}, \quad T_{133} = \frac{\Xi^{*0}}{\sqrt{3}}, \quad T_{233} = \frac{\Xi^{*-}}{\sqrt{3}}, \quad T_{333} = \Omega^-. \end{aligned}$$

# Backup: $n \rightarrow \ell^- \pi^+ X^\mu$ as an example

- $\Delta I = 3/2$  process with  $\ell = e, \mu$

$$\mathcal{O}_{X\ell} = X_{\mu\nu}(\bar{\ell}_R d_L^\alpha)(\bar{d}_L^{\beta\bar{C}} \sigma^{\mu\nu} d_L^\gamma) \epsilon_{\alpha\beta\gamma} \in \mathbf{10}_L \otimes \mathbf{1}_R \quad \rightarrow \quad \mathcal{P}_{ddd}^{\text{LL},\mu\nu} = \Lambda_{X\ell}^{-4} X^{\mu\nu} \bar{\ell}_R$$



$$\Gamma_{n \rightarrow e^- \pi^+ X} = (0.88 |\kappa_4|^2 + 0.27 |\tilde{\kappa}_4|^2 - 0.82 \Re(\kappa_4 \tilde{\kappa}_4^*)) \left( \frac{3 \times 10^6 \text{ GeV}}{\Lambda_{X\ell}} \right)^8 \frac{1}{10^{30} \text{ yr}}$$

$$\kappa_4 \equiv c_4/c_1 \quad \tilde{\kappa}_4 \equiv \tilde{c}_4/c_1$$