



Effective field theory for general baryon-number-violating nucleon decays

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Wei-Qi Fan, Yi Liao, **XDM**, Hao-Lin Wang, arXiv: 2412.20774 (PLB 862 (2025) 139335)

Yi Liao, **XDM**, Hao-Lin Wang, arXiv: 2504.14855 (PRL 135, 161801 (2025))

Yi Liao, **XDM**, Hao-Lin Wang, arXiv: 2506.05052 (PRD 112, L031704 (2025))

Wei-Qi Fan, Yi Liao, **XDM**, Hao-Lin Wang, arXiv:2507.11844

XDM, Michael Schmidt, Wei-Hang Zhang, arXiv:2510.xxxxx

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Outline

- **Introduction**
- **General BNV nucleon decay interactions in the LEFT**
- **Chiral realizations**
- **Applications**
- **Summary**

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

- Baryogenesis

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

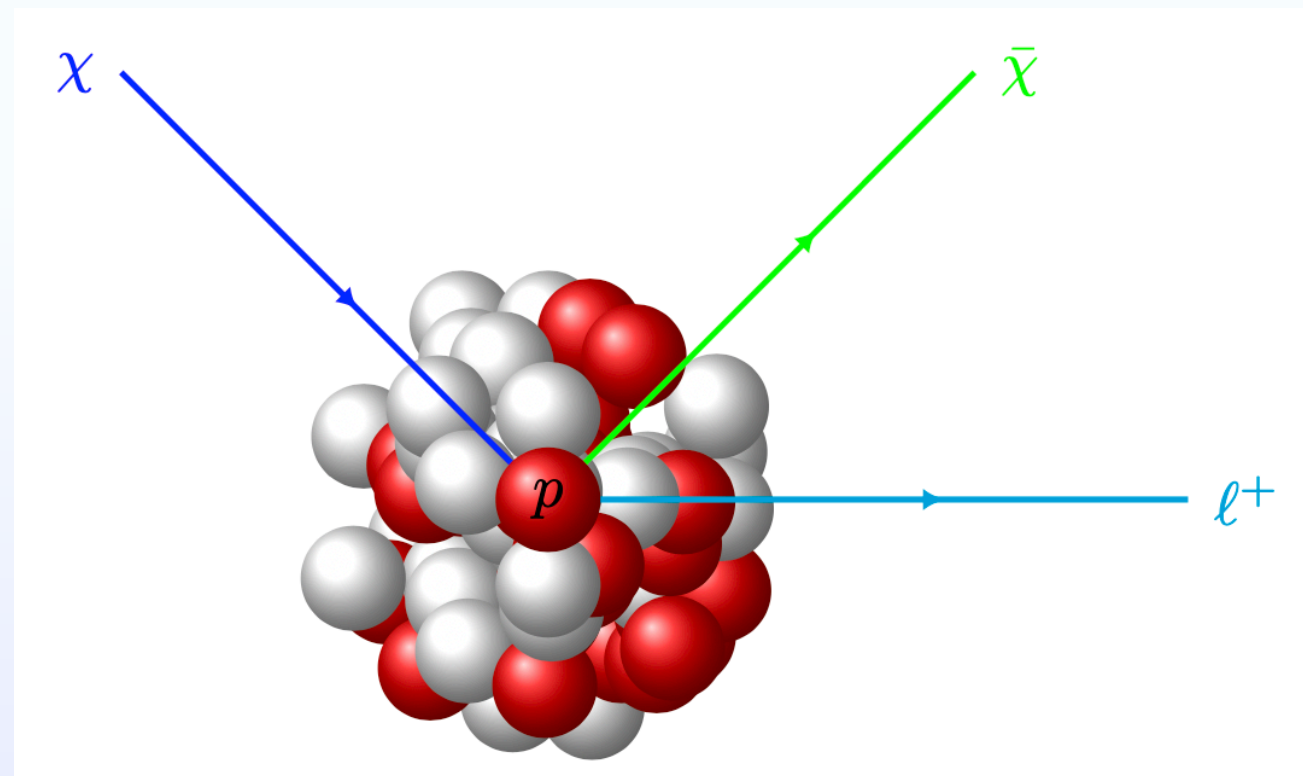
$$\eta = \frac{n_B - n_{\bar{B}}}{n_\gamma} \sim 6 \times 10^{-10}$$

Sakharov, 1967

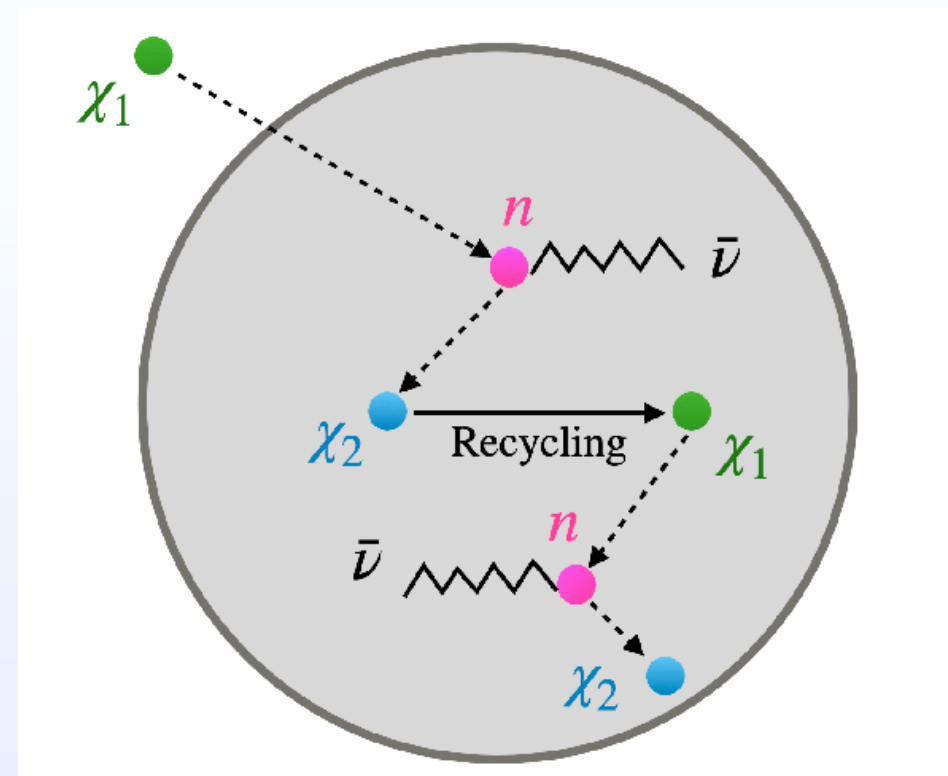
- Dark matter

Nucleon consumption induced by DM

DM-catalyzed baryon destruction inside a NS

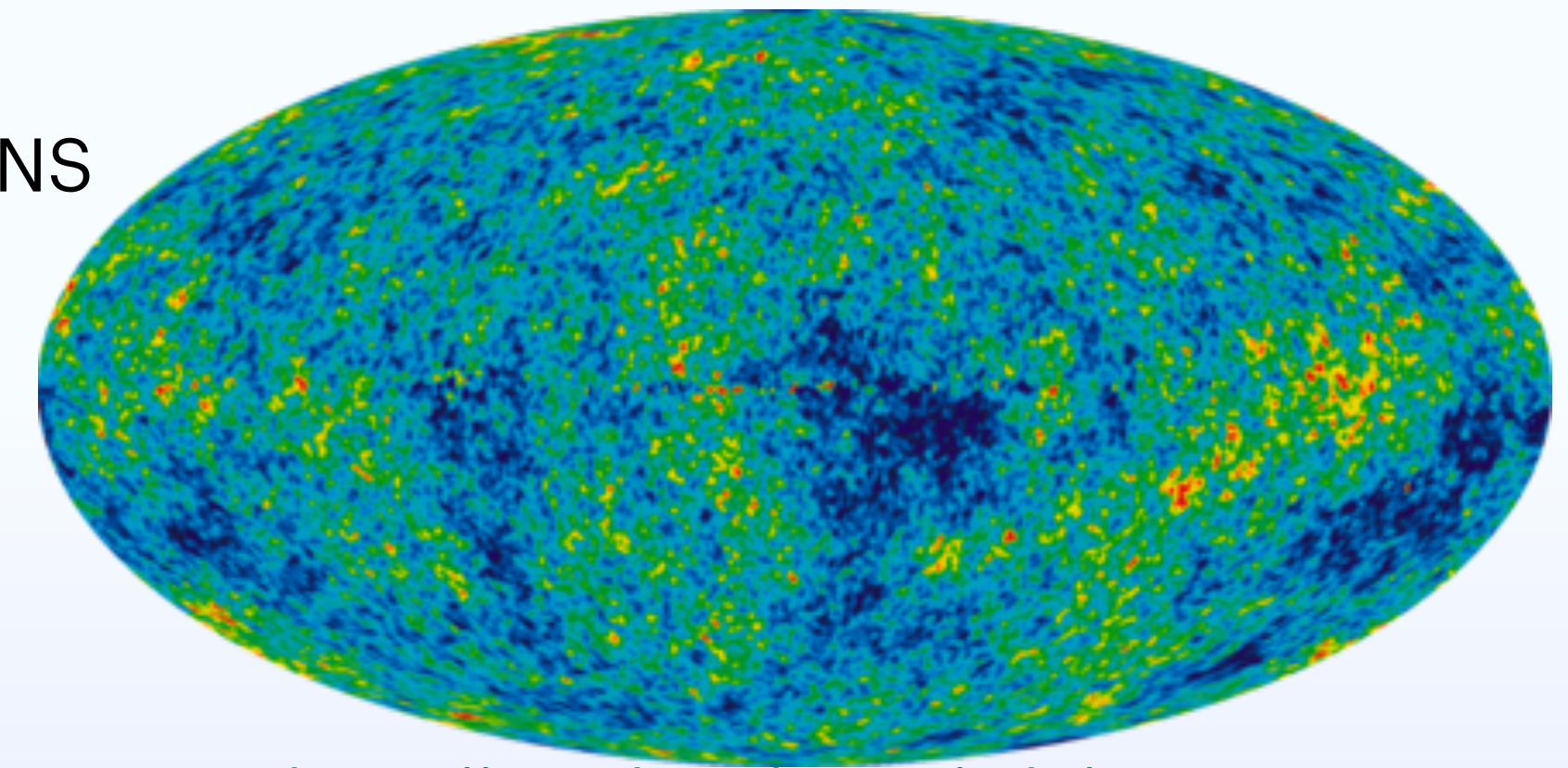


S.-F. Ge and XDM: 2406.00445



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

+ many many works along this direction

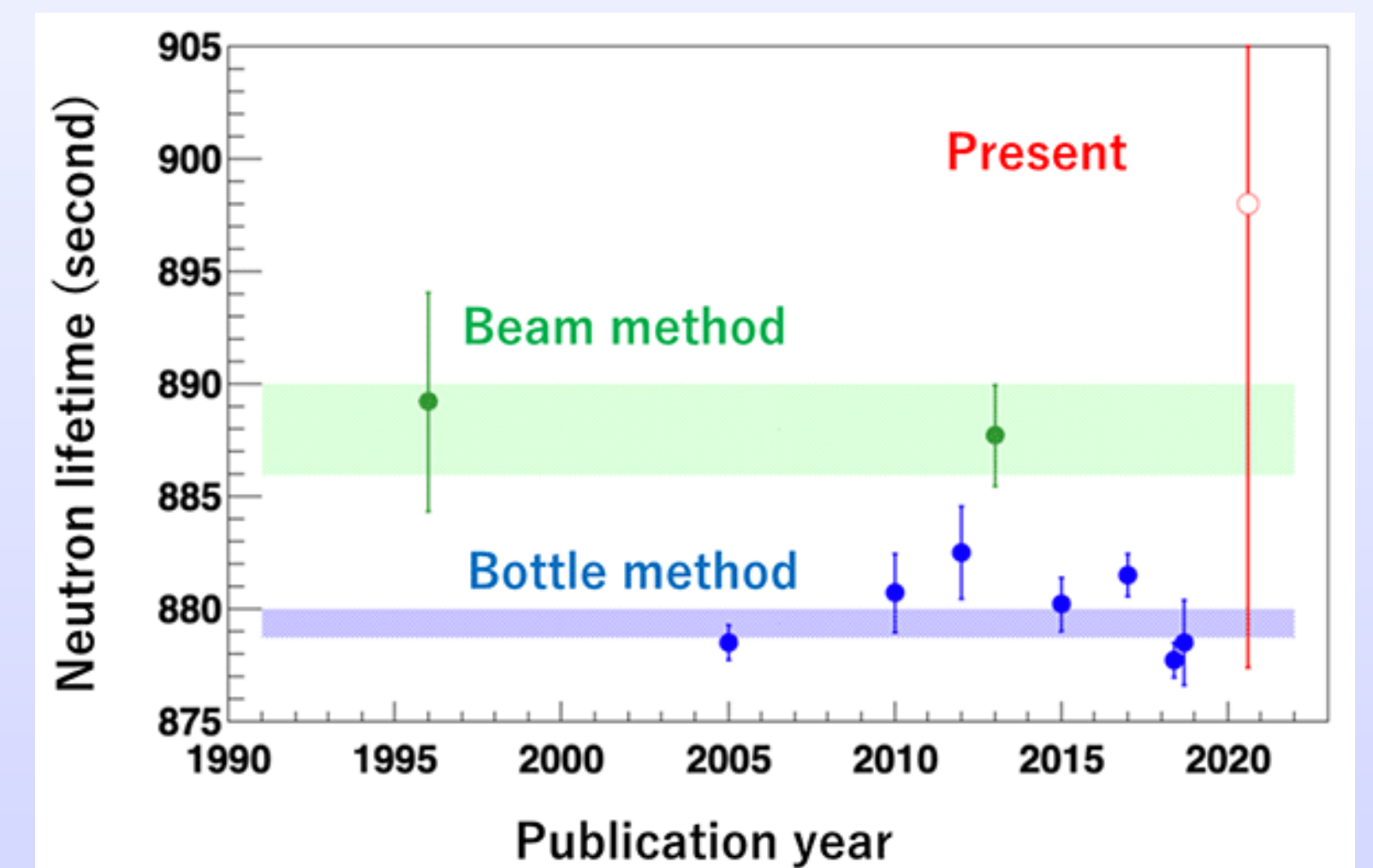


<https://en.wikipedia.org/wiki/Baryogenesis>

- Grand unified theories: SU(5), SO(10), ...

- Neutron lifetime anomaly: **Neutron dark decay**

B. Fornal and B. Grinstein: 1801.01124; 1810.00862



Low energy probes of BNV signals

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

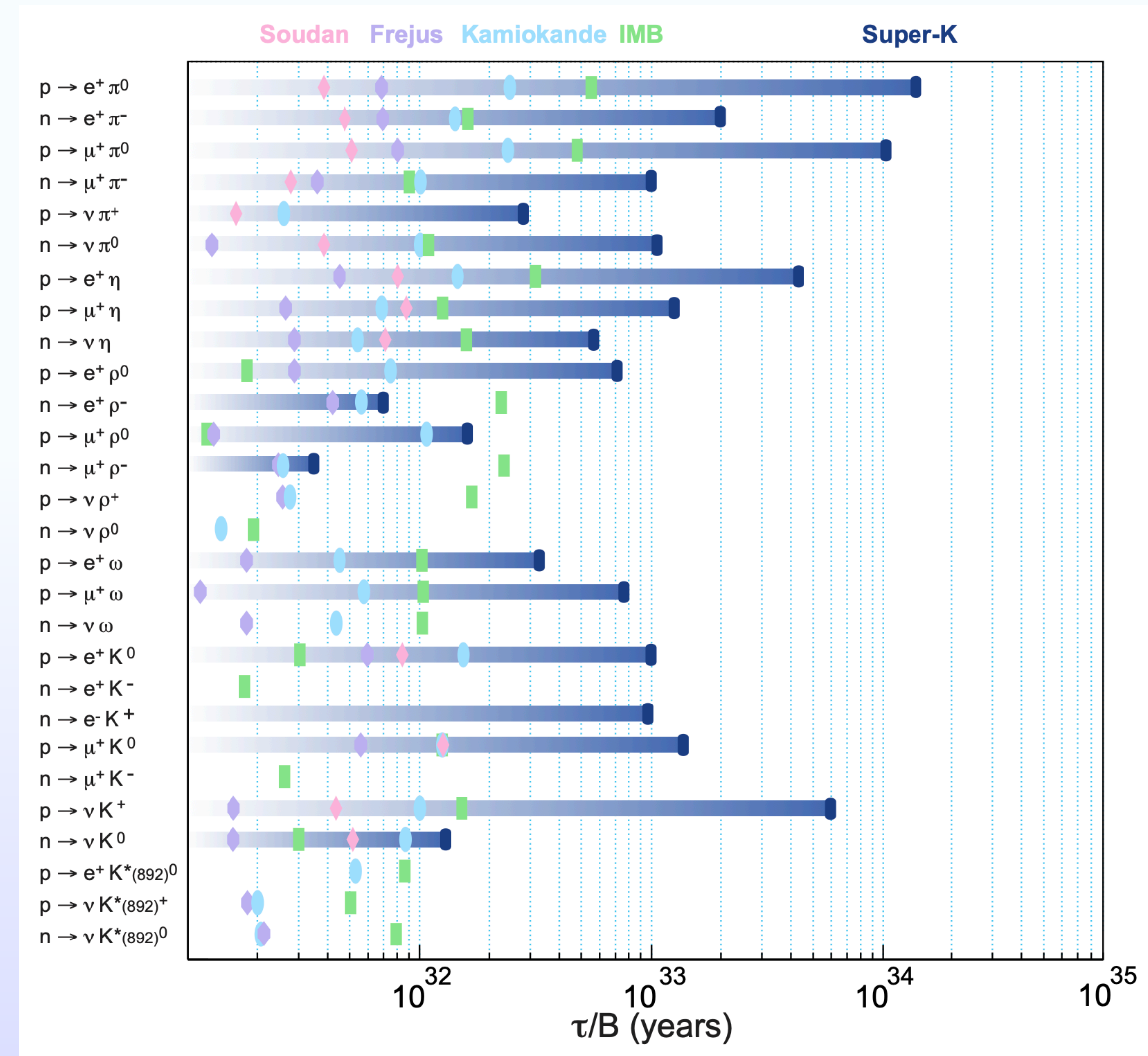
- The most sensitive probe of BNV is through **nucleon decay**
- A lot of experimental efforts in the past: **IMB, SNO+, KamLAND, Super-Kamiokande, ...**

→ 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

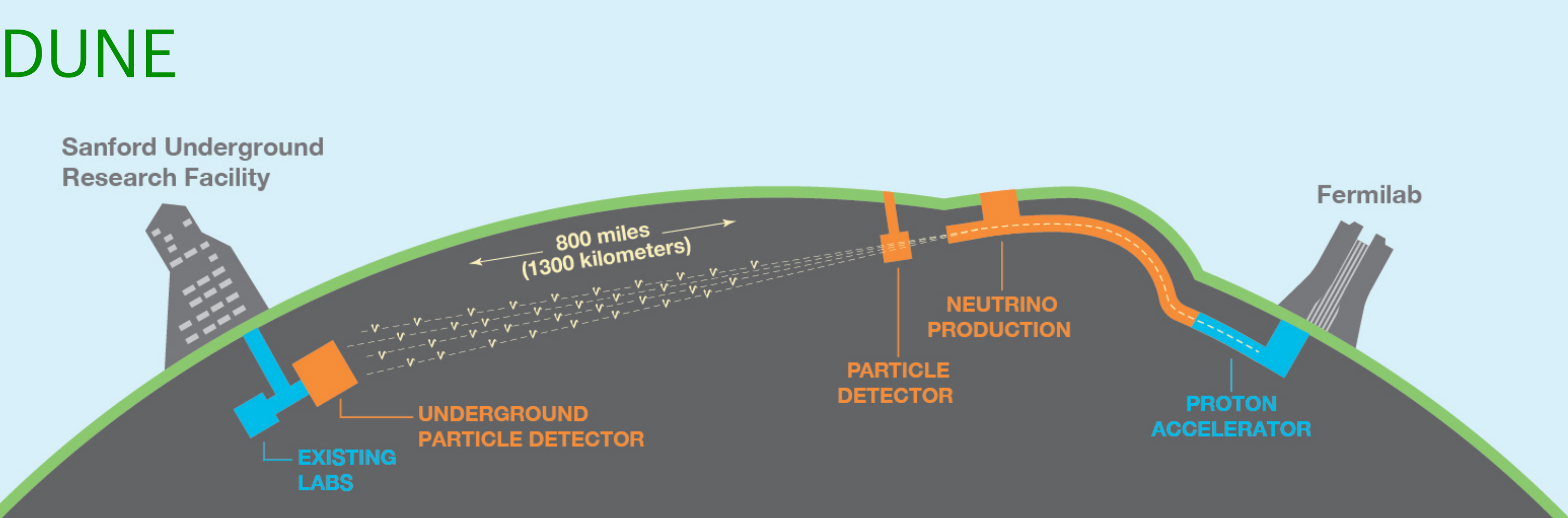
- Dinucleon decays: $NN' \rightarrow MM', \ell\ell', \ell\nu', \nu\nu'$ Xiao-Gang He and XDM, 2102.02562



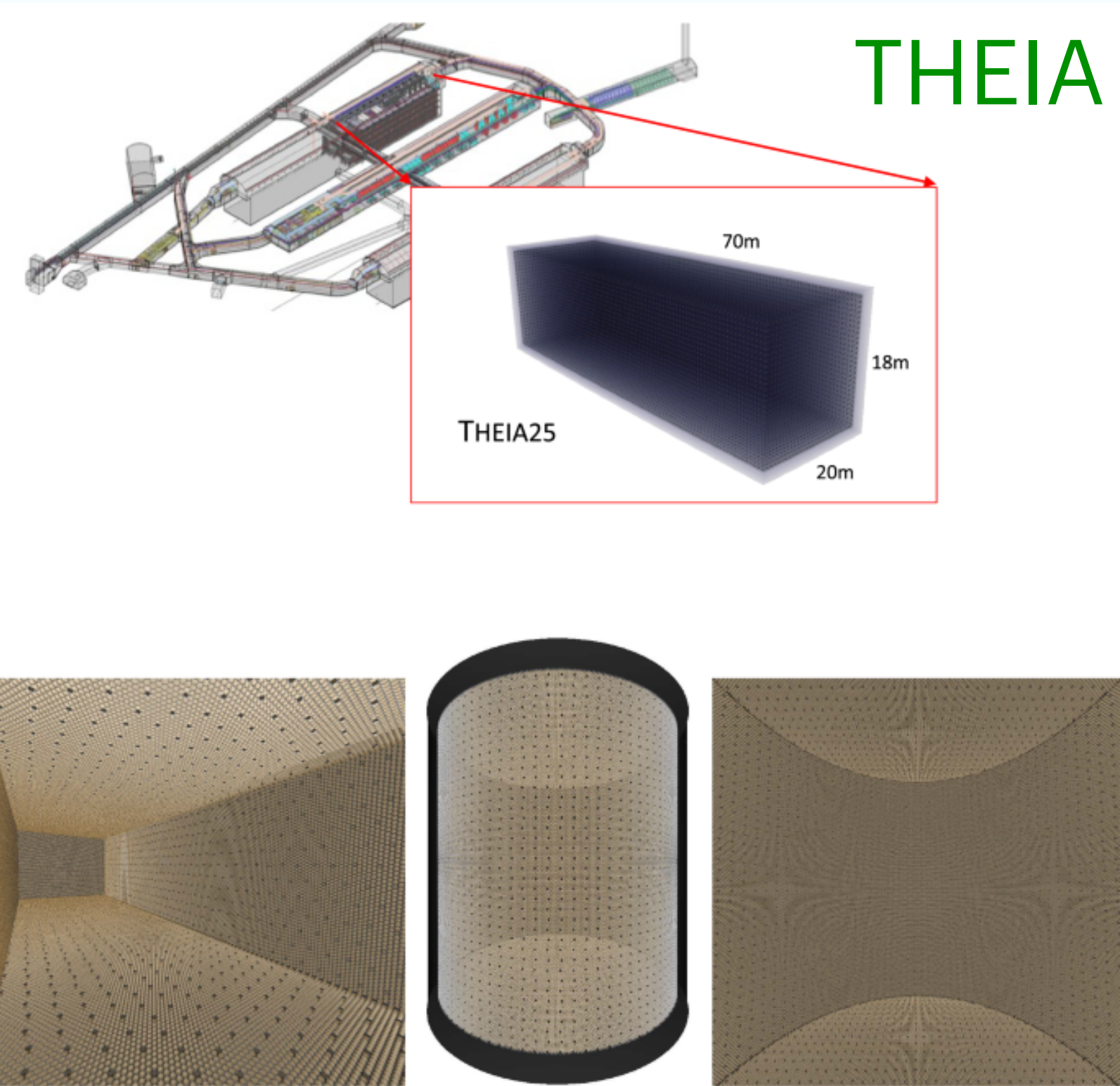
Snowmass 2013, arXiv: 1311.5285

Nucleon decay search as experimental frontiers

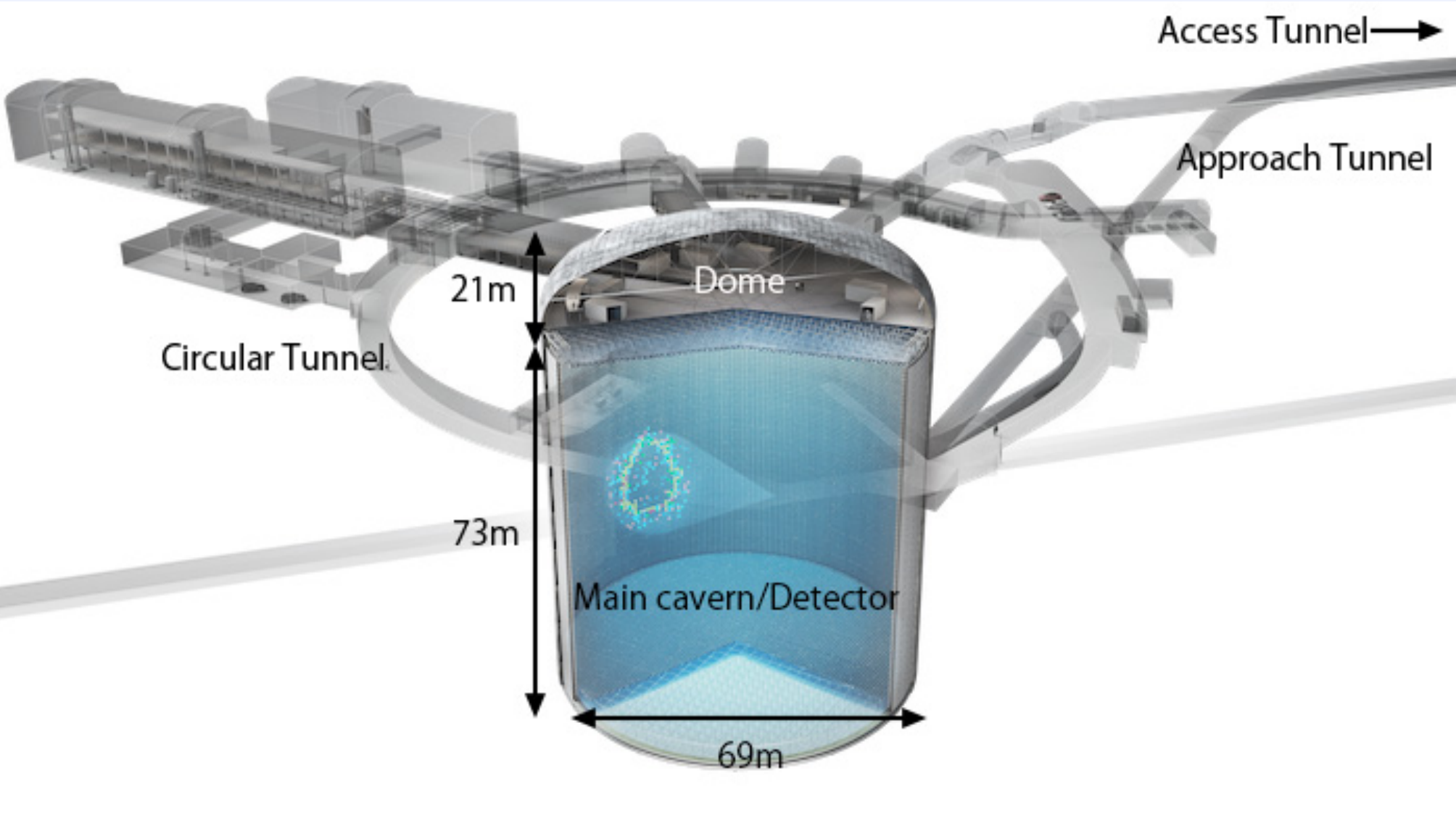
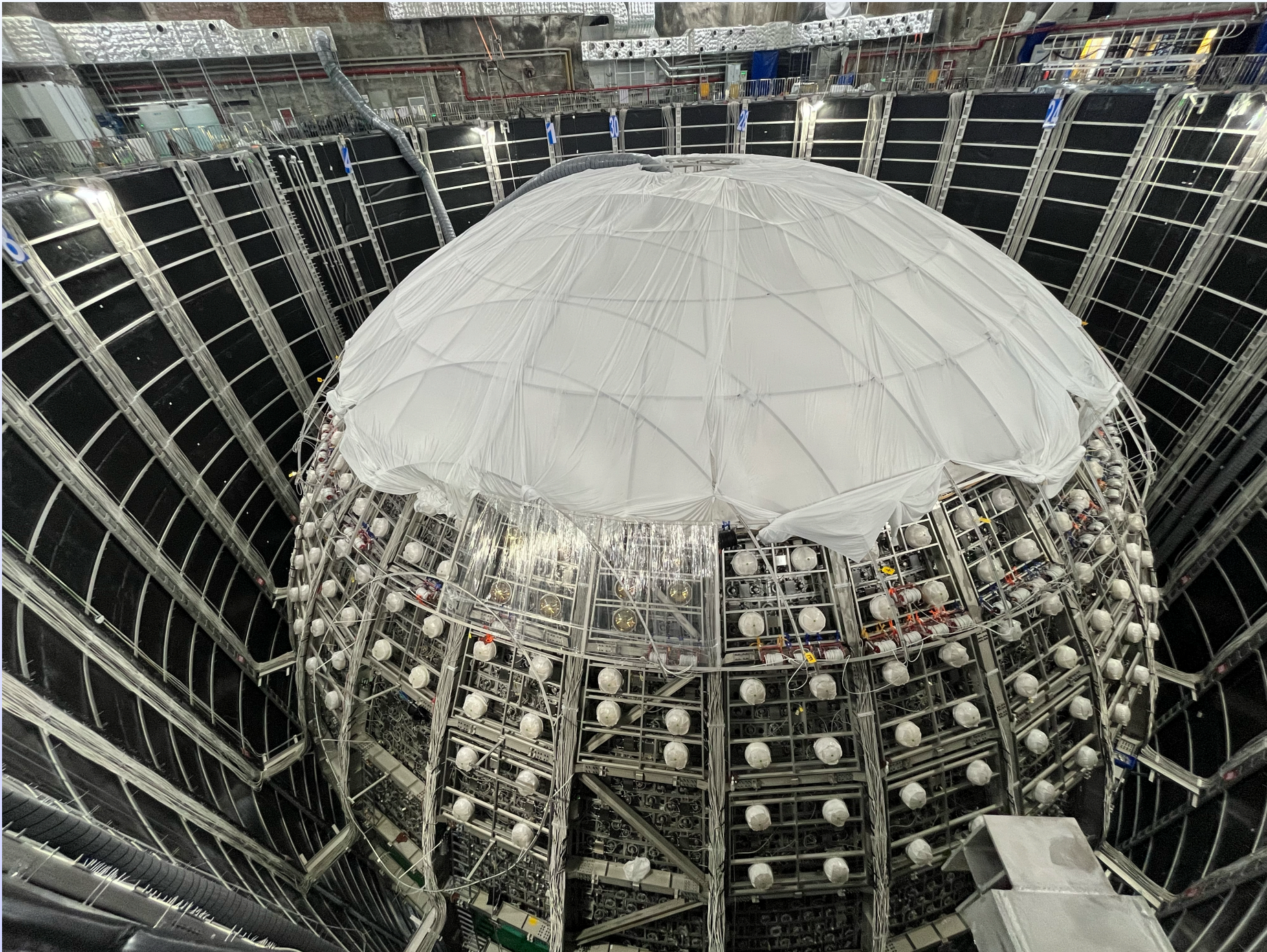
DUNE



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



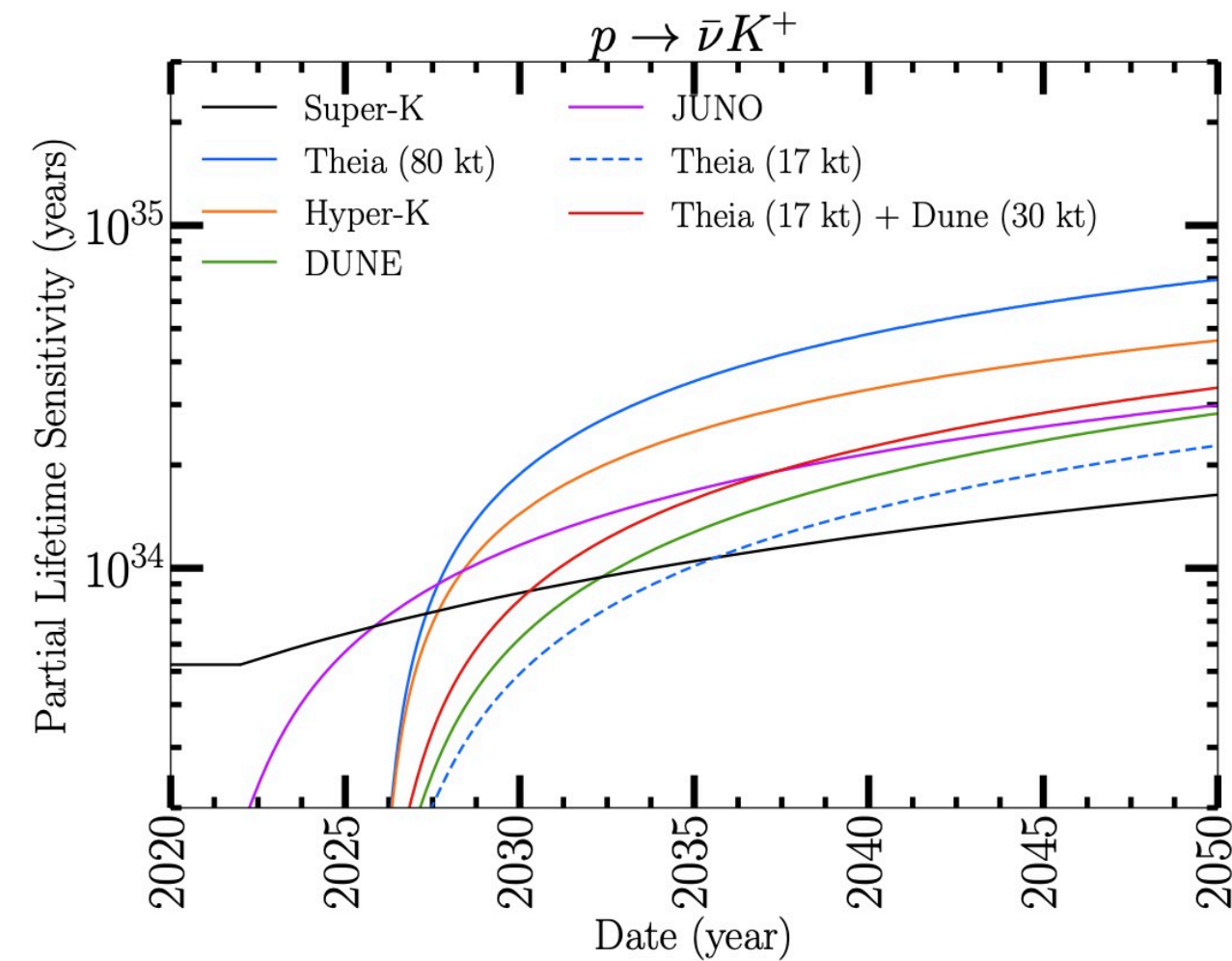
JUNO



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

Experiments meet theory

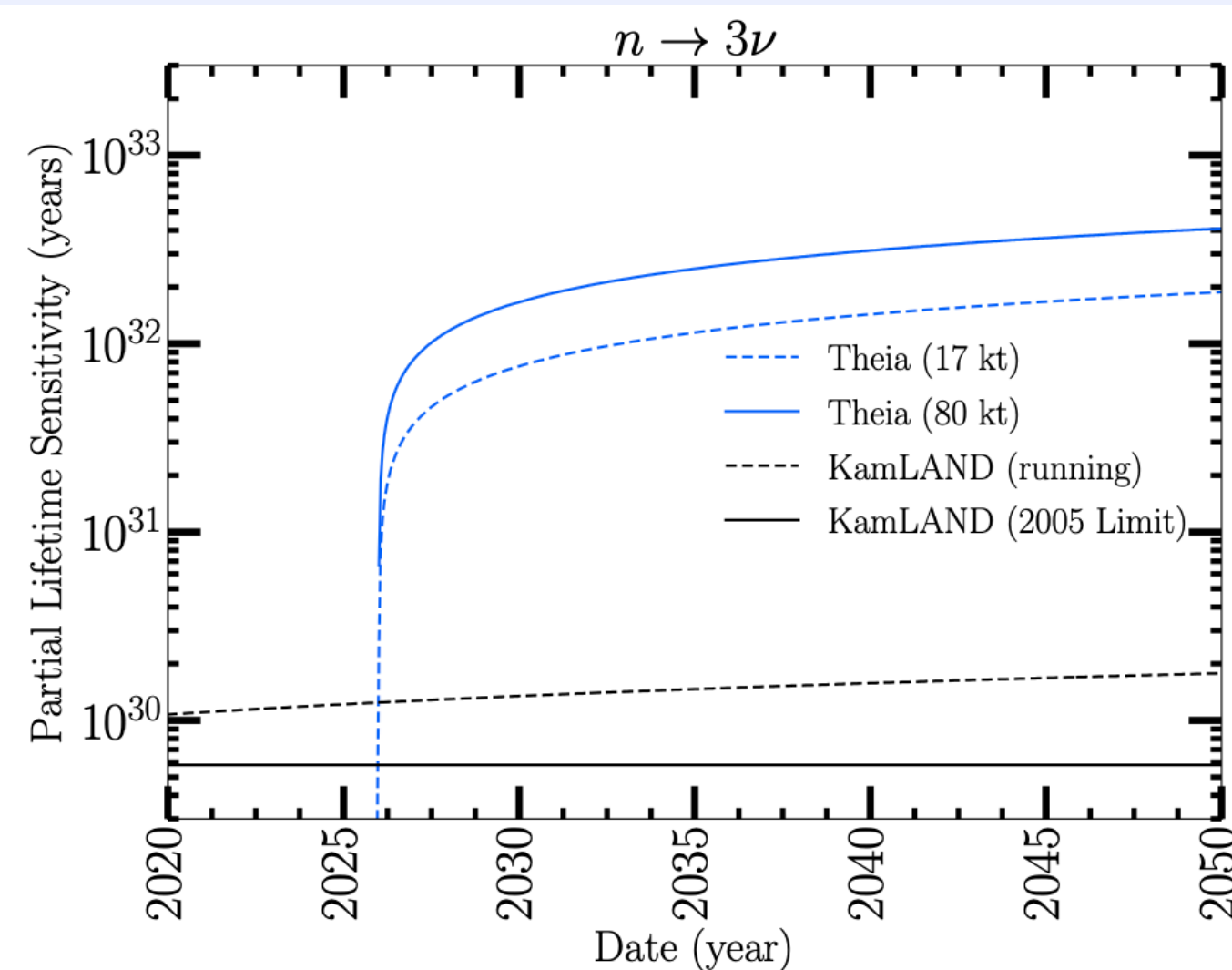
- Improving sensitivity to conventional modes



All possible decay channels should be attempted

conventional and exotic

- Searching for exotic modes



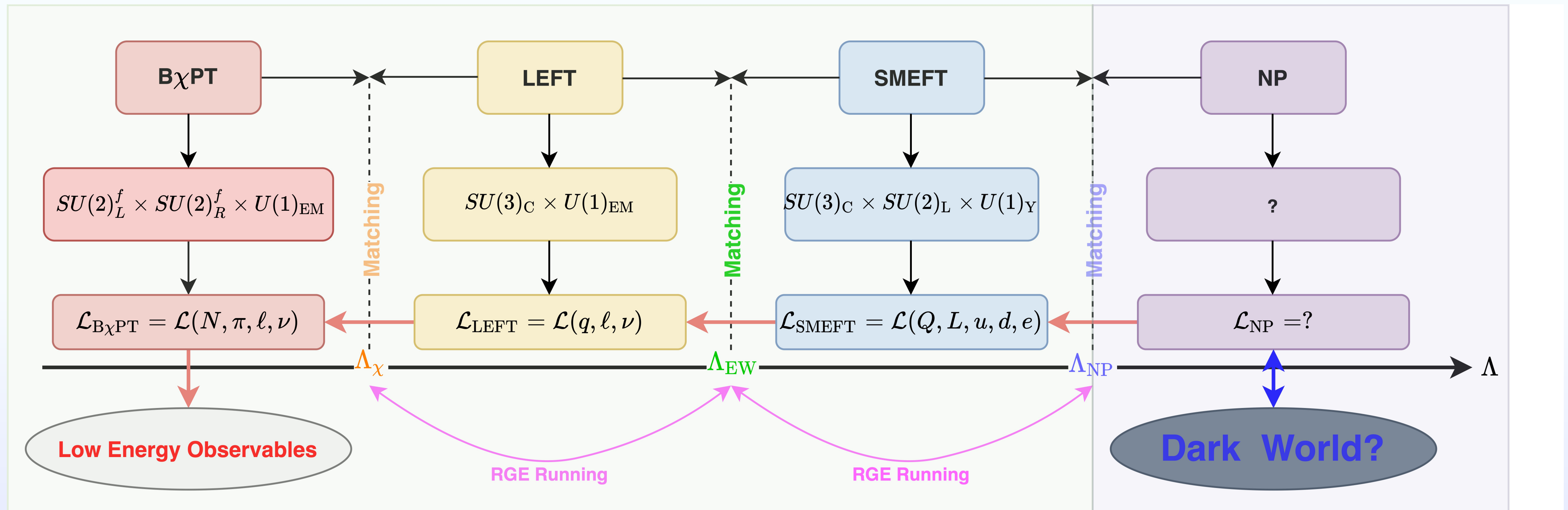
- 2-body vs 3-body modes
- Pseudoscalar vs vector meson modes
- SM particles vs new light particles
-



Needing a complete theoretical framework

- ~~Introduction~~
- **General BNV nucleon decay interactions in the LEFT**
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Nucleon decay in the effective field theory (EFT) landscape



Xiao-Gang He and XDM, 2102.02562

Hadron level: ChPT $\rightarrow$ quark level 1: LEFT $\rightarrow$ quark level 2: SMEFT

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: $\ll \Lambda_{EW}$

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

Easily to bridge with the SMEFT framework

Exotic nucleon decay involving new light particles

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

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

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

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

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

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

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

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

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



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

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

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

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

+ their **chiral partners** with $L \leftrightarrow R$

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

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

❖ $\overline{\Psi}_a, \overline{\Psi}_b, \overline{\Psi}_{c,\mu}, \overline{\Psi}_{d,\mu\nu}$: 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

Newly identified structures

- Form a basis for any triple-quark operators

Yi Liao, XDM, Hao-Lin Wang, arXiv: 2504.14855

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

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

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

$$+L \leftrightarrow R$$

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

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

Newly identified chiral structures

- Different isospin property

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

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

Non-trivial Lorentz structures

- Usual structures—spin-1/2 objects:

$$\mathcal{N}_{\mathbf{8}_L \otimes \mathbf{1}_R}, \mathcal{N}_{\mathbf{3}_L \otimes \bar{\mathbf{3}}_R} \in (1/2, 0), \quad \mathcal{N}_{\mathbf{1}_L \otimes \mathbf{8}_R}, \mathcal{N}_{\bar{\mathbf{3}}_L \otimes \mathbf{3}_R} \in (0, 1/2)$$

- New structures—spin-3/2 objects:

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

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



Complicating the chiral matching $\longrightarrow$ Needing proper Lorentz projectors

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

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

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

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

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

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

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

Chiral building blocks

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

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Chiral matching procedures

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

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

+ Spurion fields

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

- Chiral symmetry: $SU(3)_L \otimes SU(3)_R$
- Chiral power counting: momentum p :

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

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

Leading-order chiral Lagrangian for nucleon decay

Yi Liao, XDM, Hao-Lin Wang, arXiv: 2504.14855

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

Related to new structures

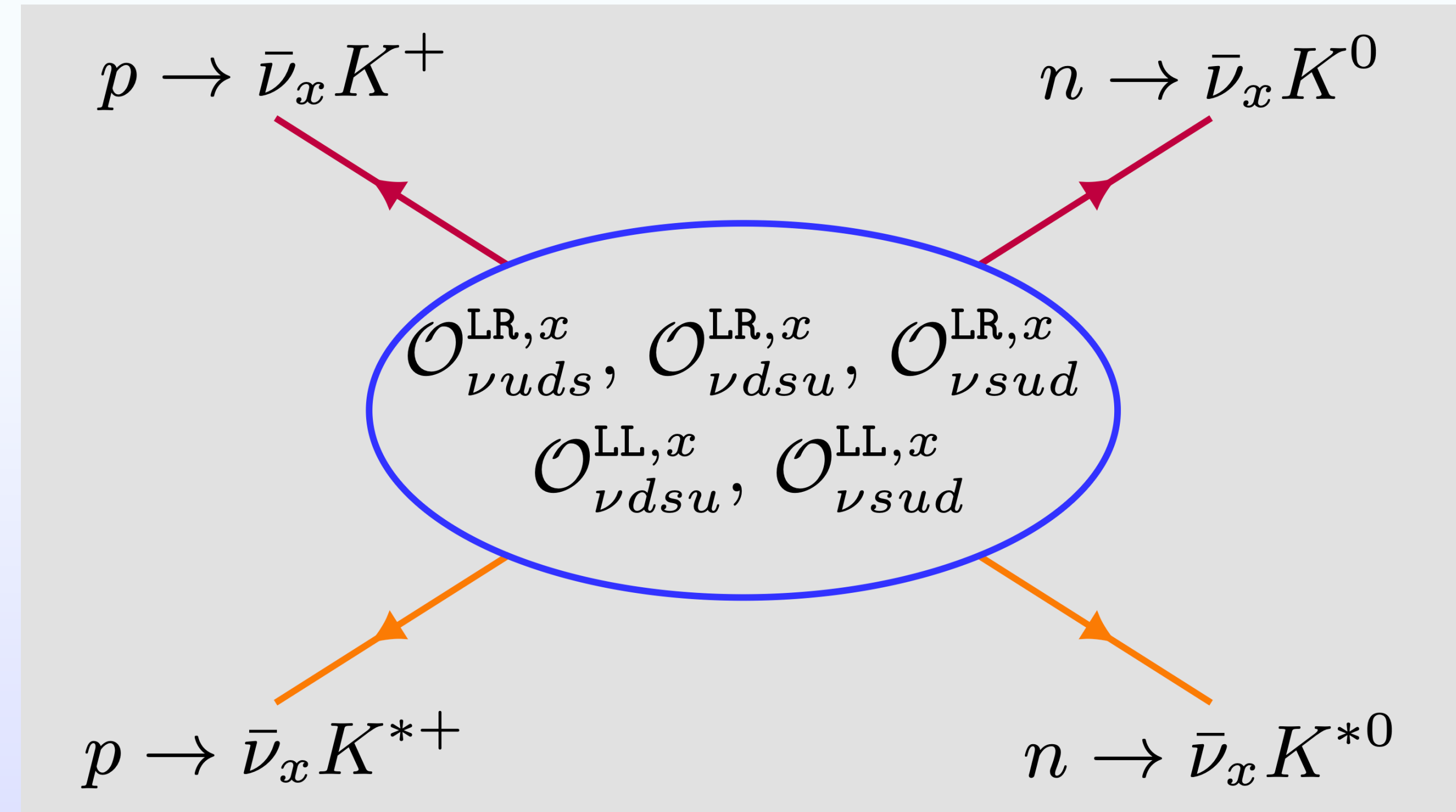
$$\Gamma_{\mu\nu}^{\text{L,R}} \equiv \left(g_{\mu\nu} - \frac{1}{4} \gamma_\mu \gamma_\nu \right) P_{\text{L,R}} \quad \hat{\Gamma}_{\mu\nu\alpha\beta}^{\text{L,R}} \equiv \frac{1}{24} \left(2 \{ \sigma_{\mu\nu}, \sigma_{\alpha\beta} \} - [\sigma_{\mu\nu}, \sigma_{\alpha\beta}] \right) P_{\text{L,R}}$$

Low energy constants can be estimated by NDA, or calculated by LQCD, etc.

Chiral Lagrangian involving octet vector mesons

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

Complementarity between
pseudoscalar and vector meson



Comparison to known results: ~40 years ago

Octet pseudoscalar case

CHIRAL LAGRANGIAN FOR DEEP MINE PHYSICS*

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Received 25 August 1981

The chiral lagrangian for baryon number violating nucleon decay is derived and applied to nucleon decays into strange and non-strange final states. The uncertainties in our predictions are discussed.

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with $SU(3) \times SU(2) \times U(1)$ symmetry are [5, 6]

$$O_{abcd}^{(1)} = (d_{\alpha\alpha R} u_{\beta\beta R})(q_{i\gamma c L} l_{jd L}) \epsilon_{\alpha\beta\gamma} \epsilon_{ij}, \quad (1a)$$

$$O_{abcd}^{(2)} = (q_{ia\alpha L} q_{j\beta b L})(u_{\gamma c R} l_{d R}) \epsilon_{\alpha\beta\gamma} \epsilon_{ij}, \quad (1b)$$

$$O_{abcd}^{(3)} = (q_{ia\alpha L} q_{j\beta b L})(q_{k\gamma c L} l_{d L}) \epsilon_{\alpha\beta\gamma} \epsilon_{ik} \epsilon_{jk}, \quad (1c)$$

$$O_{abcd}^{(4)} = (d_{\alpha\alpha R} u_{\beta\beta R})(u_{\gamma c R} l_{d R}) \epsilon_{\alpha\beta\gamma}. \quad (1d)$$

$$\begin{aligned} \mathcal{L}^{|\Delta B|=1} = & \alpha \sum_{d=1}^2 \{ C_d^{(1)} [e_{dL} \text{Tr} O \xi B_L \xi - \nu_{dL} \text{Tr} O' \xi B_L \xi] \\ & + C_d^{(2)} e_{dR} \text{Tr} O \xi^+ B_R \xi^+ + \tilde{C}_d^{(1)} [e_{dL} \text{Tr} \tilde{O} \xi B_L \xi - \nu_{dL} \text{Tr} \tilde{O}' \xi B_L \xi] \\ & + \tilde{C}_d^{(2)} e_{dR} \text{Tr} \tilde{O} \xi^+ B_R \xi^+ + \tilde{C}_d^{(5)} \nu_{dL} \text{Tr} \tilde{O}'' \xi B_L \xi \} \\ & + \beta \sum_{d=1}^2 \{ C_d^{(3)} [e_{dL} \text{Tr} O \xi B_L \xi^+ - \nu_{dL} \text{Tr} O' \xi B_L \xi^+] \\ & + C_d^{(4)} e_{dR} \text{Tr} O \xi^+ B_R \xi + \tilde{C}_d^{(3)} [e_{dL} \text{Tr} \tilde{O} \xi B_L \xi^+ - \nu_{dL} \text{Tr} \tilde{O}' \xi B_L \xi^+] \\ & + \tilde{C}_d^{(4)} e_{dR} \text{Tr} \tilde{O} \xi^+ B_R \xi + \tilde{C}_d^{(6)} \nu_{dL} \text{Tr} \tilde{O}'' \xi B_L \xi^+] + \text{h.c.}, \end{aligned} \quad (16)$$

Octet vector meson case

PHYSICAL REVIEW D

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Chiral Lagrangian for proton decay

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We extend the recent chiral model of Claudson, Wise, and Hall to include vector and axial-vector mesons as gauge bosons of an $SU(3)_L \times SU(3)_R$ chiral symmetry. The resulting baryon-number-violating interaction Lagrangian contains an additional free parameter and modifies significantly the two-body branching ratios of protons. Without some experimental input, it is not possible to predict

$$\begin{aligned} \mathcal{L}_{(2)}^{\Delta B=1} = & \frac{\gamma}{M_p} \sum_d \{ \overline{e_{dR}^+} i \gamma_\mu \text{Tr} [C_d^{(1)} \underline{\xi} (D^\mu \underline{B}) \underline{\xi}] - \overline{e_{dL}^+} i \gamma_\mu \text{Tr} [C_d^{(2)} \underline{\xi}^\dagger (D^\mu \underline{B}) \underline{\xi}^\dagger] - \overline{\nu_{dR}^c} i \gamma_\mu \text{Tr} [F_d^{(1)} \underline{\xi} (D^\mu \underline{B}) \underline{\xi}] \} + \text{H.c.} \\ & + \frac{\delta}{M_p} \sum_p \{ \overline{e_{dR}^+} i \gamma_\mu \text{Tr} [C_d^{(3)} \underline{\xi} (D^\mu \underline{B}) \underline{\xi}^\dagger] e_{dL}^+ i \gamma_\mu \text{Tr} [C_d^{(4)} \underline{\xi}^\dagger (D^\mu \underline{B}) \underline{\xi}] - \overline{\nu_{dR}^c} i \gamma_\mu \text{Tr} [F_d^{(3)} \underline{\xi} (D^\mu \underline{B}) \underline{\xi}^\dagger] \} + \text{H.c.} \end{aligned} \quad (3.7)$$

Not complete, double counting issues, ...

Our results provide a complete and consistent framework for more precise calculations of a variety of nucleon decay amplitudes.

Only for dim-6 $\Delta(B - L) = 0$ case

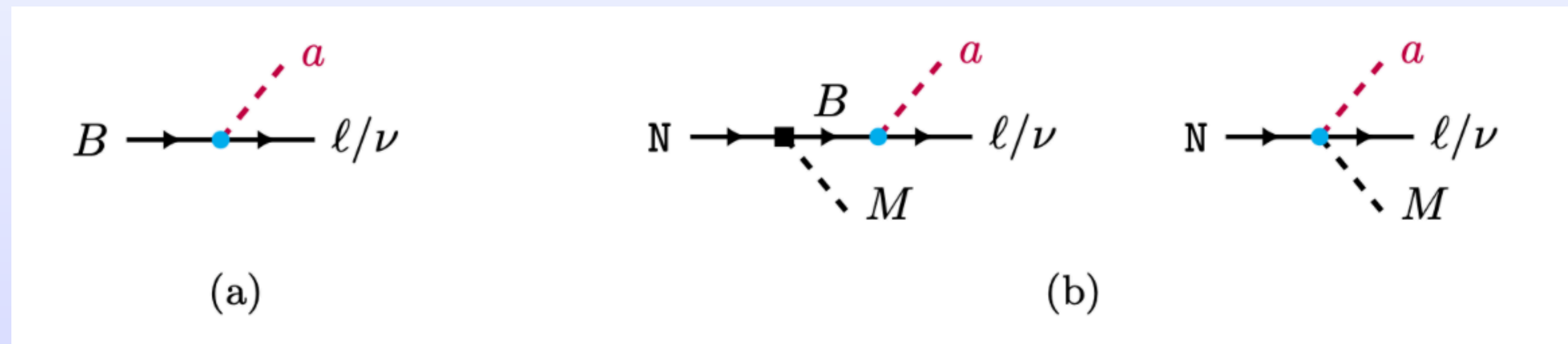
- ~~Introduction~~
- ~~General BNV nucleon decay interactions in the LEFT~~
- ~~Chiral realizations~~
- **Applications**
- ~~Summary~~

Calculation of relevant transition matrix element and decay rate

Standard ChPT interactions

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

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



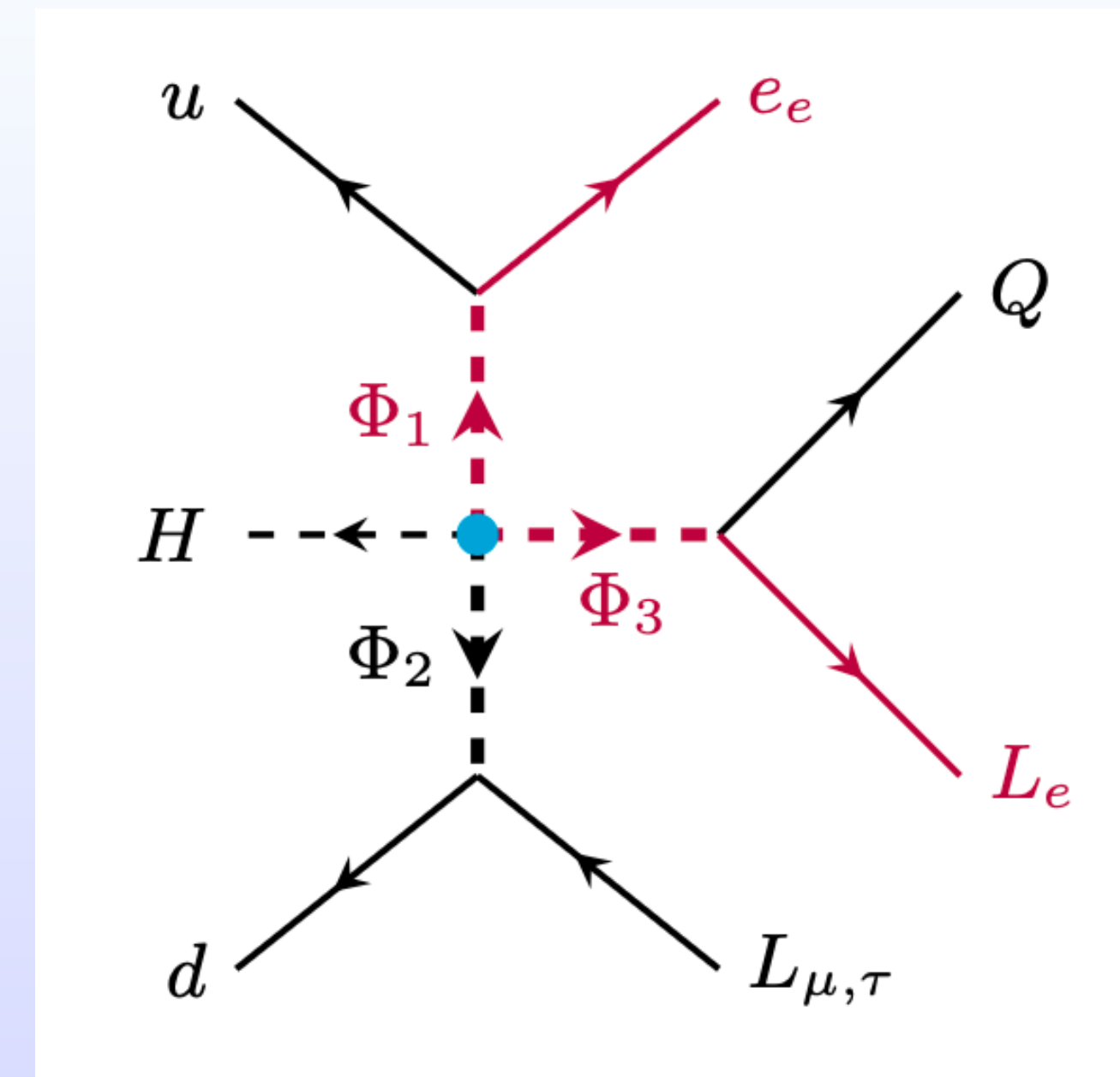
Triple-lepton example: $p \rightarrow e^+ e^+ \mu^-, \mu^+ \mu^+ e^-$

- Among the experimentally most constrained proton decay processes
- They can only be mediated by **dim-9 and higher** LEFT operators
- Associated with irreps **$6_{L(R)} \otimes 3_{R(L)}$** dim-10 or higher in SMEFT

$$\mathcal{O}_{\ell\ell'} = (\bar{\ell}_L^C \gamma_\mu \ell_R) (\bar{\ell}'_R u_L^\alpha) (u_L^{\beta C} \gamma^\mu d_R^\gamma) \epsilon_{\alpha\beta\gamma}$$

$$\mathcal{P}_{uud}^{\text{LR},\mu} = \Lambda_{\ell\ell'}^{-5} (\bar{\ell}_L^C \gamma^\mu \ell_R) \bar{\ell}'_R$$

$$\Gamma(p \rightarrow e^+ e^+ \mu^- / \mu^+ \mu^+ e^-) \sim \frac{1}{10^{34} \text{ yr}} \left(\frac{4 \times 10^5 \text{ GeV}}{\Lambda_{\mu e}} \right)^{10}$$



Leptoquark model

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

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

Dim-7 in φ SMEFT

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

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

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

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

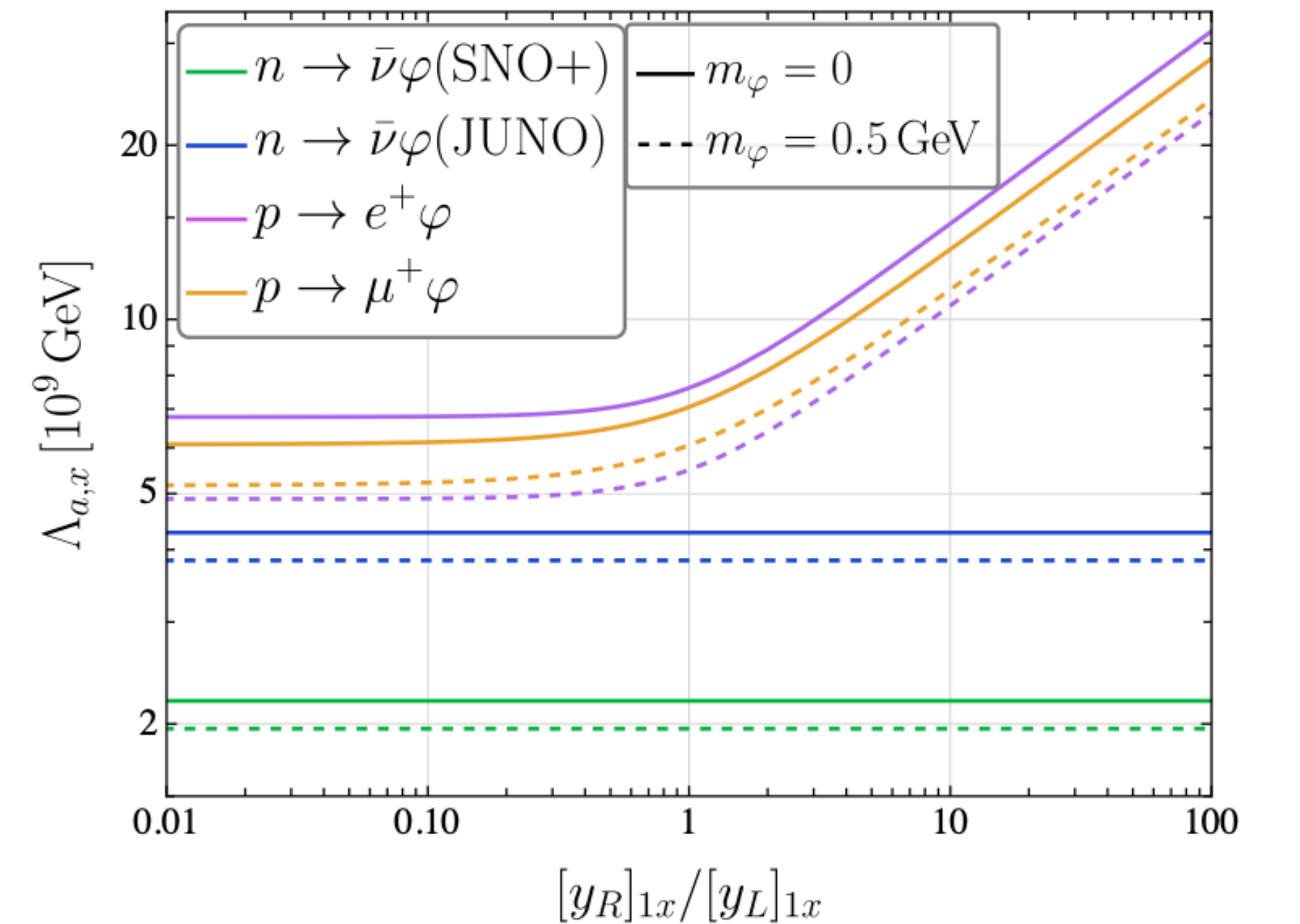
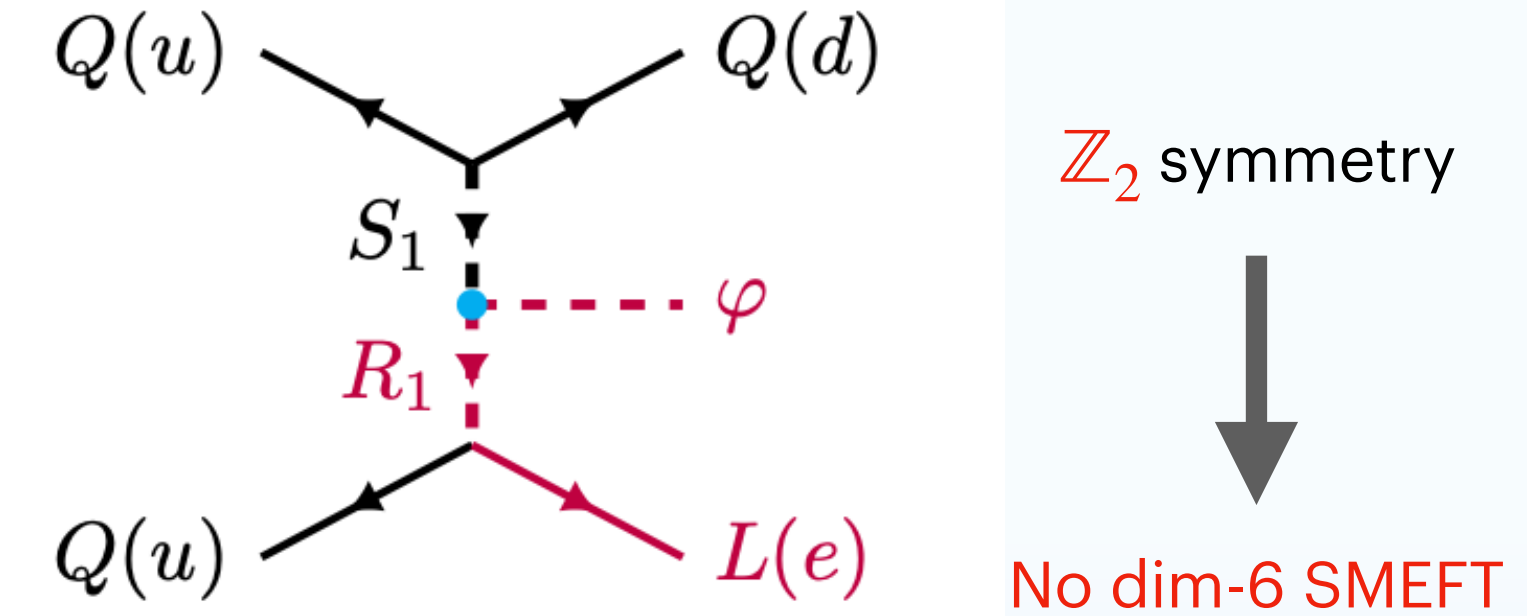
Dim-7 in φ LEFT

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

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

Spurion fields

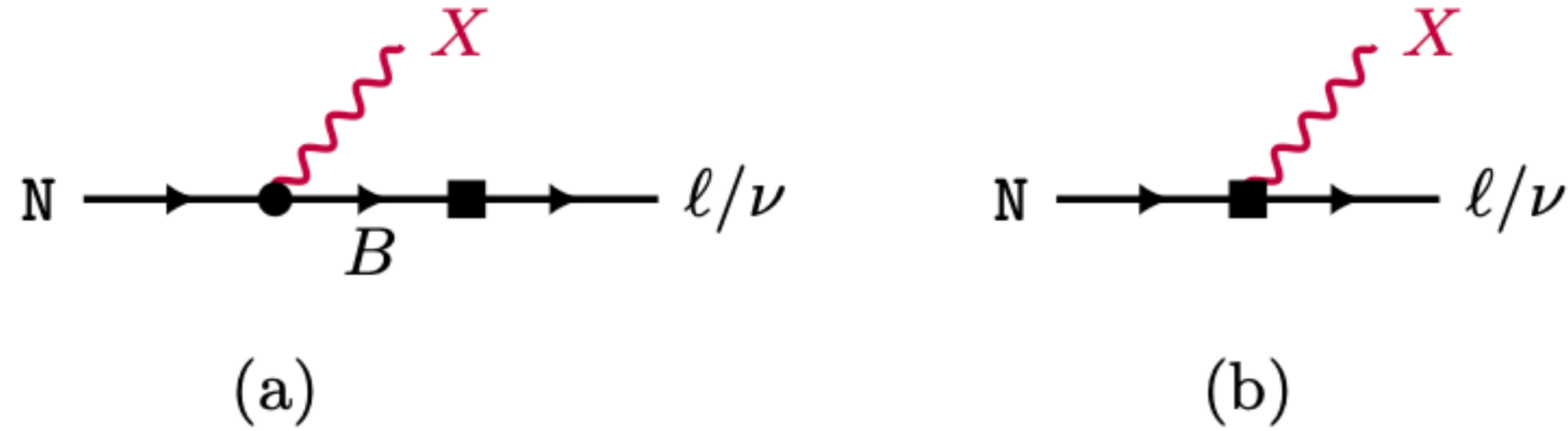
$$\mathcal{N}_{yzw}^{\text{LL}} \text{ and } \mathcal{N}_{yzw}^{\text{RL}} + L \longleftrightarrow R$$



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

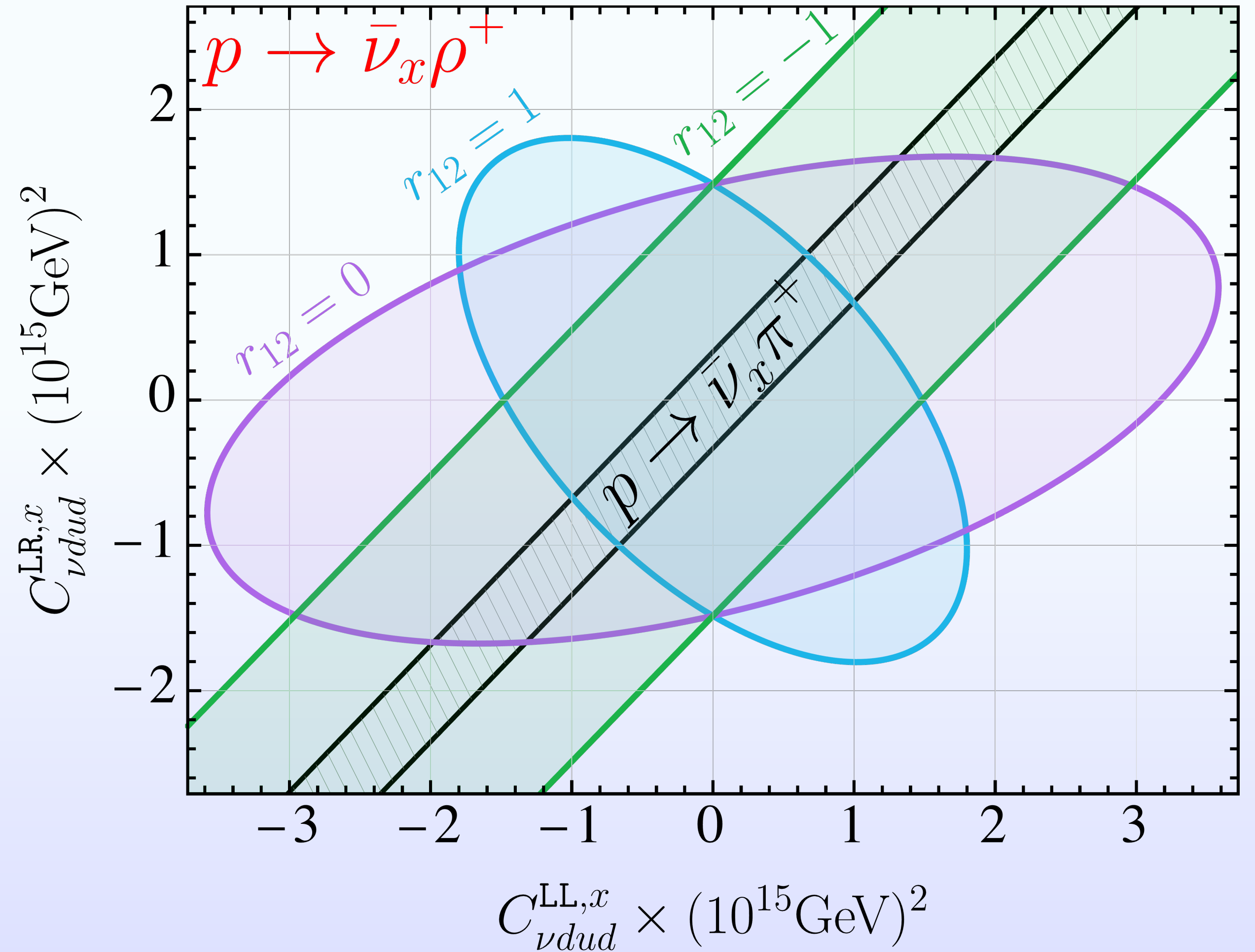
Vector meson modes help breaking degeneracy

Yi Liao, XDM, Hao-Lin Wang, 2506.05052



$$\Gamma_{p \rightarrow \bar{\nu}_x \rho^+} = \frac{m_p(1 - 3x_\rho^2 + 2x_\rho^3)}{32\pi x_\rho} \left(|d_1 C_{\nu d u d}^{\text{LR},x} + d_2 C_{\nu d u d}^{\text{LL},x}|^2 + \frac{G_F^2}{m_n^2} |c_1 C_{\nu d u d}^{\text{LR},x} + c_2 C_{\nu d u d}^{\text{LL},x}|^2 \right), \quad (15a)$$

$$\Gamma_{p \rightarrow \bar{\nu}_x \pi^+} = \frac{m_p(1 - x_\pi)^2 [1 + (D + F)m_p m_n^{-1}]^2}{64\pi F_0^2} \times |c_1 C_{\nu d u d}^{\text{LR},x} + c_2 C_{\nu d u d}^{\text{LL},x}|^2. \quad (15b)$$



Complementarity between the pseudoscalar and vector modes

Summary

- General triple-quark interactions without a ∂ related to nucleon decay 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 $\mathbf{10}_{L(R)} \otimes \mathbf{1}_{R(L)}$;
- Their LO chiral matching are realized, and the new LECs are estimated by the NDA;
- For the nucleon decay involving a vector meson, this is the first consistent chiral framework;
- Our results provide a reliable framework for further experimental and theoretical search.

Thanks for your attention!