Chiral perturbation theory for general BNV nucleon decay structures

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Wei-Qi Fan, Yi Liao, XDM, Hao-Lin Wang, arXiv: 2412.20774
Yi Liao, XDM, Hao-Lin Wang, arXiv: 2504.14855
Yi Liao, XDM, Hao-Lin Wang, arXiv: 2506.05052
Wei-Qi Fan, Yi Liao, XDM, Hao-Lin Wang, arXiv:2507.11844
+ ongoing works

International Workshop on New Opportunities for Particle Physics (NOPP) 2025
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Outline

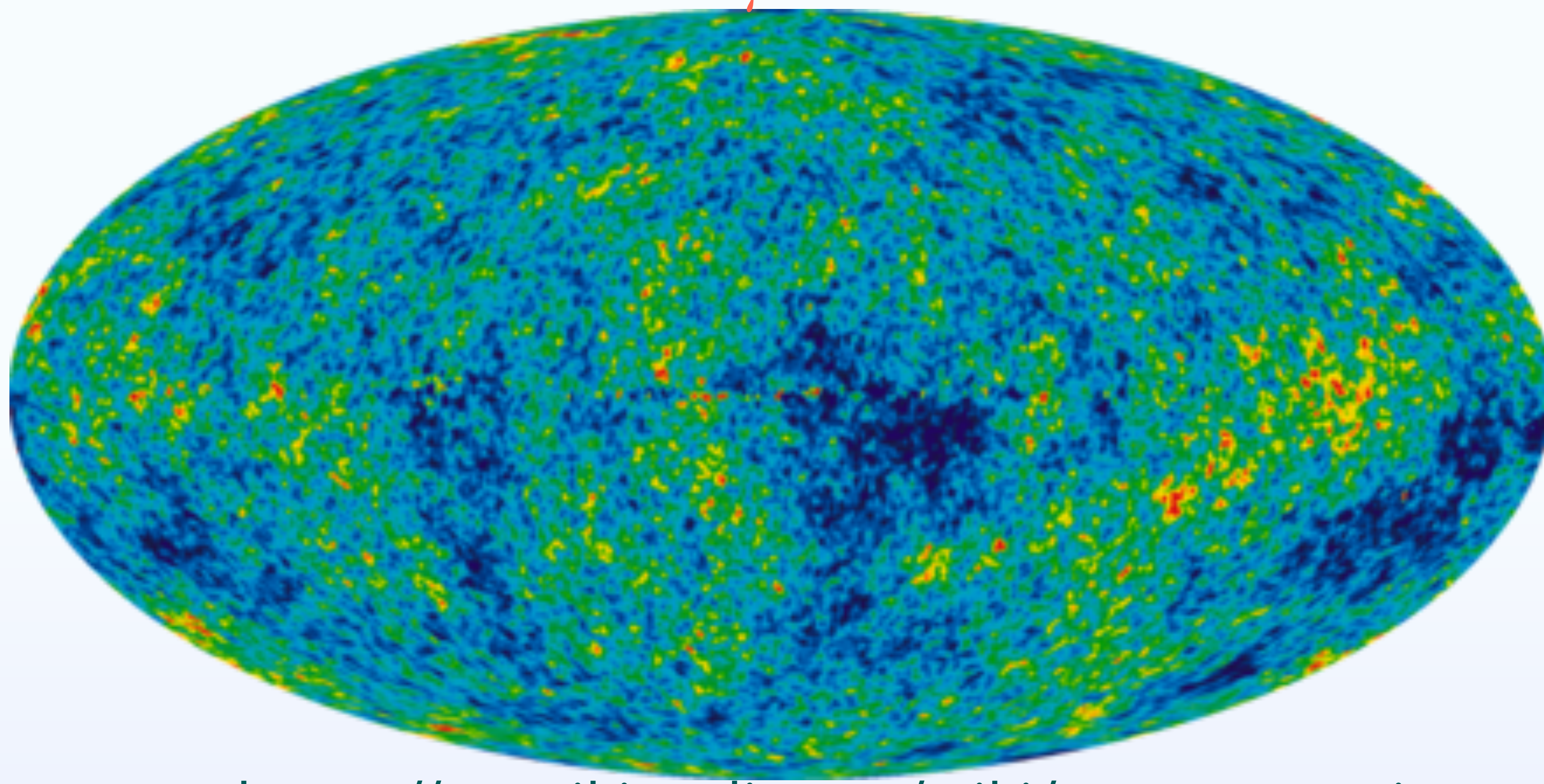
- Introduction
- General BNV nucleon decay interactions in the LEFT
- Chiral realizations
- Applications
- Summary

BNV is related to many BIG questions

- Baryogenesis

Sakharov's conditions: BNV; C, CP violation; Out of thermal equilibrium — Sakharov, 1967

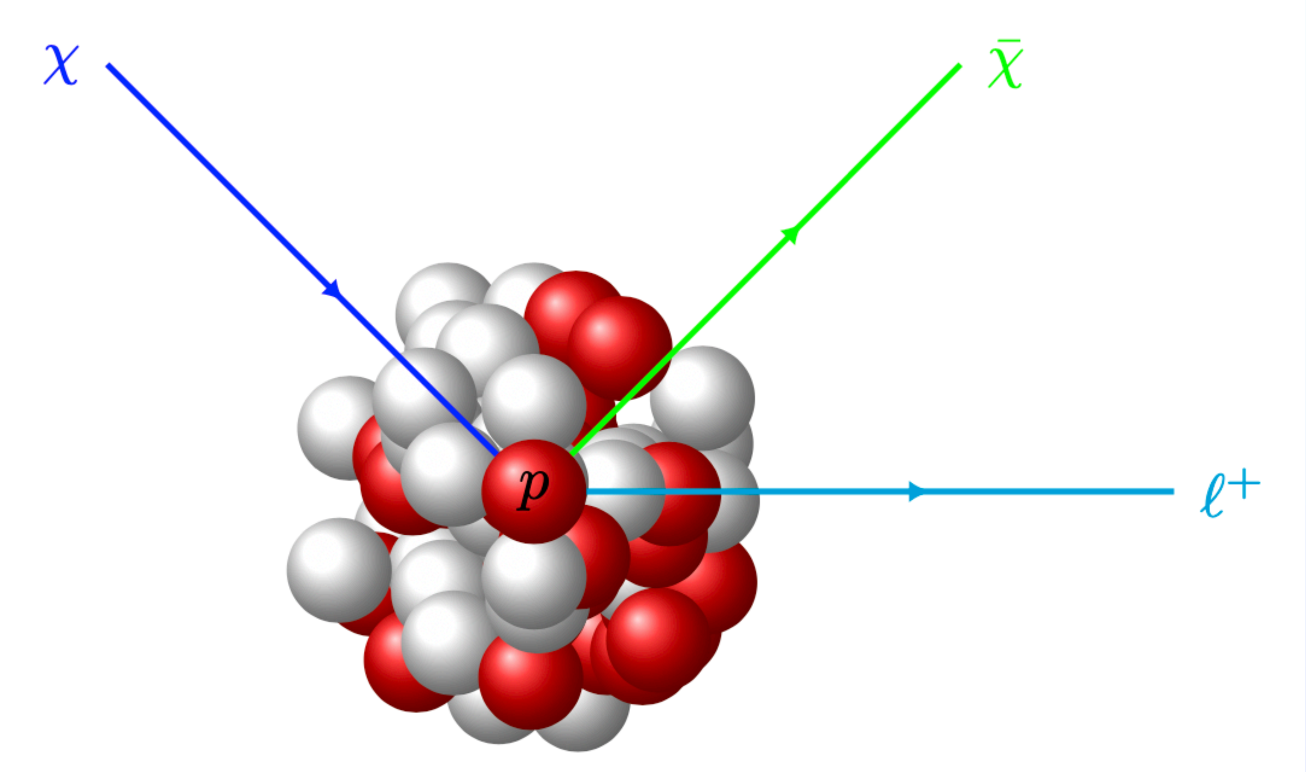
$$\eta = \frac{n_B - n_{\bar{B}}}{n_\gamma} \sim 6 \times 10^{-10}$$



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

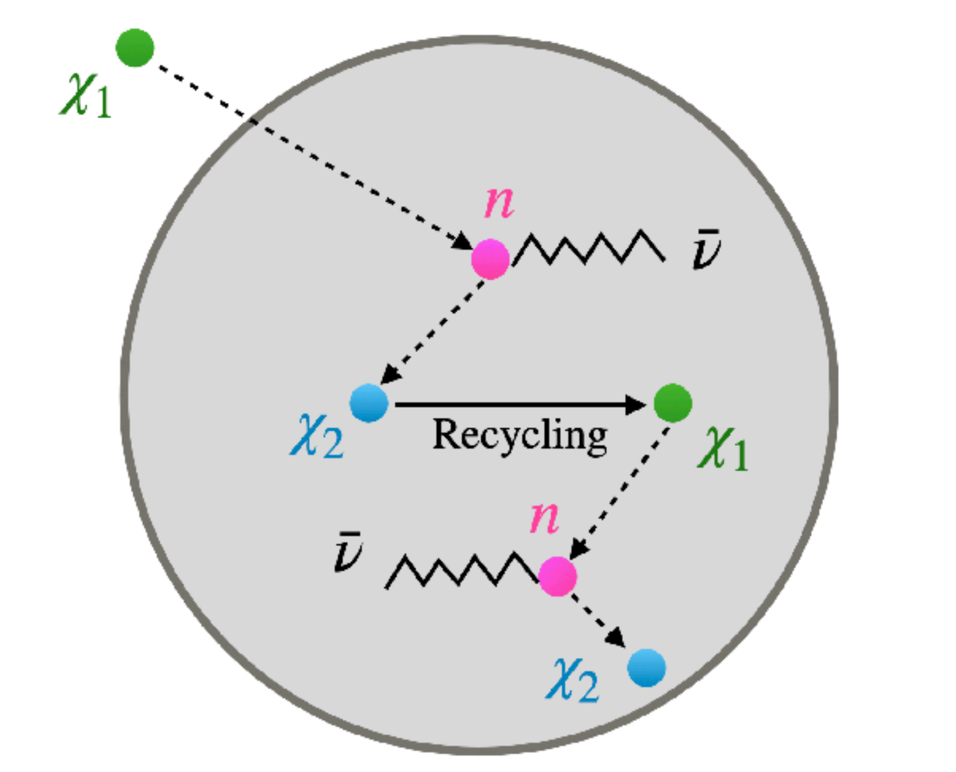
- Dark matter

Nucleon consumption induced by DM



S.-F. Ge and XDM: 2406.00445

DM-catalyzed baryon destruction inside a NS



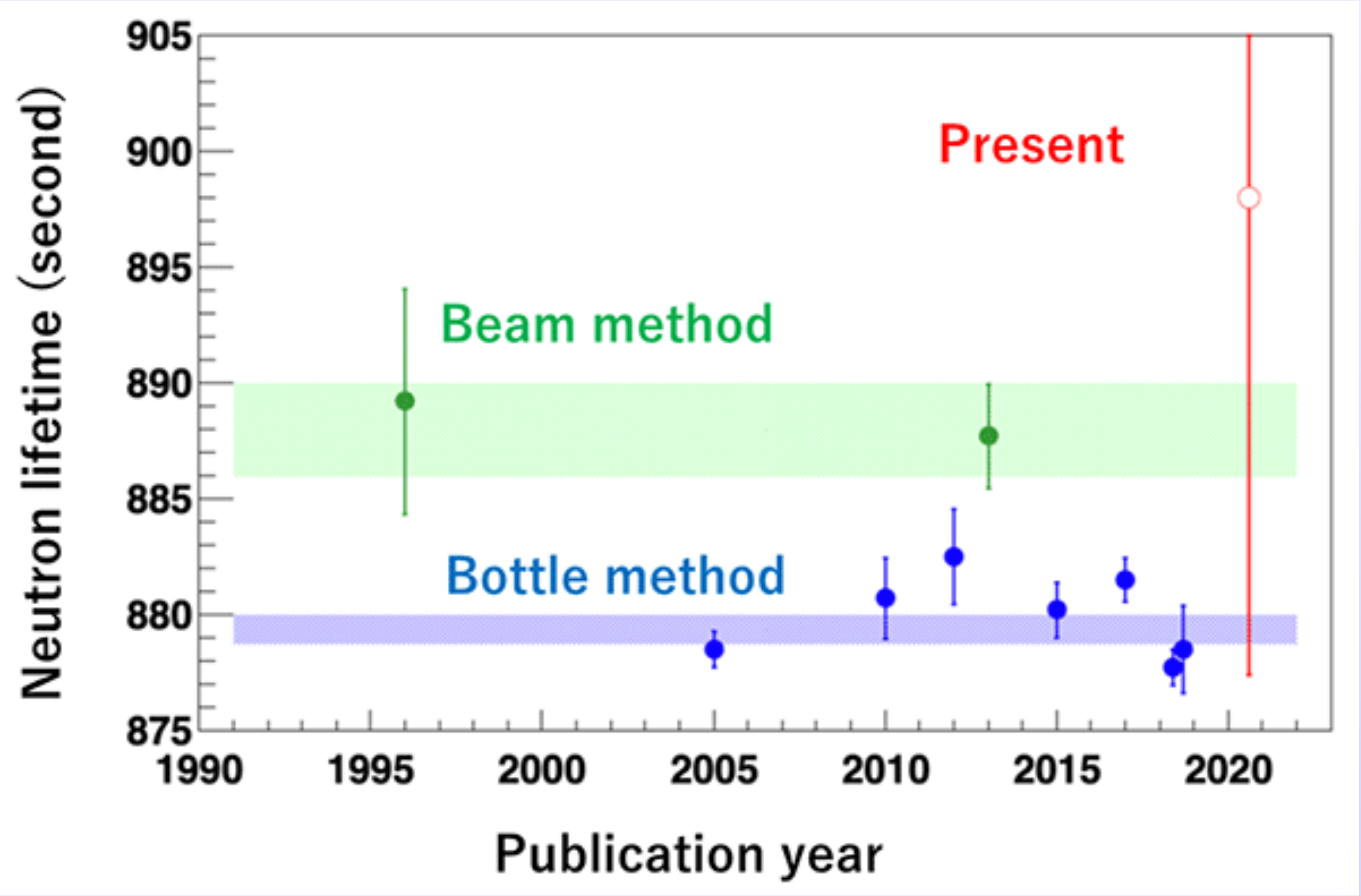
Y. Ema, R. McGehee, M. Pospelov, and A. Ray, 2405.18472

+ many many works along this direction

- Grand unified theories: $\mathrm{SU}(5),\ \mathrm{SO}(10),\ \cdots$

- Neutron lifetime anomaly: Neutron dark decay

B. Fornal and B. Grinstein: 1801.01124; 1810.00862

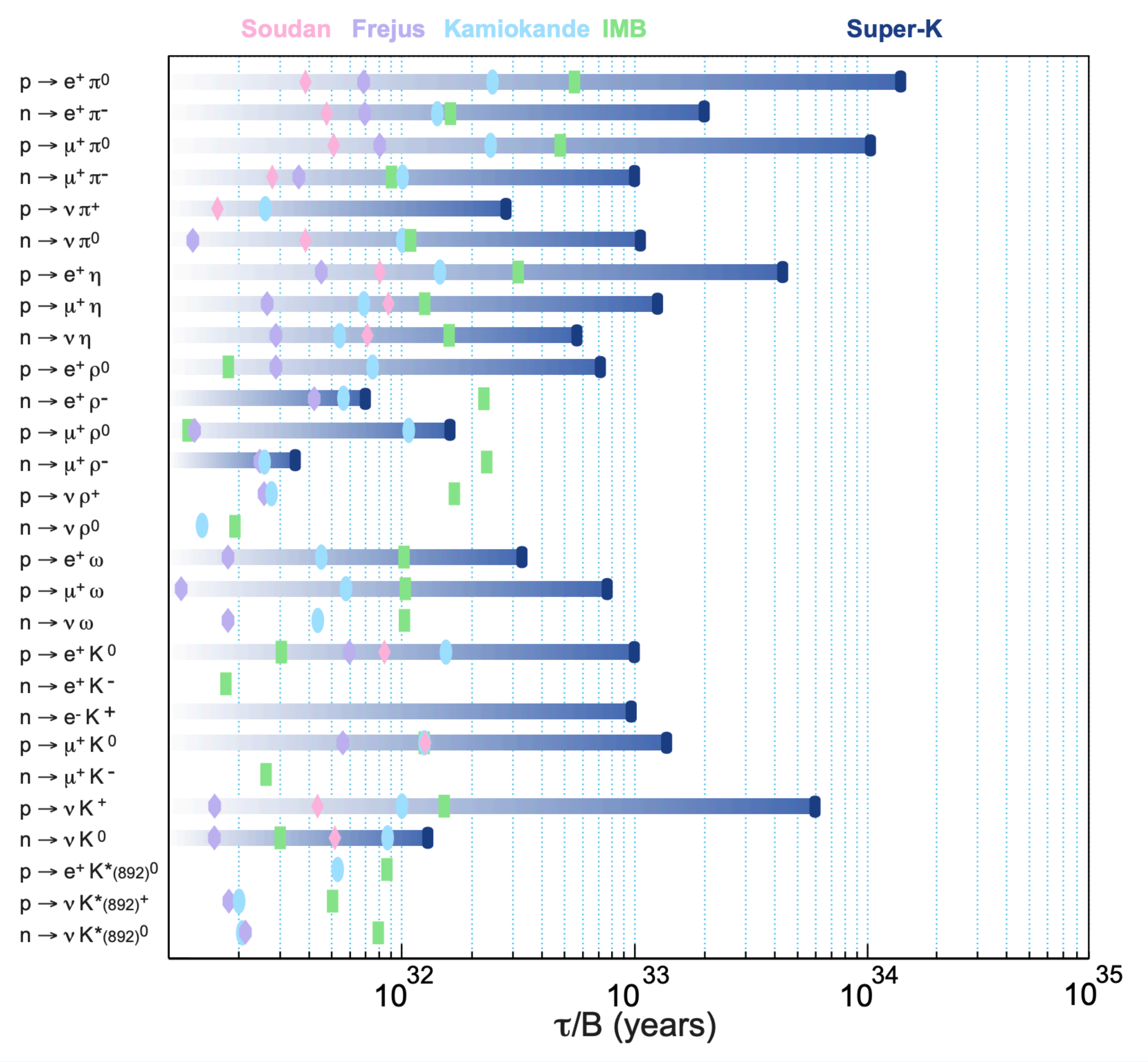


Low energy probes of BNV signals

$\Delta B = 1$ ✔

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

→ Null result but stringent bound



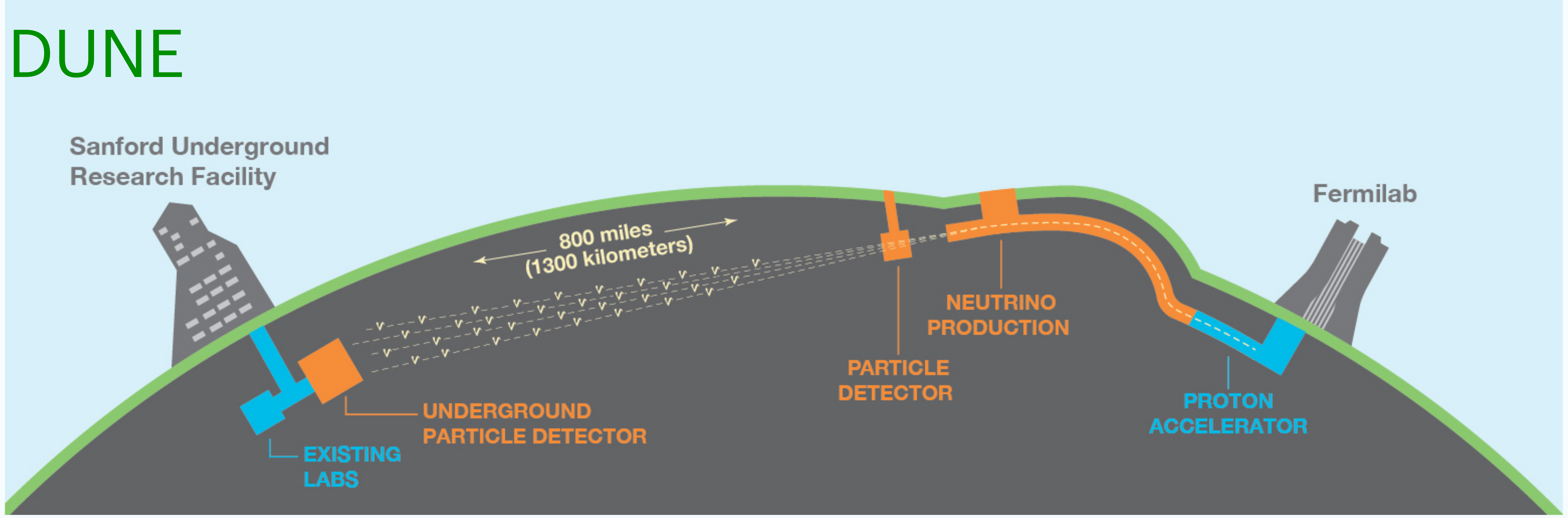
Snowmass 2013, arXiv: 1311.5285

$\Delta B = 2$

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

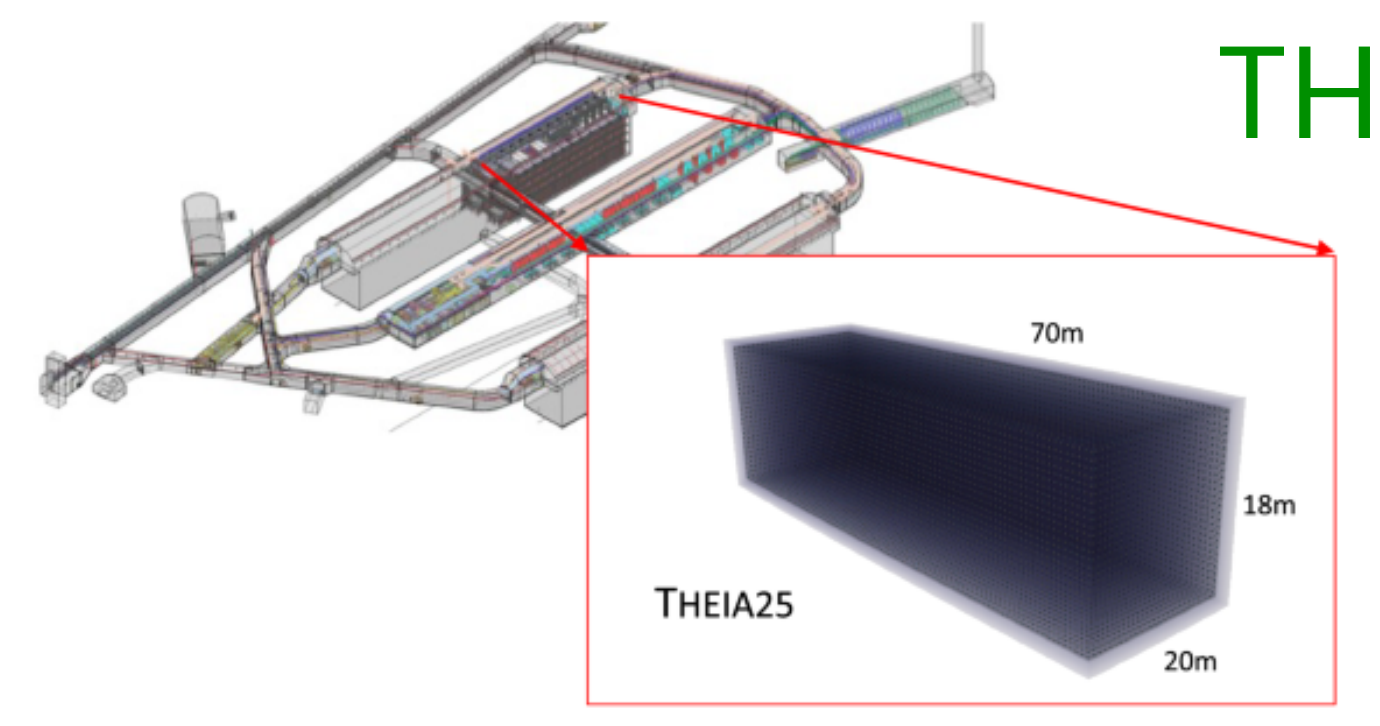
Nucleon decay search as experimental frontiers

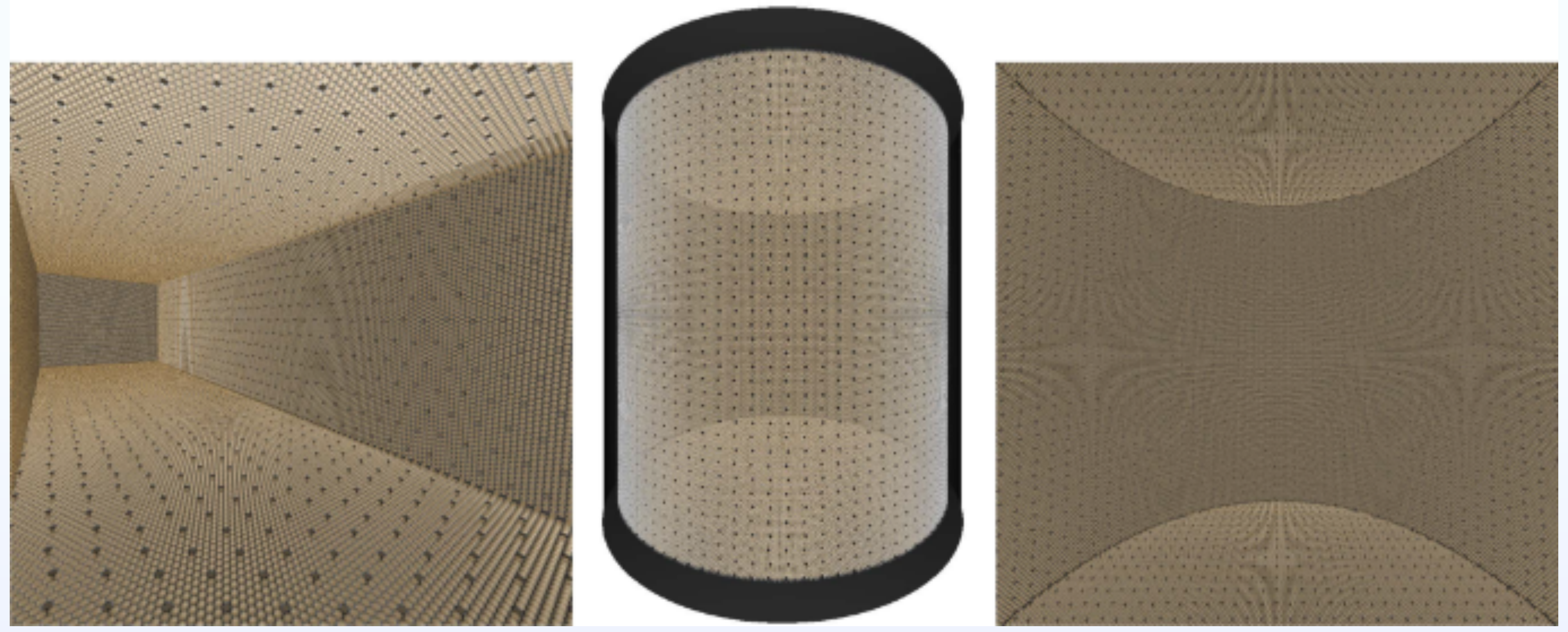
DUNE



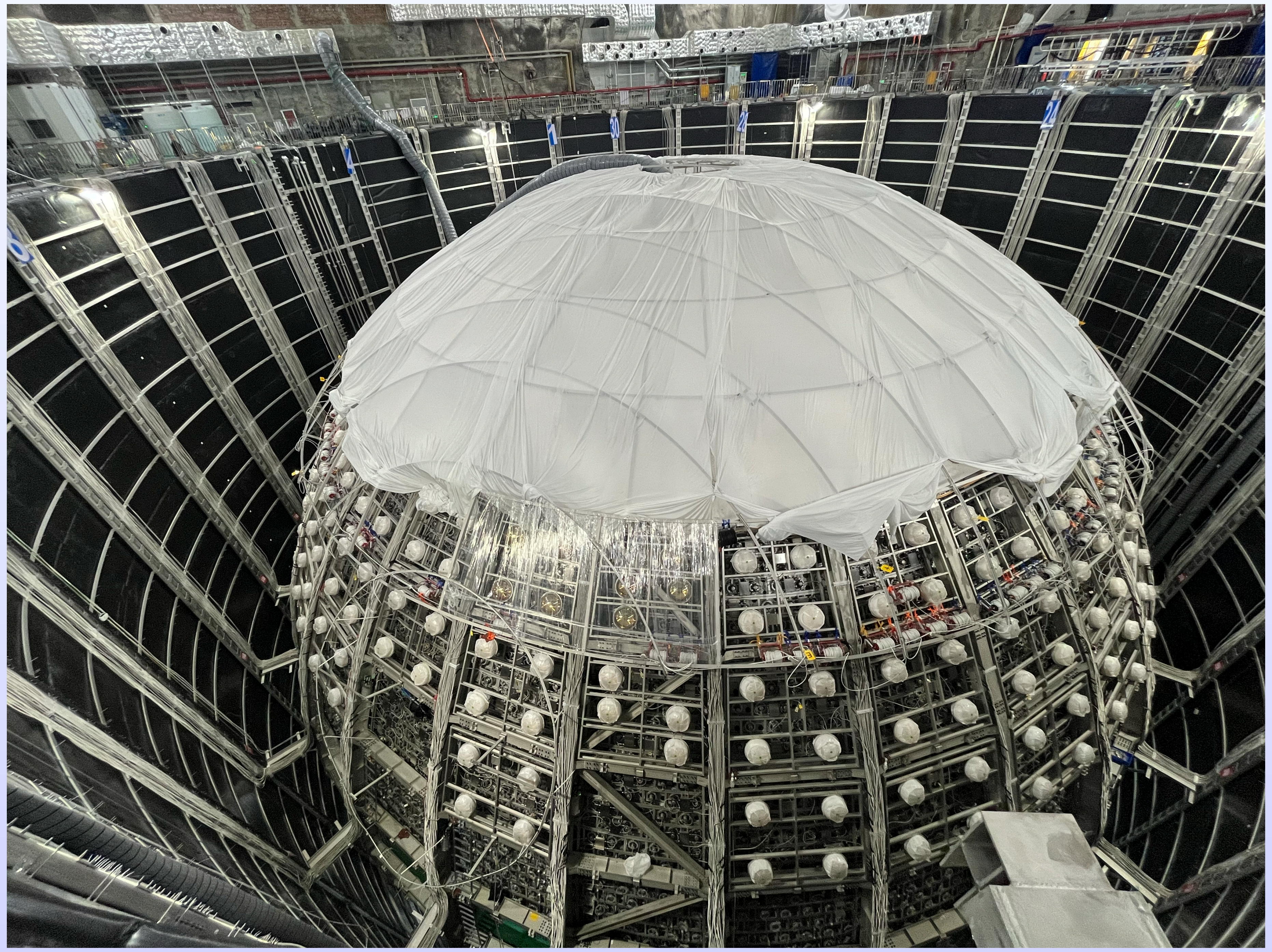
https://www.dunescience.org/

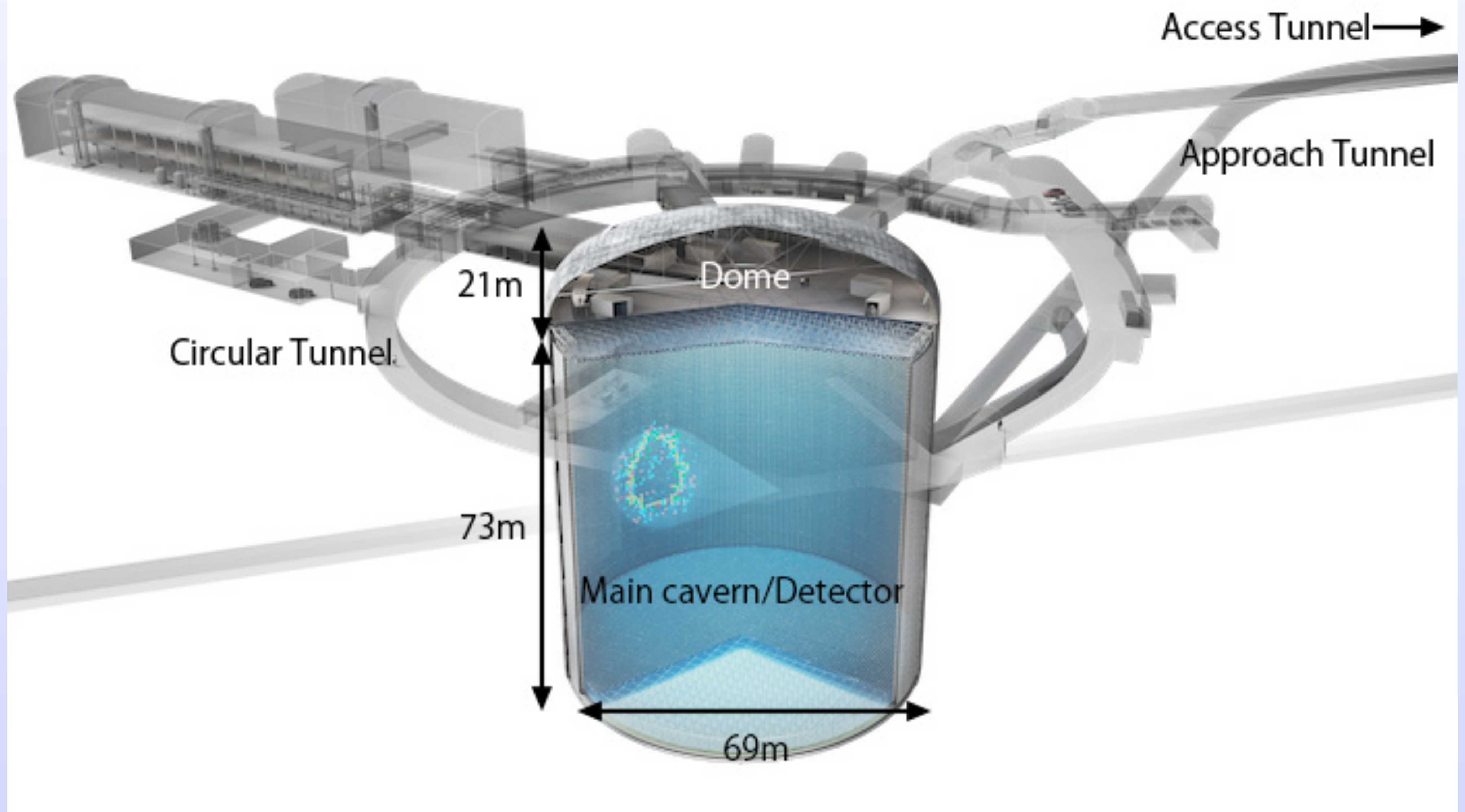
THEIA





JUNO



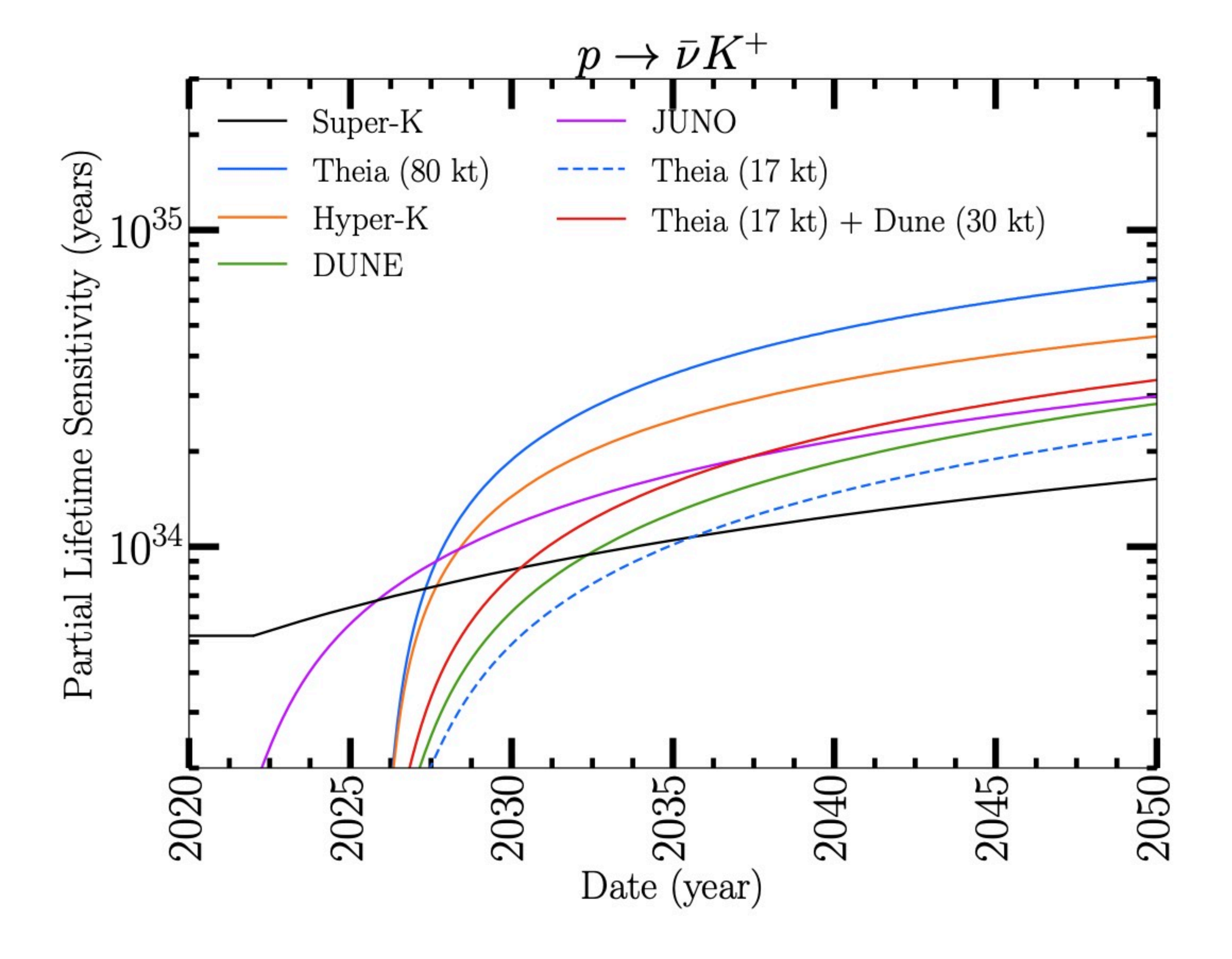


Hyper-K

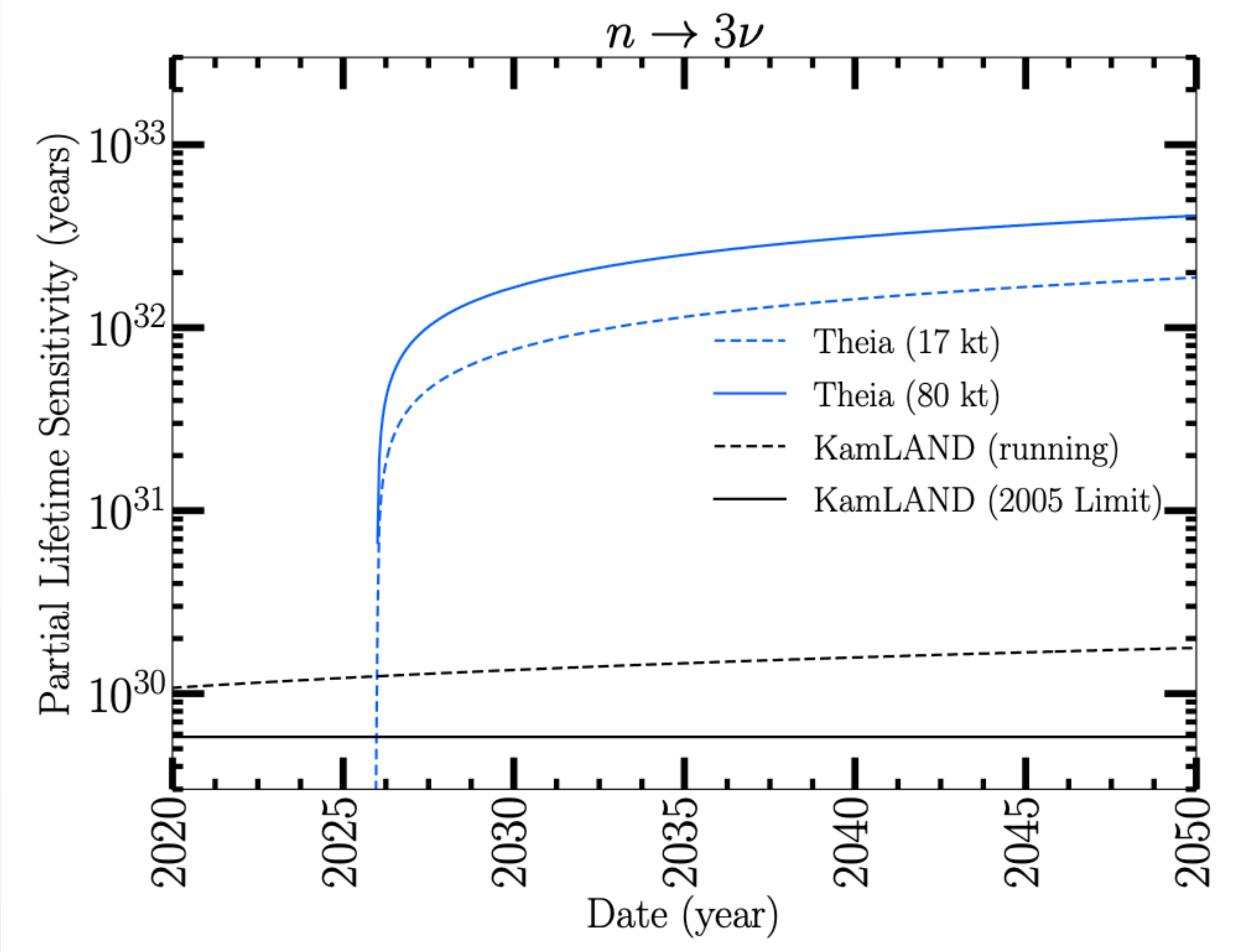
https://www-sk.icrr.u-tokyo.ac.jp/en/news/detail/684

Experiments meet theory

- Improving sensitivity to conventional modes



- Searching for exotic modes



THEIA, 2202.12839

All possible decay channels should be attempted

conventional and exotic

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

Needing a complete theoretical framework

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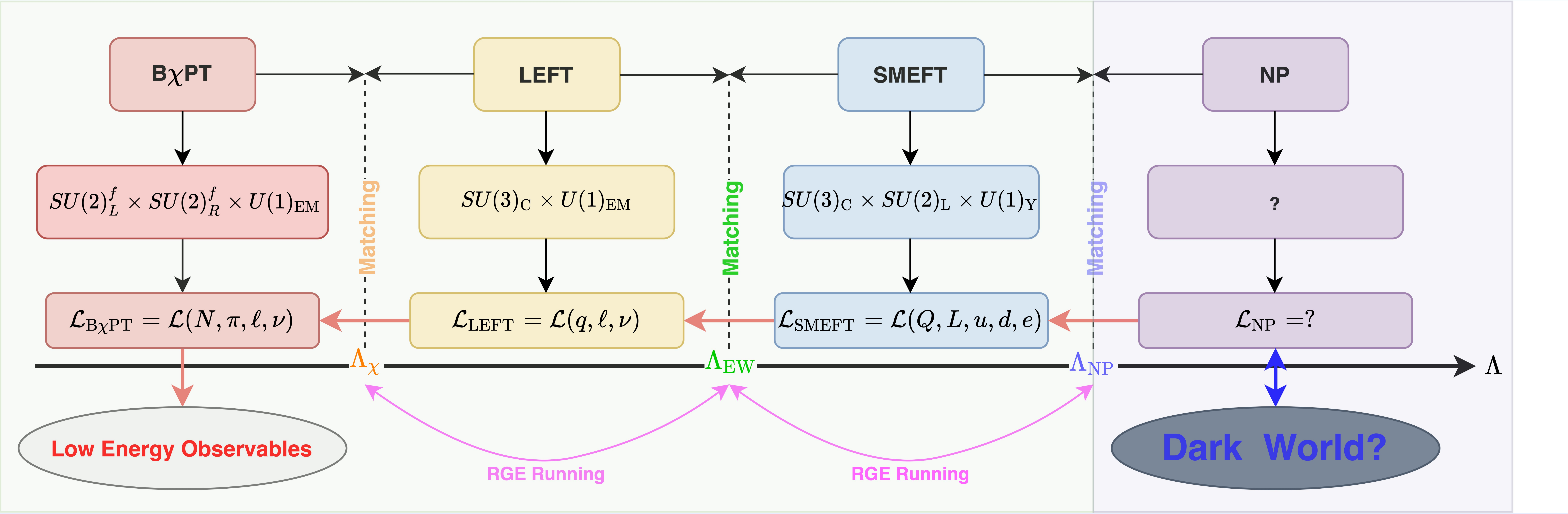
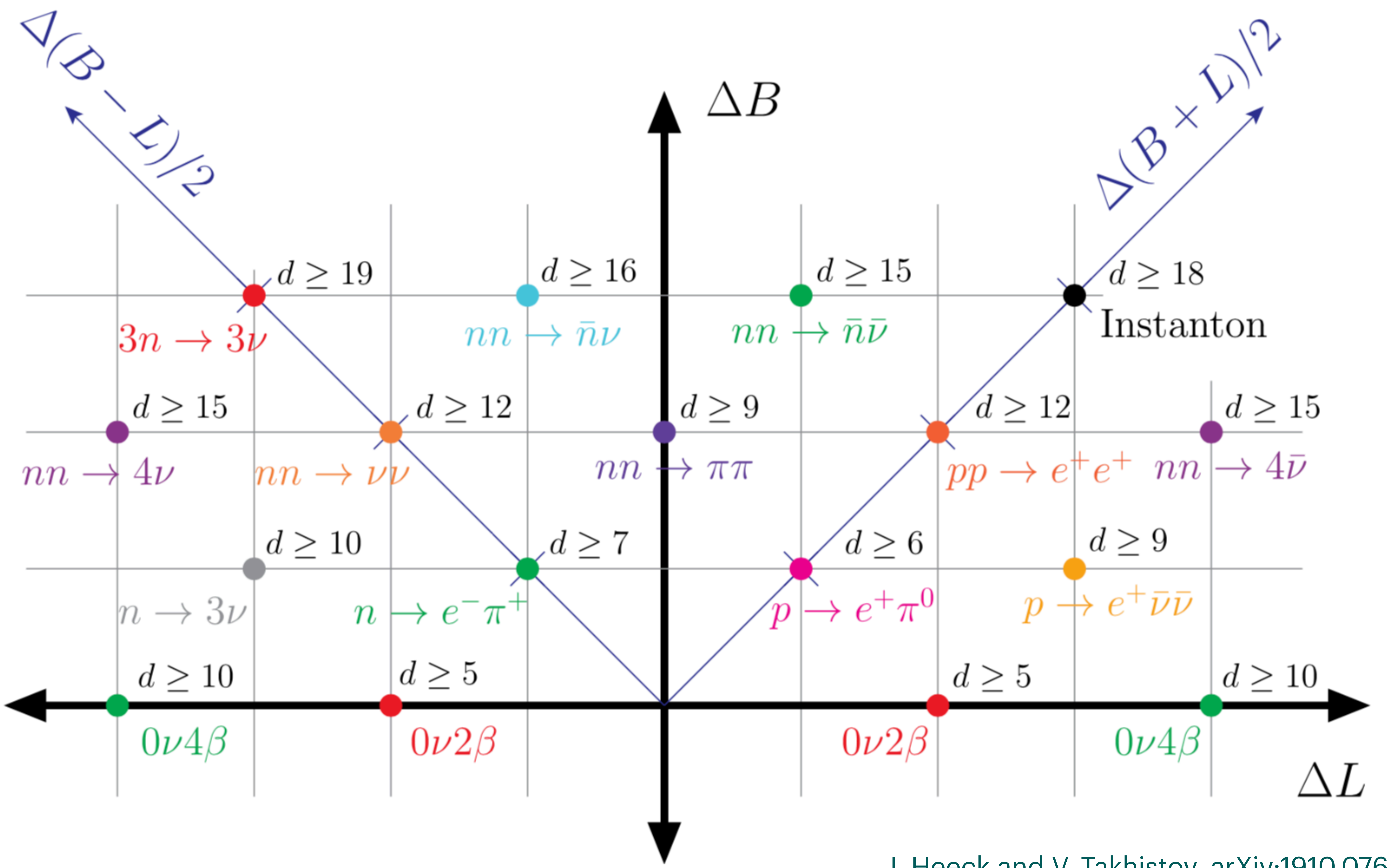
Nucleon decay in the EFT landscape



Xiao-Gang He and XDM, 2102.02562

Hadron level: ChPT → quark level 1: LEFT → quark level 2: SMEFT

BNV in the SMEFT framework



J. Heeck and V. Takhistov, arXiv:1910.07647

- Dim-6 case: $\Delta(B-L)=0$

  $p \to e^+\pi^0,\ p \to \bar{\nu}K^+, \ldots$

- Dim-7 case: $\Delta(B+L)=0$

  $n \to e^-\pi^+,\ p \to \nu K^+, \ldots$

- Exotic nucleon decay modes beyond dim 6 & 7

  $n \to 3\nu,\ p \to \ell_1^+\ell_2^+\ell_3^-, \ldots$

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: $\mathrm{SU(3)_c \times U(1)_{em}}$
- Power counting: canonical dimension d
- Range: $\ll \Lambda_{\rm EW}$

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

Jenkins, Manohar, Stoffer, 2018

Jenkins, Manohar, Stoffer, 2018

Li, Ren, Xiao, Yu, Zheng, 2020

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

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

F. Wilczek 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 ⇒ LEFT-like framework ⇒ SMEFT-like framework

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

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

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

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

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

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

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

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

Sandbox Studio, Chicago

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

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

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

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

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

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

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

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

- Form a basis for any triple-quark operators

Fierz and Dirac γ identities can be used to prove the completeness and independence

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

QCD running effect

- 1-loop RGE due to QCD correction

$$\frac{dC^{yzw}_{a,b}}{d\ln\mu} = -2\frac{\alpha_s}{2\pi}C^{yzw}_{a,b}, \quad \frac{dC^{yzw}_{c}}{d\ln\mu} = +\frac{2}{3}\frac{\alpha_s}{2\pi}C^{yzw}_{c}, \quad \frac{dC^{yzw}_{d}}{d\ln\mu} = +2\frac{\alpha_s}{2\pi}C^{yzw}_{d}$$

Known from dim-6 LEFT counterparts

E. E. Jenkins, A. V. Manohar, and P. Stoffer, arXiv:1711.05270v3

- No mixing: QCD interactions preserve chiral symmetry

- Running effects

$$C^{yzw}_{a,b}(\Lambda_\chi) \approx 1.32\, C^{yzw}_{a,b}(\Lambda_{\mathtt{EW}}), \quad C^{yzw}_{c}(\Lambda_\chi) \approx 0.91\, C^{yzw}_{c}(\Lambda_{\mathtt{EW}}), \quad C^{yzw}_{d}(\Lambda_\chi) \approx 0.76\, C^{yzw}_{d}(\Lambda_{\mathtt{EW}})$$

Enhancement by 30% Suppression

Chiral structures

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

in the massless limit

- Restrict to triple-quark sector

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

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

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

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

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

Newly identified chiral structures

- Different isospin property

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

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

Non-trivial Lorentz structures

- Usual structures—spin-1/2 objects:

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

- New structures—spin-3/2 objects:

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

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

↓

Complicating the chiral matching → Needing proper Lorentz projectors

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

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

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

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

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

The general LEFT Lagrangian involving triple quarks

Non-quark factor as spurion fields

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

Quark factor

$$C_i^{yzw}\overline{\psi} \equiv \mathscr{P}^i_{yzw} \qquad \Gamma_1 q(\overline{q^{C}}\Gamma_2 q) \equiv \mathscr{N}^i_{yzw}$$

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

Matrix form for easy chiral realization

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

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

Chiral building blocks

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

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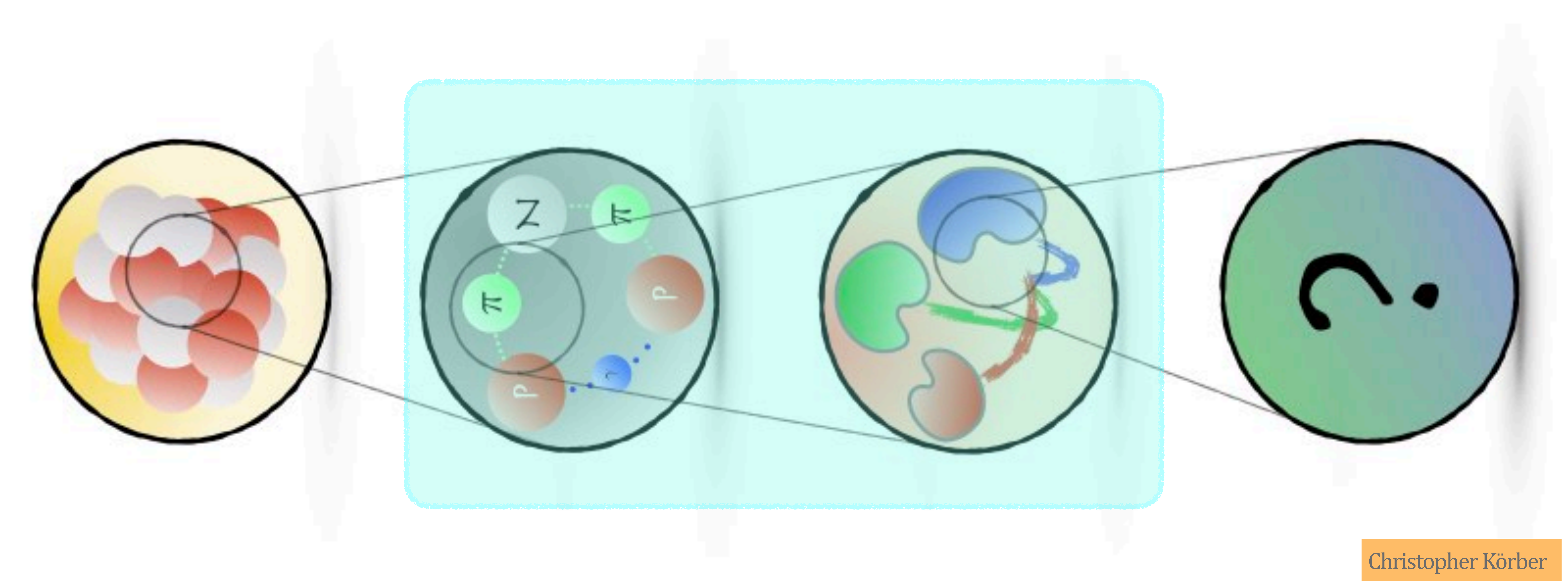
Chiral Perturbation Theory

$\mathrm{SU}(3)_\mathrm{L} \otimes \mathrm{SU}(3)_\mathrm{R}$

$u,\ d,\ s$

Nucleon level operators

Quark level operators



Chiral matching procedures

- Building blocks in ChPT:

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

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

+ Spurion fields

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

- Chiral group: $SU(3)_L \otimes SU(3)_R$: $\Sigma \to \hat{L}\Sigma\hat{R}^\dagger \qquad \xi \to \hat{L}\xi\hat{h}^\dagger = \hat{h}\xi\hat{R}^\dagger \qquad B(V) \to \hat{h}B(V)\hat{h}^\dagger$

$$\mathscr{P}_{\mathbf{8}_L\otimes\mathbf{1}_R} \to \hat{L}\mathscr{P}_{\mathbf{8}_L\otimes\mathbf{1}_R}\hat{L}^\dagger, \quad \mathscr{P}_{\mathbf{3}_L\otimes\bar{\mathbf{3}}_R} \to \hat{L}\mathscr{P}_{\mathbf{3}_L\otimes\bar{\mathbf{3}}_R}\hat{R}^\dagger$$

$$\mathscr{P}^{LR,\mu}_{yzw} \to \hat{L}^*_{yy'}\hat{L}^*_{zz'}\hat{R}^*_{ww'}\mathscr{P}^{LR,\mu}_{y'z'w'}, \quad \mathscr{P}^{LL,\mu\nu}_{yzw} \to \hat{L}^*_{yy'}\hat{L}^*_{zz'}\hat{L}^*_{ww'}\mathscr{P}^{LL,\mu\nu}_{y'z'w'}$$

- Chiral power counting: momentum p:

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

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

Leading-order chiral Lagrangian for nucleon decay

$$\mathcal{L}_B^{\not{B},0} = c_1 \mathrm{Tr}\left[\mathcal{P}_{\bar{\mathbf{3}}_\mathrm{L}\otimes\mathbf{3}_\mathrm{R}} \xi B_\mathrm{L} \xi - \mathcal{P}_{\mathbf{3}_\mathrm{L}\otimes\bar{\mathbf{3}}_\mathrm{R}} \xi^\dagger B_\mathrm{R} \xi^\dagger\right]$$
$$+ c_2 \mathrm{Tr}\left[\mathcal{P}_{\mathbf{8}_\mathrm{L}\otimes\mathbf{1}_\mathrm{R}} \xi B_\mathrm{L} \xi^\dagger - \mathcal{P}_{\mathbf{1}_\mathrm{L}\otimes\mathbf{8}_\mathrm{R}} \xi^\dagger B_\mathrm{R} \xi\right]$$
$$+ \frac{c_3}{\Lambda_\chi}\left[\mathcal{P}^{\mathrm{LR},\mu}_{yzi} \Gamma^\mathrm{L}_{\mu\nu} (\xi i D^\nu B_\mathrm{L} \xi)_{yj} \Sigma_{zk} \epsilon_{ijk} - \mathcal{P}^{\mathrm{RL},\mu}_{yzi} \Gamma^\mathrm{R}_{\mu\nu} (\xi^\dagger i D^\nu B_\mathrm{R} \xi^\dagger)_{yj} \Sigma^*_{kz} \epsilon_{ijk}\right]$$
$$+ \mathrm{h.c.},$$

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

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

Chiral Lagrangian involving octet vector mesons

Vector meson representation is not unique

- Matter field approach: V_μ
- Hidden local symmetry
- Tensor field approach: $V_{\mu\nu} = \partial_\mu V_\nu - \partial_\nu V_\mu$
- Massive Yang-Mills method:

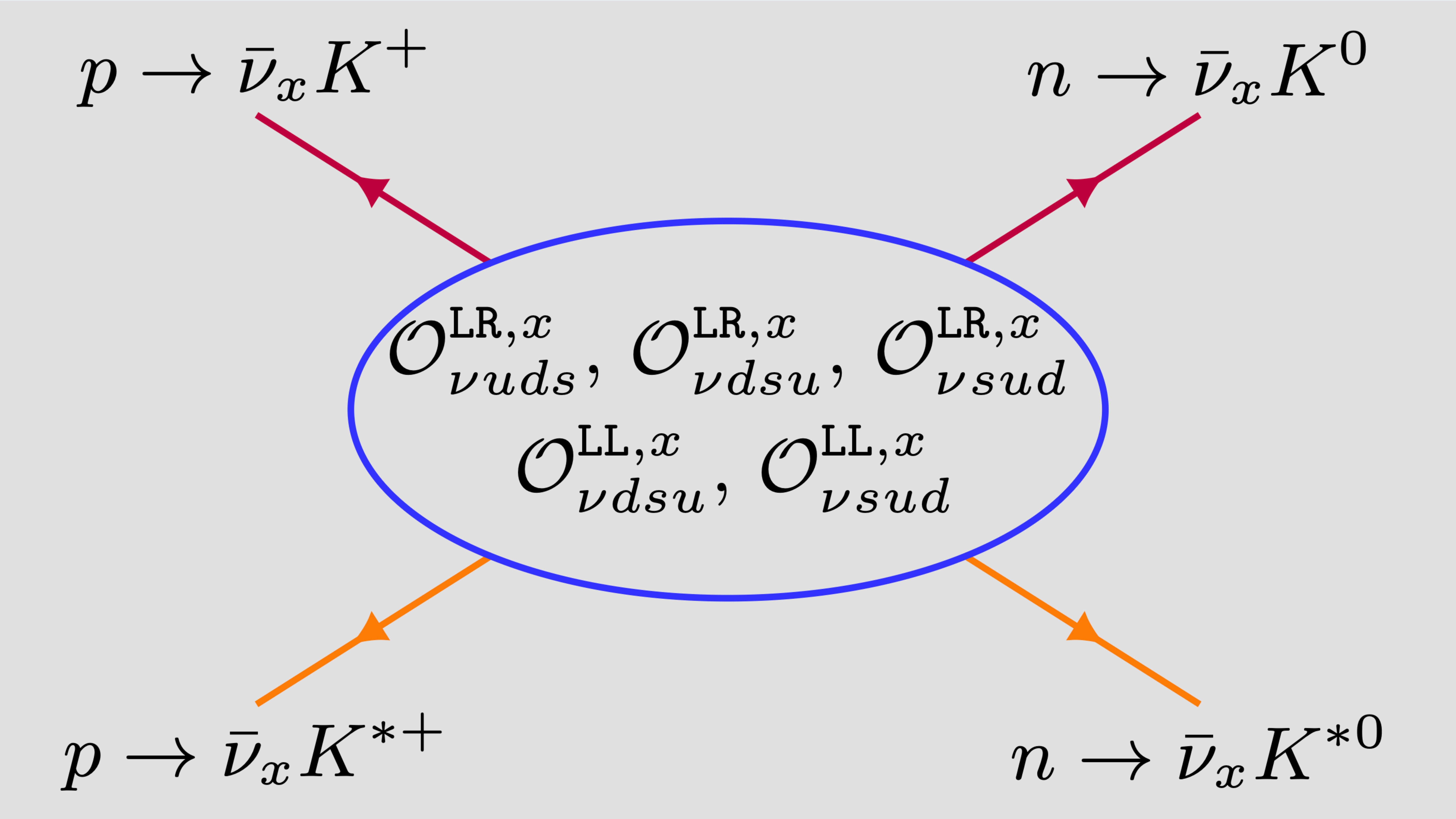
$$D_\mu = \partial_\mu + igV_\mu + \cdots$$

They are equivalent to each other

G. Ecker *et al*, Phys. Lett. B 223 (1989) 425–432
M. C. Birse, hep-ph/9603251

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

Complementarity between pseudoscalar and vector meson



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.

with SU(3)×SU(2)×U(1) symmetry are [5, 6]

$$O^{(1)}_{abcd} = (d_{\alpha a \mathrm{R}} u_{\beta b \mathrm{R}})(q_{i\gamma c \mathrm{L}} l_{jd\mathrm{L}})\varepsilon_{\alpha\beta\gamma}\varepsilon_{ij}\,, \tag{1a}$$

$$O^{(2)}_{abcd} = (q_{i\alpha a \mathrm{L}} q_{j\beta b \mathrm{L}})(u_{\gamma c \mathrm{R}} l_{d\mathrm{R}})\varepsilon_{\alpha\beta\gamma}\varepsilon_{ij}\,, \tag{1b}$$

$$O^{(3)}_{abcd} = (q_{i\alpha a \mathrm{L}} q_{j\beta b \mathrm{L}})(q_{k\gamma c \mathrm{L}} l_{ld\mathrm{L}})\varepsilon_{\alpha\beta\gamma}\varepsilon_{il}\varepsilon_{jk}\,, \tag{1c}$$

$$O^{(4)}_{abcd} = (d_{\alpha a \mathrm{R}} u_{\beta b \mathrm{R}})(u_{\gamma c \mathrm{R}} l_{d\mathrm{R}})\varepsilon_{\alpha\beta\gamma}\,. \tag{1d}$$

$$\begin{aligned}\mathscr{L}^{|\Delta B|=1} = \alpha \sum_{d=1}^{2} \{ & C^{(1)}_d [e_{d\mathrm{L}} \,\mathrm{Tr}\, O\xi B_{\mathrm{L}}\xi - \nu_{d\mathrm{L}} \,\mathrm{Tr}\, O'\xi B_{\mathrm{L}}\xi] \\ & + C^{(2)}_d e_{d\mathrm{R}} \,\mathrm{Tr}\, O\xi^+ B_{\mathrm{R}}\xi^+ + \tilde{C}^{(1)}_d [e_{d\mathrm{L}} \,\mathrm{Tr}\, \tilde{O}\xi B_{\mathrm{L}}\xi - \nu_{d\mathrm{L}} \,\mathrm{Tr}\, \tilde{O}'\xi B_{\mathrm{L}}\xi] \\ & + \tilde{C}^{(2)}_d e_{d\mathrm{R}} \,\mathrm{Tr}\, \tilde{O}\xi^+ B_{\mathrm{R}}\xi^+ + \tilde{C}^{(5)}_d \nu_{d\mathrm{L}} \,\mathrm{Tr}\, \tilde{O}''\xi B_{\mathrm{L}}\xi\} \\ & + \beta \sum_{d=1}^{2} \{ C^{(3)}_d [e_{d\mathrm{L}} \,\mathrm{Tr}\, O\xi B_{\mathrm{L}}\xi^+ - \nu_{d\mathrm{L}} \,\mathrm{Tr}\, O'\xi B_{\mathrm{L}}\xi^+] \\ & + C^{(4)}_d e_{d\mathrm{R}} \,\mathrm{Tr}\, O\xi^+ B_{\mathrm{R}}\xi + \tilde{C}^{(3)}_d [e_{d\mathrm{L}} \,\mathrm{Tr}\, \tilde{O}\xi B_{\mathrm{L}}\xi^+ - \nu_{d\mathrm{L}} \,\mathrm{Tr}\, \tilde{O}'\xi B_{\mathrm{L}}\xi^+] \\ & + \tilde{C}^{(4)}_d e_{d\mathrm{R}} \,\mathrm{Tr}\, \tilde{O}\xi^+ B_{\mathrm{R}}\xi + \tilde{C}^{(6)}_d \nu_{d\mathrm{L}} \,\mathrm{Tr}\, \tilde{O}''\xi B_{\mathrm{L}}\xi^+\} + \text{h.c.}\,, \end{aligned} \tag{16}$$

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

Octet vector meson case

PHYSICAL REVIEW D VOLUME 29, NUMBER 9 1 MAY 1984

Chiral Lagrangian for proton decay

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(Received 6 June 1983)

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

$$\begin{aligned}\mathscr{L}^{\Delta B=1}_{(2)} = \frac{\gamma}{M_p}\sum_d \{ & \overline{e^+_{dR}} i\gamma_\mu \mathrm{Tr}[\underline{C}^{(1)}_d \underline{\xi}(D^\mu \underline{B})\underline{\xi}] - \overline{e^+_{dL}} i\gamma_\mu \mathrm{Tr}[\underline{C}^{(2)}_d \underline{\xi}^\dagger(D^\mu \underline{B})\underline{\xi}^\dagger] - \overline{\nu^c_{dR}} i\gamma_\mu \mathrm{Tr}[\underline{F}^{(1)}_d \underline{\xi}(D^\mu \underline{B})\underline{\xi}]\} + \text{H.c.} \\ + \frac{\delta}{M_p}\sum_p \{ & \overline{e^+_{dR}} i\gamma_\mu \mathrm{Tr}[\underline{C}^{(3)}_d \underline{\xi}(D^\mu \underline{B})\underline{\xi}^\dagger] \overline{e^+_{dL}} i\gamma_\mu \mathrm{Tr}[\underline{C}^{(4)}_d \underline{\xi}^\dagger(D^\mu \underline{B})\underline{\xi}] - \overline{\nu^c_{dR}} i\gamma_\mu \mathrm{Tr}[\underline{F}^{(3)}_d \underline{\xi}(D^\mu \underline{B})\underline{\xi}^\dagger]\} + \text{H.c.} \end{aligned} \tag{3.7}$$

Not complete, double counting issues, ...

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

Determination of the new LECs

- Lattice QCD: $c_1 = \alpha = -0.01257(111)\,\mathrm{GeV}^3$ $\quad c_2 = \beta = 0.01269(107)\,\mathrm{GeV}^3$ J.-S. Yoo *et al*, PRD 105 (2022)

- $c_{3,4}$ and $d^{(',")}_{1,2,3,4}$ related to the new terms are unknown

- Naive dimensional analysis (NDA): S. Weinberg, PRL 63 (1989)
A. Manohar and H. Georgi, NPB 234 (1984)

Weinberg reduced coupling method for an $\mathcal{O}$

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

m: minimal # of physical fields

g: coupling constant

D: dim. of op.

→

$$c_{1,2,3} \sim \Lambda_\chi^3/(4\pi)^2 \approx 0.011\,\mathrm{GeV}^3$$

$$c_4 \sim \Lambda_\chi^2 F_0/(4\pi\sqrt{2}) \approx 0.007\,\mathrm{GeV}^3$$

$$d^{(',")}_{1,2,3,4} \sim \Lambda_\chi^2/(4\pi) \approx 0.115\,\mathrm{GeV}^2$$

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

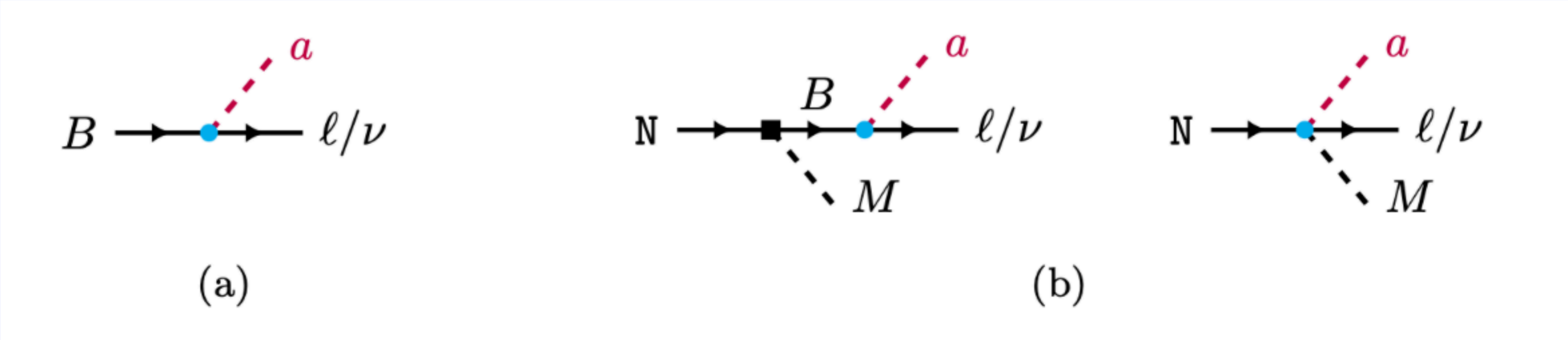
Worthy of calculation by LQCD community

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

Standard ChPT interactions

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

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



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

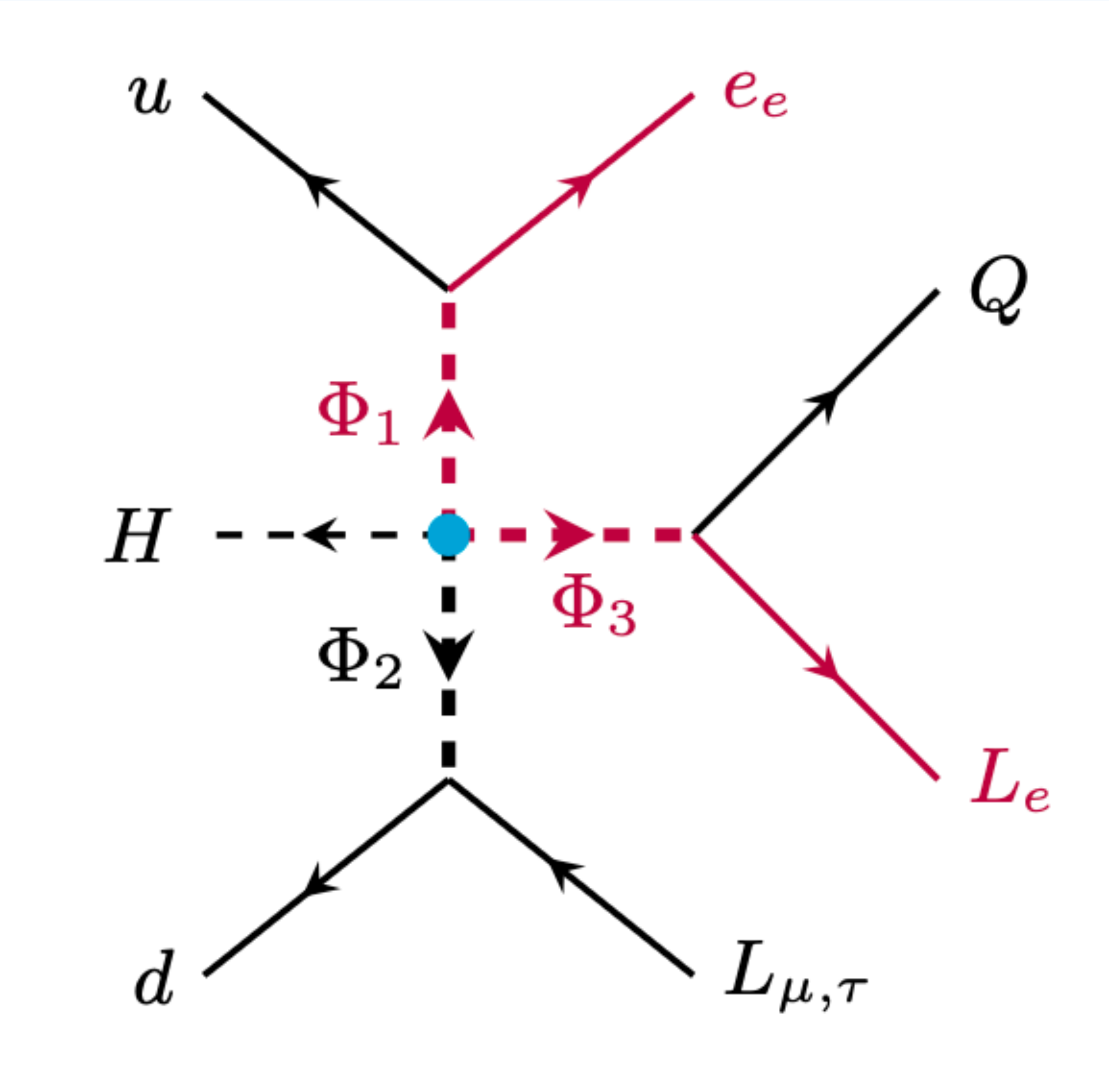
- Among the experimentally most constrained proton decay processes
- They can only be mediated by dim-9 and higher LEFT operators
- Associated with irreps $\mathbf{6}_{\mathrm{L(R)}} \otimes \mathbf{3}_{\mathrm{R(L)}}$

dim-10 or higher in SMEFT

$$\mathcal{O}_{\ell\ell'} = (\overline{\ell^{C}_{L}}\gamma_\mu \ell_R)(\overline{\ell'_R} u^\alpha_L)(\overline{u^{\beta C}_L}\gamma^\mu d^\gamma_R)\epsilon_{\alpha\beta\gamma}$$

$$\mathcal{P}^{\mathrm{LR},\mu}_{uud} = \Lambda^{-5}_{\ell\ell'}(\overline{\ell^{C}_{L}}\gamma^\mu \ell_R)\overline{\ell'_R}$$

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



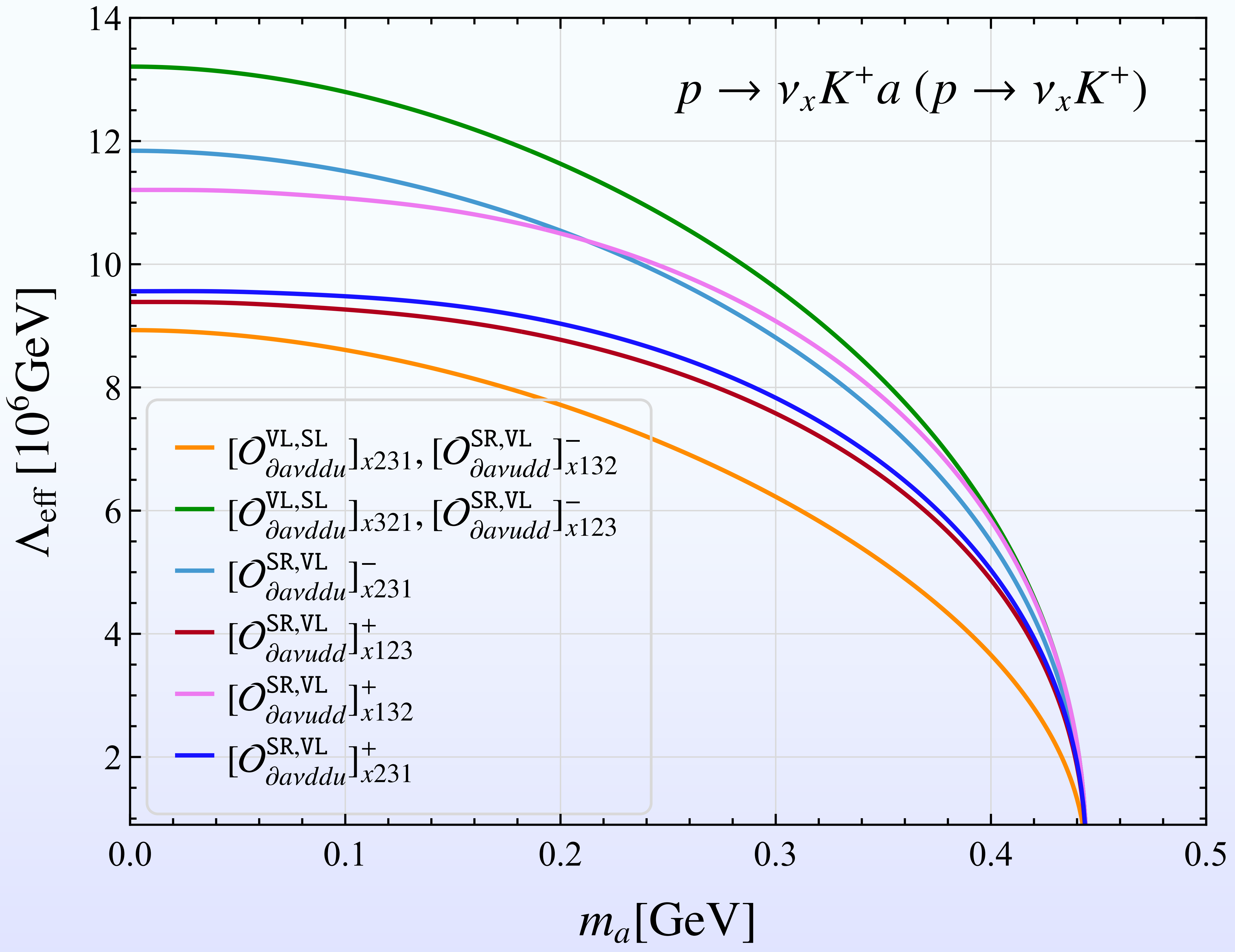
Leptoquark model

Nucleon decay involving an ALP

Some examplified operators

$\mathcal{O}^{\rm VL,SL}_{\partial aeuud}$	$\partial_\mu a(\overline{e^{\rm C}_{\rm R}}\gamma^\mu u^\alpha_{\rm L})(\overline{u^{\beta\rm C}_{\rm L}} d^\gamma_{\rm L})\epsilon_{\alpha\beta\gamma}$	$\mathbf{8}_{\rm L}\otimes\mathbf{1}_{\rm R}$
$\mathcal{O}^{\rm SL,VR}_{\partial aeuud}$	$\partial_\mu a(\overline{e^{\rm C}_{\rm L}} u^\alpha_{\rm L})(\overline{u^{\beta\rm C}_{\rm L}}\gamma^\mu d^\gamma_{\rm R})\epsilon_{\alpha\beta\gamma}$	$\mathbf{6}_{\rm L}\otimes\mathbf{3}_{\rm R}$
$\mathcal{O}^{\rm SL,VR}_{\partial aeudu}$	$\partial_\mu a(\overline{e^{\rm C}_{\rm L}} u^\alpha_{\rm L})(\overline{d^{\beta\rm C}_{\rm L}}\gamma^\mu u^\gamma_{\rm R})\epsilon_{\alpha\beta\gamma}$	$\mathbf{6}_{\rm L}\otimes\mathbf{3}_{\rm R}\oplus\bar{\mathbf{3}}_{\rm L}\otimes\mathbf{3}_{\rm R}$
$\mathcal{O}^{\rm SL,VR}_{\partial aeduu}$	$\partial_\mu a(\overline{e^{\rm C}_{\rm L}} d^\alpha_{\rm L})(\overline{u^{\beta\rm C}_{\rm L}}\gamma^\mu u^\gamma_{\rm R})\epsilon_{\alpha\beta\gamma}$	$\mathbf{6}_{\rm L}\otimes\mathbf{3}_{\rm R}\oplus\bar{\mathbf{3}}_{\rm L}\otimes\mathbf{3}_{\rm R}$
$\mathcal{O}^{\rm VR,SR}_{\partial aeuud}$	$\partial_\mu a(\overline{e^{\rm C}_{\rm L}}\gamma^\mu u^\alpha_{\rm R})(\overline{u^{\beta\rm C}_{\rm R}} d^\gamma_{\rm R})\epsilon_{\alpha\beta\gamma}$	$\mathbf{1}_{\rm L}\otimes\mathbf{8}_{\rm R}$
$\mathcal{O}^{\rm SR,VL}_{\partial aeuud}$	$\partial_\mu a(\overline{e^{\rm C}_{\rm R}} u^\alpha_{\rm R})(\overline{u^{\beta\rm C}_{\rm R}}\gamma^\mu d^\gamma_{\rm L})\epsilon_{\alpha\beta\gamma}$	$\mathbf{3}_{\rm L}\otimes\mathbf{6}_{\rm R}$
$\mathcal{O}^{\rm SR,VL}_{\partial aeudu}$	$\partial_\mu a(\overline{e^{\rm C}_{\rm R}} u^\alpha_{\rm R})(\overline{d^{\beta\rm C}_{\rm R}}\gamma^\mu u^\gamma_{\rm L})\epsilon_{\alpha\beta\gamma}$	$\mathbf{3}_{\rm L}\otimes\mathbf{6}_{\rm R}\oplus\mathbf{3}_{\rm L}\otimes\bar{\mathbf{3}}_{\rm R}$
$\mathcal{O}^{\rm SR,VL}_{\partial aeduu}$	$\partial_\mu a(\overline{e^{\rm C}_{\rm R}} d^\alpha_{\rm R})(\overline{u^{\beta\rm C}_{\rm R}}\gamma^\mu u^\gamma_{\rm L})\epsilon_{\alpha\beta\gamma}$	$\mathbf{3}_{\rm L}\otimes\mathbf{6}_{\rm R}\oplus\mathbf{3}_{\rm L}\otimes\bar{\mathbf{3}}_{\rm R}$

Tong Li, Michael A. Schmidt, Chang-Yuan Yao, 2406.11382
Wei-Qi Fan, Yi Liao, XDM, Hao-Lin Wang,2507.11844



Nucleon decay involving a dark photon

$\Delta I = 3/2$ process: $n \to \ell^- \pi^+ X^\mu$ with $\ell = e, \mu$

$$\mathcal{O}_{X\ell} = X_{\mu\nu}(\overline{\ell_{\rm R}} d^\alpha_{\rm L})(\overline{d^{\beta\rm C}_{\rm L}} \sigma^{\mu\nu} d^\gamma_{\rm L})\epsilon_{\alpha\beta\sigma} \quad \in \mathbf{10}_{\rm L} \otimes \mathbf{1}_{\rm R}$$

$$\downarrow$$

$$\mathscr{P}^{\rm LL,\mu\nu}_{ddd} = \Lambda^{-4}_{X\ell} X^{\mu\nu} \overline{\ell_{\rm R}}$$

$$\downarrow$$

$$\mathscr{L}_{n\ell\pi X} = \frac{-i\sqrt{2}c_4}{(F_0 \Lambda^2_\chi \Lambda^4_{X\ell})} X^{\mu\nu}(\overline{\ell_{\rm R}} \hat{\Gamma}^{\rm L}_{\mu\nu\alpha\beta} \partial^\alpha n)\partial^\beta \pi^-$$

$$\downarrow$$

$$\Gamma(n \to \ell^- \pi^+ X) \sim \left(\frac{3 \times 10^6\,\text{GeV}}{\Lambda_{X\ell}}\right)^8 / (10^{30}\,\text{yr})$$

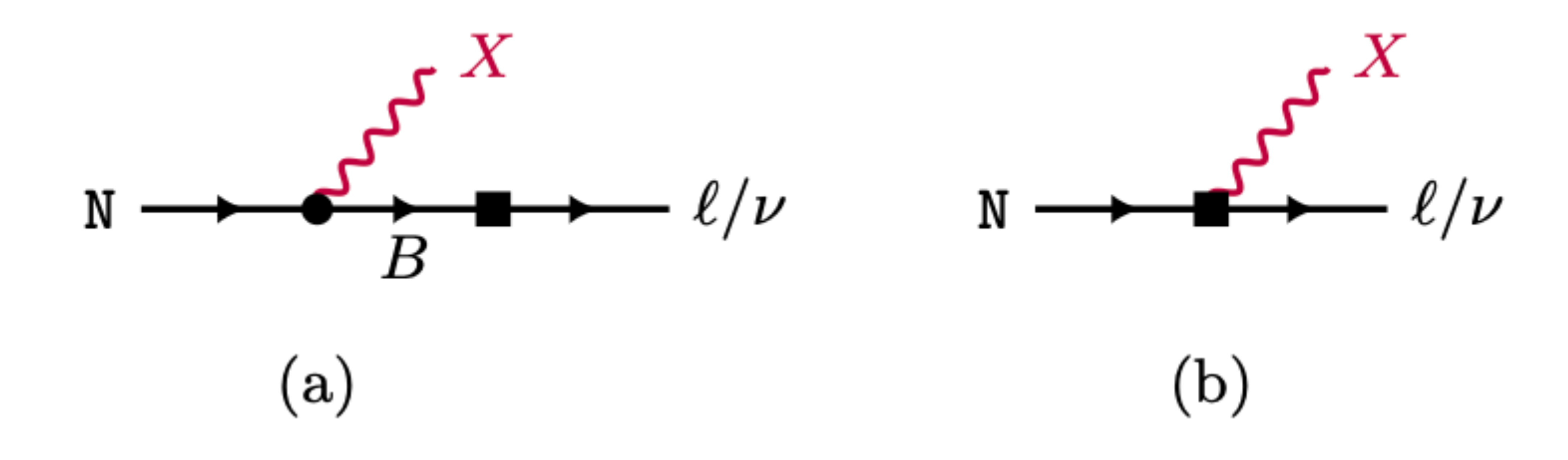
More operators with various representations

$\tilde{\mathcal{O}}^{\rm TL,SL}_{X\ell uud}$	$X_{\mu\nu}(\overline{\ell^{\rm C}_{\rm L}}\sigma^{\mu\nu}u^\alpha_{\rm L})(\overline{u^{\beta\rm C}_{\rm L}}d^\gamma_{\rm L})\epsilon_{\alpha\beta\gamma}$	$\mathbf{8}_{\rm L}\otimes\mathbf{1}_{\rm R}$
$\tilde{\mathcal{O}}^{\rm SL,TL}_{X\ell uud}$	$X_{\mu\nu}(\overline{\ell^{\rm C}_{\rm L}}u^\alpha_{\rm L})(\overline{u^{\beta\rm C}_{\rm L}}\sigma^{\mu\nu}d^\gamma_{\rm L})\epsilon_{\alpha\beta\gamma}$	$\mathbf{10}_{\rm L}\otimes\mathbf{1}_{\rm R}$
$\tilde{\mathcal{O}}^{\rm VR,VL}_{X\ell duu}$	$X_{\mu\nu}(\overline{\ell^{\rm C}_{\rm L}}\gamma^\mu d^\alpha_{\rm R})(\overline{u^{\beta\rm C}_{\rm R}}\gamma^\nu u^\gamma_{\rm L})\epsilon_{\alpha\beta\gamma}$	$\mathbf{3}_{\rm L}\otimes\mathbf{6}_{\rm R}\oplus\mathbf{3}_{\rm L}\otimes\bar{\mathbf{3}}_{\rm R}$
$\tilde{\mathcal{O}}^{\rm VR,VL}_{X\ell udu}$	$X_{\mu\nu}(\overline{\ell^{\rm C}_{\rm L}}\gamma^\mu u^\alpha_{\rm R})(\overline{d^{\beta\rm C}_{\rm R}}\gamma^\nu u^\gamma_{\rm L})\epsilon_{\alpha\beta\gamma}$	$\mathbf{3}_{\rm L}\otimes\mathbf{6}_{\rm R}\oplus\mathbf{3}_{\rm L}\otimes\bar{\mathbf{3}}_{\rm R}$
$\tilde{\mathcal{O}}^{\rm VR,VL}_{X\ell uud}$	$X_{\mu\nu}(\overline{\ell^{\rm C}_{\rm L}}\gamma^\mu u^\alpha_{\rm R})(\overline{u^{\beta\rm C}_{\rm R}}\gamma^\nu d^\gamma_{\rm L})\epsilon_{\alpha\beta\gamma}$	$\mathbf{3}_{\rm L}\otimes\mathbf{6}_{\rm R}$
$\tilde{\mathcal{O}}^{\rm TR,SR}_{X\ell uud}$	$X_{\mu\nu}(\overline{\ell^{\rm C}_{\rm R}}\sigma^{\mu\nu}u^\alpha_{\rm R})(\overline{u^{\beta\rm C}_{\rm R}}d^\gamma_{\rm R})\epsilon_{\alpha\beta\gamma}$	$\mathbf{1}_{\rm L}\otimes\mathbf{8}_{\rm R}$
$\tilde{\mathcal{O}}^{\rm SR,TR}_{X\ell uud}$	$X_{\mu\nu}(\overline{\ell^{\rm C}_{\rm R}}u^\alpha_{\rm R})(\overline{u^{\beta\rm C}_{\rm R}}\sigma^{\mu\nu}d^\gamma_{\rm R})\epsilon_{\alpha\beta\gamma}$	$\mathbf{1}_{\rm L}\otimes\mathbf{10}_{\rm R}$
$\tilde{\mathcal{O}}^{\rm VL,VR}_{X\ell duu}$	$X_{\mu\nu}(\overline{\ell^{\rm C}_{\rm R}}\gamma^\mu d^\alpha_{\rm L})(\overline{u^{\beta\rm C}_{\rm L}}\gamma^\nu u^\gamma_{\rm R})\epsilon_{\alpha\beta\gamma}$	$\mathbf{6}_{\rm L}\otimes\mathbf{3}_{\rm R}\oplus\bar{\mathbf{3}}_{\rm L}\otimes\mathbf{3}_{\rm R}$
$\tilde{\mathcal{O}}^{\rm VL,VR}_{X\ell udu}$	$X_{\mu\nu}(\overline{\ell^{\rm C}_{\rm R}}\gamma^\mu u^\alpha_{\rm L})(\overline{d^{\beta\rm C}_{\rm L}}\gamma^\nu u^\gamma_{\rm R})\epsilon_{\alpha\beta\gamma}$	$\mathbf{6}_{\rm L}\otimes\mathbf{3}_{\rm R}\oplus\bar{\mathbf{3}}_{\rm L}\otimes\mathbf{3}_{\rm R}$
$\tilde{\mathcal{O}}^{\rm VL,VR}_{X\ell uud}$	$X_{\mu\nu}(\overline{\ell^{\rm C}_{\rm R}}\gamma^\mu u^\alpha_{\rm L})(\overline{u^{\beta\rm C}_{\rm L}}\gamma^\nu d^\gamma_{\rm R})\epsilon_{\alpha\beta\gamma}$	$\mathbf{6}_{\rm L}\otimes\mathbf{3}_{\rm R}$

Yi Liao, XDM, Hao-Lin Wang, Xiang Zhao (ongoing)

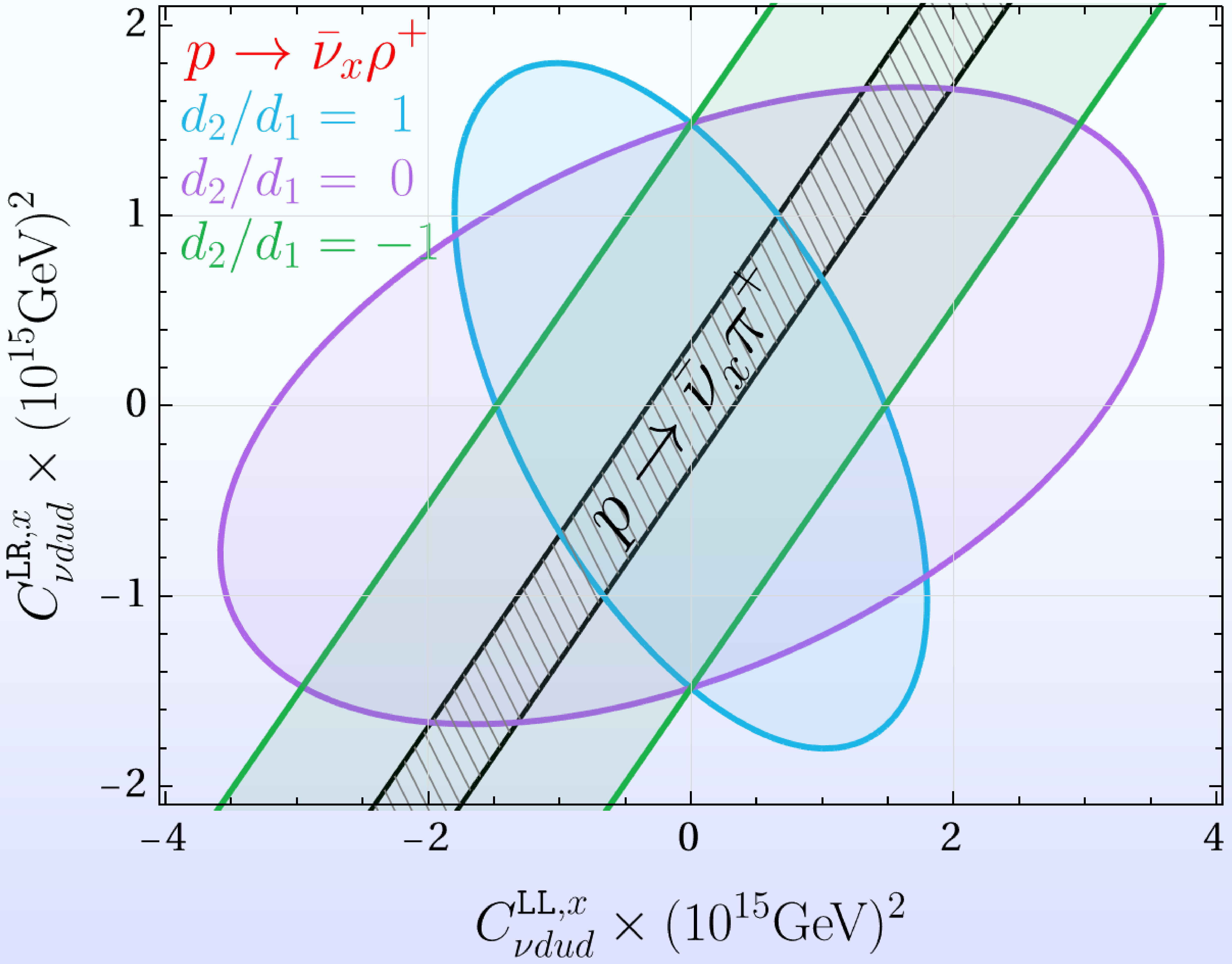
Vector meson modes help breaking degeneracy

Yi Liao, XDM, Hao-Lin Wang, 2506.05052



$$\Gamma_{p\to\bar{\nu}_x\rho^+} = \frac{m_p(1-3x_\rho^2+2x_\rho^3)}{32\pi\, x_\rho}\Big(\big|d_1 C^{\mathrm{LR},x}_{\nu dud}+d_2 C^{\mathrm{LL},x}_{\nu dud}\big|^2 + \frac{\mathrm{G}_\mathrm{F}^2}{m_n^2}\big|c_1 C^{\mathrm{LR},x}_{\nu dud}+c_2 C^{\mathrm{LL},x}_{\nu dud}\big|^2\Big), \quad (15a)$$

$$\Gamma_{p\to\bar{\nu}_x\pi^+} = \frac{m_p(1-x_\pi)^2[1+(D+F)m_p m_n^{-1}]^2}{64\pi\, F_0^2} \times \big|c_1 C^{\mathrm{LR},x}_{\nu dud}+c_2 C^{\mathrm{LL},x}_{\nu dud}\big|^2. \quad (15b)$$



Complementarity between the pseudoscalar and vector modes

Summary

- General triple-quark interactions without a ∂ related to nucleon decay are identified: $\bar{\mathbf{3}}_{\mathrm{L(R)}} \otimes \mathbf{3}_{\mathrm{R(L)}}$, $\mathbf{8}_{\mathrm{L(R)}} \otimes \mathbf{1}_{\mathrm{R(L)}}$, $\mathbf{6}_{\mathrm{L(R)}} \otimes \mathbf{3}_{\mathrm{R(L)}}$ and $\mathbf{10}_{\mathrm{L(R)}} \otimes \mathbf{1}_{\mathrm{R(L)}}$ (new);
- Their LO chiral matching are realized, and 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;
- Many things are waiting to do: determination of LECs, examination of conventional and exotic nucleon decay modes more thoroughly, etc.

Thanks for your attention！