

# Baryon Number Violating Nucleon Decay in Effective Field Theories

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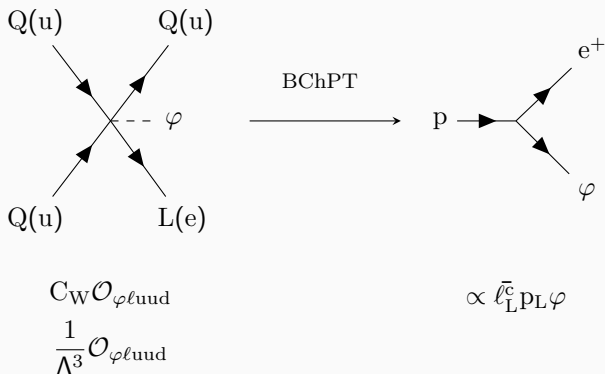
Based on arXiv:2511.02169 in collaboration with XD Ma and M.A. Schmidt and ongoing work in collaboration with V. Belocchi, K. Fuyuto, C. Hati and M.A.Schmidt

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- Proton and non standard neutron decays have been experimentally searched for since the 1980s.
- Many next generation experiments including Hyper-Kamiokande, DUNE and JUNO are or will be actively looking for these decays.
- Nuclear effects play an important role in experimental nucleon decay searches.
- Our work uses effective field theory frameworks to reinterpret existing experimental data with a thorough consideration of nuclear effects.

- In the Standard Model, baryon number is conserved and the proton is a stable particle.
- Experimentally, the proton lifetime is at least  $9 \times 10^{29}$  years.
- However, many beyond Standard Model theories, such as supersymmetry (SUSY) and Grand Unified Theories (GUTs), predict the existence of nucleon decays.
- Nucleon decays may have interesting connections to dark matter.

We work in Standard Model Effective Field Theory with a minimal extension, a singlet scalar  $\varphi$  or a sterile neutrino  $N$ , and derive constraints on the BNV effective operators.



# Nuclear Effects - Fermi Momentum and Binding Energy

All bound nucleon decays experience effects from Fermi momentum, which produces some initial momentum, and binding energy, which decrease the effective mass. We used a spectral function approach to characterise these effects.

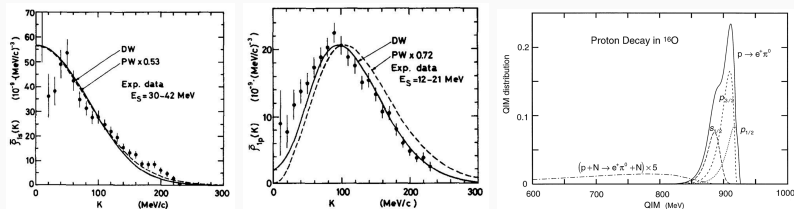


Figure 1: Fermi momentum and binding energy of  $^{16}\text{O}$ . Plots from [Nakamura et al. 1976] and [Yamazaki et al. 1999]

# Nuclear Effects - Pion Final State Interactions

Pions in the final state may interact with other nucleons when they propagate through the nuclear medium, which alters the signal distribution. We perform a full simulation of pion FSI using the GiBUU project. [Buss et al. 1106.1344]

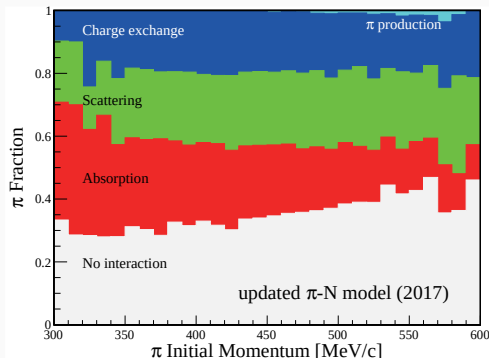


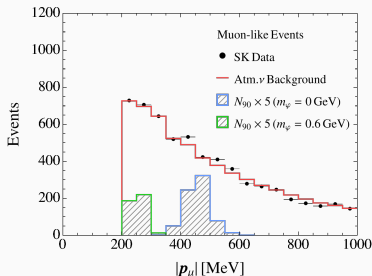
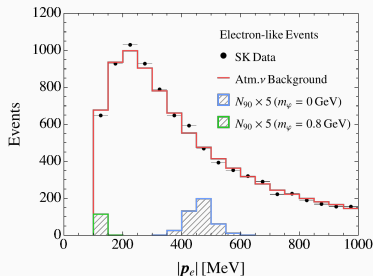
Figure 2: Pion final state interaction fractions from [Super-Kamiokande. 2510.26232]

# Scalar Extension - Nucleon Decay Modes

| Operator            | $\mathcal{O}_{\varphi\ell u u d}$   | $\mathcal{O}_{\varphi\ell u s u}$ | $\mathcal{O}_{\varphi\bar{\ell} d d s}$ | $\mathcal{O}_{\varphi\nu d u d}$                 | $\mathcal{O}_{\varphi\nu d s}$                 |
|---------------------|-------------------------------------|-----------------------------------|-----------------------------------------|--------------------------------------------------|------------------------------------------------|
| Nucleon decay modes | $p \rightarrow e^+ \varphi$         | $p \rightarrow e^+ K^0 \varphi$   | $n \rightarrow e^- K^+ \varphi$         | $n \rightarrow \bar{\nu}_x(\nu_x) \varphi$       | $p \rightarrow \bar{\nu}_x(\nu_x) K^+ \varphi$ |
|                     | $p \rightarrow \mu^+ \varphi$       | $p \rightarrow \mu^+ K^0 \varphi$ | $n \rightarrow \mu^- K^+ \varphi$       | $p \rightarrow \bar{\nu}_x(\nu_x) \pi^+ \varphi$ | $n \rightarrow \bar{\nu}_x(\nu_x) K^0 \varphi$ |
|                     | $p \rightarrow e^+ \pi^0 \varphi$   |                                   |                                         | $n \rightarrow \bar{\nu}_x(\nu_x) \pi^0 \varphi$ |                                                |
|                     | $p \rightarrow \mu^+ \pi^0 \varphi$ |                                   |                                         | $n \rightarrow \bar{\nu}_x(\nu_x) \eta \varphi$  |                                                |
|                     | $p \rightarrow e^+ \eta \varphi$    |                                   |                                         |                                                  |                                                |
|                     | $p \rightarrow \mu^+ \eta \varphi$  |                                   |                                         |                                                  |                                                |
|                     | $n \rightarrow e^+ \pi^- \varphi$   |                                   |                                         |                                                  |                                                |
|                     | $n \rightarrow \mu^+ \pi^- \varphi$ |                                   |                                         |                                                  |                                                |

# $p \rightarrow \ell^+ \varphi$ Lifetime Constraints

- The Super-Kamiokande experiment has searched for the channel  $p \rightarrow \ell^+ \varphi$  with a massless  $\varphi$ . [Super-Kamiokande. 1508.05530]
- We derive lifetime constraints for a general massive  $\varphi$  by recasting their data.



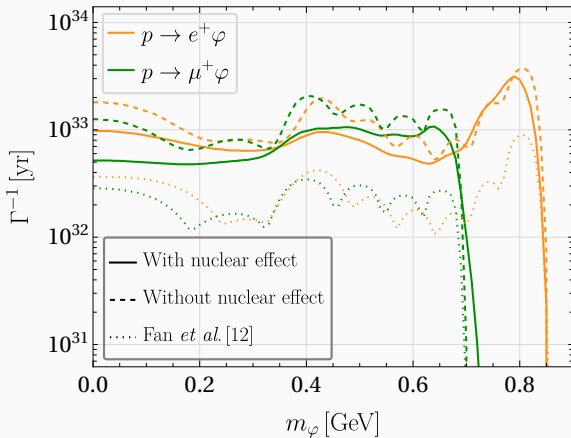
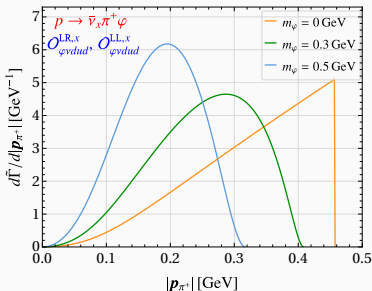
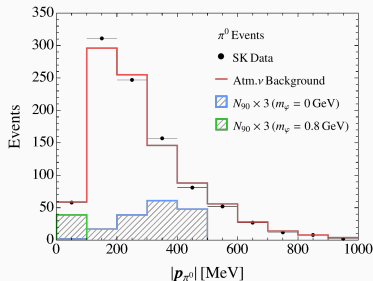


Figure 3: Recast  $p \rightarrow \ell^+ \varphi$  Super-K constraints for a massive  $\varphi$ . Solid curves indicate results including nuclear effects, dashed curves indicate results without including nuclear effects, and dotted curves represent results from previous work. Lifetime constraints in the massless limit is  $99(52) \times 10^{31}$  yrs, within 25(27)% of Super-K's limit of  $79(41) \times 10^{31}$  yrs.

# $n \rightarrow \bar{\nu}(\nu)\pi^0\varphi$ Lifetime Constraints

- Super-K provides a constraint for the decay  $n \rightarrow \bar{\nu}\pi^0$ , from which we set a constraint on the three-body decay  $n \rightarrow \bar{\nu}(\nu)\pi^0\varphi$ . [Super-Kamiokande. 1305.4391]
- Nuclear effects are not considered in this case since three-body decays are less affected by a broadening of the momentum distribution.



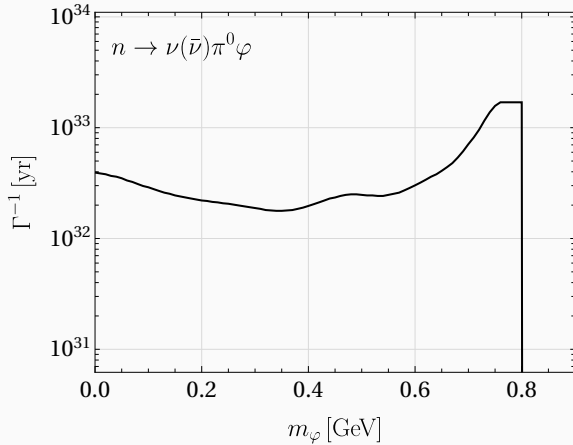


Figure 4: Recast lifetime constraints for  $n \rightarrow \bar{\nu}(\nu)\pi^0\varphi$ .

# Constraints on Effective Operators

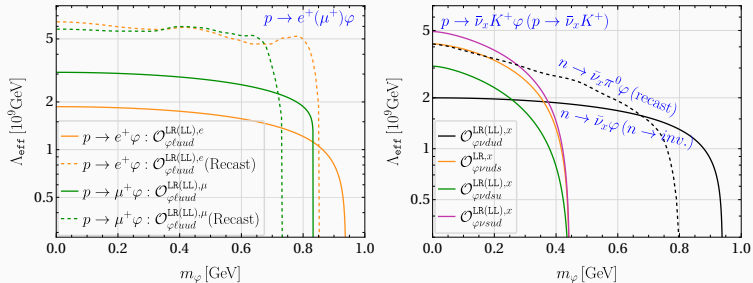
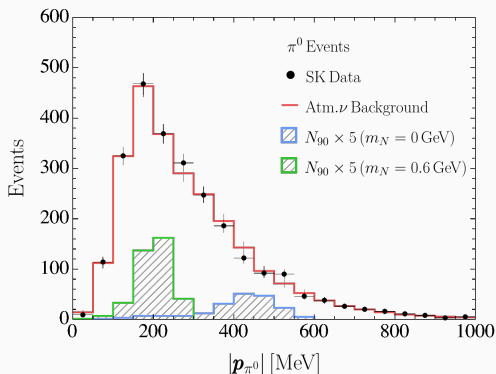


Figure 5: Translated constraints on the effective scale of operators.

## $n \rightarrow N\pi^0$ Lifetime Constraints

- The sterile neutrino  $N$  behaves like a massive neutrino, therefore we can derive constraints using any experimental searches with a neutrino final state.
- We use Super-K's new results for the decay  $n \rightarrow \bar{\nu}\pi^0$ .  
[Super-Kamiokande. 2510.26232]



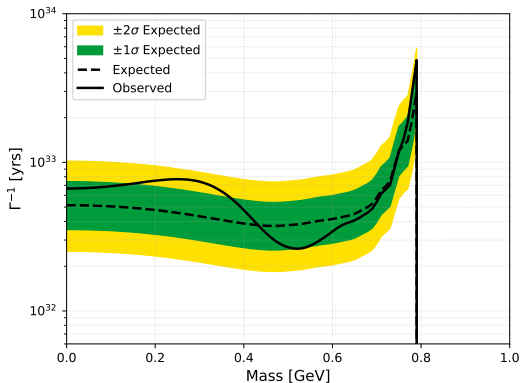
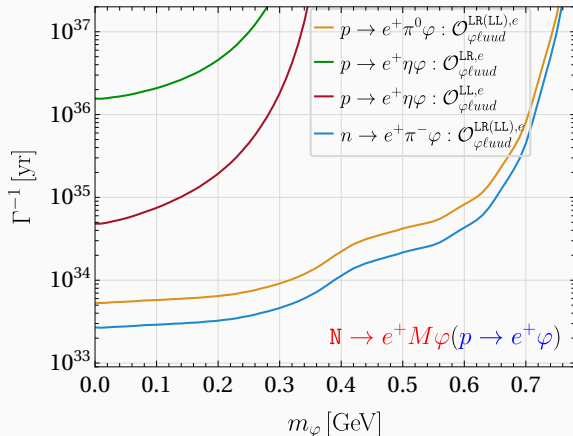


Figure 6: Recast  $n \rightarrow \bar{\nu}\pi^0$  Super-K constraints. Dashed line indicates expected lifetime constraint. Green and yellow regions indicate  $1\sigma$  and  $2\sigma$  deviation from the expected limit respectively. Solid line indicates observed lifetime constraint. Lifetime constraint in the massless limit is  $6.7 \times 10^{32}$  yrs, roughly a factor of 2 from Super-K's limit of  $14 \times 10^{32}$  yrs.

- We systematically investigate BNV nuclear decays in two extensions of SMEFT.
- Nuclear effects significantly alters the nucleon decay signal and should be considered carefully.
- Through recasting of Super-K's  $p \rightarrow \ell^+ \varphi$  and  $n \rightarrow \bar{\nu} \pi^0$  searches, we derive constraints on the nucleon lifetime and BNV effective operators.

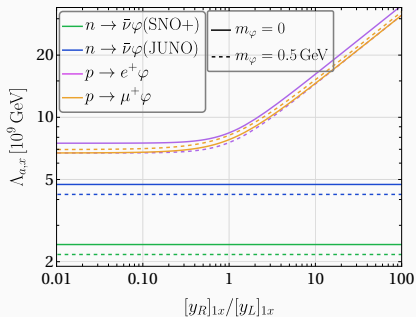
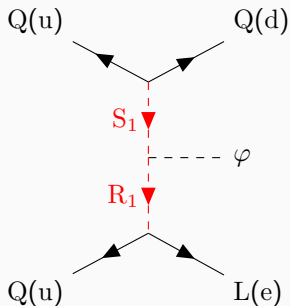
Backup Slides

# Projected Lifetime Constraints for Other Decay Modes

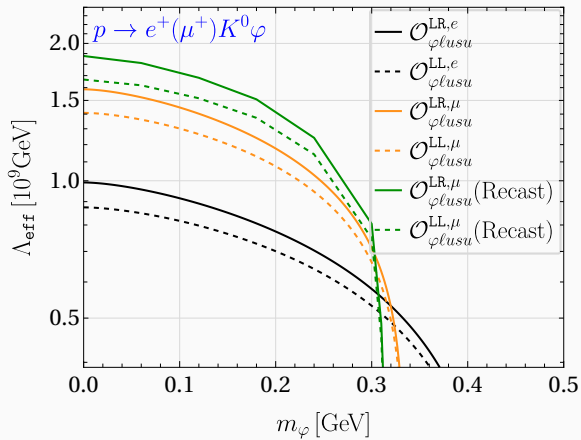


Projected lifetime constraints on other decay modes using  $p \rightarrow \ell^+ \varphi$  results.

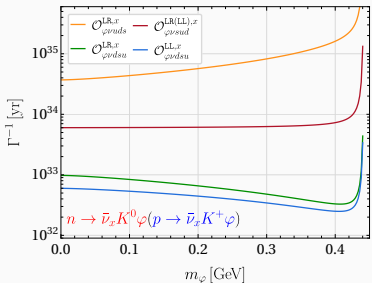
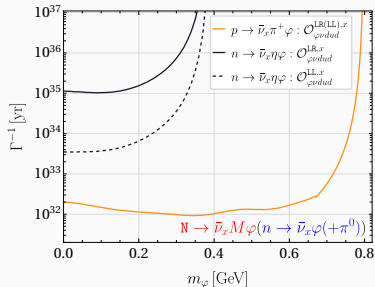
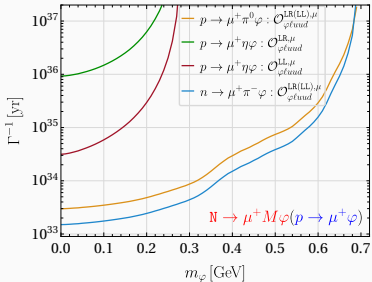
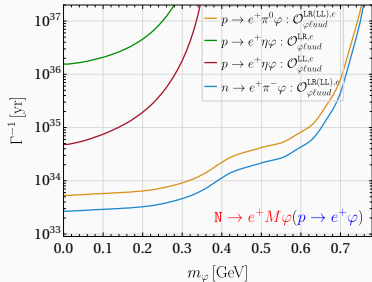
# An Example UV Model



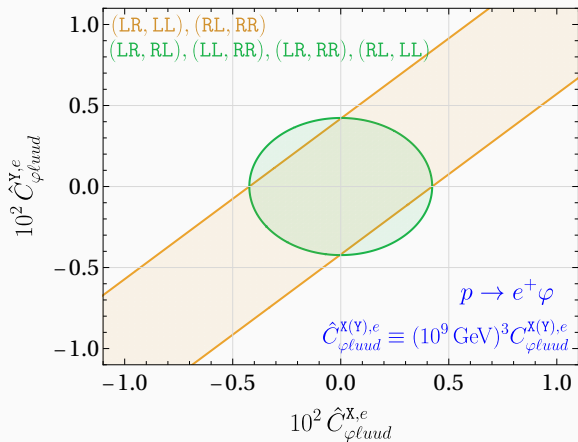
# $p \rightarrow e^+(\mu^+)K^0\varphi$ Lifetime Constraints



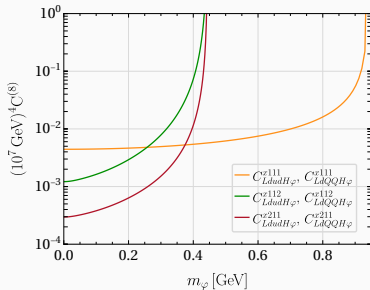
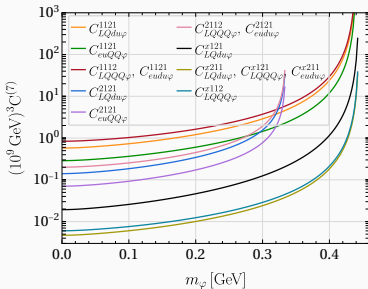
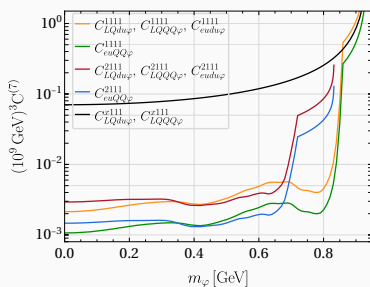
# Full Set of Projected Lifetime Constraints for Other Decay Modes



## 2D Constraints on Effective Operators



# Constraints on $\varphi$ SMEFT Operators



# Dinucleon Decay Constraints

