LIGHT NEW PHYSICS IN PROTON DECAYS

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Based on work done in collaboration with Chandan Hati (IFIC Valencia) and Volodymyr Takhistov (QUP, KEK)

arXiv:2312.13740 [hep-ph] (to be published in PRD as letter)

Conservation of baryon number B is an accidental symmetry of the SM

Based only on the symmetry group $SU(3)_c \times SU(2)_L \times U(1)_Y$ there is no reason that baryons are stable

However, the SM does not contain any fields that can mediate B-violating interactions:

$$O^{(1)}_{abcd} = \left(\overline{d^C_{\alpha aR}}\, u_{\beta bR}\right)\left(\overline{q^C_{i\gamma cL}}\, \ell_{jdL}\right)\epsilon_{\alpha\beta\gamma}\,\epsilon_{ij}$$

$$O^{(2)}_{abcd} = \left(\overline{q^C_{i\alpha aL}}\, q_{j\beta bL}\right)\left(\overline{u^C_{\gamma cR}}\, \ell_{dR}\right)\epsilon_{\alpha\beta\gamma}\,\epsilon_{ij}$$

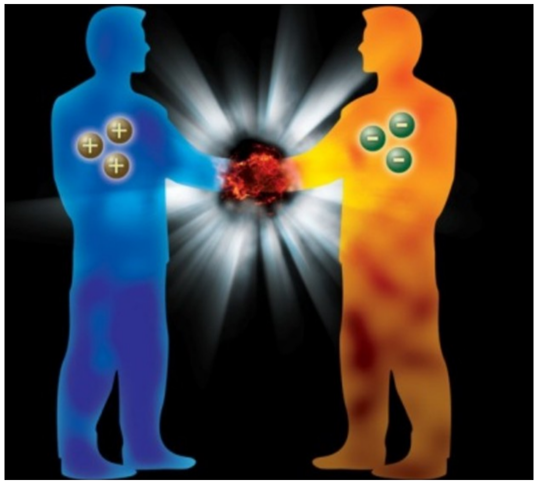
$$O^{(3)}_{abcd} = \left(\overline{q^C_{i\alpha aL}}\, q_{j\beta bL}\right)\left(\overline{q^C_{k\gamma cL}}\, \ell_{\ell dL}\right)\epsilon_{\alpha\beta\gamma}\,\epsilon_{ij}\,\epsilon_{k\ell}$$

$$O^{(4)}_{abcd} = \left(\overline{q^C_{i\alpha aL}}\, q_{j\beta bL}\right)\left(\overline{q^C_{k\gamma cL}}\, \ell_{\ell dL}\right)\epsilon_{\alpha\beta\gamma}\,(\vec{\tau}\epsilon)_{ij}\cdot(\vec{\tau}\epsilon)_{k\ell}$$

$$O^{(5)}_{abcd} = \left(\overline{d^C_{\alpha aR}}\, u_{\beta bR}\right)\left(\overline{u^C_{\gamma cR}}\, \ell_{dR}\right)\epsilon_{\alpha\beta\gamma}$$

$$O^{(6)}_{abcd} = \left(\overline{u^C_{\alpha aR}}\, u_{\beta bR}\right)\left(\overline{d^C_{\gamma cR}}\, \ell_{dR}\right)\epsilon_{\alpha\beta\gamma}$$

Weinberg, Phys.Rev.Lett. 43 (1979) 1566-1570



Baryogenesis?

GUT?

Supersymmetry?

Lepton number violation?

Dark matter?

A smoking gun signal of B-violation is proton decay

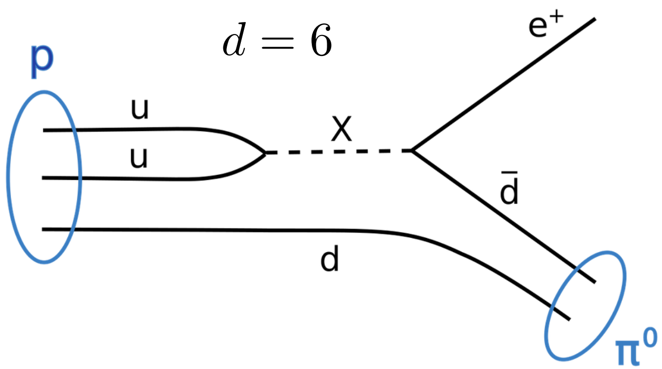
$$p \to e^+\pi^0$$
$$p \to e^+\gamma$$
$$p \to \mu^+\pi^0$$
$$p \to \bar{\nu}K^+$$

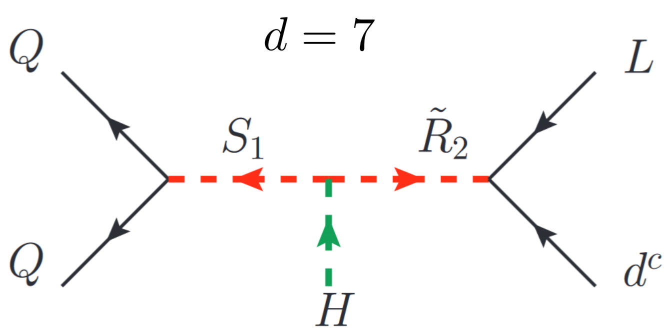
Can be realized in a wide range of different models

- Operator dimensions d=6, d=7, d=8, …
- Flavoured final states: muon, kaon, …
- Vector meson final states
- Also dinucleon decays, possible overlap with neutron-antineutron oscillation (see next talk)

$$\begin{aligned}(\Delta B,\, \Delta L) = (0,2):&\ \min(d) = 5\\ (1,-1):&\ \min(d) = 6\\ (1,1):&\ \min(d) = 7\\ (2,0):&\ \min(d) = 9\end{aligned}$$

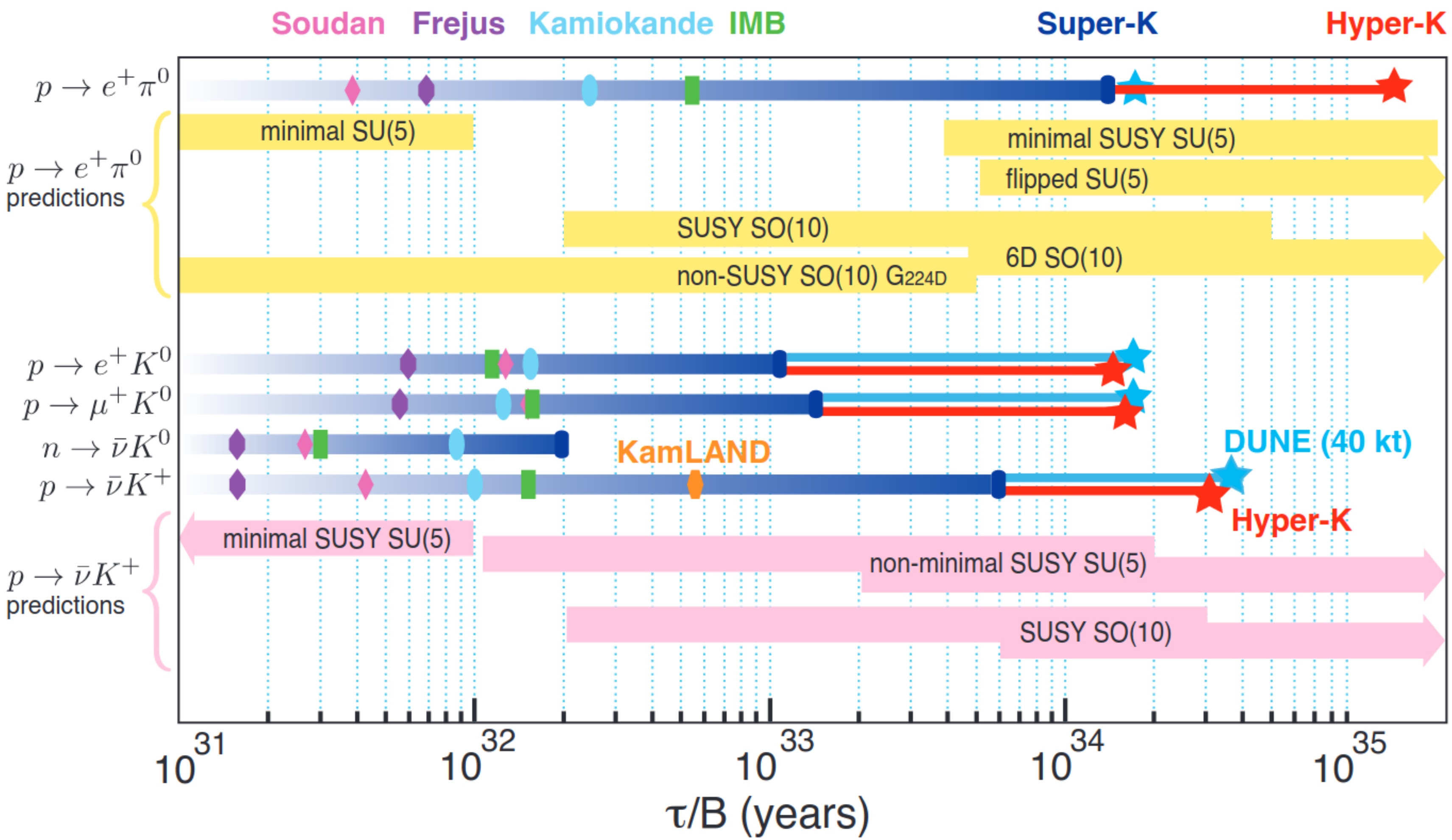
$$\mathcal{L}_{\text{eff}} \supset \sum_i \sum_d C_i^{(d)} \mathcal{O}_i^{(d)} \Rightarrow C_i^{(d)} \propto \frac{1}{\Lambda^{d-4}} \Rightarrow \tau_{p\to\ldots} \propto \frac{1}{\Lambda^{2d-8}}$$





Hati, Sarkar, Nucl.Phys.B 954 (2020) 114985

Upcoming experiments will significantly improve the sensitivity:
JUNO (scintillator), Hyper-Kamiokande (Cherenkov), DUNE (LAr TPC)



Hyper-Kamiokande collaboration, arXiv:1805.04163 [physics.ins-det]

For the neutrino modes, only the (decay products of) the charged mesons are detected

Even though these are *primarily* neutrino experiments, they cannot detect the final state neutrinos from proton decays

At the same time we are aware of the need for NP in the neutrino sector

$$\text{Dirac:}\ \nu_L \neq \nu_R^c$$

$$\text{Majorana:}\ \nu_L = \nu_R^c$$

What is the nature of neutrinos?

$$\mathcal{L}_{\text{Dirac}} \supset -y^{\nu}_{ij}\tilde{H}L_i N_j \longrightarrow y_\nu \sim 10^{-12}$$

$$\mathcal{L}_{\text{Majorana}} \supset -y^{\nu}_{ij}\tilde{H}\bar{L}_i N_j - M_{ij}\bar{N^c}_i N_j + \text{h.c.}$$

In either scenario we can have low scale RHNs such that $m_N < m_p$

This could then lead to proton decay with light HNLs in the final state $p \to \pi^+ N$

How can we distinguish HNLs from SM neutrinos?

Helo, Heeck, Ota, JHEP 06 (2018) 047

d=6 SMEFT

$$\mathcal{O}_1 = [\overline{d_R}^c u_R][\overline{Q^c} L],$$
$$\mathcal{O}_2 = [\overline{Q^c} Q][\overline{u_R}^c e_R],$$
$$\mathcal{O}_3 = [\overline{Q^c} Q]_1 [\overline{Q^c} L]_1,$$
$$\mathcal{O}_4 = [\overline{Q^c} Q]_3 [\overline{Q^c} L]_3,$$
$$\mathcal{O}_5 = [\overline{d_R}^c u_R][\overline{u_R}^c e_R],$$

d=6 N_R-SMEFT

$$\mathcal{O}_{N1} = [\overline{Q^c} Q][\overline{d_R}^c N],$$
$$\mathcal{O}_{N2} = [\overline{u_R}^c d_R][\overline{d_R}^c N].$$

Modes (p)	$\pi^+ + \not{E}$	$\pi^0 e^+$	$K^+ + \not{E}$
Current [yrs]	$3.9 \cdot 10^{32}$ [8]	$1.6 \cdot 10^{34}$ [9]	$5.9 \cdot 10^{33}$ [10]
Future [yrs]		$1.2 \cdot 10^{35}$ [48]	$> 3 \cdot 10^{34}$ [49]
$\mathcal{O}_1$	✓	✓	✓
$\mathcal{O}_2$	—	✓	—
$\mathcal{O}_3$	✓	✓	✓
$\mathcal{O}_4$	—	—	✓
$\mathcal{O}_5$	—	✓	—
$\mathcal{O}_{N1}$	✓	—	✓
$\mathcal{O}_{N2}$	✓	—	✓

Isosymmetry: $\mathcal{O}_1, \mathcal{O}_3$: $\Gamma(p \xrightarrow{\mathcal{O}_{1,3}} \pi^+ \bar{\nu}_e) = 2\Gamma(p \xrightarrow{\mathcal{O}_{1,3}} \pi^0 e^+)$

Violation of this relation can hint at the existence of HNL modes

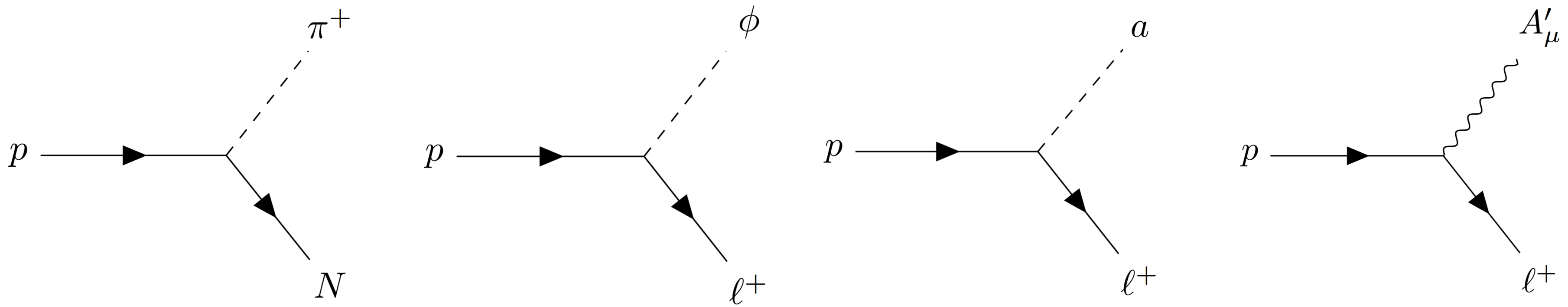
The light LLPs can also be or bosonic fields

ALPs/Majoron: $\mathcal{L} \supset \frac{\partial_\mu a}{f_a} \bar{f} \gamma^\mu \gamma_5 f$ Freeze-in scalar DM: $\mathcal{L} \supset \frac{1}{\Lambda} \phi^2 \bar{f} f$

New light gauge bosons $D_\mu \supset i g_{B-L} q_{B-L} B'_\mu$ $D_\mu \supset i g_{L_\mu - L_\tau} q_{L_\mu - L_\tau} B''_\mu$

Leads to new proton decay modes $p \to \ell^+ Z'_\mu$ $p \to \ell^+ a$ $p \to \ell^+ \phi$

In principle the only condition needed to write down a proton decay operator is $m_{\rm NP} < m_p$



Many models with light LLPs feature NP at high scales reachable in proton decay

No reason for the NP to ensure proton stability unless the symmetry is explicit

How to search for such modes with finals state LLPs?

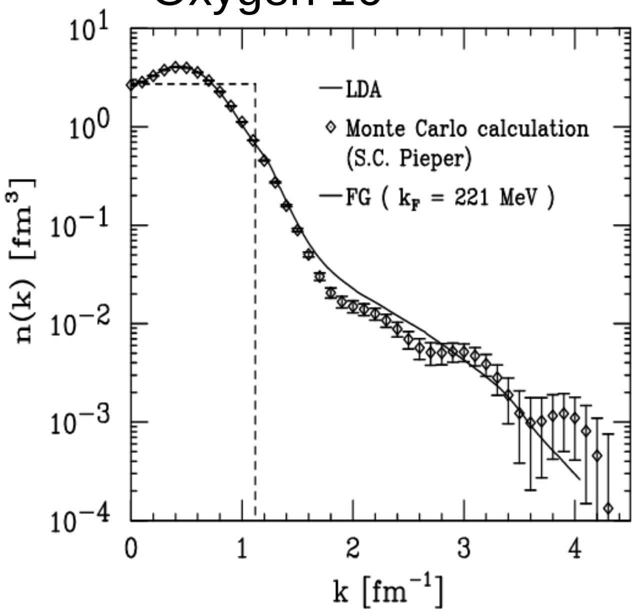
The LLP mass is a “free” parameter: few well-motivated benchmarks apart from the phenomenologically driven seesaw RHN, QCD axion, or freeze-in/out DM

Decay width generally depends on all masses involved

$$\Gamma_{\psi\to ij} = \frac{1}{16\pi}\frac{\lambda^{1/2}(m_\psi, m_i, m_j)}{m_\psi^3}|\sum_I C_I \mathcal{M}_I^{\psi\to ij}|^2 \qquad |\vec{p}_i| = \frac{\lambda^{1/2}(m_\psi^2, m_i^2, m_j^2)}{2m_\psi}$$

For 2-body decays the final state momenta are completely determined by the masses

Oxygen 16

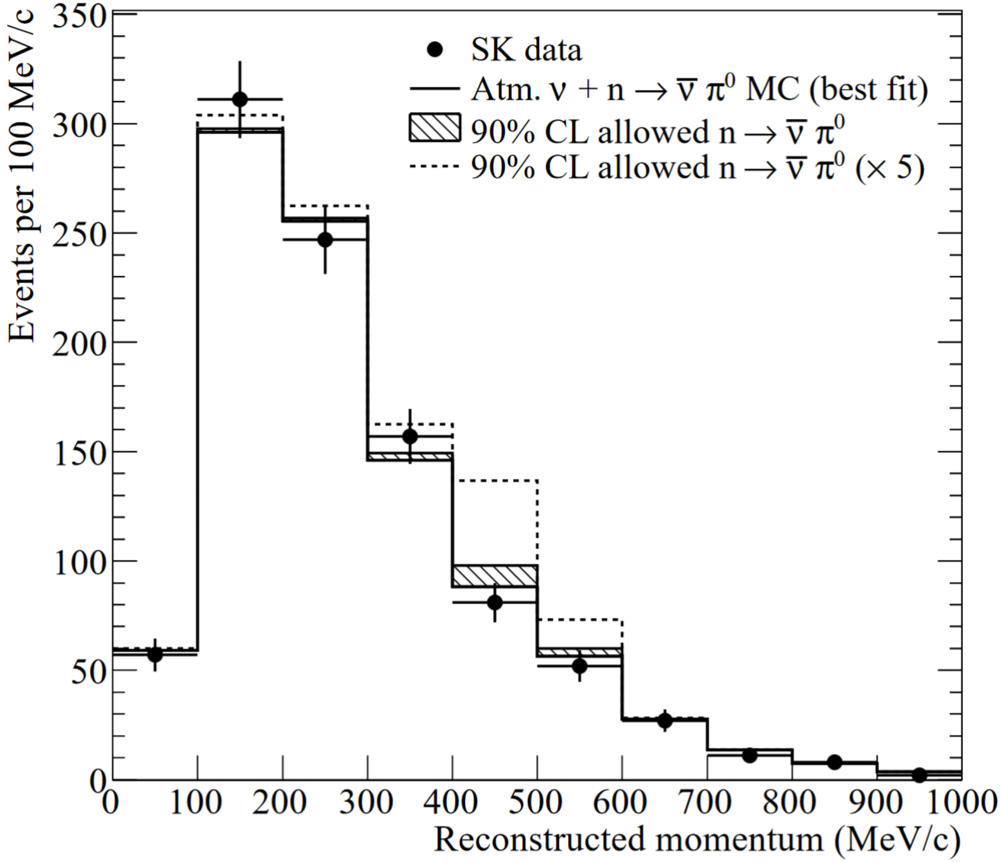


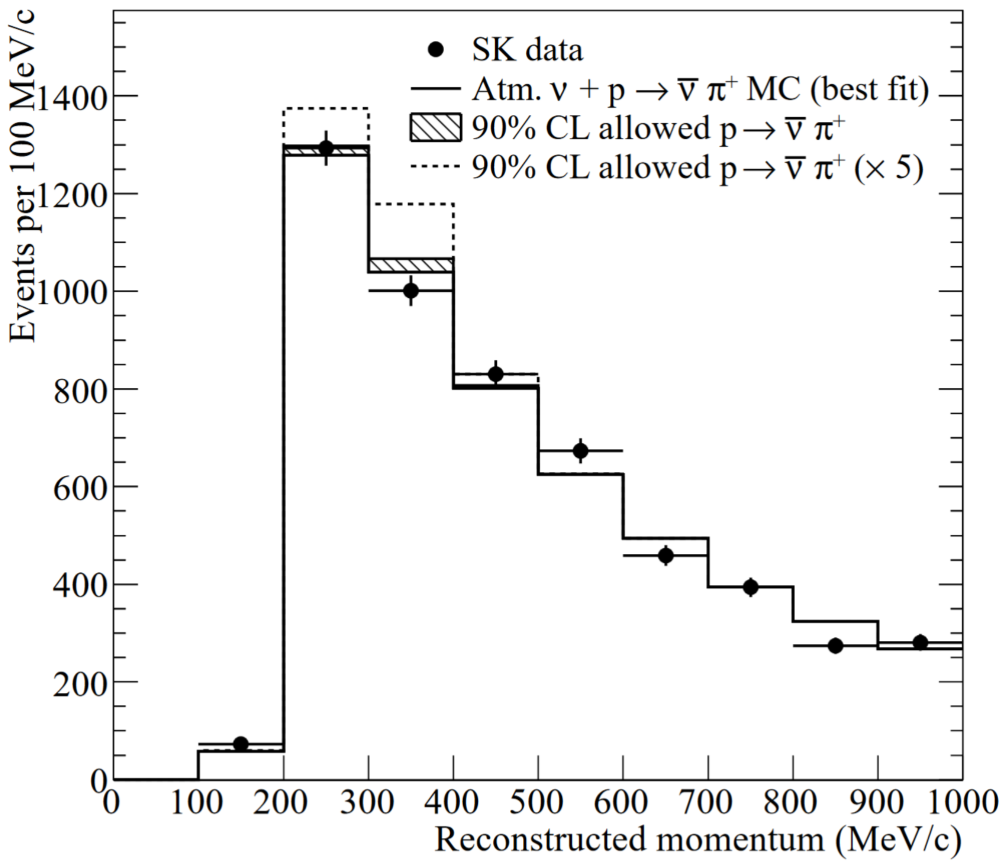
Benhar, nucl-th/0307061 [nucl-th]

In the ideal scenario this leads to a sharp peak at the given momentum

Fermi motion will “spread” this peak

Super-K and Hyper-K are both made up of water, where oxygen has most of the protons



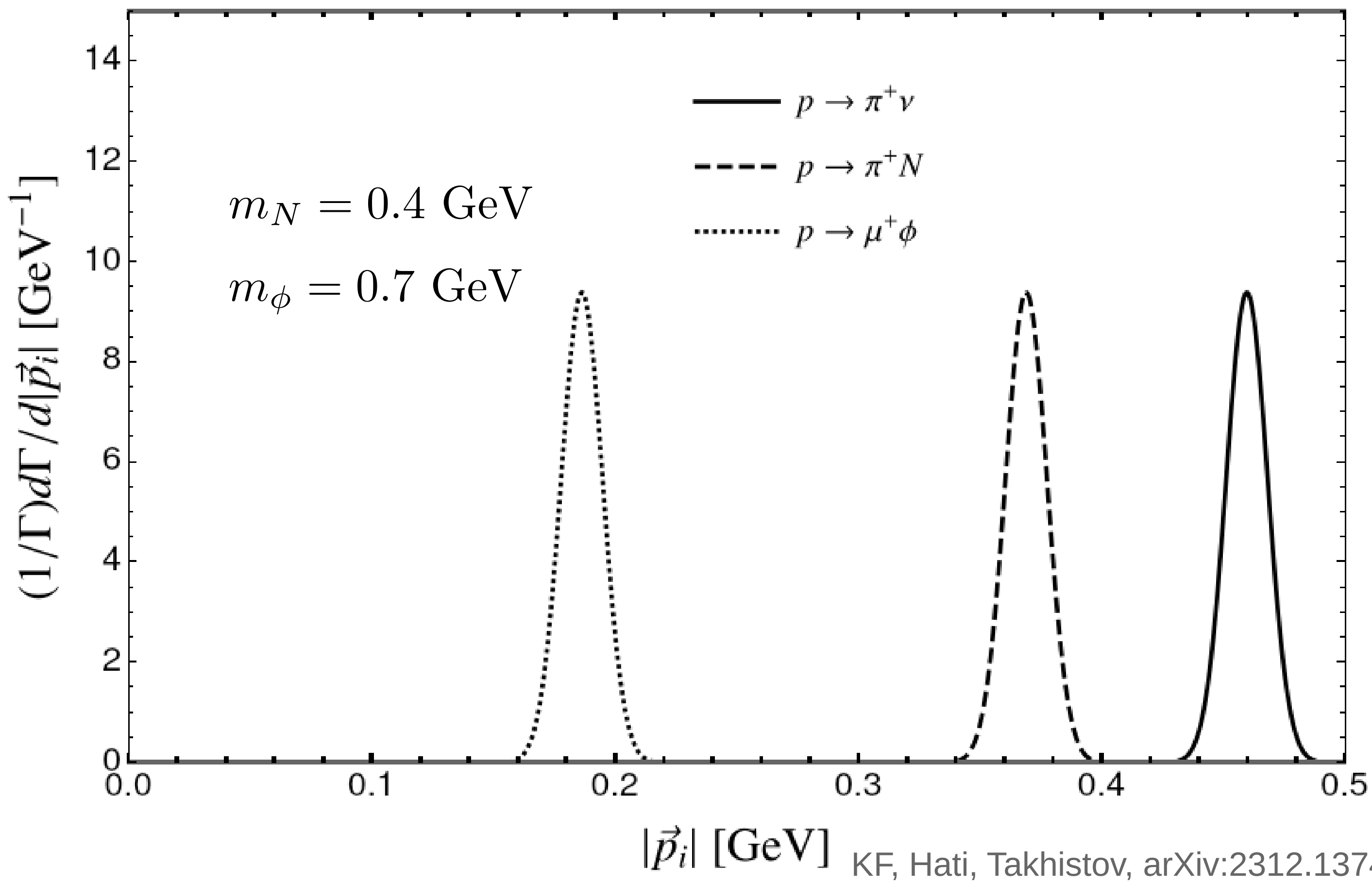


Super-Kamiokande collaboration, Phys.Rev.Lett. 113 (2014) 12, 121802

For 2-body decays $n \to \bar{\nu}\pi^0$ (left) and $p \to \bar{\nu}\pi^+$ (right)

Fermi motion and BG are simulated with MC

Since the left-handed neutrino mass is “known” the peaks are expected at specific pion momenta



KF, Hati, Takhistov, arXiv:2312.13740 [hep-ph]

For a non-zero LLP mass the peak moves to lower momenta

Super-Kamiokande has a cut at 200 MeV for $p \to \mu^+ + E_{\rm miss}$

The same cut applies for charged pions (since they decay to muons)

For 3-body decays the distribution is more spread out

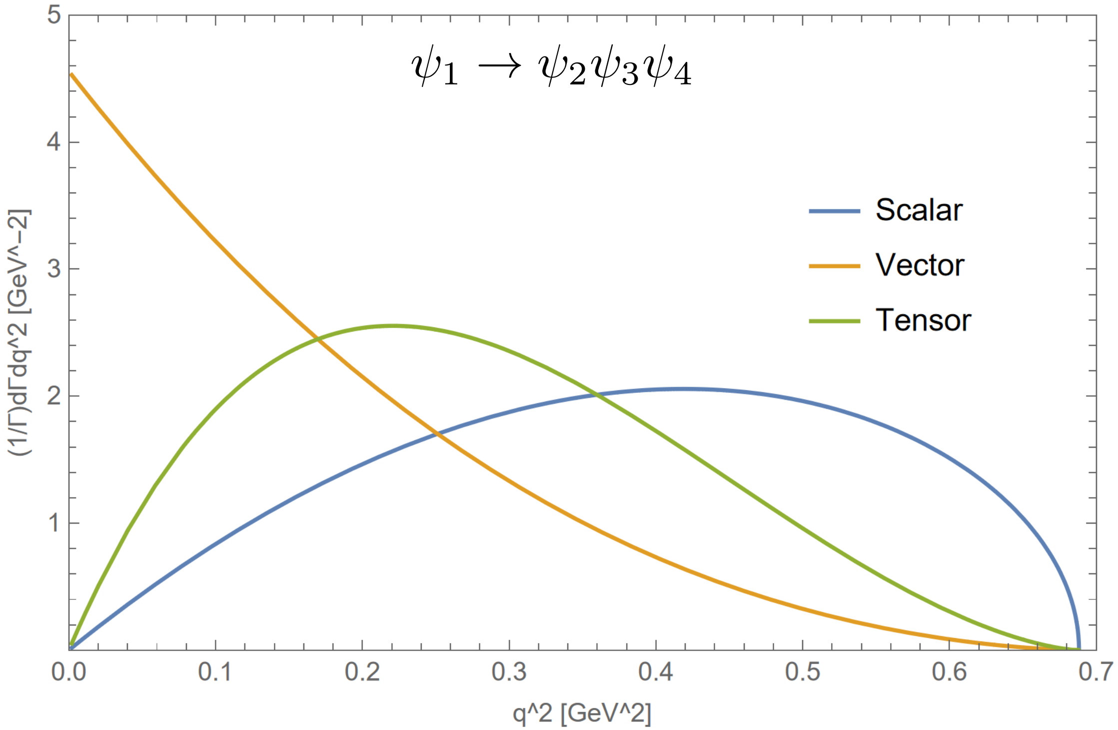
$$\frac{d\Gamma_{\psi\to ijk}}{d|\vec{p}_i|} = \frac{1}{(2\pi)^3}\frac{1}{32m_\psi^3}\frac{2m_\psi|\vec{p}_i|}{\sqrt{m_i^2+|\vec{p}_i|^2}}\int_{t^-}^{t^+} dt|\mathcal{M}_{\psi\to ijk}|^2$$

The distribution also depends on the type of interaction:

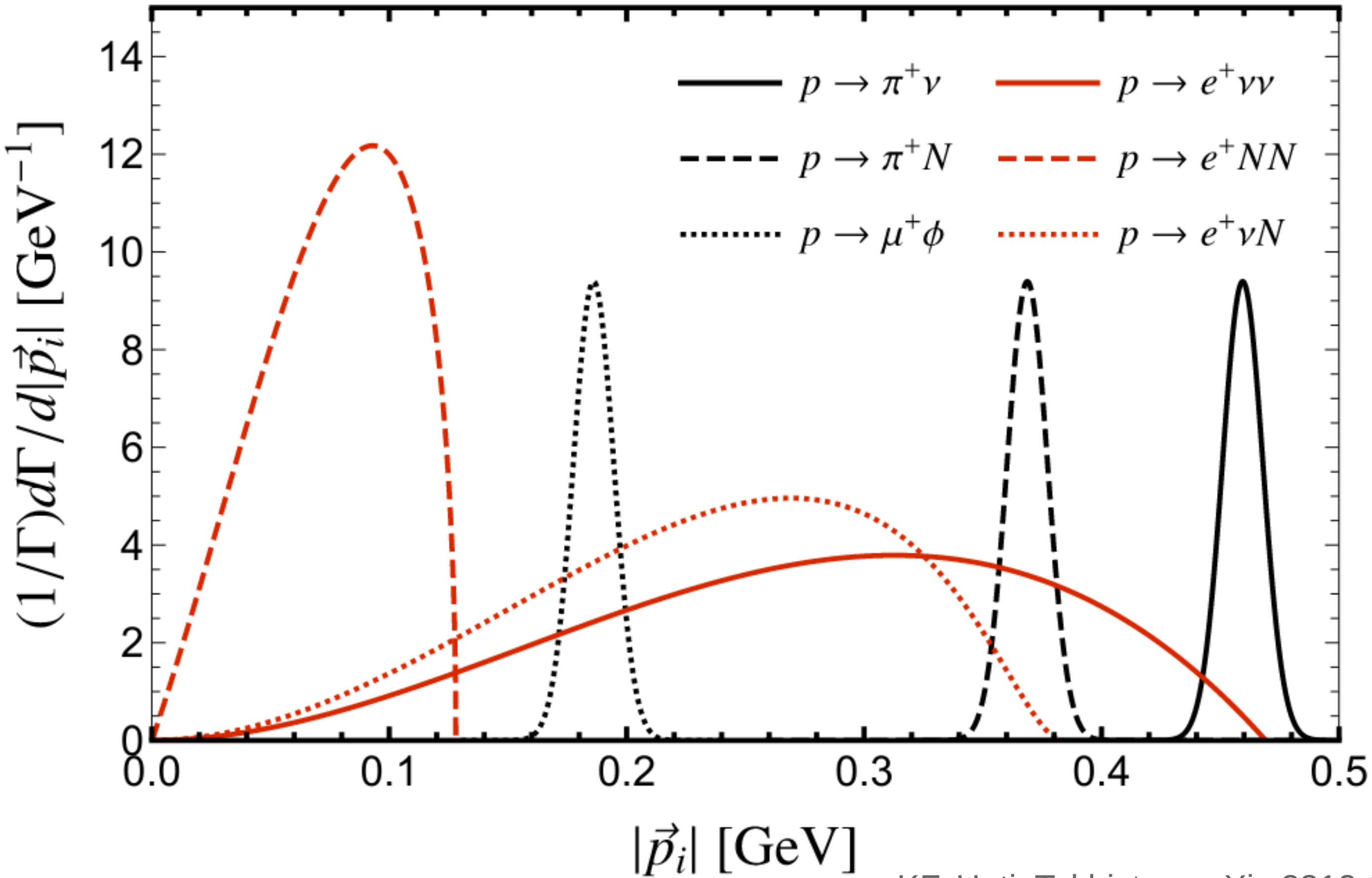
Scalar: $(\psi_1\psi_2)(\psi_3\psi_4)$

Vector: $(\psi_1\gamma_\mu\psi_2)(\psi_3\gamma^\mu\psi_4)$

Tensor: $(\psi_1\sigma_{\mu\nu}\psi_2)(\psi_3\sigma^{\mu\nu}\psi_4)$



For two LLPs in the final state we have double the mass d.o.f.s



$m_N = 0.4$ GeV

$m_\phi = 0.7$ GeV

KF, Hati, Takhistov, arXiv:2312.13740 [hep-ph]

Peak of the distribution again shifts to lower momenta for higher masses

For electrons there is a lower cut at 100 MeV

For the 3-body modes the currents are scalar (νν, NN) and vector (νN)

Explicitly these are some examples of operators with singlet NP:

$\mathcal{O}$	Operator	$(\Delta B, \Delta L)$	Dim	Decay modes	New Field(s)
$\mathcal{O}_{d^2uN}$	$\epsilon^{abc}\left(\bar{d}^c_a N\right)\left(\bar{d}^c_b u_c\right)$	$(1,1)$	6	$p(n)\to\pi^{+(0)}\bar{N}$	sterile neutrino
$\mathcal{O}_{Dd^2u\bar{N}}$	$\epsilon^{abc}\left(\bar{N}\gamma_\mu d_a\right)\left(\bar{d}^c_b D^\mu u_c\right)$	$(1,-1)$	7	$n\to N\gamma$ $p(n)\to\pi^{+(0)}N\gamma$	sterile neutrino
$\mathcal{O}_{du^2e\phi}$	$\epsilon^{abc}\left(\bar{d}^c_a u_b\right)\left(\bar{e}^c u_c\right)\phi^\dagger$	$(1,1)$	7	$p\to e^+\phi$ $p(n)\to e^+\pi^{0(-)}\phi$	dark scalar, majoron
$\mathcal{O}_{d^2Q\bar{L}X}$	$\epsilon^{abc}\left(\bar{Q}^{c\,i}_a\gamma_\mu d_b\right)\left(\bar{L}_i d_c\right)X^\mu$	$(1,-1)$	7	$n\to\nu X$ / $e^-\pi^+X$ $p(n)\to\nu\pi^{+(0)}X$	dark photon
$\mathcal{O}_{dQ^2\bar{L}\bar{H}\phi}$	$\epsilon^{abc}\left(\bar{Q}^{c\,i}_a Q^j_b\right)\left(\bar{L}_i d_c\right)H^\dagger_j\phi^\dagger$	$(1,-1)$	8	$n\to\nu\phi$ / $e^-\pi^+\phi$	dark scalar, majoron
$\mathcal{O}_{Dd^2Q\bar{L}a}$	$\epsilon^{abc}(\partial_\mu a)\left(\bar{Q}^{c\,i}_a\gamma^\mu d_b\right)\left(\bar{L}_i d_c\right)$	$(1,-1)$	8	$n\to\nu a$ / $e^-\pi^+a$	axion-like particles
$\mathcal{O}_{Dd^2u\bar{N}a}$	$\epsilon^{abc}(\partial_\mu a)\left(\bar{N}\gamma^\mu d_a\right)\left(\bar{d}^c_b u_c\right)$	$(1,-1)$	8	$n\to Na$ $p(n)\to\pi^{+(0)}Na$	axion-like particle with sterile neutrino
$\mathcal{O}_{duQe\bar{L}\bar{N}}$	$\epsilon^{abc}\left(\bar{e}^c u_a\right)\left(\bar{Q}^{ci}_b\gamma_\mu d_c\right)\left(\bar{L}_i\gamma^\mu N^c\right)$	$(1,-1)$	9	$p\to e^+\nu N$ $n\to e^+e^-N$	sterile neutrino
$\mathcal{O}_{du^2eN^2}$	$\epsilon^{abc}\left(\bar{d}^c_a u_b\right)\left(\bar{e}^c u_c\right)\left(\bar{N}^c N\right)$	$(1,3)$	9	$p\to e^+\bar{N}\bar{N}$	sterile neutrino

KF, Hati, Takhistov, arXiv:2312.13740 [hep-ph]

Explicit model example: $SO(10)$

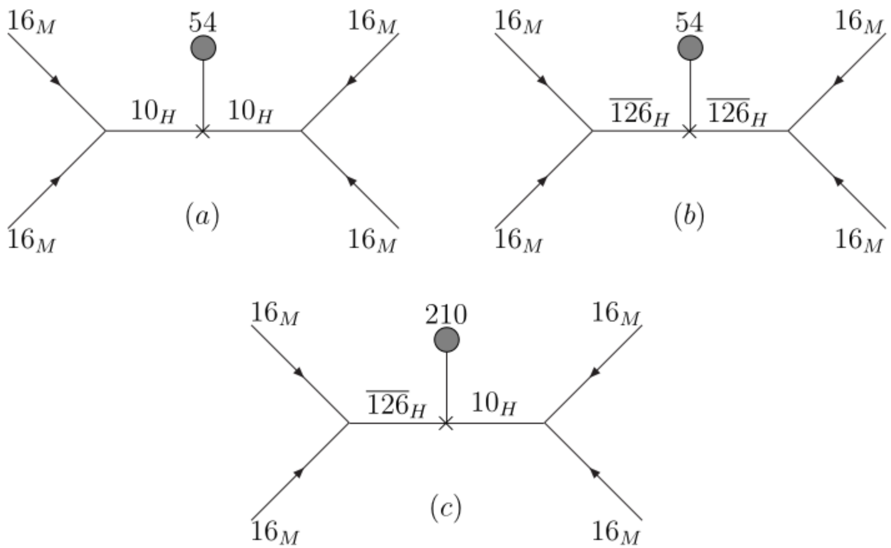
A single multiplet leads to all SM fermion fields plus a HNL:

$$16 \longrightarrow (3,2,1/6) \oplus (1,2,-1/2) \oplus (\bar{3},1,1/3) \oplus (\bar{3},1,-2/3) \oplus (1,1,1) \oplus (1,1,0)$$

A minimal model contains an intermediate $SU(3)_c \times SU(2)_L \times SU(2)_R \times U(1)_{B-L}$

Leads to proton decay at dimension 5 with supersymmetry

Supergraphs:

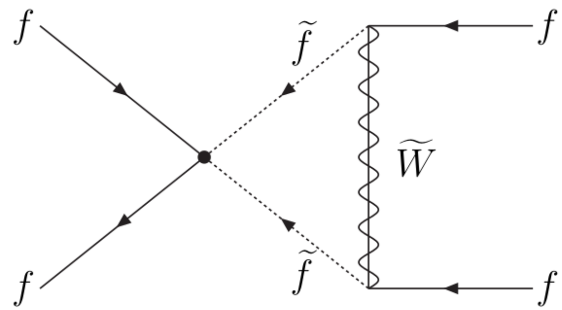


$210 \oplus 54$ breaks $SO(10)$

126 breaks $SU(2)_R \times U(1)_{B-L}$

10 breaks $SU(2)_L \times U(1)_Y$

Dressed diagram at dimension 5:



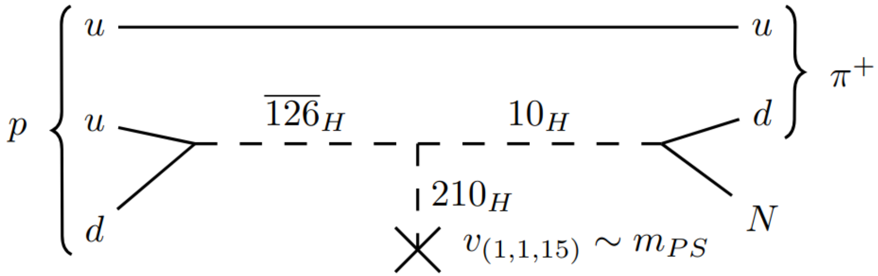
Depends also on SUSY breaking scale

Goh, Mohapatra, Nasri, Ng, Phys.Lett.B 587 (2004) 105-116

We consider a non-SUSY model with intermediate Pati-Salam symmetry and D-parity breaking

$$m_{\text{GUT}} \gg m_D > m_{\text{PS}} \gg m_R > m_{B-L} \gg m_{\text{SM}}$$

Leads to a dimension-6 operator $\mathcal{O}_{d^2uN} = \epsilon^{abc}\,(d_a N)\,(d_b u_c)$



The decay rate will depend on strong running and a nuclear form factor

$$\mathcal{M}_{p\to\pi^+N} = U'(\mu_{\text{NP}},\mu_0)F_p^{\pi^+}(\mu_0, m_N^2)u_p P_R \bar{u}_N$$

Scalar masses are generated at PS breaking, when the 210 gets a vev

$$\tau_{p\to N\pi^+} = 0.81\times 10^{35}\frac{\left(\frac{m_N^2}{\text{GeV}^2}+0.86\right)^{-1}}{\lambda^{1/2}\left(\frac{m_p^2}{\text{GeV}^2},\frac{m_N^2}{\text{GeV}^2},\frac{m_{\pi^+}^2}{\text{GeV}^2}\right)}\times\frac{\left(\frac{m_{\overline{126}_H}}{2\times10^8\ \text{GeV}}\right)^4\left(\frac{m_{10_H}}{2\times10^8\ \text{GeV}}\right)^4}{\lambda_{dN}^2\lambda_{ud}^2\left(\frac{v_{(1,1,15)}}{2\times10^8\ \text{GeV}}\right)^4}\ \text{yrs}$$

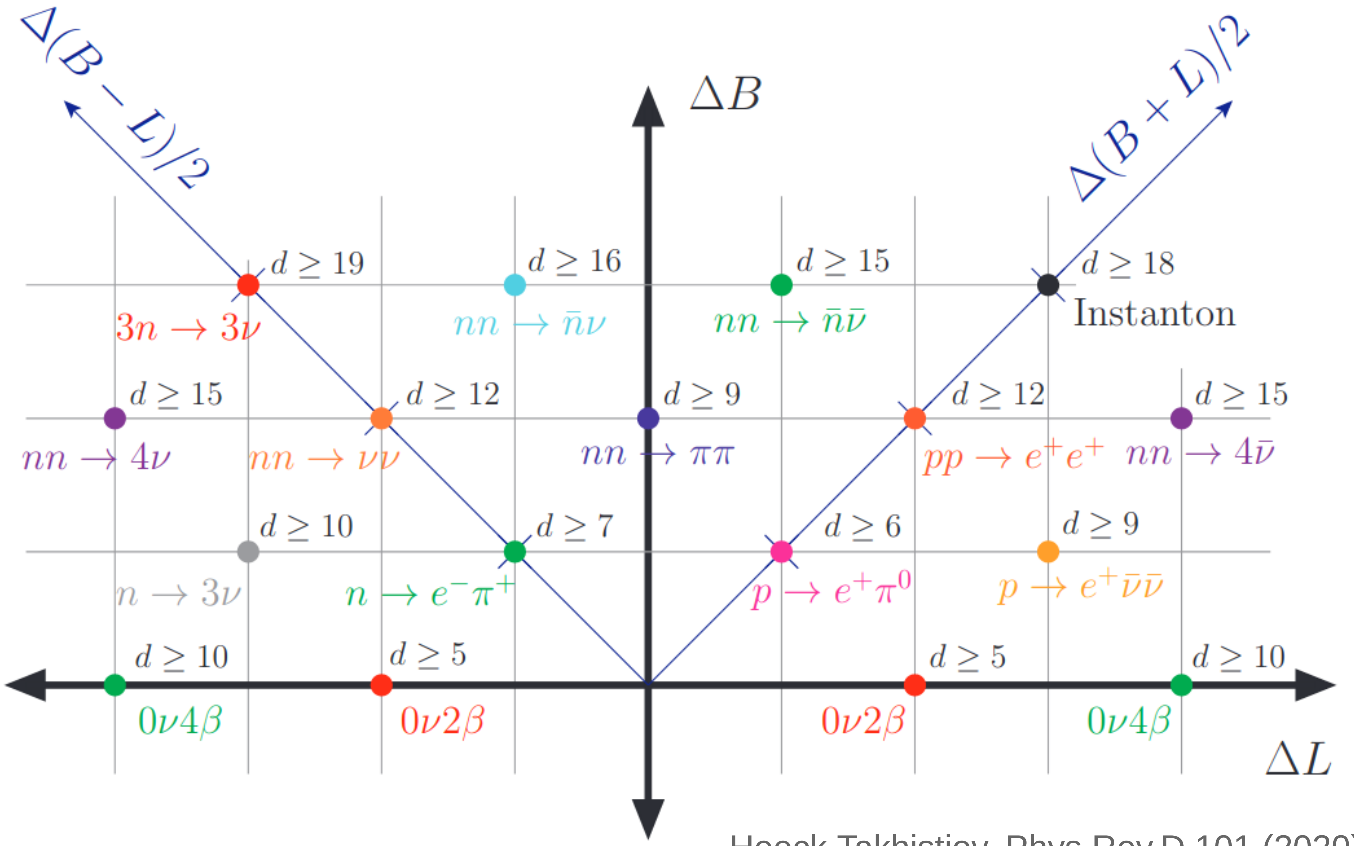
Conclusions:

- Operators with light LLPs can lead to non-canonical proton decay
- In this way proton decay can be an observable for axions, dark photons, ...
- For some LLP masses these modes may have been cut away at Super-Kamiokande

Thank you

Backup

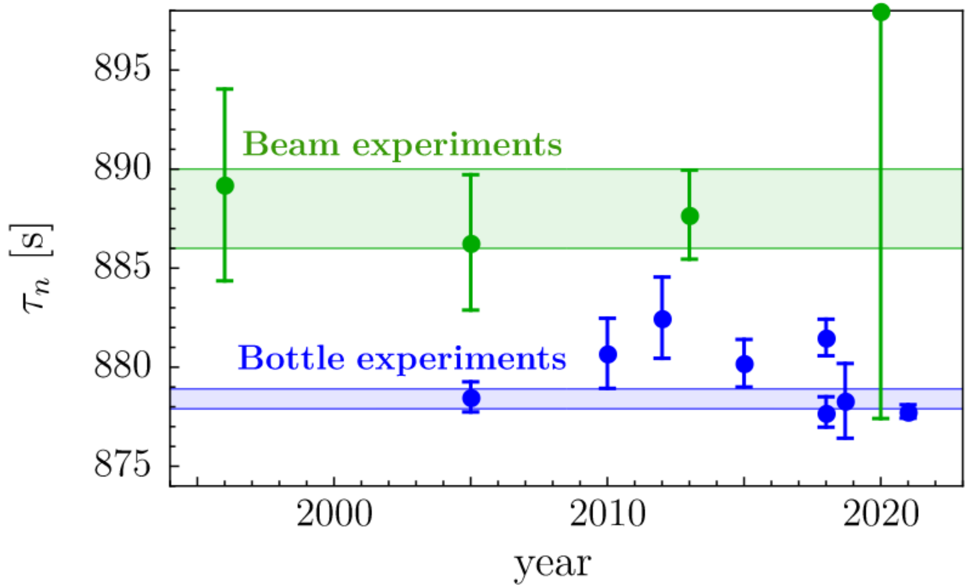
There are many more classes of modes, depending upon the dimension of the underlying operator



Heeck,Takhistiov, Phys.Rev.D 101 (2020) 1, 015005

In combination with the flavor aspect (e.g. muon or kaon final states), as well as vector mesons (ρ, ω), the number of possible decay modes is very large

Neutron lifetime anomaly



Fornal, Universe 9 (2023) 10, 449

Bottle and beam neutron lifetimes disagree

Can be solved with dark neutron decays

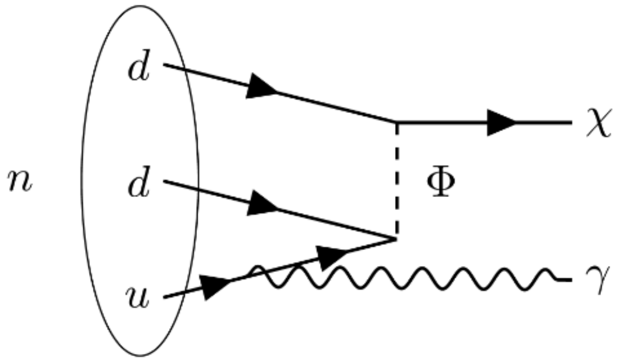
Requires very specific DM masses:

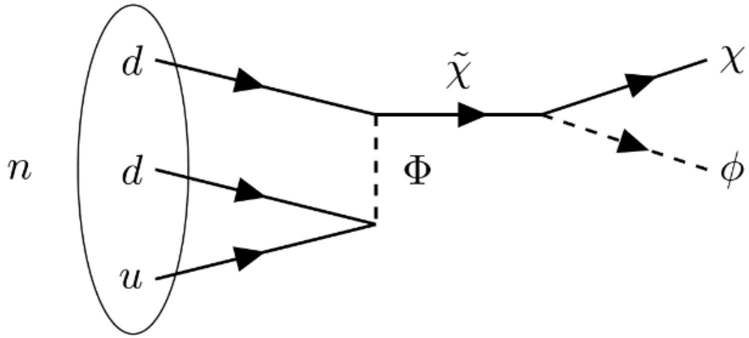
$$937.900\ \text{MeV} < m_\chi + m_\phi < 939.565\ \text{MeV}$$

$$937.900\ \text{MeV} < m_\chi < 938.783\ \text{MeV}$$

And low-scale NP:

$$\frac{|\lambda_q \lambda_\chi|}{M_\Phi^2} \approx 6.7 \times 10^{-6}\ \text{TeV}^{-2}$$

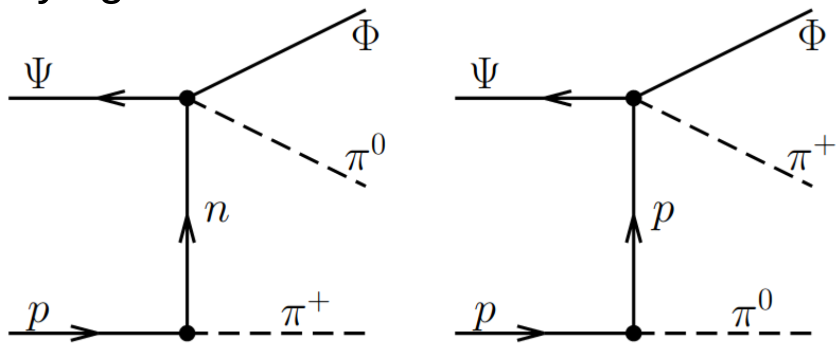




Fornal, Grinstein, Phys.Rev.Lett. 120 (2018) 19, 191801

Some related examples:

Hylogenesis:



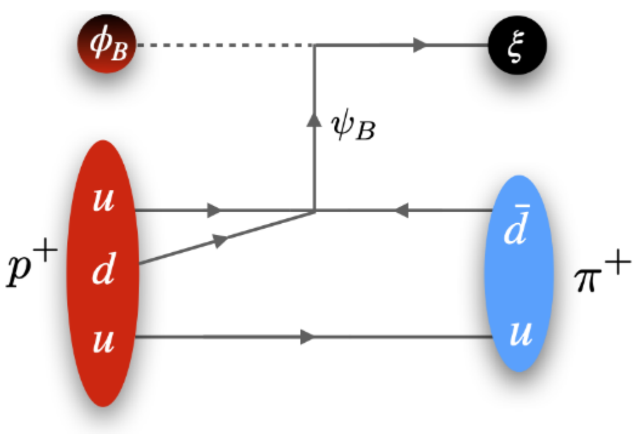
Demidov, Gorbunov, Phys.Rev.D 93 (2016) 3, 035009

Dark matter has baryon number

Simultaneous generation of the dark matter abundance and baryon asymmetry

Leads to “induced” proton decay

Mesogenesis:



Berger, Elor, Phys.Rev.Lett. 132 (2024) 8, 081002

Again dark matter and baryogenesis in a single model

CP-violation comes from B-meson oscillation

Again leads to induced proton decay

In both cases: unusual kinematics

See also:

Liang, Liao, Ma, Wang, JHEP 12 (2023) 172

Ema, McGehee, Pospelov, Ray, arXiv:2405.18472 [hep-ph]

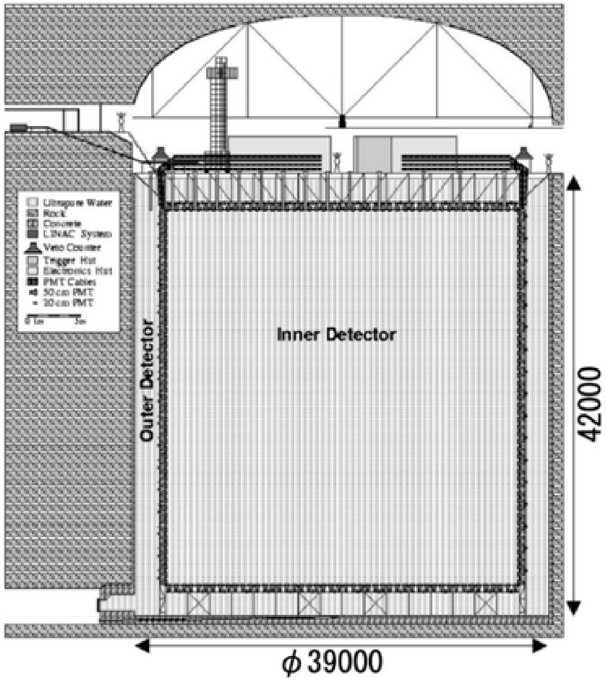
Ge, Ma, arXiv:2406.00445 [hep-ph]

+ ...

Current experimental limits on the proton lifetime imply NP scales $\Lambda_{\text{BNV}} \gtrsim 10^{15-16}$ GeV

Super-Kamiokande

1996~Present



$$\tau_{p\to e^+\pi^0} > 2.4 \times 10^{34} \text{ years @ 90\% C.L.}$$

$$\tau_{p\to \mu^+\pi^0} > 1.6 \times 10^{34} \text{ years @ 90\% C.L.}$$

Super-Kamiokande collaboration, Phys.Rev.D 102 (2020) 11, 112011

Other decay modes are typically constrained at lifetimes that are one or two orders of magnitude lower.

For contrast:

Neutrinoless double beta decay:

$$\tau_{0\nu\beta\beta}^{^{136}\text{Xe}} \geq 3.3 \times 10^{26} \text{ years @ 90\% C.L.}$$

KamLAND-Zen collaboration, Phys.Rev.Lett. 130 (2023) 5, 051801

Many GUTs come with high-scale RHNs that lead to seesaw and/or leptogenesis

We consider a non-SUSY model with intermediate Pati-Salam symmetry and D-parity breaking

$$\begin{aligned} SO(10) \longrightarrow\ & SU(4)_c \times SU(2)_L \times SU(2)_R \times D \longrightarrow \\ & SU(4)_c \times SU(2)_L \times SU(2)_R \longrightarrow \\ & SU(3)_c \times SU(2)_L \times SU(2)_R \times U(1)_{B-L} \longrightarrow \\ & SU(3)_c \times SU(2)_L \times U(1)_R \times U(1)_{B-L} \longrightarrow \\ & SU(3)_c \times SU(2)_L \times U(1)_Y \longrightarrow \\ & SU(3)_c \times U(1)_{em} \end{aligned}$$

The left- and right-handed symmetries can be related via D-parity before LR breaking

Here a scalar field $\sigma \sim (1,1,0)$ aquires a vev that breaks the D-parity

Leads to a separation of the RHN mass and LR symmetry breaking

Active neutrino gets a type-ii seesaw mass