Covering baryon number violation with inclusive searches

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Amherst Center for Fundamental Interactions Workshop

Theoretical Innovations for Future Experiments Regarding Baryon Number Violation, Part 1

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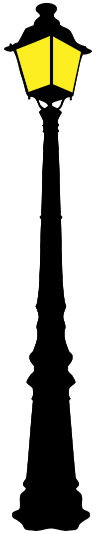
Search under which lamppost?



- No signals in any ΔL & ΔB searches:
  - No $0\nu\beta\beta$, no $p \to e^+\pi^0$, no $n \to \bar{n}$, …
  - How far can we push these limits?
- Best motivated and cleanest signatures, but no guarantee.
- ∃ models with different *dominating* processes:
  - $p \to e^-\mu^+\mu^+$ or $\mu^-e^+e^+$. [Hambye, **JH**, PRL ‘18]
  - $n \to K^+\mu^+e^-e^-$. [Pati, PRD ‘84; **JH**, Takhistov, PRD ‘20]
  - $pp \to e^+e^+$ or τ^+e^+… [Arnellos & Marciano; Mohapatra & Senjanović, ‘82]
- Weaker limits, plenty of room for improvement!

$p \to \mu^+\mu^+e^-$

- Minimal leptoquark example:

  $$\phi_1 \sim (\mathbf{3},\mathbf{3},-2/3)\,,\ \phi_2 \sim (\mathbf{3},\mathbf{2},7/3)\,.$$

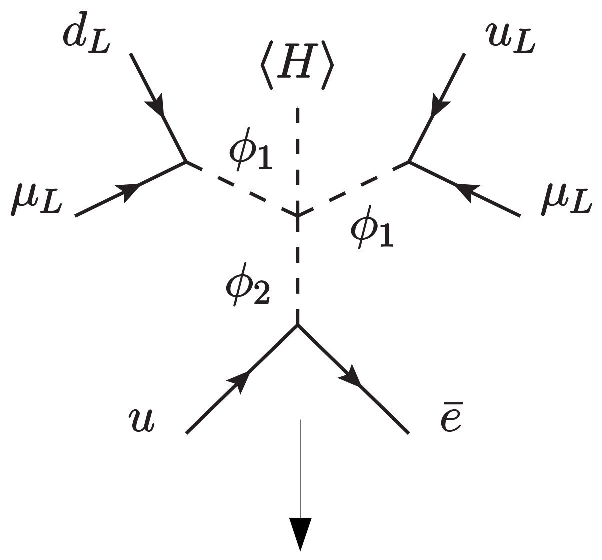
- $U(1)_{L_\mu+2L_e-3L_\tau}$ gives structure

  $$y_j \overline{L}_\mu \phi_1 Q_j^c + f_j \overline{u}_j \phi_2 L_e + \lambda \phi_1^2 \phi_2 H\,.$$

- Final ΔB=1 d=10 operator:

  $$\frac{1}{\Lambda^6} Q Q u L_\mu L_\mu \overline{L}_e H.$$

- Also conserves B-L & lepton flavor.



$$\frac{1}{\Lambda^6} \sim \frac{\lambda y_1^2 f_1}{m_{\phi_1}^4 m_{\phi_2}^2}$$

[Hambye, **JH**, PRL ‘18]

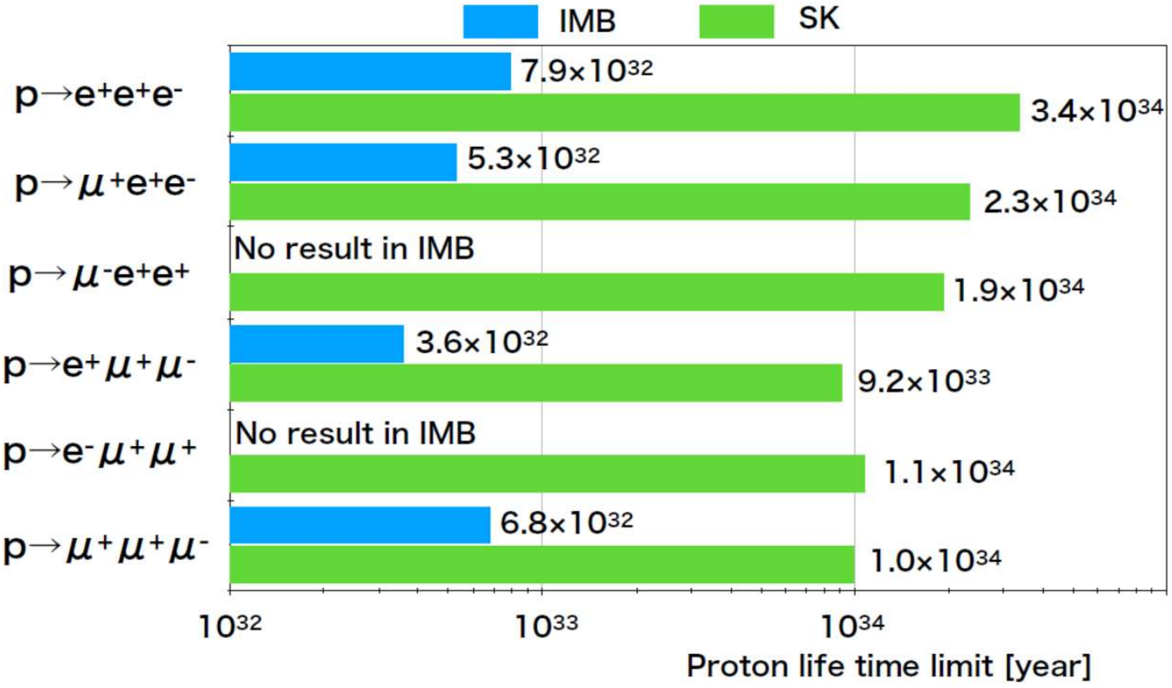
- ϕ_1 can resolve R(K) & R(K*) for $m_{\phi_1} \simeq 30\,\mathrm{TeV}\sqrt{y_2 y_3}\,.$

$$\boxed{\Gamma(p \to \mu^+\mu^+e^-) \simeq \frac{\langle H\rangle^2 \beta^2 m_p^5}{6144\pi^3\Lambda^{12}} \simeq \frac{(100\,\mathrm{TeV}/\Lambda)^{12}}{10^{33}\,\mathrm{yr}}}$$

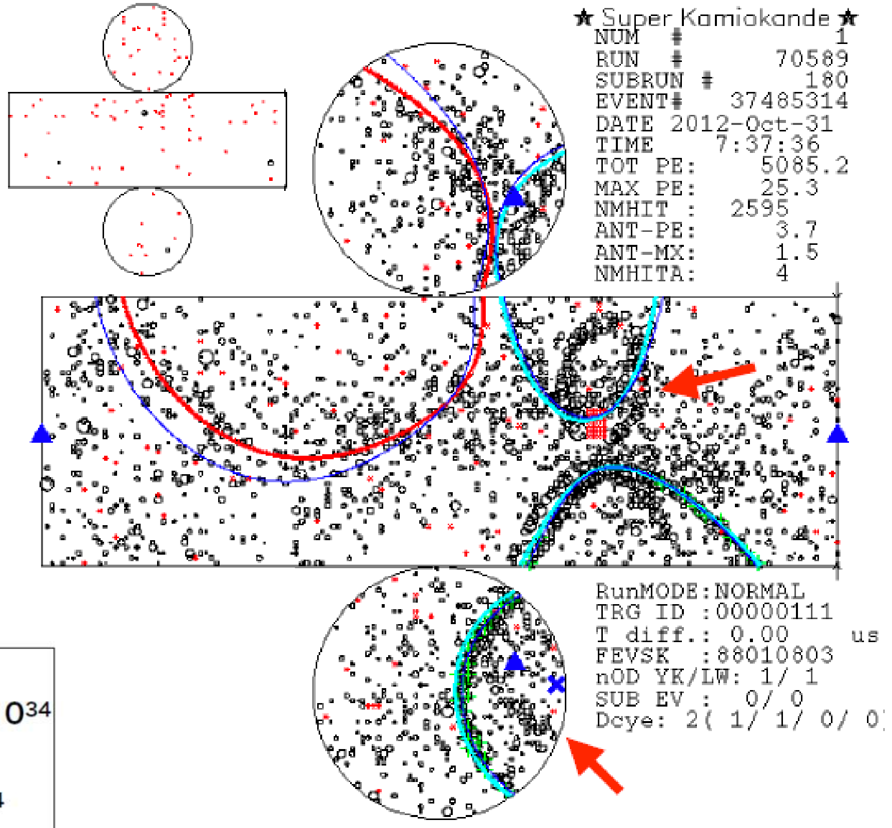
Limits

- Super-K searched for p → ℓℓℓ!
- Presented by M. Miura at BLV 2019.

[full paper: 2001.08011, PRD ‘20]

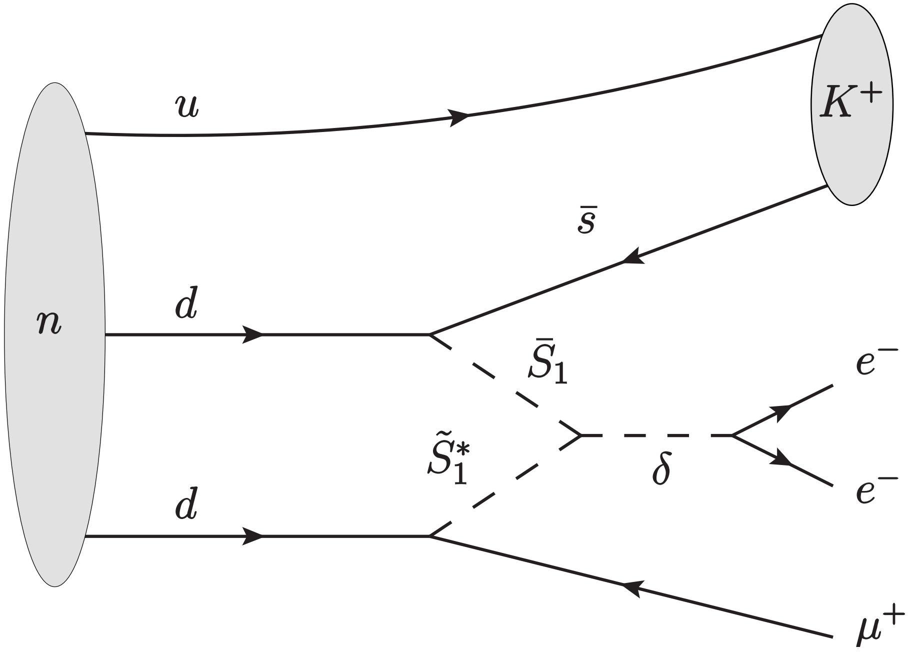


p→eμμ



Compatible with background, limits around 10^{34} yr.

$n \to K^+\mu^+e^-e^-$



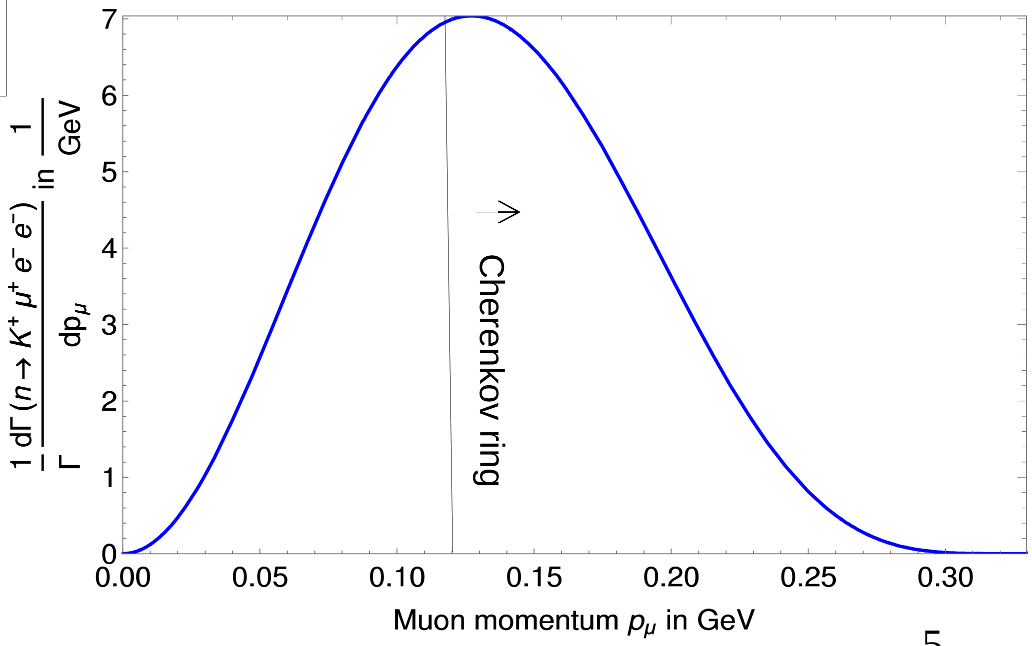
- Same model building as p → $\mu^+\mu^+e^-$.
- Final ΔB=1 d=9 operator:

  $\frac{1}{\Lambda^5}(ds)(d\mu)(\overline{e}\overline{e})$.

$$\Gamma(n \to K^+\mu^+e^-e^-) \simeq \frac{(100\,\text{TeV}/\Lambda)^{10}}{5\times10^{31}\,\text{yr}}$$

- No direct searches yet.
- No Cherenkov from K^+ and half the muons.
- Clean tracks for DUNE?

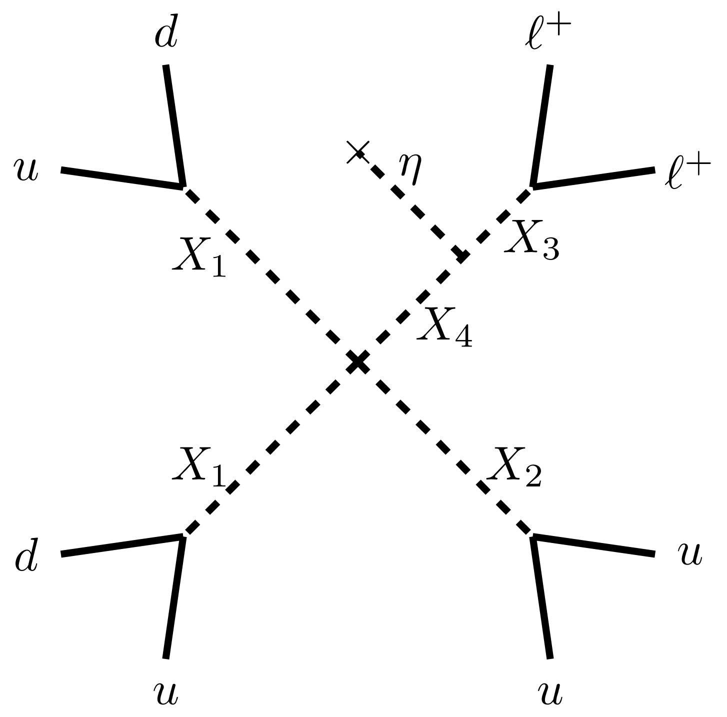
[**JH**, Takhistov, PRD '20]



pp → $\ell^+\ell^+$

- ΔB = ΔL = 2.
- d = 12 operators:

$$\frac{1}{\Lambda^8}(QQ)(QQ)(Q\ell)(Q\ell).$$



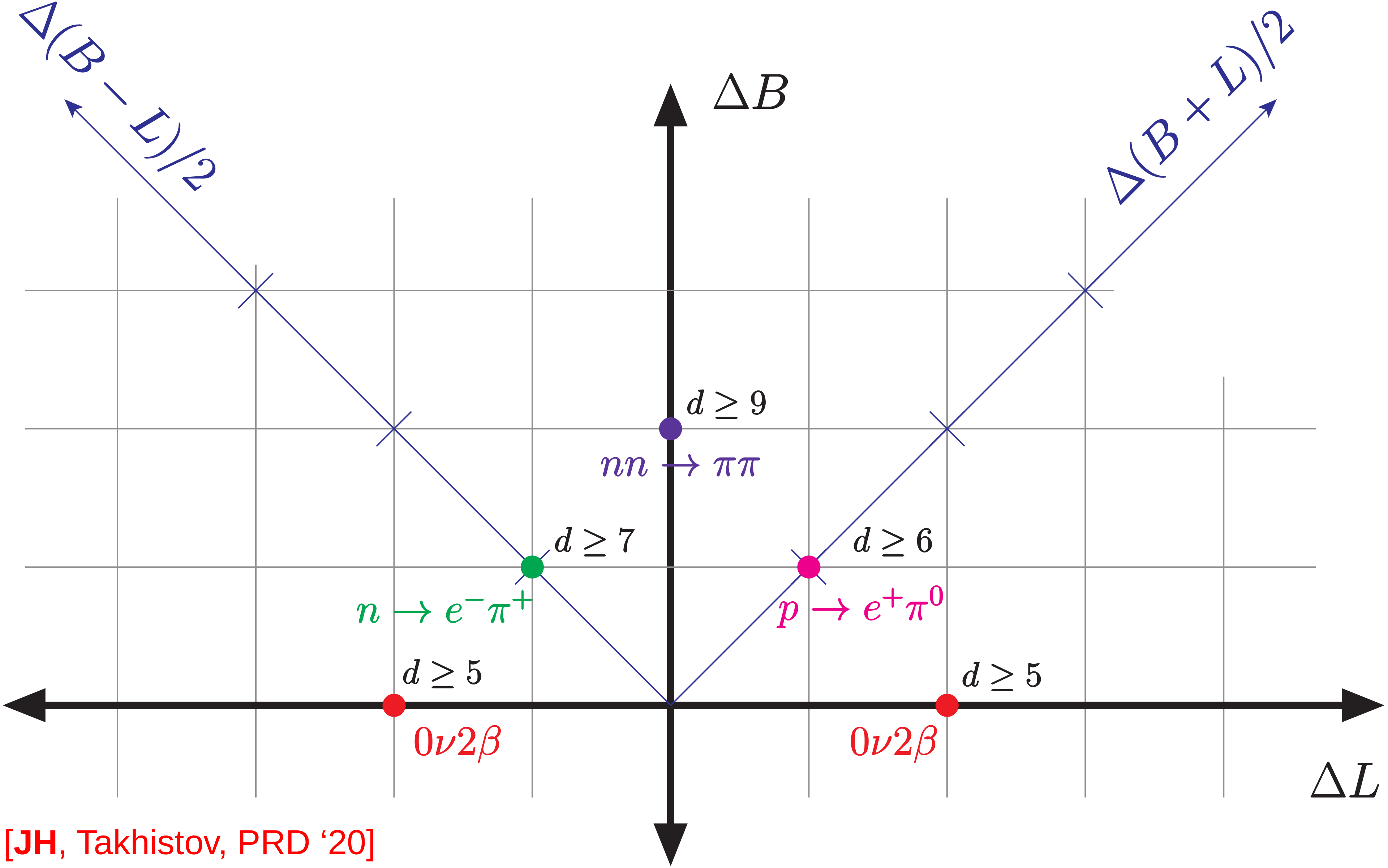
$$\boxed{\Gamma(^{16}\mathrm{O} \to {}^{14}\mathrm{C}\,\ell^+\ell^+) \simeq \frac{(2\,\mathrm{TeV}/\Lambda)^{16}}{2\times 10^{32}\,\mathrm{yr}}}$$

[Bramante, Kumar, Learned, PRD ‘15] Rate further suppressed! [Gardner, Yan, PLB ‘19]

- SK limits of 4x10^{33} yr
  on ee, eμ, μμ, no limits on eτ. [SK, 1811.12430]
- pp → $\tau^+\mu^+$ or $\tau^+\tau^+$ only at LHC *or* (indirectly) via
  - pn → $\mu^+\overline{\nu}_\tau$ or $\tau^+\overline{\nu}_\tau$. [SK, PRL ‘15]
  - nn → $\overline{\nu\nu}$. [KamLAND, PRL ‘06]

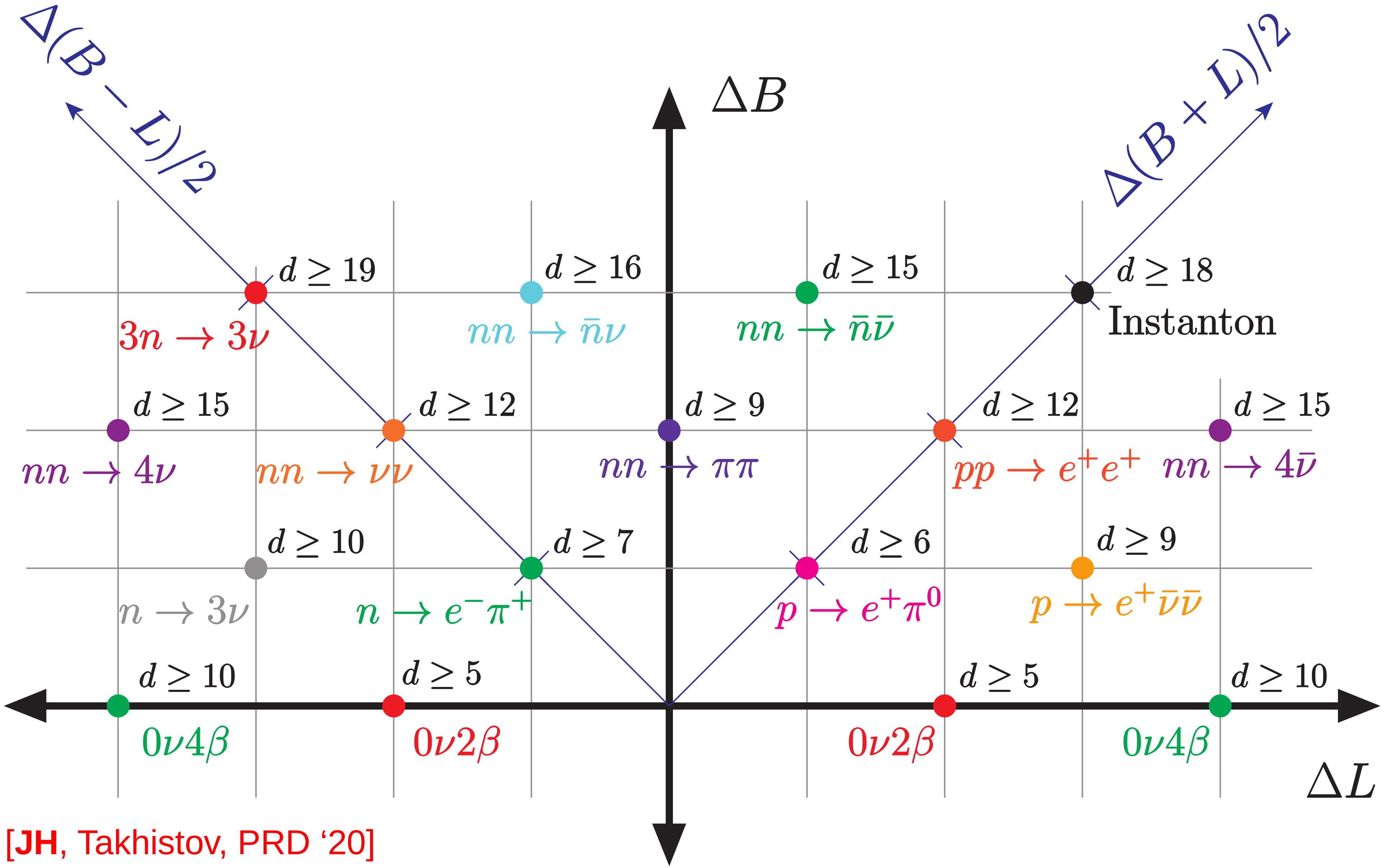
Improve with JUNO?

Baryon and lepton number

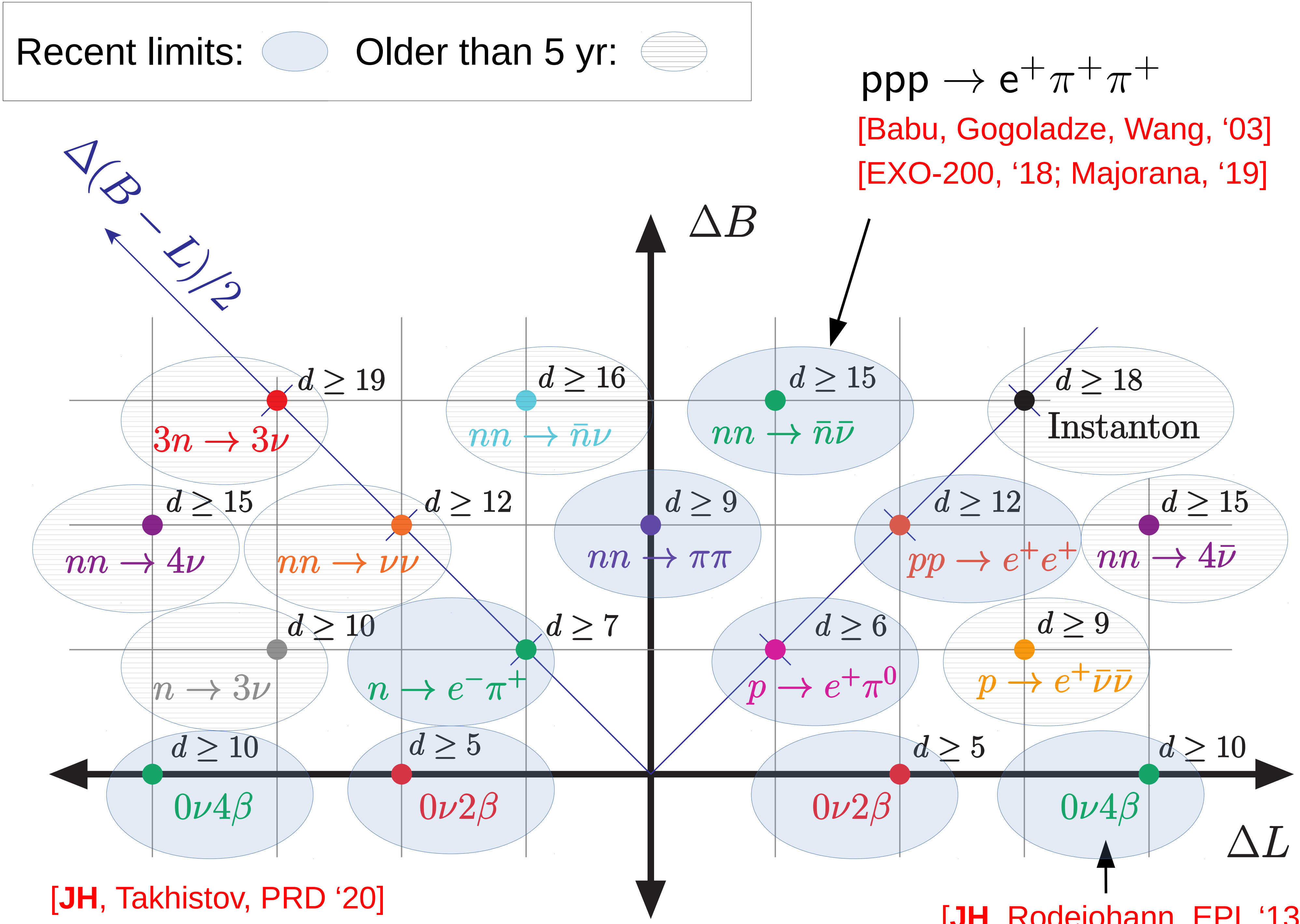


[**JH**, Takhistov, PRD ‘20]

Exotic ΔB and ΔL



[**JH**, Takhistov, PRD ‘20]



ppp $\to$ e$^+\pi^+\pi^+$

[Babu, Gogoladze, Wang, ‘03]

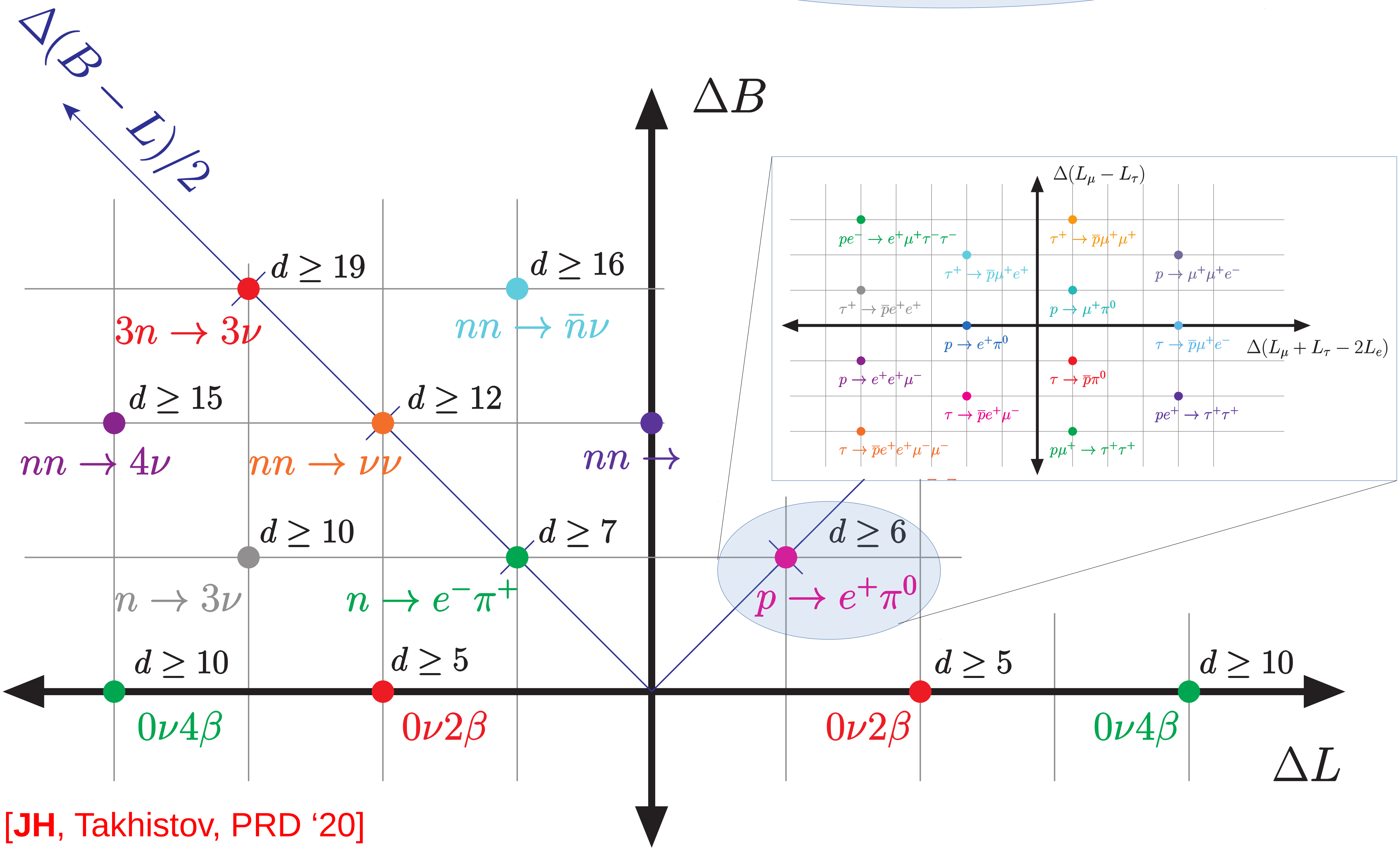
[EXO-200, ‘18; Majorana, ‘19]

[**JH**, Takhistov, PRD ‘20]

[**JH**, Rodejohann, EPL ‘13]

[NEMO-3, PRL ‘17]

$$\mathbb{Z}_3^{(\mathsf{B}+\mathsf{L})/2} \times \mathsf{U}(1)_{\mathsf{B}-\mathsf{L}} \times \mathsf{U}(1)_{\mathsf{L}_\mu-\mathsf{L}_\tau} \times \mathsf{U}(1)_{\mathsf{L}_\mu+\mathsf{L}_\tau-2\mathsf{L}_e}$$



[**JH**, Takhistov, PRD ‘20]

Full ΔB coverage possible?

- Cannot to go through all $\Delta B > 0$ decays:
  - 38 two-body $\Delta B = 1$ modes: $N \to A B$. 36 limits.
  - 76 three-body $\Delta B = 1$ modes: $N \to A B C$. 33 limits.
  - 300 four-body $\Delta B = 1$ modes: $N \to A B C D$. 0 limits.
  - 118 two-body $\Delta B = 2$ modes: $N N \to A B$. 18 limits.
  - 500 three-body $\Delta B = 2$ modes: $N N \to A B C$. 0 limits.
  - ...
- *Exclusive* searches up to $t \sim 10^{34}$ yr in SK.

Inclusive searches to the rescue!

Inclusive searches

- Current limits:

$$\Gamma^{-1}(\mathrm{N} \to \mathrm{e} + \mathrm{anything}) > 0.6 \times 10^{30}\,\mathrm{yr},$$ [Learned, Reines, Soni, '79]

$$\Gamma^{-1}(\mathrm{N} \to \mu + \mathrm{anything}) > 12 \times 10^{30}\,\mathrm{yr}.$$ [Cherry, Deakyne, Lande, Lee, Steinberg, Cleveland, '81]

- 40 years old, improve with new tech! [**JH**, Takhistov, PRD '20]
- $p \to e^+ + \text{anything}$ in SK could reach 10^{32} yr, judging by

$$\Gamma^{-1}(\mathrm{p} \to \mathrm{e}^+\nu\nu) > 1.7 \times 10^{32}\,\mathrm{yr}.$$ [Super-K, PRL '14]

- Do inclusive searches for N → ℓ/meson + anything.
- Also probes ΔB > 1, light new physics, and dark matter!

$n \to \pi^0 \chi$, $p \to e^+ \chi$,…

DM p → DM' e^+,…

Invisible neutron decay

- Special case of inclusive searches:

$$\Gamma^{-1}(\text{n} \to \text{neutrinos}) > 0.58 \times 10^{30}\,\text{yr},$$
$$\Gamma^{-1}(\text{nn} \to \text{neutrinos}) > 1.4 \times 10^{30}\,\text{yr},$$
$$\Gamma^{-1}(\text{nnn} \to \text{neutrinos}) > 1.8 \times 10^{23}\,\text{yr},$$
$$\Gamma^{-1}(\text{nnnn} \to \text{neutrinos}) > 1.4 \times 10^{23}\,\text{yr}.$$

[KamLAND, PRL '06; see also SNO+, PRD '19]

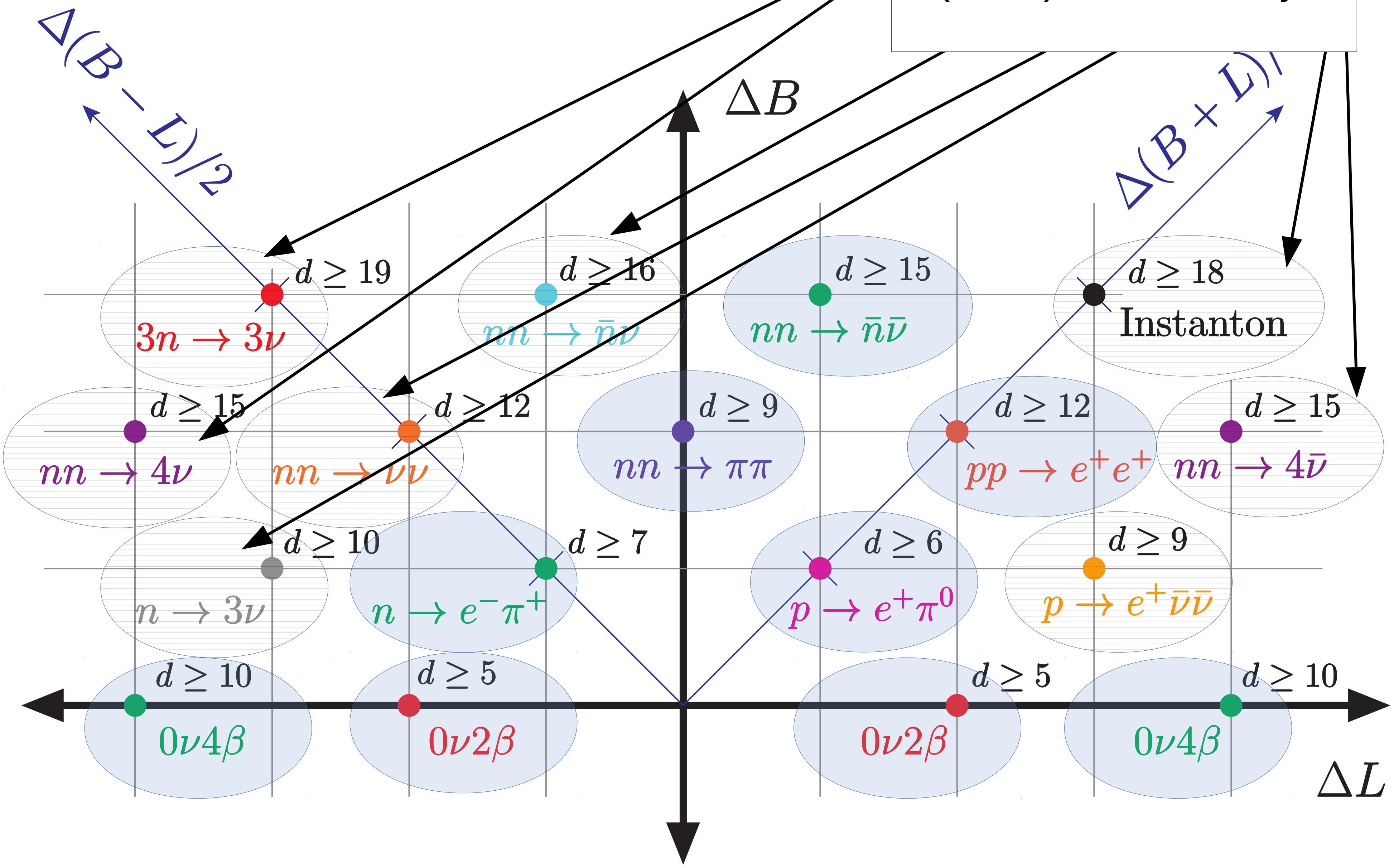
[Hazama, Ejiri, Fushimi, Ohsumi, PRC '94]

- Only signature is de-excitation of daughter nucleus. [Ejiri, '93]
- Every ΔB = k operator gives rise to k neutrons → neutrinos.
- Neutrinos carry away arbitrary lepton number & flavor!
- Also probes light new physics and dark matter.
- Can JUNO improve KamLAND limit? DUNE?

[**JH**, Takhistov, PRD '20]

Recent limits: ● Older than 5 yr: ▨

Limits from invisible
(multi-)neutron decay!



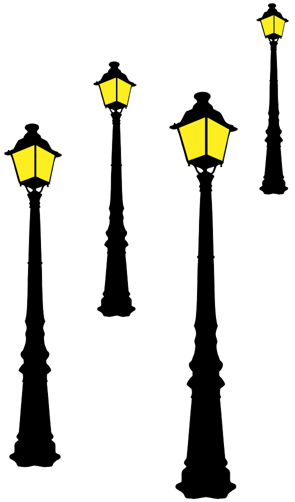
Summary

- ΔB is more than just $p \to e^+\pi^0$ or $n \to \bar{n}$.
- ΔB (& ΔL) probe
  - high *scales* (10^{15} GeV) *or*
  - high *multiplicities* ($N \to 15$ particles) *or*
  - high operator *dimensions* ($d \sim 15$)!

SK/HK,
DUNE,
JUNO,
0νββ exp.?

- Cover ground with inclusive searches!
  - $N \to \ell$/meson + anything, invisible neutron decay,…
- Still untapped areas:
  - Light new physics ($p \to \ell^+ + X$, $X \to$ SM?).
  - Dark matter induced ΔB & ΔL.

Plenty of lampposts to light the way!



Backup

Exotic ΔB and ΔL

A) $\Delta B > 1$, $\Delta L > 1$, … in EFT (heavy new physics). [Weinberg, '80]

- E.g. $pp \rightarrow e^+e^+$ or $p \rightarrow e^+\overline{\nu\nu}$.

B) Flavored ΔB & ΔL.

- E.g. $p \rightarrow e^-\mu^+\mu^+$ or $t \rightarrow \overline{cb}\,\tau^+$ ($\rightsquigarrow$ $n \rightarrow \pi^0\,\overline{\nu}_\tau$).

[Hambye, **JH**, PRL '18] [Marciano '95; Hou, Nagashima, Soddu, '05]

C) ΔB & ΔL with *light* new particles.

- E.g. $n \rightarrow \pi^0\,\chi$ or $p \rightarrow e^+\,\chi$.

D) Dark matter induced ΔB & ΔL.

- E.g. $\mathrm{DM}\ p \rightarrow n\ e^+$, $\mathrm{DM}\ p \rightarrow \mathrm{DM}'\ e^+$, $\mathrm{DM}\ n \rightarrow \mathrm{DM}'\ \pi^0$.

[Kile, Soni, '09; Davoudiasl, Morrissey, Sigurdson, Tulin, PRL '10 & PRD '11; ...]

Homework: everything together.

Symmetries of the Standard Model

- Rephasing lepton and quark fields:

$$\mathrm{U}(1)_\mathrm{B} \times \mathrm{U}(1)_{\mathrm{L_e}} \times \mathrm{U}(1)_{\mathrm{L}_\mu} \times \mathrm{U}(1)_{\mathrm{L}_\tau}$$

$$= \mathrm{U}(1)_\mathrm{B+L} \times \mathrm{U}(1)_\mathrm{B-L} \times \mathrm{U}(1)_{\mathrm{L}_\mu-\mathrm{L}_\tau} \times \mathrm{U}(1)_{\mathrm{L}_\mu+\mathrm{L}_\tau-2\mathrm{L_e}}\,.$$

- $\mathrm{U}(1)_{\mathrm{B+L}}$ broken non-perturbatively to $\mathbb{Z}_3$,

$$\Delta \mathrm{B} = 3 \quad \wedge \quad \Delta \mathrm{L_e} = \Delta \mathrm{L}_\mu = \Delta \mathrm{L}_\tau = 1\,,$$

  but unobservable at low temperatures. ['t Hooft, PRL '76]

- True accidental global symmetry:

$$\boxed{\mathbb{Z}_3^{(\mathrm{B+L})/2} \times \mathrm{U}(1)_\mathrm{B-L} \times \mathrm{U}(1)_{\mathrm{L}_\mu-\mathrm{L}_\tau} \times \mathrm{U}(1)_{\mathrm{L}_\mu+\mathrm{L}_\tau-2\mathrm{L_e}}\,.}$$

Standard Model effective field theory

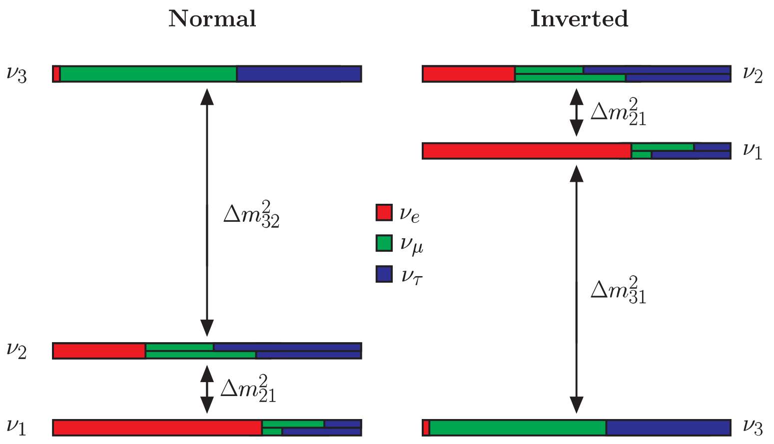
- EFT with Majorana neutrinos: [Weinberg, '79 & '80]

$$L = L_{SM} + \underset{\substack{\uparrow\\ \Delta L = 2}}{\frac{LLHH}{\Lambda}} + \sum_j \underset{\substack{\uparrow\\ \Delta B = \Delta L = 1}}{\frac{\mathcal{O}_j}{\Lambda^2}} + \sum_j \underset{\substack{\nwarrow\\ \Delta B = -\Delta L = 1}}{\frac{\mathcal{O}'_j}{\Lambda^3}} + \sum_j \frac{\mathcal{O}''_j}{\Lambda^4} + \dots$$

- $d_{\min} \geq \frac{9}{2}|\Delta B| + \frac{3}{2}|\Delta L|$. [Kobach '16; Helset, Kobach, '19]
- ΔB dominated by d = 6, unless forbidden by symmetry! [Weinberg, '80]

Get global view on ΔB and ΔL.

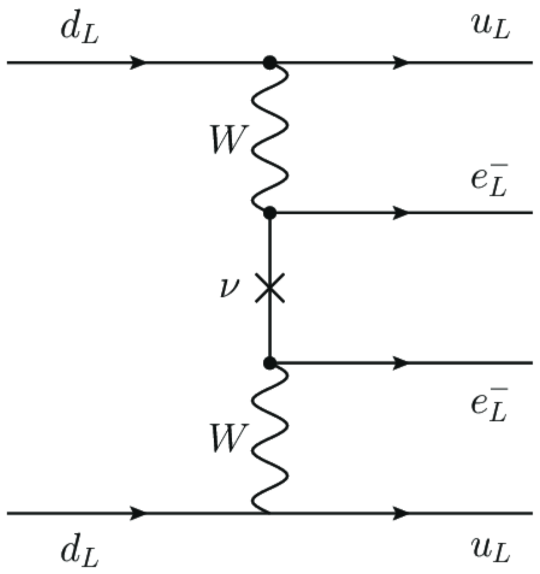
ΔL = 2

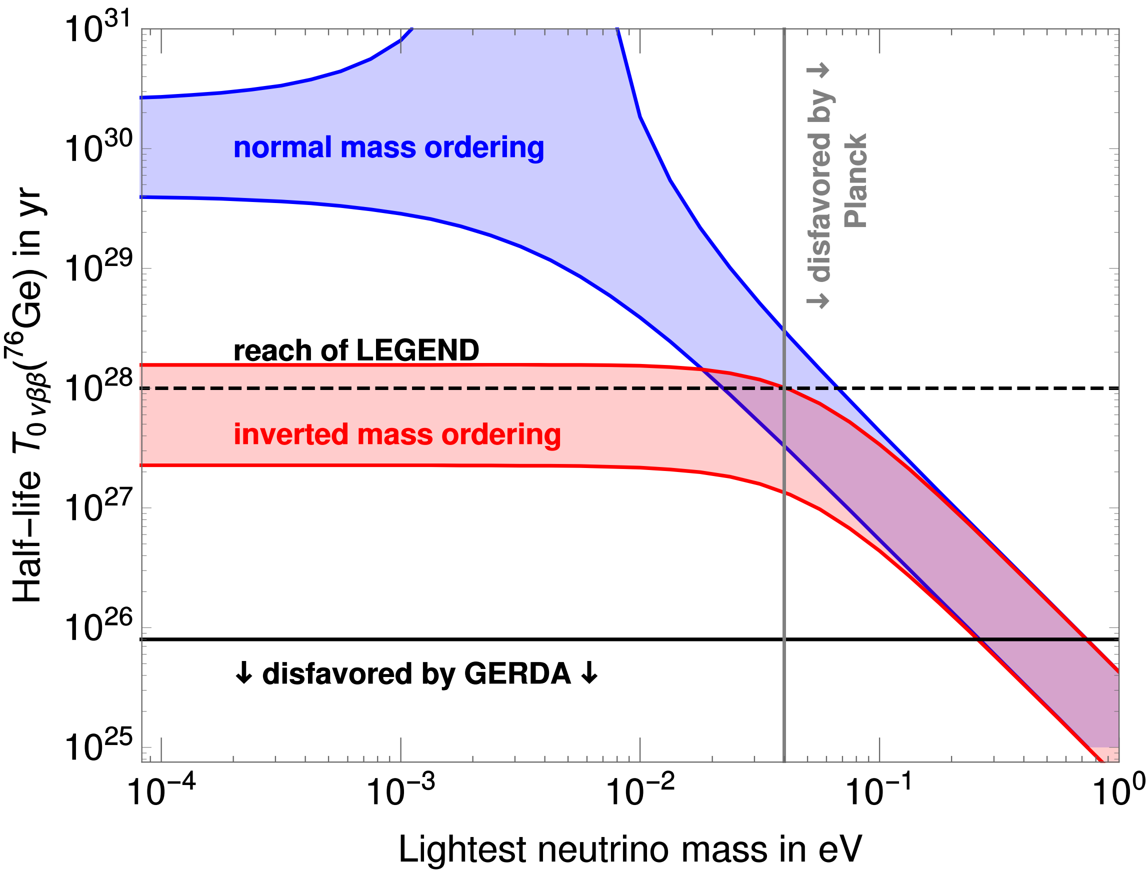


- Neutrinoless double β decay:

  (A,Z) → (A,Z+2) + 2 e^-

  in β stable isotopes.
- Current limits ~ 10^{26} yr.
- 0ν2β ⇔ Majorana ν.





ΔL = 4

- ΔL = 4 in rare decays?

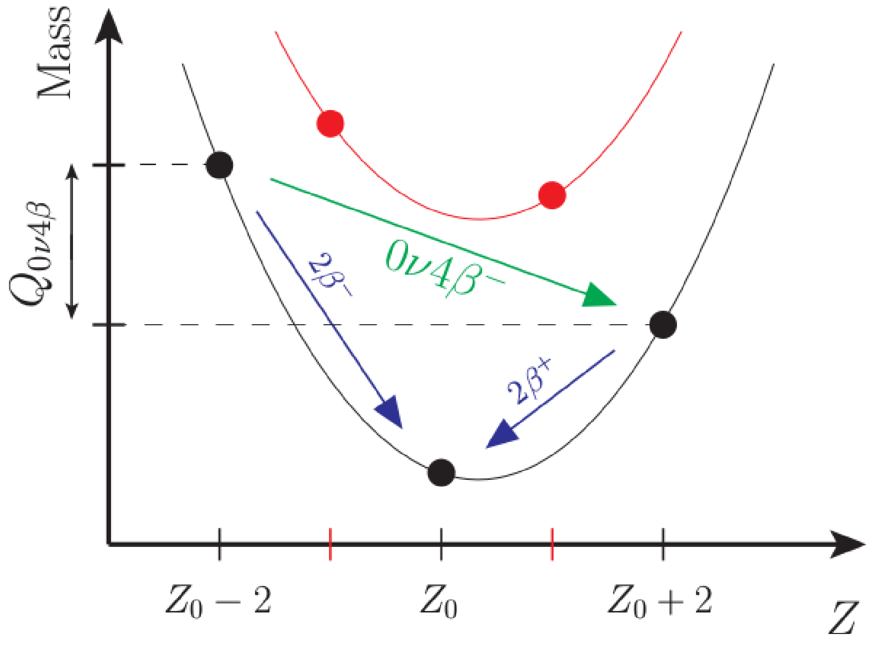
  (A,Z) → (A,Z+4) + 4 e^- !
- 3 candidates: ^{96}Zr, ^{136}Xe, ^{150}Nd.

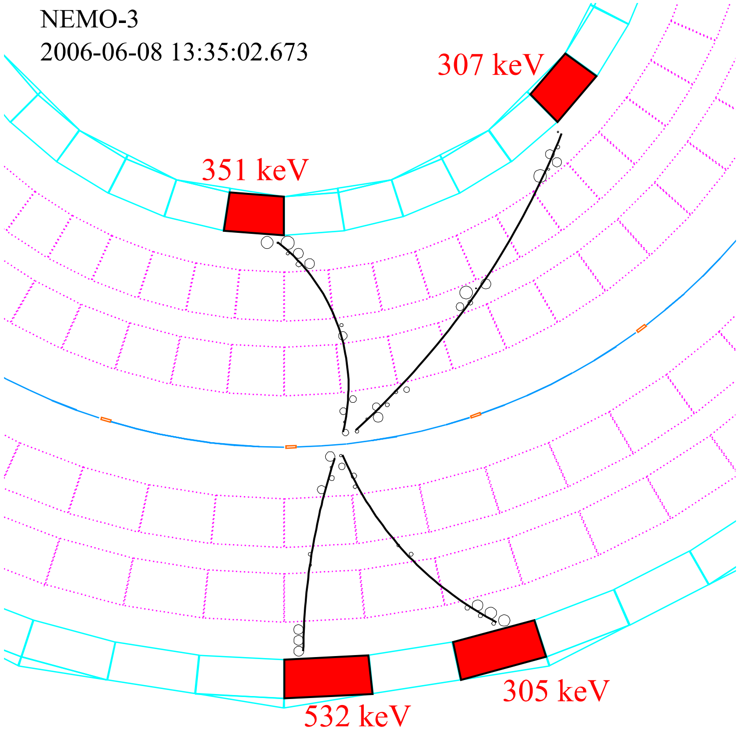
  [**JH**, Rodejohann, EPL '13]
- First limit: $\tau_{0\nu4\beta}(^{150}\mathrm{Nd}) > 10^{21}$yr.

  [NEMO-3, PRL '17]
- Hard to find testable models.

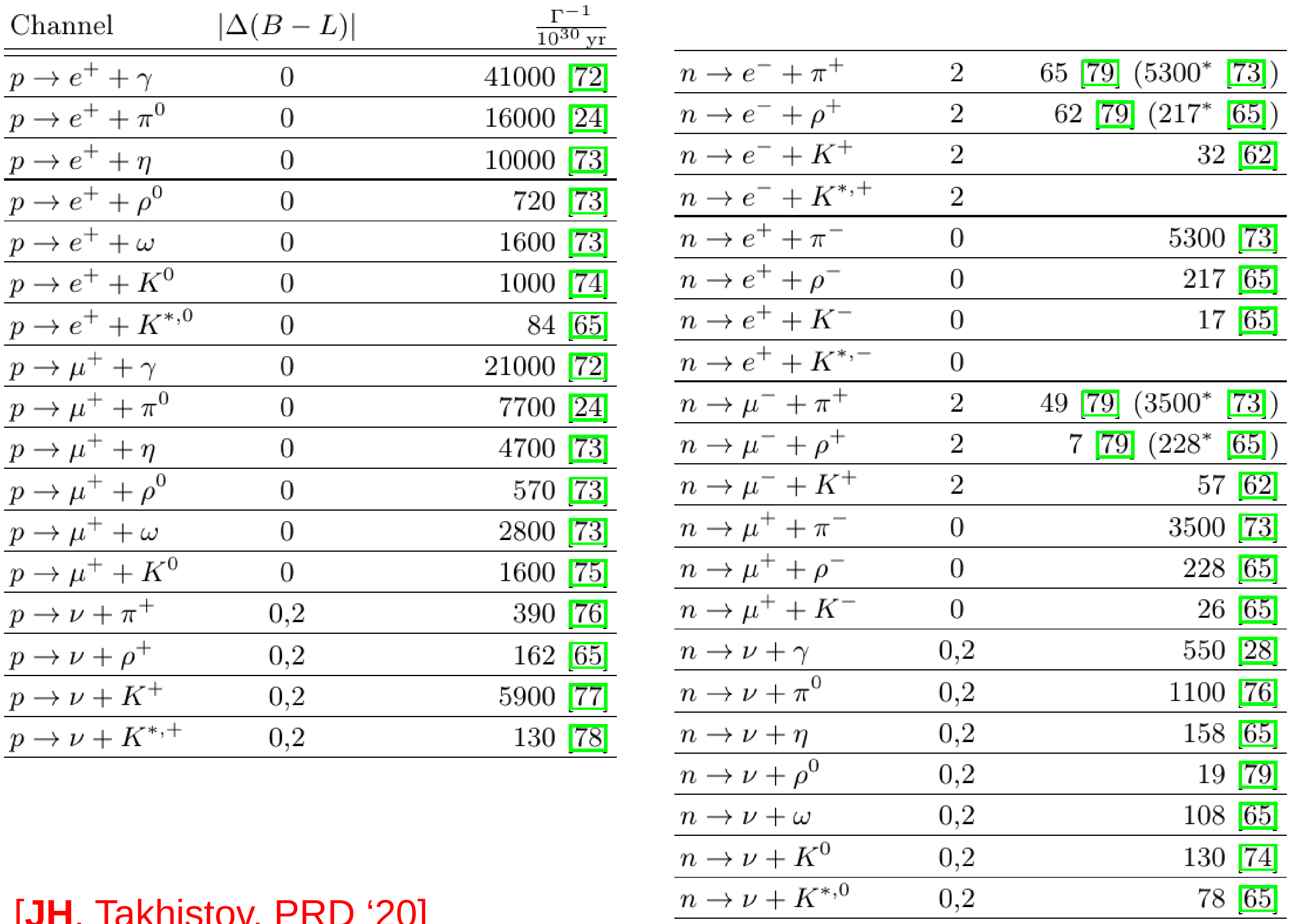
  [Fonseca, Hirsch, PRD '18; see however Dasgupta, Kang, Popov, PRD '19]
- Could still explain matter-antimatter asymmetry.

  [**JH**, PRD '13]





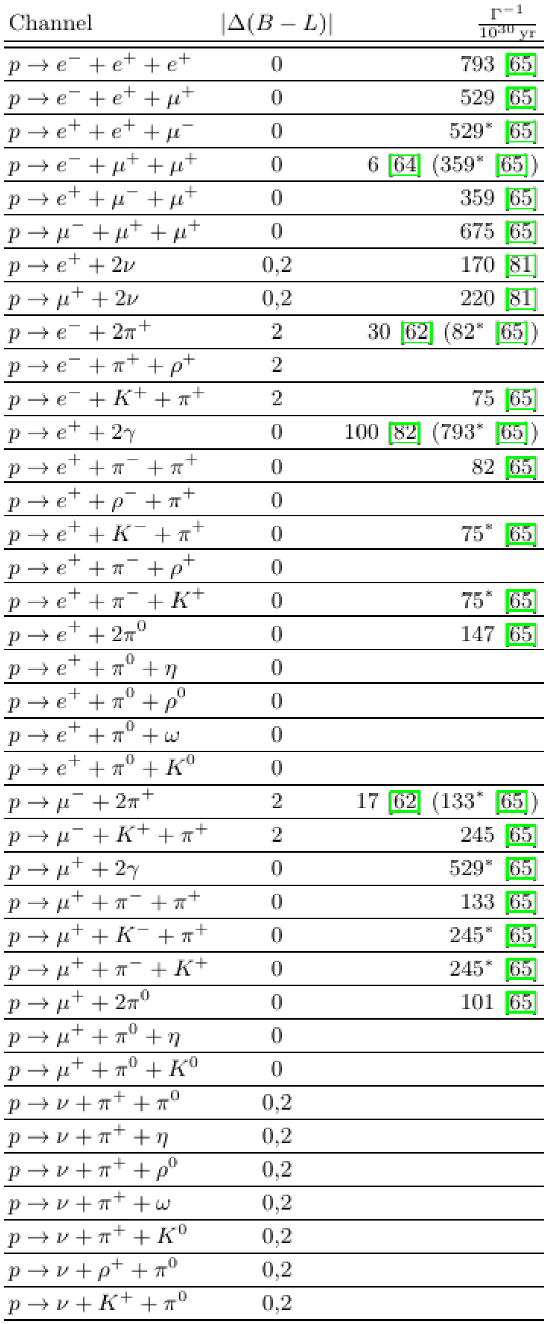
Two-body nucleon decays



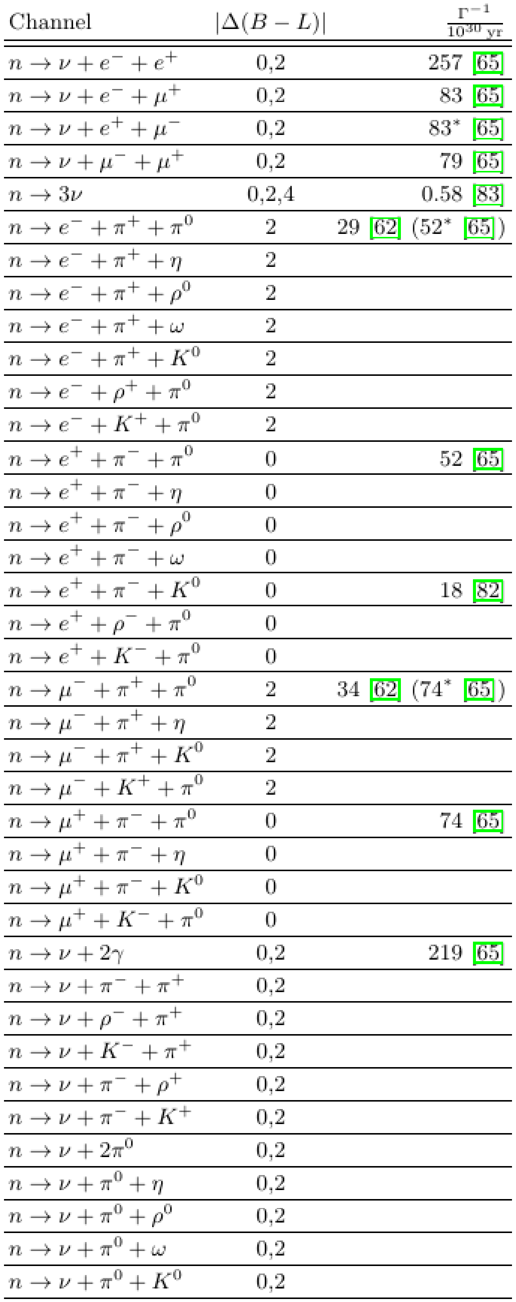
Channel	$\lvert\Delta(B-L)\rvert$	$\frac{\Gamma^{-1}}{10^{30}\,\mathrm{yr}}$
$p \to e^+ + \gamma$	0	41000 [72]
$p \to e^+ + \pi^0$	0	16000 [24]
$p \to e^+ + \eta$	0	10000 [73]
$p \to e^+ + \rho^0$	0	720 [73]
$p \to e^+ + \omega$	0	1600 [73]
$p \to e^+ + K^0$	0	1000 [74]
$p \to e^+ + K^{*,0}$	0	84 [65]
$p \to \mu^+ + \gamma$	0	21000 [72]
$p \to \mu^+ + \pi^0$	0	7700 [24]
$p \to \mu^+ + \eta$	0	4700 [73]
$p \to \mu^+ + \rho^0$	0	570 [73]
$p \to \mu^+ + \omega$	0	2800 [73]
$p \to \mu^+ + K^0$	0	1600 [75]
$p \to \nu + \pi^+$	0,2	390 [76]
$p \to \nu + \rho^+$	0,2	162 [65]
$p \to \nu + K^+$	0,2	5900 [77]
$p \to \nu + K^{*,+}$	0,2	130 [78]
$n \to e^- + \pi^+$	2	65 [79] (5300* [73])
$n \to e^- + \rho^+$	2	62 [79] (217* [65])
$n \to e^- + K^+$	2	32 [62]
$n \to e^- + K^{*,+}$	2	
$n \to e^+ + \pi^-$	0	5300 [73]
$n \to e^+ + \rho^-$	0	217 [65]
$n \to e^+ + K^-$	0	17 [65]
$n \to e^+ + K^{*,-}$	0	
$n \to \mu^- + \pi^+$	2	49 [79] (3500* [73])
$n \to \mu^- + \rho^+$	2	7 [79] (228* [65])
$n \to \mu^- + K^+$	2	57 [62]
$n \to \mu^+ + \pi^-$	0	3500 [73]
$n \to \mu^+ + \rho^-$	0	228 [65]
$n \to \mu^+ + K^-$	0	26 [65]
$n \to \nu + \gamma$	0,2	550 [28]
$n \to \nu + \pi^0$	0,2	1100 [76]
$n \to \nu + \eta$	0,2	158 [65]
$n \to \nu + \rho^0$	0,2	19 [79]
$n \to \nu + \omega$	0,2	108 [65]
$n \to \nu + K^0$	0,2	130 [74]
$n \to \nu + K^{*,0}$	0,2	78 [65]

[**JH**, Takhistov, PRD ‘20]

Three-body nucleon decays



Channel	$\lvert\Delta(B-L)\rvert$	$\frac{\Gamma^{-1}}{10^{30}\,\mathrm{yr}}$
$p \to e^- + e^+ + e^+$	0	793 [65]
$p \to e^- + e^+ + \mu^+$	0	529 [65]
$p \to e^+ + e^+ + \mu^-$	0	529* [65]
$p \to e^- + \mu^+ + \mu^+$	0	6 [64] (359* [65])
$p \to e^+ + \mu^- + \mu^+$	0	359 [65]
$p \to \mu^- + \mu^+ + \mu^+$	0	675 [65]
$p \to e^+ + 2\nu$	0,2	170 [81]
$p \to \mu^+ + 2\nu$	0,2	220 [81]
$p \to e^- + 2\pi^+$	2	30 [62] (82* [65])
$p \to e^- + \pi^+ + \rho^+$	2	
$p \to e^- + K^+ + \pi^+$	2	75 [65]
$p \to e^+ + 2\gamma$	0	100 [82] (793* [65])
$p \to e^+ + \pi^- + \pi^+$	0	82 [65]
$p \to e^+ + \rho^- + \pi^+$	0	
$p \to e^+ + K^- + \pi^+$	0	75* [65]
$p \to e^+ + \pi^- + \rho^+$	0	
$p \to e^+ + \pi^- + K^+$	0	75* [65]
$p \to e^+ + 2\pi^0$	0	147 [65]
$p \to e^+ + \pi^0 + \eta$	0	
$p \to e^+ + \pi^0 + \rho^0$	0	
$p \to e^+ + \pi^0 + \omega$	0	
$p \to e^+ + \pi^0 + K^0$	0	
$p \to \mu^- + 2\pi^+$	2	17 [62] (133* [65])
$p \to \mu^- + K^+ + \pi^+$	2	245 [65]
$p \to \mu^+ + 2\gamma$	0	529* [65]
$p \to \mu^+ + \pi^- + \pi^+$	0	133 [65]
$p \to \mu^+ + K^- + \pi^+$	0	245* [65]
$p \to \mu^+ + \pi^- + K^+$	0	245* [65]
$p \to \mu^+ + 2\pi^0$	0	101 [65]
$p \to \mu^+ + \pi^0 + \eta$	0	
$p \to \mu^+ + \pi^0 + K^0$	0	
$p \to \nu + \pi^+ + \pi^0$	0,2	
$p \to \nu + \pi^+ + \eta$	0,2	
$p \to \nu + \pi^+ + \rho^0$	0,2	
$p \to \nu + \pi^+ + \omega$	0,2	
$p \to \nu + \pi^+ + K^0$	0,2	
$p \to \nu + \rho^+ + \pi^0$	0,2	
$p \to \nu + K^+ + \pi^0$	0,2	

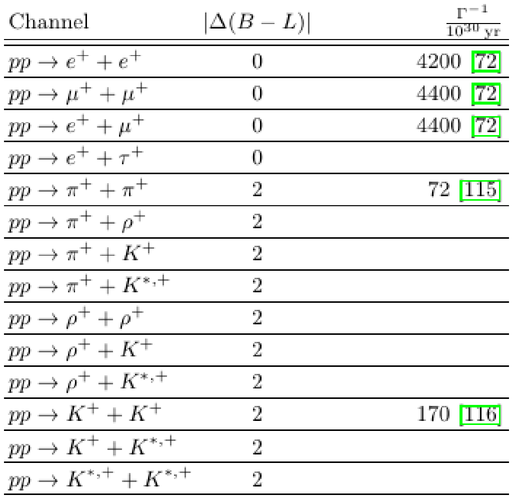


Channel	$\lvert\Delta(B-L)\rvert$	$\frac{\Gamma^{-1}}{10^{30}\,\mathrm{yr}}$
$n \to \nu + e^- + e^+$	0,2	257 [65]
$n \to \nu + e^- + \mu^+$	0,2	83 [65]
$n \to \nu + e^+ + \mu^-$	0,2	83* [65]
$n \to \nu + \mu^- + \mu^+$	0,2	79 [65]
$n \to 3\nu$	0,2,4	0.58 [83]
$n \to e^- + \pi^+ + \pi^0$	2	29 [62] (52* [65])
$n \to e^- + \pi^+ + \eta$	2	
$n \to e^- + \pi^+ + \rho^0$	2	
$n \to e^- + \pi^+ + \omega$	2	
$n \to e^- + \pi^+ + K^0$	2	
$n \to e^- + \rho^+ + \pi^0$	2	
$n \to e^- + K^+ + \pi^0$	2	
$n \to e^+ + \pi^- + \pi^0$	0	52 [65]
$n \to e^+ + \pi^- + \eta$	0	
$n \to e^+ + \pi^- + \rho^0$	0	
$n \to e^+ + \pi^- + \omega$	0	
$n \to e^+ + \pi^- + K^0$	0	18 [82]
$n \to e^+ + \rho^- + \pi^0$	0	
$n \to e^+ + K^- + \pi^0$	0	
$n \to \mu^- + \pi^+ + \pi^0$	2	34 [62] (74* [65])
$n \to \mu^- + \pi^+ + \eta$	2	
$n \to \mu^- + \pi^+ + K^0$	2	
$n \to \mu^- + K^+ + \pi^0$	2	
$n \to \mu^+ + \pi^- + \pi^0$	0	74 [65]
$n \to \mu^+ + \pi^- + \eta$	0	
$n \to \mu^+ + \pi^- + K^0$	0	
$n \to \mu^+ + K^- + \pi^0$	0	
$n \to \nu + 2\gamma$	0,2	219 [65]
$n \to \nu + \pi^- + \pi^+$	0,2	
$n \to \nu + \rho^- + \pi^+$	0,2	
$n \to \nu + K^- + \pi^+$	0,2	
$n \to \nu + \pi^- + \rho^+$	0,2	
$n \to \nu + \pi^- + K^+$	0,2	
$n \to \nu + 2\pi^0$	0,2	
$n \to \nu + \pi^0 + \eta$	0,2	
$n \to \nu + \pi^0 + \rho^0$	0,2	
$n \to \nu + \pi^0 + \omega$	0,2	
$n \to \nu + \pi^0 + K^0$	0,2	

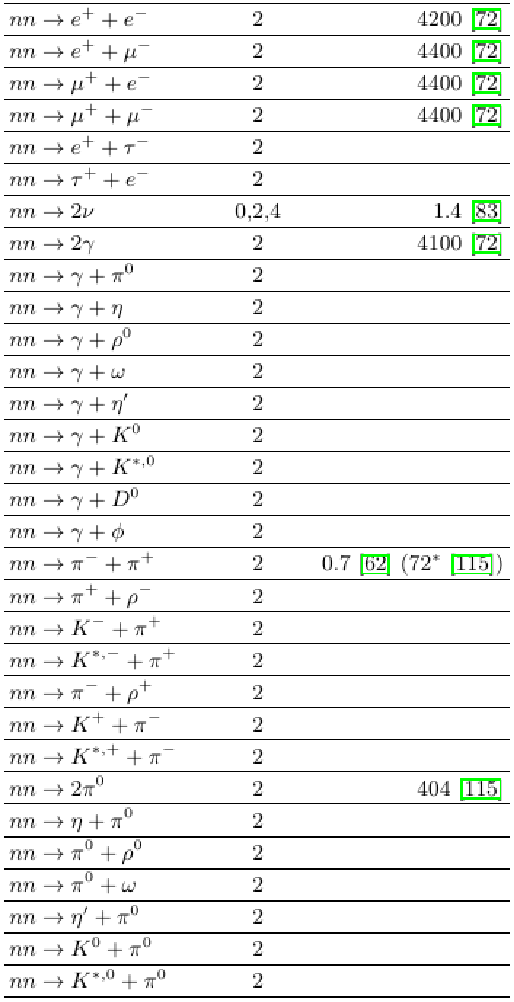
[**JH**, Takhistov, PRD '20]

Does not include SK's 2020 limits on p → ℓℓℓ.

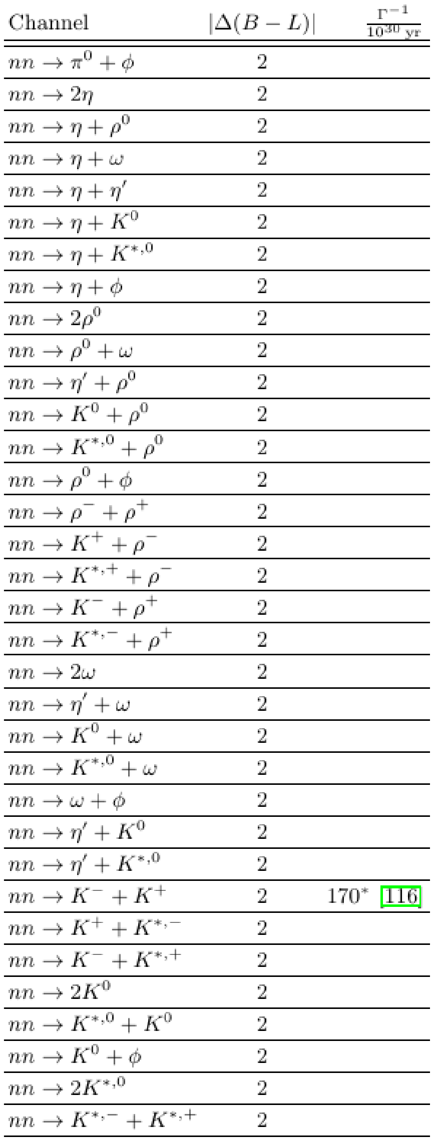
Two-body di-nucleon decays



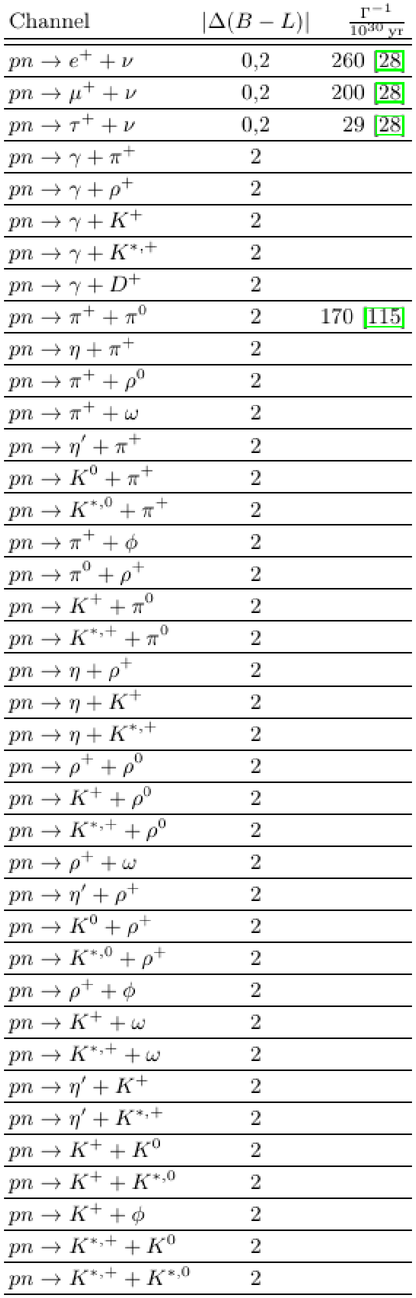
Channel	$\lvert\Delta(B-L)\rvert$	$\frac{\Gamma^{-1}}{10^{30}\,\text{yr}}$
$pp \to e^+ + e^+$	0	4200 [72]
$pp \to \mu^+ + \mu^+$	0	4400 [72]
$pp \to e^+ + \mu^+$	0	4400 [72]
$pp \to e^+ + \tau^+$	0	
$pp \to \pi^+ + \pi^+$	2	72 [115]
$pp \to \pi^+ + \rho^+$	2	
$pp \to \pi^+ + K^+$	2	
$pp \to \pi^+ + K^{*,+}$	2	
$pp \to \rho^+ + \rho^+$	2	
$pp \to \rho^+ + K^+$	2	
$pp \to \rho^+ + K^{*,+}$	2	
$pp \to K^+ + K^+$	2	170 [116]
$pp \to K^+ + K^{*,+}$	2	
$pp \to K^{*,+} + K^{*,+}$	2	



$nn \to e^+ + e^-$	2	4200 [72]
$nn \to e^+ + \mu^-$	2	4400 [72]
$nn \to \mu^+ + e^-$	2	4400 [72]
$nn \to \mu^+ + \mu^-$	2	4400 [72]
$nn \to e^+ + \tau^-$	2	
$nn \to \tau^+ + e^-$	2	
$nn \to 2\nu$	0,2,4	1.4 [83]
$nn \to 2\gamma$	2	4100 [72]
$nn \to \gamma + \pi^0$	2	
$nn \to \gamma + \eta$	2	
$nn \to \gamma + \rho^0$	2	
$nn \to \gamma + \omega$	2	
$nn \to \gamma + \eta'$	2	
$nn \to \gamma + K^0$	2	
$nn \to \gamma + K^{*,0}$	2	
$nn \to \gamma + D^0$	2	
$nn \to \gamma + \phi$	2	
$nn \to \pi^- + \pi^+$	2	0.7 [62] (72^* [115])
$nn \to \pi^+ + \rho^-$	2	
$nn \to K^- + \pi^+$	2	
$nn \to K^{*,-} + \pi^+$	2	
$nn \to \pi^- + \rho^+$	2	
$nn \to K^+ + \pi^-$	2	
$nn \to K^{*,+} + \pi^-$	2	
$nn \to 2\pi^0$	2	404 [115]
$nn \to \eta + \pi^0$	2	
$nn \to \pi^0 + \rho^0$	2	
$nn \to \pi^0 + \omega$	2	
$nn \to \eta' + \pi^0$	2	
$nn \to K^0 + \pi^0$	2	
$nn \to K^{*,0} + \pi^0$	2	



Channel	$\lvert\Delta(B-L)\rvert$	$\frac{\Gamma^{-1}}{10^{30}\,\text{yr}}$
$nn \to \pi^0 + \phi$	2	
$nn \to 2\eta$	2	
$nn \to \eta + \rho^0$	2	
$nn \to \eta + \omega$	2	
$nn \to \eta + \eta'$	2	
$nn \to \eta + K^0$	2	
$nn \to \eta + K^{*,0}$	2	
$nn \to \eta + \phi$	2	
$nn \to 2\rho^0$	2	
$nn \to \rho^0 + \omega$	2	
$nn \to \eta' + \rho^0$	2	
$nn \to K^0 + \rho^0$	2	
$nn \to K^{*,0} + \rho^0$	2	
$nn \to \rho^0 + \phi$	2	
$nn \to \rho^- + \rho^+$	2	
$nn \to K^+ + \rho^-$	2	
$nn \to K^{*,+} + \rho^-$	2	
$nn \to K^- + \rho^+$	2	
$nn \to K^{*,-} + \rho^+$	2	
$nn \to 2\omega$	2	
$nn \to \eta' + \omega$	2	
$nn \to K^0 + \omega$	2	
$nn \to K^{*,0} + \omega$	2	
$nn \to \omega + \phi$	2	
$nn \to \eta' + K^0$	2	
$nn \to \eta' + K^{*,0}$	2	
$nn \to K^- + K^+$	2	170^* [116]
$nn \to K^+ + K^{*,-}$	2	
$nn \to K^- + K^{*,+}$	2	
$nn \to 2K^0$	2	
$nn \to K^{*,0} + K^0$	2	
$nn \to K^0 + \phi$	2	
$nn \to 2K^{*,0}$	2	
$nn \to K^{*,-} + K^{*,+}$	2	



Channel	$\lvert\Delta(B-L)\rvert$	$\frac{\Gamma^{-1}}{10^{30}\,\text{yr}}$
$pn \to e^+ + \nu$	0,2	260 [28]
$pn \to \mu^+ + \nu$	0,2	200 [28]
$pn \to \tau^+ + \nu$	0,2	29 [28]
$pn \to \gamma + \pi^+$	2	
$pn \to \gamma + \rho^+$	2	
$pn \to \gamma + K^+$	2	
$pn \to \gamma + K^{*,+}$	2	
$pn \to \gamma + D^+$	2	
$pn \to \pi^+ + \pi^0$	2	170 [115]
$pn \to \eta + \pi^+$	2	
$pn \to \pi^+ + \rho^0$	2	
$pn \to \pi^+ + \omega$	2	
$pn \to \eta' + \pi^+$	2	
$pn \to K^0 + \pi^+$	2	
$pn \to K^{*,0} + \pi^+$	2	
$pn \to \pi^+ + \phi$	2	
$pn \to \pi^0 + \rho^+$	2	
$pn \to K^+ + \pi^0$	2	
$pn \to K^{*,+} + \pi^0$	2	
$pn \to \eta + \rho^+$	2	
$pn \to \eta + K^+$	2	
$pn \to \eta + K^{*,+}$	2	
$pn \to \rho^+ + \rho^0$	2	
$pn \to K^+ + \rho^0$	2	
$pn \to K^{*,+} + \rho^0$	2	
$pn \to \rho^+ + \omega$	2	
$pn \to \eta' + \rho^+$	2	
$pn \to K^0 + \rho^+$	2	
$pn \to K^{*,0} + \rho^+$	2	
$pn \to \rho^+ + \phi$	2	
$pn \to K^+ + \omega$	2	
$pn \to K^{*,+} + \omega$	2	
$pn \to \eta' + K^+$	2	
$pn \to \eta' + K^{*,+}$	2	
$pn \to K^+ + K^0$	2	
$pn \to K^+ + K^{*,0}$	2	
$pn \to K^+ + \phi$	2	
$pn \to K^{*,+} + K^0$	2	
$pn \to K^{*,+} + K^{*,0}$	2	

[**JH**, Takhistov, PRD ‘20]

ppp → $e^+\pi^+\pi^+$

- Symmetry

	Q	u^c	d^c	ℓ	e^c	ν^c	H
Z_6	6	5	1	2	5	3	1

$\mathbb{Z}_6 \subset \mathrm{U}(1)_{2Y-B+3L}$

[Babu, Gogoladze, Wang, ‘03]

allows for d = 15 $\Delta B = 3\Delta L = 3$ operators $\frac{1}{\Lambda^{11}} Q^5 d^4 \overline{\ell}, \ldots$

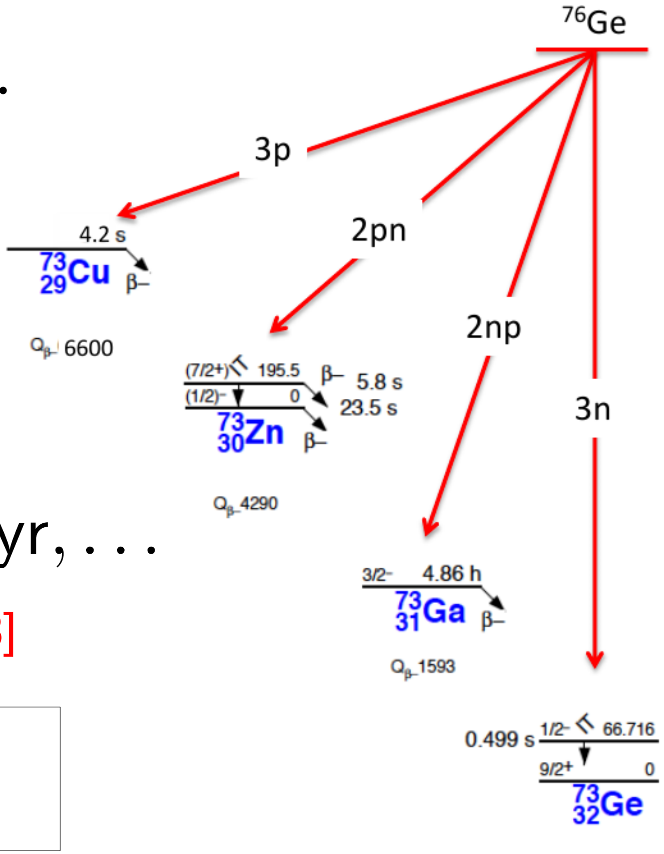
- $ppp \to e^+\pi^+\pi^+$, $ppn \to e^+\pi^+$, $pnn \to e^+\pi^0$, $nn \to \bar{n}\bar{\nu}, \ldots$
- $\tau(pnn \to e^+\pi^0) \simeq 3 \times 10^{33}\,\mathrm{yr}\left(\frac{\Lambda}{100\,\mathrm{GeV}}\right)^{22}.$
- Limits:

$\tau(^{73}\mathrm{Ge}(pnn) \to {}^{70}\mathrm{Ga}\, e^+\pi^0) > 7 \times 10^{23}\,\mathrm{yr},$

$\tau(^{76}\mathrm{Ge}(ppn) \to {}^{73}\mathrm{Zn}\, e^+\pi^+) > 5 \times 10^{25}\,\mathrm{yr},$

$\tau(^{76}\mathrm{Ge}(ppp) \to {}^{73}\mathrm{Cu}\, e^+\pi^+\pi^+) > 5 \times 10^{25}\,\mathrm{yr}, \ldots$

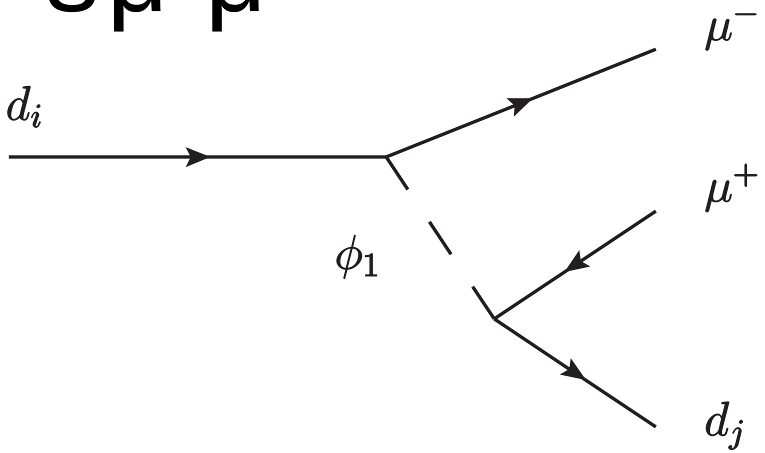
[Majorana Demonstrator, PRD ‘19; see also EXO-200, ‘18]



SK, JUNO, DUNE, HK?

[Hambye, **JH**, PRL ‘18]

Lepton universality in $b\to s\mu^-\mu^+$



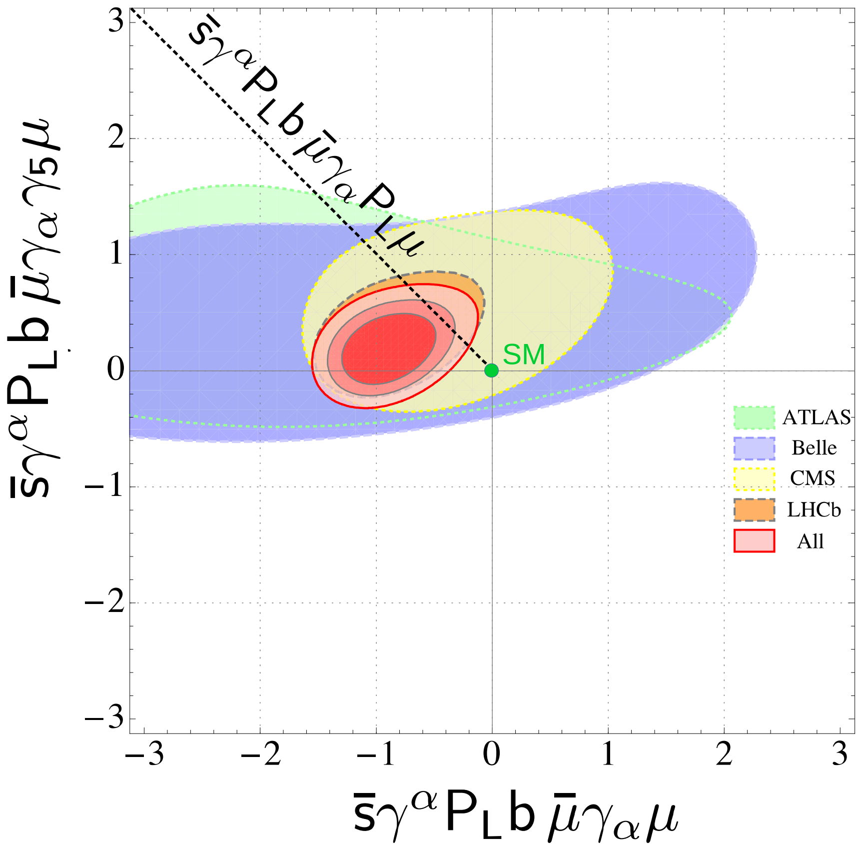
- $\frac{y_j\bar{y}_i}{m^2_{\phi_1}}(\overline{L}_\mu Q^c_j)(Q_i L_\mu)$.
- Modifies $b\to s\mu^-\mu^+$:

$$R(K^{(*)}) = \frac{B\to K^{(*)}\mu^+\mu^-}{B\to K^{(*)}e^+e^-} .$$

- LHCb: R(K)~0.85,
  R(K*)~0.67.
- Improve fit with

$$m_{\phi_1} \simeq 30\,\mathrm{TeV}\sqrt{y_2 y_3} .$$

[Alok+, PRD ‘17; Dorsner+, JHEP ‘17;
Capdevila+, JHEP ‘18, Algueró+, EPJC ‘19]



[Algueró+, EPJC ‘19]