The landscape of baryon number violation

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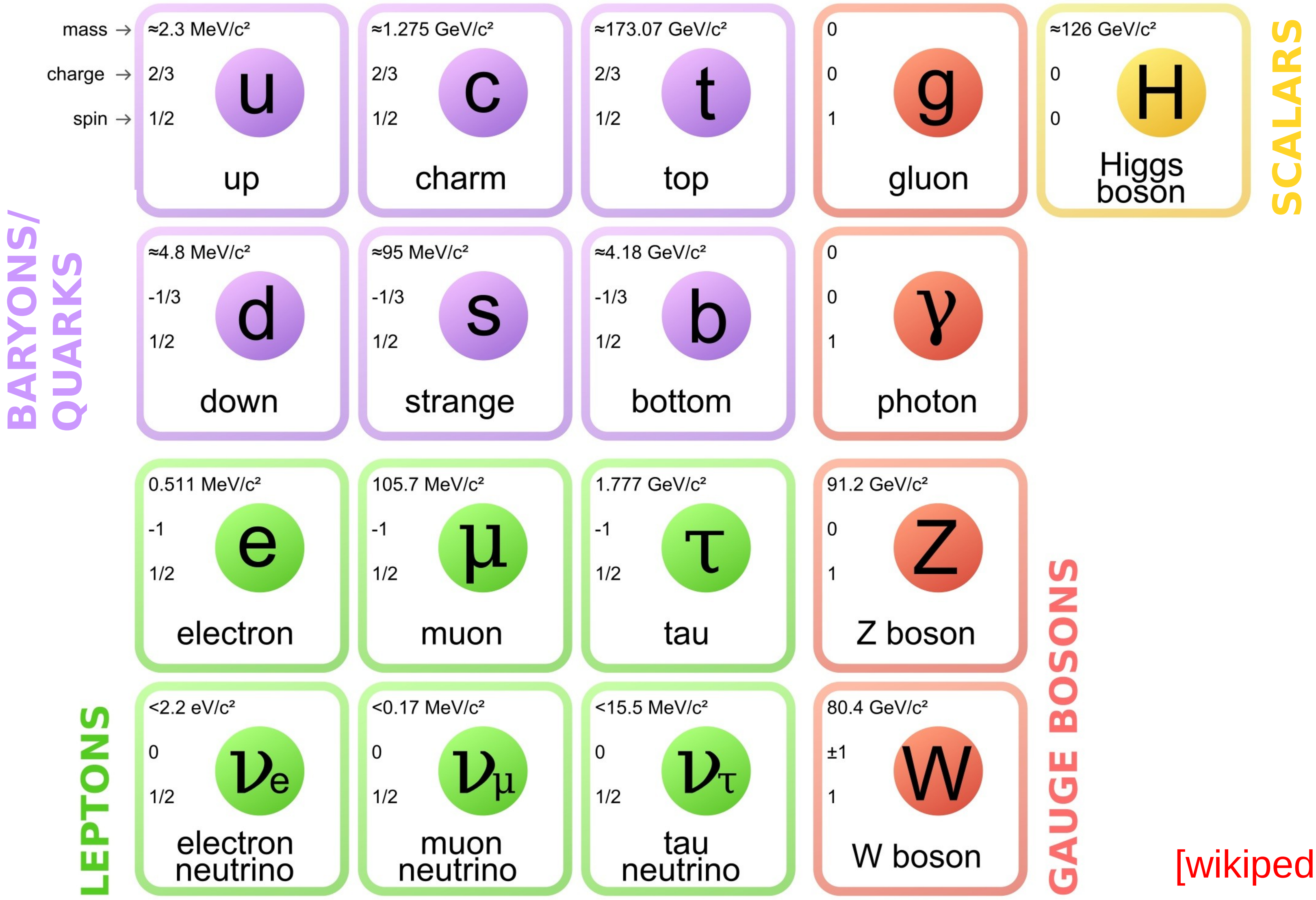
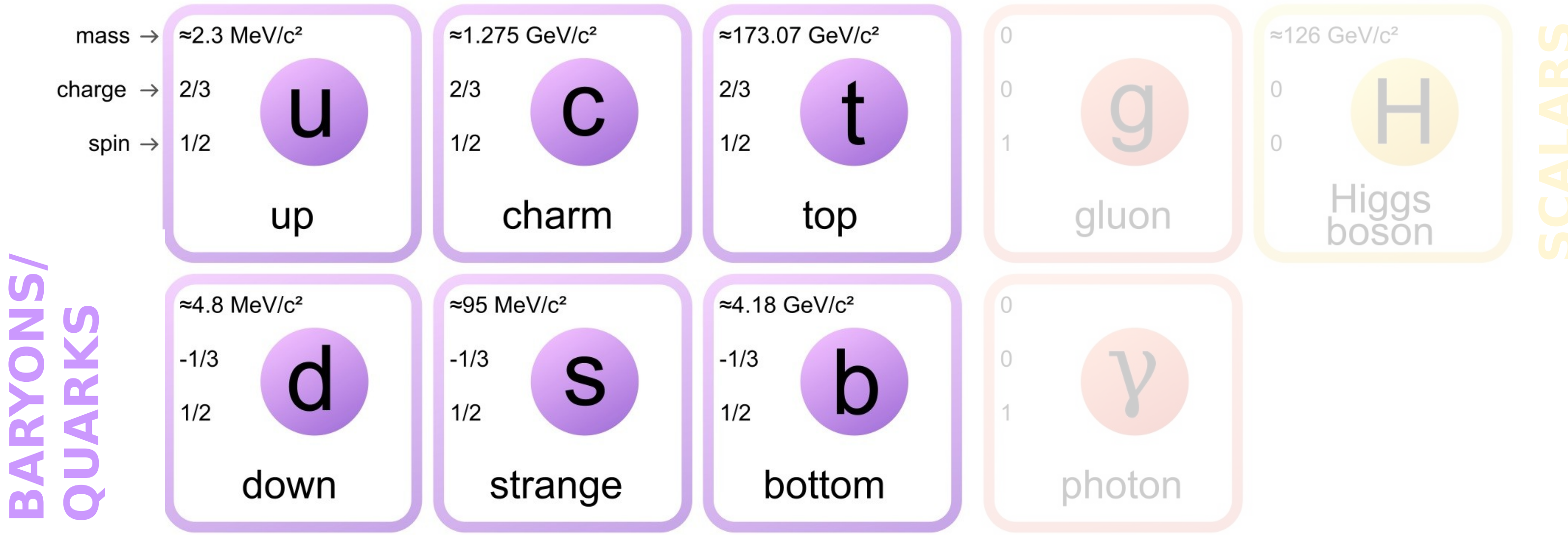
Elementary particles



[wikipedia]

Elementary particles



Assign $U(1)_B$ charge 1/3, rest uncharged.
(Proton & neutron then have B = 1.)

► global symmetry of SM Lagrangian!

Why baryon number violation?

- Tests prediction/symmetry of Standard Model:

$$\underbrace{U(1)_B}_{\text{BNV}} \times \underbrace{U(1)_L}_{\text{LNV}} \times \underbrace{U(1)_{L_\mu - L_\tau} \times U(1)_{L_\mu + L_\tau - 2L_e}}_{\text{LFV}} .$$

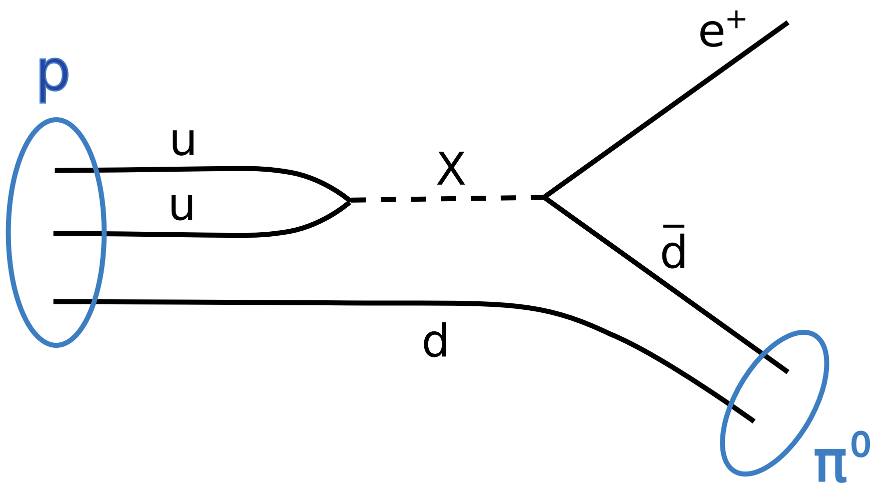
- Testable signatures in many extensions (GUTs, SUSY,…).
- Needed for spontaneous generation of matter asymmetry.

BNV is special: *most sensitive* probe of new physics because it probes decay of stable [*sic*] matter!

(LNV & LFV have to use unstable particles.)

Best example: proton decay

- First suggested in grand unified theories, predict lifetimes $\tau_p \sim m_X^4/m_p^5$
  [Pati & Salam '73; Georgi & Glashow, '74]
- Huge improvement in limits over ~50 yrs.

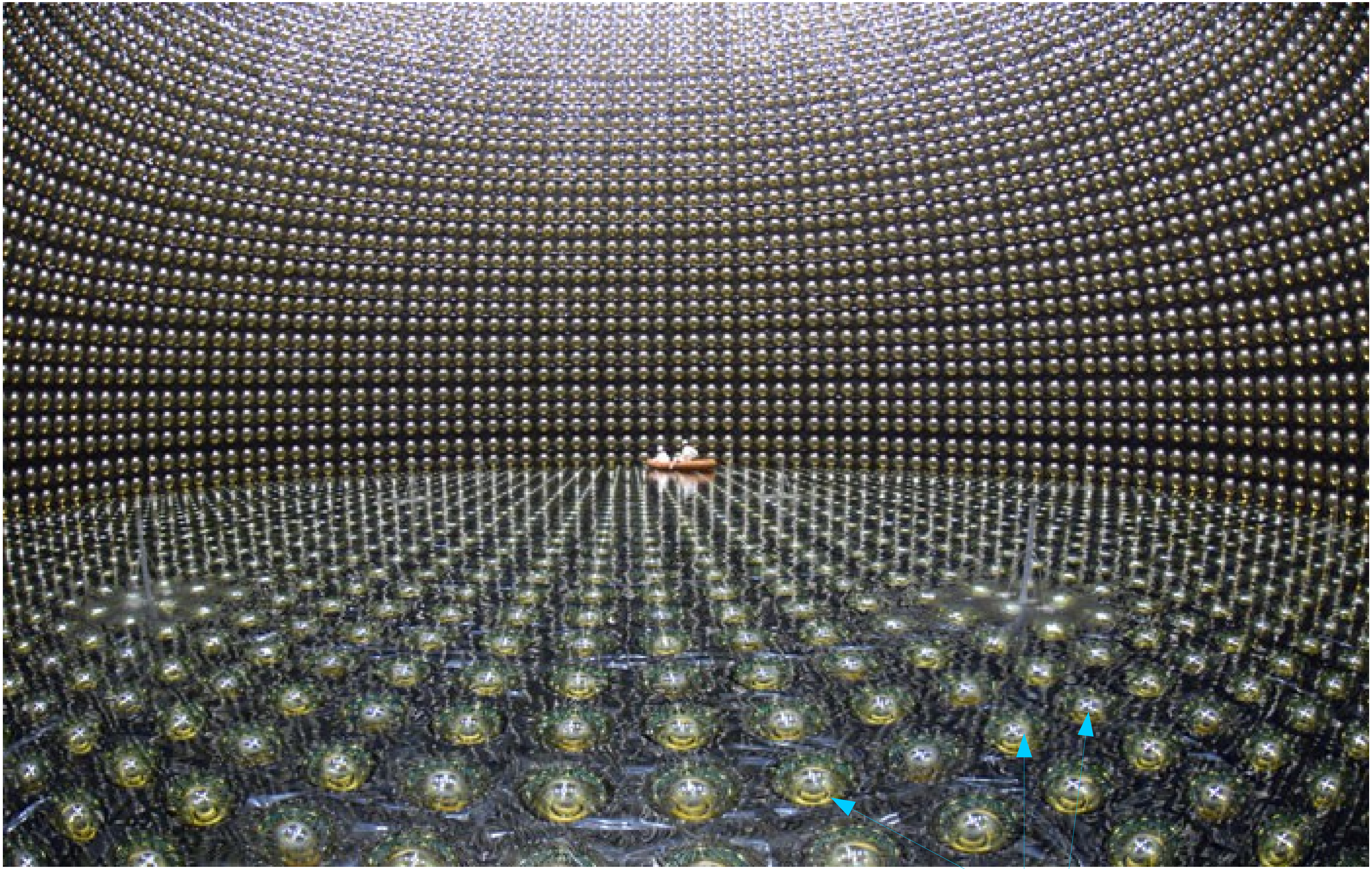


[wikipedia]

- Current best: Super-KamiokaNDE.
  - 50k tons of water in deep underground tank.
  - 13k photomultipliers to search for Cherenkov radiation.
  - Running for two decades, observing 10^{35} protons.

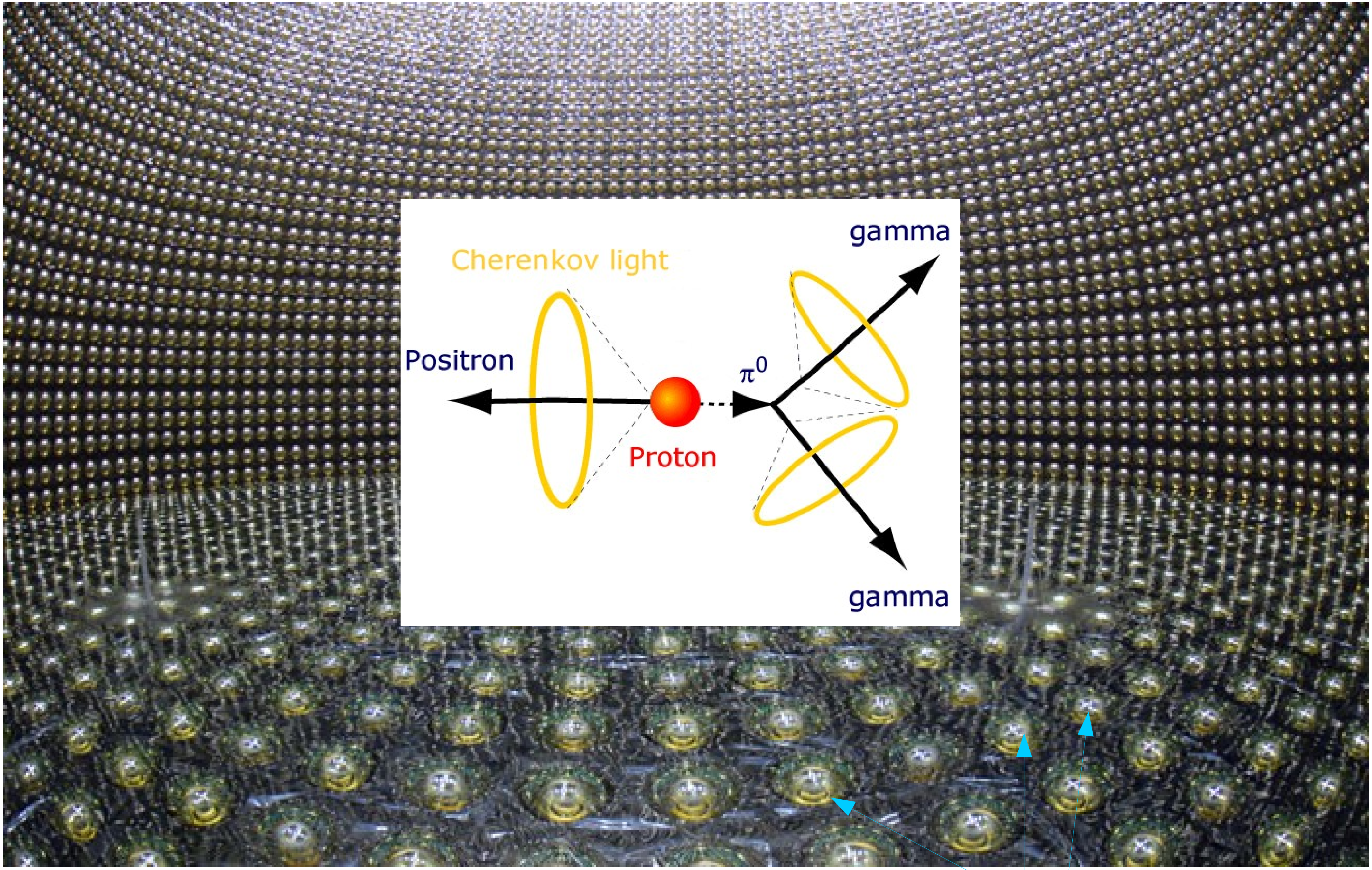
$$\tau_p(p \to e^+\pi^0) > 10^{34}\,\text{yr.}$$ [Super-K, 2010.16098]

  - Implies $m_X > 10^{15}$ GeV! [Fileviez Pérez, Pocar, **JH** et al, 2208.00010]



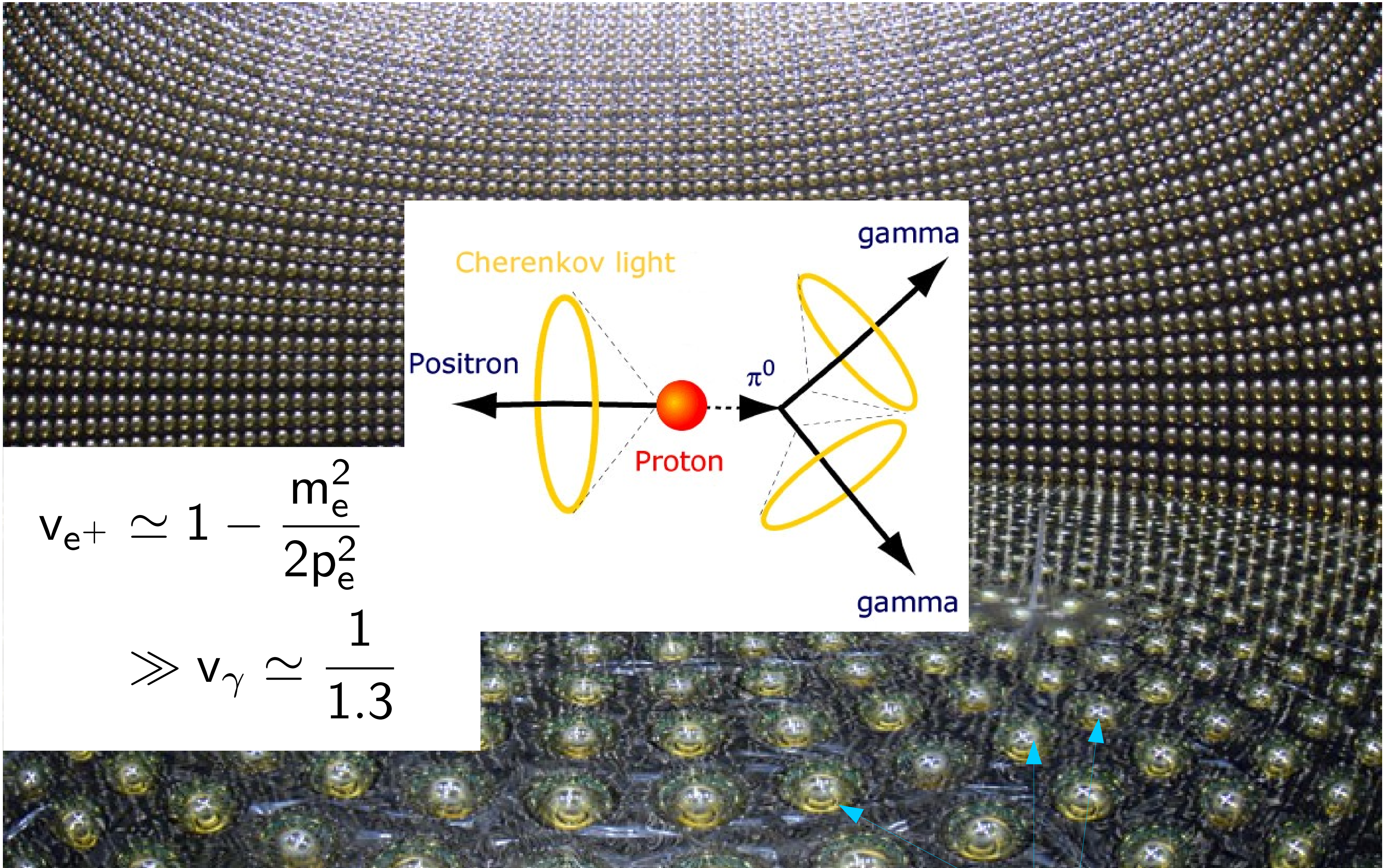
Super-Kamiokande

Photomultipliers



Super-Kamiokande

Photomultipliers

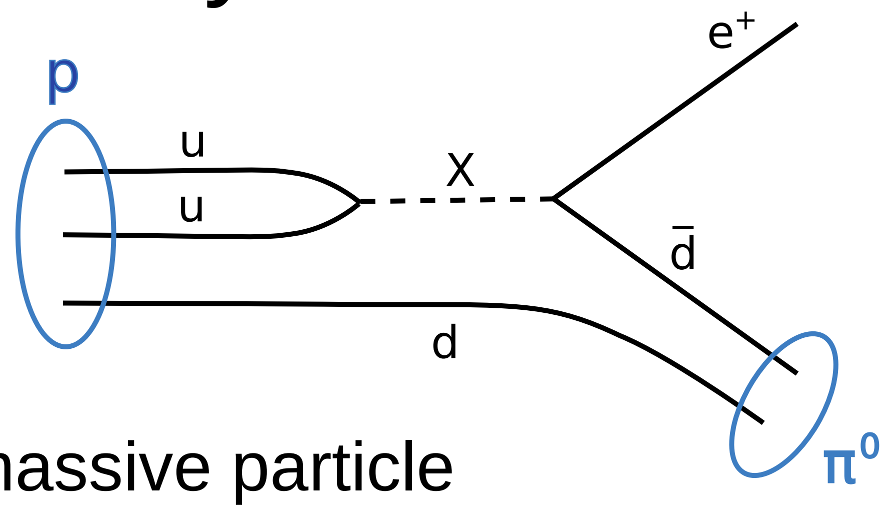


$$v_{e^+} \simeq 1 - \frac{m_e^2}{2p_e^2}$$

$$\gg v_\gamma \simeq \frac{1}{1.3}$$

Super-Kamiokande

Best example: proton decay



- Super-Kamiokande:

  $\tau_{\mathrm{p}}(\mathrm{p} \to \mathrm{e}^+\pi^0) > 10^{34}\,\mathrm{yr}.$

  $m_X > 10^{15}\,\mathrm{GeV}!$

- Makes proton the most stable massive particle we know, lifetime exceeds age of universe by 10^{24}, a million billion billion!

- Indirect probe of mass scales up to 10^{11} x E_{LHC}!

Sensitivity of BNV also allows to probe other models, initial states, final states, $\underbrace{\Delta B > 1}_{\text{Tank is not pure hydrogen!}}$, ...

[Fileviez Pérez, Pocar, **JH** et al, 2208.00010]

Underground detectors

	Super-K	**JUNO**	**Hyper-K**	**DUNE**
Location	Japan	China	Japan	USA
Geometry	Cylinder 42m height × 39m diameter	Sphere 35.4m diameter	Cylinder 60m height × 74m diameter	Cuboid (4 modules) 58.2m × 14.0m × 12.0m
Detector Material	Water	LABs	Water	Liquid Argon
Working Principle	Cherenkov	Scintillation	Cherenkov	Scintillation
Fiducial Mass	22.5kt	20kt	187kt	40kt
# protons	8×10^{33}	7×10^{33}	6×10^{34}	1×10^{34}
# neutrons	6×10^{33}	5×10^{33}	5×10^{34}	1×10^{34}
Approx. Start Year	1996	2024	2027	2028

[adapted from Dreiner ++, 2403.18502]

- Hyper-K has generically the best sensitivity, will probe up to $\tau_p(p \to e^+\pi^0) \sim 10^{35}$ yr. [Hyper-K, 2203.02029]
- JUNO & DUNE could be useful for modes *without* Cherenkov radiation. [**JH**, Shoemaker, D. Sokhashvili, in progress]

Standard **M**odel **E**ffective **F**ield **T**heory

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

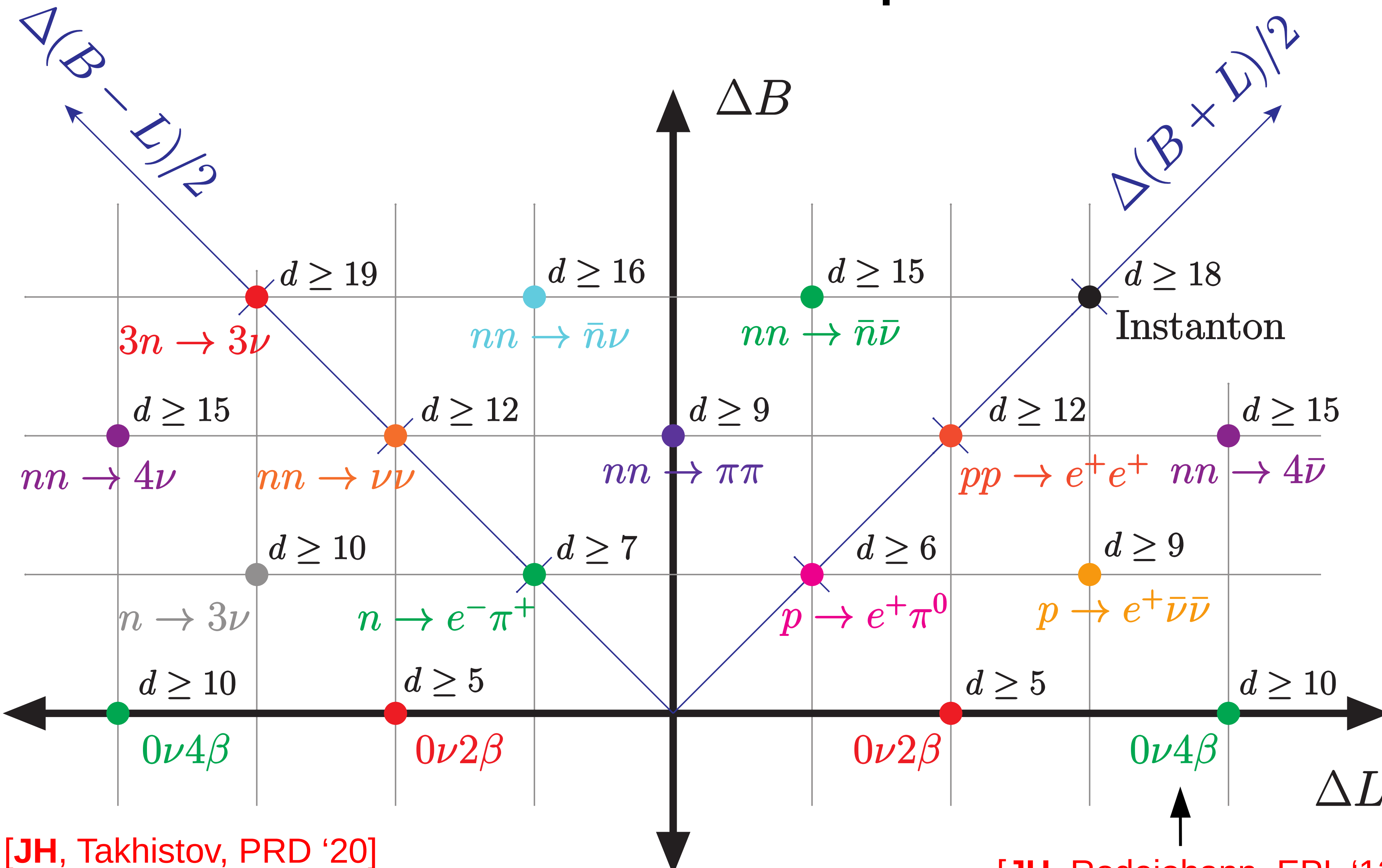
$$\mathrm{L} = \mathrm{L}_{\rm SM} + \frac{\mathrm{LLHH}}{\Lambda} + \sum_j \frac{\mathcal{O}_j}{\Lambda^2} + \sum_j \frac{\mathcal{O}'_j}{\Lambda^3} + \sum_j \frac{\mathcal{O}''_j}{\Lambda^4} + \ldots$$

$$\Delta L = 2 \qquad \Delta B = \Delta L = 1 \qquad \Delta B = -\Delta L = 1$$

- $d_{\rm min} \geq \frac{9}{2}|\Delta B| + \frac{3}{2}|\Delta L|\,.$ [Kobach '16; Helset, Kobach, '19]
- BNV sensitive to d >> 6, unlike any other experiment.
- ΔB dominated by d = 6, unless forbidden by symmetry! [Weinberg, '80]
- Some symmetry/hierarchy has to exist, otherwise

$$\Lambda \sim \langle H\rangle^2/M_\nu \sim 10^{14}\,\mathrm{GeV} \longrightarrow$$ Fast proton decay!

BNV landscape



[**JH**, Takhistov, PRD ‘20]

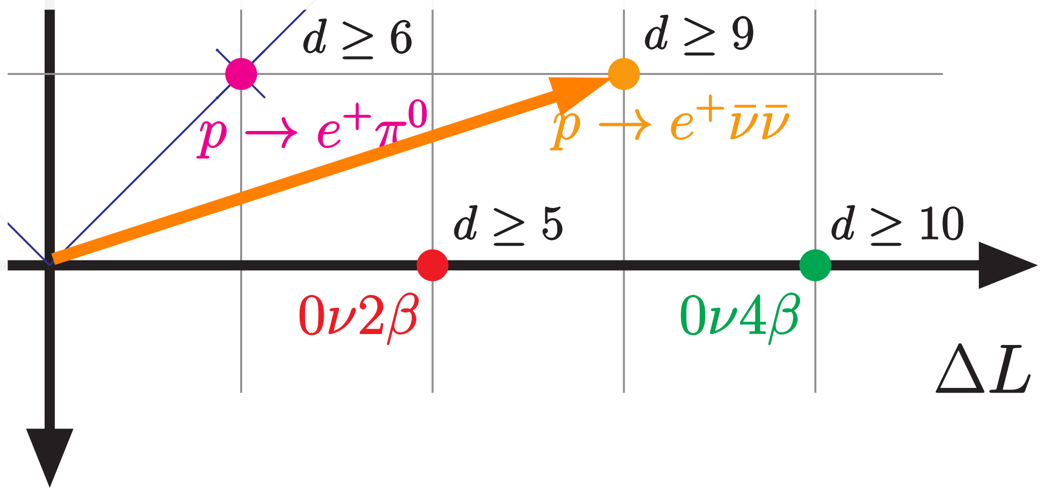
[**JH**, Rodejohann, EPL ‘13]
[NEMO-3, PRL ‘17]

Example for Weinberg's selection rules:

Impose $\mathrm{U}(1)_{3B-L}$ on SMEFT,
then the lowest BNV operators have ΔB = ΔL/3 = 1 and arise at d = 9.

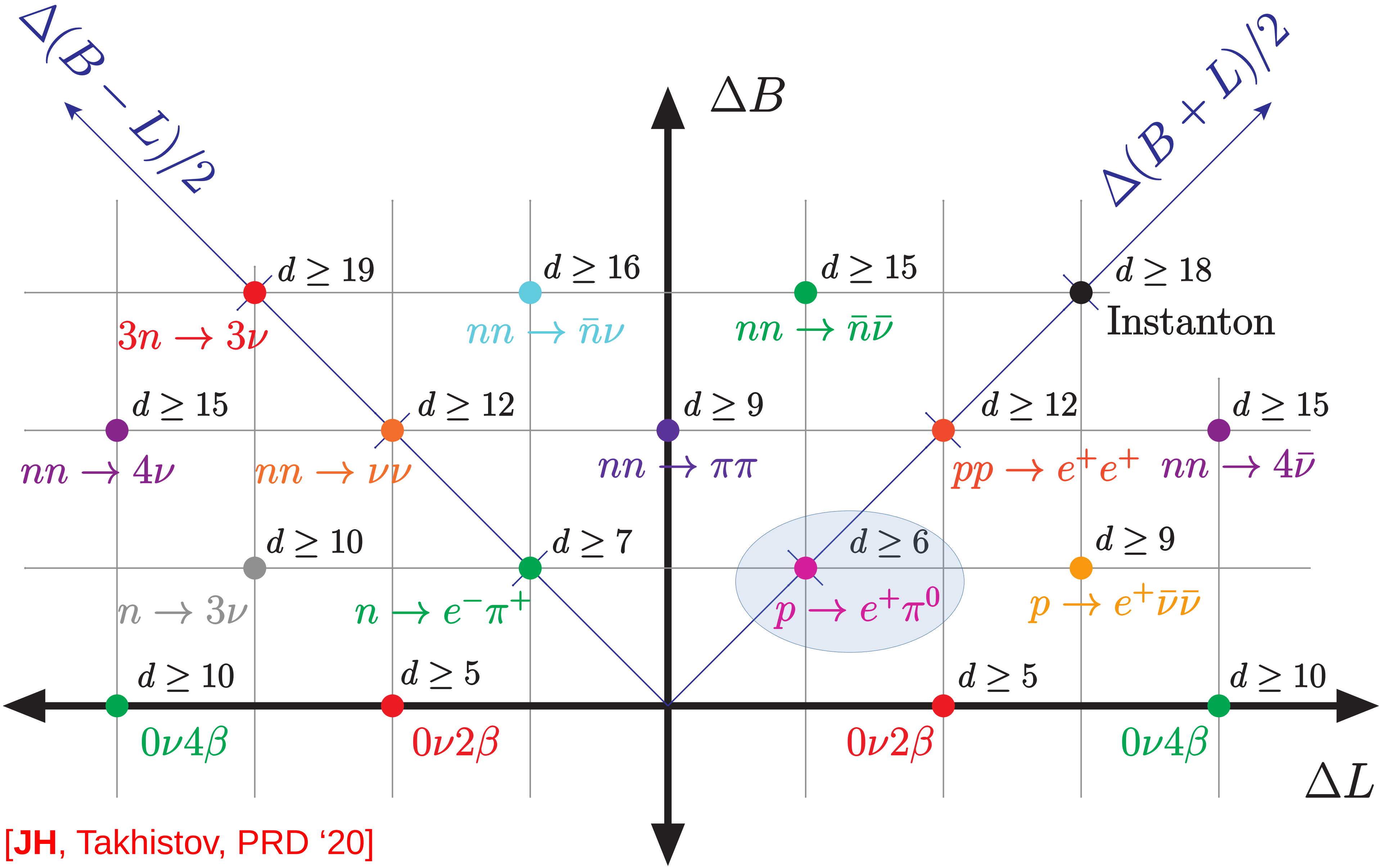
$$\tau(p \to e^+\bar{\nu}\bar{\nu}) \simeq \underbrace{2 \times 10^{32}\,\mathrm{yr}}_{\text{Super-K limit '14}} \left(\frac{\Lambda}{300\,\mathrm{TeV}}\right)^{10} .$$

BNV sensitive to d >> 6 and multi-body final states!



[JH, Takhistov, PRD '20]

Probing the landscape point by point?



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

$\Delta B = \Delta L = 1$

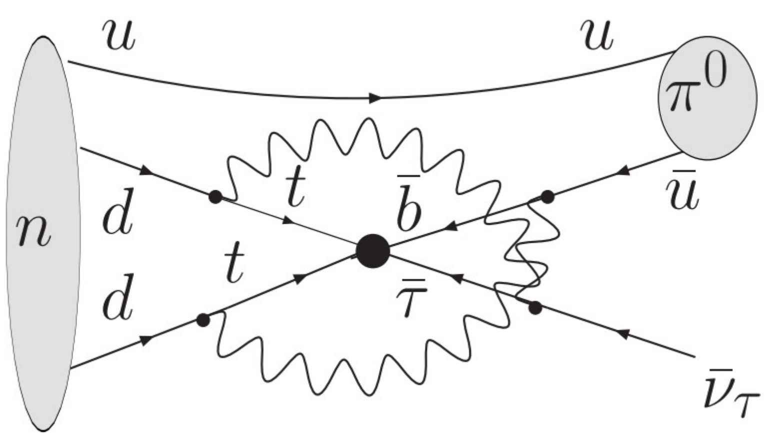
- 546 d=6 operators:

$$y^1_{abcd}\epsilon^{\alpha\beta\gamma}(\overline{d}^C_{a,\alpha}u_{b,\beta})(\overline{Q}^C_{i,c,\gamma}\epsilon_{ij}L_{j,d})$$
$$+\,y^2_{abcd}\epsilon^{\alpha\beta\gamma}(\overline{Q}^C_{i,a,\alpha}\epsilon_{ij}Q_{j,b,\beta})(\overline{u}^C_{c,\gamma}\ell_d)$$
$$+\,y^3_{abcd}\epsilon^{\alpha\beta\gamma}\epsilon_{il}\epsilon_{jk}(\overline{Q}^C_{i,a,\alpha}Q_{j,b,\beta})(\overline{Q}^C_{k,c,\gamma}L_{l,d})$$
$$+\,y^4_{abcd}\epsilon^{\alpha\beta\gamma}(\overline{d}^C_{a,\alpha}u_{b,\beta})(\overline{u}^C_{c,\gamma}\ell_d) + \text{h.c.}$$

  [Weinberg, ‘79 & ‘80;
  Wilczek & Zee ‘79]

- All induce 2-body nucleon decays, even those with c,b,t,τ.

  [Marciano, NPB ‘95;
  Hou, Nagashima, Soddu, PRD ‘05;
  Gargalionis, Herrero-García, Schmidt, 2401.04768;
  Gisbert++, 2409.00218]



- d=6 BNV “covered” via simple two-body searches.

  [**JH**, Takhistov, PRD ‘20]

Two-body nucleon decays (38)

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]

Many of these limits are 25 years old (IMB).

$n \to e^- + \pi^+$	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]

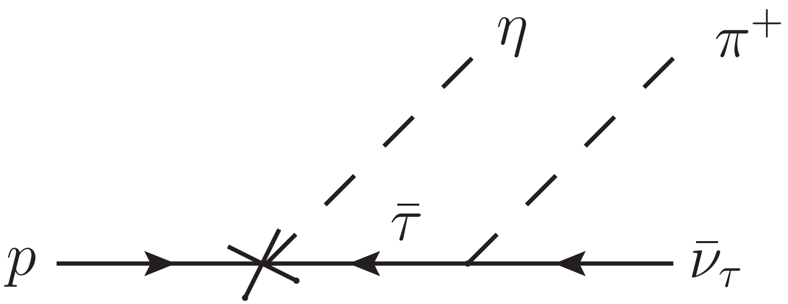
Subdominant two-body decays

- Heavier fermions induce multi-body decays, e.g. tau:

$$\frac{y^1}{\Lambda^2}\mathrm{duQL}_\tau + \frac{y^2}{\Lambda^2}\mathrm{QQQL}_\tau + \frac{y^3}{\Lambda^2}\mathrm{QQu}\ell_\tau + \frac{y^4}{\Lambda^2}\mathrm{duu}\ell_\tau$$

- Set $y^1 = y^2 = 0$ and $y^3 = y^4$, then dominant tree-level decay

$$\tau(\underbrace{p \to \eta\pi^+\bar{\nu}_\tau}_{\begin{array}{l}\text{Only old inclusive limits}\\ \text{[JH \& Takhistov, PRD '20],}\\ \text{could easily be improved by Super-K!}\end{array}}) \simeq 100\,\mathrm{yr}\left(\frac{10^{-5}}{\underbrace{\mathrm{BR}(\tau\to\bar{p}\eta)}_{\text{[CLEO '99]}}}\right)$$



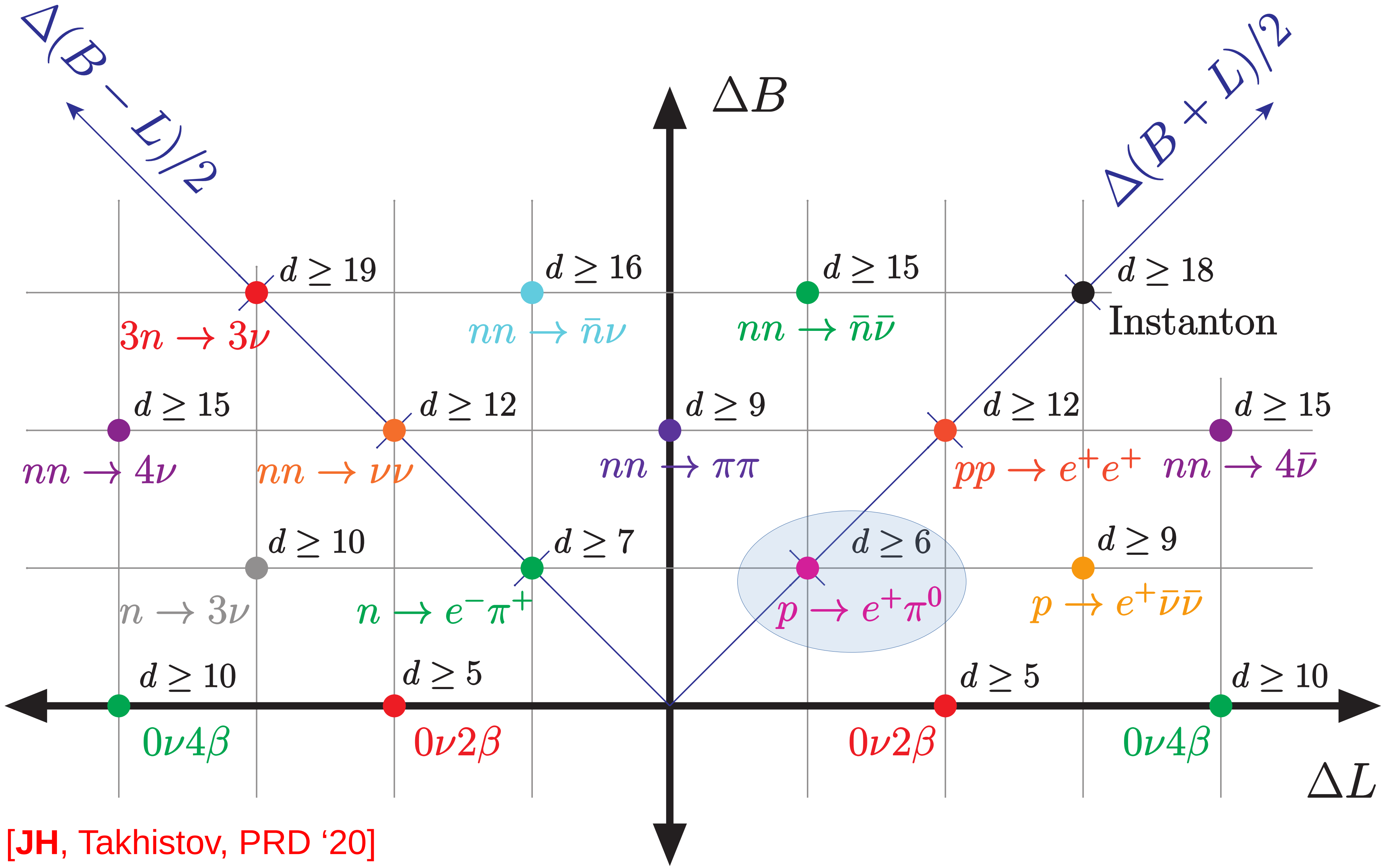
[**JH** & Watkins, 2405.18478]

- Similar for heavy quarks, multi-body decays could beat loop-induced two-body decays.

[related: Beneke, Finauri, Petrov, 2404.09642]

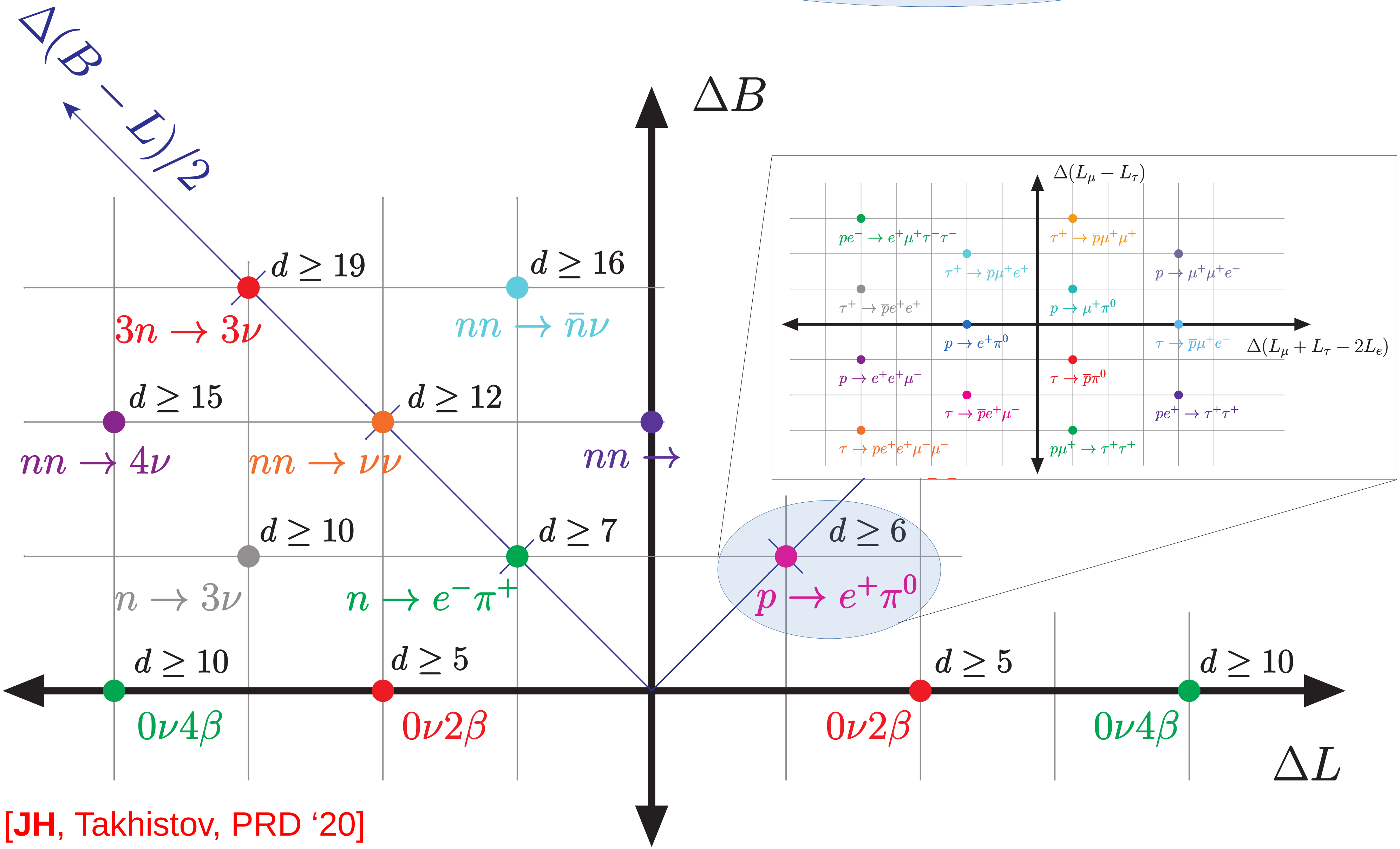
Only few multi-body limits from Super-K

ΔB = ΔL = 1 covered?



[**JH**, Takhistov, PRD ‘20]

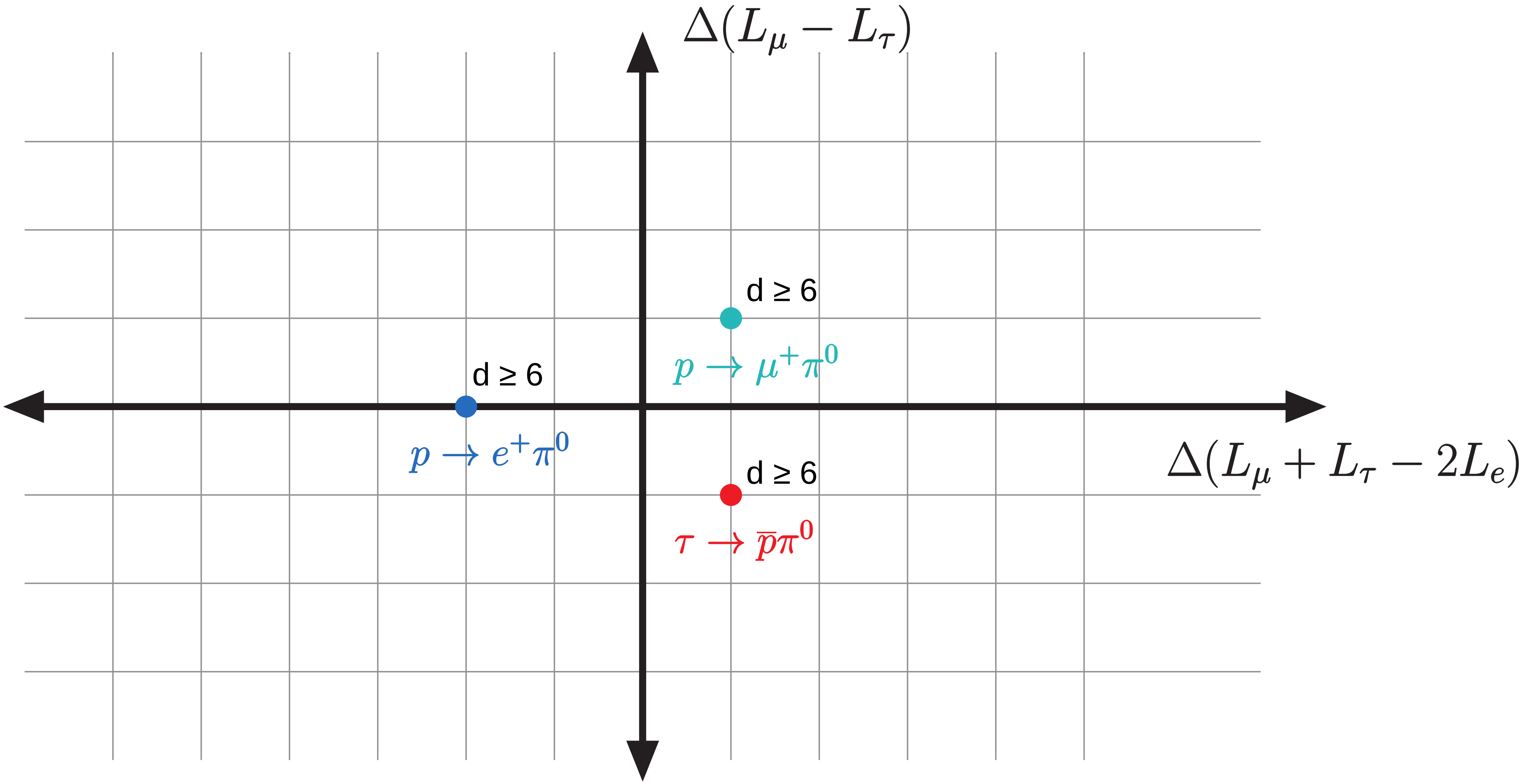
$$\mathrm{U(1)_B \times U(1)_L \times U(1)_{L_\mu - L_\tau} \times U(1)_{L_\mu + L_\tau - 2L_e}}\,.$$



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

Proton decay = lepton flavor violation

ΔB = ΔL = 1



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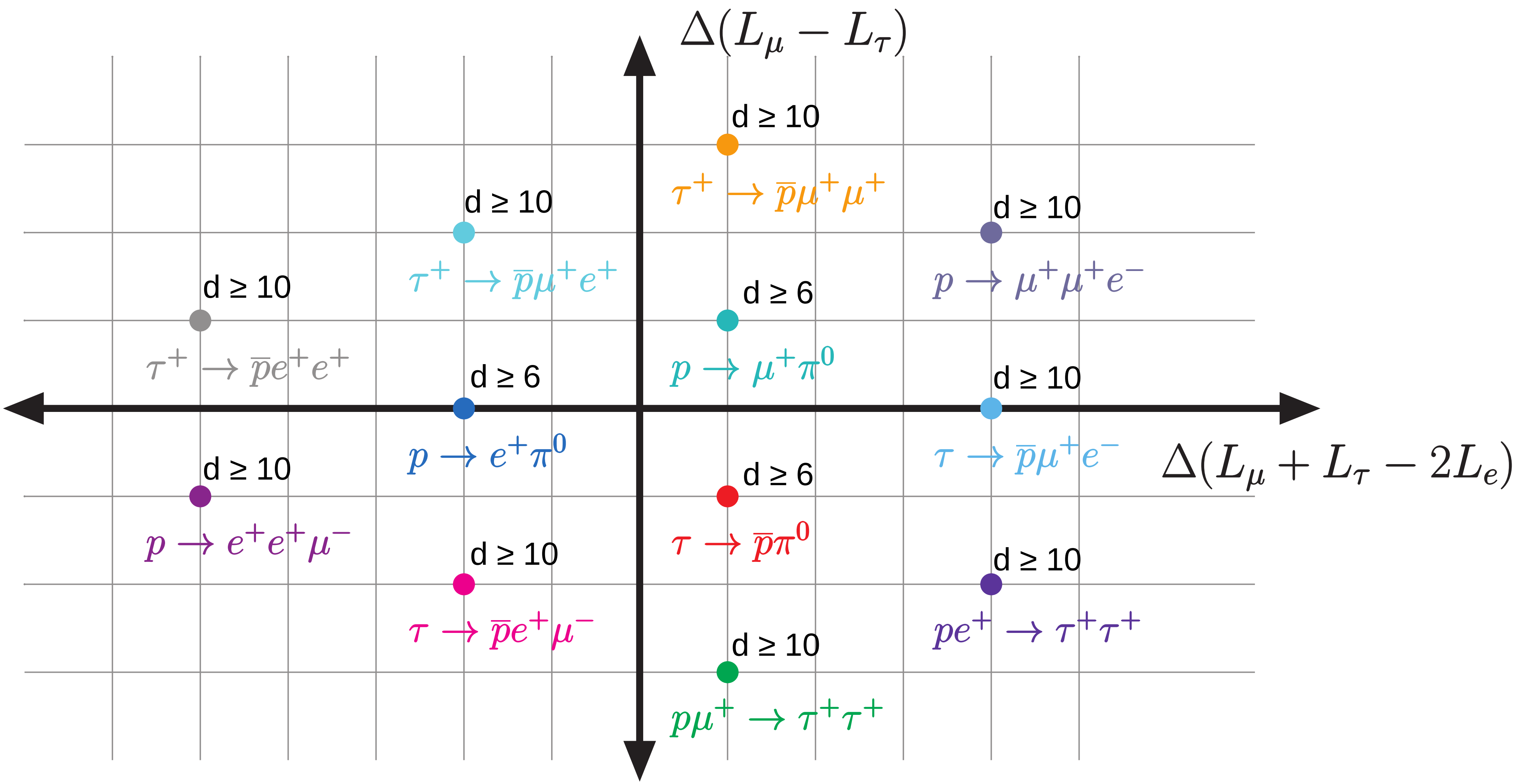

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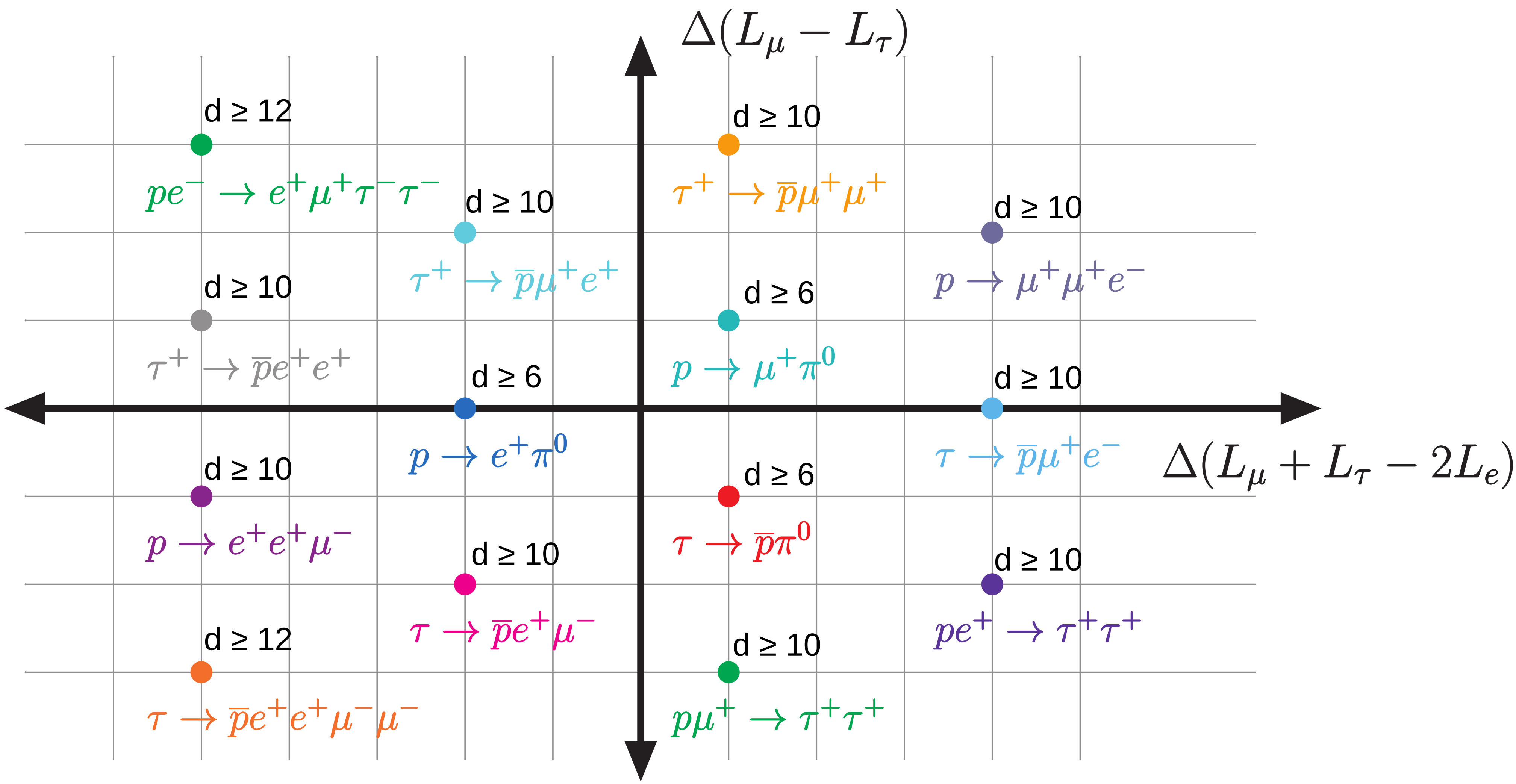
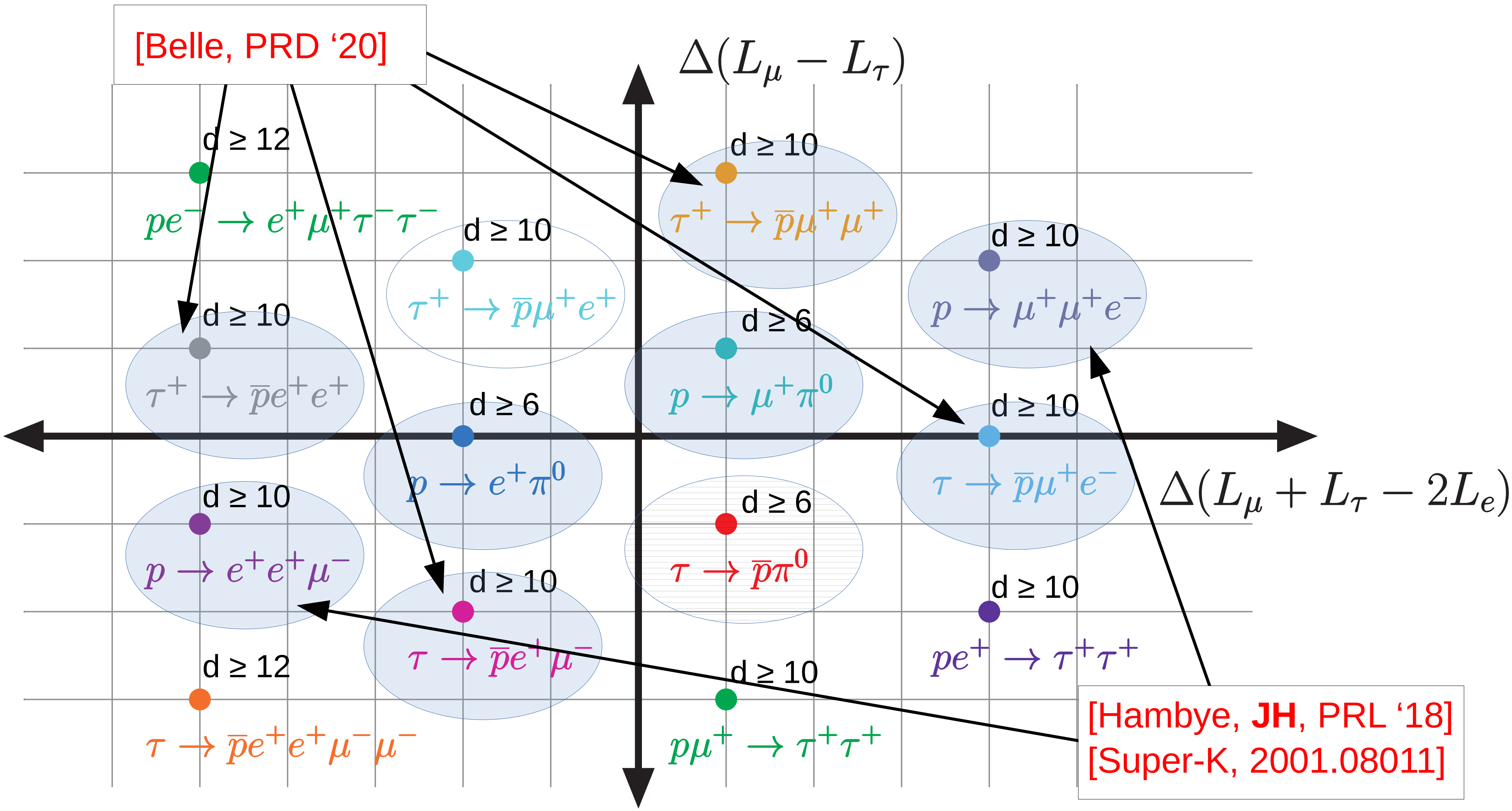


Currently being probed: Old results: Doable:

ΔB = ΔL = 1

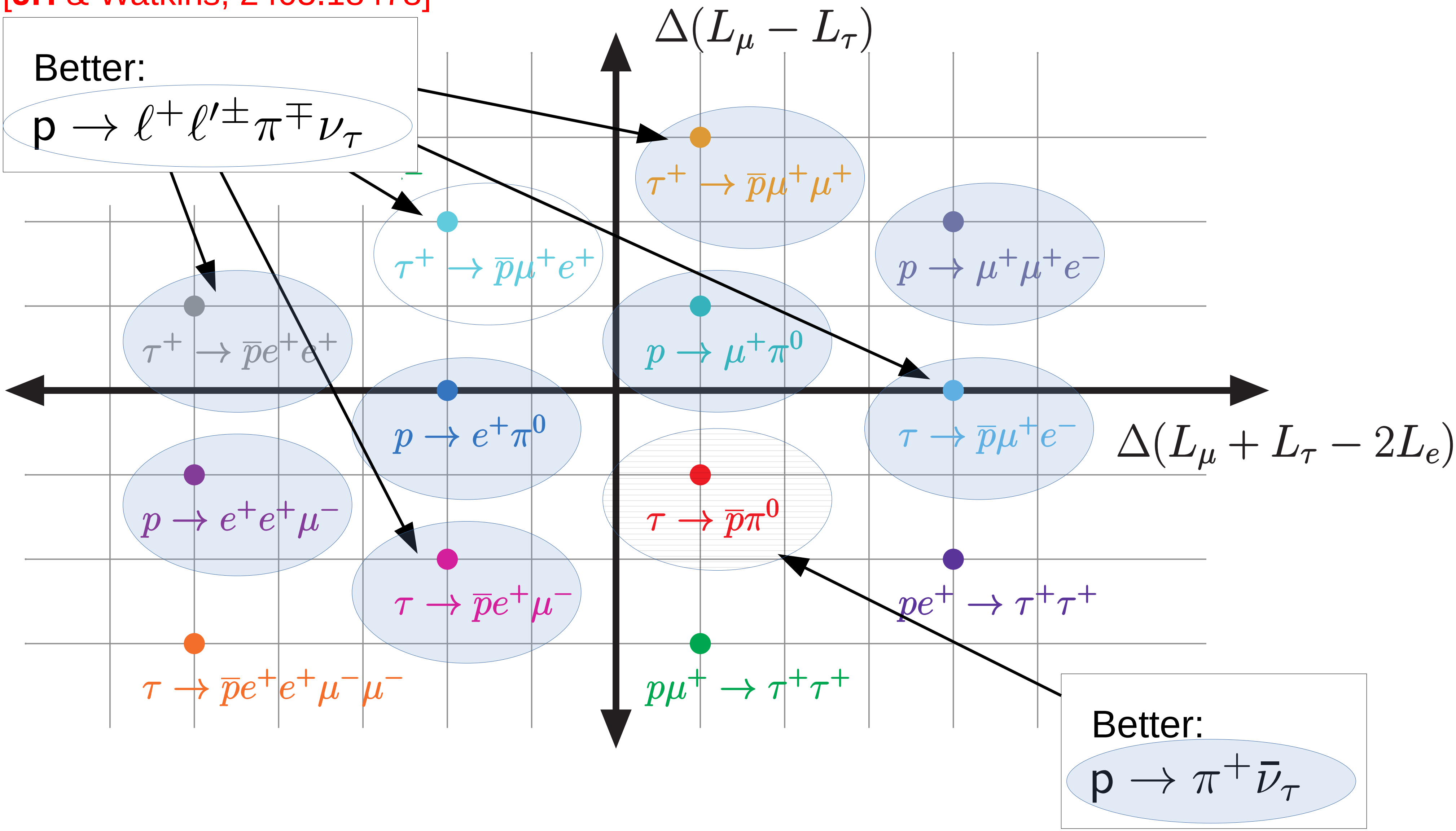


$$\tau(\mathrm{p} \to \mu^+\mu^+\mathrm{e}^-)$$
$$\simeq 10^{33}\mathrm{yr}\left(\frac{\Lambda}{100\mathrm{TeV}}\right)^{12}$$

Currently being probed: Old results: Doable:

ΔB = ΔL = 1

[**JH** & Watkins, 2405.18478]



[Marciano, NPB ‘95]

Full BNV coverage possible?

- Cannot to go through all $\Delta B > 0$ decays:
  - 38 two-body $\Delta B = 1$ modes: $N \to AB$. 36 limits.
  - 76 three-body $\Delta B = 1$ modes: $N \to ABC$. 33 limits.
  - 300 four-body $\Delta B = 1$ modes: $N \to ABCD$. 0 limits.
  - 118 two-body $\Delta B = 2$ modes: $NN \to AB$. 18 limits.
  - 500 three-body $\Delta B = 2$ modes: $NN \to ABC$. 0 limits.
  - ...
- *Exclusive* searches can reach $t \sim 10^{34}$ yr in Super-K.

Inclusive searches to the rescue!

Inclusive searches

- Current limits:

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

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

- 45 years old, improve with new tech!
- $p \to e^+ + \text{anything}$ 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 $N \to \ell$/meson + anything.
- Also probes $\Delta B > 1$, light new physics, and dark matter!

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

Invisible neutron decay

- Special case of inclusive searches:

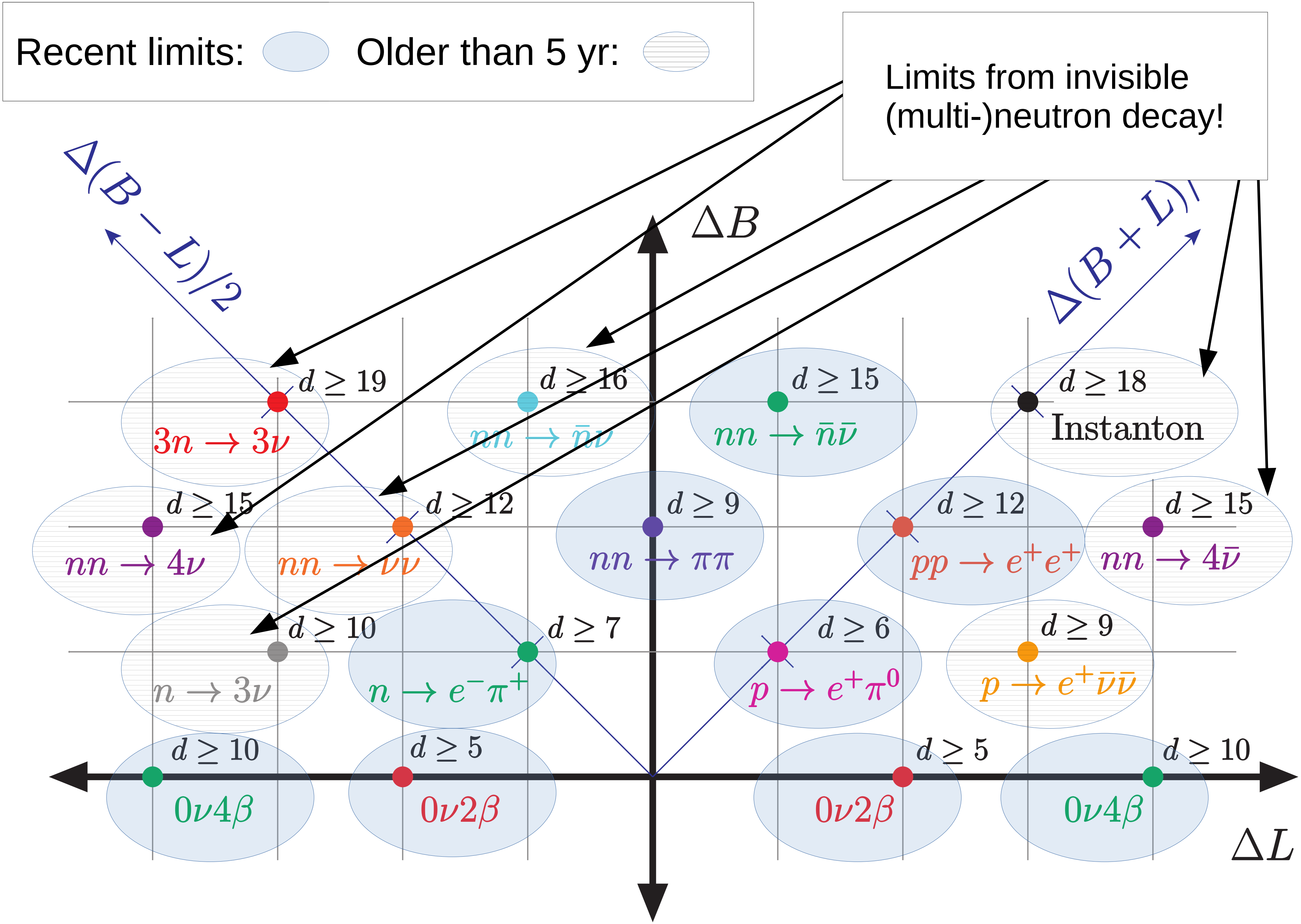
$$\Gamma^{-1}(\text{n} \to \text{neutrinos}) > 0.58 \times 10^{30}\,\text{yr},$$
$$\Gamma^{-1}(\text{nn} \to \text{neutrinos}) > 1.4 \times 10^{30}\,\text{yr},$$
$$\Gamma^{-1}(\text{nnn} \to \text{neutrinos}) > 1.8 \times 10^{23}\,\text{yr},$$
$$\Gamma^{-1}(\text{nnnn} \to \text{neutrinos}) > 1.4 \times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

[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.
- JUNO can improve KamLAND limit. [JUNO, 2405.17792]

[**JH**, Takhistov, PRD ‘20]



Recent limits:
Older than 5 yr:
Limits from invisible (multi-)neutron decay!
ΔB
ΔL
$\Delta(B-L)/2$
$\Delta(B+L)/2$
$d \geq 19$
$3n \to 3\nu$
$d \geq 16$
$nn \to \bar{n}\nu$
$d \geq 15$
$nn \to \bar{n}\bar{\nu}$
$d \geq 18$
Instanton
$d \geq 15$
$nn \to 4\nu$
$d \geq 12$
$nn \to \nu\nu$
$d \geq 9$
$nn \to \pi\pi$
$d \geq 12$
$pp \to e^+e^+$
$d \geq 15$
$nn \to 4\bar{\nu}$
$d \geq 10$
$n \to 3\nu$
$d \geq 7$
$n \to e^-\pi^+$
$d \geq 6$
$p \to e^+\pi^0$
$d \geq 9$
$p \to e^+\bar{\nu}\bar{\nu}$
$d \geq 10$
$0\nu4\beta$
$d \geq 5$
$0\nu2\beta$
$d \geq 5$
$0\nu2\beta$
$d \geq 10$
$0\nu4\beta$

Beyond SMEFT

- So far: SMEFT + “ $U(1)_B \times U(1)_L \times U(1)_{L_\mu - L_\tau} \times U(1)_{L_\mu + L_\tau - 2L_e}$“ to identify potentially dominant BNV.
- Now, find UV completions for BNV operators:
  - Generates a *physically motivated* operator basis;
  - Could have interesting *accidental symmetries*;
  - Useful to have in case of a *BNV observation*.
- Analogous to UV completions of ΔL=2 Weinberg operator. [too many to cite; exhaustive up to d=11: Gargalionis & Volkas, 2009.13537]
- UV completions for all SMEFT operators exist up to d = 8. [Li ++, 2309.15933]

Opening up d=6 operators

Leptoquark	spin	representation	Leptoquark	spin	representation
$\mathcal{S}_1$	0	$(\bar{\mathbf{3}},\mathbf{1},1/3)$	$\mathcal{S}_3$	0	$(\bar{\mathbf{3}},\mathbf{3},1/3)$
$\tilde{\mathcal{S}}_1$	0	$(\bar{\mathbf{3}},\mathbf{1},4/3)$	$\mathcal{V}_2$	1	$(\bar{\mathbf{3}},\mathbf{2},5/6)$
$\bar{\mathcal{S}}_1$	0	$(\bar{\mathbf{3}},\mathbf{1},-2/3)$	$\tilde{\mathcal{V}}_2$	1	$(\bar{\mathbf{3}},\mathbf{2},-1/6)$

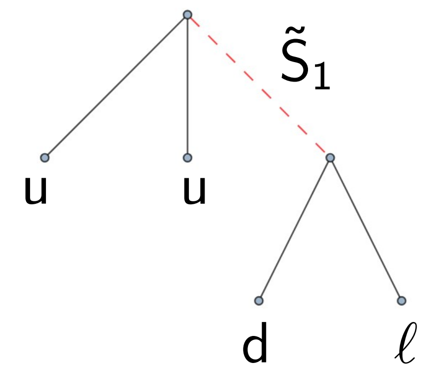
$duQL$	$\mathcal{S}_1,\ \mathcal{V}_2,\ \tilde{\mathcal{V}}_2$
$QQu\ell$	$\mathcal{S}_1,\ \mathcal{V}_2$
$QQQL$	$\mathcal{S}_1,\ \mathcal{S}_3$
$duu\ell$	$\mathcal{S}_1,\ \tilde{\mathcal{S}}_1$

[Buchmuller, Ruckl, Weyler, '87; Dorsner++, 1603.04993]

- For example:

$$\mathcal{L}_{\tilde{\mathcal{S}}_1} \supset -m^2_{\tilde{\mathcal{S}}_1}|\tilde{\mathcal{S}}_1|^2 + \left(\tilde{y}^{RR}_{1\,ab}\,\bar{d}^c_{R\,a}\tilde{\mathcal{S}}_1 e_{R\,b} + \tilde{z}^{RR}_{1\,ab}\,\bar{u}^c_{R\,a}\tilde{\mathcal{S}}^*_1 u_{R\,b} + \text{h.c.}\right)$$

$$\to \frac{2\,\tilde{y}^{RR}_{1\,ad}\ \tilde{z}^{RR}_{1\,bc}}{m^2_{\tilde{\mathcal{S}}_1}}\epsilon^{\alpha\beta\gamma}(\overline{d}^C_{a,\alpha}u_{b,\beta})(\overline{u}^C_{c,\gamma}\ell_d)\ + \text{h.c.}$$



- $\tilde{z}^{RR}_{1\,ab}$ is antisymmetric $\to$ charm or top quark BNV!

[Dong++, 1107.3805; Dorsner, Fajfer, Kosnik, 1204.0674]

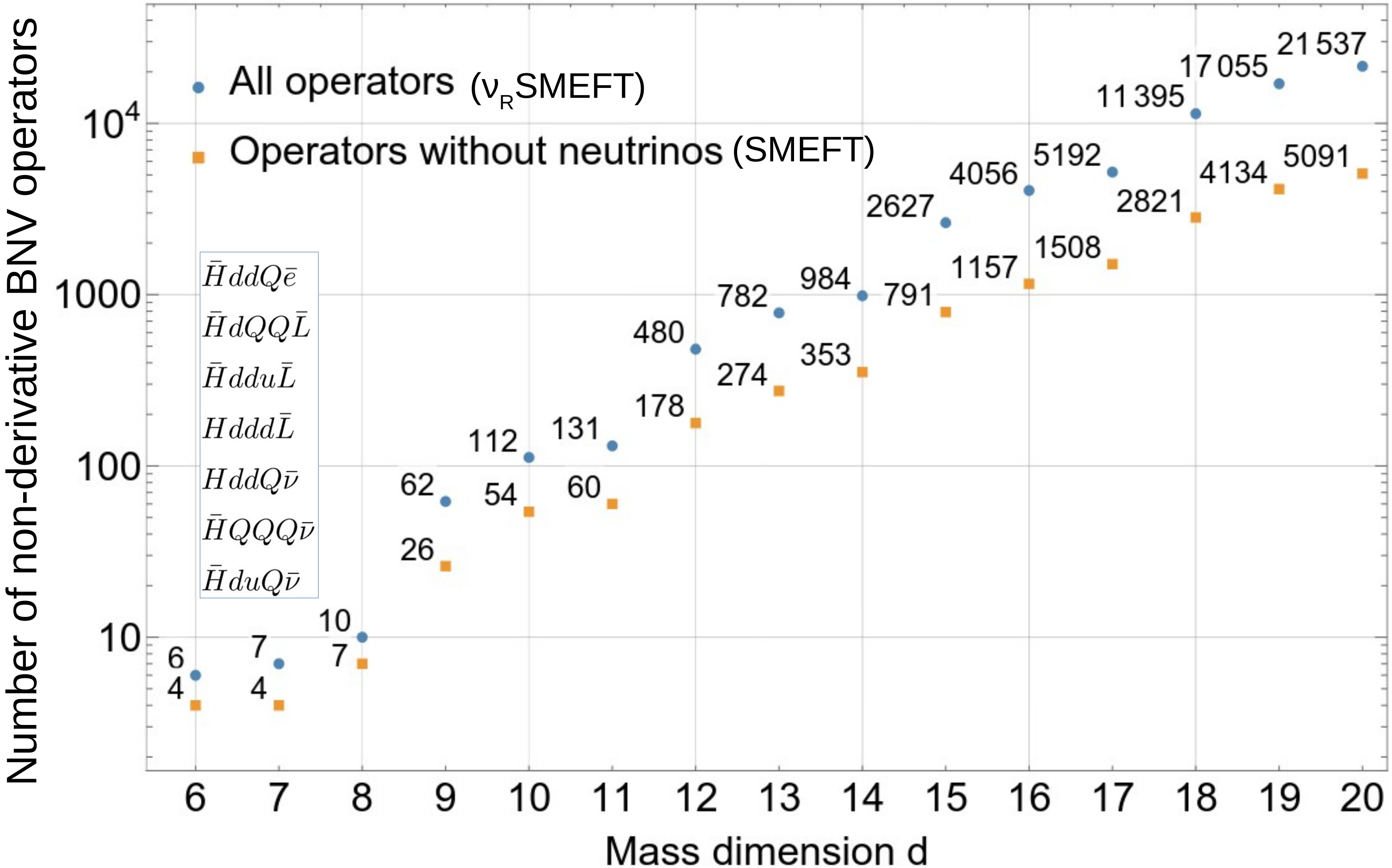
UV completions shed different light on BNV

Opening up *all* BNV operators

- Collect all ν_RSMEFT BNV operators, trivial with Sym2Int.

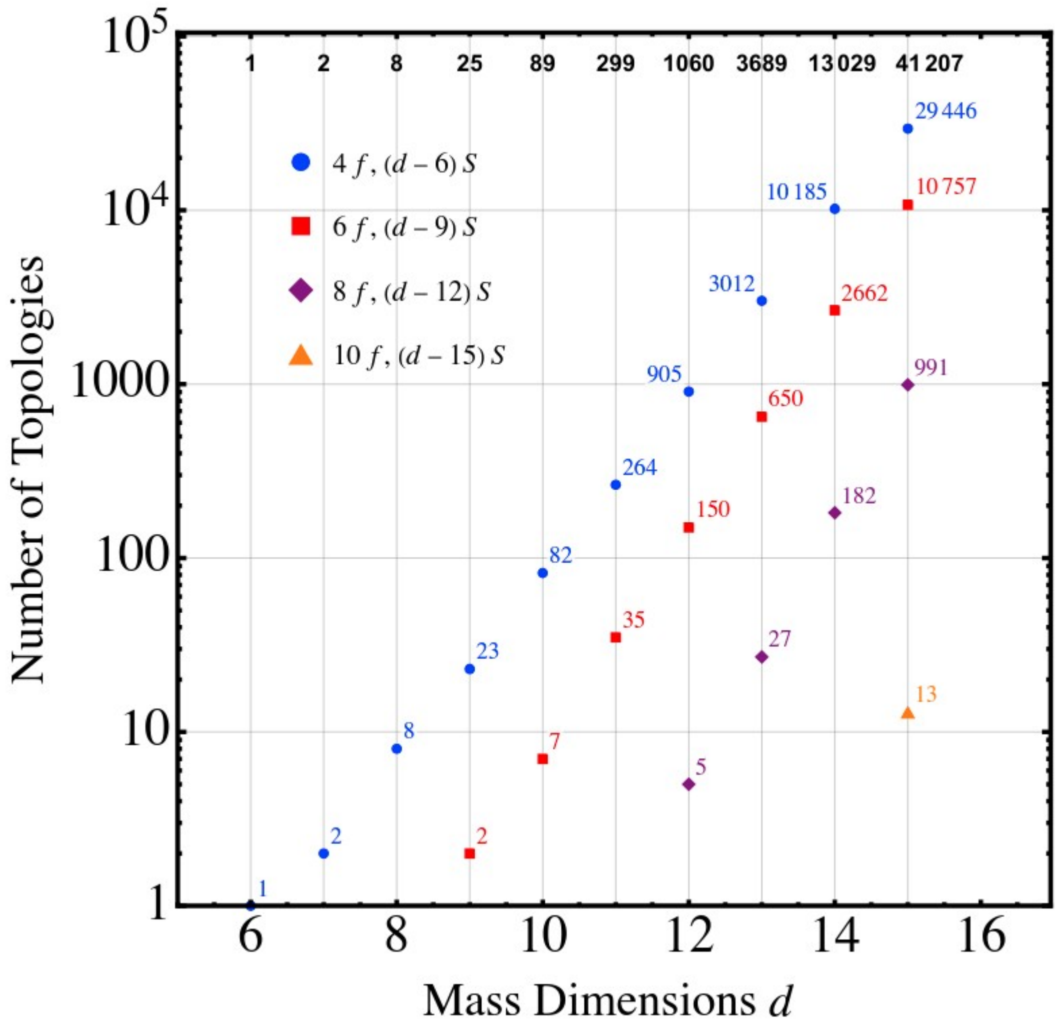
[Renato M. Fonseca, 1703.05221 & 1907.12584]

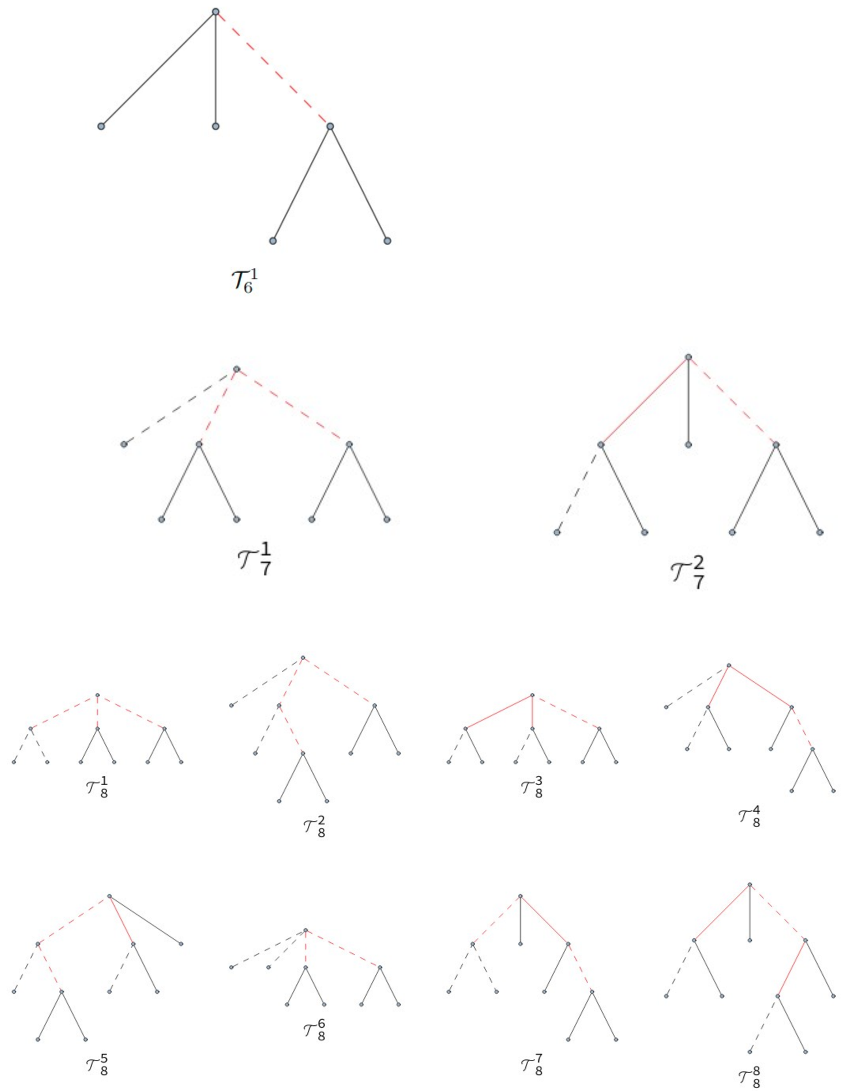
- Exponential growth of "operators" (~field strings):



Opening up *all* BNV operators

- Generate all irreducible tree-level topologies.
- Exponential growth:

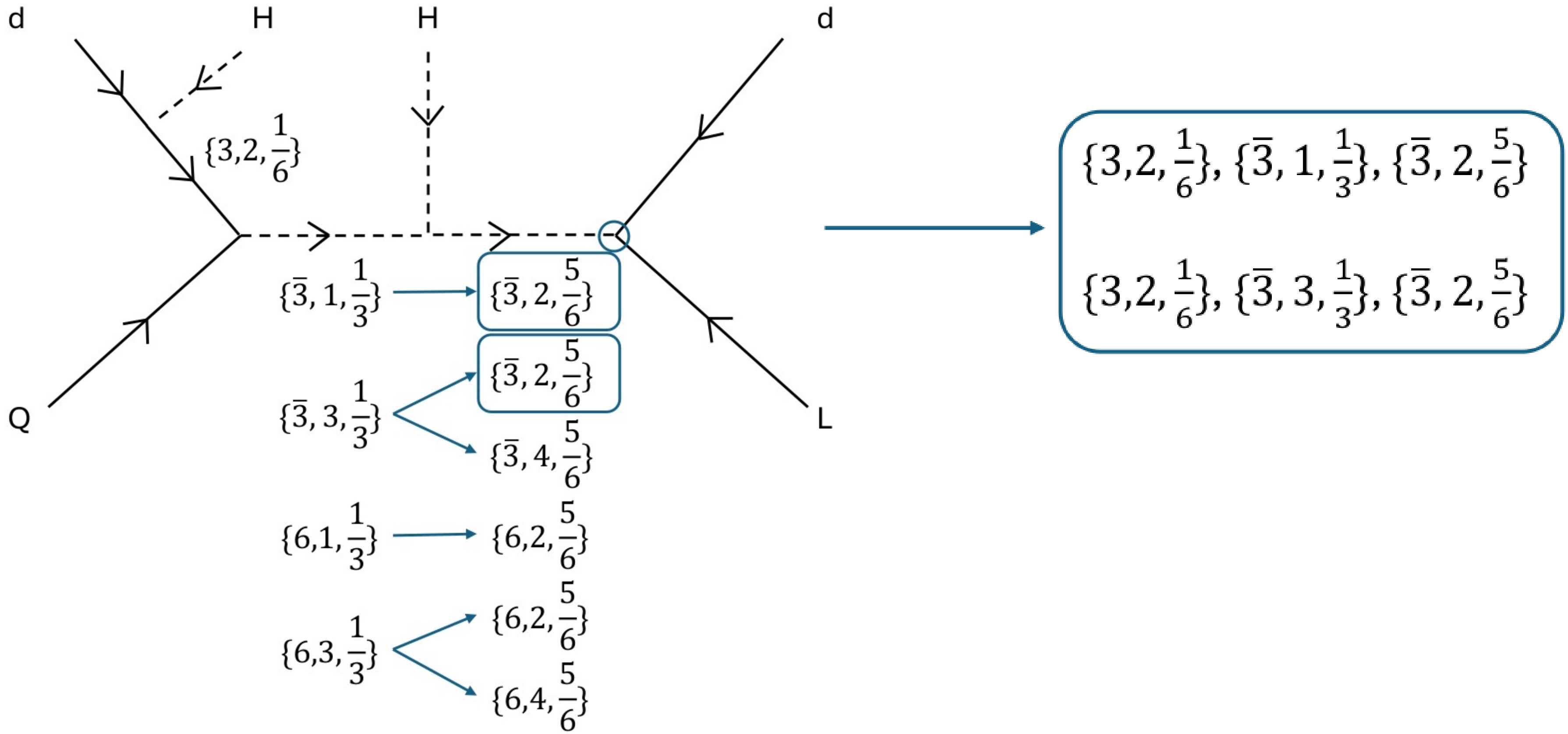




Opening up *all* BNV operators

- For each operator, pick topology and distribute fields.
- Multiply group representations using GroupMath.
- E.g. ddLQHH:

[Renato M. Fonseca, 2011.01764]



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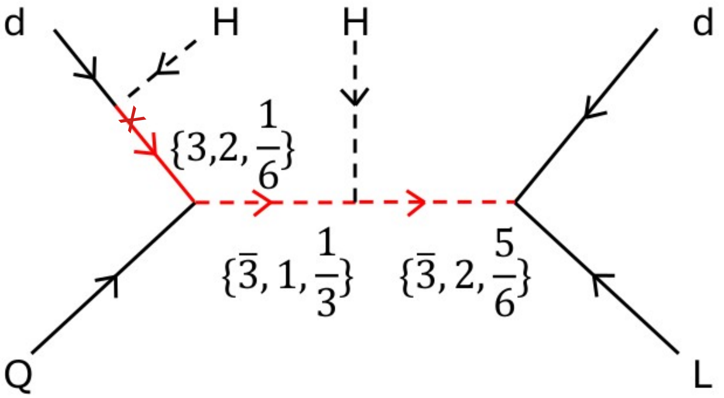
- For each operator, pick topology and distribute fields.
- Multiply group representations using GroupMath.

[Renato M. Fonseca, 2011.01764]

- E.g. ddLQHH:



$$\boxed{\left\{3,2,\tfrac{1}{6}\right\}_F, \left\{\bar{3},1,\tfrac{1}{3}\right\}_V, \left\{\bar{3},2,\tfrac{5}{6}\right\}_V}$$

[**JH**, D. Sokhashvili, Thapa, to appear]

- Also include global $SU(2)_{\text{left}} \times SU(2)_{\text{right}}$ for spin.
- Then permute external particles over topology and repeat...

Opening up *all* BNV operators

- Code fast enough to reach $d \sim 15$.
- Similar code developed for $\Delta L=2$ operators. [Gargalionis & Volkas, ‘21]
- Already revealed some mistakes in literature.
- Can be used to open up **any** (non-derivative) EFT operator.

Opening up *all* BNV operators

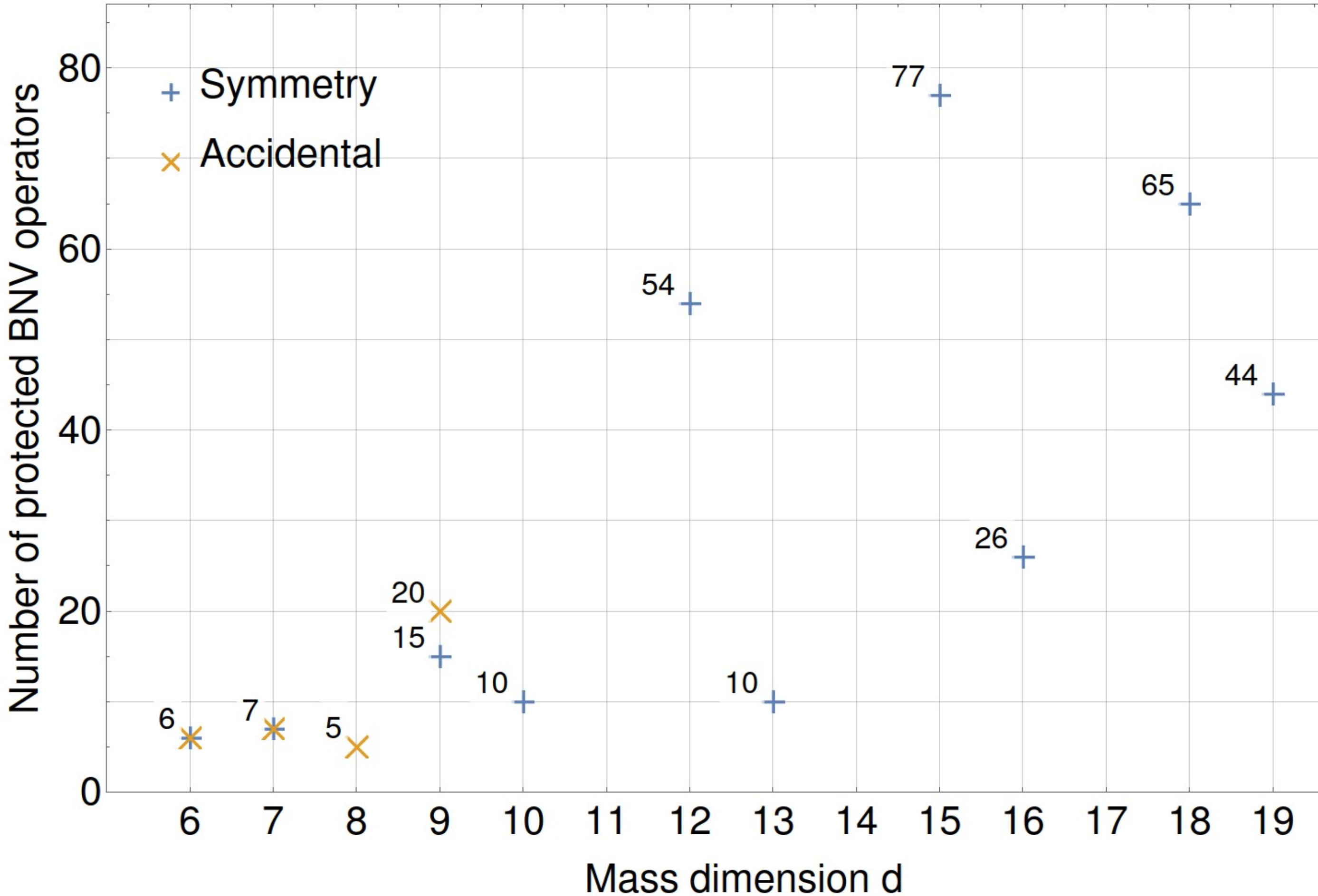
- Code fast enough to reach d ~ 15.
- Similar code developed for ΔL=2 operators. [Gargalionis & Volkas, '21]
- Already revealed some mistakes in literature.
- Can be used to open up **any** (non-derivative) EFT operator.
- Find accidentally protected operators.
- E.g. add Dirac fermion (**3**,**3**,2/3) and vector LQ (**3**,**3**,-1/3).
  - Only generates BNV operator QQdeHH (d=8, B=L=1).
  - Could be dominant but *not* protected by symmetry.
  - Gives genuine loop realization of d=6 BNV operator.
- Find these at d = 7, 8, 9, but not d > 9 *(preliminary)*.

[**JH**, D. Sokhashvili, Thapa, to appear]

Protected operators

- d > 6 operators could dominate either because we impose a B/L symmetry à la Weinberg or due to UV structure.
- Gives *manageable* set of interesting BNV operators.
- (Most of them contain ν_R.)
- Explore pheno & tree vs loop next.

[**JH**, D. Sokhashvili, in progress]



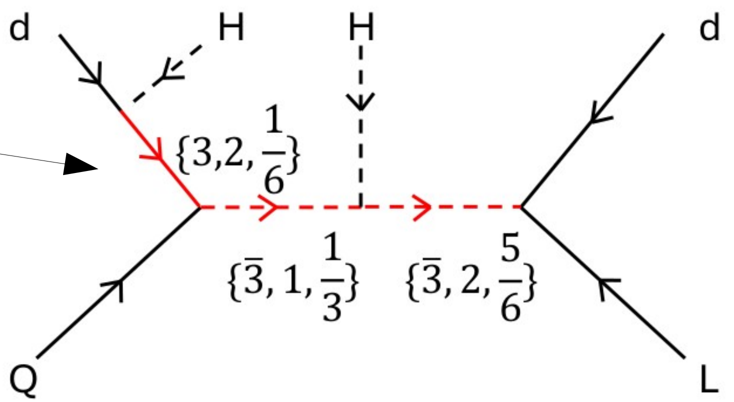
Derivative operators

- So far only BNV operators without derivatives. Why?
- More complicated, not always tree-level completion.
- Generically sub-dominant at tree-level:

$$\frac{1}{\not p - M} \simeq -\frac{1}{M} - \frac{\not p}{M^2}$$

Non-derivative operator

derivative operator



- Same UV completions, dominant only through finetuning.
- Exception: operators with $HD_\mu H$ that vanish without D_μ.

[Gargalionis & Volkas, 2009.13537]

Beyond SMEFT II

- BNV induced by heavy particles gives hundreds of potentially dominant testable SMEFT operators.
  - Great limits from *exclusive* searches.
  - Moderate global coverage by *inclusive* searches.

- What if new particles are light?
  - $n \to \pi^0 \chi$ or $p \to e^+ \chi$, followed by χ decays?
  - New signatures, new model building!

[recent work:
Císcar-Monsalvatje, Ibarra, Vandecasteele, 2307.02592;
Fridell, Hati, Takhistov, 2312.13740;
Domingo, Dreiner, Köhler, Nangia, Shah, 2403.18502; …]

Sterile neutron: fermion with B=1

- Effective Lagrangian:

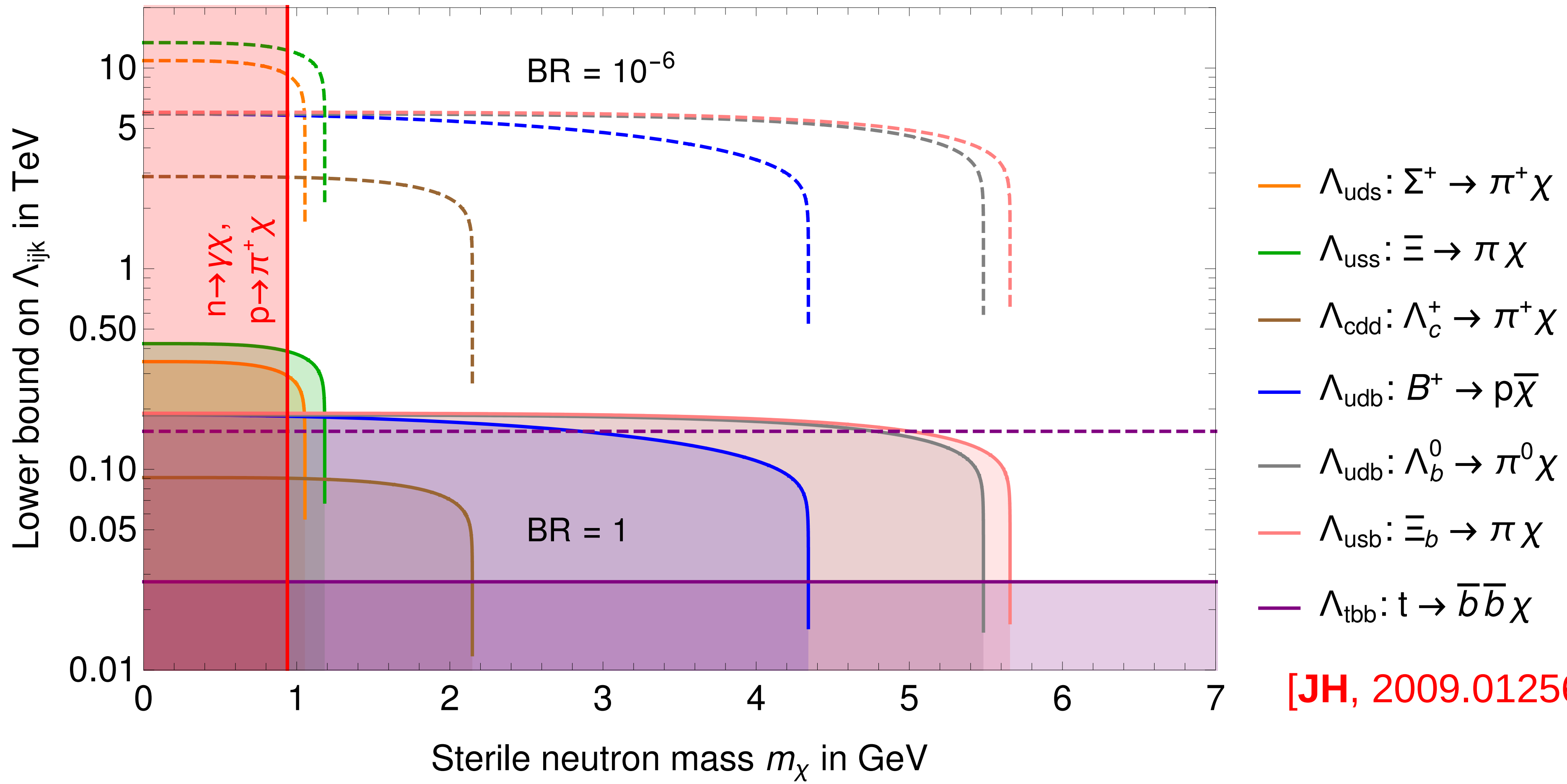
$$\mathcal{L}_\chi = \bar{\chi}(\mathrm{i}\partial\!\!\!/ - m_\chi)\chi + \left(\frac{u_i d_j d_k \chi_L^c}{\Lambda_{ijk}^2} + \frac{Q_i Q_j d_k \chi_L^c}{\tilde{\Lambda}_{ijk}^2} + \mathrm{h.c.}\right)$$

- For $m_\chi \lesssim m_n$, one has search channels
  - $n \to \chi\, \gamma$, [Davoudiasl, PRL '15; Fornal & Grinstein, 1801.01124]
    hydrogen $\to \chi\, \nu$, [Berezhiani, 1812.11089; McKeen & Pospelov, 2003.02270]
    $p \to \chi\, e^+ \nu$, [McKeen & Pospelov, 2003.02270]
    $n \to \pi^0 \chi$, $p \to \pi^+ \chi$, [Davoudiasl, PRD '13 & PRL '15; Helo et al, 1803.00035]
  - The latter probe $\Lambda_{udd} < 10^{15}$ GeV if $m_\chi \sim 0$.
  - All couplings Λ_{ijk} lead to these channels at loop level!
- Notice that χ is stable here and thus (asymmetric) DM.

Sterile neutron: fermion with B=1

- For $m_\chi > m_n$, no more proton/neutron decays!
- Still possible to look for rare decays in b/c/τ factories via

$$\text{baryon} \to \text{meson} + \chi$$
$$\text{meson} \to \text{baryon} + \bar{\chi}$$



[JH, 2009.01256]

Summary

- BNV nuclear decays probe
  - high *scales* (10^{15} GeV) *or*
  - high *multiplicities* (N → 15 particles) *or*
  - high operator *dimensions* (d~15)!

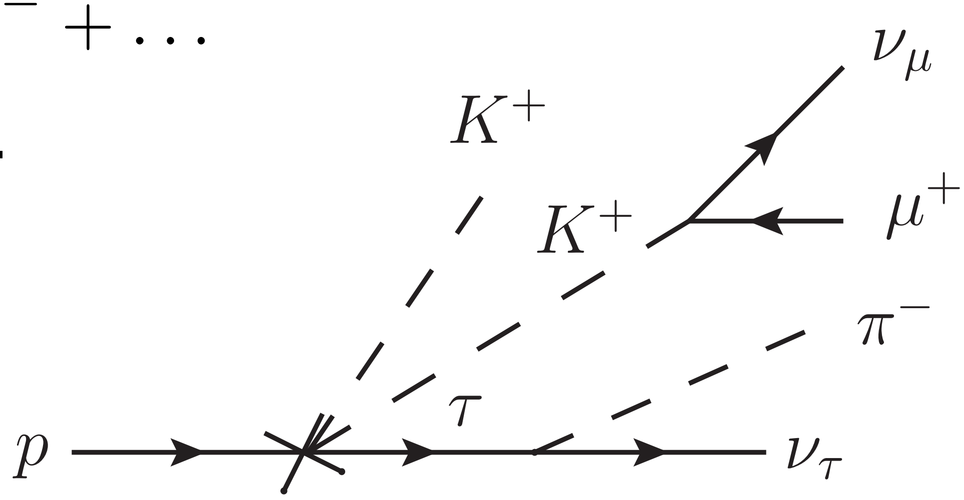
SK/HK,
DUNE,
JUNO,
0νββ exp.?

- Oodles of testable SMEFT operators.
- Embarrassment of riches, BNV landscape much more difficult to map than e.g. ΔL =2 operators.
  - Inclusive searches + few theory-motivated exclusives?
- Still more:
  - Light new physics ($p \to \ell^+ + X$, $X \to$ SM?).
  - Dark matter induced ΔB & ΔL.

Backup

$\Delta B = -\Delta L_\tau = 1$ operators

- d=7 operator: $\mathrm{dssH}\bar{\mathrm{L}}_\tau \propto \bar{\tau}\Xi^- + \ldots$
- No neutrinos, two s quarks.
- Two-body tau decays but five-body nucleon decays!
- Off-shell τ and K, double suppression by G_F:



$$\tau(\mathrm{p} \to \mathrm{K}^+\mu^+\nu_\mu\pi^-\nu_\tau) \simeq \mathcal{O}(10^{28})\,\mathrm{yr}\left(\frac{10^{-8}}{\mathrm{BR}(\tau\to\Xi\pi)}\right)$$

$\hookrightarrow \Lambda\pi$

$\hookrightarrow \mathrm{N}\pi$

[**JH** & Watkins, 2405.18478]

- ΔB tau decays most competitive in hyperon channels.

New channels for Super-K & Belle II

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 $\mathbb{Z}_3$,

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

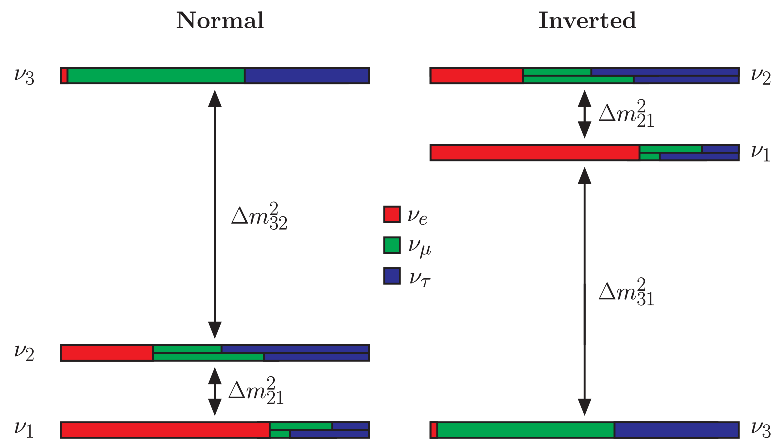
  but unobservable at low temperatures. ['t Hooft, PRL '76]

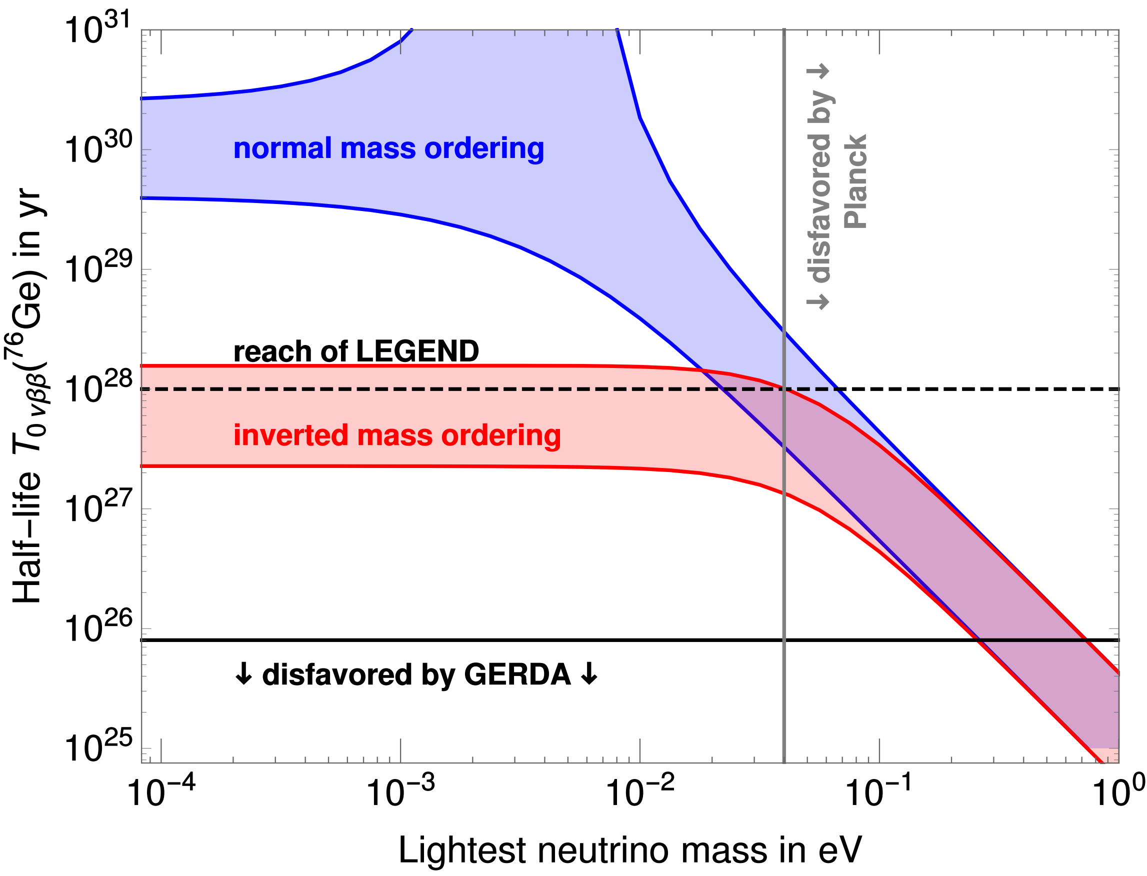
- True accidental global symmetry:

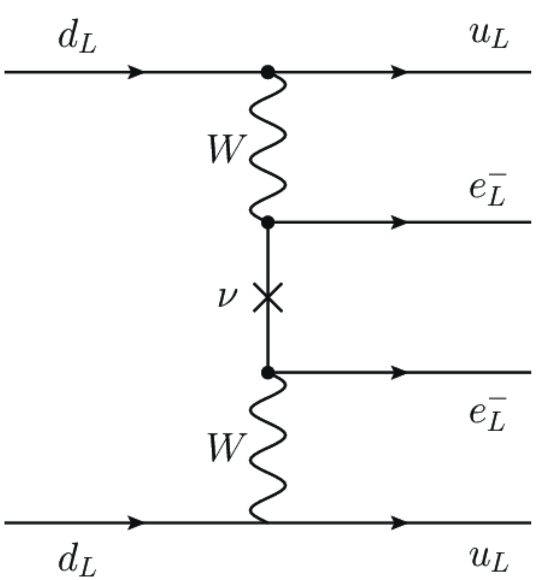
$$\boxed{\mathbb{Z}_3^{(\mathrm{B+L})/2}\times\mathrm{U}(1)_{\mathrm{B-L}}\times\mathrm{U}(1)_{\mathrm{L}_\mu-\mathrm{L}_\tau}\times\mathrm{U}(1)_{\mathrm{L}_\mu+\mathrm{L}_\tau-2\mathrm{L}_e}\,.}$$

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.

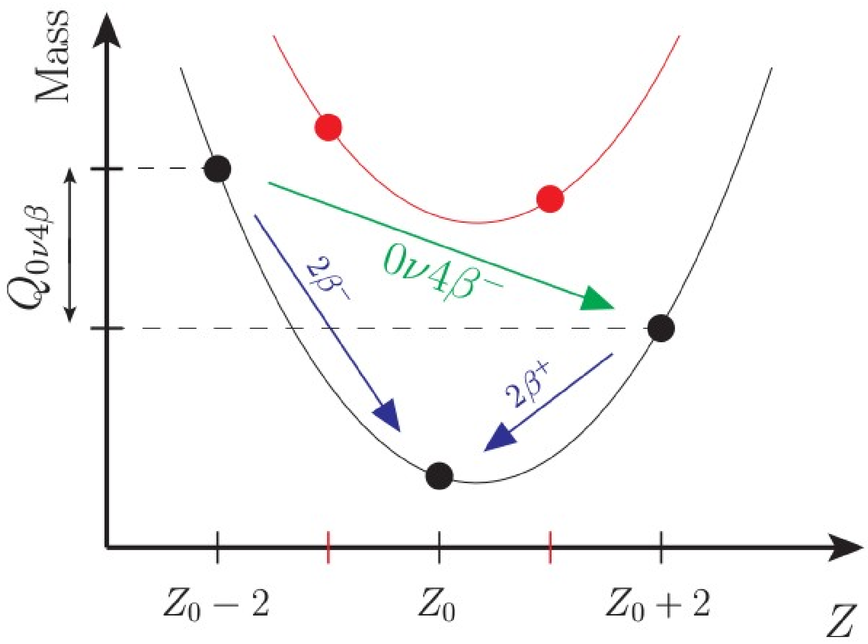


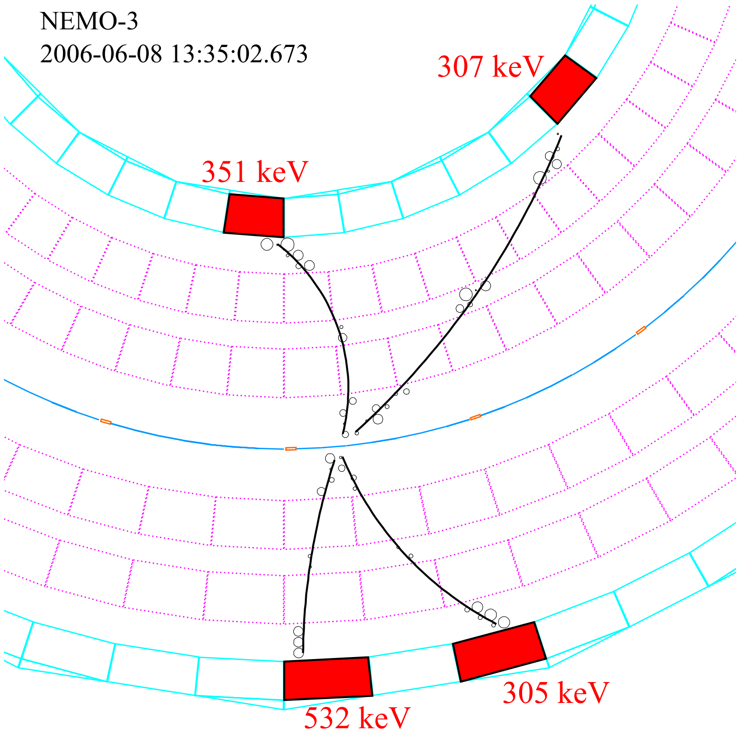




ΔL = 4

- 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: $\tau_{0\nu 4\beta}(^{150}\text{Nd}) > 10^{21}$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]





p → μ⁺μ⁺e⁻

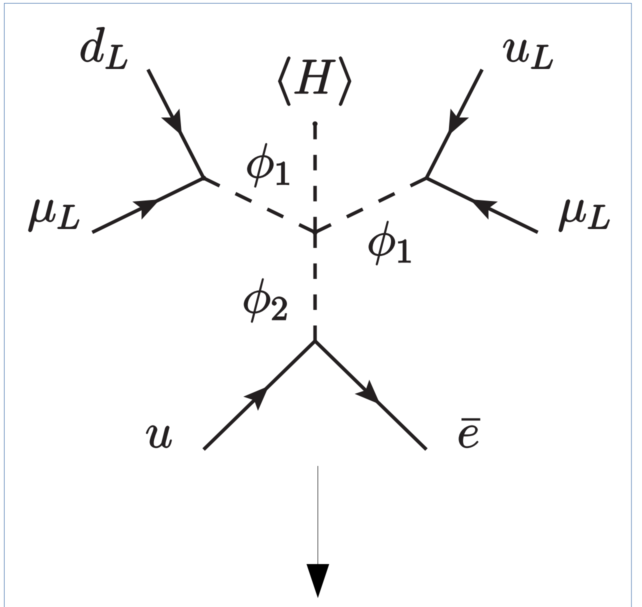
- Minimal leptoquark example:

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

- $L_\mu+2L_e-3L_\tau$ ensures simple 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 operator: $\frac{1}{\Lambda^6} QQuL_\mu L_\mu \overline{L}_e H$.
- Lattice QCD input: $\langle 0|uud|p\rangle$.



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

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

[Hambye, **JH**, PRL ‘18]

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 $\to \ell\ell\ell$.

Two-body di-nucleon decays

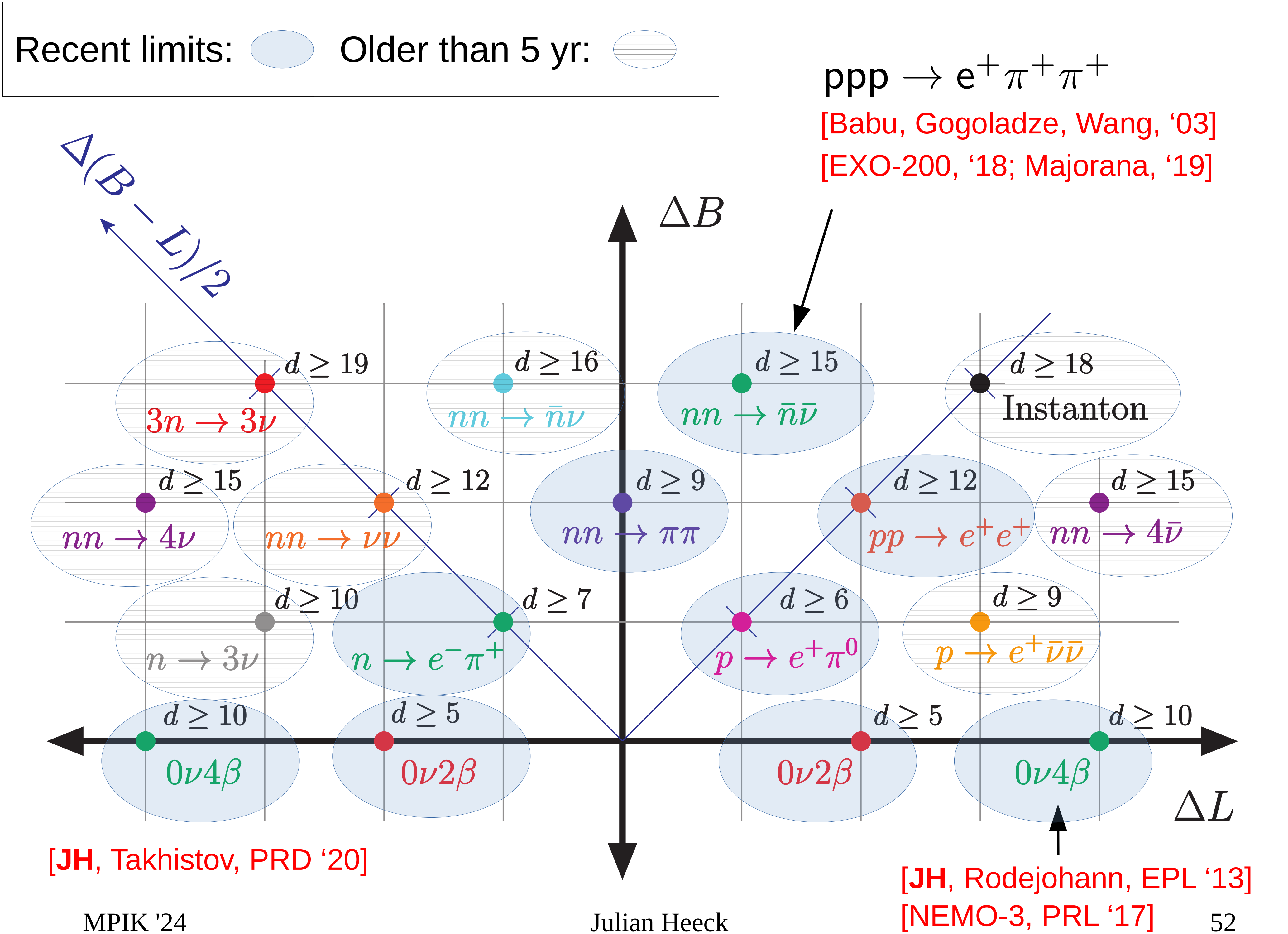
Channel	$\lvert\Delta(B-L)\rvert$	$\frac{\Gamma^{-1}}{10^{30}\,\text{yr}}$
$pp \to e^+ + e^+$	0	4200 [72]
$pp \to \mu^+ + \mu^+$	0	4400 [72]
$pp \to e^+ + \mu^+$	0	4400 [72]
$pp \to e^+ + \tau^+$	0	
$pp \to \pi^+ + \pi^+$	2	72 [115]
$pp \to \pi^+ + \rho^+$	2	
$pp \to \pi^+ + K^+$	2	
$pp \to \pi^+ + K^{*,+}$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


Recent limits:
Older than 5 yr:
ppp $\to e^+\pi^+\pi^+$
[Babu, Gogoladze, Wang, ‘03]
[EXO-200, ‘18; Majorana, ‘19]
$\Delta(B-L)/2$
ΔB
ΔL
$d \geq 19$
$3n \to 3\nu$
$d \geq 16$
$nn \to \bar{n}\nu$
$d \geq 15$
$nn \to \bar{n}\bar{\nu}$
$d \geq 18$
Instanton
$d \geq 15$
$nn \to 4\nu$
$d \geq 12$
$nn \to \nu\nu$
$d \geq 9$
$nn \to \pi\pi$
$d \geq 12$
$pp \to e^+e^+$
$d \geq 15$
$nn \to 4\bar{\nu}$
$d \geq 10$
$n \to 3\nu$
$d \geq 7$
$n \to e^-\pi^+$
$d \geq 6$
$p \to e^+\pi^0$
$d \geq 9$
$p \to e^+\bar{\nu}\bar{\nu}$
$d \geq 10$
$0\nu4\beta$
$d \geq 5$
$0\nu2\beta$
$d \geq 5$
$0\nu2\beta$
$d \geq 10$
$0\nu4\beta$
[JH, Takhistov, PRD ‘20]
[JH, Rodejohann, EPL ‘13]
[NEMO-3, PRL ‘17]

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 $\frac{1}{\Lambda^{11}} Q^5 d^4 \bar{\ell}, \ldots$

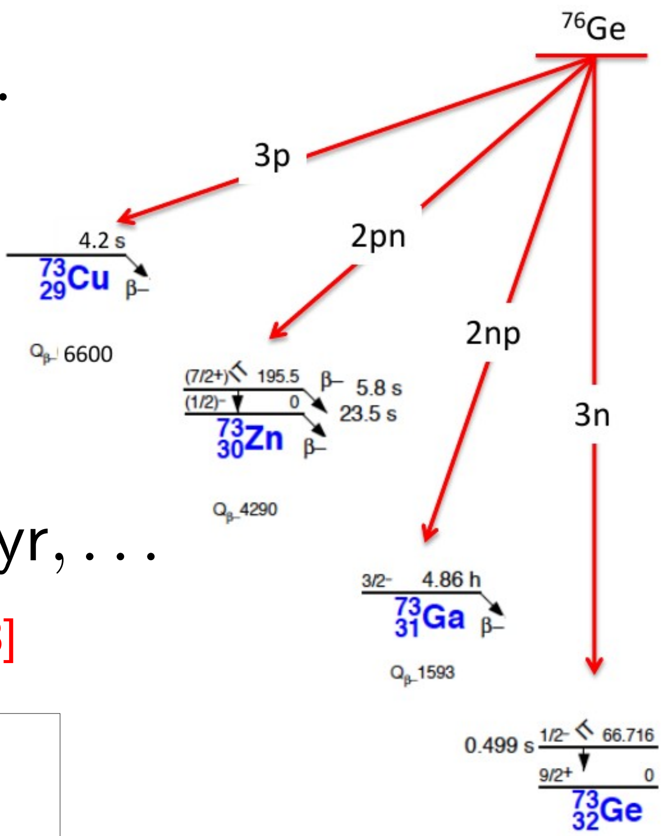
- $ppp \to e^+\pi^+\pi^+$, $ppn \to e^+\pi^+$, $pnn \to e^+\pi^0$, $nn \to \bar{n}\bar{\nu}, \ldots$
- $\tau(pnn \to e^+\pi^0) \simeq 3 \times 10^{33}\,\mathrm{yr}\,\left(\frac{\Lambda}{100\,\mathrm{GeV}}\right)^{22}$.
- Limits:

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

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

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

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



SK, JUNO, DUNE, HK?

ppp → $e^+\pi^+\pi^+$

- Symmetry

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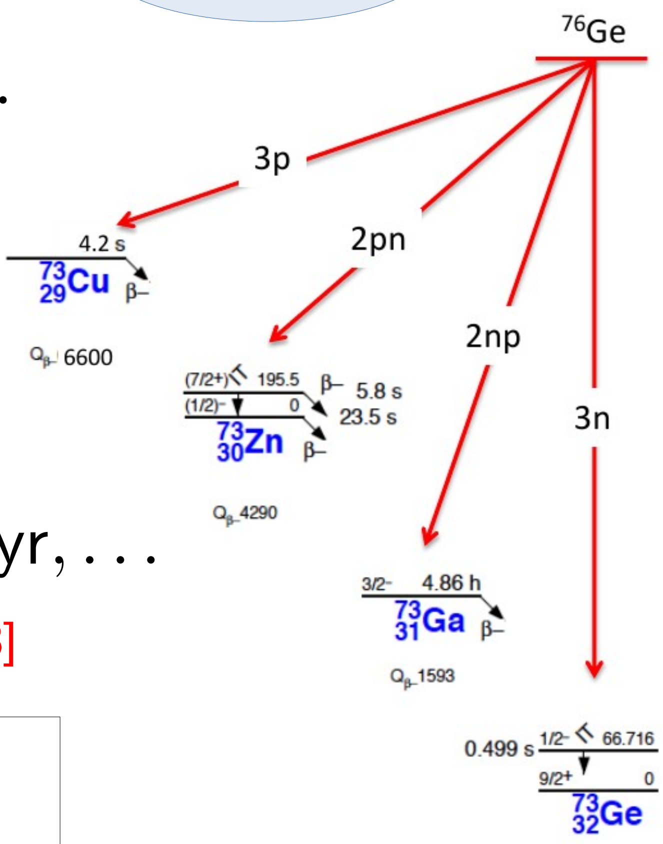
[Majorana Demonstrator, PRD ‘19; see also EXO-200, ‘18]



SK, JUNO, DUNE, HK?