Opening up baryon-number-violating operators

Julian Heeck

INT Workshop on *Baryon Number Violation*

1/16/2025

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

- EFT (with Majorana neutrinos): [Weinberg, ‘79 & ‘80]

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

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

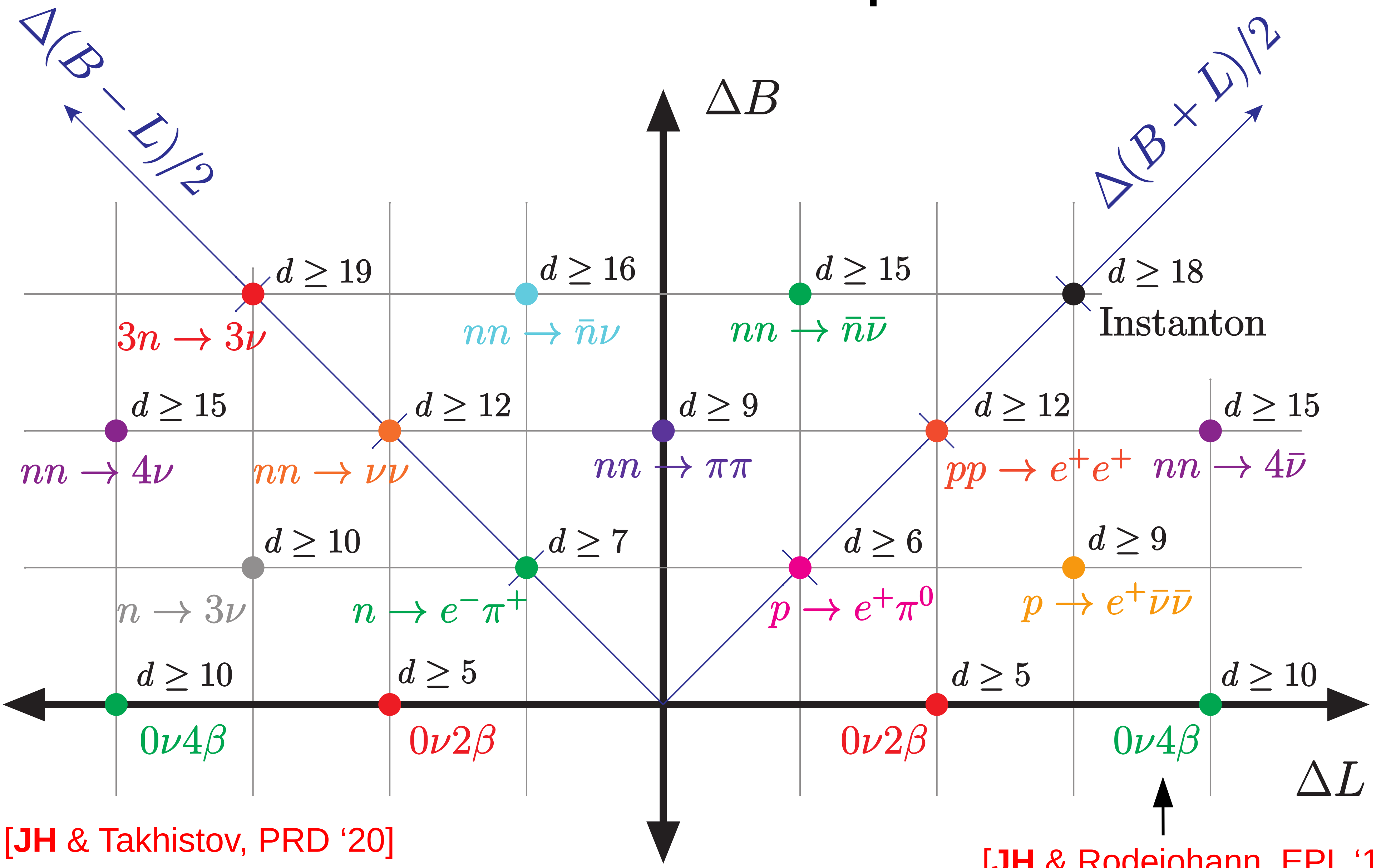
- Some symmetry/hierarchy has to exist, otherwise

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

- BNV sensitive to d >> 6, unlike any other experiment.
- ΔB dominated by d = 6, unless forbidden by symmetry!

[Weinberg, ‘80]

BNV landscape



[**JH** & Takhistov, PRD ‘20]

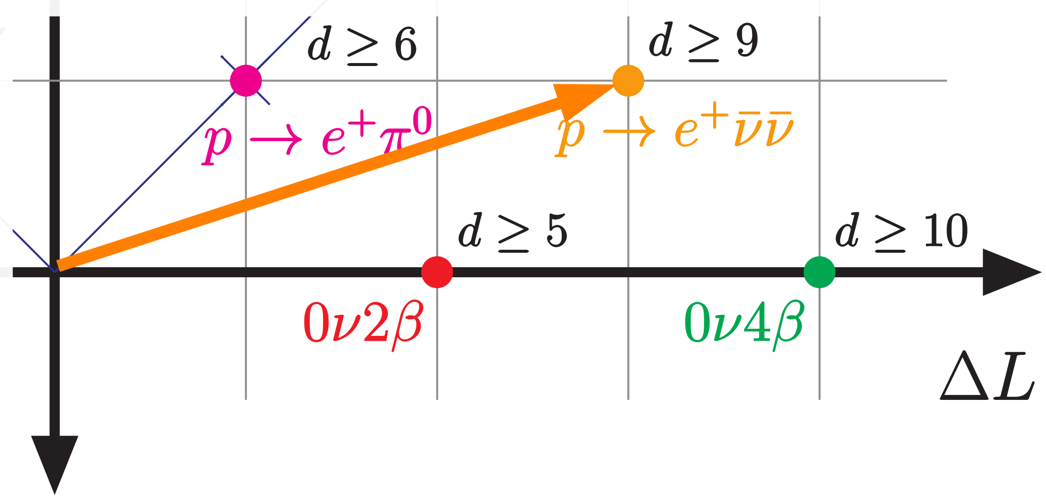
[**JH** & Rodejohann, EPL ‘13]
[NEMO-3, PRL ‘17]

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.

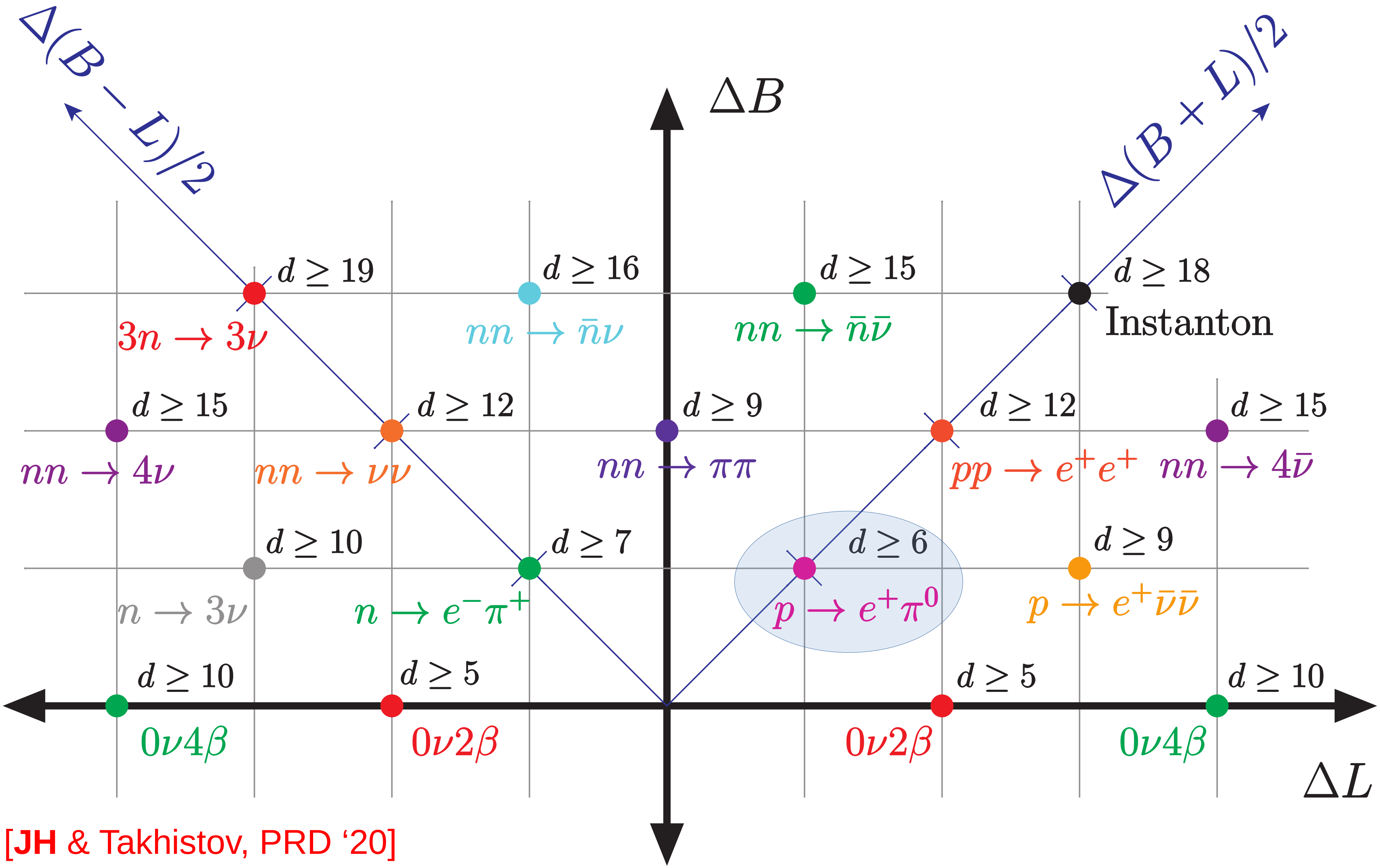
$$\tau(p \to e^+\bar{\nu}\bar{\nu}) \simeq \underbrace{2 \times 10^{32}\mathrm{yr}}_{\text{Super-K limit '14}} \left(\frac{\Lambda}{300\,\mathrm{TeV}}\right)^{10} .$$

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:

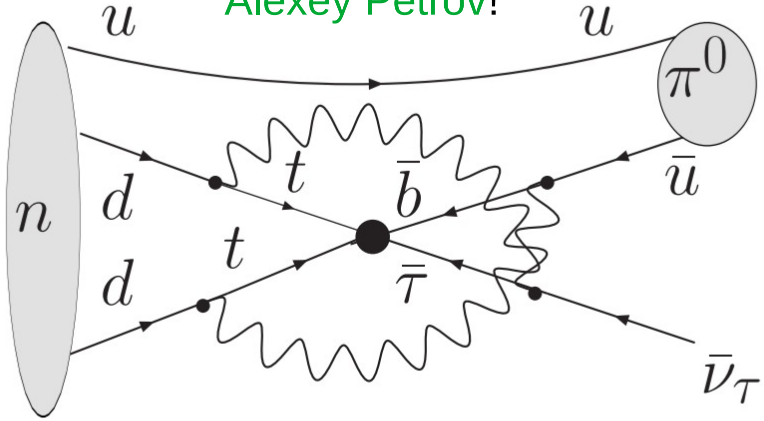
$$y^1_{abcd}\epsilon^{\alpha\beta\gamma}(\overline{d}^C_{a,\alpha}u_{b,\beta})(\overline{Q}^C_{i,c,\gamma}\epsilon_{ij}L_{j,d})$$
$$+y^2_{abcd}\epsilon^{\alpha\beta\gamma}\epsilon_{il}\epsilon_{jk}(\overline{Q}^C_{i,a,\alpha}Q_{j,b,\beta})(\overline{Q}^C_{k,c,\gamma}L_{l,d})$$
$$+y^3_{abcd}\epsilon^{\alpha\beta\gamma}(\overline{Q}^C_{i,a,\alpha}\epsilon_{ij}Q_{j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

[Weinberg '79 & '80; Wilczek & Zee '79]

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

[Marciano, NPB '95; Hou++, hep-ph/0509006; Dong++, 1107.3805; Gargalionis++, 2401.04768; Beneke++, 2404.09642; **JH** & Watkins, 2405.18478; Gisbert++, 2409.00218]

See also talk by Alexey Petrov!



Not necessarily the fastest mode!

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

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

Two-body nucleon decays (38)

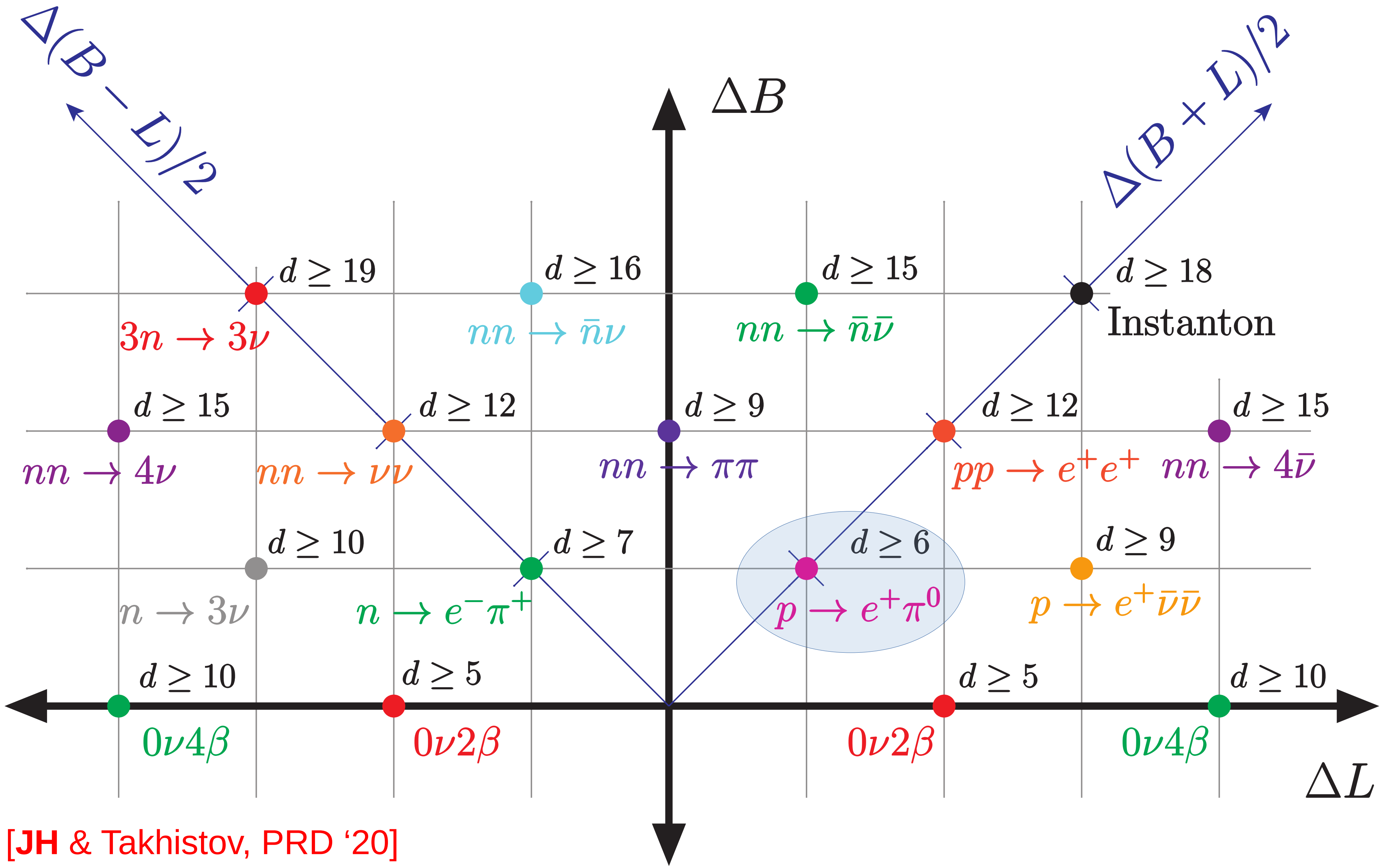
Channel	$\Gamma^{-1}/10^{30}$ yr	Year
$p \to e^+ + \gamma$	41000	2018
$p \to e^+ + \pi^0$	16000	2016
$p \to e^+ + \eta$	10000	2017
$p \to e^+ + \rho^0$	720	2017
$p \to e^+ + \omega$	1600	2017
$p \to e^+ + K^0$	1000	2005
$p \to e^+ + K^{*,0}$	84	1999
$p \to \mu^+ + \gamma$	21000	2018
$p \to \mu^+ + \pi^0$	7700	2016
$p \to \mu^+ + \eta$	4700	2017
$p \to \mu^+ + \rho^0$	570	2017
$p \to \mu^+ + \omega$	2800	2017
$p \to \mu^+ + K^0$	1600	2012
$p \to \nu + \pi^+$	390	2013
$p \to \nu + \rho^+$	162	1999
$p \to \nu + K^+$	5900	2014
$p \to \nu + K^{*,+}$	130	2007

$n \to e^- + \pi^+$	65	1988
$n \to e^- + \rho^+$	62	1988
$n \to e^- + K^+$	32	1991
$n \to e^- + K^{*,+}$		
$n \to e^+ + \pi^-$	5300	2017
$n \to e^+ + \rho^-$	217	1999
$n \to e^+ + K^-$	17	1999
$n \to e^+ + K^{*,-}$		
$n \to \mu^- + \pi^+$	49	1988
$n \to \mu^- + \rho^+$	7	1988
$n \to \mu^- + K^+$	57	1991
$n \to \mu^+ + \pi^-$	3500	2017
$n \to \mu^+ + \rho^-$	228	1999
$n \to \mu^+ + K^-$	26	1999
$n \to \nu + \gamma$	550	2015
$n \to \nu + \pi^0$	1100	2013
$n \to \nu + \eta$	158	1999
$n \to \nu + \rho^0$	19	1988
$n \to \nu + \omega$	108	1999
$n \to \nu + K^0$	130	2005
$n \to \nu + K^{*,0}$	78	1999

Many of these limits are decades old.

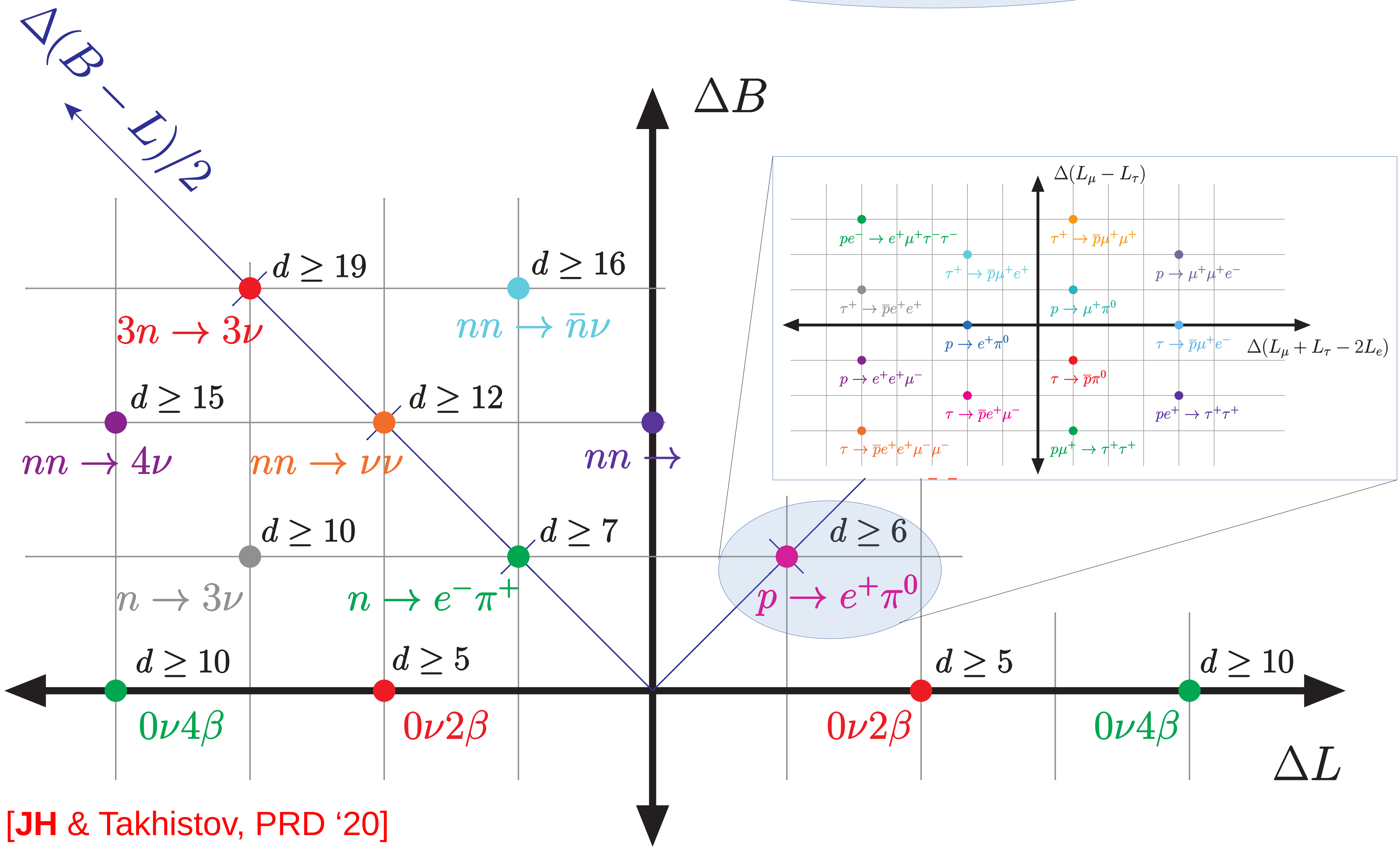
[**JH** & Takhistov, PRD ‘20]

ΔB = ΔL = 1 covered?



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

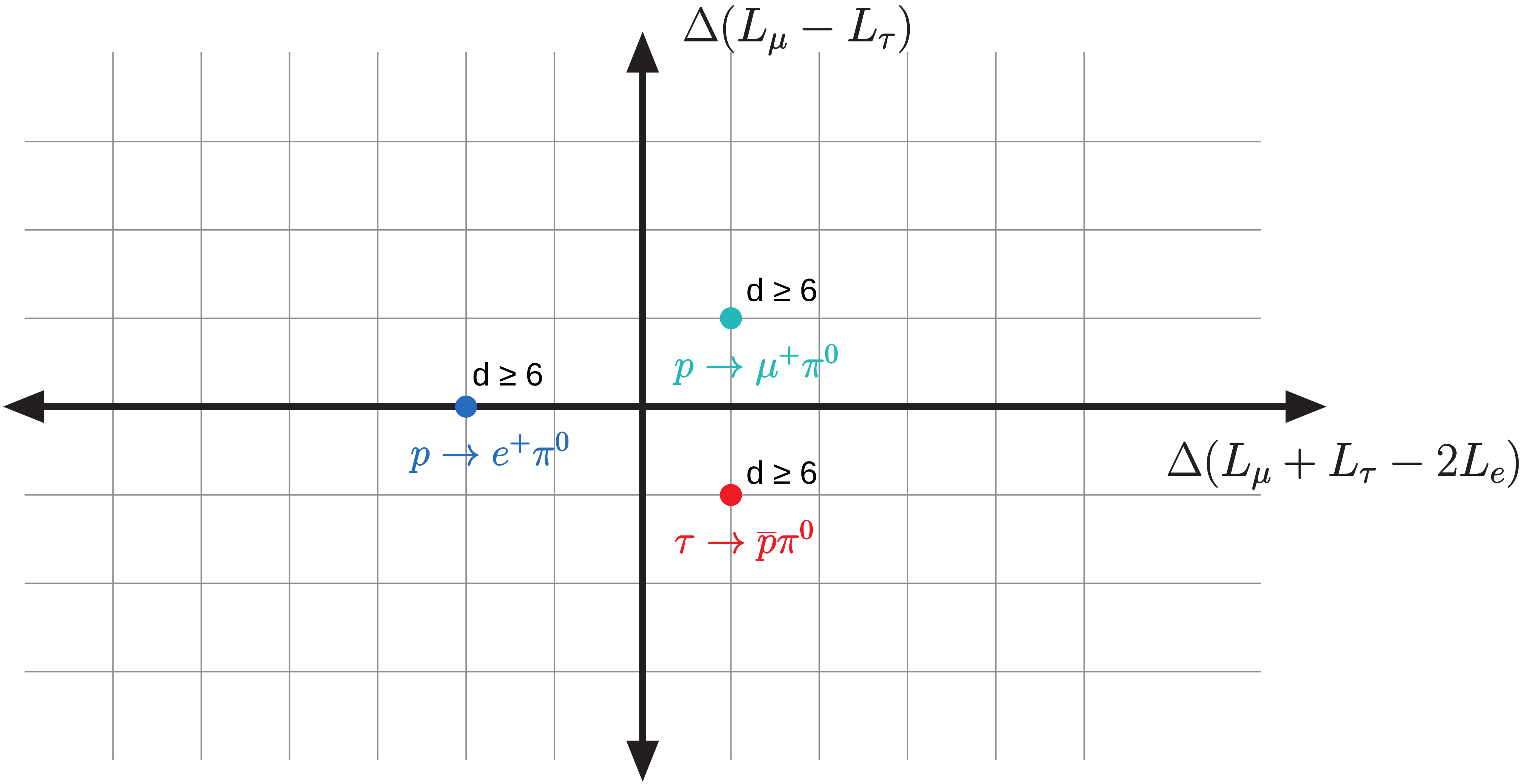
$$\mathrm{U(1)_B \times U(1)_L \times U(1)_{L_\mu - L_\tau} \times U(1)_{L_\mu + L_\tau - 2L_e}}\,.$$



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

Proton decay = lepton flavor violation

$\Delta B = \Delta L = 1$



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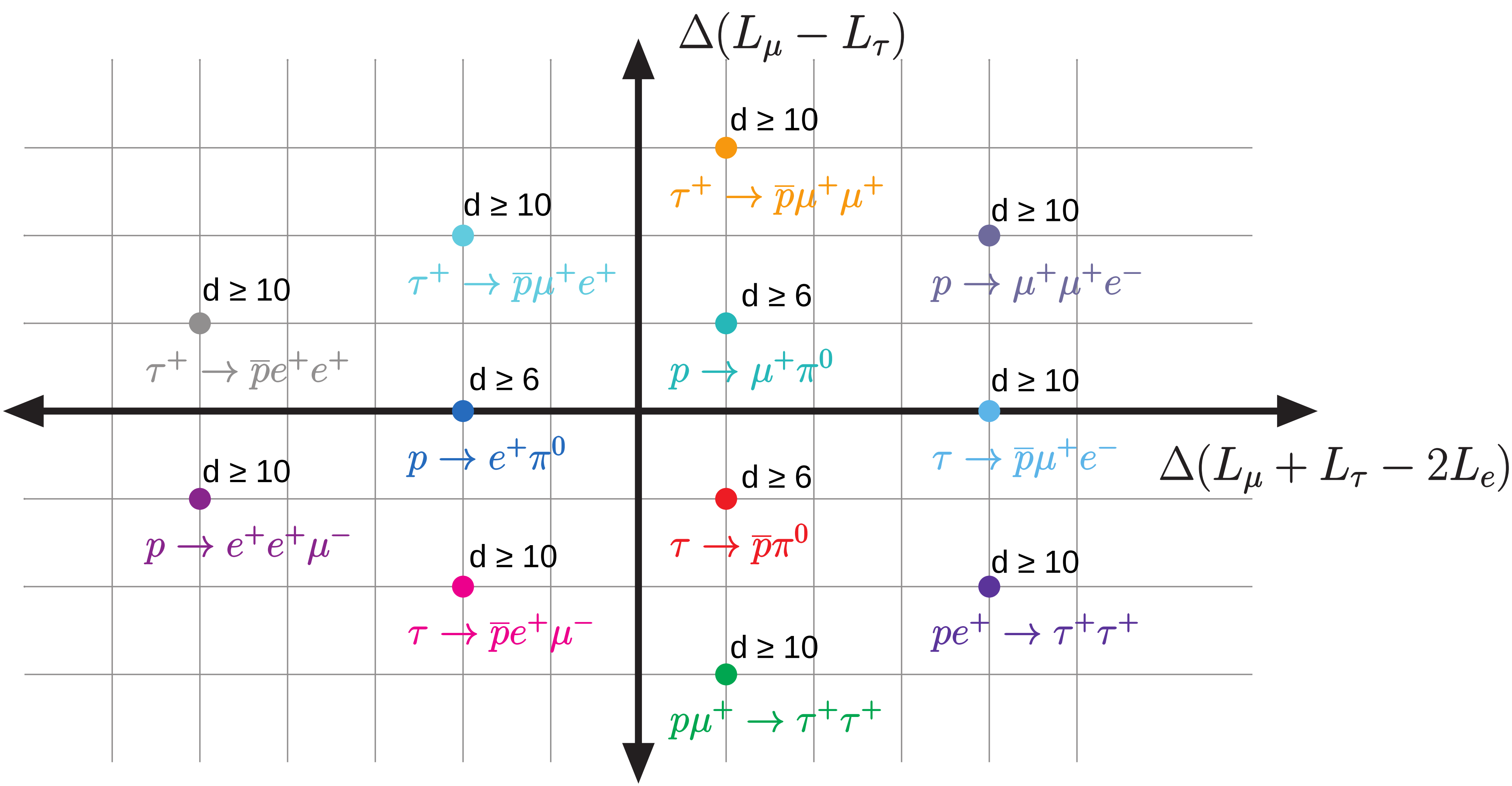

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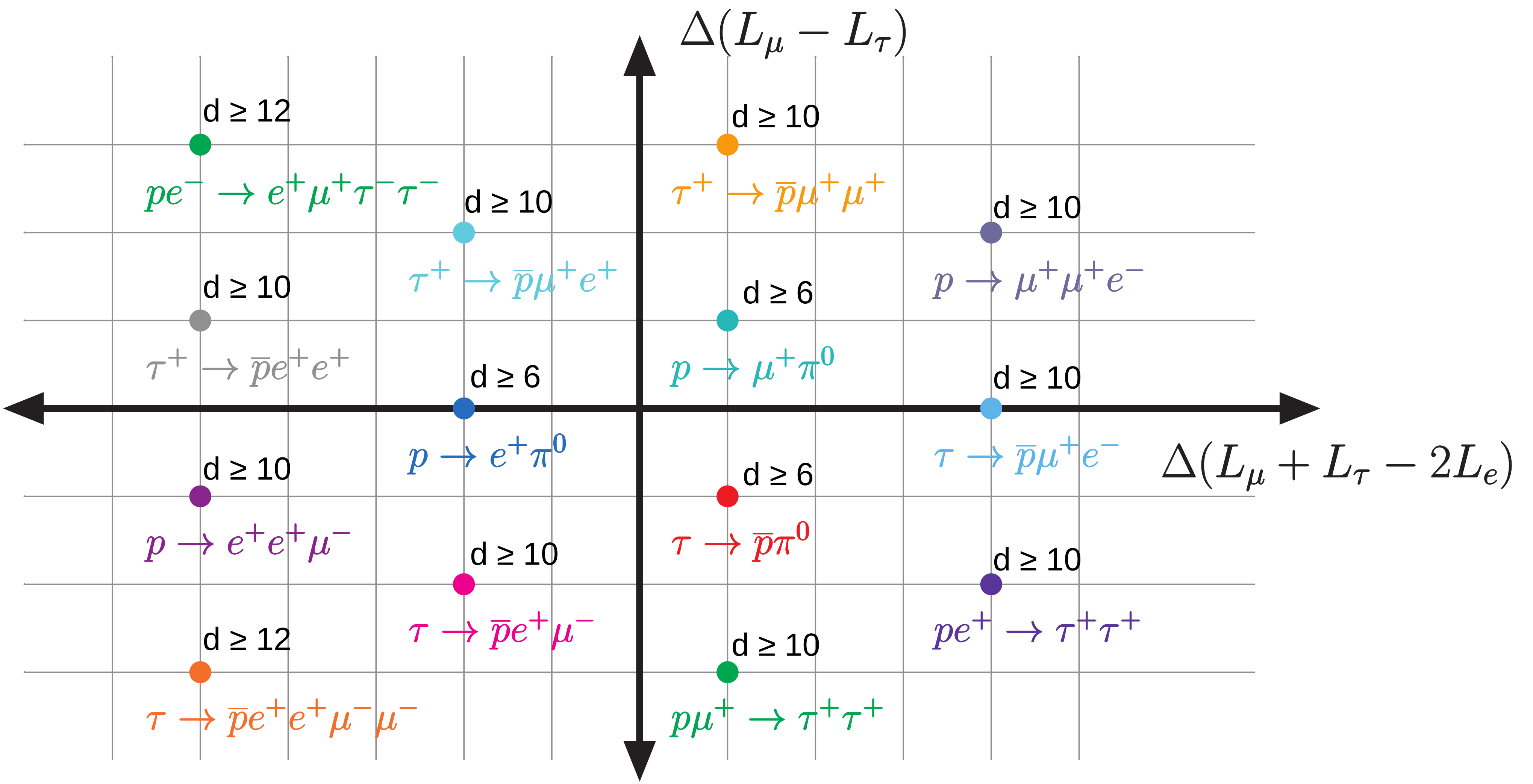
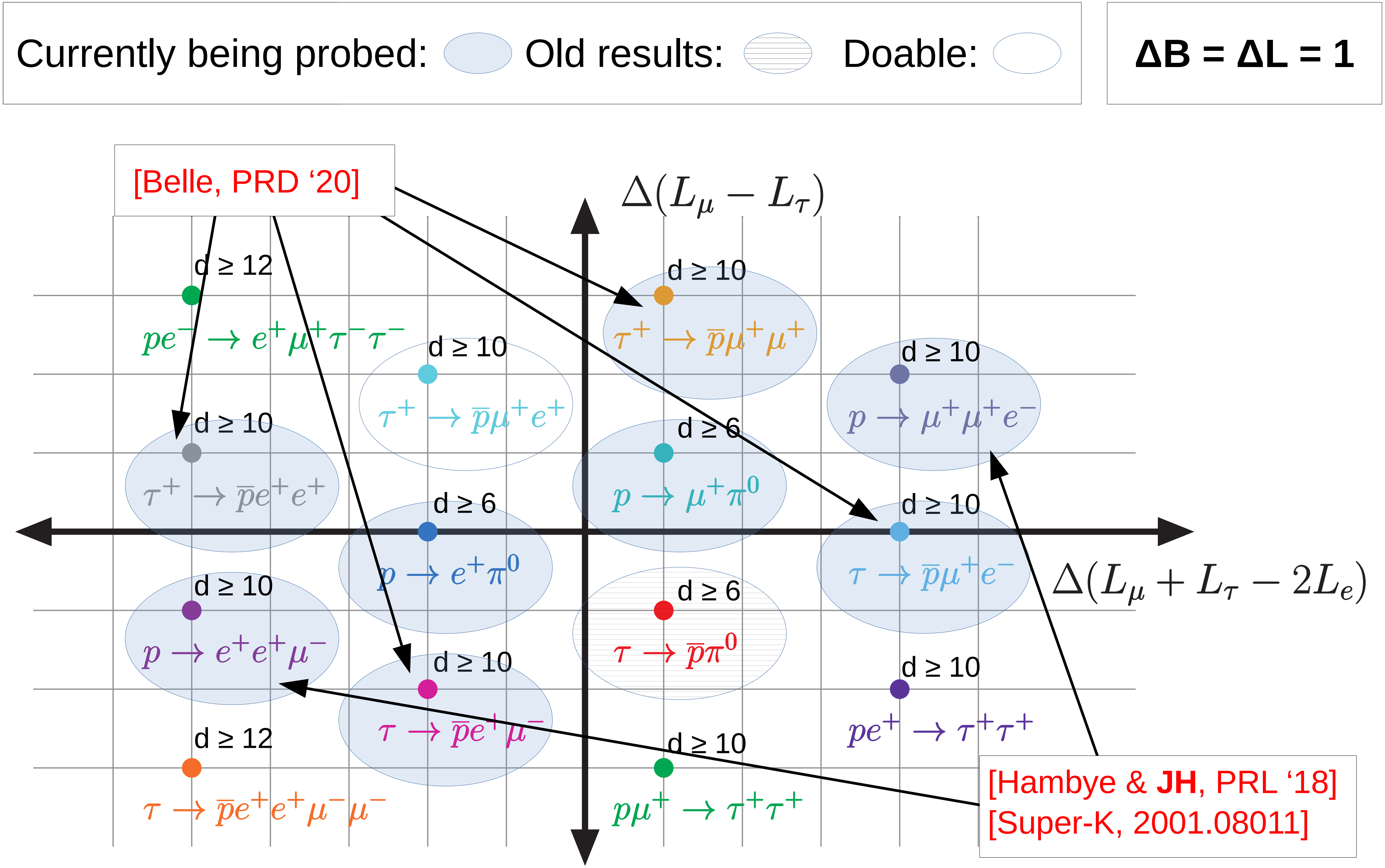


$\Delta B = \Delta L = 1$

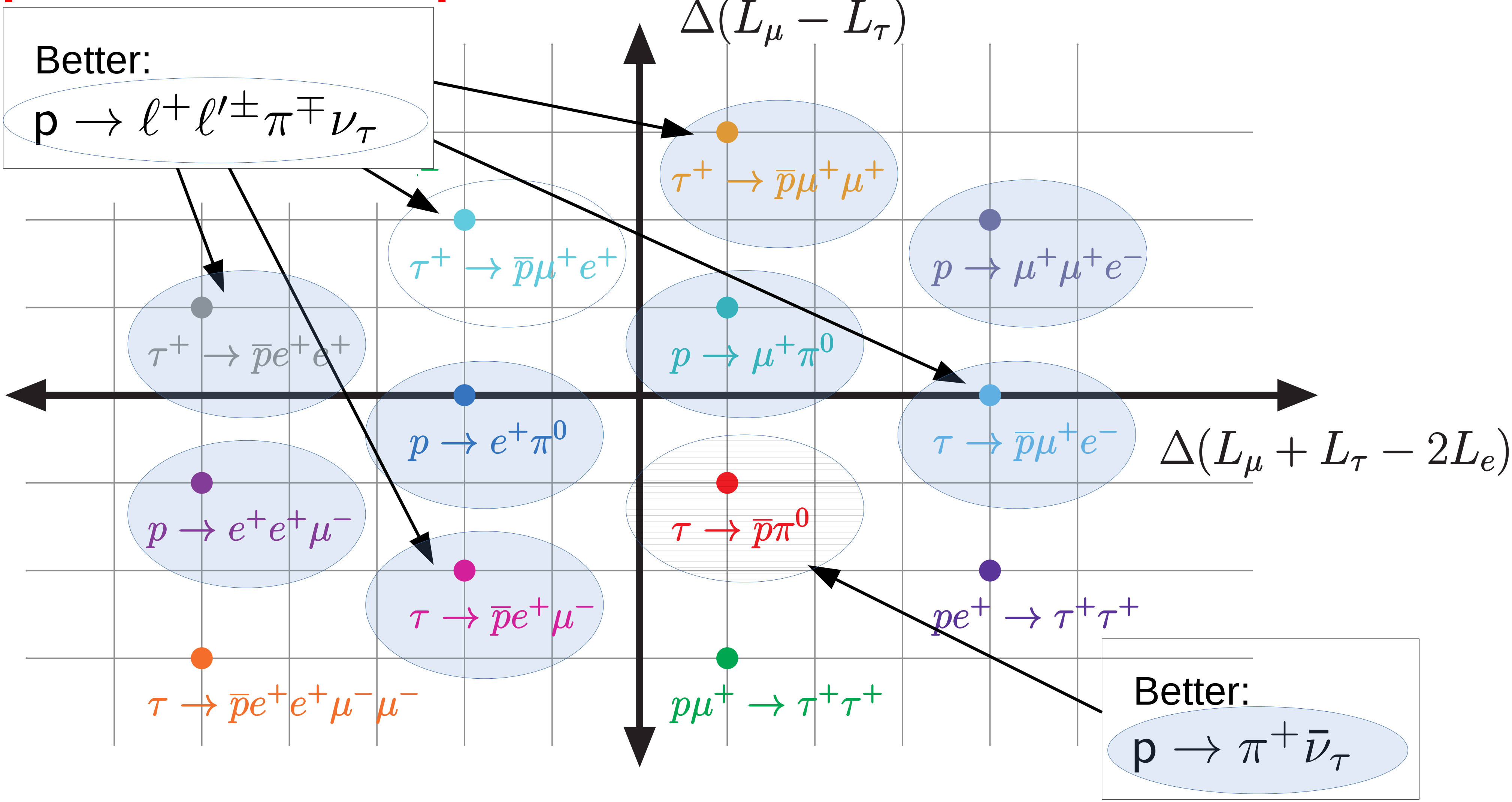


$$\tau(\mathrm{p} \to \mu^+\mu^+\mathrm{e}^-)$$
$$\simeq 10^{33}\mathrm{yr}\left(\frac{\Lambda}{100\mathrm{TeV}}\right)^{12}$$

Currently being probed: Old results: Doable:

ΔB = ΔL = 1

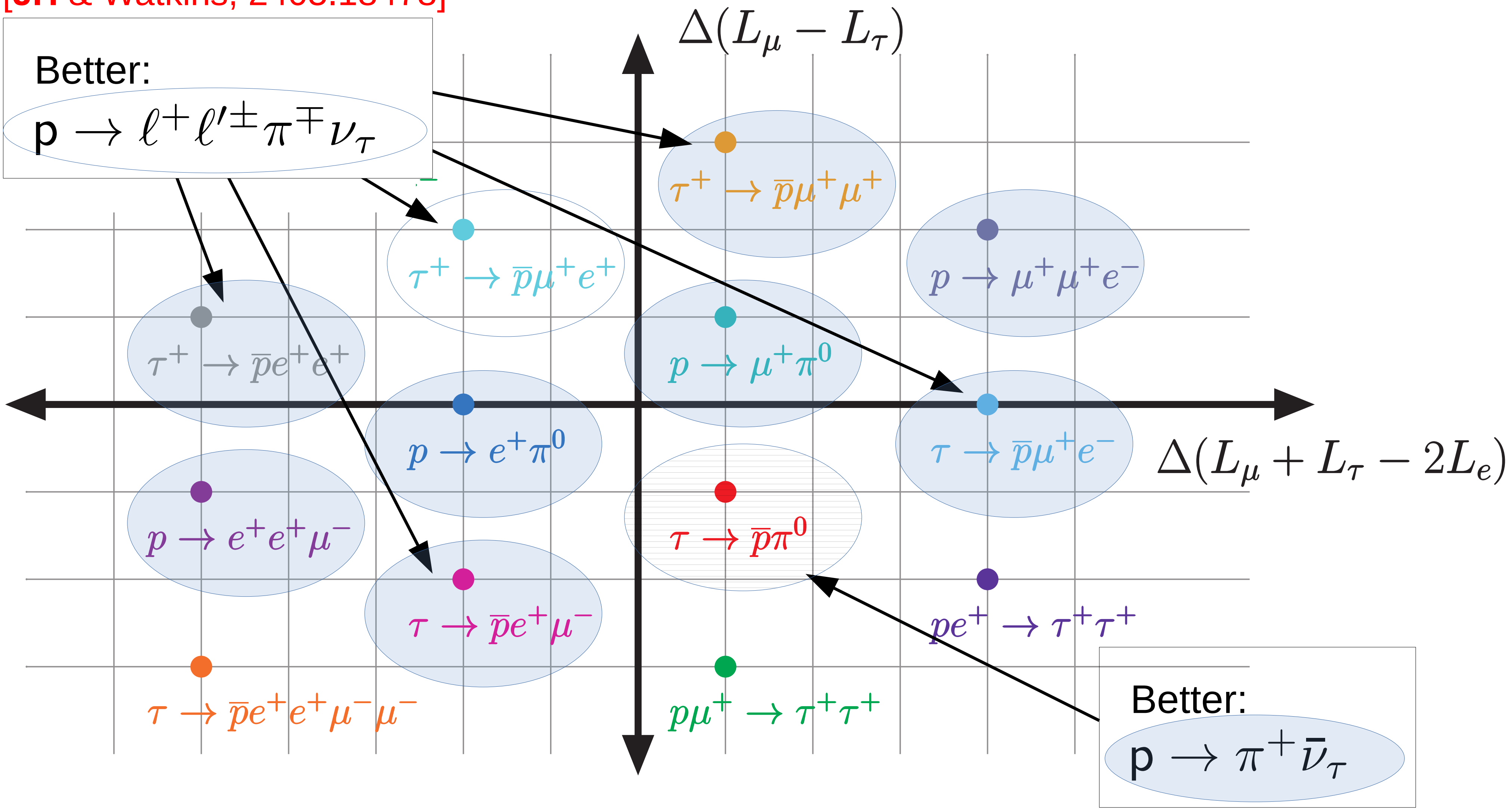
[**JH** & Watkins, 2405.18478]



[Marciano, NPB ‘95]
[**JH** & Watkins, 2405.18478]

ΔB = ΔL = 1 covered now?

[**JH** & Watkins, 2405.18478]



[Marciano, NPB '95]
[**JH** & Watkins, 2405.18478]

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	$(\bar{\mathbf{3}}, \mathbf{2}, -1/6)$

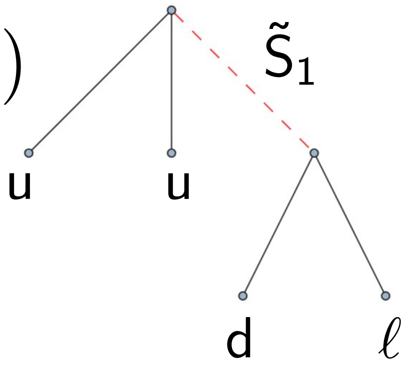
$duQL$	$\mathcal{S}_1,\ \mathcal{V}_2,\ \tilde{\mathcal{V}}_2$
$QQu\ell$	$\mathcal{S}_1,\ \mathcal{V}_2$
$QQQL$	$\mathcal{S}_1,\ \mathcal{S}_3$
$duu\ell$	$\mathcal{S}_1,\ \tilde{\mathcal{S}}_1$

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

- For example:

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

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



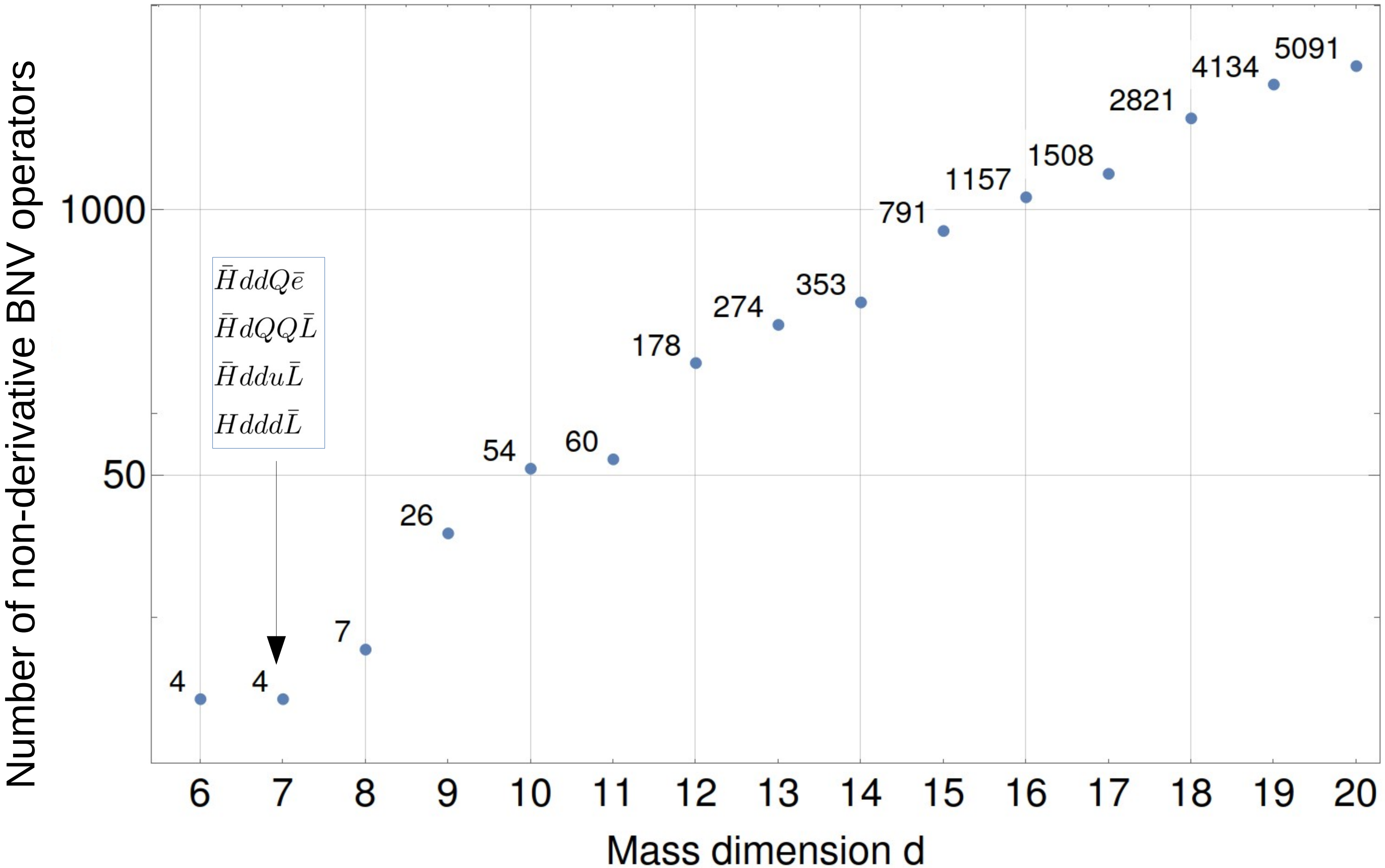
- $\tilde{z}^{RR}_{1\,ab}$ is antisymmetric → charm or top quark BNV!

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

UV completions shed different light on BNV

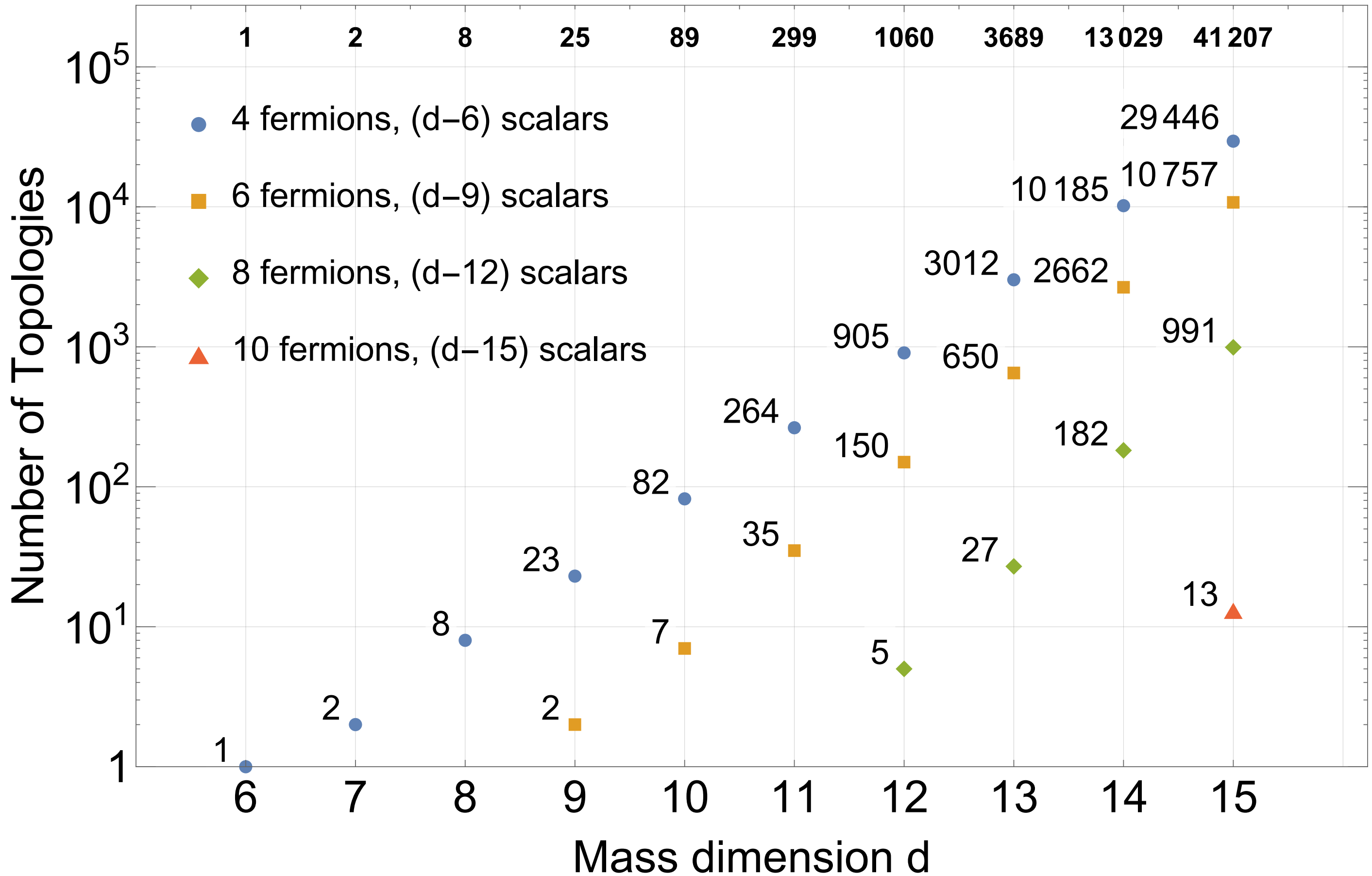
Opening up *all* BNV operators

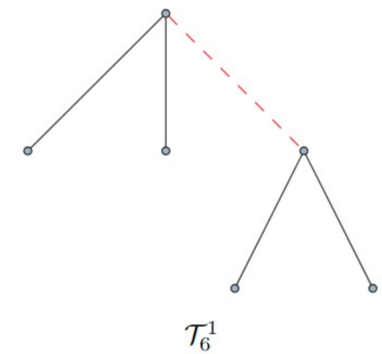
- Collect all SMEFT BNV operators, trivial with Sym2Int.
  [Renato M. Fonseca, 1703.05221 & 1907.12584]
- Exponential growth of "operators" (~field strings):

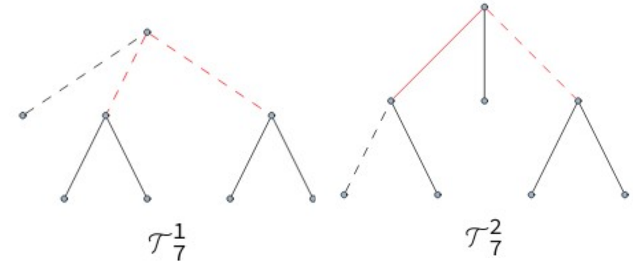


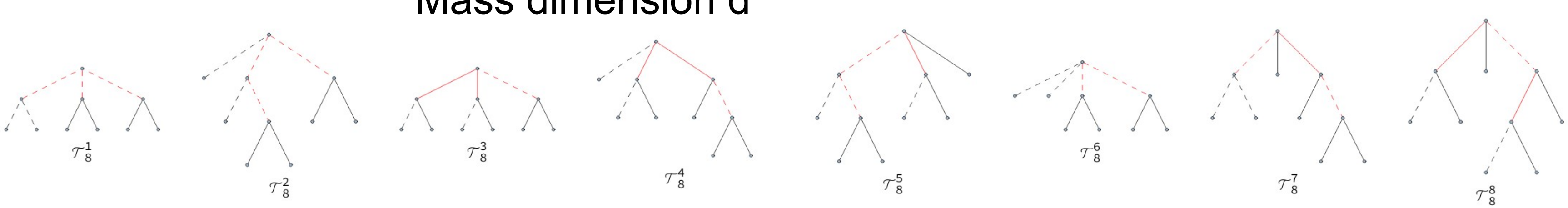
Opening up *all* BNV operators

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





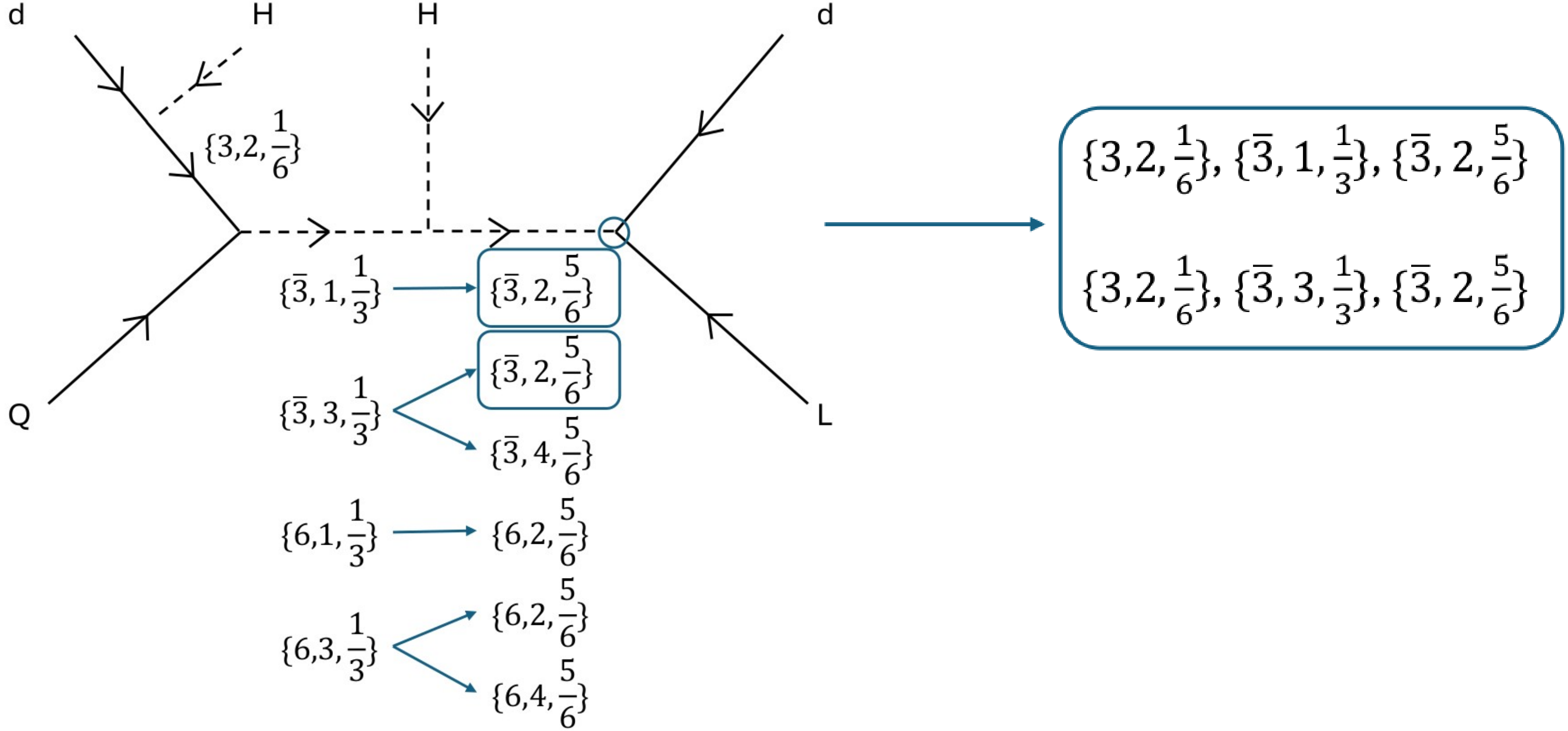




Opening up *all* BNV operators

- 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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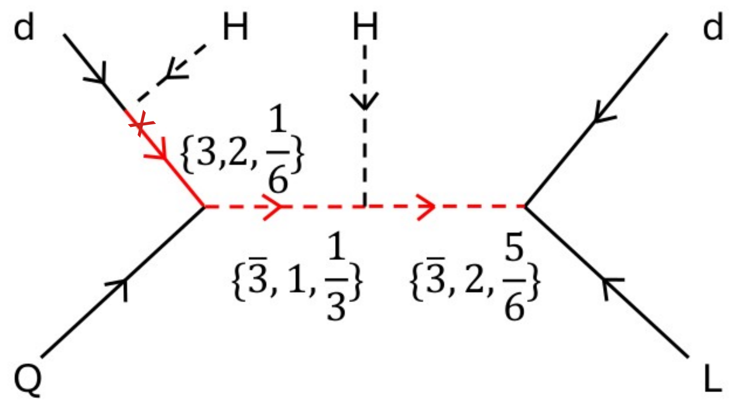


$$\left\{3,2,\tfrac{1}{6}\right\}_F, \left\{\bar{3},1,\tfrac{1}{3}\right\}_V, \left\{\bar{3},2,\tfrac{5}{6}\right\}_V$$

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

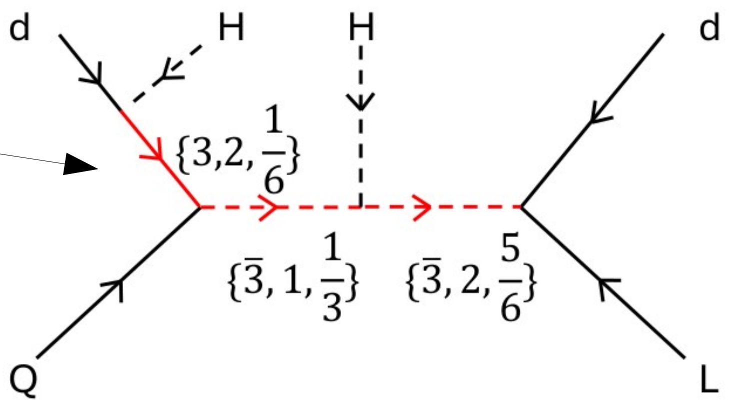
- Also include global Lorentz $SU(2)_{\text{left}} \times SU(2)_{\text{right}}$ for spin.
- Then permute external particles over topology and repeat...

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]

Opening up *all* BNV operators

- Code fast enough to reach $d \sim 15$.
- 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.

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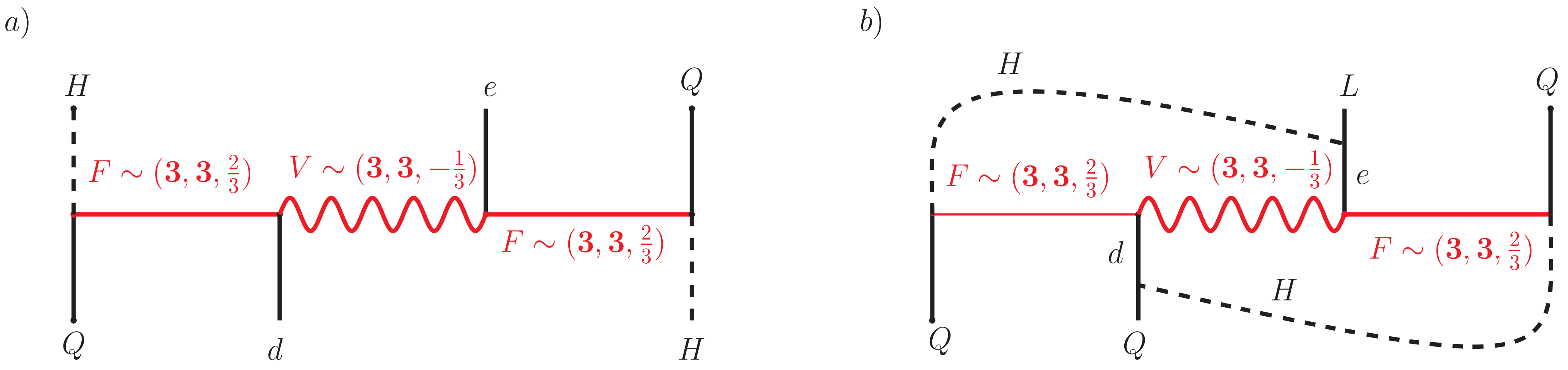
- Already revealed some mistakes in literature.
- Can be used to open up **any** (non-derivative) EFT operator.
- Find accidentally protected operators. [Weinberg, ‘80]
- E.g. add Dirac fermion (**3**,**3**,2/3) and vector LQ (**3**,**3**,-1/3).
  - Only generates BNV operator QQdeHH (d=8, B=L=1).
  - Could be dominant but *not* protected by symmetry.
  - Gives genuine loop realization of d=6 BNV operator.

    [also discussed in Gargalionis, Herrero-Garcia, Schmidt, 2401.04768]

    See also talk by Svjetlana Fajfer about BNV loops!

Opening up *all* BNV operators



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Protected operators

- d > 6 operators could dominate either because we impose a B/L symmetry à la Weinberg or due to **UV structure**.
- Can make *any* d=7 or d=8 operator dominant through UV:

$$HHddQL,\ \bar{H}\bar{H}uuQL,\ H\bar{H}duQL,\ H\bar{H}duue,\ HHdQQe,\ H\bar{H}QQQL,\ H\bar{H}uQQe$$

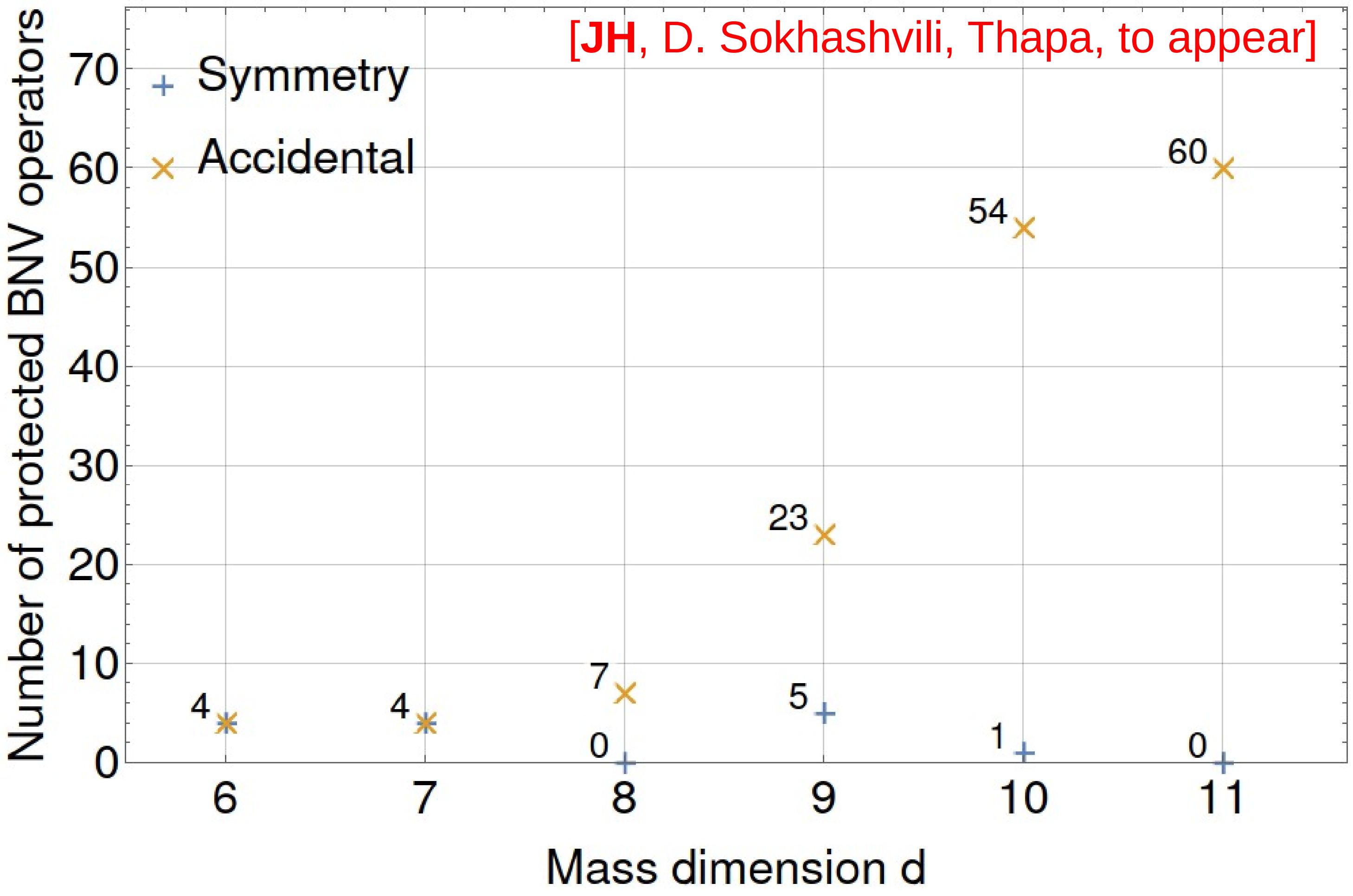
- Can make *most* d=9 operators (23/26), e.g.

$$dddd\bar{d}\bar{e},\ ddde\bar{e}\bar{e},\ ddue\bar{L}\bar{L},\ ddu\bar{u}Q\bar{L},\ H\bar{H}\bar{H}ddQ\bar{e},\ \ldots$$

- Can make *all* 54 d=10 operators, *all* 60 d=11 operators, …
- More abundant than symmetry-protected operators!
- These either have accidental B/L symmetry or give loop realization of lower-dim operators.

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

Protected operators



…so many operators, many with multi-particle BNV final states.
Can we test all of them?

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 from PDG:

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

- 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 $N \to \ell/\text{meson} + \text{anything}$.
- Also probes $\Delta B > 1$, light new physics, and dark matter!

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

Invisible neutron decay

- Special case of inclusive searches:

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

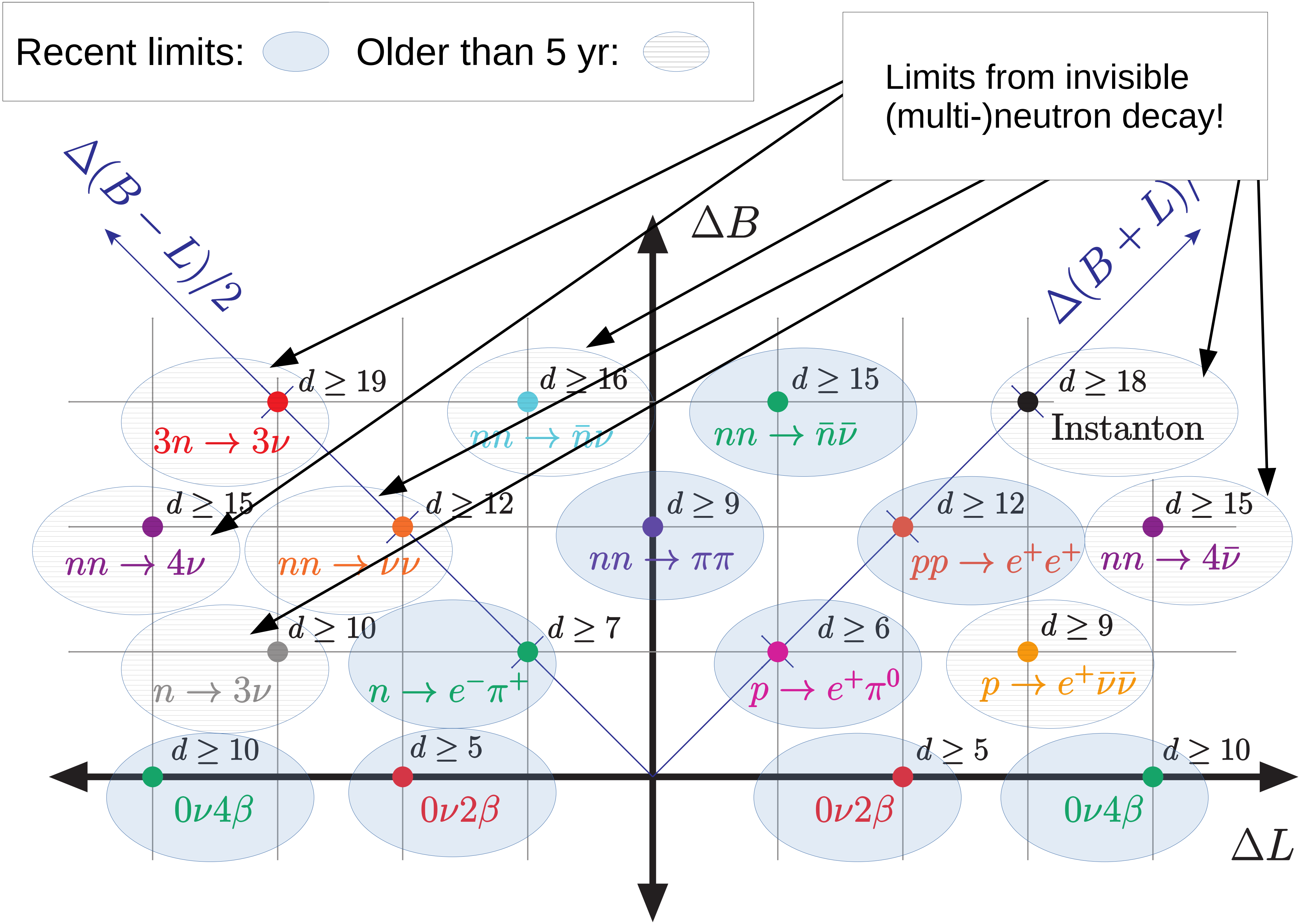
[KamLAND, PRL '06; see also SNO+, PRD '19]

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

- Only signature is de-excitation of daughter nucleus. [Ejiri, '93]
- Every $\Delta B = k$ 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]

See also talk by Cailian Jiang!

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


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

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, $0\nu\beta\beta$ exp.?

- Nearly every d≥6 BNV operator could be the starting point, either because of B/L/L_α symmetry or UV completion!
- 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, dark matter induced ΔB...

Time to cast a wider net!

Backup

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

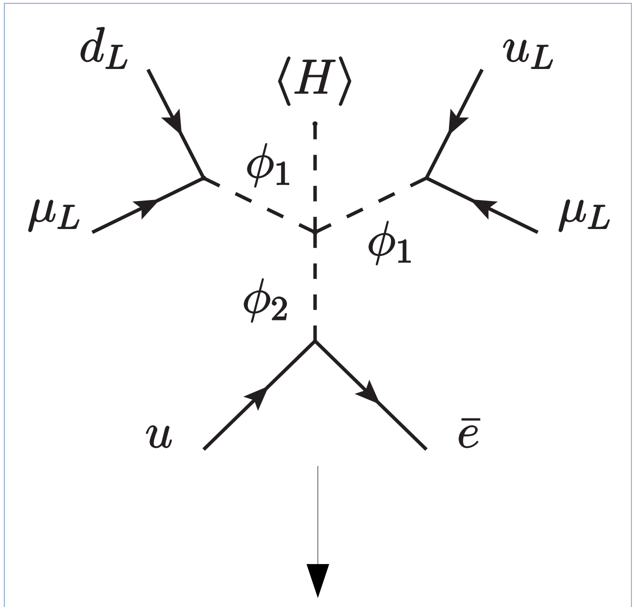
- Minimal leptoquark example:

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

- $L_\mu+2L_e-3L_\tau$ 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: $\langle 0|uud|p\rangle$.



[Hambye, **JH**, PRL '18]

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

Two-body nucleon decays

Channel	$\|\Delta(B-L)\|$	$\frac{\Gamma^{-1}}{10^{30}\,\mathrm{yr}}$
$p \to e^+ + \gamma$	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	$\lvert\Delta(B-L)\rvert$	$\frac{\Gamma^{-1}}{10^{30}\,\text{yr}}$
$p \to e^- + e^+ + e^+$	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	$\lvert\Delta(B-L)\rvert$	$\frac{\Gamma^{-1}}{10^{30}\,\text{yr}}$
$n \to \nu + e^- + e^+$	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

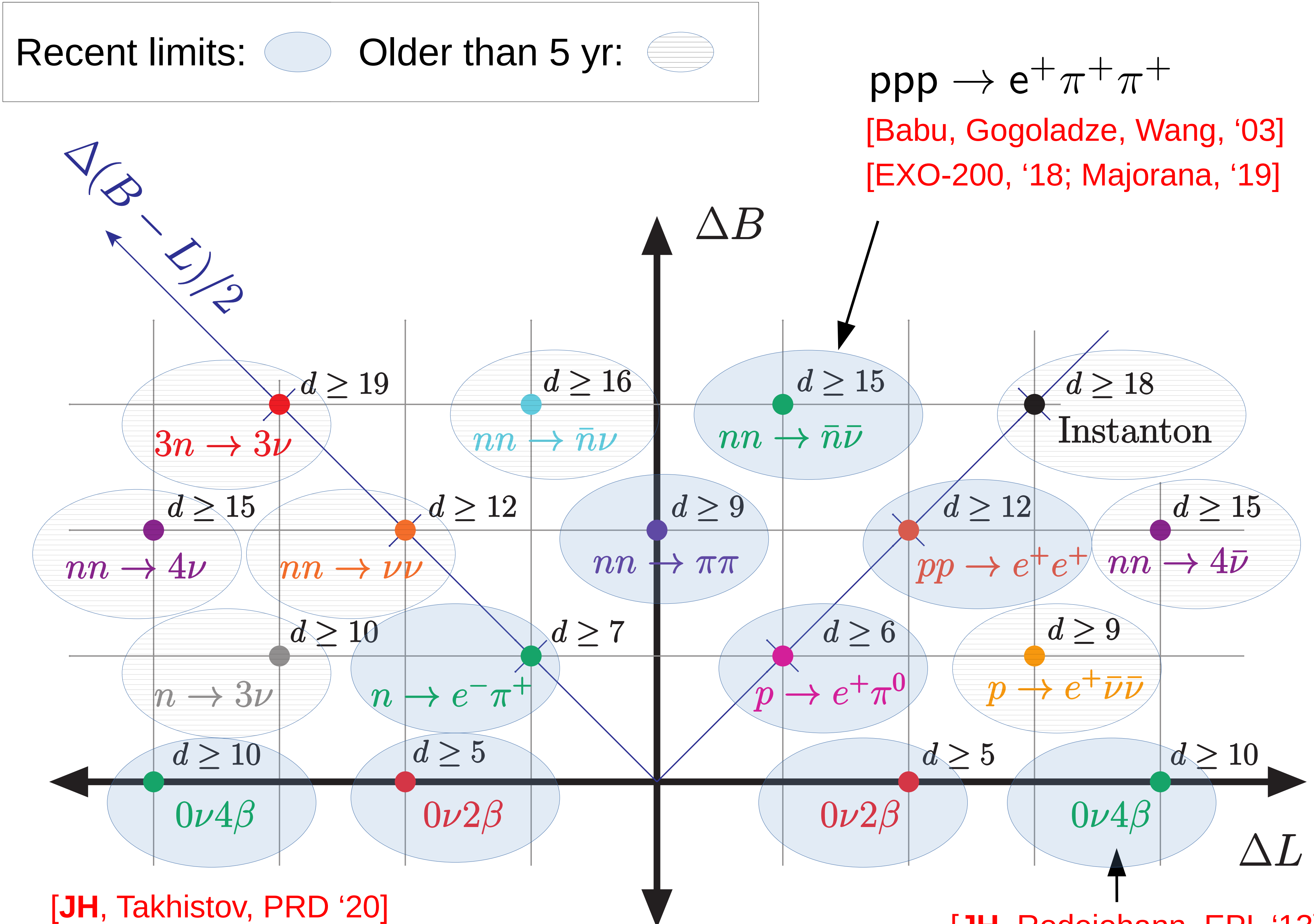
Channel	$\|\Delta(B-L)\|$	$\frac{\Gamma^{-1}}{10^{30}\,\text{yr}}$
$pp \to e^+ + e^+$	0	4200 [72]
$pp \to \mu^+ + \mu^+$	0	4400 [72]
$pp \to e^+ + \mu^+$	0	4400 [72]
$pp \to e^+ + \tau^+$	0	
$pp \to \pi^+ + \pi^+$	2	72 [115]
$pp \to \pi^+ + \rho^+$	2	
$pp \to \pi^+ + K^+$	2	
$pp \to \pi^+ + K^{*,+}$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



[**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

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

[Babu, Gogoladze, Wang, '03]

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

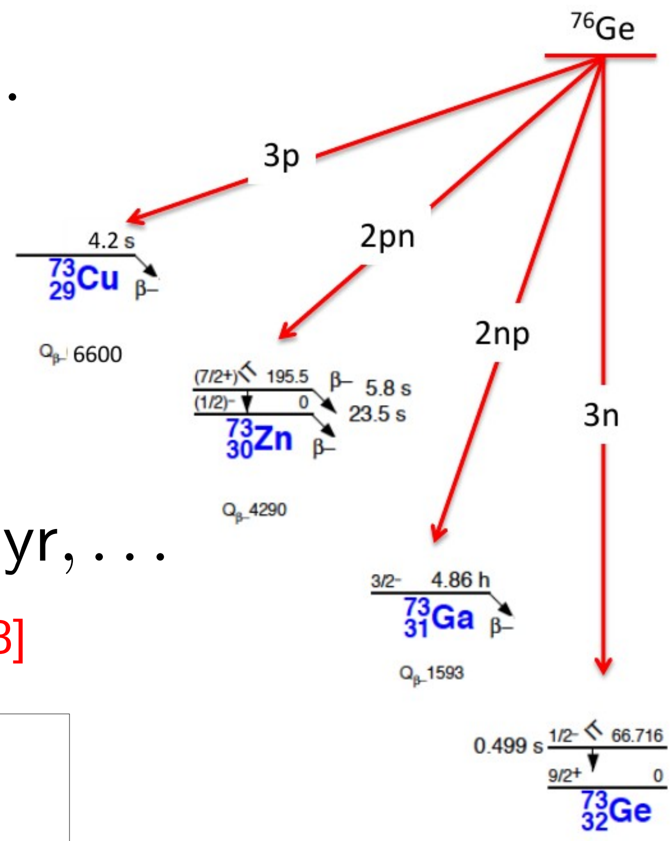
- $\mathrm{ppp} \to e^+\pi^+\pi^+$, $\mathrm{ppn} \to e^+\pi^+$, $\mathrm{pnn} \to e^+\pi^0$, $\mathrm{nn} \to \bar{n}\bar{\nu}, \ldots$
- $\tau(\mathrm{pnn} \to e^+\pi^0) \simeq 3 \times 10^{33}\,\mathrm{yr}\,\left(\frac{\Lambda}{100\,\mathrm{GeV}}\right)^{22}$.
- Limits:

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

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

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

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



SK, JUNO, DUNE, HK?

$$\mathcal{O}^1_{7,\,(1,-1)} \equiv \bar{H}ddQ\bar{e}\,,$$
$$\mathcal{O}^2_{7,\,(1,-1)} \equiv \bar{H}dQQ\bar{L}\,,$$
$$\mathcal{O}^3_{7,\,(1,-1)} \equiv \bar{H}ddu\bar{L}\,,$$
$$\mathcal{O}^4_{7,\,(1,-1)} \equiv Hddd\bar{L}$$

$$\mathcal{O}^1_{8,\,(1,1)} \equiv HHddQL\,,$$
$$\mathcal{O}^2_{8,\,(1,1)} \equiv HHdQQe\,,$$
$$\mathcal{O}^3_{8,\,(1,1)} \equiv \bar{H}\bar{H}uuQL\,,$$
$$\mathcal{O}^4_{8,\,(1,1)} \equiv H\bar{H}QQQL\,,$$
$$\mathcal{O}^5_{8,\,(1,1)} \equiv H\bar{H}duQL\,,$$
$$\mathcal{O}^6_{8,\,(1,1)} \equiv H\bar{H}uQQe\,,$$
$$\mathcal{O}^7_{8,\,(1,1)} \equiv H\bar{H}duue\,,$$

$$\mathcal{O}^1_{9,\,(1,-1)} \equiv dddd\bar{d}\bar{e}\,,$$
$$\mathcal{O}^2_{9,\,(1,-1)} \equiv ddde\bar{e}\bar{e}\,,$$
$$\mathcal{O}^3_{9,\,(1,-1)} \equiv dddQ\bar{Q}\bar{e}\,,$$
$$\mathcal{O}^4_{9,\,(1,-1)} \equiv dd\bar{u}QQ\bar{e}\,,$$
$$\mathcal{O}^5_{9,\,(1,-1)} \equiv dddu\bar{u}\bar{e}\,,$$
$$\mathcal{O}^6_{9,\,(1,-1)} \equiv ddd\bar{d}Q\bar{L}\,,$$
$$\mathcal{O}^7_{9,\,(1,-1)} \equiv ddd\bar{e}L\bar{L}\,,$$
$$\mathcal{O}^8_{9,\,(1,-1)} \equiv ddQe\bar{e}\bar{L}\,,$$
$$\mathcal{O}^9_{9,\,(1,-1)} \equiv ddQL\bar{L}\bar{L}\,,$$
$$\mathcal{O}^{10}_{9,\,(1,-1)} \equiv dQQe\bar{L}\bar{L}\,,$$
$$\mathcal{O}^{11}_{9,\,(1,-1)} \equiv ddue\bar{L}\bar{L}\,,$$
$$\mathcal{O}^{12}_{9,\,(1,-1)} \equiv ddQQ\bar{Q}\bar{L}\,,$$
$$\mathcal{O}^{13}_{9,\,(1,-1)} \equiv dddu\bar{Q}\bar{L}\,,$$
$$\mathcal{O}^{14}_{9,\,(1,-1)} \equiv d\bar{u}QQQ\bar{L}\,,$$
$$\mathcal{O}^{15}_{9,\,(1,-1)} \equiv ddu\bar{u}Q\bar{L}\,,$$

$$\mathcal{O}^{39}_{9,\,(1,-1)} \equiv H\bar{H}\bar{H}ddQ\bar{e}\,,$$
$$\mathcal{O}^{40}_{9,\,(1,-1)} \equiv H\bar{H}\bar{H}dQQ\bar{L}\,,$$
$$\mathcal{O}^{41}_{9,\,(1,-1)} \equiv H\bar{H}\bar{H}ddu\bar{L}\,,$$
$$\mathcal{O}^{42}_{9,\,(1,-1)} \equiv HH\bar{H}ddd\bar{L}\,,$$
$$\mathcal{O}^{43}_{9,\,(1,-1)} \equiv \bar{H}\bar{H}\bar{H}QQQ\bar{e}\,,$$
$$\mathcal{O}^{44}_{9,\,(1,-1)} \equiv \bar{H}\bar{H}\bar{H}uQQ\bar{L}\,,$$

$$\mathcal{O}^1_{9,\,(1,3)} \equiv uuQLLL\,,$$
$$\mathcal{O}^2_{9,\,(1,3)} \equiv uuueLL\,,$$

$$\mathcal{O}^1_{9,\,(2,0)} \equiv ddQQQQ\,,$$
$$\mathcal{O}^2_{9,\,(2,0)} \equiv ddduQQ\,,$$
$$\mathcal{O}^3_{9,\,(2,0)} \equiv dddduu$$

$$\mathcal{O}^{1}_{10,\,(1,1)} \equiv H d d \bar{d} Q Q L\,,$$
$$\mathcal{O}^{2}_{10,\,(1,1)} \equiv H d \bar{d} Q Q Q e\,,$$
$$\mathcal{O}^{3}_{10,\,(1,1)} \equiv H d d d \bar{d} u L\,,$$
$$\mathcal{O}^{4}_{10,\,(1,1)} \equiv H d d \bar{d} u Q e\,,$$
$$\mathcal{O}^{5}_{10,\,(1,1)} \equiv H d d Q \bar{e} L L\,,$$
$$\mathcal{O}^{6}_{10,\,(1,1)} \equiv H d Q Q e \bar{e} L\,,$$
$$\mathcal{O}^{7}_{10,\,(1,1)} \equiv H Q Q Q e e \bar{e}\,,$$
$$\mathcal{O}^{8}_{10,\,(1,1)} \equiv H d d u e \bar{e} L\,,$$
$$\mathcal{O}^{9}_{10,\,(1,1)} \equiv H d u Q e e \bar{e}\,,$$
$$\mathcal{O}^{10}_{10,\,(1,1)} \equiv \bar{H} \bar{d} Q Q Q Q L\,,$$
$$\mathcal{O}^{11}_{10,\,(1,1)} \equiv \bar{H} d \bar{d} u Q Q L\,,$$
$$\mathcal{O}^{12}_{10,\,(1,1)} \equiv \bar{H} \bar{d} u Q Q Q e\,,$$
$$\mathcal{O}^{13}_{10,\,(1,1)} \equiv \bar{H} d d \bar{d} u u L\,,$$
$$\mathcal{O}^{14}_{10,\,(1,1)} \equiv \bar{H} d \bar{d} u u Q e\,,$$
$$\mathcal{O}^{15}_{10,\,(1,1)} \equiv \bar{H} Q Q Q \bar{e} L L\,,$$
$$\mathcal{O}^{16}_{10,\,(1,1)} \equiv \bar{H} d u Q \bar{e} L L\,,$$
$$\mathcal{O}^{17}_{10,\,(1,1)} \equiv \bar{H} u Q Q e \bar{e} L\,,$$
$$\mathcal{O}^{18}_{10,\,(1,1)} \equiv \bar{H} d u u e \bar{e} L\,,$$
$$\mathcal{O}^{19}_{10,\,(1,1)} \equiv \bar{H} u u Q e e \bar{e}\,,$$
$$\mathcal{O}^{20}_{10,\,(1,1)} \equiv \bar{H} u Q Q L L \bar{L}\,,$$
$$\mathcal{O}^{21}_{10,\,(1,1)} \equiv \bar{H} d u u L L \bar{L}\,,$$
$$\mathcal{O}^{22}_{10,\,(1,1)} \equiv \bar{H} u u Q e L \bar{L}\,,$$
$$\mathcal{O}^{23}_{10,\,(1,1)} \equiv \bar{H} u u u e e \bar{L}\,,$$
$$\mathcal{O}^{24}_{10,\,(1,1)} \equiv \bar{H} u Q Q Q \bar{Q} L\,,$$
$$\mathcal{O}^{25}_{10,\,(1,1)} \equiv \bar{H} d u u Q \bar{Q} L\,,$$
$$\mathcal{O}^{26}_{10,\,(1,1)} \equiv \bar{H} u u Q Q \bar{Q} e\,,$$
$$\mathcal{O}^{27}_{10,\,(1,1)} \equiv \bar{H} d u u u \bar{Q} e\,,$$
$$\mathcal{O}^{28}_{10,\,(1,1)} \equiv \bar{H} u u \bar{u} Q Q L\,,$$
$$\mathcal{O}^{29}_{10,\,(1,1)} \equiv \bar{H} d u u u \bar{u} L\,,$$
$$\mathcal{O}^{30}_{10,\,(1,1)} \equiv \bar{H} u u u \bar{u} Q e\,,$$
$$\mathcal{O}^{31}_{10,\,(1,1)} \equiv H d Q Q L L \bar{L}\,,$$
$$\mathcal{O}^{32}_{10,\,(1,1)} \equiv H Q Q Q e L \bar{L}\,,$$
$$\mathcal{O}^{33}_{10,\,(1,1)} \equiv H d d u L L \bar{L}\,,$$
$$\mathcal{O}^{34}_{10,\,(1,1)} \equiv H d u Q e L \bar{L}\,,$$
$$\mathcal{O}^{35}_{10,\,(1,1)} \equiv H u Q Q e e \bar{L}\,,$$
$$\mathcal{O}^{36}_{10,\,(1,1)} \equiv H d u u e e \bar{L}\,,$$
$$\mathcal{O}^{37}_{10,\,(1,1)} \equiv H d Q Q Q \bar{Q} L\,,$$
$$\mathcal{O}^{38}_{10,\,(1,1)} \equiv H Q Q Q Q \bar{Q} e\,,$$
$$\mathcal{O}^{39}_{10,\,(1,1)} \equiv H d d u Q \bar{Q} L\,,$$
$$\mathcal{O}^{40}_{10,\,(1,1)} \equiv H d u Q Q \bar{Q} e\,,$$
$$\mathcal{O}^{41}_{10,\,(1,1)} \equiv H d d u u \bar{Q} e\,,$$
$$\mathcal{O}^{42}_{10,\,(1,1)} \equiv H \bar{u} Q Q Q Q L\,,$$
$$\mathcal{O}^{43}_{10,\,(1,1)} \equiv H d u \bar{u} Q Q L\,,$$
$$\mathcal{O}^{44}_{10,\,(1,1)} \equiv H u \bar{u} Q Q Q e\,,$$
$$\mathcal{O}^{45}_{10,\,(1,1)} \equiv H d d u u \bar{u} L\,,$$
$$\mathcal{O}^{46}_{10,\,(1,1)} \equiv H d u u \bar{u} Q e\,,$$
$$\mathcal{O}^{93}_{10,\,(1,1)} \equiv H H H \bar{H} d d Q L\,,$$
$$\mathcal{O}^{94}_{10,\,(1,1)} \equiv H H H \bar{H} d Q Q e\,,$$
$$\mathcal{O}^{95}_{10,\,(1,1)} \equiv H \bar{H} \bar{H} \bar{H} u u Q L\,,$$
$$\mathcal{O}^{96}_{10,\,(1,1)} \equiv H H \bar{H} \bar{H} Q Q Q L\,,$$
$$\mathcal{O}^{97}_{10,\,(1,1)} \equiv H H \bar{H} \bar{H} d u Q L\,,$$
$$\mathcal{O}^{98}_{10,\,(1,1)} \equiv H H \bar{H} \bar{H} u Q Q e\,,$$
$$\mathcal{O}^{99}_{10,\,(1,1)} \equiv H H \bar{H} \bar{H} d u u e\,,$$

$$\mathcal{O}^{1}_{10,\,(1,-3)} \equiv \bar{H} d d d \bar{L} \bar{L} \bar{L}\,,$$