Exotic B and L Violating Processes

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BLV circa 2020

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How exotic?

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

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

B) Flavored ΔB & ΔL.

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

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

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

- E.g. $n \to \pi^0 \chi$ or $p \to e^+ \chi$. See talks by Fornal and McKeen.

D) Dark matter induced ΔB & ΔL.

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

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

Homework: everything together.

Standard Model effective field theory

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

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

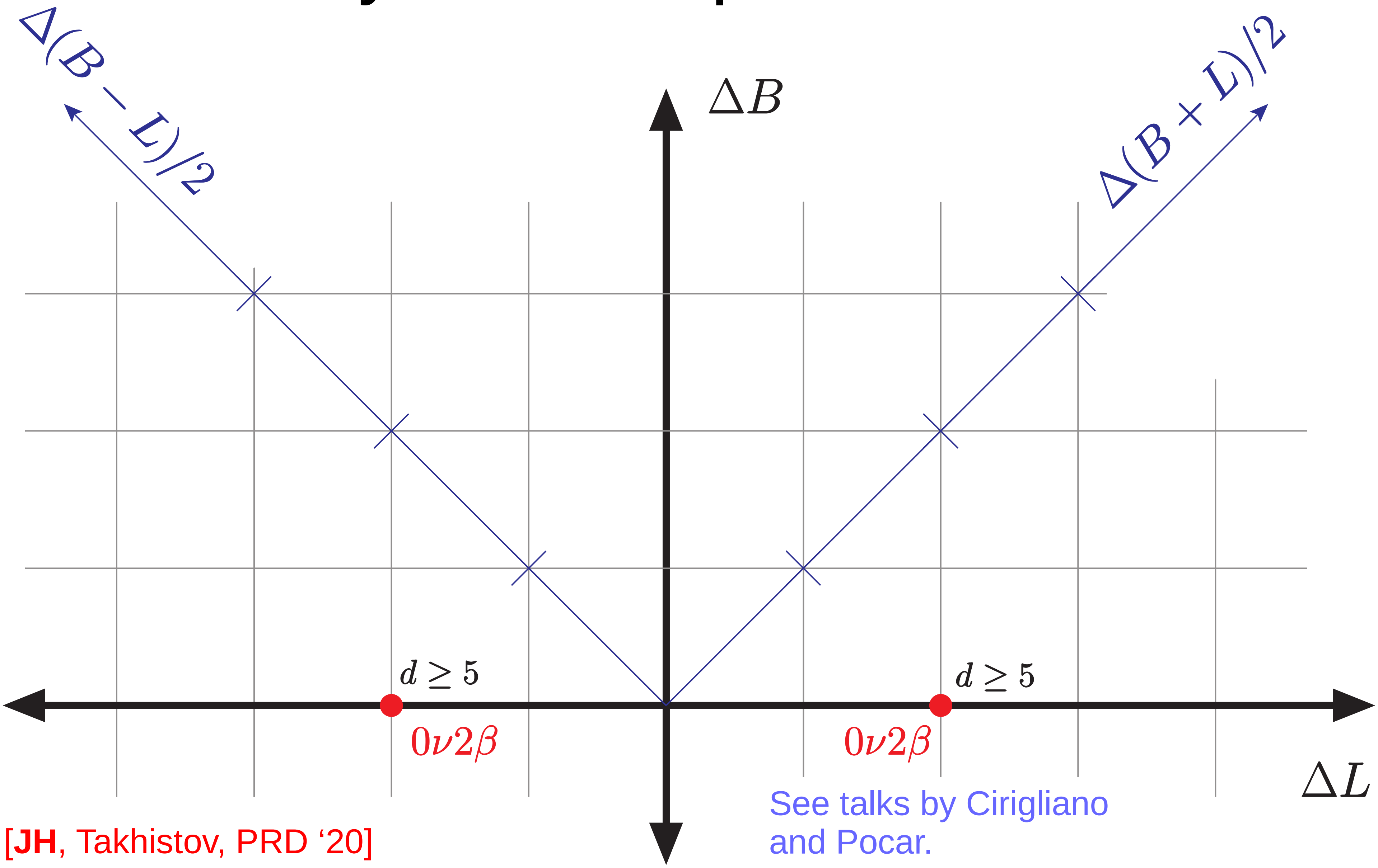
$\Delta L = 2$ $\qquad$ $\Delta B = \Delta L = 1$ $\qquad$ $\Delta B = -\Delta L = 1$

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

[Weinberg, '80]

Get global view on ΔB and ΔL.

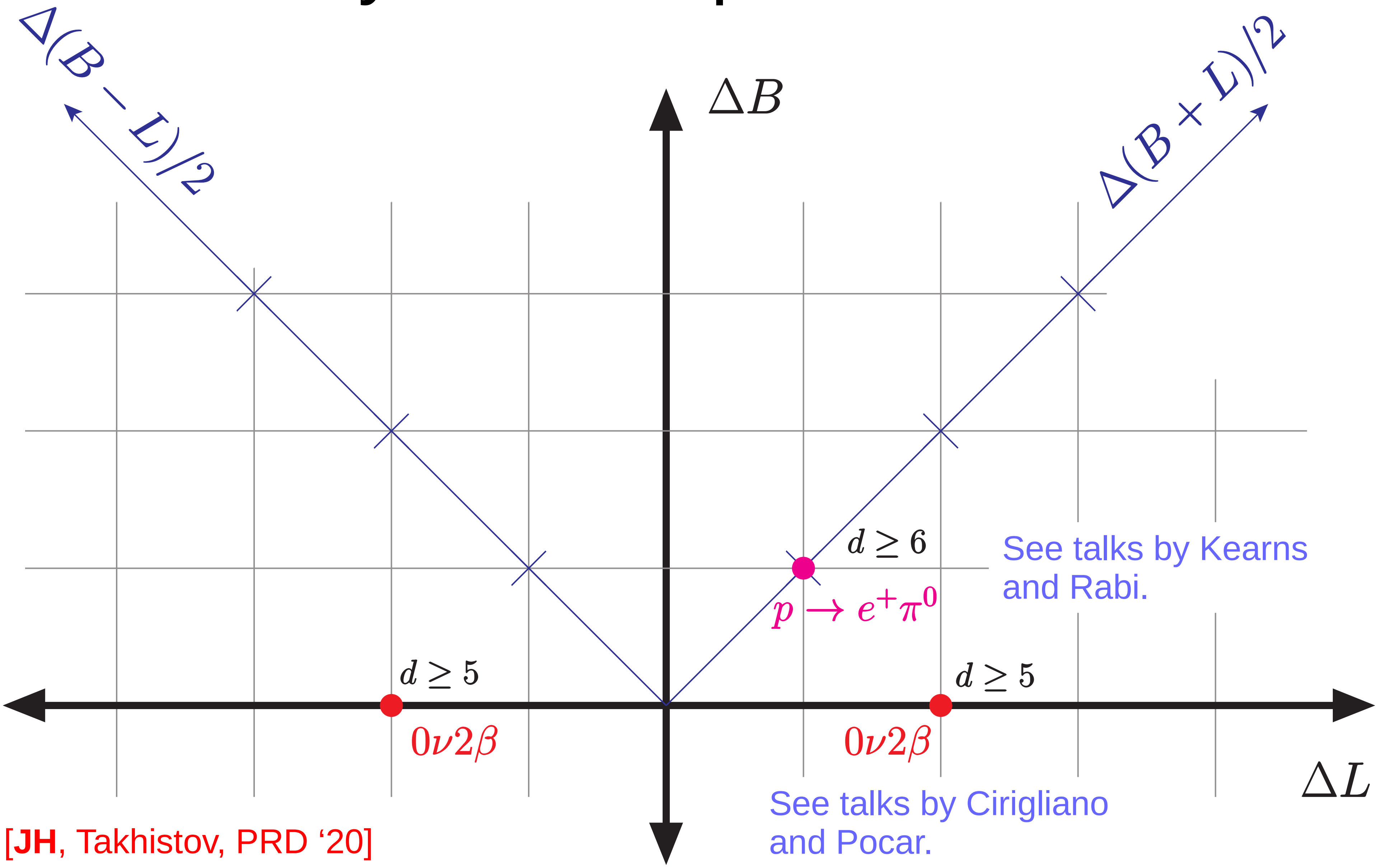
Baryon and lepton number



See talks by Cirigliano and Pocar.

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

Baryon and lepton number



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See talks by Cirigliano and Pocar.

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

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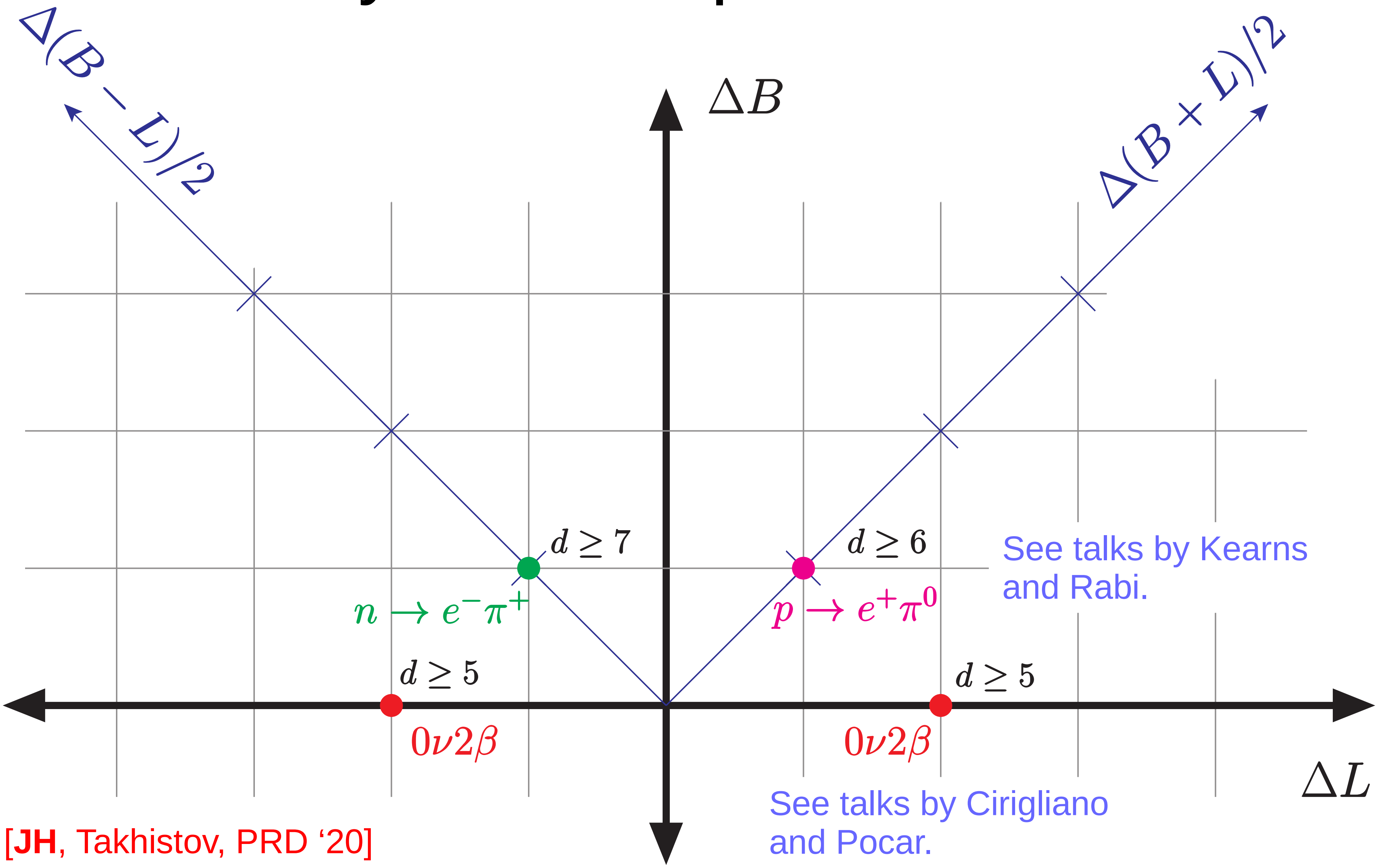

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[**JH**, Takhistov, PRD '20]

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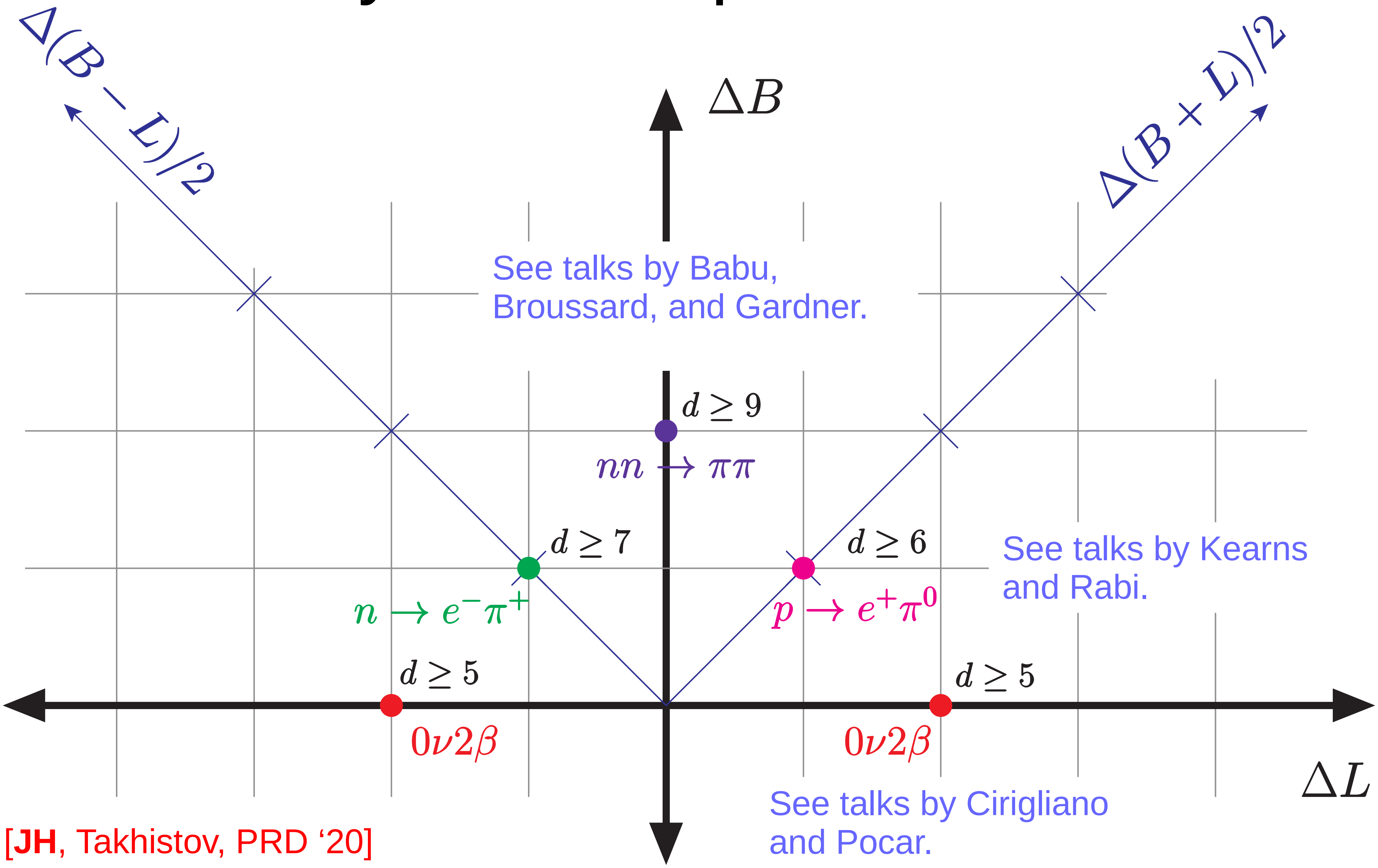
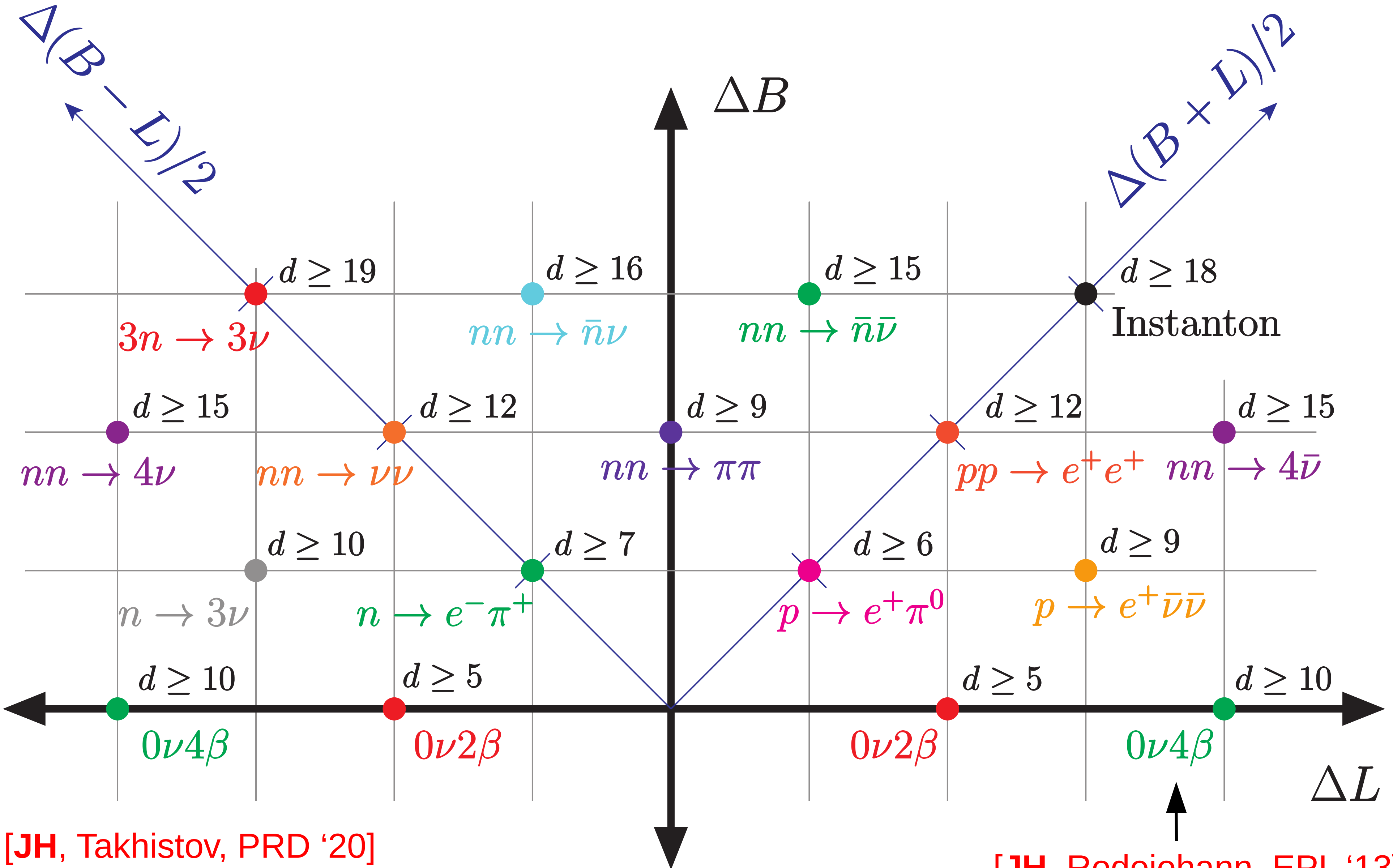


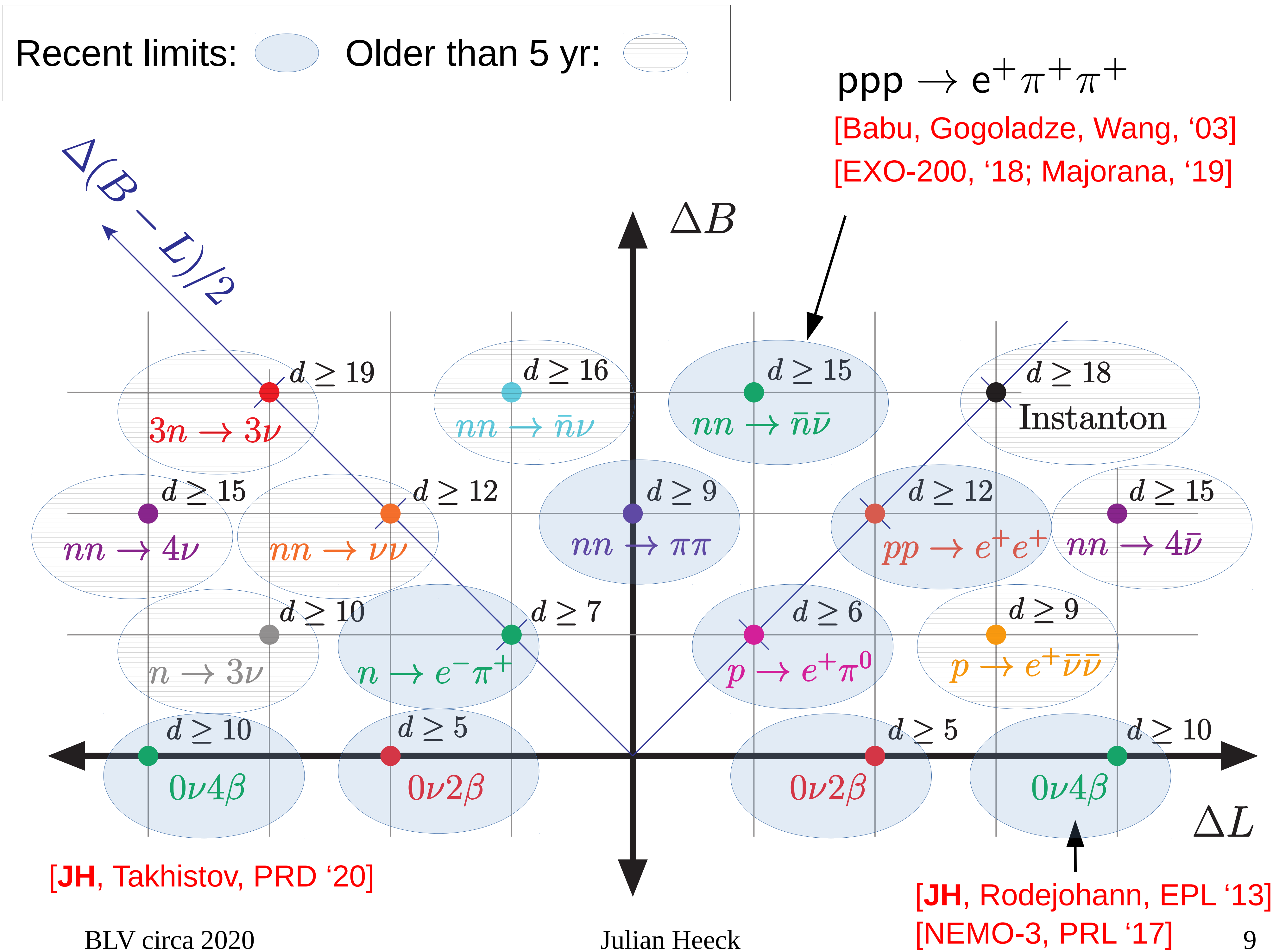
[**JH**, Takhistov, PRD '20]

Exotic B and L



[**JH**, Takhistov, PRD ‘20]

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



Recent limits:
Older than 5 yr:
ppp → e⁺π⁺π⁺
[Babu, Gogoladze, Wang, ‘03]
[EXO-200, ‘18; Majorana, ‘19]
Δ(B − L)/2
ΔB
ΔL
d ≥ 19
3n → 3ν
d ≥ 16
nn → n̄ν
d ≥ 15
nn → n̄ν̄
d ≥ 18
Instanton
d ≥ 15
nn → 4ν
d ≥ 12
nn → νν
d ≥ 9
nn → ππ
d ≥ 12
pp → e⁺e⁺
d ≥ 15
nn → 4ν̄
d ≥ 10
n → 3ν
d ≥ 7
n → e⁻π⁺
d ≥ 6
p → e⁺π⁰
d ≥ 9
p → e⁺ν̄ν̄
d ≥ 10
0ν4β
d ≥ 5
0ν2β
d ≥ 5
0ν2β
d ≥ 10
0ν4β
[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

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

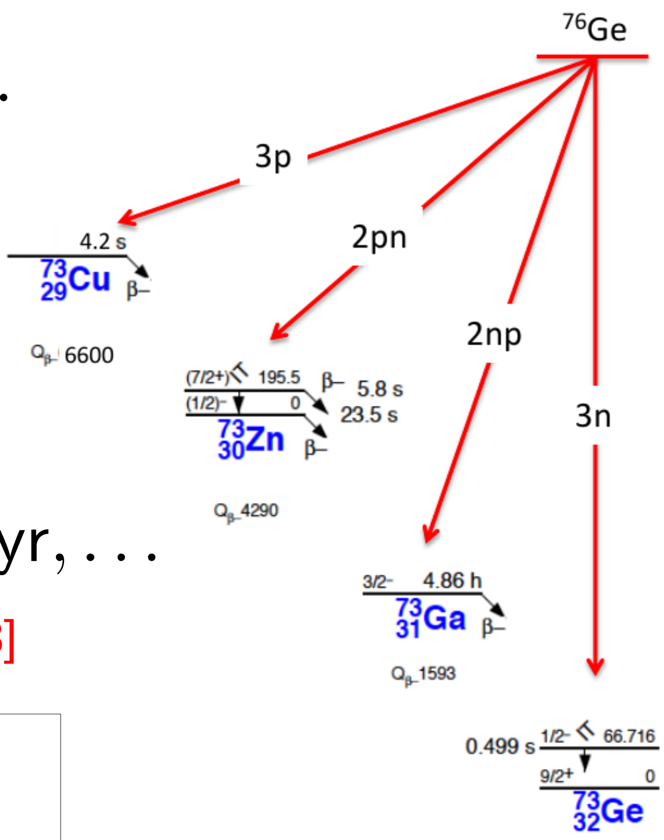
[Babu, Gogoladze, Wang, '03]

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

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

$$\tau(^{73}\mathrm{Ge}(\mathrm{pnn}) \to {}^{70}\mathrm{Ga}\, e^+\pi^0) > 7 \times 10^{23}\,\mathrm{yr},$$
$$\tau(^{76}\mathrm{Ge}(\mathrm{ppn}) \to {}^{73}\mathrm{Zn}\, e^+\pi^+) > 5 \times 10^{25}\,\mathrm{yr},$$
$$\tau(^{76}\mathrm{Ge}(\mathrm{ppp}) \to {}^{73}\mathrm{Cu}\, e^+\pi^+\pi^+) > 5 \times 10^{25}\,\mathrm{yr}, \ldots$$

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



SK, JUNO, DUNE, HK?

ppp → $e^+\pi^+\pi^+$

- Symmetry

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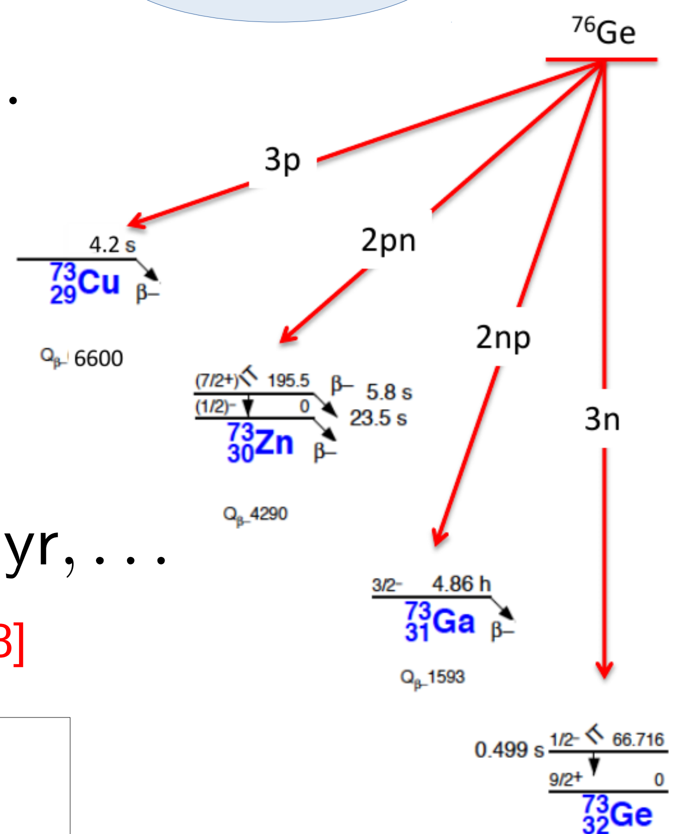
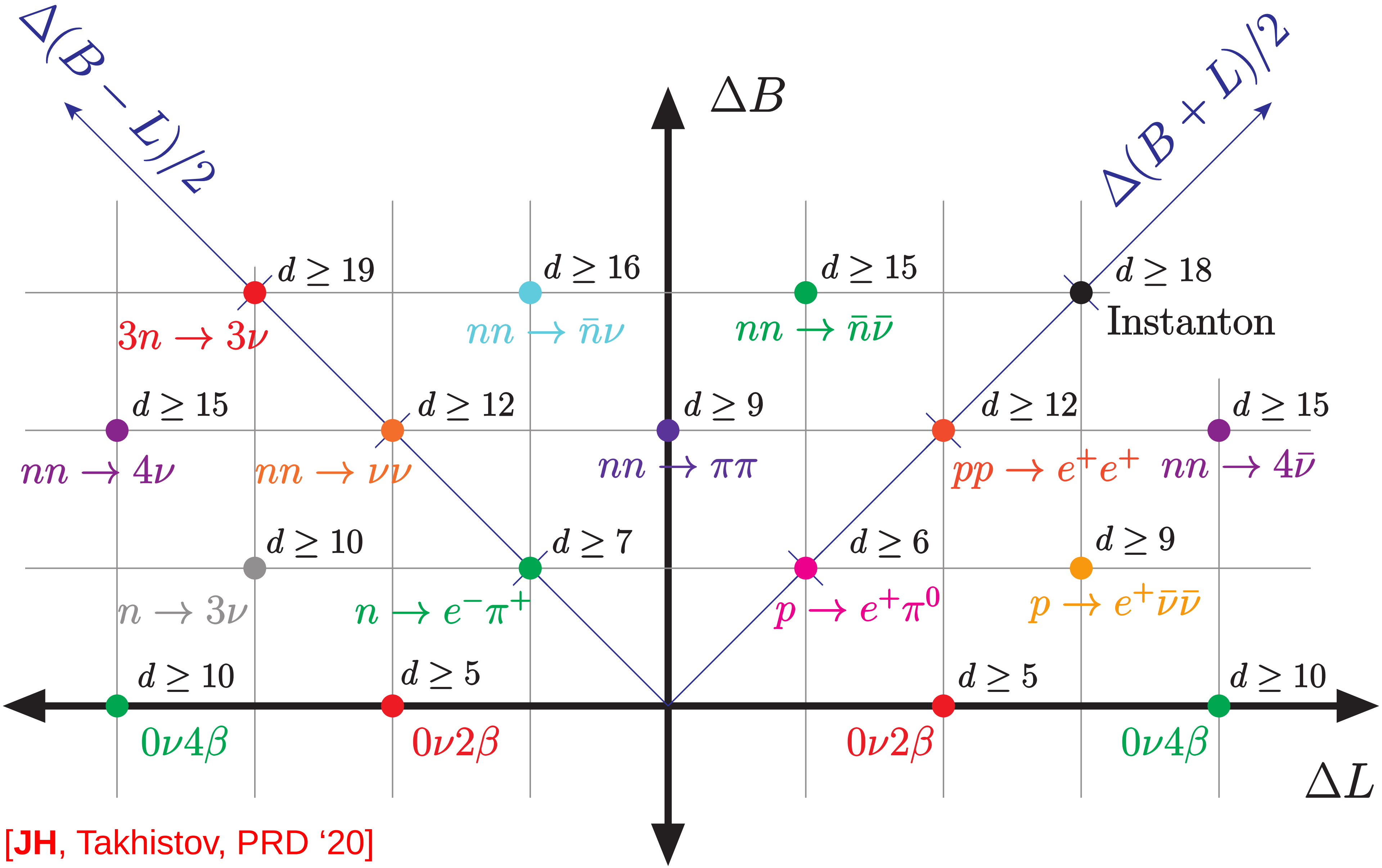
[Majorana Demonstrator, PRD '19; see also EXO-200, '18]



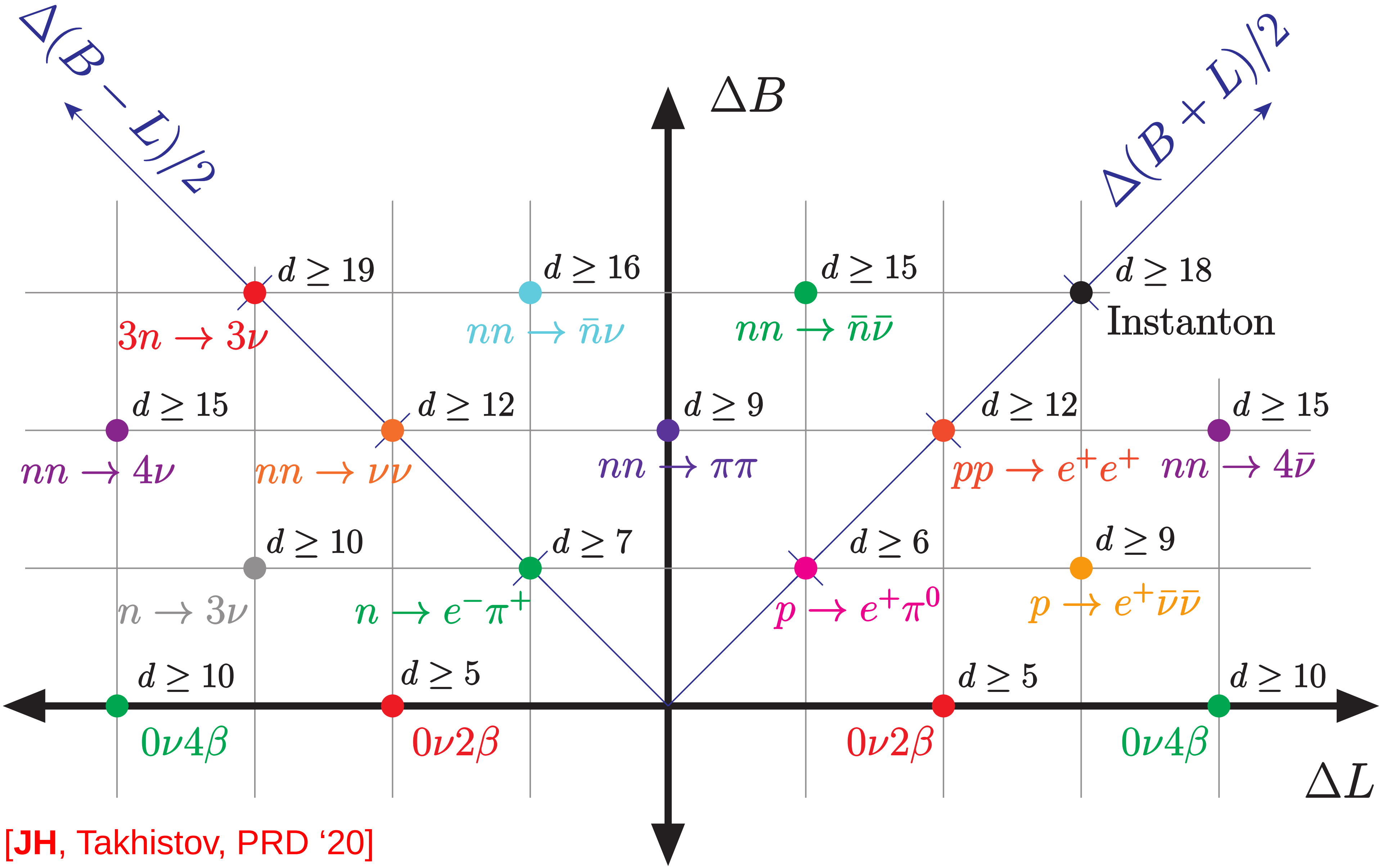
SK, JUNO, DUNE, HK?

Exotic B and L



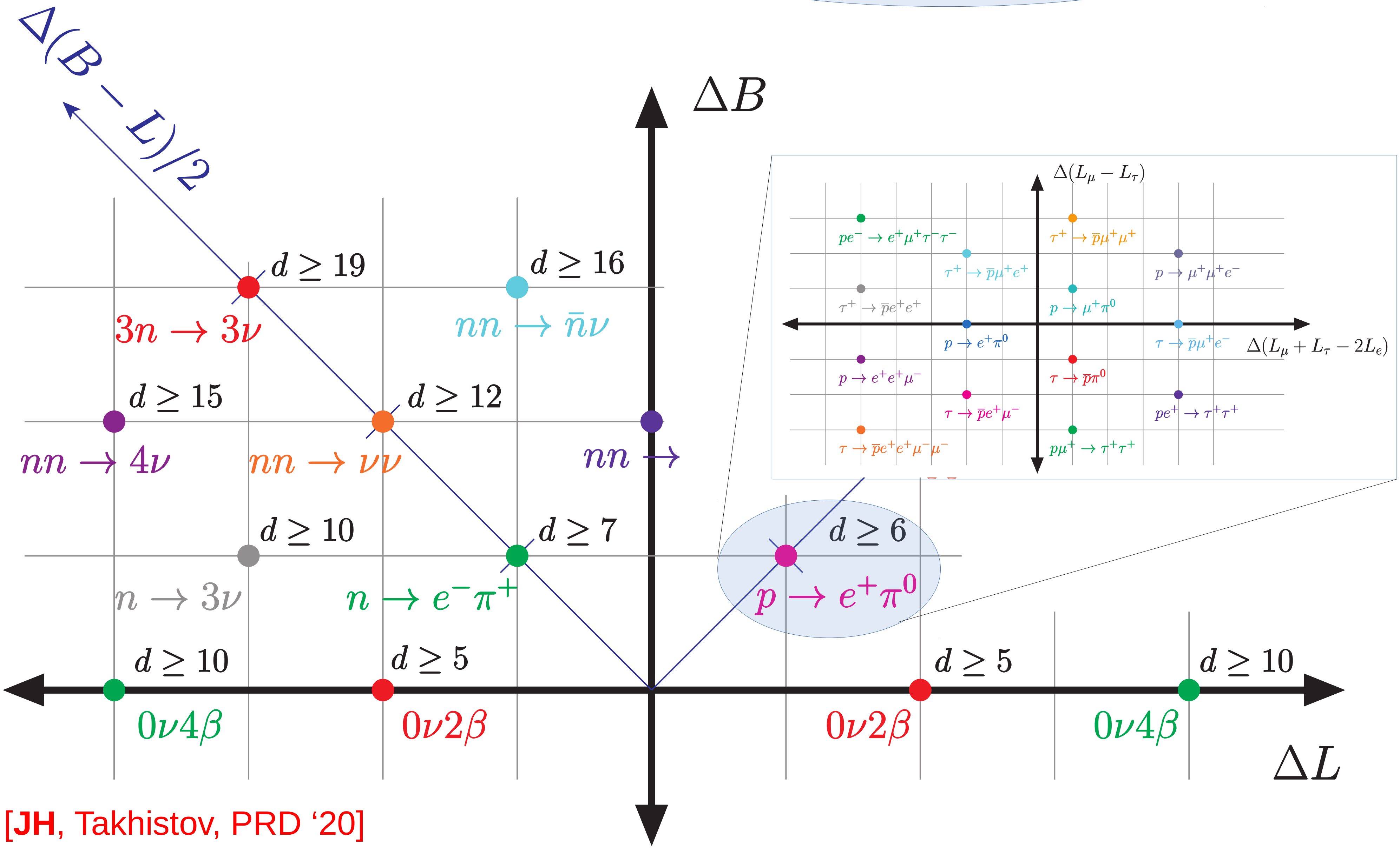
[**JH**, Takhistov, PRD ‘20]

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



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

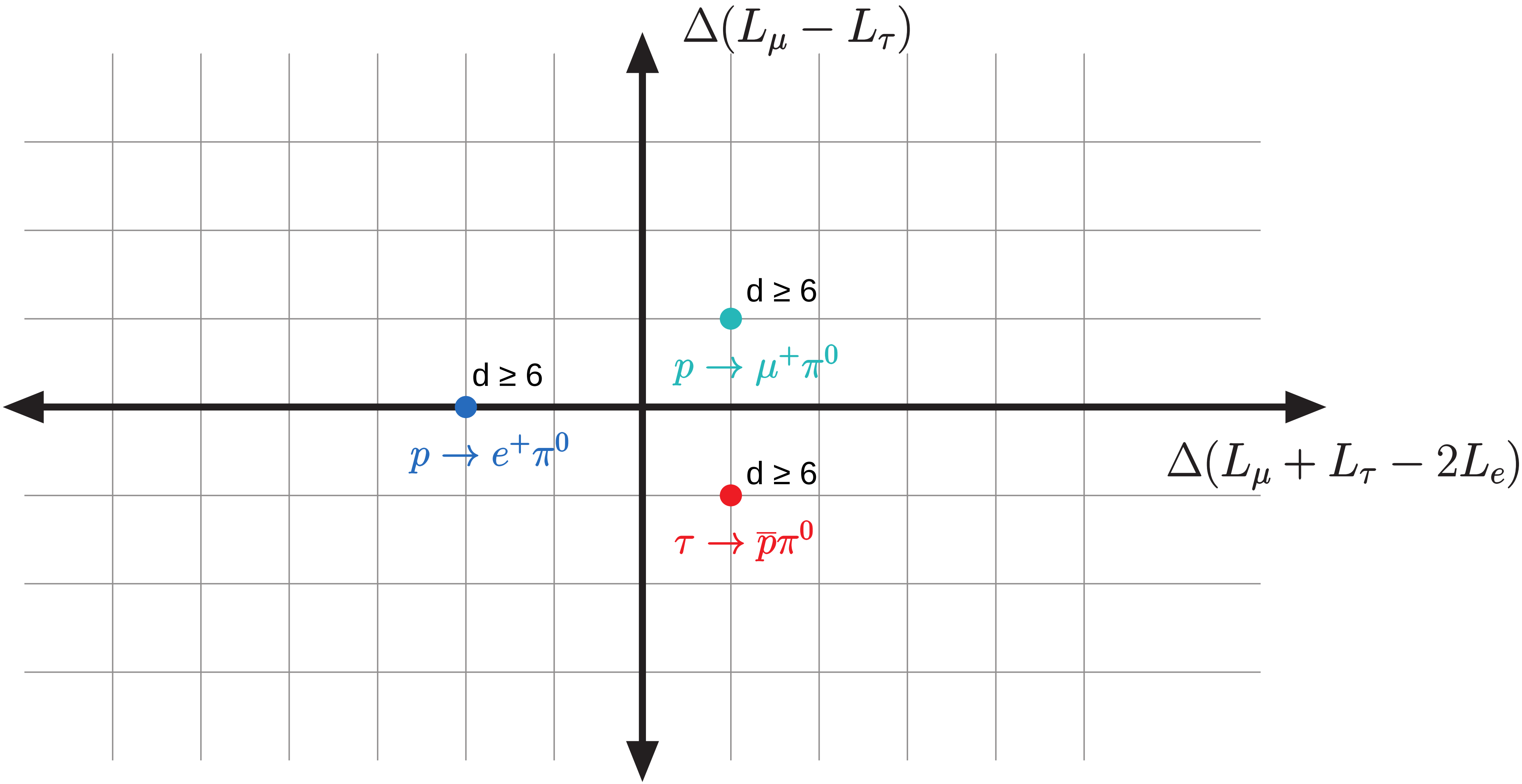
$$\mathbb{Z}_3^{(\mathrm{B+L})/2} \times \mathrm{U}(1)_{\mathrm{B-L}} \times \mathrm{U}(1)_{\mathrm{L}_\mu - \mathrm{L}_\tau} \times \mathrm{U}(1)_{\mathrm{L}_\mu + \mathrm{L}_\tau - 2\mathrm{L}_e}$$



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

Proton decay = lepton flavor violation

ΔB = ΔL = 1



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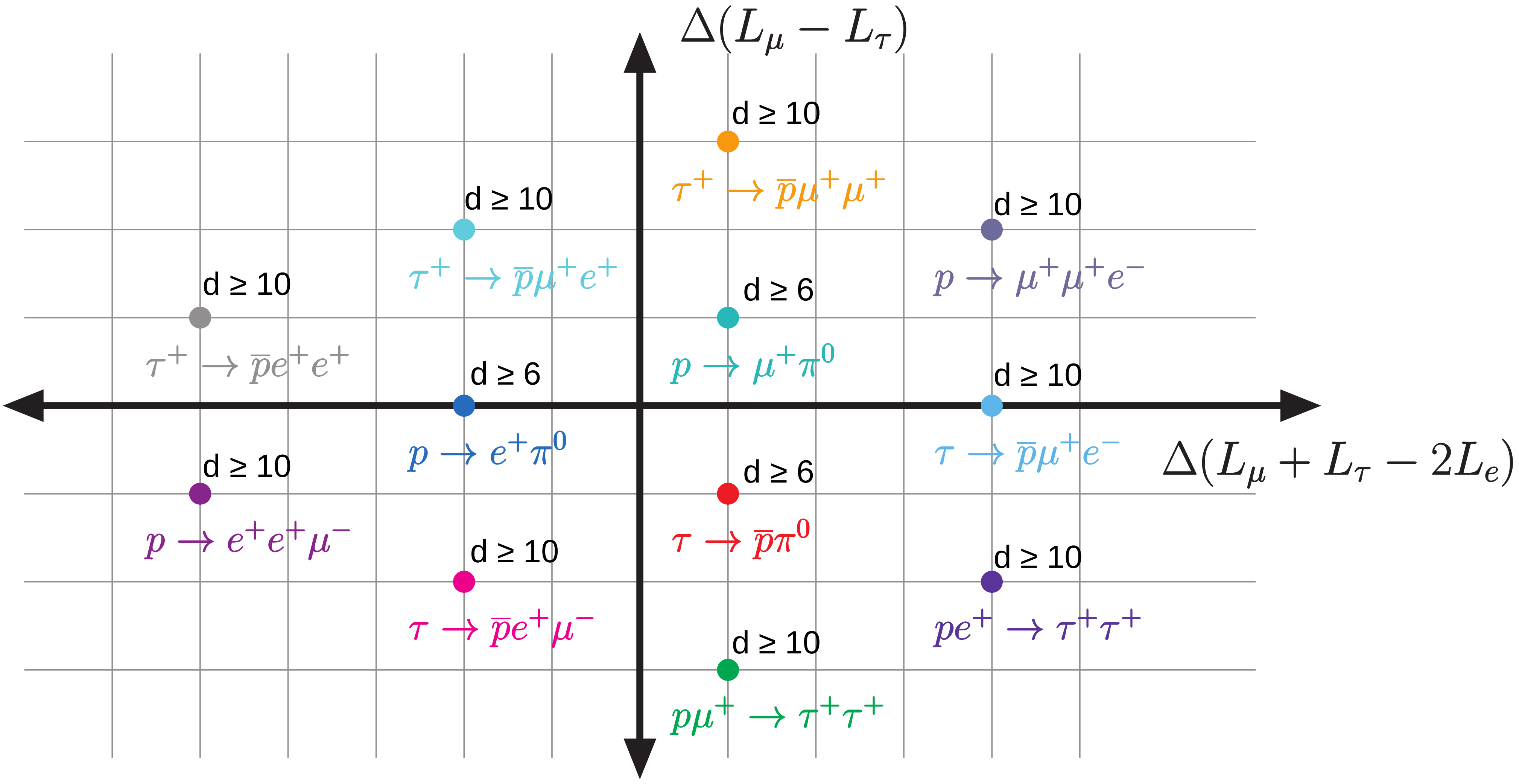

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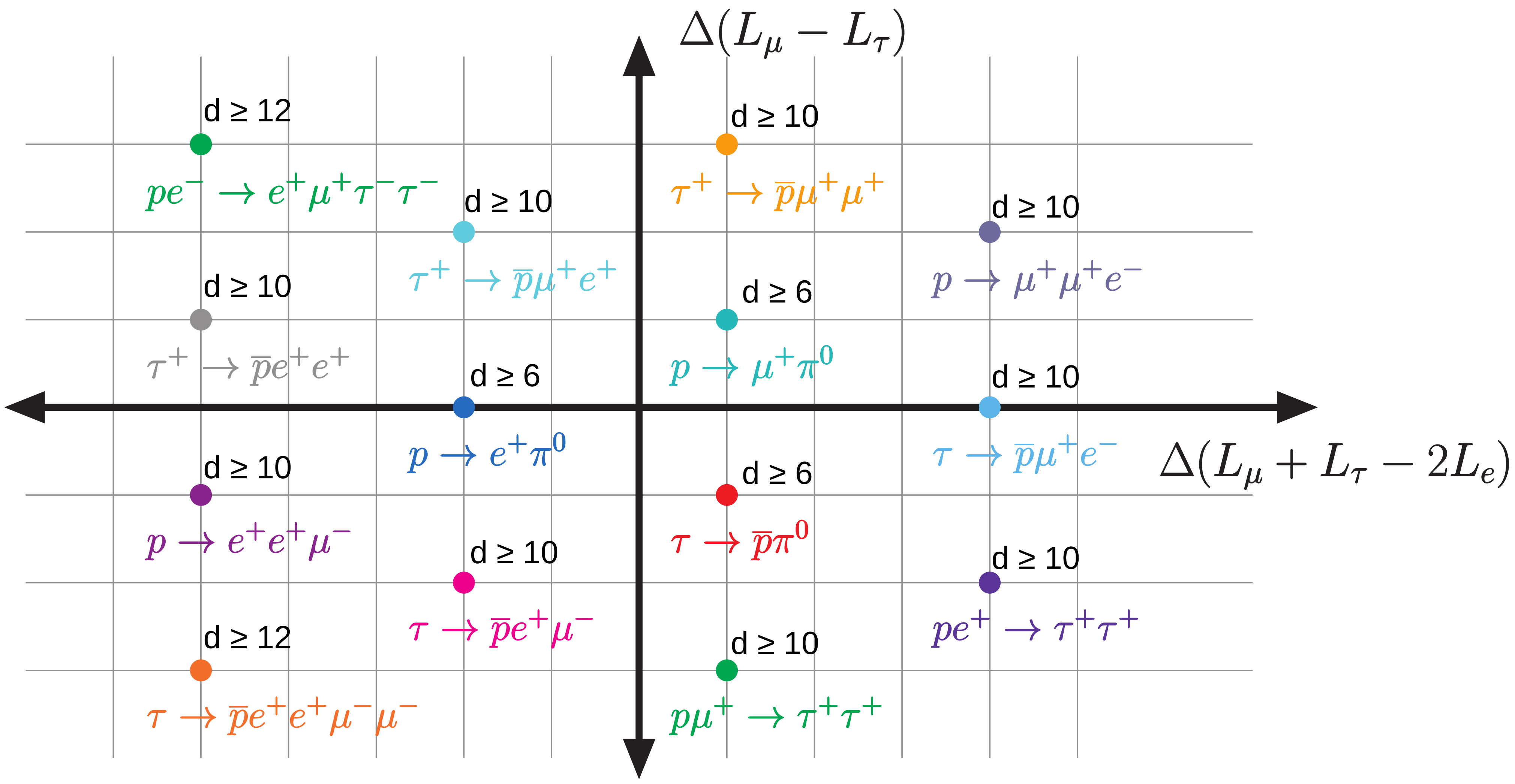
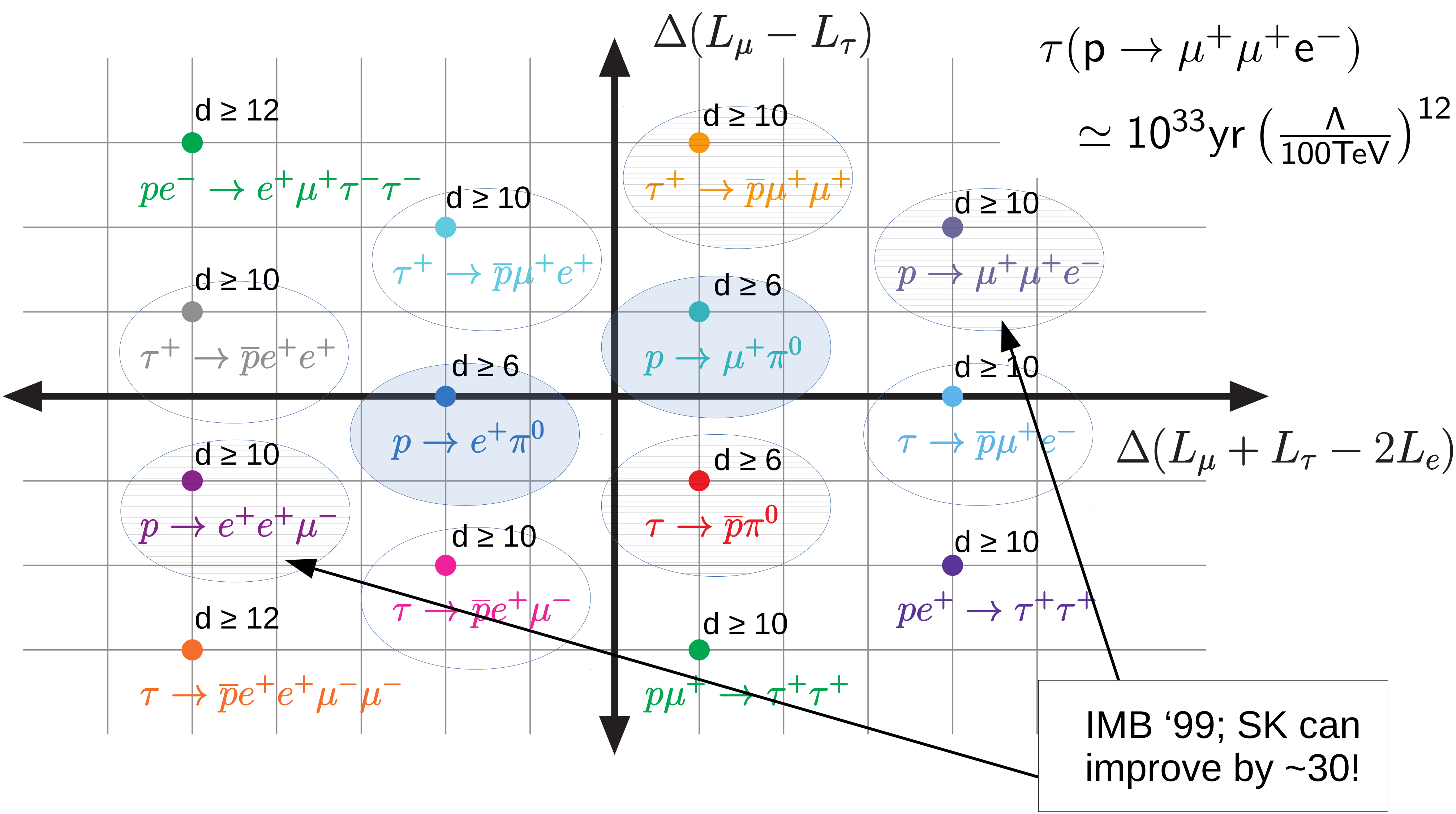


Currently being probed: Old results: Doable:

ΔB = ΔL = 1



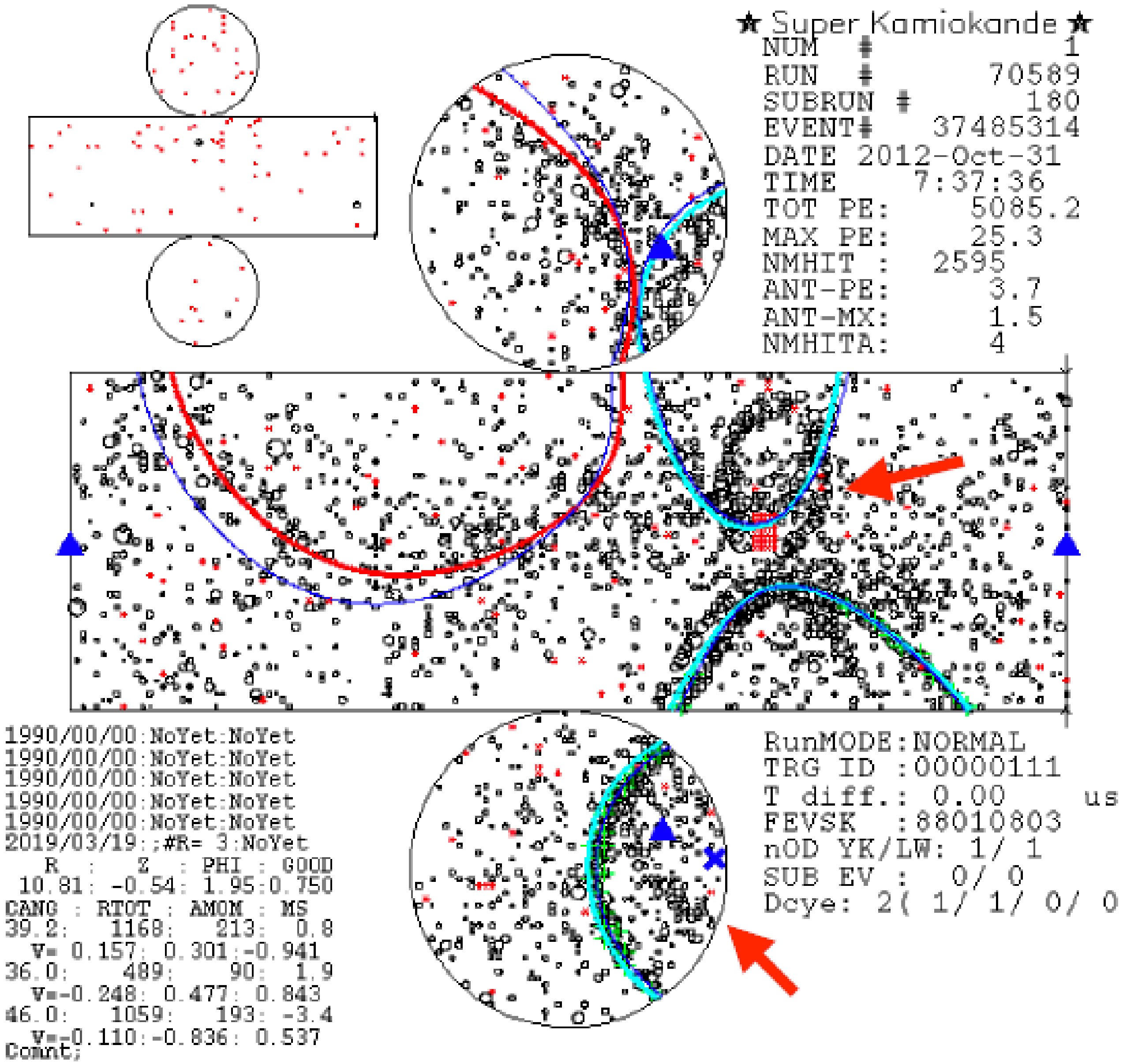
[Hambye, **JH**, PRL '18]

Done!

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

[full paper: PRD ‘20]

p→eμμ



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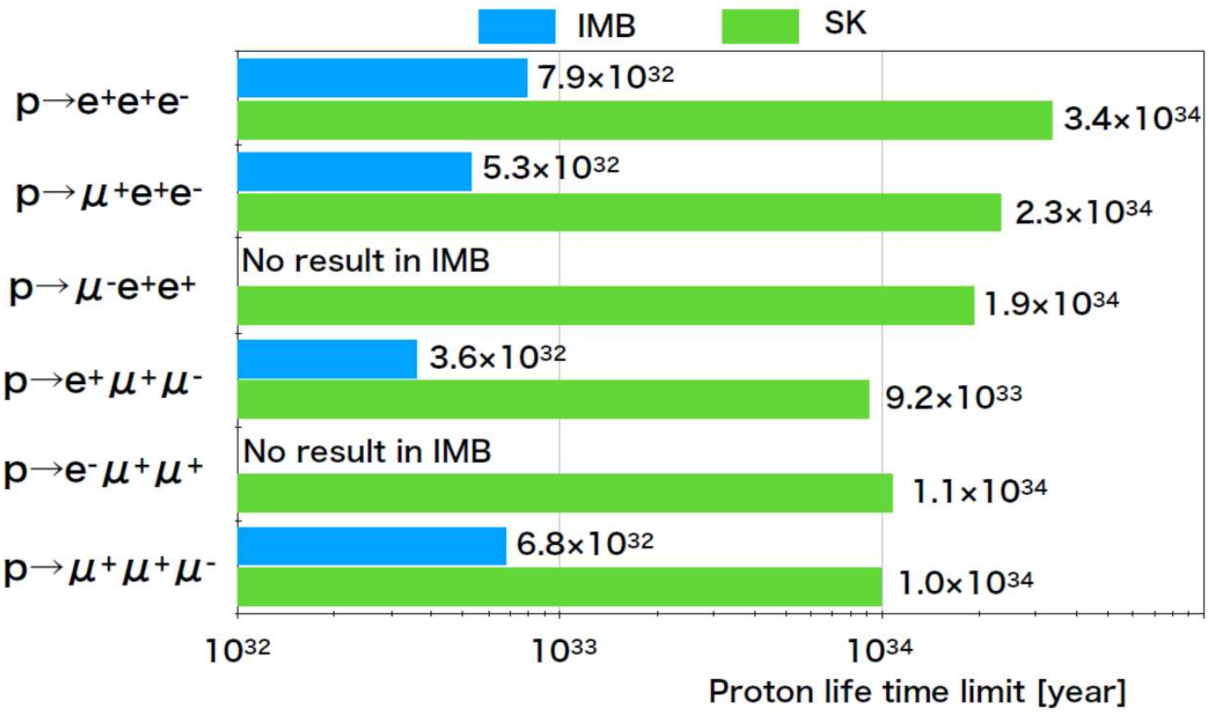
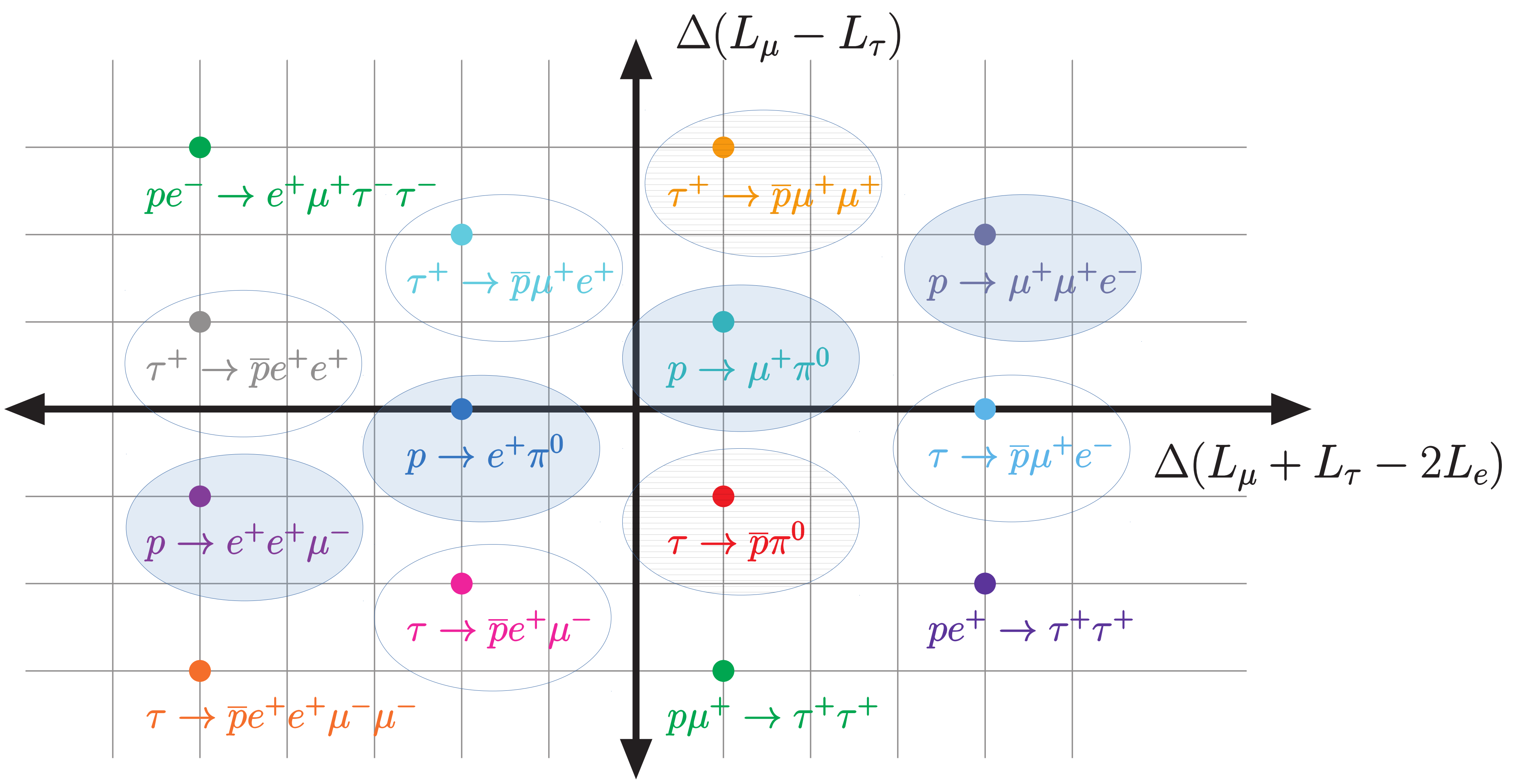


Compatible with background, limits around 10^{34} yr.

Currently being probed: Old results: Doable:

ΔB = ΔL = 1



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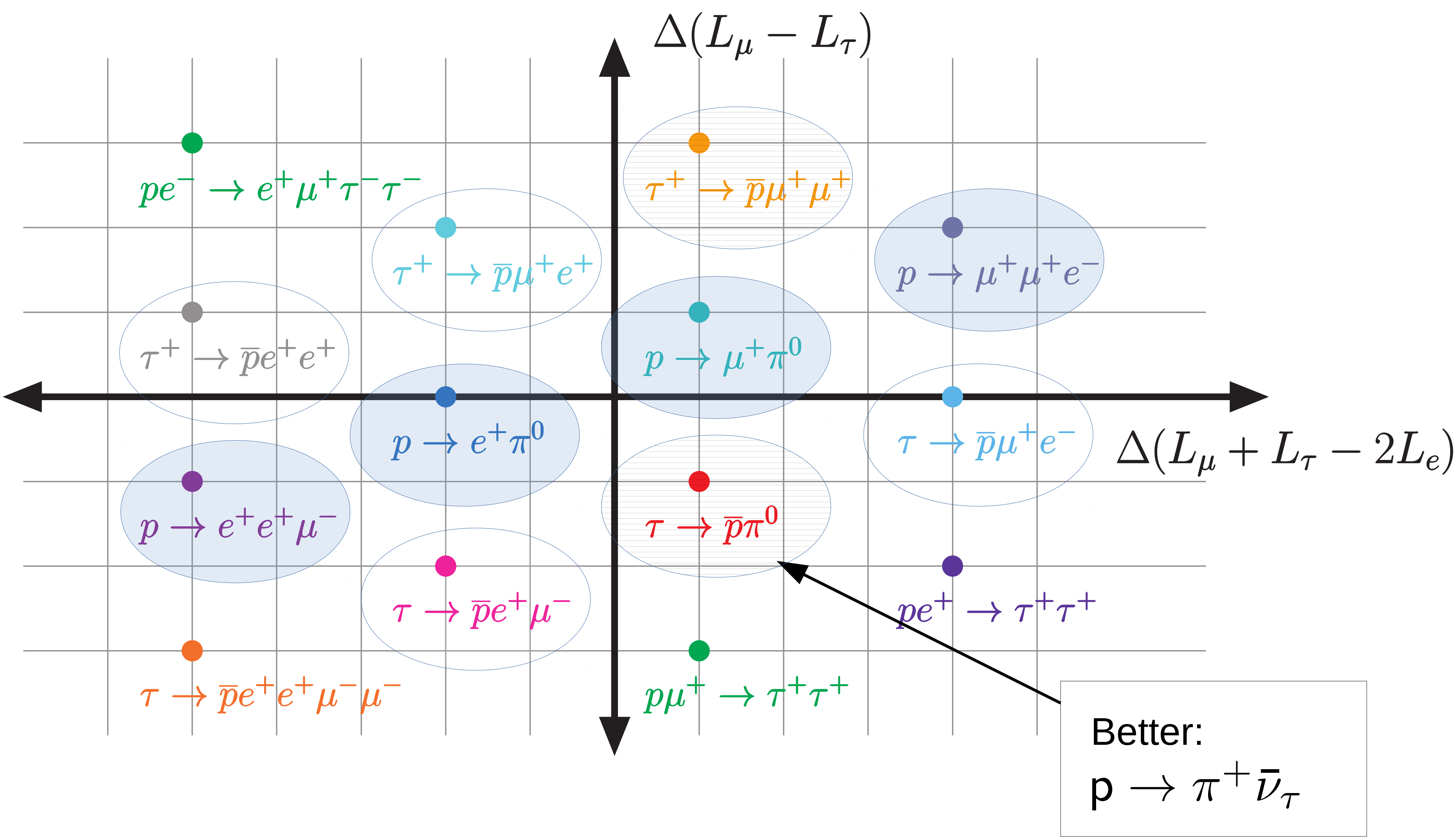

[Marciano, NPB ‘95]

Currently being probed: Old results: Doable:

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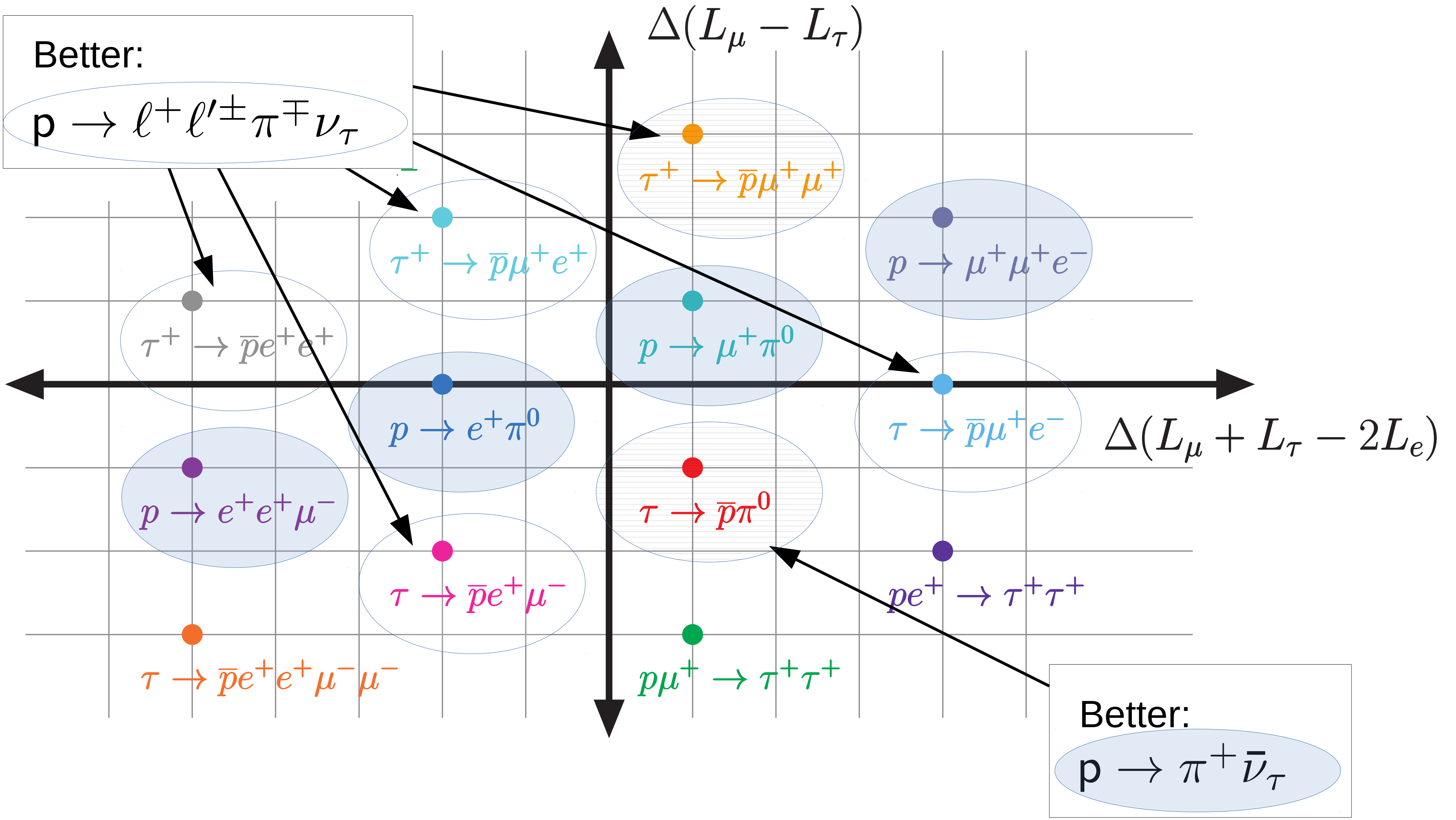


[Marciano, NPB '95]

Full ΔB coverage possible?

- Cannot to go through all ΔB > 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 can reach $t \sim 10^{34}$ yr in SK.

Inclusive searches to the rescue!

Inclusive searches

- Current limits:

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

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

- 40 years old, improve with new tech!
- $p \to e^+ + \text{anything}$ in SK could reach 10^{32} yr, judging by

$$\Gamma^{-1}(\mathrm{p} \to \mathrm{e}^+ \nu\nu) > 1.7 \times 10^{32}\,\text{yr}.$$ [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:

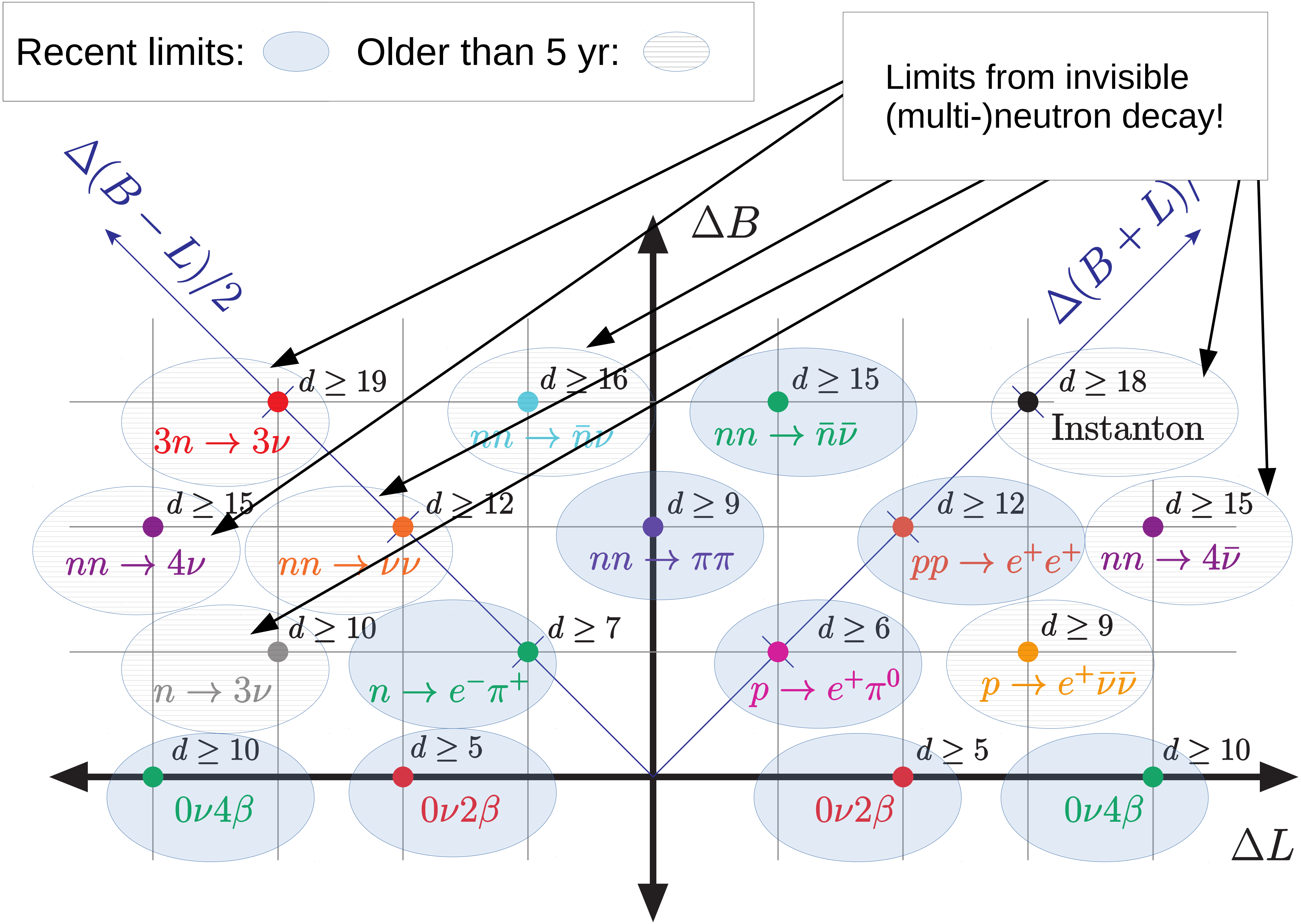
$$\Gamma^{-1}(\text{n} \to \text{neutrinos}) > 0.58 \times 10^{30}\,\text{yr},$$
$$\Gamma^{-1}(\text{nn} \to \text{neutrinos}) > 1.4 \times 10^{30}\,\text{yr},$$
$$\Gamma^{-1}(\text{nnn} \to \text{neutrinos}) > 1.8 \times 10^{23}\,\text{yr},$$
$$\Gamma^{-1}(\text{nnnn} \to \text{neutrinos}) > 1.4 \times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

[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 $\Delta B = k$ operator gives rise to k neutrons → neutrinos.
- Neutrinos carry away arbitrary lepton number & flavor!
- Also probes light new physics and dark matter.
- Can JUNO improve KamLAND limit? DUNE?

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



Recent limits:
Older than 5 yr:
Limits from invisible (multi-)neutron decay!
$\Delta(B-L)/2$
ΔB
$\Delta(B+L)/2$
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

- SM: $\mathbb{Z}_3^{(B+L)/2} \times U(1)_{B-L} \times U(1)_{L_\mu - L_\tau} \times U(1)_{L_\mu + L_\tau - 2L_e}$.
- Violated? New particles! How? New structure!
- ΔB (& ΔL) probe
  - high *scales* (10^{15} GeV) *or*
  - high *multiplicities* (N → 15 particles) *or*
  - high operator *dimensions* (d~15)!

SK/HK, DUNE, JUNO, 0νββ exp.?

- Go beyond two-body proton decay, do inclusive searches!
- Still untapped areas:
  - Light new physics ($p \to \ell^+ + X$, $X \to$ SM?).
  - Dark matter induced ΔB & ΔL.

Exotic = new normal!

Backup

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:

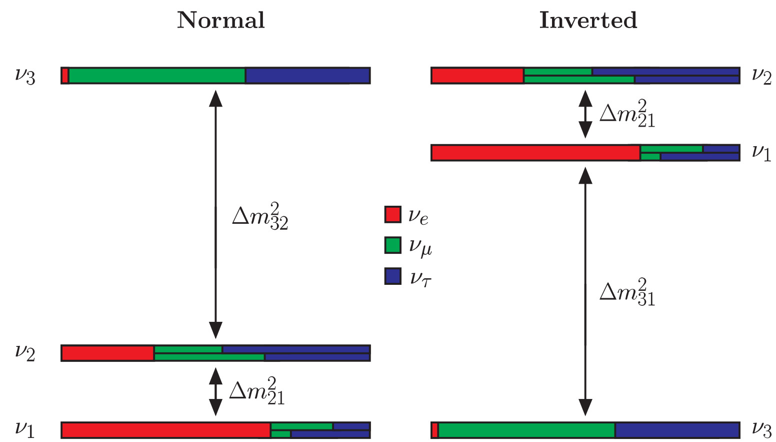
$$\mathbb{Z}_3^{(\mathrm{B+L})/2} \times \mathrm{U}(1)_{\mathrm{B-L}} \times \mathrm{U}(1)_{\mathrm{L}_\mu - \mathrm{L}_\tau} \times \mathrm{U}(1)_{\mathrm{L}_\mu + \mathrm{L}_\tau - 2\mathrm{L}_e} \,.$$

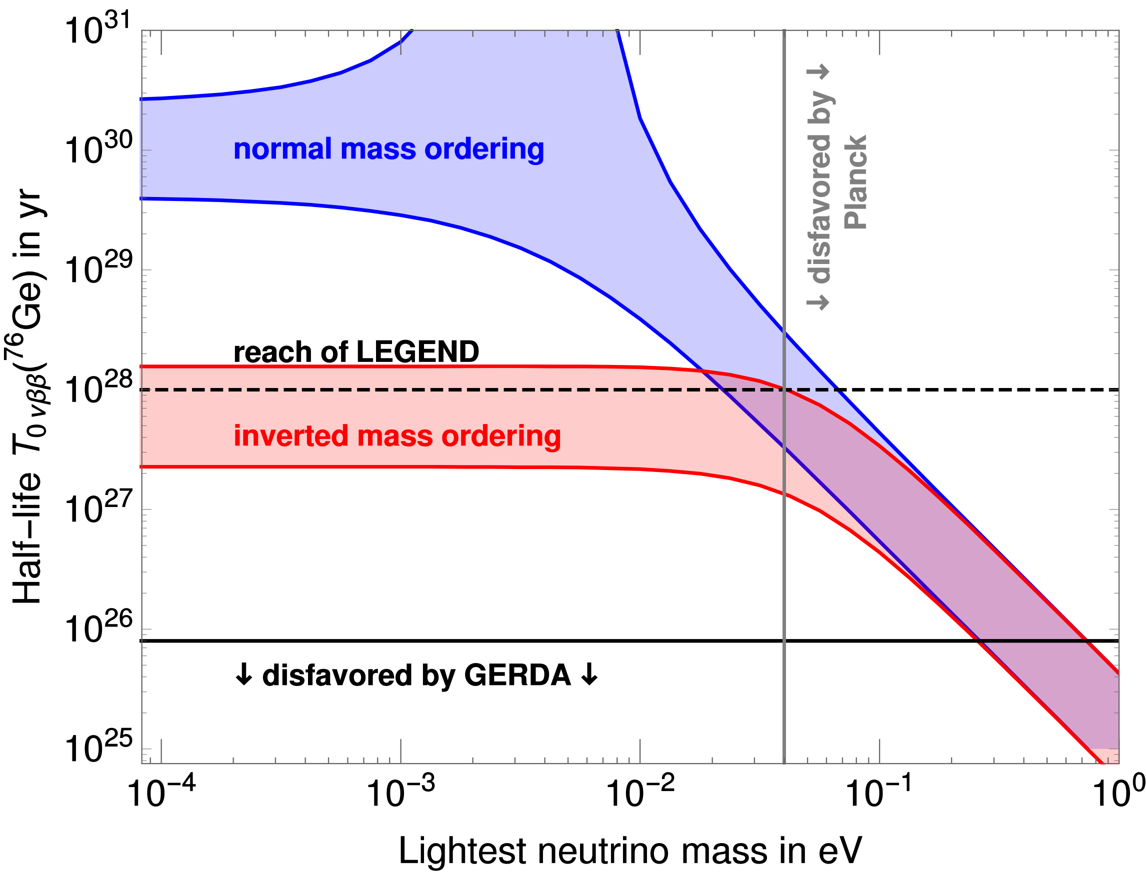
ΔL = 2

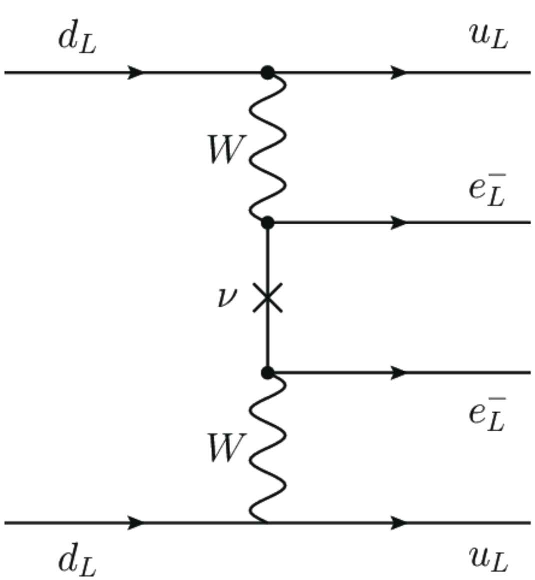
- Neutrinoless double β decay:

  (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?

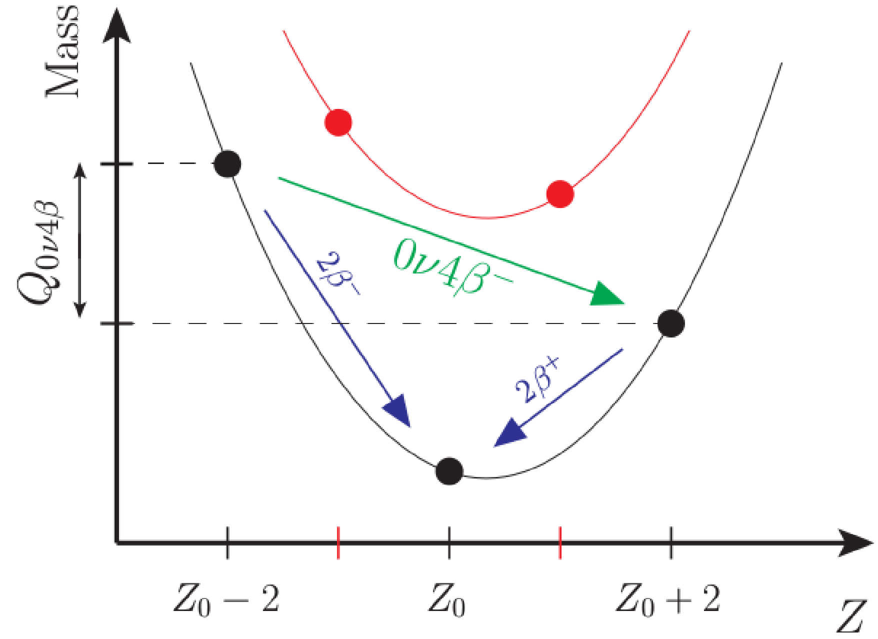
  (A,Z) → (A,Z+4) + 4 e^- !
- 3 candidates: ^{96}Zr, ^{136}Xe, ^{150}Nd.

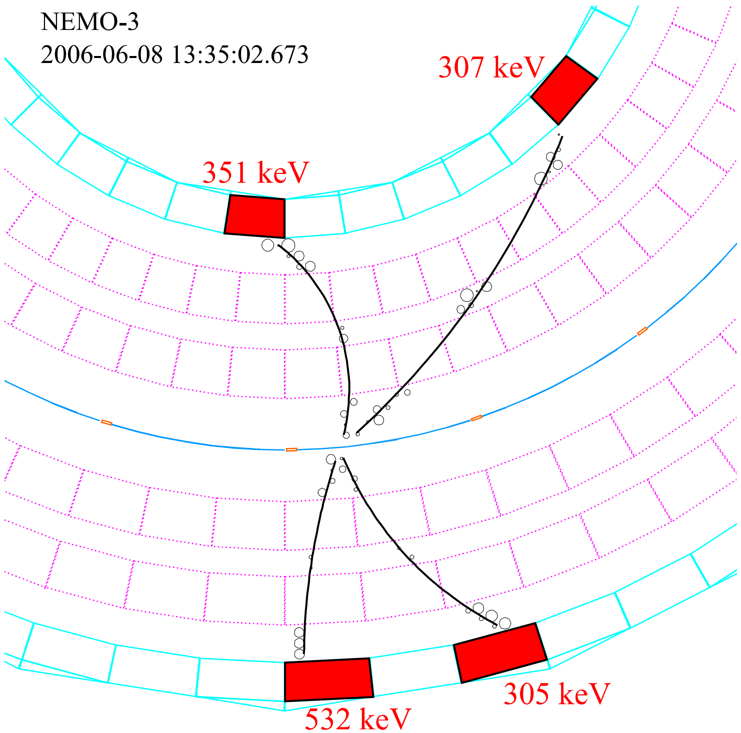
  [**JH**, Rodejohann, EPL '13]
- First limit: $\tau_{0\nu4\beta}(^{150}\mathrm{Nd}) > 10^{21}$yr.

  [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]





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

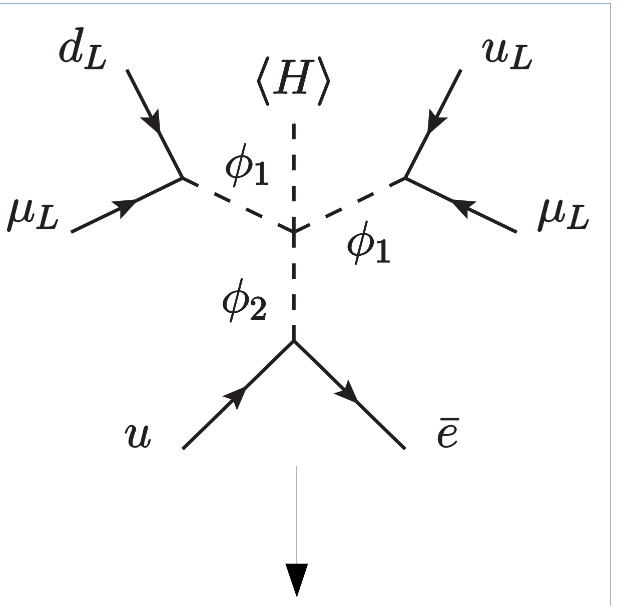
- Minimal leptoquark example:

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

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



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

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

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

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

- $\frac{y_j \bar{y}_i}{m_{\phi_1}^2} (\bar{L}_\mu Q_j^c)(Q_i L_\mu)$.

- Modifies $b \to s\mu^-\mu^+$:

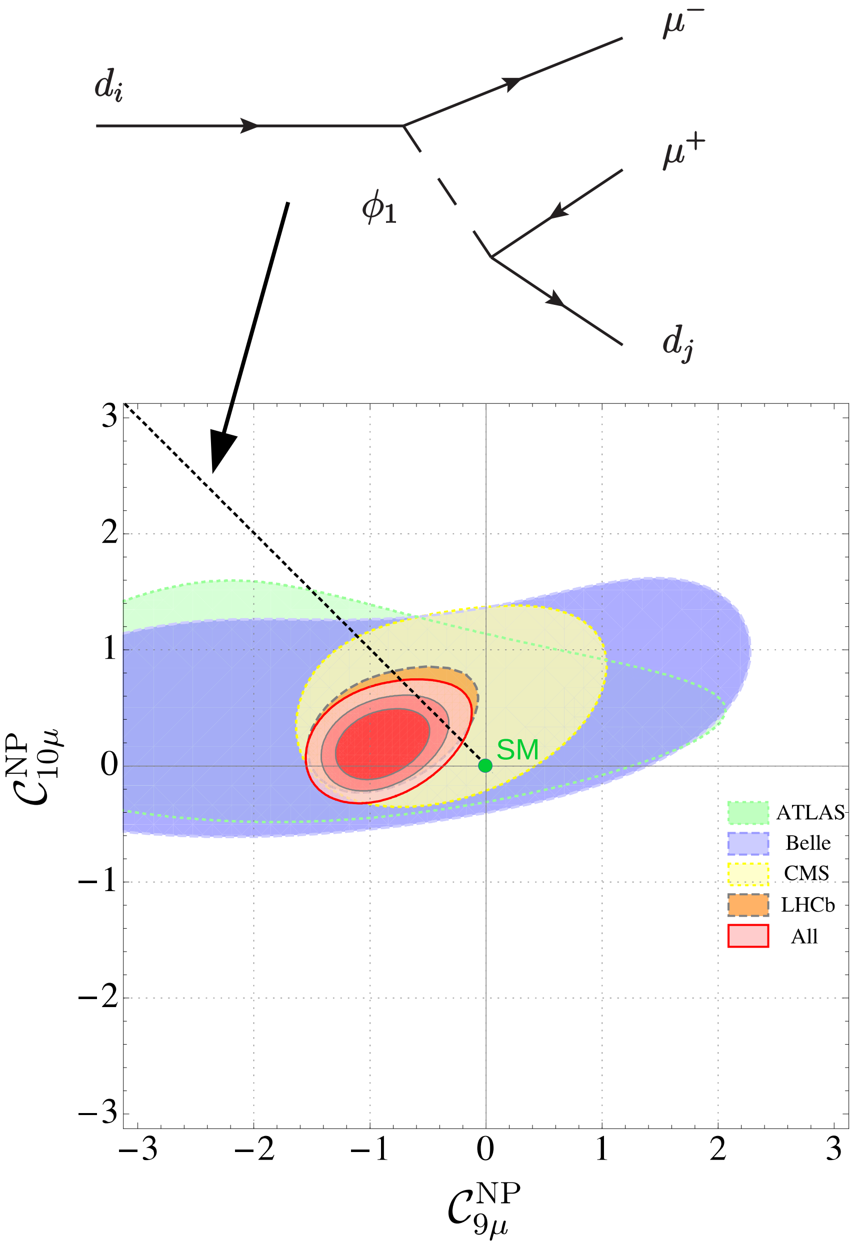
  $R(K^{(*)}) = \frac{B \to K^{(*)}\mu^+\mu^-}{B \to K^{(*)}e^+e^-}$.

- LHCb: $R(K) \sim 0.85$,
  $R(K^*) \sim 0.67$.

- 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]

BLV circa 2020

Two-body nucleon decays

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

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Three-body nucleon decays

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

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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	

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