Baryon Number Violation Involving Tauons

[**JH** & Dima Watkins, 2405.18478]

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Why baryon number violation?

- Tests prediction/symmetry of Standard Model:

$$\underbrace{\mathrm{U}(1)_{\mathrm{B}}}_{\text{BNV}} \times \underbrace{\mathrm{U}(1)_{\mathrm{L}}}_{\text{LNV}} \times \underbrace{\mathrm{U}(1)_{\mathrm{L}_\mu - \mathrm{L}_\tau} \times \mathrm{U}(1)_{\mathrm{L}_\mu + \mathrm{L}_\tau - 2\mathrm{L}_e}}_{\text{LFV}}$$

- 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.)

[Recent review: Perez, Pocar, **JH** *et al.*, arXiv:2208.00010]

See also talks by Vasja Susič & Patrick Stengel.

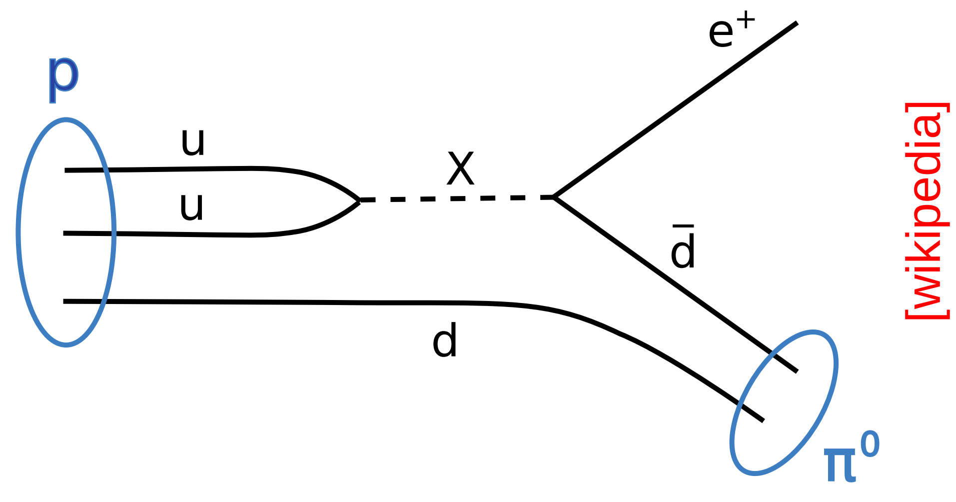
Best example: proton decay

- First suggested in GUTs, predict $\tau_\mathrm{p} \sim \mathrm{m}_\mathrm{X}^4/\mathrm{m}_\mathrm{p}^5$.
  [Pati & Salam '73; Georgi & Glashow, '74]
- Violates ΔB = ΔL = ΔL_e = 1.
- *All matter* contains protons, easy to observe for long times.
- Current best: Super-KamiokaNDE.
  - 50k ton water tank & 13k PMTs for Cherenkov radiation.
  - Running for two decades, observing 10^{35} protons:

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

[Super-K, 2010.16098]

  - Implies $\mathrm{m}_\mathrm{X} > 10^{15}$ GeV!

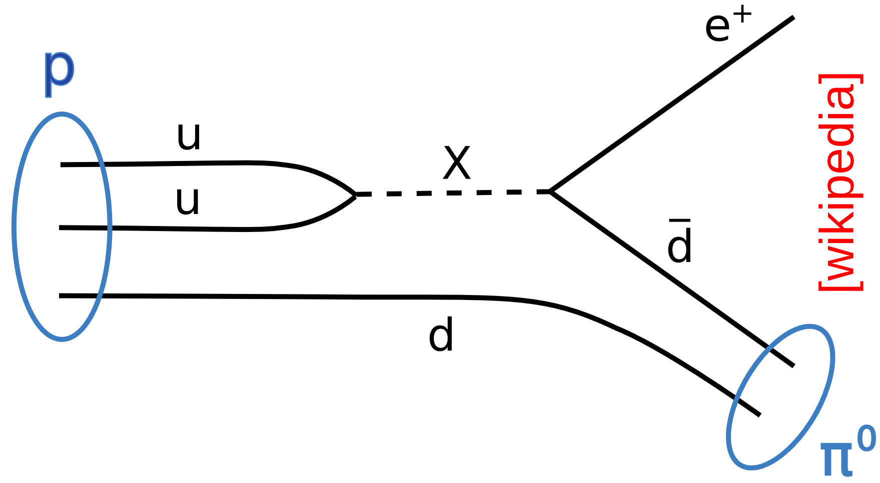


Best example: proton decay

- Super-Kamiokande:

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

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



- Similarly:

  $\tau(\mathrm{p} \to \mu^+\pi^0) \gtrsim 10^{34}\,\mathrm{yr}, \quad \tau(\mathrm{n} \to \bar{\nu}_{e,\mu,\tau}\pi^0) \gtrsim 10^{33}\,\mathrm{yr}.$ [Super-K, '13]

  What about τ^+?

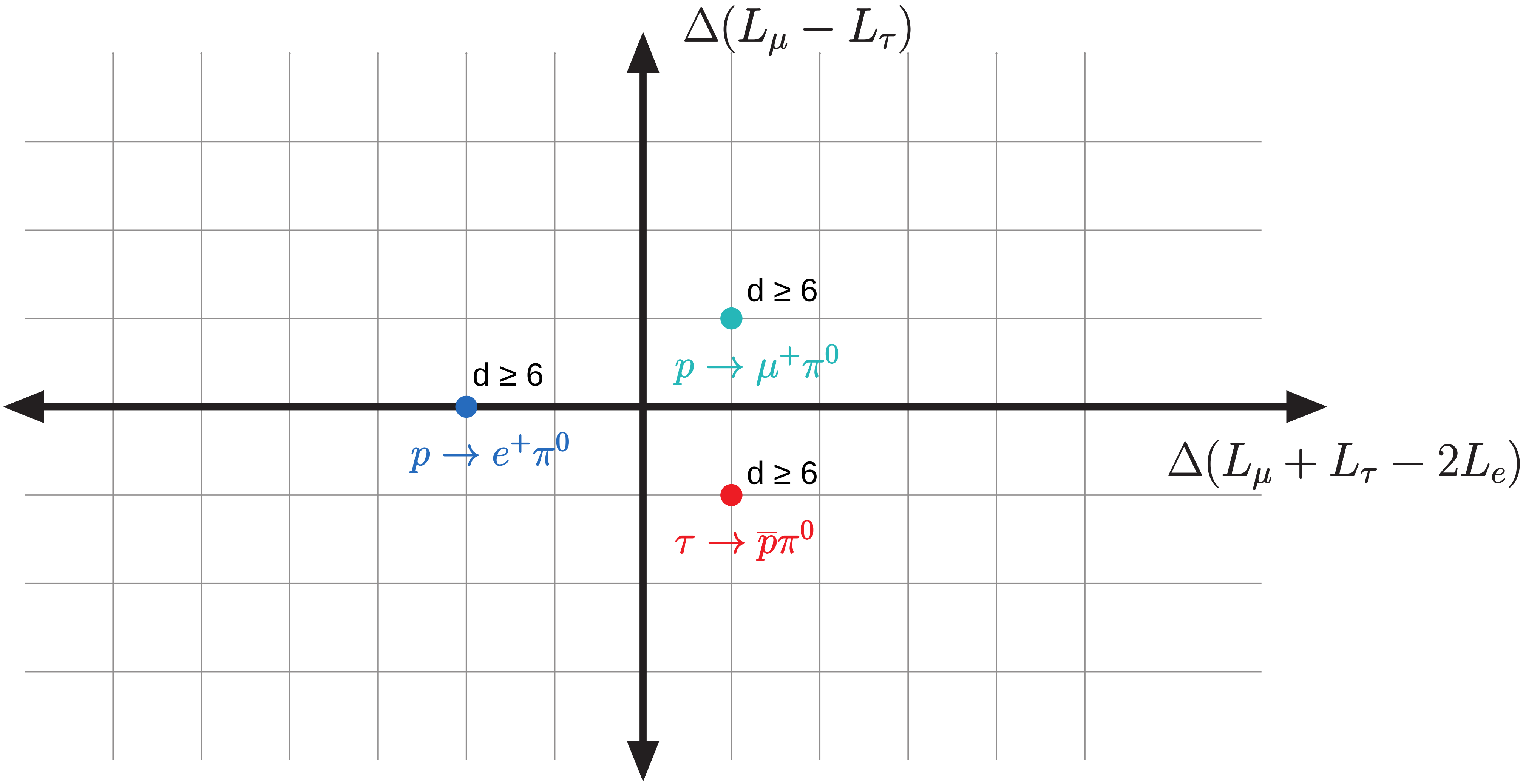
- Tauon heavier than proton:

  $\mathrm{BR}(\tau \to \bar{\mathrm{p}}\pi^0) < 10^{-5}$ [CLEO, '99] $\Rightarrow m_X > 10^3\,\mathrm{GeV}.$

- Tauon limits weaker, but probe *different* couplings;
  could even be dominant ΔB channel due to flavor symmetry.

Proton decay = lepton flavor violation

ΔB = ΔL = 1



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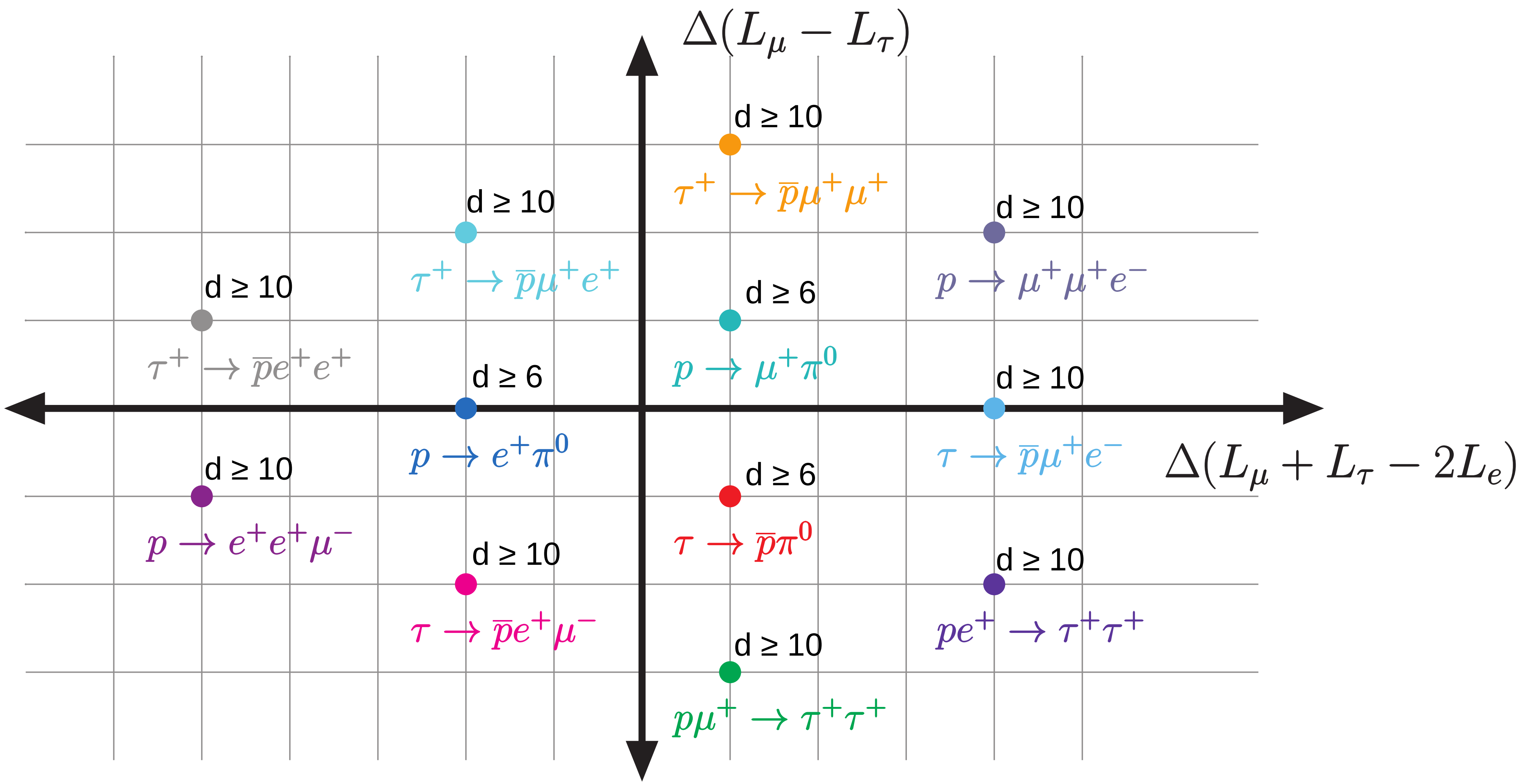

Proton decay = lepton flavor violation

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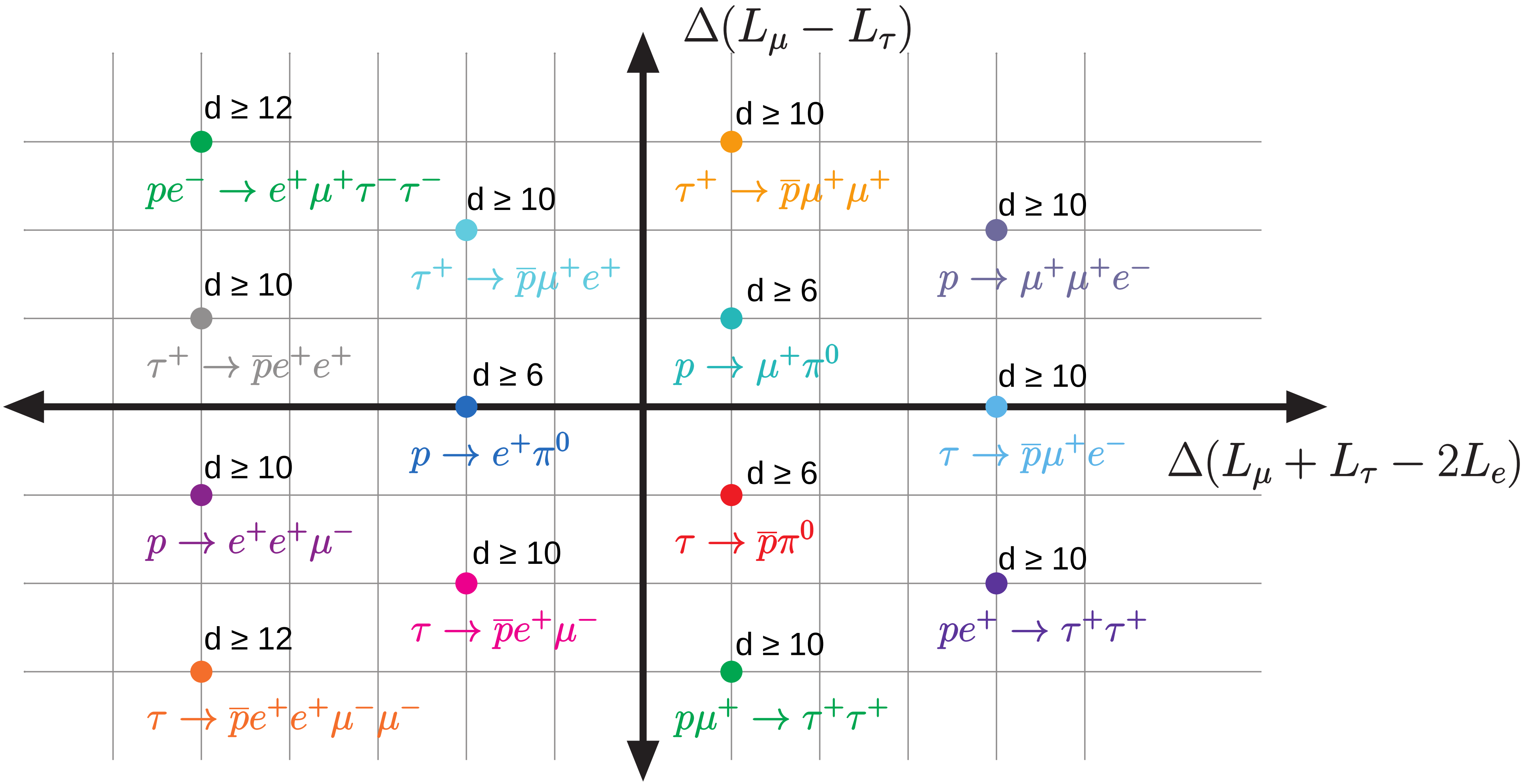
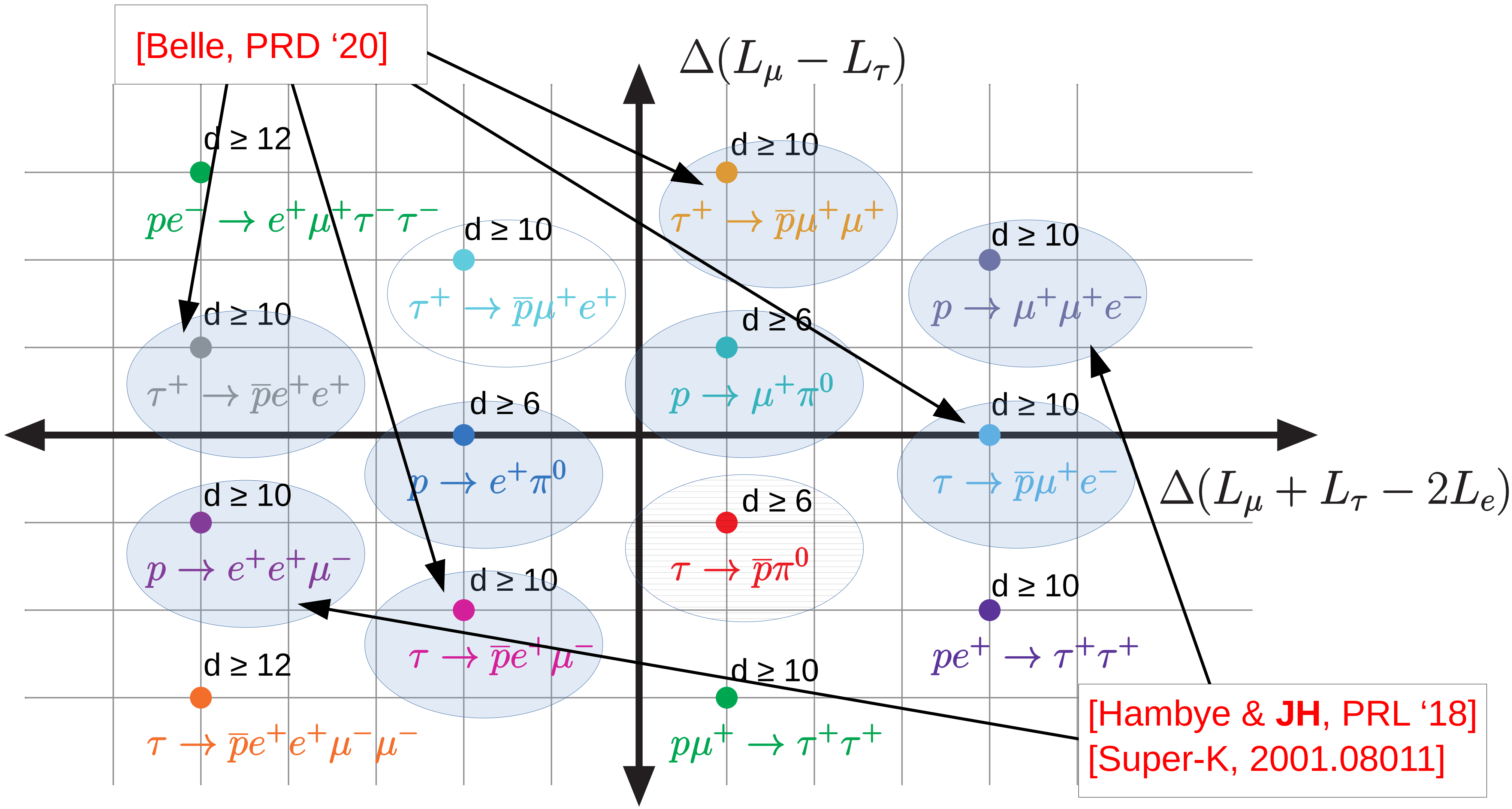


Currently being probed: Old results: Doable:

ΔB = ΔL = 1

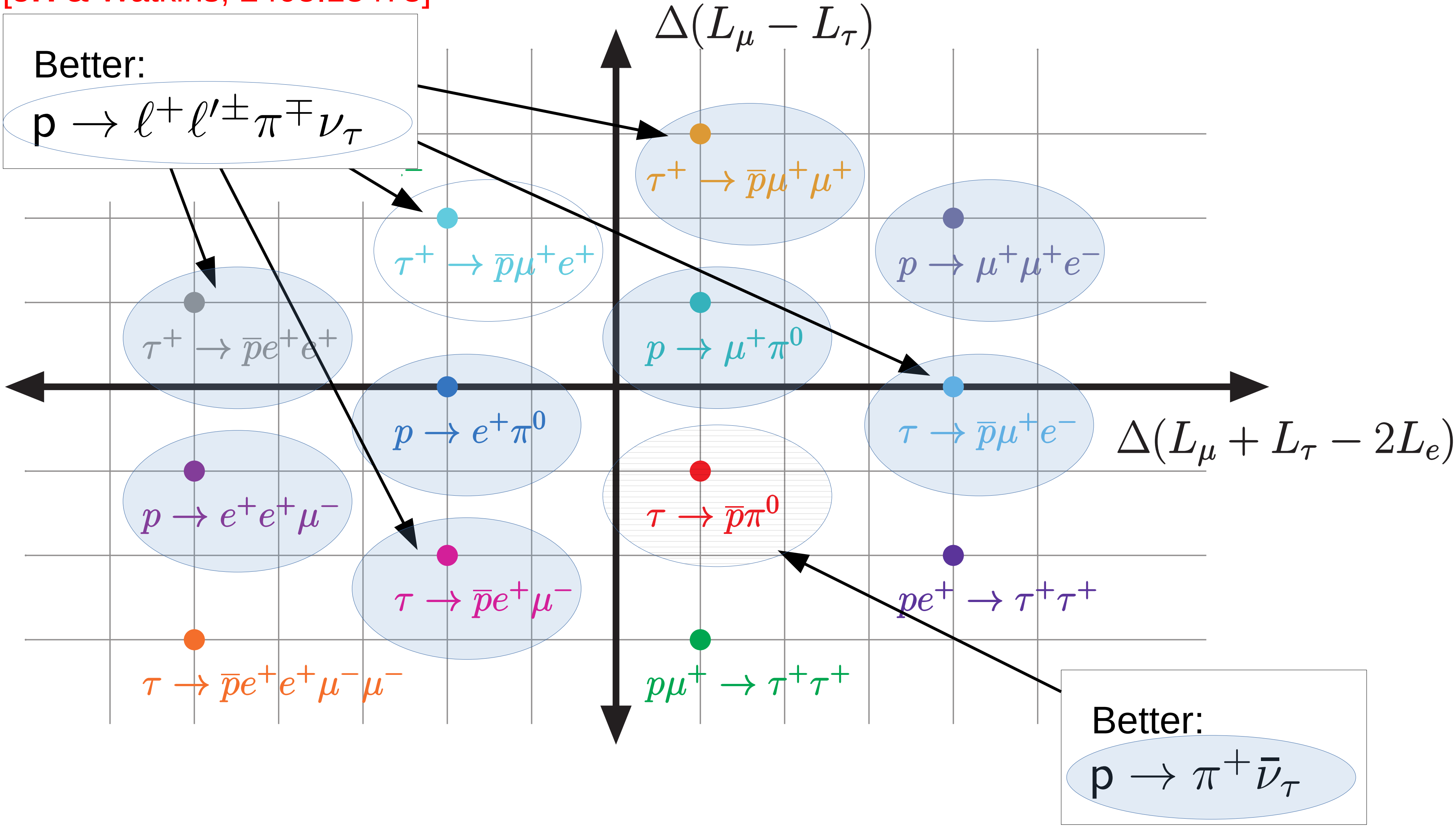


$$\tau(p \to \mu^+\mu^+e^-) \simeq 10^{33}\text{yr}\left(\frac{\Lambda}{100\text{TeV}}\right)^{12}$$

Currently being probed: Old results: Doable:

ΔB = ΔL = 1

[**JH** & Watkins, 2405.18478]



[Marciano, NPB '95]

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

- d=6 operators: $\mathsf{y}^1 \mathsf{duQL}_\tau + \mathsf{y}^2 \mathsf{QQQL}_\tau + \mathsf{y}^3 \mathsf{QQu}\tau_\mathsf{R} + \mathsf{y}^4 \mathsf{duu}\tau_\mathsf{R}$
- All induce $\tau^- \to \bar{\mathsf{p}}\pi^0, \bar{\mathsf{p}}\eta$.
- But y^1 and y^2 immediately give $\mathsf{n} \to \bar{\nu}_\tau \pi^0, \bar{\nu}_\tau \eta$:

$$\tau(\mathsf{n} \to \bar{\nu}_\tau \pi^0) \simeq 10^{-8}\,\mathsf{s} \left(\frac{10^{-5}}{\mathsf{BR}(\tau \to \bar{\mathsf{p}}\pi^0)}\right) \simeq 10^{33}\,\mathsf{yr} \left(\frac{3\times 10^{-54}}{\mathsf{BR}(\tau \to \bar{\mathsf{p}}\pi^0)}\right)$$

- Neutron decays into tau neutrinos give ***far*** better limits.

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- d=6 operators: $y^1 duQL_\tau + y^2 QQQL_\tau + y^3 QQu\underline{\tau_R} + y^4 duu\underline{\tau_R}$
- All induce $\tau^- \to \bar{p}\pi^0, \bar{p}\eta$.
- But y^1 and y^2 immediately give $n \to \bar{\nu}_\tau \pi^0, \bar{\nu}_\tau \eta$:

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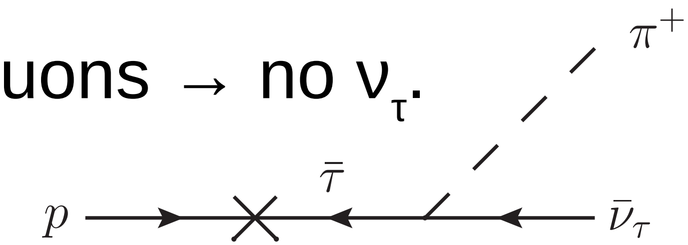
- Neutron decays into tau neutrinos give ***far*** better limits.
- How about y^3 and y^4? Right-handed tauons → no ν_τ.
  - Can still go through off-shell tauon:



$$\tau(p \to \pi^+ \bar{\nu}_\tau) \simeq \frac{16\pi (m_p^2 - m_\tau^2)^2}{f_\pi^2 G_F^2 m_p^3 m_\tau^2 \beta^2} \left|y^3 - y^4\right|^{-2} \simeq 6\,\text{s} \left(\frac{10^{-5}}{\text{BR}(\tau \to \bar{p}\pi^0)}\right)$$

[Hou, Nagashima, Soddu, PRD ‘05]

[see also Crivellin & Hoferichter, PLB ‘23, for $p \to \pi^0 e^+ \nu\nu$ etc, which are weaker.]

ΔB = ΔL$_\tau$ = 1 operators

- d=6 operators: $y^1 duQL_\tau + y^2 QQQL_\tau + y^3 QQu\tau_R + y^4 duu\tau_R$
- Set $y^1 = y^2 = 0$ and $y^3 = y^4$ to eliminate nucleon decays?
- Chiral perturbation theory: [Claudson, Wise, Hall, '82]

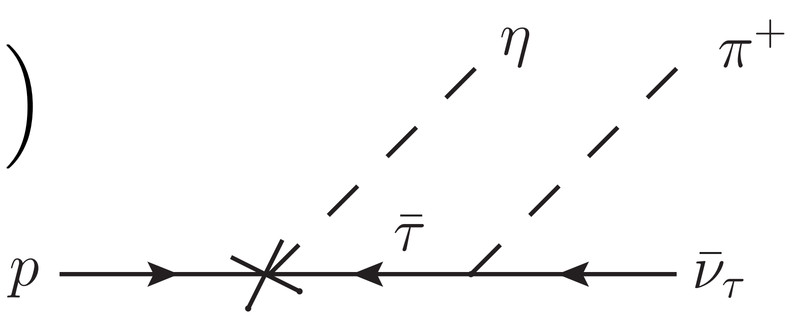
$$y^3 QQu\tau_R = y^3\beta\left[p\tau_R - \frac{i\pi^0}{\sqrt{2}f_\pi}p\tau_R - \frac{i\pi^+}{f_\pi}n\tau_R + \frac{i\eta}{\sqrt{6}f_\pi}p\tau_R + \dots\right]$$

$$y^4 duu\tau_R = -y^4\beta\left[p\tau_R - \frac{i\pi^0}{\sqrt{2}f_\pi}p\tau_R - \frac{i\pi^+}{f_\pi}n\tau_R - \frac{i\sqrt{3}\eta}{\sqrt{2}f_\pi}p\tau_R + \dots\right]$$

- $y^3 = y^4$ only eliminates *two-body* nucleon decays:

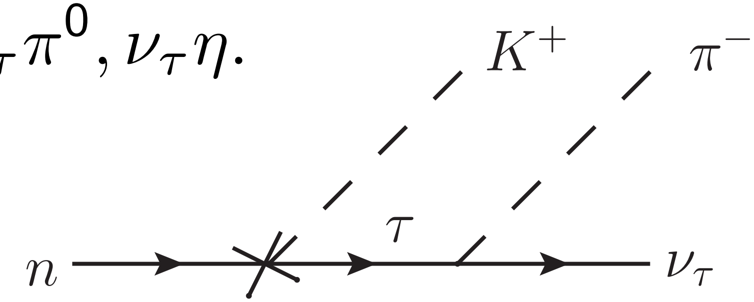
$$\underbrace{\tau(p\to\eta\pi^+\bar{\nu}_\tau)}\simeq 100\,\mathrm{yr}\left(\frac{10^{-5}}{\mathrm{BR}(\tau\to\bar{p}\eta)}\right)$$

Only old inclusive limits
[**JH** & Takhistov, PRD '20]
could easily be improved by Super-K!



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

- d=7 operators: $z^1 dud\bar{H}\bar{L}_\tau + z^2 QQd\bar{H}\bar{L}_\tau + z^3 ddQ\bar{H}\bar{\tau}_R + z^4 dddH\bar{L}_\tau$
- z^1 and z^2 immediately give $n \to \nu_\tau \pi^0, \nu_\tau \eta$.
- z^3 and z^4 have s quark and no ν_τ:



$$\tau(n \to K^+\pi^-\nu_\tau) \simeq 7000\,\text{yr} \left(\frac{7\times 10^{-8}}{\text{BR}(\tau\to\Lambda\pi^-)}\right)_{z^4=0}$$

$$\underbrace{\tau(n \to K^+\pi^-\nu_\tau)}_{\text{Only old inclusive limits: [JH \& Takhistov, PRD '20]}} \simeq 2\times 10^5\,\text{yr} \underbrace{\left(\frac{7\times 10^{-8}}{\text{BR}(\tau\to\Lambda\pi^-)}\right)}_{\text{[Belle, '06]}}{}_{z^3=0}$$

Only old inclusive limits:
[**JH** & Takhistov, PRD '20]

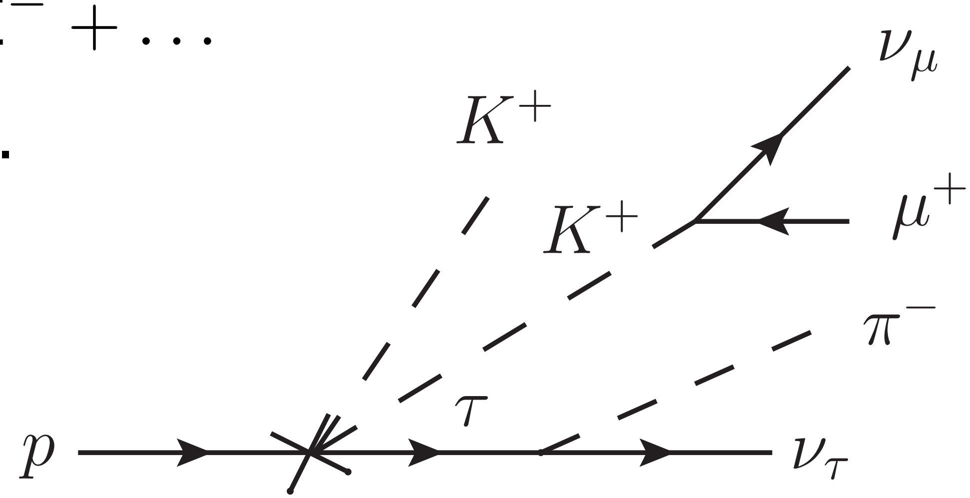
[Belle, '06]

- How about dss operator?

For ΔB with top quarks, see talk by Antonio Rodríguez-Sánchez.

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

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



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

$\Lambda\pi$

$\mathrm{N}\pi$

[JH & Watkins, 2405.18478]

- ΔB tau decays most competitive in hyperon channels.

New channels for Super-K & Belle II

More ΔB = ΔL = 1 operators

- d=10 operator: $QQu\ell\bar{\ell}LH/\Lambda^6 \to u_L d_L u_R \overline{\tau_R} \ell_\alpha \ell_\beta v/\Lambda^6$.
- For $\{\alpha,\beta\} \in \{e,\mu\}$: different lepton flavor content than d=6, not related to d=6 operators. [Hambye & **JH**, PRL ‘18]
- Still proton decays $p \to \ell^+ \ell'^\pm \pi^\mp \nu_\tau$ more sensitive:

$$\underbrace{\tau(p \to e^+_\alpha e^+_\beta \pi^- \nu_\tau)}_{\text{Only old inclusive limits: [JH \& Takhistov, PRD '20]}} \simeq 2 \times 10^4\,\text{yr} \underbrace{\left(\frac{3 \times 10^{-8}}{\text{BR}(\tau^- \to p e^-_\alpha e^-_\beta)}\right)}_{\text{[Belle, 2010.15361]}}$$

[**JH** & Watkins, 2405.18478]

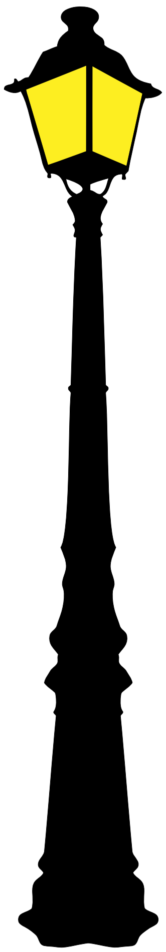
- Common pattern:
Nucleon decays into ν_τ far more sensitive than τ decays, but lacking exclusive or inclusive searches at Super-K. Could easily improve bounds by orders of magnitude!
[**JH** & Takhistov, PRD ‘20]

Summary

- ΔB = 1 decays are our most sensitive probe of new physics via clean two-body decays into electrons, muons, neutrinos.
- ΔB = 1 with tauons more involved: [**JH** & Watkins, 2405.18478]

  $\tau^- \to \bar{\mathrm{p}}\pi^0$ clean, but can't compete with
  $\mathrm{p} \to \pi^+ \nu_\tau$ through virtual tau.
- Finetuning can't *eliminate* nucleon decays, but can push them into *untested* multi-body channels.
- Don't be discouraged to look for ΔB tau decays!
- Be encouraged to broaden nucleon decay searches.

Explore every corner of our lamppost!



Backup

Standard Model Effective Field Theory

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

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

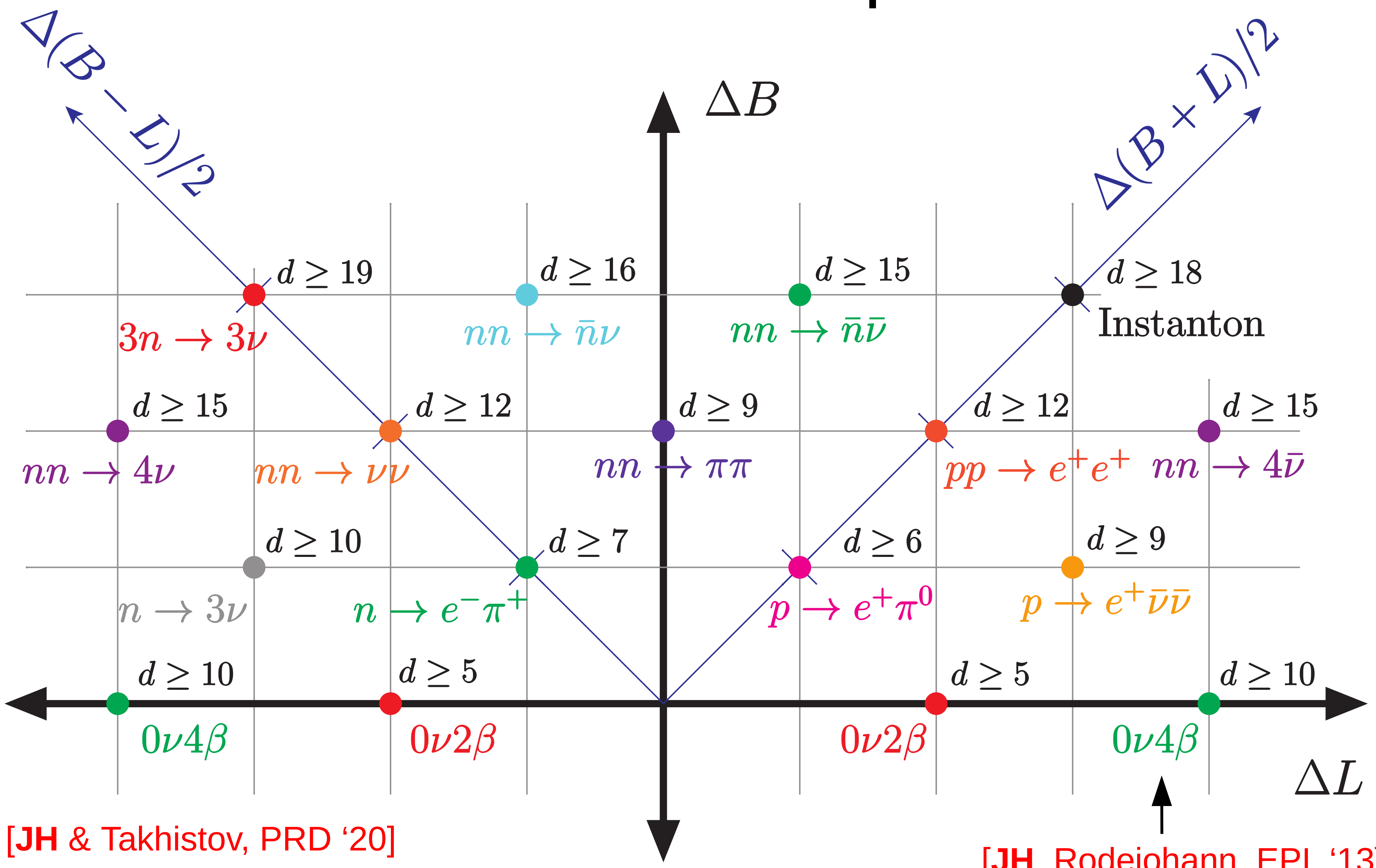
$$\Delta \mathrm{L} = 2 \qquad \Delta \mathrm{B} = \Delta \mathrm{L} = 1 \qquad \Delta \mathrm{B} = -\Delta \mathrm{L} = 1$$

- $\mathrm{d}_{\rm min} \geq \frac{9}{2}|\Delta \mathrm{B}| + \frac{3}{2}|\Delta \mathrm{L}|\,.$ [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

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

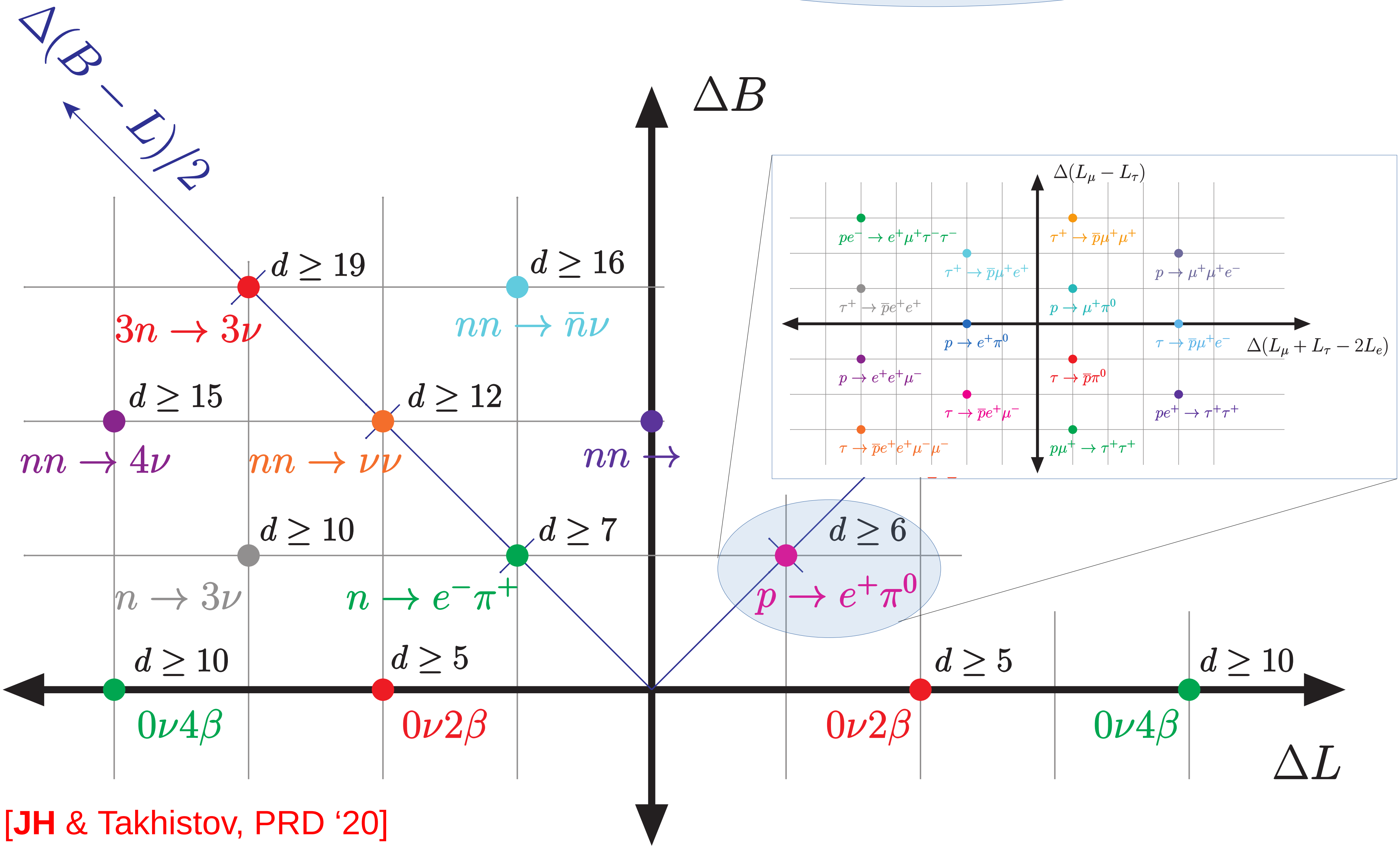
BNV landscape



[**JH** & Takhistov, PRD ‘20]

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

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



[**JH** & Takhistov, PRD ‘20]

All 38 two-body nucleon decay modes

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]

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 $\tau_p(p \to e^+\pi^0) \sim 10^{35}\,\mathrm{yr}$. [Hyper-K, 2203.02029]
- JUNO & DUNE could be useful for specific channels.