Baryon Number Violation Involving Tauons

[**JH** & Dima Watkins, to appear]

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Why baryon number violation?

- Tests prediction/symmetry of Standard Model:

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

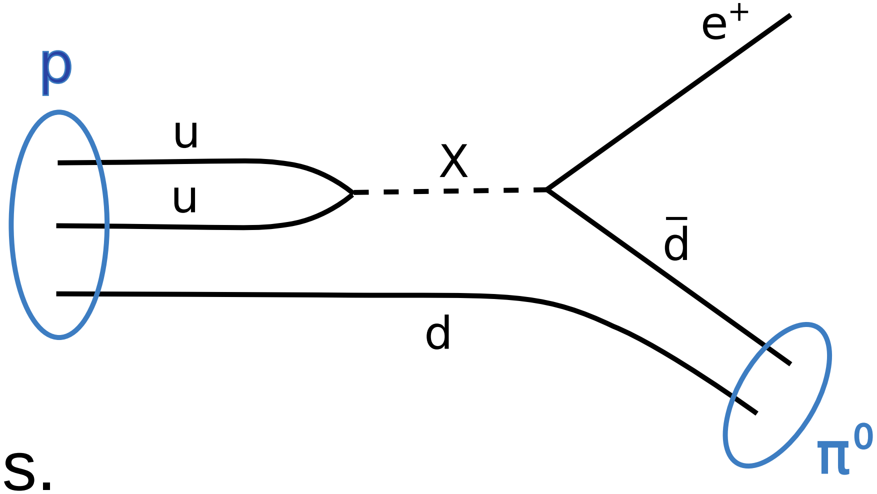
- Testable signatures in many extensions (GUTs, SUSY,…).
- Needed for spontaneous generation of matter asymmetry.

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]

Best example: proton decay



[wikipedia]

- First suggested in GUTs, predict $\tau_p \sim m_X^4/m_p^5$.
- Violates $\Delta B = \Delta L = \Delta L_e = 1$.
- *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:

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

[Super-K, 2010.16098]

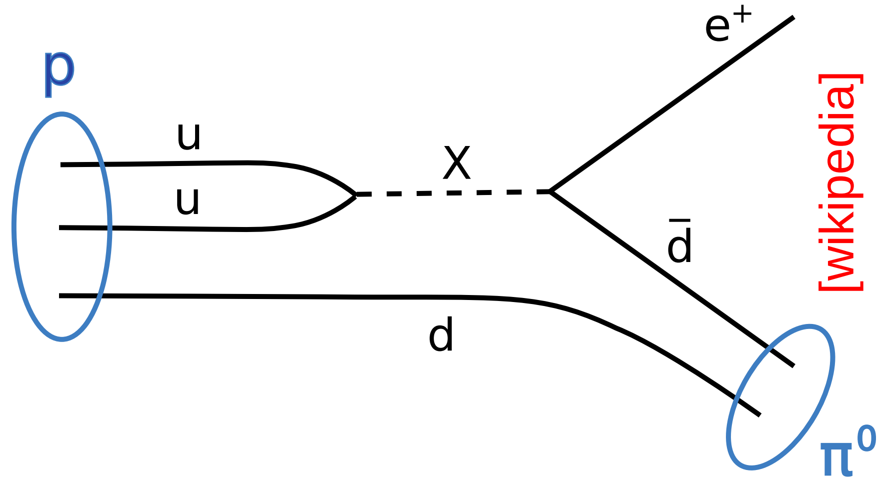
  - Implies $m_X > 10^{15}$ GeV!

Best example: proton decay

- Super-Kamiokande:

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

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



[wikipedia]

- 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] $\Rightarrow m_X > 10^3\,\mathrm{GeV}.$

- Better: nucleon decay with *off-shell* tauon. [Marciano, NPB '95]

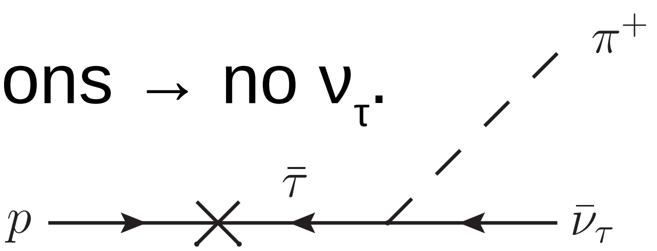
Explore this quantitatively

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

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

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

- 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:



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

[Hou, Nagashima, Soddu, PRD ‘05]

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

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

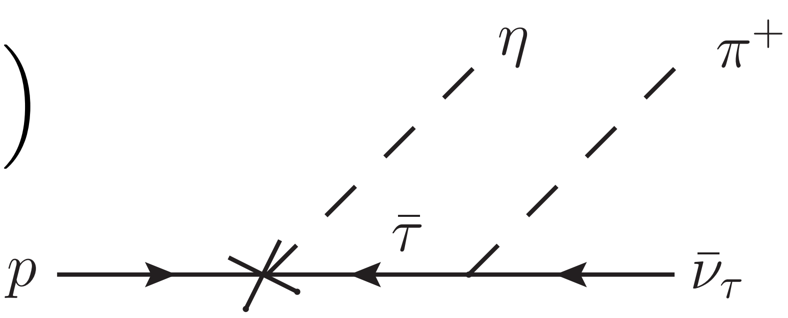
$$y^3 QQu\tau_R = y^3\beta\left[p\tau_R - \frac{i\pi^0}{\sqrt{2}f_\pi}p\tau_R - \frac{i\pi^+}{f_\pi}n\tau_R + \frac{i\eta}{\sqrt{6}f_\pi}p\tau_R + \dots\right]$$

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

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

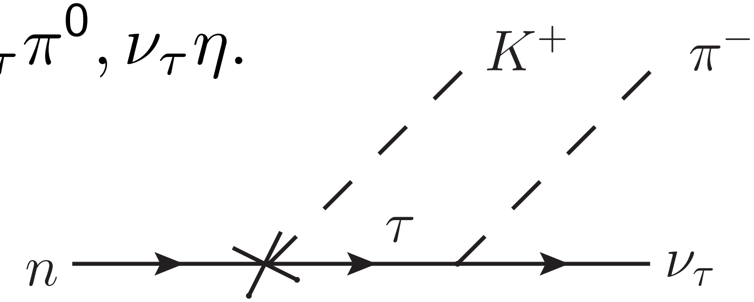
$$\underbrace{\tau(p \to \eta\pi^+\bar{\nu}_\tau)} \simeq 100\,\text{yr}\left(\frac{10^{-5}}{\text{BR}(\tau\to\bar{p}\eta)}\right)$$

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:



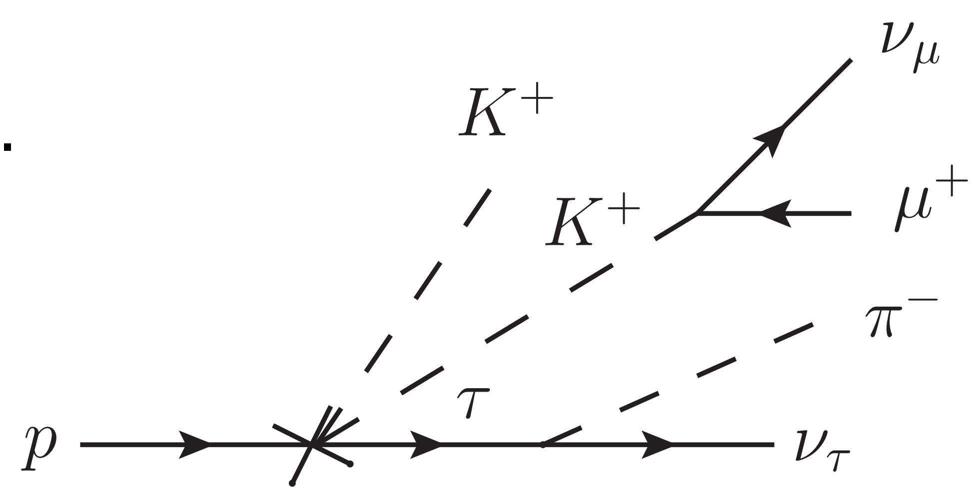
$$\tau(n \to K^+\pi^-\nu_\tau) \simeq 7000\,\text{yr} \left(\frac{7\times 10^{-8}}{\text{BR}(\tau\to\Lambda\pi^-)}\right)_{z^4=0}$$

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

- How about ssd operator?

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

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



$$\tau(\mathrm{p} \to \mathrm{K}^+\pi^+\pi^0\pi^-\nu_\tau) \simeq 10^{\mathcal{O}(20)}\,\mathrm{yr}\left(\frac{10^{-7}}{\mathrm{BR}(\tau\to\Xi\pi)}\right)$$

τ limits still 10 orders of magnitude short

More ΔB = ΔL = 1 operators

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

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

[**JH** & Watkins, in progress]

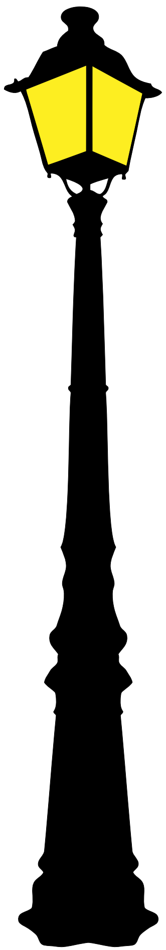
- Common pattern:
Nucleon decays into ν_τ far more sensitive than τ decays, but lacking exclusive or inclusive searches at Super-K. Could easily improve bounds by orders of magnitude!
[**JH**, Takhistov, PRD '20]

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, in progress]

  $\tau^- \to \bar{\mathrm{p}}\pi^0$ clean, but can't compete with
  $\mathrm{p} \to \pi^+ \nu_\tau$ through virtual tau.
- Even 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]

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \underbrace{\frac{LLHH}{\Lambda}}_{\Delta L = 2} + \underbrace{\sum_j \frac{\mathcal{O}_j}{\Lambda^2}}_{\Delta B = \Delta L = 1} + \underbrace{\sum_j \frac{\mathcal{O}_j'}{\Lambda^3}}_{\Delta B = -\Delta L = 1} + \sum_j \frac{\mathcal{O}_j''}{\Lambda^4} + \dots$$

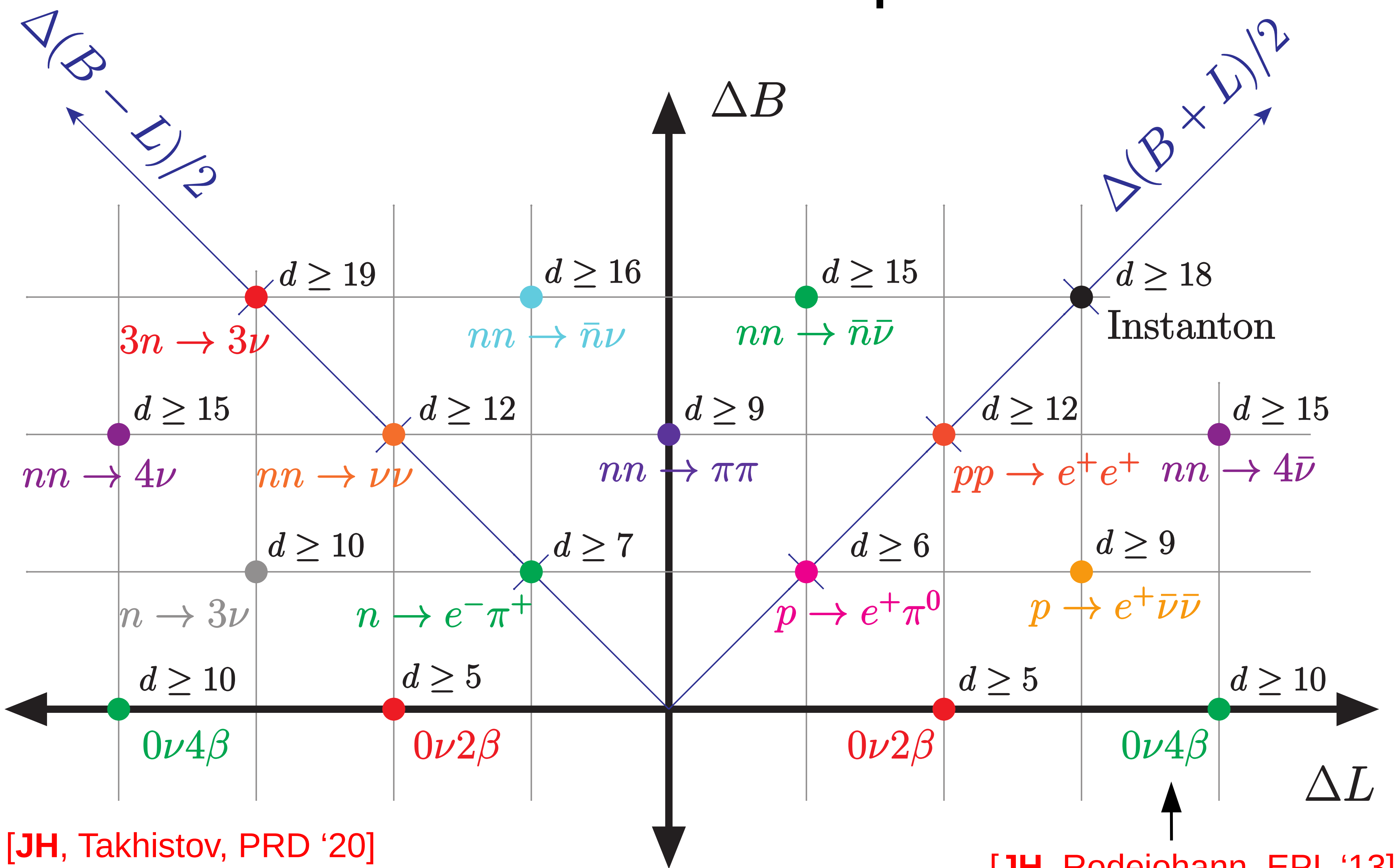
- $d_{\rm min} \geq \frac{9}{2}|\Delta B| + \frac{3}{2}|\Delta L|\,.$ [Kobach ‘16; Helset, Kobach, ‘19]
- BNV sensitive to d >> 6, unlike any other experiment.
- ΔB dominated by d = 6, unless forbidden by symmetry!

[Weinberg, ‘80]

- Some symmetry/hierarchy has to exist, otherwise

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

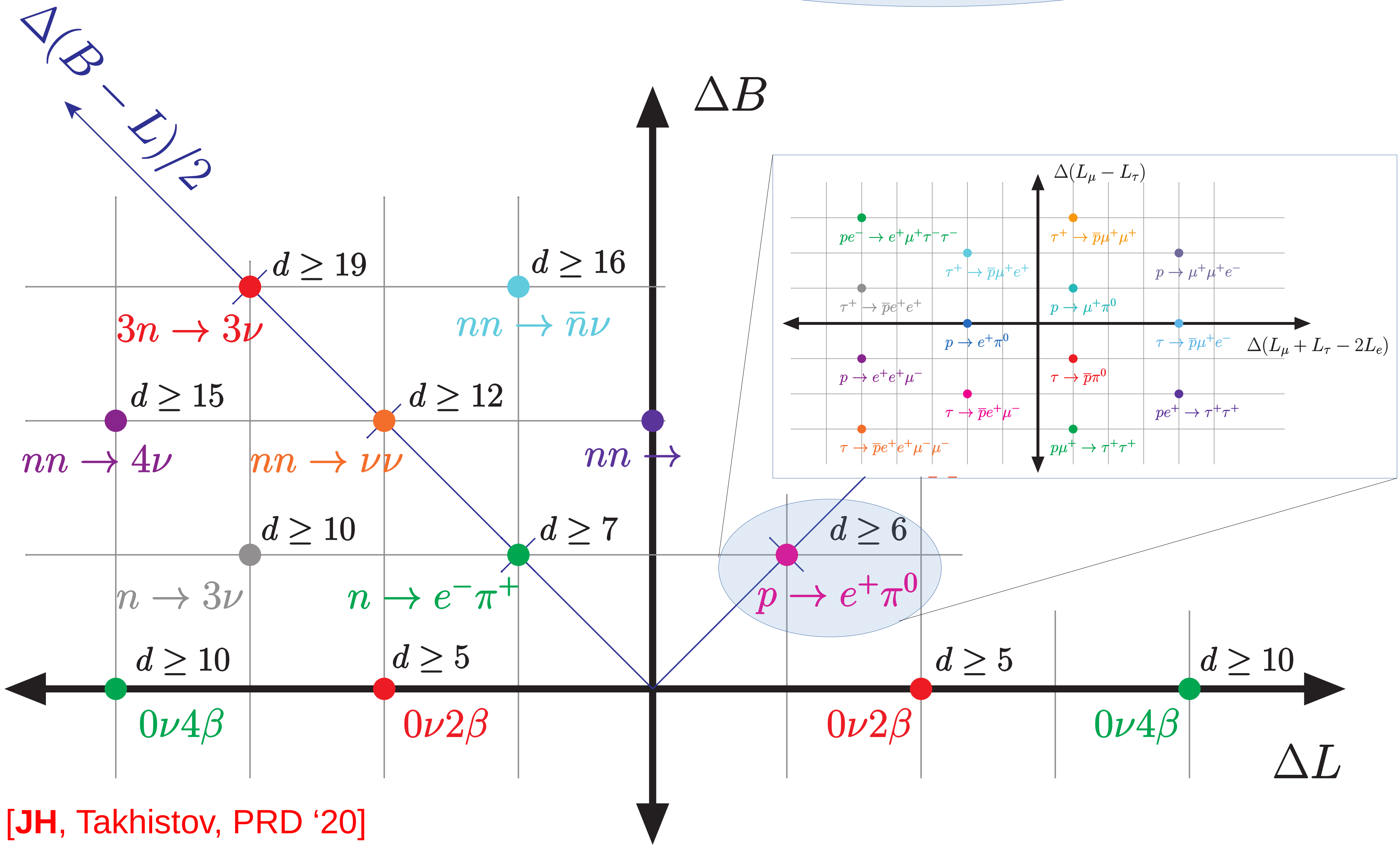
BNV landscape



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

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

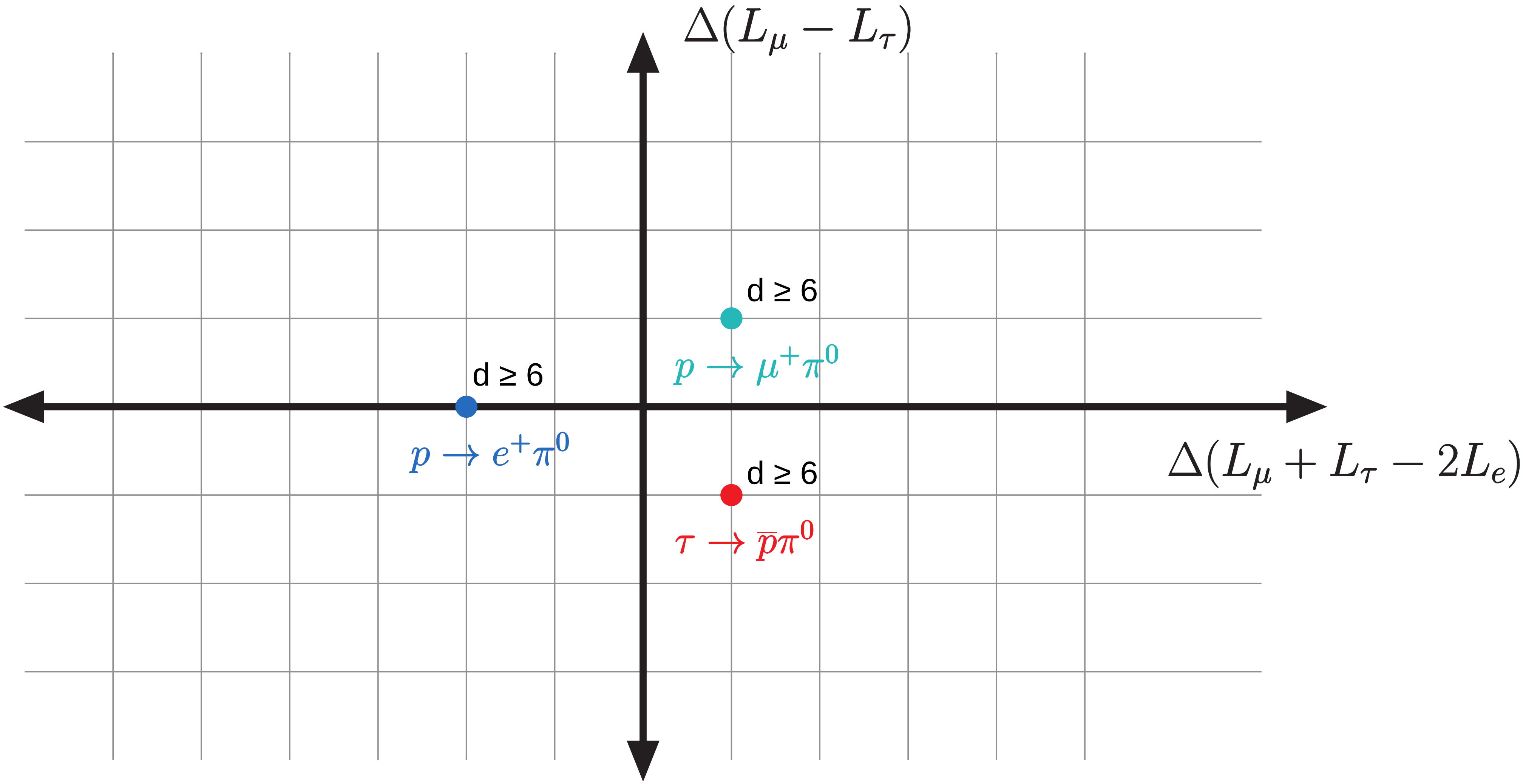
$$\mathrm{U}(1)_\mathrm{B} \times \mathrm{U}(1)_\mathrm{L} \times \mathrm{U}(1)_{\mathrm{L}_\mu - \mathrm{L}_\tau} \times \mathrm{U}(1)_{\mathrm{L}_\mu + \mathrm{L}_\tau - 2\mathrm{L}_e} \,.$$



[**JH**, Takhistov, PRD ‘20]

Proton decay = lepton flavor violation

ΔB = ΔL = 1



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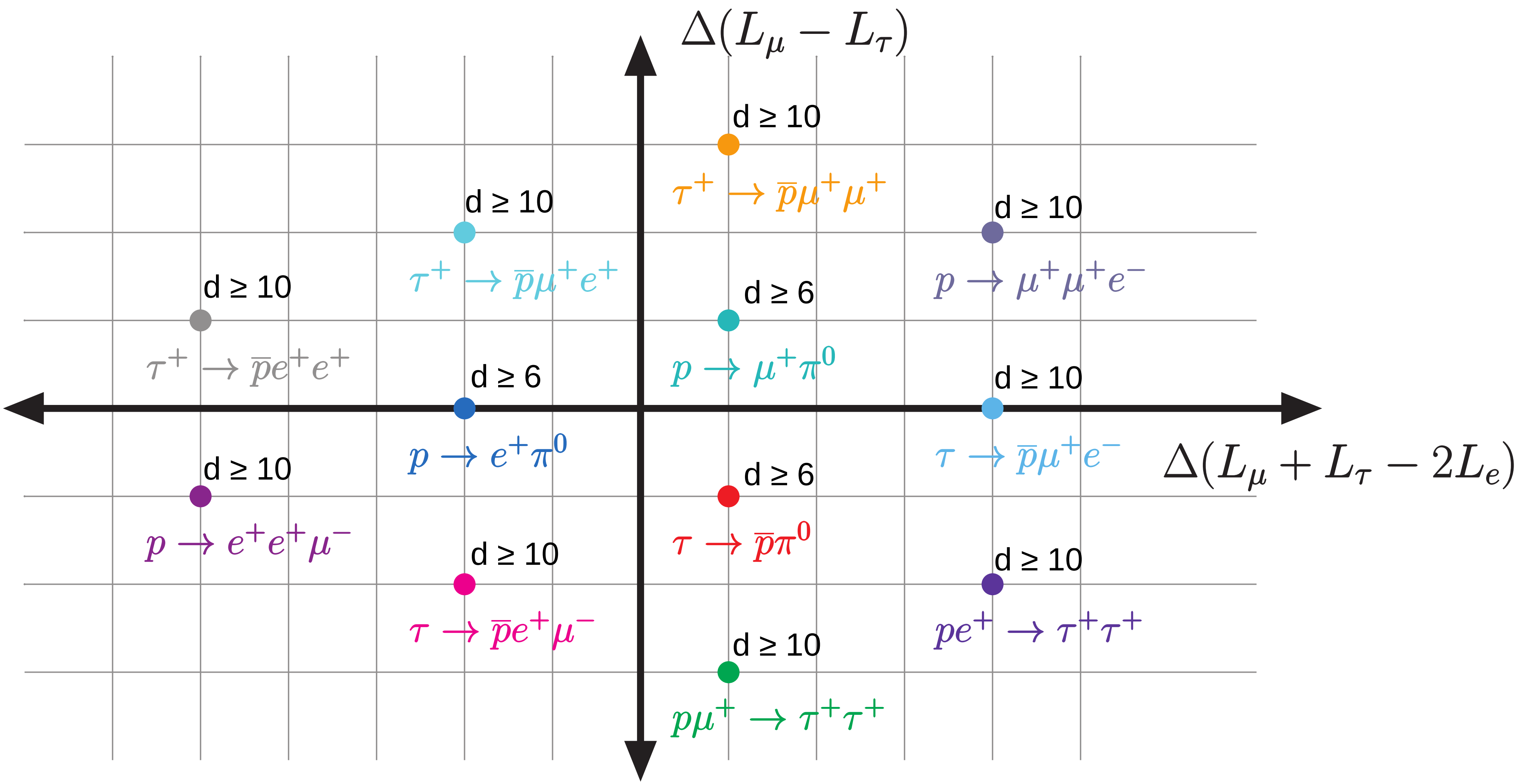

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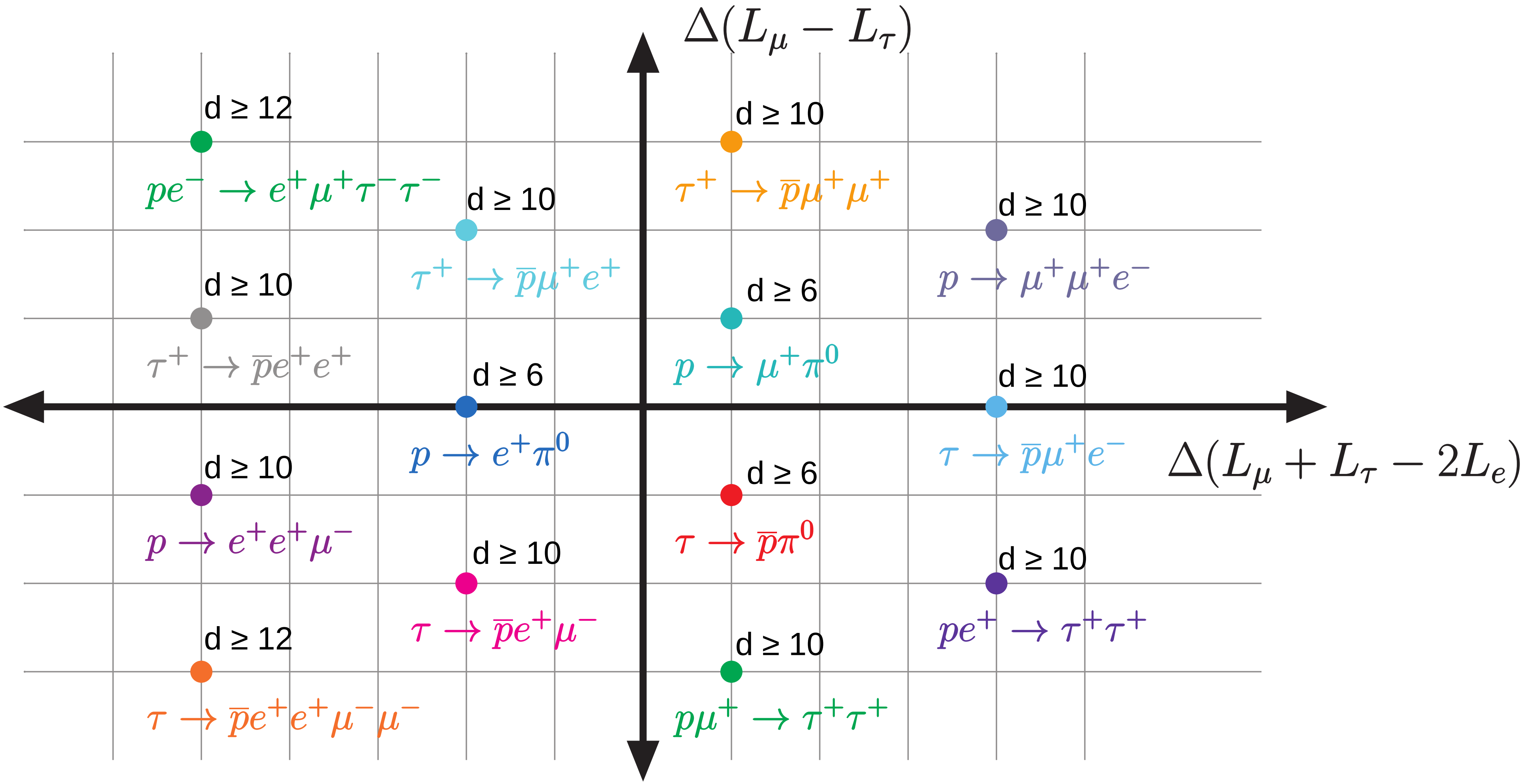
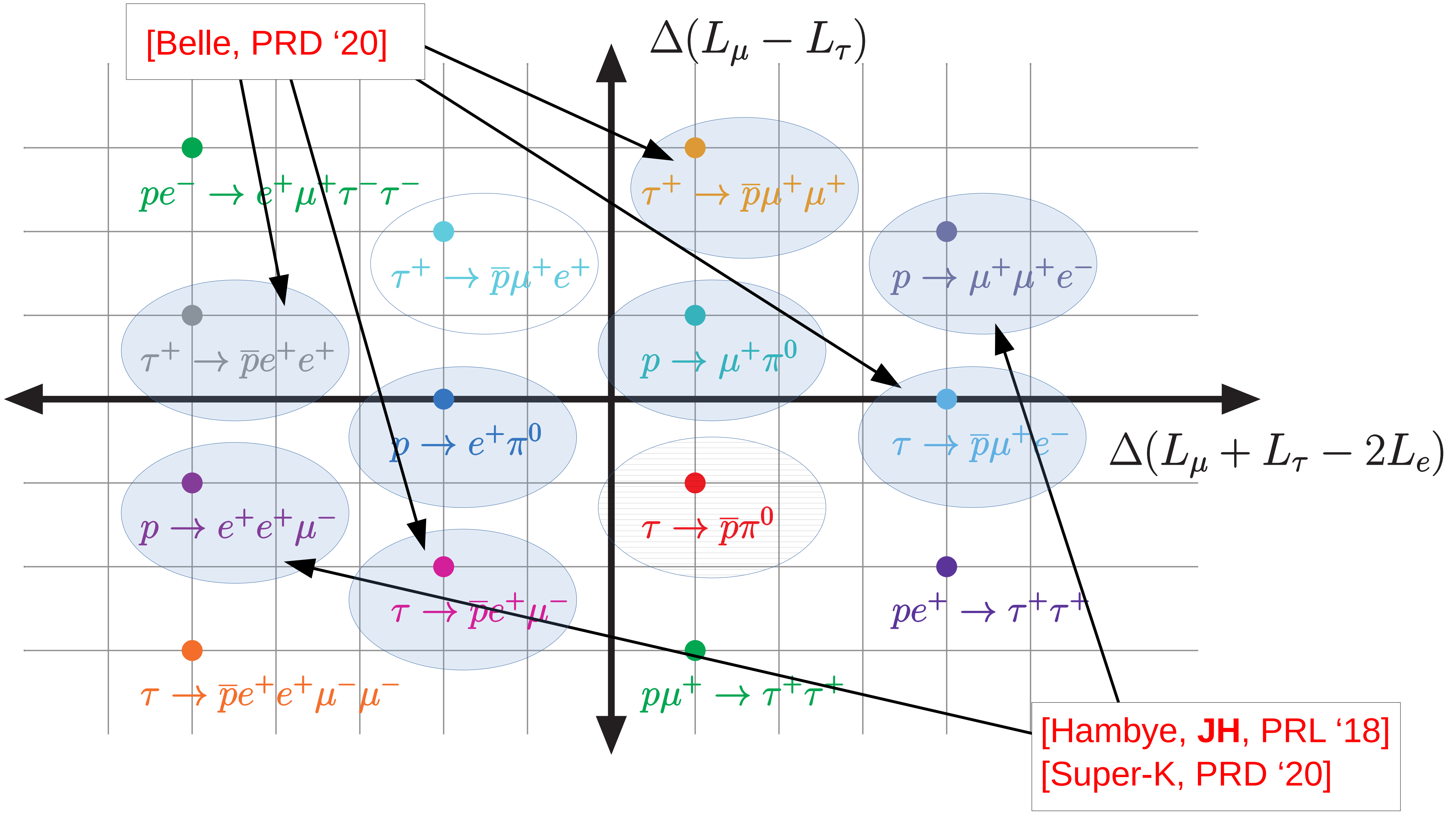


Currently being probed: Old results: Doable:

ΔB = ΔL = 1



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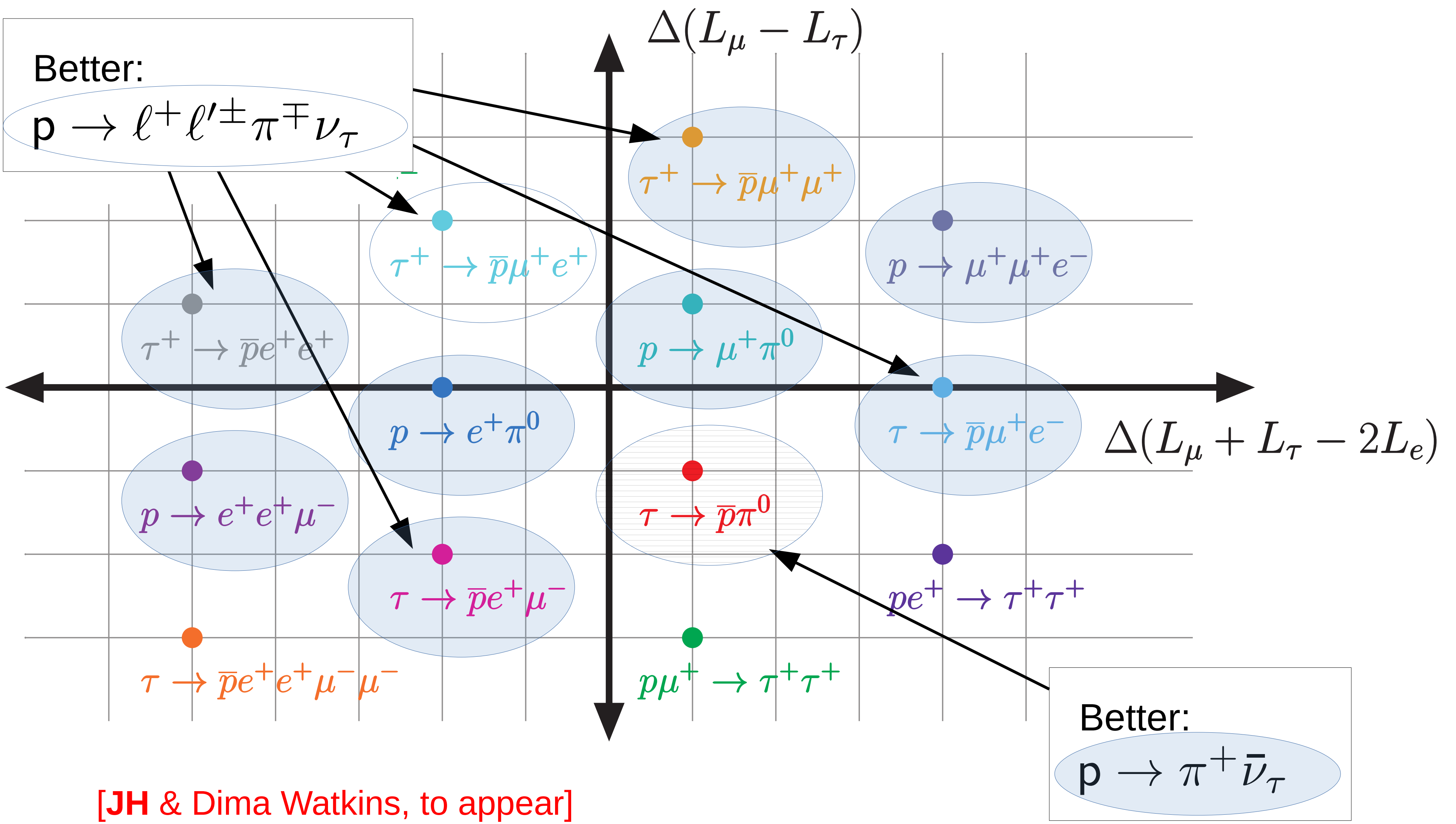

[JH & Dima Watkins, to appear]

[Marciano, NPB ‘95]

Two-body nucleon decays (38)

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

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

Many of these limits are 20 years old (IMB).