Rare processes and the fate of baryon and lepton numbers

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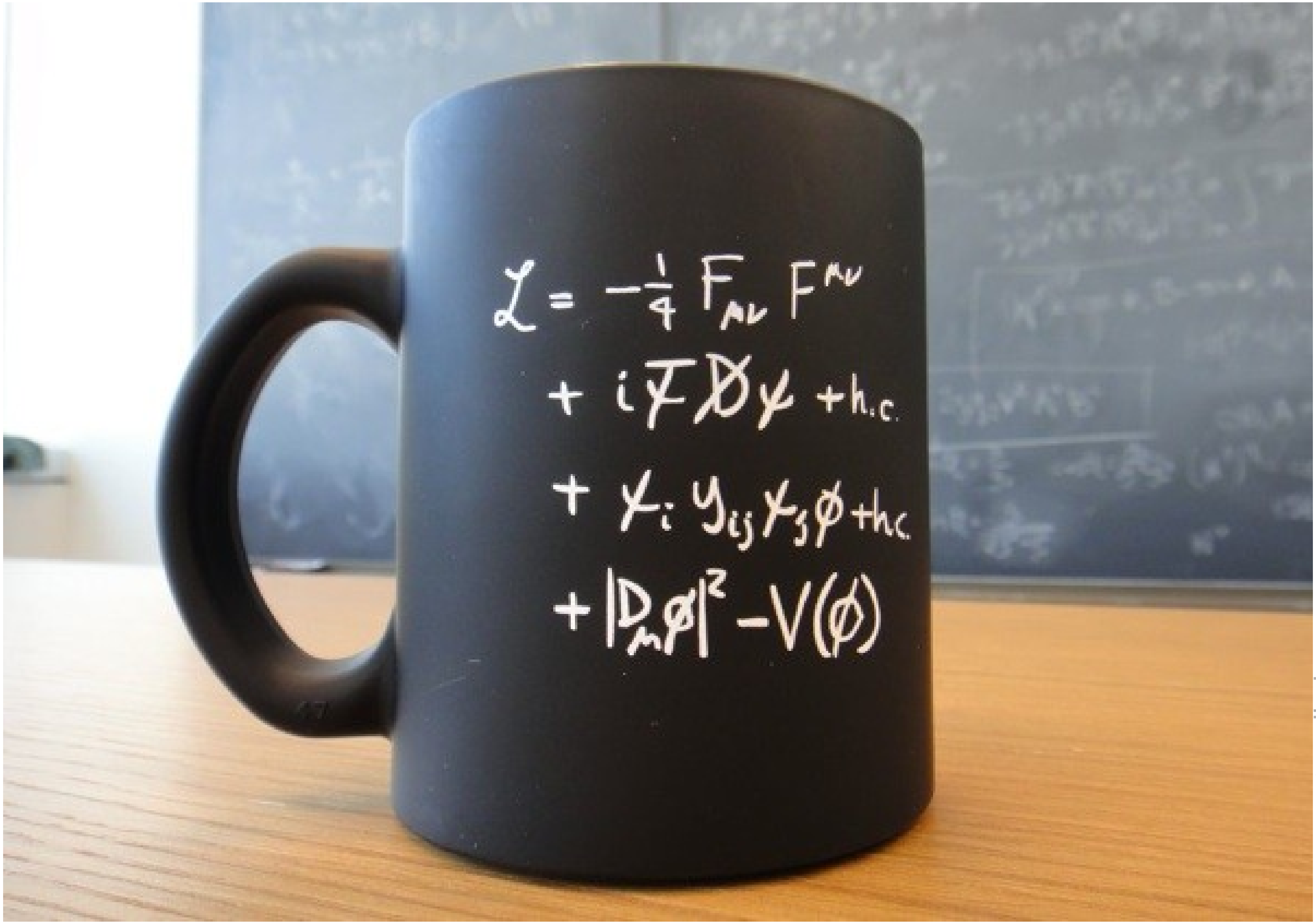
The Standard Model



Symmetries of the Standard Model

- Rephasing lepton and quark fields:

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

- B+L broken non-perturbatively,

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

  but unobservably suppressed at low temperatures. ['t Hooft '76]

- Real global symmetry of SM:

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

- Can even promote to gauge symmetry by adding 3 N_R.
  [Araki, Heeck, Kubo, 1203.4951. Without N_R: L_i-L_j, He, Joshi, Lew, Volkas, '91]

Neutrino oscillations

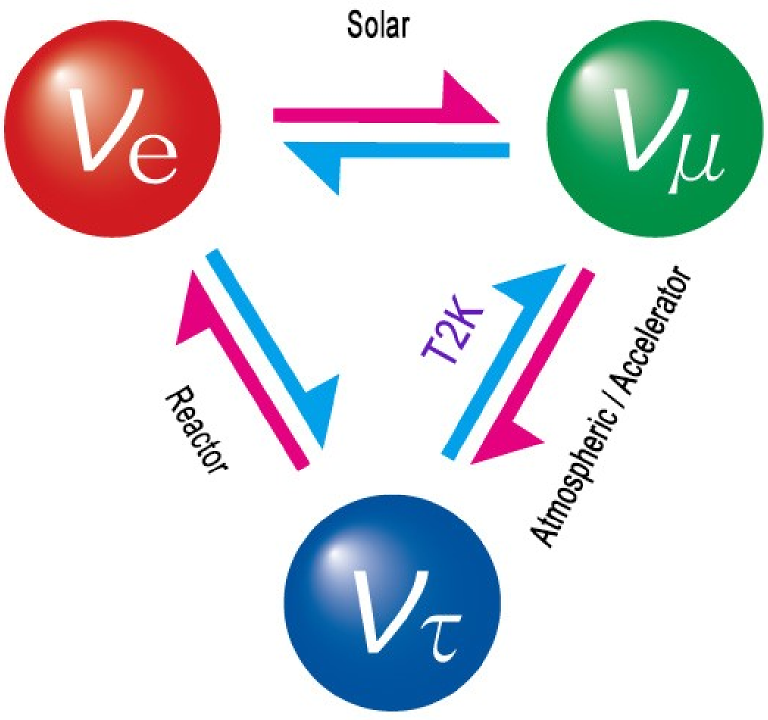
- Observations of $\nu_\alpha \to \nu_\beta$ prove that $M_\nu \neq 0$ and

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

  is broken!

- B – L could still be conserved if neutrinos are Dirac.

  [Heeck, 1408.6845]



Neutrino oscillation between three generations

Lepton flavor definitely violated, so where is it?

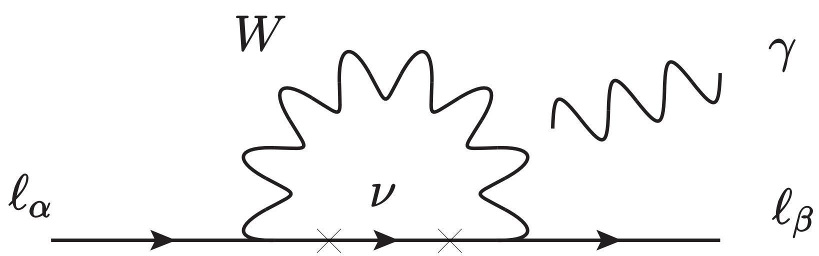
Charged lepton flavor violation?

group	process	current	future
$\Delta(L_e - L_\mu) = 2$	$\mu \to e\gamma$	4.2×10^{-13}	4×10^{-14}
	$\mu \to e\bar{e}e$	1.0×10^{-12}	10^{-16}
	$\mu \to e$ conv.	$\mathcal{O}(10^{-12})$	10^{-17}
	$h \to e\bar{\mu}$	3.5×10^{-4}	2×10^{-4}
	$Z \to e\bar{\mu}$	7.5×10^{-7}	–
	had$\to e\bar{\mu}$(had)	4.7×10^{-12}	10^{-12}

Lepton flavor definitely violated, so where is it?

Neutrino mass ⇒ charged LFV?

- SM + Dirac neutrinos: $\mathrm{L} = \mathrm{L}_{\mathrm{SM}} - \underbrace{(\mathrm{y}\overline{\mathrm{L}}\mathrm{H}\nu_{\mathrm{R}} + \mathrm{h.c.})} + \mathrm{i}\overline{\nu}_{\mathrm{R}}\not{\partial}\nu_{\mathrm{R}}$



$$\begin{aligned} \mathrm{m}_\nu &= \mathrm{y}\langle \mathrm{H}\rangle \\ &= \mathrm{U}\,\mathrm{diag}(\mathrm{m}_1, \mathrm{m}_2, \mathrm{m}_3)\mathrm{V}_{\mathrm{R}} \\ &\overset{!}{\lesssim} \mathrm{eV} \end{aligned}$$

- *All* CLFV is GIM suppressed:

$$\frac{\Gamma(\ell_\alpha \to \ell_\beta \gamma)}{\Gamma(\ell_\alpha \to \ell_\beta \nu_\alpha \overline{\nu}_\beta)} \simeq \frac{3\alpha_{\mathrm{EM}}}{32\pi} \left| \sum_{\mathrm{j}=2,3} \mathrm{U}_{\alpha \mathrm{j}} \frac{\Delta \mathrm{m}^2_{\mathrm{j}1}}{\mathrm{M}_{\mathrm{W}}^2} \mathrm{U}^\dagger_{\mathrm{j}\beta} \right|^2 < 5 \times 10^{-53}\,.$$

[Petcov '77; Cheng & Li '77]

Seesaw mass ⇒ charged LFV?

- SM + seesaw neutrinos: $$\mathsf{L} = \mathsf{L}_{\rm SM} + i\overline{N}_R \partial\!\!\!/ N_R - \left(\tfrac{1}{2} M_R \overline{N}_R^c N_R + \underbrace{y \overline{L} H N_R}_{m_D \overline{\nu}_L N_R} + \text{h.c.}\right)$$
- Violates ΔL = 2. For large M_R:

$$M_N \simeq M_R \,, \qquad M_\nu \simeq -m_D M_R^{-1} m_D^T = U^* \,\mathrm{diag}(m_1, m_2, m_3) U^\dagger .$$

- Majorana neutrinos!
- LFV: $$\frac{\Gamma(\ell_\alpha \to \ell_\beta \gamma)}{\Gamma(\ell_\alpha \to \ell_\beta \nu_\alpha \overline{\nu}_\beta)} \simeq \frac{3\alpha_{\rm EM}}{8\pi} \underbrace{|(m_D M_R^{-2} m_D^\dagger)_{\alpha\beta}|^2}_{M_\nu^2/M_R^2} .$$

[Cheng & Li '80]

Not true with fine-tuning or structure in m_D.

Neutrino mass $\not\Rightarrow$ charged LFV!

- Neutrino-mass induced charged LFV is unobservable.

> Observation of CLFV → beyond SM *and* beyond M_ν!

- (Only exception: $0\nu\beta\beta$ can probe LFV ($\Delta L_e = 2$) via M_ν.)
- arXiv: many ν-mass models *can* actually give large LFV:
  - Low-scale/inverse/linear seesaw;
  - SUSY seesaw;
  - Radiative seesaw (Zee-Babu, Ma,…); [Cai++, 1706.08524]
- $M_\nu \Leftrightarrow$ LFV connection possible but not necessary.

Approximate symmetries

- Flavor still *approximate* symmetry in *charged* lepton sector.
- Unavoidably broken by M_ν, but this is unobservable.

Search for CLFV to learn more about flavor!

- Assuming *heavy new physics*, the best channels are

$$\ell \to \ell'\gamma,\ \ell \to \ell'\ell''\ell''',\ \mu \to \mathsf{e}\ \text{conv.},\ \mathsf{h} \to \ell\ell',\ \text{had} \to \ell\ell',\ \ldots$$

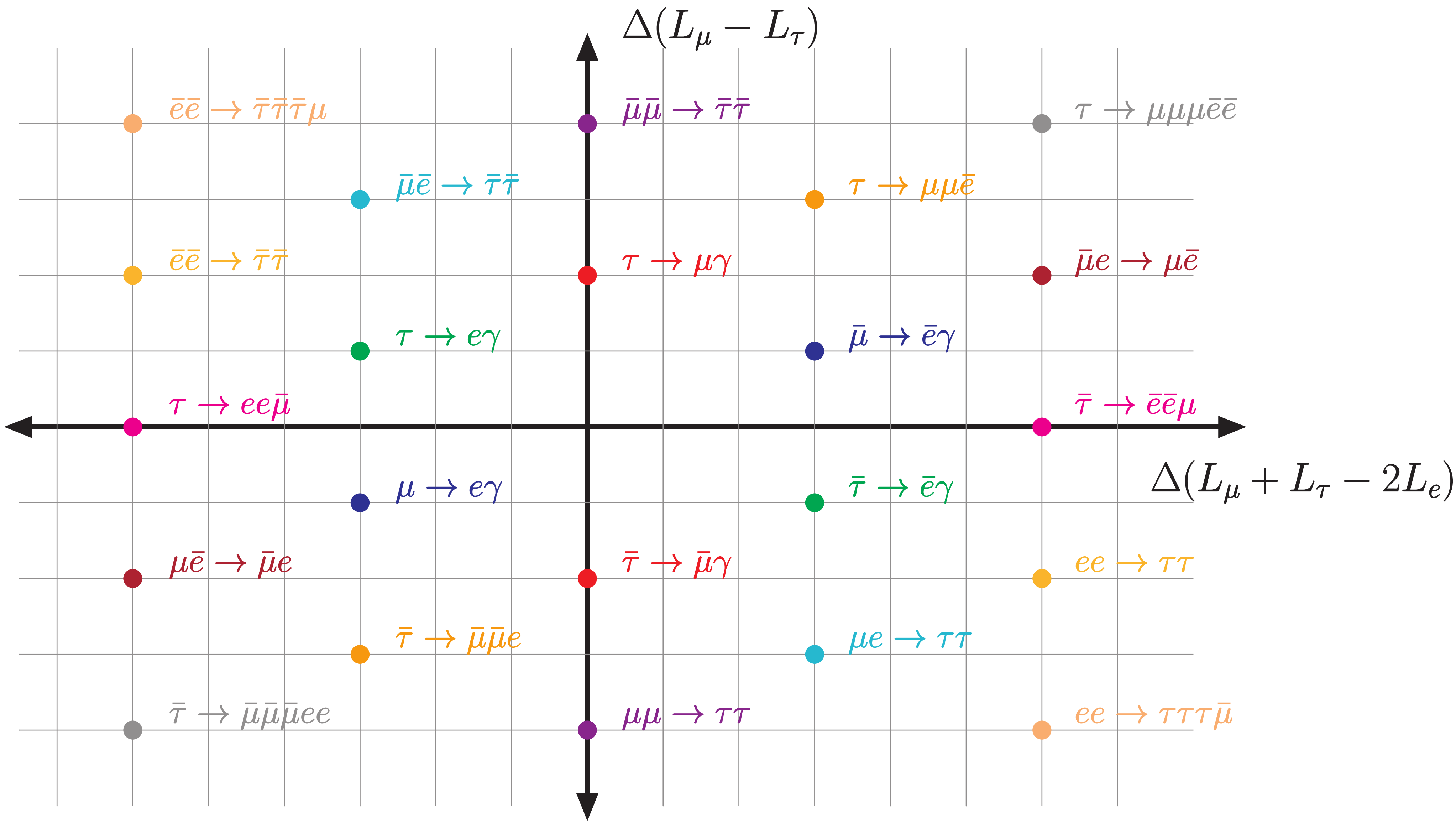
- Organize operators/processes by quantum numbers under

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

[Lew, Volkas, 9410277]

$\Delta B = \Delta L = 0$

[Heeck, 1610.07623]



$\Delta B = \Delta L = 0$

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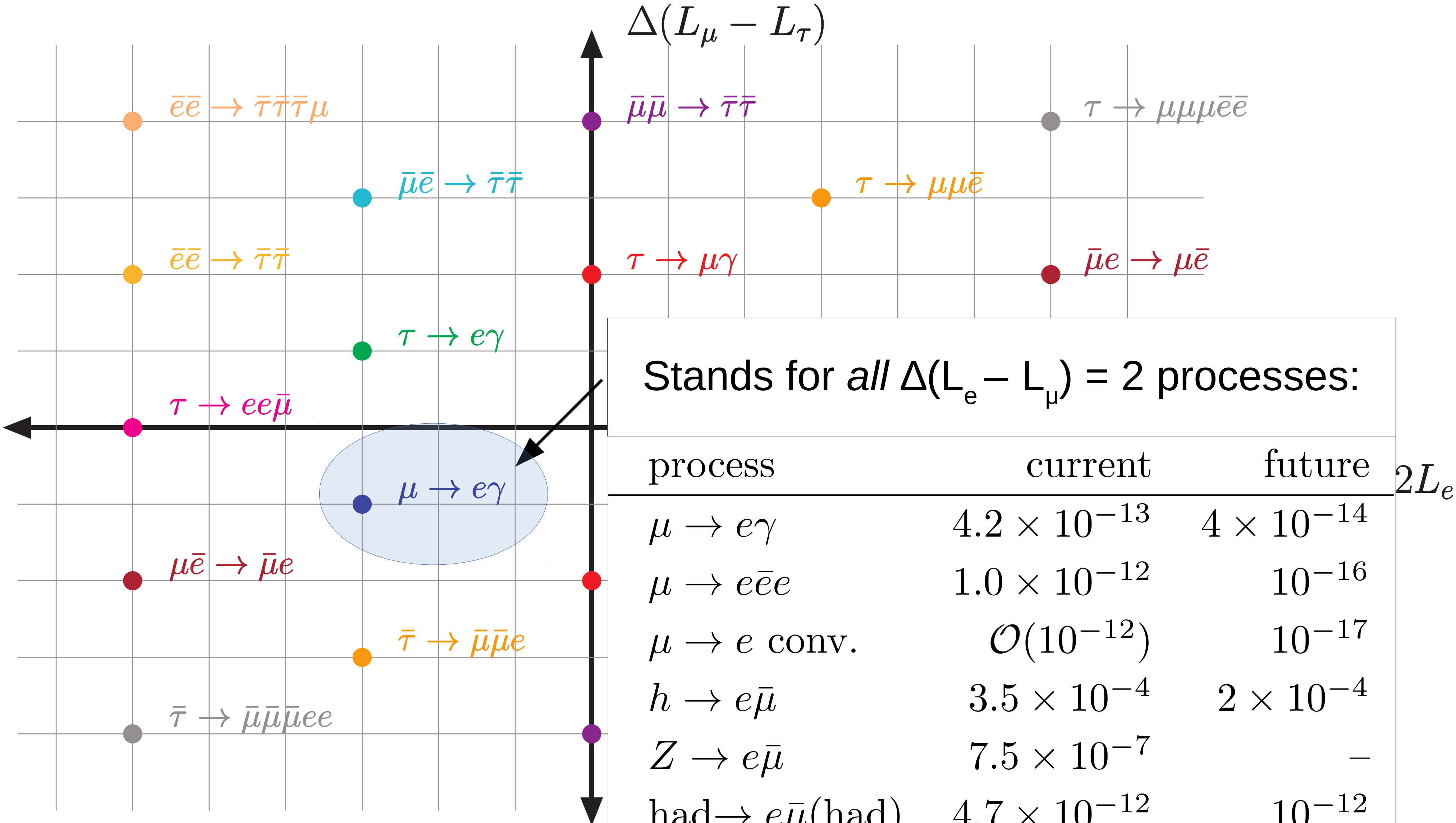

Stands for *all* $\Delta(L_e - L_\mu) = 2$ processes:

process	current	future
$\mu \to e\gamma$	4.2×10^{-13}	4×10^{-14}
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Currently being probed.

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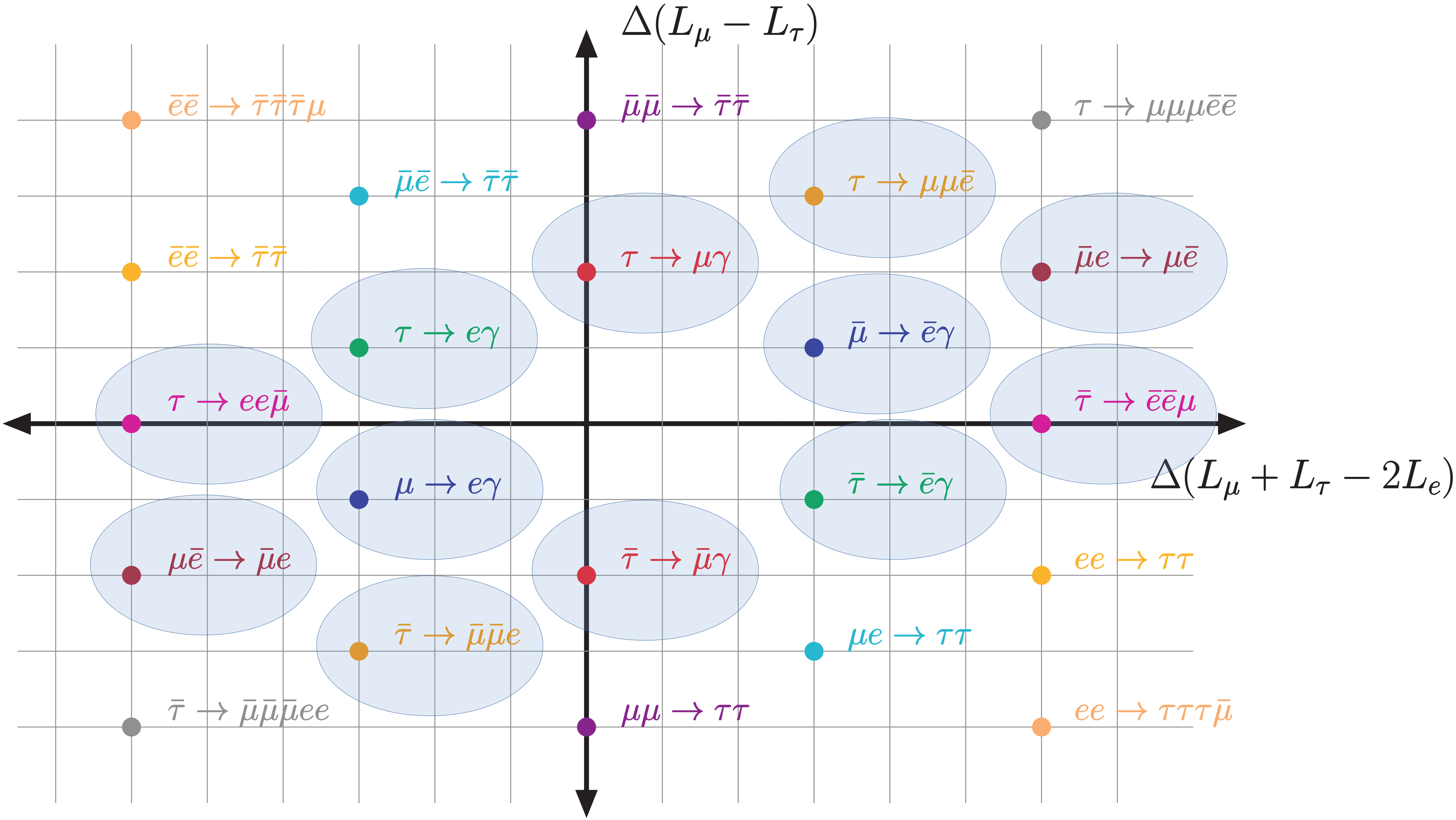
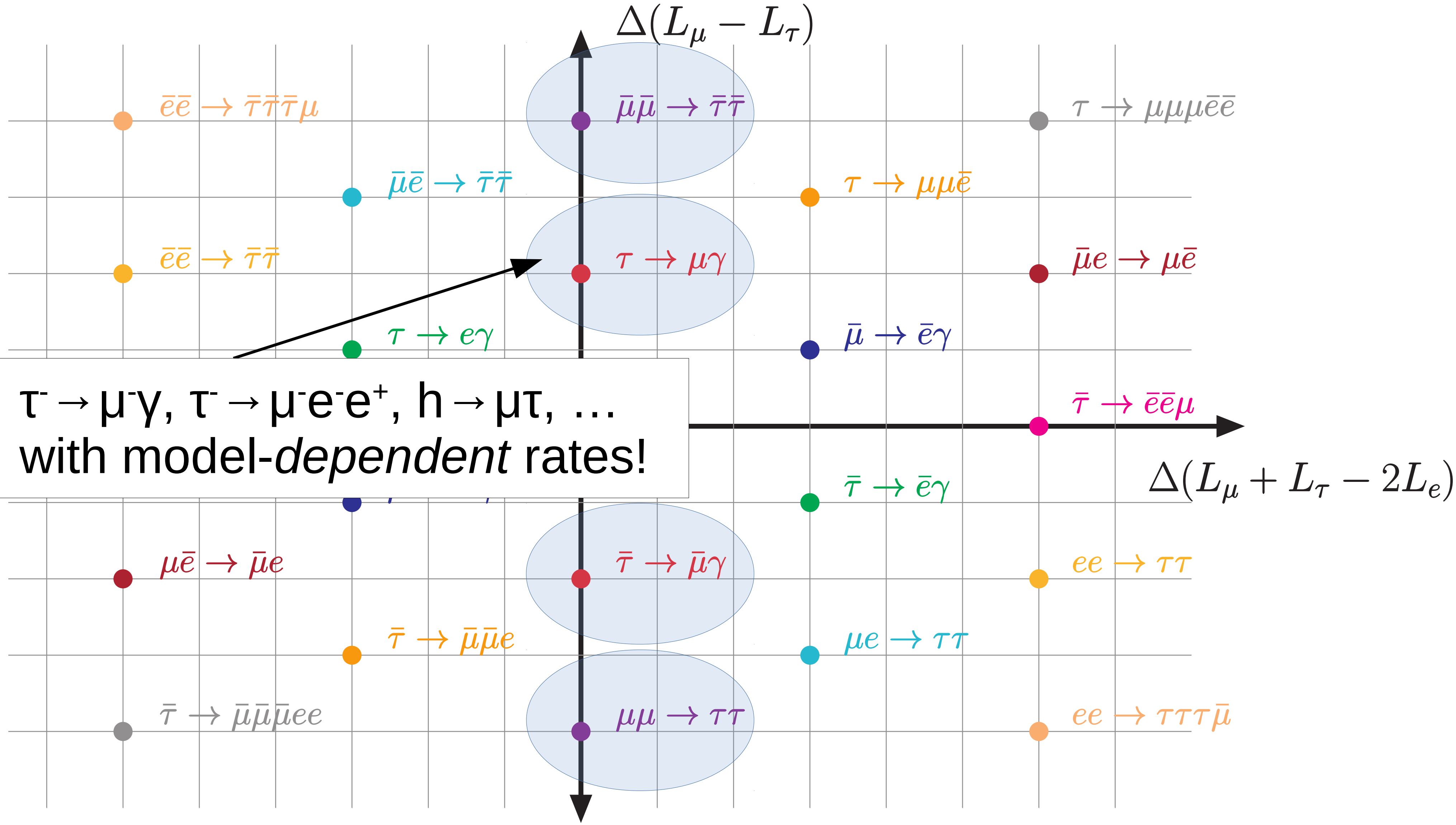


If you see $\tau\rightarrow\mu\gamma$: still $U(1)(L_\mu+L_\tau-2L_e)$ symmetry.

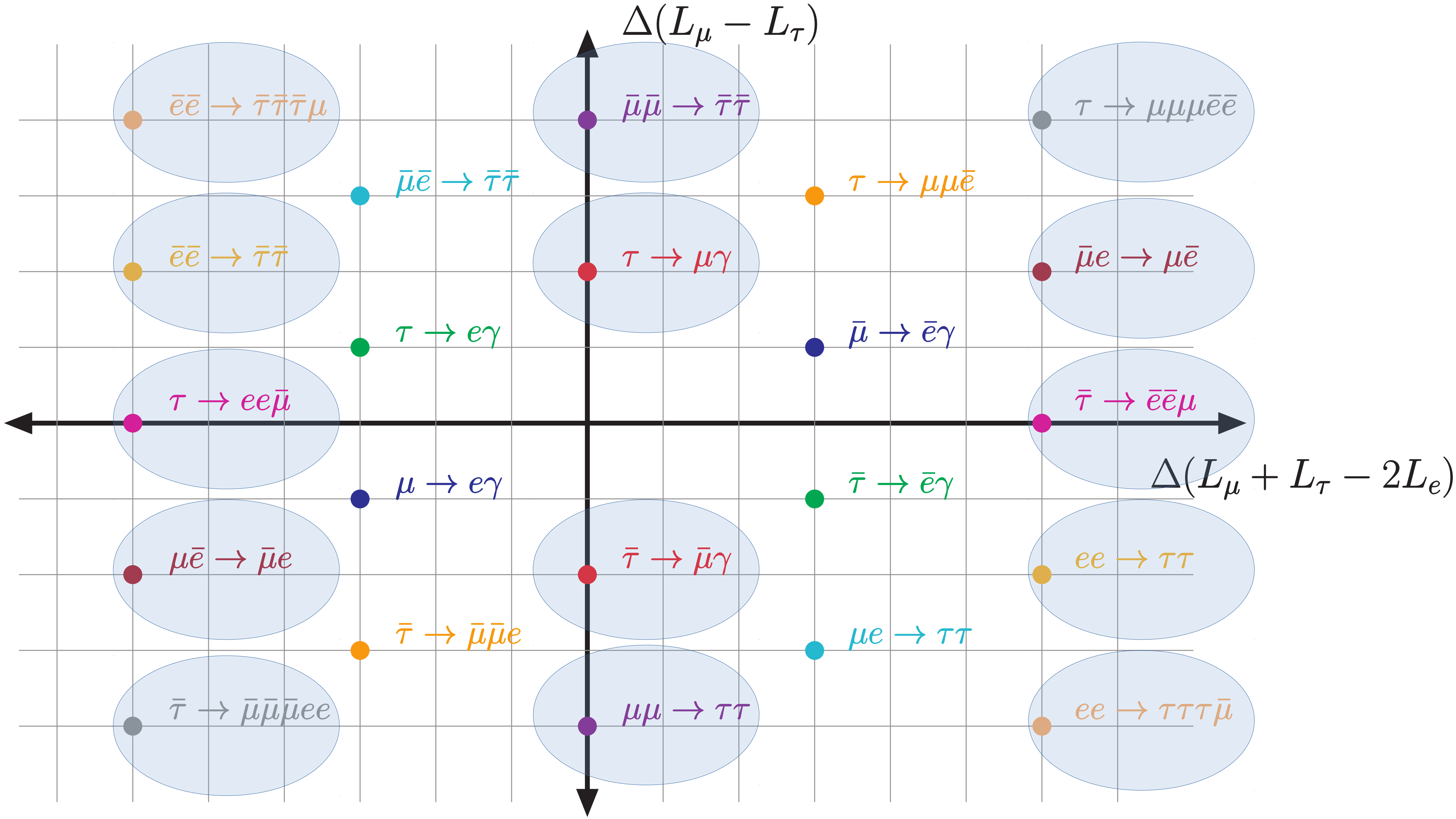
[Heeck, 1610.07623]



$\tau^-\rightarrow\mu^-\gamma$, $\tau^-\rightarrow\mu^-e^-e^+$, $h\rightarrow\mu\tau$, …
with model-*dependent* rates!

If you see $\tau\to\mu\gamma$ *and* $\tau\to ee\bar{\mu}$: still $Z_2(e\to -e)$.

[Heeck, 1610.07623]



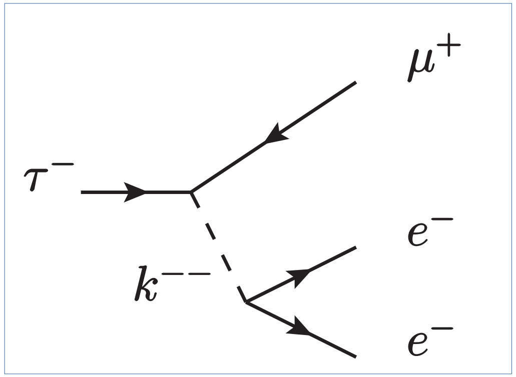
Interpretation of LFV

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

Observation of charged lepton flavor violation	$\Rightarrow$	Remaining symmetry
$\Delta(L_\alpha - L_\beta) = 2$		$U(1)_{L_\alpha+L_\beta-2L_\gamma}$
$\Delta(L_\alpha + L_\beta - 2L_\gamma) = 6$		$U(1)_{L_\alpha-L_\beta}$
$\Delta(L_\alpha + L_\beta - 2L_\gamma) = 6$ and $\Delta(L_\alpha - L_\beta) = 2$		$\mathbb{Z}_2$: $\ell_\gamma \to -\ell_\gamma$
$\Delta(L_\alpha + L_\beta - 2L_\gamma) = 6$ and $\Delta(L_\alpha + L_\gamma - 2L_\beta) = 6$		$\mathbb{Z}_3$: $(\ell_\alpha, \ell_\beta, \ell_\gamma) \sim (0,1,2)$
$\Delta(L_\alpha - L_\beta) = 2$ and $\Delta(L_\alpha - L_\gamma) = 2$		–
$\Delta(L_\alpha - L_\beta) = 2$ and $\Delta(L_\alpha + L_\gamma - 2L_\beta) = 6$		–

- *At least* two orthogonal channels required for *full* LFV.
- Flavor violation by higher units more challenging.
- Easy to build models that single out certain channels, e.g. $\tau^- \to \mu^-\gamma$ or $\tau^- \to e^-e^-\mu^+$.

Example: $\tau^- \to e^- e^- \mu^+$



- Conserves $L_\mu - L_\tau$, so impose this symmetry.
- Simplest UV model: add $SU(2)_L$ singlet k^{++}:

$$\mathcal{L} \supset \left(g_{\mu\tau} \overline{\mu}_R^c \tau_R + g_{ee} \overline{e}_R^c e_R \right) k^{++} + \text{h.c.}$$

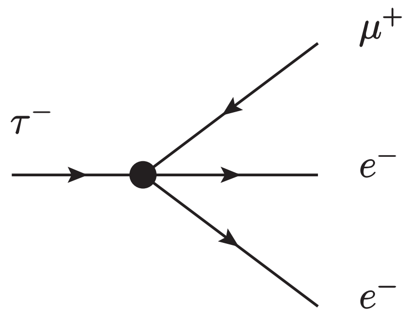
- $\tau^- \to e^- e^- \mu^+$ allowed, everything else forbidden.
- Add N_R and singlet scalars S_j to break $L_\mu - L_\tau$ in M_R:

$$\mathcal{L} \supset y \overline{L} H N_R + \tfrac{1}{2} M_R^{\text{sym}} \overline{N}_R^c N_R + \kappa_j S_j \overline{N}_R^c N_R + \text{h.c.}$$

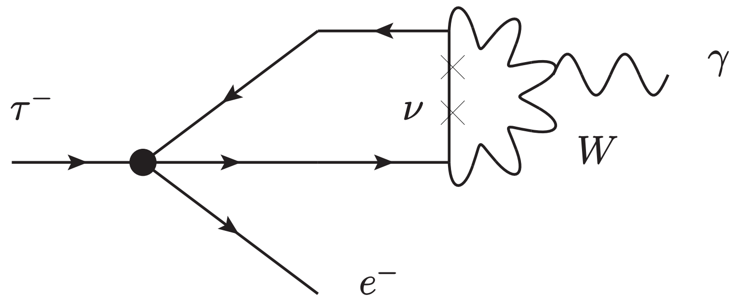
- Could even use symmetry for texture zeroes in M_ν.
  [Araki, Heeck, Kubo, 1203.4951]

$\boxed{\nu \text{ oscillations but approximate symmetry in } \ell^- \text{ sector.}}$ ✓

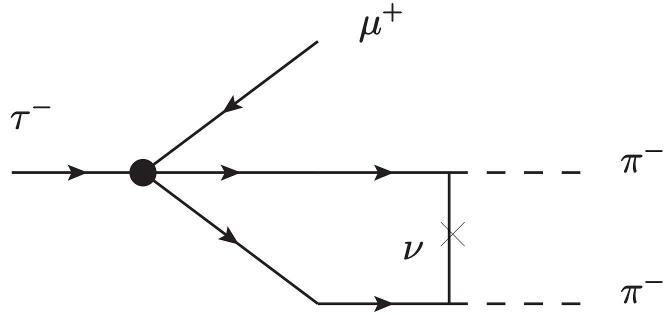
$\tau^- \to e^- e^- \mu^+$ plus M_ν breaks U(1)



$\propto \frac{1}{\Lambda^2}$ ← Conserves $L_\mu - L_\tau$



$\propto \frac{1}{\Lambda^2}\,\alpha\,\frac{\Delta m_\nu^2}{M_W^2}$



$\propto \frac{1}{\Lambda^2}\frac{(m_\nu)_{ee}}{m_e}$

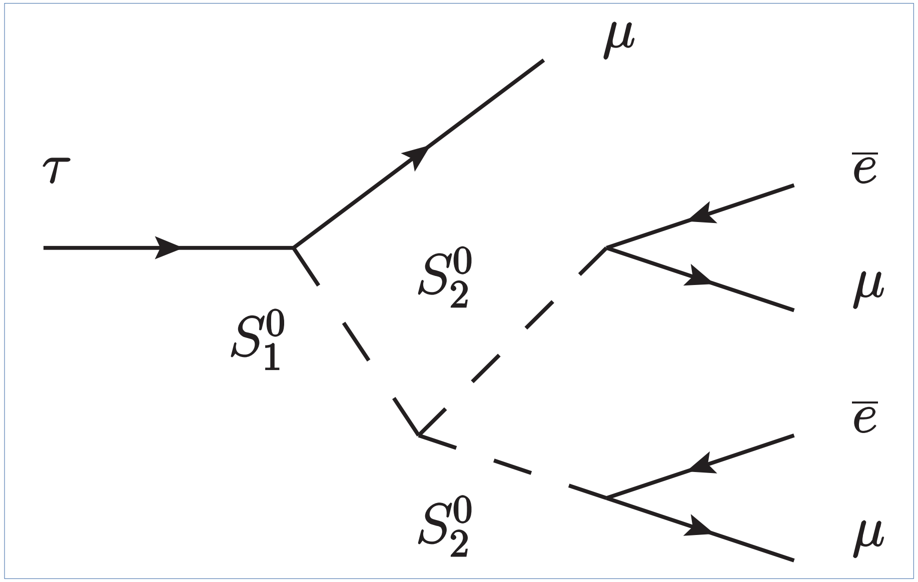
Additional suppression factors from loops, phase space and lepton mass flips depending on actual operator.

⇒ All heavily suppressed!

$\tau^- \to \mu^-\mu^-\mu^-e^+e^+$?

- Conserves $L_\mu + 4L_e - 5L_\tau$, impose to kill other modes.
- Not difficult to build, but rate is

$$\Gamma \propto \langle H \rangle^2 \frac{m_\tau^{11}}{m_S^{12}} \,.$$



- Secretly dimension 10 operator.
- Would need new particles at 10 GeV for observable rate!

Only possible for neutral fields, otherwise $Z \to SS$.

Not pretty...

Baryon number violation

- So far assumed $\Delta B = 0$, but can also do LFV with $\Delta B \neq 0$.
- Example: proton decay ($\Delta B = 1$).
- Super-K limits on $p \to e^+\pi^0$, $\mu^+\pi^0$ are 10^{34} yrs!

Baryon number violation

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- Example: proton decay ($\Delta B = 1$).
- Super-K limits on $p \to e^+\pi^0, \mu^+\pi^0$ are 10^{34} yrs!
- More interesting for flavor: $p \to \overline{\ell}\ell\ell$:

channel	$(\Delta L_e, \Delta L_\mu)$	limit/years
$p \to e^+e^+e^-$	$(1,0)$	793×10^{30}
$p \to e^+\mu^+\mu^-$	$(1,0)$	359×10^{30}
$p \to \mu^+e^+e^-$	$(0,1)$	529×10^{30}
$p \to \mu^+\mu^+\mu^-$	$(0,1)$	675×10^{30}
$p \to \mu^+\mu^+e^-$	$(-1,2)$	359×10^{30}
$p \to e^+e^+\mu^-$	$(2,-1)$	529×10^{30}

IMB '99; SK can improve by ~30!

Different flavor from $p \to \ell^+\pi^0$!

Effective operators

- $\Delta B = 1$ proton decay operators:
  - $QQQL$: $d=6$, $\Delta L = 1$, e.g. $p \to e^+ \pi^0$.
  - $QQ\overline{L}Hd$: $d=7$, $\Delta L = -1$, e.g. $p \to e^- \pi^+ K^+$.
  - $\overline{LL}\ell udd$: $d=9$, $\Delta L = -1$, e.g. $p \to \nu\, e^- e^+ K^+$.
  - $QQQL\overline{L}H\ell$: $d=10$, $\Delta L = 1$, e.g. $p \to e^+ e^- e^+$.
  - $ddd\overline{LLL}H$: $d=10$, $\Delta L = -3$, e.g. $p \to e^- \nu\nu\, \pi^+ \pi^+$.
  - $QudLLLHH$: $d=11$, $\Delta L = 3$, e.g. $p \to e^+ \overline{\nu\nu}$.

[Weinberg, '79 & '80]

Different symmetry properties

Effective operators

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Impose B+L

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  - ~~QudLLLHH: d=11, $\Delta L = 3$, e.g. $p \to e^+ \overline{\nu\nu}$.~~

Impose B+3L

Effective operators

- $\Delta B = 1$ proton decay operators:
  - $QQQL$: $d=6$, $\Delta L = 1$, e.g. $p \to e^+ \pi^0$.
  - ~~$QQ\overline{L}Hd$: $d=7$, $\Delta L = -1$, e.g. $p \to e^- \pi^+ K^+$.~~
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$\boxed{\text{Impose B–L}}$

Effective operators

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  - $\overline{LL}\ell udd$: d=9, $\Delta L = -1$, e.g. $p \to \nu_e\, e^-\, \mu^+ K^+$.
  - $QQQL\bar{L}H\ell$: d=10, $\Delta L = 1$, e.g. $p \to e^+ e^+ \mu^-$.
  - $ddd\overline{LLLH}$: d=10, $\Delta L = -3$, e.g. $p \to e^-\, \nu_\mu \nu_\tau\, \pi^+ \pi^+$.
  - $QudLLLHH$: d=11, $\Delta L = 3$, e.g. $p \to \mu^+\, \bar{\nu}_e \bar{\nu}_\tau$.

$\boxed{\text{Impose } L_e + 2L_\mu - 3L_\tau}$

Effective operators

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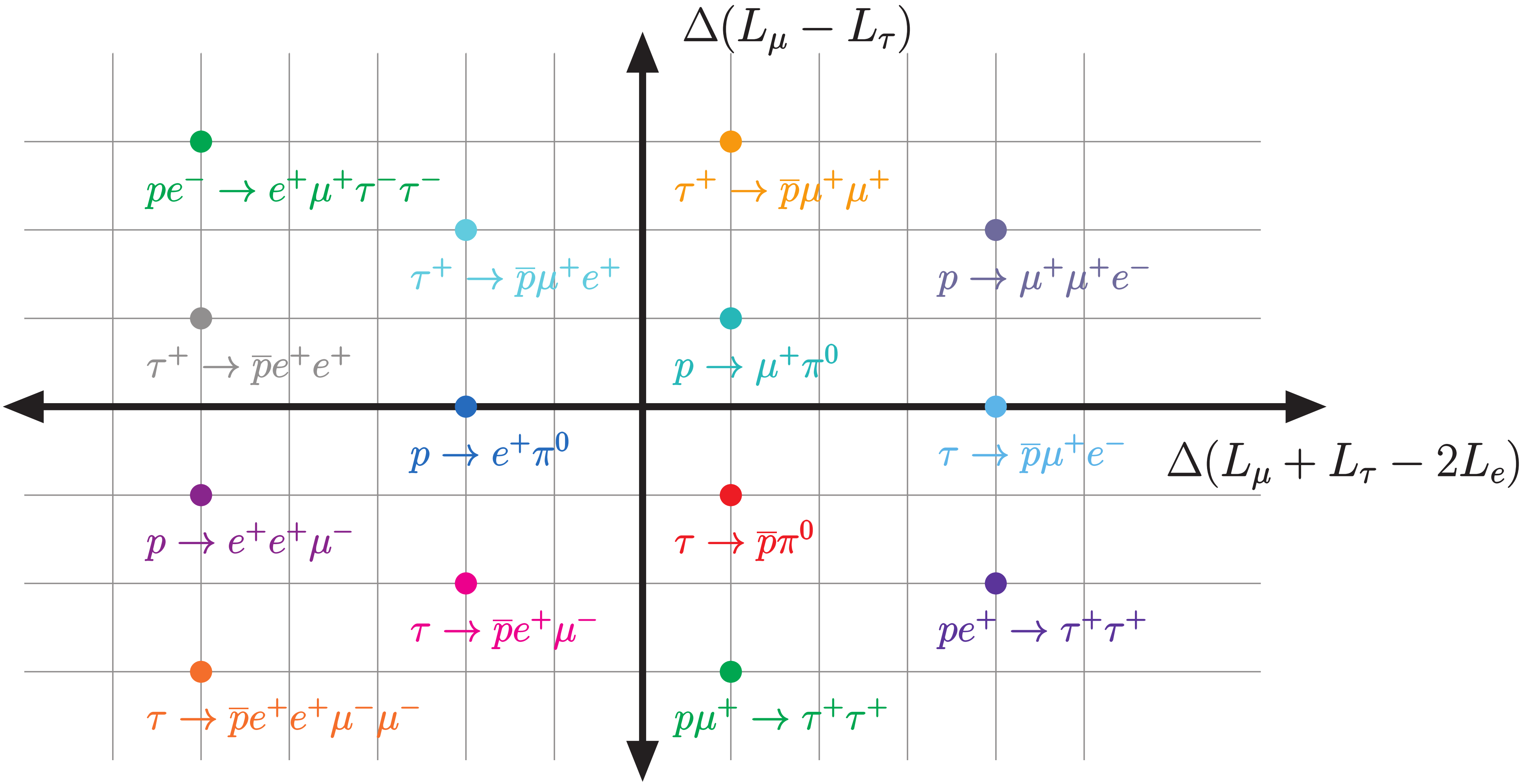
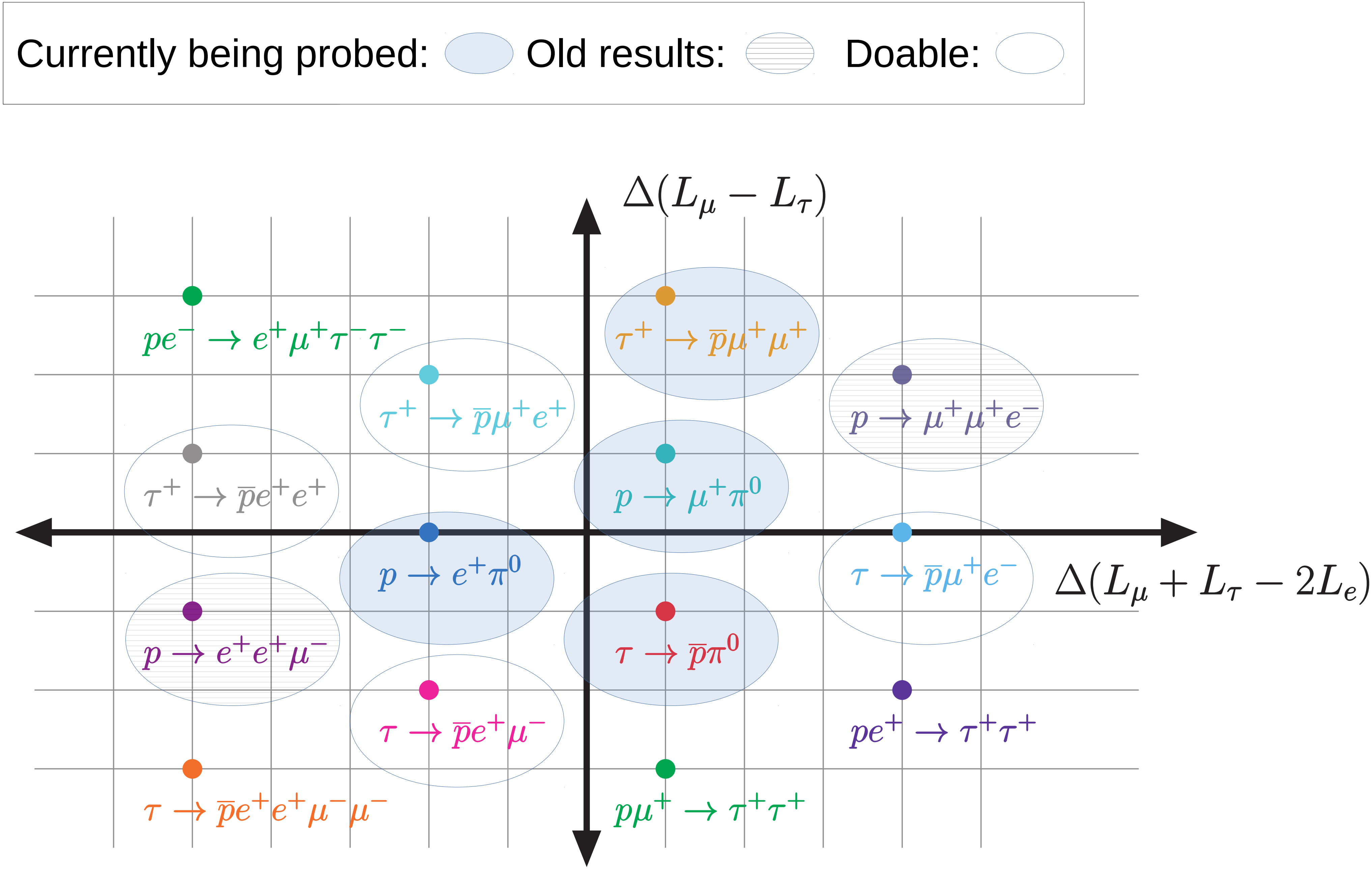
  - ~~$QudLLLHH$: $d=11$, $\Delta L = 3$, e.g. $p \to \mu^+ \bar{\nu}_e \bar{\nu}_\tau$.~~

$\boxed{\text{Impose } L_e+2L_\mu-3L_\tau \text{ and } B-L}$

$\Delta B = \Delta L = 1$




Currently being probed:
Old results:
Doable:
$\Delta(L_\mu - L_\tau)$
$\Delta(L_\mu + L_\tau - 2L_e)$
$pe^- \to e^+\mu^+\tau^-\tau^-$
$\tau^+ \to \overline{p}\mu^+\mu^+$
$\tau^+ \to \overline{p}\mu^+e^+$
$p \to \mu^+\mu^+e^-$
$\tau^+ \to \overline{p}e^+e^+$
$p \to \mu^+\pi^0$
$p \to e^+\pi^0$
$\tau \to \overline{p}\mu^+e^-$
$p \to e^+e^+\mu^-$
$\tau \to \overline{p}\pi^0$
$\tau \to \overline{p}e^+\mu^-$
$pe^+ \to \tau^+\tau^+$
$\tau \to \overline{p}e^+e^+\mu^-\mu^-$
$p\mu^+ \to \tau^+\tau^+$

Lepton-flavored proton decay

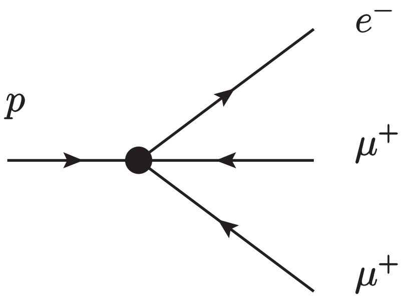
- The decay $p \to e^+ e^+ \mu^-$ (or $p \to \mu^+ \mu^+ e^-$) could be dominant!
- Conserves B–L, L_τ, and $L_e + 2L_\mu - 3L_\tau$ (or $L_\mu + 2L_e - 3L_\tau$).
- 35 d=10 operators of the form $QQQL\overline{L}H\ell/\Lambda^6$.
- Rate suppressed:

$$\Gamma \propto \langle H \rangle^2 \frac{m_p^{11}}{\Lambda^{12}} \sim (10^{33}\,\mathrm{yr})^{-1} (100\,\mathrm{TeV}/\Lambda)^{12}\,.$$

- Easy channels, Super-K can probe 10^{34} yrs!
- UV completion @ 100 TeV could show up in flavor physics.
- Other channels, e.g. $p \to e^+ \pi^0$, suppressed by ν mass.

[Hambye, Heeck, 1712.04871, PRL]

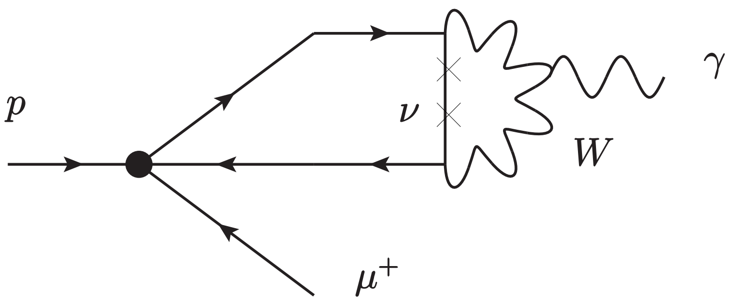
$p \to \mu^+\mu^+e^-$ plus M_ν breaks U(1)



$$\Delta B = \Delta L = 1, d = 10:$$

$$\mathcal{A}_{10} \propto \frac{\langle H \rangle}{\Lambda^6}$$

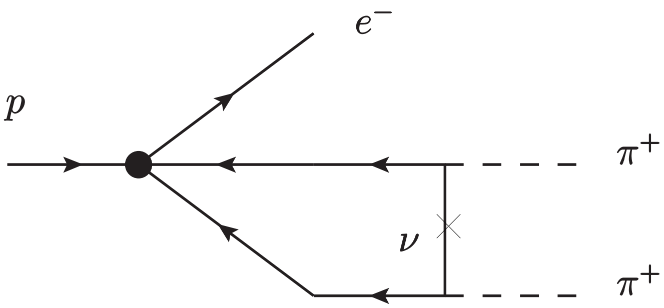
Conserves U(1)



$$\Delta B = \Delta L = 1, d = 6:$$

$$\mathcal{A}_6 \propto \frac{\langle H \rangle m_p}{\Lambda^6} \alpha \frac{\Delta m_\nu^2}{16\pi^2}$$

GIM: Not dangerous



$$\Delta B = -\Delta L = 1, d = 7:$$

$$\mathcal{A}_7 \propto \frac{\langle H \rangle m_p}{\Lambda^6} \frac{(m_\nu)_{\mu\mu}}{16\pi^2}$$

Small enough!

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

- Minimal leptoquark example:

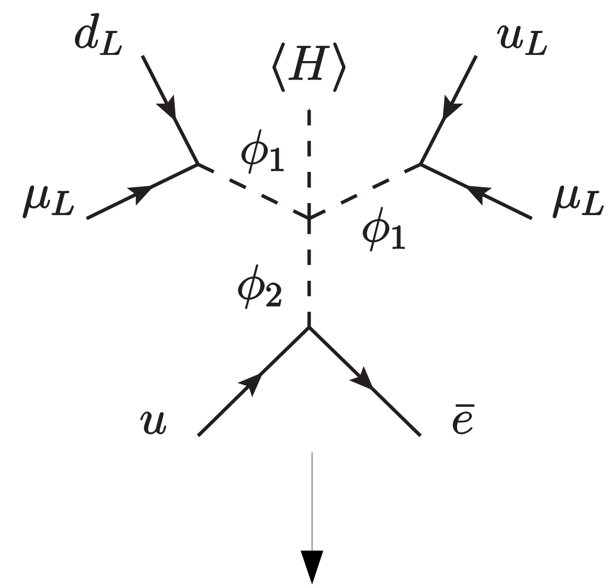
$$\phi_1 \sim (\mathbf{3}, \mathbf{3}, -2/3)\,,\; \phi_2 \sim (\mathbf{3}, \mathbf{2}, 7/3)\,.$$

- $L_\mu + 2L_e - 3L_\tau$ ensures simple structure

$$y_j \overline{L}_\mu \phi_1 Q_j^c + f_j \overline{u}_j \phi_2 L_e + \lambda \phi_1^2 \phi_2 H\,.$$

- Also conserves B-L and lepton flavor, but gives lepton non-universality via

$$\frac{y_j \overline{y}_i}{m_{\phi_1}^2} (\overline{L}_\mu Q_j^c)(Q_i L_\mu) + \frac{f_j \overline{f}_i}{m_{\phi_2}^2} (\overline{L}_e u_j)(\overline{u}_i L_e)\,.$$



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

[Hambye, Heeck, 1712.04871, PRL]

- Triplet LQ perfect for $b \to s\mu\mu$ anomalies: $m_{\phi_1} \simeq 30\,\mathrm{TeV}\sqrt{y_2 y_3}\,.$

[Alok+, 1703.09247; Dorsner+, 1706.07779; Capdevila+, 1704.05340]

b → sμμ

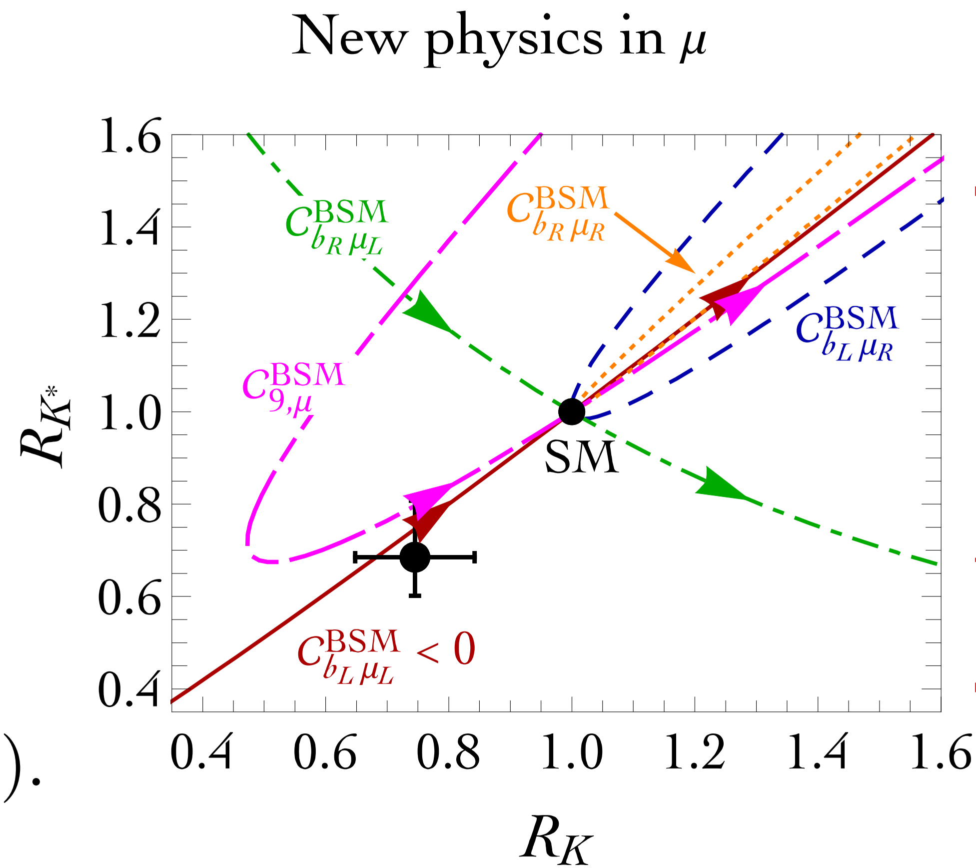
- Hints for lepton flavor non-universality in

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

- LHCb: R(K)~0.75, R(K*)~0.67.

- 4-6σ improvement with

$$-\frac{1}{(30\ \text{TeV})^2}(\overline{\mu}\gamma_\alpha P_L \mu)(\overline{b}\gamma^\alpha P_L s).$$



[D'Amico+, 1704.05438]

- Also explains anomalies in other b → sμμ observables.

- Resolution via Z' or leptoquarks.

Triplet LQ and b→sμμ

- Assume $m_{\phi_1} \ll m_{\phi_2}$, $\phi_1 \sim (\mathbf{3},\mathbf{3},-2/3)$, $\phi_2 \sim (\mathbf{3},\mathbf{2},7/3)$.
- $L_\mu+2L_e-3L_\tau$ ensures simple structure

$$\mathcal{L} \propto \frac{y_j \overline{y}_i}{m_{\phi_1}^2} (\overline{L}_\mu Q_j^c)(Q_i L_\mu) \propto \frac{y_j \overline{y}_i}{m_{\phi_1}^2} (\overline{L}_\mu \gamma_\alpha P_L L_\mu)(\overline{Q}_j \gamma^\alpha P_L Q_i).$$

- Generates $C^\mu_{9,LL}$ operator preferred by b→ sμμ:

$m_{\phi_1} \simeq 30\,\mathrm{TeV}\sqrt{y_2 y_3}$ improves fit by 4-6σ.

[Alok+, 1703.09247; Dorsner+, 1706.07779; Capdevila+, 1704.05340]

- Flavor symmetry ensures lepton non-universality and kills coupling $QQ\phi_1$ that would lead to d=6 proton decay.

Summary so far

- SM symmetry: $G = U(1)_{B-L} \times U(1)_{L_\mu - L_\tau} \times U(1)_{L_\mu + L_\tau - 2L_e}$.
- Effective field theory with Majorana ν:

$$L = L_{\mathrm{SM}} + \overbrace{\frac{LLHH}{\Lambda}}^{M_\nu} + \underbrace{\sum_j \frac{\mathcal{O}_j}{\Lambda^2} + \sum_j \frac{\mathcal{O}'_j}{\Lambda^3} + \sum_j \frac{\mathcal{O}''_j}{\Lambda^4} + \dots}_{\text{could conserve G or subgroup}}$$

conserves G

violates G

could conserve G or subgroup

⇒ ‘weird’ channels dominate!?

But what if new physics is light?

Simple example: majoron

- 3 singlets N_R + new scalar $\sigma = (\mathsf{f} + \sigma^0 + \mathsf{i}\mathsf{J})/\sqrt{2}.$

B – L breaking scale

Heavy scalar (inflaton?)

Goldstone boson: **majoron**

[Chikashige, Mohapatra, Peccei, '81; Schechter, Valle, '82]

- Break $U(1)_{B\text{-}L}$ spontaneously: $\mathcal{L} = -\overline{\mathsf{L}}\mathsf{y}\mathsf{H}\mathsf{N}_\mathsf{R} - \frac{1}{2}\overline{\mathsf{N}}^\mathsf{c}_\mathsf{R}\underbrace{\lambda\sigma}\mathsf{N}_\mathsf{R} + \mathsf{h.c.}$

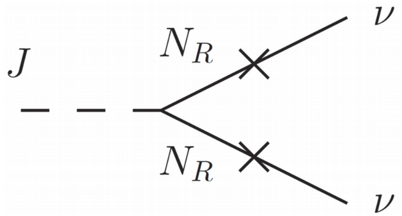
$$\mathsf{M}_\mathsf{R} = \frac{\lambda \mathsf{f}}{\sqrt{2}}$$

- For $\mathsf{M}_\mathsf{R} \gg \mathsf{m}_\mathsf{D} : \mathsf{M}_\nu \simeq -\mathsf{m}_\mathsf{D}\mathsf{M}_\mathsf{R}^{-1}\mathsf{m}_\mathsf{D}^\mathsf{T}$

$$\simeq 1\mathsf{eV}\left(\frac{\mathsf{m}_\mathsf{D}}{100\mathsf{GeV}}\right)^2\left(\frac{10^{13}\mathsf{GeV}}{\mathsf{M}_\mathsf{R}}\right).$$

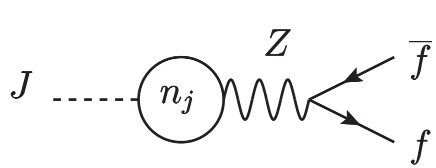
Majoron couplings

- Tree level coupling only to neutrinos:



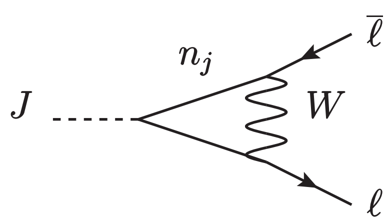
$$\frac{iJ}{2f}\overline{\nu}^c_\alpha \gamma_5 (m_D^* M_R^{-1} m_D^\dagger)_{\alpha\beta}\nu_\beta = -\frac{iJ}{2f}\sum_k \overline{\nu}_k\gamma_5 m_k \nu_k$$

- One loop:



$$\frac{iJ}{f}\overline{f}\gamma_5 f \, \frac{m_f T_3^f}{8\pi^2 v^2} \, \mathrm{tr}\left(m_D m_D^\dagger\right)$$

Off-diagonal!



$$\frac{iJ}{f}\overline{\ell}_\alpha\left(\frac{m_\beta}{8\pi^2v^2}P_R - \frac{m_\alpha}{8\pi^2 v^2}P_L\right)\ell_\beta \left(m_D m_D^\dagger\right)_{\alpha\beta}$$

- Two loop: $\Gamma(J\to\gamma\gamma)\simeq \frac{\alpha^2\, \mathrm{tr}\left(m_D m_D^\dagger\right)^2}{4096\pi^7}\frac{m_J^3}{v^4 f^2}\left|\sum_f N_c^f T_3^f Q_f^2\, g\left(\frac{m_J^2}{4m_f^2}\right)\right|^2$

[Heeck, Camilo Garcia-Cely, 1701.07209; see also Pilaftsis ‘94]

Properties

- Crucial observation: the two matrices are independent!

$$\{\mathsf{m_D}, \mathsf{M_R}\} \leftrightarrow \{\mathsf{M}_\nu, \mathsf{m_D}\mathsf{m_D}^\dagger\}.$$

[Davidson, Ibarra, hep-ph/0104076]

- J$\bar{\ell}\ell$' coupling can be *large* and of arbitrary structure.
- Similar couplings arise for familons or flavor Z'.

[Wilczek, '82; Reiss, '82; Grinstein, Preskill, Wise, 85; ...]

- Boson not necessarily massless, e.g. *pseudo*-Goldstone.
- Experimental signature depends on decay channel:

$$\ell \to \ell' \mathsf{J}, \quad \mathsf{J} \to \mathrm{inv}\,, \ell''\ell''', \gamma\gamma.$$

$\ell \to \ell'$ J with J$\to$ invisible

- Standard LFV in seesaw:

$$\frac{\Gamma(\ell\to\ell'\gamma)}{\Gamma(\ell\to\ell'\nu_\ell\overline{\nu}_{\ell'})} \simeq \frac{3\alpha}{8\pi}\left|(m_D M_R^{-2} m_D^\dagger)_{\ell\ell'}\right|^2.$$

- Great signature, but requires light $N_{R.}$
- With majoron: look for mono-energetic lepton:

[Pilaftsis, '94; Feng, Moroi, Murayama, Schnapka, '98; Hirsch, Vicente, Meyer, Porod, '09]

$$\frac{\Gamma(\ell\to\ell' J)}{\Gamma(\ell\to\ell'\nu_\ell\overline{\nu}_{\ell'})} \simeq \frac{3}{16\pi^2}\frac{1}{m_\ell^2 f^2}\left|(m_D m_D^\dagger)_{\ell\ell'}\right|^2.$$

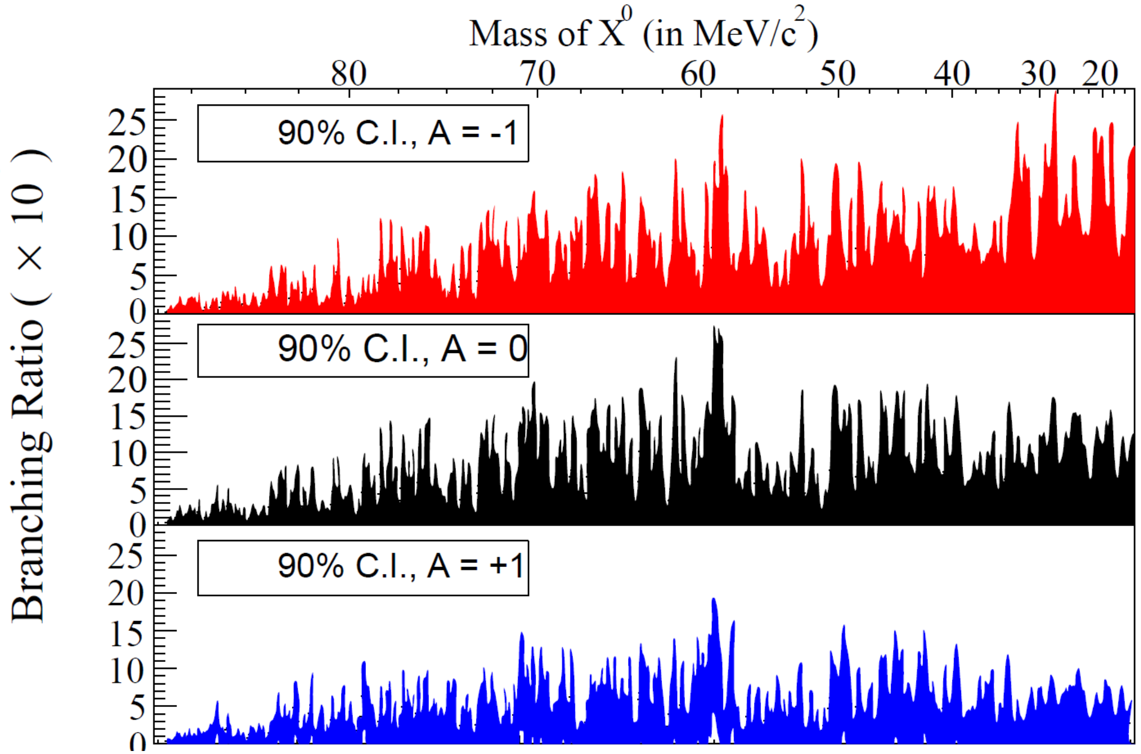
- If M_R= diag(M): $\frac{\Gamma(\ell\to\ell'\gamma)}{\Gamma(\ell\to\ell' J)} \simeq 2\pi\alpha\frac{m_\ell^2}{M^2}\frac{f^2}{M^2}\begin{cases} \gg 1 \text{ for } M \ll f\,, \\ \ll 1 \text{ for } , M \sim f \gg m_\ell\,. \end{cases}$

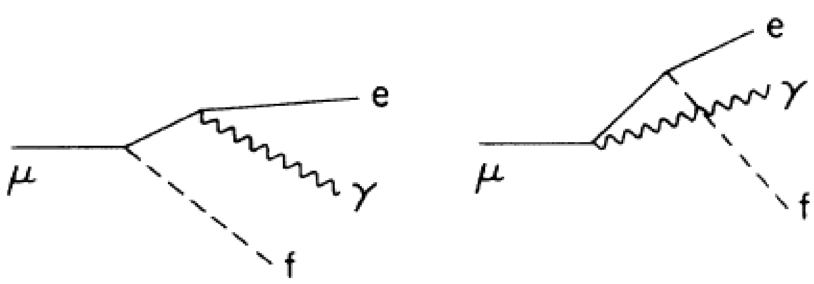
$\mu \to e\, J$ with $J \to$ invisible

- TWIST, ‘15: limits on different anisotropies.
- Chiral coupling $\overline{\mu} P_L e J$ suppresses sensitivity!

  [Heeck, Garcia-Cely, 1701.07209]
- Bremsstrahlung is competitive: $\mu \to e\, J\, \gamma$.
  [Goldman et al, ‘87]
- Approximate limit

$$\frac{|(m_D m_D^\dagger)_{\mu e}|}{v f} \lesssim 10^{-5}.$$

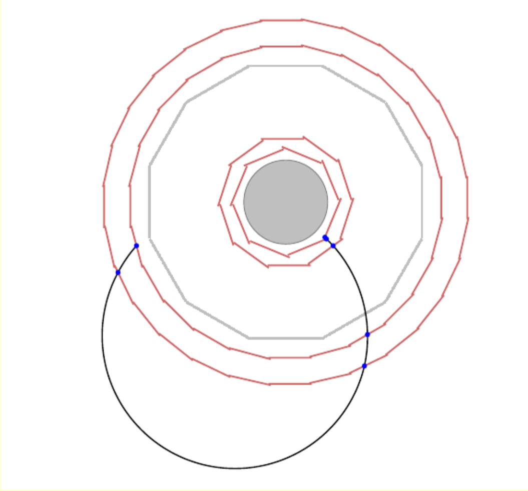


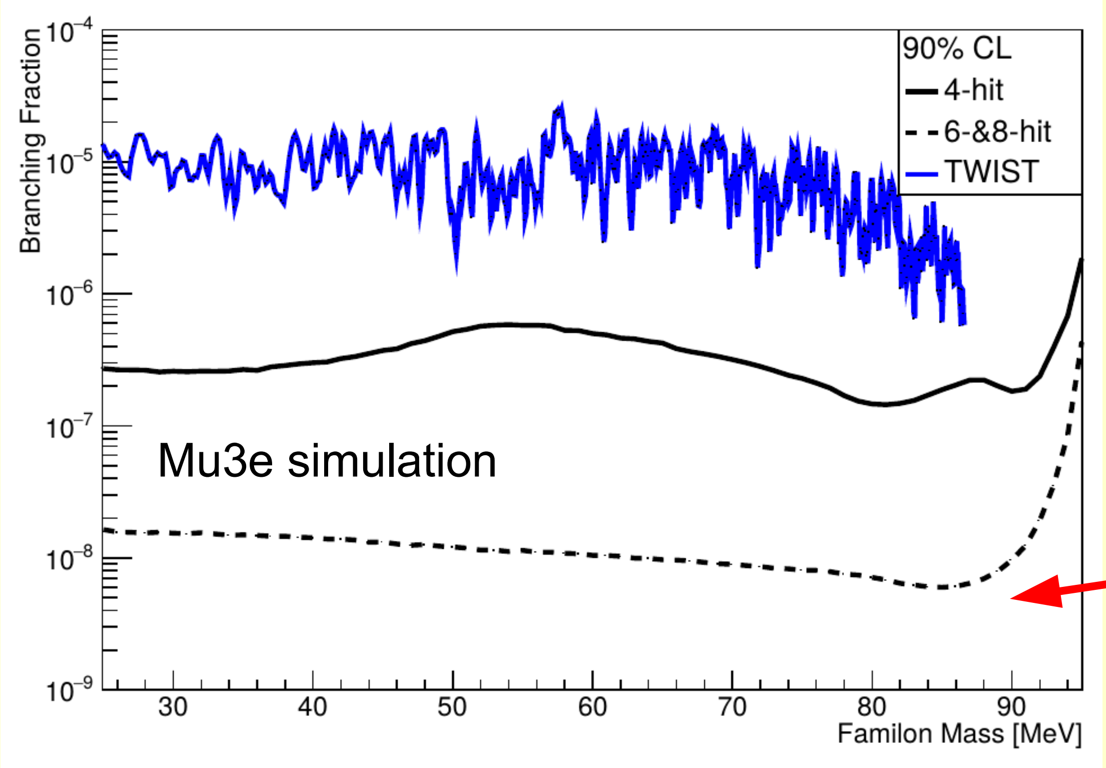


(a) (b)

Searches for μ → e X with Mu3e

- Full reconstruction of all Michel decays is a big challenged for data acquisition
- B(μ → e X) ~ 10^{-8} at 90 % CL

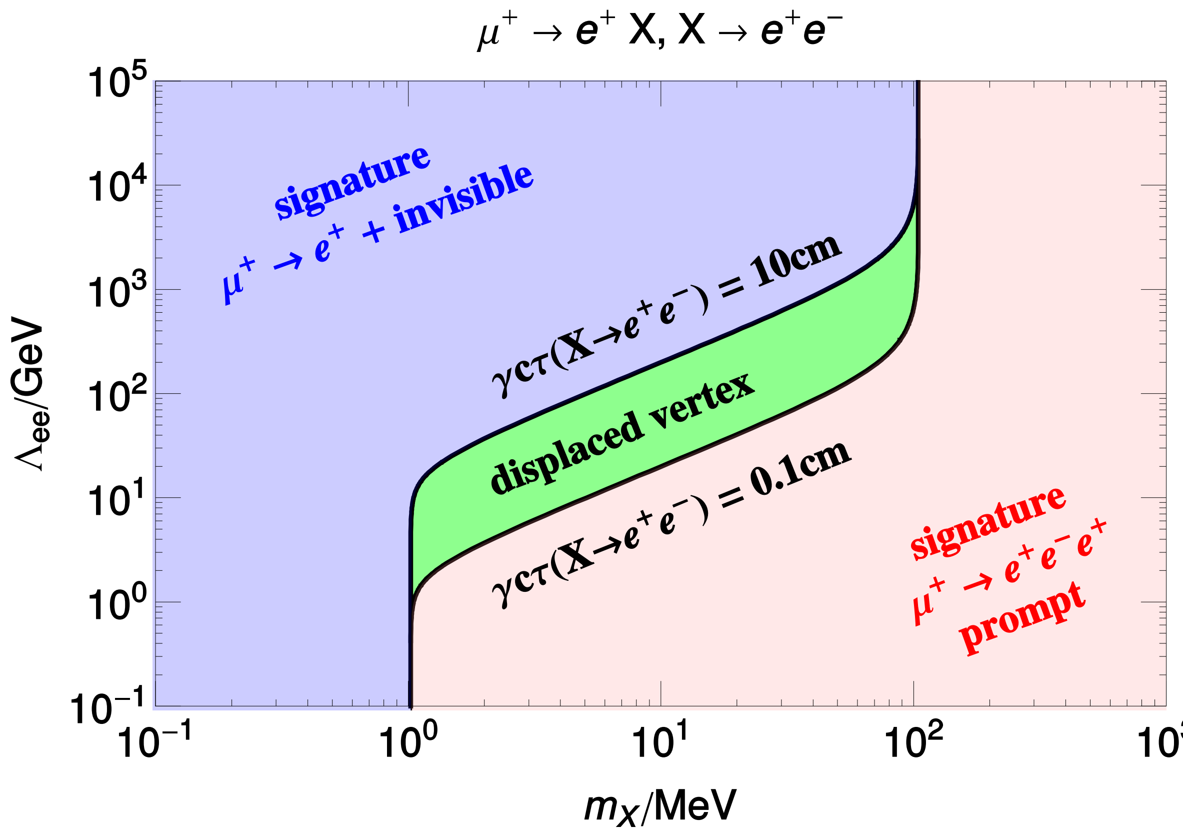




required full reconstruction of “recurlers”

$\mu \to e\, X$ with $X \to$ visible

- Take $X \bar{e} \gamma_5 e \; m_e/\Lambda_{ee}$.
- Decay length determines signature.
- Displaced vertex gives new observable.
  [Heeck, Rodejohann, 1710.02062]
- Muon at rest:



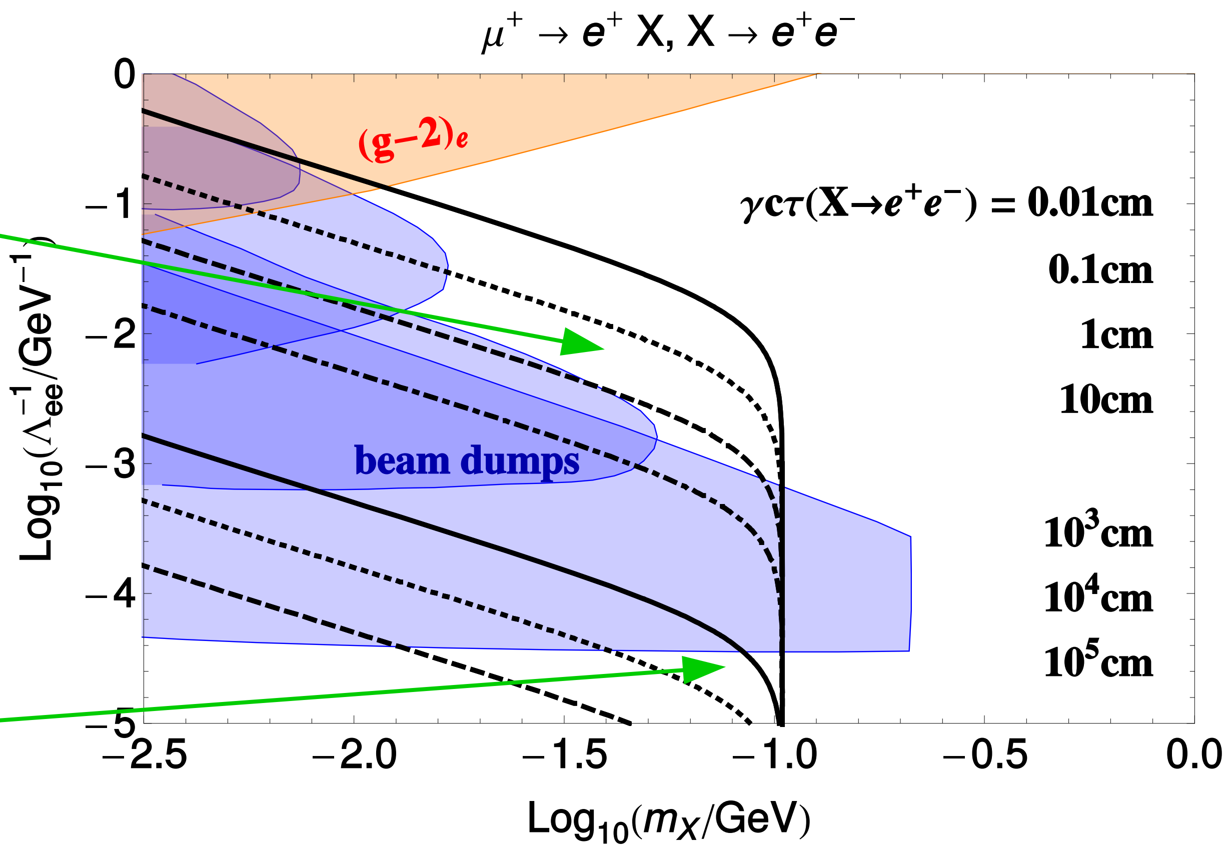
$$\gamma c \tau \simeq \frac{\pi m_\mu \Lambda_{ee}^2}{m_e^2 m_X^2} \simeq 2.5\,\mathrm{cm} \left(\frac{\Lambda_{ee}}{100\,\mathrm{GeV}}\right)^2 \left(\frac{10\,\mathrm{MeV}}{m_X}\right)^2 .$$

Sub-GeV X with ee coupling allowed?

[Heeck, Rodejohann, 1710.02062]

$\mu \to e\, X$ with $X \to \bar{e}e$

- Decay length typically below cm. => looks prompt.
- Below beam dump: Λ_{ee} > 30 TeV; mostly invisible, but some DV!

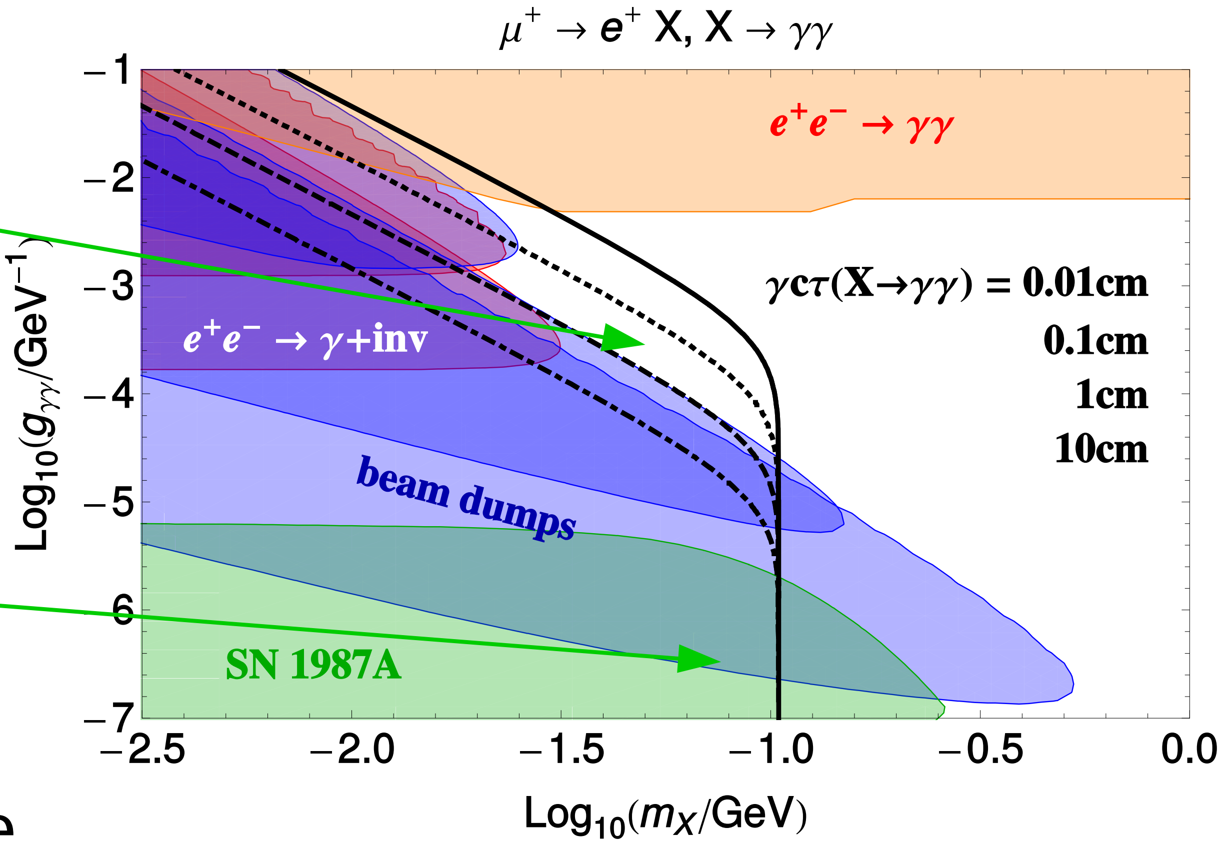


$$\mathrm{BR}(\mu \to eX)\mathrm{BR}(X \to ee)(1 - P(l_{\mathrm{dec}}))$$
$$\simeq \mathrm{BR}(\mu \to eX)\frac{l_{\mathrm{dec}}}{\gamma c\tau}\,.$$

Possible in Mu3e!

$\mu \to e\, X$ with $X \to \gamma\gamma$

- Decay length always below cm. ⇒ looks prompt.
- Below beam dump: supernova constraints!
- Prompt channel still interesting, maybe MEG(II) or Mu3e extension?

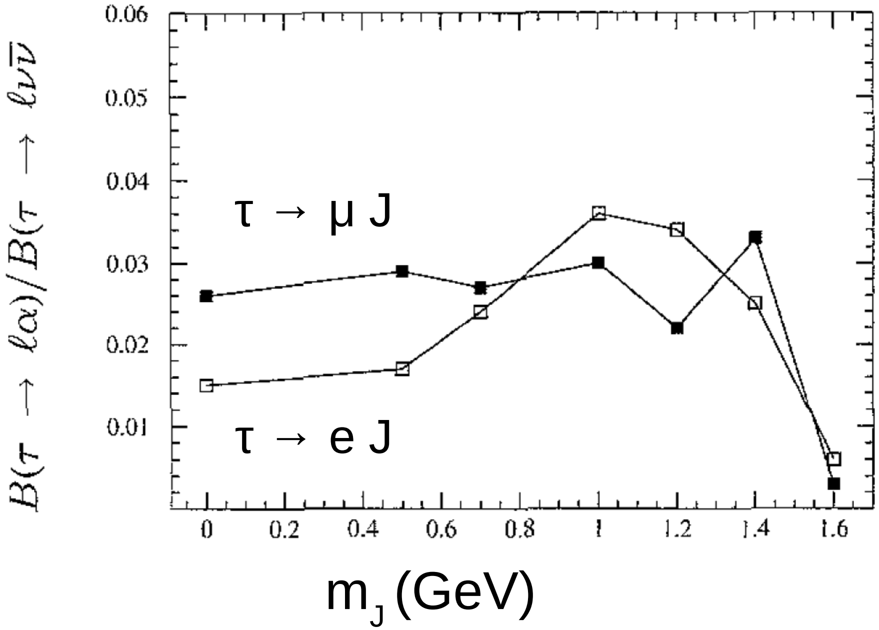


[Recent limits: Dolan et al, 1709.00009]

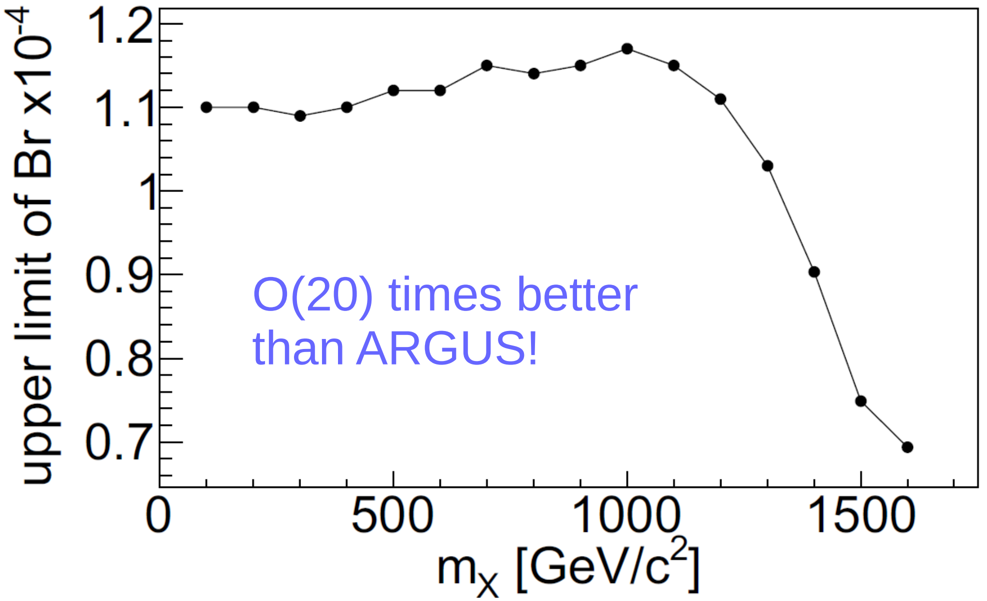
Muons difficult, taus easier.

$\tau \to \ell J$ with $J \to$ invisible

- ARGUS, '95; 5e5 taus.



- Belle, '16 prelim.; 1e9 taus.



- Also interesting for LFV Z'.

[Foot, He, Lew, Volkas, '94; Heeck, 1602.03810; Altmannshofer et al, 1607.06832]

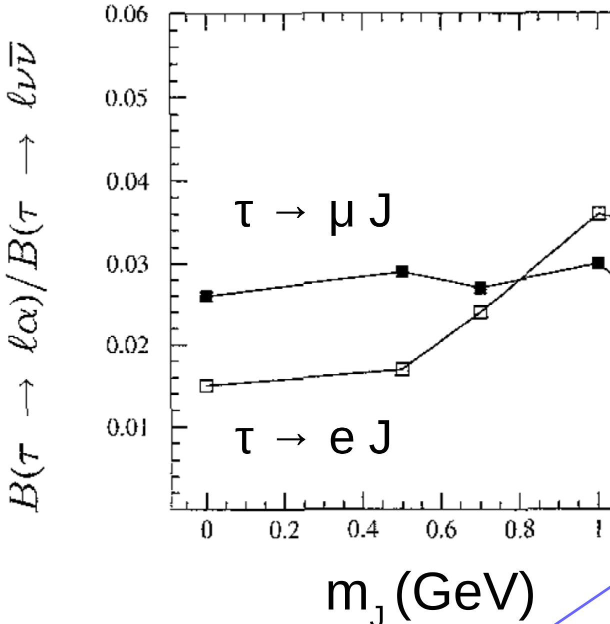
- Improvement with Belle-II.

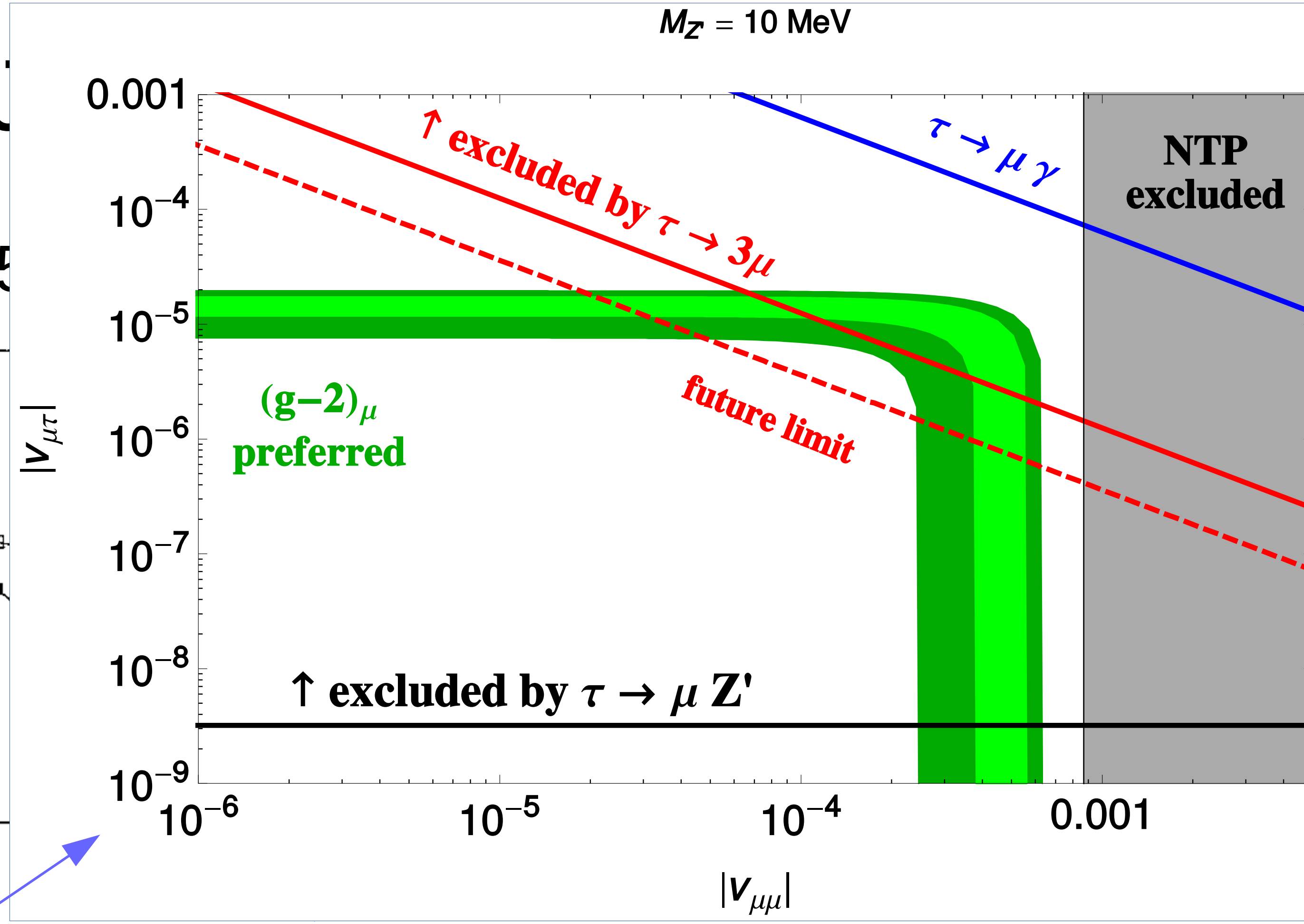
$$\frac{|(m_D m_D^\dagger)_{\tau e}|}{vf} \lesssim 6 \times 10^{-3},$$

$$\frac{|(m_D m_D^\dagger)_{\tau \mu}|}{vf} \lesssim 10^{-3}.$$

$\tau \to \ell J$ with J

- ARGUS, '95; 5e5





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- Improvement with Belle-II.

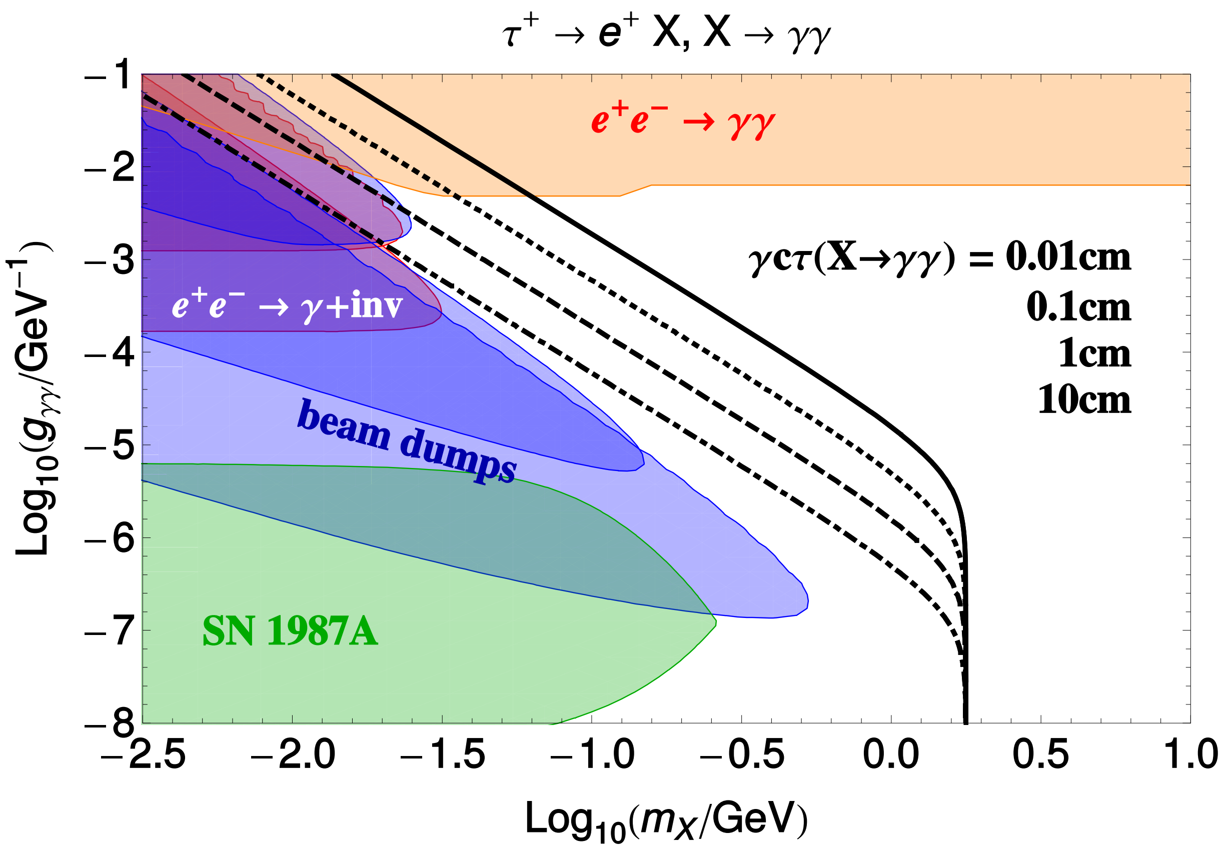
$$\frac{|(m_D m_D^\dagger)_{\tau e}|}{vf} \lesssim 6 \times 10^{-3},$$

$$\frac{|(m_D m_D^\dagger)_{\tau \mu}|}{vf} \lesssim 10^{-3}.$$

τ→e X with X→ visible

[Heeck, Rodejohann, 1710.02062]

- Tau at rest, higher X boost.
- Arbitrary decay lengths possible.
- Similar for X → ee, μμ, μe.
- Worthwhile in LHCb and Belle (II).



[Recent limits: Dolan et al, 1709.00009]

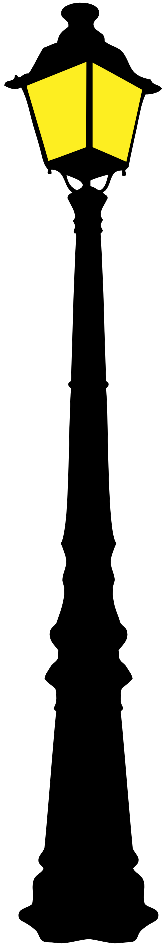
Muons difficult, taus easier...

Summary

- Charged LFV gives info *complementary* to ν oscillations.
- Not simple yes/no question, need to find out if/how

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

  is broken in ℓ^- sector.
  ⇒ Need to search all possible channels!
- Non-trivial breaking: $\tau\to ee\bar{\mu}$, $\tau\to\mu\mu\bar{e}$, $p\to e\overline{\mu\mu}$, $p\to\mu\overline{ee}$,…
- Keep light new physics in mind: $\ell\to\ell' X$, $X \to \mathrm{inv}, \ell\ell, \gamma\gamma$.
- $R(K^{(*)})$ hint at lepton non-universality.
- Hope for sign in Mu3e, MEG-II, Belle-II, Mu2e, LHC(b),...



Still some streetlights to search under!

Backup

Neutrino oscillation parameters

NuFIT 3.2 (2018)

	Normal Ordering (best fit)		Inverted Ordering ($\Delta\chi^2 = 4.14$)		Any Ordering
	bfp $\pm 1\sigma$	3σ range	bfp $\pm 1\sigma$	3σ range	3σ range
$\sin^2\theta_{12}$	$0.307^{+0.013}_{-0.012}$	$0.272 \to 0.346$	$0.307^{+0.013}_{-0.012}$	$0.272 \to 0.346$	$0.272 \to 0.346$
$\theta_{12}/^\circ$	$33.62^{+0.78}_{-0.76}$	$31.42 \to 36.05$	$33.62^{+0.78}_{-0.76}$	$31.43 \to 36.06$	$31.42 \to 36.05$
$\sin^2\theta_{23}$	$0.538^{+0.033}_{-0.069}$	$0.418 \to 0.613$	$0.554^{+0.023}_{-0.033}$	$0.435 \to 0.616$	$0.418 \to 0.613$
$\theta_{23}/^\circ$	$47.2^{+1.9}_{-3.9}$	$40.3 \to 51.5$	$48.1^{+1.4}_{-1.9}$	$41.3 \to 51.7$	$40.3 \to 51.5$
$\sin^2\theta_{13}$	$0.02206^{+0.00075}_{-0.00075}$	$0.01981 \to 0.02436$	$0.02227^{+0.00074}_{-0.00074}$	$0.02006 \to 0.02452$	$0.01981 \to 0.02436$
$\theta_{13}/^\circ$	$8.54^{+0.15}_{-0.15}$	$8.09 \to 8.98$	$8.58^{+0.14}_{-0.14}$	$8.14 \to 9.01$	$8.09 \to 8.98$
$\delta_{\rm CP}/^\circ$	234^{+43}_{-31}	$144 \to 374$	278^{+26}_{-29}	$192 \to 354$	$144 \to 374$
$\frac{\Delta m^2_{21}}{10^{-5}\ \rm eV^2}$	$7.40^{+0.21}_{-0.20}$	$6.80 \to 8.02$	$7.40^{+0.21}_{-0.20}$	$6.80 \to 8.02$	$6.80 \to 8.02$
$\frac{\Delta m^2_{3\ell}}{10^{-3}\ \rm eV^2}$	$+2.494^{+0.033}_{-0.031}$	$+2.399 \to +2.593$	$-2.465^{+0.032}_{-0.031}$	$-2.562 \to -2.369$	$\begin{bmatrix} +2.399 \to +2.593 \\ -2.536 \to -2.395 \end{bmatrix}$

[www.nu-fit.org]

Limits on CLFV

Group	Process	Current	Future
$\Delta(L_e - L_\mu) = 2$	$\mu \to e\gamma$	4.2×10^{-13} [15]	4×10^{-14} [16]
	$\mu \to e\bar{e}e$	1.0×10^{-12} [17]	10^{-16} [18]
	$\mu \to e$ conv.	$\mathcal{O}(10^{-12})$ [19]	10^{-17} [20, 21]
	$h \to e\bar{\mu}$	3.5×10^{-4} [22]	2×10^{-4} [23]
	$Z \to e\bar{\mu}$	7.5×10^{-7} [24]	–
	had$\to e\bar{\mu}$(had)	4.7×10^{-12} [25]	10^{-12} [26]
$\Delta(L_e - L_\tau) = 2$	$\tau \to e\gamma$	3.3×10^{-8} [27]	10^{-9} [28]
	$\tau \to e\bar{e}e$	2.7×10^{-8} [29]	10^{-9} [28]
	$\tau \to e\bar{\mu}\mu$	2.7×10^{-8} [29]	10^{-9} [28]
	$\tau \to e$ had	$\mathcal{O}(10^{-8})$ [30]	10^{-9} [28]
	$h \to e\bar{\tau}$	6.9×10^{-3} [22]	5×10^{-3} [23]
	$Z \to e\bar{\tau}$	9.8×10^{-6} [31]	–
	had$\to e\bar{\tau}$(had)	$\mathcal{O}(10^{-6})$ [32, 33]	–
$\Delta(L_\mu - L_\tau) = 2$	$\tau \to \mu\gamma$	4.4×10^{-8} [27]	10^{-9} [28]
	$\tau \to \mu\bar{e}e$	1.8×10^{-8} [29]	10^{-9} [28]
	$\tau \to \mu\bar{\mu}\mu$	2.1×10^{-8} [29]	10^{-9} [28]
	$\tau \to \mu$ had	$\mathcal{O}(10^{-8})$ [30]	10^{-9} [28]
	$h \to \mu\bar{\tau}$	1.2×10^{-2} [7]	5×10^{-3} [23]
	$Z \to \mu\bar{\tau}$	1.2×10^{-5} [34]	–
	had$\to \mu\bar{\tau}$(had)	$\mathcal{O}(10^{-6})$ [32, 33]	–

TABLE I: CLFV with conserved L and B, omitting CP conjugate processes. Current limits on the branching ratios are at 90% C.L. (h/Z decays at 95% C.L.). A full list of CLFV involving hadrons (had) can be found in the PDG [30].

Group	Process	Current	Future
$\Delta(L_\mu + L_\tau - 2L_e) = 6$	$\tau \to ee\bar{\mu}$	1.5×10^{-8} [29]	10^{-9} [28]
$\Delta(L_\tau + L_e - 2L_\mu) = 6$	$\tau \to \mu\mu\bar{e}$	1.7×10^{-8} [29]	10^{-9} [28]
$\Delta(L_e + L_\mu - 2L_\tau) = 6$	$\mu e \to \tau\tau$	–	–

TABLE II: CLFV with conserved L and B, omitting CP conjugate processes. Current limits at 90% C.L.

Group	Process	Current	Future
$\Delta L_e = 2$	$0\nu\beta\beta$	$\mathcal{O}(10^{25}\,\text{yr})$ [44]	10^{26} yr [44]
	had$\to ee$ had	6.4×10^{-10} [45]	10^{-12} [26]
$\Delta L_\mu = 2$	had$\to \mu\mu$ had	8.6×10^{-11} [46]	10^{-12} [26]
$\Delta L_\tau = 2$	had$\to \tau\tau$ had	–	–
$\Delta(L_e + L_\mu) = 2$	$\mu \to \bar{e}$ conv.	3.6×10^{-11} [47]	$\ll 10^{-11}$ [48]
	had$\to \mu e$ had	5.0×10^{-10} [45]	10^{-12} [26]
$\Delta(L_e + L_\tau) = 2$	$\tau \to \bar{e}$ had	2.0×10^{-8} [49]	10^{-9} [28]
	had$\to \tau e$ had	–	–
$\Delta(L_\mu + L_\tau) = 2$	$\tau \to \bar{\mu}$ had	3.9×10^{-8} [49]	10^{-9} [28]
	had$\to \tau\mu$ had	–	–

TABLE IV: Processes violating total lepton number L by two units (90% C.L. limits), assuming conserved baryon number.

[Heeck, 1610.07623]

d=10 operators for p → $\overline{\ell\ell}\ell$

$$\mathcal{O}^{10}_{1,2} = (QQ)_{1,1}\,(QL)_{1,3}\,(\bar{L}\ell\bar{H})_{1,3}\,,$$
$$\mathcal{O}^{10}_{3,4} = (QQ)_{1,1}\,(QL)_{1,3}\,(\bar{\ell}LH)_{1,3}\,,$$
$$\mathcal{O}^{10}_{5} = (QQ)_{1}\,(LL)_{3}\,(\bar{\ell}QH)_{3}\,,$$
$$\mathcal{O}^{10}_{6} = (QQ)_{1}\,(\ell\ell)_{1}\,(\bar{\ell}Q\bar{H})_{1}\,,$$
$$\mathcal{O}^{10}_{7} = (QQ)_{1}\,(LL)_{3}\,(\bar{L}uH)_{3}\,,$$
$$\mathcal{O}^{10}_{8} = (QQ)_{1}\,(\ell\ell)_{1}\,(\bar{L}u\bar{H})_{1}\,,$$
$$\mathcal{O}^{10}_{9} = (QQ)_{1}\,(u\ell)_{1}\,(\bar{L}\ell\bar{H})_{1}\,,$$
$$\mathcal{O}^{10}_{10} = (QQ)_{1}\,(u\ell)_{1}\,(\bar{\ell}LH)_{1}\,,$$
$$\mathcal{O}^{10}_{11,12} = (QL)_{1,3}\,(QL)_{3,3}\,(\bar{\ell}QH)_{3,3}\,,$$
$$\mathcal{O}^{10}_{13,14} = (QL)_{1,3}\,(QL)_{3,3}\,(\bar{L}uH)_{3,3}\,,$$
$$\mathcal{O}^{10}_{15,16} = (QL)_{1,3}\,(u\ell)_{1,1}\,(\bar{\ell}QH)_{1,3}\,,$$
$$\mathcal{O}^{10}_{17,18} = (QL)_{1,3}\,(d\ell)_{1,1}\,(\bar{\ell}Q\bar{H})_{1,3}\,,$$
$$\mathcal{O}^{10}_{19} = (QL)_{3}\,(u\ell)_{1}\,(\bar{L}uH)_{3}\,,$$
$$\mathcal{O}^{10}_{20,21} = (QL)_{1,3}\,(d\ell)_{1,1}\,(\bar{L}u\bar{H})_{1,3}\,,$$
$$\mathcal{O}^{10}_{22,23} = (QL)_{1,3}\,(u\ell)_{1,1}\,(\bar{L}d\bar{H})_{1,3}\,,$$
$$\mathcal{O}^{10}_{24,25} = (QL)_{1,3}\,(ud)_{1,1}\,(\bar{L}\ell\bar{H})_{1,3}\,,$$
$$\mathcal{O}^{10}_{26,27} = (QL)_{1,3}\,(ud)_{1,1}\,(\bar{\ell}LH)_{1,3}\,,$$
$$\mathcal{O}^{10}_{28} = (LL)_{3}\,(ud)_{1}\,(\bar{\ell}QH)_{3}\,,$$
$$\mathcal{O}^{10}_{29} = (ud)_{1}\,(\ell\ell)_{1}\,(\bar{\ell}Q\bar{H})_{1}\,,$$
$$\mathcal{O}^{10}_{30} = (u\ell)_{1}\,(d\ell)_{1}\,(\bar{\ell}Q\bar{H})_{1}\,,$$
$$\mathcal{O}^{10}_{31} = (LL)_{3}\,(ud)_{1}\,(\bar{L}uH)_{3}\,,$$
$$\mathcal{O}^{10}_{32} = (ud)_{1}\,(u\ell)_{1}\,(\bar{L}\ell\bar{H})_{1}\,,$$
$$\mathcal{O}^{10}_{33} = (ud)_{1}\,(\ell\ell)_{1}\,(\bar{L}u\bar{H})_{1}\,,$$
$$\mathcal{O}^{10}_{34} = (u\ell)_{1}\,(d\ell)_{1}\,(\bar{L}u\bar{H})_{1}\,,$$
$$\mathcal{O}^{10}_{35} = (ud)_{1}\,(u\ell)_{1}\,(\bar{\ell}LH)_{1}\,,$$
$$\mathcal{O}^{10}_{36,37} = (QL)_{1,3}\,(QL)_{1,3}\,(\bar{\ell}QH)_{1,1}\,,$$
$$\mathcal{O}^{10}_{38,39,40} = (QL)_{1,1,3}\,(QL)_{1,3,3}\,(\bar{L}d\bar{H})_{1,3,1}\,,$$
$$\mathcal{O}^{10}_{41} = (u\ell)_{1}\,(u\ell)_{1}\,(\bar{l}QH)_{1}\,,$$
$$\mathcal{O}^{10}_{42} = (u\ell)_{1}\,(u\ell)_{1}\,(\bar{L}d\bar{H})_{1}\,,$$

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