Interpretation of Charged Lepton Flavor Violation and Connection to Neutrino Physics

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Searching for Physics Beyond the Standard Models Using Charged Leptons
COFI, San Juan, Puerto Rico

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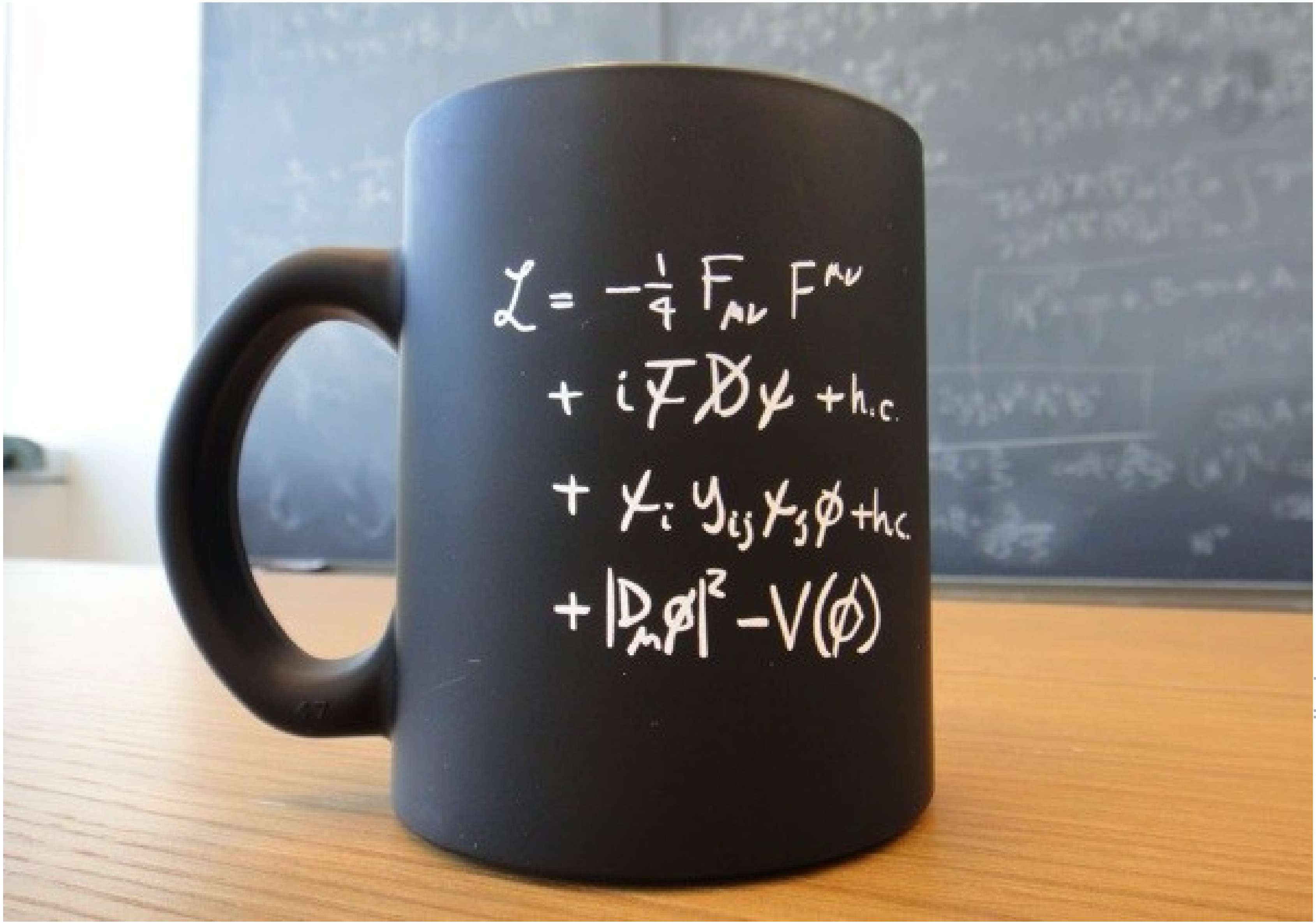
The Standard Model



www.quantumdiaries.org

Symmetries of the Standard Model

- Rephasing lepton and quark fields:

$$U(1)_B \times U(1)_{L_e} \times U(1)_{L_\mu} \times U(1)_{L_\tau} \,.$$

- B+L broken non-perturbatively,

$$\Delta B = 3 \quad \wedge \quad \Delta L_e = \Delta L_\mu = \Delta L_\tau = 1 \,,$$

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

- Real global symmetry of SM:

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

- 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]

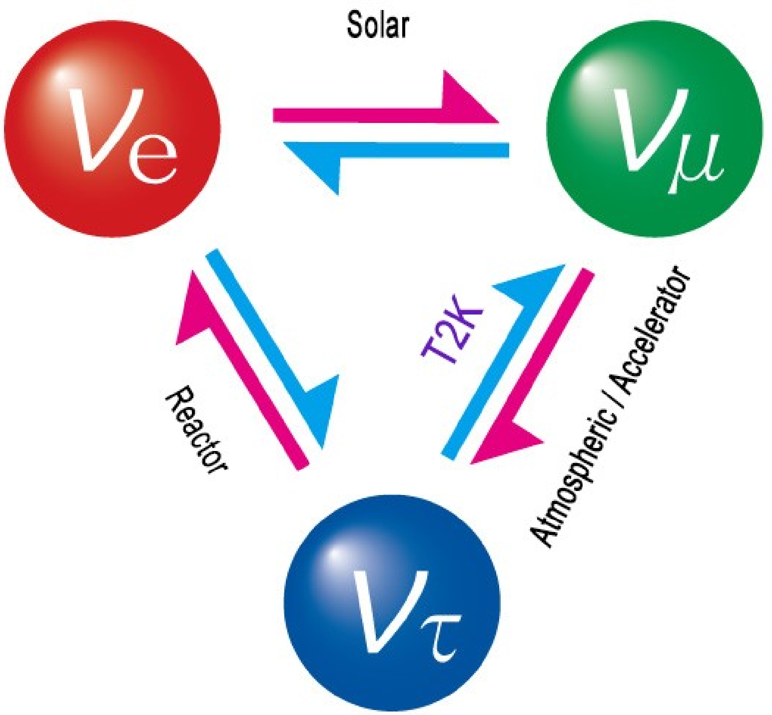
Neutrino oscillations

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

  $$U(1)_{L_\mu - L_\tau} \times U(1)_{L_\mu + L_\tau - 2L_e}$$

  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?

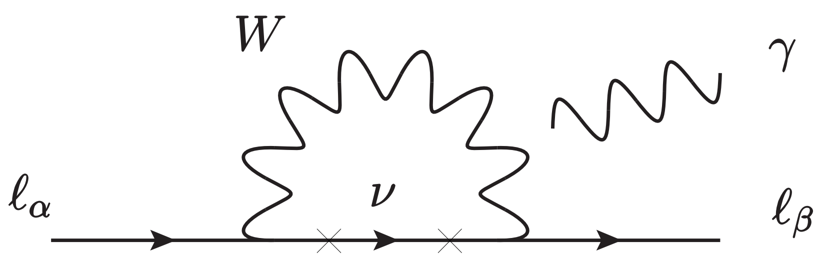
group	process	current	future
$\Delta(L_e - L_\mu) = 2$	$\mu \to e\gamma$	4.2×10^{-13}	4×10^{-14}
	$\mu \to e\bar{e}e$	1.0×10^{-12}	10^{-16}
	$\mu \to e$ conv.	$\mathcal{O}(10^{-12})$	10^{-17}
	$h \to e\bar{\mu}$	3.5×10^{-4}	2×10^{-4}
	$Z \to e\bar{\mu}$	7.5×10^{-7}	–
	had$\to e\bar{\mu}$(had)	4.7×10^{-12}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

Lepton flavor definitely violated, so where is it?

Neutrino mass ⇒ charged LFV?

- SM + Dirac neutrinos: $L = L_{\rm SM} - (y\bar{L}H\nu_R + \text{h.c.}) + i\overline{\nu}_R \partial\!\!\!/ \nu_R$

$$m_\nu = y\langle H\rangle = U\,\mathrm{diag}(m_1, m_2, m_3) V_R \overset{!}{\lesssim} \text{eV}$$



- *All* CLFV is GIM suppressed:

$$\frac{\Gamma(\ell_\alpha \to \ell_\beta \gamma)}{\Gamma(\ell_\alpha \to \ell_\beta \nu_\alpha \overline{\nu}_\beta)} \simeq \frac{3\alpha_{\rm EM}}{32\pi}\left|\sum_{j=2,3} U_{\alpha j}\frac{\Delta m^2_{j1}}{M_W^2} U^\dagger_{j\beta}\right|^2 < 5\times 10^{-53}\,.$$

[Petcov ‘77; Cheng & Li ‘77]

Seesaw mass ⇒ charged LFV?

- SM + seesaw neutrinos: $L = L_{\rm SM} + i\overline{N}_R \not\partial N_R$

$$- \left(\tfrac{1}{2} M_R \overline{N^c_R} N_R + \underbrace{y\overline{L}HN_R}_{m_D \overline{\nu}_L N_R} + \text{h.c.}\right)$$

- Violates $\Delta L = 2$. For large M_R:

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

- 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.

Seesaw parameters

$$\mathsf{L} = \mathsf{L}_{\rm SM} + i\overline{\mathsf{N}}_\mathsf{R}\not{\partial}\mathsf{N}_\mathsf{R} - \left(\tfrac{1}{2}\mathsf{M}_\mathsf{R}\overline{\mathsf{N}^c_\mathsf{R}}\mathsf{N}_\mathsf{R} + \mathsf{m}_\mathsf{D}\overline{\nu}_\mathsf{L}\mathsf{N}_\mathsf{R} + \text{h.c.}\right)$$

$$\Rightarrow \quad \mathsf{M}_\nu \simeq -\mathsf{m}_\mathsf{D}\mathsf{M}_\mathsf{R}^{-1}\mathsf{m}_\mathsf{D}^\mathsf{T} \quad \& \quad \mathrm{BR}(\ell_\alpha \to \ell_\beta\gamma) \propto |(\mathsf{m}_\mathsf{D}\mathsf{M}_\mathsf{R}^{-2}\mathsf{m}_\mathsf{D}^\dagger)_{\alpha\beta}|^2 .$$

- One to one correspondence

$$\{\mathsf{m}_\mathsf{D}, \mathsf{M}_\mathsf{R}\} \leftrightarrow \{\mathsf{M}_\nu, \mathsf{m}_\mathsf{D}\mathsf{M}_\mathsf{R}^{-2}\mathsf{m}_\mathsf{D}^\dagger\}.$$

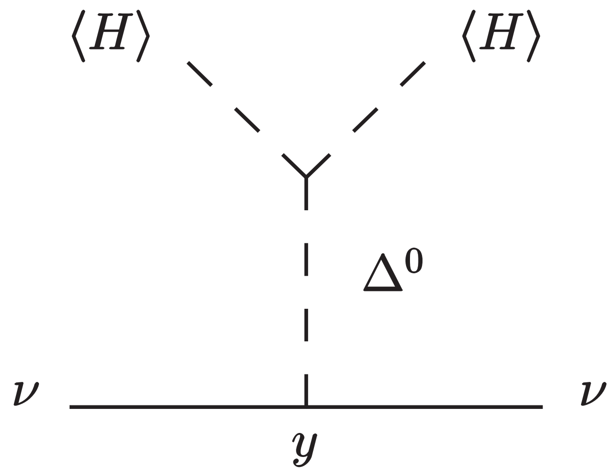
[Broncano, Gavela, Jenkins, hep-ph/0210271]

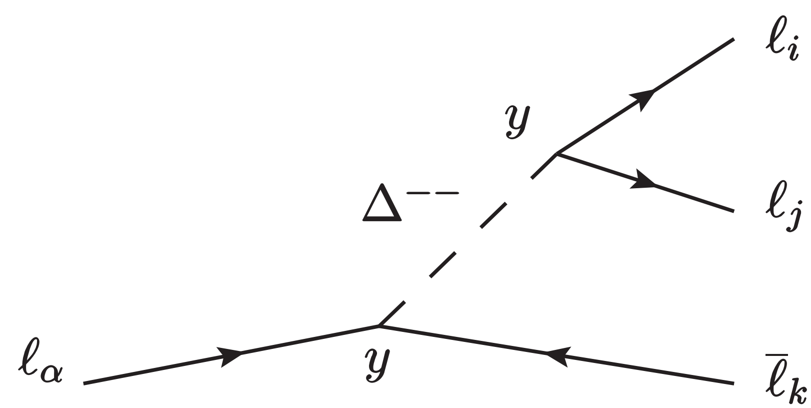
- Or: unique d=6 operator $(\mathsf{y}\mathsf{M}_\mathsf{R}^{-2}\mathsf{y}^\dagger)(\overline{\mathsf{L}}\mathsf{H})(i\not{\partial})(\mathsf{H}^\dagger\mathsf{L})$.
- Gives LFV and non-unitary PMNS.

LFV complementary to M_ν!

Scalar-triplet seesaw

$$\mathsf{L} = \mathsf{L}_{\rm SM} + |\mathsf{D}_\alpha \Delta|^2 - (\mathsf{y}\overline{\mathsf{L}}^c \Delta \mathsf{L} + \mu \mathsf{H}\Delta\mathsf{H} + \mathsf{h.c.})$$

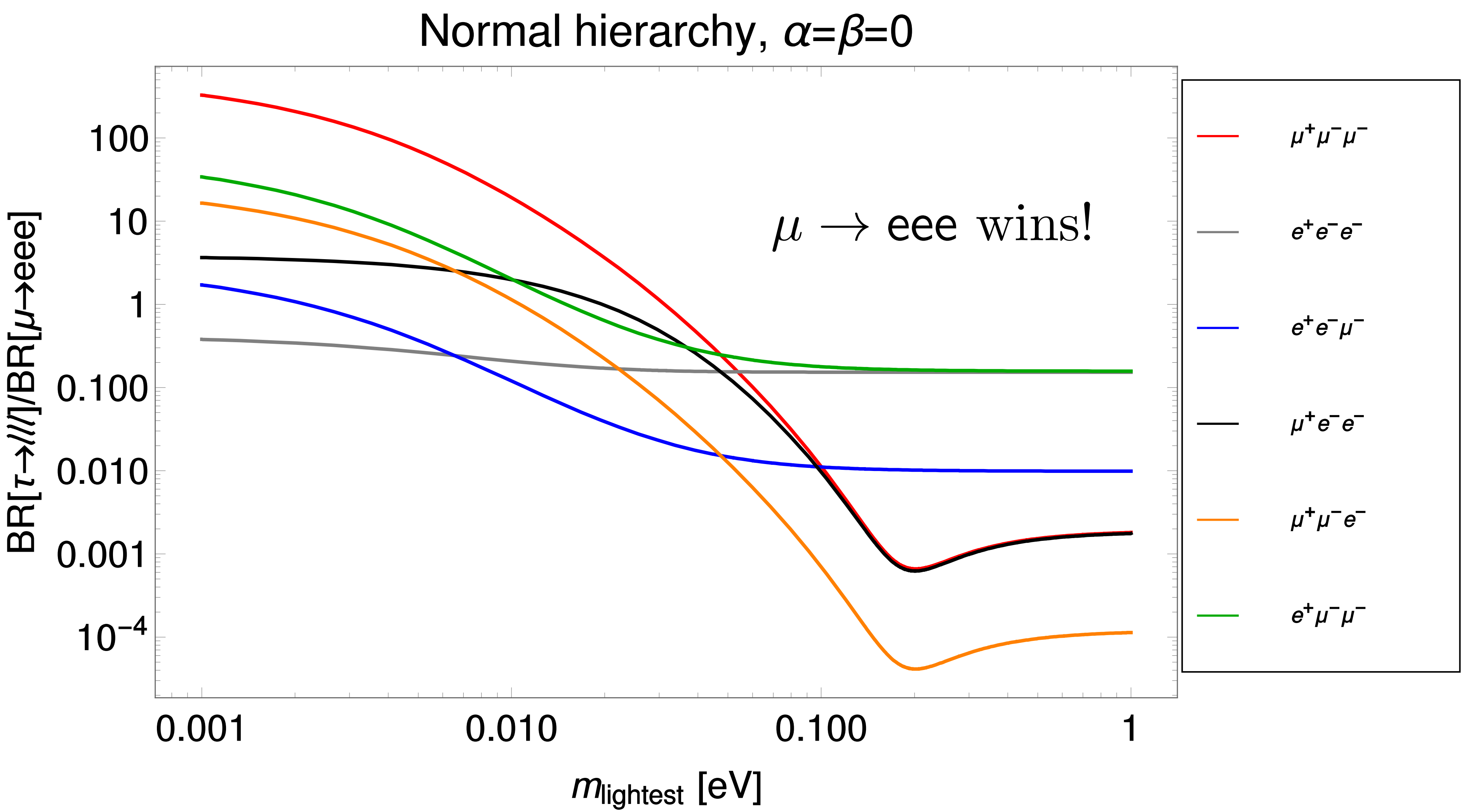




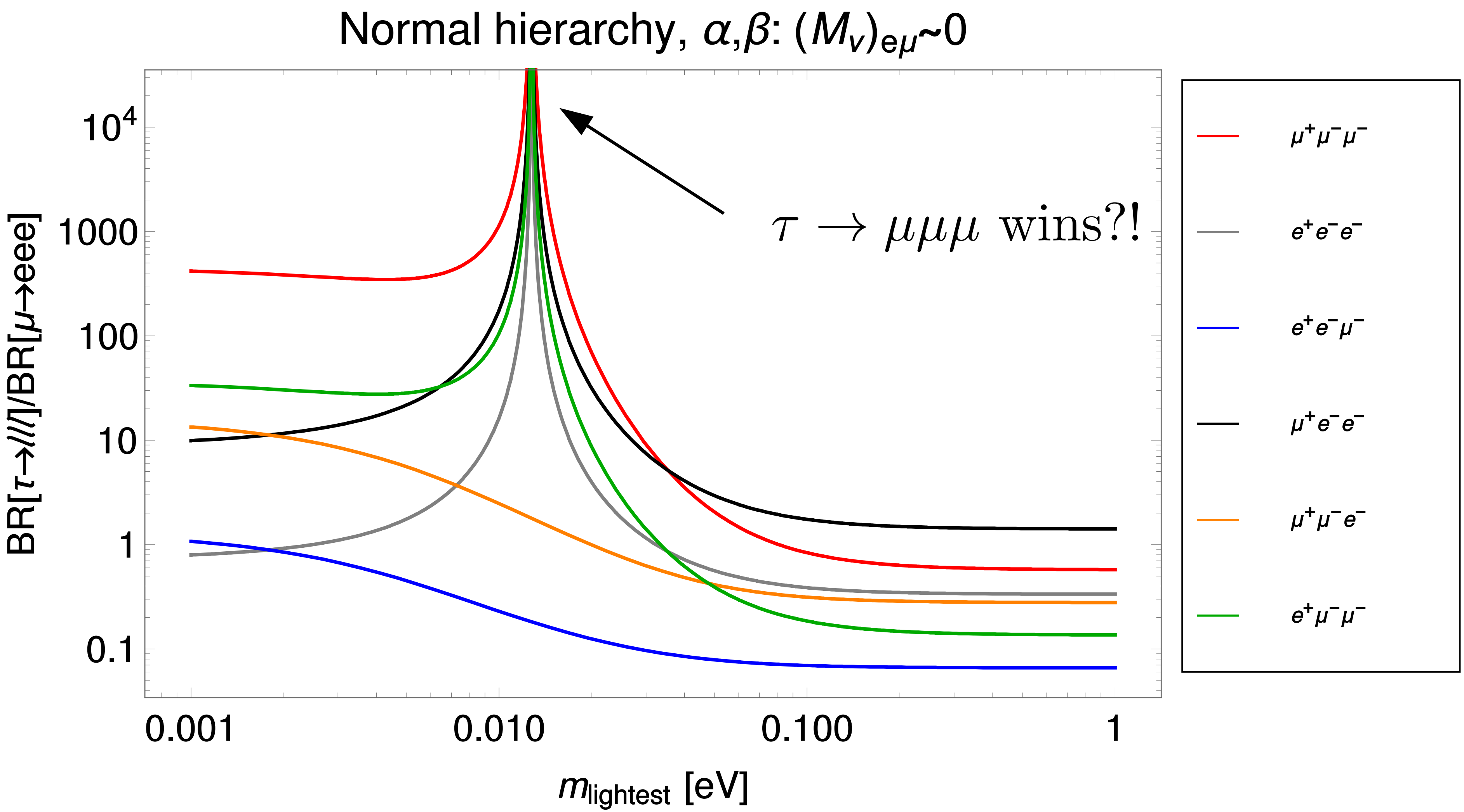
$$\Rightarrow \quad (\mathsf{M}_\nu)_{\alpha\beta} \simeq \mathsf{y}_{\alpha\beta}\frac{2\mu \mathsf{v}^2}{\mathsf{M}_\Delta^2} \quad \& \quad \mathrm{BR}(\ell_\alpha \to \ell_i \ell_j \overline{\ell}_k) \propto |\mathsf{y}_{\alpha k}|^2 |\mathsf{y}_{ij}|^2 / \mathsf{M}_\Delta^4 .$$

[Abada++, 0707.4058]

Prediction of LFV ratios via M_ν!



$$(M_\nu)_{\alpha\beta} \simeq y_{\alpha\beta}\frac{2\mu v^2}{M_\Delta^2} \quad \& \quad \mathrm{BR}(\ell_\alpha \to \ell_i \ell_j \bar{\ell}_k) \propto |y_{\alpha k}|^2 |y_{ij}|^2 / M_\Delta^4 .$$

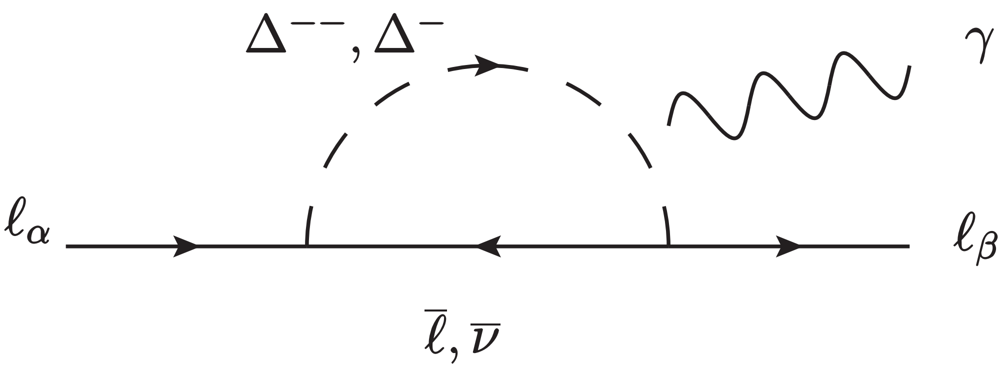


$$(M_\nu)_{\alpha\beta} \simeq y_{\alpha\beta} \frac{2\mu v^2}{M_\Delta^2} \quad \& \quad \mathrm{BR}(\ell_\alpha \to \ell_i \ell_j \bar{\ell}_k) \propto |y_{\alpha k}|^2 |y_{ij}|^2 / M_\Delta^4 .$$

Scalar-triplet seesaw

$$(M_\nu)_{\alpha\beta} \simeq y_{\alpha\beta}\frac{2\mu v^2}{M_\Delta^2} \quad \& \quad \mathrm{BR}(\ell_\alpha \to \ell_i \ell_j \overline{\ell}_k) \propto |y_{\alpha k}|^2 |y_{ij}|^2 / M_\Delta^4 .$$

- But at loop level:



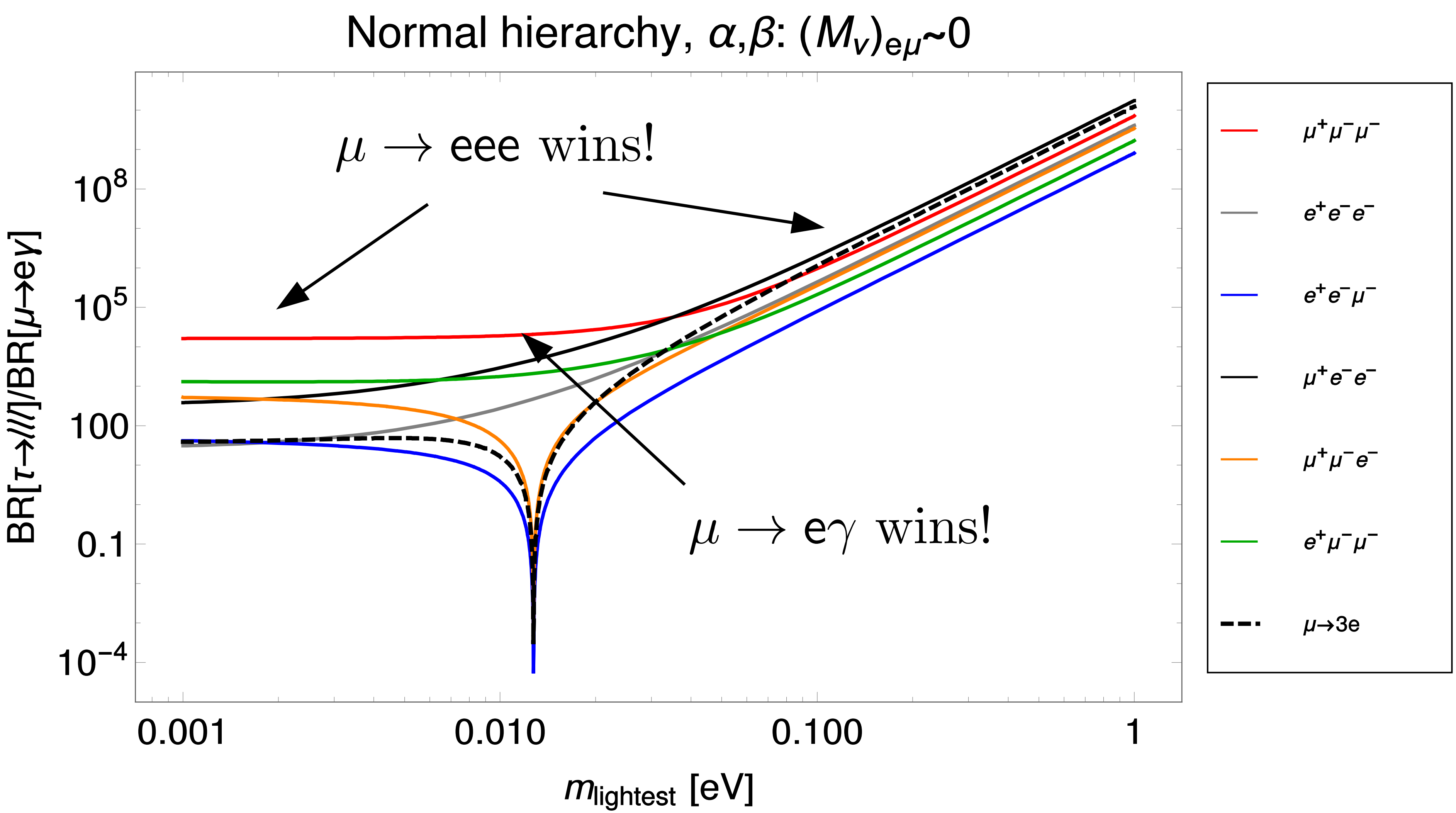
$$\mathrm{BR}(\ell_\alpha \to \ell_\beta \gamma) \propto \frac{|(y^\dagger y)_{\alpha\beta}|^2}{M_\Delta^4} .$$

[Pich, Santamaria, Bernabeu, '84]

- $\mu \to 3e$ could be 0, but $\mu \to e\gamma$ cannot (since θ_{13}).

[Chakrabortty++, 1204.1000]

Prediction of LFV ratios via M_ν!



Prediction of LFV ratios via M_ν!

Neutrino mass ⇏ charged LFV!

- Neutrino-mass induced charged LFV is unobservable.

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

- (Only exception: 0νββ 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_ν ⇔ 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

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

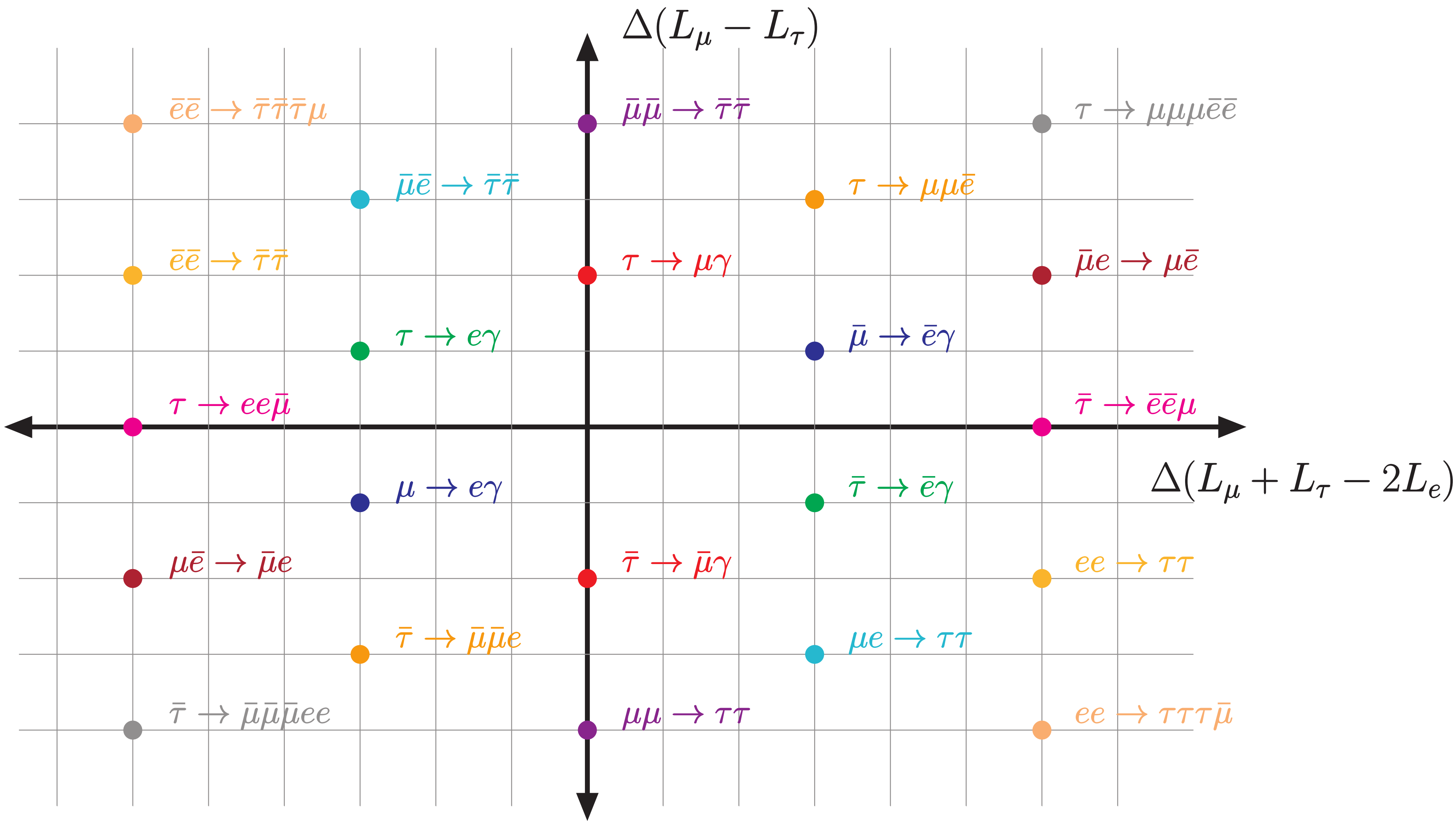
- Organize operators/processes by quantum numbers under

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

[Lew, Volkas, 9410277]

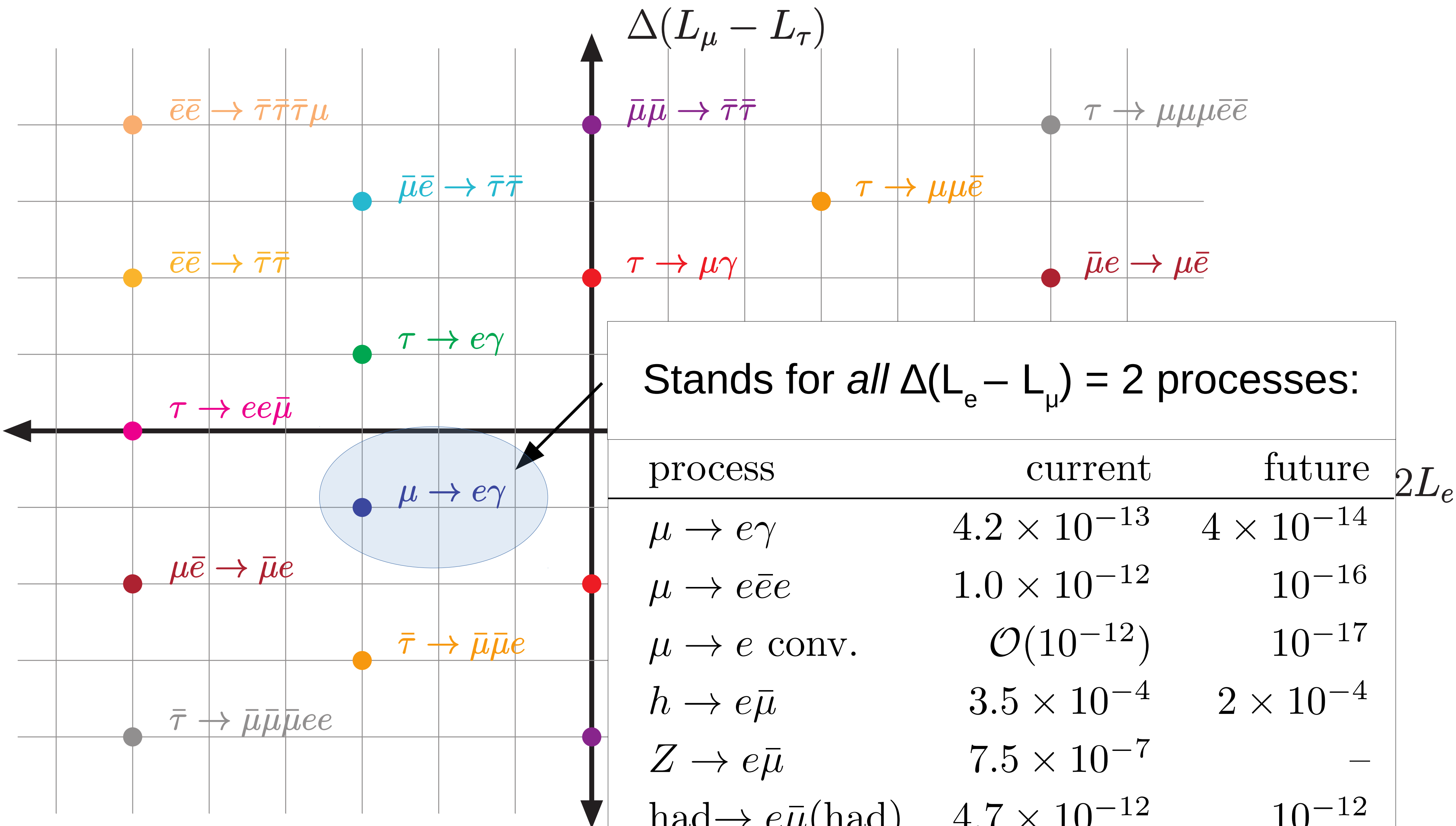
$\Delta B = \Delta L = 0$

[Heeck, 1610.07623]



ΔB = ΔL = 0

[Heeck, 1610.07623]

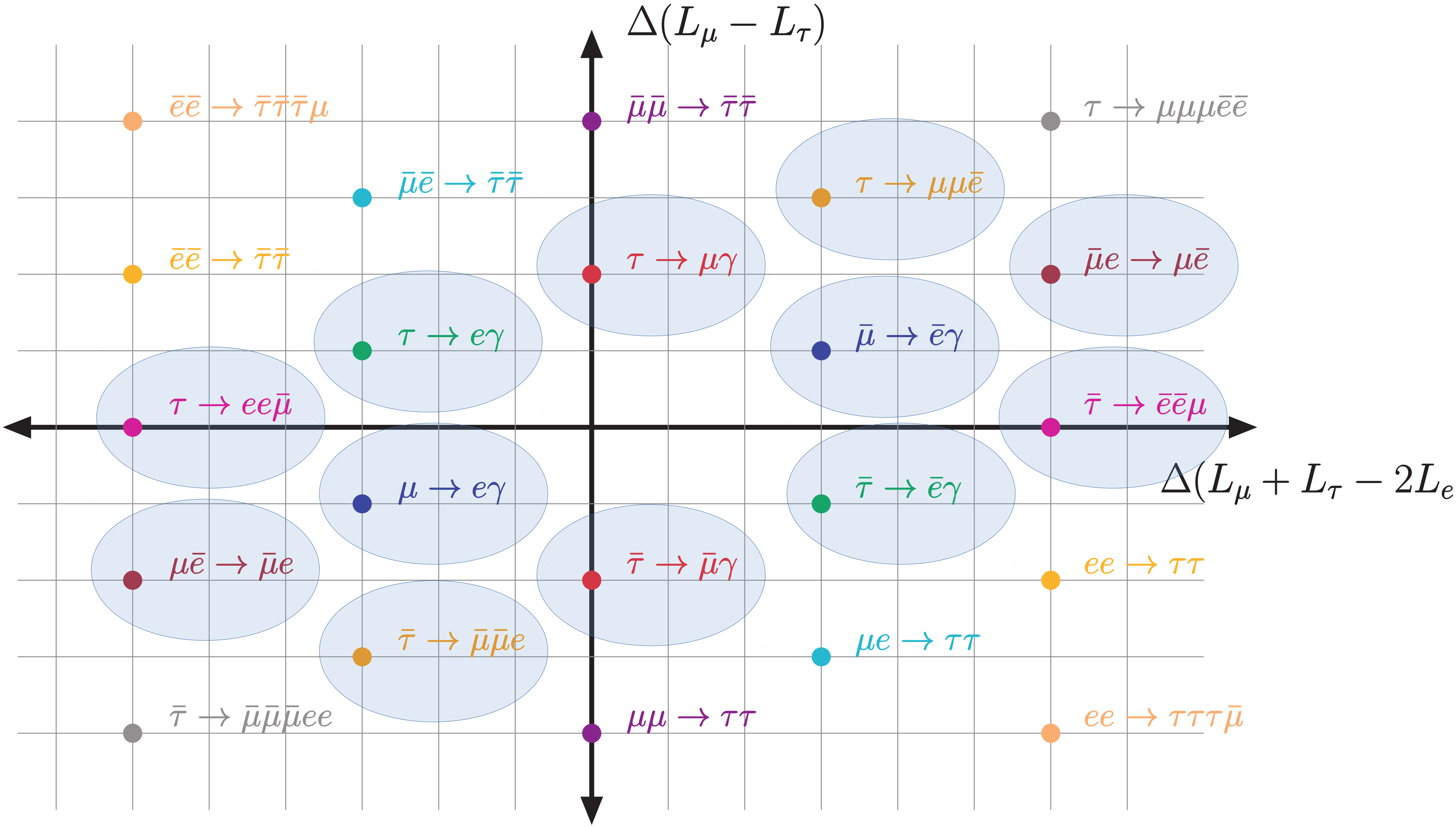


Stands for *all* $\Delta(L_e - L_\mu) = 2$ processes:

process	current	future
$\mu \to e\gamma$	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}

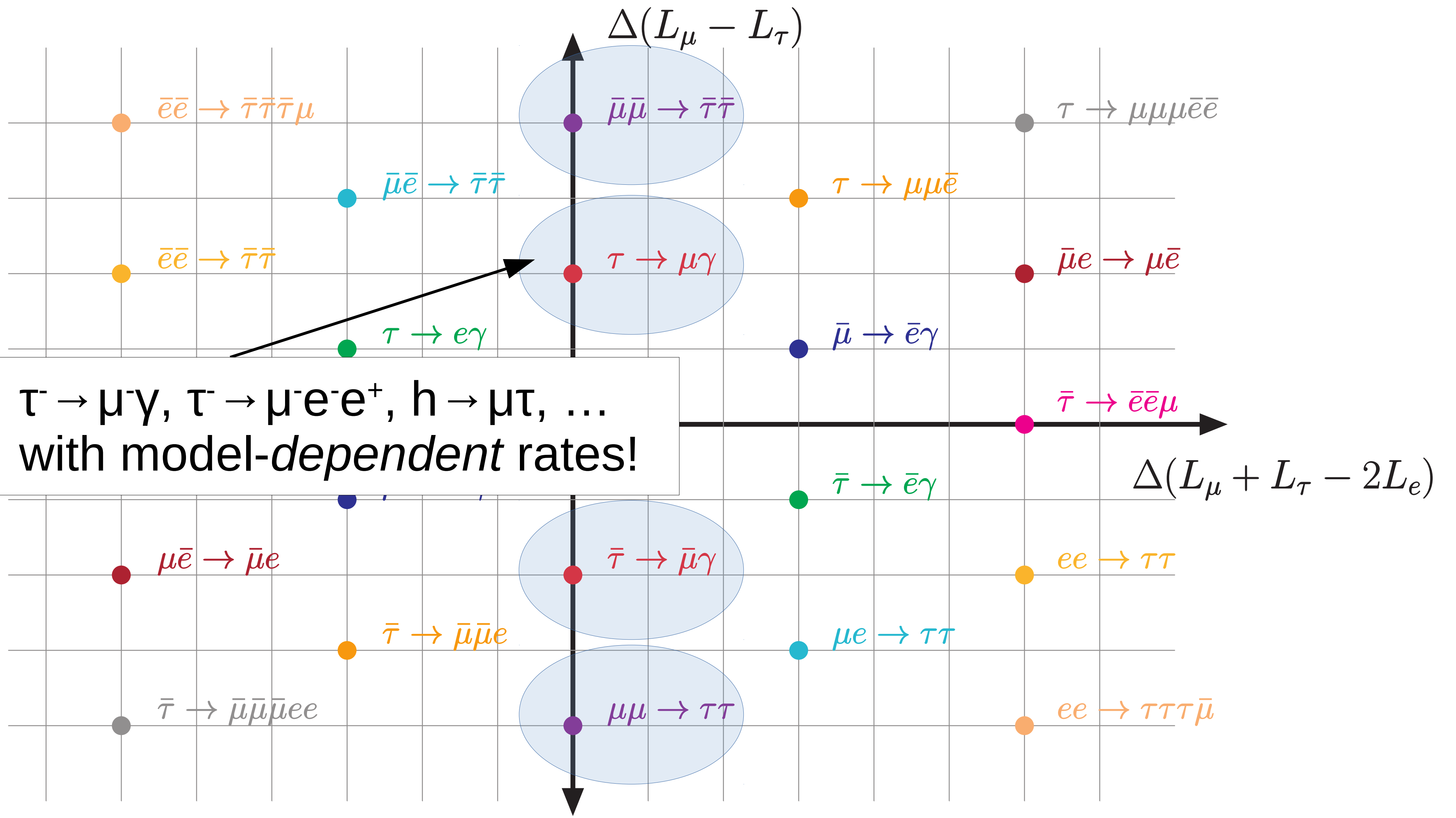
Currently being probed.

[Heeck, 1610.07623]



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

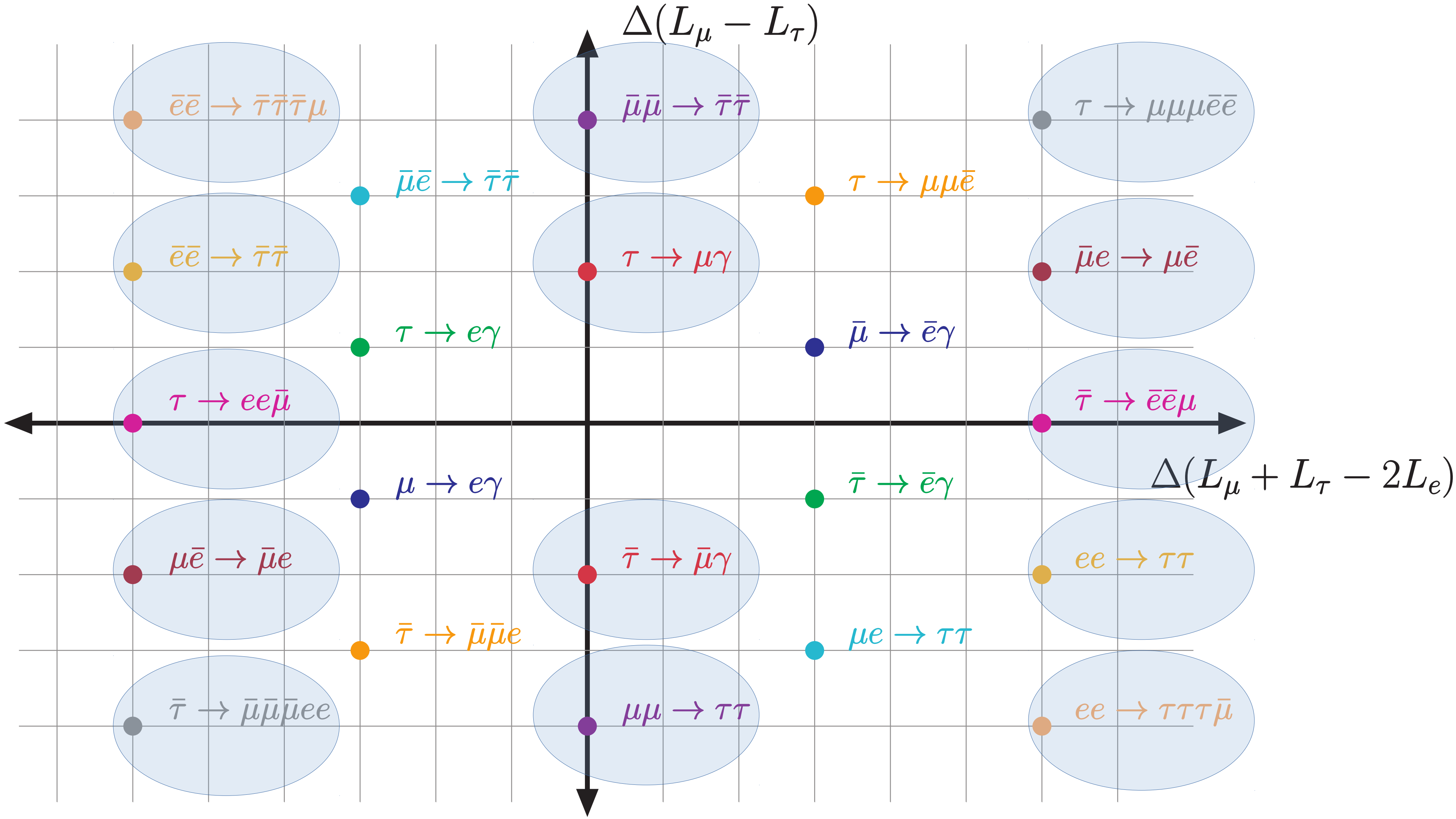
[Heeck, 1610.07623]



$\tau^- \to \mu^-\gamma$, $\tau^- \to \mu^- e^- e^+$, $h \to \mu\tau$, …
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]



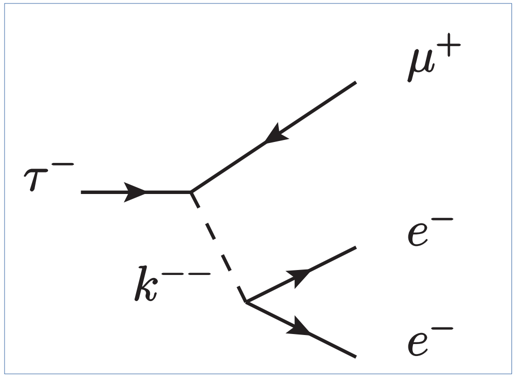
Interpretation of LFV

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

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^{++}:

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

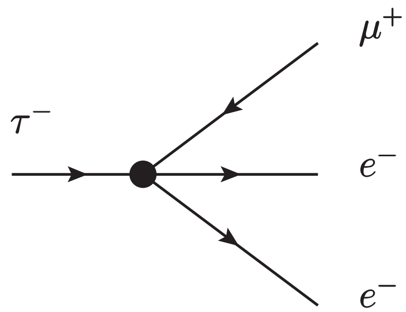
- $\tau^- \to e^- e^- \mu^+$ allowed, everything else forbidden.
- Add N_R and singlet scalars S_j to break $L_\mu - L_\tau$ in M_R:

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

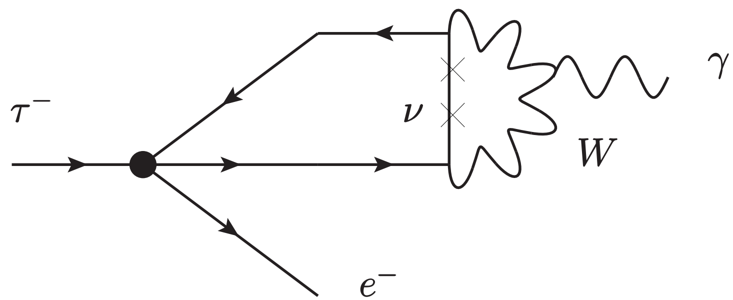
- Could even use symmetry for texture zeroes in M_ν.
  [Araki, Heeck, Kubo, 1203.4951]

ν oscillations but approximate symmetry in ℓ^- sector. ✓

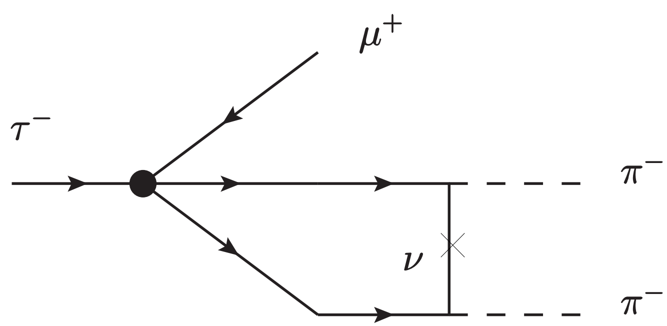
$\tau^- \rightarrow e^- e^- \mu^+$ plus M_ν breaks U(1)



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



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



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

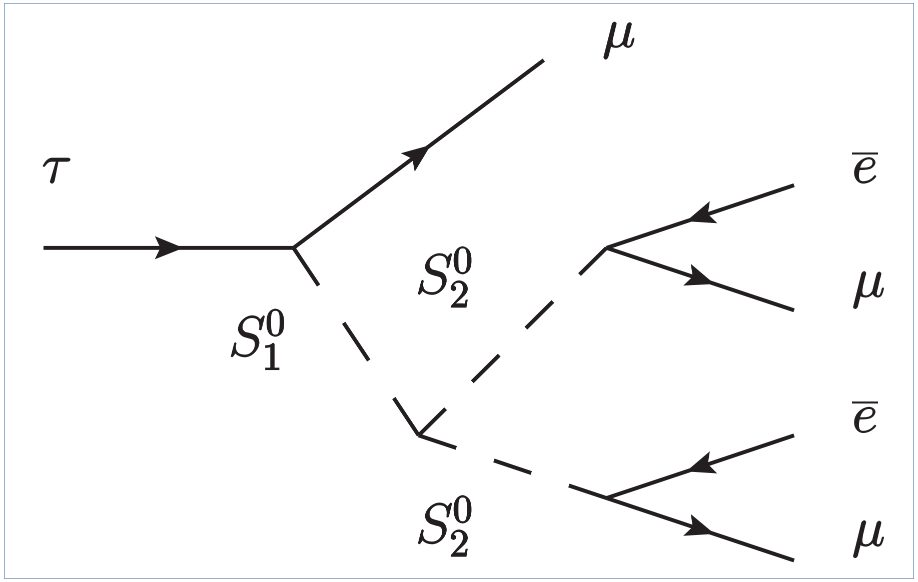
Additional suppression factors from loops, phase space and lepton mass flips depending on actual operator.

⇒ 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 → 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

- 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!
- 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

- $\Delta B = 1$ 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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Impose B+L

Effective operators

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

Impose B+3L

Effective operators

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

Impose B–L

Effective operators

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

Impose $L_e + 2L_\mu - 3L_\tau$

Effective operators

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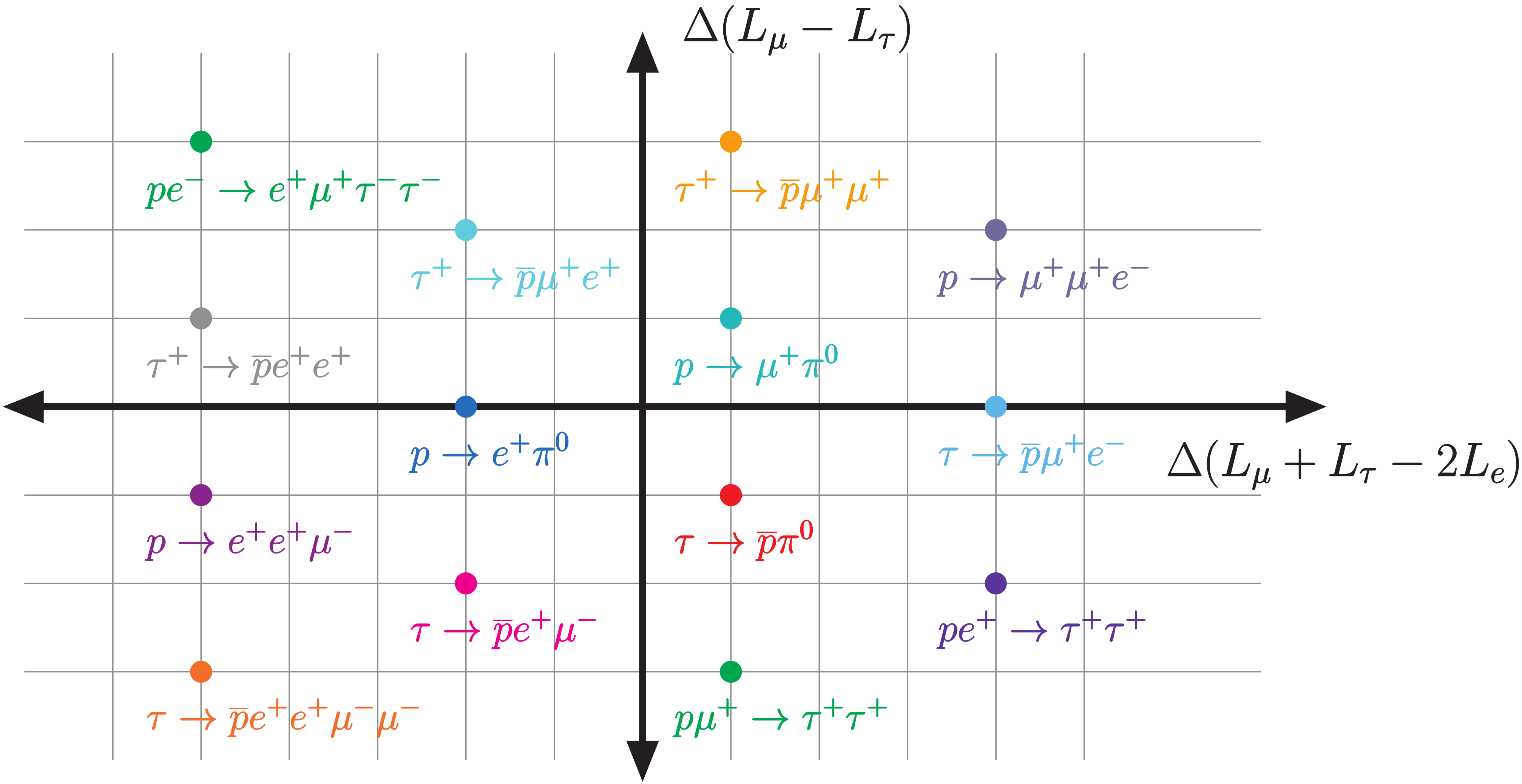
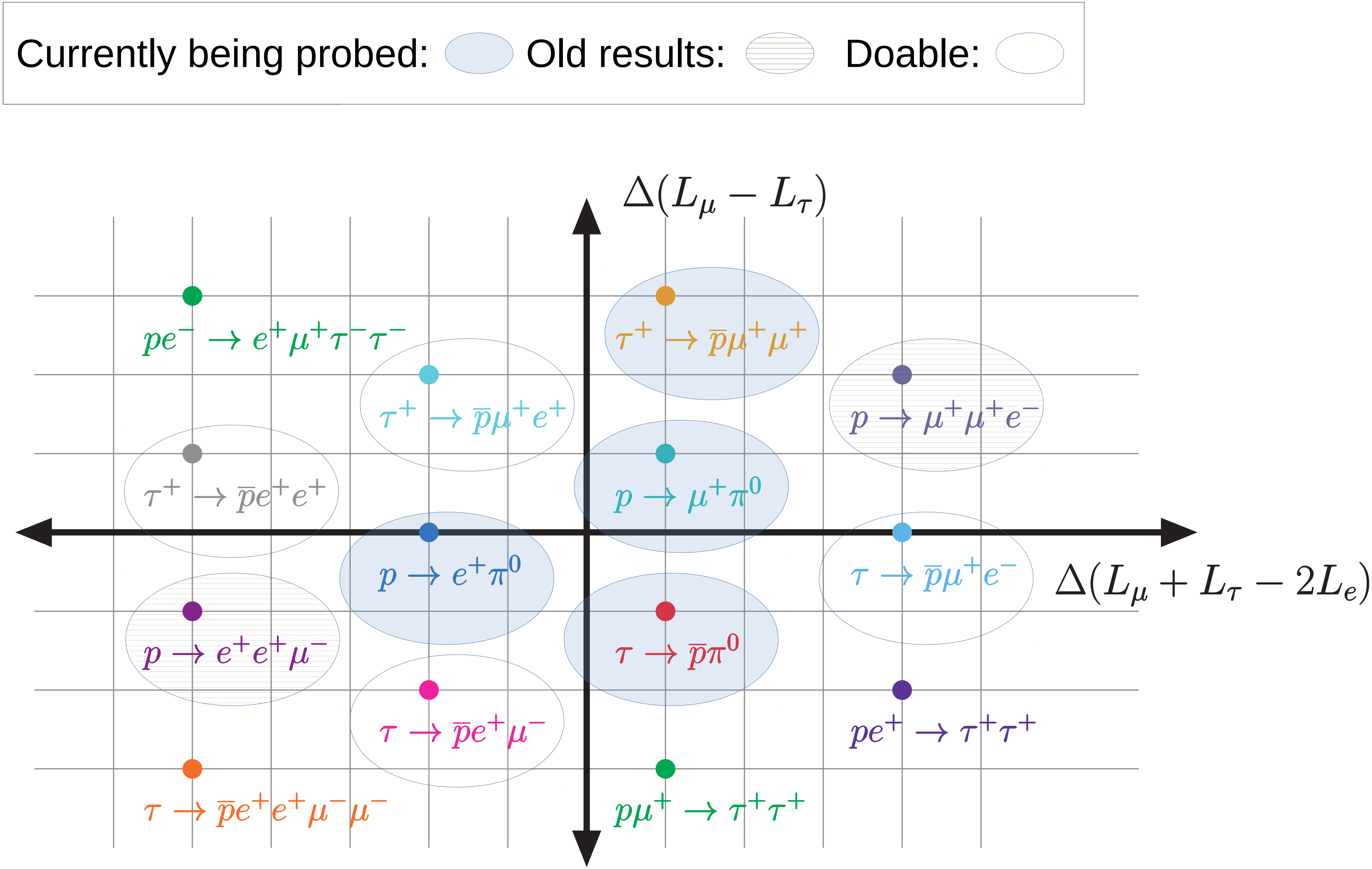
  - ~~$ddd\overline{LLL}H$: $d=10$, $\Delta L = -3$, e.g. $p \to e^- \nu_\mu \nu_\tau \pi^+ \pi^+$.~~
  - ~~$QudLLLHH$: $d=11$, $\Delta L = 3$, e.g. $p \to \mu^+ \overline{\nu}_e \overline{\nu}_\tau$.~~

Impose $L_e + 2L_\mu - 3L_\tau$ and $B-L$

ΔB = ΔL = 1



$\Delta(L_\mu - L_\tau)$
$\Delta(L_\mu + L_\tau - 2L_e)$
$pe^- \to e^+\mu^+\tau^-\tau^-$
$\tau^+ \to \overline{p}\mu^+\mu^+$
$\tau^+ \to \overline{p}\mu^+e^+$
$p \to \mu^+\mu^+e^-$
$\tau^+ \to \overline{p}e^+e^+$
$p \to \mu^+\pi^0$
$p \to e^+\pi^0$
$\tau \to \overline{p}\mu^+e^-$
$p \to e^+e^+\mu^-$
$\tau \to \overline{p}\pi^0$
$\tau \to \overline{p}e^+\mu^-$
$pe^+ \to \tau^+\tau^+$
$\tau \to \overline{p}e^+e^+\mu^-\mu^-$
$p\mu^+ \to \tau^+\tau^+$


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

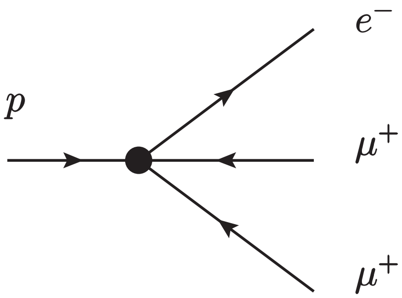
- The decay $p \to e^+e^+\mu^-$ (or $p \to \mu^+\mu^+e^-$) could be dominant!
- Conserves B–L, L_τ, and $L_e+2L_\mu-3L_\tau$ (or $L_\mu+2L_e-3L_\tau$).
- 35 d=10 operators of the form $QQQL\overline{L}H\ell/\Lambda^6$.
- Rate suppressed:

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

- 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]

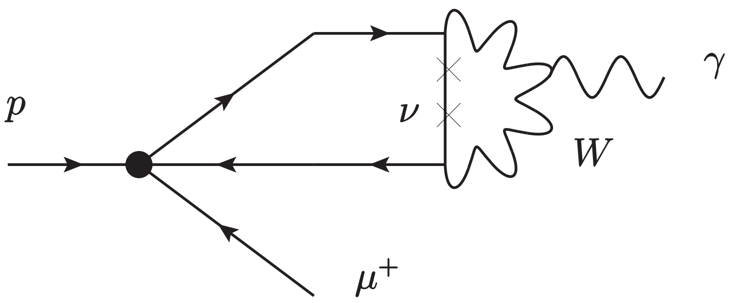
p → $\mu^+\mu^+e^-$ plus M_ν breaks U(1)



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

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

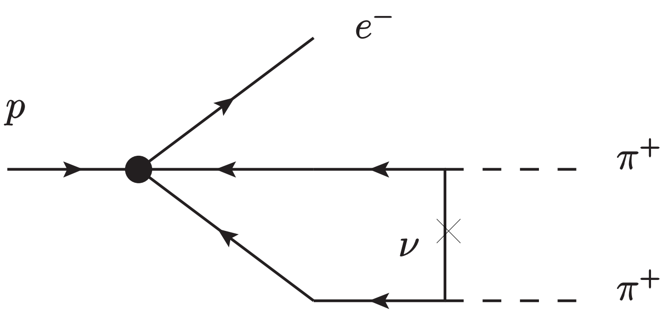
Conserves U(1)



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

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

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 → $\mu^+\mu^+e^-$

- Minimal leptoquark example:

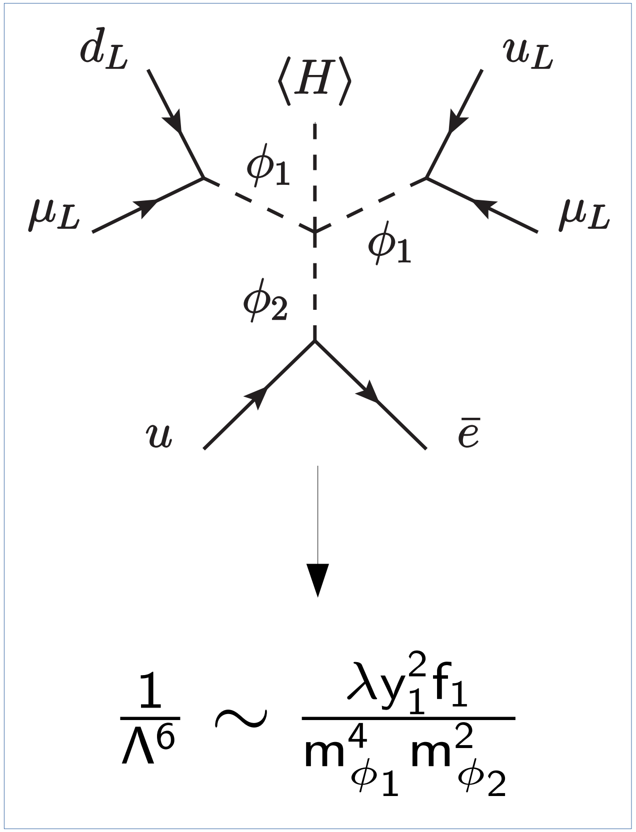
$$\phi_1 \sim (\mathbf{3}, \mathbf{3}, -2/3)\,,\ \phi_2 \sim (\mathbf{3}, \mathbf{2}, 7/3)\,.$$

- $L_\mu + 2L_e - 3L_\tau$ 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

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



[Hambye, Heeck, 1712.04871, PRL]

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

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

b → sμμ

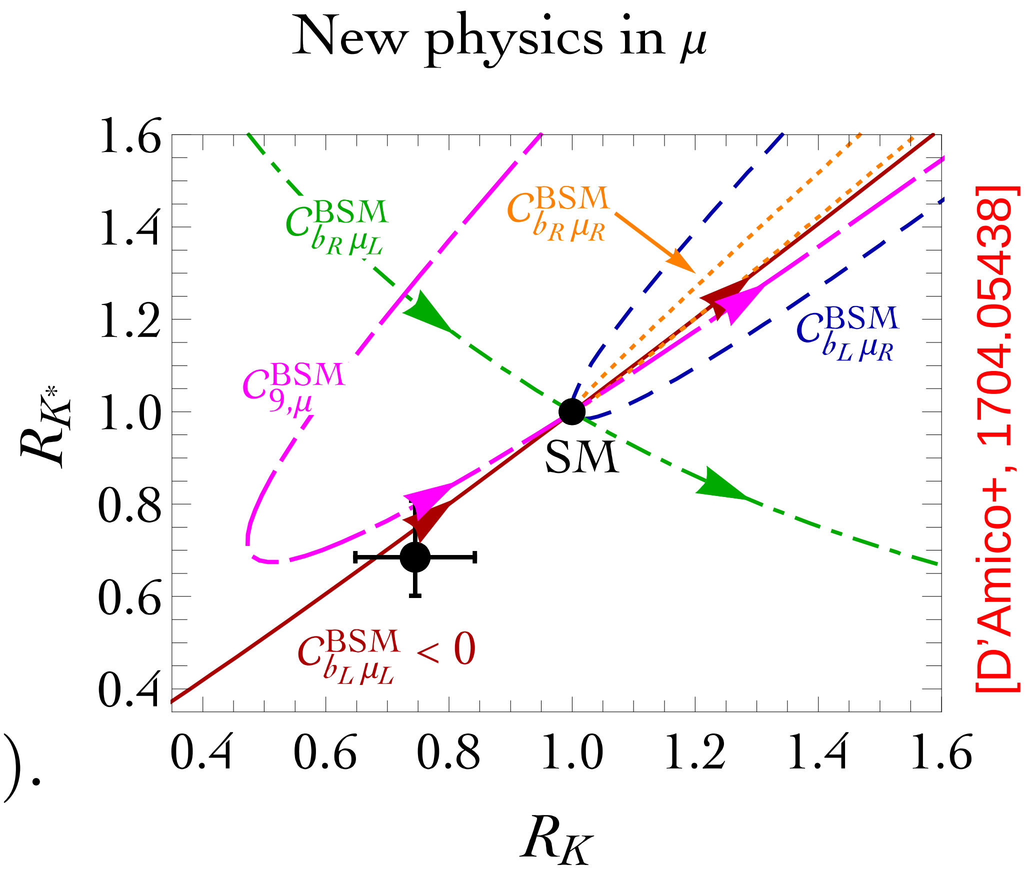
- Hints for lepton flavor non-universality in

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

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

- 4-6σ improvement with

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



- Also explains anomalies in other b→sμμ observables.

- Resolution via Z' or leptoquarks.

Triplet LQ and b→sμμ

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

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

- 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:

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

$\mathcal{L}_{\rm SM}$: conserves G

$\frac{LLHH}{\Lambda}$: violates G

$\sum_j \frac{\mathcal{O}_j}{\Lambda^2} + \sum_j \frac{\mathcal{O}'_j}{\Lambda^3} + \sum_j \frac{\mathcal{O}''_j}{\Lambda^4} + \dots$: could conserve G or subgroup

⇒ ‘weird’ channels dominate!?

Scales probed by LFV

LFV channel	Example operator	Coefficient limit
$\mu \to e\gamma$	$\overline{L}_\mu \sigma^{\alpha\beta} e_R H B_{\alpha\beta}$	$(6 \times 10^4\,\text{TeV})^{-2}$
$\mu \to ee\overline{e}$	$\overline{e}_R \gamma^\alpha \mu_R \overline{e}_R \gamma_\alpha e_R$	$(200\,\text{TeV})^{-2}$
$\tau \to ee\overline{\mu}$	$\overline{e}_R \gamma^\alpha \tau_R \overline{e}_R \gamma_\alpha \mu_R$	$(10\,\text{TeV})^{-2}$
$K_L \to \overline{\mu} e$	$\overline{s}_L \gamma^\alpha d_L \overline{\mu}_R \gamma_\alpha e_R$	$(460\,\text{TeV})^{-2}$
$0\nu\beta\beta$	$L_e H H L_e$	$(10^{11}\,\text{TeV})^{-1}$
$p \to \overline{e}\pi^0$	$QQQL_e$	$(3 \times 10^{12}\,\text{TeV})^{-2}$
$p \to \overline{e}\overline{e}\mu$	$QQQL_e \overline{L}_\mu H e_R$	$(100\,\text{TeV})^{-6}$

$\Delta L = 2$

$\Delta L = 1$
$\Delta B = 1$

Summary

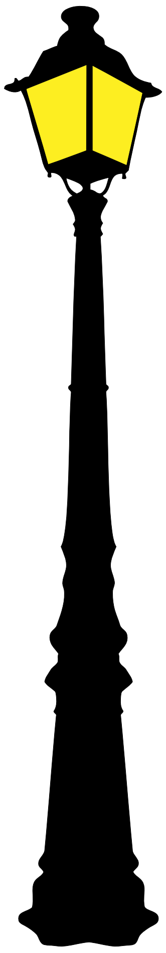
- Charged LFV gives info *complementary* to ν oscillations.
- Not simple yes/no question, need to find out if/how

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

  is broken in ℓ^- sector.

  ⇒ Need to search all possible channels!

- Non-trivial breaking: $\tau \to ee\bar{\mu}$, $\tau \to \mu\mu\bar{e}$, $p \to e\overline{\mu\mu}$, $p \to \mu\overline{ee}$,…
- $R(K^{(*)})$ 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}	$192 \to 354$	$144 \to 374$
$\frac{\Delta m^2_{21}}{10^{-5}\ \text{eV}^2}$	$7.40^{+0.21}_{-0.20}$	$6.80 \to 8.02$	$7.40^{+0.21}_{-0.20}$	$6.80 \to 8.02$	$6.80 \to 8.02$
$\frac{\Delta m^2_{3\ell}}{10^{-3}\ \text{eV}^2}$	$+2.494^{+0.033}_{-0.031}$	$+2.399 \to +2.593$	$-2.465^{+0.032}_{-0.031}$	$-2.562 \to -2.369$	$\begin{bmatrix} +2.399 \to +2.593 \\ -2.536 \to -2.395 \end{bmatrix}$

[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]

Upcoming CLFV

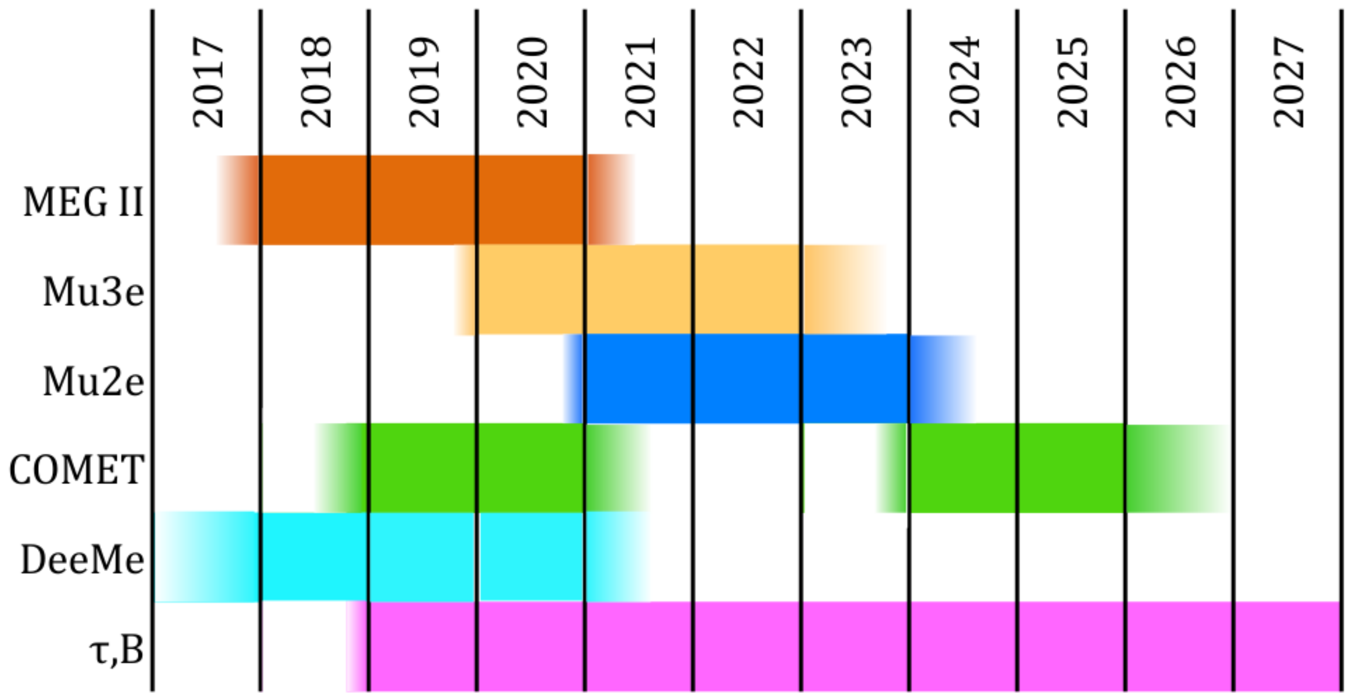


Figure 47. – Projected time lines for different projects searching for CLFV decays. MEG IIis expected to start data taking in 2018 after an engineering run in 2017; Mu3e magnet and detectors are expected at the end of 2019; Mu2e foresees three years of data taking starting in 2021; COMET Phase-I is expected to start commissioning and data taking in 2018 for two-three years, followed by a stop to develop and deploy the beamline and detectors for Phase-II; DeeMe is expected to start soon and take data with graphite and silicon carbide targets in sequence; Belle II is schedule to start data taking at end 2018.

[Calibbi & Signorelli, 1709.00294]

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

$$\begin{aligned}
\mathcal{O}^{10}_{1,2} &= (QQ)_{1,1}\,(QL)_{1,3}\,(\bar{L}\ell\bar{H})_{1,3}\,,\\
\mathcal{O}^{10}_{3,4} &= (QQ)_{1,1}\,(QL)_{1,3}\,(\bar{\ell}LH)_{1,3}\,,\\
\mathcal{O}^{10}_{5} &= (QQ)_{1}\,(LL)_{3}\,(\bar{\ell}QH)_{3}\,,\\
\mathcal{O}^{10}_{6} &= (QQ)_{1}\,(\ell\ell)_{1}\,(\bar{\ell}Q\bar{H})_{1}\,,\\
\mathcal{O}^{10}_{7} &= (QQ)_{1}\,(LL)_{3}\,(\bar{L}uH)_{3}\,,\\
\mathcal{O}^{10}_{8} &= (QQ)_{1}\,(\ell\ell)_{1}\,(\bar{L}u\bar{H})_{1}\,,\\
\mathcal{O}^{10}_{9} &= (QQ)_{1}\,(u\ell)_{1}\,(\bar{L}\ell\bar{H})_{1}\,,\\
\mathcal{O}^{10}_{10} &= (QQ)_{1}\,(u\ell)_{1}\,(\bar{\ell}LH)_{1}\,,\\
\mathcal{O}^{10}_{11,12} &= (QL)_{1,3}\,(QL)_{3,3}\,(\bar{\ell}QH)_{3,3}\,,\\
\mathcal{O}^{10}_{13,14} &= (QL)_{1,3}\,(QL)_{3,3}\,(\bar{L}uH)_{3,3}\,,\\
\mathcal{O}^{10}_{15,16} &= (QL)_{1,3}\,(u\ell)_{1,1}\,(\bar{\ell}QH)_{1,3}\,,\\
\mathcal{O}^{10}_{17,18} &= (QL)_{1,3}\,(d\ell)_{1,1}\,(\bar{\ell}Q\bar{H})_{1,3}\,,\\
\mathcal{O}^{10}_{19} &= (QL)_{3}\,(u\ell)_{1}\,(\bar{L}uH)_{3}\,,\\
\mathcal{O}^{10}_{20,21} &= (QL)_{1,3}\,(d\ell)_{1,1}\,(\bar{L}u\bar{H})_{1,3}\,,
\end{aligned}$$

$$\begin{aligned}
\mathcal{O}^{10}_{22,23} &= (QL)_{1,3}\,(u\ell)_{1,1}\,(\bar{L}d\bar{H})_{1,3}\,,\\
\mathcal{O}^{10}_{24,25} &= (QL)_{1,3}\,(ud)_{1,1}\,(\bar{L}\ell\bar{H})_{1,3}\,,\\
\mathcal{O}^{10}_{26,27} &= (QL)_{1,3}\,(ud)_{1,1}\,(\bar{\ell}LH)_{1,3}\,,\\
\mathcal{O}^{10}_{28} &= (LL)_{3}\,(ud)_{1}\,(\bar{\ell}QH)_{3}\,,\\
\mathcal{O}^{10}_{29} &= (ud)_{1}\,(\ell\ell)_{1}\,(\bar{\ell}Q\bar{H})_{1}\,,\\
\mathcal{O}^{10}_{30} &= (u\ell)_{1}\,(d\ell)_{1}\,(\bar{\ell}Q\bar{H})_{1}\,,\\
\mathcal{O}^{10}_{31} &= (LL)_{3}\,(ud)_{1}\,(\bar{L}uH)_{3}\,,\\
\mathcal{O}^{10}_{32} &= (ud)_{1}\,(u\ell)_{1}\,(\bar{L}\ell\bar{H})_{1}\,,\\
\mathcal{O}^{10}_{33} &= (ud)_{1}\,(\ell\ell)_{1}\,(\bar{L}u\bar{H})_{1}\,,\\
\mathcal{O}^{10}_{34} &= (u\ell)_{1}\,(d\ell)_{1}\,(\bar{L}u\bar{H})_{1}\,,\\
\mathcal{O}^{10}_{35} &= (ud)_{1}\,(u\ell)_{1}\,(\bar{\ell}LH)_{1}\,,\\
\mathcal{O}^{10}_{36,37} &= (QL)_{1,3}\,(QL)_{1,3}\,(\bar{\ell}QH)_{1,1}\,,\\
\mathcal{O}^{10}_{38,39,40} &= (QL)_{1,1,3}\,(QL)_{1,3,3}\,(\bar{L}d\bar{H})_{1,3,1}\,,\\
\mathcal{O}^{10}_{41} &= (u\ell)_{1}\,(u\ell)_{1}\,(\bar{l}QH)_{1}\,,\\
\mathcal{O}^{10}_{42} &= (u\ell)_{1}\,(u\ell)_{1}\,(\bar{L}d\bar{H})_{1}\,,
\end{aligned}$$

[Hambye, Heeck, 1712.04871, PRL]