Lepton flavor violation with tau leptons

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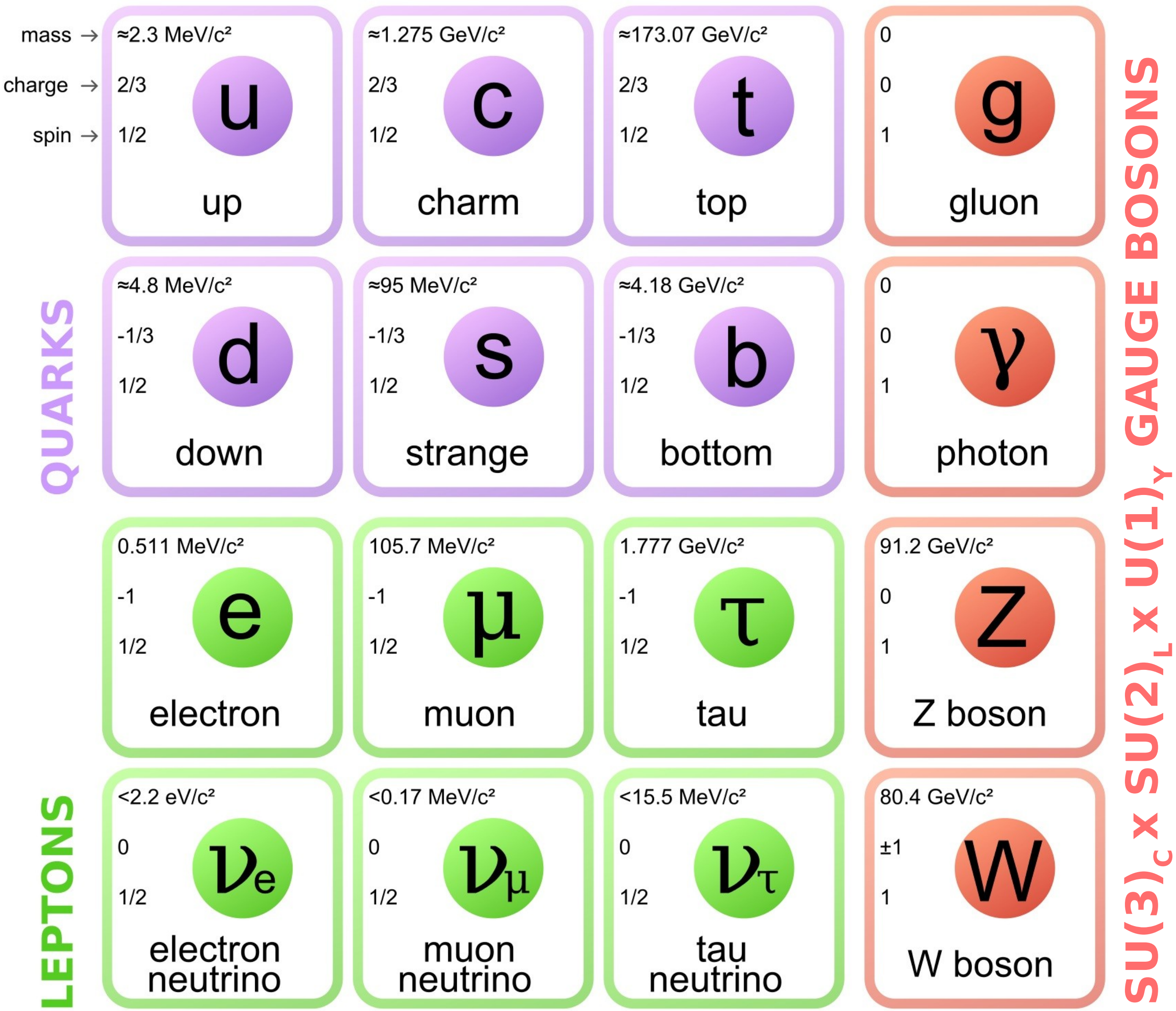
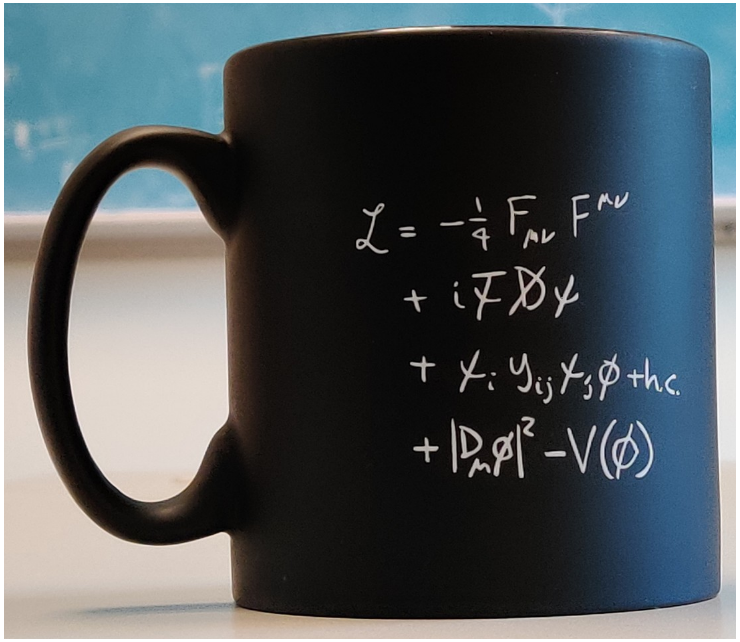
Standard Model of Particle Physics



Englert & Higgs ‘13



[wikipedia]

Symmetries of the Standard Model

- Rephasing lepton and quark fields:

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

$$=$$

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

- Broken non-perturbatively, but unobservable. ['t Hooft, PRL '76]

- True accidental global symmetry:

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

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Lepton flavor conservation!

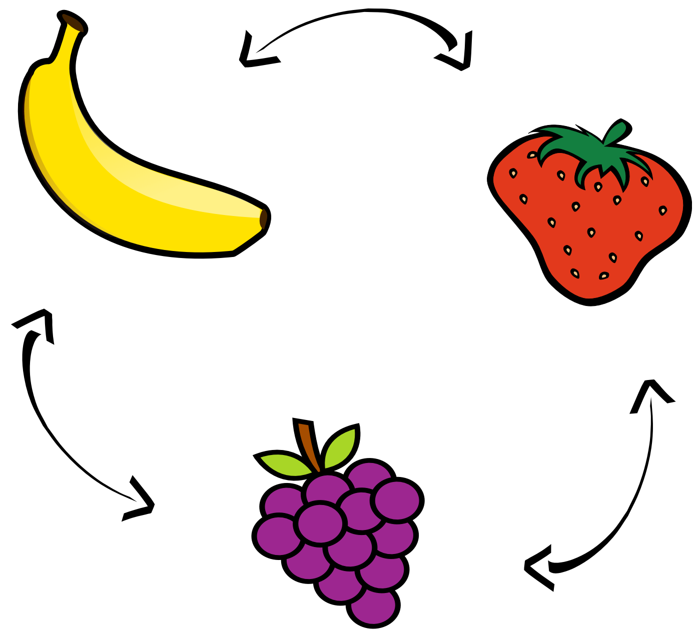
Neutrino oscillations = flavor violation

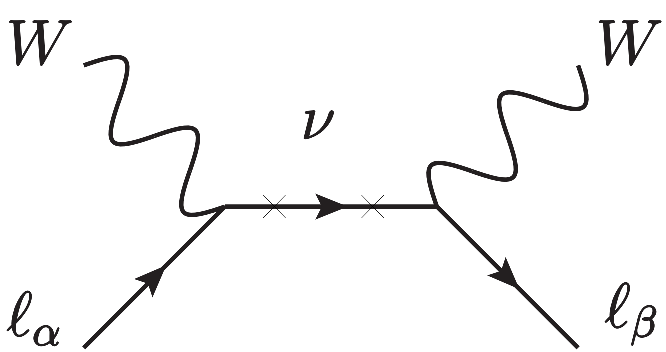
- Observations of $\nu_\alpha \to \nu_\beta$ prove that $M_\nu \neq 0$ and

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

  is broken!

- Amplitudes for charged lepton flavor violation are suppressed:





$$\mathcal{A}(\ell_\alpha^- \to \ell_\beta^-) \propto \frac{(M_\nu M_\nu^\dagger)_{\alpha\beta}}{M_W^2} < 10^{-24}\,.$$

Neutrino mass $\not\Rightarrow$ charged LFV!

- Neutrino-mass induced charged LFV is unobservable.

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

- $M_\nu \Leftrightarrow$ CLFV connection possible but not necessary.

  ⇒ Can ignore M_ν in CLFV studies!

- (How) Is $U(1)_{L_\mu - L_\tau} \times U(1)_{L_\mu + L_\tau - 2L_e}$ broken in CLFV?

  [Lew & Volkas, 9410277; **JH**, '16]

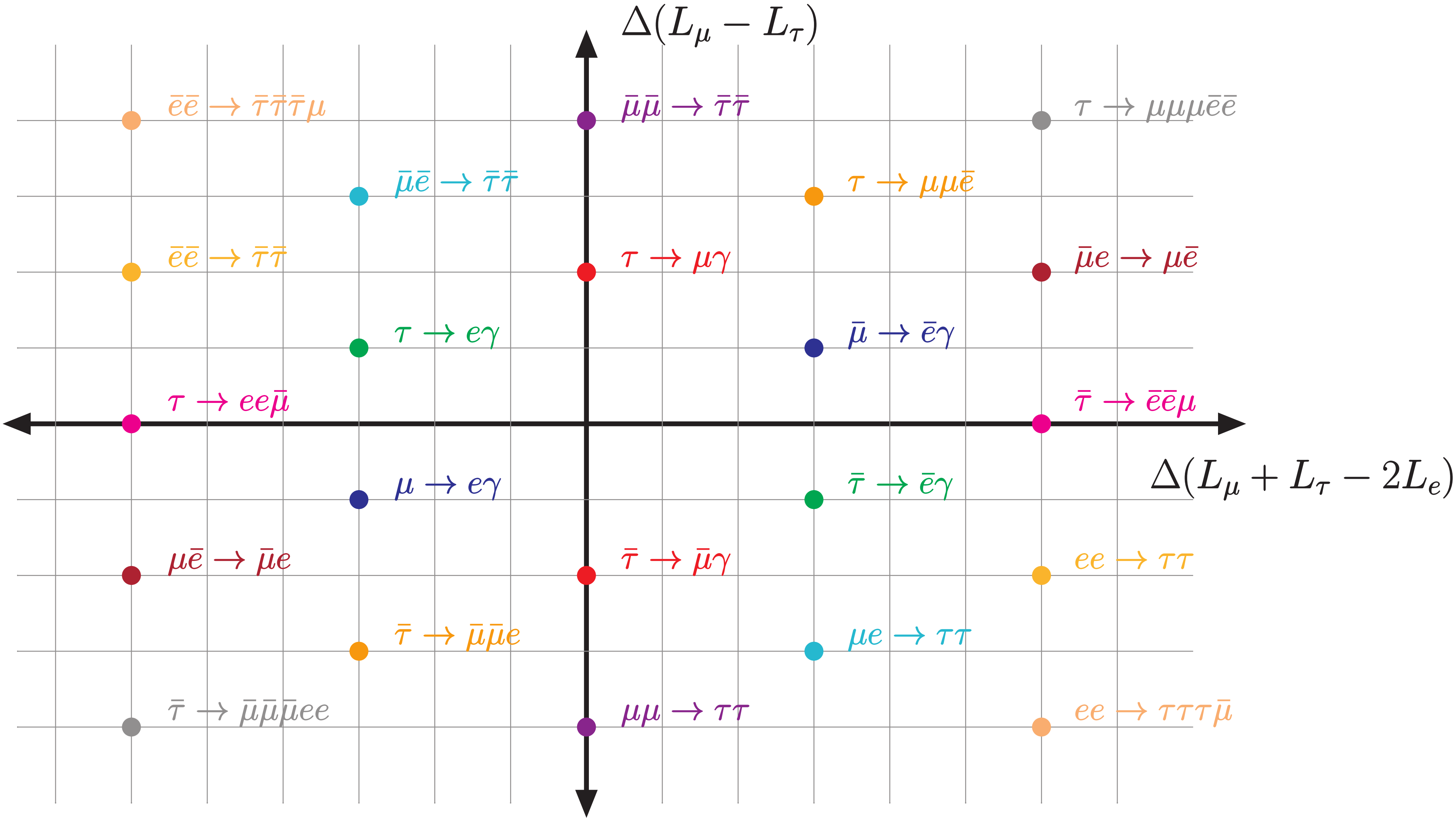
- Heavy new physics: SMEFT!
  - 888 CLFV operators at d=6:

$$\frac{C_{ijnm}}{\Lambda^2}\ell_i^c \ell_j \ell_n^c \ell_m \,, \frac{C_{ijnm}}{\Lambda^2}\ell_i^c \ell_j d_n^c d_m \,, \frac{C_{ij}}{\Lambda^2}\ell_i^c \sigma_{\alpha\beta}\ell_j H F^{\alpha\beta} \,, \ldots$$

[Weinberg '79; Buchmüller & Wyler, '86; Grzadkowski++, '10; Fonseca, '17]

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

[**JH**, 1610.07623]



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

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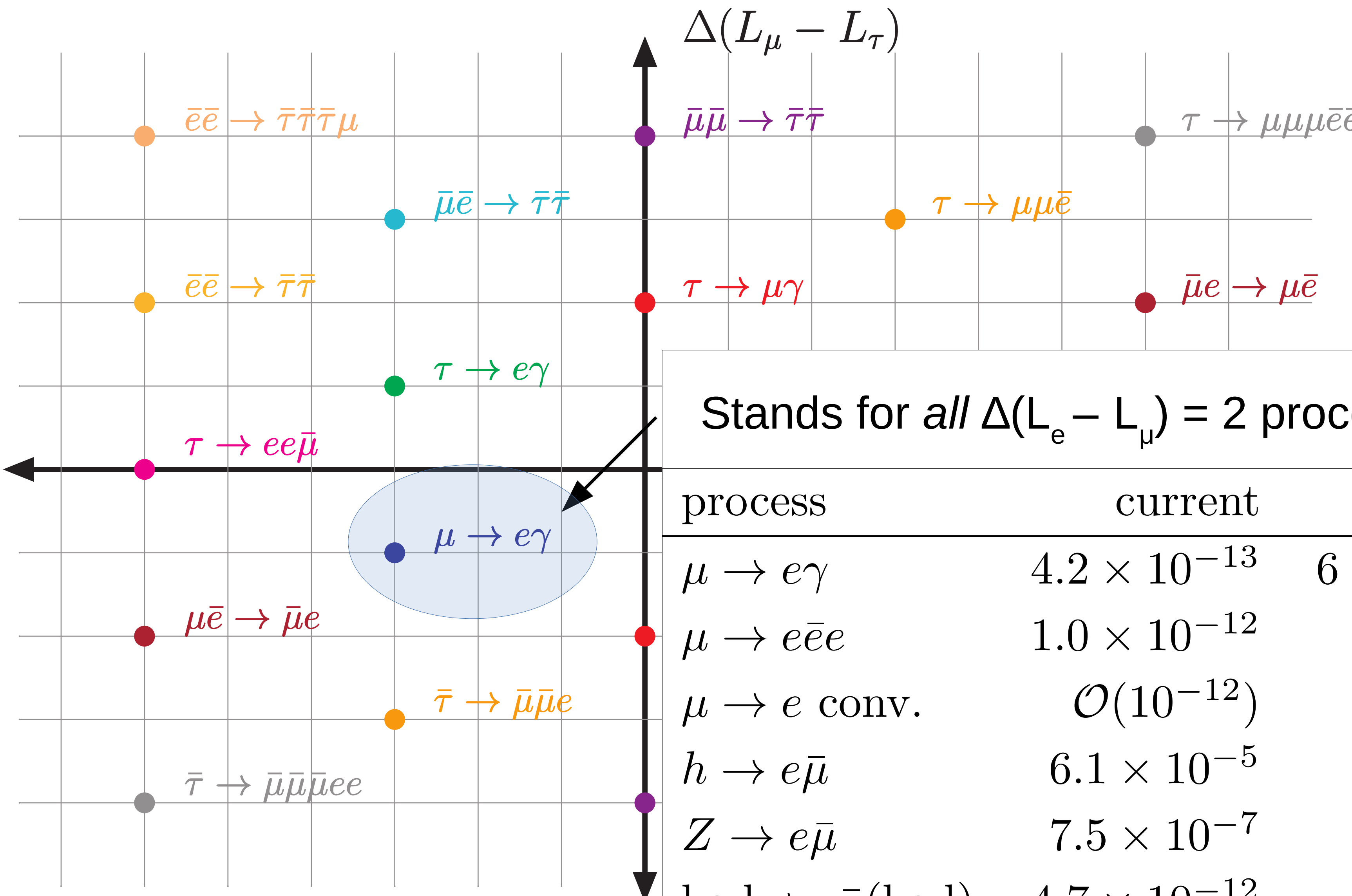

Stands for *all* $\Delta(L_e - L_\mu) = 2$ processes:

process	current	future
$\mu \to e\gamma$	4.2×10^{-13}	6×10^{-14}
$\mu \to e\bar{e}e$	1.0×10^{-12}	10^{-16}
$\mu \to e$ conv.	$\mathcal{O}(10^{-12})$	10^{-16}
$h \to e\bar{\mu}$	6.1×10^{-5}	10^{-5}
$Z \to e\bar{\mu}$	7.5×10^{-7}	10^{-10}
had$\to e\bar{\mu}$(had)	4.7×10^{-12}	10^{-12}

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

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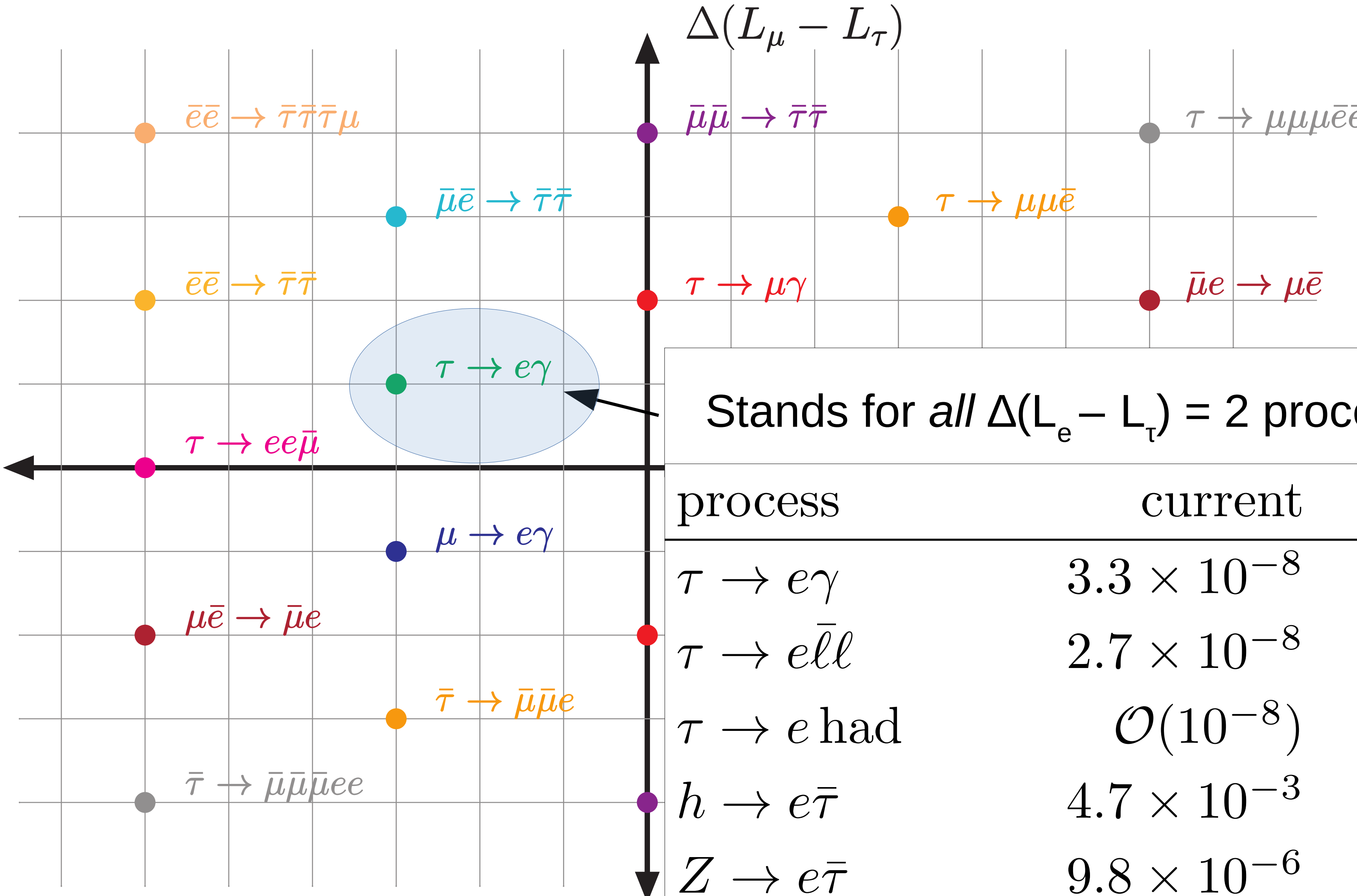
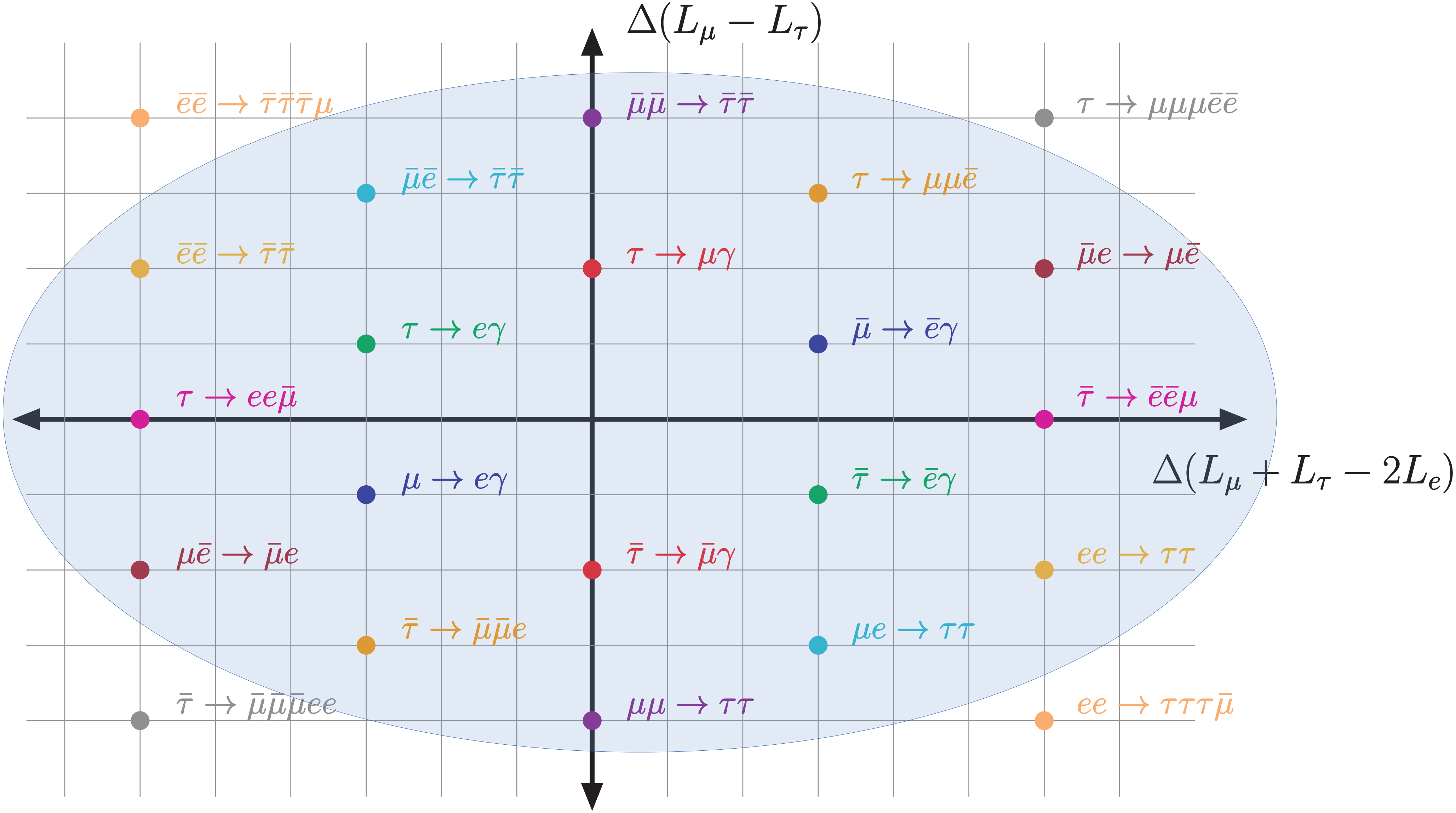


Stands for *all* $\Delta(L_e - L_\tau) = 2$ processes:

process	current	future
$\tau \to e\gamma$	3.3×10^{-8}	10^{-9}
$\tau \to e\bar{\ell}\ell$	2.7×10^{-8}	10^{-9}
$\tau \to e\,\text{had}$	$\mathcal{O}(10^{-8})$	10^{-9}
$h \to e\bar{\tau}$	4.7×10^{-3}	10^{-4}
$Z \to e\bar{\tau}$	9.8×10^{-6}	10^{-9}
had$\to e\bar{\tau}(\text{had})$	$\mathcal{O}(10^{-6})$	–

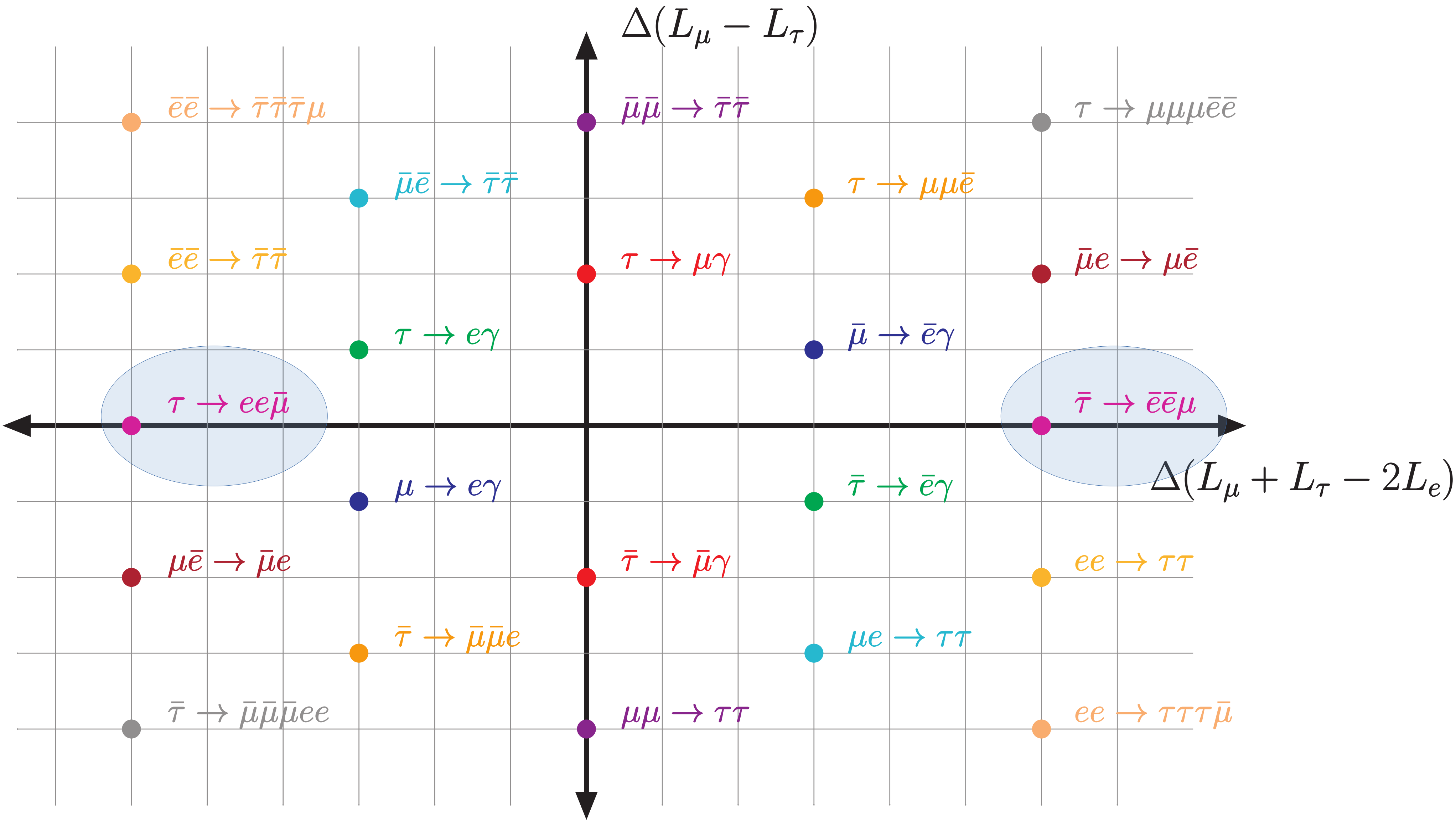
Dimension 6 operators

[JH, 1610.07623]



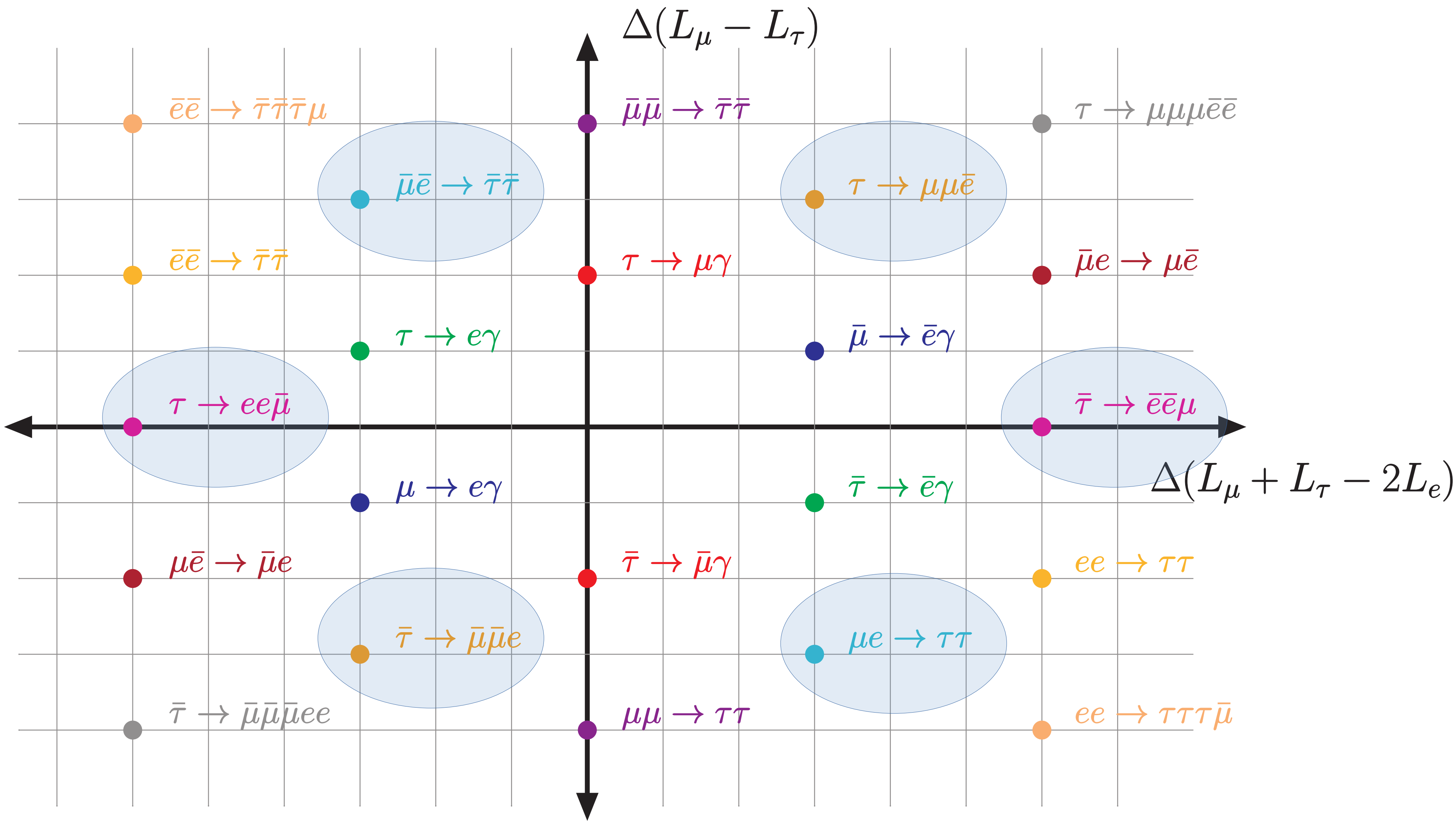
Impose $U(1)_{L_\mu - L_\tau}$ to make $\tau \to ee\bar{\mu}$ dominant.

[**JH**, 1610.07623]



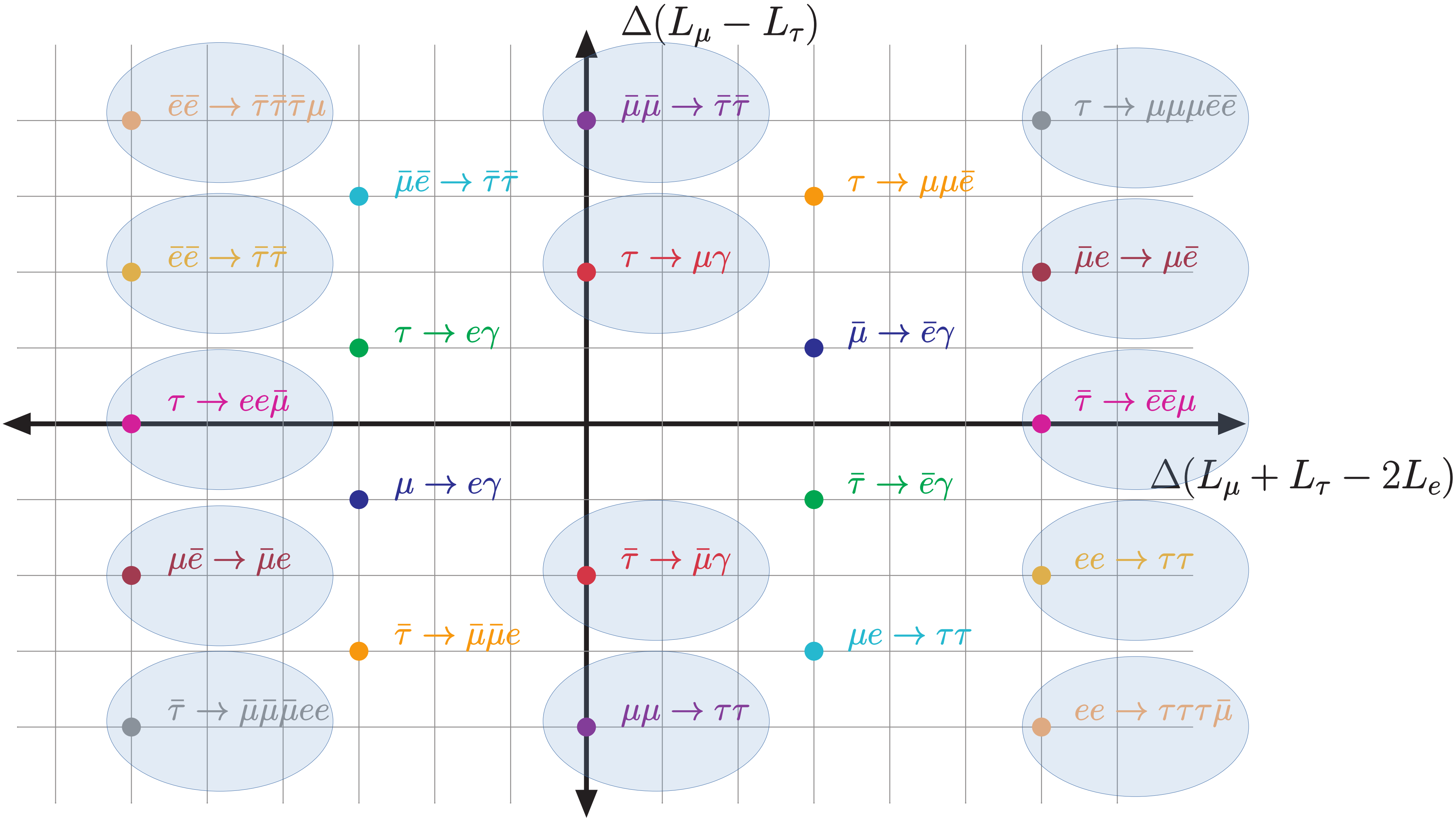
Impose *lepton triality* $\mathbb{Z}_3$. (See talk by Innes Bigaran.)

[**JH**, 1610.07623]



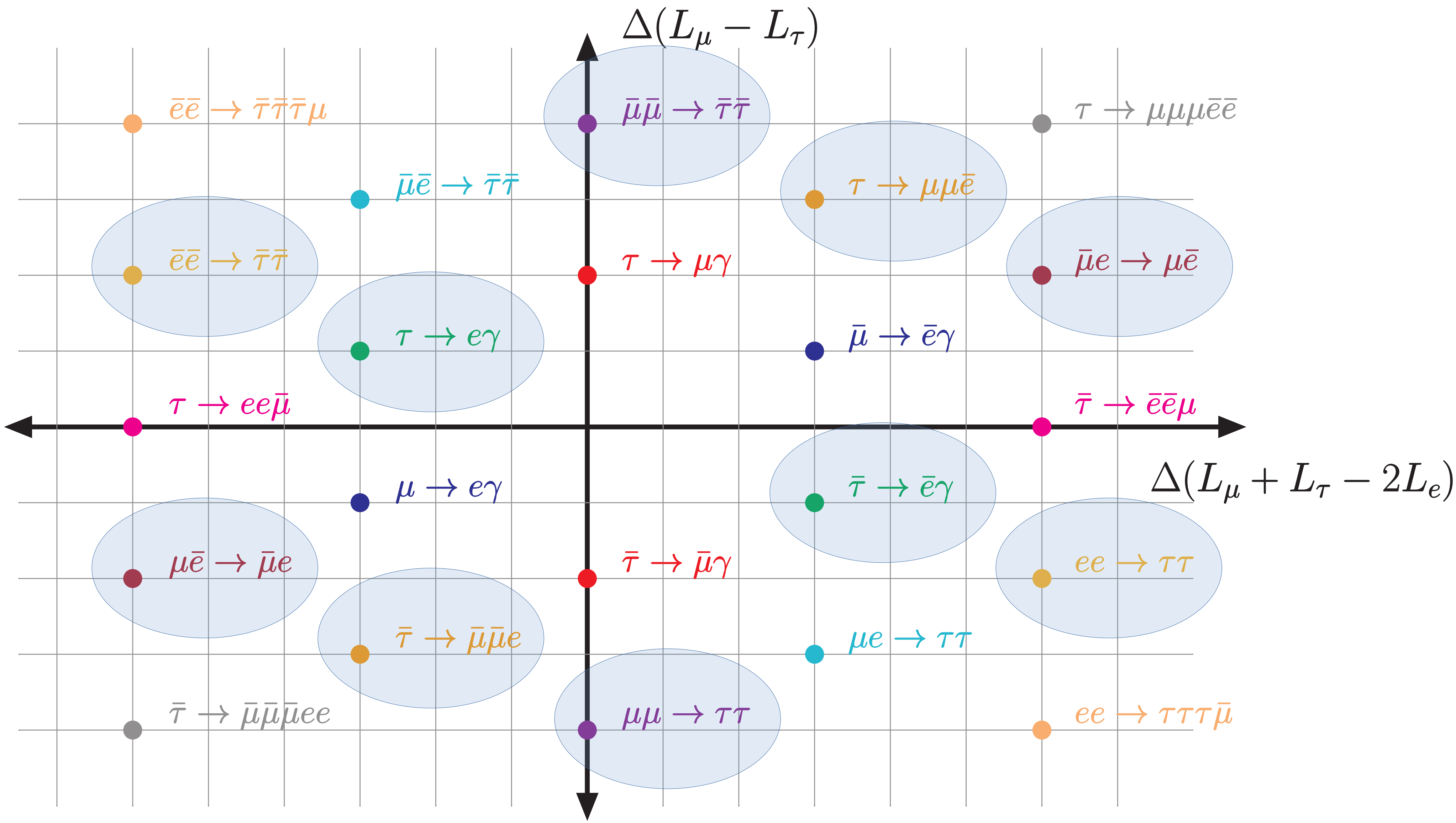
Impose $\mathbb{Z}_2$ under which e is *odd*.

[**JH**, 1610.07623]



Impose $\mathbb{Z}_2$ under which μ is *odd*.

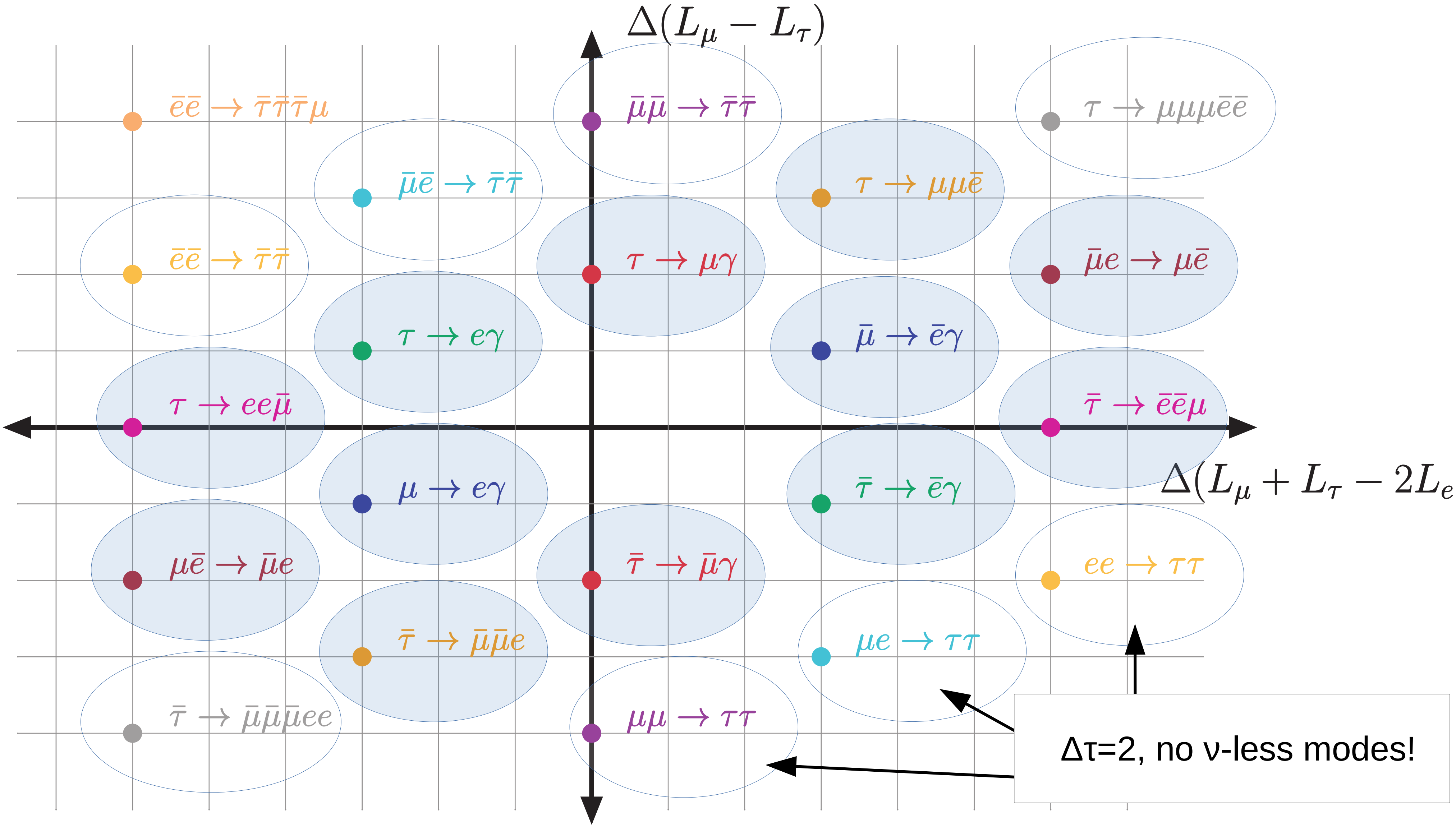
[**JH**, 1610.07623]



Etc. etc. etc.

Currently being probed: Future:

[**JH**, 1610.07623]



$\Delta\tau = 2$ operators

- 10 complex d=6 SMEFT operators, e.g. $\bar{\tau}\,\bar{\tau}\,\mu\,\mu$:

$$\mathsf{y}^{\mathsf{LL}}_{\tau\mu\tau\mu}\bar{\mathsf{L}}_\tau\gamma^\alpha\mathsf{L}_\mu\,\bar{\mathsf{L}}_\tau\gamma_\alpha\mathsf{L}_\mu \;+\mathsf{y}^{\mathsf{LR}}_{\tau\mu\tau\mu}\bar{\mathsf{L}}_\tau\gamma^\alpha\mathsf{L}_\mu\,\bar{\ell}_\tau\gamma_\alpha\ell_\mu+\mathsf{y}^{\mathsf{RR}}_{\tau\mu\tau\mu}\bar{\ell}_\tau\gamma^\alpha\ell_\mu\,\bar{\ell}_\tau\gamma_\alpha\ell_\mu$$

- No neutrinoless decay modes, no limits for d=6 LFV op?!

$\Delta\tau = 2$ operators

- 10 complex d=6 SMEFT operators, e.g. $\bar{\tau}\,\bar{\tau}\,\mu\,\mu$:

$$y^{LL}_{\tau\mu\tau\mu}\bar{L}_\tau\gamma^\alpha L_\mu\,\bar{L}_\tau\gamma_\alpha L_\mu + y^{LR}_{\tau\mu\tau\mu}\bar{L}_\tau\gamma^\alpha L_\mu\,\bar{\ell}_\tau\gamma_\alpha\ell_\mu + y^{RR}_{\tau\mu\tau\mu}\bar{\ell}_\tau\gamma^\alpha\ell_\mu\,\bar{\ell}_\tau\gamma_\alpha\ell_\mu$$

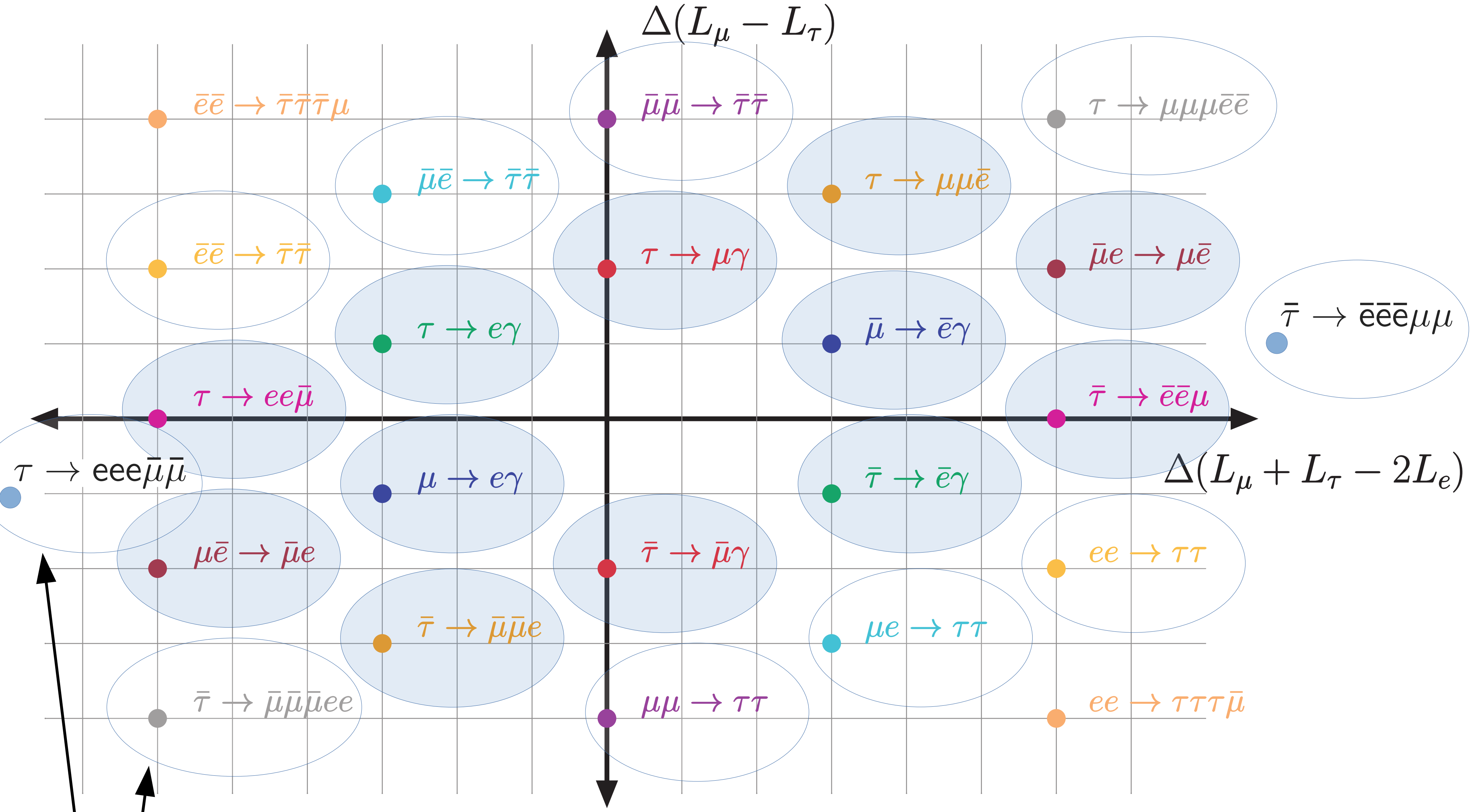
- No neutrinoless decay modes, no limits for d=6 LFV op?!
- For y^{LL} and y^{LR} still have wrong-ν-flavor decays: $\tau^- \to \mu^-\nu_\mu\bar{\nu}_\tau$
  - Only modifies τ lifetime, not spectrum. [**JH** & M. Sokhashvili, in progress]
  - Violates flavor universality, comparison with $\mu^- \to e^-\nu_\mu\bar{\nu}_e$ gives limits around $|y^{LL,LR}| < (0.6\,\text{TeV})^{-2}$. (See talk by P. Feichtinger.)
- y^{RR} is difficult, either $Z \to \bar{\tau}\,\bar{\tau}\,\mu\,\mu$ or $\mu\,\mu \to \tau\,\tau$ at new collider, or analyze UV completions (Z' or k^{++}). (See talk by W. Altmannshofer.)

[Altmannshofer++, PLB ‘16; Altmannshofer++, 2205.10576; Bigaran++, 2212.09760]

Not done with d=6 LFV yet!

Currently being probed: Future:

[JH, 1610.07623]

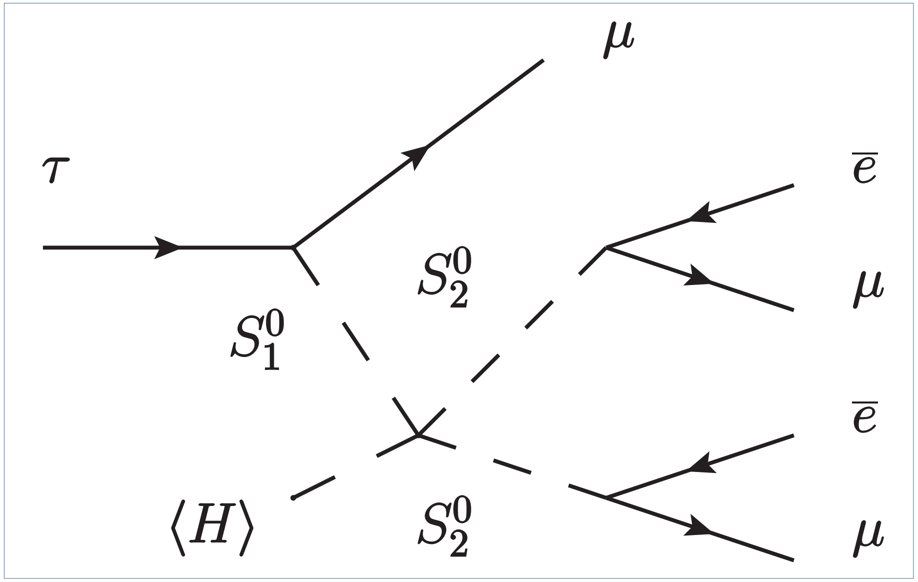


Belle II, but d=10 operator!

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

- Impose $L_\mu+4L_e-5L_\tau$ to kill other LFV.
- Not difficult, but rate is suppressed:

$$\mathrm{BR} \sim 5 \times 10^{-10} \left(\frac{30\,\mathrm{GeV}}{m_S}\right)^{12}.$$



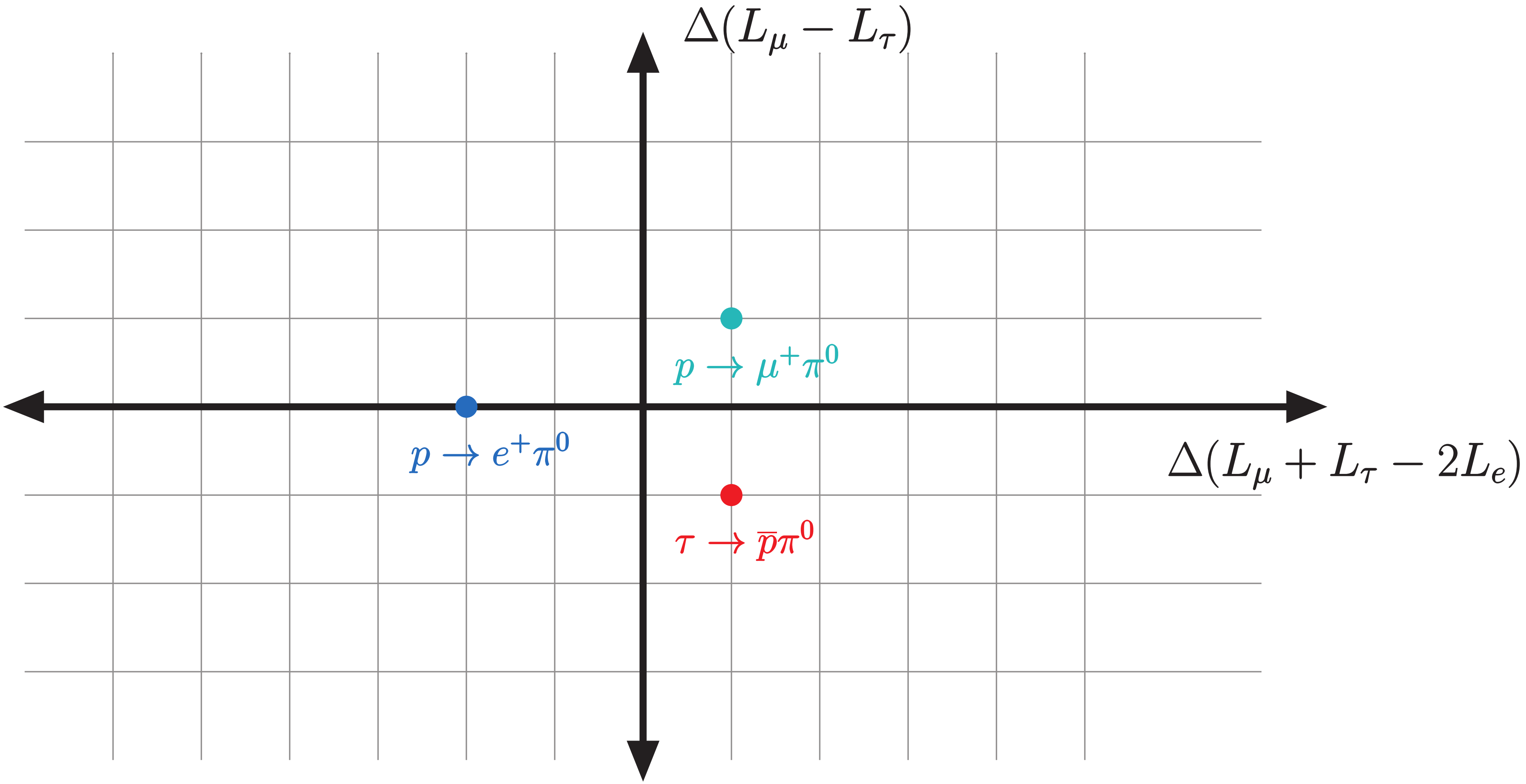
- Secretly dimension 10 operator.
- Better constraints on S from Z→ SS etc.? [**JH**, in progress]

Requires full models

Baryon number violation

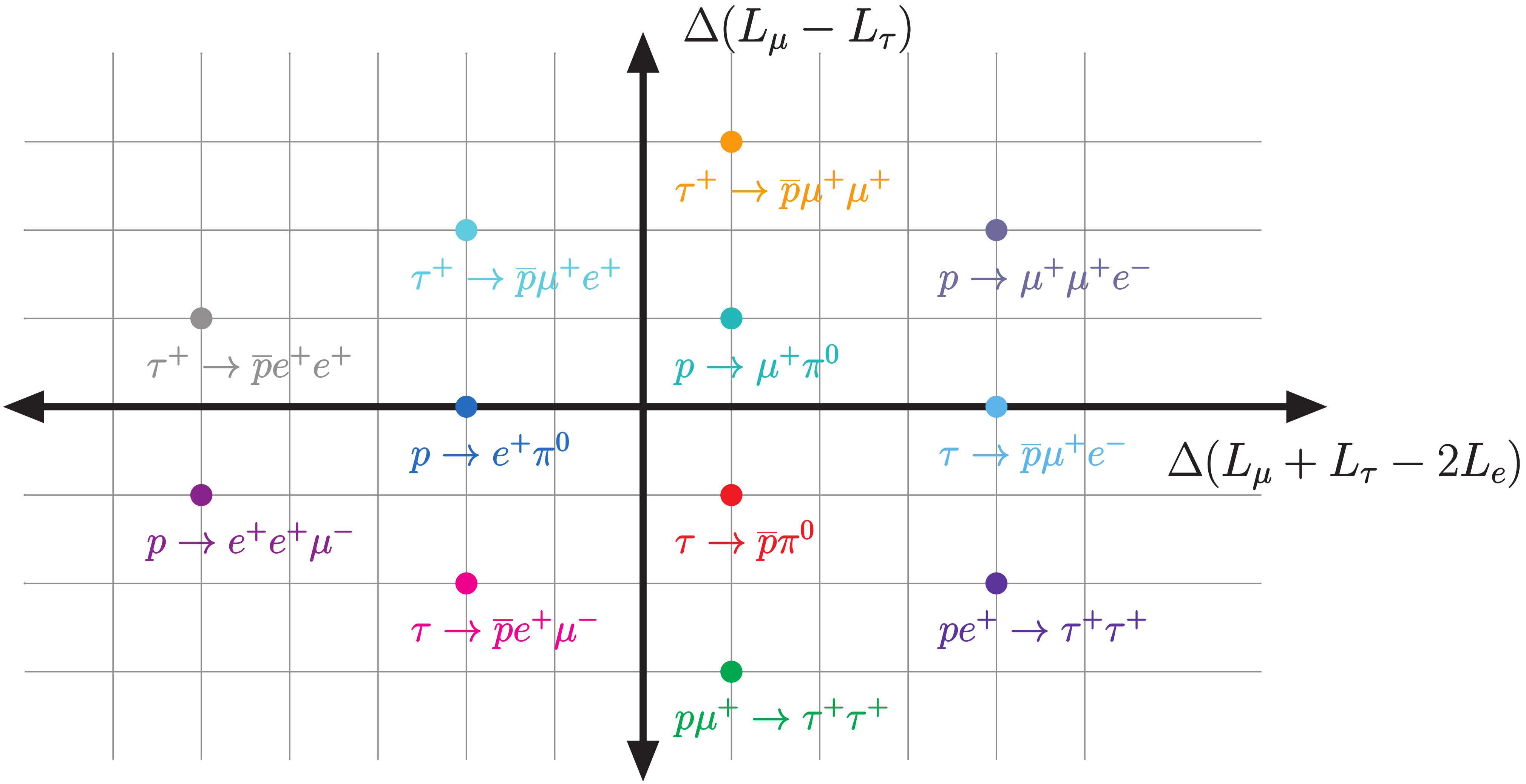
- So far assumed $\Delta B = 0$, but can also do LFV with $\Delta B \neq 0$.
- Example: proton decay ($\Delta B = 1$).
- Super-K limits on $p \to e^+\pi^0$, $\mu^+\pi^0$ are 10^{34} years!
- Probes scales up to 10^{15} GeV!
- Future: JUNO (China), DUNE (US), Hyper-K (Japan).

ΔB = ΔL = 1



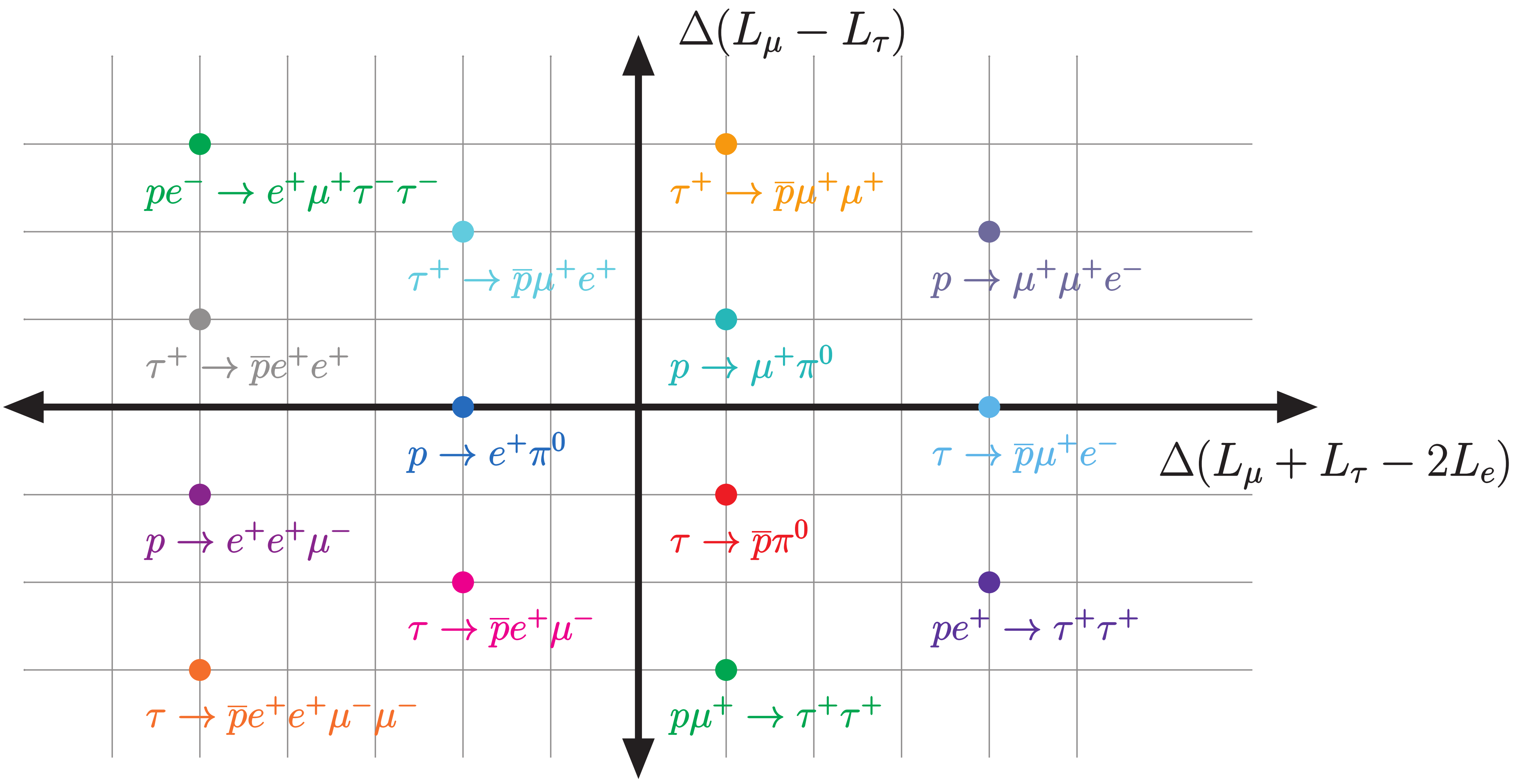
$\Delta(L_\mu - L_\tau)$
$p \to \mu^+\pi^0$
$p \to e^+\pi^0$
$\Delta(L_\mu + L_\tau - 2L_e)$
$\tau \to \overline{p}\pi^0$

ΔB = ΔL = 1



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

ΔB = ΔL = 1


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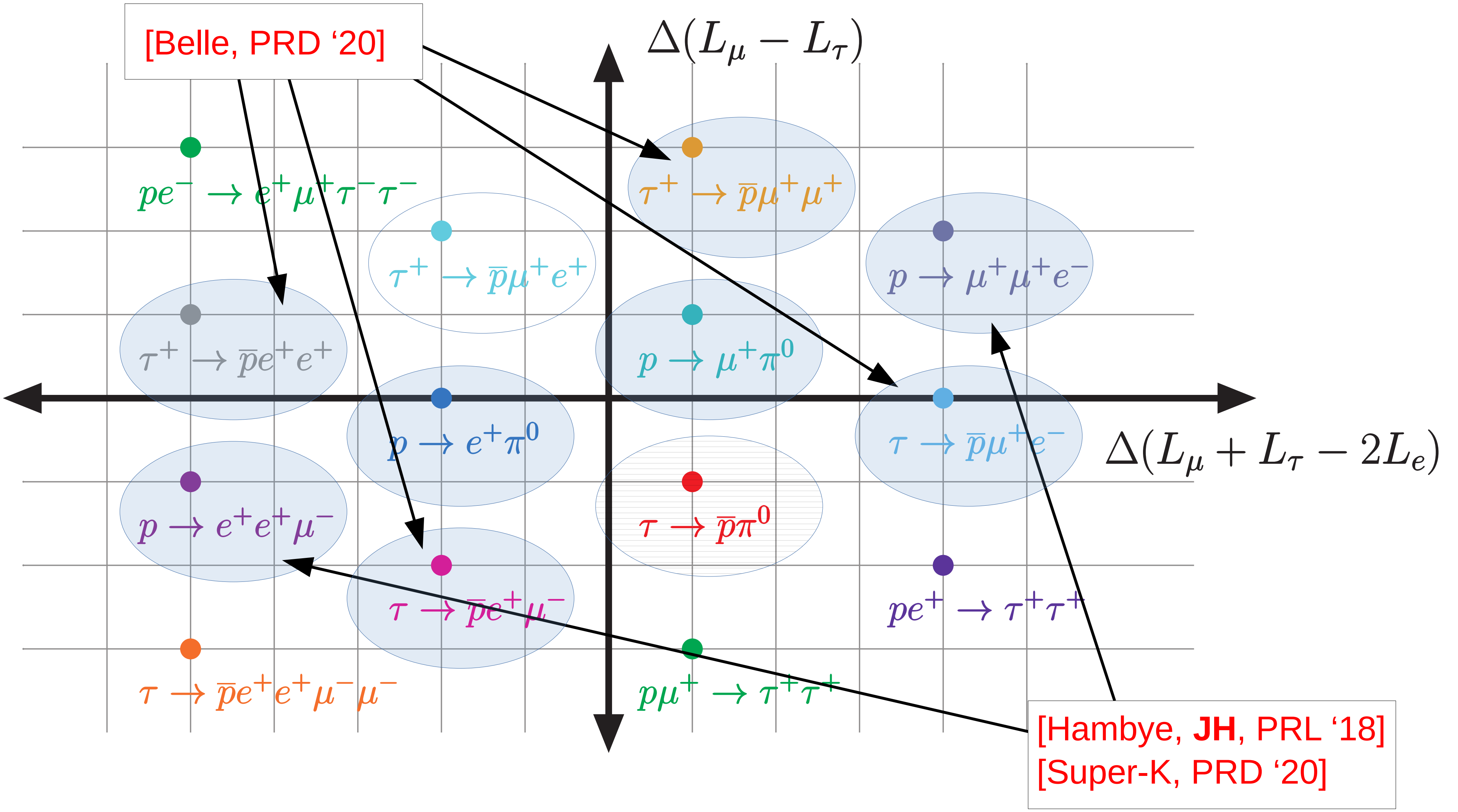
$\tau \to \overline{p}e^+\mu^-$
$pe^+ \to \tau^+\tau^+$
$\tau \to \overline{p}e^+e^+\mu^-\mu^-$
$p\mu^+ \to \tau^+\tau^+$

Currently being probed: Old results: Doable:

ΔB = ΔL = 1



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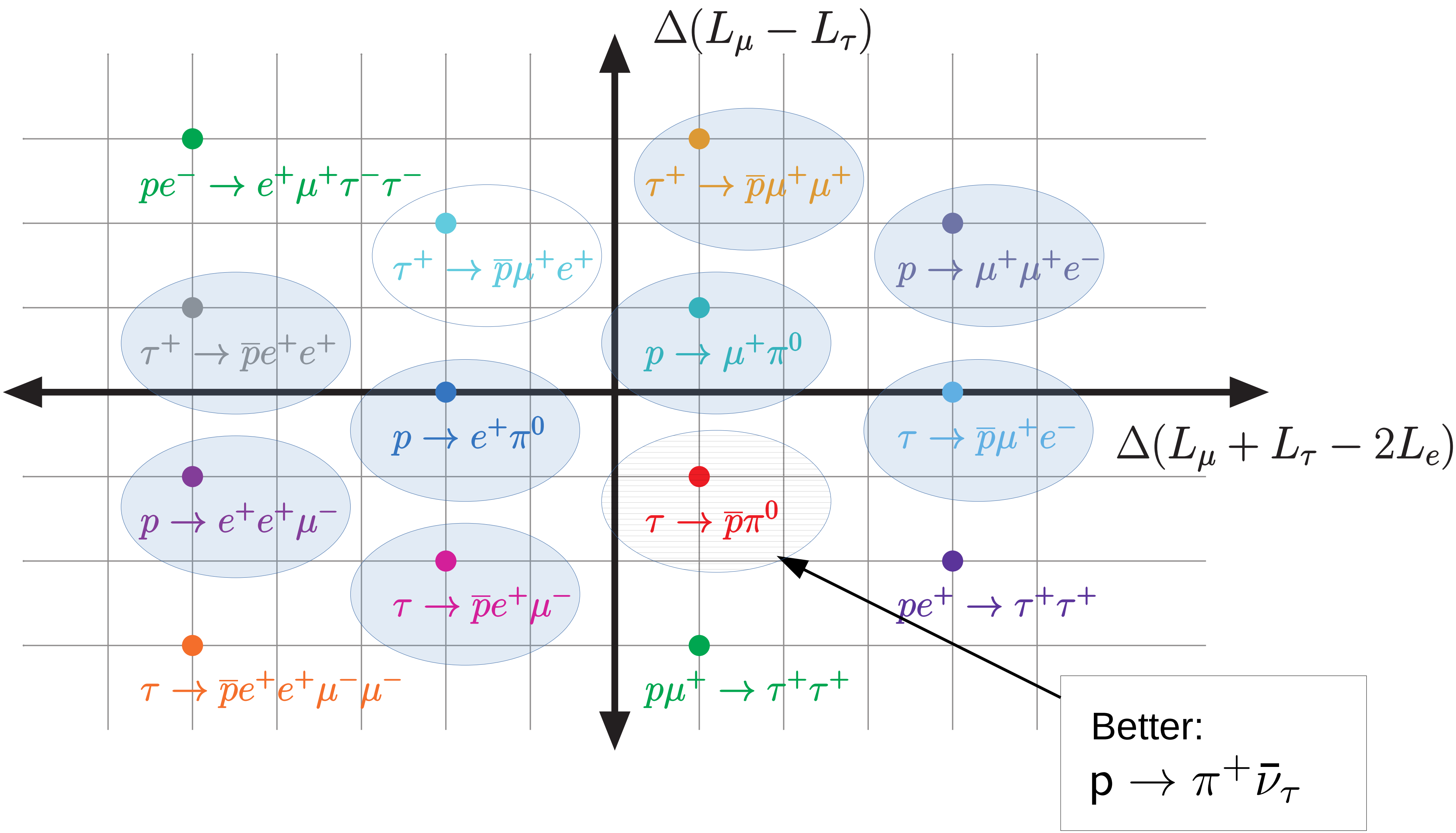
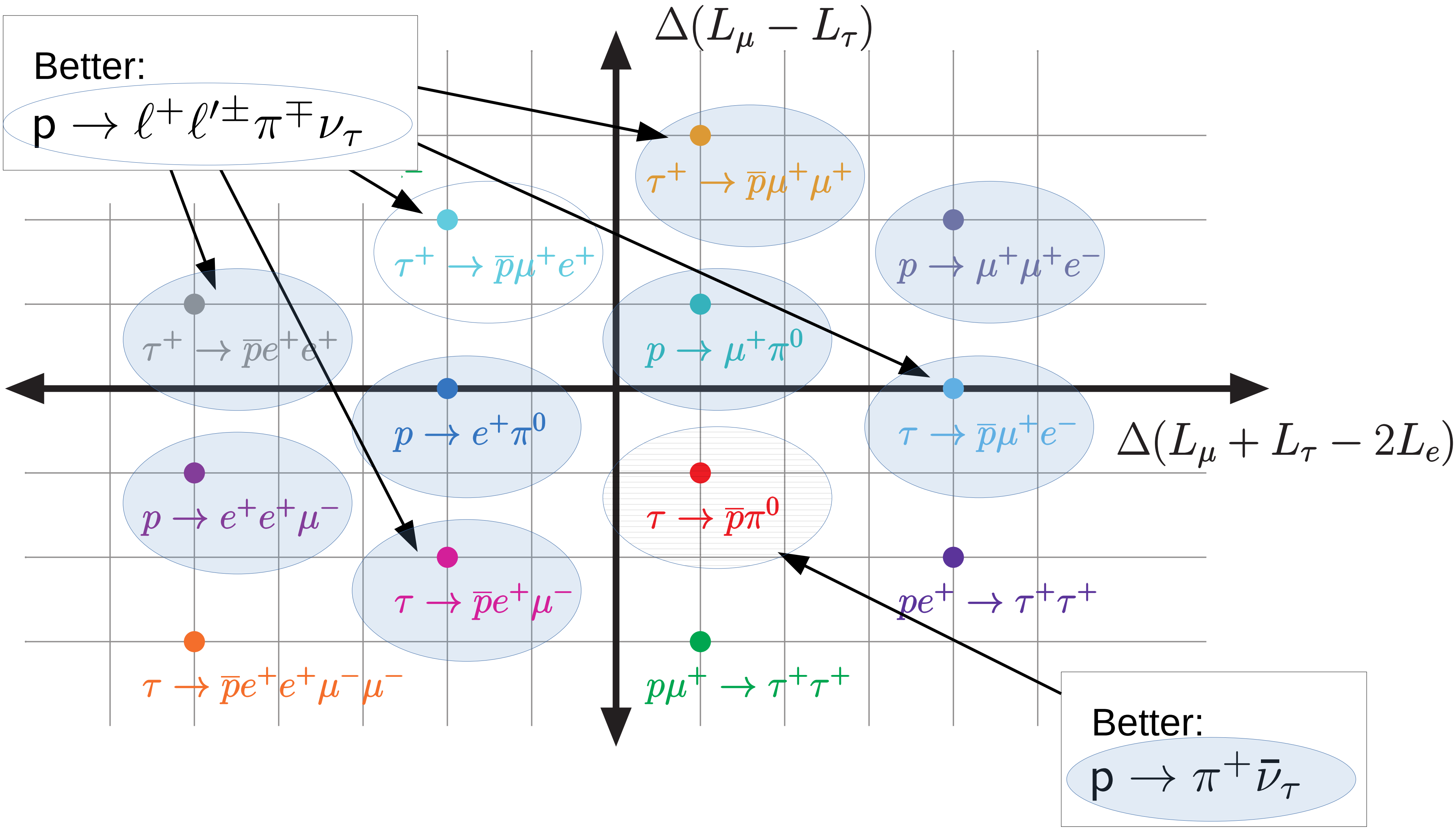


[Marciano, NPB '95]

Currently being probed: Old results: Doable:

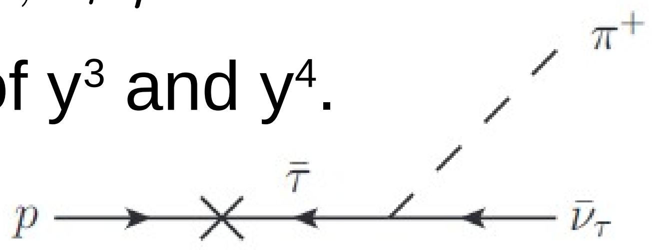
$\Delta B = \Delta L = 1$



[Marciano, NPB '95]

Δτ = ΔB = 1 operators

- d=6 operators: $y^1 duQL_\tau + y^2 QQQL_\tau + y^3 QQu\ell_\tau + y^4 duu\ell_\tau$
- All induce $\tau^- \to \bar{p}\pi^0, \bar{p}\eta$.
- But y^1 and y^2 immediately give $n \to \bar{\nu}_\tau \pi^0, \bar{\nu}_\tau \eta$.
- $p \to \bar{\nu}_\tau \pi^+$ probes a linear combination of y^3 and y^4.
- Last linear combination induces $\boxed{p \to \bar{\nu}_\tau \pi^+ \eta}$, only ancient inclusive limits! [JH & Watkins, in progress]



- Still, even with finetuning it seems difficult to get $\tau^- \to \bar{p}\pi^0, \bar{p}\eta$.
- Currently analyzing d>6 Δτ = ΔB = 1 operators in analogy.

Don't be discouraged to look for ΔB tau decays!

Probing *light* particles

- SMEFT only works for *heavy* new particles!
- *Light* new particles X give new signatures:
- $\mu \to e\, X$ or $\tau \to \ell\, X$, followed by (displaced) $X \to \ell^+\ell^-$, $\gamma\gamma$?

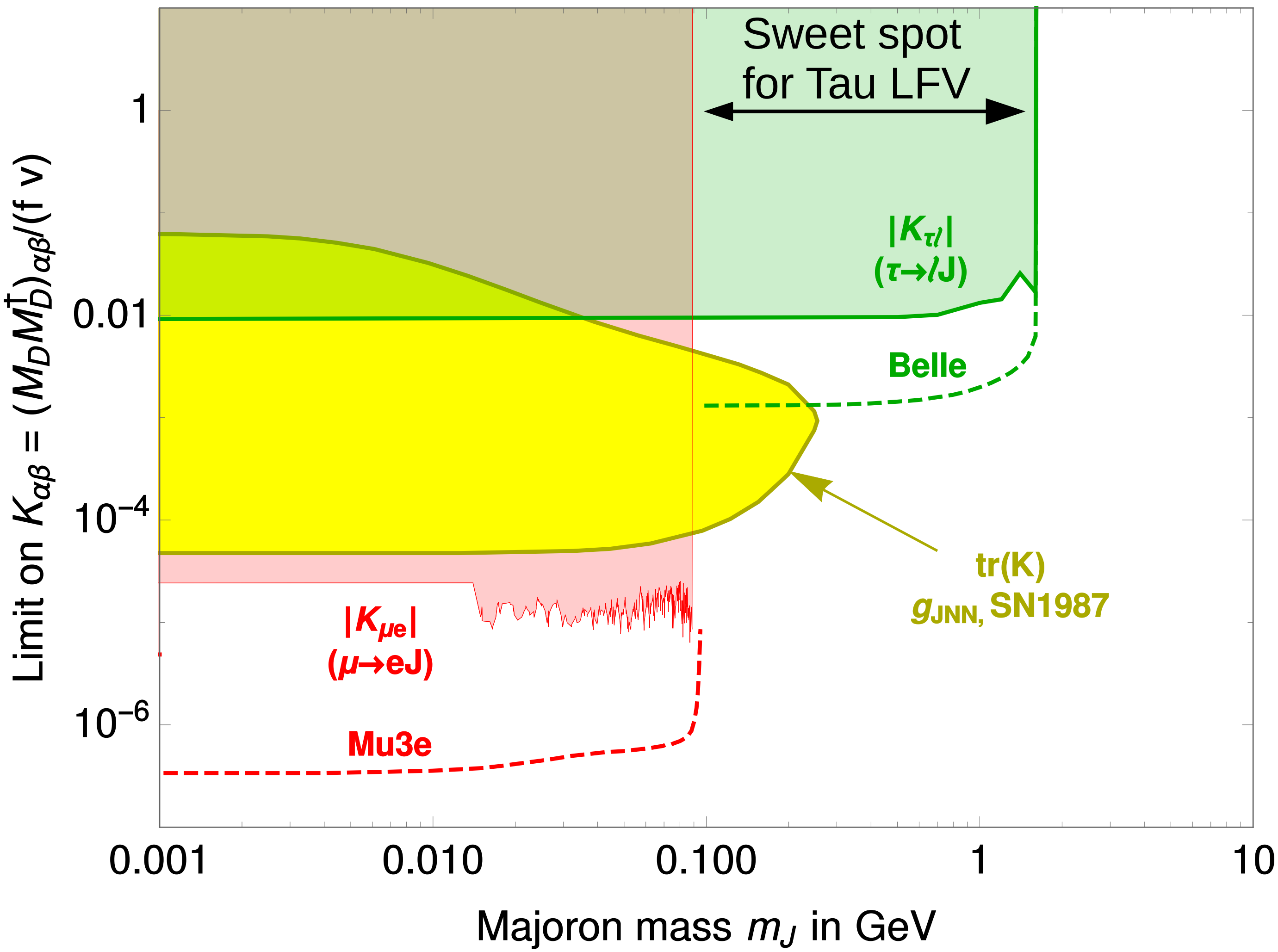
  [**JH** & Rodejohann, PLB '18; Cheung++, JHEP '21]
- Mu3e and Belle II can improve limits, maybe others too?

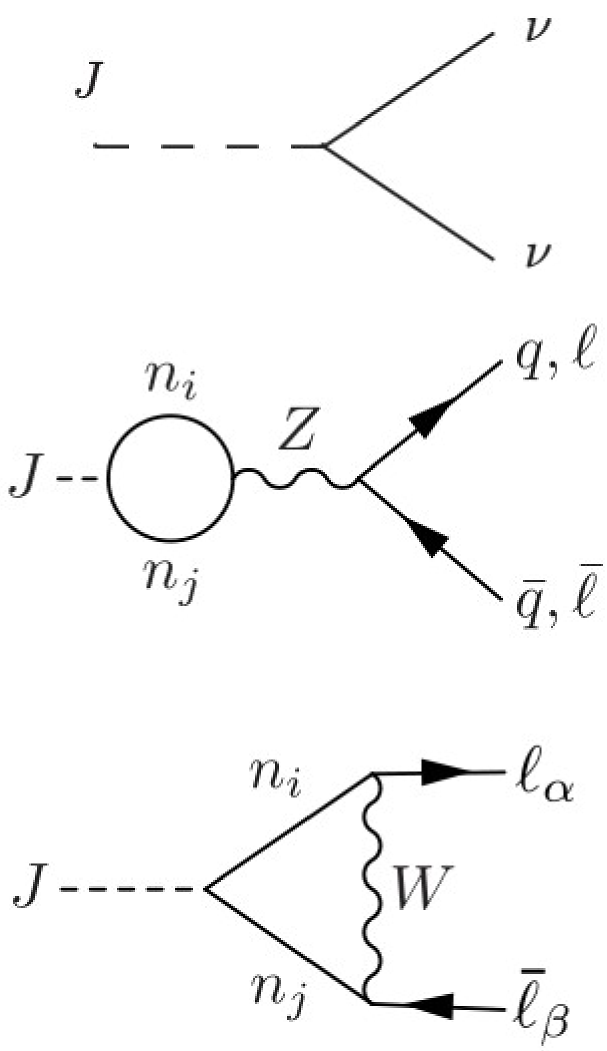
  [i Tormo++, PRD '11; Uesaka, PRD '20; Calibbi, Redigolo, Ziegler, Zupan, JHEP '21]
- Light particles as mediators change rate expectations.
- X = axion/ALP/majoron/familon/Z', connected to DM?
- Or: SMEFT + X.

  [Georgi, Kaplan, Randall, '86; Brivio++, '17; Dror, Lasenby, Pospelov, '17 & '19]

Far from finished!

Example: Majoron



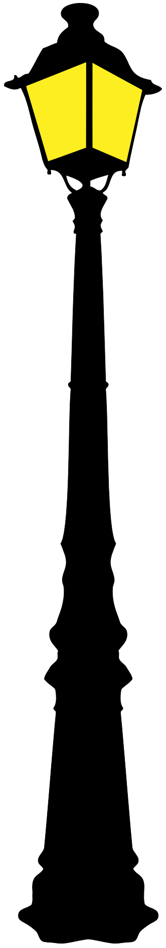


[**JH**, Garcia-Cely, JHEP '17]

Summary

- Charged LFV gives info *complementary* to ν oscillations.
- Tau LFV fertile ground for new-physics searches:
  - Access to many directions in flavor space.
  - Essential to study fate of $U(1)_{L_\mu - L_\tau} \times U(1)_{L_\mu + L_\tau - 2L_e}$ even if $\mu \to e\gamma$ found tomorrow.
- Future goals: tackle $\Delta\tau = 2$ and $d > 6$ operators at Belle-II and future colliders.
- Light new physics open new avenues, can probe particles up to m_τ.

Explore every corner of our lamppost!



Backup

Effective field theory view

- 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

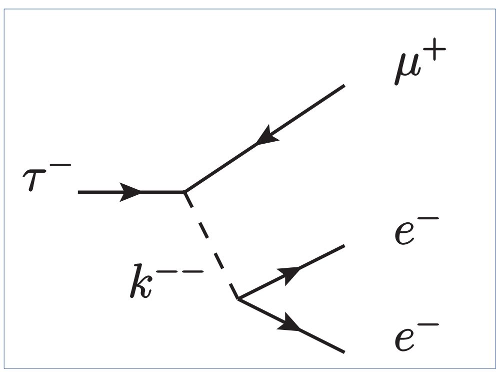
⇒ ‘weird’ channels dominate!?

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

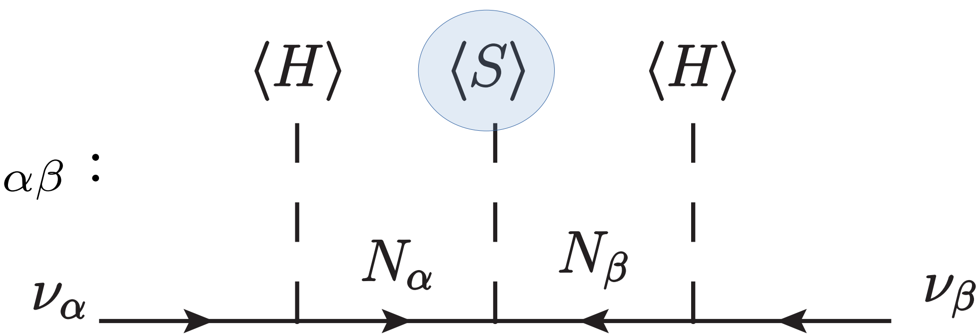
	$U(1)_Y$	$U(1)_{L_\mu - L_\tau}$
k^{++}	$+2$	0
S	0	$+1$
$N_{e,\mu,\tau}$	0	$0,\ +1,\ -1$

- Conserves $L_\mu - L_\tau$, so impose this!
- Simplest UV model:

$$\underbrace{\left(g_{\mu\tau}\overline{\mu}^c_R \tau_R + g_{ee}\overline{e}^c_R e_R\right) k^{++}}_{} + \underbrace{y\overline{L}HN_R + \tfrac{1}{2}\overline{N}^c_R\left(M_R^{\mathrm{sym}} + y_S\langle S\rangle\right) N_R}_{} \,.$$



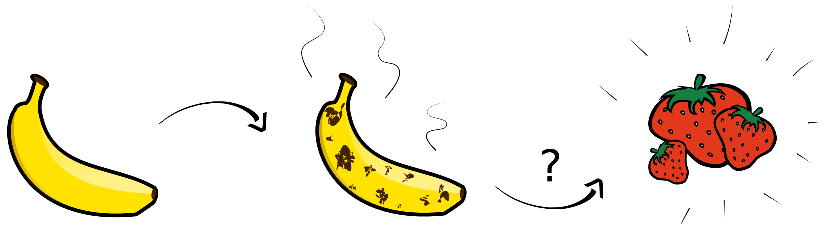
$(M_\nu)_{\alpha\beta}$:



- Only $\tau^- \to e^- e^- \mu^+$ is unsuppressed by M_ν.

ν oscillations but approximate symmetry in ℓ^- sector.

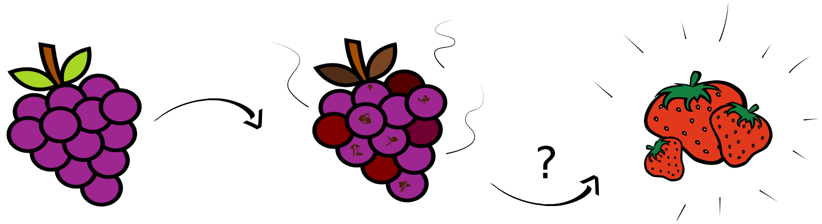
Flavor violating decays



- Prime example: $\mu \to e\gamma$ @ MEG.
- Observation = new particles (beyond SM *and* M_ν).
- $\mu \to e$ conversion @ Mu2e can probe scales up to 10^7 GeV.

LFV	process	current	future	exp
$\lvert\Delta L_e\rvert = \lvert\Delta L_\mu\rvert = 1$	$\mu \to e\gamma$	4.2×10^{-13}	6×10^{-14}	MEG-II
	$\mu \to e\bar{e}e$	1.0×10^{-12}	10^{-16}	Mu3e
	$\mu \to e$ conv.	$\mathcal{O}(10^{-12})$	10^{-16}	Mu2e, COMET
	$h \to e\bar{\mu}$	6.1×10^{-5}	10^{-5}	LHC
	$Z \to e\bar{\mu}$	7.5×10^{-7}	10^{-10}	FCC-ee
	had$\to e\bar{\mu}$(had)	4.7×10^{-12}	10^{-12}	NA62

Flavor violating decays



- Produce tauons at B factories (BaBar, Belle, LHCb).
- Observation = new particles (beyond SM *and* M_ν).
- $\tau^- \to e^- e^+ e^-$ @ Belle II will probe scales up to $2 \times 10^4\,\text{GeV}$.

LFV	process	current	future	exp
$\lvert\Delta L_e\rvert = \lvert\Delta L_\tau\rvert = 1$	$\tau \to e\gamma$	3.3×10^{-8}	10^{-9}	Belle II
	$\tau \to e\bar{\ell}\ell$	2.7×10^{-8}	10^{-9}	Belle II
	$\tau \to e\,\text{had}$	$\mathcal{O}(10^{-8})$	10^{-9}	Belle II
	$h \to e\bar{\tau}$	4.7×10^{-3}	10^{-4}	LHC
	$Z \to e\bar{\tau}$	9.8×10^{-6}	10^{-9}	FCC-ee
	had$\to e\bar{\tau}(\text{had})$	$\mathcal{O}(10^{-6})$	–	Belle II

Upcoming CLFV

84 LORENZO CALIBBI and GIOVANNI SIGNORELLI

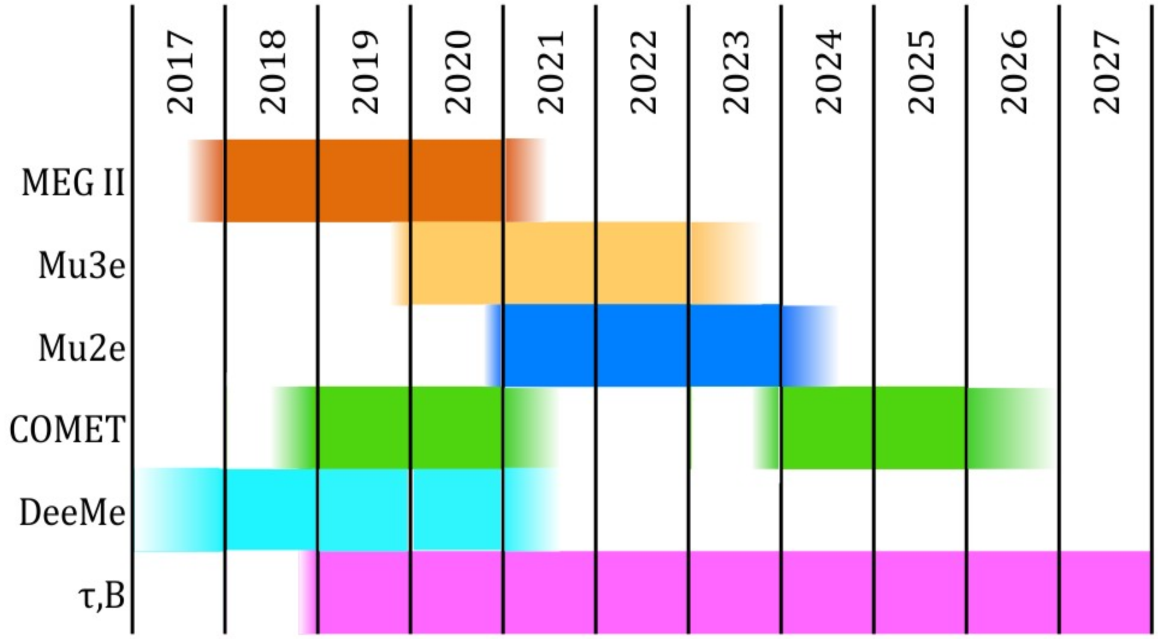
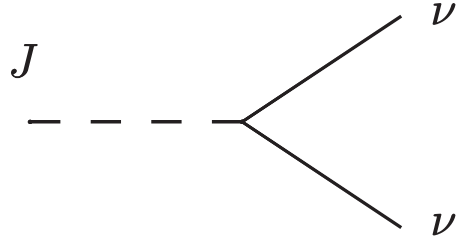


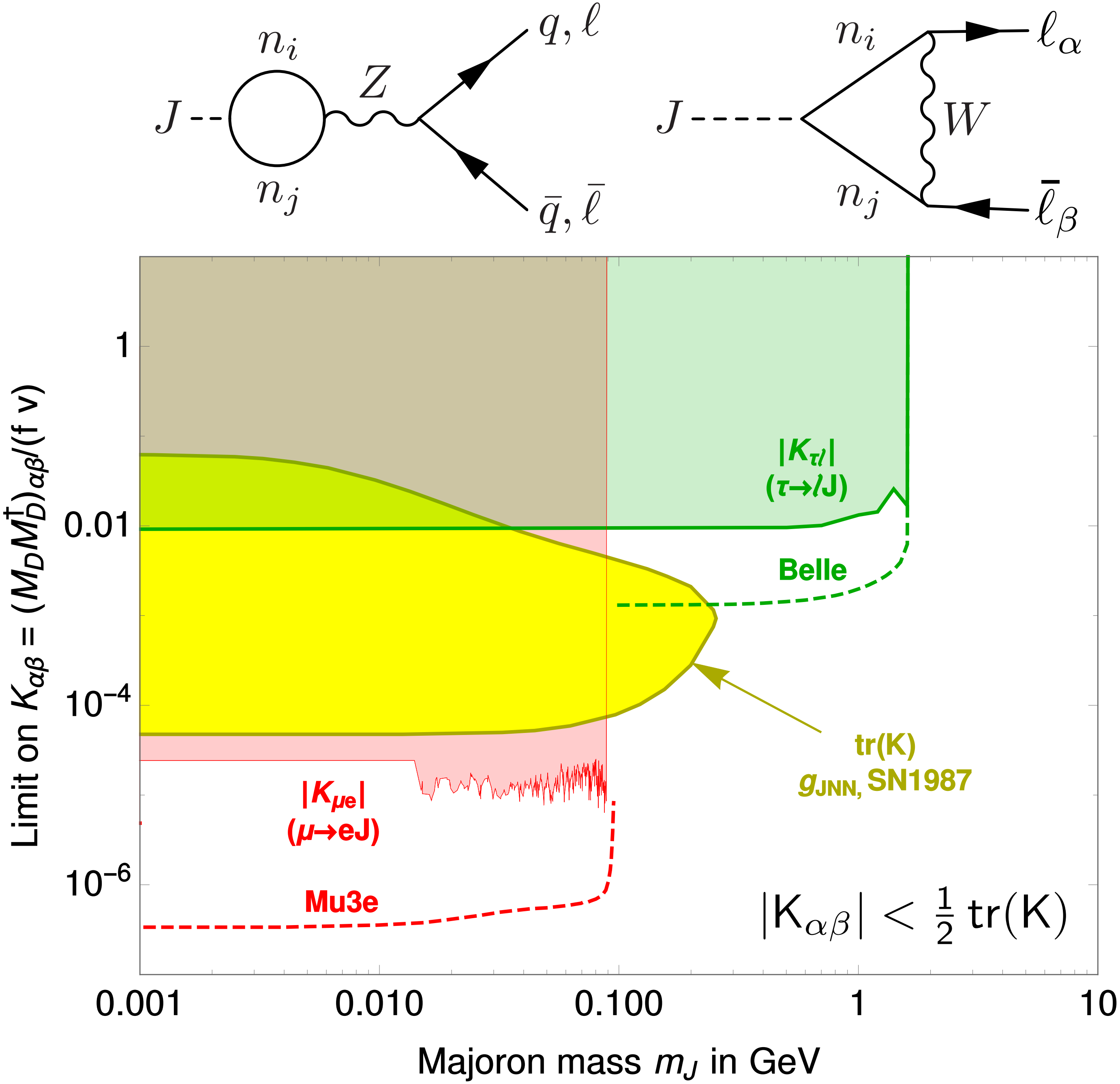
Figure 47. – Projected time lines for different projects searching for CLFV decays. MEG IIis expected to start data taking in 2018 after an engineering run in 2017; Mu3e magnet and detectors are expected at the end of 2019; Mu2e foresees three years of data taking starting in 2021; COMET Phase-I is expected 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]

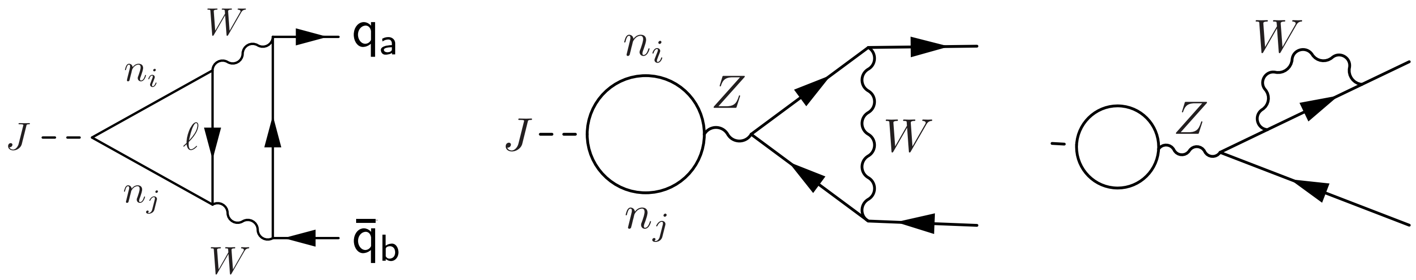
Probing light particles

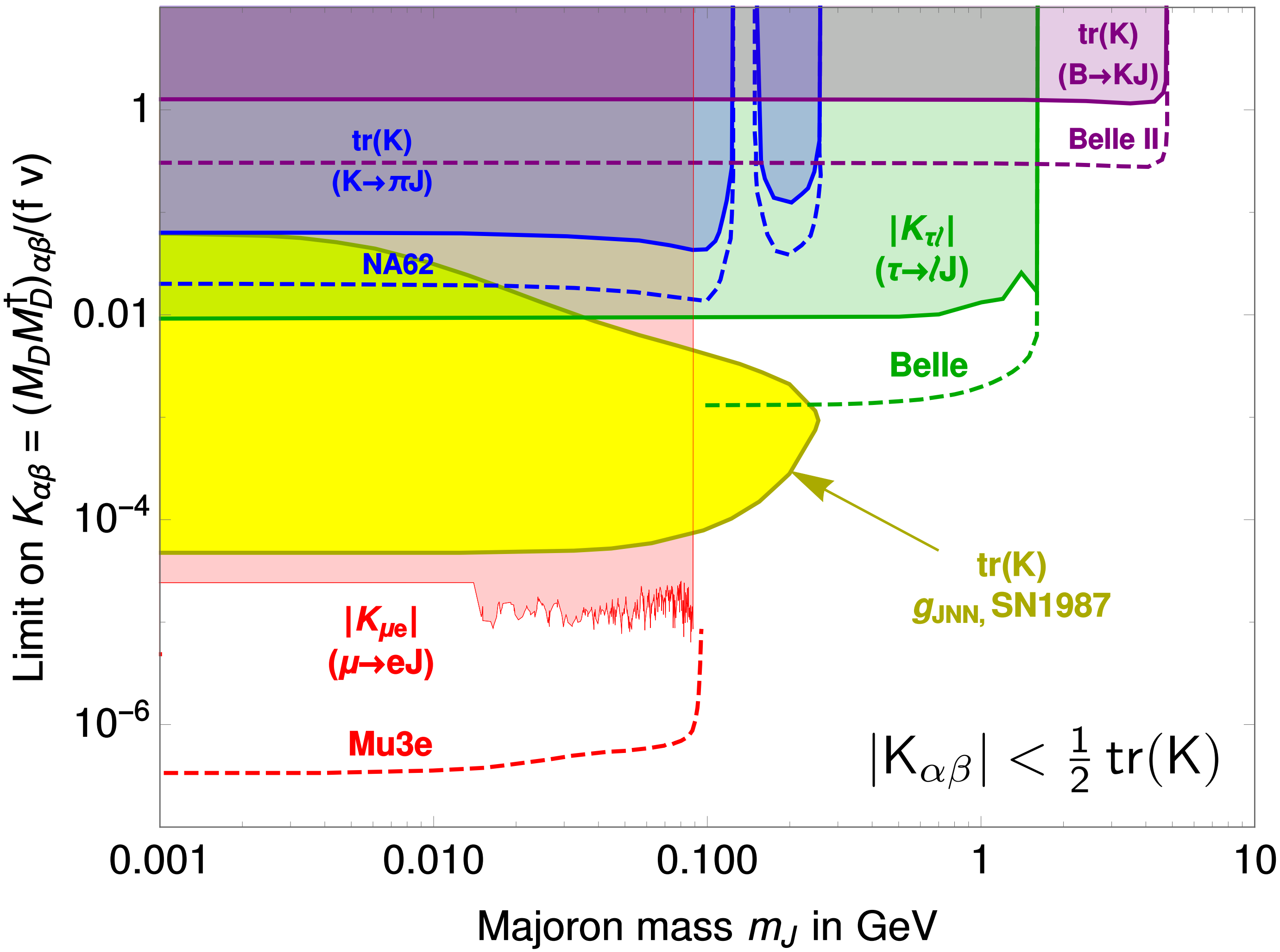
- Mu3e: BR($\mu \to e\, X$) from 10^{-6} to 10^{-8}.
- Belle II: BR($\tau \to \ell\, X$) from 10^{-3} to 10^{-5}. [**JH**, PLB ‘16]
- Followed by (displaced) $X \to \ell^+\ell^-$, $\gamma\gamma$? [**JH**, Rodejohann, PLB ‘18]
- Example: Majoron.
  - Pseudo-Goldstone boson of lepton number.
  - Potential dark matter candidate. [**JH**, Garcia-Cely, JHEP ‘17]
  - Tree-level coupling only to neutrinos.





[**JH**, Garcia-Cely, JHEP '17]

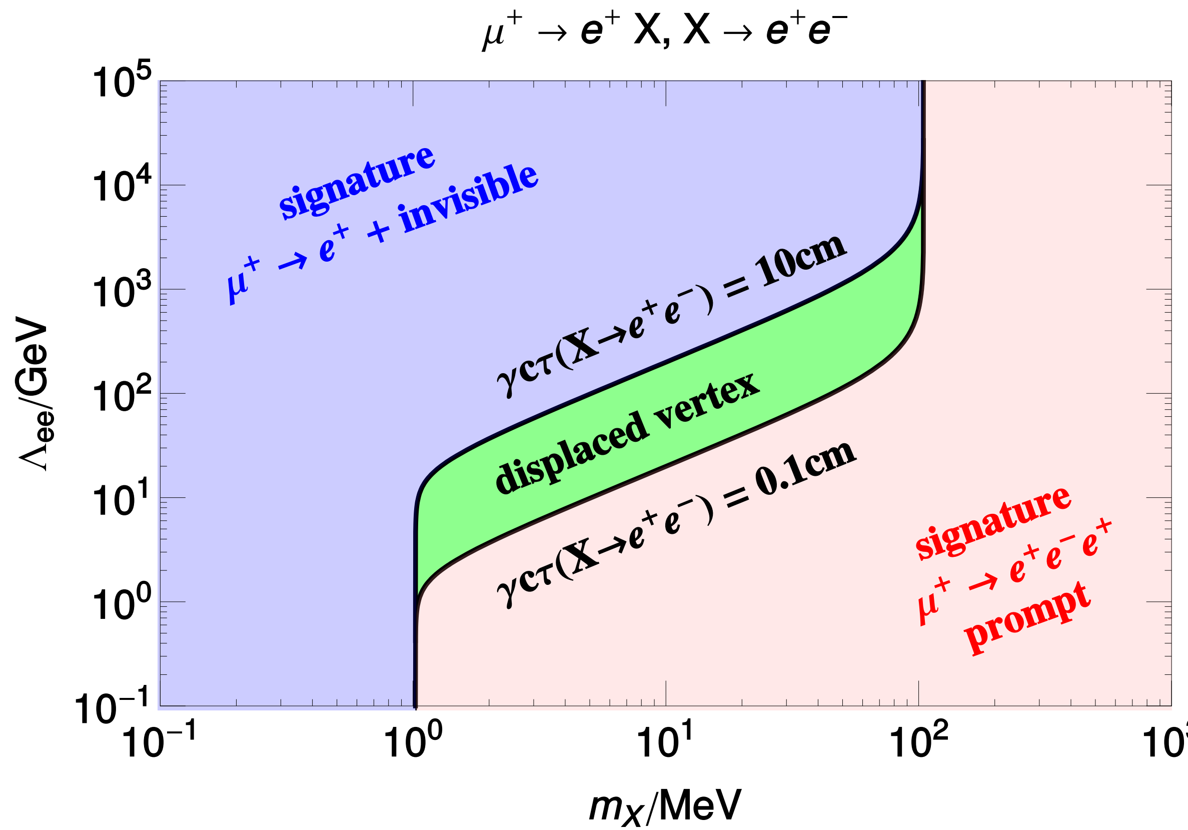




[**JH**, Patel, PRD '19]

μ → e X with X → visible

- Take $X\bar{e}\gamma_5 e\, m_e/\Lambda_{ee}$.
- Decay length determines signature.
- Displaced vertex gives new observable. [**JH**, Rodejohann, PLB '18]



- Muon at rest:

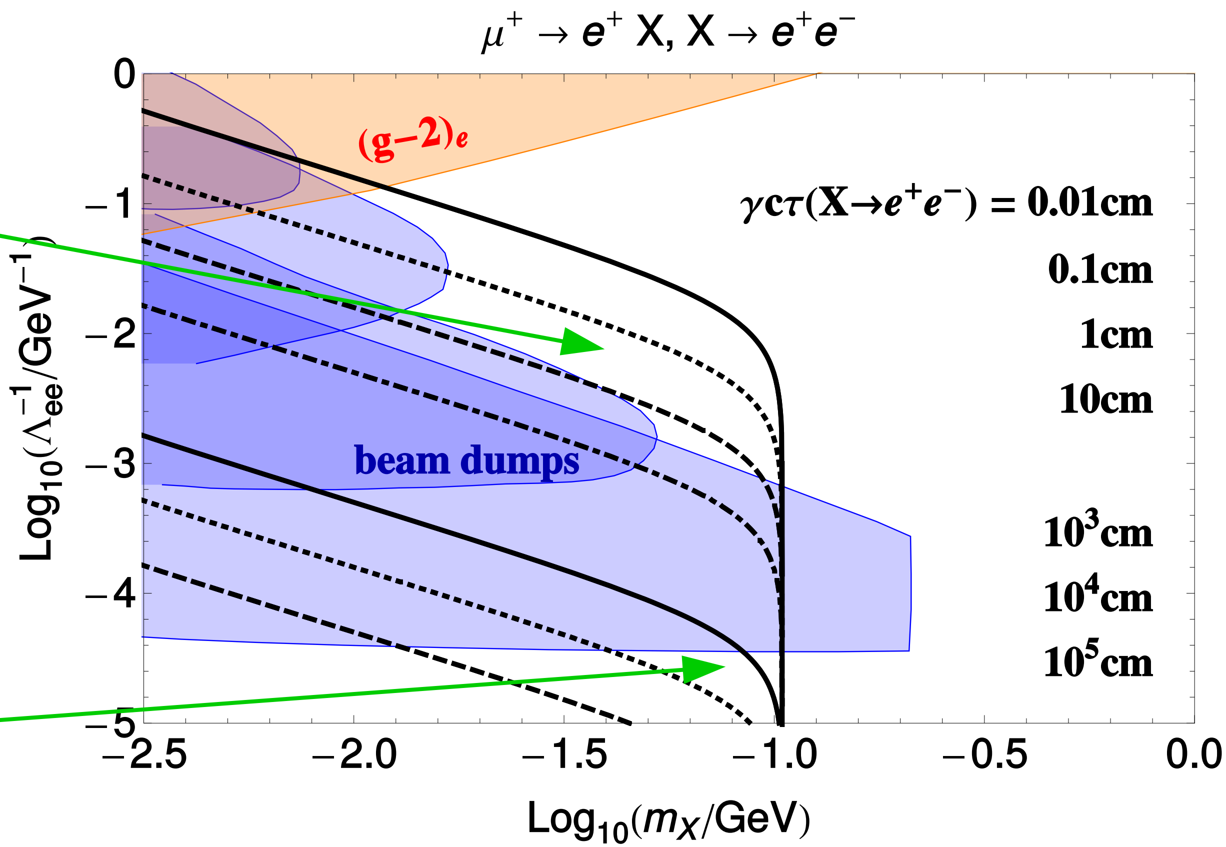
$$\gamma c\tau \simeq \frac{\pi m_\mu \Lambda_{ee}^2}{m_e^2 m_X^2} \simeq 2.5\,\mathrm{cm}\left(\frac{\Lambda_{ee}}{100\ \mathrm{GeV}}\right)^2 \left(\frac{10\ \mathrm{MeV}}{m_X}\right)^2 .$$

Sub-GeV X with ee coupling allowed?

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

[**JH**, Rodejohann, PLB '18]

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



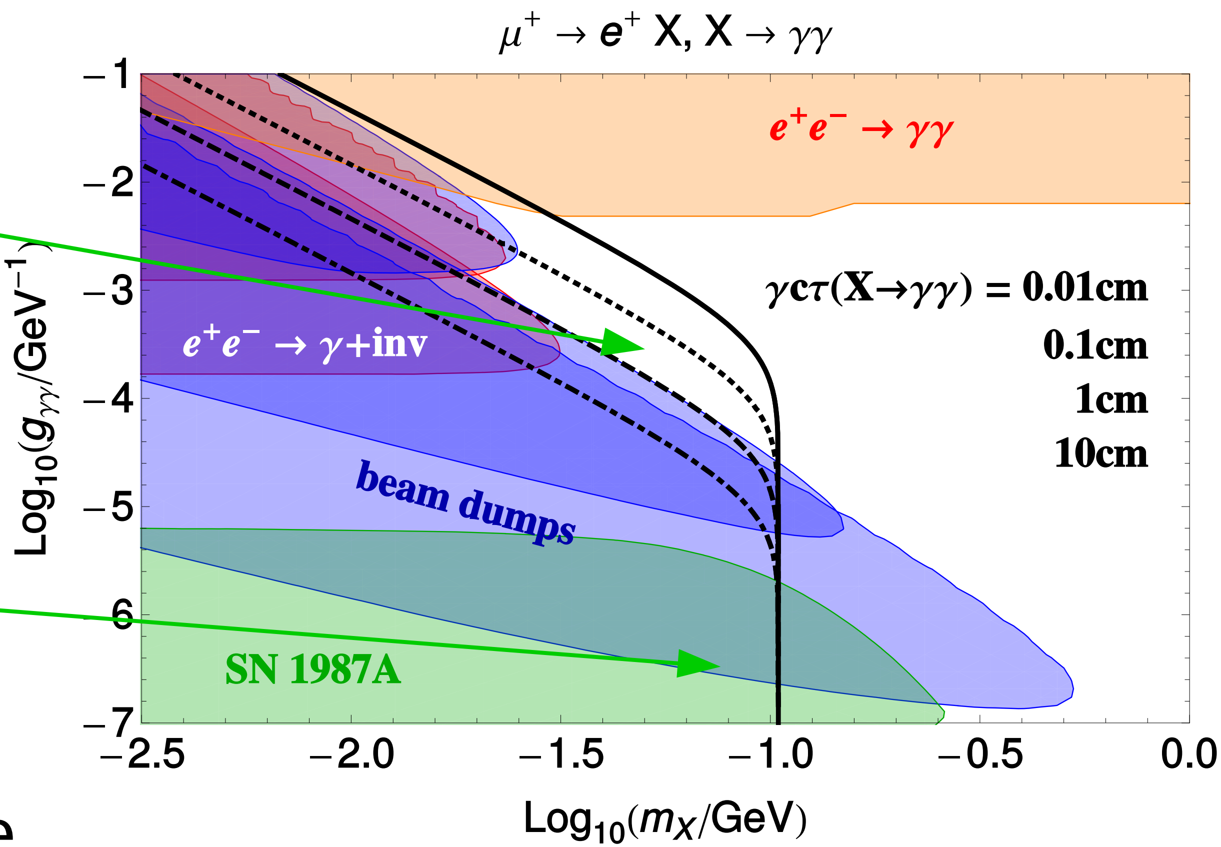
$$\mathrm{BR}(\mu \to \mathrm{e}X)\mathrm{BR}(X \to \mathrm{ee})(1 - P(l_{\mathrm{dec}})) \simeq \mathrm{BR}(\mu \to \mathrm{e}X)\frac{l_{\mathrm{dec}}}{\gamma c \tau}\,.$$

Possible in Mu3e!

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

[JH, Rodejohann, PLB '18]

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



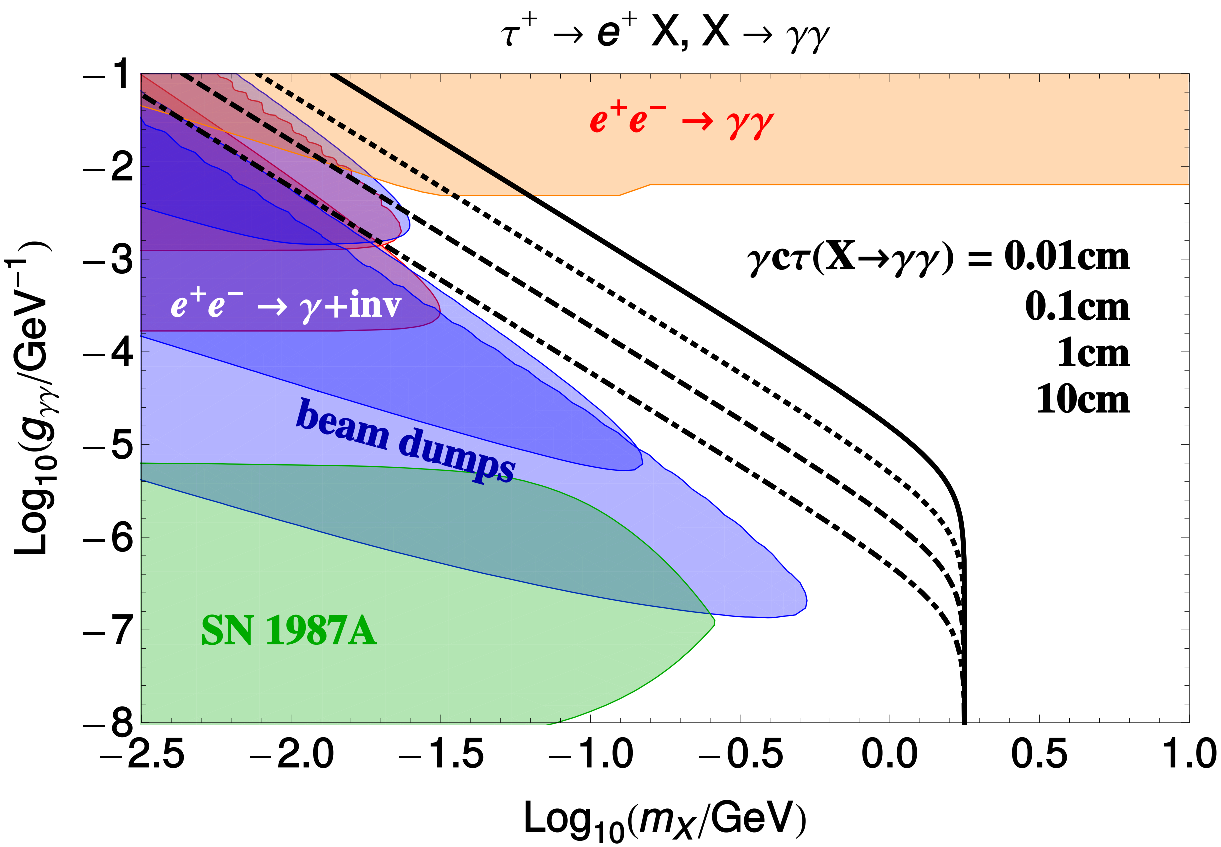
[Limits: Dolan et al, JHEP '17]

Muons difficult, taus easier.

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

[**JH**, Rodejohann, PLB '18]

- Tau at rest, higher X boost.
- Arbitrary decay lengths possible.
- Similar for $X \to ee, \mu\mu, \mu e$.
- Worthwhile in LHCb and Belle (II).

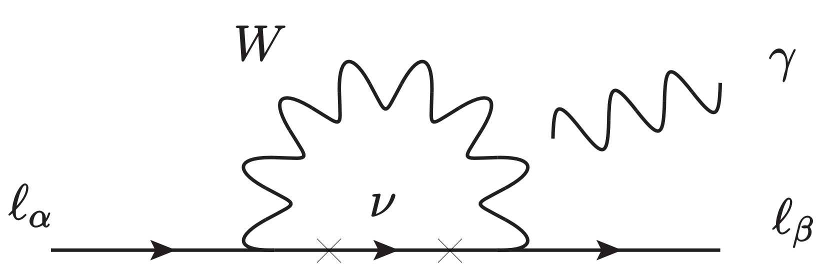


[Limits: Dolan et al, JHEP '17]

New signatures from light physics!

Neutrino mass ⇒ charged LFV?

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



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

- *All* CLFV is GIM suppressed:

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

[1977: Petcov; Bilenky, Petcov, Pontecorvo; Marciano, Sanda; Lee, Pakvasa, Shrock, Sugawara]

Seesaw mass ⇒ charged LFV?

- SM + seesaw neutrinos: $$\mathrm{L} = \mathrm{L}_{\mathrm{SM}} + i\overline{\mathrm{N}}_{\mathrm{R}}\not{\partial}\mathrm{N}_{\mathrm{R}} - \left(\tfrac{1}{2}\mathrm{M}_{\mathrm{R}}\overline{\mathrm{N}}_{\mathrm{R}}^{c}\mathrm{N}_{\mathrm{R}} + \underbrace{y\overline{\mathrm{L}}\mathrm{H}\mathrm{N}_{\mathrm{R}}}_{\mathrm{m}_{\mathrm{D}}\overline{\nu}_{\mathrm{L}}\mathrm{N}_{\mathrm{R}}} + \mathrm{h.c.}\right)$$
- Violates $\Delta L = 2$. For large M_R:

$$\mathrm{M}_{\mathrm{N}} \simeq \mathrm{M}_{\mathrm{R}}\,, \qquad \mathrm{M}_{\nu} \simeq -\mathrm{m}_{\mathrm{D}}\mathrm{M}_{\mathrm{R}}^{-1}\mathrm{m}_{\mathrm{D}}^{T} = \mathrm{U}^{*}\,\mathrm{diag}(\mathrm{m}_1, \mathrm{m}_2, \mathrm{m}_3)\mathrm{U}^{\dagger}.$$

- Majorana neutrinos!
- LFV:

$$\frac{\Gamma(\ell_\alpha \to \ell_\beta \gamma)}{\Gamma(\ell_\alpha \to \ell_\beta \nu_\alpha \overline{\nu}_\beta)} \simeq \frac{3\alpha_{\mathrm{EM}}}{8\pi}\underbrace{\left|(\mathrm{m}_{\mathrm{D}}\mathrm{M}_{\mathrm{R}}^{-2}\mathrm{m}_{\mathrm{D}}^{\dagger})_{\alpha\beta}\right|^2}_{\mathcal{O}(\mathrm{M}_\nu^4/\mathrm{m}_{\mathrm{D}}^4)}.$$

[Cheng & Li ‘80]

Not true with fine-tuning or structure in m_D.

Neutrino-mass models *can* give LFV

$$\mathsf{L}_{\text{seesaw}} = \mathsf{L}_{\text{SM}} + i\overline{N}_R \partial\!\!\!/ N_R - \left(\tfrac{1}{2} M_R \overline{N}_R^c N_R + m_D \overline{\nu}_L N_R + \text{h.c.}\right)$$

$$\Rightarrow \quad M_\nu \simeq -m_D M_R^{-1} m_D^T \quad \& \quad \mathrm{BR}(\ell_\alpha \to \ell_\beta \gamma) \propto |(m_D M_R^{-2} m_D^\dagger)_{\alpha\beta}|^2 .$$

- One to one correspondence

$$\boxed{\{m_D, M_R\} \leftrightarrow \{M_\nu, m_D M_R^{-2} m_D^\dagger\}.}$$

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

- Matrix structure decouples LFV from M_ν.

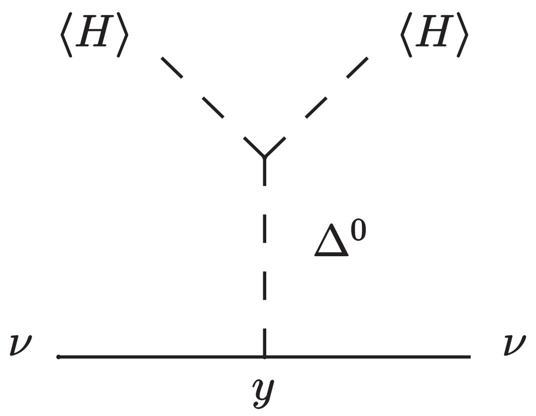
$$\boxed{\text{LFV } \textit{complementary} \text{ to } M_\nu!}$$

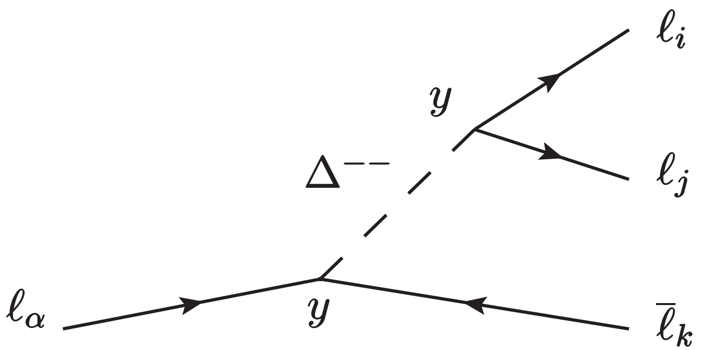
- Fairly generic conclusion, makes it difficult to predict LFV.

Scalar-triplet seesaw

[Konetschny & Kummer '77; Magg & Wetterich, '80; Schechter & Valle '80; Cheng & Li, '80; Mohapatra & Senjanovic, '81]

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





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

[Pich, Santamaria, Bernabeu, '84; Abada++, 0707.4058]

Prediction of LFV *ratios* via M_ν!

CDF's W-mass first hint for this triplet with O(100 GeV) mass? [Heeck, 2204.10274]