Lepton Flavor Violation by Two Units

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Based on: PLB ‘24 [2401.09580] with Mikheil Sokhashvili

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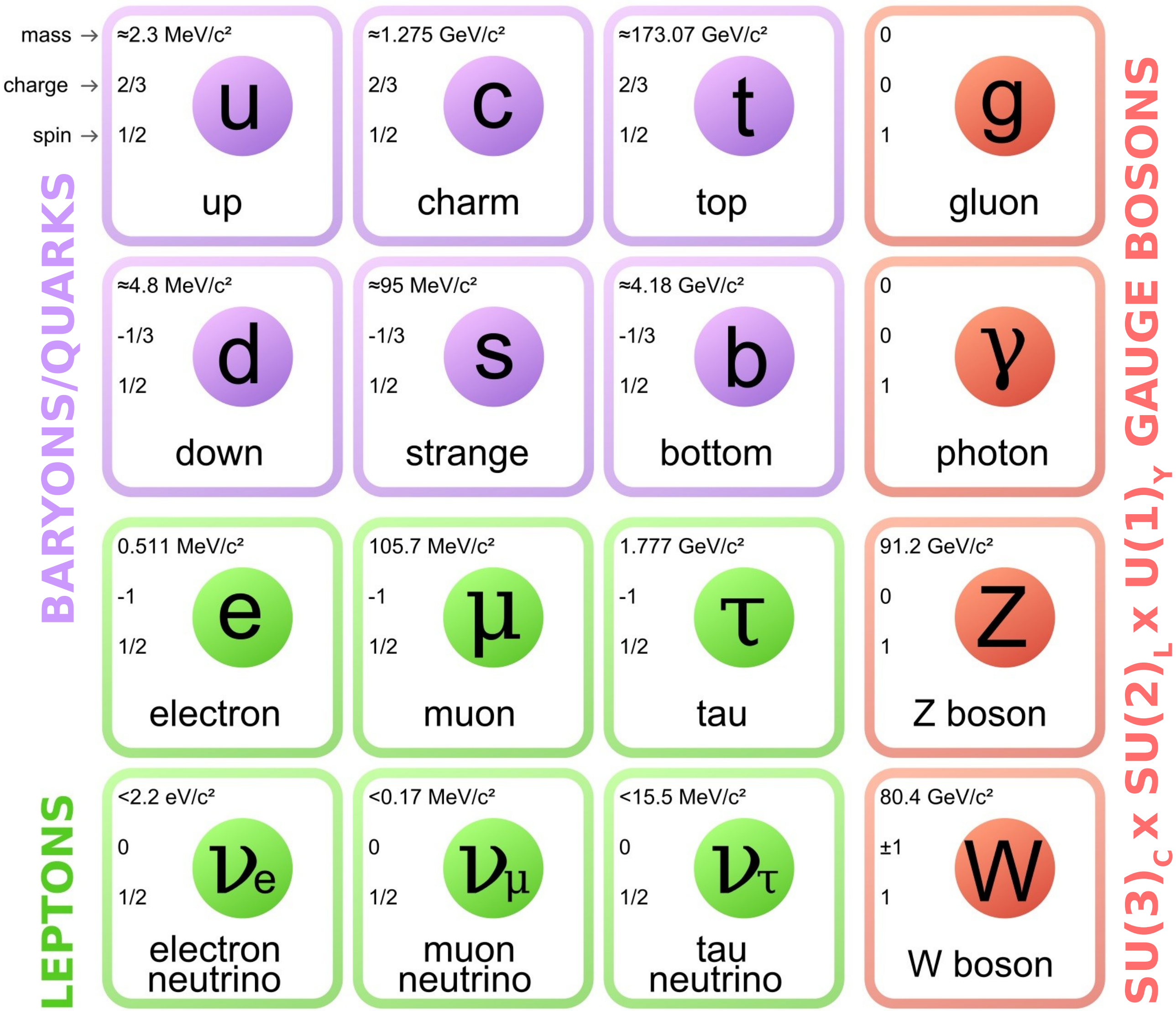
NSF

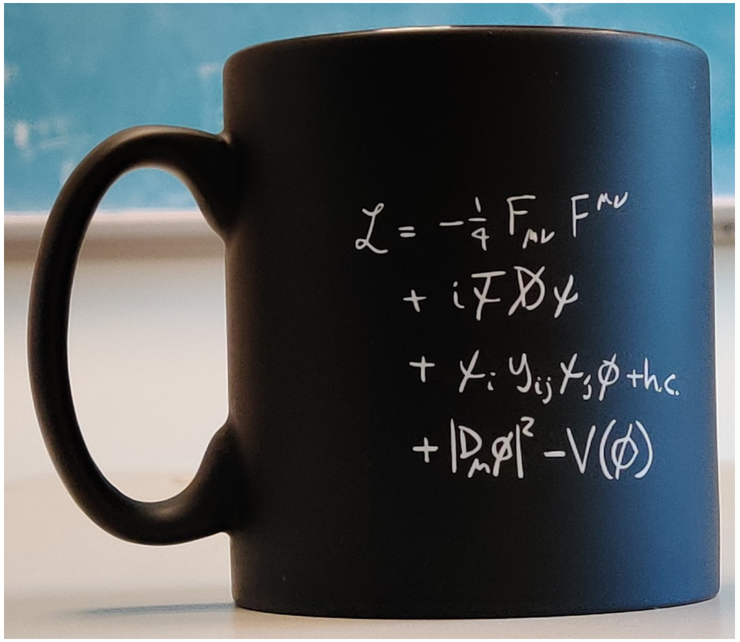
Standard Model of Particle Physics



≈126 GeV/c²
0
0
H
Higgs boson

SCALARS

Englert & Higgs '13



[wikipedia]

Symmetries of the Standard Model

- Rephasing quark and lepton fields:

$$U(1)_B \times U(1)_{L_e} \times U(1)_{L_\mu} \times U(1)_{L_\tau}$$
$$=$$
$$U(1)_B \times U(1)_L \times U(1)_{L_\mu - L_\tau} \times U(1)_{L_\mu + L_\tau - 2L_e} \, .$$

⇒ Lepton flavor conservation

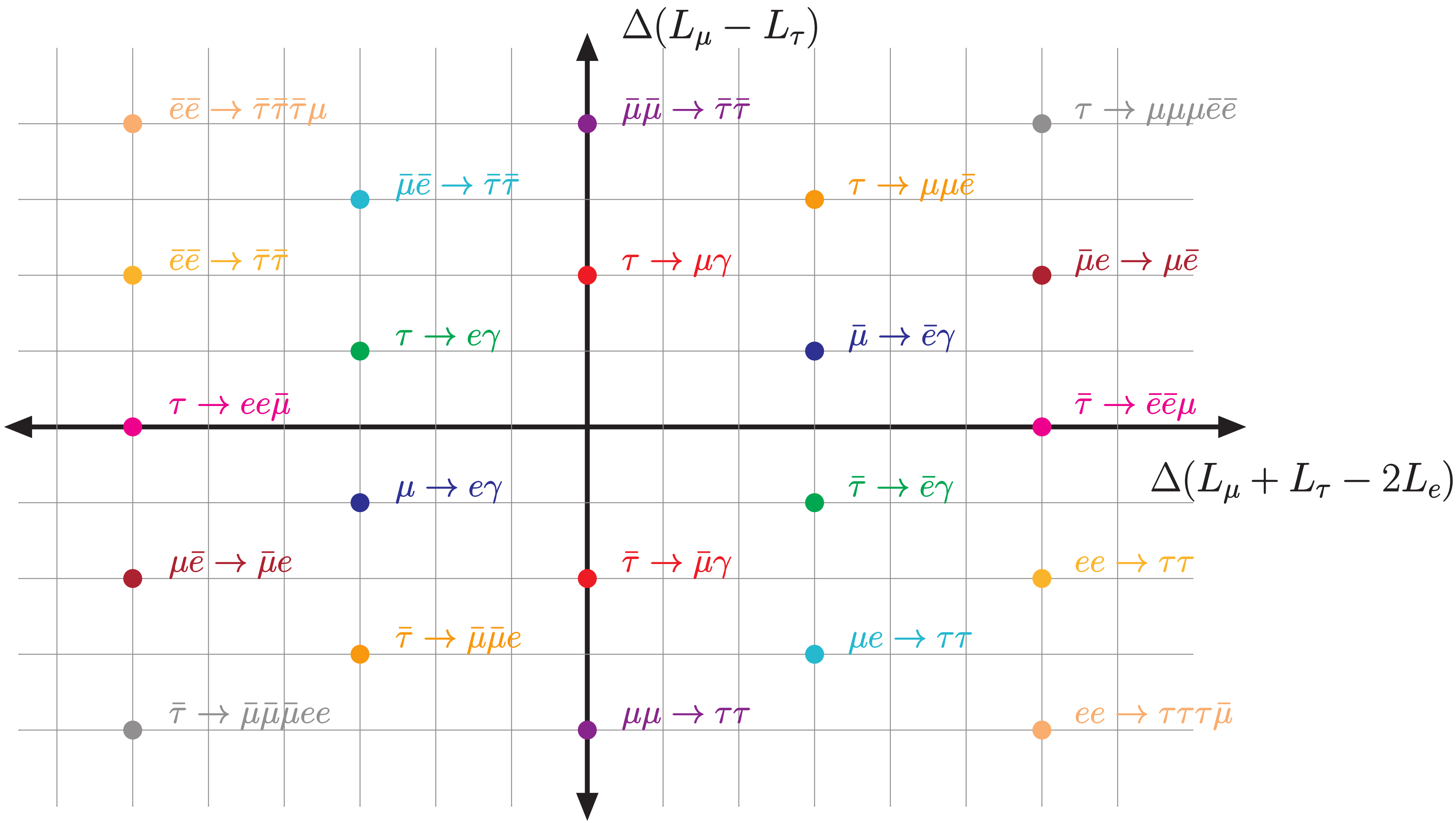
- $(U(1)_{B+L}$ broken to Z_3 non-perturbatively, but unobservable.)

['t Hooft, PRL '76]

Four conservation laws predicted by SM

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

[**JH**, 1610.07623]



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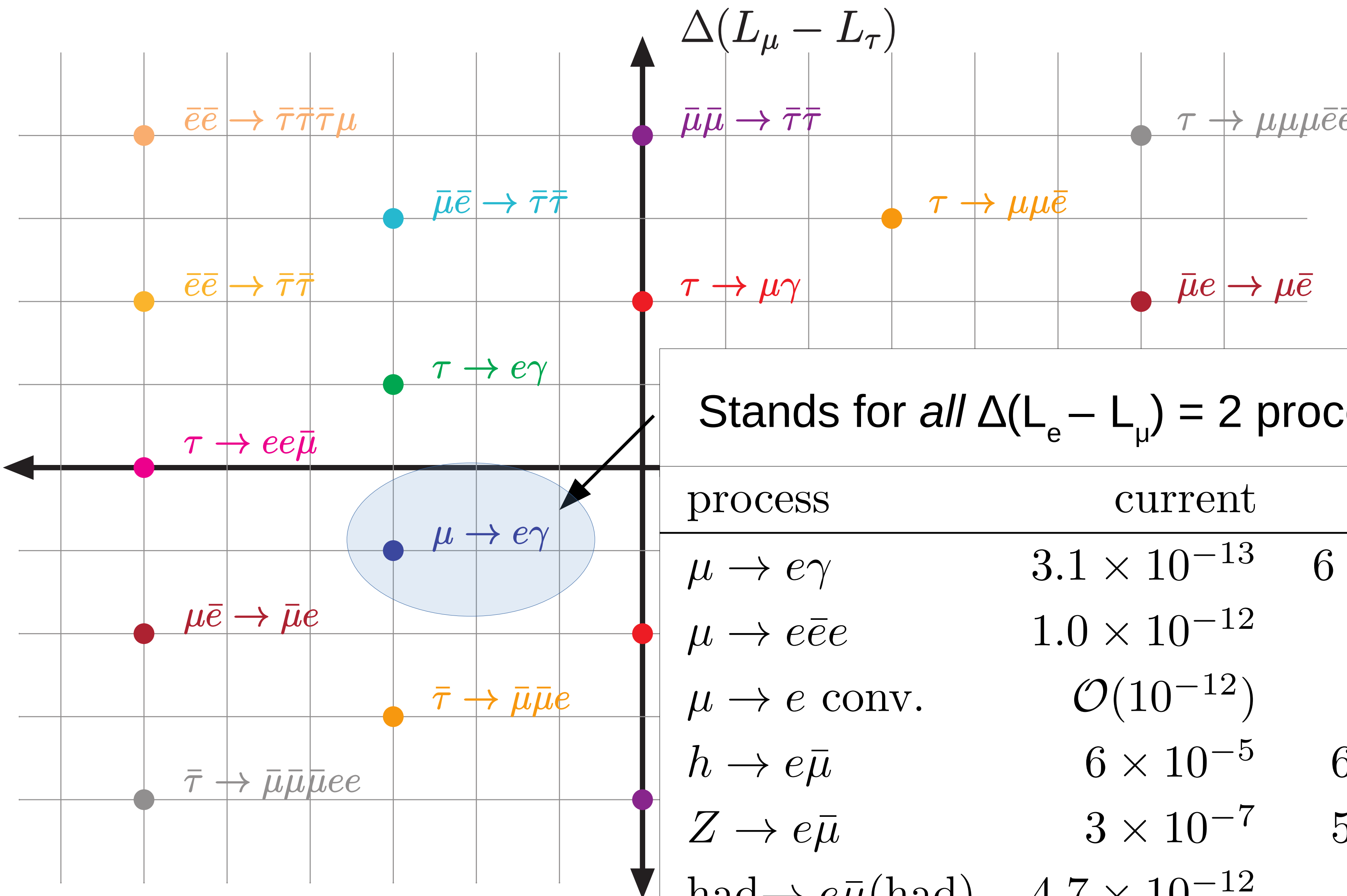


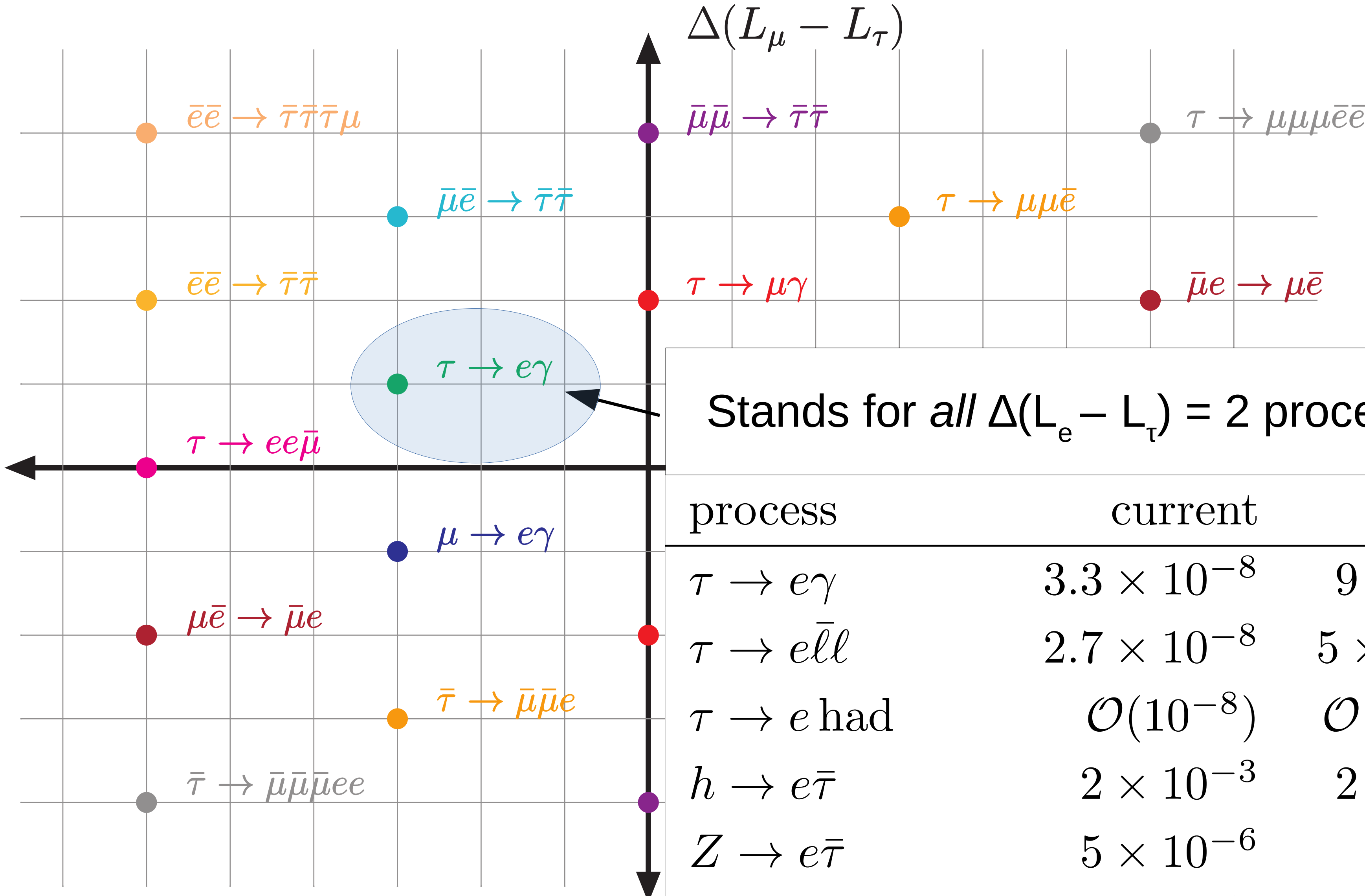
Stands for *all* $\Delta(L_e - L_\mu) = 2$ processes:

process	current	future
$\mu \to e\gamma$	3.1×10^{-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}
$h \to e\bar\mu$	6×10^{-5}	6×10^{-6}
$Z \to e\bar\mu$	3×10^{-7}	5×10^{-8}
had$\to e\bar\mu$(had)	4.7×10^{-12}	–

(See talk by Ana Teixeira.)

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

[JH, 1610.07623]



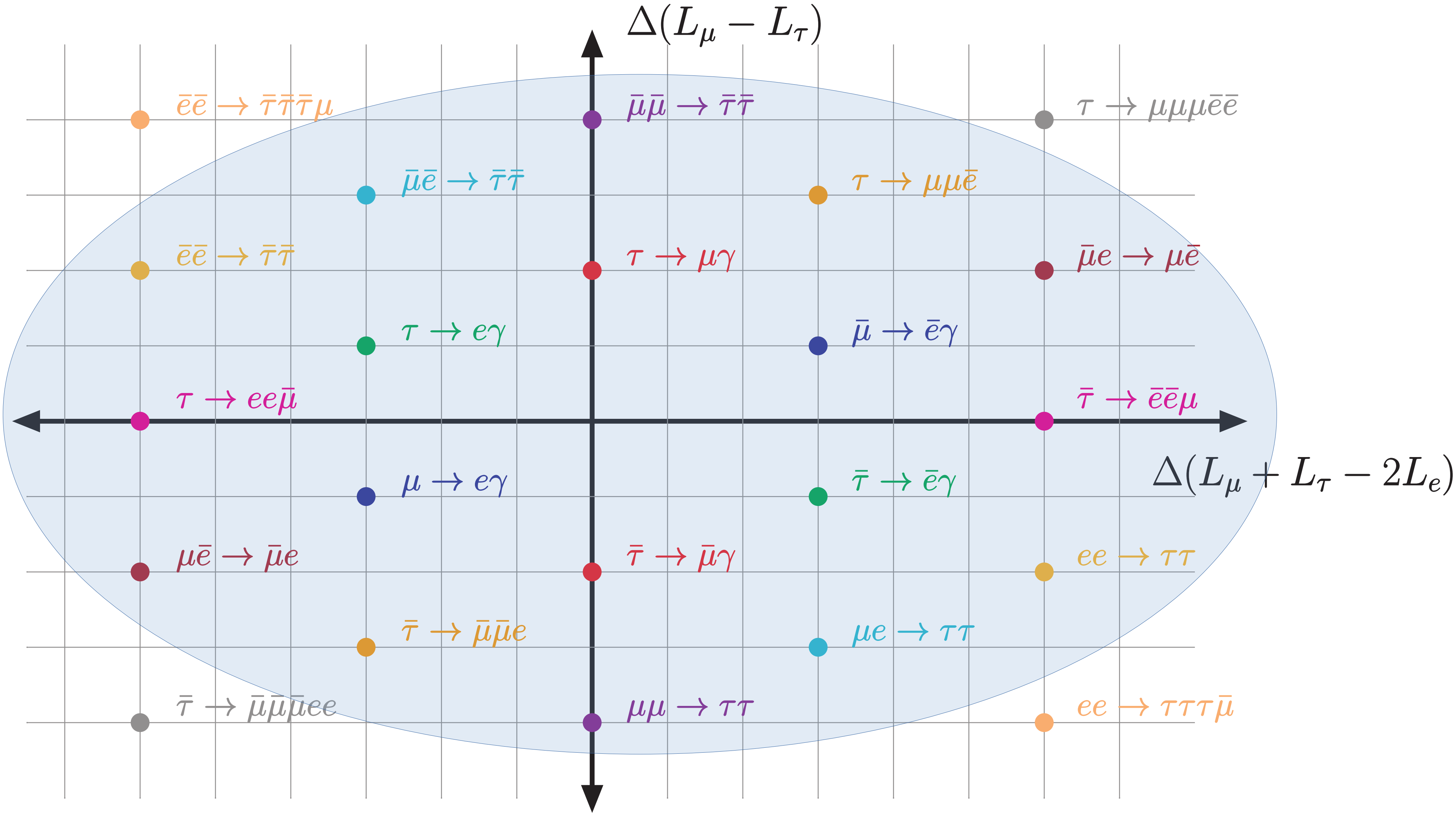
Stands for *all* $\Delta(L_e - L_\tau) = 2$ processes:

process	current	future
$\tau \to e\gamma$	3.3×10^{-8}	9×10^{-9}
$\tau \to e\bar{\ell}\ell$	2.7×10^{-8}	5×10^{-10}
$\tau \to e\,\text{had}$	$\mathcal{O}(10^{-8})$	$\mathcal{O}(10^{-10})$
$h \to e\bar{\tau}$	2×10^{-3}	2×10^{-4}
$Z \to e\bar{\tau}$	5×10^{-6}	10^{-6}
had$\to e\bar{\tau}(\text{had})$	$\mathcal{O}(10^{-5})$	$\mathcal{O}(10^{-6})$

(See talk by Ana Teixeira.)

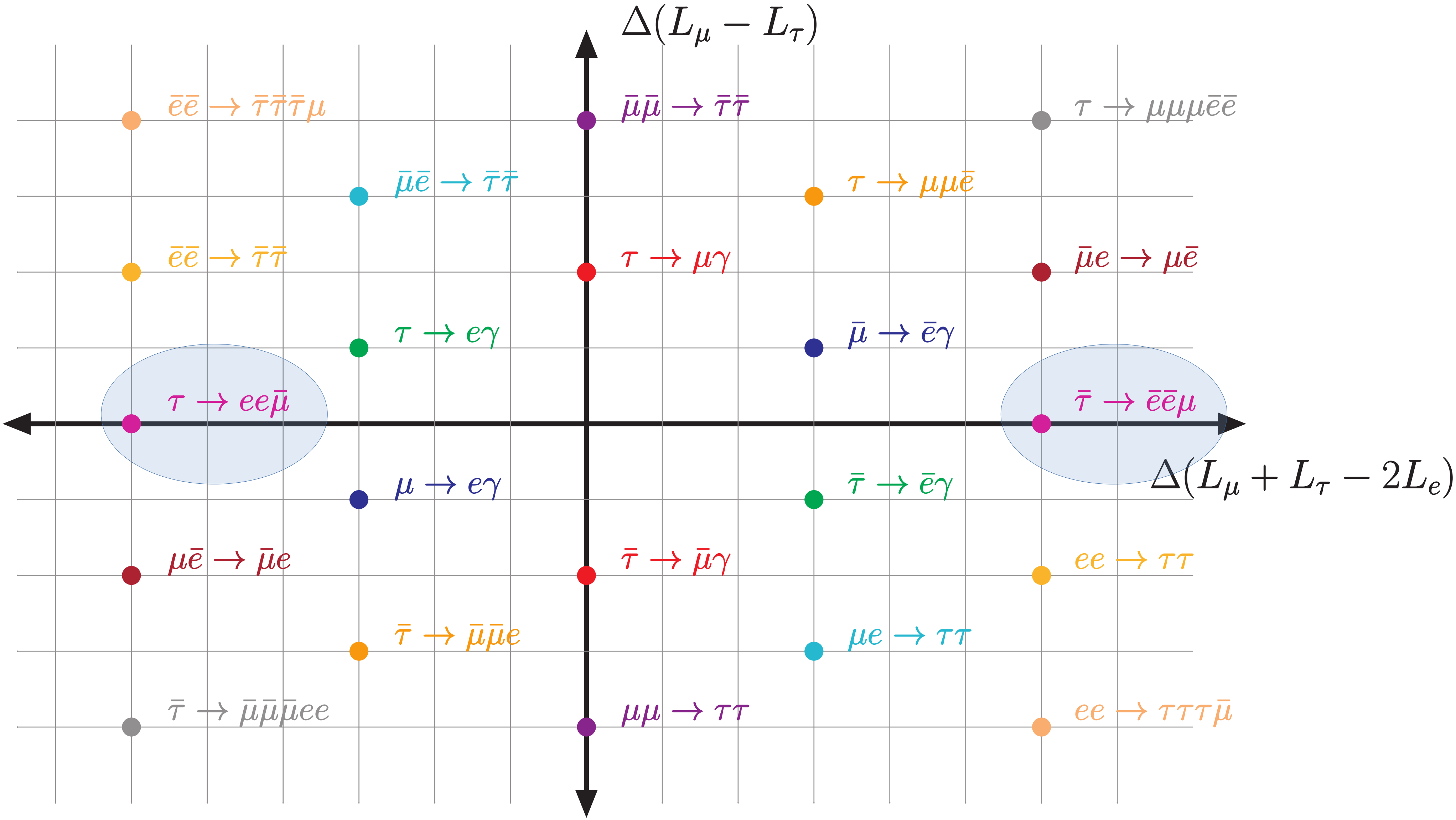
Dimension 6 SMEFT operators

[**JH**, 1610.07623]



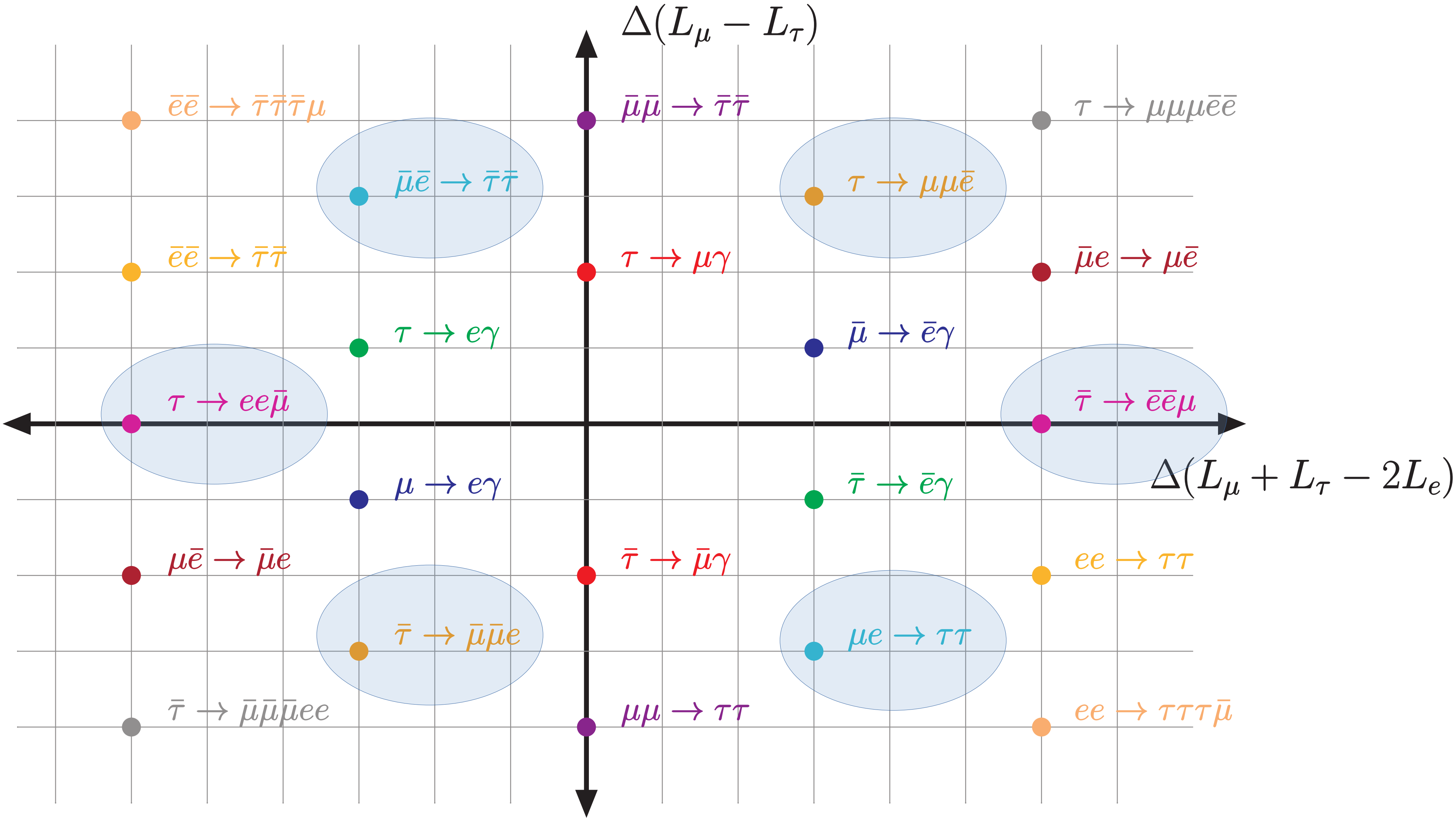
Impose $U(1)_{L_\mu - L_\tau}$ to make $\tau \to e e \bar{\mu}$ dominant.

[**JH**, 1610.07623]



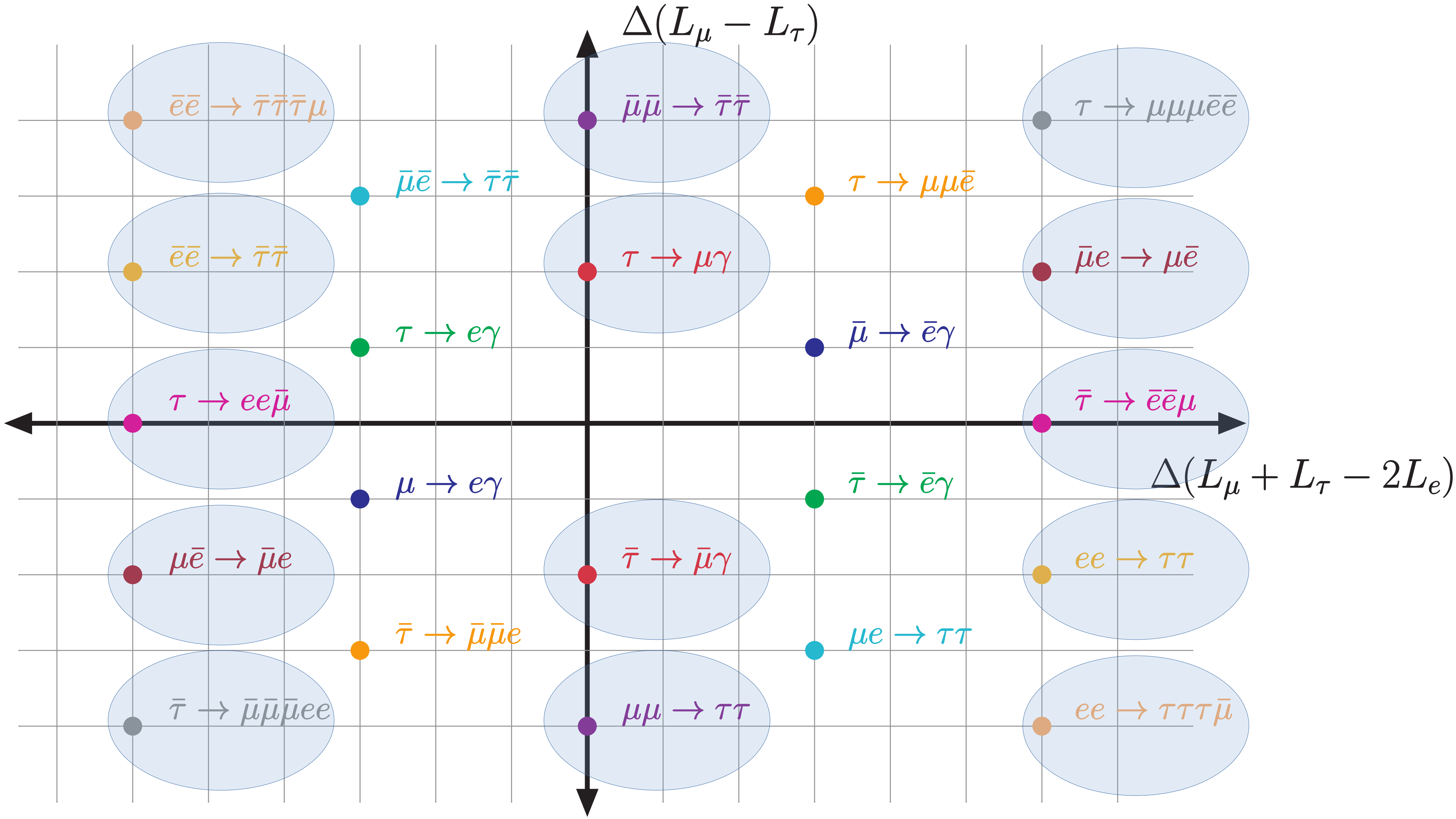
Impose *lepton triality* $\mathbb{Z}_3$. [Altarelli & Feruglio, NPB ‘06]

[**JH**, 1610.07623]



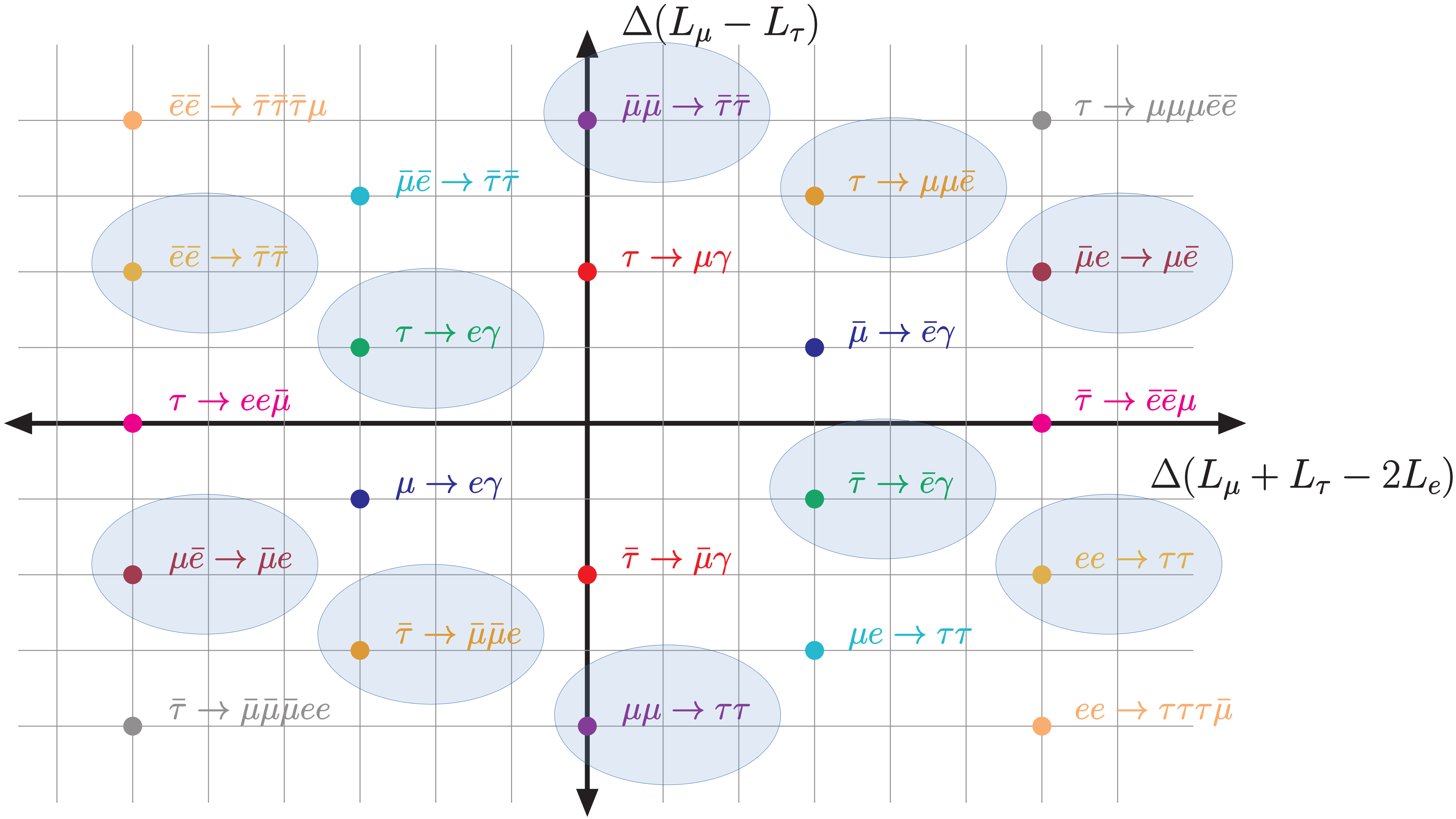
Impose $\mathbb{Z}_2$ under which e is *odd*.

[**JH**, 1610.07623]



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

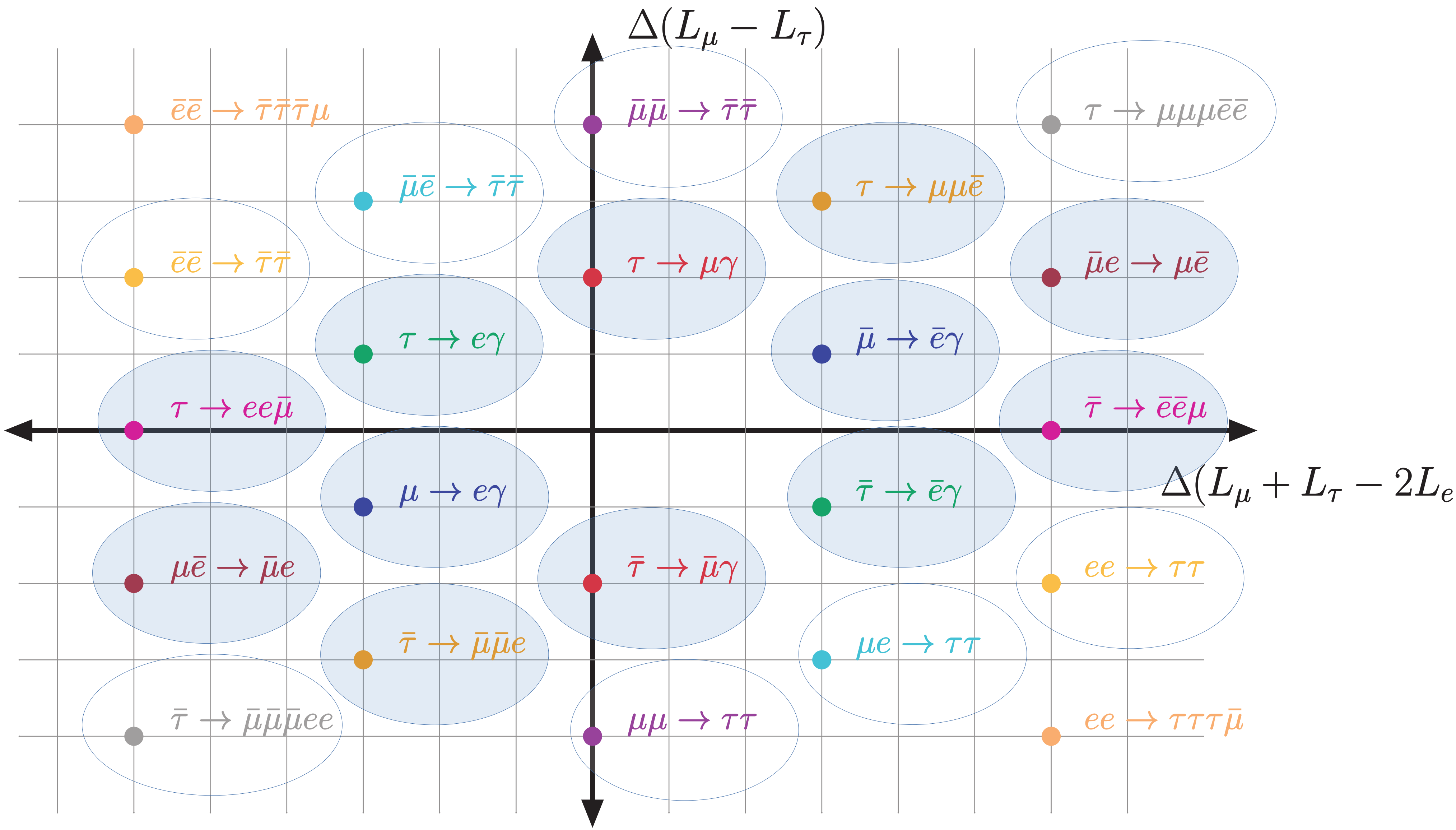
[**JH**, 1610.07623]



Etc. etc. etc.

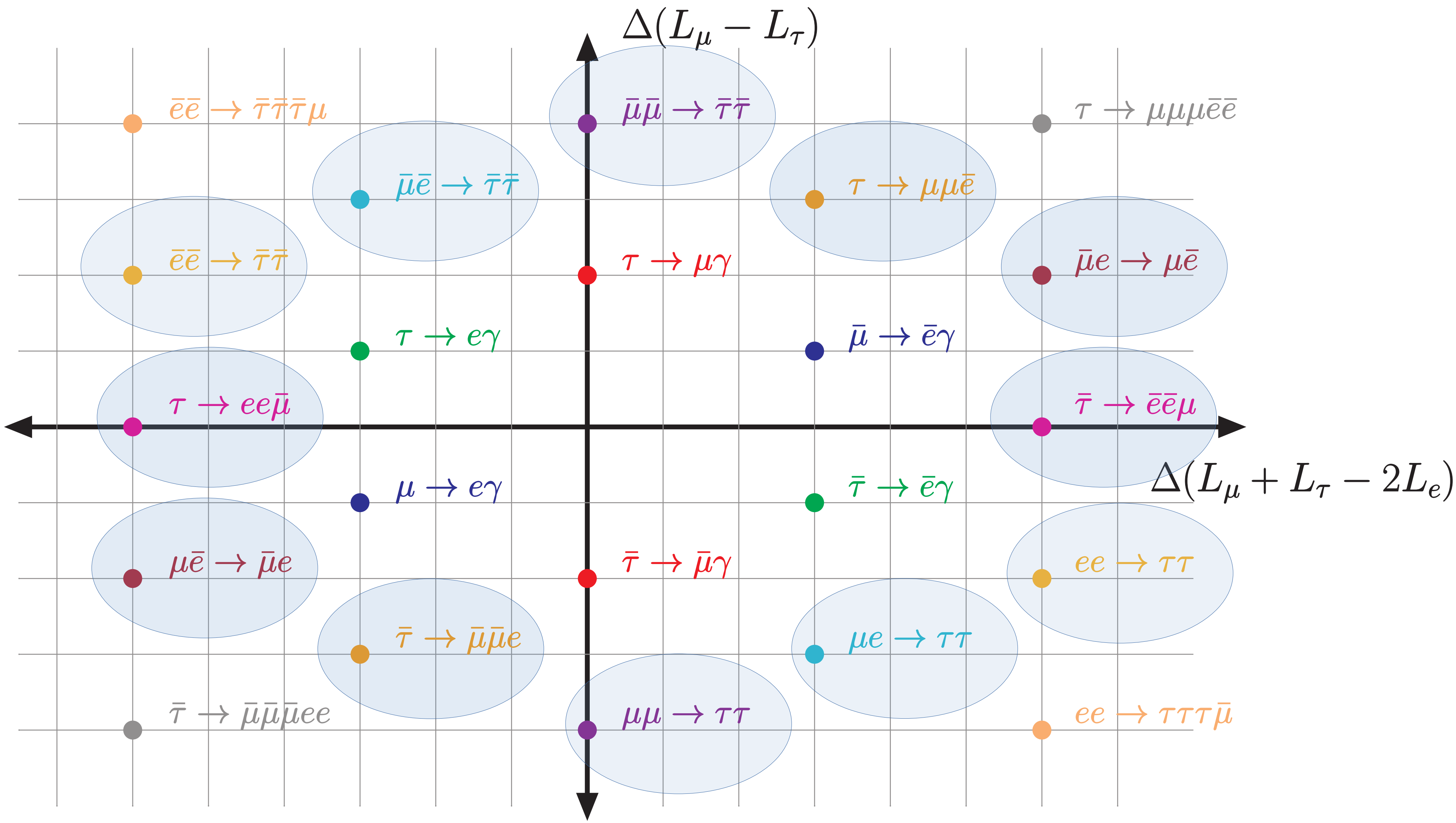
Currently being probed: Future:

[**JH**, 1610.07623]



This talk: LFV by two units

[JH, 1610.07623]



Standard Model Effective Field Theory

- 888 CLFV operators at d=6:

$$\frac{C_{ij}}{\Lambda^2}\ell_i^c\sigma_{\alpha\beta}\ell_j H F^{\alpha\beta}\,,\ \frac{C_{ij}}{\Lambda^2}\ell_i^c\gamma^\alpha\ell_j\, H^\dagger D_\alpha H\,,\ \frac{C_{ijnm}}{\Lambda^2}\ell_i^c\ell_j q_n^c q_m\,,\ \frac{C_{ijnm}}{\Lambda^2}\ell_i^c\ell_j\ell_n^c\ell_m$$

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

- Model-dependent coefficients, easy to UV complete.

Standard **M**odel **E**ffective **F**ield **T**heory

- 888 CLFV operators at d=6:

$$\frac{C_{ij}}{\Lambda^2}\ell_i^c\sigma_{\alpha\beta}\ell_j H F^{\alpha\beta}\,,\ \frac{C_{ij}}{\Lambda^2}\ell_i^c\gamma^\alpha\ell_j\, H^\dagger D_\alpha H\,,\ \frac{C_{ijnm}}{\Lambda^2}\ell_i^c\ell_j q_n^c q_m\,,\ \frac{C_{ijnm}}{\Lambda^2}\ell_i^c\ell_j\ell_n^c\ell_m$$

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

- Model-dependent coefficients, easy to UV complete.
- Four-lepton operators can break lepton flavor by 2 units:

$$\mathcal{L} \supset \sum_{a,b,c,d=e,\mu,\tau} \left[y^{LL}_{abcd}\bar{L}_a\gamma^\alpha L_b\,\bar{L}_c\gamma_\alpha L_d \right. \\ \left. + y^{LR}_{abcd}\bar{L}_a\gamma^\alpha L_b\,\bar{\ell}_c\gamma_\alpha\ell_d + y^{RR}_{abcd}\bar{\ell}_a\gamma^\alpha\ell_b\,\bar{\ell}_c\gamma_\alpha\ell_d\right] + \text{h.c.}$$

- UV completions by neutral or doubly-charged bosons.
- 21 different operators; how do we look for them?

ΔL_μ = - ΔL_e = 2, ΔL_τ = 0

- Well-known scenario, 3 operators:

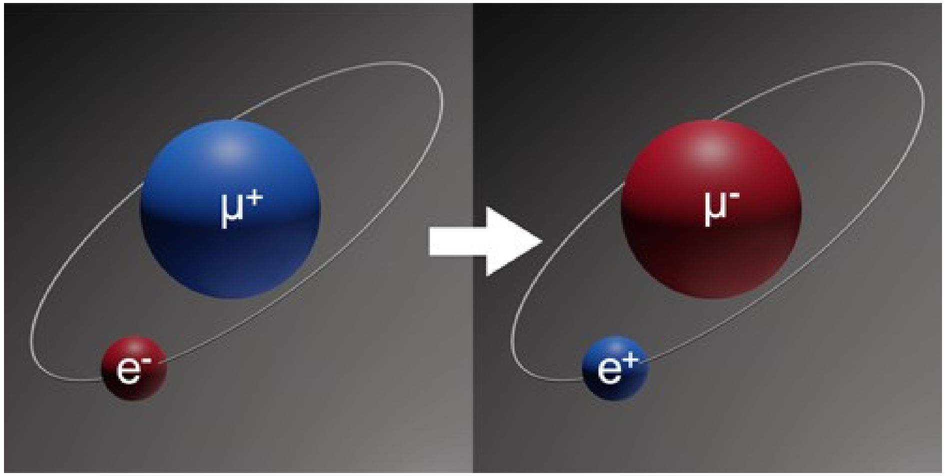
$$\mathcal{L} \supset y^{LL}_{\mu e \mu e} \bar{L}_\mu \gamma^\alpha L_e \, \bar{L}_\mu \gamma_\alpha L_e + y^{LR}_{\mu e \mu e} \bar{L}_\mu \gamma^\alpha L_e \, \bar{\ell}_\mu \gamma_\alpha \ell_e + y^{RR}_{\mu e \mu e} \bar{\ell}_\mu \gamma^\alpha \ell_e \, \bar{\ell}_\mu \gamma_\alpha \ell_e$$

- Contribute to muonium-antimuonium conversion:

$$P \simeq \frac{7.58 \times 10^{-7}}{G_F^2} |y^{LL}_{\mu e \mu e} + y^{RR}_{\mu e \mu e} - 1.68 y^{LR}_{\mu e \mu e}|^2 + \frac{4.27 \times 10^{-7}}{G_F^2} |y^{LL}_{\mu e \mu e} + y^{RR}_{\mu e \mu e} + 0.68 y^{LR}_{\mu e \mu e}|^2$$

[Conlin & Petrov, 2005.10276; Fukuyama, Mimura, Uesaka, 2108.10736; ...]

- MACS@PSI ‘99: P < 8×10^{-11}, improve e.g. at MACE. [2203.11406]



[APS, Physics 15, s9]

$\Delta L_\mu = - \Delta L_e = 2, \Delta L_\tau = 0$

- Well-known scenario, 3 operators:

$$\mathcal{L} \supset y^{LL}_{\mu e \mu e} \bar{L}_\mu \gamma^\alpha L_e \, \bar{L}_\mu \gamma_\alpha L_e + y^{LR}_{\mu e \mu e} \bar{L}_\mu \gamma^\alpha L_e \, \bar{\ell}_\mu \gamma_\alpha \ell_e + y^{RR}_{\mu e \mu e} \bar{\ell}_\mu \gamma^\alpha \ell_e \, \bar{\ell}_\mu \gamma_\alpha \ell_e$$

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[Conlin & Petrov, 2005.10276; Fukuyama, Mimura, Uesaka, 2108.10736; ...]

- MACS@PSI '99: $P < 8 \times 10^{-11}$, improve e.g. at MACE. [2203.11406]
- Probes only *2 linear combinations* of the 3 couplings:

$$|y^{LL}_{\mu e \mu e} + y^{RR}_{\mu e \mu e}| < (2.9\,\text{TeV})^{-2} \quad \& \quad |y^{LR}_{\mu e \mu e}| < (3.4\,\text{TeV})^{-2}$$

- $y^{LL}_{\mu e \mu e} - y^{RR}_{\mu e \mu e}$ is unconstrained, comes from $\bar{\mu}\gamma_\alpha e \, \bar{\mu}\gamma^\alpha \gamma_5 e$.

$\Delta L_\mu = - \Delta L_e = 2, \Delta L_\tau = 0$

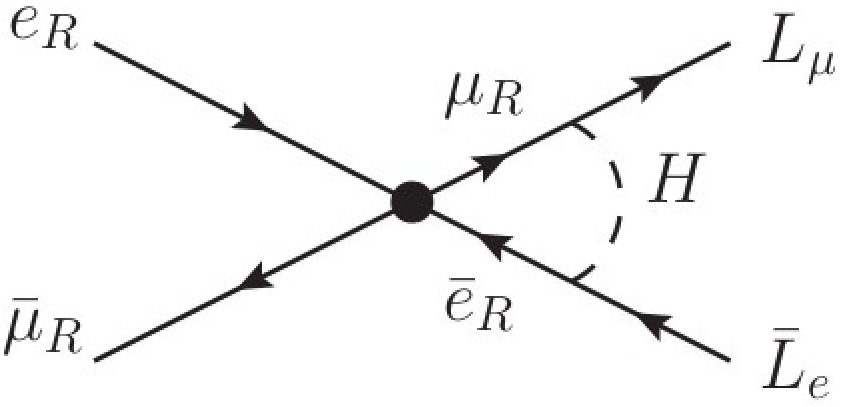
- Well-known scenario, 3 operators:

$$\mathcal{L} \supset y^{LL}_{\mu e \mu e} \bar{L}_\mu \gamma^\alpha L_e \, \bar{L}_\mu \gamma_\alpha L_e + y^{LR}_{\mu e \mu e} \bar{L}_\mu \gamma^\alpha L_e \, \bar{\ell}_\mu \gamma_\alpha \ell_e + y^{RR}_{\mu e \mu e} \bar{\ell}_\mu \gamma^\alpha \ell_e \, \bar{\ell}_\mu \gamma_\alpha \ell_e$$

- $y^{LL}_{\mu e \mu e} - y^{RR}_{\mu e \mu e}$ is unconstrained, comes from $\bar{\mu} \gamma_\alpha e \, \bar{\mu} \gamma^\alpha \gamma_5 e$.
- Also contributes to μ conversion, but G_F suppressed.

[Conlin & Petrov, 2005.10276]

- RGE mixing?



$$y^{LR}_{\mu e \mu e} \simeq \underbrace{\frac{y_e y_\mu}{16\pi^2}}_{10^{-11}} \left(y^{LL}_{\mu e \mu e} - y^{RR}_{\mu e \mu e} \right)$$

Too small...

$\Delta L_\mu = - \Delta L_e = 2, \Delta L_\tau = 0$

- Well-known scenario, 3 operators:

$$\mathcal{L} \supset y^{LL}_{\mu e \mu e} \bar{L}_\mu \gamma^\alpha L_e \, \bar{L}_\mu \gamma_\alpha L_e + y^{LR}_{\mu e \mu e} \bar{L}_\mu \gamma^\alpha L_e \, \bar{\ell}_\mu \gamma_\alpha \ell_e + y^{RR}_{\mu e \mu e} \bar{\ell}_\mu \gamma^\alpha \ell_e \, \bar{\ell}_\mu \gamma_\alpha \ell_e$$

- $y^{LL}_{\mu e \mu e} - y^{RR}_{\mu e \mu e}$ is unconstrained, comes from $\bar{\mu}\gamma_\alpha e \, \bar{\mu}\gamma^\alpha \gamma_5 e$.
- Also contributes to μ conversion, but G_F suppressed.
- Operator contains neutrinos: contributes to μ decay!
  - No interference, but same electron spectrum:

$$\Gamma(\mu \to e \nu \bar{\nu}) = \Gamma^{\rm SM}_\mu \left(1 + \frac{|2 y^{LL}_{\mu e \mu e}|^2 + |y^{LR}_{\mu e \mu e}|^2}{(2\sqrt{2} G_F)^2} \right)$$

  - Lepton universality $\Gamma(\mu \to e \nu \bar{\nu}) / \Gamma(\tau \to \mu \nu \bar{\nu})$ gives limit

$$|y^{LL}_{\mu e \mu e} - y^{RR}_{\mu e \mu e}| < (0.74\,\mathrm{TeV})^{-2}$$

[HFLAV, PDG]
[Belle II, 2405.14625]

$\Delta L_e = 2$, $\Delta L_\tau = \Delta L_\mu = -1$

- Easiest scenario, 4 operators:

$$\mathcal{L} \supset y^{LL}_{\mu e \tau e} \bar{L}_\mu \gamma^\alpha L_e \, \bar{L}_\tau \gamma_\alpha L_e + y^{LR}_{\mu e \tau e} \bar{L}_\mu \gamma^\alpha L_e \, \bar{\ell}_\tau \gamma_\alpha \ell_e$$
$$+ y^{LR}_{\tau e \mu e} \bar{L}_\tau \gamma^\alpha L_e \, \bar{\ell}_\mu \gamma_\alpha \ell_e \;\; + y^{RR}_{\mu e \tau e} \bar{\ell}_\mu \gamma^\alpha \ell_e \, \bar{\ell}_\tau \gamma_\alpha \ell_e$$

- Leads to $\tau^+ \to e^+ e^+ \mu^-$: $\Gamma \simeq \dfrac{m_\tau^5 \left(|y^{LL}_{\mu e \tau e}|^2 + |y^{LR}_{\mu e \tau e}|^2 + |y^{LR}_{\tau e \mu e}|^2 + |y^{RR}_{\tau e \mu e}|^2\right)}{1536\pi^3}$
- All coefficients < $(10\,\mathrm{TeV})^{-2}$ from Belle, [Belle, 1001.3221]
  to be improved with Belle II to $(29.0\,\mathrm{TeV})^{-2}$. [Banerjee, 2209.11639]
- Analogous for the four $\Delta L_\mu = 2$, $\Delta L_\tau = \Delta L_e = -1$ operators:
  $\tau^+ \to \mu^+ \mu^+ e^-$ gives coefficient limits $(8.8\,\mathrm{TeV})^{-2}$.

$\Delta L_\tau = 1$ is easy due to clean tau decays

$\Delta L_e = -\Delta L_\tau = 2$

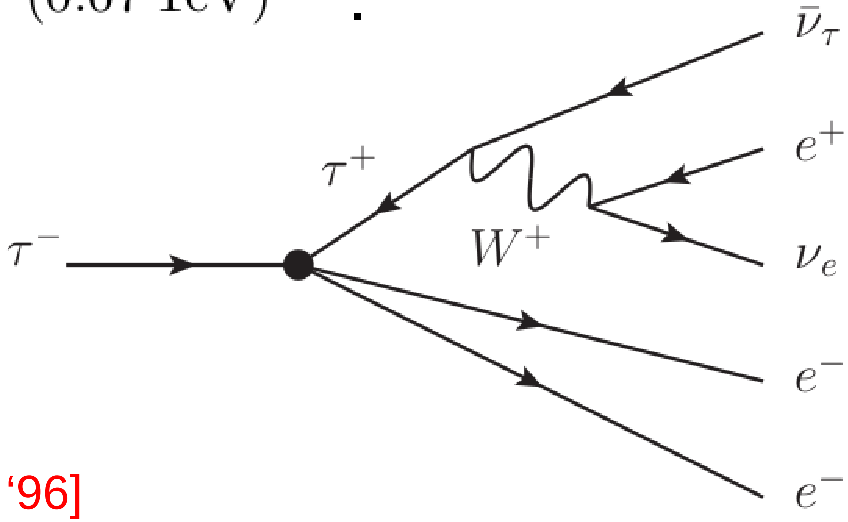
- Difficult scenario, 3 operators:

$$\mathcal{L} \supset y^{LL}_{\tau e \tau e} \bar{L}_\tau \gamma^\alpha L_e \, \bar{L}_\tau \gamma_\alpha L_e + y^{LR}_{\tau e \tau e} \bar{L}_\tau \gamma^\alpha L_e \, \bar{\ell}_\tau \gamma_\alpha \ell_e + y^{RR}_{\tau e \tau e} \bar{\ell}_\tau \gamma^\alpha \ell_e \, \bar{\ell}_\tau \gamma_\alpha \ell_e$$

- No tauonium conversion to look for.
- Left-handed operators: contribution to tau decay.

$$\Gamma_{\tau \to e\nu\nu} = \Gamma^{\rm SM}_{\tau \to e\nu\nu} \left(1 + \frac{|2 y^{LL}_{\tau e \tau e}|^2 + |y^{LR}_{\tau e \tau e}|^2}{(2\sqrt{2} G_F)^2} \right)$$

- Flavor universality: $|2 y^{LL}_{\tau e \tau e}|, |y^{LR}_{\tau e \tau e}| < (0.67\,{\rm TeV})^{-2}$.
- Right-handed operator?
  - $\mathrm{BR}(\tau^- \to e^- e^- \ell^+ \nu_\ell \bar{\nu}_\tau) \simeq 8.2 \times 10^{-15} \left| \frac{y^{RR}_{\tau e \tau e}}{(0.1\,{\rm TeV})^{-2}} \right|^2$
  - CLEO: $|y^{RR}_{\tau e \tau e}| < (0.5\,{\rm GeV})^{-2}$ [PRL '96]



$\Delta L_e = -\Delta L_\tau = 2$

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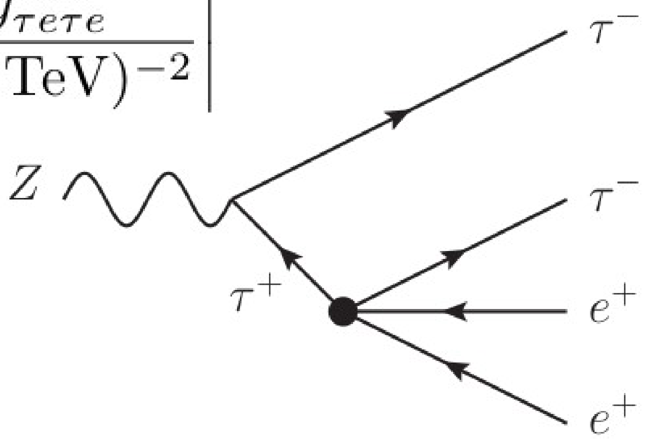
- Flavor universality: $|2 y^{LL}_{\tau e \tau e}|, |y^{LR}_{\tau e \tau e}| < (0.67\,\mathrm{TeV})^{-2}$.
- Right-handed operator?
  - $\mathrm{BR}(Z \to \tau^\pm \tau^\pm e^\mp e^\mp) \simeq 4.18 \times 10^{-11} \left| \frac{y^{RR}_{\tau e \tau e}}{(0.1\,\mathrm{TeV})^{-2}} \right|^2$
  - Z width: $|y^{RR}_{\tau e \tau e}| < (1.2\,\mathrm{GeV})^{-2}$
  - Z factory reach: $|y^{RR}_{\tau e \tau e}| < (250\,\mathrm{GeV})^{-2}$



Similar for other $\Delta L_\tau = 2$ operators.

Summary

[**JH** & M. Sokhashvili, 2401.09580]

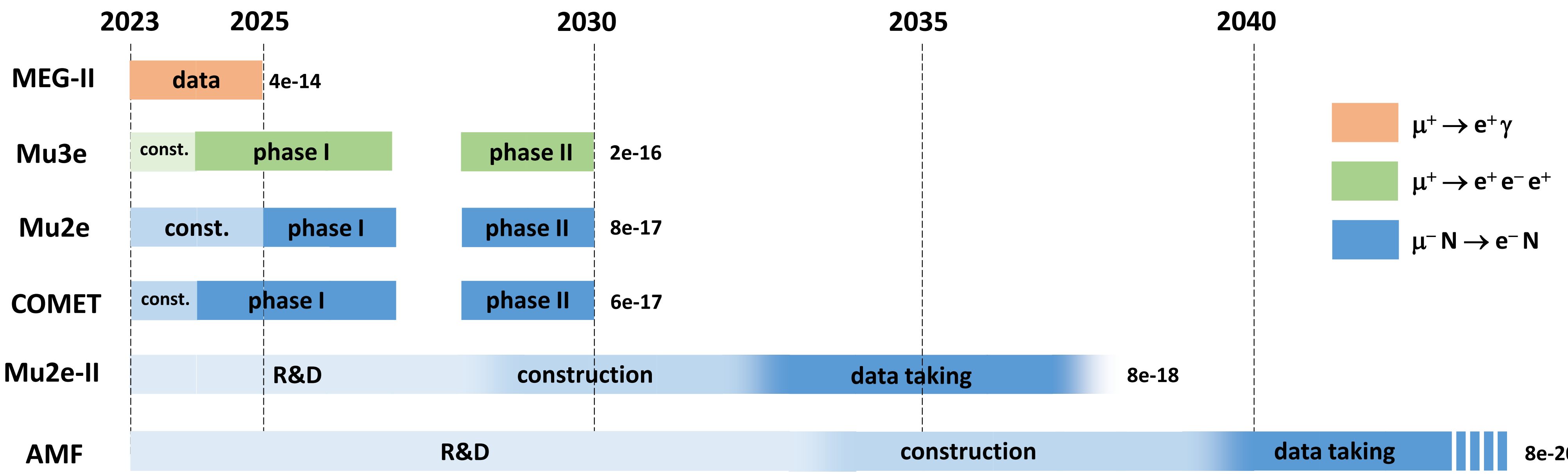
Wilson coefficient	Upper limit	Process	Violated quantum numbers
$\lvert y^{LL}_{\mu e \mu e} + y^{RR}_{\mu e \mu e}\rvert$	$(3.2\,\text{TeV})^{-2}$ [90% C.L.]	Mu-to-$\overline{\text{Mu}}$	$\Delta L_\mu = -\Delta L_e = 2$
$\lvert y^{LR}_{\mu e \mu e}\rvert$	$(3.8\,\text{TeV})^{-2}$ [90% C.L.]	Mu-to-$\overline{\text{Mu}}$	$\Delta L_\mu = -\Delta L_e = 2$
$\lvert y^{LL}_{\mu e \mu e} - y^{RR}_{\mu e \mu e}\rvert$	$(0.74\,\text{TeV})^{-2}$ [95% C.L.]	$\Gamma(\mu \to e\nu\bar{\nu})/\Gamma(\tau \to \mu\nu\bar{\nu})$	$\Delta L_\mu = -\Delta L_e = 2$
$\lvert 2y^{LL}_{\tau e \tau e}\rvert, \lvert y^{LR}_{\tau e \tau e}\rvert$	$(0.67\,\text{TeV})^{-2}$ [95% C.L.]	$\Gamma(\tau \to e\nu\bar{\nu})/\Gamma(\tau \to \mu\nu\bar{\nu})$	$\Delta L_\tau = -\Delta L_e = 2$
$\lvert y^{RR}_{\tau e \tau e}\rvert$	$(1.2\,\text{GeV})^{-2}$ [95% C.L.]	$Z \to \tau^\pm\tau^\pm e^\mp e^\mp$	$\Delta L_\tau = -\Delta L_e = 2$
$\lvert 2y^{LL}_{\tau \mu \tau \mu}\rvert, \lvert y^{LR}_{\tau \mu \tau \mu}\rvert$	$(0.63\,\text{TeV})^{-2}$ [95% C.L.]	$\Gamma(\tau \to \mu\nu\bar{\nu})/\Gamma(\tau \to e\nu\bar{\nu})$	$\Delta L_\tau = -\Delta L_\mu = 2$
$\lvert y^{RR}_{\tau \mu \tau \mu}\rvert$	$(1.2\,\text{GeV})^{-2}$ [95% C.L.]	$Z \to \tau^\pm\tau^\pm \mu^\mp \mu^\mp$	$\Delta L_\tau = -\Delta L_\mu = 2$
$\lvert y^{LL}_{e \tau \mu \tau}\rvert, \lvert y^{LR}_{\mu \tau e \tau}\rvert$	$(0.60\,\text{TeV})^{-2}$ [95% C.L.]	$\Gamma(\tau \to e\nu\bar{\nu})/\Gamma(\mu \to e\nu\bar{\nu})$	$\Delta L_\tau = -2\Delta L_\mu = -2\Delta L_e = 2$
$\lvert y^{LR}_{e \tau \mu \tau}\rvert$	$(0.55\,\text{TeV})^{-2}$ [95% C.L.]	$\Gamma(\tau \to e\nu\bar{\nu})/\Gamma(\tau \to \mu\nu\bar{\nu})$	$\Delta L_\tau = -2\Delta L_\mu = -2\Delta L_e = 2$
$\lvert y^{RR}_{e \tau \mu \tau}\rvert$	$(1\,\text{GeV})^{-2}$ [95% C.L.]	$Z \to \tau^\pm\tau^\pm e^\mp \mu^\mp$	$\Delta L_\tau = -2\Delta L_\mu = -2\Delta L_e = 2$
$\lvert y^{LL}_{\mu e \tau e}\rvert, \lvert y^{LR}_{\mu e \tau e}\rvert, \lvert y^{LR}_{\tau e \mu e}\rvert, \lvert y^{RR}_{\mu e \tau e}\rvert$	$(10\,\text{TeV})^{-2}$ [90% C.L.]	$\tau \to \bar{\mu} e e$	$\Delta L_e = -2\Delta L_\tau = -2\Delta L_\mu = 2$
$\lvert y^{LL}_{e \mu \tau \mu}\rvert, \lvert y^{LR}_{e \mu \tau \mu}\rvert, \lvert y^{LR}_{\tau \mu e \mu}\rvert, \lvert y^{RR}_{e \mu \tau \mu}\rvert$	$(8.8\,\text{TeV})^{-2}$ [90% C.L.]	$\tau \to \bar{e} \mu\mu$	$\Delta L_\mu = -2\Delta L_\tau = -2\Delta L_e = 2$

- The 21 d=6 SMEFT CLFV ops with $\Delta L_\alpha=2$ often overlooked.
- Overall less clean than $\Delta L_\alpha=1$, but good/relevant limits for 18.
- The 3 right-right $\Delta L_\tau=2$ ops need Z factory or μ collider.

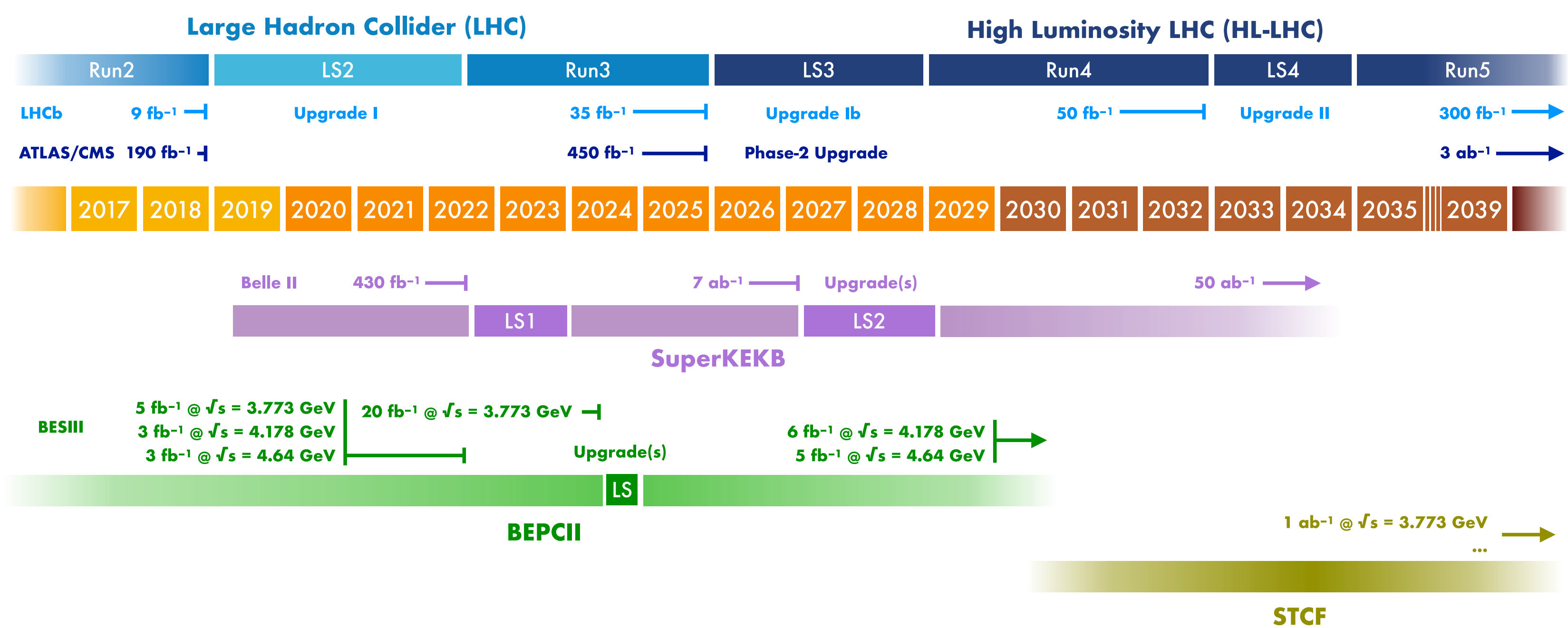
CLFV not always as clean as we think!

Backup

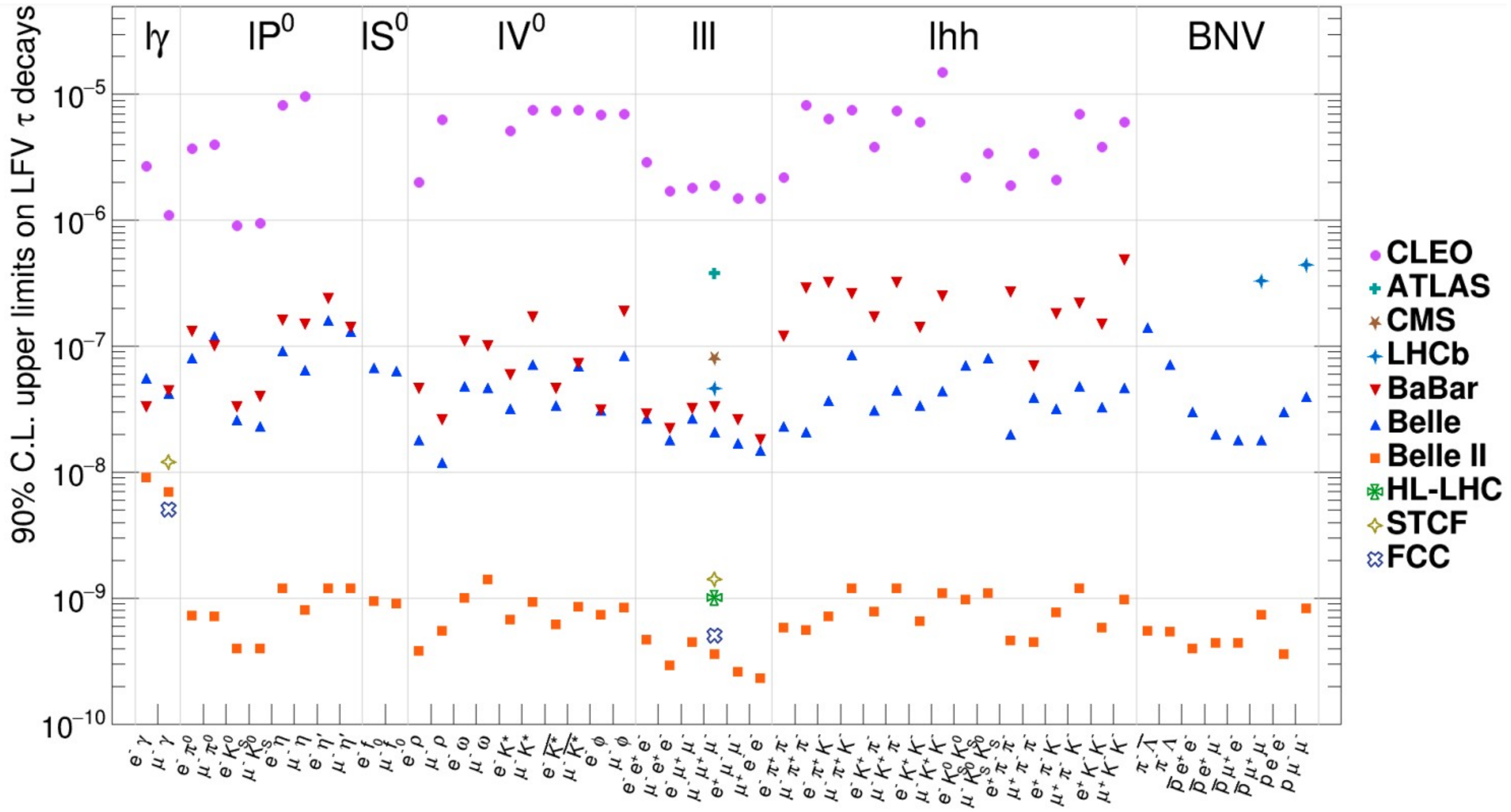
LFV Timelines



[Artuso, Bernstein, Petrov, *Snowmass 2021 Rare and Precision Frontier Report*, 2210.04765]



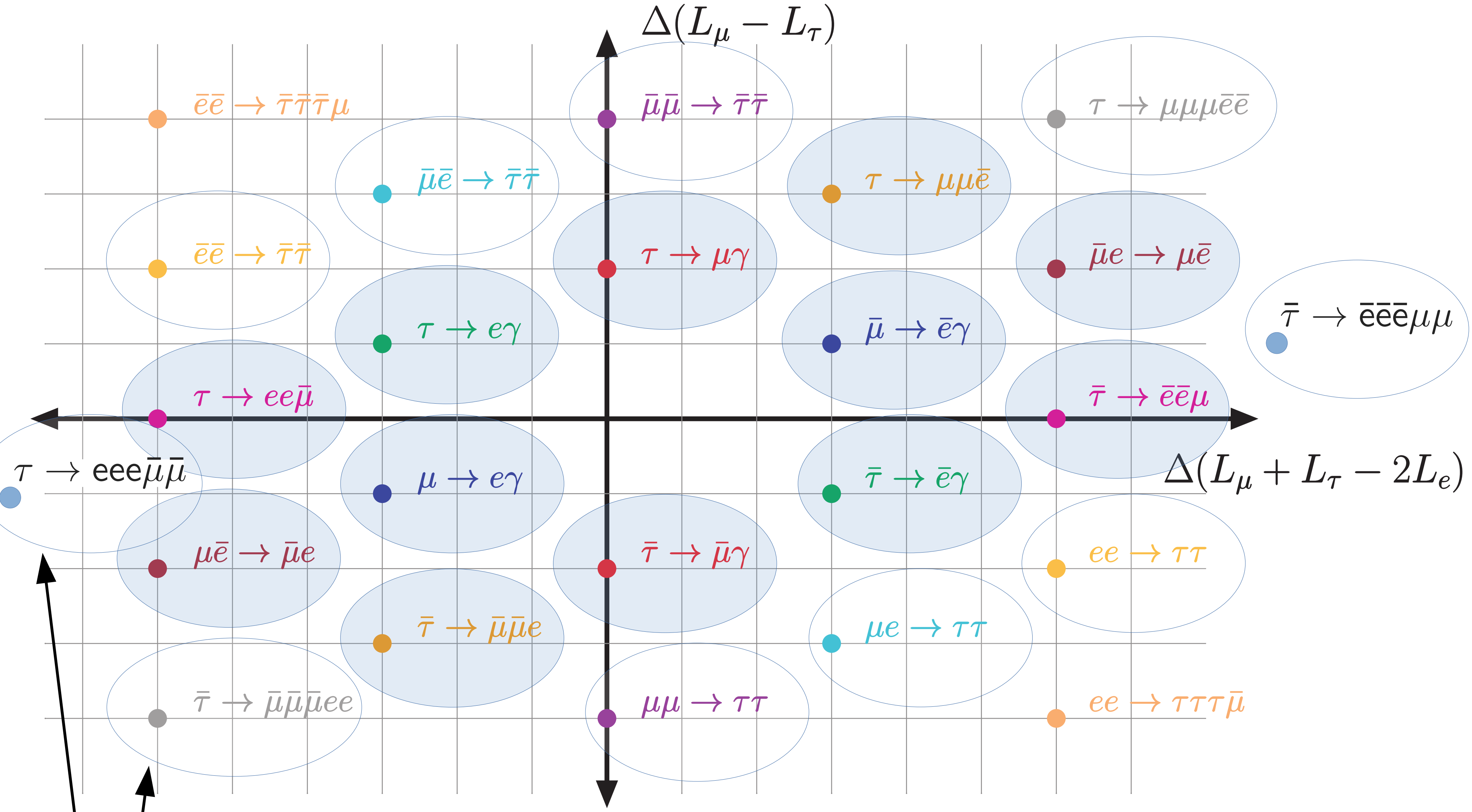
LFV in tau sector



[Banerjee++, 2203.14919]

Currently being probed: Future:

[**JH**, 1610.07623]

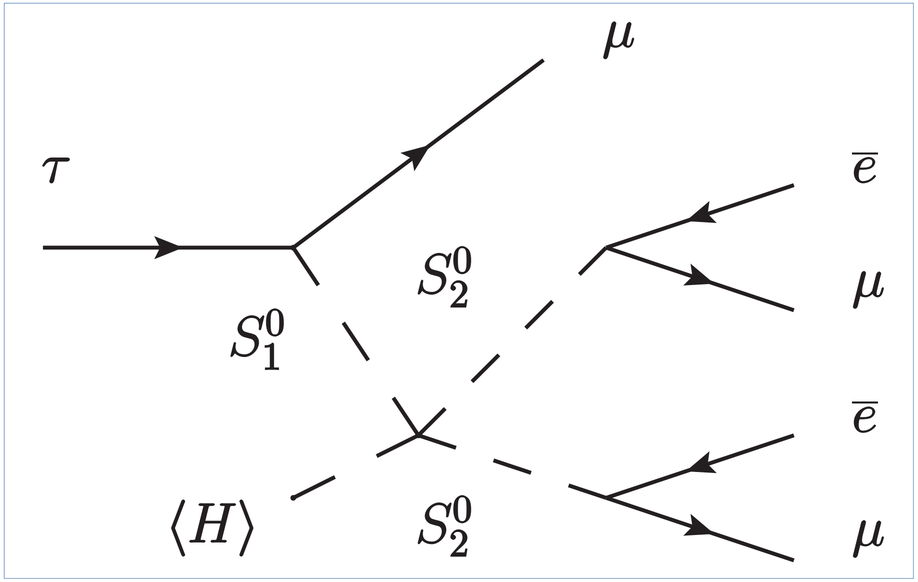


Belle II, but d=10 operator!

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

- Impose $L_\mu + 4L_e - 5L_\tau$ to forbid all other LFV.
- Experimentally clean, but rate is suppressed:

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



- Secretly dimension 10 operator.
- Better constraints on S from $Z \to SS$ etc.?

[**JH**, M. Sokhashvili, Thapa, in progress]

Requires full models