Neutrino masses and lepton flavor violation

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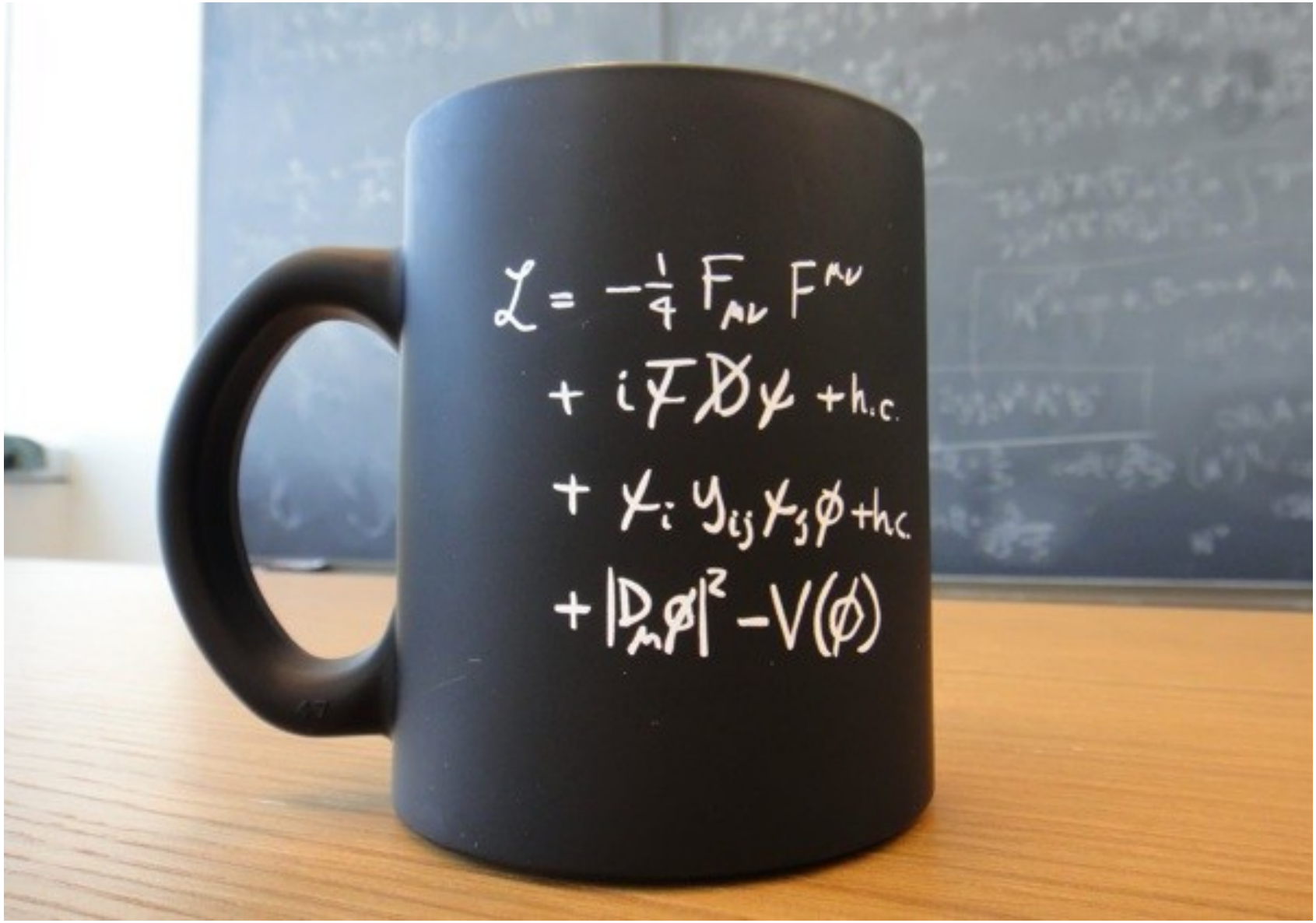
The Standard Model



www.quantumdiaries.org, Flip Tanedo

Symmetries of the Standard Model

- Rephasing lepton and quark fields:

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

- B+L broken non-perturbatively,

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

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

- Real global symmetry of SM:

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

Flavor!

- Can even promote to gauge symmetry by adding 3 N_R.

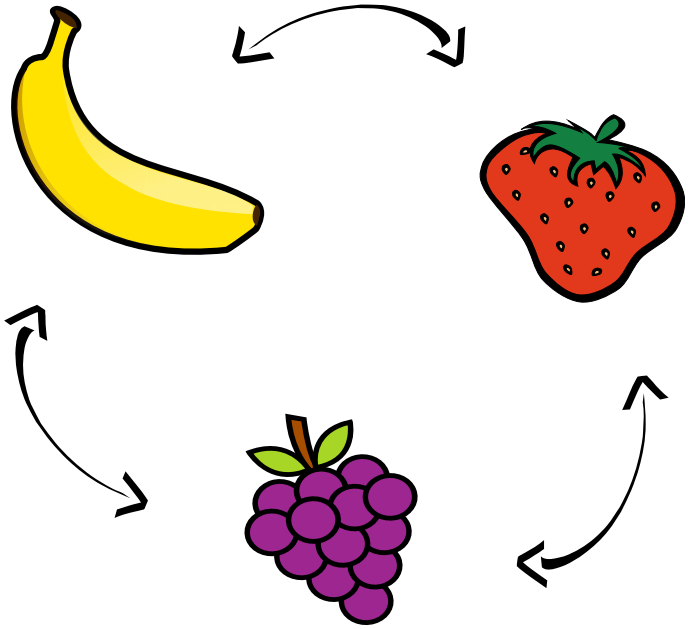
  [Araki, **JH**, Kubo, 1203.4951. Without N_R: L_i-L_j, He, Joshi, Lew, Volkas, '91]

Neutrino oscillations = flavor violation

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

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

  is broken!



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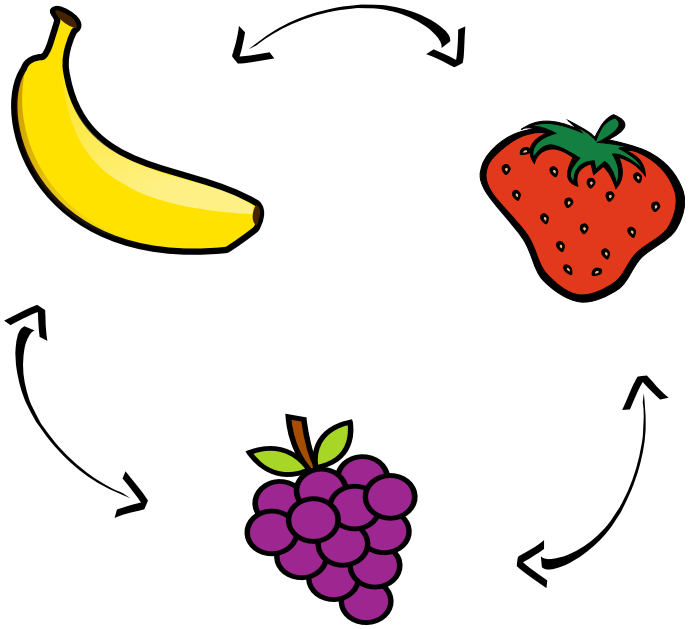
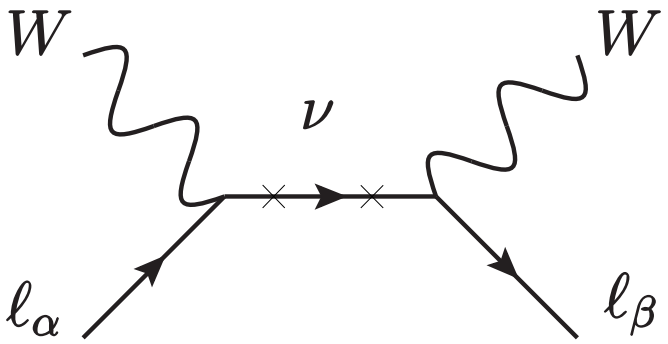


- Amplitudes for charged lepton flavor violation are suppressed:



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

Flavor-violating decay?

- hep-ph: $$\frac{\Gamma(\ell_\alpha \to \ell_\beta \gamma)}{\Gamma(\ell_\alpha \to \ell_\beta \nu_\alpha \overline{\nu}_\beta)} = \frac{3\alpha_{\rm EM}}{32\pi} \left| \frac{(\mathsf{M}_\nu \mathsf{M}_\nu^\dagger)_{\alpha\beta}}{\mathsf{M}_{\rm W}^2} \right|^2 < 5 \times 10^{-53} \, .$$

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- hep-ex:

LFV	process	current	future	exp
$\Delta(L_e - L_\mu) = 2$	$\mu \to e\gamma$	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^{-18}	Mu2e, COMET
	$h \to e\bar{\mu}$	3.5×10^{-4}	3×10^{-5}	LHC
	$Z \to e\bar{\mu}$	7.5×10^{-7}	–	Z factory?
	had$\to e\bar{\mu}$(had)	4.7×10^{-12}	10^{-12}	NA62

[Calibbi & Signorelli, 1709.00294; Renga, 1902.06291]

[see talk by Terence Libeiro on MEG-II]

Flavor-violating decay?

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- hep-ex:

LFV	process	current	future	exp
$\Delta(L_e - L_\tau) = 2$	$\tau \to e\gamma$	3.3×10^{-8}	10^{-9}	Belle-II
	$\tau \to e\bar{\ell}\ell$	2.7×10^{-8}	10^{-9}	Belle-II
	$\tau \to e\,\mathrm{had}$	$\mathcal{O}(10^{-8})$	10^{-9}	Belle-II
	$h \to e\bar{\tau}$	6.9×10^{-3}	3×10^{-4}	LHC
	$Z \to e\bar{\tau}$	9.8×10^{-6}	–	Z factory?
	had$\to e\bar{\tau}$(had)	$\mathcal{O}(10^{-6})$	–	–

[see talk by Ami Rostomyan on Belle-II]

Neutrino mass ⇏ CLFV!

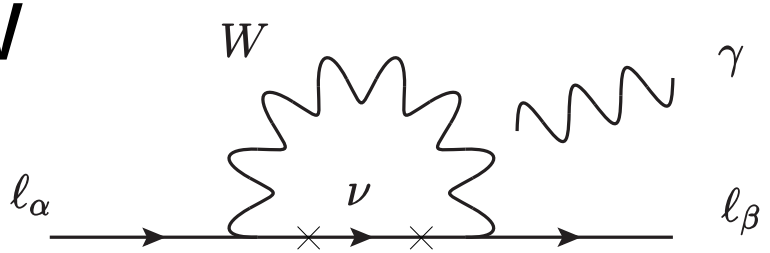
- Neutrino-mass induced charged LFV is unobservable.

> 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/SUSY/type-II seesaw;
  - Radiative seesaw (Zee-Babu, Ma,…).
- $M_\nu \Leftrightarrow$ LFV connection possible but not necessary.

Example 1: type-I seesaw

- SM + heavy seesaw neutrinos:

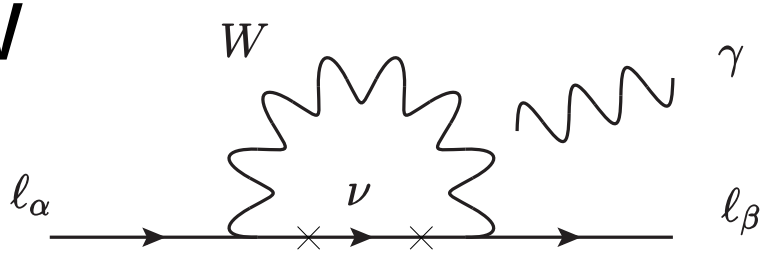


$$\frac{\Gamma(\ell_\alpha \to \ell_\beta \gamma)}{\Gamma(\ell_\alpha \to \ell_\beta \nu_\alpha \overline{\nu}_\beta)} \simeq \frac{3\alpha_{\rm EM}}{32\pi} \underbrace{\left|(M_\nu M_W^{-2} M_\nu^\dagger)_{\alpha\beta}\right|^2}_{\text{light neutrinos}} + \frac{3\alpha_{\rm EM}}{8\pi} \underbrace{\left|(m_D M_R^{-2} m_D^\dagger)_{\alpha\beta}\right|^2}_{\text{heavy neutrinos}}.$$

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

- Seesaw mass $M_\nu \simeq -m_D M_R^{-1} m_D^T$.

Example 1: type-I seesaw



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

- Seesaw mass $\mathsf{M}_\nu \simeq -\mathsf{m}_{\rm D} \mathsf{M}_{\rm R}^{-1} \mathsf{m}_{\rm D}^{\rm T}$.
- One to one: $\{\mathsf{m}_{\rm D}, \mathsf{M}_{\rm R}\} \leftrightarrow \{\mathsf{M}_\nu, \mathsf{m}_{\rm D} \mathsf{M}_{\rm R}^{-2} \mathsf{m}_{\rm D}^\dagger\}.$

[Broncano, Gavela, Jenkins, '02]

CLFV *complementary* to M_ν!

Example 1: type-I seesaw

- No LFV predictions, but still possible?
- Heavy N_R: integrate out N_R and match to SMEFT.

[Coy & Frigerio, 1812.03165]

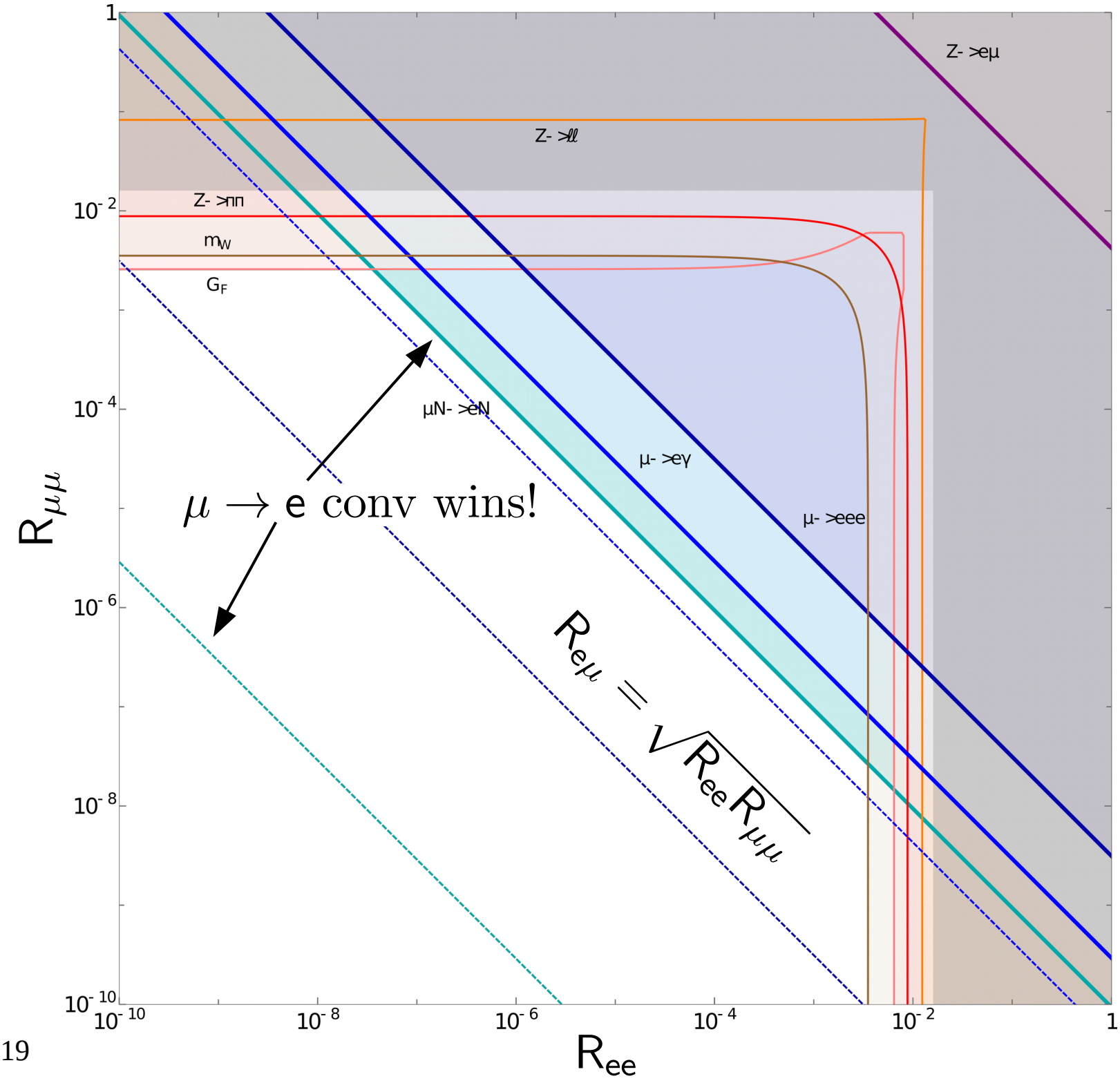
- All N_R effects depend on

$$S \propto m_D M_R^{-2} m_D^\dagger \,, \qquad R \propto m_D \log(M_R/M_W) M_R^{-2} m_D^\dagger \,.$$

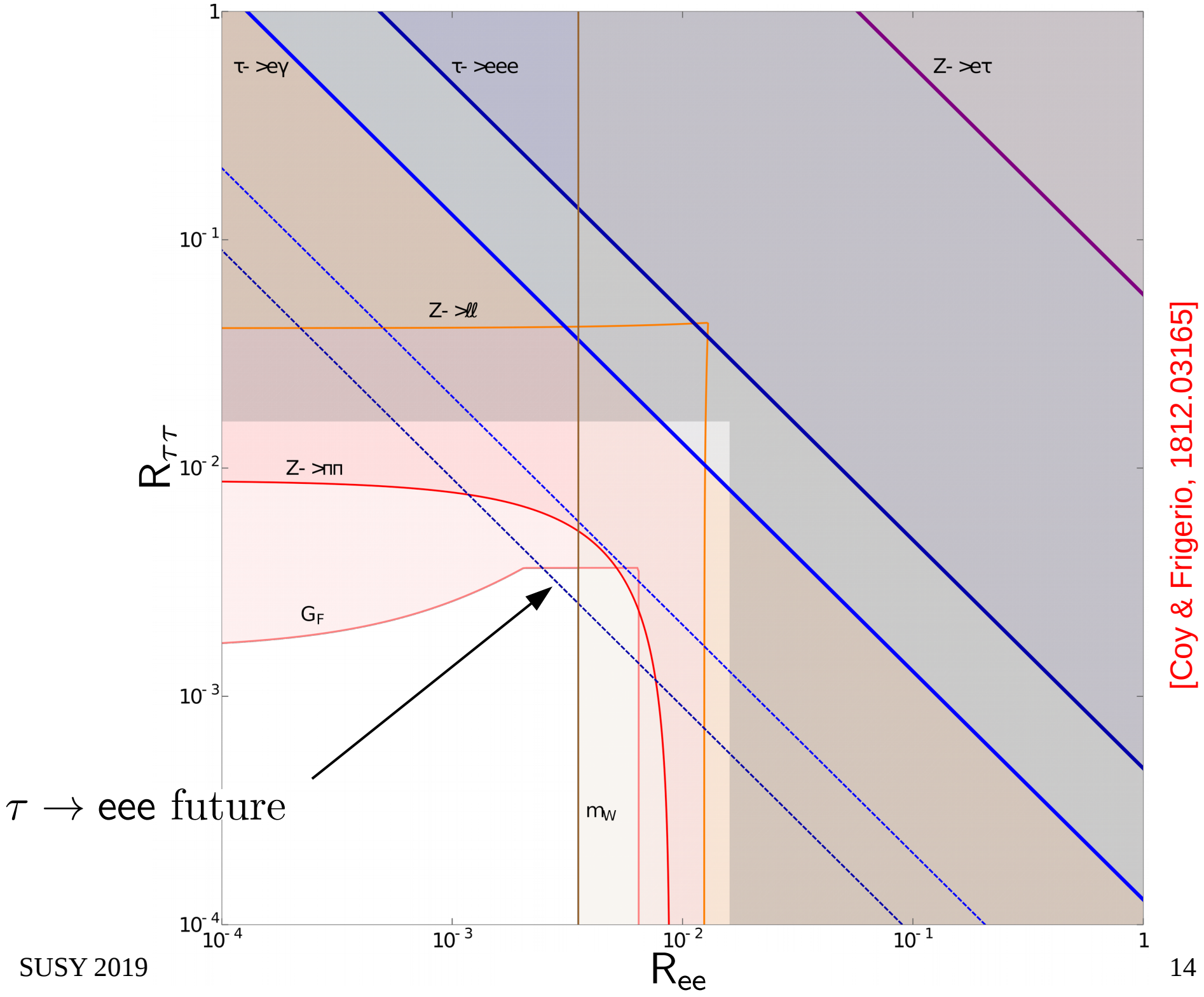
- Important inequalities:

$$|S_{\alpha\beta}| \leq \sqrt{S_{\alpha\alpha} S_{\beta\beta}} \,, \qquad |R_{\alpha\beta}| \leq \sqrt{R_{\alpha\alpha} R_{\beta\beta}} \,.$$

- LFV constrained by flavor *conserving* observables.



[Coy & Frigerio, 1812.03165]



$\tau \to$ eee future

[Coy & Frigerio, 1812.03165]

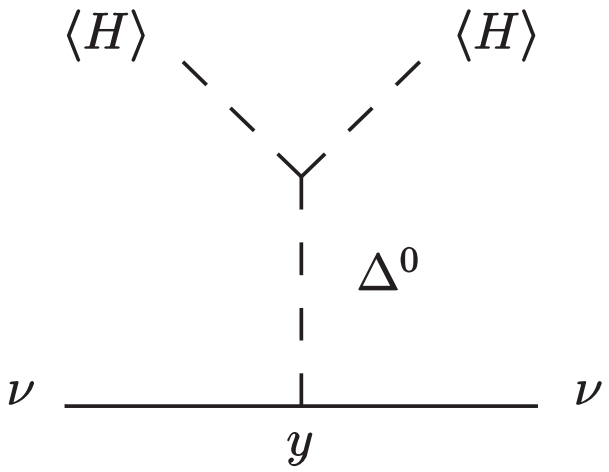
Summary 1: type-I seesaw

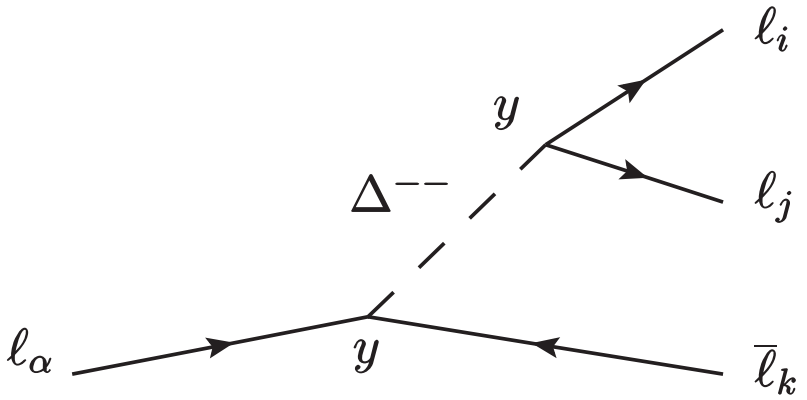
- LFV *complementary* to M_ν, no predictions…
- LFV potentially visible in muon sector.
- Best channel: $\mu \rightarrow e$ conversion (Mu2e, COMET, DeeMe).
- Requires texture in m_D, e.g. inverse seesaw.
- Lepton flavor universality excludes LFV in taus.

Example 2: type-II seesaw

$\Delta = (\Delta^{++}, \Delta^{+}, \Delta^{0})$

$$\mathcal{L} = \mathcal{L}_{\rm SM} + |D_\alpha \Delta|^2 - (y \bar{L}^c \Delta L + \mu H \Delta H + \text{h.c.})$$



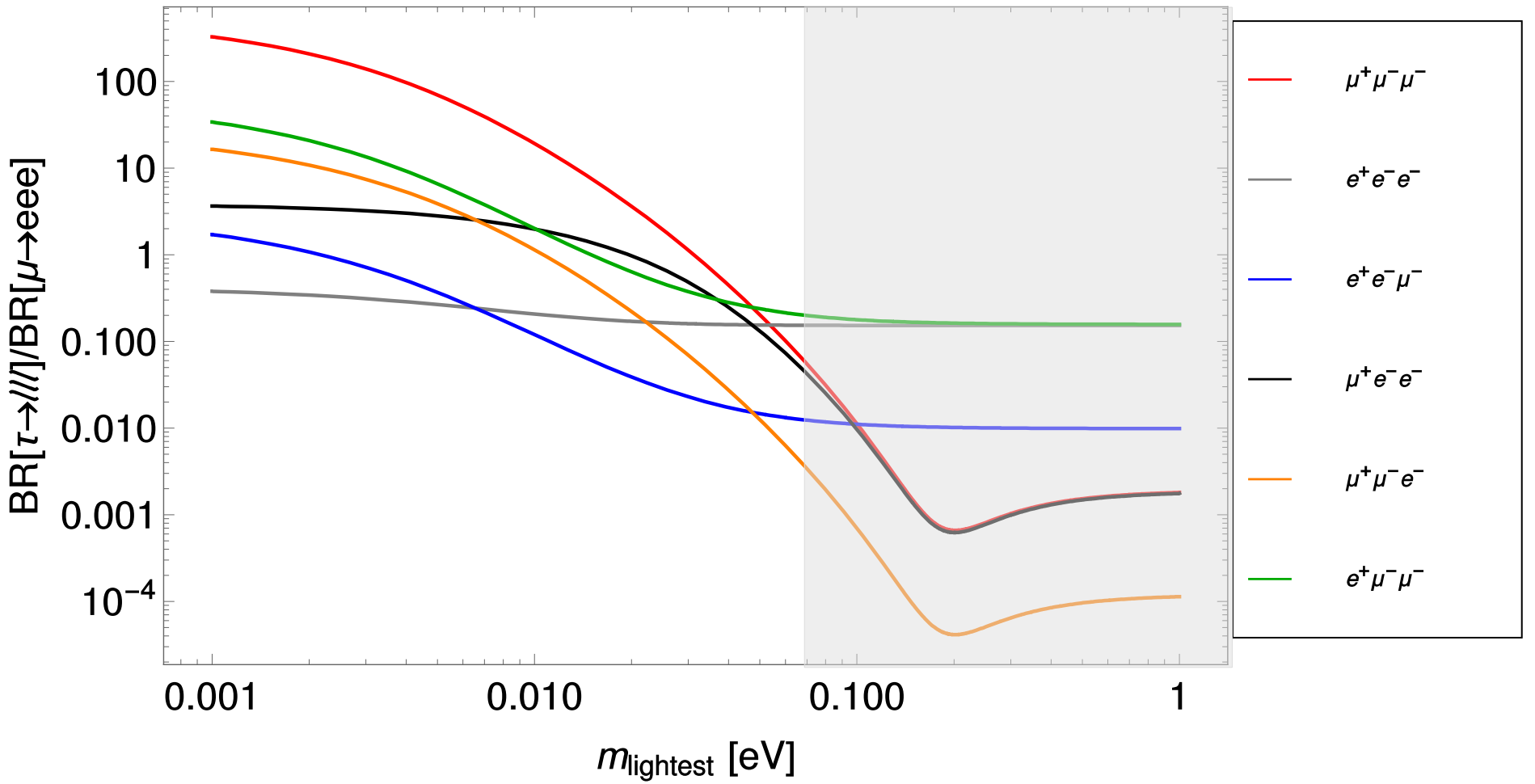


$$\Rightarrow \quad (M_\nu)_{\alpha\beta} \simeq y_{\alpha\beta} \frac{2\mu v^2}{M_\Delta^2} \quad \& \quad \text{BR}(\ell_\alpha \to \ell_i \ell_j \bar{\ell}_k) \propto |y_{\alpha k}|^2 |y_{ij}|^2 / M_\Delta^4 .$$

[Abada++, 0707.4058]

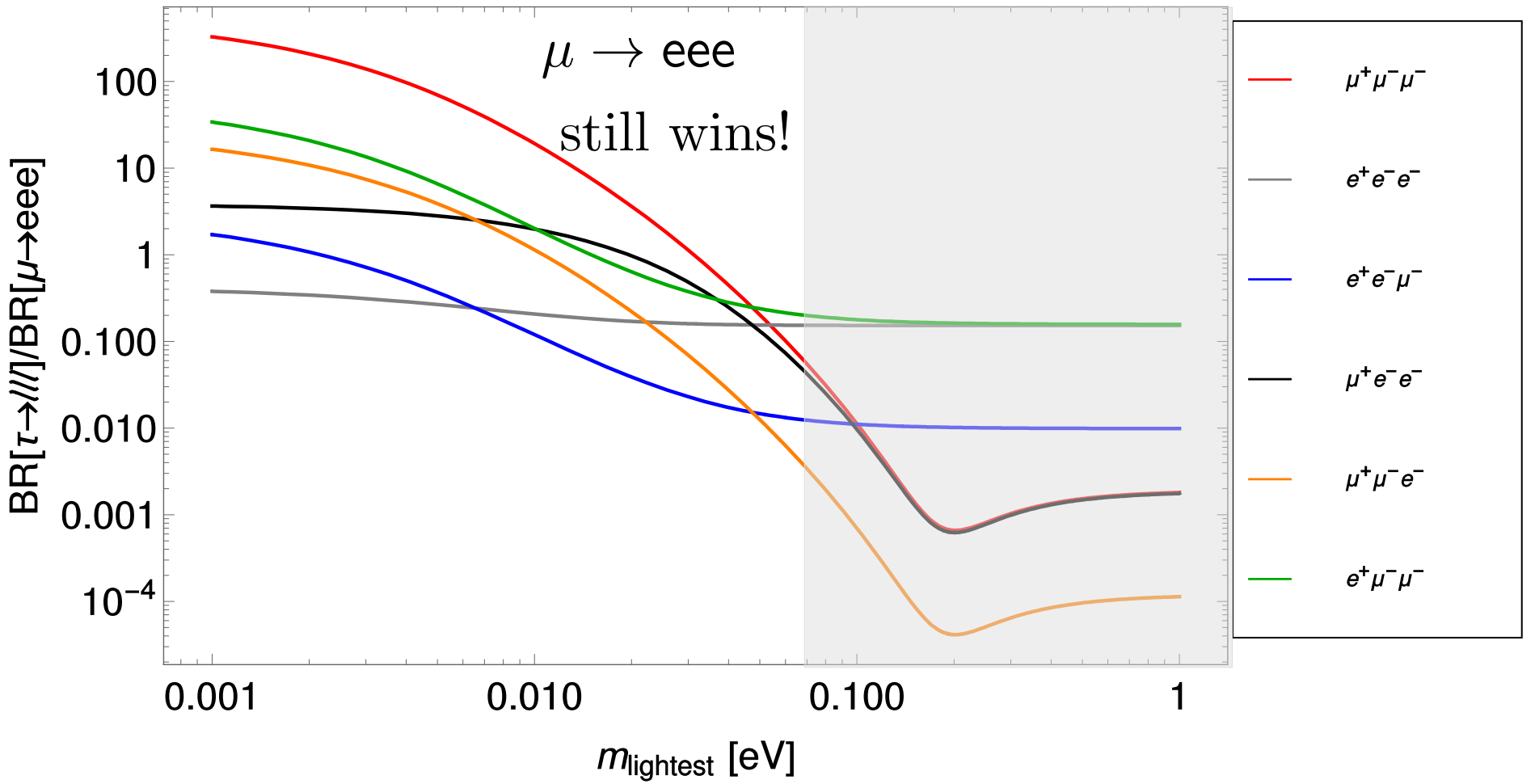
Prediction of LFV ratios via M_ν!

Normal ordering, $\alpha=\beta=0$



$$\mathrm{BR}(\ell_\alpha \to \ell_i \ell_j \bar{\ell}_k) \propto |(\mathrm{M}_\nu)_{\alpha k}|^2 |(\mathrm{M}_\nu)_{ij}|^2. \qquad \mathrm{M}_\nu^{\mathrm{NH}} \sim \begin{pmatrix} \epsilon & \epsilon & \epsilon \\ \epsilon & 1 & 1 \\ \epsilon & 1 & 1 \end{pmatrix}$$

Normal ordering, α=β=0



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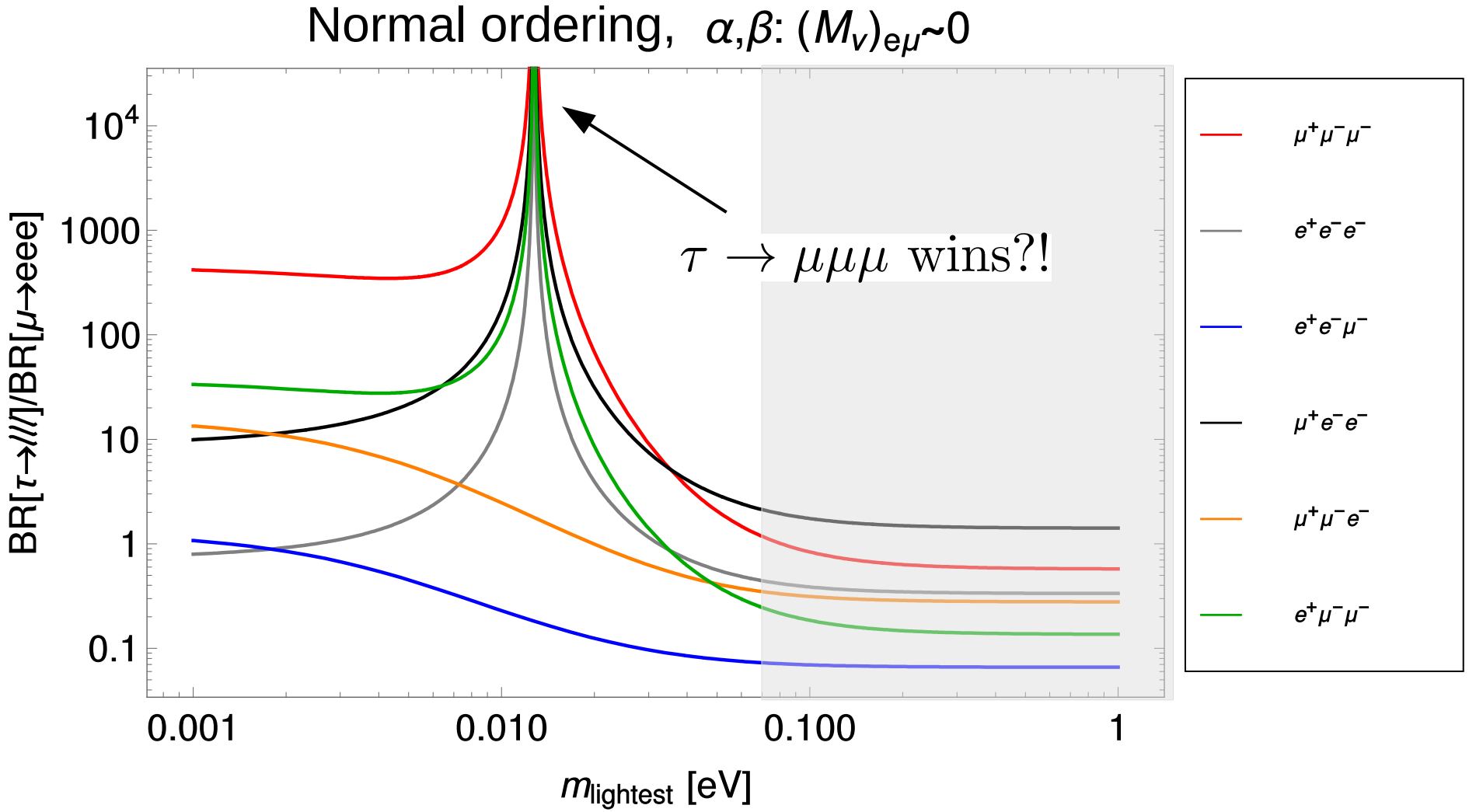

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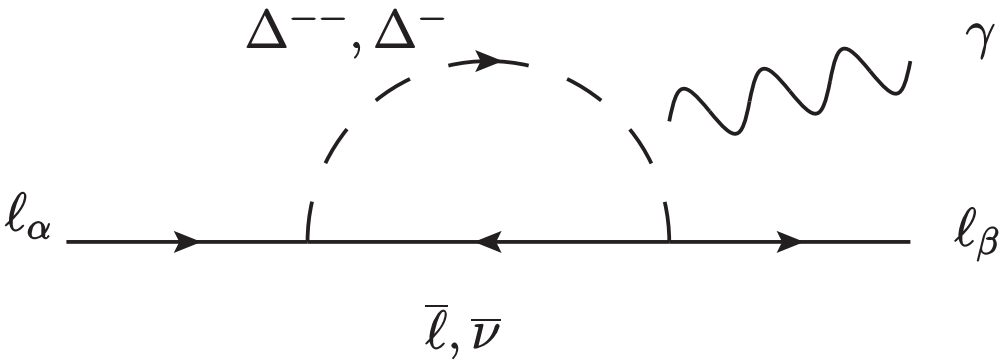
Scalar-triplet seesaw

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

- But at loop level:



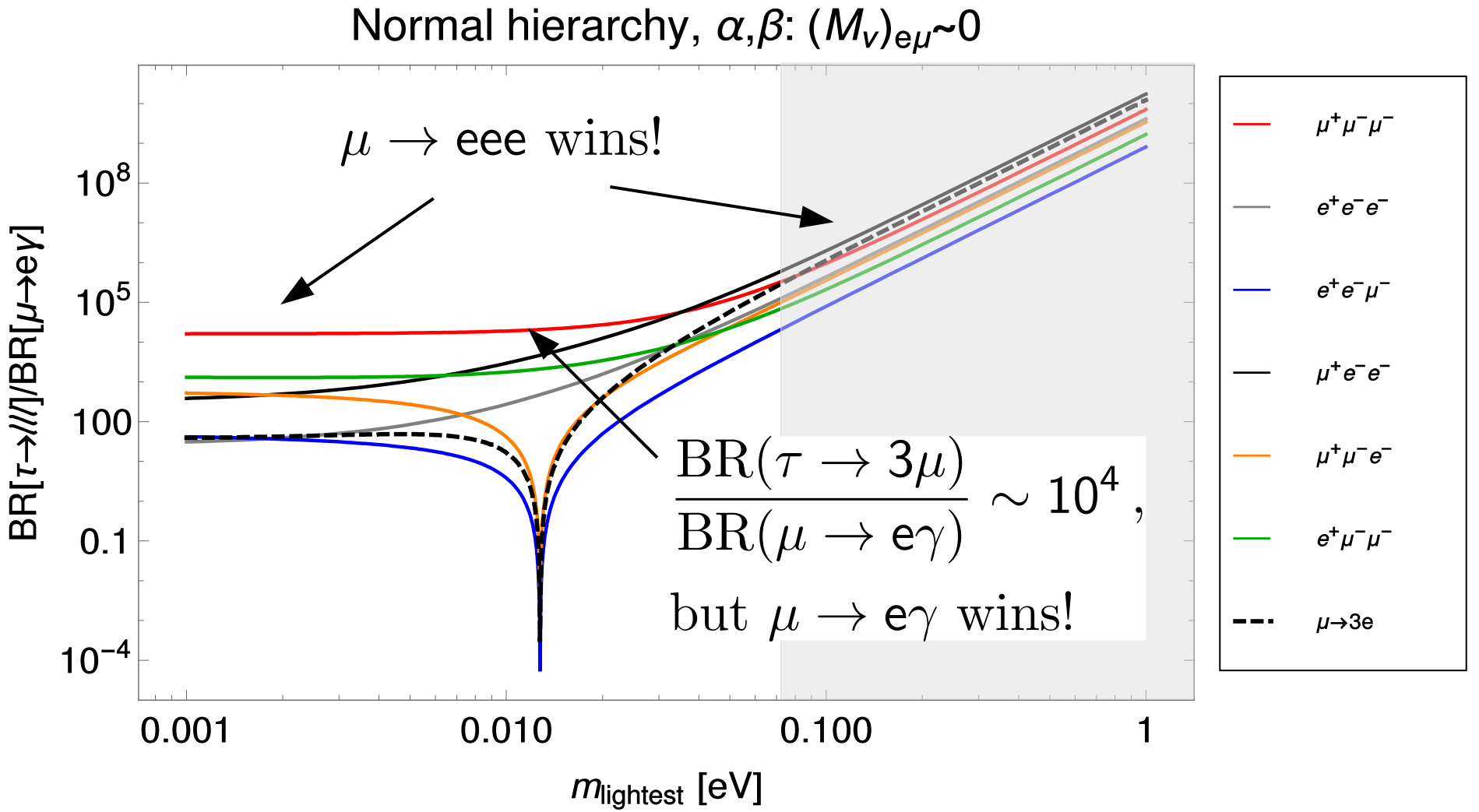
$$\mathrm{BR}(\ell_\alpha \to \ell_\beta \gamma) \propto \frac{|(y^\dagger y)_{\alpha\beta}|^2}{M_\Delta^4} .$$

[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!

Summary 2: type-II seesaw

- LFV *ratios* determined by M_ν, depends on CP phases.
- LFV in muon sector dominant due to experiments.
- $\tau \to \mu\mu\mu$ next for normal hierarchy if we see μLFV.
- Reason for connection:

$$y\bar{L}^c \Delta L = y\Delta^0 \nu\nu + y\Delta^+ \nu\ell + y\Delta^{++} \ell\ell$$

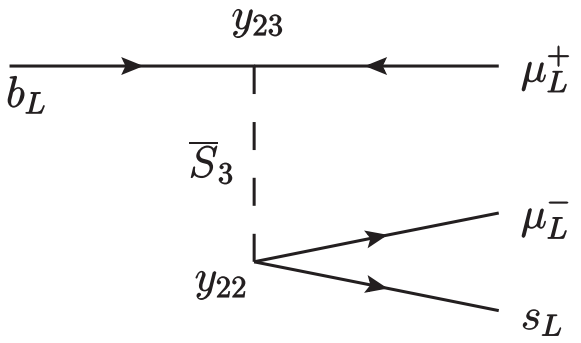
M_ν $\quad \ell_\alpha \to \ell_\beta \gamma$ $\quad \ell_\alpha \to \ell_\beta \ell_\rho \bar{\ell}_\eta$

- Same coupling $y \propto M_\nu$.

Connecting M_ν to quark flavor violation

- Embed $\overline{L}^c \Delta L$ in grand unified theory!
- E.g. Pati-Salam $SU(4) \times SU(2)_L \times SU(2)_R$:
  - $\Psi_L \sim (\mathbf{4}, \mathbf{2}, \mathbf{1}) \to Q_L \oplus L_L$.
  - $\Delta_L \sim (\overline{\mathbf{10}}, \mathbf{3}, \mathbf{1}) = \Sigma_3 \oplus \Delta \oplus S_3$.
  - $y \overline{\Psi}_L^c \Delta_L \Psi_L \supset \underbrace{y \overline{L}_L^c L_L \Delta}_{\text{type-II seesaw}} + \underbrace{y \overline{Q}_L^c L_L S_3}_{R_{K^{(*)}}}$.
  - Connect M_ν with $b \to s \ell_\alpha \overline{\ell}_\beta$.

Triplet leptoquark



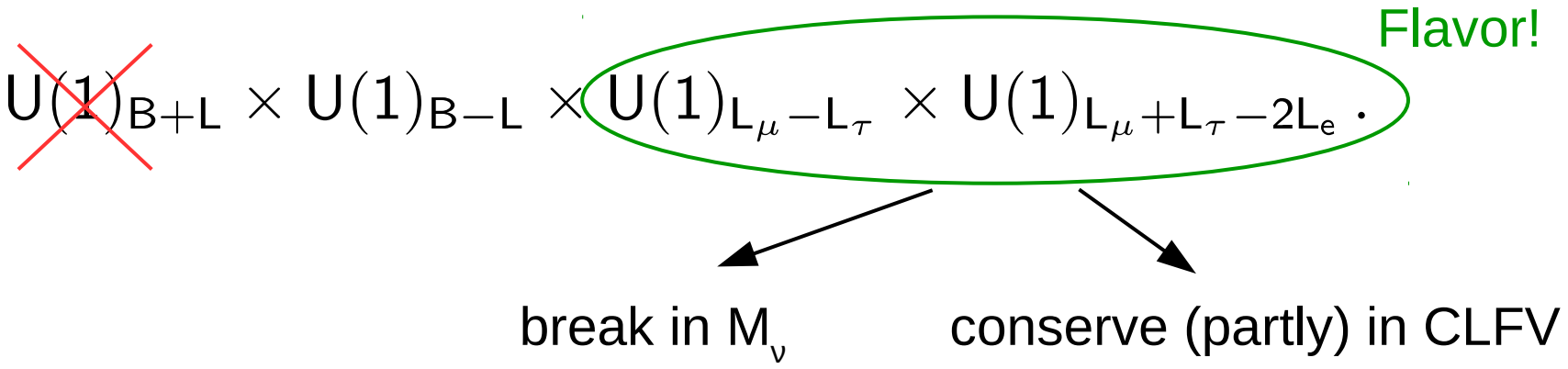
[**JH**, Teresi, 1808.07492]

[see flavor session Thursday and X.-G. He Friday for B anomalies!]

- SO(10): $\mathbf{16} \times \mathbf{16} \times \mathbf{126} =$ M_ν plus *all* leptoquarks!

How to get LFV in taus?

- Go back to SM symmetry:



- E.g. break $\Delta(L_e - L_\mu) = 2$ only in M_ν: τLFV only!
- Can also modify proton decay modes!

[**JH**, 1610.07623]

[Hambye, **JH**, 1712.04871, PRL]

Partially conserved lepton flavor!

Summary

- Charged LFV complementary to ν oscillations.
- Model-*dependent* connections to M_ν possible.
- Muon LFV typically dominant, more sensitive.
- Tau LFV possible for non-trivial flavor breaking.

  ⇒ Need to probe all possible channels!
- Amazing improvement soon:
  Mu3e, MEG-II, Belle-II, Mu2e, COMET, DeeMe, LHC(b).

Backup

Scales probed by LFV

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

Upcoming CLFV

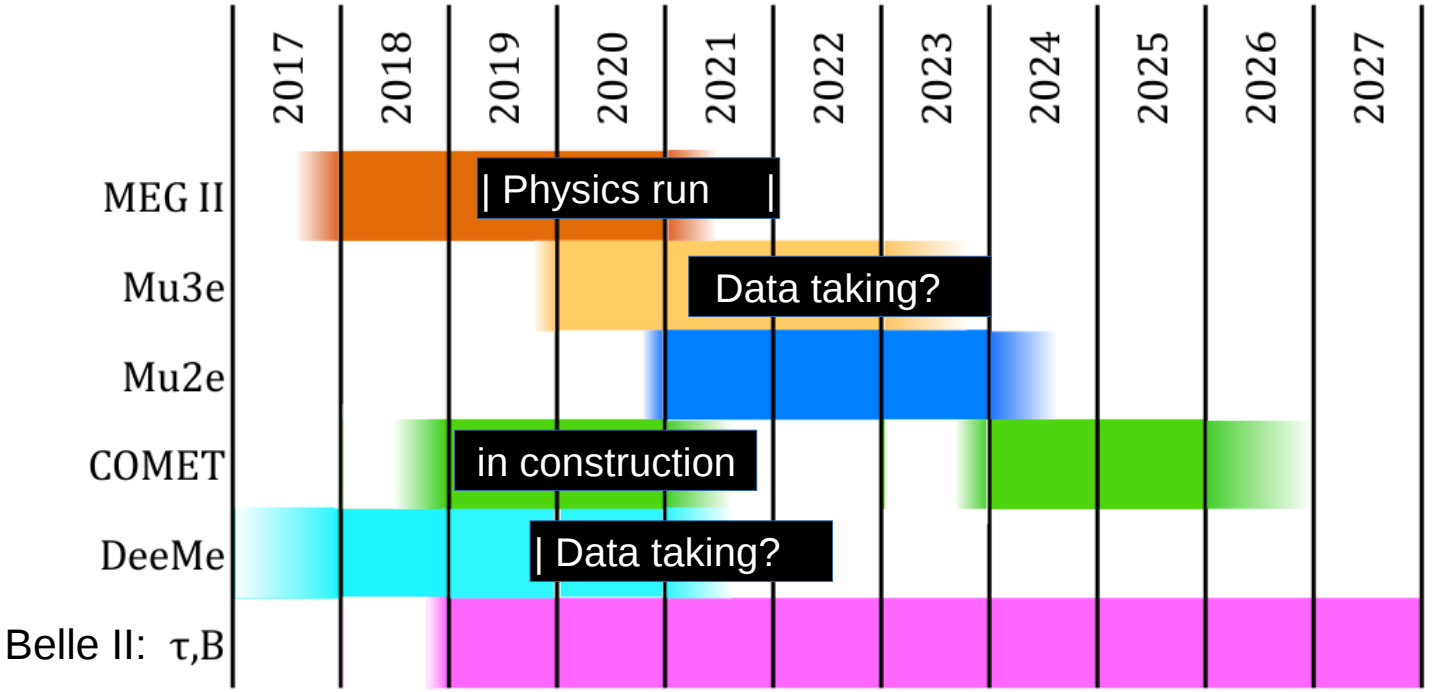


Figure 47. – Projected time lines for different projects searching for CLFV decays. MEG IIis expected to start data taking in 2018 after an engineering run in 2017; Mu3e magnet and detectors are expected at the end of 2019; Mu2e foresees three years of data taking starting in 2021; COMET Phase-I is expected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

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:

$$L = L_{SM} + \frac{LLHH}{\Lambda} + \sum_j \frac{\mathcal{O}_j}{\Lambda^2} + \sum_j \frac{\mathcal{O}'_j}{\Lambda^3} + \sum_j \frac{\mathcal{O}''_j}{\Lambda^4} + \dots$$

M_ν

conserves G

violates G

could conserve G or subgroup

⇒ ‘weird’ channels dominate!?

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].

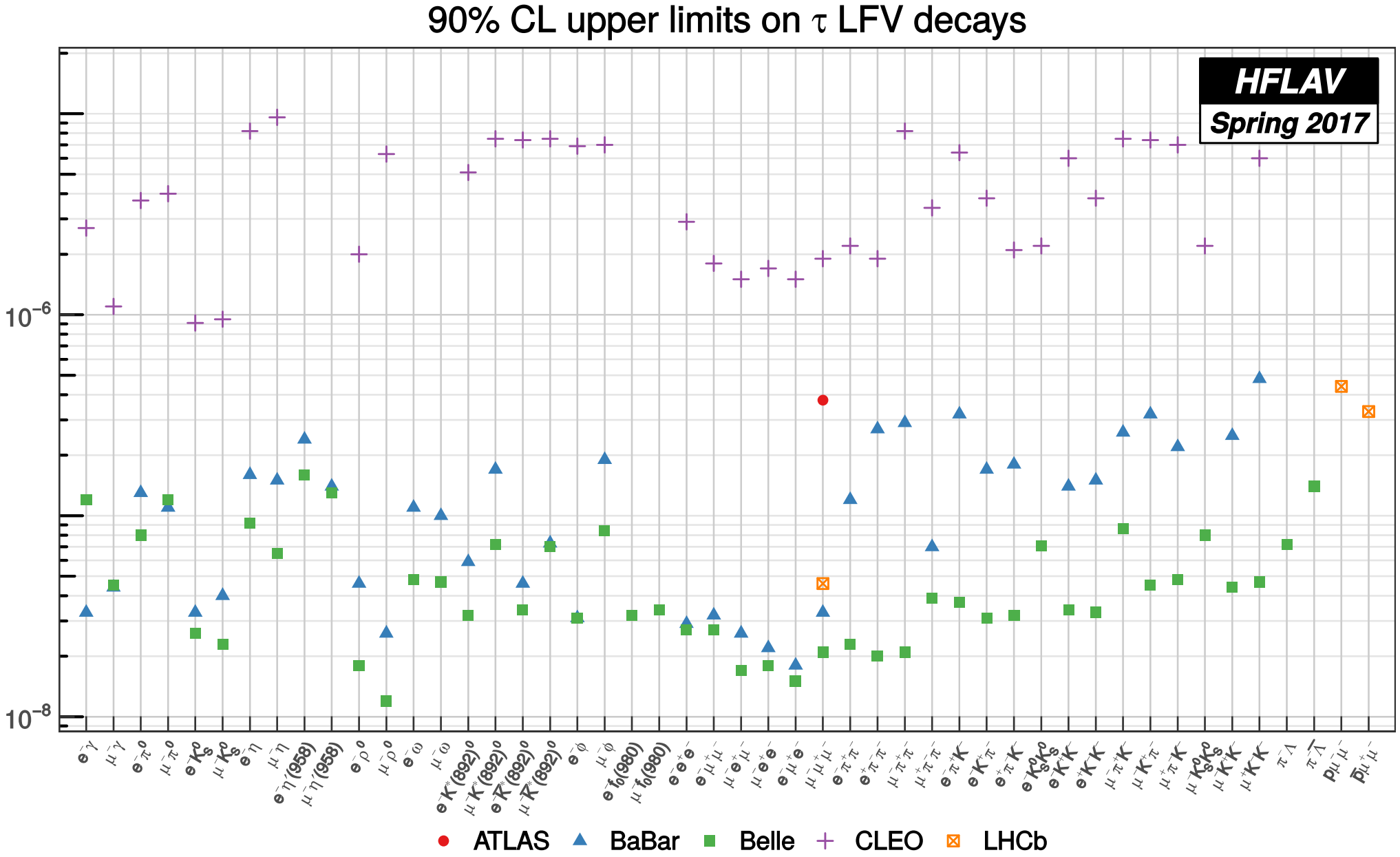
Group	Process	Current	Future
$\Delta(L_\mu + L_\tau - 2L_e) = 6$	$\tau \to ee\bar{\mu}$	1.5×10^{-8} [29]	10^{-9} [28]
$\Delta(L_\tau + L_e - 2L_\mu) = 6$	$\tau \to \mu\mu\bar{e}$	1.7×10^{-8} [29]	10^{-9} [28]
$\Delta(L_e + L_\mu - 2L_\tau) = 6$	$\mu e \to \tau\tau$	–	–

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]	$10^{26}\,\text{yr}$ [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.

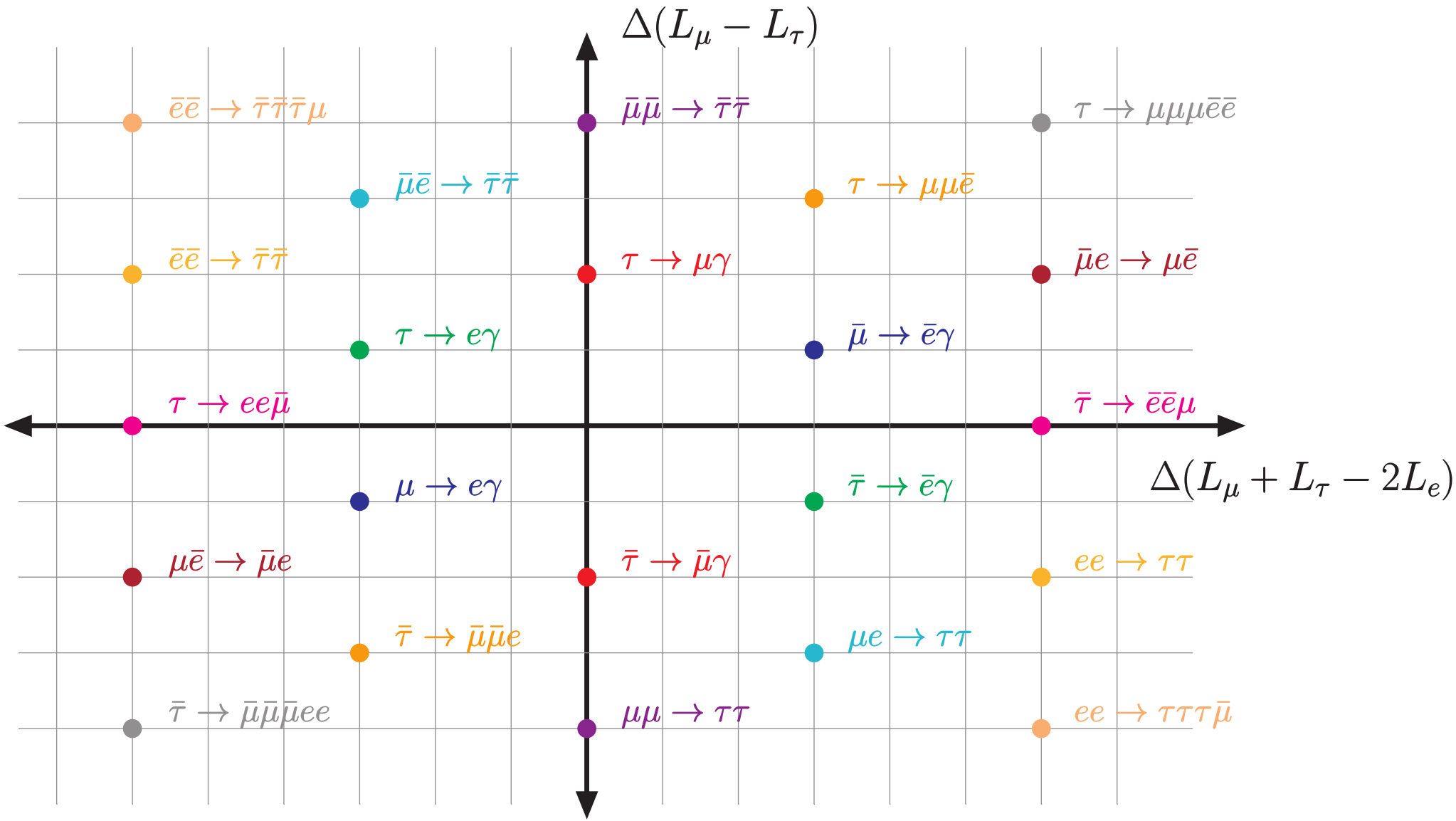
[Heeck, 1610.07623]


90% CL upper limits on τ LFV decays
HFLAV
Spring 2017
10^{-6}
10^{-8}
ATLAS
BaBar
Belle
CLEO
LHCb

$\Delta B = \Delta L = 0$

[Heeck, 1610.07623]

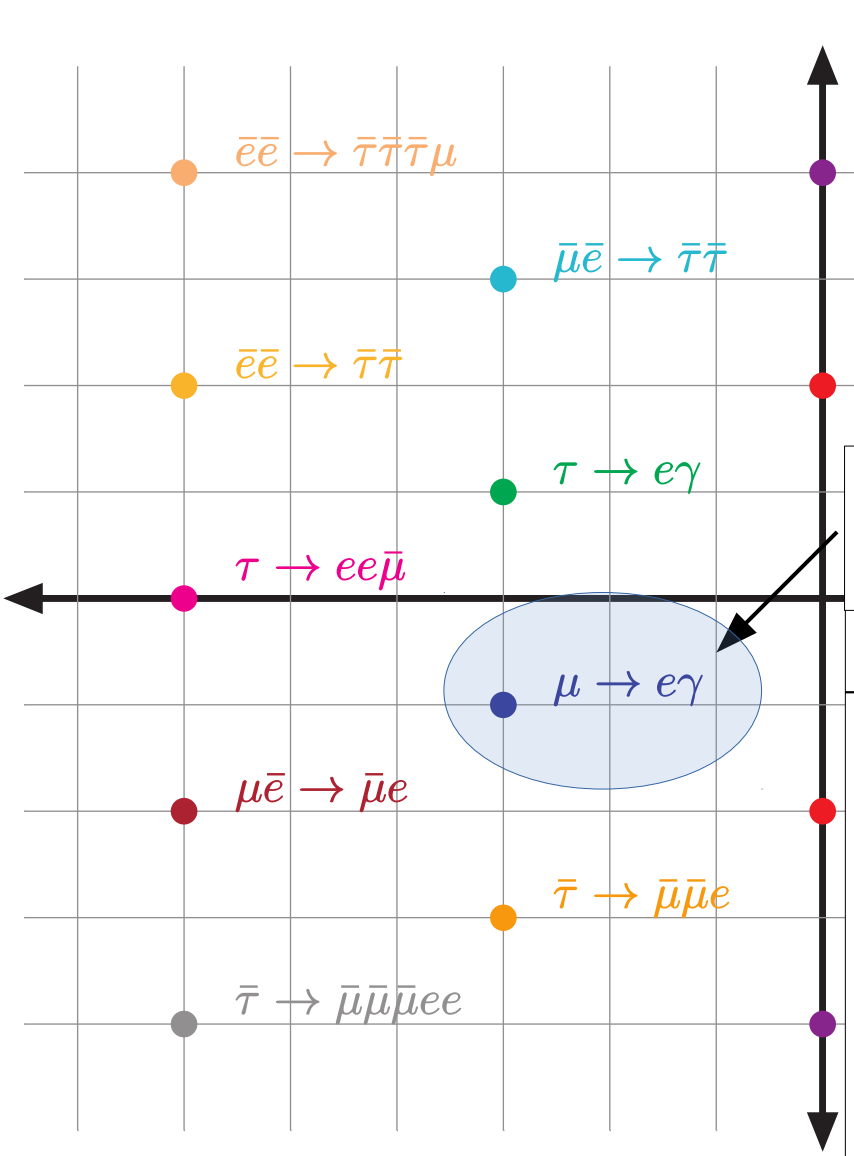
[Lew, Volkas, 9410277]



$\Delta B = \Delta L = 0$

[Heeck, 1610.07623]

[Lew, Volkas, 9410277]



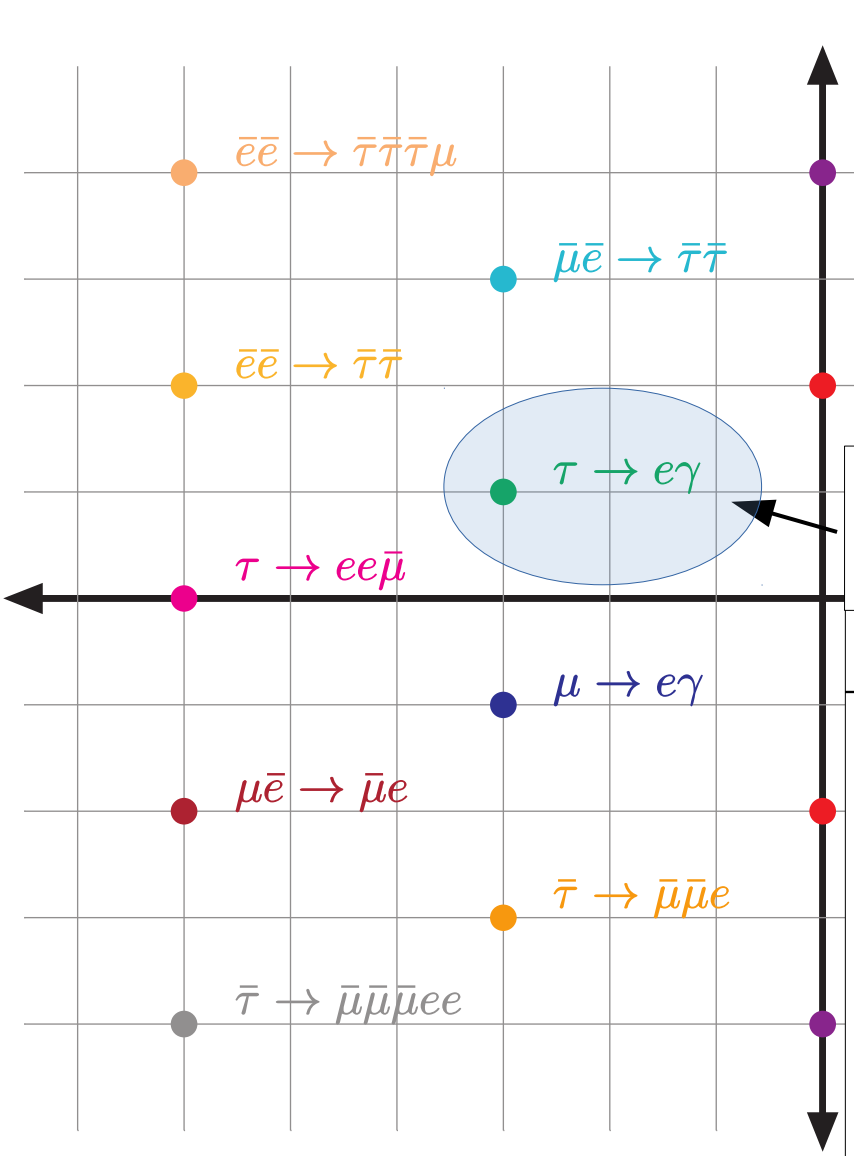
Stands for *all* $\Delta(L_e - L_\mu) = 2$ processes:

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}

$\Delta B = \Delta L = 0$

[Heeck, 1610.07623]

[Lew, Volkas, 9410277]

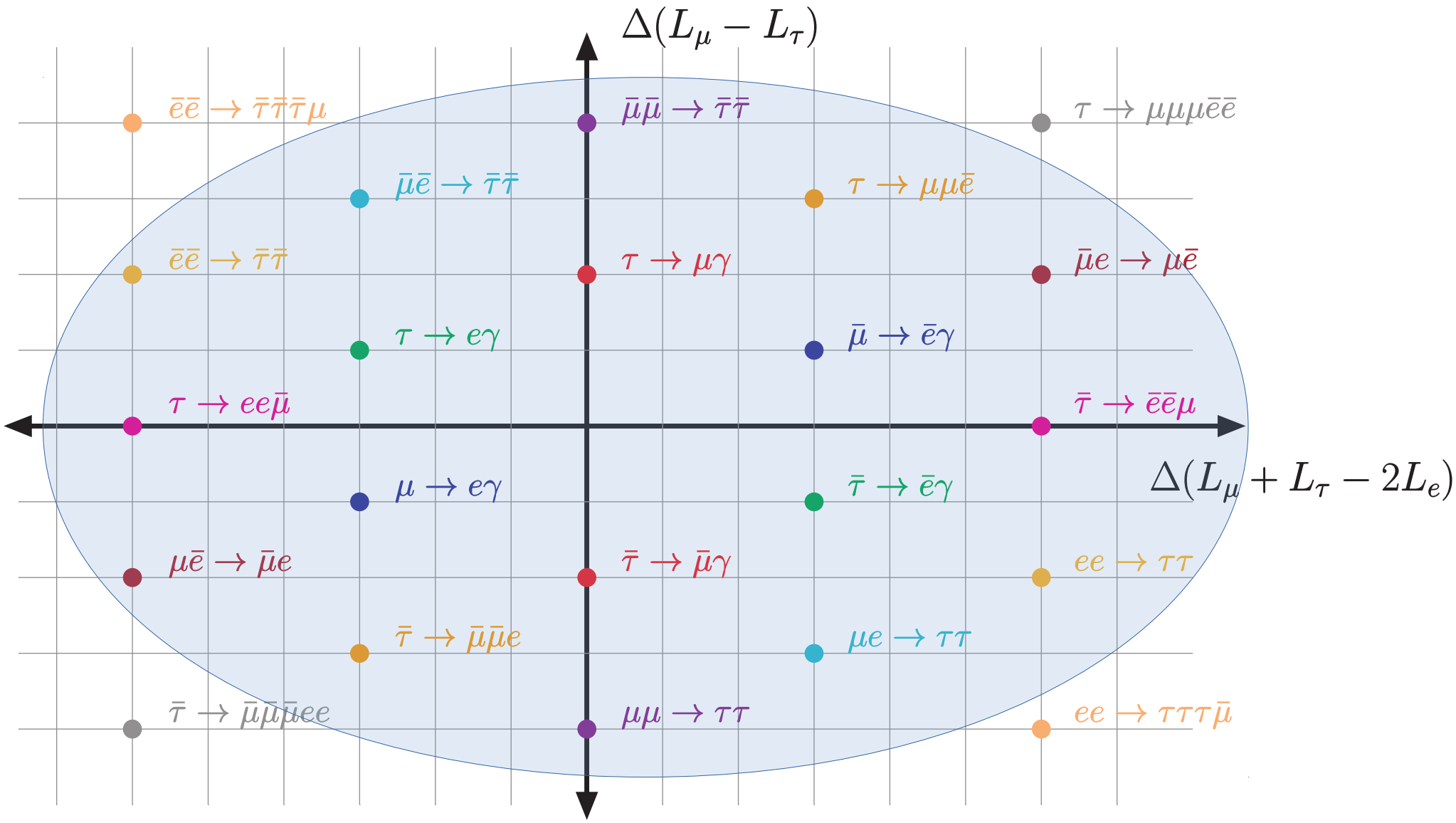


Stands for *all* $\Delta(L_e - L_\tau) = 2$ processes:

process	current	future
$\tau \to e\gamma$	3.3×10^{-8}	10^{-9}
$\tau \to e\bar{e}e$	2.7×10^{-8}	10^{-9}
$\tau \to e\bar{\mu}\mu$	2.7×10^{-8}	10^{-9}
$\tau \to e\,\mathrm{had}$	$\mathcal{O}(10^{-8})$	10^{-9}
$h \to e\bar{\tau}$	6.9×10^{-3}	5×10^{-3}
$Z \to e\bar{\tau}$	9.8×10^{-6}	–
$\mathrm{had} \to e\bar{\tau}(\mathrm{had})$	$\mathcal{O}(10^{-6})$	–

Dimension 6 operators

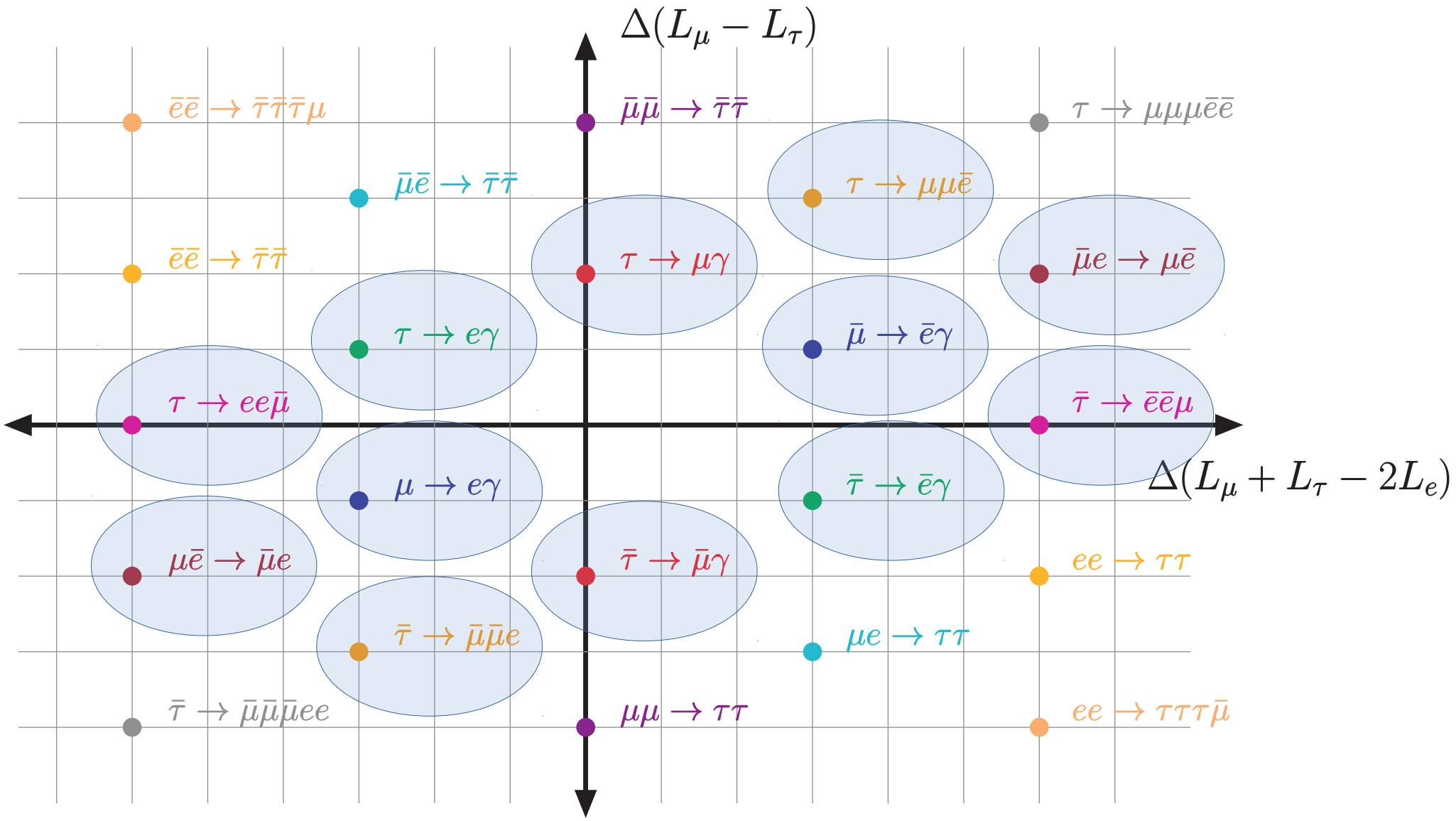
[Heeck, 1610.07623]
[Lew, Volkas, 9410277]



Currently being probed.

[Heeck, 1610.07623]

[Lew, Volkas, 9410277]



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:

$$(g_{\mu\tau}\overline{\mu}_R^c \tau_R + g_{ee}\overline{e}_R^c e_R)\, k^{++} + y\bar{L}HN_R + \tfrac{1}{2}\bar{N}_R^c\,(M_R^{\rm sym} + y_S\ S\ )\,N_R\,.$$

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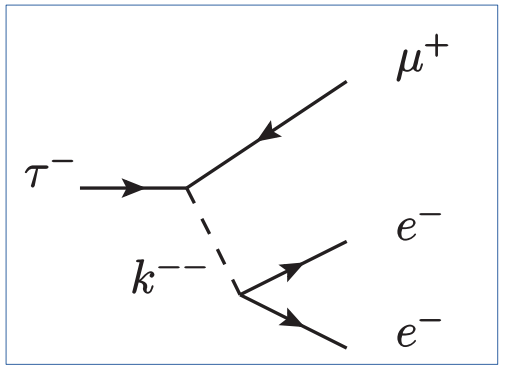
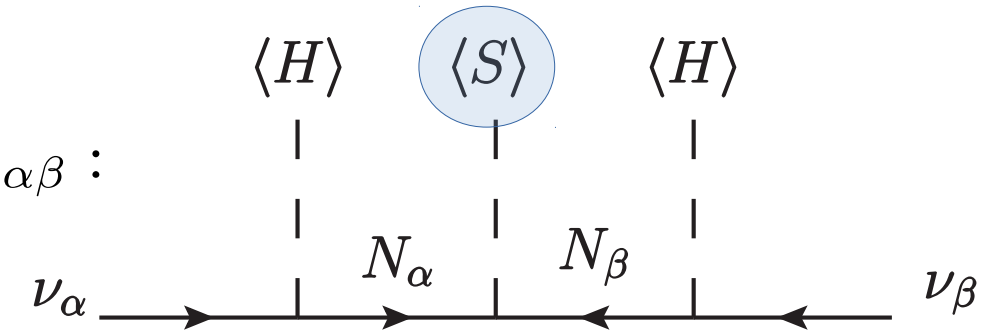


$(M_\nu)_{\alpha\beta}$:



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

ν oscillations but approximate symmetry in ℓ^- sector.

Baryon number violation

=

The violation of

$$\mathrm{U}(1)_B \quad \left[\times \mathrm{U}(1)_L \times \mathrm{U}(1)_{L_\mu - L_\tau} \times \mathrm{U}(1)_{L_\mu + L_\tau - 2L_e}\right]$$

in processes

$p \to \text{leptons} + \text{had}$, n-$\bar{\text{n}}$ osc , $pp \to \ell^+\ell^{+\prime}$, $nn \to \text{had}$, . . .*

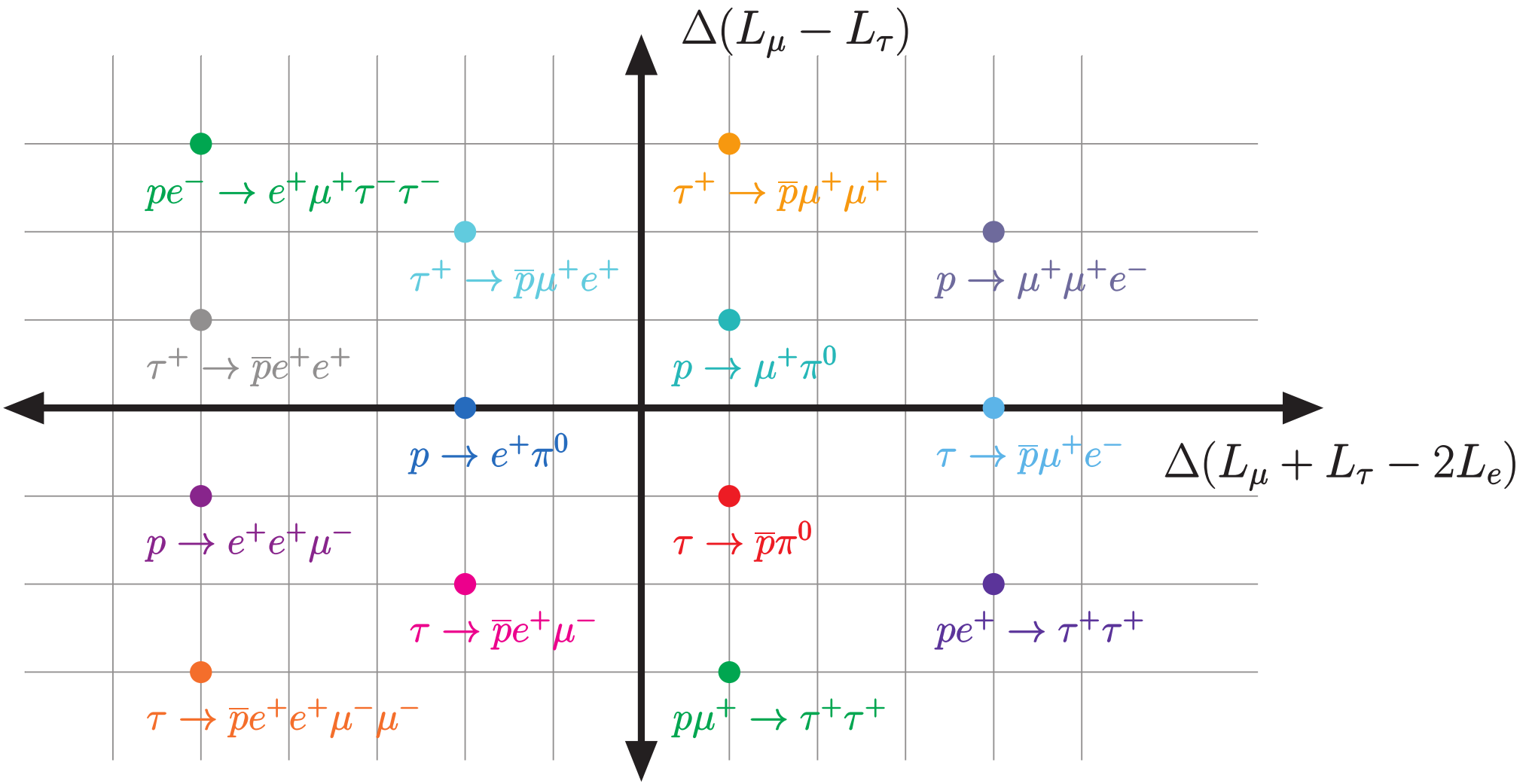
*Assuming *heavy* new physics.

$\Delta B = 1$ and $\Delta L = 1, 3, \ldots$

[Weinberg, '79 & '80]

[Hambye, Heeck, 1712.04871] [Fonseca, Hirsch, Srivastava, 1802.04814]

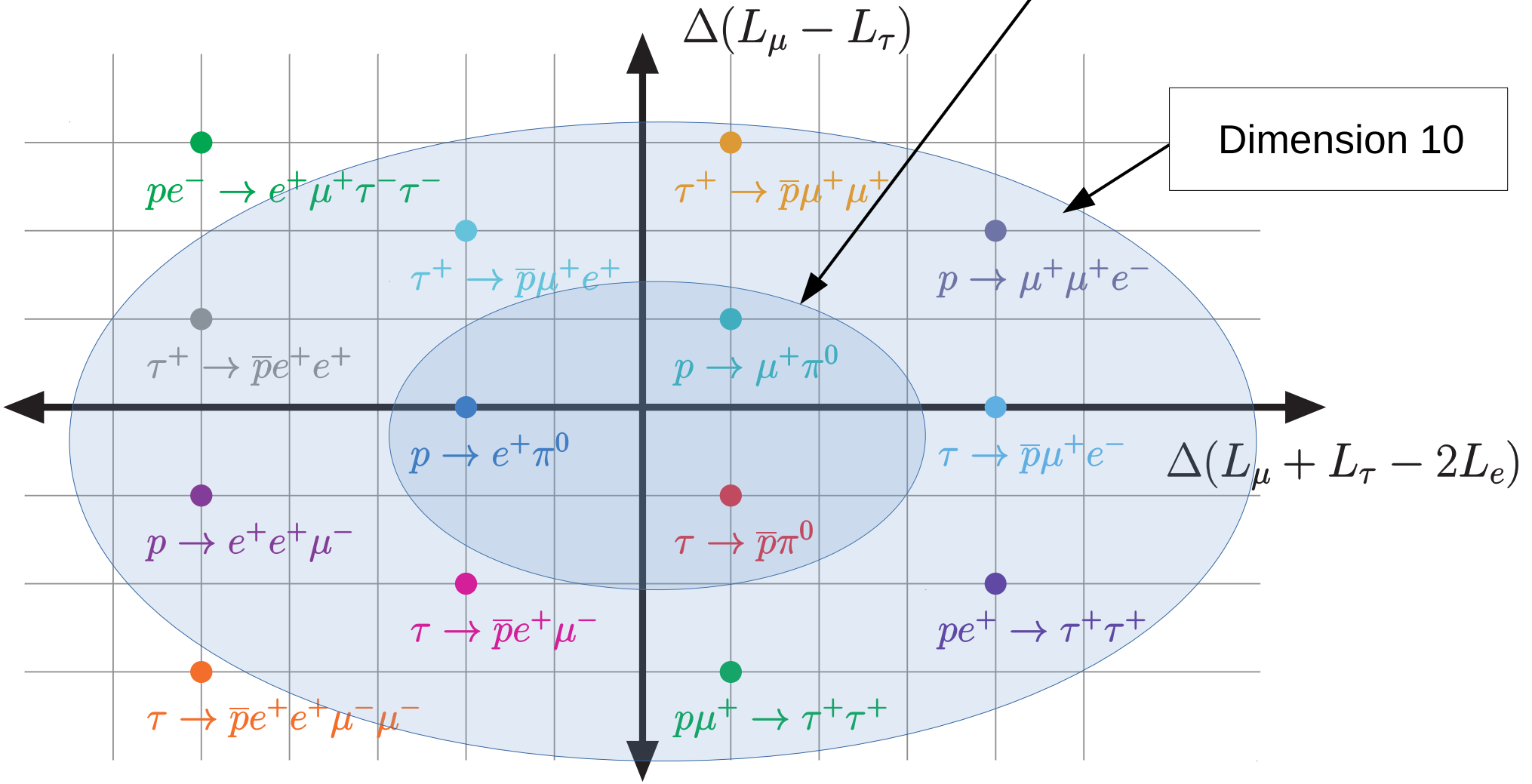
$\Delta B = \Delta L = 1$



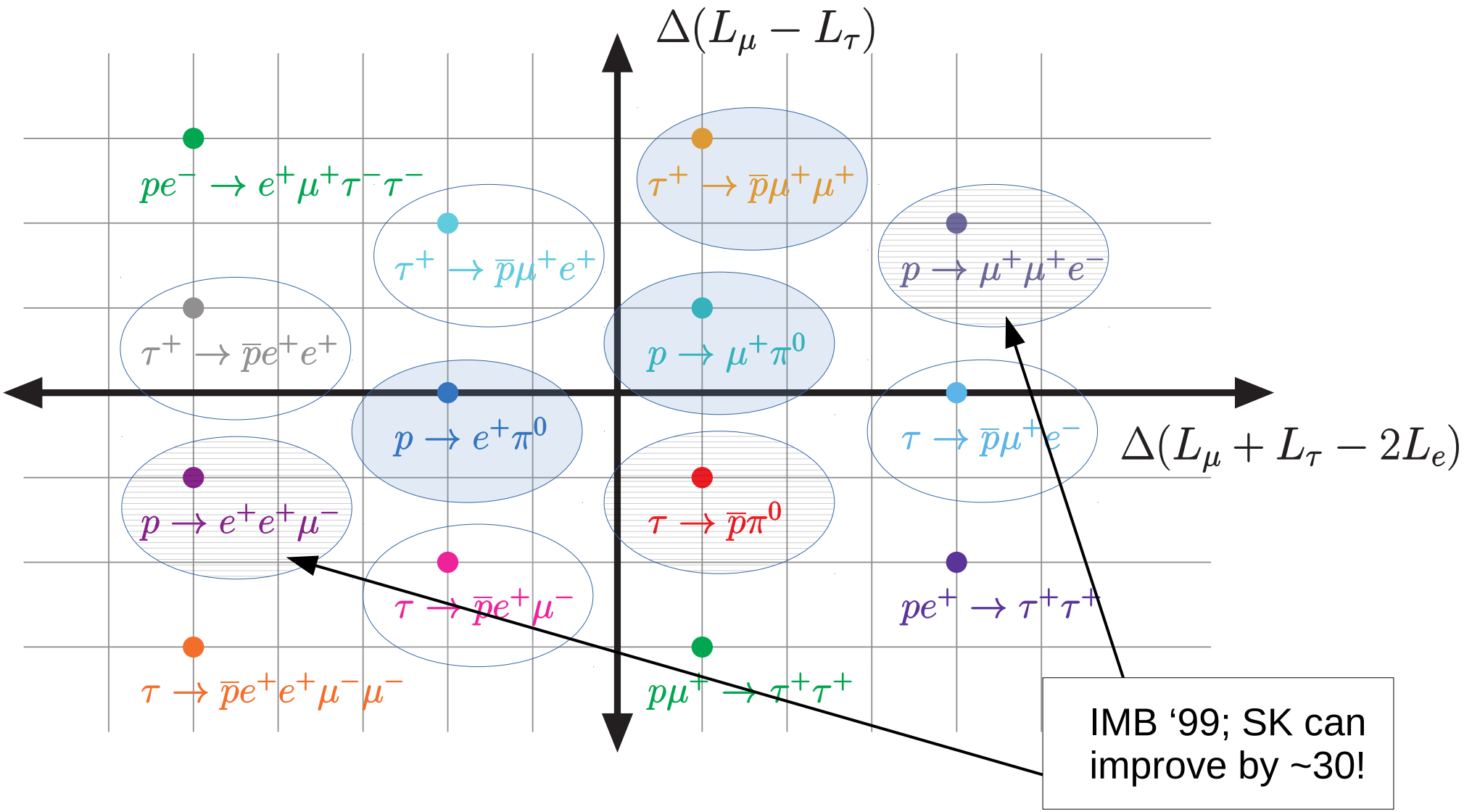
$\Delta B = \Delta L = 1$

Dimension 6 operators

Dimension 10



Currently being probed: Old results: Doable:



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 $QQQL\bar{L}H\ell/\Lambda^6$.
- 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]

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

- Minimal scalar leptoquark example,

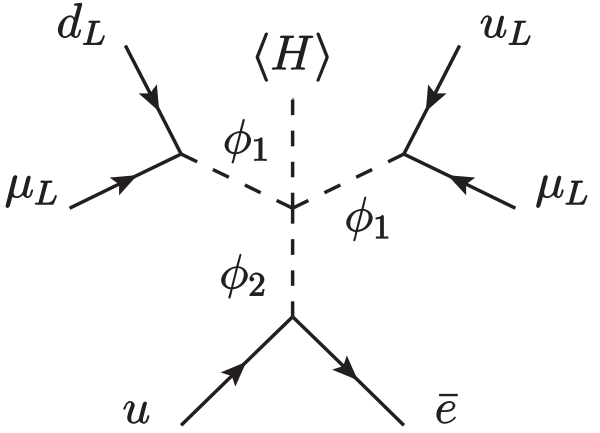
  $L_\mu(\phi_1) = 1,\ L_e(\phi_2) = -1.$

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

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

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

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



[Hambye, Heeck, 1712.04871, PRL]

- B–L and lepton flavor conserved: only $p \to \mu^+\mu^+e^-$!

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

- Minimal scalar leptoquark example,

  $L_\mu(\phi_1) = 1,\ L_e(\phi_2) = -1.$

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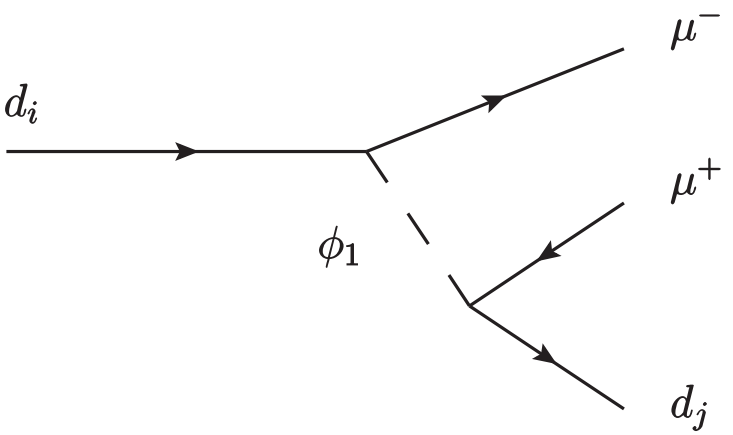
$$y_j \bar{L}_\mu \phi_1 Q_j^c + f_j \bar{u}_j \phi_2 L_e + \lambda \phi_1^2 \phi_2 H\,.$$

- d = 6 operators:

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



⇒ Lepton universality violation!