New Perspectives on Lepton Flavor Violation

Julian Heeck

Paul Scherrer Institute

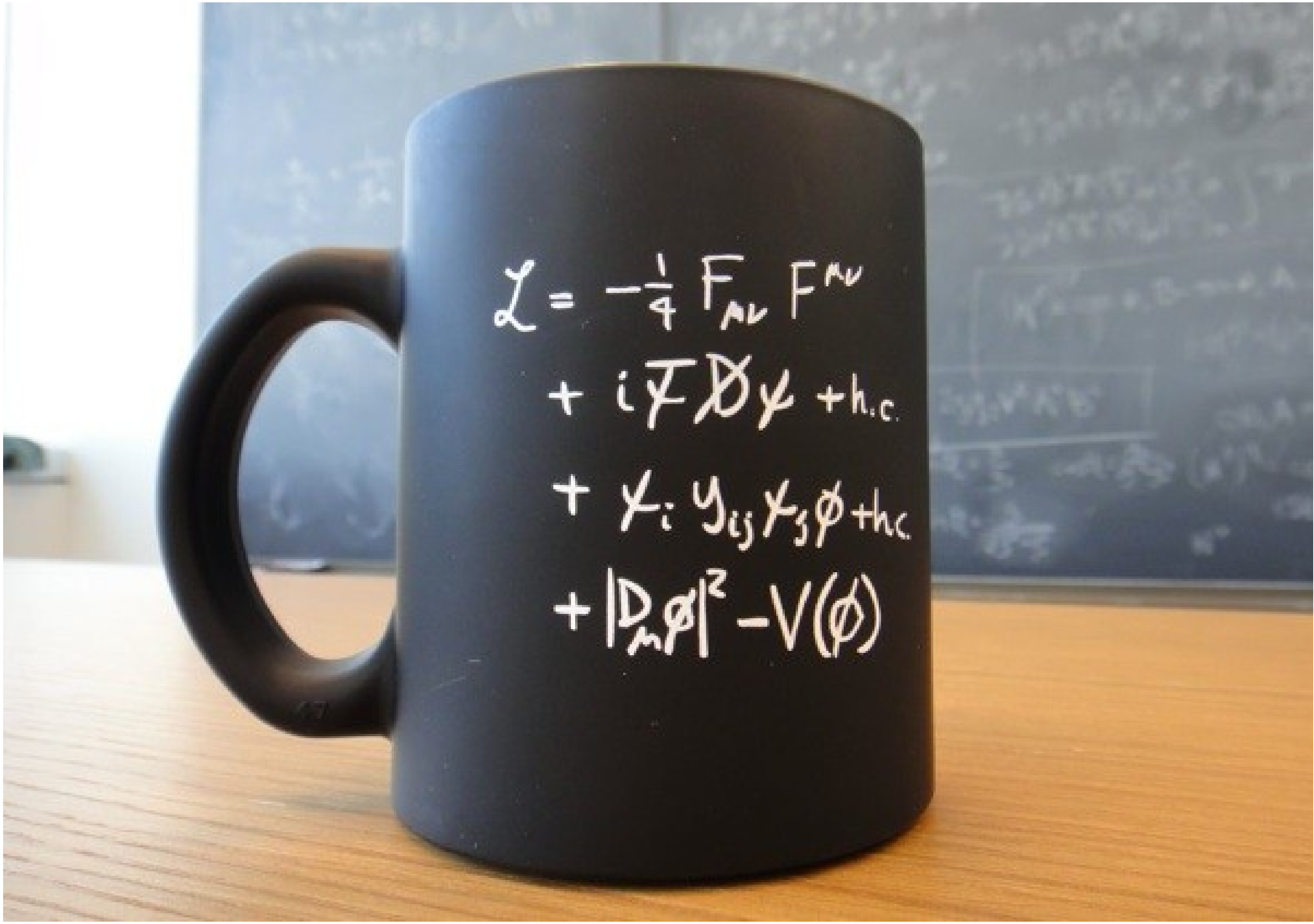
4.12.2017

Fundamental .be Interactions

fnrs LA LIBERTÉ DE CHERCHER

UNIVERSITÉ LIBRE DE BRUXELLES ULB

The Standard Model



www.quantumdiaries.org

Symmetries of the Standard Model

- Rephasing lepton and quark fields:

$$\mathsf{U}(1)_{\mathsf{B}} \times \mathsf{U}(1)_{\mathsf{L_e}} \times \mathsf{U}(1)_{\mathsf{L}_\mu} \times \mathsf{U}(1)_{\mathsf{L}_\tau} .$$

- B+L broken non-perturbatively,

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

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

- Real global symmetry of SM:

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

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

  [Araki, Heeck, Kubo, 1203.4951]

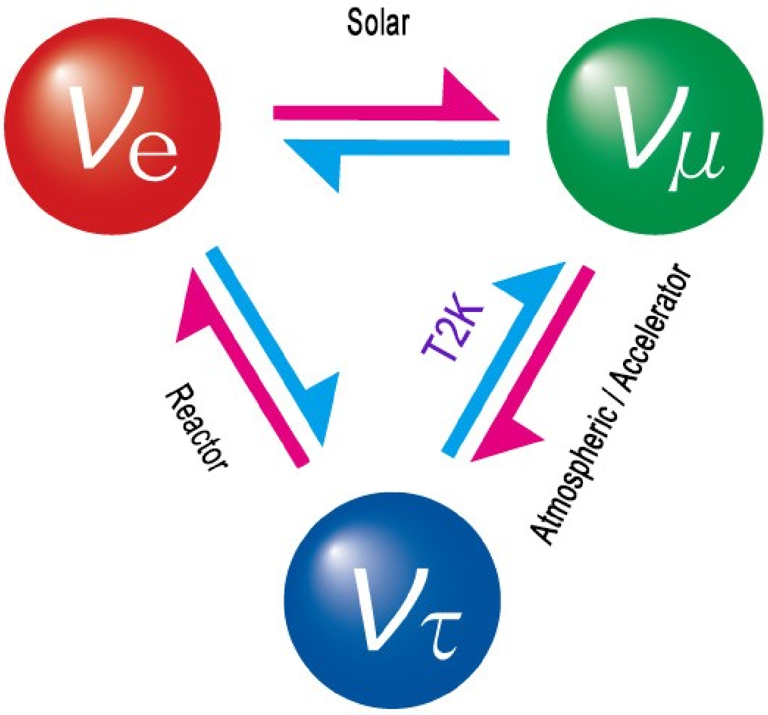
Neutrino oscillations

- 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

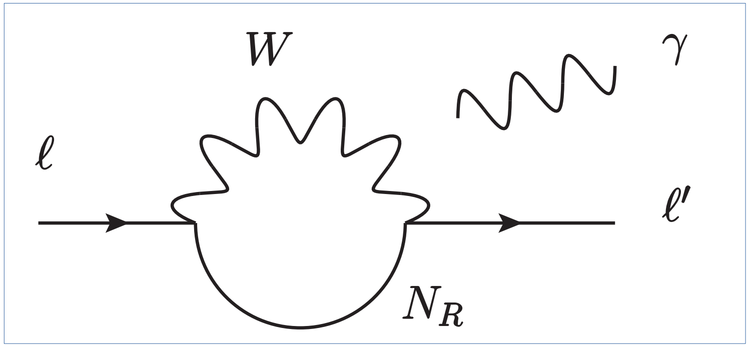
Lepton flavor definitely violated, so where is it?

Neutrino mass ⇒ charged LFV?

- SM + Dirac neutrinos: *all* LFV is GIM suppressed:

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

[Petcov ‘77; Cheng & Li ‘77]



- SM + heavy seesaw neutrinos:

$$\frac{\Gamma(\ell_\alpha \to \ell_\beta \gamma)}{\Gamma(\ell_\alpha \to \ell_\beta \nu_\alpha \overline{\nu}_\beta)} \simeq \frac{3\alpha_{\mathrm{EM}}}{8\pi} \underbrace{|(m_D M_R^{-2} m_D^\dagger)_{\alpha\beta}|^2}_{M^2_\nu / M^2_R} .$$

[Cheng & Li ‘80]

Not true with fine-tuning or structure in m_D.

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,…);
- 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!

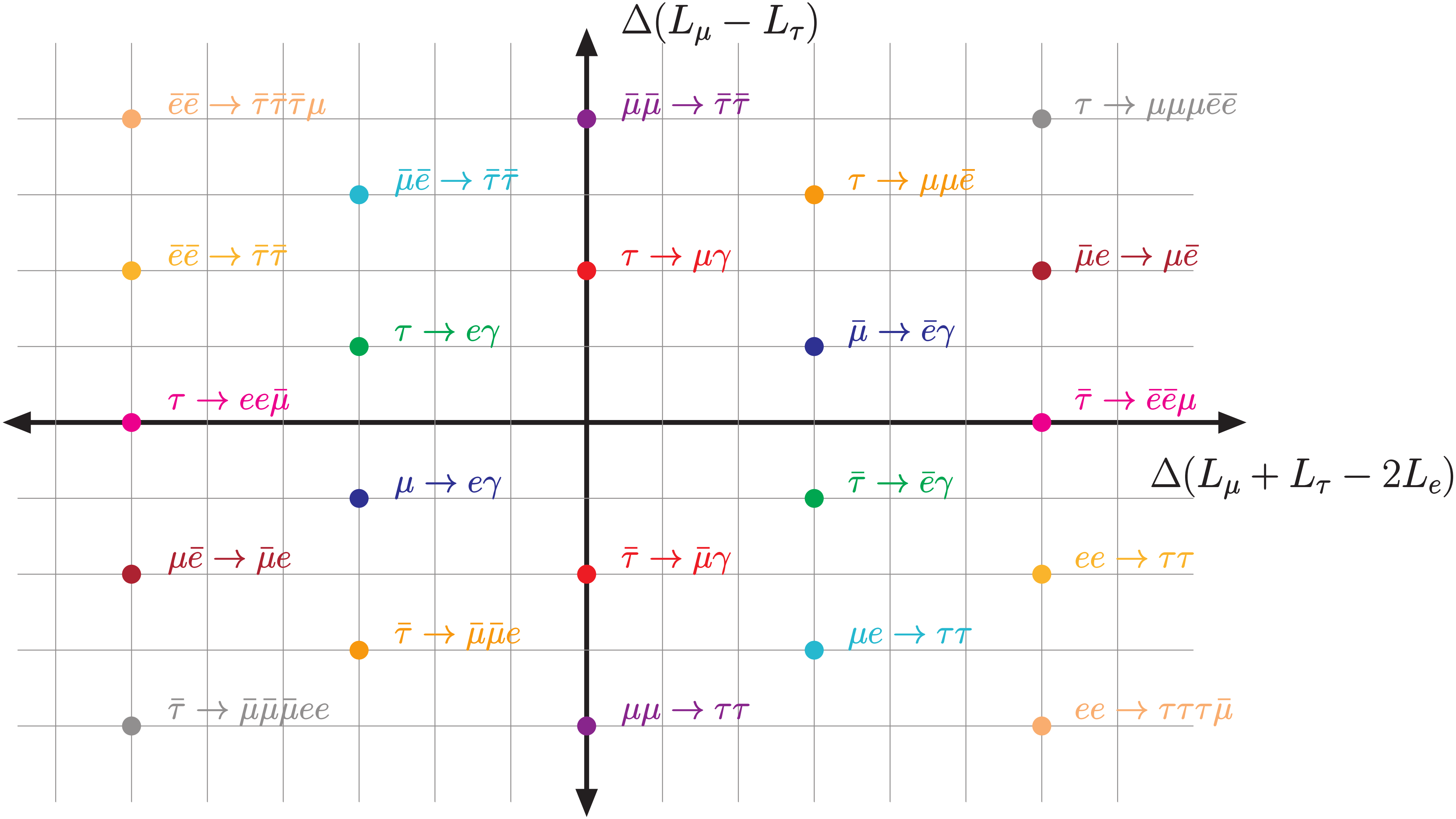
- Assuming *heavy new physics*, the best channels are

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

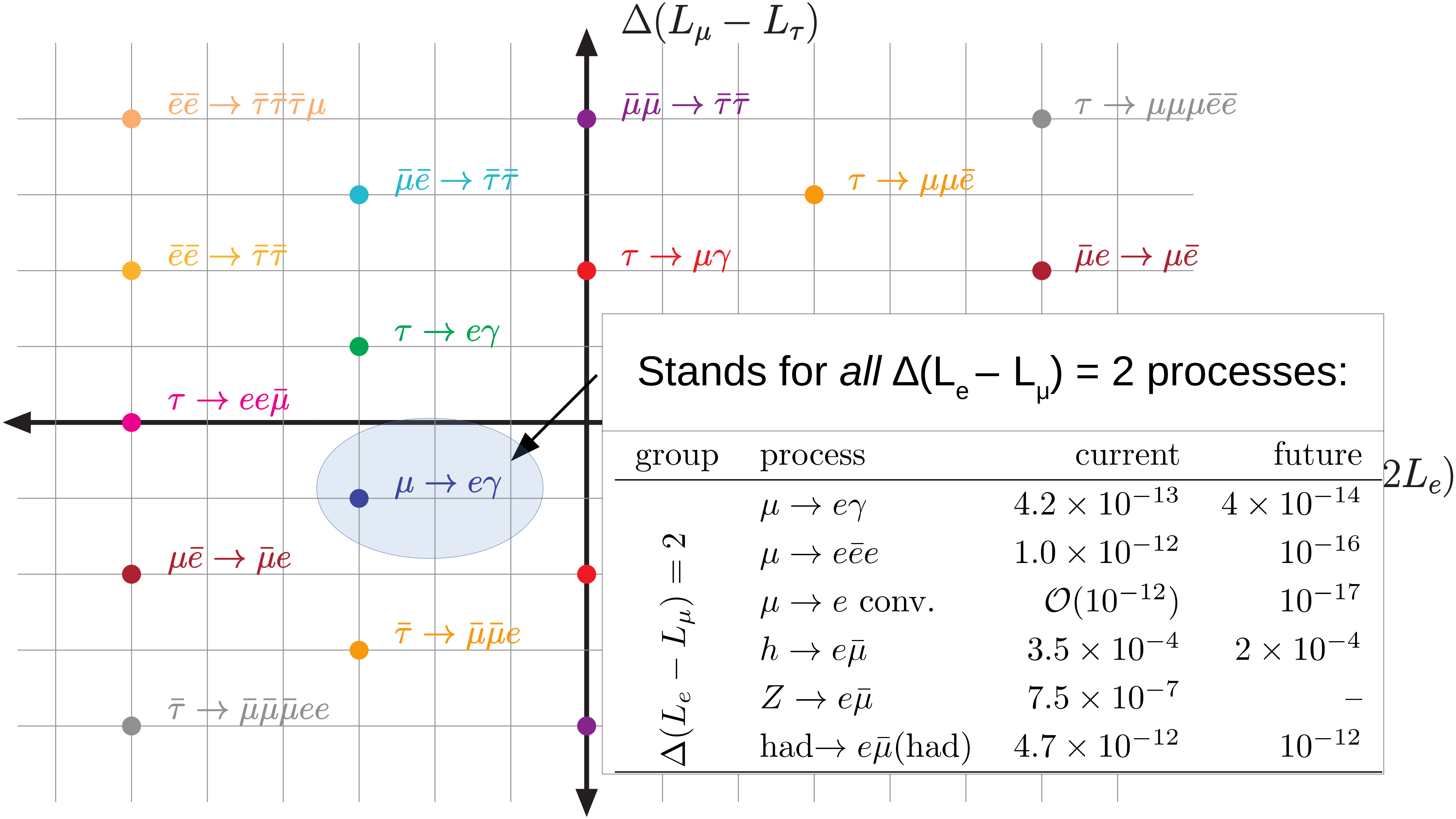
- Organize operators/processes by quantum numbers under

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

[Heeck, 1610.07623]



[Heeck, 1610.07623]

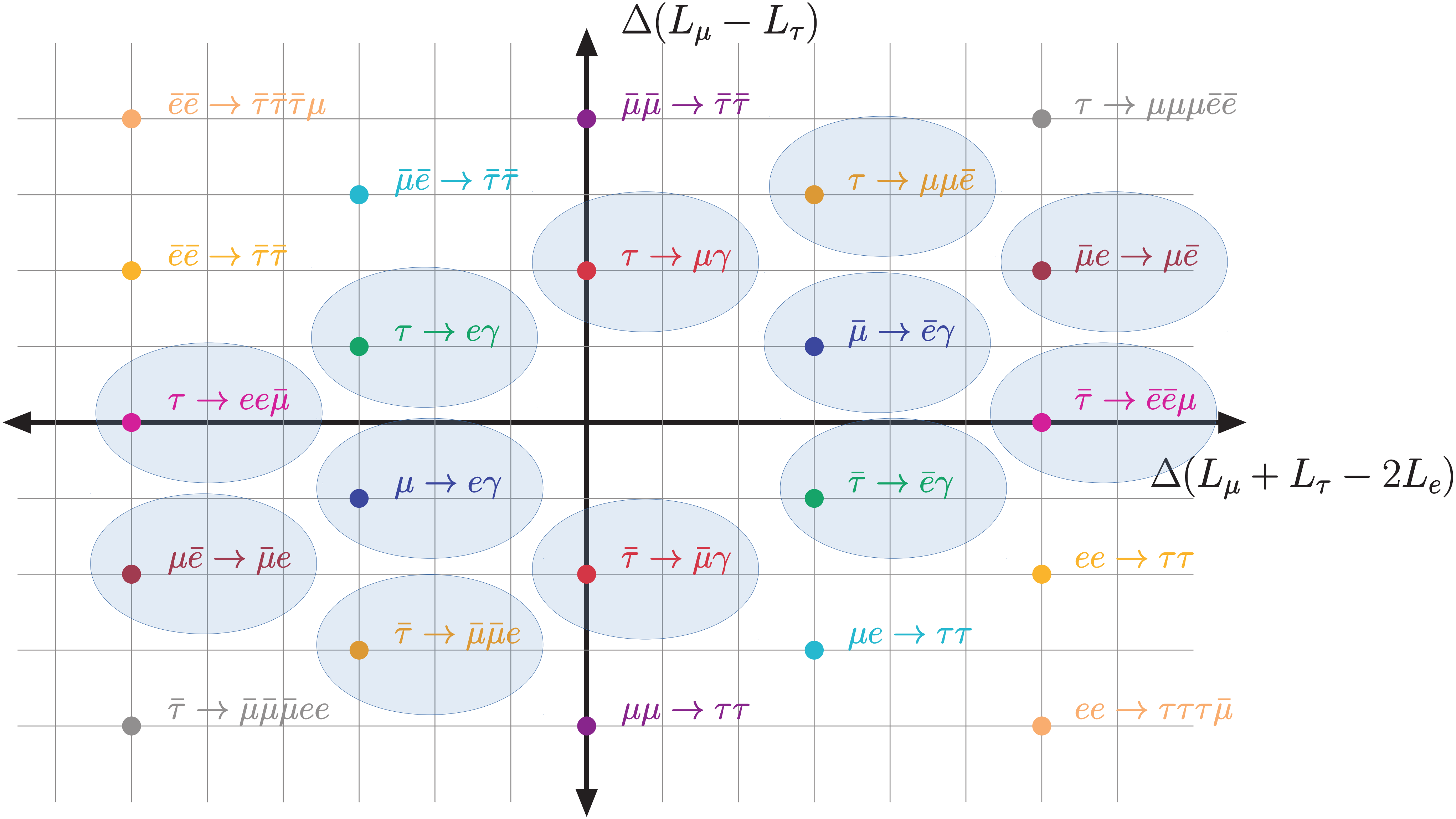


Stands for *all* $\Delta(L_e - L_\mu) = 2$ processes:

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}

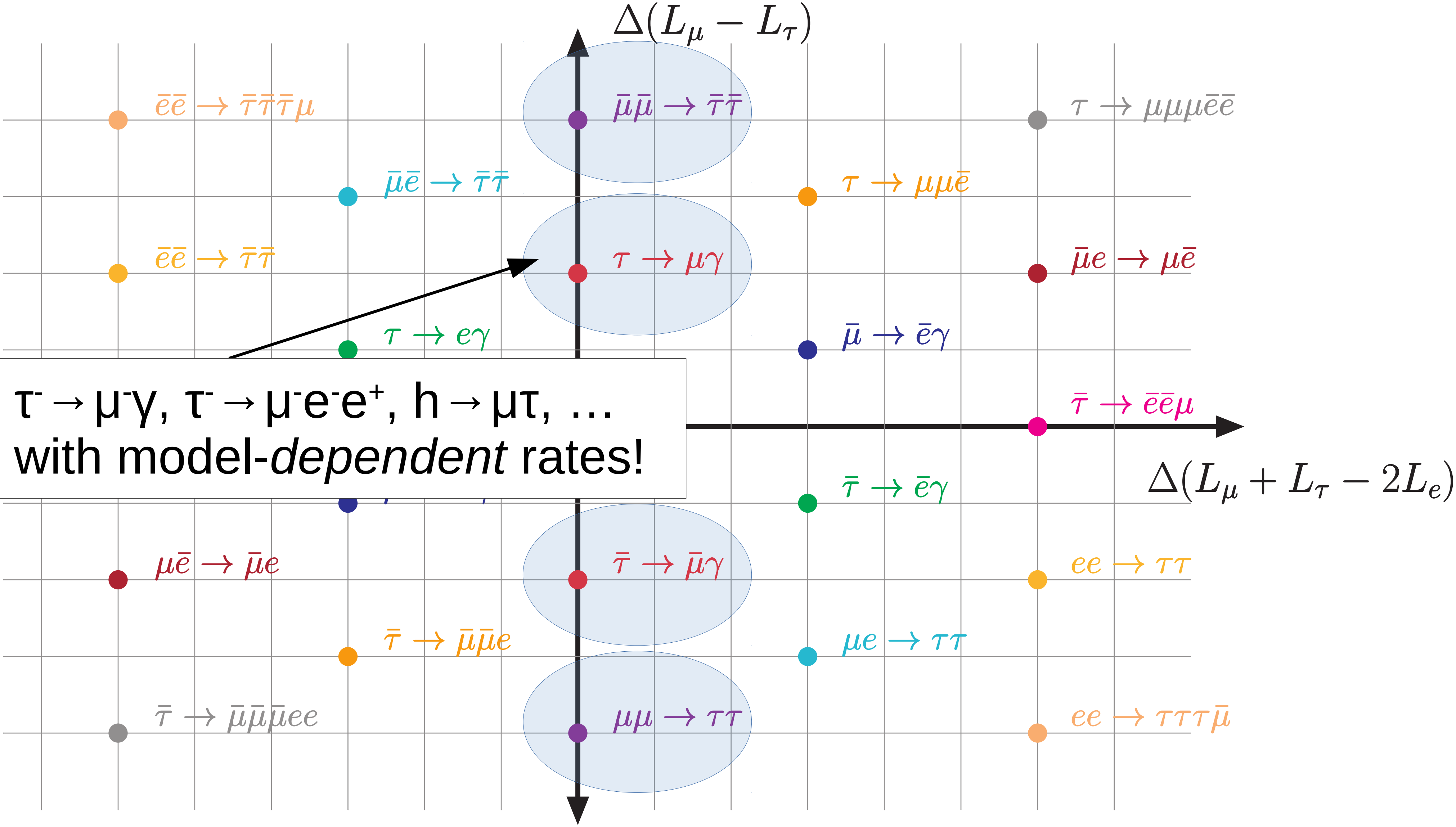
Currently being probed.

[Heeck, 1610.07623]



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

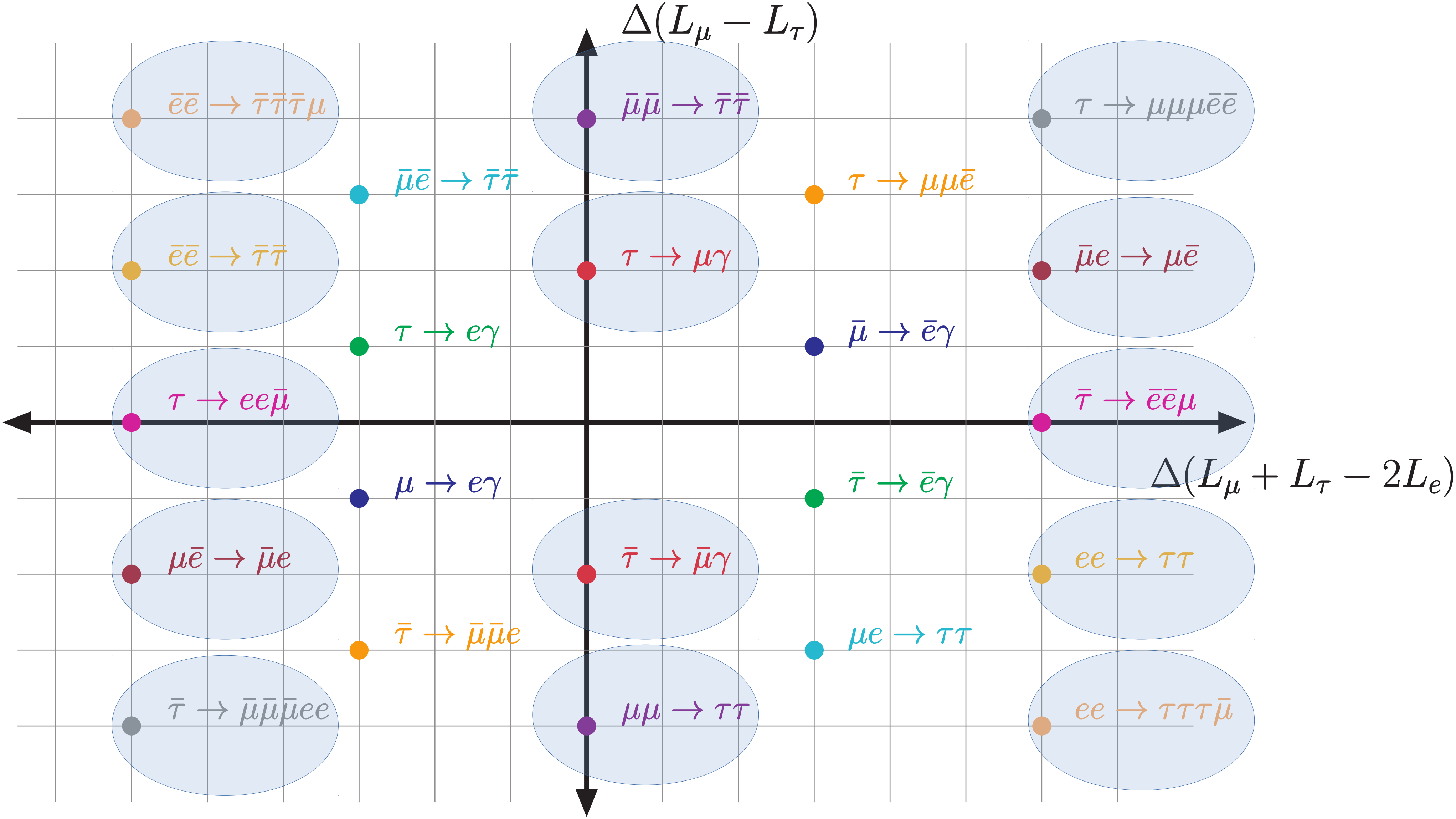
[Heeck, 1610.07623]



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



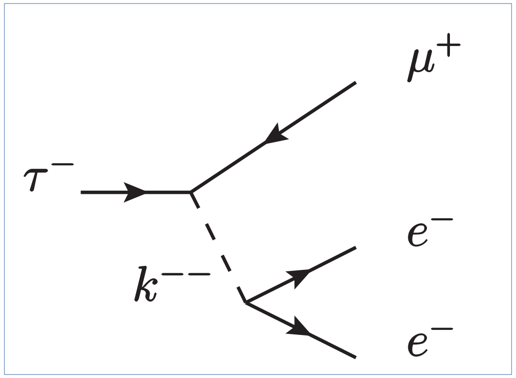
Interpretation of LFV

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. $\tau^- \rightarrow \mu^-\gamma$ or $\tau^- \rightarrow e^-e^-\mu^+$.

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 to break $L_\mu - L_\tau$ in M_R.
- Could even use symmetry for texture zeroes in M_ν.

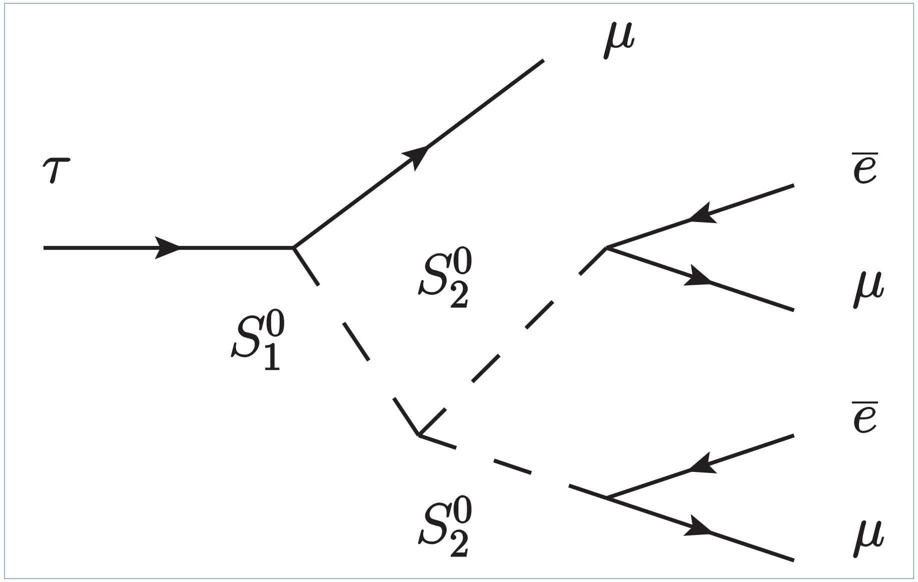
[Araki, Heeck, Kubo, 1203.4951]

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

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

- 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

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 ΔB = 0, but can also do LFV with ΔB ≠ 0.
- Example: proton decay (ΔB = 1).
- Super-K limits on p → $e^+\pi^0$, $\mu^+\pi^0$ are 10^{34} yrs!
- More interesting for flavor: p → $\overline{\ell\ell}\ell$:

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 → $\ell^+\pi^0$!

Effective operators

[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. $p \to e^- \pi^+ K^+$.
  - $QQQL\overline{L}H\ell$: $d=10$, $\Delta L = 1$, 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

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. $p \to e^- \pi^+ K^+$.
  - ~~$QQQL\bar{L}H\ell$: 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

Impose B+3L

Effective operators

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

Impose B+3L

Effective operators

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. $p \to e^- \pi^+ K^+$.~~
  - $QQQL\bar{L}H\ell$: 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

Impose $L_e+2L_\mu–3L_\tau$

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. $p \to e^- \pi^+ K^+$.~~
  - $QQQL\overline{L}H\ell$: d=10, $\Delta L = 1$, e.g. $p \to e^+ e^+ \mu^-$.
  - $ddd\overline{LLL}H$: d=10, $\Delta L = -3$, e.g. $p \to e^- \nu_e \overline{\nu}_\mu \pi^+ \pi^+$.
  - QudLLLHH: d=11, $\Delta L = 3$, e.g. $p \to \mu^+ \overline{\nu}_e \overline{\nu}_e$.

Impose $L_e + 2L_\mu – 3L_\tau$

Lepton-flavored proton decay

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

[Hambye, Heeck, in progress]

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 $QQQL\overline{L}H\ell$.
- 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.

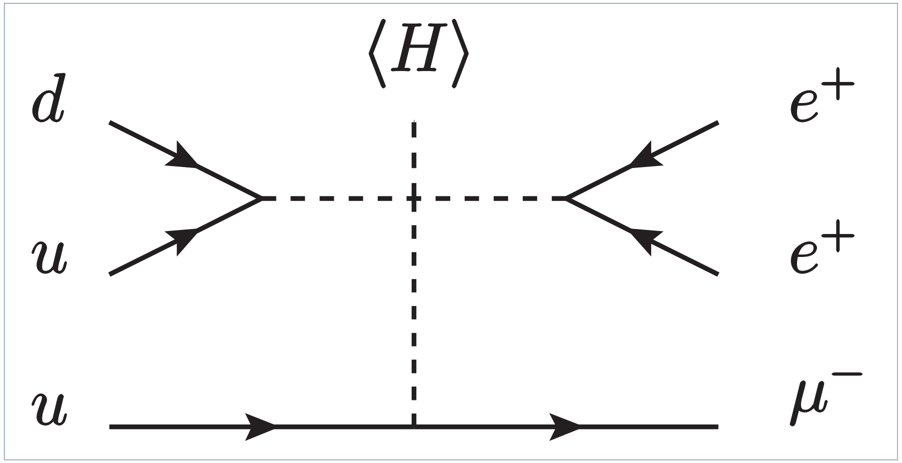
[Hambye, Heeck, in progress]

[Hambye, Heeck, in progress]

p → $e^+e^+\mu^-$

- Conserves $L_e+2L_\mu-3L_\tau$; Impose!
- Only d = 10 survives:

$$\cancel{\frac{\mathrm{QQQL}}{\Lambda^2}} + \cancel{\frac{\mathrm{QQQ\overline{L}H}}{\Lambda^3}} + \cancel{\cdots} + \frac{\mathrm{QQQL\overline{L}He}}{\Lambda^6} .$$



- Rate very suppressed:

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

- UV complete with leptoquarks. Analogous for p → $\mu^+\mu^+e^-$.
- More extreme: p → $e^+e^+e^+\mu^-\mu^-$ etc., probes Λ ~ few TeV!

Low-hanging fruit for Super-K.

[Hambye, Heeck, in progress]

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

- Minimal leptoquark example:

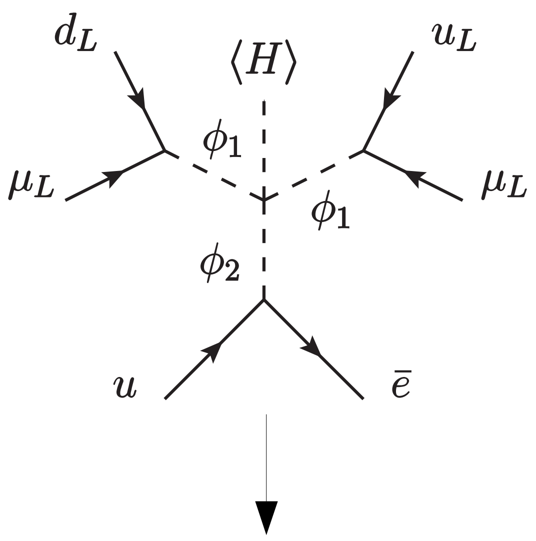
$$\phi_1 \sim (\mathbf{3}, \mathbf{3}, -2/3)\,,\ \phi_2 \sim (\mathbf{3}, \mathbf{2}, 7/3)\,.$$

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

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

- Also conserves B-L and lepton flavor, but gives lepton non-universality.
- Triplet LQ perfect for b→sμμ anomalies:

$$m_{\phi_1} \simeq 30\,\mathrm{TeV}\sqrt{y_2 y_3}\,.$$



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

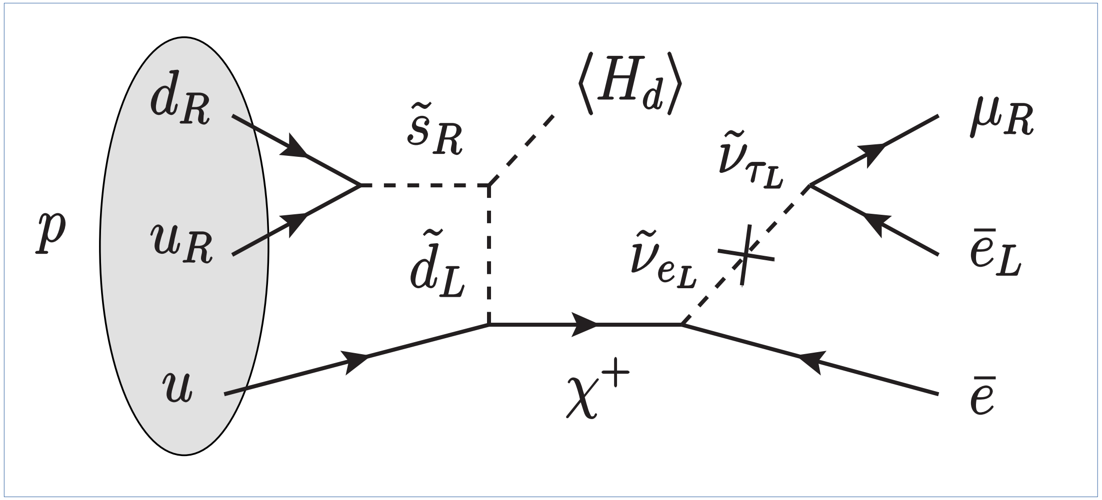
Interesting pheno from proton decay @ 100 TeV!

[Hambye, Heeck, in progress]

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

- R-parity violating MSSM:

$$\lambda_{ijk} L_i L_j \overline{l_k} + \lambda''_{ijk} \overline{u_i}\,\overline{d_j}\,\overline{d_k}$$
$$+\lambda'_{ijk} L_i Q_j \bar{d}_k + \mu'_i L_i H_u\,.$$



- Impose $L_\mu+2L_e+L_\tau$ for $\lambda' = 0 = \mu'$ and $\lambda = \lambda_{132}$.
- Add soft terms for sfermion mixing: $A_{d_{ij}} H_d \tilde{\bar{d}}_i \tilde{Q}_j - m^2_{ij} \tilde{L}_i \tilde{L}_j\,.$
- $\tau^- \rightarrow e^- \gamma$ and n-$\overline{\text{n}}$ oscillations also allowed.
- Known for neutrino modes $p \rightarrow e^+\nu\nu$, $\mu^+\nu\nu$, $K^+\mu^+e^-\nu$…

  [Carlson, Roy, Sher, ‘95; Bhattacharyya, Pal, ‘99; Faroughy, Prabhu, Zheng, ‘15]
- Rich phenomenology.

Summary so far

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

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

conserves G

violates G

could conserve G or subgroup
⇒ ‘weird’ channels dominate!?

But what if new physics is light?

Simple example: majoron

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

B – L breaking scale

Heavy scalar
(inflaton?)

Goldstone boson:
majoron

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

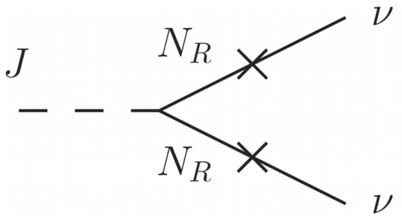
- Break $U(1)_{B\text{-}L}$ spontaneously: $\mathcal{L} = -\overline{L} y H N_R - \frac{1}{2}\overline{N}_R^c \underbrace{\lambda\sigma}_{M_R = \frac{\lambda f}{\sqrt{2}}} N_R + h.c.$

- For $M_R \gg m_D : M_\nu \simeq -m_D M_R^{-1} m_D^T$

$$\simeq 1\text{eV}\left(\frac{m_D}{100\text{GeV}}\right)^2\left(\frac{10^{13}\text{GeV}}{M_R}\right).$$

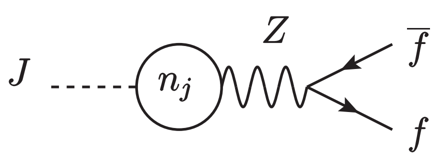
Majoron couplings

- Tree level coupling only to neutrinos:



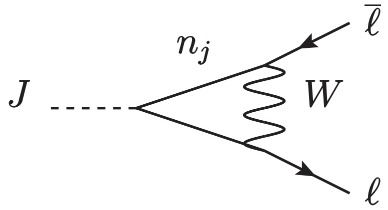
$$\frac{iJ}{2f}\overline{\nu}^c_\alpha\gamma_5(m_D^* M_R^{-1} m_D^\dagger)_{\alpha\beta}\nu_\beta = -\frac{iJ}{2f}\sum_k \overline{\nu}_k\gamma_5 m_k\nu_k$$

- One loop:



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

Off-diagonal!



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

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

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

Properties

- Crucial observation: the two matrices are independent!

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

[Davidson, Ibarra, hep-ph/0104076]

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

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

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

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

ℓ → ℓ’ J with J → invisible

- Standard LFV in seesaw:

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

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

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

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

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

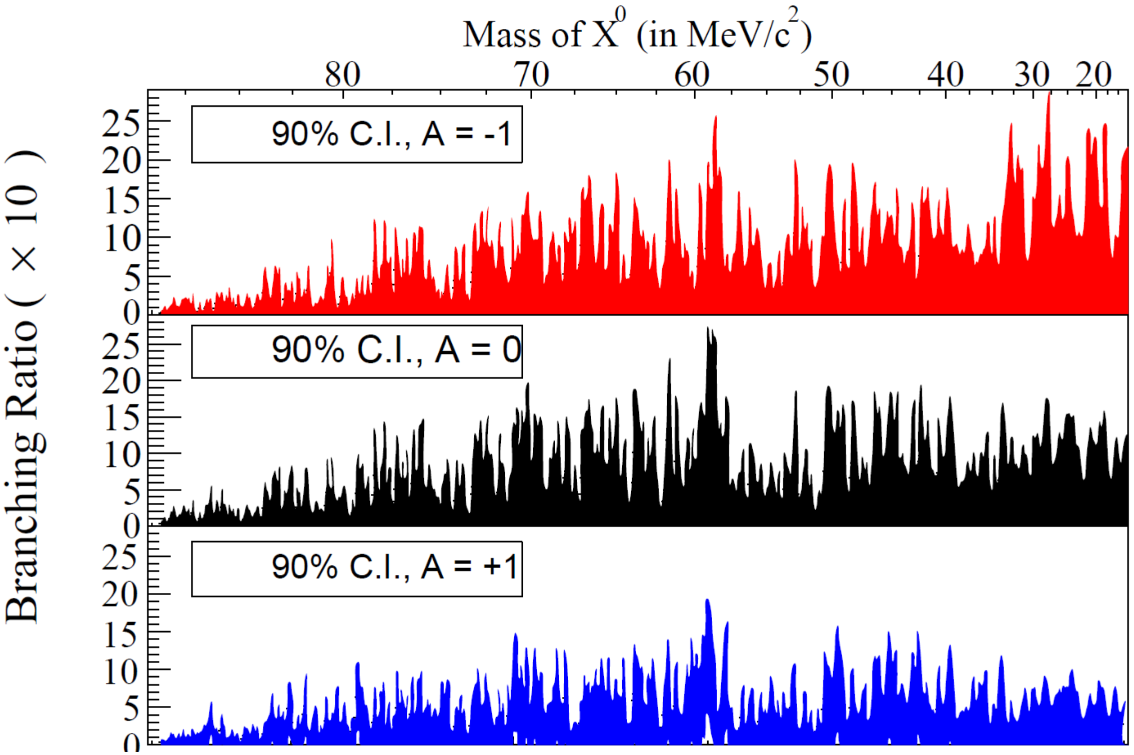
μ→e J with J→ invisible

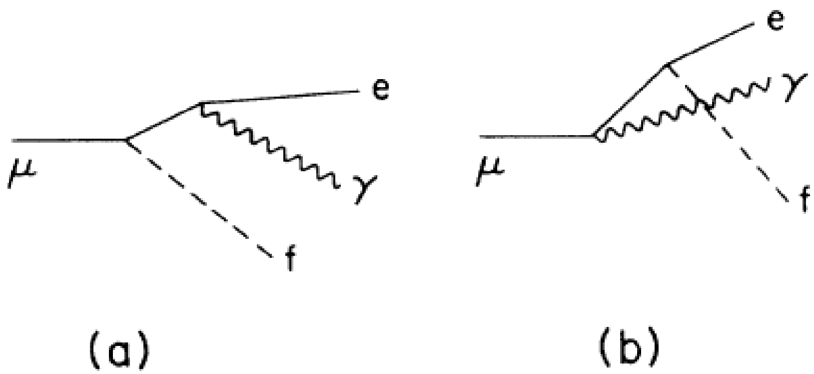
- TWIST, ‘15: limits on different anisotropies.
- Chiral coupling $\overline{\mu} P_L e J$ suppresses sensitivity!

  [Heeck, Garcia-Cely, 1701.07209]
- Bremsstrahlung is competitive: μ→e J γ.

  [Goldman et al, ‘87]
- Approximate limit

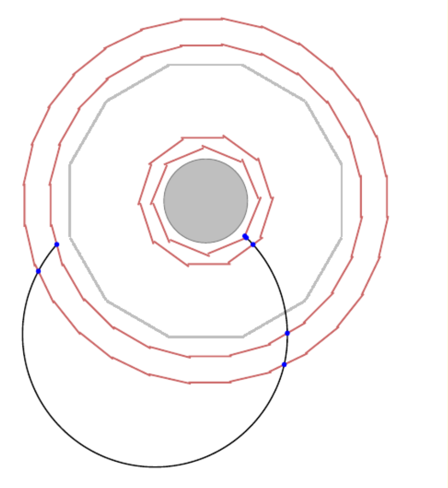
$$\boxed{\frac{|(m_D m_D^\dagger)_{\mu e}|}{vf} \lesssim 10^{-5}.}$$



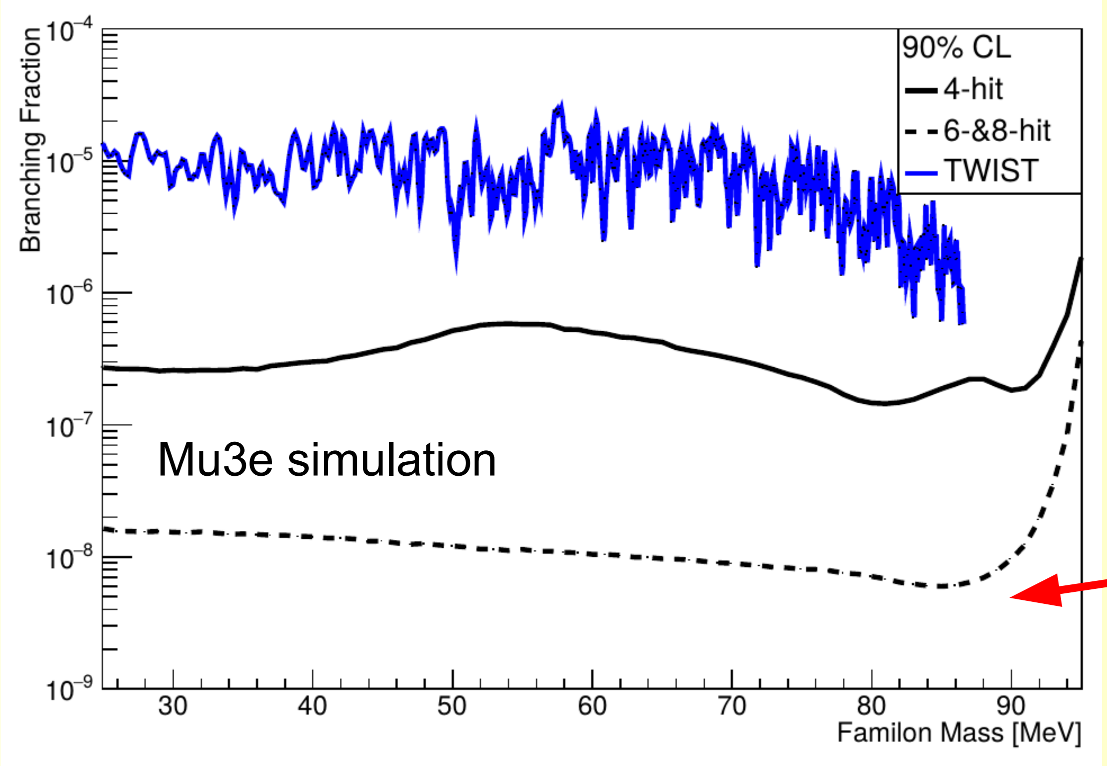


Searches for μ → e X with Mu3e

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



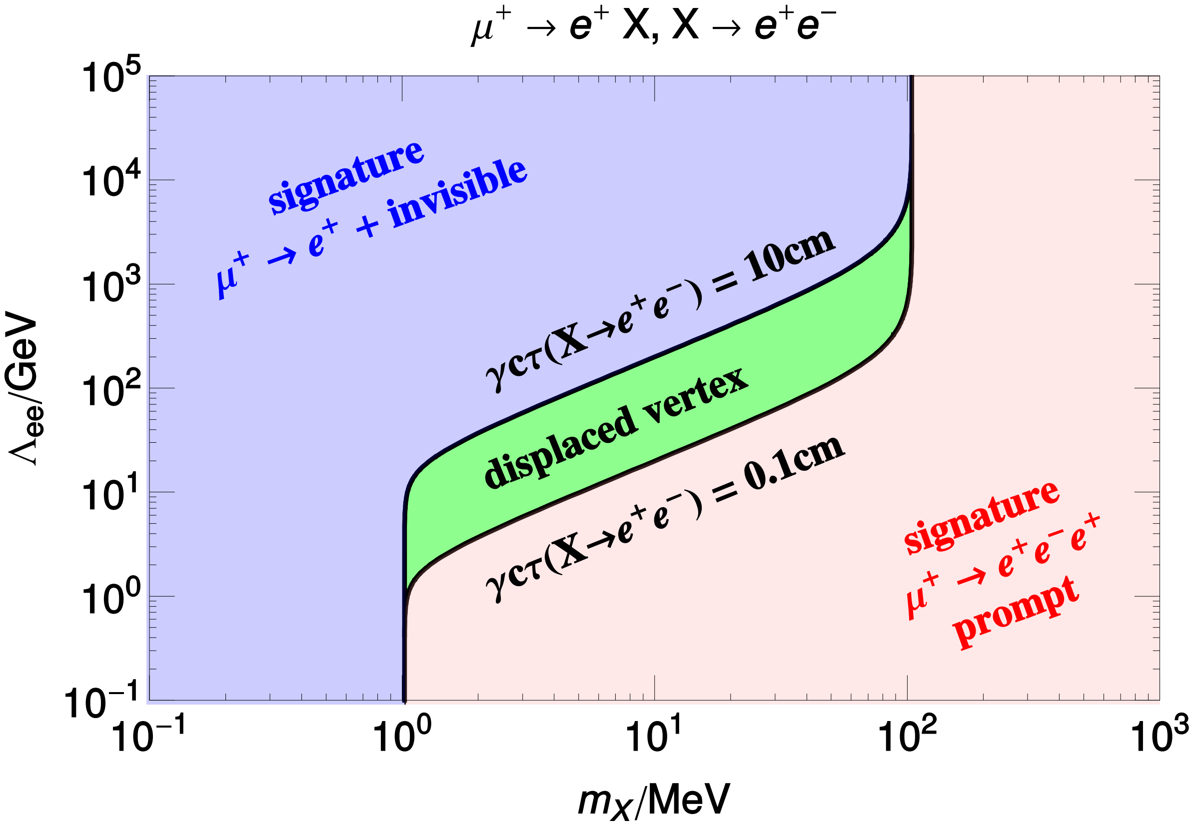
recurling track in Mu3e



required full reconstruction of “recurlers”

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.
  [Heeck, Rodejohann, 1710.02062]



- Muon at rest:

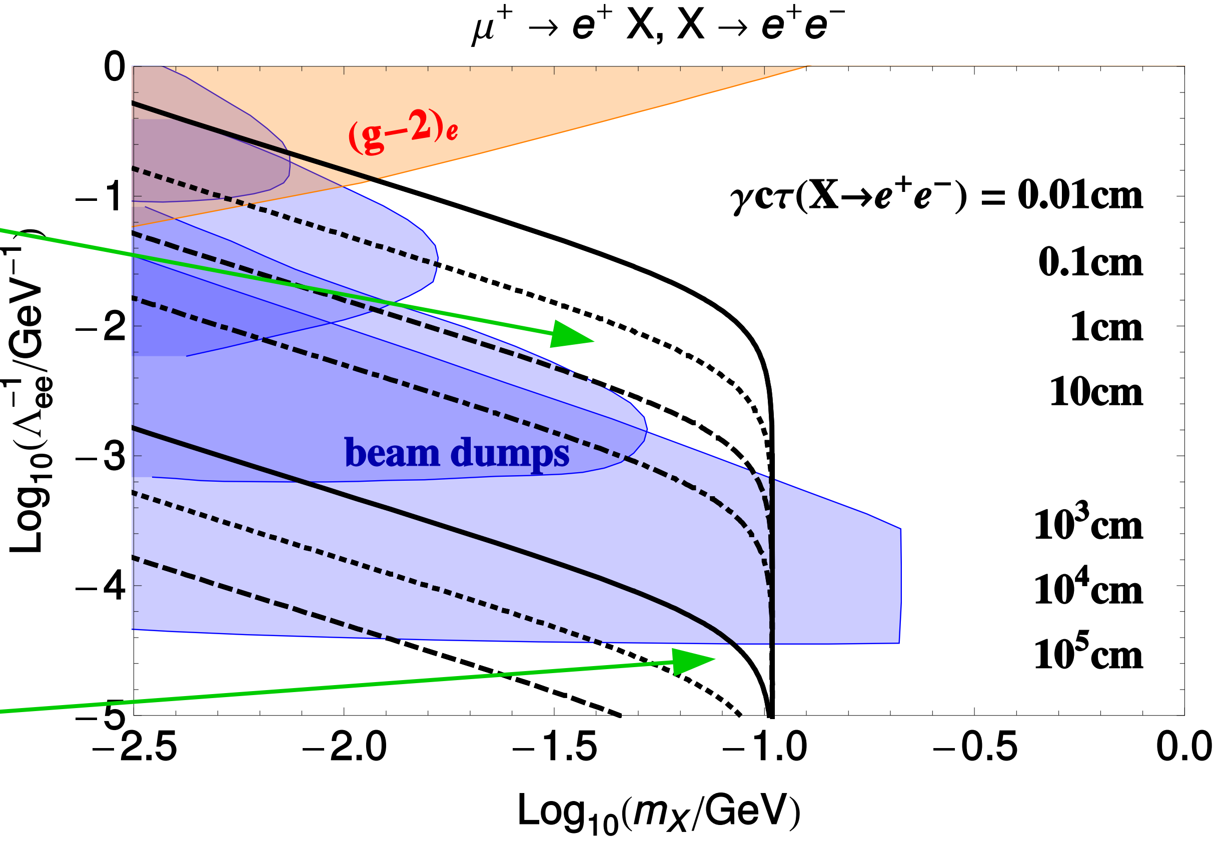
$$\gamma c\tau \simeq \frac{\pi m_\mu \Lambda_{ee}^2}{m_e^2 m_X^2} \simeq 2.5\,\mathrm{cm}\left(\frac{\Lambda_{ee}}{100\,\mathrm{GeV}}\right)^2\left(\frac{10\,\mathrm{MeV}}{m_X}\right)^2 .$$

Sub-GeV X with ee coupling allowed?

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

[Heeck, Rodejohann, 1710.02062]

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



$$\mathrm{BR}(\mu \to eX)\mathrm{BR}(X \to ee)(1 - P(l_{\mathrm{dec}}))$$

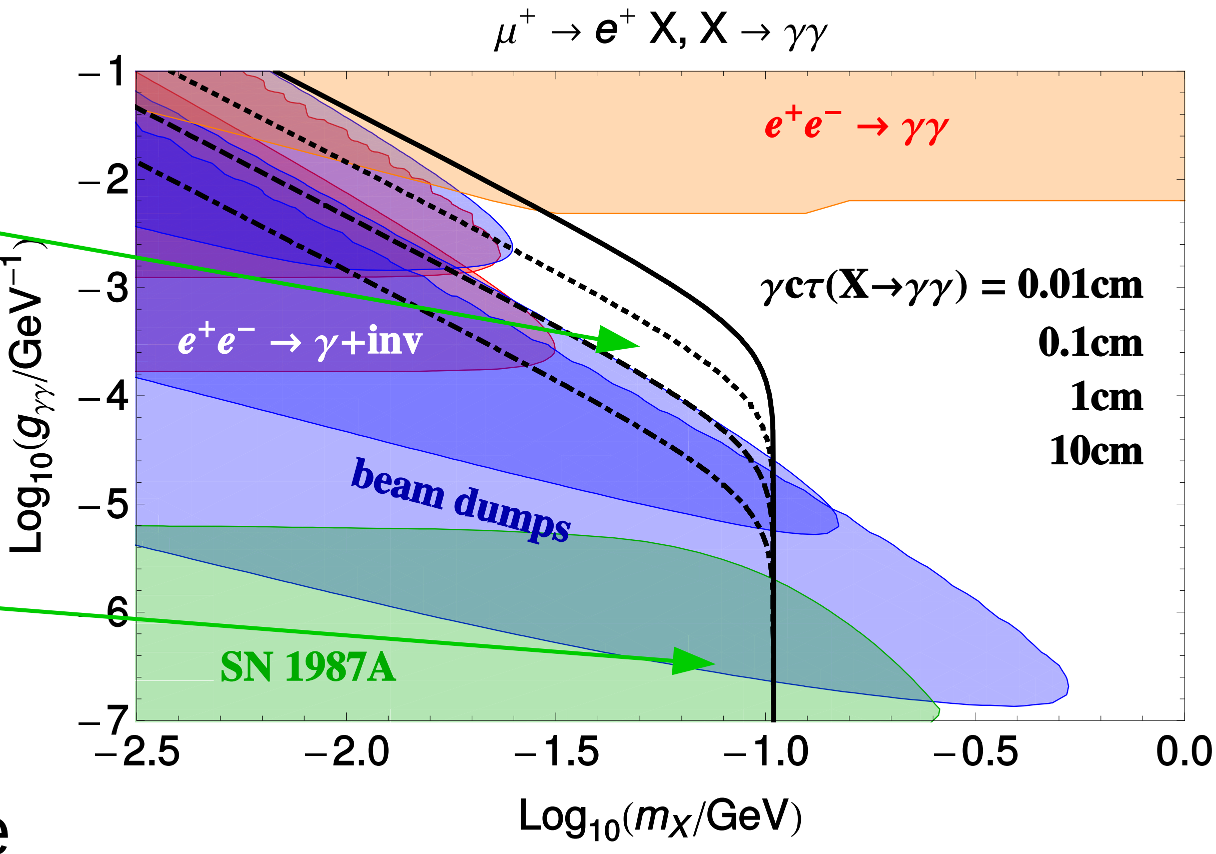
$$\simeq \mathrm{BR}(\mu \to eX)\frac{l_{\mathrm{dec}}}{\gamma c \tau} \,.$$

Possible in Mu3e!

[Heeck, Rodejohann, 1710.02062]

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

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

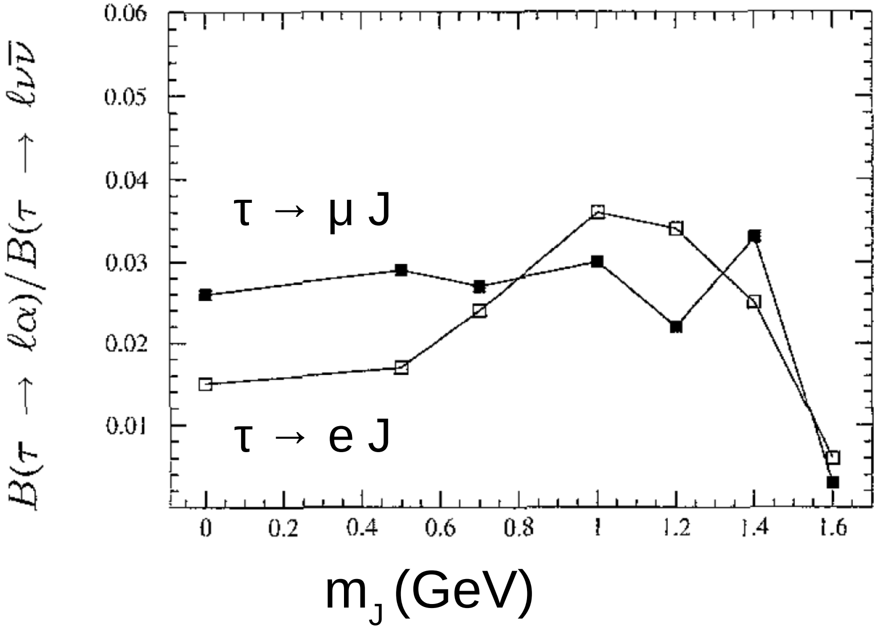


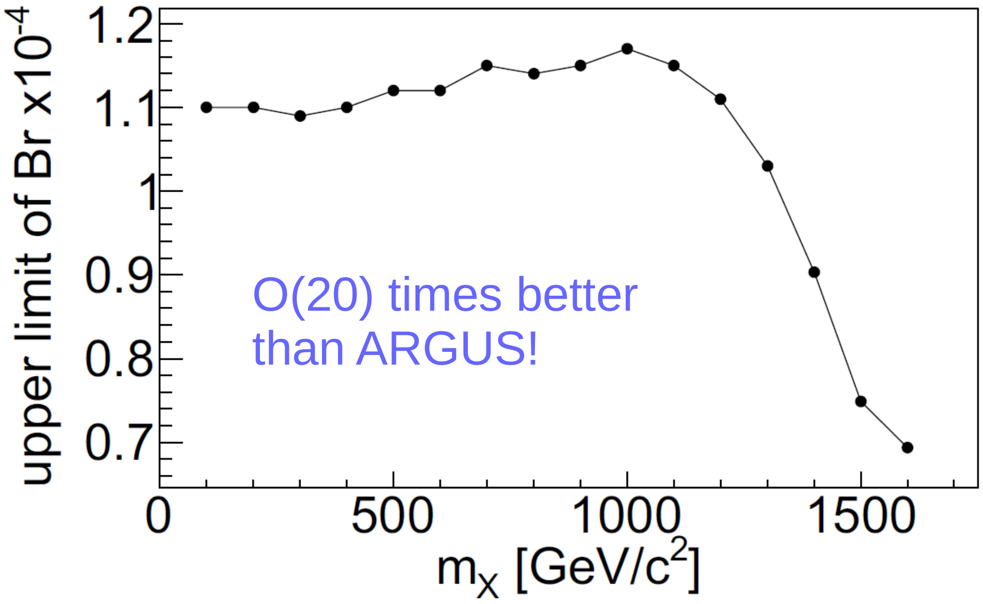
[Recent limits: Dolan et al, 1709.00009]

Muons difficult, taus easier.

τ → ℓ J with J→ invisible

- ARGUS, ‘95; 5e5 taus.
- Belle, ‘16 prelim.; 1e9 taus.





O(20) times better than ARGUS!

- Also interesting for LFV Z’.

[Heeck, 1602.03810; Altmannshofer et al, 1607.06832]

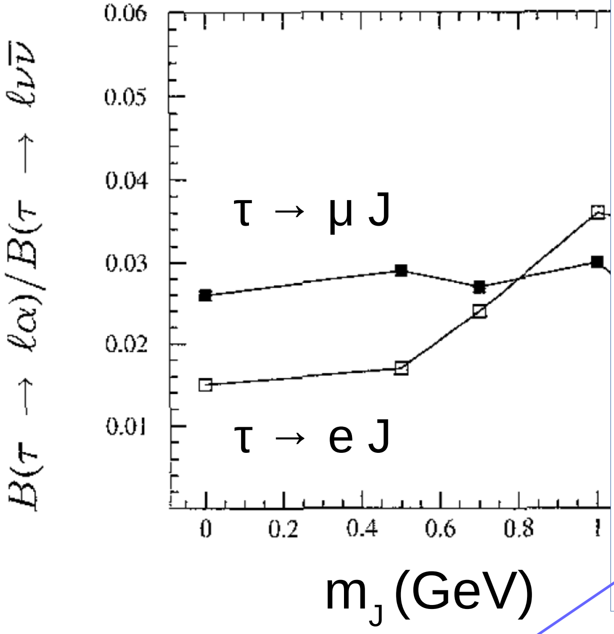
- Improvement with Belle-II.

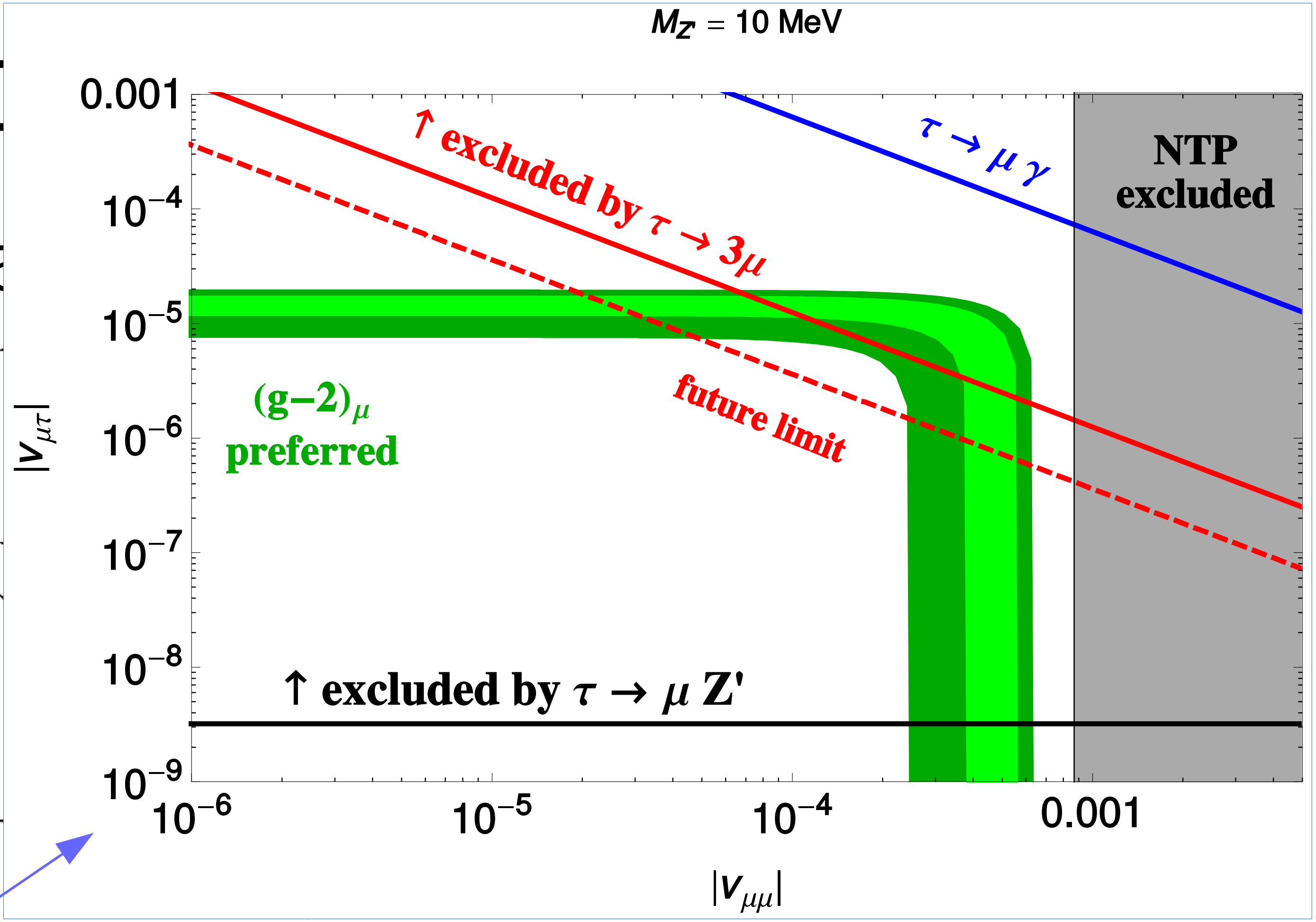
$$\frac{|(m_D m_D^\dagger)_{\tau e}|}{vf} \lesssim 6 \times 10^{-3},$$

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

τ → ℓ J with J

- ARGUS, '95; 5e5





- Also interesting for LFV Z'.

[Heeck, 1602.03810; Altmannshofer et al, 1607.06832]

- Improvement with Belle-II.

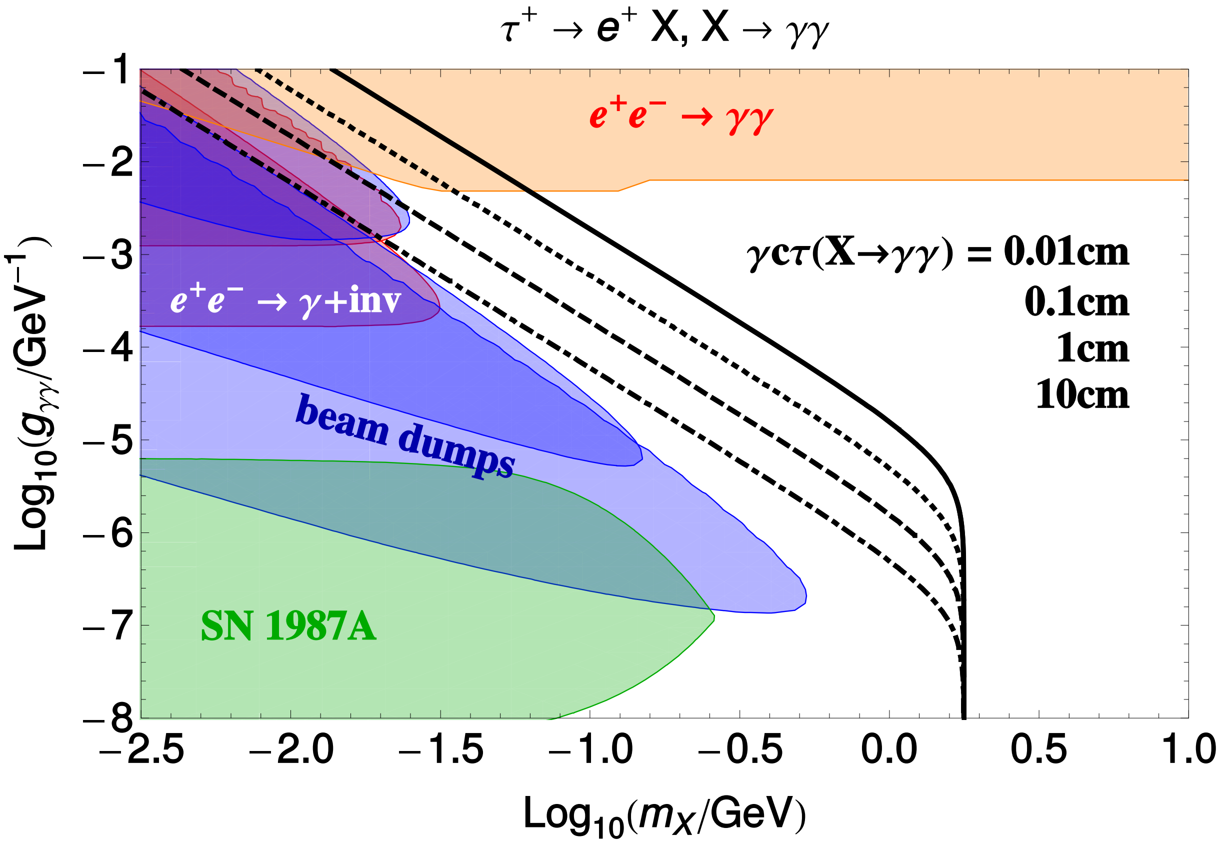
$$\frac{|(m_D m_D^\dagger)_{\tau e}|}{vf} \lesssim 6 \times 10^{-3},$$

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

[Heeck, Rodejohann, 1710.02062]

τ→e X with X→ visible

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



[Recent limits: Dolan et al, 1709.00009]

Muons difficult, taus easier...

Summary

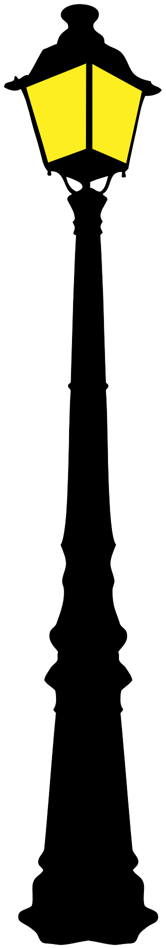
- Charged LFV gives info *complementary* to ν oscillations.
- Not simple yes/no question, need to find out if/how

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

is broken in ℓ^- sector.

⇒ Need to search all possible channels!

- Non-trivial breaking: $\tau \to ee\bar{\mu}$, $\tau \to \mu\mu\bar{e}$, $p \to e\overline{\mu\mu}$, $p \to \mu\overline{ee}$,…
- Keep light new physics in mind: $\ell \to \ell' X$, $X \to$ inv, $\ell\ell$, $\gamma\gamma$.
- Hope for sign in Mu3e, MEG-II, Belle-II, Mu2e, LHC,...



Still some streetlights to search under!