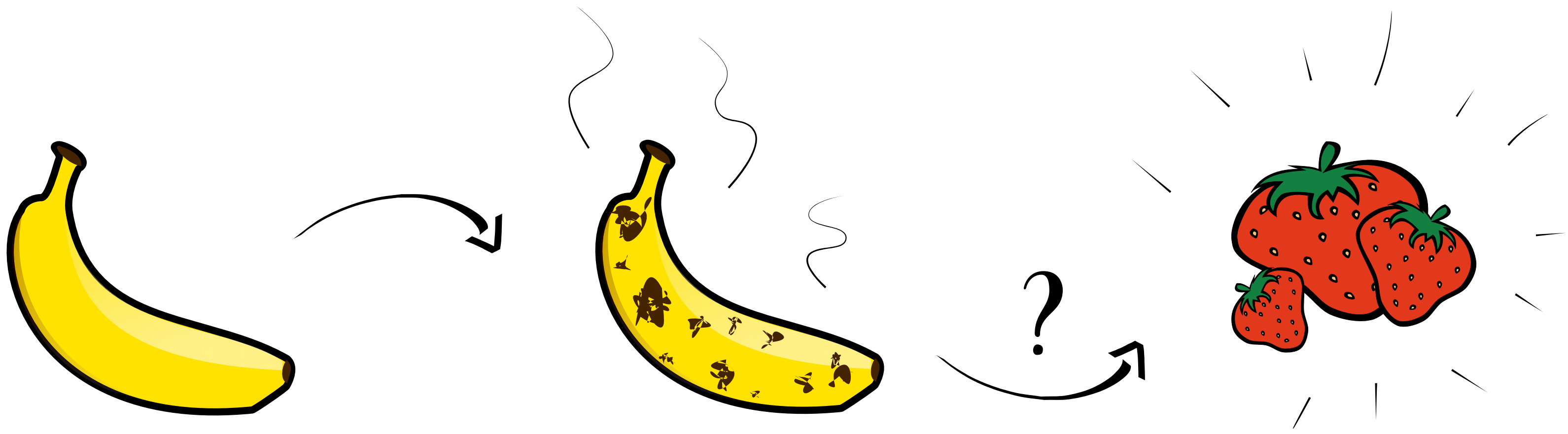
Rare decays with flavor



Julian Heeck

June 8, 2018 @ Neutrino 2018, Heidelberg

Fundamental Interactions .be

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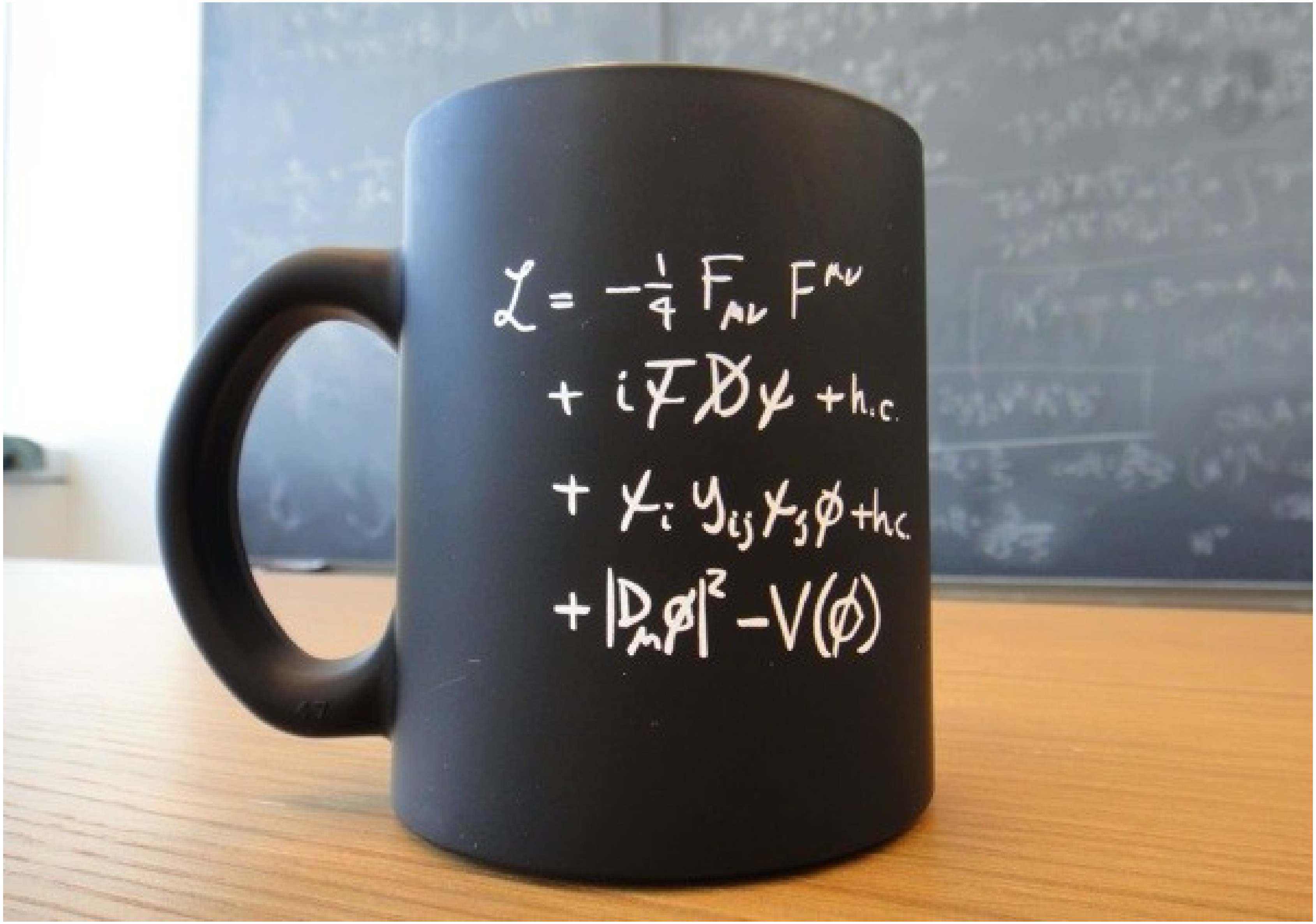
The Standard Model



www.quantumdiaries.org, Flip Tanedo

Symmetries of the Standard Model

- Rephasing lepton and quark fields:

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

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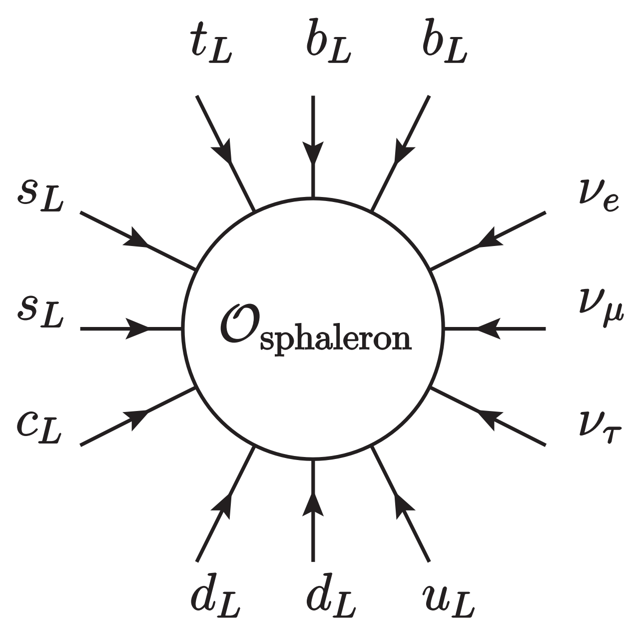
- B+L broken non-perturbatively,

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

but unobservably suppressed at low temperatures by

$$\mathrm{e}^{-2\pi/\alpha_\mathrm{w}} \sim 10^{-173}.$$ ['t Hooft '76]



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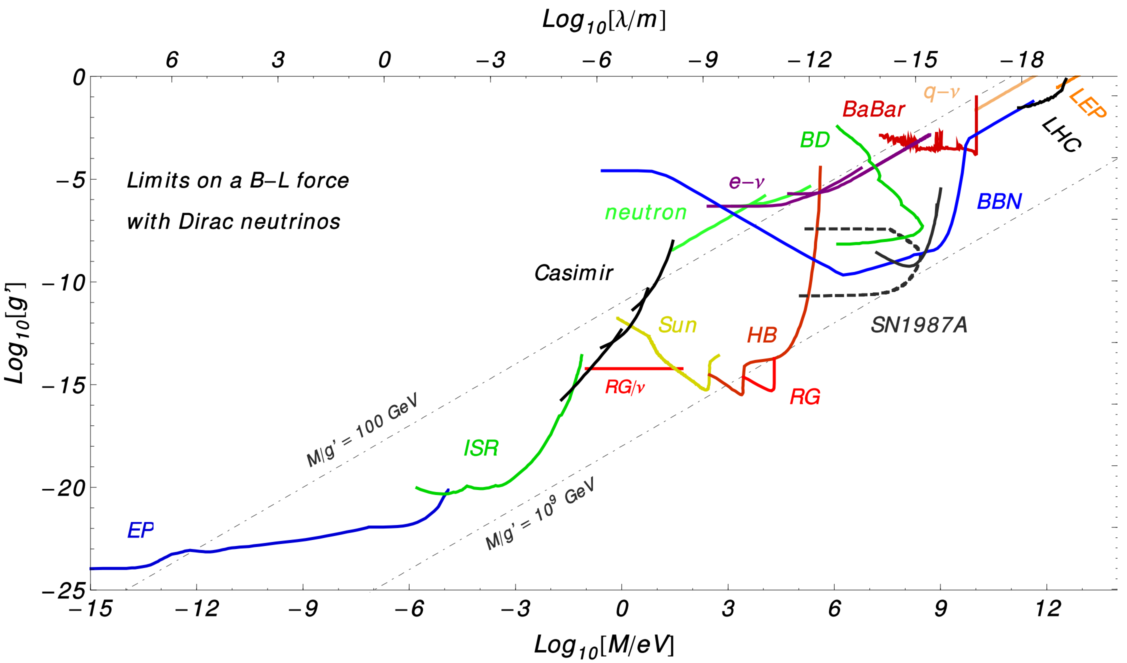
- B – L could be conserved if neutrinos are Dirac.

  [Heeck, 1408.6845]

- No 0νββ.
- Dirac leptogenesis.

  [Dick, Lindner, Ratz, Wright, '00]



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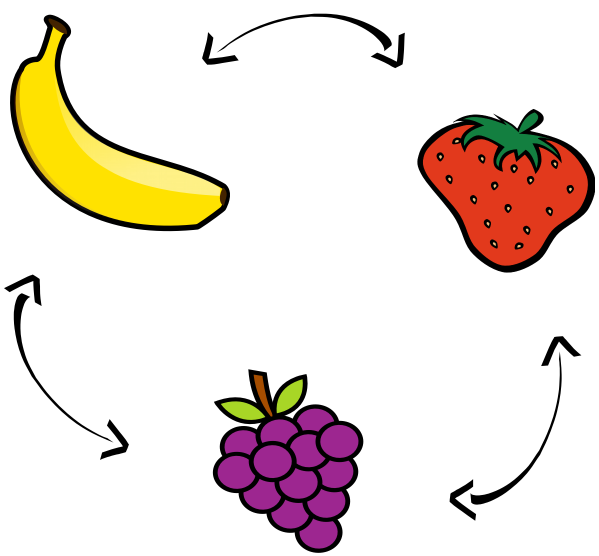


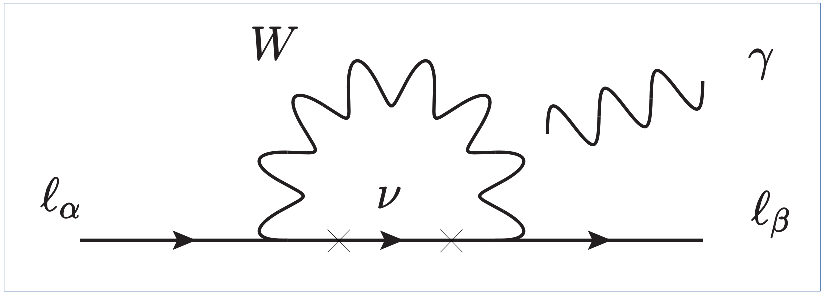
- Broken by $\nu_\alpha \rightarrow \nu_\beta$:

$$\Delta(\mathrm{L}_\alpha - \mathrm{L}_\beta) = 2\,.$$

- *Charged* lepton flavor violation suppressed by M_ν.

Neutrino mass ⇒ charged LFV?

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



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

- SM + heavy seesaw neutrinos:

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

Not true with fine-tuning or structure in m_D.

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

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/SUSY/type-II seesaw;
  - Radiative seesaw (Zee-Babu, Ma,…). [Cai++, 1706.08524]
- M_ν ⇔ LFV connection possible but not necessary.

Symmetries of the Standard Model

- Rephasing lepton and quark fields:

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

Still amazing approximate symmetry for charged leptons!

(SM + 3 N_R: $U(1)_{B-L} \times U(1)_{L_\mu - L_\tau} \times U(1)_{L_\mu + L_\tau - 2L_e}$ anomaly free.)

[Araki, Heeck, Kubo, 1203.4951. Without N_R just L_i-L_j, He, Joshi, Lew, Volkas, '91]

Charged lepton flavor violation

=

The violation of

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

in neutrinoless decays

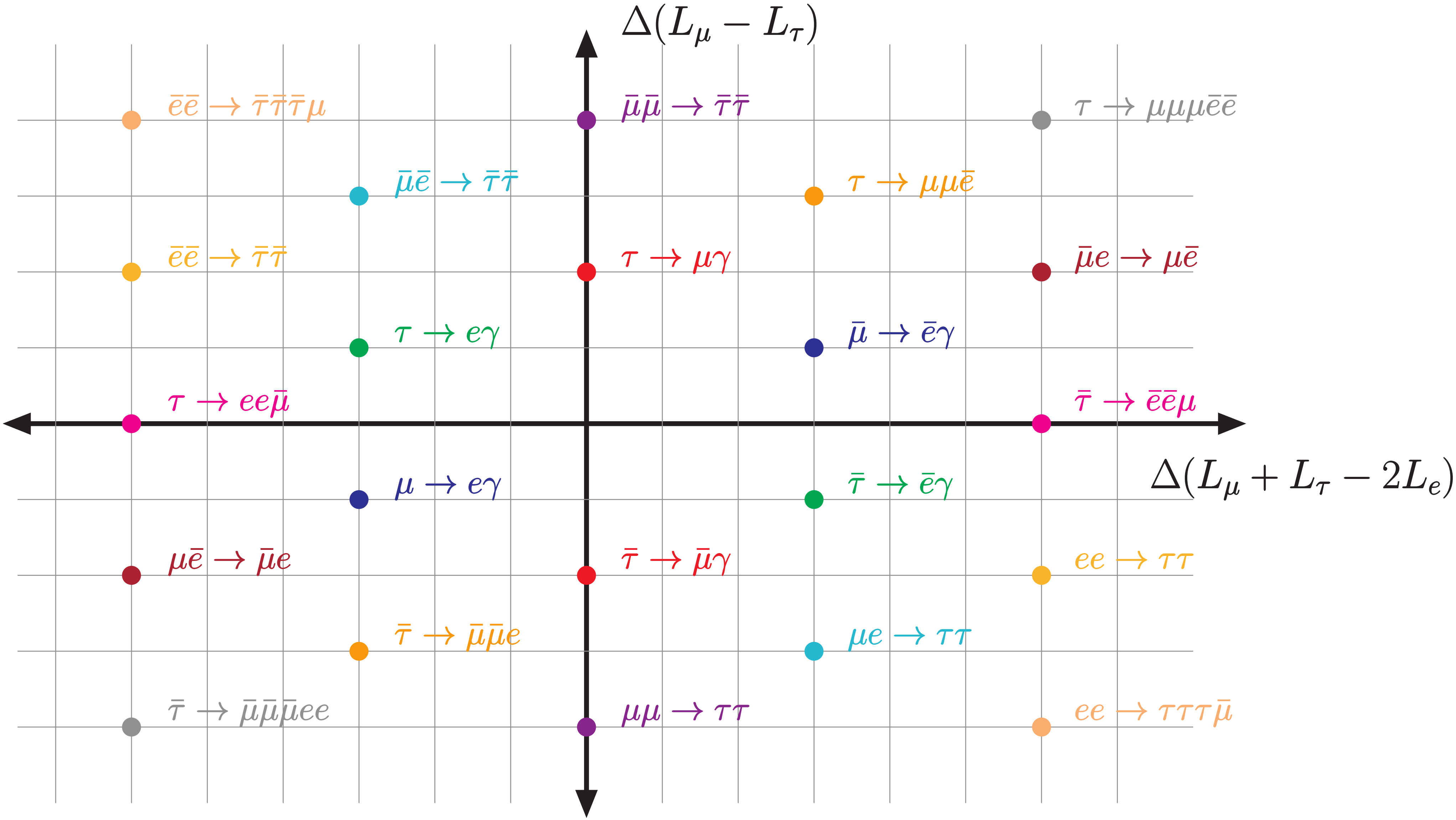
$$\ell \to \ell'\gamma,\ \ell \to \ell'\ell''\ell''',\ \mu \to \mathsf{e}\ \mathrm{conv.},\ \mathsf{h} \to \ell\ell',\ \mathrm{had} \to \ell\ell',\ \ldots^*$$

*Assuming *heavy* new physics.

[recent review: Lindner, Platscher, Queiroz, 1610.06587]

$\Delta B = \Delta L = 0$

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



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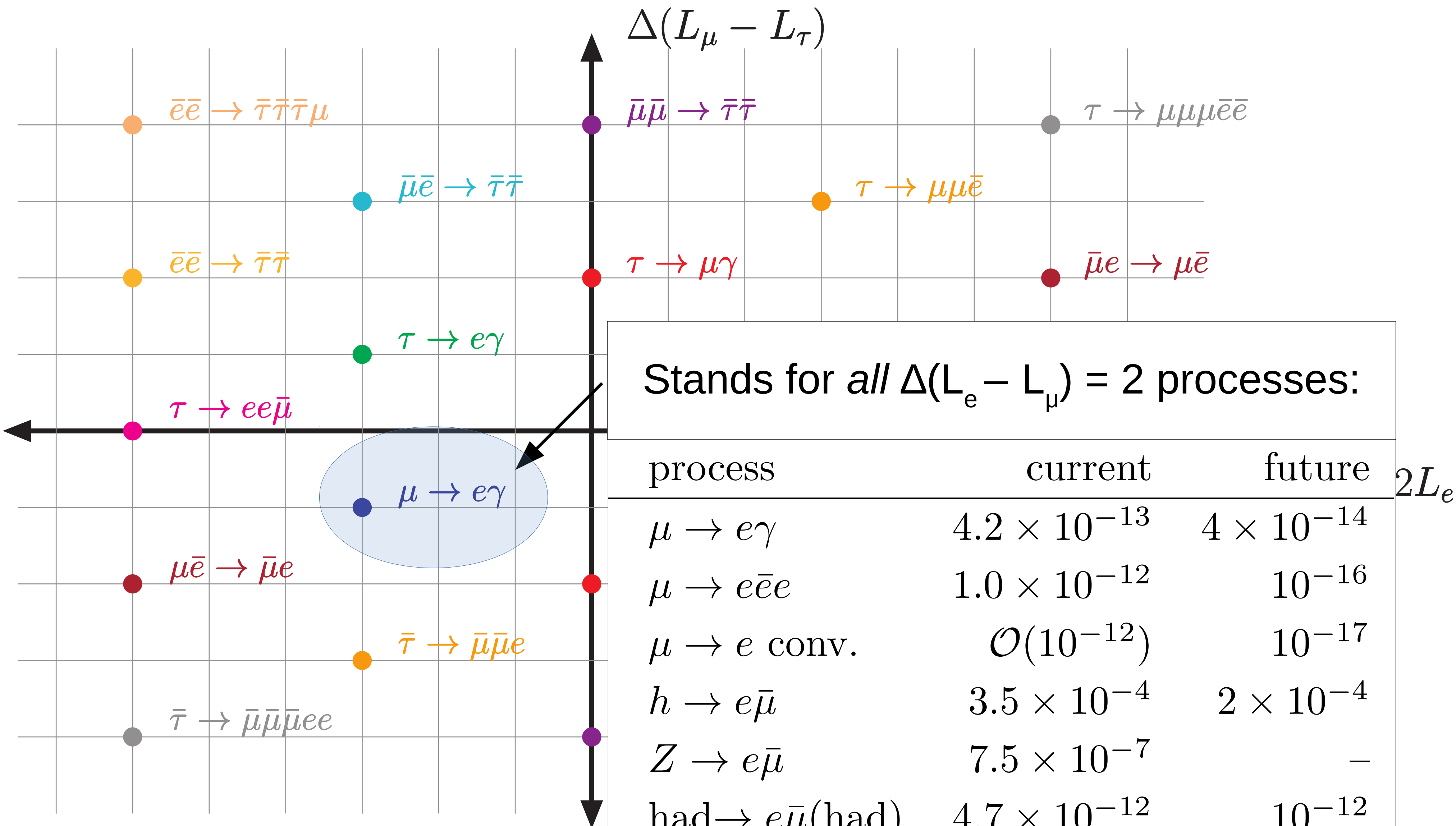

Stands for *all* $\Delta(L_e - L_\mu) = 2$ processes:

process	current	future
$\mu \to e\gamma$	4.2×10^{-13}	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}

ΔB = ΔL = 0

[Heeck, 1610.07623]
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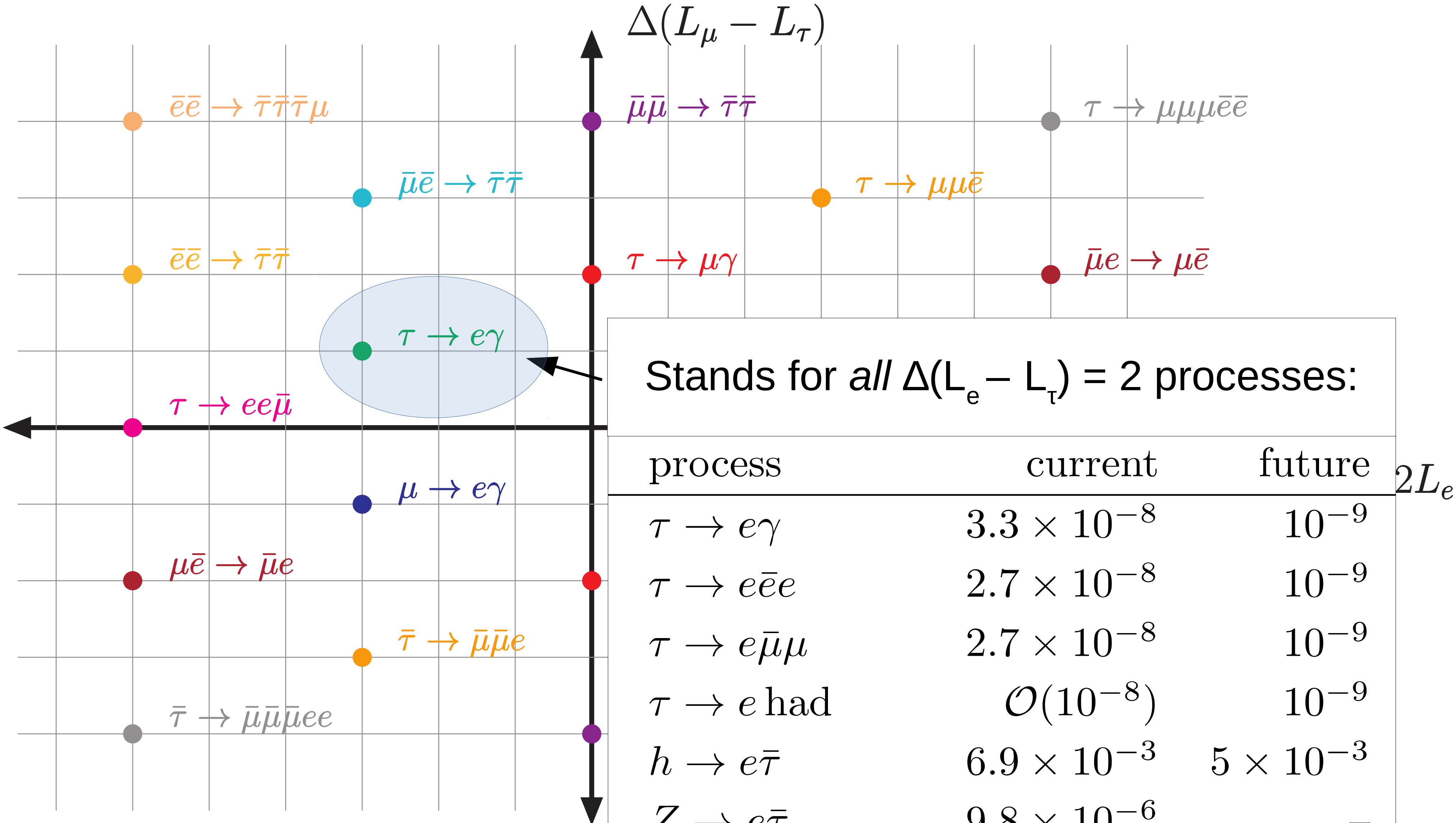
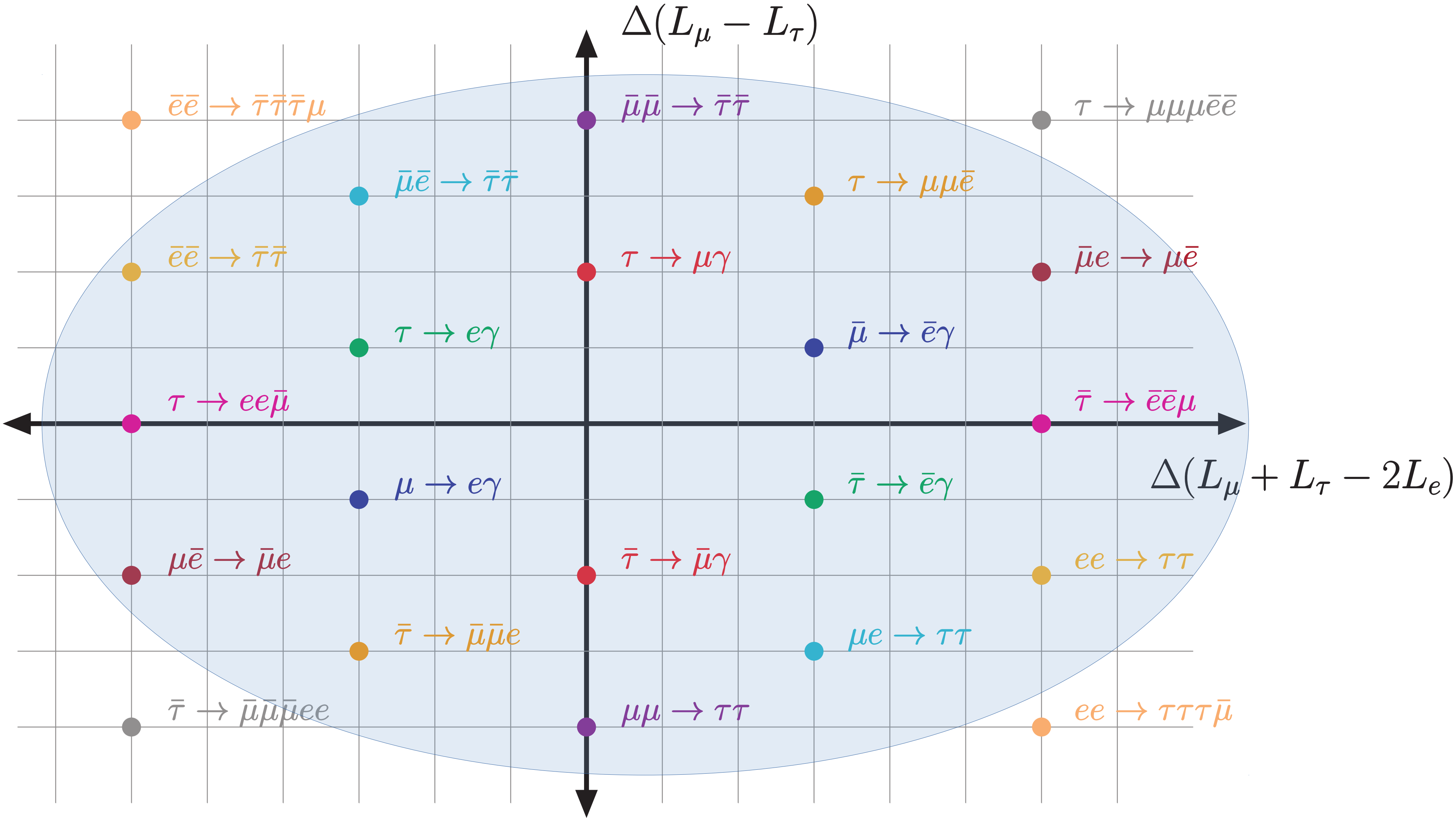


Stands for *all* Δ(L_e – L_τ) = 2 processes:

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}
$\tau \to e\,\text{had}$	$\mathcal{O}(10^{-8})$	10^{-9}
$h \to e\bar{\tau}$	6.9×10^{-3}	5×10^{-3}
$Z \to e\bar{\tau}$	9.8×10^{-6}	–
had$\to e\bar{\tau}$(had)	$\mathcal{O}(10^{-6})$	–

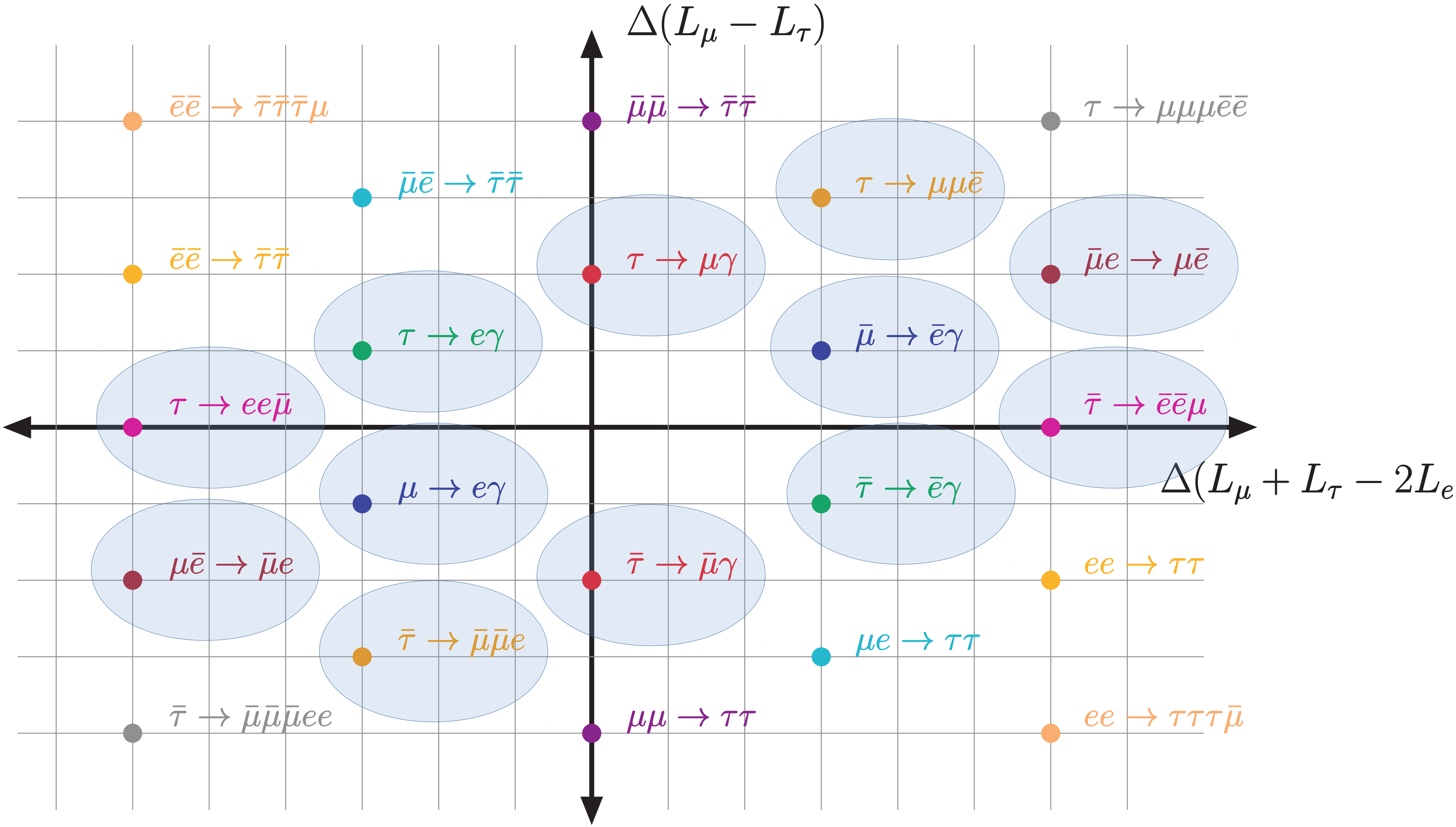
Dimension 6 operators

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



Currently being probed.

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



Interpretation of LFV

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

Observation of charged lepton flavor violation	$\Rightarrow$	Remaining symmetry
$\Delta(L_\alpha - L_\beta) = 2$		$U(1)_{L_\alpha + L_\beta - 2L_\gamma}$
$\Delta(L_\alpha + L_\beta - 2L_\gamma) = 6$		$U(1)_{L_\alpha - L_\beta}$
$\Delta(L_\alpha + L_\beta - 2L_\gamma) = 6$ and $\Delta(L_\alpha - L_\beta) = 2$		$\mathbb{Z}_2$: $\ell_\gamma \to -\ell_\gamma$
$\Delta(L_\alpha + L_\beta - 2L_\gamma) = 6$ and $\Delta(L_\alpha + L_\gamma - 2L_\beta) = 6$		$\mathbb{Z}_3$: $(\ell_\alpha, \ell_\beta, \ell_\gamma) \sim (0, 1, 2)$
$\Delta(L_\alpha - L_\beta) = 2$ and $\Delta(L_\alpha - L_\gamma) = 2$		–
$\Delta(L_\alpha - L_\beta) = 2$ and $\Delta(L_\alpha + L_\gamma - 2L_\beta) = 6$		–

- *At least* two orthogonal channels required for *full* LFV.
- Flavor violation by higher units more challenging.
- Easy to build models that single out certain channels, e.g. $\tau^- \to \mu^-\gamma$ or $\tau^- \to e^-e^-\mu^+$.

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

	$U(1)_Y$	$U(1)_{L_\mu - L_\tau}$
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:

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

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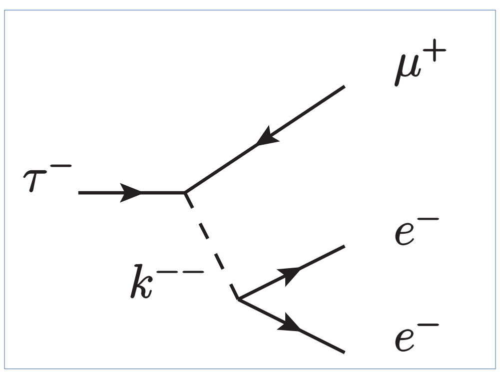
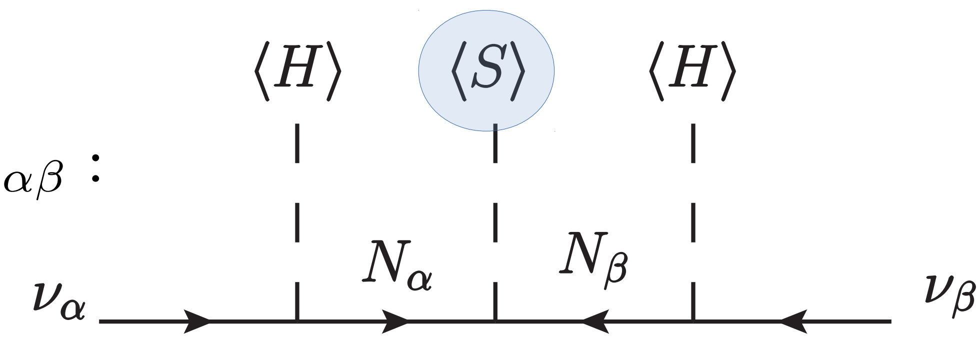


$(M_\nu)_{\alpha\beta}$:



- 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

$$\mathsf{U}(1)_\mathsf{B} \quad \left[\times \mathsf{U}(1)_\mathsf{L} \times \mathsf{U}(1)_{\mathsf{L}_\mu - \mathsf{L}_\tau} \times \mathsf{U}(1)_{\mathsf{L}_\mu + \mathsf{L}_\tau - 2\mathsf{L}_e}\right]$$

in processes

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

*Assuming *heavy* new physics.

[Weinberg, ‘79 & ‘80]

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in processes

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

$$\Delta\mathsf{B} = 1 \ \text{ and } \Delta\mathsf{L} = 1\,, 3\,, \ldots$$

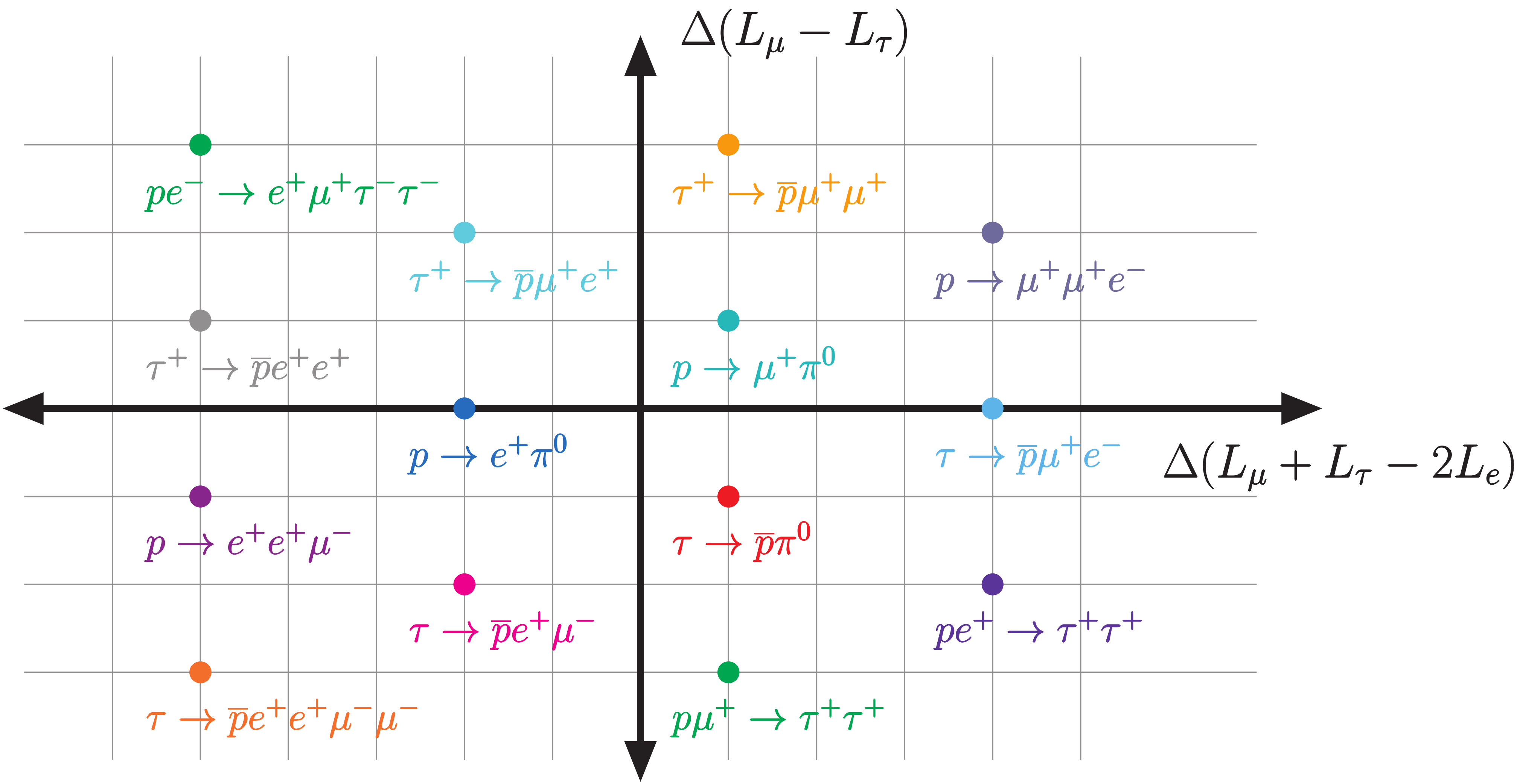
*Assuming *heavy* new physics.

[Weinberg, '79 & '80]

[Hambye, Heeck, 1712.04871]

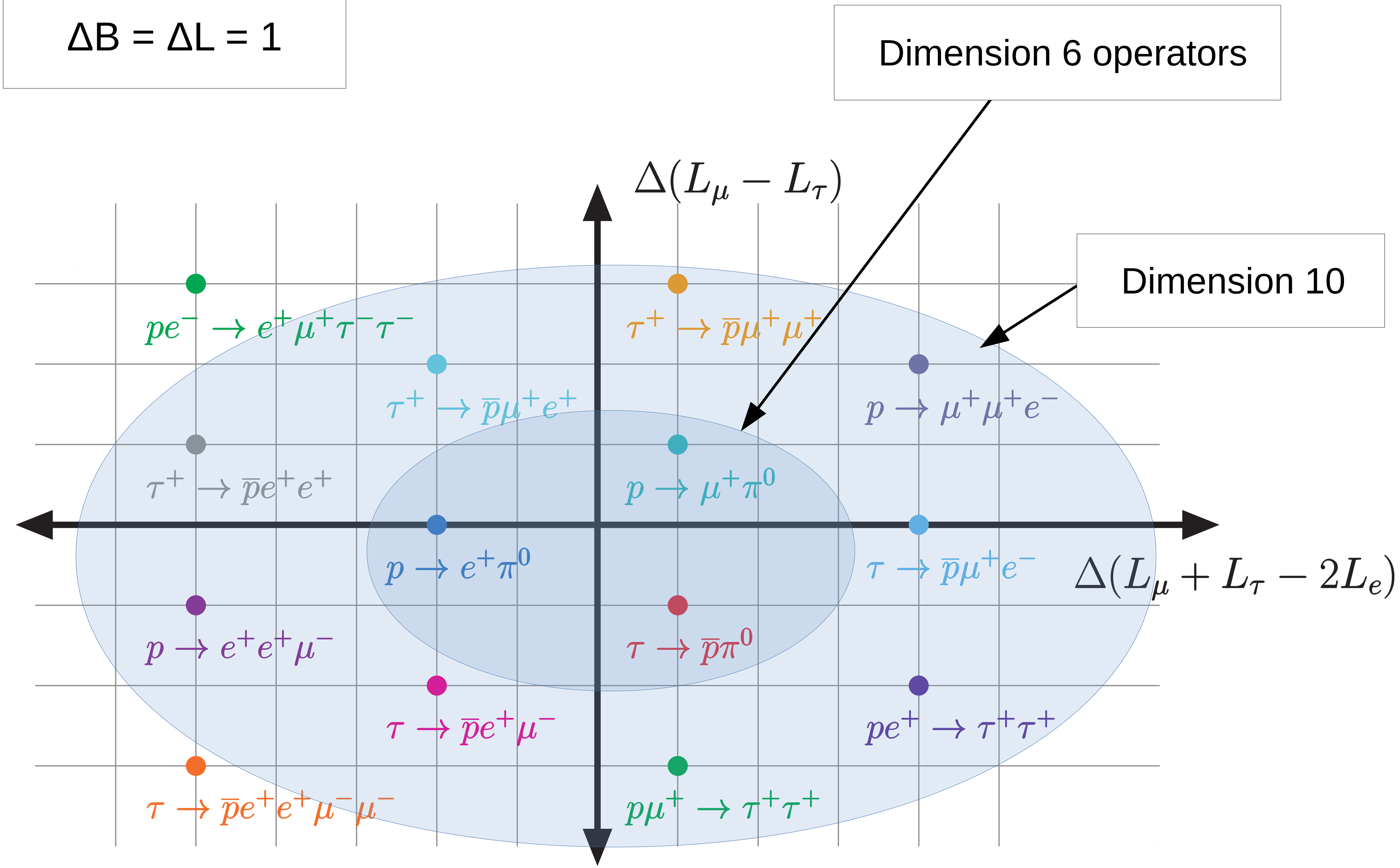
[Fonseca, Hirsch, Srivastava, 1802.04814]

ΔB = ΔL = 1



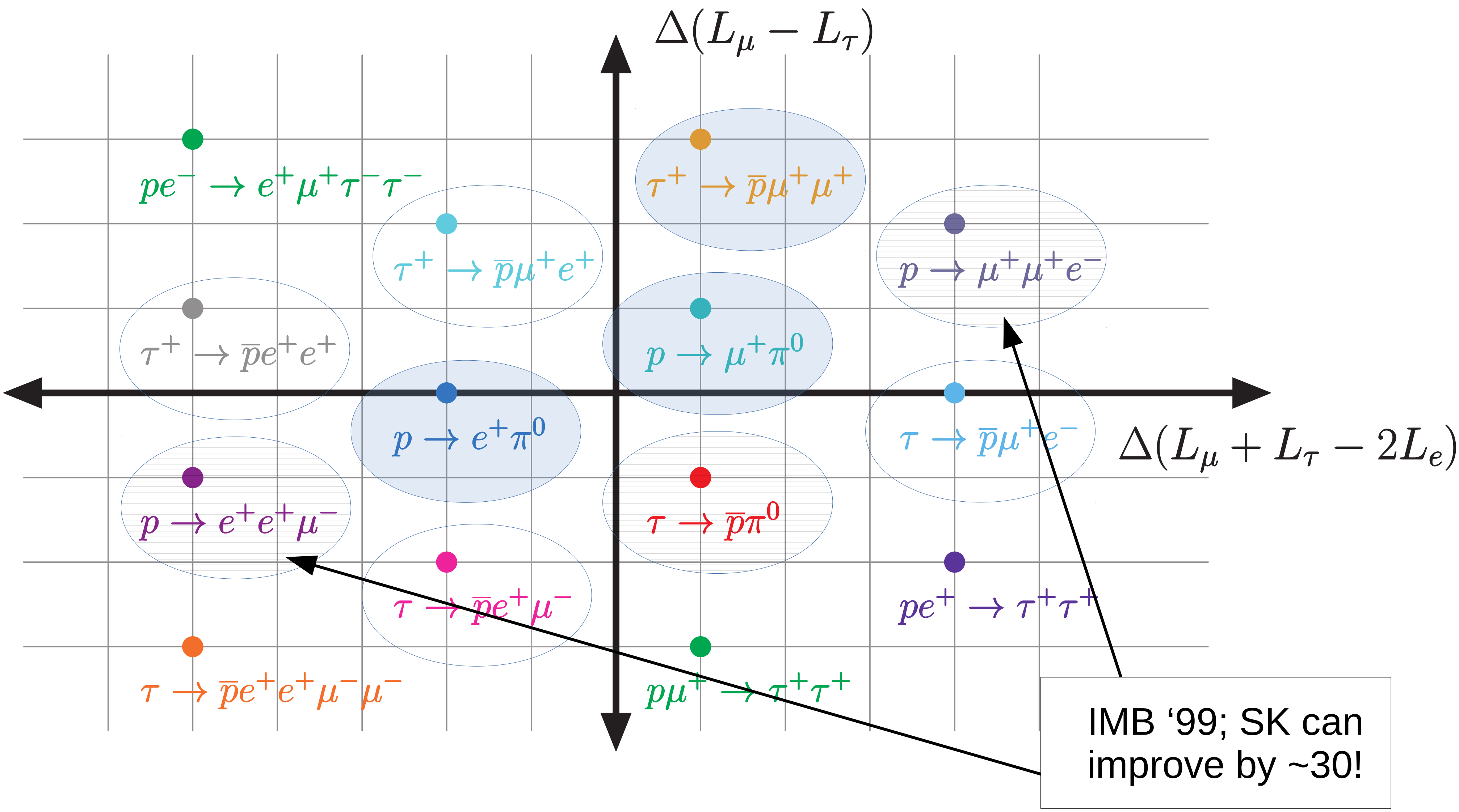
$\Delta(L_\mu - L_\tau)$
$\Delta(L_\mu + L_\tau - 2L_e)$
$pe^- \to e^+\mu^+\tau^-\tau^-$
$\tau^+ \to \overline{p}\mu^+\mu^+$
$\tau^+ \to \overline{p}\mu^+e^+$
$p \to \mu^+\mu^+e^-$
$\tau^+ \to \overline{p}e^+e^+$
$p \to \mu^+\pi^0$
$p \to e^+\pi^0$
$\tau \to \overline{p}\mu^+e^-$
$p \to e^+e^+\mu^-$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

ΔB = ΔL = 1



Dimension 6 operators
Dimension 10
$\Delta(L_\mu - L_\tau)$
$\Delta(L_\mu + L_\tau - 2L_e)$
$pe^- \to e^+\mu^+\tau^-\tau^-$
$\tau^+ \to \overline{p}\mu^+\mu^+$
$\tau^+ \to \overline{p}\mu^+e^+$
$p \to \mu^+\mu^+e^-$
$\tau^+ \to \overline{p}e^+e^+$
$p \to \mu^+\pi^0$
$p \to e^+\pi^0$
$\tau \to \overline{p}\mu^+e^-$
$p \to e^+e^+\mu^-$
$\tau \to \overline{p}\pi^0$
$\tau \to \overline{p}e^+\mu^-$
$pe^+ \to \tau^+\tau^+$
$\tau \to \overline{p}e^+e^+\mu^-\mu^-$
$p\mu^+ \to \tau^+\tau^+$

Currently being probed: Old results: Doable:



Lepton-flavored proton decay

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

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

- Easy channels, Super-K can probe 10^{34} yrs!
- UV completion @ 100 TeV could show up in flavor physics.
- Other channels, e.g. $p \to e^+ \pi^0$, suppressed by ν mass.

[Hambye, Heeck, 1712.04871, PRL]

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

- Minimal scalar leptoquark example,

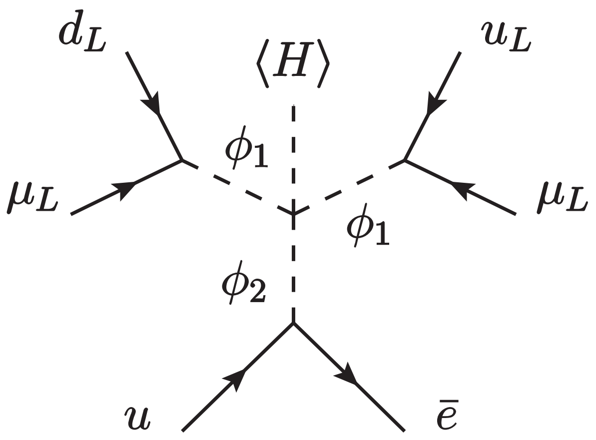
  $L_\mu(\phi_1) = 1,\ L_e(\phi_2) = -1.$

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

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

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

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



[Hambye, Heeck, 1712.04871, PRL]

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

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

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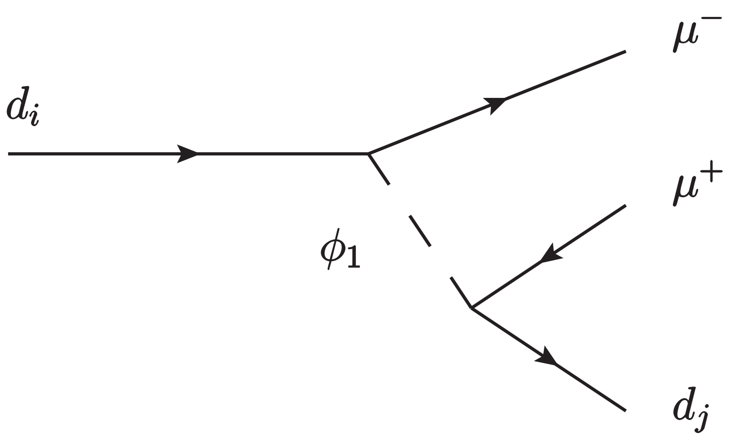
- d = 6 operators:

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



⇒ Lepton universality violation!

Lepton universality violation

=

The violation of

$$\mathsf{SU}(3)_\ell$$

(in SM broken down to $\mathsf{U}(1)_{\mathsf{L}_\mu - \mathsf{L}_\tau} \times \mathsf{U}(1)_{\mathsf{L}_\mu + \mathsf{L}_\tau - 2\mathsf{L}_e}$ by m_ℓ)

in processes

$$\mathsf{Z} \to \ell^- \ell^+, \mathsf{B} \to \mathsf{K}^{(*)} \ell^- \ell^+, \mathsf{W} \to \ell \overline{\nu}_\ell, \mathsf{B} \to \mathsf{D}^{(*)} \ell \overline{\nu}_\ell, \ldots^\dagger$$

†Assuming *heavy* new physics.

Lepton universality violation

=

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$$\mathsf{SU}(3)_\ell$$

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$$\mathsf{Z} \to \ell^- \ell^+, \mathsf{B} \to \mathsf{K}^{(*)} \ell^- \ell^+, \mathsf{W} \to \ell \overline{\nu}_\ell, \mathsf{B} \to \mathsf{D}^{(*)} \ell \overline{\nu}_\ell, \ldots^\dagger$$

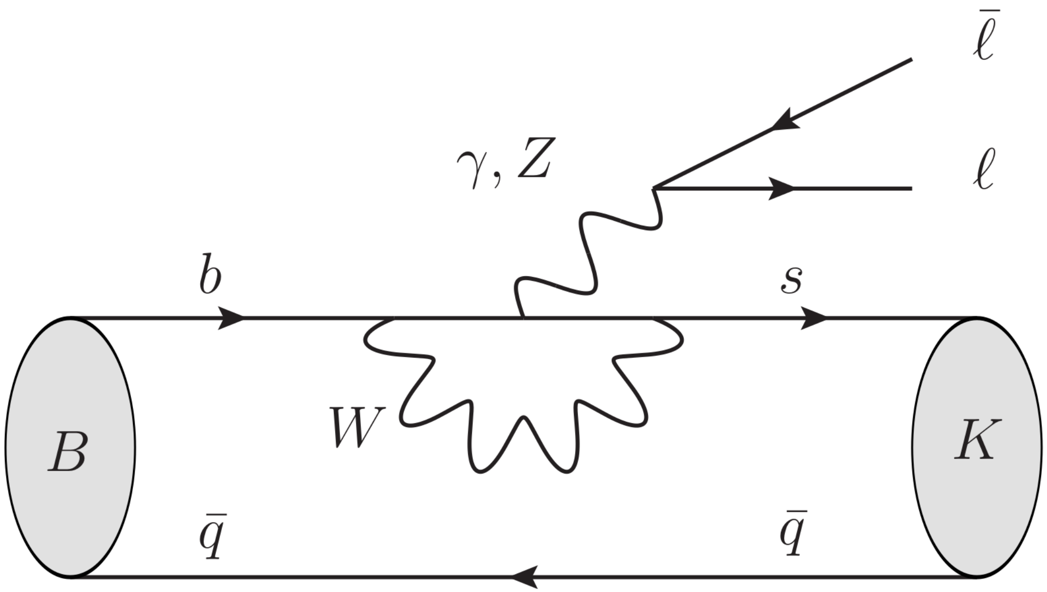
†Assuming *heavy* new physics.

b→sμμ

- Hints for lepton flavor non-universality in

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

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



- 4-6σ improvement with

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

- Also explains anomalies in other b→sμμ observables.
- Resolution via Z' or leptoquarks.

$b \to s\mu\mu$

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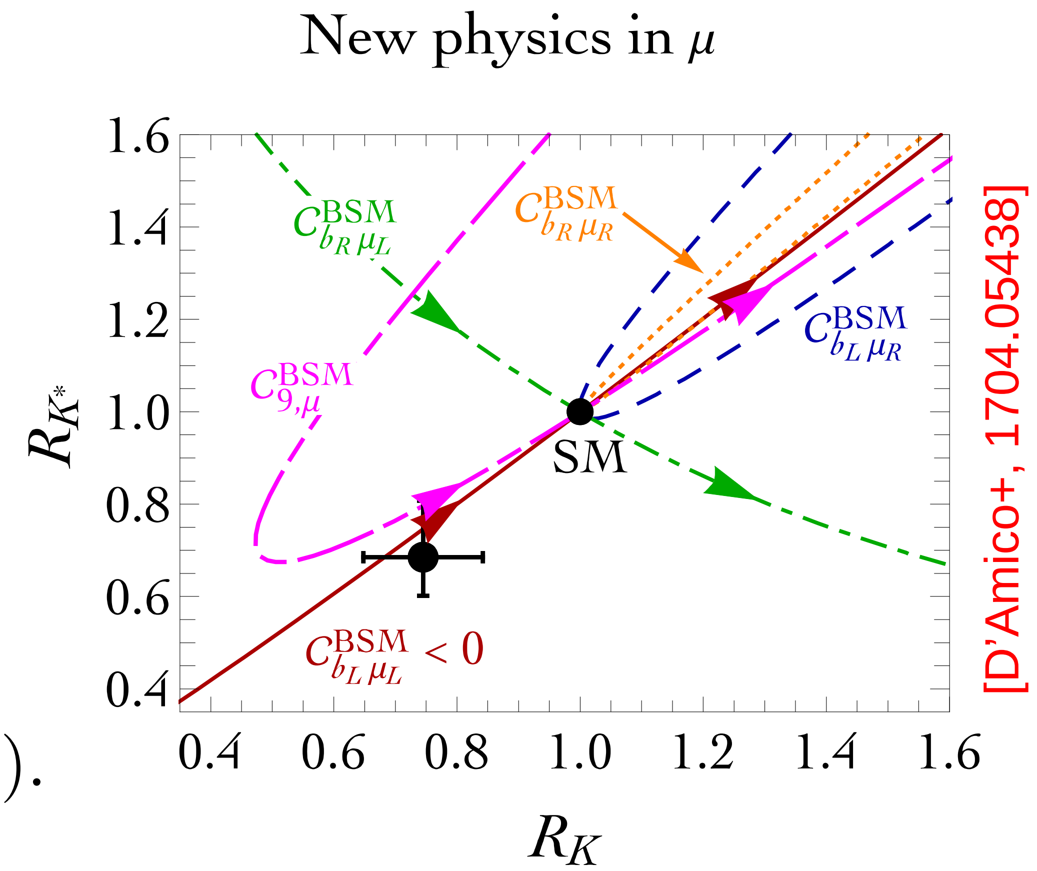


- Also explains anomalies in other $b \to s\mu\mu$ observables.

- Resolution via Z' or leptoquarks.

Triplet leptoquark and b→sμμ

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

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

- Generates $C_{9,LL}^\mu$ operator preferred by b→ sμμ:

$m_{\phi_1} \simeq 30\,\mathrm{TeV}\sqrt{y_2 y_3}$ improves fit by 4-6σ.

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

- Flavor symmetry ensures lepton non-universality and kills coupling $QQ\phi_1$ that would lead to d=6 proton decay.

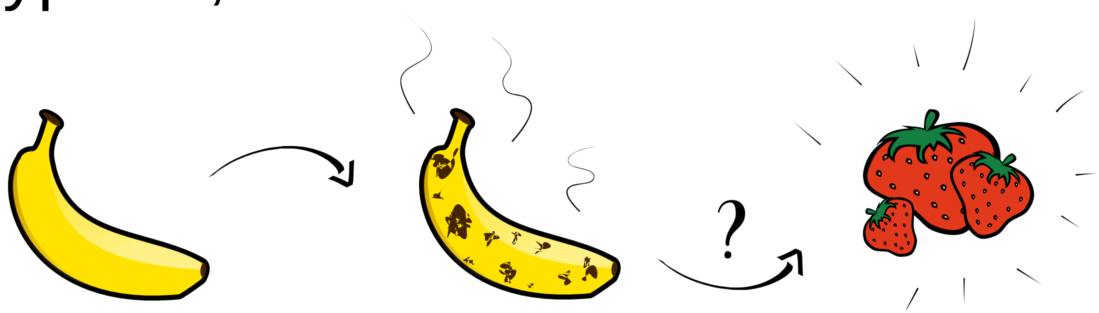
[Hambye, Heeck, 1712.04871, PRL]

Summary

- Charged LFV gives info *complementary* to ν oscillations.
- Is $U(1)_{B+L} \times U(1)_{B-L} \times U(1)_{L_\mu - L_\tau} \times U(1)_{L_\mu + L_\tau - 2L_e}$ broken in ℓ^- sector?

  ⇒ Need to probe all possible channels!

- Non-trivial breaking: $\tau \to ee\bar{\mu}$, $\tau \to \mu\mu\bar{e}$, $p \to e\overline{\mu\mu}$, $p \to \mu\overline{ee}$,…
- $R(K^{(*)})$ hint at lepton non-universality.
- Wait for Mu3e, MEG-II, Belle-II, Mu2e, COMET, DeeMe, LHC(b), Hyper-K,...



Backup

Upcoming CLFV

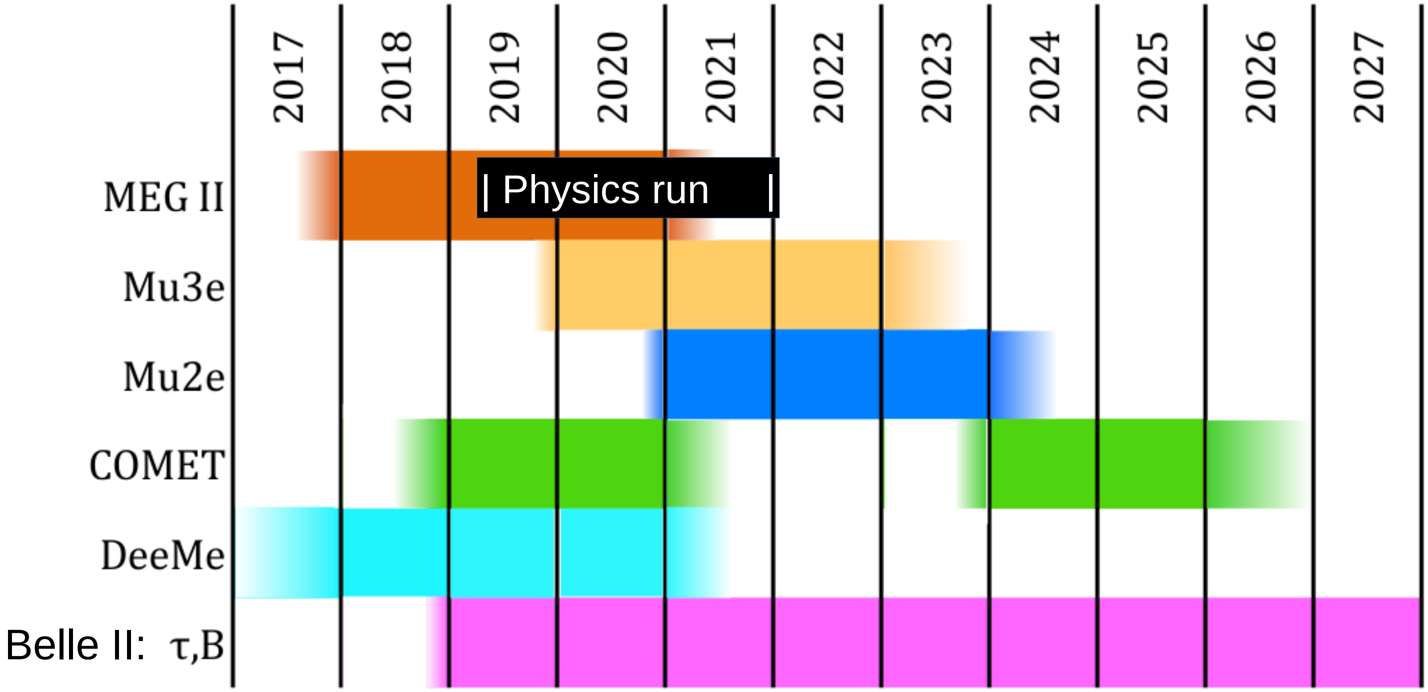


Figure 47. – Projected time lines for different projects searching for CLFV decays. MEG IIis expected to start data taking in 2018 after an engineering run in 2017; Mu3e magnet and detectors are expected at the end of 2019; Mu2e foresees three years of data taking starting in 2021; COMET Phase-I is expected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

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

conserves G (the $\mathcal{L}_{SM}$ term)

violates G (the $\frac{LLHH}{\Lambda}$ term)

could conserve G or subgroup (the $\mathcal{O}_j$, $\mathcal{O}'_j$, $\mathcal{O}''_j$ terms)
⇒ 'weird' channels dominate!?

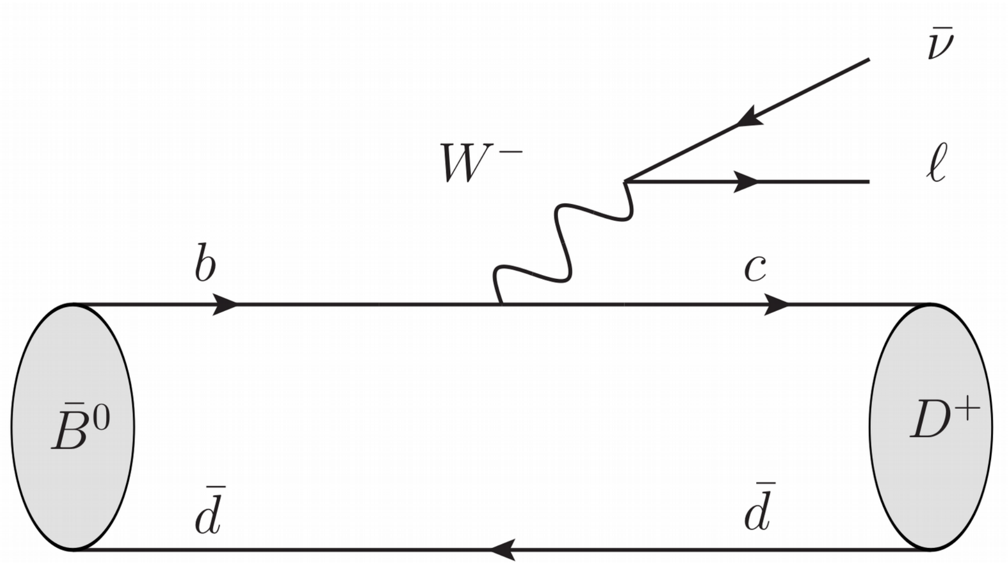
Scales probed by LFV

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

$\Delta L = 2$

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

$b \to c\ell\overline{\nu}$



- Hints for lepton flavor non-universality in

$$R(D^{(*)}) = \frac{\overline{B}\to D^{(*)}\tau\overline{\nu}}{\overline{B}\to D^{(*)}\ell\overline{\nu}}\,.$$

- Belle, BaBar, LHCb: $R(D^{(*)}) \sim 1.2\, R(D^{(*)})_{\text{SM}}$.
- 4σ improvement with

$$\frac{1}{(2\,\text{TeV})^2}(\overline{c}\gamma^\alpha P_L b)(\overline{\tau}\gamma_\alpha P_L \nu).$$

- Strong constraints from $pp \to \tau\tau,\, B_c \to \tau\nu$. [e.g. Alonso, Grinstein, Martin Camalich, PRL '16]
- Resolution via leptoquarks.

$b \to c\ell\overline{\nu}$

- Hints for lepton flavor non-universality in

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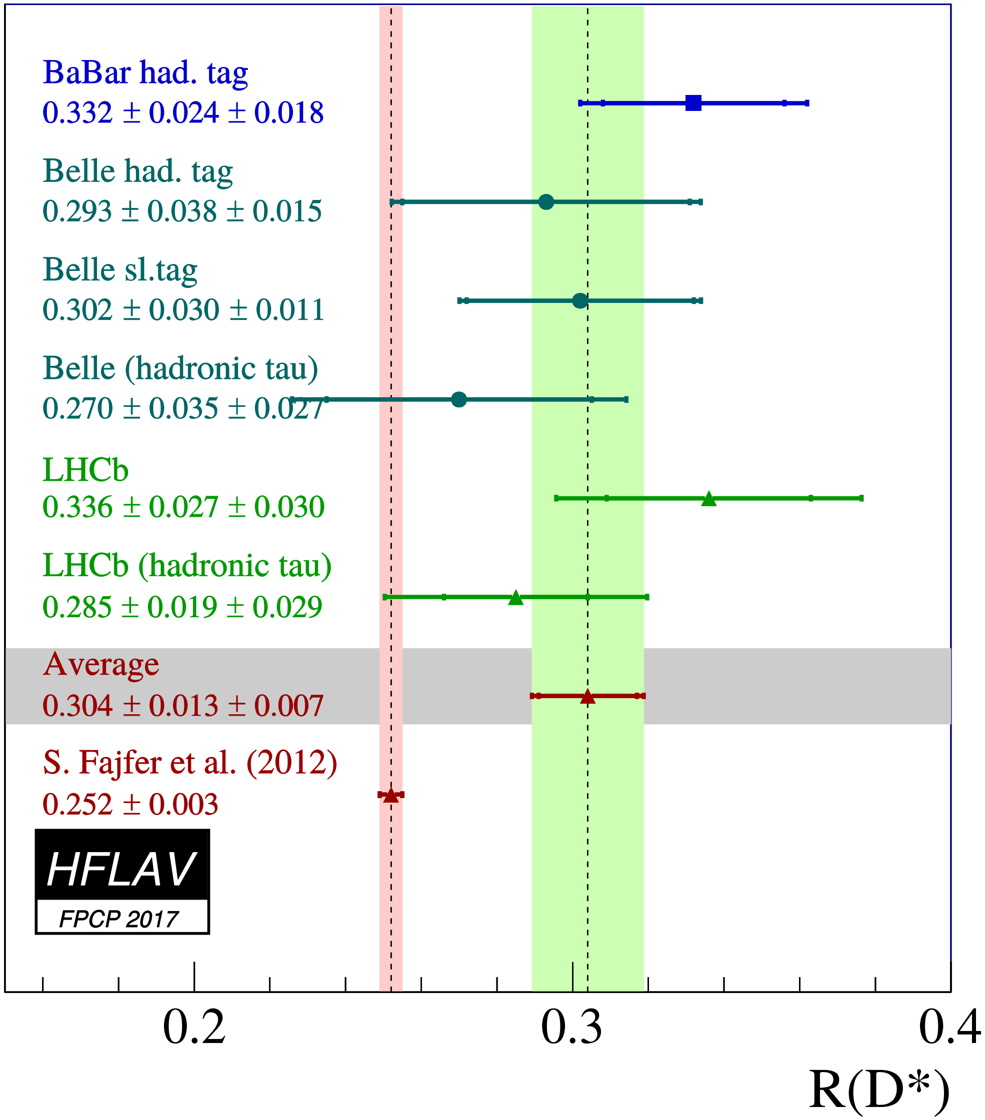

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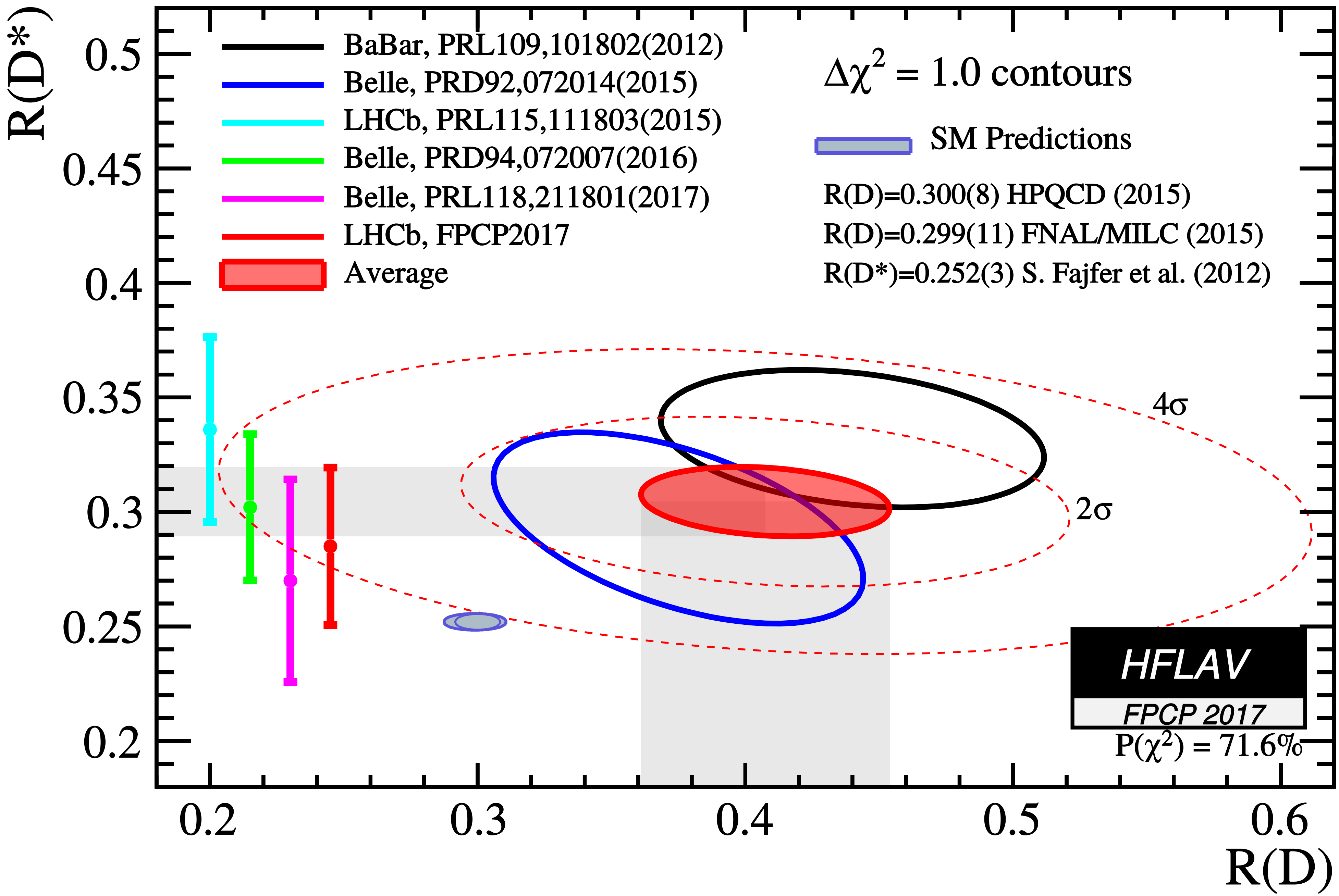


R(D*)
0.5
0.45
0.4
0.35
0.3
0.25
0.2
0.2
0.3
0.4
0.5
0.6
R(D)
BaBar, PRL109,101802(2012)
Belle, PRD92,072014(2015)
LHCb, PRL115,111803(2015)
Belle, PRD94,072007(2016)
Belle, PRL118,211801(2017)
LHCb, FPCP2017
Average
$\Delta\chi^2 = 1.0$ contours
SM Predictions
R(D)=0.300(8) HPQCD (2015)
R(D)=0.299(11) FNAL/MILC (2015)
R(D*)=0.252(3) S. Fajfer et al. (2012)
4σ
2σ
HFLAV
FPCP 2017
$P(\chi^2) = 71.6\%$

Neutrino oscillation parameters

NuFIT 3.2 (2018)

	Normal Ordering (best fit)		Inverted Ordering ($\Delta\chi^2 = 4.14$)		Any Ordering
	bfp $\pm 1\sigma$	3σ range	bfp $\pm 1\sigma$	3σ range	3σ range
$\sin^2\theta_{12}$	$0.307^{+0.013}_{-0.012}$	$0.272 \to 0.346$	$0.307^{+0.013}_{-0.012}$	$0.272 \to 0.346$	$0.272 \to 0.346$
$\theta_{12}/^\circ$	$33.62^{+0.78}_{-0.76}$	$31.42 \to 36.05$	$33.62^{+0.78}_{-0.76}$	$31.43 \to 36.06$	$31.42 \to 36.05$
$\sin^2\theta_{23}$	$0.538^{+0.033}_{-0.069}$	$0.418 \to 0.613$	$0.554^{+0.023}_{-0.033}$	$0.435 \to 0.616$	$0.418 \to 0.613$
$\theta_{23}/^\circ$	$47.2^{+1.9}_{-3.9}$	$40.3 \to 51.5$	$48.1^{+1.4}_{-1.9}$	$41.3 \to 51.7$	$40.3 \to 51.5$
$\sin^2\theta_{13}$	$0.02206^{+0.00075}_{-0.00075}$	$0.01981 \to 0.02436$	$0.02227^{+0.00074}_{-0.00074}$	$0.02006 \to 0.02452$	$0.01981 \to 0.02436$
$\theta_{13}/^\circ$	$8.54^{+0.15}_{-0.15}$	$8.09 \to 8.98$	$8.58^{+0.14}_{-0.14}$	$8.14 \to 9.01$	$8.09 \to 8.98$
$\delta_{CP}/^\circ$	234^{+43}_{-31}	$144 \to 374$	278^{+26}_{-29}	$192 \to 354$	$144 \to 374$
$\frac{\Delta m^2_{21}}{10^{-5}\ \text{eV}^2}$	$7.40^{+0.21}_{-0.20}$	$6.80 \to 8.02$	$7.40^{+0.21}_{-0.20}$	$6.80 \to 8.02$	$6.80 \to 8.02$
$\frac{\Delta m^2_{3\ell}}{10^{-3}\ \text{eV}^2}$	$+2.494^{+0.033}_{-0.031}$	$+2.399 \to +2.593$	$-2.465^{+0.032}_{-0.031}$	$-2.562 \to -2.369$	$\begin{bmatrix}+2.399 \to +2.593 \\ -2.536 \to -2.395\end{bmatrix}$

[JHEP 01 (2017) 087 [arXiv:1611.01514], see www.nu-fit.org]

Limits on CLFV

Group	Process	Current	Future
$\Delta(L_e - L_\mu) = 2$	$\mu \to e\gamma$	4.2×10^{-13} [15]	4×10^{-14} [16]
	$\mu \to e\bar{e}e$	1.0×10^{-12} [17]	10^{-16} [18]
	$\mu \to e$ conv.	$\mathcal{O}(10^{-12})$ [19]	10^{-17} [20, 21]
	$h \to e\bar{\mu}$	3.5×10^{-4} [22]	2×10^{-4} [23]
	$Z \to e\bar{\mu}$	7.5×10^{-7} [24]	–
	had$\to e\bar{\mu}$(had)	4.7×10^{-12} [25]	10^{-12} [26]
$\Delta(L_e - L_\tau) = 2$	$\tau \to e\gamma$	3.3×10^{-8} [27]	10^{-9} [28]
	$\tau \to e\bar{e}e$	2.7×10^{-8} [29]	10^{-9} [28]
	$\tau \to e\bar{\mu}\mu$	2.7×10^{-8} [29]	10^{-9} [28]
	$\tau \to e$ had	$\mathcal{O}(10^{-8})$ [30]	10^{-9} [28]
	$h \to e\bar{\tau}$	6.9×10^{-3} [22]	5×10^{-3} [23]
	$Z \to e\bar{\tau}$	9.8×10^{-6} [31]	–
	had$\to e\bar{\tau}$(had)	$\mathcal{O}(10^{-6})$ [32, 33]	–
$\Delta(L_\mu - L_\tau) = 2$	$\tau \to \mu\gamma$	4.4×10^{-8} [27]	10^{-9} [28]
	$\tau \to \mu\bar{e}e$	1.8×10^{-8} [29]	10^{-9} [28]
	$\tau \to \mu\bar{\mu}\mu$	2.1×10^{-8} [29]	10^{-9} [28]
	$\tau \to \mu$ had	$\mathcal{O}(10^{-8})$ [30]	10^{-9} [28]
	$h \to \mu\bar{\tau}$	1.2×10^{-2} [7]	5×10^{-3} [23]
	$Z \to \mu\bar{\tau}$	1.2×10^{-5} [34]	–
	had$\to \mu\bar{\tau}$(had)	$\mathcal{O}(10^{-6})$ [32, 33]	–

TABLE I: CLFV with conserved L and B, omitting CP conjugate processes. Current limits on the branching ratios are at 90% C.L. (h/Z decays at 95% C.L.). A full list of CLFV involving hadrons (had) can be found in the PDG [30].

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

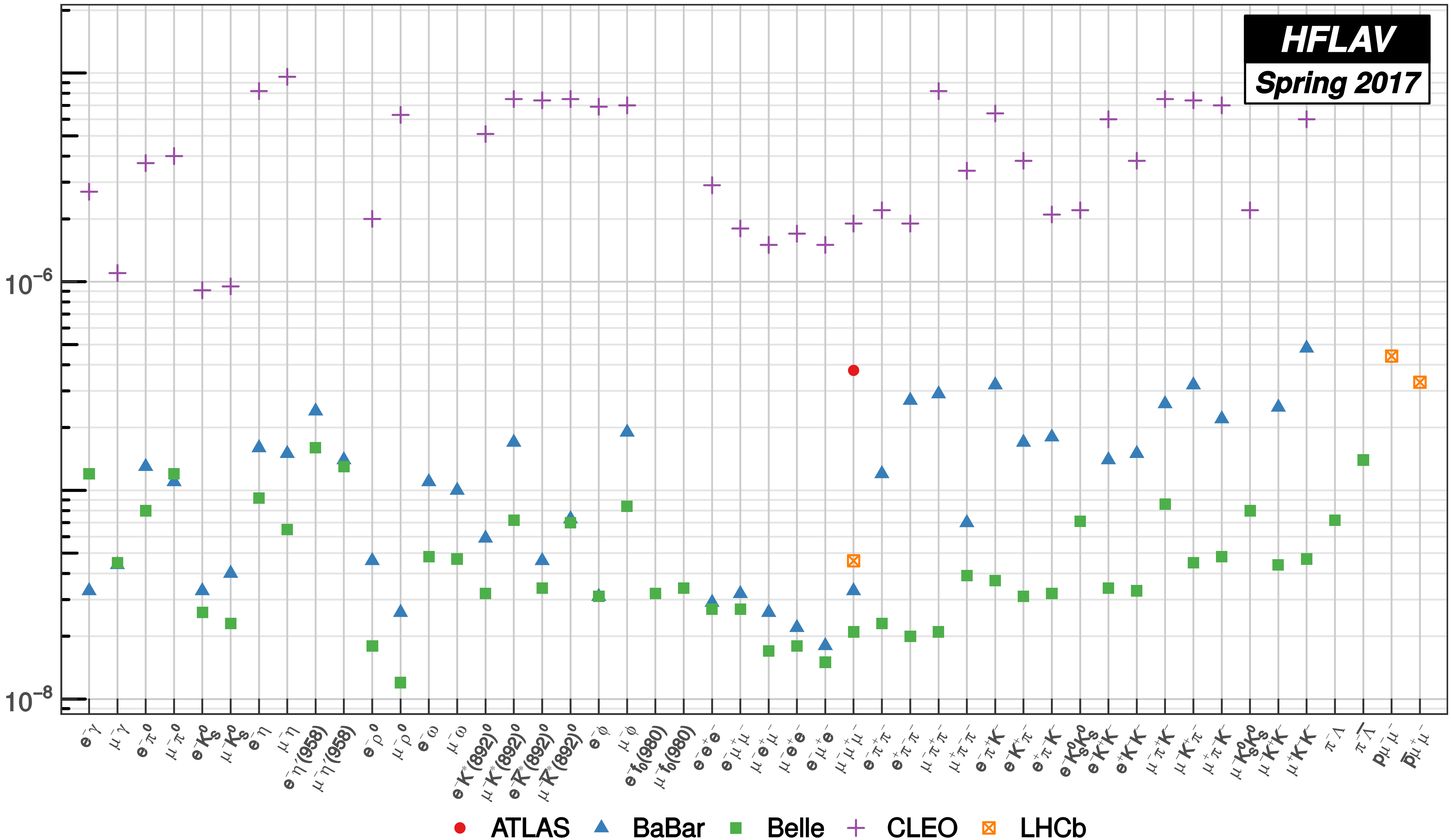
TABLE II: CLFV with conserved L and B, omitting CP conjugate processes. Current limits at 90% C.L.

Group	Process	Current	Future
$\Delta L_e = 2$	$0\nu\beta\beta$	$\mathcal{O}(10^{25}\,\text{yr})$ [44]	10^{26} yr [44]
	had$\to ee$ had	6.4×10^{-10} [45]	10^{-12} [26]
$\Delta L_\mu = 2$	had$\to \mu\mu$ had	8.6×10^{-11} [46]	10^{-12} [26]
$\Delta L_\tau = 2$	had$\to \tau\tau$ had	–	–
$\Delta(L_e + L_\mu) = 2$	$\mu \to \bar{e}$ conv.	3.6×10^{-11} [47]	$\ll 10^{-11}$ [48]
	had$\to \mu e$ had	5.0×10^{-10} [45]	10^{-12} [26]
$\Delta(L_e + L_\tau) = 2$	$\tau \to \bar{e}$ had	2.0×10^{-8} [49]	10^{-9} [28]
	had$\to \tau e$ had	–	–
$\Delta(L_\mu + L_\tau) = 2$	$\tau \to \bar{\mu}$ had	3.9×10^{-8} [49]	10^{-9} [28]
	had$\to \tau\mu$ had	–	–

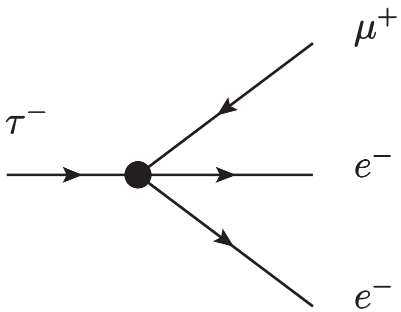
TABLE IV: Processes violating total lepton number L by two units (90% C.L. limits), assuming conserved baryon number.

[Heeck, 1610.07623]

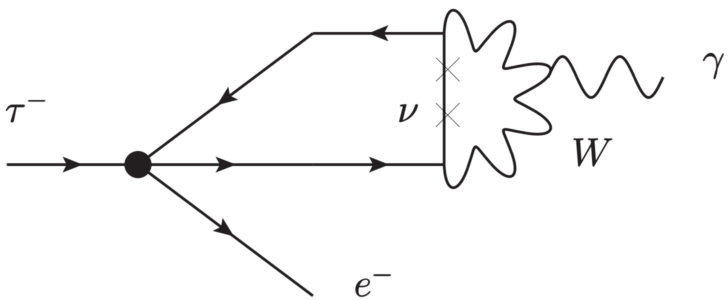
90% CL upper limits on τ LFV decays



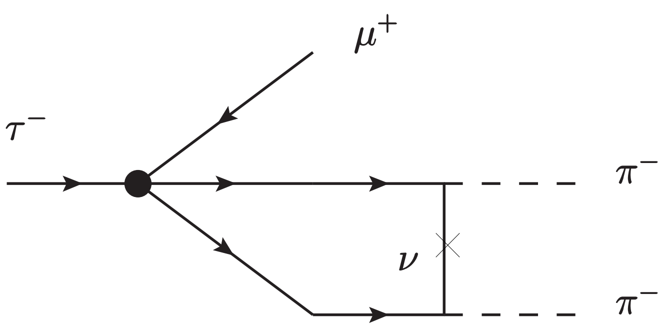
$\tau^- \to e^- e^- \mu^+$ plus M_ν breaks U(1)



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



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



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

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

⇒ All heavily suppressed!

Baryon number violation

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

channel	$(\Delta L_e, \Delta L_\mu)$	limit/years
$p \to e^+e^+e^-$	$(1,0)$	793×10^{30}
$p \to e^+\mu^+\mu^-$	$(1,0)$	359×10^{30}
$p \to \mu^+e^+e^-$	$(0,1)$	529×10^{30}
$p \to \mu^+\mu^+\mu^-$	$(0,1)$	675×10^{30}
$p \to \mu^+\mu^+e^-$	$(-1,2)$	359×10^{30}
$p \to e^+e^+\mu^-$	$(2,-1)$	529×10^{30}

IMB '99; SK can improve by ~30!

Different flavor from $p \to \ell^+\pi^0$!

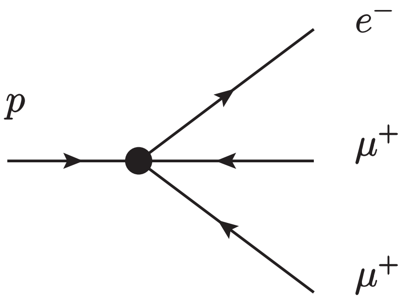
d=10 operators for p → $\overline{\ell}\ell\ell$

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

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

[Hambye, Heeck, 1712.04871, PRL]

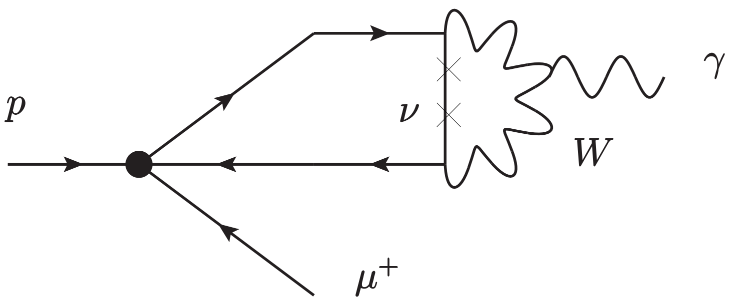
p → $\mu^+\mu^+e^-$ plus M_ν breaks U(1)



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

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

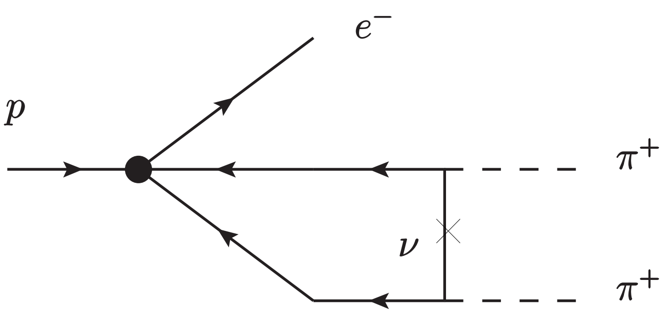
Conserves U(1)



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

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

GIM: Not dangerous



$$\Delta B = -\Delta L = 1, d = 7:$$

$$\mathcal{A}_7 \propto \frac{\langle H \rangle m_p}{\Lambda^6} \frac{(m_\nu)_{\mu\mu}}{16\pi^2}$$

Small enough!

Effective operators

- $\Delta B = 1$ proton decay operators:
  - $QQQL$: $d=6$, $\Delta L = 1$, e.g. $p \to e^+ \pi^0$.
  - $QQ\overline{L}Hd$: $d=7$, $\Delta L = -1$, e.g. $p \to e^- \pi^+ K^+$.
  - $\overline{LL}\ell udd$: $d=9$, $\Delta L = -1$, e.g. $p \to \nu\, e^- e^+ K^+$.
  - $QQQL\overline{L}H\ell$: $d=10$, $\Delta L = 1$, e.g. $p \to e^+ e^- e^+$.
  - $ddd\overline{LLL}H$: $d=10$, $\Delta L = -3$, e.g. $p \to e^- \nu\nu\, \pi^+ \pi^+$.
  - $QudLLLHH$: $d=11$, $\Delta L = 3$, e.g. $p \to e^+ \overline{\nu\nu}$.

[Weinberg, ‘79 & ‘80]

Different symmetry properties

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 $U(1)_{B-L}$ spontaneously: $\mathcal{L} = -\overline{L}yHN_R - \frac{1}{2}\overline{N}_R^c\lambda\sigma N_R + h.c.$

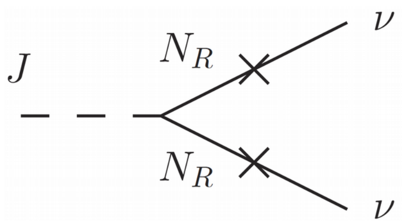
$$M_R = \frac{\lambda f}{\sqrt{2}}$$

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

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

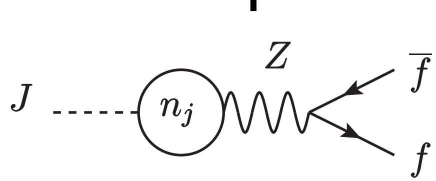
Majoron couplings

- Tree level coupling only to neutrinos:



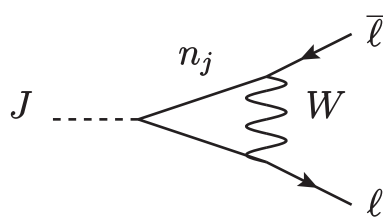
$$\frac{iJ}{2f}\overline{\nu}^c_\alpha \gamma_5 \left(m_D^* M_R^{-1} m_D^\dagger\right)_{\alpha\beta}\nu_\beta = -\frac{iJ}{2f}\sum_k \overline{\nu}_k\gamma_5 m_k \nu_k$$

- One loop:



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

Off-diagonal!



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

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

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

Properties

- Crucial observation: the two matrices are independent!

$$\{\mathsf{m_D}, \mathsf{M_R}\} \leftrightarrow \{\mathsf{M}_\nu, \mathsf{m_D} \mathsf{m_D}^\dagger\}.$$

[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: *pseudo*-Goldstone.
- Experimental signature depends on decay channel:

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

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

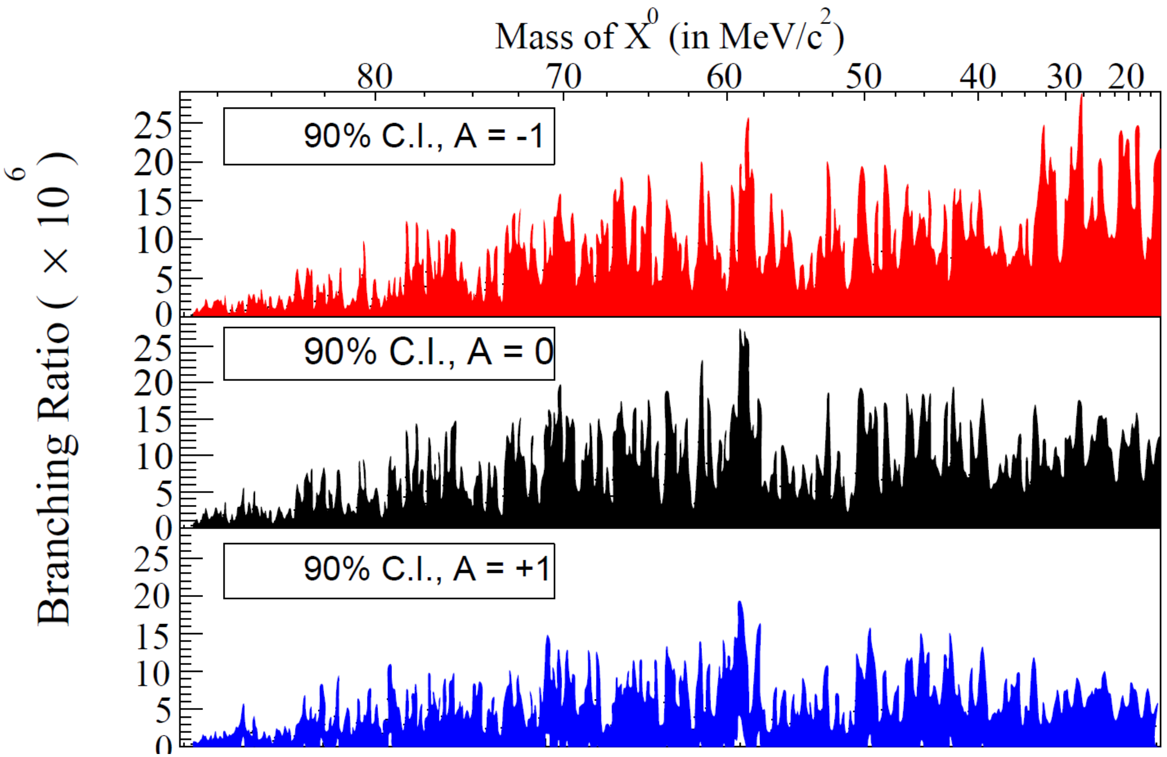
$\mu \rightarrow e\, J$ with $J \rightarrow$ invisible

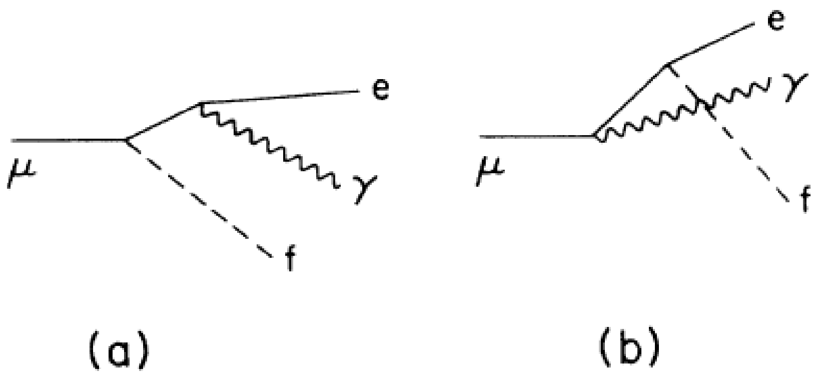
- TWIST, ‘15: limits on different anisotropies.
- Chiral coupling $\overline{\mu} P_L e J$ suppresses sensitivity!

  [Heeck, Garcia-Cely, 1701.07209]
- Bremsstrahlung is competitive: $\mu \rightarrow e\, J\, \gamma$.

  [Goldman et al, ‘87]
- Approximate limit

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





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, 1701.0720…]

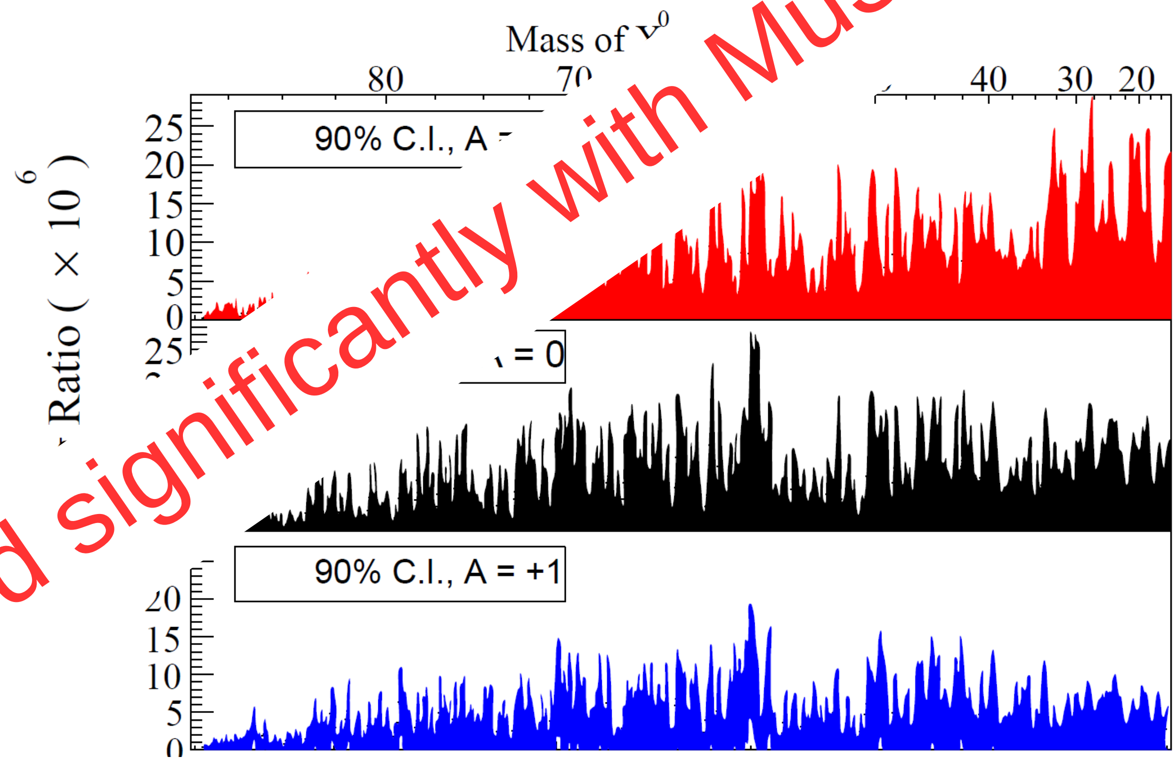
- Bremsstrahlun… competitive…

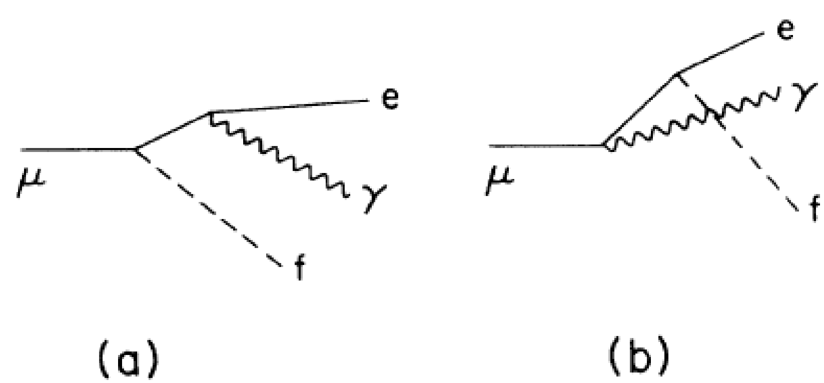
[Goldman et …]

- Ap… …imit

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

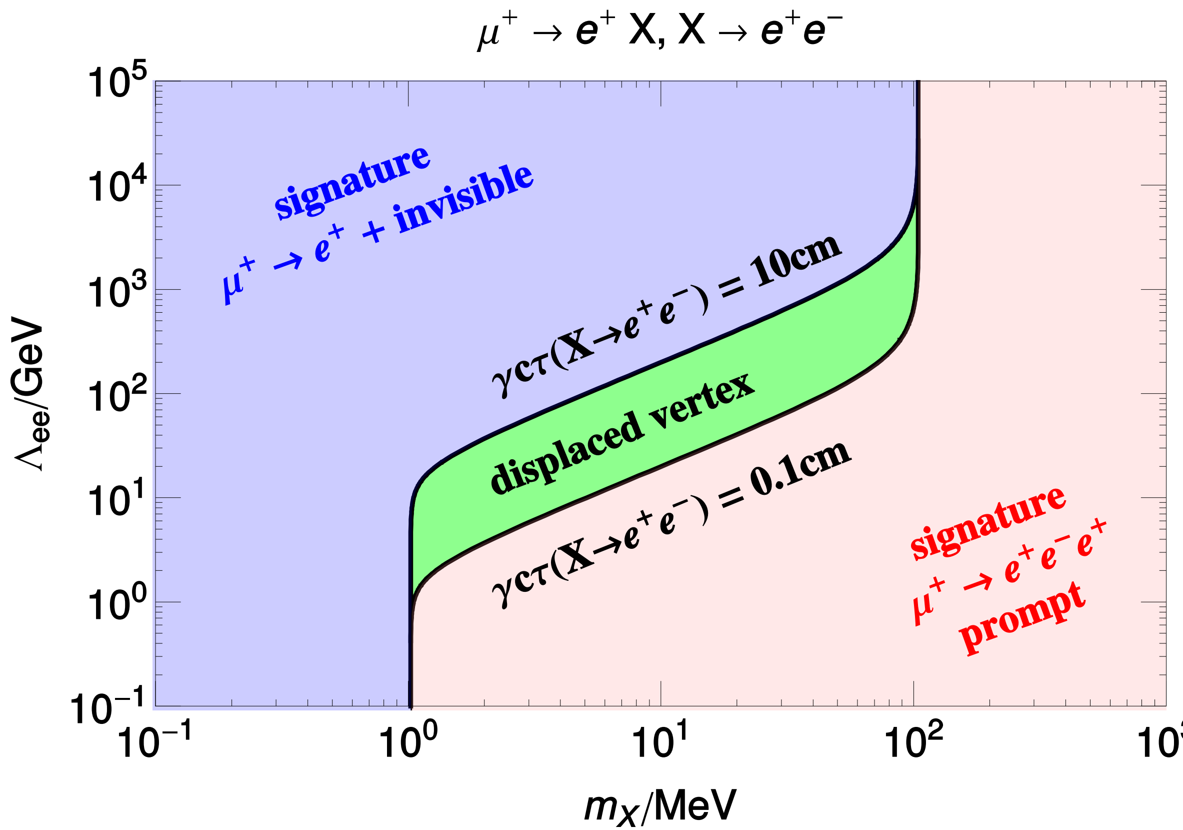
Can be improved significantly with Mu3e!





$\mu \to e X$ with $X \to$ 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:

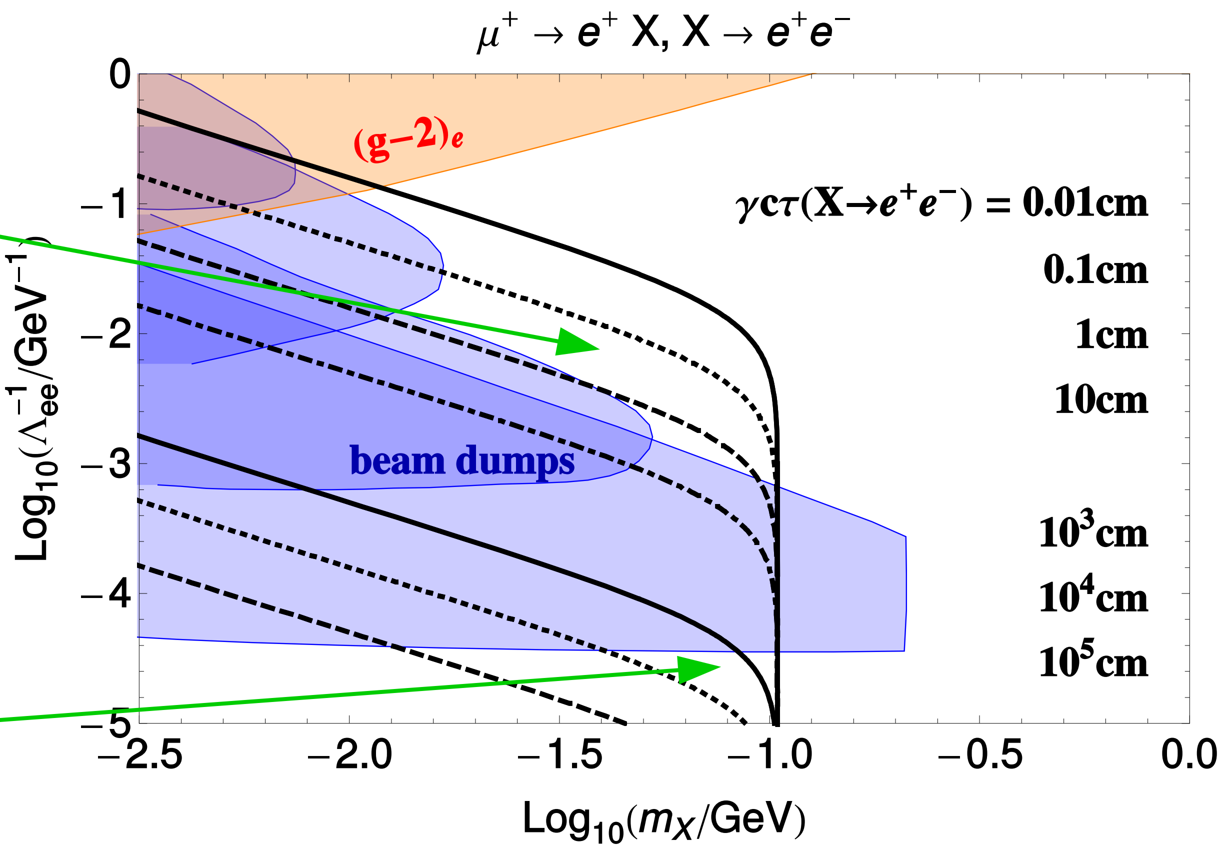
$$\gamma c \tau \simeq \frac{\pi m_\mu \Lambda_{ee}^2}{m_e^2 m_X^2} \simeq 2.5\,\mathrm{cm}\left(\frac{\Lambda_{ee}}{100\,\mathrm{GeV}}\right)^2 \left(\frac{10\,\mathrm{MeV}}{m_X}\right)^2 .$$

Sub-GeV X with ee coupling allowed?

[Heeck, Rodejohann, 1710.02062]

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

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



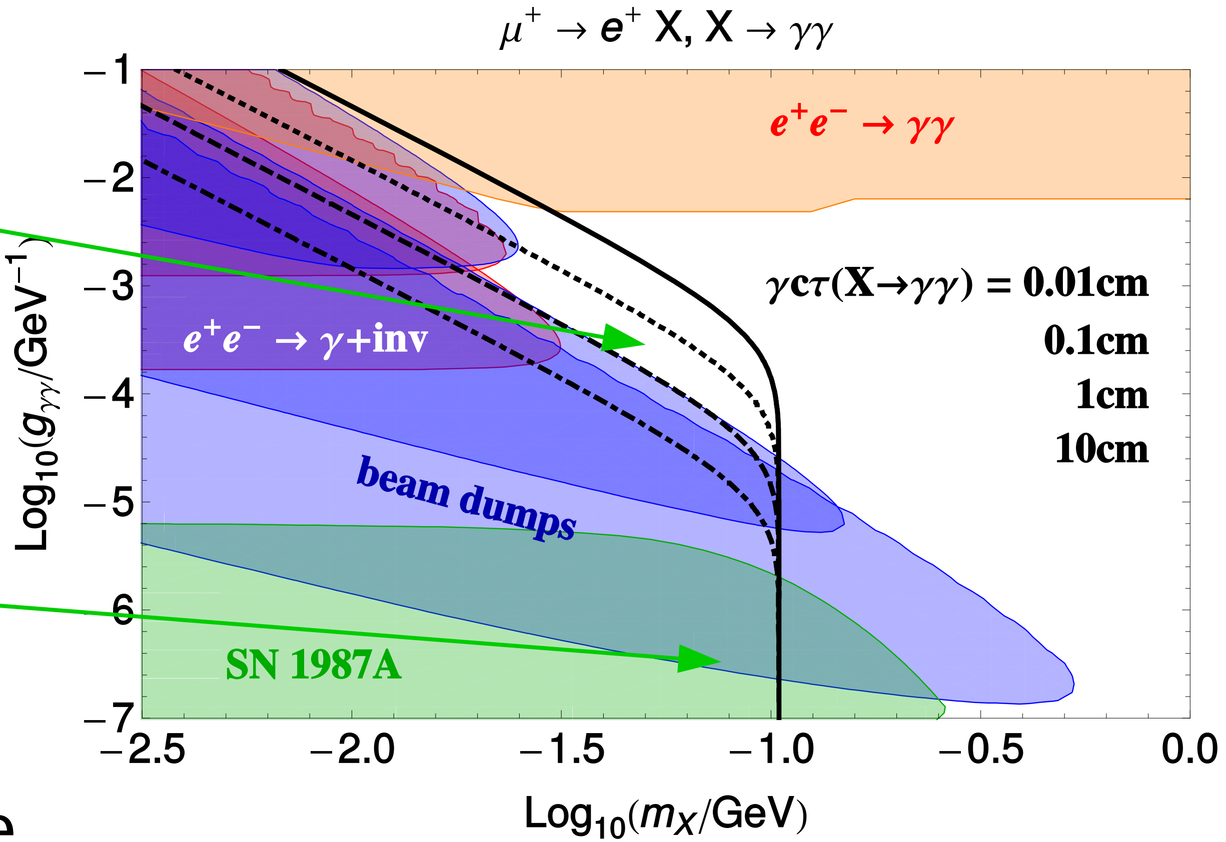
$$\mathrm{BR}(\mu \to \mathrm{e}X)\mathrm{BR}(X \to \mathrm{ee})(1 - \mathrm{P}(l_{\mathrm{dec}}))$$
$$\simeq \mathrm{BR}(\mu \to \mathrm{e}X)\frac{l_{\mathrm{dec}}}{\gamma c \tau}\,.$$

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?

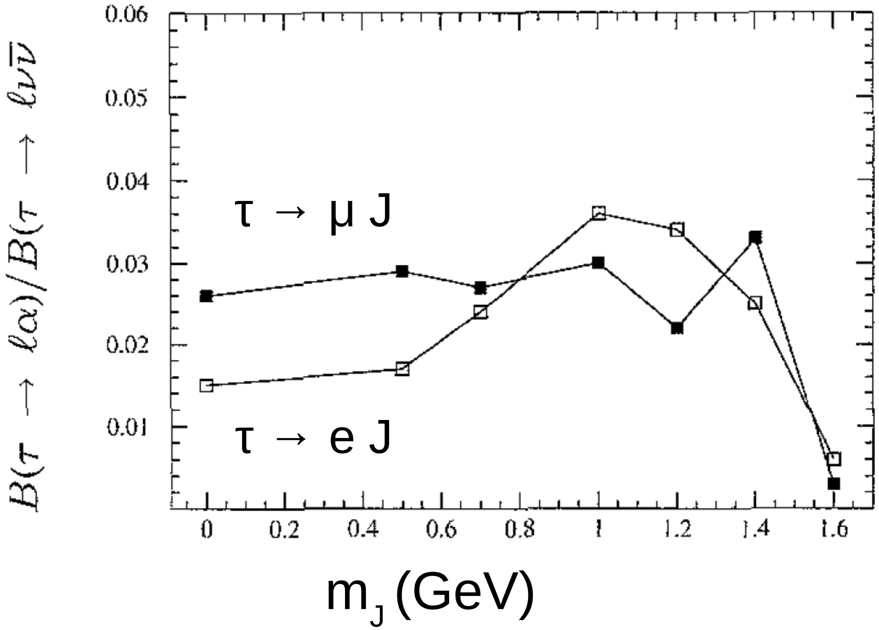


[Recent limits: Dolan et al, 1709.00009]

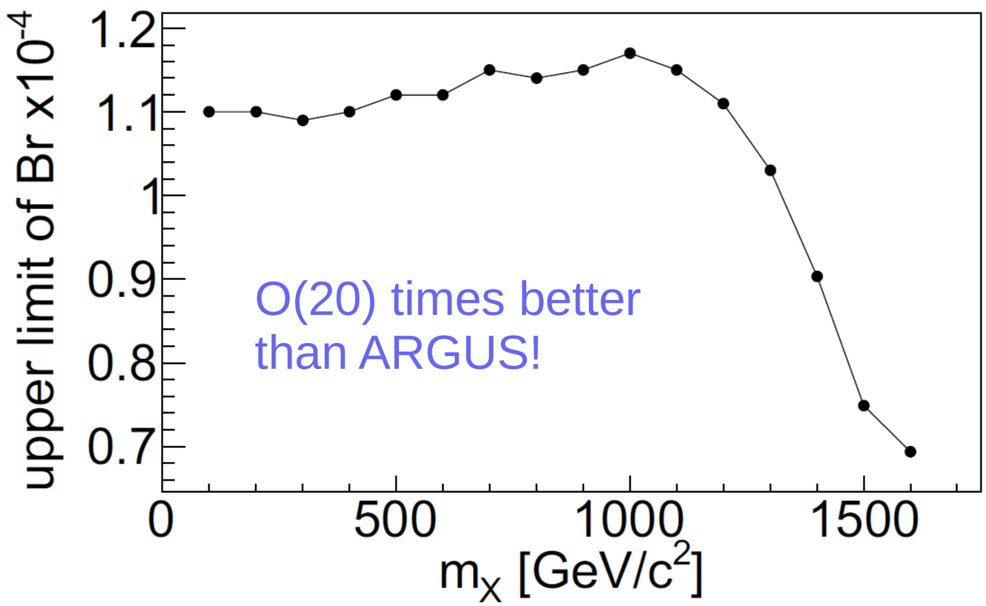
Muons difficult, taus easier.

τ → ℓ J with J→ invisible

- ARGUS, ‘95; 5e5 taus.



- Belle, ‘16 prelim.; 1e9 taus.



- Also interesting for LFV Z’.

[Foot, He, Lew, Volkas, ‘94; Heeck, 1602.03810; Altmannshofer et al, 1607.06832]

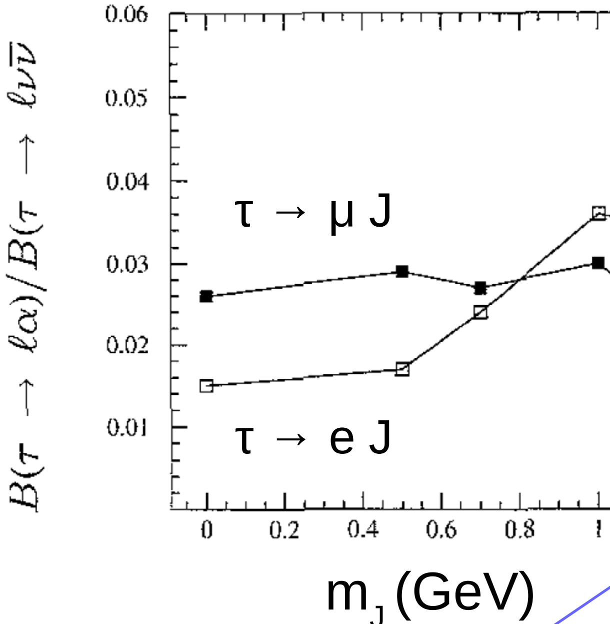
- Improvement with Belle-II.

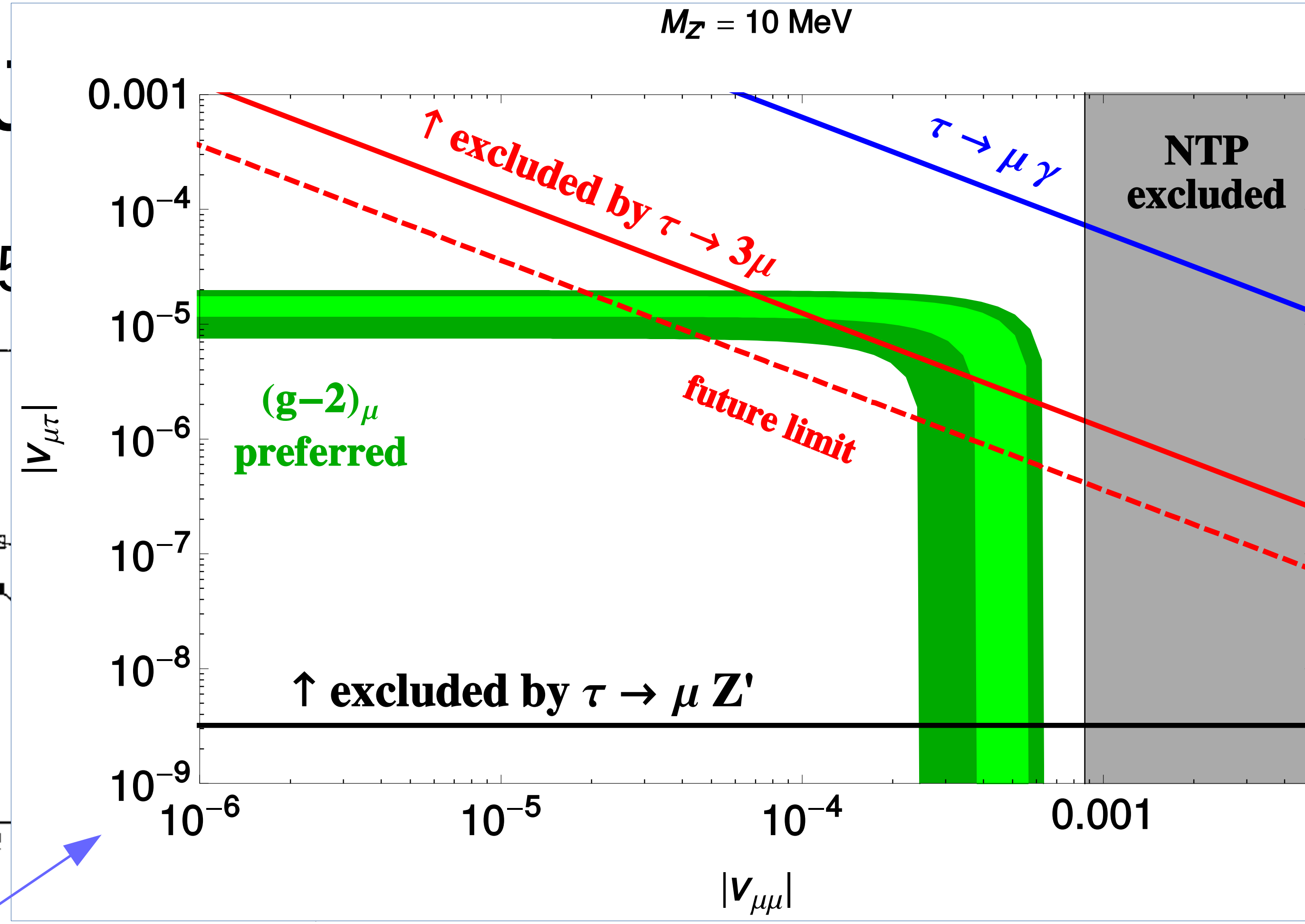
$$\frac{|(m_D m_D^\dagger)_{\tau e}|}{vf} \lesssim 6 \times 10^{-3},$$

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

τ → ℓ J with J

- ARGUS, '95; 5e5





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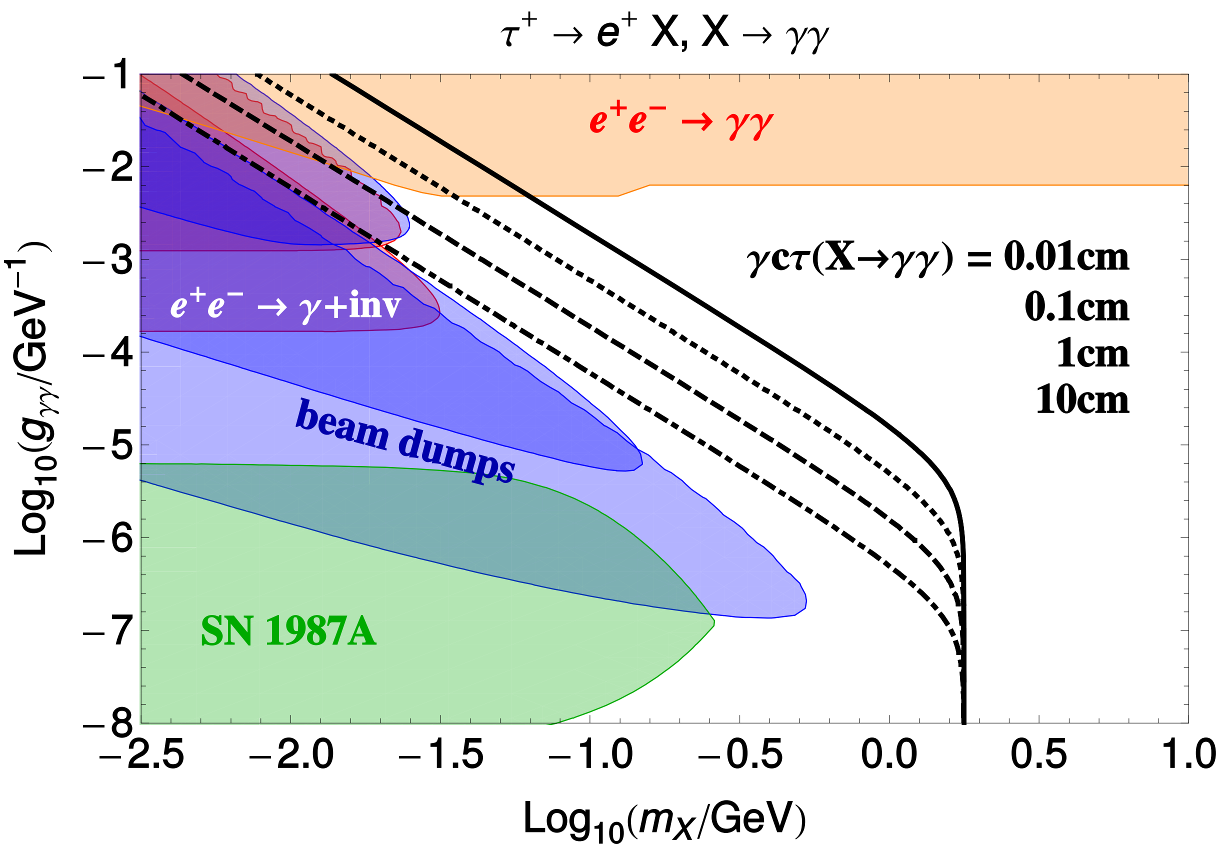
$$\frac{|(m_D m_D^\dagger)_{\tau\mu}|}{vf} \lesssim 10^{-3}.$$

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...