Lepton Flavor Violation by Two Units

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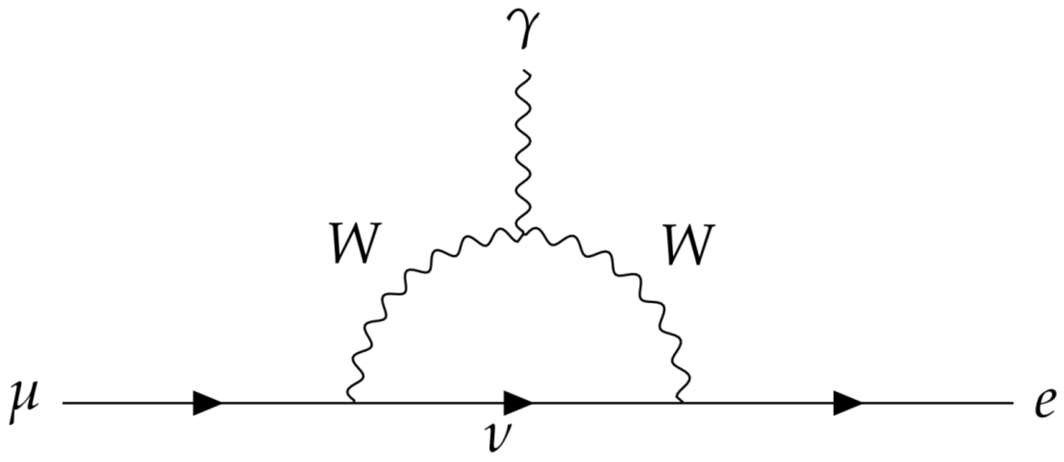
Research Advisor: Prof. Julian Heeck

Lepton Flavor is an exact symmetry in Standard Model
if neutrinos are massless

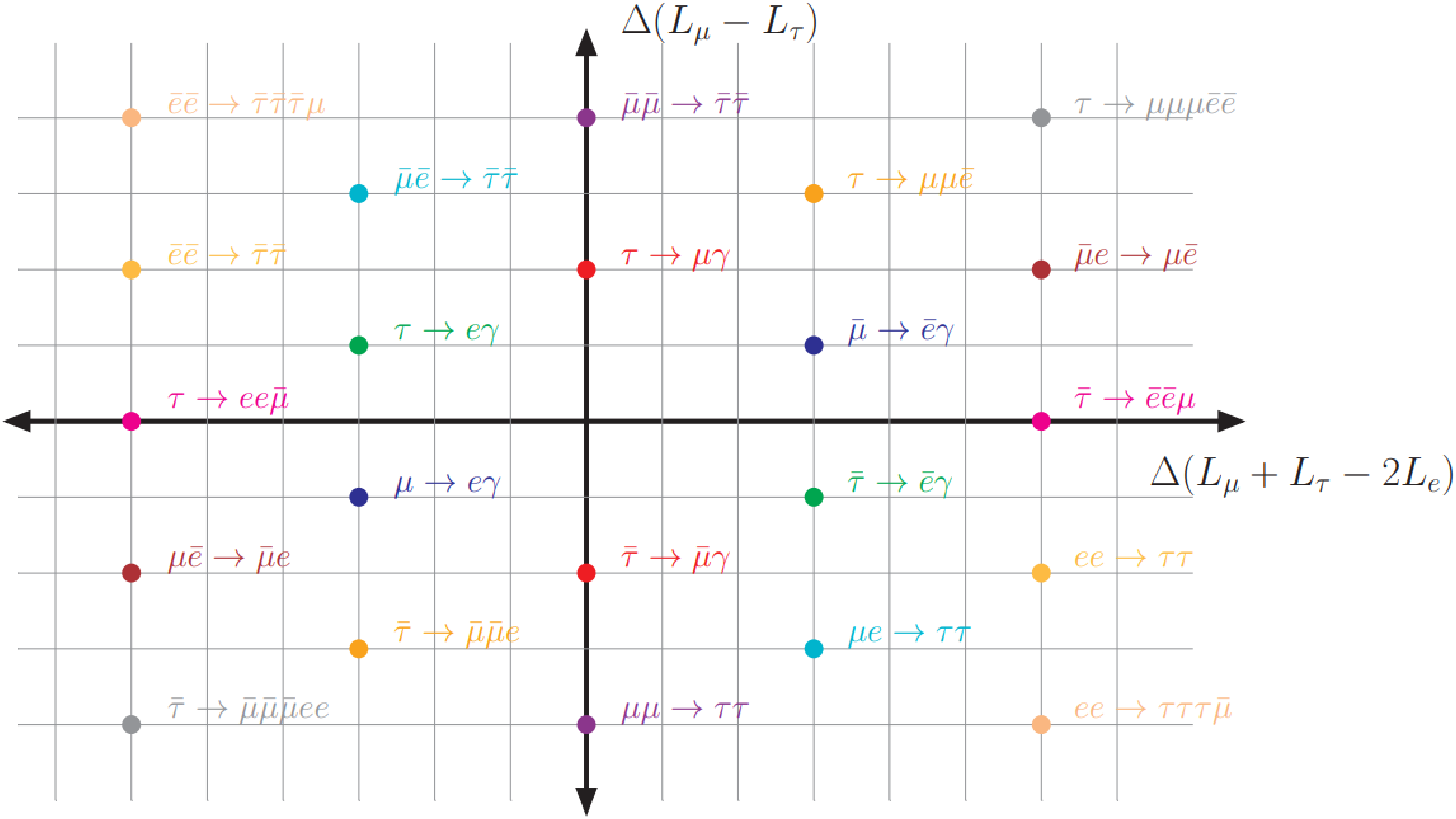


$$\mathrm{BR}(\mu \to e\gamma) \sim \left(\frac{\delta m_\nu^2}{m_W^2}\right)^2 < 10^{-54}$$

- This process is invisible for our experiments (probably forever)
- Detection of any lepton flavor violation process is a clear indication of a New Physics beyond SM

CLFV Classification

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



J.Heeck, 2017 [1610.07623]

SMEFT

Standard Model Effective Field Theory Lagrangian can be decomposed in SM part and effective corrections

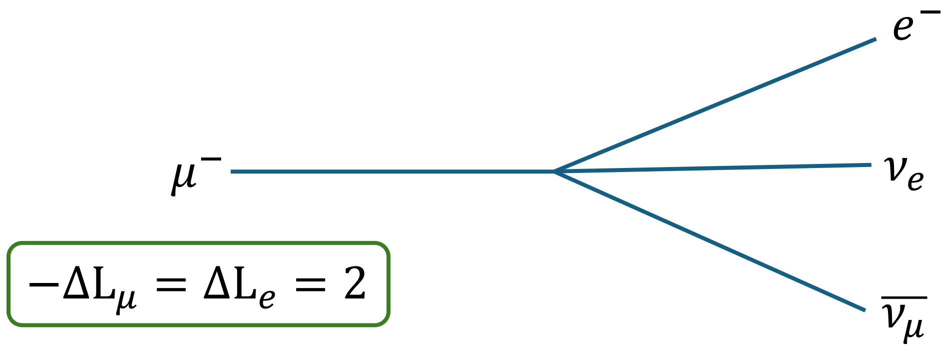
$$\mathcal{L} = \mathcal{L}_{\mathrm{SM}} + \sum_{d=5}^{\infty} \sum_{i=1}^{n_d} \frac{C_i^{(d)}}{\Lambda^{(d-4)}} Q_i^{(d)}$$

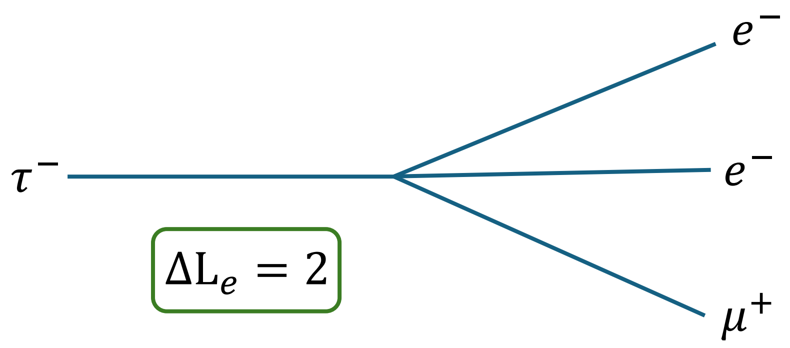
Dimensionless Coefficients

Effective Operators

Energy(Mass) Scale

Our research is focused on dimension six (d = 6) operators that violate lepton number by two units.





Notation

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

Wilson Coefficients Including Dimensionless Coefficient and the Energy Scale

Right-handed Charged Lepton

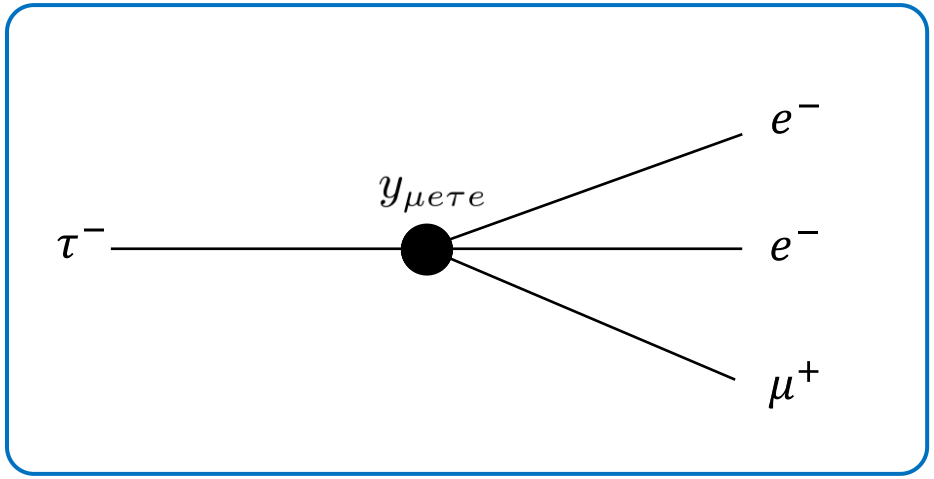
Left-handed Lepton Doublet

- There are 21 dimension six (d = 6) operators that violate lepton flavor number by two units.
- We split these 21 operators in several groups and put limits on the Wilson Coefficients assuming only one group at a time is present in Lagrangian.

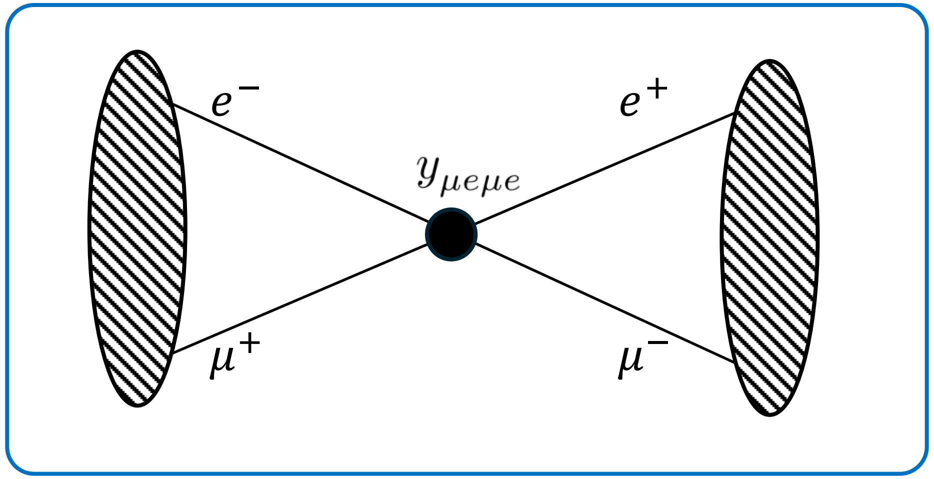
$\bar{\mu}\bar{\mu}ee$ $\bar{\tau}\bar{\tau}\mu\mu$ $\bar{\tau}\bar{\tau}ee$ $\bar{\tau}\bar{\tau}e\mu$ $\bar{\tau}\bar{\mu}ee$ $\bar{\mu}\bar{\mu}e\tau$

Relevant Observables

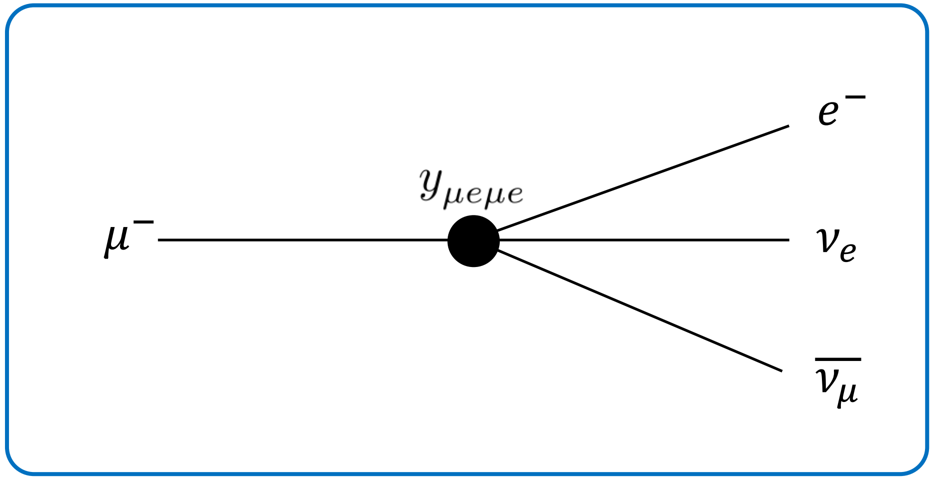
Neutrinoless Lepton-flavor-violating decay



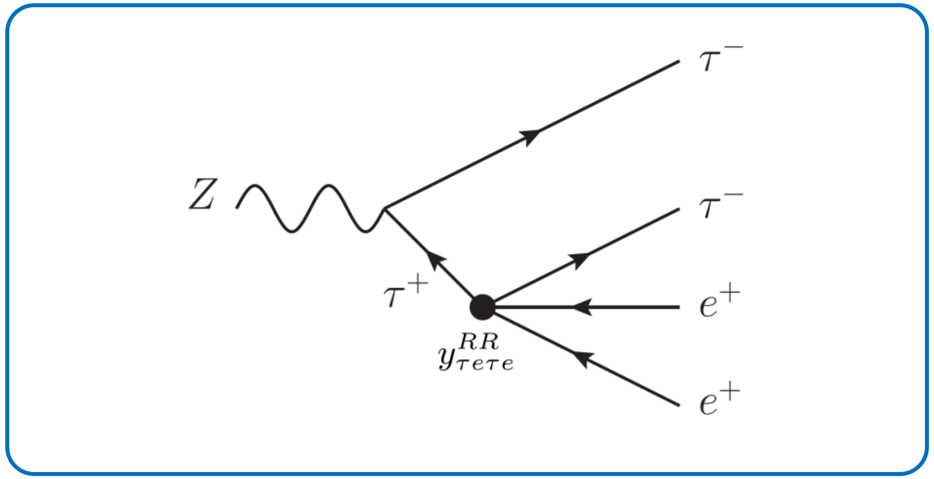
Muonium Conversion



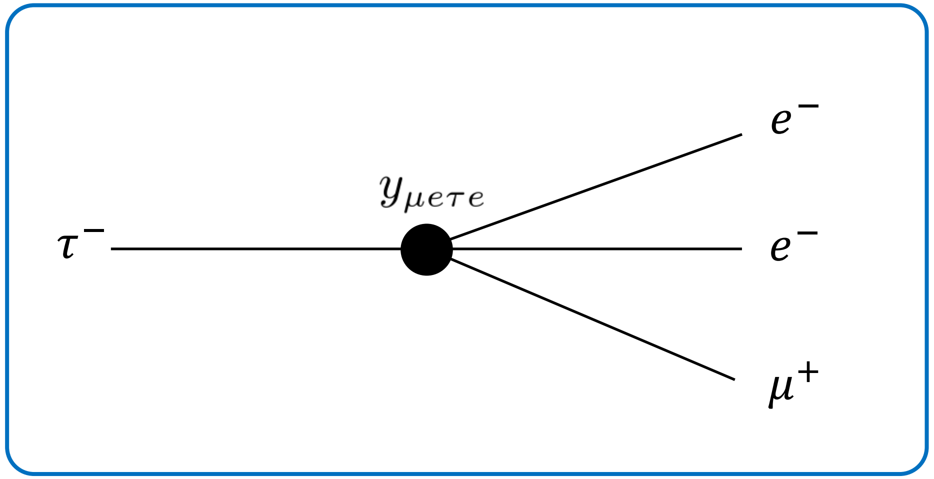
Lepton Flavor Universality



Z decay



Neutrinoless Lepton-flavor-violating decay



$$\Gamma \simeq \frac{m_\tau^5 \left(|y^{LL}_{\mu e \tau e}|^2 + |y^{LR}_{\mu e \tau e}|^2 + |y^{LR}_{\tau e \mu e}|^2 + |y^{RR}_{\tau e \mu e}|^2 \right)}{1536\pi^3}$$

- Only the cases where we have one tauon can be probed with this method.
- This approach puts the strongest limits of them all as it is the simplest one experimentally.

Current

$$BR(\tau^- \to \mu^+ e^- e^-) < 1.5 \times 10^{-8}$$

$$|y^{LL}_{\mu e \tau e}|, \ldots, |y^{RR}_{\tau e \mu e}| < (10\ \text{TeV})^{-2}$$

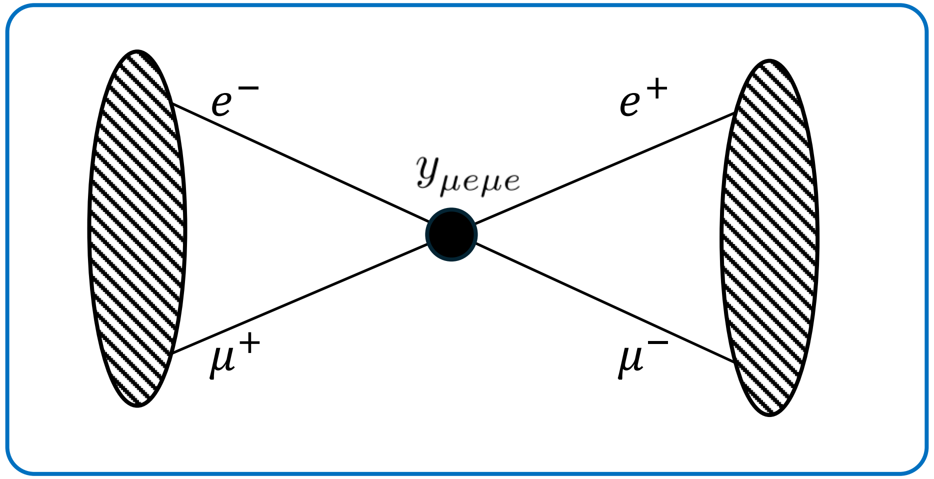
Future

- Belle II projected branching ratio:

$$BR(\tau^- \to \mu^+ e^- e^-) < 2.3 \times 10^{-10}$$

$$|y^{LL}_{\mu e \tau e}|, \ldots, |y^{RR}_{\tau e \mu e}| < (30\ \text{TeV})^{-2}$$

Muonium Conversion



- This puts limits on two of the three linearly independent combinations of Wilson Coefficients.
- We can refer to another observable to put better limit on the third one.

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

R. Conlin & A. A. Petrov, 2020 [2005.10276]

$$P < 8.3 \times 10^{-11}$$

L. Willmann et al. 1998 [hep-ex/9807011]

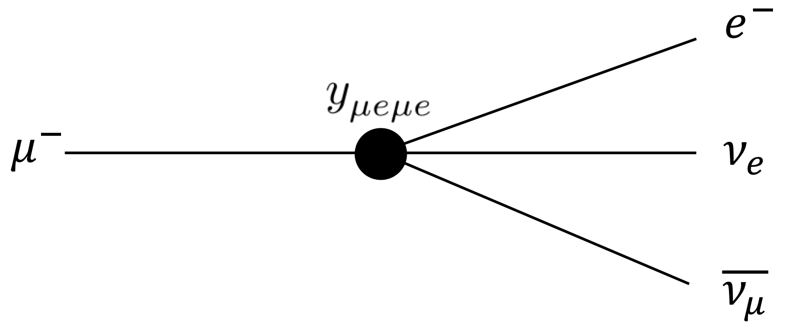
✓ $|y_{\mu e \mu e}^{LL} + y_{\mu e \mu e}^{RR}| < (2.9\,\text{TeV})^{-2}$

✓ $|y_{\mu e \mu e}^{LR}| < (3.4\,\text{TeV})^{-2}$

✗ $|y_{\mu e \mu e}^{LL} - y_{\mu e \mu e}^{RR}| < (1.2\,\text{GeV})^{-2}$

R. Conlin & A. A. Petrov, 2020 [2005.10276]

Lepton Flavor Universality



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

- EFT operators generate exactly the same electron energy spectrum as the SM decay, so the Michel spectrum remains unperturbed.
- The overall muon lifetime or decay rate is rescaled.

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

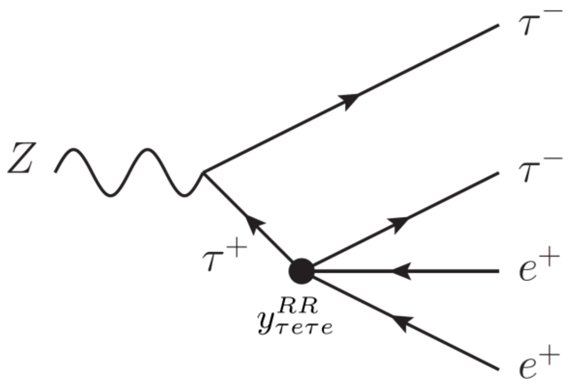
$$|y^{LL}_{\mu e\mu e} - y^{RR}_{\mu e\mu e}| < (1.2\,\text{GeV})^{-2}$$

Improved limit

$$|y^{LL}_{\mu e\mu e} - y^{RR}_{\mu e\mu e}| < (0.75\ \text{TeV})^{-2}$$

Lepton Flavor Universality works for all operators that contain at least two neutrinos.

Z decay



- For some of the right-handed operators we do not have neutrinos, "tauonium conversion" or clean decays.
- We compare how much does the addition those operators affect Z decay rate.

$$\mathrm{BR}(Z \to \tau^\pm \tau^\pm e^\mp e^\mp) \simeq 1.4 \frac{M_Z^5}{49152\pi^5} \frac{e^2 s_W^2}{c_W^2 \Gamma_Z} |y^{RR}_{\tau e \tau e}|^2$$

- The total Z width agrees very well with the SM prediction, which can be translated into a 2σ upper bound of 2×10^{-3} on any non-SM Z branching ratio.
- Can be improved with future colliders.

$$|y^{RR}_{\tau e \tau e}| < (1.2\,\mathrm{GeV})^{-2}$$

$$|y^{RR}_{\tau \mu \tau \mu}| < (1.2\,\mathrm{GeV})^{-2}$$

$$|y^{RR}_{e \tau \mu \tau}| < (1\,\mathrm{GeV})^{-2}$$

Table of the strongest limits on Wilson coefficients

Wilson coefficient	Upper limit	Process	Violated quantum numbers
$\lvert y^{LL}_{\mu e\mu e} + y^{RR}_{\mu e\mu e}\rvert$	$(3.2\,\mathrm{TeV})^{-2}$ [90% C.L.]	Mu-to-$\overline{\mathrm{Mu}}$ [20]	$\Delta L_\mu = -\Delta L_e = 2$
$\lvert y^{LR}_{\mu e\mu e}\rvert$	$(3.8\,\mathrm{TeV})^{-2}$ [90% C.L.]	Mu-to-$\overline{\mathrm{Mu}}$ [20]	$\Delta L_\mu = -\Delta L_e = 2$
$\lvert y^{LL}_{\mu e\mu e} - y^{RR}_{\mu e\mu e}\rvert$	$(0.74\,\mathrm{TeV})^{-2}$ [95% C.L.]	$\Gamma(\mu \to e\nu\bar{\nu})/\Gamma(\tau \to \mu\nu\bar{\nu})$ [21]	$\Delta L_\mu = -\Delta L_e = 2$
$\lvert 2y^{LL}_{\tau e\tau e}\rvert, \lvert y^{LR}_{\tau e\tau e}\rvert$	$(0.67\,\mathrm{TeV})^{-2}$ [95% C.L.]	$\Gamma(\tau \to e\nu\bar{\nu})/\Gamma(\tau \to \mu\nu\bar{\nu})$ [21] [22]	$\Delta L_\tau = -\Delta L_e = 2$
$\lvert y^{RR}_{\tau e\tau e}\rvert$	$(1.2\,\mathrm{GeV})^{-2}$ [95% C.L.]	$Z \to \tau^\pm\tau^\pm e^\mp e^\mp$	$\Delta L_\tau = -\Delta L_e = 2$
$\lvert 2y^{LL}_{\tau\mu\tau\mu}\rvert, \lvert y^{LR}_{\tau\mu\tau\mu}\rvert$	$(0.63\,\mathrm{TeV})^{-2}$ [95% C.L.]	$\Gamma(\tau \to \mu\nu\bar{\nu})/\Gamma(\tau \to e\nu\bar{\nu})$ [21] [22]	$\Delta L_\tau = -\Delta L_\mu = 2$
$\lvert y^{RR}_{\tau\mu\tau\mu}\rvert$	$(1.2\,\mathrm{GeV})^{-2}$ [95% C.L.]	$Z \to \tau^\pm\tau^\pm \mu^\mp \mu^\mp$	$\Delta L_\tau = -\Delta L_\mu = 2$
$\lvert y^{LL}_{e\tau\mu\tau}\rvert, \lvert y^{LR}_{\mu\tau e\tau}\rvert$	$(0.60\,\mathrm{TeV})^{-2}$ [95% C.L.]	$\Gamma(\tau \to e\nu\bar{\nu})/\Gamma(\mu \to e\nu\bar{\nu})$ [21]	$\Delta L_\tau = -2\Delta L_\mu = -2\Delta L_e = 2$
$\lvert y^{LR}_{e\tau\mu\tau}\rvert$	$(0.55\,\mathrm{TeV})^{-2}$ [95% C.L.]	$\Gamma(\tau \to e\nu\bar{\nu})/\Gamma(\tau \to \mu\nu\bar{\nu})$ [21] [22]	$\Delta L_\tau = -2\Delta L_\mu = -2\Delta L_e = 2$
$\lvert y^{RR}_{e\tau\mu\tau}\rvert$	$(1\,\mathrm{GeV})^{-2}$ [95% C.L.]	$Z \to \tau^\pm\tau^\pm e^\mp \mu^\mp$	$\Delta L_\tau = -2\Delta L_\mu = -2\Delta L_e = 2$
$\lvert y^{LL}_{\mu e\tau e}\rvert, \lvert y^{LR}_{\mu e\tau e}\rvert, \lvert y^{LR}_{\tau e\mu e}\rvert, \lvert y^{RR}_{\mu e\tau e}\rvert$	$(10\,\mathrm{TeV})^{-2}$ [90% C.L.]	$\tau \to \bar{\mu} e e$ [23]	$\Delta L_e = -2\Delta L_\tau = -2\Delta L_\mu = 2$
$\lvert y^{LL}_{e\mu\tau\mu}\rvert, \lvert y^{LR}_{e\mu\tau\mu}\rvert, \lvert y^{LR}_{\tau\mu e\mu}\rvert, \lvert y^{RR}_{e\mu\tau\mu}\rvert$	$(8.8\,\mathrm{TeV})^{-2}$ [90% C.L.]	$\tau \to \bar{e}\mu\mu$ [23]	$\Delta L_\mu = -2\Delta L_\tau = -2\Delta L_e = 2$

Thank you for your attention!

Speaker: Mikheil Sokhashvili

I would like to thank my advisor Prof. Julian Heeck