New Physics and $\mu^- \to e^+$-Conversion

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LEPTON NUMBER VIOLATION (LNV)

TOTAL LEPTON NUMBER

Violation of total lepton number conservation also implies violation of lepton family number conservation.

$\Gamma(Z \to pe)/\Gamma_{total}$		$<1.8 \times 10^{-6}$, CL = 95%
$\Gamma(Z \to p\mu)/\Gamma_{total}$		$<1.8 \times 10^{-6}$, CL = 95%
limit on $\mu^- \to e^+$ conversion		
$\sigma(\mu^- {}^{32}\mathrm{S} \to e^+ {}^{32}\mathrm{Si}^*)$ / $\sigma(\mu^- {}^{32}\mathrm{S} \to \nu_\mu {}^{32}\mathrm{P}^*)$		$<9 \times 10^{-10}$, CL = 90%
$\sigma(\mu^- {}^{127}\mathrm{I} \to e^+ {}^{127}\mathrm{Sb}^*)$ / $\sigma(\mu^- {}^{127}\mathrm{I} \to$ anything)		$<3 \times 10^{-10}$, CL = 90%
$\sigma(\mu^- \mathrm{Ti} \to e^+ \mathrm{Ca})$ / $\sigma(\mu^- \mathrm{Ti} \to$ capture)		$<3.6 \times 10^{-11}$, CL = 90%
$\Gamma(\tau^- \to e^+\pi^-\pi^-)/\Gamma_{total}$		$<2.0 \times 10^{-8}$, CL = 90%
$\Gamma(\tau^- \to \mu^+\pi^-\pi^-)/\Gamma_{total}$		$<3.9 \times 10^{-8}$, CL = 90%
$\Gamma(\tau^- \to e^+\pi^- K^-)/\Gamma_{total}$		$<3.2 \times 10^{-8}$, CL = 90%
$\Gamma(\tau^- \to e^+ K^- K^-)/\Gamma_{total}$		$<3.3 \times 10^{-8}$, CL = 90%
$\Gamma(\tau^- \to \mu^+\pi^- K^-)/\Gamma_{total}$		$<4.8 \times 10^{-8}$, CL = 90%
$\Gamma(\tau^- \to \mu^+ K^- K^-)/\Gamma_{total}$		$<4.7 \times 10^{-8}$, CL = 90%
$\Gamma(\tau^- \to p\mu^-\mu^-)/\Gamma_{total}$		$<4.4 \times 10^{-7}$, CL = 90%
$\Gamma(\tau^- \to \overline{p}\mu^+\mu^-)/\Gamma_{total}$		$<3.3 \times 10^{-7}$, CL = 90%
$\Gamma(\tau^- \to \overline{p}\gamma)/\Gamma_{total}$		$<3.5 \times 10^{-6}$, CL = 90%
$\Gamma(\tau^- \to \overline{p}\pi^0)/\Gamma_{total}$		$<1.5 \times 10^{-5}$, CL = 90%
$\Gamma(\tau^- \to \overline{p}2\pi^0)/\Gamma_{total}$		$<3.3 \times 10^{-5}$, CL = 90%
$\Gamma(\tau^- \to \overline{p}\eta)/\Gamma_{total}$		$<8.9 \times 10^{-6}$, CL = 90%
$\Gamma(\tau^- \to \overline{p}\pi^0\eta)/\Gamma_{total}$		$<2.7 \times 10^{-5}$, CL = 90%
$\Gamma(\tau^- \to \Lambda\pi^-)/\Gamma_{total}$		$<7.2 \times 10^{-8}$, CL = 90%
$\Gamma(\tau^- \to \overline{\Lambda}\pi^-)/\Gamma_{total}$		$<1.4 \times 10^{-7}$, CL = 90%
$t_{1/2}({}^{76}\mathrm{Ge} \to {}^{76}\mathrm{Se} + 2\,e^-)$ $\Leftarrow 0\nu\beta\beta$		$>1.9 \times 10^{25}$ yr, CL = 90%
$\Gamma(\pi^+ \to \mu^+\overline{\nu}_e)/\Gamma_{total}$	[q]	$<1.5 \times 10^{-3}$, CL = 90%
$\Gamma(K^+ \to \pi^-\mu^+e^+)/\Gamma_{total}$		$<5.0 \times 10^{-10}$, CL = 90%
$\Gamma(K^+ \to \pi^- e^+ e^+)/\Gamma_{total}$		$<6.4 \times 10^{-10}$, CL = 90%
$\Gamma(K^+ \to \pi^-\mu^+\mu^+)/\Gamma_{total}$	[q]	$<1.1 \times 10^{-9}$, CL = 90%
$\Gamma(K^+ \to \mu^+\overline{\nu}_e)/\Gamma_{total}$	[q]	$<3.3 \times 10^{-3}$, CL = 90%
$\Gamma(K^+ \to \pi^0 e^+\overline{\nu}_e)/\Gamma_{total}$		$<3 \times 10^{-3}$, CL = 90%
$\Gamma(D^+ \to \pi^- 2e^+)/\Gamma_{total}$		$<1.1 \times 10^{-6}$, CL = 90%
$\Gamma(D^+ \to \pi^- 2\mu^+)/\Gamma_{total}$		$<2.2 \times 10^{-8}$, CL = 90%
$\Gamma(D^+ \to \pi^- e^+\mu^+)/\Gamma_{total}$		$<2.0 \times 10^{-6}$, CL = 90%
$\Gamma(D^+ \to \rho^- 2\mu^+)/\Gamma_{total}$		$<5.6 \times 10^{-4}$, CL = 90%
$\Gamma(D^+ \to K^- 2e^+)/\Gamma_{total}$		$<9 \times 10^{-7}$, CL = 90%
$\Gamma(D^+ \to K^- 2\mu^+)/\Gamma_{total}$		$<1.0 \times 10^{-5}$, CL = 90%
$\Gamma(D^+ \to K^- e^+\mu^+)/\Gamma_{total}$		$<1.9 \times 10^{-6}$, CL = 90%
$\Gamma(D^+ \to K^*(892)^- 2\mu^+)/\Gamma_{total}$		$<8.5 \times 10^{-4}$, CL = 90%
$\Gamma(D^0 \to 2\pi^- 2e^+ + \text{c.c.})/\Gamma_{total}$		$<1.12 \times 10^{-4}$, CL = 90%
$\Gamma(D^0 \to 2\pi^- 2\mu^+ + \text{c.c.})/\Gamma_{total}$		$<2.9 \times 10^{-5}$, CL = 90%
$\Gamma(D^0 \to K^-\pi^- 2e^+ + \text{c.c.})/\Gamma_{total}$		$<2.06 \times 10^{-4}$, CL = 90%
$\Gamma(D^0 \to K^-\pi^- 2\mu^+ + \text{c.c.})/\Gamma_{total}$		$<3.9 \times 10^{-4}$, CL = 90%
$\Gamma(D^0 \to 2K^- 2e^+ + \text{c.c.})/\Gamma_{total}$		$<1.52 \times 10^{-4}$, CL = 90%
$\Gamma(D^0 \to 2K^- 2\mu^+ + \text{c.c.})/\Gamma_{total}$		$<9.4 \times 10^{-5}$, CL = 90%
$\Gamma(D^0 \to \pi^-\pi^- e^+\mu^+ + \text{c.c.})/\Gamma_{total}$		$<7.9 \times 10^{-5}$, CL = 90%
$\Gamma(D^0 \to K^-\pi^- e^+\mu^+ + \text{c.c.})/\Gamma_{total}$		$<2.18 \times 10^{-4}$, CL = 90%
$\Gamma(D^0 \to 2K^- e^+\mu^+ + \text{c.c.})/\Gamma_{total}$		$<5.7 \times 10^{-5}$, CL = 90%
$\Gamma(D^0 \to pe^-)/\Gamma_{total}$	[r]	$<1.0 \times 10^{-5}$, CL = 90%
$\Gamma(D^0 \to \overline{p}e^+)/\Gamma_{total}$	[s]	$<1.1 \times 10^{-5}$, CL = 90%
$\Gamma(D_s^+ \to \pi^- 2e^+)/\Gamma_{total}$		$<4.1 \times 10^{-6}$, CL = 90%
$\Gamma(D_s^+ \to \pi^- 2\mu^+)/\Gamma_{total}$		$<1.2 \times 10^{-7}$, CL = 90%
$\Gamma(D_s^+ \to \pi^- e^+\mu^+)/\Gamma_{total}$		$<8.4 \times 10^{-6}$, CL = 90%
$\Gamma(D_s^+ \to K^- 2e^+)/\Gamma_{total}$		$<5.2 \times 10^{-6}$, CL = 90%
$\Gamma(D_s^+ \to K^- 2\mu^+)/\Gamma_{total}$		$<1.3 \times 10^{-5}$, CL = 90%
$\Gamma(D_s^+ \to K^- e^+\mu^+)/\Gamma_{total}$		$<6.1 \times 10^{-6}$, CL = 90%
$\Gamma(D_s^+ \to K^*(892)^- 2\mu^+)/\Gamma_{total}$		$<1.4 \times 10^{-3}$, CL = 90%
$\Gamma(B^+ \to \pi^- e^+ e^+)/\Gamma_{total}$		$<2.3 \times 10^{-8}$, CL = 90%
$\Gamma(B^+ \to \pi^-\mu^+\mu^+)/\Gamma_{total}$		$<4.0 \times 10^{-9}$, CL = 95%
$\Gamma(B^+ \to \pi^- e^+\mu^+)/\Gamma_{total}$		$<1.5 \times 10^{-7}$, CL = 90%
$\Gamma(B^+ \to \rho^- e^+ e^+)/\Gamma_{total}$		$<1.7 \times 10^{-7}$, CL = 90%
$\Gamma(B^+ \to \rho^-\mu^+\mu^+)/\Gamma_{total}$		$<4.2 \times 10^{-7}$, CL = 90%
$\Gamma(B^+ \to \rho^- e^+\mu^+)/\Gamma_{total}$		$<4.7 \times 10^{-7}$, CL = 90%
$\Gamma(B^+ \to K^- e^+ e^+)/\Gamma_{total}$		$<3.0 \times 10^{-8}$, CL = 90%
$\Gamma(B^+ \to K^-\mu^+\mu^+)/\Gamma_{total}$		$<4.1 \times 10^{-8}$, CL = 90%
$\Gamma(B^+ \to K^- e^+\mu^+)/\Gamma_{total}$		$<1.6 \times 10^{-7}$, CL = 90%
$\Gamma(B^+ \to K^*(892)^- e^+ e^+)/\Gamma_{total}$		$<4.0 \times 10^{-7}$, CL = 90%
$\Gamma(B^+ \to K^*(892)^-\mu^+\mu^+)/\Gamma_{total}$		$<5.9 \times 10^{-7}$, CL = 90%
$\Gamma(B^+ \to K^*(892)^- e^+\mu^+)/\Gamma_{total}$		$<3.0 \times 10^{-7}$, CL = 90%
$\Gamma(B^+ \to D^- e^+ e^+)/\Gamma_{total}$		$<2.6 \times 10^{-6}$, CL = 90%
$\Gamma(B^+ \to D^- e^+\mu^+)/\Gamma_{total}$		$<1.8 \times 10^{-6}$, CL = 90%
$\Gamma(B^+ \to D^-\mu^+\mu^+)/\Gamma_{total}$		$<6.9 \times 10^{-7}$, CL = 95%
$\Gamma(B^+ \to D^{*-}\mu^+\mu^+)/\Gamma_{total}$		$<2.4 \times 10^{-6}$, CL = 95%
$\Gamma(B^+ \to D_s^-\mu^+\mu^+)/\Gamma_{total}$		$<5.8 \times 10^{-7}$, CL = 95%
$\Gamma(B^+ \to \overline{D}^0\pi^-\mu^+\mu^+)/\Gamma_{total}$		$<1.5 \times 10^{-6}$, CL = 95%
$\Gamma(B^+ \to \Lambda^0\mu^+)/\Gamma_{total}$		$<6 \times 10^{-8}$, CL = 90%
$\Gamma(B^+ \to \Lambda^0 e^+)/\Gamma_{total}$		$<3.2 \times 10^{-8}$, CL = 90%
$\Gamma(B^+ \to \overline{\Lambda}^0\mu^+)/\Gamma_{total}$		$<6 \times 10^{-8}$, CL = 90%
$\Gamma(B^+ \to \overline{\Lambda}^0 e^+)/\Gamma_{total}$		$<8 \times 10^{-8}$, CL = 90%

TOTAL LEPTON NUMBER

Violation of total lepton number conservation also implies violation of lepton family number conservation.

$\Gamma(Z \to pe)/\Gamma_{\rm total}$		$<1.8 \times 10^{-6}$, CL = 95%
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limit on $\mu^- \to e^+$ conversion		
$\sigma(\mu^- {}^{32}\mathrm{S} \to e^+ {}^{32}\mathrm{Si}^*)$ / $\sigma(\mu^- {}^{32}\mathrm{S} \to \nu_\mu {}^{32}\mathrm{P}^*)$		$<9 \times 10^{-10}$, CL = 90%
$\sigma(\mu^- {}^{127}\mathrm{I} \to e^+ {}^{127}\mathrm{Sb}^*)$ / $\sigma(\mu^- {}^{127}\mathrm{I} \to \text{anything})$		$<3 \times 10^{-10}$, CL = 90%
$\sigma(\mu^- \mathrm{Ti} \to e^+ \mathrm{Ca})$ / $\sigma(\mu^- \mathrm{Ti} \to \text{capture})$		$<3.6 \times 10^{-11}$, CL = 90%
$\Gamma(\tau^- \to e^+\pi^-\pi^-)/\Gamma_{\rm total}$		$<2.0 \times 10^{-8}$, CL = 90%
$\Gamma(\tau^- \to \mu^+\pi^-\pi^-)/\Gamma_{\rm total}$		
$\Gamma(\tau^- \to e^+\pi^-K^-)/\Gamma_{\rm total}$		
$\Gamma(\tau^- \to e^+K^-K^-)/\Gamma_{\rm total}$		
$\Gamma(\tau^- \to \mu^+\pi^-K^-)/\Gamma_{\rm total}$		
$\Gamma(\tau^- \to \mu^+K^-K^-)/\Gamma_{\rm total}$		
$\Gamma(\tau^- \to p\mu^-\mu^-)/\Gamma_{\rm total}$		
$\Gamma(\tau^- \to \overline{p}\mu^+\mu^-)/\Gamma_{\rm total}$		
$\Gamma(\tau^- \to \overline{p}\gamma)/\Gamma_{\rm total}$		
$\Gamma(\tau^- \to \overline{p}\pi^0)/\Gamma_{\rm total}$		
$\Gamma(\tau^- \to \overline{p}2\pi^0)/\Gamma_{\rm total}$		
$\Gamma(\tau^- \to \overline{p}\eta)/\Gamma_{\rm total}$		
$\Gamma(\tau^- \to \overline{p}\pi^0\eta)/\Gamma_{\rm total}$		
$\Gamma(\tau^- \to \Lambda\pi^-)/\Gamma_{\rm total}$		
$\Gamma(\tau^- \to \overline{\Lambda}\pi^-)/\Gamma_{\rm total}$		
$t_{1/2}({}^{76}\mathrm{Ge} \to {}^{76}\mathrm{Se} + 2\,e^-)$		
$\Gamma(\pi^+ \to \mu^+\overline{\nu}_e)/\Gamma_{\rm total}$		
$\Gamma(K^+ \to \pi^-\mu^+e^+)/\Gamma_{\rm total}$		
$\Gamma(K^+ \to \pi^-e^+e^+)/\Gamma_{\rm total}$		
$\Gamma(K^+ \to \pi^-\mu^+\mu^+)/\Gamma_{\rm total}$	[q]	$<1.1 \times 10^{-9}$, CL = 90%
$\Gamma(K^+ \to \mu^+\overline{\nu}_e)/\Gamma_{\rm total}$	[q]	$<3.3 \times 10^{-3}$, CL = 90%
$\Gamma(K^+ \to \pi^0e^+\overline{\nu}_e)/\Gamma_{\rm total}$		$<3 \times 10^{-3}$, CL = 90%
$\Gamma(D^+ \to \pi^-2e^+)/\Gamma_{\rm total}$		$<1.1 \times 10^{-6}$, CL = 90%
$\Gamma(D^+ \to \pi^-2\mu^+)/\Gamma_{\rm total}$		$<2.2 \times 10^{-8}$, CL = 90%
$\Gamma(D^+ \to \pi^-e^+\mu^+)/\Gamma_{\rm total}$		$<2.0 \times 10^{-6}$, CL = 90%
$\Gamma(D^+ \to \rho^-2\mu^+)/\Gamma_{\rm total}$		$<5.6 \times 10^{-4}$, CL = 90%
$\Gamma(D^+ \to K^-2e^+)/\Gamma_{\rm total}$		$<9 \times 10^{-7}$, CL = 90%
$\Gamma(D^+ \to K^-2\mu^+)/\Gamma_{\rm total}$		$<1.0 \times 10^{-5}$, CL = 90%
$\Gamma(D^+ \to K^-e^+\mu^+)/\Gamma_{\rm total}$		$<1.9 \times 10^{-6}$, CL = 90%

$\Gamma(B^0 \to \Lambda_c^+\mu^-)/\Gamma_{\rm total}$	$<1.4 \times 10^{-6}$, CL = 90%
$\Gamma(B^0 \to \Lambda_c^+e^-)/\Gamma_{\rm total}$	$<4 \times 10^{-6}$, CL = 90%
$\Gamma(\Lambda \to \pi^+e^-)/\Gamma_{\rm total}$	$<6 \times 10^{-7}$, CL = 90%
$\Gamma(\Lambda \to \pi^+\mu^-)/\Gamma_{\rm total}$	$<6 \times 10^{-7}$, CL = 90%
$\Gamma(\Lambda \to \pi^-e^+)/\Gamma_{\rm total}$	$<4 \times 10^{-7}$, CL = 90%
$\Gamma(\Lambda \to \pi^-\mu^+)/\Gamma_{\rm total}$	$<6 \times 10^{-7}$, CL = 90%
$\Gamma(\Lambda \to K^+e^-)/\Gamma_{\rm total}$	$<2 \times 10^{-6}$, CL = 90%
$\Gamma(\Lambda \to K^+\mu^-)/\Gamma_{\rm total}$	$<3 \times 10^{-6}$, CL = 90%
$\Gamma(\Lambda \to K^-e^+)/\Gamma_{\rm total}$	$<2 \times 10^{-6}$, CL = 90%
$\Gamma(\Lambda \to K^-\mu^+)/\Gamma_{\rm total}$	$<3 \times 10^{-6}$, CL = 90%
$\Gamma(\Lambda \to K^0_S\nu)/\Gamma_{\rm total}$	$<2 \times 10^{-5}$, CL = 90%
$\Gamma(\Xi^- \to p\mu^-\mu^-)/\Gamma_{\rm total}$	$<4 \times 10^{-8}$, CL = 90%
$\Gamma(\Lambda_c^+ \to \overline{p}2e^+)/\Gamma_{\rm total}$	$<2.7 \times 10^{-6}$, CL = 90%
$\Gamma(\Lambda_c^+ \to \overline{p}2\mu^+)/\Gamma_{\rm total}$	$<9.4 \times 10^{-6}$, CL = 90%
$\Gamma(\Lambda_c^+ \to \overline{p}e^+\mu^+)/\Gamma_{\rm total}$	$<1.6 \times 10^{-5}$, CL = 90%
$\Gamma(\Lambda_c^+ \to \Sigma^-\mu^+\mu^+)/\Gamma_{\rm total}$	$<7.0 \times 10^{-4}$, CL = 90%

$\Gamma(D^+ \to K^*(892)^-2\mu^+)/\Gamma_{\rm total}$		$<8.5 \times 10^{-4}$, CL = 90%
$\Gamma(D^0 \to 2\pi^-2e^+ + \text{c.c.})/\Gamma_{\rm total}$		$<1.12 \times 10^{-4}$, CL = 90%
$\Gamma(D^0 \to 2\pi^-2\mu^+ + \text{c.c.})/\Gamma_{\rm total}$		$<2.9 \times 10^{-5}$, CL = 90%
$\Gamma(D^0 \to K^-\pi^-2e^+ + \text{c.c.})/\Gamma_{\rm total}$		$<2.06 \times 10^{-4}$, CL = 90%
$\Gamma(D^0 \to K^-\pi^-2\mu^+ + \text{c.c.})/\Gamma_{\rm total}$		$<3.9 \times 10^{-4}$, CL = 90%
$\Gamma(D^0 \to 2K^-2e^+ + \text{c.c.})/\Gamma_{\rm total}$		$<1.52 \times 10^{-4}$, CL = 90%
$\Gamma(D^0 \to 2K^-2\mu^+ + \text{c.c.})/\Gamma_{\rm total}$		$<9.4 \times 10^{-5}$, CL = 90%
$\Gamma(D^0 \to \pi^-\pi^-e^+\mu^+ + \text{c.c.})/\Gamma_{\rm total}$		$<7.9 \times 10^{-5}$, CL = 90%
$\Gamma(D^0 \to K^-\pi^-e^+\mu^+ + \text{c.c.})/\Gamma_{\rm total}$		$<2.18 \times 10^{-4}$, CL = 90%
$\Gamma(D^0 \to 2K^-e^+\mu^+ + \text{c.c.})/\Gamma_{\rm total}$		$<5.7 \times 10^{-5}$, CL = 90%
$\Gamma(D^0 \to pe^-)/\Gamma_{\rm total}$	[r]	$<1.0 \times 10^{-5}$, CL = 90%
$\Gamma(D^0 \to \overline{p}e^+)/\Gamma_{\rm total}$	[s]	$<1.1 \times 10^{-5}$, CL = 90%
$\Gamma(D_s^+ \to \pi^-2e^+)/\Gamma_{\rm total}$		$<4.1 \times 10^{-6}$, CL = 90%
		$<1.2 \times 10^{-7}$, CL = 90%
		$<8.4 \times 10^{-6}$, CL = 90%
		$<5.2 \times 10^{-6}$, CL = 90%
		$<1.3 \times 10^{-5}$, CL = 90%
		$<6.1 \times 10^{-6}$, CL = 90%
		$<1.4 \times 10^{-3}$, CL = 90%
		$<2.3 \times 10^{-8}$, CL = 90%
		$<4.0 \times 10^{-9}$, CL = 95%
		$<1.5 \times 10^{-7}$, CL = 90%
		$<1.7 \times 10^{-7}$, CL = 90%
		$<4.2 \times 10^{-7}$, CL = 90%
		$<4.7 \times 10^{-7}$, CL = 90%
		$<3.0 \times 10^{-8}$, CL = 90%
		$<4.1 \times 10^{-8}$, CL = 90%
		$<1.6 \times 10^{-7}$, CL = 90%
		$<4.0 \times 10^{-7}$, CL = 90%
		$<5.9 \times 10^{-7}$, CL = 90%
$\Gamma(B^+ \to K^*(892)^-e^+\mu^+)/\Gamma_{\rm total}$		$<3.0 \times 10^{-7}$, CL = 90%
$\Gamma(B^+ \to D^-e^+e^+)/\Gamma_{\rm total}$		$<2.6 \times 10^{-6}$, CL = 90%
$\Gamma(B^+ \to D^-e^+\mu^+)/\Gamma_{\rm total}$		$<1.8 \times 10^{-6}$, CL = 90%
$\Gamma(B^+ \to D^-\mu^+\mu^+)/\Gamma_{\rm total}$		$<6.9 \times 10^{-7}$, CL = 95%
$\Gamma(B^+ \to D^{*-}\mu^+\mu^+)/\Gamma_{\rm total}$		$<2.4 \times 10^{-6}$, CL = 95%
$\Gamma(B^+ \to D_s^-\mu^+\mu^+)/\Gamma_{\rm total}$		$<5.8 \times 10^{-7}$, CL = 95%
$\Gamma(B^+ \to \overline{D}^0\pi^-\mu^+\mu^+)/\Gamma_{\rm total}$		$<1.5 \times 10^{-6}$, CL = 95%
$\Gamma(B^+ \to \Lambda^0\mu^+)/\Gamma_{\rm total}$		$<6 \times 10^{-8}$, CL = 90%
$\Gamma(B^+ \to \Lambda^0e^+)/\Gamma_{\rm total}$		$<3.2 \times 10^{-8}$, CL = 90%
$\Gamma(B^+ \to \overline{\Lambda}^0\mu^+)/\Gamma_{\rm total}$		$<6 \times 10^{-8}$, CL = 90%
$\Gamma(B^+ \to \overline{\Lambda}^0e^+)/\Gamma_{\rm total}$		$<8 \times 10^{-8}$, CL = 90%

June 28, 2018 $\mu^- \to e^+$

$\mu^- \to e^+$-conversion in nuclei, and the origin of neutrino masses

The results presented here are from Berryman *et al*, arXiv:1611.00032.

Other recent studies include Geib *et al*, arXiv:1609.09088 and

Geib and Merle, arXiv:1612.00452

TOTAL LEPTON NUMBER

Violation of total lepton number conservation also implies violation of lepton family number conservation.

$\Gamma(Z \to pe)/\Gamma_{total}$	$<1.8 \times 10^{-6}$, CL = 95%
$\Gamma(Z \to p\mu)/\Gamma_{total}$	$<1.8 \times 10^{-6}$, CL = 95%
$\Rightarrow$ limit on $\mu^- \to e^+$ conversion $\Leftarrow$ (We Are Here)	
$\sigma(\mu^- \, {}^{32}\text{S} \to e^+ \, {}^{32}\text{Si}^*)$ / $\sigma(\mu^- \, {}^{32}\text{S} \to \nu_\mu \, {}^{32}\text{P}^*)$	$<9 \times 10^{-10}$, CL = 90%
$\sigma(\mu^- \, {}^{127}\text{I} \to e^+ \, {}^{127}\text{Sb}^*)$ /	$<3 \times 10^{-10}$, CL = 90%

“Higher Order” Neutrino Masses from $\Delta L = 2$ Physics

Imagine that there is new physics that breaks lepton number by 2 units at some energy scale Λ, but that it does not, necessarily, lead to neutrino masses at the tree level.

We know that neutrinos will get a mass at some order in perturbation theory – which order is model dependent!

For example: (old list of references)

- SUSY with trilinear R-parity violation – neutrino masses at one-loop;
- Zee models – neutrino masses at one-loop;
- Babu and Ma – neutrino masses at two loops;
- Chen et al, 0706.1964 – neutrino masses at two loops;
- Angel et al, 1308.0463 – neutrino masses at two loops;
- etc.

EFT approach (as model-independent as possible). More assumptions:

- Only consider $\Delta L = 2$ operators;
- Operators made up of only standard model fermions and the Higgs doublet (no gauge bosons);
- Electroweak symmetry breaking characterized as prescribed in SM;
- Effective operator couplings assumed to be "flavor indifferent", unless otherwise noted;
- Operators "turned on" one at a time, assumed to be leading order (tree-level) contribution of new lepton number violating physics.
- We can use the effective operator to estimate the coefficient of all other lepton-number violating lower-dimensional effective operators (loop effects, computed with a hard cutoff).

All results presented are order of magnitude *estimates*, <u>not</u> precise quantitative results. Precise estimates require a model.

On Higher Dimensional Operators [Kobach, arXiv:1604.05726 + refs therein]

Very generically, there is relationship between ΔL, the lepton number of a given operator, ΔB, the baryon number of a given operator, and D, the mass-dimension of the operator, assuming only Lorentz and hypercharge invariance.

$$\left|\frac{1}{2}\Delta B + \frac{3}{2}\Delta L\right| \in \mathbb{N} \begin{cases} \text{odd} & \leftrightarrow \quad D \text{ is odd,} \\ \text{even} & \leftrightarrow \quad D \text{ is even.} \end{cases}$$

- Operators with $|\Delta L| = 2$, $\Delta B = 0$ have odd mass dimension. The lowest such operator is dimension five.
- Operators with odd mass-dimension must have non-zero ΔB or ΔL. In more detail, it is easy to show that, for operators with odd mass-dimension, $|\Delta(B-L)|$ is an even number not divisible by four $(2, 6, 10, \ldots)$. All odd-dimensional operators violate $B-L$ by at least two units. For operators with even mass-dimension, $|\Delta(B-L)|$ is a multiple of four, including zero $(0, 4, 8, 12, \ldots)$.

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$\mu^- \to e^+$-conversion is qualitatively different from $\mu^- \to e^-$-conversion.

The effective operators are different – different dimensions! – and establishing relations in a semi-model-independent way is impossible.

Compare, for example,

$$\frac{(L_\mu Q)e^c_e u^c}{\Lambda^2} \quad [\text{dimension} - 6]$$

to

$$\frac{(L_\mu Q)(L_e H)d^c}{\Lambda^3} \quad [\text{dimension} - 7]$$

One general comment: $\mu^- \to e^+$-conversion generically implies $\mu^- \to e^-$-conversion (though not necessarily at an observable rate). The converse need not be true.

Other issues to consider:

- Effective Λ can be qualitatively different. E.g.

$$\frac{(L_\mu Q)(L_e H)d^c}{\Lambda^3} \rightarrow \frac{v}{\Lambda^3}(L_\mu Q)\nu_e d^c = \frac{1}{\Lambda^2_{\rm eff}}(L_\mu Q)\nu_e d^c$$

- The Majorana neutrino exchange contribution is

$$R_{\mu^- e^+} = \left(2.6\times 10^{-22}\right)|\mathcal{M}_{e\mu^+}|^2\frac{|m_{e\mu}|^2}{m_e^2},$$

where $|\mathcal{M}_{e\mu^+}|^2 \sim 0.1$

$)$

$\mathcal{O}$	Operator	Λ [TeV]
$\mathcal{O}_1$	$(LH)(LH)$	$6 \times 10^{10-11}$

$\mathcal{O}_2$	$(LL)(LH)e^c$	$4 \times 10^{6-7}$
$\mathcal{O}_{3_a}$	$(LL)(QH)d^c$	$2 \times 10^{4-5}$
$\mathcal{O}_{3_b}$	$(LQ)(LH)d^c$	$1 \times 10^{7-8}$
$\mathcal{O}_{4_a}$	$(L\overline{Q})(LH)\overline{u^c}$	$4 \times 10^{8-9}$
$\mathcal{O}_{4_b}$	$(LL)(\overline{Q}H)\overline{u^c}$	$2-7$
$\mathcal{O}_8$	$(LH)\overline{e^c}\overline{u^c}d^c$	$6 \times 10^{2-3}$

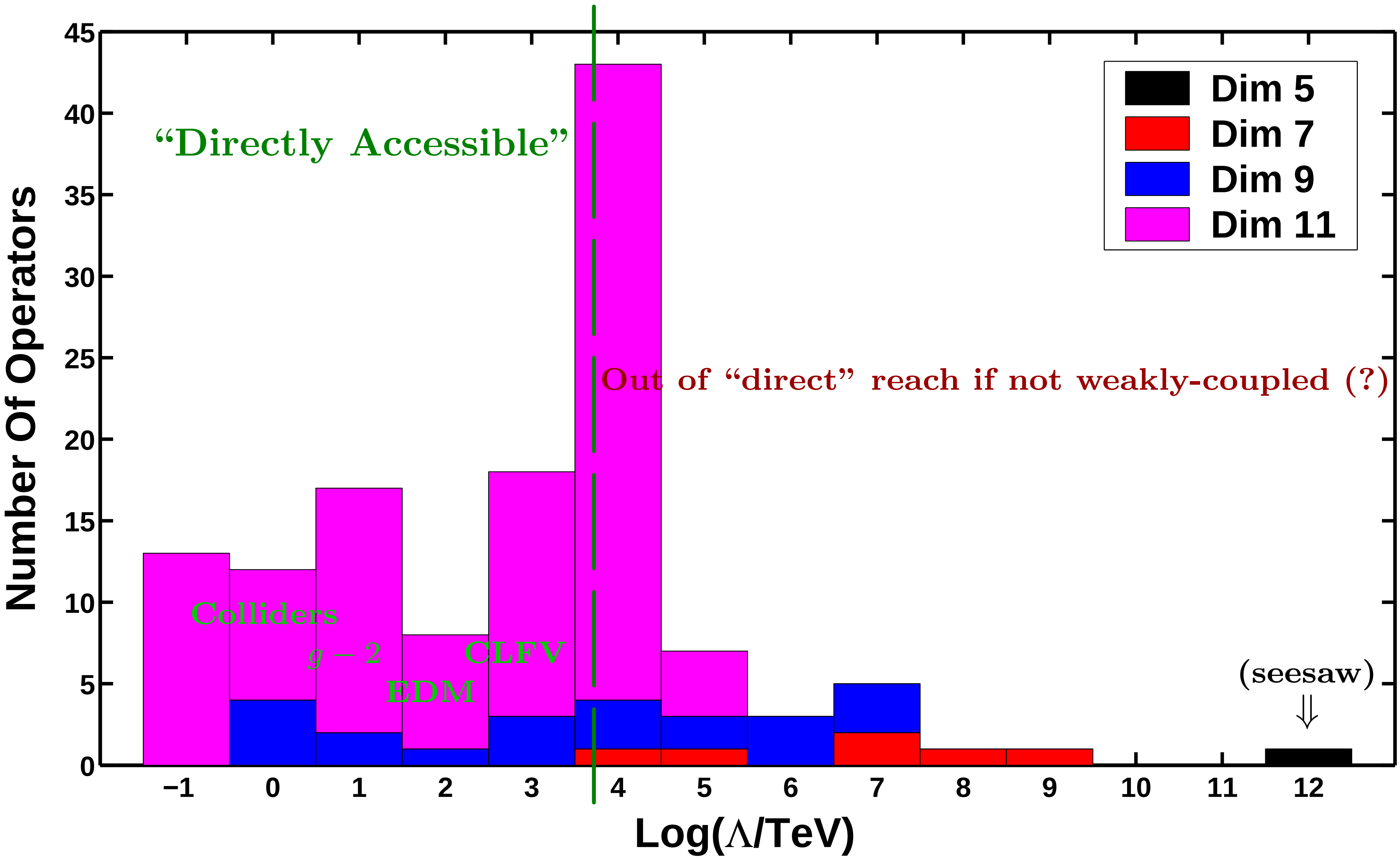
$\mathcal{O}$	Operator	Λ [TeV]
$\mathcal{O}_5$	$(L\overline{H})(LH)(QH)d^c$	$6 \times 10^{4-5}$
$\mathcal{O}_6$	$(LH)(L\overline{H})(\overline{Q}H)\overline{u^c}$	$2 \times 10^{6-7}$
$\mathcal{O}_7$	$(LH)(QH)(\overline{Q}H)\overline{e^c}$	$4 \times 10^{1-2}$
$\mathcal{O}_9$	$(LL)(LL)e^ce^c$	$3 \times 10^{2-3}$
$\mathcal{O}_{10}$	$(LL)(LQ)e^cd^c$	$6 \times 10^{2-3}$
$\mathcal{O}_{11_a}$	$(LL)(QQ)d^cd^c$	$3-30$
$\mathcal{O}_{11_b}$	$(LQ)(LQ)d^cd^c$	$2 \times 10^{3-4}$

$\mathcal{O}_{12_a}$	$(L\overline{Q})(L\overline{Q})\overline{u^c}\overline{u^c}$	$2 \times 10^{6-7}$
$\mathcal{O}_{12_b}$	$(LL)(\overline{Q}\overline{Q})\overline{u^c}\overline{u^c}$	$0.3-0.6$
$\mathcal{O}_{13}$	$(L\overline{Q})(LL)\overline{u^c}e^c$	$2 \times 10^{4-5}$
$\mathcal{O}_{14_a}$	$(LL)(Q\overline{Q})\overline{u^c}d^c$	10^{2-3}
$\mathcal{O}_{14_b}$	$(L\overline{Q})(LQ)\overline{u^c}d^c$	$6 \times 10^{4-5}$
$\mathcal{O}_{15}$	$(LL)(L\overline{L})d^c\overline{u^c}$	10^{2-3}
$\mathcal{O}_{16}$	$(LL)e^cd^c\overline{e^c}\overline{u^c}$	$0.2-2$
$\mathcal{O}_{17}$	$(LL)d^cd^c\overline{d^c}\overline{u^c}$	$0.2-2$

$\mathcal{O}_{18}$	$(LL)d^cu^c\overline{u^c}\overline{u^c}$	$0.2-2$
$\mathcal{O}_{19}$	$(LQ)d^cd^c\overline{e^c}\overline{u^c}$	$0.1-1$
$\mathcal{O}_{20}$	$(L\overline{Q})d^c\overline{u^c}\overline{e^c}\overline{u^c}$	$4-40$
$\mathcal{O}_s$	$e^ce^cu^cu^c\overline{d^c}\overline{d^c}$	10^{-3}

- Ignore Lorentz, $SU(3)_C$ structure
- $SU(2)_L$ contractions denoted with parentheses
- Λ indicates range in which $m_\nu \in [0.05\text{ eV}, 0.5\text{ eV}]$

hep-ph/0106054; K.S. Babu & C.N. Leung
arXiv:0708.1344; A. de Gouvêa & J. Jenkins
arXiv:1212.6111; P.W. Angel, et al.
arXiv:1404.4057; A. de Gouvêa, at al.

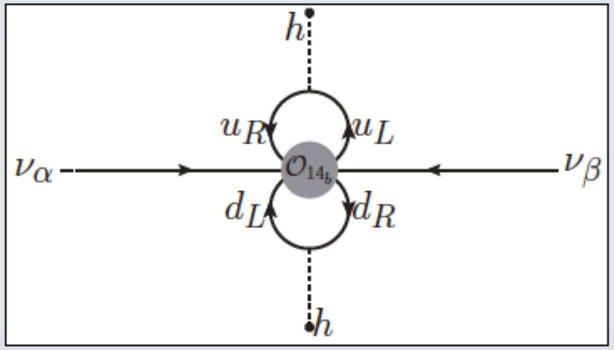

45
40
35
30
25
20
15
10
5
0
Number Of Operators
−1
0
1
2
3
4
5
6
7
8
9
10
11
12
Log(Λ/TeV)
Dim 5
Dim 7
Dim 9
Dim 11
“Directly Accessible”
Out of “direct” reach if not weakly-coupled (?)
Colliders
$g-2$
EDM
CLFV
(seesaw)
⇓

LNV from Effective Operators

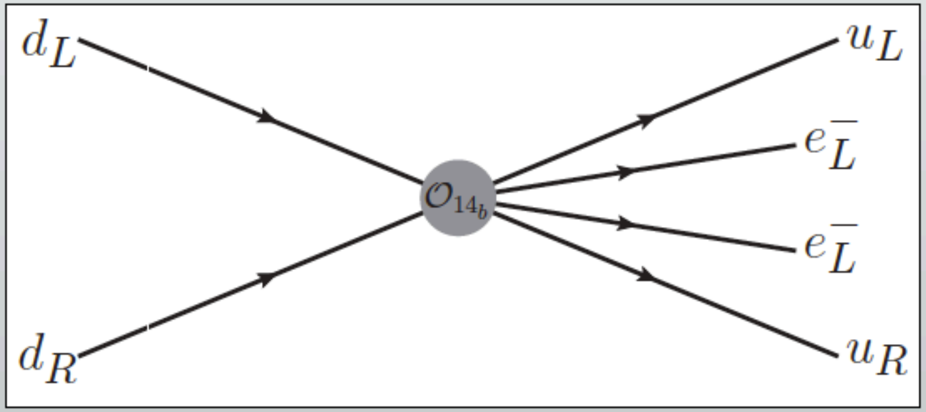
What do these operators do? Consider $\mathcal{O}_{14b} = (LQ)(LQ)u^c d^c$.

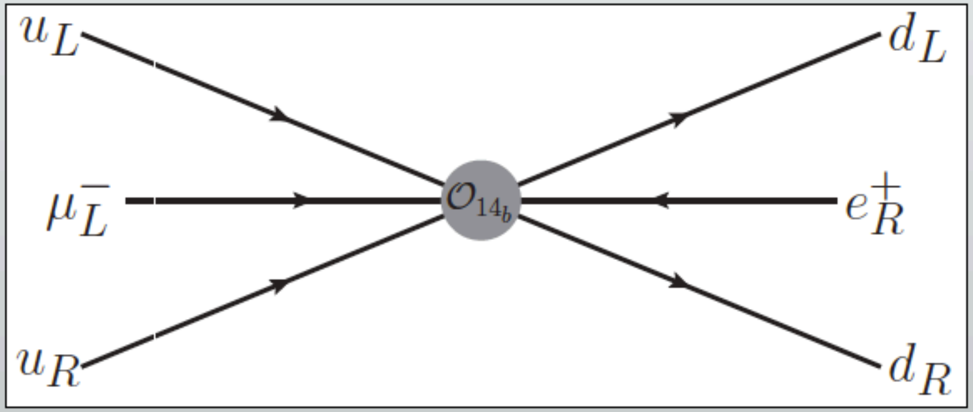
e.g., $\boxed{\mathcal{O}_{14_b} = (L\overline{Q})(LQ)\overline{u^c}d^c}$

- They generate neutrino masses:



- They generate various LNV phenomena:





Relating Different LNV Processes (e.g. $\mu^- \to e^+$ and $0\nu\beta\beta$)

- navy The observation on any LNV process establishes that neutrinos are Majorana fermions. Conversely, if the neutrinos are Majorana fermions, LNV processes are, in principle observable. None, however, need to be observable in practice…
- Relating the rates of different LNV processes is very model dependent. Neutrino masses and lepton mixing can help.
- Simplest example: LNV processes dominated by light Majorana neutrino exchange ($\mathcal{O}_1$).

$$\Gamma_{0\nu\beta\beta} \propto |m_{ee}|^2 \equiv \left|U_{e1}^2 m_1 + U_{e2}^2 m_2 e^{i\alpha_1} + U_{e3}^2 m_3 e^{i\alpha_2}\right|^2,$$
$$R_{\mu^-\to e^+} \propto |m_{e\mu}|^2 \equiv \left|U_{e1}U_{\mu 1} m_1 + U_{e2}U_{\mu 2} m_2 e^{i\alpha_1} + U_{e3}U_{\mu 3} m_3 e^{i\alpha_2}\right|^2$$

- Two of the effective operators – $\mathcal{O}_{4_b}$ and $\mathcal{O}_{12_b}$ – are flavor antisymmetric. $\Gamma_{0\nu\beta\beta}$ vanishes.

Experimental Sensitivities

KamLAND-Zen: $T_{0\nu\beta\beta} > 1.07 \times 10^{26}$ yr (90% CL; ^{136}Xe)

arXiv:1605.02889; KamLAND-ZEN Collaboration

SINDRUM II:

- $\mu^- \to e^-$ conversion: $$R^{\mathrm{Au}}_{\mu^- e^-} \equiv \frac{\Gamma(\mu^- + \mathrm{Au} \to e^- + \mathrm{Au})}{\Gamma(\mu^- + \mathrm{Au} \to \nu_\mu + \mathrm{Pt})} < 7 \times 10^{-13} \ (90\%\ \mathrm{CL})$$
- $\mu^- \to e^+$ conversion: $$R^{\mathrm{Ti}}_{\mu^- e^+} \equiv \frac{\Gamma(\mu^- + \mathrm{Ti} \to e^+ + \mathrm{Ca})}{\Gamma(\mu^- + \mathrm{Ti} \to \nu_\mu + \mathrm{Sc})} < \begin{cases} 1.7 \times 10^{-12} \ (\mathrm{GS},\ 90\%\ \mathrm{CL}) \\ 3.6 \times 10^{-11} \ (\mathrm{GDR},\ 90\%\ \mathrm{CL}) \end{cases}$$

*Eur. Phys. J. **C47**, 337 (2006); SINDRUM II Collaboration*
*Phys. Lett. **B422**, 334 (1998); SINDRUM II Collaboration*

Apples–to–apples comparison of $\mu^- \to e^-$ and $\mu^- \to e^+$?

- 1993 – simultaneous analysis!
- Apply this to future experiments

$$R^{\mathrm{Ti}}_{\mu^- e^-} < 4.3 \times 10^{-12} \ (90\%\ \mathrm{CL})$$
$$R^{\mathrm{Ti}}_{\mu^- e^+} < 4.3 \times 10^{-12} \ (90\%\ \mathrm{CL})$$

*Phys. Lett. **B317**, 631 (1993); SINDRUM II Collaboration*

Experimental Sensitivities

Upcoming experiments:

DeeMe:	$R^{\mathrm{SiC}}_{\mu^- e^-} > 5 \times 10^{-14}$ (90% CL),
Mu2e:	$R^{\mathrm{Al}}_{\mu^- e^-} > 6.6 \times 10^{-17}$ (90% CL),
COMET Phase-I:	$R^{\mathrm{Al}}_{\mu^- e^-} > 7.2 \times 10^{-15}$ (90% CL),
COMET Phase-II:	$R^{\mathrm{Al}}_{\mu^- e^-} > 6 \times 10^{-17}$ (90% CL),
PRISM:	$R^{\mathrm{Al}}_{\mu^- e^-} > 5 \times 10^{-19}$ (90% CL).

Who could do this measurement?

- *Possibly* Mu2e and COMET Phase-I – similar to SINDRUM II
- *Probably* not DeeMe, COMET Phase-II or PRISM

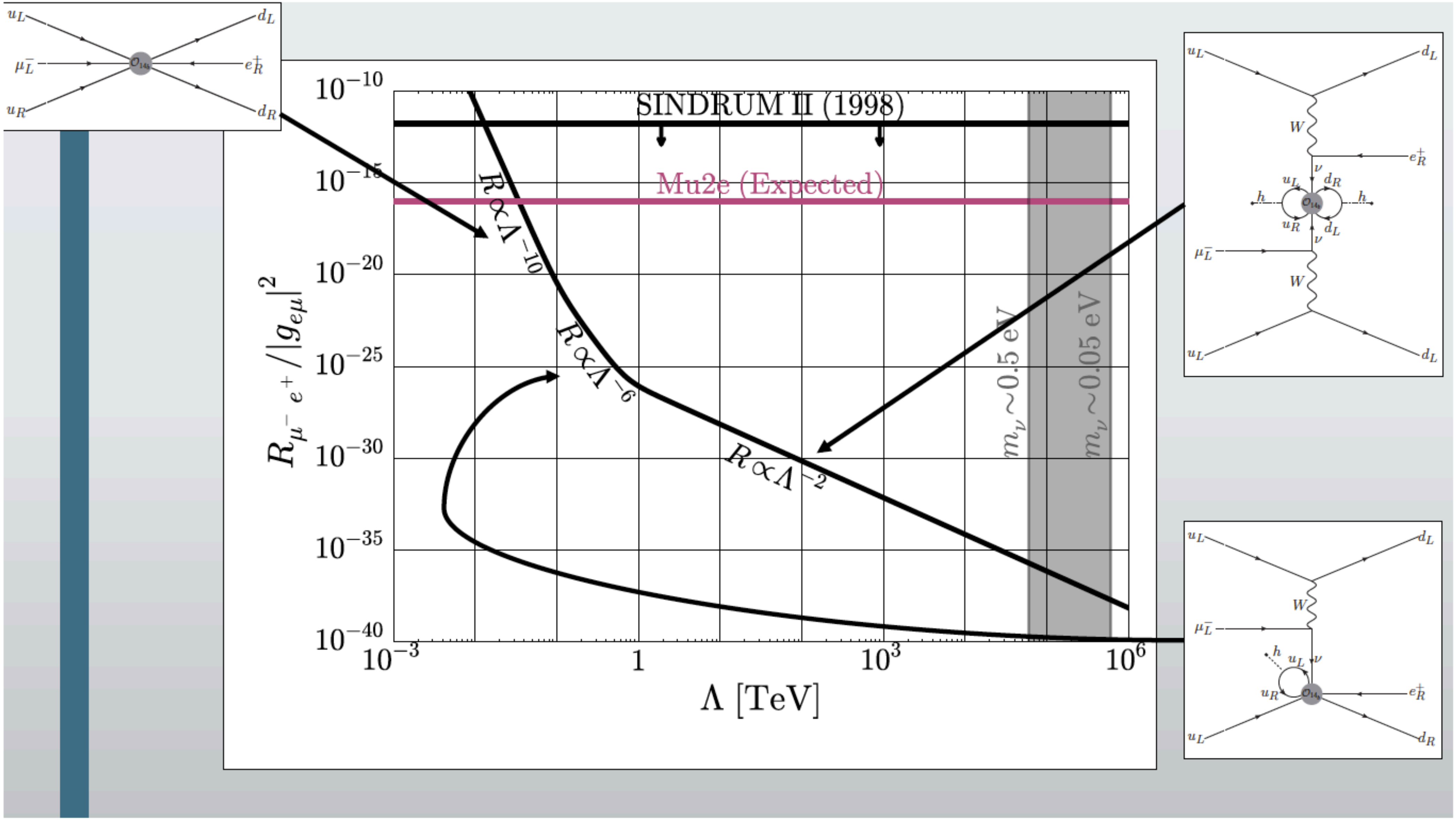
Mu2e:	$R^{\mathrm{Al}}_{\mu^- e^+} \gtrsim 10^{-16}$
COMET Phase-I:	$R^{\mathrm{Al}}_{\mu^- e^+} \gtrsim 10^{-14}$

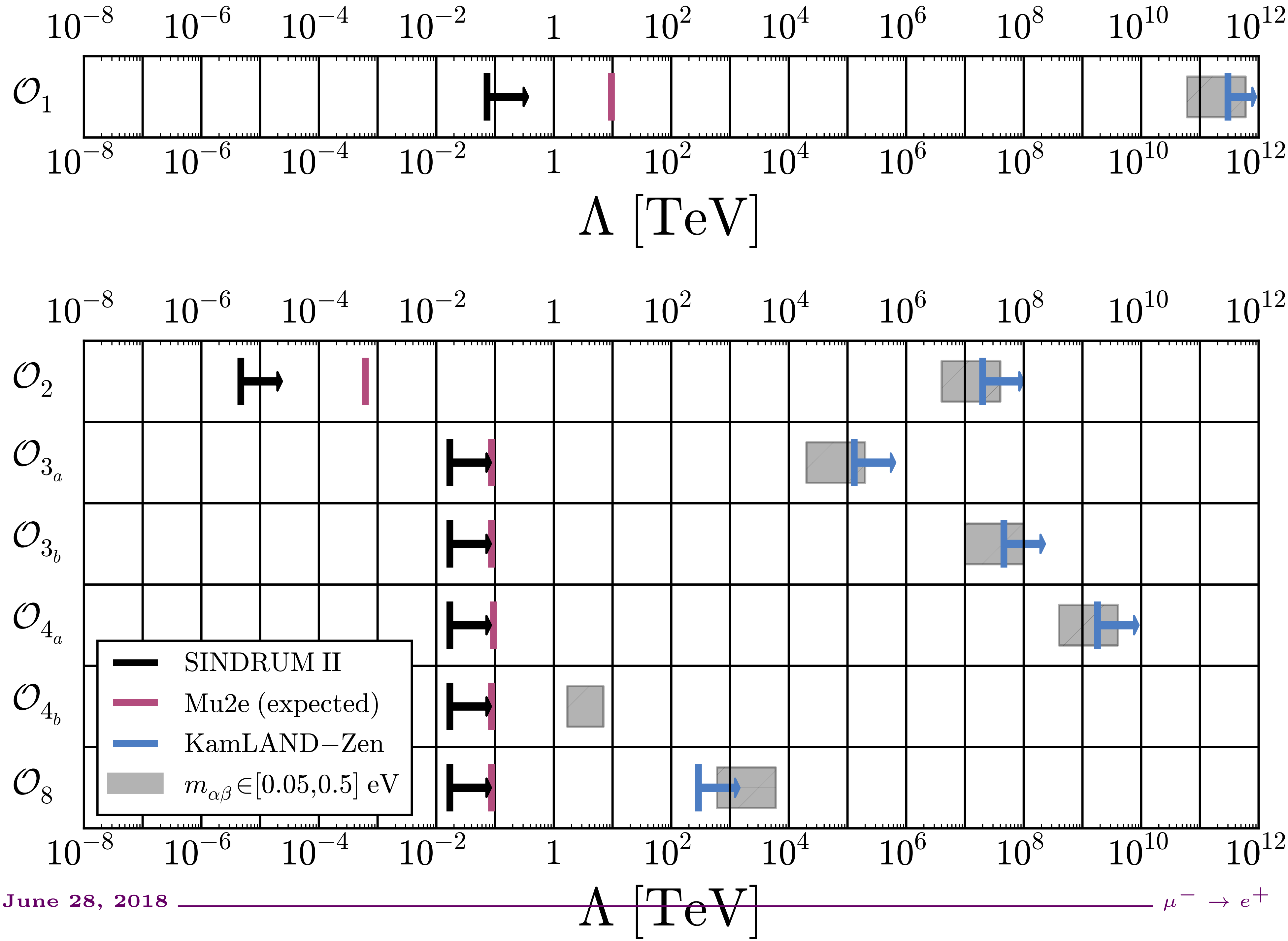
Results

- Estimates:

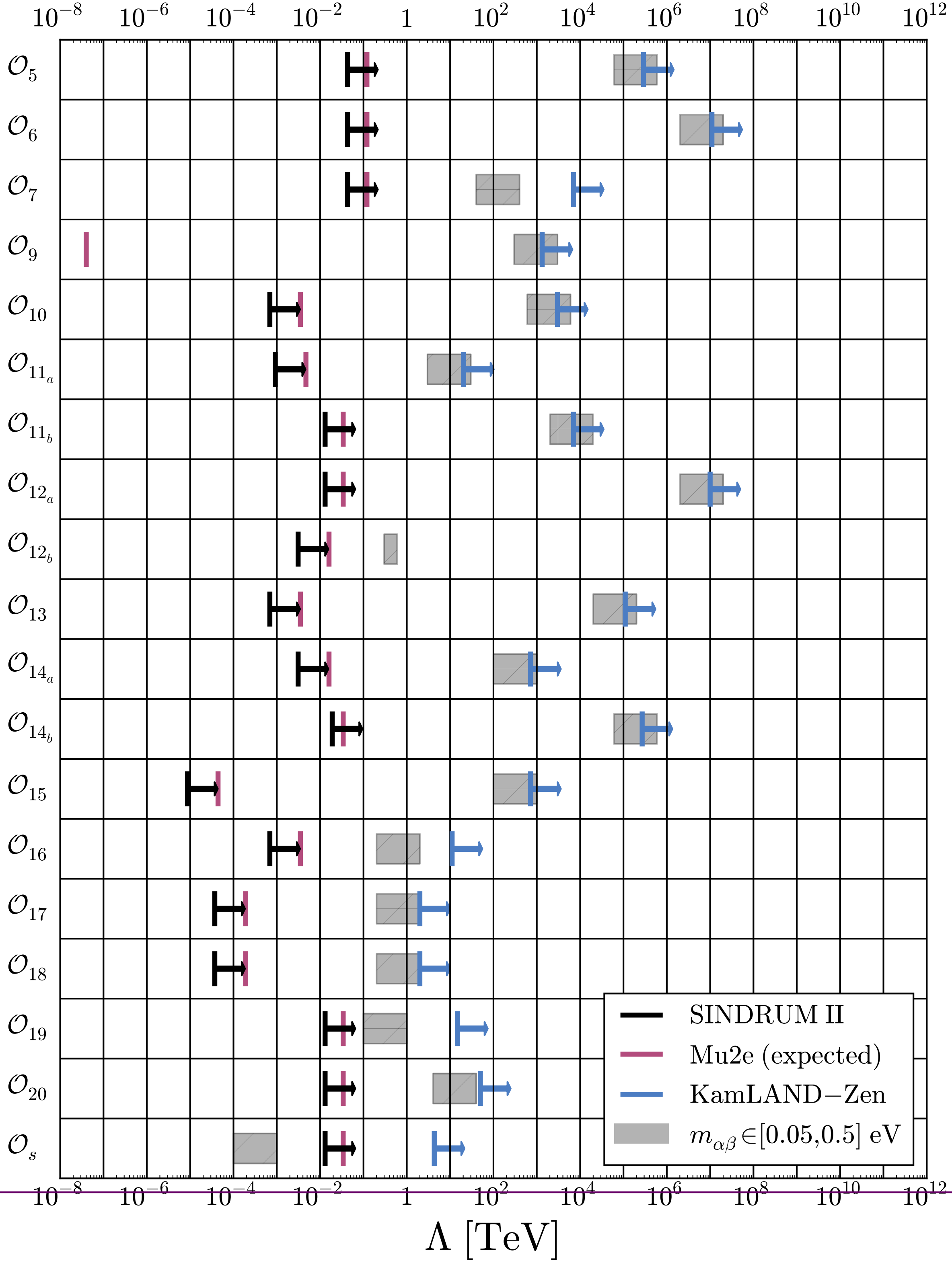
$\mathcal{O}$	Operator	Λ [TeV]	$T_{0\nu\beta\beta}$
			$R_{\mu^-e^+}$
$\mathcal{O}_{12_a}$	$(L\overline{Q})(L\overline{Q})\overline{u^c u^c}$	$2\times10^{6-7}$	$\ln(2)\frac{\Lambda^2}{Q^{11}}\left[\left(\frac{G_F}{\sqrt{2}}\right)^4\frac{1}{q^4}\left(\frac{y_t^2v^2}{(16\pi^2)^2}\right)^2+\left(\frac{G_F}{\sqrt{2}}\right)^2\frac{1}{q^2}\left(\frac{y_tv}{16\pi^2\Lambda^2}\right)^2+\frac{1}{\Lambda^8}\right]^{-1}$ $\sim 10^{25}-10^{27}$ yr
			$\frac{Q^6}{\Lambda^2}\left[\left(\frac{G_F}{\sqrt{2}}\right)^2\frac{1}{q^4}\left(\frac{y_t^2v^2}{(16\pi^2)^2}\right)^2+\frac{1}{q^2}\left(\frac{y_tv}{16\pi^2\Lambda^2}\right)^2+\left(\frac{\sqrt{2}}{G_F}\right)^2\frac{1}{\Lambda^8}\right]$ $\sim 10^{-38}-10^{-36}$
$\mathcal{O}_{12_b}$	$(LL)(\overline{QQ})\overline{u^c u^c}$	$0.3-0.6$	This operator can not contribute to $0\nu\beta\beta$.
			$\frac{1}{q^2}\frac{Q^6}{\Lambda^2}\left[\left(\frac{G_F}{\sqrt{2}}\right)^2\left(\frac{vy_t^2y_d}{(16\pi^2)^2g^2}\right)^2+\left(\frac{vy_t}{16\pi^2}\right)^2\frac{1}{\Lambda^4}\right]$ $\sim 10^{-25}-10^{-23}$
$\mathcal{O}_{13}$	$(L\overline{Q})(LL)\overline{u^c}e^c$	$2\times10^{4-5}$	$\ln(2)\left(\frac{\sqrt{2}}{G_F}\right)^2 q^2\frac{\Lambda^2}{Q^{11}}\left[\left(\frac{G_F}{\sqrt{2}}\right)^2\frac{1}{q^2}\left(\frac{y_\tau y_tv^2}{(16\pi^2)^2}\right)^2+\left(\frac{y_\tau v}{16\pi^2\Lambda^2}\right)^2\right]^{-1}$ $\sim 10^{25}-10^{27}$ yr
			$\frac{1}{q^2}\frac{Q^6}{\Lambda^2}\left[\left(\frac{G_F}{\sqrt{2}}\right)^2\frac{1}{q^2}\left(\frac{y_\tau y_tv^2}{(16\pi^2)^2}\right)^2+\left(\frac{y_\tau v}{16\pi^2\Lambda^2}\right)^2\right]$ $\sim 10^{-37}-10^{-35}$
$\mathcal{O}_{14_a}$	$(LL)(Q\overline{Q})\overline{u^c}d^c$	10^{2-3}	$\ln(2)\left(\frac{\sqrt{2}}{G_F}\right)^2 q^2\frac{\Lambda^2}{Q^{11}}\left[\left(\frac{G_F}{\sqrt{2}}\right)^2\frac{1}{q^2}\left(\frac{y_ty_bg^2v^2}{(16\pi^2)^3}\right)^2+\left(\frac{y_tv}{16\pi^2\Lambda^2}\right)^2\right]^{-1}$ $\sim 10^{24}-10^{26}$ yr
			$\frac{1}{q^2}\frac{Q^6}{\Lambda^2}\left[\left(\frac{G_F}{\sqrt{2}}\right)^2\frac{1}{q^2}\left(\frac{y_ty_bg^2v^2}{(16\pi^2)^3}\right)^2+\left(\frac{y_tv}{16\pi^2\Lambda^2}\right)^2\right]$ $\sim 10^{-37}-10^{-35}$
$\mathcal{O}_{14_b}$	$(L\overline{Q})(LQ)\overline{u^c}d^c$	$6\times10^{4-5}$	$\ln(2)\frac{\Lambda^2}{Q^{11}}\left[\left(\frac{G_F}{\sqrt{2}}\right)^4\frac{1}{q^4}\left(\frac{y_ty_bv^2}{(16\pi^2)^2}\right)^2+\left(\frac{G_F}{\sqrt{2}}\right)^2\frac{1}{q^2}\left(\frac{y_tv}{16\pi^2\Lambda^2}\right)^2+\frac{1}{\Lambda^8}\right]^{-1}$ $\sim 10^{25}-10^{27}$ yr
			$\frac{Q^6}{\Lambda^2}\left[\left(\frac{G_F}{\sqrt{2}}\right)^2\frac{1}{q^4}\left(\frac{y_ty_bv^2}{(16\pi^2)^2}\right)^2+\frac{1}{q^2}\left(\frac{y_tv}{16\pi^2\Lambda^2}\right)^2+\left(\frac{\sqrt{2}}{G_F}\right)^2\frac{1}{\Lambda^8}\right]$ $\sim 10^{-38}-10^{-36}$

[“Cartoon Plot”. For interferences, etc see Berryman et al, arXiv:1611.00032]





$\mathcal{O}_1$
Λ [TeV]
$\mathcal{O}_2$
$\mathcal{O}_{3_a}$
$\mathcal{O}_{3_b}$
$\mathcal{O}_{4_a}$
$\mathcal{O}_{4_b}$
$\mathcal{O}_8$
SINDRUM II
Mu2e (expected)
KamLAND−Zen
$m_{\alpha\beta} \in [0.05, 0.5]$ eV
Λ [TeV]


10^{-8} 10^{-6} 10^{-4} 10^{-2} 1 10^{2} 10^{4} 10^{6} 10^{8} 10^{10} 10^{12}
$\mathcal{O}_5$
$\mathcal{O}_6$
$\mathcal{O}_7$
$\mathcal{O}_9$
$\mathcal{O}_{10}$
$\mathcal{O}_{11_a}$
$\mathcal{O}_{11_b}$
$\mathcal{O}_{12_a}$
$\mathcal{O}_{12_b}$
$\mathcal{O}_{13}$
$\mathcal{O}_{14_a}$
$\mathcal{O}_{14_b}$
$\mathcal{O}_{15}$
$\mathcal{O}_{16}$
$\mathcal{O}_{17}$
$\mathcal{O}_{18}$
$\mathcal{O}_{19}$
$\mathcal{O}_{20}$
$\mathcal{O}_s$
SINDRUM II
Mu2e (expected)
KamLAND−Zen
$m_{\alpha\beta} \in [0.05, 0.5]$ eV
Λ [TeV]

Toy example: add two scalar fields to the SM particle content

$$\rho \sim (\mathbf{3},\mathbf{1})_{-1/3}, \qquad \Phi = \begin{pmatrix} \varphi_1 \\ \varphi_2 \end{pmatrix} \sim (\mathbf{3},\mathbf{2})_{1/6}$$

The symmetries of the SM allow for the following interactions:

$$\Delta\mathcal{L} = -\mu\rho(\Phi^\dagger H) - \lambda_1^\alpha \rho^\dagger (L_\alpha Q) - \lambda_2^\beta (\Phi L_\beta) d^c - \kappa^\alpha \rho\, e^c_\alpha u^c + H.c.\ ,$$

α, β are lepton-flavor indices; all other indices suppressed.

Integrating out ρ and Φ leads to the operator $\mathcal{O}_{3b}$ at tree-level.

$$\mathcal{O}_{3b} = \frac{g_{\alpha\beta}}{\Lambda^3}(L^\alpha Q)(L^\beta H)d^c,$$

where

$$\frac{g_{\alpha\beta}}{\Lambda^3} = \frac{\lambda_1^\alpha \lambda_2^\beta \mu}{M^4}.$$

M are the masses of ρ and Φ (assumed identical).

[Also get $\mathcal{O}_8 \propto \kappa$. Not important]

Lots of Outstanding Questions:

- Kinematics? Different nuclear final states?
- Backgrounds and other real-world challenges?
- Nuclear matrix elements? Should we care?
- Models? Is there a "nice" scenario where $\mu^- \to e^+$ is (a) competitive with or complementary to $0\nu\beta\beta$ and (b) within reach? How about a "less-than-nice" scenario? Should we care?
- What is this "good for"? (How do we learn more?)

Piecing the Neutrino Mass Puzzle

Understanding the origin of neutrino masses and exploring the new physics in the lepton sector will require unique **theoretical** and **experimental** efforts, including ...

- a comprehensive long baseline neutrino program, towards precision oscillation physics.
- precision studies of charged-lepton properties ($g-2$, edm), and searches for rare processes ($\mu^- \to e^-$-conversion the best bet at the moment).
- collider experiments. The LHC may end up revealing the new physics behind small neutrino masses.
- cosmic surveys. Neutrino properties affect, in a significant way, the history of the universe. Will we learn about neutrinos from cosmology, or about cosmology from neutrinos?
- **understanding the fate of lepton-number. Neutrinoless double beta decay! What else? All other probes are not competitive ... or are they? Important to look everywhere!**
- $\mu^- \to e^+$**-conversion is an intriguing probe and we can anticipate (vastly?) improved sensitivity in the next several years.**
- searches for baryon-number violating processes.