Theory of rare decays of leptons

Michael A. Schmidt

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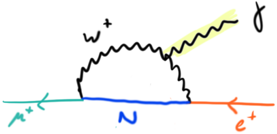
The University of New South Wales Sydney
Sydney-CPPC

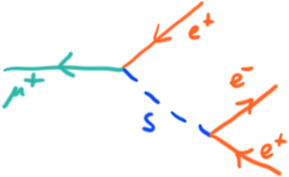
Lepton flavour violation

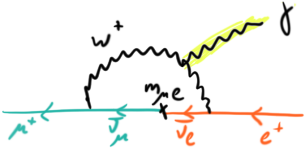
- Individual lepton flavour is conserved in the Standard Model
- Neutrino oscillations ⇒ lepton flavour violation (LFV)
- LFV processes with charged leptons are very suppressed in SM + m_ν

$$\mathcal{B}(\ell^- \to \ell' + X) \propto \left| G_F U^*_{\ell i} U_{\ell' i} m^2_{\nu,i} \right|^2 \to \mathcal{B}(\ell \to \ell' + X) \lesssim 10^{-54}$$

- Observation would be a smoking gun sign for physics beyond the SM + m_ν



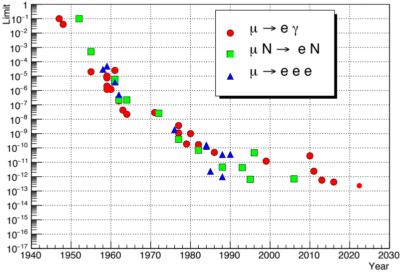




Brief summary of experimental status

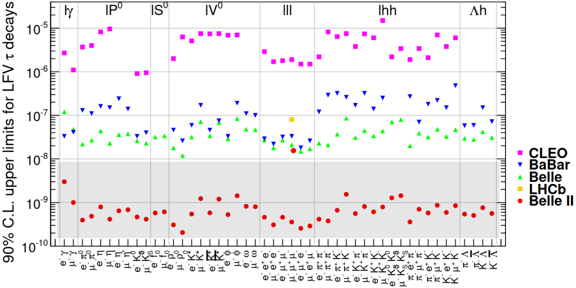
$\mu \to e$ transition

Calibbi+1709.0029



$\tau \to \ell$ transition

Belle II 1808.10567



Latest upper limits at 90% CL

$$\mathcal{B}(\mu \to e\gamma) < 3.1 \times 10^{-13}$$

MEG II 2310.12614

$$\mathcal{B}(\tau \to 3\mu) < \begin{cases} 1.9 \times 10^{-8} \\ 2.9 \times 10^{-8} \\ 1.8 \times 10^{-8} \end{cases}$$

Belle II 2405.07386

CMS 2312.02371

expected LHCb; CERN-THESIS-2023-233

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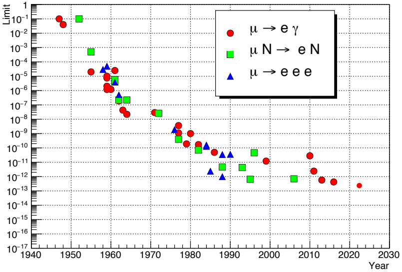

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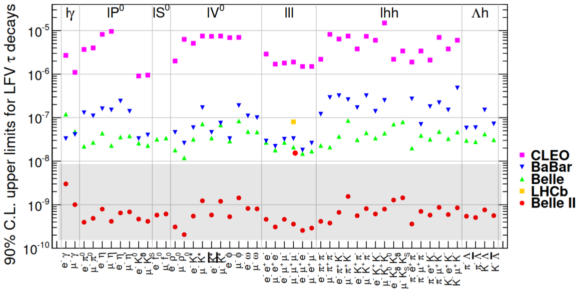


A bright future for LFV searches

- MEG II probes $\mathcal{B}(\mu \to e\gamma) \sim 6 \times 10^{-14}$
- Mu3E probes $\mathcal{B}(\mu \to 3e) \sim 10^{-15} \to 10^{-16}$
- DeeMee, Mu2E, COMET probe $\mathcal{CR}(\mu + \mathrm{Al} \to e + \mathrm{Al}) \sim 10^{-13} \to 3 \times 10^{-17}$

- Improvements by 1-2 orders of magnitude for $\tau \to \ell$ LFV decays
- . . .

Outline

Charged lepton flavour violation and the origin of neutrino masses

Large τ LFV from lepton triality

LFV decays into axion-like particles

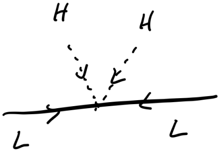
Final comments

Charged lepton flavour violation and the origin of neutrino masses

Charged lepton flavour violation and origin of neutrino masses

- Majorana neutrino masses generated via dimension-5 operator

$$\frac{\kappa}{\Lambda_{\rm LNV}} LHLH \qquad \Rightarrow \quad m_\nu \sim \frac{\kappa v^2}{\Lambda_{\rm LNV}}$$



- cLFV processes via operators of dimension $D \geq 6$

$$\frac{C_{e\gamma}}{\Lambda^2_{\rm LFV}} \bar{L} H \sigma^{\mu\nu} P_R \ell F_{\mu\nu} + \frac{C_i}{\Lambda^2_{\rm LFV}} Q_i$$

5 types of operators
dipole operator, 4-lepton, 2-lepton-2-quark, 2-lepton-Higgs, 2-lepton-gauge boson

- For $\Lambda_{\rm LNV} \sim \Lambda_{\rm LFV}$ we find for the dipole operator

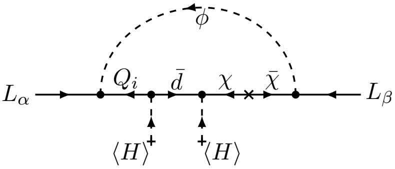
$$\frac{C_{e\gamma}}{\Lambda^2_{\rm LFV}} \sim \frac{C_{e\gamma} m_\nu^2}{\kappa^2 v^4} \qquad \Rightarrow \quad \mathcal{B}(\mu \to e + X) \lesssim 10^{-34} \left(\frac{C_{e\gamma}}{16\pi^2 \kappa^2} \right)^2$$

Conservative estimate for $C_{e\gamma}$; it is often smaller like in seesaw model

$\Rightarrow$ Observable cLFV processes only if $\Lambda_{\rm LNV} \gg \Lambda_{\rm LFV}$

Example – radiative neutrino mass generation **[Cai+ 1410.0689]**

Leptoquark $\phi \sim (\bar{3}, 1, \frac{1}{3})$
VL quark: $\chi = (B, Y) \sim (3, 2, -\frac{5}{6})$



$$(m_\nu)_{ij} = \frac{3}{16\pi^2} m_{bB} \frac{m_b m_B}{m_\phi^2 - m_B^2} \ln \frac{m_B^2}{m_\phi^2} \left(Y_{i3}^{LQ\phi} Y_j^{L\bar{\chi}\phi} + (i \leftrightarrow j) \right)$$

- two massive neutrinos
- Neutrino phenomenology fixes Yukawa couplings $Y_{i3}^{LQ\phi}$ and $Y_j^{L\bar{\chi}\phi}$ up to overall scaling with ζ and a discrete choice
- $\mu \to e$ processes most constraining
- testable predictions for ratios, e.g.

$$\frac{\mathcal{B}(\tau \to e\gamma)}{\mathcal{B}(\tau \to \mu\gamma)} = \frac{|Y_{13}^{LQ\phi}|^2}{|Y_{23}^{LQ\phi}|^2} = \frac{|\sqrt{m_2} U_{e2} \pm i\sqrt{m_3} U_{e3}|^2}{|\sqrt{m_2} U_{\mu 2} \pm i\sqrt{m_3} U_{\mu 3}|^2}$$

for normal ordering and $m_\chi \simeq m_B \gg m_\phi$ in terms of neutrino masses $m_2 \simeq \sqrt{\Delta m^2_{\rm sol}}$, $m_3 \simeq \sqrt{\Delta m^2_{\rm atm}}$ and PMNS matrix elements $U_{\alpha i}$

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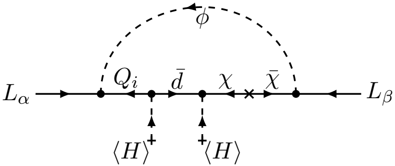

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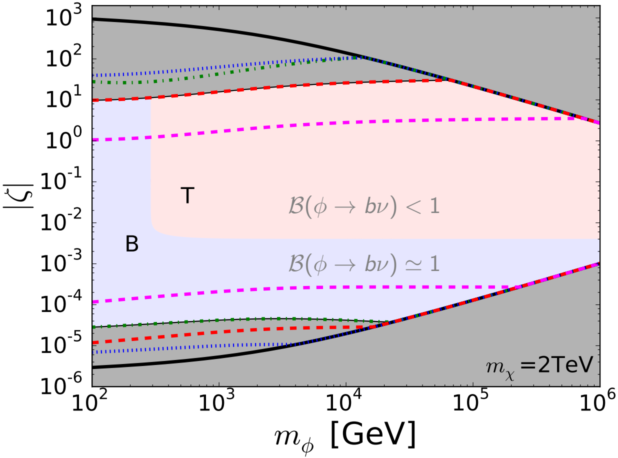
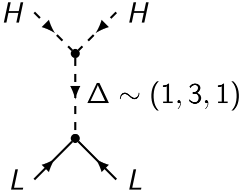


perturbativity (black); $\mu \to e\gamma$ (green dot-dashed);
$\mu \to 3e$ (blue dotted); $\mu\mathrm{Au} \to e\mathrm{Au}$ (red dashed);
$\mu\mathrm{Ti} \to e\mathrm{Ti}$ (proj, magenta dashed);

Example – large τ LFV in the type II seesaw model [Ardu+ 2401.06214]

Type II seesaw model



$$m_\nu \simeq -\frac{\lambda \Lambda_6 v^2}{M_\Delta^2}$$

Cosmological mass limit

$\sum_i m_i \lesssim 0.1\mathrm{eV}$

- cLFV interactions $\lambda_{ij} \propto (m_\nu)_{ij}$
- testable predictions, e.g.

$$\frac{\mathcal{B}(\tau \to \mu\gamma)}{\mathcal{B}(\tau \to e\gamma)} \simeq \left|\frac{(m_\nu m_\nu^\dagger)_{\mu\tau}}{(m_\nu m_\nu^\dagger)_{e\tau}}\right|^2$$

$\Rightarrow$ measuring several cLFV processes can support or exclude type-II seesaw model

- $\mu \to 3e$ mediated by Δ^{++} exchange at tree-level and thus generally most sensitive
- tree-level contribution to $\mu \to 3e$ suppressed for $(m_\nu)_{e\mu} \to 0$

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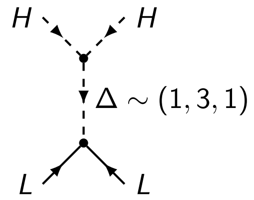
Type II seesaw model



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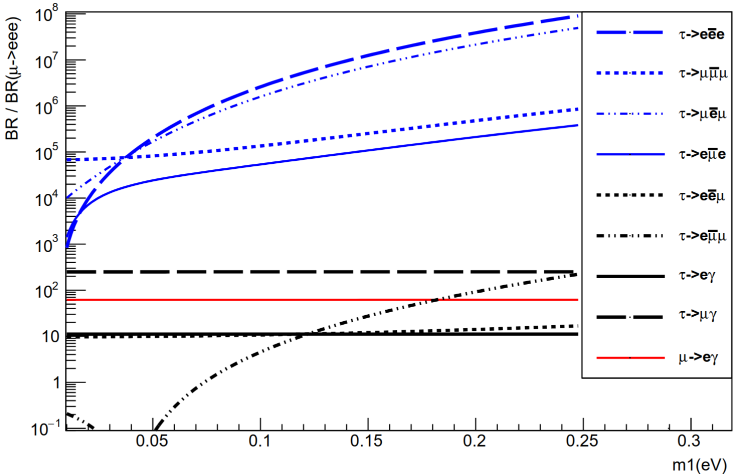


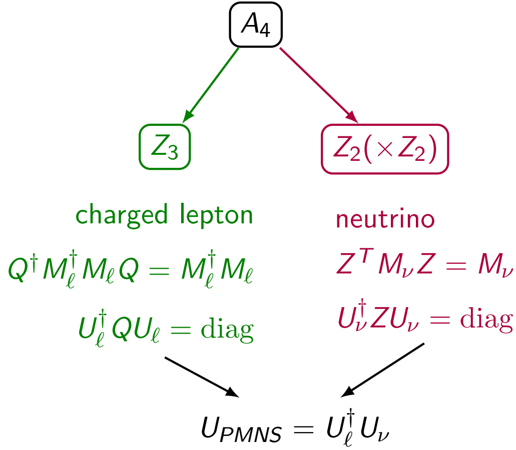
m_1 lightest neutrino mass

Large τ LFV from lepton triality

τ LFV – lepton flavour triality

Flavour symmetry breaking → mixing

Altarelli, Feruglio hep-ph/0512103 He, Keum, Volkas hep-ph/0601001



A_4

Z_3

$Z_2(\times Z_2)$

charged lepton

$$Q^\dagger M_\ell^\dagger M_\ell Q = M_\ell^\dagger M_\ell$$

$$U_\ell^\dagger Q U_\ell = \mathrm{diag}$$

neutrino

$$Z^T M_\nu Z = M_\nu$$

$$U_\nu^\dagger Z U_\nu = \mathrm{diag}$$

$$U_{PMNS} = U_\ell^\dagger U_\nu$$

Remnant symmetries

emergence of lepton flavour triality Z_3 symmetry for charged leptons

charged leptons distinguished by Z_3 charges

⇒ (certain) flavour transitions forbidden by symmetry

triality introduced by Ma 1006.3524

Bottom-up perspective

Lepton triality symmetry: $\ell_k \to \omega^k \ell_k$ with $\omega = e^{2\pi i/3}$, $\omega^3 = 1$

Implications

- All transitions $\ell_i \to \ell_j$ with $i \neq j$ forbidden
- Allowed processes: $\tau^\pm \to \mu^\pm \mu^\pm e^\mp$, $\tau^\pm \to \mu^\mp e^\pm e^\pm$

→ induced by higher-dimensional operator or e.g. bileptons

Models with bileptons: Z_3 charge $T = 2$

- doubly-charged scalar k_2: $\mathcal{L} = \frac{1}{2}\left(2g_1 \overline{\tau_R^c} e_R + g_2 \overline{\mu_R^c} \mu_R\right) k_2$
- EW triplet $\Delta_2 \sim (\mathbf{3}, 1)$: $\mathcal{L} = \frac{1}{2}\left(2g_1 \overline{L_3^c} \cdot \mathbf{\Delta}_2 L_1 + g_2 \overline{L_2^c} \cdot \mathbf{\Delta}_2 L_2\right)$

⇒ prediction $\tau^\pm \to \mu^\pm \mu^\pm e^\mp$

$T = 1$ bileptons result in $\tau^\pm \to e^\pm e^\pm \mu^\mp$

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$\Rightarrow$ prediction $\tau^\pm \to \mu^\pm \mu^\pm e^\mp$

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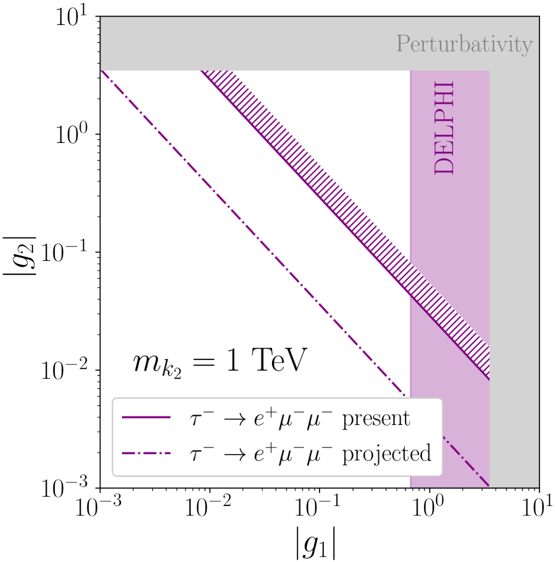
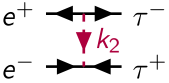
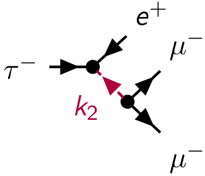
Electroweak singlet model – $T = 2$ [Bigaran+ 2212.09760]



$$k_2 \to \omega^2 k_2$$

$$\mathcal{L} = \frac{1}{2}\left(2g_1\overline{\tau^c_R}e_R + g_2\overline{\mu^c_R}\mu_R\right)k_2$$





$m_{k_2} \gtrsim \mathcal{O}(0.9)$TeV

ATLAS 2211.07505

Lepton flavour triality at lepton colliders [Lichtenstein+ 2307.11369]

Model	Process		Lepton Collider
T=1	$\mu^+e^- \to e^+\tau^-$	u	μTRISTAN
T=1	$e^+e^- \to e^+e^-$	u	e^+e^-
T=1	$e^-e^- \to e^-e^-$	s	-
T=1	$e^-e^- \to \tau^-\mu^-$	s	-
T=2	$\mu^+\mu^+ \to \tau^+e^+$	s	μTRISTAN
T=2	$\mu^+\mu^+ \to \mu^+\mu^+$	s	μTRISTAN
T=2	$\mu^+e^- \to \tau^+\mu^-$	u	μTRISTAN
T=2	$\mu^+\mu^- \to \mu^+\mu^-$	s	$\mu^+\mu^-$
T=3	$\mu^+e^- \to \mu^+e^-$	u	μTRISTAN
T=3	$\mu^+e^+ \to \tau^+\tau^+$	s	-

For electroweak triplet see Fridell+ 2304.14020

$T = 1$

$$\mathcal{L}_{k_1} = \frac{1}{2}\left(2f_1\overline{\tau_R^c}\mu_R + f_2\overline{e_R^c}e_R\right)k_1$$

$T = 2$

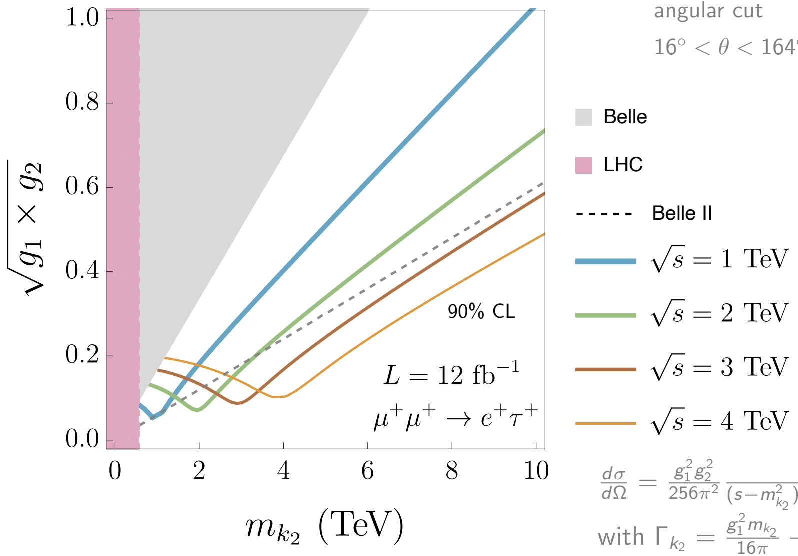
$$\mathcal{L}_{k_2} = \frac{1}{2}\left(2g_1\overline{\tau_R^c}e_R + g_2\overline{\mu_R^c}\mu_R\right)k_2$$

$T = 3$

$$\mathcal{L}_{k_3} = \frac{1}{2}\left(2h_1\overline{\mu_R^c}e_R + h_2\overline{\tau_R^c}\tau_R\right)k_3$$

$$\ell_k \to \omega^k\ell_k k_T \to \omega^T k_T \quad \text{with} \quad \omega = e^{2\pi i/3}, \omega^3 = 1$$

Lepton flavour violation: $T = 2$ at $\mu^+\mu^+$ [Lichtenstein+ 2307.11369]



angular cut

$16^\circ < \theta < 164^\circ$

Simple scaling in EFT limit

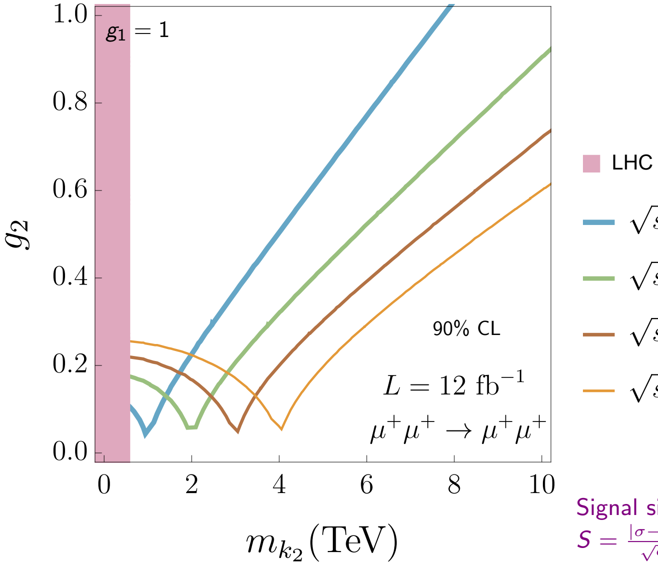
$\sqrt{g_1 g_2} \lesssim 0.15 \left(\frac{N}{Ls}\right)^{1/4} \frac{m_{k_2}}{\text{TeV}}$

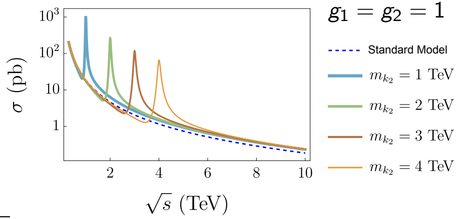
for N events

$$\frac{d\sigma}{d\Omega} = \frac{g_1^2 g_2^2}{256\pi^2} \frac{s}{(s - m_{k_2}^2)^2 + m_{k_2}^2 \Gamma_{k_2}^2}$$

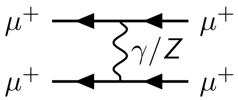
with $\Gamma_{k_2} = \frac{g_1^2 m_{k_2}}{16\pi} + \frac{g_2^2 m_{k_2}}{32\pi}$

$T = 2$ model: $\mu^+\mu^+ \to k_2^* \to \mu^+\mu^+$ [Lichtenstein+ 2307.11369]





SM background



Signal significance
$S = \frac{|\sigma - \sigma_{\text{SM}}|}{\sqrt{\sigma_{\text{SM}}}}\sqrt{L}$

Simple scaling in EFT limit
$g_2 \lesssim 0.18 \left(\frac{S^2}{Ls}\right)^{1/4} \sqrt{L}$

Exotic lepton flavour violating signals

LFV by two units Heeck 2401.09580 – effective operators

could be generated from bileptons, see e.g. Cuypers hep-ph/9609487; Li+ 1809.07924, 1907.06963

$$y^{LL}_{abcd}\bar{L}_a\gamma^\alpha L_b\bar{L}_c\gamma_\alpha L_d + y^{LR}_{abcd}\bar{L}_a\gamma^\alpha L_b\bar{\ell}_c\gamma_\alpha\ell_d + y^{RR}_{abcd}\bar{\ell}_a\gamma^\alpha\ell_b\bar{\ell}_c\gamma_\alpha\ell_d$$

$\Delta L_\mu = -\Delta L_e = 2$

- $M - \bar{M}$ oscillations Willmann+ hep-ex/9807011

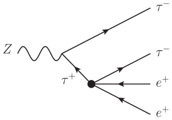
$$|y^{LL}_{\mu e\mu e} + y^{RR}_{\mu e\mu e}| < (3.2\mathrm{TeV})^{-2}$$
$$|y^{LR}_{\mu e\mu e}| < (3.8\mathrm{TeV})^{-2}$$

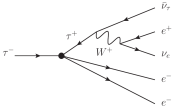
- MACE promises $\mathcal{O}(100)$ improvement
- LFU tests $\frac{\Gamma(\mu\to e\nu\bar{\nu})}{\Gamma(\tau\to\mu\nu\bar{\nu})}$: $|y^{LL}_{\mu e\mu e}| < (1.1\mathrm{TeV})^{-2}$
- μTRISTAN: $|y_{\mu e\mu e}| \sim (10\mathrm{TeV})^{-2}$

Hamada+ 2210.11083; Fridell+ 2304.14020

$\Delta L_\tau = -\Delta L_e = 2$

- LFU $\frac{\Gamma(\tau\to e\nu\bar{\nu})}{\Gamma(\tau\to\mu\nu\bar{\nu})}$: $|2y^{LL}_{\tau e\tau e}|, |y^{LR}_{\tau e\tau e}| < (0.67\mathrm{TeV})^2$
- Z and τ decays probe scales $\mathcal{O}(1-100)\mathrm{GeV}$





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$\Delta L_\mu = -\Delta L_e = 2$

- $M - \bar{M}$ oscillations Willmann+ hep-ex/9807011

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Hamada+ 2210.11083; Fridell+ 2304.14020

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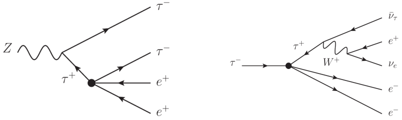

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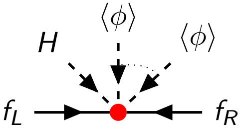
LFV decays into axion-like particles

Fermion mass hierarchy from a flavour symmetry [Froggatt, Nielsen NPB147 (1979) 277]

- Most Yukawa couplings are forbidden by the flavour symmetry
- Yukawa couplings emerge from high-dimensional operators after the flavour symmetry is spontaneously broken by VEV of scalar field (flavon) $\langle\phi\rangle$

$$\mathcal{L}_{\rm Yuk} = \left(\frac{\langle\phi\rangle}{\Lambda}\right)^{n^f_{ij}} \bar{f}_{Li} f_{Rj} H$$



- For $\langle\phi\rangle \ll \Lambda$ a hierarchy emerges among effective Yukawa couplings depending on n^f_{ij} which are fixed by the flavour symmetry

$U(1)$ **with charges** $Q(\phi) = -1$, $Q(H) = 0$, $Q(\bar{L}_{Li}) = [L]_i$, $Q(e_{Ri}) = [e]_i$

$$[L]_i = [e]_i = 3 - i \qquad \Rightarrow \qquad \left[n^\ell_{ij}\right] = \begin{pmatrix} 4 & 3 & 2 \\ 3 & 2 & 1 \\ 2 & 1 & 0 \end{pmatrix} \qquad \Rightarrow \qquad m_\ell \sim \begin{pmatrix} \epsilon^4 & \epsilon^3 & \epsilon^2 \\ \epsilon^3 & \epsilon^2 & \epsilon^1 \\ \epsilon^2 & \epsilon^1 & 1 \end{pmatrix}$$

LFV couplings for ALPs

$U(1)$ **with charges** $Q(\phi) = -1$, $Q(H) = 0$, $Q(\bar{L}_{Li}) = [L]_i$, $Q(e_{Ri}) = [e]_i$

Spontaneously broken symmetry results in a (pseudo-)Nambu-Goldstone boson α

$$\phi = \frac{f+\varphi}{\sqrt{2}} e^{i\alpha/f} \qquad \overset{E \ll f}{\Longrightarrow} \qquad \mathcal{L}_{\text{eff}} = \frac{\partial_\mu \alpha}{f} \bar{\ell}_i \gamma^\mu \left(C_V^{ij} + C_A^{ij} \gamma_5 \right) \ell_k$$

may also solve strong CP problem Wilczek 1982; Ema+ 1612.05492; Calibbi+ 1612.08040

Flavour non-universal charges result in flavour-violating ALP couplings

$$C_{V,A} = V_R^\dagger X_R V_R \pm V_L^\dagger X_L V_L \qquad \text{with} \qquad V_L^\dagger Y_e V_R = Y_e^{\text{diag}}$$

$$X_R = \begin{pmatrix} [e]_1 & & \\ & [e]_2 & \\ & & [e]_3 \end{pmatrix} \qquad X_L = \begin{pmatrix} [L]_1 & & \\ & [L]_2 & \\ & & [L]_3 \end{pmatrix}$$

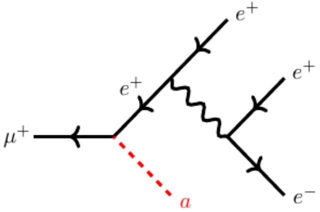
$$(V_R)_{ij} \approx \epsilon^{|[e]_i - [e]_j|}$$

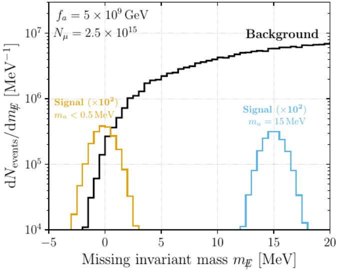
$$(V_L)_{ij} \approx \epsilon^{|[L]_i - [L]_j|}$$

and thus flavour-violating decays

$$\mu \to ea \qquad \mu \to ea\gamma \qquad \mu \to 3e + a \qquad \tau \to \ell a$$

LFV axions at Mu3E [Knapen+ 2311.17915]





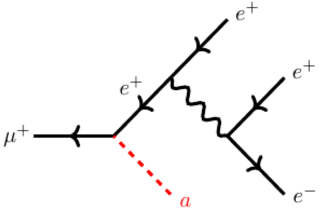
$\mu \to ea$

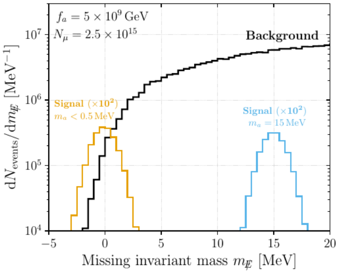
- TRIUMF $\mu \to ea$ search Jodidio+ 1986; 1409.0638: $f_a > 2.45 \times 10^9$ GeV
- Mu3E at PSI will search for monochromatic line from $\mu \to ea$ on top of Michel spectrum using 10^{15} muons on target
- for $m_a \lesssim 20$ MeV because line too close to kinematic edge of Michel spectrum which is used for calibration

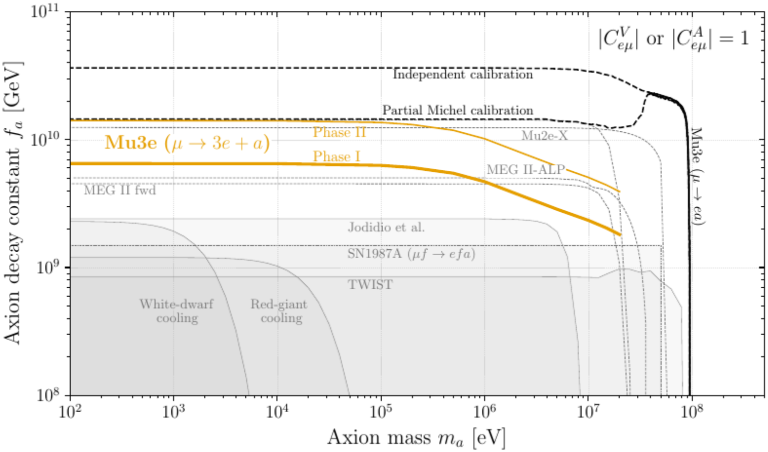
$\mu \to 3e + a$

- circumvents calibration challenge
- reduced signal and background
- main background $\mu \to 3e + 2\nu$
- background reduced for $m_{\not{E}} \to 0 \Rightarrow$ increased sensitivity

LFV axions at Mu3E [Knapen+ 2311.17915]





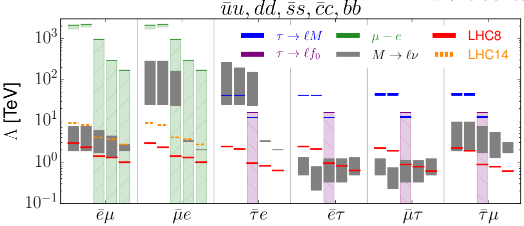


Final comments

How about high-energy colliders? – LHC vs low-energy observables

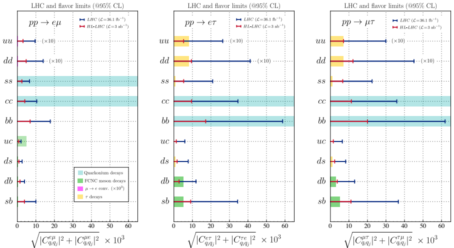
Operators: $(\bar{L}e)(\bar{d}Q)$, $(\bar{L}e)\cdot(\bar{Q}u)$

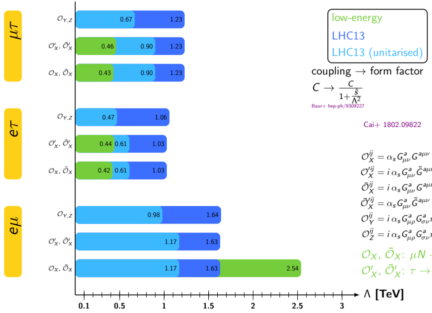
Cai+ 1510.02486



Operators: $\frac{C}{v^2}(\bar{Q}\gamma^\mu Q)(\bar{L}\gamma_\mu L)$

Angelescu+ 2002.05684





coupling → form factor

$C \to \frac{C}{1+\frac{\hat{s}}{\Lambda^2}}$

Baur+ hep-ph/9309227

Cai+ 1802.09822

$$\mathcal{O}^{ij}_X = \alpha_s G^a_{\mu\nu} G^{a\mu\nu} \left(\bar{e}_{Ri} L_j \cdot \phi^* + \bar{L}_j \cdot \phi e_{Ri}\right)$$
$$\mathcal{O}'^{ij}_X = i\,\alpha_s G^a_{\mu\nu} \tilde{G}^{a\mu\nu} \left(\bar{e}_{Ri} L_j \cdot \phi^* - \bar{L}_j \cdot \phi e_{Ri}\right)$$
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$$\mathcal{O}^{ij}_Y = i\,\alpha_s G^a_{\mu\rho} G^a_{\sigma\nu} \eta^{\rho\sigma} \bar{L}_i \gamma^\mu D^\nu L_j$$
$$\mathcal{O}^{ij}_Z = i\,\alpha_s G^a_{\mu\rho} G^a_{\sigma\nu} \eta^{\rho\sigma} \bar{e}_{Ri} \gamma^\mu D^\nu e_{Rj}$$

$\mathcal{O}_X, \bar{\mathcal{O}}_X$: $\mu N \to eN$, $\tau \to \ell M^+ M^-$

$\mathcal{O}'_X, \bar{\mathcal{O}}'_X$: $\tau \to \ell M^0$

- LE experiments better for light quarks
- LHC competitive for heavy quarks and RH τ
- $\Lambda \gtrsim 600 - 800$ GeV

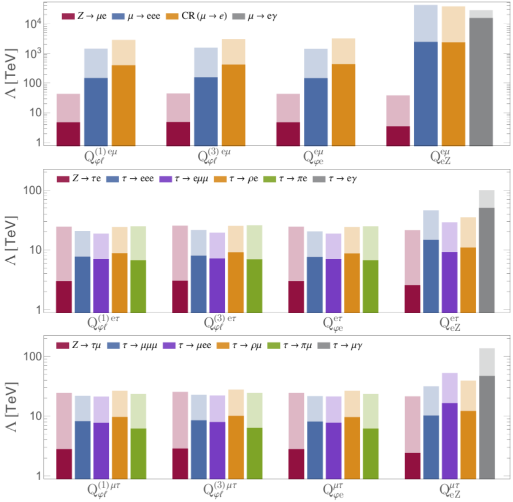
Flavour-violating Z boson decays [Calibbi+ 2107.10273]

5 SMEFT operators directly contribute to LFV Z boson decays

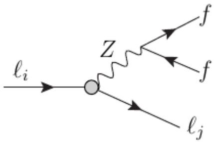
$$Q_{eB} = (\bar{L}\sigma^{\mu\nu}E)\phi B_{\mu\nu} \qquad Q_{eW} = (\bar{L}\sigma^{\mu\nu}E)\tau^I\phi W^I_{\mu\nu}$$

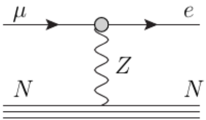
$$Q^{(1)}_{\varphi\ell} = (\phi^\dagger i\overleftrightarrow{D}_\mu\phi)(\bar{L}\gamma^\mu L) \qquad Q^{(3)}_{\varphi\ell} = (\phi^\dagger\tau^I i\overleftrightarrow{D}_\mu\phi)(\bar{L}\tau^I\gamma^\mu L)$$

$$Q_{\varphi e} = (\phi^\dagger i\overleftrightarrow{D}_\mu\phi)(\bar{E}\gamma^\mu E)$$



Indirect constraints





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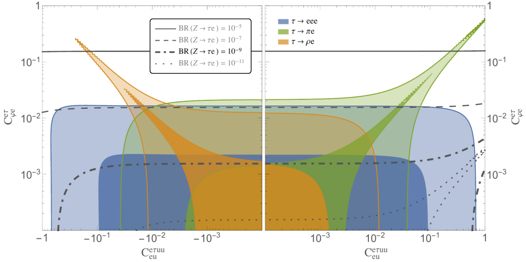

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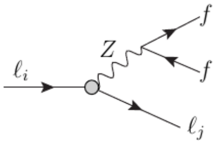

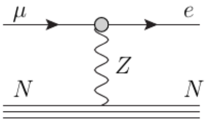

- LE constraints cannot be avoided
- currently LFV Z decays not competitive
- $Z \to \mu e$ not competitive at Tera-Z factory
- complementary sensitivity for $Z \to \tau\ell$

Takeaway – Observation of cLFV smoking gun signature for new physics

neutrino mass and cLFV

- observable cLFV processes only if $\Lambda_{\mathrm{LNV}} \gg \Lambda_{\mathrm{LFV}}$
- $\mu \to e + X$ generally most sensitive
- type II seesaw may explain large τ LFV

lepton triality

- $\mu \to e$ LFV could be forbidden/suppressed

→ most important constraints from LFV τ decays and colliders

A bright future for cLFV searches

- up to 4 orders of magnitude improved sensitivity for $\mu \to 3e$ and $\mu N \to eN$
- 1-2 orders of magnitude improved sensitivity for τ LFV
- new interesting ideas for light particle searches

International Joint Workshop on the Standard Model and Beyond 2024

Dates: 9-13 December 2024
Venue: UNSW Kensington Campus
https://indico.cern.ch/event/1318443/

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Thank you!

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