

Theory of rare decays of leptons

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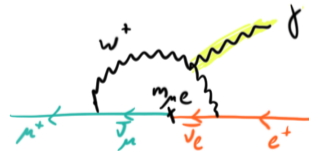
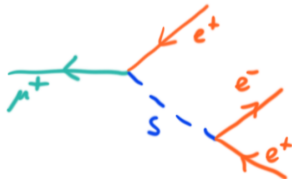
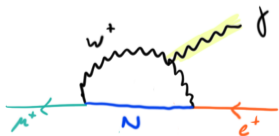


Lepton flavour violation

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

$$\mathcal{B}(l^- \rightarrow l' + X) \propto |G_F U_{li}^* U_{l'i} m_{\nu,i}^2|^2 \rightarrow \mathcal{B}(l \rightarrow l' + X) \lesssim 10^{-54}$$

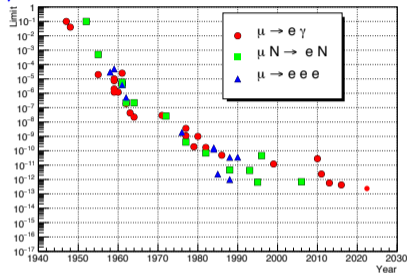
- Observation would be a smoking gun sign for physics beyond the SM + m_ν



Brief summary of experimental status

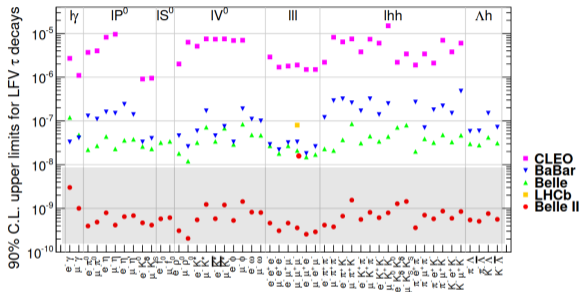
$\mu \rightarrow e$ transition

Calibbi+1709.0029



$\tau \rightarrow \ell$ transition

Belle II 1808.10567



Latest upper limits at 90% CL

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

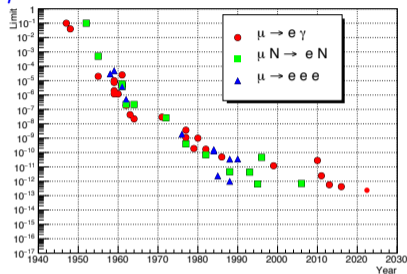
MEG II 2310.12614

$$B(\tau \rightarrow 3\mu) < \begin{cases} 1.9 \times 10^{-8} & \text{Belle II 2405.07386} \\ 2.9 \times 10^{-8} & \text{CMS 2312.02371} \\ 1.8 \times 10^{-8} & \text{expected LHCb; CERN-THESIS-2023-233} \end{cases}$$

Brief summary of experimental status

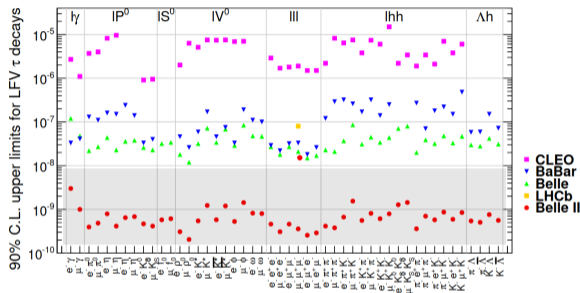
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A bright future for LFV searches

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

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

Charged lepton flavour violation and the origin of neutrino masses

Large τ LFV from lepton triality

LFV decays into axion-like particles

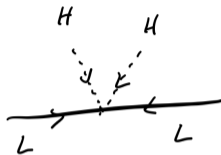
Final comments

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

$$\frac{\kappa}{\Lambda_{\text{LNV}}} LHLH \quad \Rightarrow \quad m_\nu \sim \frac{\kappa V^2}{\Lambda_{\text{LNV}}}$$



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

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

5 types of operators

dipole operator, 4-lepton, 2-lepton-2-quark,
2-lepton-Higgs, 2-lepton-gauge boson

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

$$\frac{C_{e\gamma}}{\Lambda_{\text{LFV}}^2} \sim \frac{C_{e\gamma} m_\nu^2}{\kappa^2 V^4} \quad \Rightarrow \quad \mathcal{B}(\mu \rightarrow e + X) \lesssim 10^{-34} \left(\frac{C_{e\gamma}}{16\pi^2 \kappa^2} \right)^2$$

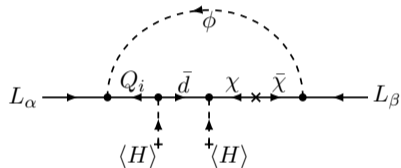
Conservative estimate for $C_{e\gamma}$; it is often smaller like in seesaw model

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

Example – radiative neutrino mass generation [Cai+ 1410.0689]

Leptoquark $\phi \sim (\bar{3}, 1, \frac{1}{3})$

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



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

- 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
- $\mu \rightarrow e$ processes most constraining
- testable predictions for ratios, e.g.

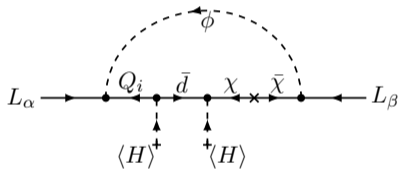
$$\frac{\mathcal{B}(\tau \rightarrow e\gamma)}{\mathcal{B}(\tau \rightarrow \mu\gamma)} = \frac{|Y_{13}^{LQ\phi}|^2}{|Y_{23}^{LQ\phi}|^2} = \frac{|\sqrt{m_2} U_{e2} \pm i\sqrt{m_3} U_{e3}|^2}{|\sqrt{m_2} U_{\mu 2} \pm i\sqrt{m_3} U_{\mu 3}|^2}$$

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

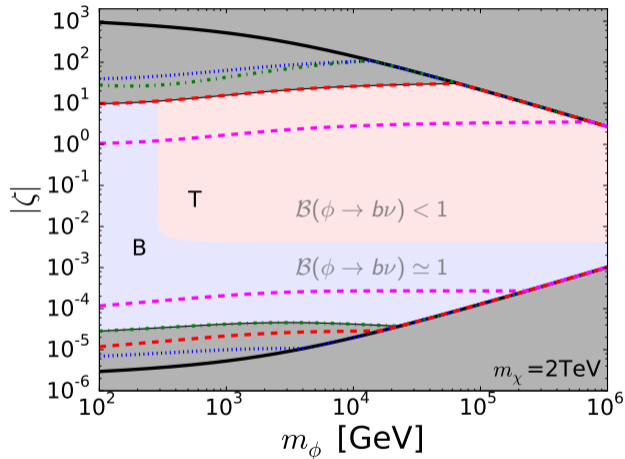
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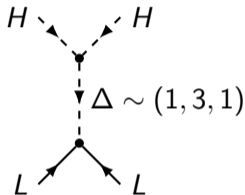


$$(m_\nu)_{ij} = \frac{3}{16\pi^2} m_b m_B \frac{m_b m_B}{m_\phi^2 - m_B^2} \ln \frac{m_B^2}{m_\phi^2} \left(Y_{i3}^{LQ\phi} Y_j^{L\bar{\chi}\phi} + (i \leftrightarrow j) \right)$$



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

Type II seesaw model



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

Cosmological mass limit

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

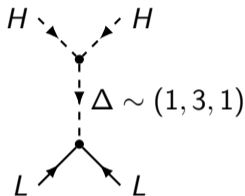
- cLFV interactions $\lambda_{ij} \propto (m_\nu)_{ij}$
- testable predictions, e.g.

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

- \Rightarrow measuring several cLFV processes can support or exclude type-II seesaw model
- $\mu \rightarrow 3e$ mediated by Δ^{++} exchange at tree-level and thus generally most sensitive
 - tree-level contribution to $\mu \rightarrow 3e$ suppressed for $(m_\nu)_{e\mu} \rightarrow 0$

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

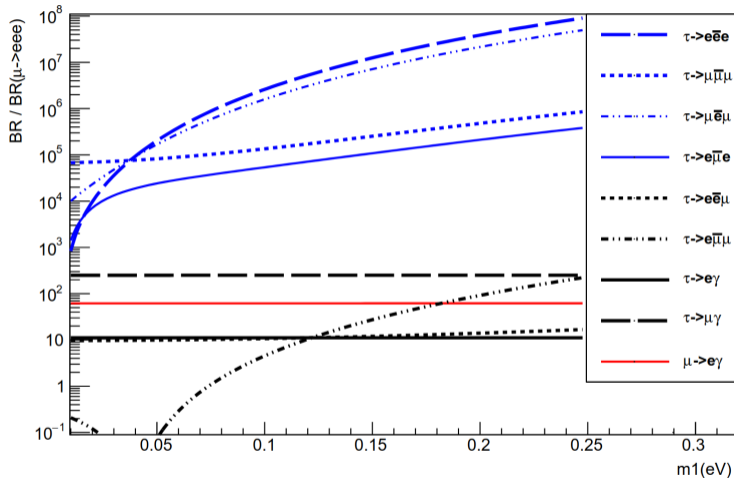
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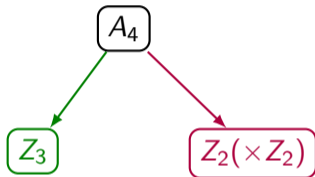
m_1 lightest neutrino mass

$$[m_\nu]_{e\mu} = 0$$

Large τ LFV from lepton triality

Flavour symmetry breaking \rightarrow mixing

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



charged lepton

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

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

neutrino

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

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

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

Remnant symmetries

emergence of lepton flavour triality Z_3 symmetry for charged leptons

charged leptons distinguished by Z_3 charges

\Rightarrow (certain) flavour transitions forbidden by symmetry

triality introduced by [Ma 1006.3524](#)

Bottom-up perspective

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

Implications

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

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

Models with bileptons: Z_3 charge $T = 2$

- doubly-charged scalar k_2 : $\mathcal{L} = \frac{1}{2} (2g_1 \overline{\tau}_R^c e_R + g_2 \overline{\mu}_R^c \mu_R) k_2$
- EW triplet $\Delta_2 \sim (\mathbf{3}, 1)$: $\mathcal{L} = \frac{1}{2} (2g_1 \overline{L}_3^c \cdot \Delta_2 L_1 + g_2 \overline{L}_2^c \cdot \Delta_2 L_2)$

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

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

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

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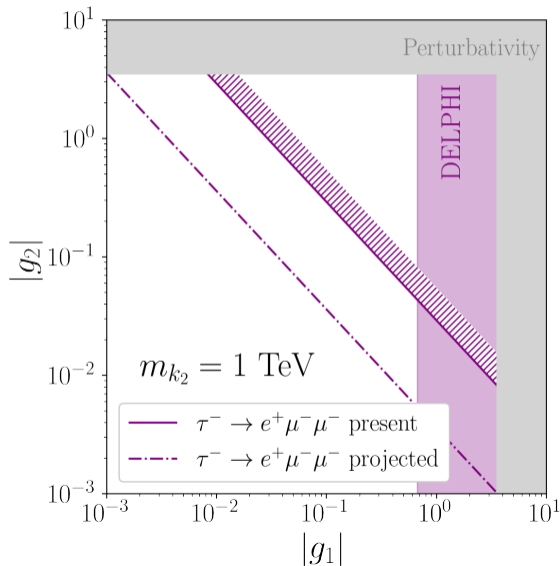
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⇒ prediction $\tau^\pm \rightarrow \mu^\pm \mu^\pm e^\mp$

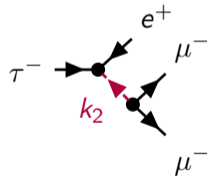
$T = 1$ bileptons result in $\tau^\pm \rightarrow e^\pm e^\pm \mu^\mp$

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



$$k_2 \rightarrow \omega^2 k_2$$

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



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

ATLAS 2211.07505

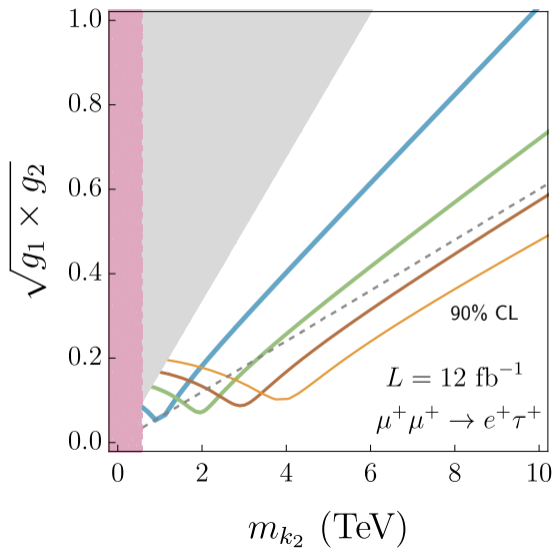
Lepton flavour triality at lepton colliders [Lichtenstein+ 2307.11369]

Model	Process	Lepton Collider	
T=1	$\mu^+ e^- \rightarrow e^+ \tau^-$	u μ TRISTAN	$T = 1$
T=1	$e^+ e^- \rightarrow e^+ e^-$	u $e^+ e^-$	$\mathcal{L}_{k_1} = \frac{1}{2} (2f_1 \overline{T_R^c} \mu_R + f_2 \overline{e_R^c} e_R) k_1$
T=1	$e^- e^- \rightarrow e^- e^-$	s -	
T=1	$e^- e^- \rightarrow \tau^- \mu^-$	s -	
T=2	$\mu^+ \mu^+ \rightarrow \tau^+ e^+$	s μ TRISTAN	$T = 2$
T=2	$\mu^+ \mu^+ \rightarrow \mu^+ \mu^+$	s μ TRISTAN	$\mathcal{L}_{k_2} = \frac{1}{2} (2g_1 \overline{T_R^c} e_R + g_2 \overline{\mu_R^c} \mu_R) k_2$
T=2	$\mu^+ e^- \rightarrow \tau^+ \mu^-$	u μ TRISTAN	
T=2	$\mu^+ \mu^- \rightarrow \mu^+ \mu^-$	s $\mu^+ \mu^-$	
T=3	$\mu^+ e^- \rightarrow \mu^+ e^-$	u μ TRISTAN	$T = 3$
T=3	$\mu^+ e^+ \rightarrow \tau^+ \tau^+$	s -	$\mathcal{L}_{k_3} = \frac{1}{2} (2h_1 \overline{\mu_R^c} e_R + h_2 \overline{T_R^c} T_R) k_3$

For electroweak triplet see [Fridell+ 2304.14020](#)

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

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



angular cut

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

Simple scaling in EFT limit

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

for N events

■ Belle

■ LHC

--- Belle II

— $\sqrt{s} = 1$ TeV

— $\sqrt{s} = 2$ TeV

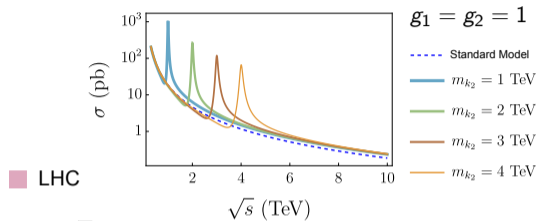
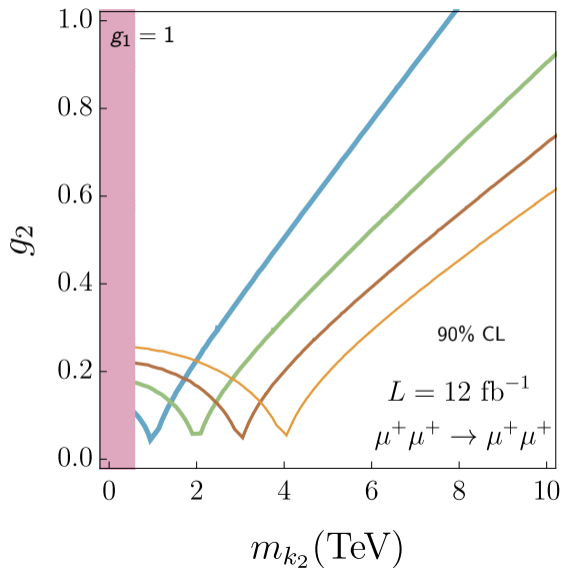
— $\sqrt{s} = 3$ TeV

— $\sqrt{s} = 4$ TeV

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

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

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



LHC

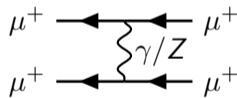
$\sqrt{s} = 1 \text{ TeV}$

$\sqrt{s} = 2 \text{ TeV}$

$\sqrt{s} = 3 \text{ TeV}$

$\sqrt{s} = 4 \text{ TeV}$

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 Heck 2401.09580 – effective operators

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

$$y_{abcd}^{LL} \bar{L}_a \gamma^\alpha L_b \bar{L}_c \gamma_\alpha L_d + y_{abcd}^{LR} \bar{L}_a \gamma^\alpha L_b \bar{l}_c \gamma_\alpha l_d + y_{abcd}^{RR} \bar{l}_a \gamma^\alpha l_b \bar{l}_c \gamma_\alpha l_d$$

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

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

$$|y_{\mu e \mu e}^{LL} + y_{\mu e \mu e}^{RR}| < (3.2 \text{ TeV})^{-2}$$

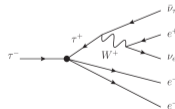
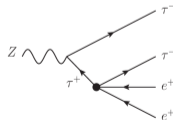
$$|y_{\mu e \mu e}^{LR}| < (3.8 \text{ TeV})^{-2}$$

- MACE promises $\mathcal{O}(100)$ improvement
- LFU tests $\frac{\Gamma(\mu \rightarrow e \nu \bar{\nu})}{\Gamma(\tau \rightarrow \mu \nu \bar{\nu})}$: $|y_{\mu e \mu e}^{LL}| < (1.1 \text{ TeV})^{-2}$
- μ TRISTAN: $|y_{\mu e \mu e}| \sim (10 \text{ TeV})^{-2}$

Hamada+ 2210.11083; Fridell+ 2304.14020

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

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



Similar conclusions apply for $\Delta L_\tau = -\Delta L_\mu = 2$

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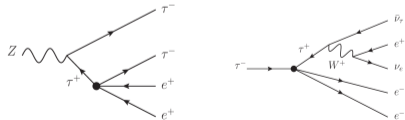
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Hamada+ 2210.11083; Fridell+ 2304.14202

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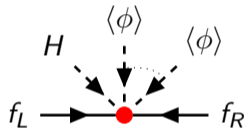


Similar conclusions apply for $\Delta L_\tau = -\Delta L_\mu = 2$

LFV decays into axion-like particles

- 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) $\langle\phi\rangle$

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



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

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

$$[L]_i = [e]_i = 3 - i \quad \Rightarrow \quad [n_{ij}^f] = \begin{pmatrix} 4 & 3 & 2 \\ 3 & 2 & 1 \\ 2 & 1 & 0 \end{pmatrix} \quad \Rightarrow \quad m_\ell \sim \begin{pmatrix} \epsilon^4 & \epsilon^3 & \epsilon^2 \\ \epsilon^3 & \epsilon^2 & \epsilon^1 \\ \epsilon^2 & \epsilon^1 & 1 \end{pmatrix}$$

LFV couplings for ALPs

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

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

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

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

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

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

$\begin{pmatrix} [e]_1 \\ [e]_2 \\ [e]_3 \end{pmatrix}$

$\begin{pmatrix} [L]_1 \\ [L]_2 \\ [L]_3 \end{pmatrix}$

$\begin{matrix} (V_R)_{ij} \approx \epsilon^{|[e]_i - [e]_j|} \\ (V_L)_{ij} \approx \epsilon^{|[L]_i - [L]_j|} \end{matrix}$

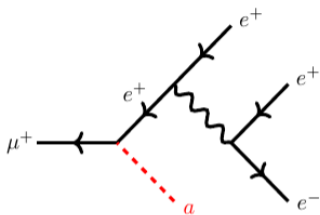
and thus flavour-violating decays

$\mu \rightarrow ea$

$\mu \rightarrow ea\gamma$

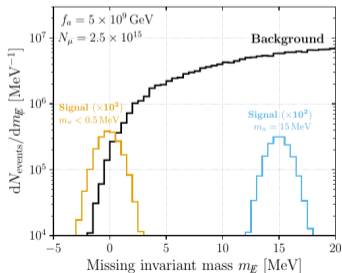
$\mu \rightarrow 3e + a$

$\tau \rightarrow la$



$$\mu \rightarrow ea$$

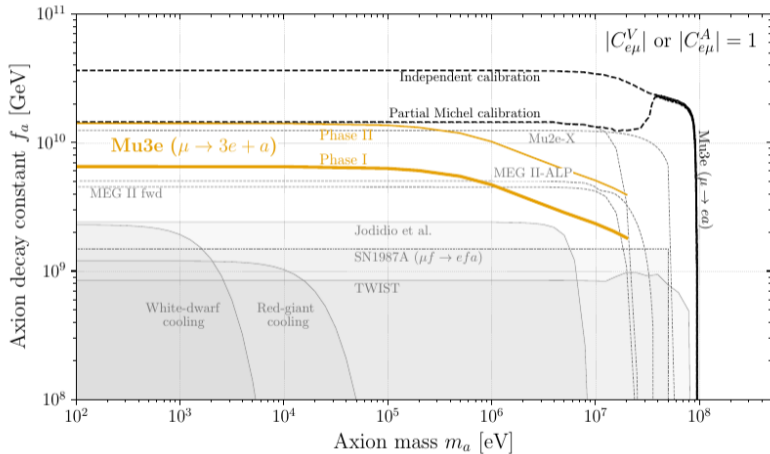
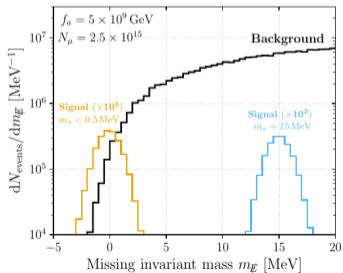
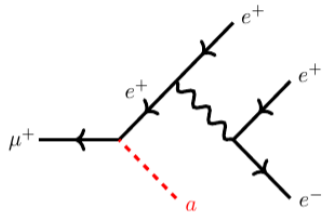
- TRIUMF $\mu \rightarrow ea$ search [Jodidio+ 1986; 1409.0638](#): $f_a > 2.45 \times 10^9$ GeV
- Mu3E at PSI will search for monochromatic line from $\mu \rightarrow ea$ on top of Michel spectrum using 10^{15} muons on target
- for $m_a \lesssim 20$ MeV because line too close to kinematic edge of Michel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



$$\mu \rightarrow 3e + a$$

- circumvents calibration challenge
- reduced signal and background
- main background $\mu \rightarrow 3e + 2\nu$
- background reduced for $m_{\cancel{E}} \rightarrow 0 \Rightarrow$ increased sensitivity

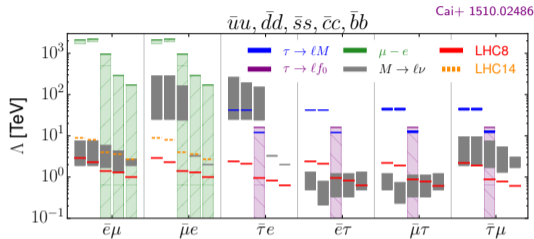
LFV axions at Mu3E [Knapen+ 2311.17915]



Final comments

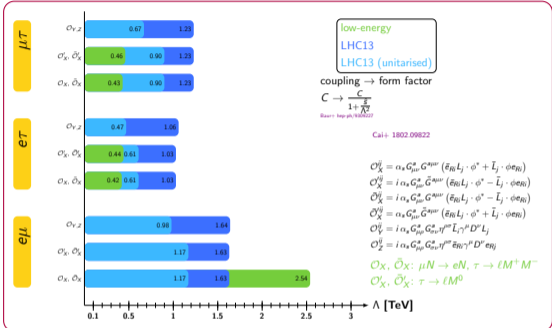
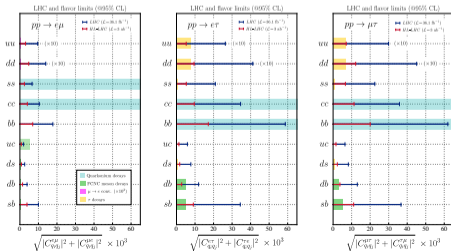
How about high-energy colliders? – LHC vs low-energy observables

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



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

Angelescu+ 2002.05684



- 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

$$Q_{eB} = (\bar{L}\sigma^{\mu\nu} E)\phi B_{\mu\nu}$$

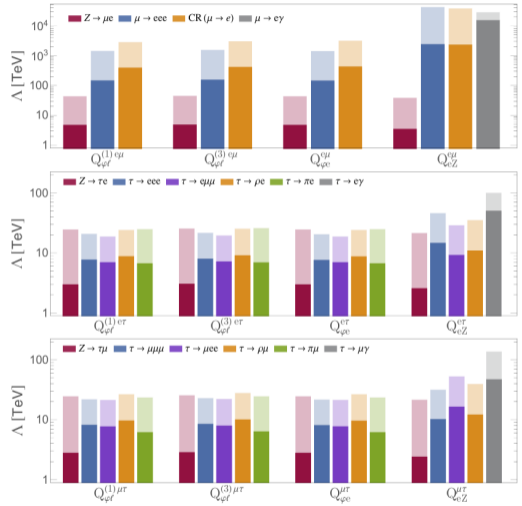
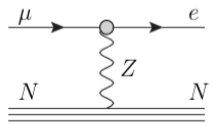
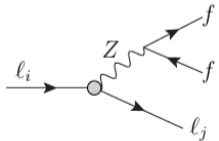
$$Q_{\varphi\ell}^{(1)} = (\phi^\dagger i\overleftrightarrow{D}_\mu\phi)(\bar{L}\gamma^\mu L)$$

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

$$Q_{eW} = (\bar{L}\sigma^{\mu\nu} E)\tau^I\phi W'_{\mu\nu}$$

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

Indirect constraints



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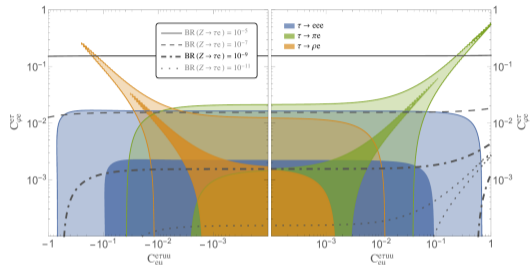
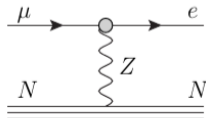
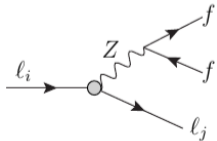
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$$Q_{\varphi e} = (\phi^\dagger i\overleftrightarrow{D}_\mu\phi)(\bar{E}\gamma^\mu E)$$

Indirect constraints



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

Takeaway – Observation of cLFV smoking gun signature for new physics

neutrino mass and cLFV

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

lepton triality

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

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Thank you!