τ LFV decays in the presence of heavy neutrinos

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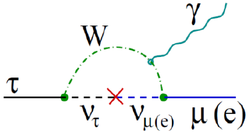
Motivation

- Original formulation of the SM (massless neutrinos) $\Rightarrow$ conservation of LF and LN.

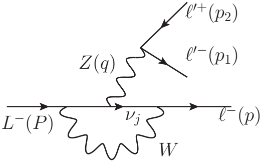
- **Experimental evidence of neutrino oscillation $\Rightarrow$ LF numbers are not conserved, being required an extended model with tiny neutrino mass.**

- Minimal extension (νSM) $\Rightarrow$ already results in cLFV transitions at one loop level, although strongly suppressed



- $BR(\mu \to e\gamma) \simeq \frac{\Gamma(\mu \to e\gamma)}{\Gamma(\mu \to e\nu\bar{\nu})} = \frac{3\alpha}{32\pi} \left| \sum_{k=1,3} \frac{U_{\mu k} U^*_{ek} m^2_{\nu k}}{m^2_W} \right|^2 \sim 10^{-54}$.
  - T. P. Cheng and L. F. Li, S. T. Petcov, Sov. J. Nucl. Phys. 25, 340 (1977).
- $BR(Z \to \ell' \ell) \sim 10^{-54}$
  - J. I. Illana and T. Riemann, Phys. Rev. D 63, 053004 (2001).
- $BR(h \to \ell' \ell) \sim 10^{-55}$
  - E. Arganda, A. M. Curiel, M. J. Herrero and D. Temes, Phys. Rev. D 71, 035011 (2005).
- $\mathrm{BR}(\mu^\pm \to e^\pm e^\pm e^\mp) \sim 10^{-53}$
  - S. T. Petcov, Sov. J. Nucl. Phys. 25, 340 (1977).

cLFV in νSM



An reported unexpected value for

- $\mathrm{BR}(\tau^\pm \to \mu^\pm \ell^\pm \ell^\mp) > 10^{-14}$

$$\mathcal{M} \sim \sum_{j=1}^{3} U_{\mu j}^{*} U_{\tau j} \log\left(\frac{m_W^2}{m_j^2}\right).$$

  - X. Y. Pham, Eur. Phys. J. C 8, 513 (1999).

- $\mathrm{BR}(\tau^\pm \to \mu^\pm \ell^\pm \ell^\mp) \sim 10^{-54}$ $\quad \mathcal{M} \sim \sum_{j=1}^{3} U_{\mu j}^{*} U_{\tau j} m_j^2 \log\left(\frac{m_W^2}{m_j^2}\right).$
  - G. Hernández-Tomé, G. López Castro and P. Roig, Eur. Phys. J. C 79. (2018)

Type-I seesaw

- Minimal extension (νSM) (incorporates further features)
  - **Very tiny Yukawa couplings in order to explain the observed neutrino masses**
  - **Possible invariant Majorana mass terms $\frac{1}{2}MN_RN_R$? $(\Delta L = 2)$**

Type-I see-saw scenario

- Natural explanation for the tiny ν masses via new dynamics with a heavy scale

$$m_\nu(\sim 0{,}05\,\text{eV}) \simeq \frac{m_D^2(\sim 10^4 \;\; \text{GeV}^2)}{M(\sim 10^{14}\,\text{GeV})}, \qquad \theta(\sim 10^{-6}) \simeq \sqrt{\frac{m_v}{M}}.$$

with $m_D = y_\nu v$.

New Heavy effects decoupled. Any evidence of cLFV would be a clear evidence of new physics beyond these minimal extensions.

Some interesting scenarios

- Low scale seesaws. They are based on approximate symmetries, some fine tunning or ansatz on the neutrino matrix that alter the general relations.

Rich phenomenology at high-intensities! (and also at LHC)

- Simplified "(3+1) toy"model (No assumption on the mechanism of neutrino mass generation)

Modified neutral and charged leptonic currents A. Ilakovac and A. Pilaftsis, Nucl. Phys. B 437, 491 (1995), F. del Aguila and J. A. Aguilar-Savedra, Nucl. Phys. B 813, 22 (2009)

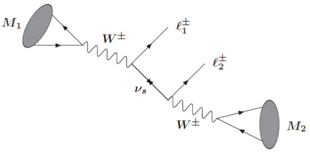
$$\mathcal{L}_{W^\pm} = -\frac{g}{\sqrt{2}} W_\mu^- \sum_{\alpha=1}^{3} \sum_{j=1}^{3+n_S} U_{\alpha j} \bar{\ell}_\alpha \gamma^\mu P_L \nu_j + \text{H.c.},$$

$$\mathcal{L}_Z = -\frac{g}{4c_W} Z_\mu \sum_{i,j=1}^{3+n_S} \bar{\nu}_i \gamma^\mu \left(P_L C_{ij} - P_R C_{ij}^*\right) \nu_j - \frac{g}{4c_W} Z_\mu \sum_{\alpha=1}^{3} \bar{\ell}_\alpha \gamma^\mu \left(C_V - C_A \gamma_5\right) \ell_\alpha,$$

LNV Observables (Testing the nature of Majorana neutrinos.)

- Beyond the extensive search of neutrinoless double beta-decay $0\nu\beta\beta$
- Extensions via the addition of Majorana sterile fermions, with nonnegligible mixings open the door to a long list of accessible $\Delta L = 2$ processes.

LNV decay	Current Bound	
	$\ell = e,\ \ell' = e$	$\ell = \mu,\ \ell' = \mu$
$K^- \to \ell^- \ell'^- \pi^+$	6.4×10^{-10}	1.1×10^{-9}
$D^- \to \ell^- \ell'^- \pi^+$	1.1×10^{-6}	2.2×10^{-8}
$D^- \to \ell^- \ell'^- K^+$	9.0×10^{-7}	1.0×10^{-5}
$B^- \to \ell^- \ell'^- \pi^+$	2.3×10^{-8}	4.0×10^{-9}
$B^- \to \ell^- \ell'^- K^+$	3.0×10^{-8}	4.1×10^{-8}
$B^- \to \ell^- \ell'^- \rho^+$	1.7×10^{-7}	4.2×10^{-7}
$B^- \to \ell^- \ell'^- D^+$	2.6×10^{-6}	6.9×10^{-7}



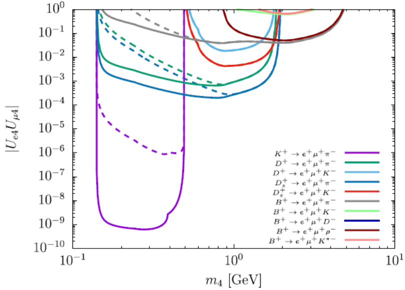
A. Atre, T. Han, S. Pascoli and B. Zhang, JHEP 0905, 030 (2009), A. Abada, V. De Romeri, M. Lucente, A. M. Teixeira and T. Toma, JHEP 1802, 169 (2018),... .

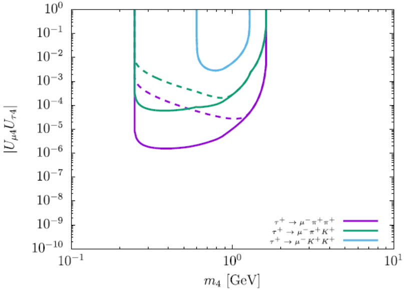
- The Majorana neutrino mass must be in the kinematical range allowed to be produced on-shell "Resonant-enhancement"
- Neutrinos with well defined width in order to decay inside the detector.

LNV decay	Current Bound	
	$\ell = e$	$\ell = \mu$
$\tau^- \to \ell^+ \pi^- \pi^-$	2.0×10^{-8}	3.9×10^{-8}
$\tau^- \to \ell^+ \pi^- K^-$	3.2×10^{-8}	4.8×10^{-8}
$\tau^- \to \ell^+ K^- K^-$	3.3×10^{-8}	4.7×10^{-8}

LNV Observables (Testing the nature of Majorana neutrinos.)

Constraints from the simplified “3+1”SM extension





- The no observation of these decays set important constraints on the relevant combination of leptonic mixing matrix elements
- Future improvements in the sensitivity of some channels are planned by the LCHb and Belle II collaborations.

A. Abada, V. De Romeri, M. Lucente, A. M. Teixeira and T. Toma, JHEP 1802, 169 (2018),... .

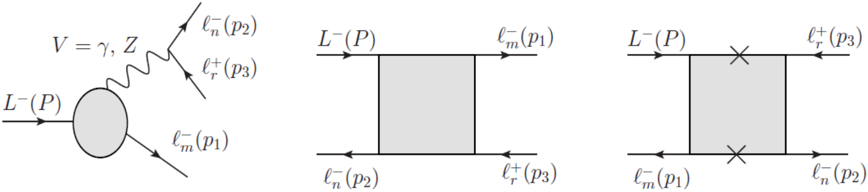
cLFV Observables

- Another outstanding effect in a higher regime for the masses of the new neutrino states.

	$L^-(P) \to \ell_m^-(p_1)\ell_n^-(p_2)\ell_r^+(p_3)$
Type 1 ($m = n = r$)	$\mu^- \to e^- e^- e^+$ $\tau^- \to \mu^- \mu^- \mu^+$ $\tau^- \to e^- e^- e^+$
Type 2 ($m \neq n = r$)	$\tau^- \to \mu^- e^- e^+$ $\tau^- \to e^- \mu^- \mu^+$
Type 3 ($m = n \neq r$)	$\tau^- \to \mu^- \mu^- e^+$ $\tau^- \to e^- e^- \mu^+$

M. C. Gonzalez-Garcia and J. W. F. Valle, Mod. Phys. Lett. A 7, 477 (1992), A. Ilakovac and A. Pilaftsis, Nucl. Phys. B 437, 491 (1995).

- The presence of heavy neutrinos inside the loop would produce a non-decoupling effect in cLFV transitions.



Owing to the conservation of electric charge, diagrams (I) and (II) involved only LNC interactions, whereas the (III) box contributions involve LNV vertices.

cLFV Observables

- The total number of Feynman diagrams contributions are different for each type. The channels of the type-1 and type-2 have contributions of penguin and box diagram. On the other hand, type-3 only involve box contributions.
- We have obtained analytical formulas for the BR of all the channels in agreement with the reference A. Ilakovac and A. Pilaftsis, Nucl. Phys. B 437, 491 (1995).
- Previous predictions $B(\tau^- \to e^- e^- e^+) \sim 10^{-6}$ and $B(\tau^- \to e^- \mu^- \mu^+) \sim 10^{-6}$ for $m_N = 3$ TeV. Above the current limits.
- An updated numerical analysis in progress.

Experimental limits

Reaction	Present limit	C.L.	Experiment	Year
$\mu^+ \to e^+\gamma$	$< 4.2 \times 10^{-13}$	90%	MEG at PSI	2016
$\mu^+ \to e^+e^-e^+$	$< 1.0 \times 10^{-12}$	90%	SINDRUM	1988
$\tau \to e\gamma$	$< 3.3 \times 10^{-8}$	90%	BaBar	2010
$\tau \to \mu\gamma$	$< 4.4 \times 10^{-8}$	90%	BaBar	2010
$\tau \to eee$	$< 2.7 \times 10^{-8}$	90%	Belle	2010
$\tau \to \mu\mu\mu$	$< 2.1 \times 10^{-8}$	90%	Belle	2010
$Z \to \mu e$	$< 7.5 \times 10^{-7}$	95%	LHC ATLAS	2014
$Z \to \tau e$	$< 9.8 \times 10^{-6}$	95%	LEP OPAL	1995
$Z \to \tau\mu$	$< 1.2 \times 10^{-5}$	95%	LEP DELPHI	1997
$h \to e\mu$	$< 3.5 \times 10^{-4}$	95%	LHC CMS	2016
$h \to \tau\mu$	$< 2.5 \times 10^{-3}$	95%	LHC CMS	2017
$h \to \tau e$	$< 6.1 \times 10^{-3}$	95%	LHC CMS	2017

- **The Mu3e experiment will search for LFV in $\mu \to 3e$ decay with a sensitivity down to 10^{-16}.**
  - Nucl. Part. Phys. Proc. 287-288, 169 (2017).
- **Belle-II shall be able to set limits on the $\tau^- \to \ell^-\ell'^+\ell'^-$ decays at the level of O(10^{-9})-O(10^{-10}) with their full data set ($50\, ab^{-1}$).**
  - Belle-II Physics Book, Belle-II Collaboration and B2TIP-Community

Conclusions

- LNV and cLFV processes are forbidden or strong suppressed in the νSM and the usual $Type - I$ seesaw model. However ...
- Scenarios with new Heavy Neutrinos state in the multi-GeV region plays a fundamental role in the current search of new physics.
- Depending on the properties of the new Heavy state they can produce measurable LNV or cLFV effects.
- The no observation of such effects set strong limits on the hypothetical scenarios.

Thank you!