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Colloquia: Pontecorvo100

Lepton flavor violation

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Summary. — We present a concise review of the status of charged lepton flavor violation (cLFV) in scenarios beyond the SM. We emphasize that the current experimental resolutions on cLFV processes are already testing territories of new physics (NP) models well beyond the LHC reach. On the other hand, with the expected sensitivities of next-generation experiments, cLFV will become the most powerful probe of NP signals at our disposal.

1. – Introduction: a tribute to Pontecorvo

Bruno Pontecorvo has played a leading and pioneering role in many aspects of neutrino physics, as it has been throughly reviewed at this Conference [1]. Referring to ref. [1] for a lucid and detailed account of his main contributions, in the following, we limit ourselves to briefly summarize some of them.

In 1946 Pontecorvo proposed a radiochemical method of neutrino detection [2] which was realized by R. Davis in his pioneering solar neutrino experiment (as well as in the GALLEX and SAGE experiments) for which he was awarded in 2002 the Nobel Prize.

Pontecorvo was also the first who came to the idea of the existence of an universal weak interaction which includes interactions of nucleons with $e - \nu$ and $\mu - \nu$ pairs [3].

In 1947-49 in Canada Pontecorvo and Hincks made pioneering experiments on the investigation of muon decay [4, 5]. They found that i) the charged particle produced in the muon decay is an electron, ii) the decay $\mu \to e + \gamma$ is forbidden, iii) the muon decays into three particles.

Pontecorvo was one of the first who understood the feasibility of experiments with accelerator neutrino and he proposed the experiment which allowed to proof that ν_μ and ν_e are different particles [6]. His proposal was realized in the famous Brookhaven experiment in 1962 [7]. In 1988 Lederman, Steinberger and Schwartz were awarded the Nobel prize for the discovery of the muon type of neutrino.

Pontecorvo was also the pioneer of neutrino oscillations. In 1957, he put forward the idea of oscillation between active and sterile neutrinos when only one type of neutrino was known. After discovery of ν_μ, in 1967 Pontecorvo extended his idea of oscillations

TABLE I. – *Future sensitivities of next-generation experiments* [19].

LFV process	Experiment	Future limits	Year (expected)
$BR(\mu \to e\gamma)$	MEG [11]	$\mathcal{O}(10^{-14})$	~ 2019
	Project X [12]	$\mathcal{O}(10^{-15})$	> 2021
$BR(\mu \to eee)$	Mu3e [13]	$\mathcal{O}(10^{-15})$	~ 2017
	”	$\mathcal{O}(10^{-16})$	> 2017
	MUSIC [14]	$\mathcal{O}(10^{-16})$	~ 2017
	Project X [12]	$\mathcal{O}(10^{-17})$	> 2021
$CR(\mu \to e)$	COMET [14]	$\mathcal{O}(10^{-17})$	~ 2017
	Mu2e [15]	$\mathcal{O}(10^{-17})$	~ 2020
	PRISM/PRIME [16,14]	$\mathcal{O}(10^{-18})$	~ 2020
	Project X [12]	$\mathcal{O}(10^{-19})$	> 2021
$BR(\tau \to \mu\gamma)$	Belle II [17]	$\mathcal{O}(10^{-8})$	> 2020
$BR(\tau \to \mu\mu\mu)$	Belle II [17]	$\mathcal{O}(10^{-10})$	> 2020
$BR(\tau \to e\gamma)$	Super B [18]	$\mathcal{O}(10^{-9})$	> 2020

to the case of two types of neutrinos [8]. Before R. Davis published his first result on the detection of solar neutrinos Pontecorvo wrote a paper in collaboration with Gribov [9] pointing out that, if the total lepton number is violated, it is possible to introduce neutrino (Majorana) mass terms. In such a scheme, transitions between active neutrinos and antineutrinos are allowed.

In the last two decades, dedicated experiments have firmly established the existence of neutrino oscillations as envisaged by Pontecorvo and most of the neutrino parameters have been measured (see [10]). Despite of the tremendous experimental progress, it is fair to say that the same is not true in the theoretical side. Indeed, the current data might be reproduced in a number of different ways, spanning from anarchy to discrete flavour symmetries (see [10]). As a result, the flavour structure of the three fermion generations remains a mystery.

2. – Charged lepton flavor violation (CLFV)

The origin of flavor remains, to a large extent, an open problem. However, significant progress has been achieved in the phenomenological investigation of the sources of flavour symmetry breaking which are accessible at low energies, ruling out models with significant misalignments from the SM Yukawa couplings at the TeV scale.

The search for LFV in charged leptons is probably the most interesting goal of flavour physics in the next years. The observation of neutrino oscillations has clearly demonstrated that lepton flavour is not conserved. The question is whether LFV effects can be visible also in other sectors of the theory, or if we can observe LFV in processes that conserve total lepton number. The most promising LFV low-energy channels are probably $\mu \to e\gamma$, $\mu \to eee$, $\mu \to e$ conversion in Nuclei as well as τ LFV processes which will be further investigated at the Super-Belle machine. The future sensitivities of next-generation experiments are collected in table I.

Moreover, the flavour-conserving component of the same diagrams generating $\mu \to e\gamma$

induces non-vanishing contributions to the anomalous magnetic moment of leptons as well as to the leptonic EDMs. In this context, the current anomaly for the muon $(g-2)$, reinforces the expectation of detecting $\mu \to e\gamma$ within the reach of the MEG experiment. Once some clear deviation from the SM is established, the next most important step is to identify correlations among different non-standard effects that can reveal the flavour-breaking pattern of the new degrees of freedom providing, at the same time, a powerful tool to disentangle among different New Physics scenarios. The above program represents one of the most exciting proofs of the synergy and interplay existing between the LHC, i.e. the *high-energy frontier*, and high-precision low-energy experiments, i.e. the *high-intensity frontier*.

The physics responsible for neutrino masses and mixing might or might not be related to the physics related to cLFV. On general grounds, we can say that:

- neutrino masses might be naturally explained within see-saw scenarios which introduce heavy right-handed Majorana neutrinos typically at the grand-unification (GUT) scale. These scenarios can also explain the baryon-antibaryon asymmetry in the universe through the leptogenesis mechanism. The new interactions of the model generally violate lepton-number $L = L_e + L_\mu + L_\tau$ (LNV).
- In the Standard Model (SM) with massive neutrinos, where the only source of LFV is coming from the operators responsible for the neutrino masses, the LFV effects are loop suppressed and proportional to the GIM factor $(m_\nu/M_W)^4$, therefore, completely negligible. For instance, it turns out that $\mathrm{Br}(\mu \to e\gamma) \sim 10^{-54}$.
- On the other hand, generic models for new physics (NP) at the TeV scale contain new sources for LFV (but not necessarily for LNV), leading to decay rates accessible with future experiments.

From the low-energy point of view, these observations can be accounted for by considering the SM as an effective theory and extending its Lagrangian,

$$\mathcal{L}_{\mathrm{eff}} = \mathcal{L}_{\mathrm{SM}} + \frac{1}{\Lambda_{\mathrm{LNV}}}\,\mathcal{O}^{\mathrm{dim}-5} + \frac{1}{\Lambda^2_{\mathrm{LFV}}}\,\mathcal{O}^{\mathrm{dim}-6} + \dots \tag{1}$$

Here, the dimension-5 operator responsible for the neutrino masses is uniquely given in terms of the lepton doublets L^i and the Higgs doublet H in the SM,

$$\mathcal{O}^{\mathrm{dim}-5} = (g_\nu)^{ij}\,(\bar{L}^i \widetilde{H})(\widetilde{H}^\dagger L^j)^c + \mathrm{h.c.} \tag{2}$$

and the misalignment between the flavour matrix g_ν and the Yukawa coupling matrix Y_E in the charged-lepton sector leads to a non-trivial mixing matrix U_{PMNS} for neutrino oscillations.

For instance, within scenarios with right-handed Majorana neutrinos (type-I see saw), one can identify $g_\nu/\Lambda_{\mathrm{LNV}} = Y_\nu\, M^{-1}\, Y_\nu^T$, where Y_ν is the Yukawa matrix in the neutrino sector, and M the Majorana mass matrix.

Examples for a dimension-6 operator are

$$\mathcal{O}^{\mathrm{dim}-6} \ni \;\; \bar{\mu}_R\,\sigma^{\mu\nu}\,H\,e_L\,F_{\mu\nu}\,, \quad (\bar{\mu}_L\gamma^\mu e_L)\left(\bar{f}_L\gamma^\mu f_L\right)\,, \quad (\bar{\mu}_R e_L)\left(\bar{f}_R f_L\right)\,, \tag{3}$$

where $f = e, u, d$ and the first dipole-operator leads to LFV decays like $\mu \to e\gamma$ while the second and third ones generate, at the leading order, only processes like $\mu \to eee$ and

$\mu \leftrightarrow e$ conversion in Nuclei. Obviously, the underlying dipole-transition $\mu \to e\gamma^\star$ with a virtual γ also contributes to $\mu \to eee$ and $\mu \leftrightarrow e$ conversion in Nuclei.

In particular, within NP theories where the dominant LFV effects are captured by the dipole-operator, the following model-independent relations hold

$$\begin{aligned} &\frac{\mathrm{BR}(\ell_i \to \ell_j \ell_k \bar{\ell}_k)}{\mathrm{BR}(\ell_i \to \ell_j \bar{\nu}_j \nu_i)} \simeq \frac{\alpha_{el}}{3\pi}\left(\log\frac{m^2_{\ell_i}}{m^2_{\ell_k}} - 3\right)\frac{\mathrm{BR}(\ell_i \to \ell_j \gamma)}{\mathrm{BR}(\ell_i \to \ell_j \bar{\nu}_j \nu_i)}\,, \\ &\mathrm{CR}(\mu \to e \text{ in N}) \simeq \alpha_{\mathrm{em}} \times \mathrm{BR}(\mu \to e\gamma)\,, \end{aligned} \tag{4}$$

and therefore, the current MEG bound $\mathrm{BR}(\mu \to e\gamma) \sim 5 \times 10^{-13}$ already implies that $\mathrm{BR}(\mu \to eee) \leq 3 \times 10^{-15}$ and $\mathrm{CR}(\mu \to e \text{ in N}) \leq 3 \times 10^{-15}$.

However, it is worth stressing that in many NP scenarios non-dipole operators, such as those shown in eq. 3, provide the dominant sources of LFV effects. Therefore, in such cases, $\mu \to eee$ and $\mu \leftrightarrow e$ conversion in Nuclei represent the best probes of LFV.

Dipole transitions $\ell \to \ell'\gamma$ in the leptonic sector are accounted for by means of the effective Lagrangian

$$\mathcal{L} = e\frac{m_\ell}{2}\left(\bar{\ell}_R \sigma_{\mu\nu} A_{\ell\ell'} \ell'_L + \bar{\ell}'_L \sigma_{\mu\nu} A^\star_{\ell\ell'} \ell_R\right) F^{\mu\nu} \qquad \ell, \ell' = e, \mu, \tau\,. \tag{5}$$

Starting from eq. (5), we can evaluate LFV processes, such as $\mu \to e\gamma$,

$$\frac{\mathrm{BR}(\ell \to \ell'\gamma)}{\mathrm{BR}(\ell \to \ell'\nu_\ell \bar{\nu}_{\ell'})} = \frac{48\pi^3\alpha}{G_F^2}\left(|A_{\ell\ell'}|^2 + |A_{\ell'\ell}|^2\right)\,. \tag{6}$$

The underlying $\ell \to \ell'\gamma$ transition can generate, in addition to LFV processes, also lepton flavor conserving processes like the anomalous magnetic moments Δa_ℓ as well as leptonic electric dipole moments (EDMs, d_ℓ). In terms of the effective Lagrangian of eq. (5) we can write Δa_ℓ and d_ℓ as

$$\Delta a_\ell = 2m_\ell^2\ \mathrm{Re}(A_{\ell\ell})\,, \qquad \frac{d_\ell}{e} = m_\ell\ \mathrm{Im}(A_{\ell\ell})\,. \tag{7}$$

On general grounds, one would expect that, in concrete NP scenarios, Δa_ℓ, d_ℓ and $\mathrm{BR}(\ell \to \ell'\gamma)$, are correlated. In practice, their correlations depend on the unknown flavor and CP structure of the NP couplings and thus we cannot draw any firm conclusion.

Parametrizing the amplitude $A_{\ell\ell'}$ as $A_{\ell\ell'} = c_{\ell\ell'}/\Lambda^2$, where Λ refers to the NP scale, we can evaluate which are the values of Λ probed by $\mu \to e\gamma$. We find that

$$\mathrm{BR}(\mu \to e\gamma) \approx 10^{-12}\left(\frac{500\ \mathrm{TeV}}{\Lambda}\right)^4\left(|c_{\mu e}|^2 + |c_{e\mu}|^2\right)\,, \tag{8}$$

and therefore, for $c_{\mu e} \sim 1$ and/or $c_{e\mu} \sim 1$, we are left with $\Lambda > 500$ TeV.

Since the anomalous magnetic moment of the muon $a_\mu = (g-2)_\mu/2$ exhibits a $\sim 3.5\sigma$ discrepancy between the SM prediction and the experimental value [20] $\Delta a_\mu = a_\mu^{\mathrm{EXP}} -$

$a_\mu^{\rm SM} = 2.90\,(90) \times 10^{-9}$, it is interesting to monitor the implications for BR$(\ell \to \ell'\gamma)$ assuming that such a discrepancy is due to NP. In particular, we find that

$$
\begin{aligned}
(9)\qquad & \mathrm{BR}(\mu \to e\gamma) \approx 10^{-12} \left(\frac{\Delta a_\mu}{3\times 10^{-9}}\right)^2 \left(\frac{\theta_{e\mu}}{2\times 10^{-5}}\right)^2 ,\\
& \mathrm{BR}(\tau \to \ell\gamma) \approx 10^{-8} \left(\frac{\Delta a_\mu}{3\times 10^{-9}}\right)^2 \left(\frac{\theta_{\ell\tau}}{5\times 10^{-3}}\right)^2 ,
\end{aligned}
$$

where $\theta_{\ell\ell'} = \sqrt{|c_{\ell\ell'}|^2 + |c_{\ell'\ell}|^2}/c_{\mu\mu}$. Therefore, we learn that the a_μ anomaly can be accommodated while satisfying the BR$(\mu \to e\gamma)$ bound only for extremely small flavor mixing angles $\theta_{e\mu}$.

Similarly, from eq. 7, we find that $d_e \simeq 10^{-24} \times [\mathrm{Im}(c_{ee})/\mathrm{Re}(c_{\mu\mu})]$ e cm whenever $\Delta a_\mu \approx 3\times 10^{-9}$. Therefore, also the electron EDM exceeds the current experimental bound by many orders of magnitudes unless there exists a dynamical mechanism suppressing the relevant CP violating phases.

3. – LFV in specific NP models

The phenomenology of cLFV observables has been worked out in a number of well motivated NP scenarios. Among the most important questions are (i) which are the best probes among cLFV processes for any given NP model, (ii) how the predictions compare with the present/foreseen experimental bounds, (iii) what the constraints are on new sources of LFV and new-particle masses, (iv) what are the correlations among different LFV observables.

Concerning the latter point, it should be stressed that 1) ratios for branching ratios of processes such as $\mu \to e\gamma$ and $\tau \to \mu\gamma$ would provide a direct access to the flavor structure of the NP model while 2) a comparative analysis of processes with the same underlying flavor transition (such as $\mu \to e\gamma$ and $\mu \to eee$) would provide information about the operators which are generating potential LFV signals.

In the following, we briefly discuss three classes of NP models: supersymmetric (SUSY) extensions of the SM, littlest Higgs models with T-parity, and a model with a sequential 4$^{\rm th}$ generation (SM4).

3˙1. *CLFV in SUSY models.* – In SUSY models, new sources for LFV stem from the soft SUSY-breaking sector since the lepton and slepton mass matrices are generally misaligned. The leading effects for cLFV processes arise from sneutrino-chargino and slepton-neutralino loops. In the generic MSSM, it is useful to stick to the mass-insertion approximation, assuming small off-diagonal entries in the slepton mass matrices $(\delta^{ij}_{AB})_f = (m^2_{\tilde A\tilde B})_{ij}/m^2_{\tilde\ell}$, where $A,B = L,R$ and $m_{\tilde\ell}$ is an average slepton mass.

Low-energy SUSY models with arbitrary soft-breaking terms would induce unacceptably large flavor-violating effects and this motivates scenarios with flavor-universality in the SUSY-breaking mechanism. Yet, even assuming such a flavor-blind scenario, sizable flavor-mixing effects may be generated at the weak scale by the running of soft-breaking parameters from the scale of SUSY-breaking mediation [21], as for instance in the case of a see-saw mechanism [22].

In such a case, the dominant LFV effects are induced in the left-handed entries of the

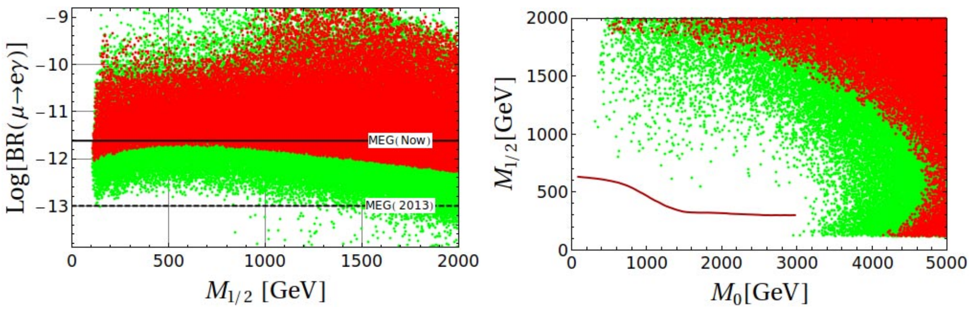

Fig. 1. – Left: BR($\mu \to e\gamma$) in mSUGRA for fixed $\tan\beta = 10$ and $U_{e3} = 0.11$. The red (blue) colored points correspond to PMNS (CKM) case. Right: allowed space in the $m_0 - m_{1/2}$ plane which satisfy the current MEG bound. For more details, see ref. [19].

slepton mass matrix. As a result, one gets [22]:

$$(m^2_{\tilde{L}\tilde{L}})_{i\neq j} \approx -\frac{3m_0^2 + A_0^2}{8\pi^2} \sum_k (Y_\nu^*)_{ik} (Y_\nu)_{jk} \log\left(\frac{M_X}{M_{R_k}}\right), \tag{10}$$

where M_X represents the GUT scale, M_{R_k} the scale of right-handed neutrinos, and m_0 and A_0 stand for the universal soft mass and trilinear terms at the high scale.

On general ground, it is not possible to correlate the LFV sources in the see-saw mechanism, stemming from the Yukawa matrix Y_ν, with the low-energy observables from the neutrino sector [23]. Therefore, we cannot draw any firm conclusion about the branching ratios of cLFV processes. Two extreme scenarios for mixing are typically considered to be present in Y_ν [24-26]:

$$Y_\nu = Y_u \qquad \text{(CKM Case)} \tag{11}$$

$$Y_\nu = Y_u^{\rm diag}\, \mathbf{U}_{\rm PMNS} \qquad \text{(PMNS Case)}, \tag{12}$$

where $Y_u = \mathbf{V}_{\rm CKM} Y_u^{\rm diag} \mathbf{V}^\dagger_{\rm CKM}$. In fig. 1, we show the predictions for BR($\mu \to e\gamma$) in the CKM and PMNS cases in the light of recent experimental results on the neutrino reactor angle $U_{e3} \approx 0.15$ and the Higgs-like boson with mass $m_h \approx$ 125 GeV. The major lesson we learn is that, especially for the large mixing case, only a small range of parameter space is still allowed.

Another scenario which has received particular attention after the discovery of the Higgs-like boson at the LHC is the so-called "disoriented A-terms" scenario [27]. The assumption of disoriented A-terms is that flavor violation is restricted to the trilinear terms

$$(\delta^{ij}_{LR})_f \sim \frac{A_f \theta^f_{ij} m_{f_j}}{m_{\tilde{f}}} \qquad f = u, d, \ell\ , \tag{13}$$

where θ^f_{ij} are generic mixing angles. This pattern can be obtained when the trilinear terms have the same hierarchical pattern as the corresponding Yukawa matrices but they do not respect exact proportionality. A natural realization of this ansatz arises in scenarios with partial compositeness [28], where also the SM flavor puzzle can be

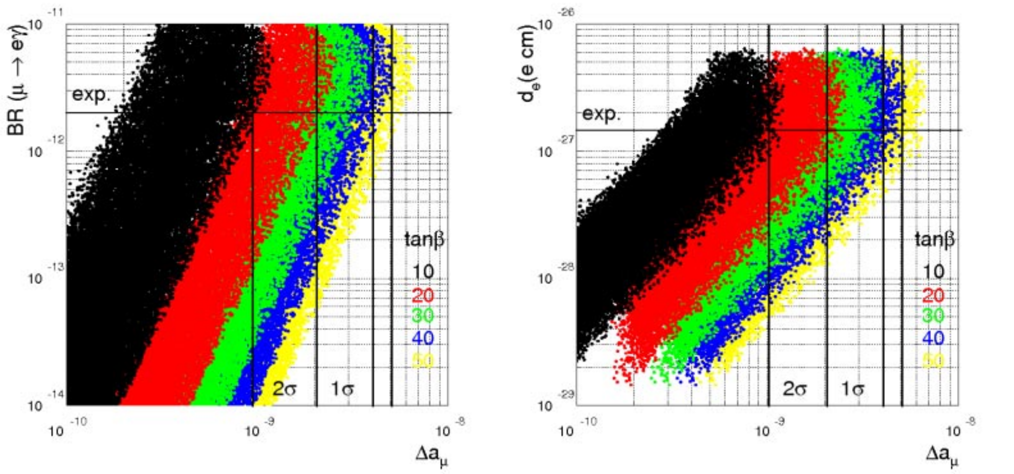

Fig. 2. – Predictions of the disoriented A-term scenario [29]. Left: $\mu \to e\gamma$ vs. Δa_μ. Right: d_e vs. Δa_μ.

accounted for. Interestingly, the structure of eq. (13) allows us to naturally satisfy the very stringent flavor bounds of the down-sector thanks to the smallness of down-type quark masses. On the other hand, sizable A-terms help to account for a Higgs boson with mass around 125 GeV while keeping the SUSY scale not too far from the TeV.

The bounds from the lepton sector can be satisfied under the (natural) assumption that the unknown leptonic flavor mixing angles are of the form $\theta^\ell_{ij} \sim \sqrt{m_i/m_j}$ [28]. In particular, we get the following predictions [29]

$$\text{(14)} \qquad \mathrm{BR}(\mu \to e\gamma) \approx 6 \times 10^{-13} \left| \frac{A_\ell}{\mathrm{TeV}} \frac{\theta^\ell_{12}}{\sqrt{m_e/m_\mu}} \right|^2 \left(\frac{\mathrm{TeV}}{m_{\tilde{\ell}}} \right)^4 ,$$
$$d_e \approx 4 \times 10^{-28}\ \mathrm{Im} \left(\frac{A_\ell\, \theta^\ell_{11}}{\mathrm{TeV}} \right) \left(\frac{\mathrm{TeV}}{m_{\tilde{\ell}}} \right)^2 e \text{ cm} ,$$
$$\Delta a_\mu \approx 1 \times 10^{-9} \left(\frac{\mathrm{TeV}}{m_{\tilde{\ell}}} \right)^2 \left(\frac{\tan\beta}{30} \right) .$$

where we have assumed that the only possible sources of CP violation arise from A terms, as well. These estimates are fully confirmed by the numerical analysis shown in fig. 2 which has been obtained by means of the following scan: $0.5 \leq |A_e|/\tilde{m} \leq 2$ with $\sin\phi_{A_e}$=1, $\tilde{m} \leq 2$ TeV, $(M_2, \mu, M_1) \leq 1$ TeV and $10 \leq \tan\beta \leq 50$ [29].

It is interesting that disoriented A-terms can account for $(g-2)_\mu$, satisfy the bounds on $\mu \to e\gamma$ and d_e, while giving predictions within experimental reach [29].

3·2. *CLFV in Little Higgs Models.* – Little Higgs models with T-parity, originally proposed as an alternative solution to SUSY for the hierarchy problem, also contain extra sources of LFV. Indeed, besides new heavy gauge bosons, T-parity requires the existence of new heavy mirror SM fermions with masses of the order TeV, which contribute to

TABLE II. – *Comparison of ratios of LFV branching ratios in the LHT model* [30], *the MSSM* [31], *and the SM4 model* [32].

ratio	LHT	MSSM	SM4
$\frac{\mathcal{B}(\mu^-\to e^-e^+e^-)}{\mathcal{B}(\mu\to e\gamma)}$	$0.02\ldots 1$	$\sim 6\cdot 10^{-3}$	$0.06\ldots 2.2$
$\frac{\mathcal{B}(\tau^-\to e^-e^+e^-)}{\mathcal{B}(\tau\to e\gamma)}$	$0.04\ldots 0.4$	$\sim 1\cdot 10^{-2}$	$0.07\ldots 2.2$
$\frac{\mathcal{B}(\tau^-\to \mu^-\mu^+\mu^-)}{\mathcal{B}(\tau\to \mu\gamma)}$	$0.04\ldots 0.4$	$\sim 2\cdot 10^{-3}$	$0.06\ldots 2.2$
$\frac{\mathcal{B}(\tau^-\to e^-\mu^+\mu^-)}{\mathcal{B}(\tau\to e\gamma)}$	$0.04\ldots 0.3$	$\sim 2\cdot 10^{-3}$	$0.03\ldots 1.3$
$\frac{\mathcal{B}(\tau^-\to \mu^-e^+e^-)}{\mathcal{B}(\tau\to \mu\gamma)}$	$0.04\ldots 0.3$	$\sim 1\cdot 10^{-2}$	$0.04\ldots 1.4$
$\frac{\mathcal{B}(\tau^-\to e^-e^+e^-)}{\mathcal{B}(\tau^-\to e^-\mu^+\mu^-)}$	$0.8\ldots 2$	~ 5	$1.5\ldots 2.3$
$\frac{\mathcal{B}(\tau^-\to \mu^-\mu^+\mu^-)}{\mathcal{B}(\tau^-\to \mu^-e^+e^-)}$	$0.7\ldots 1.6$	~ 0.2	$1.4\ldots 1.7$
$\frac{\mathrm{R}(\mu\mathrm{Ti}\to e\mathrm{Ti})}{\mathcal{B}(\mu\to e\gamma)}$	$10^{-3}\ldots 10^{2}$	$\sim 5\cdot 10^{-3}$	$10^{-12}\ldots 26$

LFV processes via penguin and box diagrams [30]. The fundamental parameters of the model are the scale parameter f, the three mirror lepton masses: $M^{\ell}_{H_{1,2,3}}$, the three mirror-lepton mixing angles: θ^{ℓ}_{ij}, and three new (Dirac) CP phases δ^{ℓ}_{ij}. In general, the potential LFV effects in the LHT model exceed the experimental bounds by many orders of magnitude unless we push the scale f far away from the TeV scale and/or we assume small mirror-lepton mixing angles.

3$\cdot$3. *CLFV in SM4*. – Important LFV effects are generally expected also within models with an additional fourth generation (SM4) of leptons (and quarks), introducing a new heavy charged lepton τ' and a (Dirac-)neutrino $\nu_{\tau'}$, together with an extended 4×4 mixing matrix U_{ij} in the lepton sector [32]. In this set-up, the radiative μ and τ decays, fulfill the simple relations

$$\begin{aligned}
\frac{\mathcal{B}(\tau\to\mu\gamma)}{\mathcal{B}(\mu\to e\gamma)} &\simeq \left|\frac{U_{\tau 4}}{U_{e4}}\right|^2 \mathcal{B}(\tau^-\to\nu_\tau\mu^-\bar{\nu}_\mu)\,,\\
\frac{\mathcal{B}(\tau\to\mu\gamma)}{\mathcal{B}(\tau\to e\gamma)} &\simeq \left|\frac{U_{\mu 4}}{U_{e4}}\right|^2 \frac{\mathcal{B}(\tau^-\to\nu_\tau\mu^-\bar{\nu}_\mu)}{\mathcal{B}(\tau^-\to\nu_\tau e^-\bar{\nu}_e)} \approx \left|\frac{U_{\mu 4}}{U_{e4}}\right|^2,\\
\frac{\mathcal{B}(\tau\to e\gamma)}{\mathcal{B}(\mu\to e\gamma)} &\simeq \left|\frac{U_{\tau 4}}{U_{\mu 4}}\right|^2 \mathcal{B}(\tau^-\to\nu_\tau e^-\bar{\nu}_e)\,.
\end{aligned}\tag{15}$$

which put stringent constraints on the elements $|U_{i4}|$, independent of the heavy neutrino mass. Concerning μ-e conversion and $\mu\to e\gamma$, the foreseen experiments have the potential to further tighten the constraints on $|U_{e4}U_{\mu 4}|$.

A comparison for LFV branching ratios from various models is shown in Table II.

4. – Conclusions

Despite of the fact that the origin of flavor remains a major open problem, significant progress has been achieved in the phenomenological investigation of the sources of flavour symmetry breaking which are accessible at low energies, ruling out models with significant misalignments from the SM Yukawa couplings at the TeV scale.

The search for LFV in charged leptons is probably the most interesting goal of flavour physics in the next years (see table I). The observation of neutrino oscillations has clearly demonstrated that lepton flavour is not conserved. The question is whether LFV effects can be visible also in other sectors of the theory. The most promising LFV low-energy channels are probably $\mu \to e\gamma$, $\mu \to eee$, $\mu \to e$ conversion in Nuclei as well as τ LFV processes. The current experimental resolutions on cLFV processes are already testing territories of new physics (NP) models well beyond the LHC reach. On the other hand, with the expected sensitivities of next-generation experiments, cLFV will become the most powerful probe of NP signals at our disposal.

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