

## Theoretical review on lepton flavour violation

P. PARADISI

*Technical University Munich, Physics Department - D-85748 Garching, Germany*

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**Summary.** — The synergy and interplay of high energy data with flavour precision data are expected to shed some light on the “Flavour Problem”. Lepton flavor violating processes like  $\mu \rightarrow e\gamma$  represent “golden channels” where to look for New Physics effects, given their high New Physics sensitivity and the outstanding experimental progress we expect in the upcoming years. If LFV is observed, the next crucial step will be to trace back the New Physics model at work by means of a correlated analysis of various observables.

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### 1. – Introduction

The most important achievement we expect to reach at the beginning of the LHC era is the understanding of the underlying mechanism accounting for the electroweak symmetry breaking, in particular, whether the Higgs mechanism is realized in nature or not. Moreover, the LHC is also expected to shed light on the hierarchy problem, since a natural solution of it calls for a TeV scale New Physics (NP).

On the other hand, low-energy flavour physics observables provide the most powerful tool to unveil the symmetry properties of the NP theory that will emerge at the LHC, if any. In fact, high-precision measurements at the LHC are made typically challenging by the huge background and by irreducible hadronic uncertainties.

The last decade has established that flavour-changing and CPV processes in  $B_{s,d}$  and K systems are well described by the SM. The same is true for electroweak precision tests. This implies automatically tight constraints on flavour-changing phenomena beyond the SM and a potential problem for a natural solution of the hierarchy problem.

On general ground, the main lesson we learned so far from the flavour data is that a TeV scale NP must have a highly non-generic flavour structure in order to satisfy all the existing constraints. Moreover, in order to avoid fine tuning of parameters, natural protection mechanisms suppressing FCNCs generated by NP are required. Famous examples of such mechanisms are MFV, alignment and degeneracy, as arising from Abelian and non-Abelian flavour symmetries.

TABLE I. – Present [2] and upcoming experimental limits on various leptonic processes at 90% C.L.

Process	Present bounds	Future bounds	Experiments
$\text{BR}(\mu \rightarrow e\gamma)$	$1.2 \times 10^{-11}$	$\mathcal{O}(10^{-13})$	MEG, PSI
$\text{BR}(\mu \rightarrow eee)$	$1.1 \times 10^{-12}$	$\mathcal{O}(10^{-13}\text{--}10^{-14})$	–
$\text{BR}(\mu \rightarrow e \text{ in Ti})$	$1.1 \times 10^{-12}$	$\mathcal{O}(10^{-18})$	J-PARC
$\text{BR}(\tau \rightarrow e\gamma)$	$1.1 \times 10^{-7}$	$\mathcal{O}(10^{-8})$	SuperB
$\text{BR}(\tau \rightarrow eee)$	$2.7 \times 10^{-7}$	$\mathcal{O}(10^{-8})$	SuperB
$\text{BR}(\tau \rightarrow e\mu\mu)$	$2. \times 10^{-7}$	$\mathcal{O}(10^{-8})$	SuperB
$\text{BR}(\tau \rightarrow \mu\gamma)$	$6.8 \times 10^{-8}$	$\mathcal{O}(10^{-8})$	SuperB
$\text{BR}(\tau \rightarrow \mu\mu\mu)$	$2 \times 10^{-7}$	$\mathcal{O}(10^{-8})$	LHCb
$\text{BR}(\tau \rightarrow \mu ee)$	$2.4 \times 10^{-7}$	$\mathcal{O}(10^{-8})$	SuperB

The SM mechanism of flavour mixing has been tested with high accuracy in the quark sector, where all flavour-violating phenomena seem to be well described by the SM Yukawa interaction [1]. Flavour mixing has been observed also in the neutrino sector, indicating the existence of a non-vanishing neutrino mass matrix which cannot be accommodated within the SM.

However, the origin of flavour is still far from being established. The most important open questions can be summarized as follow:

- Which is the organizing principle behind the observed pattern of fermion masses and mixing angles?
- Are there extra sources of flavour symmetry breaking beside the SM Yukawa couplings which are relevant at the TeV scale?

The search for LFV in charged leptons is probably the most interesting goal of flavour physics in the next few years. The observation of neutrino oscillations has clearly demonstrated that lepton flavour is not conserved; however, the smallness of neutrino masses provides a strong indication that neutrinos are generated by an underlying dynamics that violates also the total lepton number. The question is if LFV effects can be visible also in other sectors of the theory, or if we can observe LFV in processes which conserve the total lepton number.

## 2. – Experimental status for LFV

The status of searches for some selected LFV channels in  $\tau$  and  $\mu$  decays is summarized in table I.

In particular, the MEG experiment at PSI [3] should be able to test  $Br(\mu \rightarrow e\gamma)$  at the level of  $\mathcal{O}(10^{-13})$ , and the Super Flavour Factory [4] is planned to reach a sensitivity for  $Br(\tau \rightarrow \mu\gamma)$  of  $\mathcal{O}(10^{-9})$  and also the planned resolution of SuperKEKB for  $\tau \rightarrow \mu\gamma$  is of  $\mathcal{O}(10^{-8})$ . An impressive improvement is also expected for the upper bound on  $\mu - e$  conversion in Ti. The dedicated J-PARC and PRISM/PRIME experiment [5] should

reach the sensitivity of  $\mathcal{O}(10^{-18})$ , almost six orders of magnitude better than the current upper bound from SINDRUM II at PSI [6].

### 3. – Flavour violation in charged lepton decays

In the SM with massive neutrinos, the branching ratio for LFV processes like  $\mu \rightarrow e\gamma$  is of order  $Br(\mu \rightarrow e\gamma)_{\text{SM}} \approx 10^{-54}$ , to be compared with the 90% C.L. upper bound from the MEGA Collaboration [7]  $Br(\mu \rightarrow e\gamma) < 1.2 \cdot 10^{-11}$ . Therefore any observation of LFV would be a clear signal of NP.

On general grounds, if the breaking of the total lepton number occurs at a very high energy scale ( $\Lambda_{\text{LN}} > 10^{12}$  GeV), as expected by the smallness of neutrino masses, and the theory has new degrees of freedom carrying lepton-flavour quantum numbers around the TeV scale ( $\Lambda_{\text{LFV}} < 10^4$  GeV), then  $\mu \rightarrow e\gamma$  should be visible. Indeed, employing an effective theory approach with a minimal breaking of lepton flavour, we find [8]

$$(1) \quad \mathcal{B}(\mu \rightarrow e\gamma) \approx 10^{-13} \left( \frac{\Lambda_{\text{LN}}}{10^{13} \text{ GeV}} \right)^4 \left( \frac{10^4 \text{ GeV}}{\Lambda_{\text{LFV}}} \right)^4.$$

A typical concrete example where this occurs is the MSSM with heavy right-handed neutrinos, where renormalization-group effects generate LFV entries in the left-handed slepton mass matrices at the TeV scale [9]. Once non-vanishing LFV entries in the slepton mass matrices are generated, LFV rare decays are naturally induced by one-loop diagrams with the exchange of gauginos and sleptons. The flavour-conserving component of the same diagrams induces a non-vanishing contribution to the anomalous magnetic moment of the muon,  $\Delta a_\mu = (g_\mu - g_\mu^{\text{SM}})/2$ . As shown in fig. 1, a strong link between these two observable naturally emerges (see, *e.g.*, [10]). In this context, the value  $\Delta a_\mu = \mathcal{O}(10^{-9})$ , presently indicated by detailed analyses of  $g_\mu$  [11], reinforce the expectation of  $\mu \rightarrow e\gamma$  within the reach of the MEG experiment.

Beside supersymmetry, there are many other NP models like the Little Higgs model and the Randall-Sundrum models which are able to reach the present bounds and in fact this bounds put already rather stringent constraints on the parameters of these models.

In order to distinguish various NP scenarios, it will be essential to study a large set of decays to three leptons in the final state. Indeed, while in the MSSM [12-14] the dominant role in the decays with three leptons in the final state and in  $\mu - e$  conversion in nuclei is played by the dipole operator, in [15,16] it was found that this operator is much less relevant in the LHT model, with  $Z^0$  penguin and box diagrams being the dominant contributions. This implies a striking difference between various ratios of branching ratios of type  $Br(l_i \rightarrow 3l_j)/Br(l_i \rightarrow l_j\gamma)$  in the MSSM, where they are typically  $\mathcal{O}(10^{-2} - 10^{-3})$  and in the LHT model, where they are  $\mathcal{O}(10^{-1})$  [17]. The expected correlations among the branching ratios for the most relevant LFV processes are reported in table II from ref. [18].

### 4. – Conclusions

The origin of flavour is still, to a large extent, an open question. The synergy and interplay of high energy data with flavour precision data are expected to shed (some) light on this ‘‘Flavour Problem’’. Despite of the remarkable agreement of flavour data with the SM predictions, we still expect New Physics effects to show up in some selected ‘‘golden channels’’ such as LFV processes like  $\mu \rightarrow e\gamma$ , where an outstanding experimental

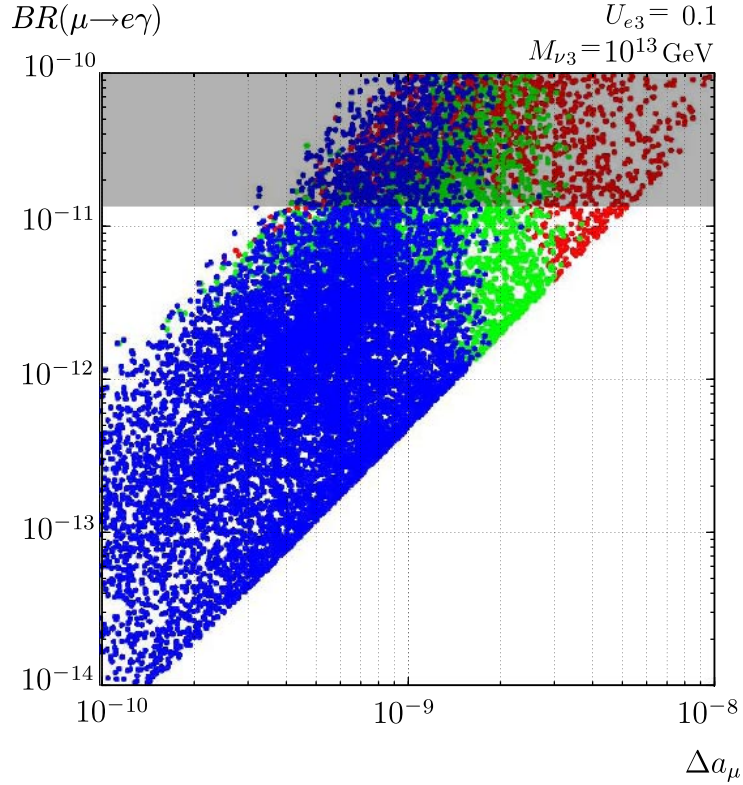


Fig. 1. – Correlation between  $\mathcal{B}(\mu \rightarrow e\gamma)$  and  $\Delta a_\mu$  in the MSSM with heavy RH neutrinos [10].

TABLE II. – Comparison of various ratios of branching ratios in the LHT model, the MSSM and the SM4. From ref. [18].

Ratio	LHT	MSSM	SM4
$\frac{Br(\mu \rightarrow eee)}{Br(\mu \rightarrow e\gamma)}$	0.02 ... 1	$\sim 2 \cdot 10^{-3}$	0.06 ... 2.2
$\frac{Br(\tau \rightarrow eee)}{Br(\tau \rightarrow e\gamma)}$	0.04 ... 0.4	$\sim 1 \cdot 10^{-2}$	0.07 ... 2.2
$\frac{Br(\tau \rightarrow \mu\mu\mu)}{Br(\tau \rightarrow \mu\gamma)}$	0.04 ... 0.4	$\sim 2 \cdot 10^{-3}$	0.06 ... 2.2
$\frac{Br(\tau \rightarrow e\mu\mu)}{Br(\tau \rightarrow e\gamma)}$	0.04 ... 0.3	$\sim 2 \cdot 10^{-3}$	0.03 ... 1.3
$\frac{Br(\tau \rightarrow \mu ee)}{Br(\tau \rightarrow \mu\gamma)}$	0.04 ... 0.3	$\sim 1 \cdot 10^{-2}$	0.04 ... 1.4
$\frac{Br(\tau \rightarrow eee)}{Br(\tau \rightarrow e\mu\mu)}$	0.8 ... 2	$\sim 5$	1.5 ... 2.3
$\frac{Br(\tau \rightarrow \mu\mu\mu)}{Br(\tau \rightarrow \mu ee)}$	0.7 ... 1.6	$\sim 0.2$	1.4 ... 1.7
$\frac{R(\mu Ti \rightarrow e Ti)}{Br(\mu \rightarrow e\gamma)}$	$10^{-3} \dots 10^2$	$\sim 5 \cdot 10^{-3}$	$10^{-12} \dots 26$

progress is expected in the upcoming years. Once some clear non-standard effects will be established, the next crucial step will be to trace back the New Physics model at work by means of a careful analysis of correlations among various observables.

## REFERENCES

- [1] CABIBBO N., *Phys. Rev. Lett.*, **10** (1963) 531; KOBAYASHI M. and MASKAWA T., *Prog. Theor. Phys.*, **49** (1973) 652.
- [2] AMSLER C. *et al.* (PARTICLE DATA GROUP COLLABORATION), *Phys. Lett. B*, **667** (2008) 1.
- [3] YAMADA S., *Nucl. Phys. Proc. Suppl.*, **144** (2005) 185.
- [4] BONA M. *et al.*, *SuperB: A High-Luminosity Asymmetric  $e^+e^-$  Super Flavor Factory*, Conceptual Design Report [arXiv:0709.0451].
- [5] MORI Y. *et al.* (PRISM/PRIME WORKING GROUP COLLABORATION), *LOI at J-PARC 50-GeV PS, LOI-25*, <http://psux1.kek.jp/~jhf-np/LOIlist/LOIlist.html>.
- [6] DOHMEN C. *et al.* (SINDRUM II. COLLABORATION), *Phys. Lett. B*, **317** (1993) 631.
- [7] BROOKS M. L. *et al.* (MEGA COLLABORATION), *Phys. Rev. Lett.*, **83** (1999) 1521 [hep-ex/9905013].
- [8] CIRIGLIANO V., GRINSTEIN B., ISIDORI G. and WISE M. B., *Nucl. Phys. B*, **728** (2005) 121 [arXiv:hep-ph/0507001].
- [9] BORZUMATI F. and MASIERO A., *Phys. Rev. Lett.*, **57** (1986) 961.
- [10] HISANO J., NAGAI M., PARADISI P. and SHIMIZU Y., *JHEP*, **0912** (2009) 030 [arXiv:0904.2080 [hep-ph]].
- [11] DAVIER M., HOECKER A., MALAESCU B. and ZHANG Z., arXiv:1010.4180 [hep-ph].
- [12] ELLIS J. R., HISANO J., RAIDAL M. and SHIMIZU Y., *Phys. Rev. D*, **66** (2002) 115013.
- [13] BRIGNOLE A. and ROSSI A., *Nucl. Phys. B*, **701** (2004) 3.
- [14] ARGANDA E. and HERRERO M. J., *Phys. Rev. D*, **73** (2006) 055003.
- [15] BLANKE M., BURAS A. J., DULING B., POSCHENRIEDER A. and TARANTINO C., *JHEP*, **05** (2007) 013.
- [16] DEL AGUILA F., ILLANA J. I. and JENKINS M. D., *JHEP*, **01** (2009) 080.
- [17] BLANKE M., BURAS A. J., DULING B., RECKSIEGEL S. and TARANTINO C., *Acta Phys. Pol. B*, **41** (2010) 657 [arXiv:0906.5454 [hep-ph]].
- [18] BURAS A. J., DULING B., FELDMANN T., HEIDSIECK T. and PROMBERGER C., *JHEP*, **1009** (2010) 104 [arXiv:1006.5356 [hep-ph]].