Complementarity in lepton-flavour violating muon decay experiments

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This note presents an analysis of lepton-flavour-violating muon decays within the framework of a low-energy effective field theory that contains higher-dimensional operators allowed by QED and QCD symmetries. The decay modes $\mu \rightarrow e\gamma$ and $\mu \rightarrow 3e$ are investigated below the electroweak symmetry-breaking scale, down to energies at which such processes occur, i.e. the muon mass scale. The complete class of dimension-5 and dimension-6 operators is studied systematically at the tree level, and one-loop contributions to the renormalisation group equations are fully taken into account. Current experimental limits are used to extract bounds on the Wilson coefficients of some of the operators and, ultimately, on the effective couplings at any energy level below the electroweak symmetry-breaking scale. Correlations between two couplings relevant to both processes illustrate the complementarity of searches planned for the MEG II and Mu3e experiments.

1 Introduction

This note presents a specific example of a correlation that occurs in lepton-flavour-violating (LFV) muonic decays in the context of effective field theories (EFTs).

Whilst in the neutrino sector evidence for LFV is now established beyond doubt\textsuperscript{1,2,3}, the absence of experimental hints of LFV in the charged lepton sector, together with the smallness of the neutrino mass scale, indicate that a very incisive flavour conservation mechanism is at work. Although allowed in the Standard Model (SM) with right-handed neutrinos, the branching ratios (BRs) of such transitions are suppressed by $(m_\nu/M_W)^4$, making them too small to be observable in any conceivable experiment. Consequently, any LFV production channel or decay mode offers a promising benchmark against which to search for physics beyond the SM.

Among charged LFV processes, muonic transition occurs in a relatively clean experimental environment, to the point that the MEG experiment has recently set a stringent limit\textsuperscript{4} on BR ($\mu \rightarrow e\gamma$). This represents the strongest existing bound on ‘forbidden’ decays, while the SINDRUM result\textsuperscript{5} obtained almost three decades ago is still very competitive with regard to the current experimental status of other sectors. The well-known outcomes of these experiments

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are:

\[
\text{Br} (\mu \rightarrow e\gamma) \leq 4.2 \times 10^{-13},
\]

\[
\text{Br} (\mu \rightarrow 3e) \leq 1.0 \times 10^{-12}.
\]

Furthermore, there are good prospects for future MEG II and Mu3e experiments. The former is expected\(^6\) to reach a limit of \(4 \times 10^{-14}\), while the latter might even achieve a four-orders-of-magnitude improvement\(^7,8\) on the existing limit. All the aforementioned experiments are being carried out at the Paul Scherrer Institut’s experimental facilities. The present analysis does not consider LFV transitions in a nuclear environment (coherent and incoherent muon conversion in nuclei). See Refs\(^9\) and\(^10\) for extensive treatments of this topic.

From a theoretical perspective, LFV processes have been studied in many specific extensions of the SM. In some cases the matching of such extensions to a low-energy effective theory has also been considered\(^11,12\). However, this analysis follows a bottom-up approach in which effective interactions are included in a low-energy Lagrangian\(^13\) that respects the \(SU(3)_c\) and \(U(1)_{EM}\) gauge symmetries. In exploiting the Appelquist-Carazzone theorem\(^14\), it is possible to extend the QCD and QED Lagrangian\(^8\) with higher-dimensional operators

\[
\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{QED+QCD}} + \frac{1}{\Lambda} \sum_k C_k^{(5)} Q_k^{(5)} + \frac{1}{\Lambda^2} \sum_k C_k^{(6)} Q_k^{(6)} + \mathcal{O} \left( \frac{1}{\Lambda^3} \right).\]

Here, \(\Lambda\) is the ultraviolet (UV) completion energy scale, which in this context is required not to exceed the electroweak symmetry-breaking (EWSB) scale, where the SM dynamic degrees of freedom and symmetries must be adequately restored\(^15,16\) and matched with those of the low-energy theory.

Having established the theoretical background, the main focus is on the interpretation of correlations between operators in the BRs of both \(\mu \rightarrow e\gamma\) and \(\mu \rightarrow 3e\) at the muon mass energy scale and beyond. Experimental limits are then applied to the parameter space in a search for allowed regions.

The popular parametrisation of dipole and four-fermion LFV operators\(^17\)

\[
\mathcal{L} = \frac{m_{\mu}}{(k+1)\Lambda^2} (\bar{\mu}_R \sigma_{\mu\nu} e_L) F^{\mu\nu} + \frac{k}{(k+1)\Lambda^2} (\bar{\mu}_L \gamma_\mu e_L) (\bar{f} \gamma^\mu f),
\]

where \(k\) is an ad hoc parameter to be interpreted strictly at the muon mass energy scale, allows to switch from a pure dipole interaction \((k \sim 0)\) to a pure four-fermion interaction \((k \sim \infty)\). Although this approach ensures a descriptive phenomenological understanding of the contributions of different operators to different observables, a more consistent theoretical approach can be achieved without losing interpretive power.

The advantage of a systematic effective QFT approach lies in the fact that it can be used to link phenomenological observables at different energy scales unambiguously through the renormalisation-group evolution (RGE) of the Wilson coefficients. In this regard, the RGE between the muon mass energy scale and the EWSB scale is calculated at the leading order (up to the one-loop level) in QED and QCD for any operator contributing to LFV muon decays. This encompasses possible mixing effects among operators, which in this study are taken into account in a similar way to recent theoretical works\(^18\). From this analysis, it is possible to extract limits both on the Wilson coefficients defined at the phenomenological energy scale and on the coefficients defined at the UV matching scale.

This paper is organised as follows. Section 2 introduces the LFV effective Lagrangian, and in Section 3 the observables connected with the \(\mu \rightarrow e\gamma\) and \(\mu \rightarrow 3e\) searches are briefly discussed. Section 4 provides a brief phenomenological analysis, and in Section 5 conclusions are drawn. Formulae relevant to the RGE of the Wilson coefficients are provided in the appendix.

\(^8\)Without the top quark field.
2 LFV effective Lagrangian at the muon energy scale

The Appelquist-Carazzone theorem is exploited to construct an effective Lagrangians valid below the EWSB scale, with higher-dimensional operators that respect the QCD $SU(3)_{c}$ and QED $U(1)_{EM}$ symmetries. This allows for an interpretation of BSM effects at high energy scales in terms of new, non-renormalisable interactions at the low energy scale.

In this respect, all possible QCD and QED invariant operators relevant to $\mu \rightarrow e$ transitions are considered up to dimension 6. These can be arranged in the following effective Lagrangian with dimensionless Wilson coefficients $C$ and the decoupling energy scale $M_{W} \geq \Lambda \gg m_{b}$:

$$L_{\text{eff}} = L_{\text{QED+QCD}} + \frac{1}{\Lambda^{2}} \left\{ C^{D}_{L} O^{D}_{L} + \sum_{f=q,\ell} \left( C^{V LL}_{f} O^{V LL}_{f} + C^{V LR}_{f} O^{V LR}_{f} + C^{S LL}_{f} O^{S LL}_{f} \right) + \sum_{f=q,\tau} \left( C^{T LL}_{f} O^{T LL}_{f} + C^{T LR}_{f} O^{T LR}_{f} \right) + L \leftrightarrow R \right\} + H.c.,$$

where $q$ and $l$ specify that sums run over the quark and lepton flavours, respectively. The explicit structure of the operators is given by

$$O^{D}_{L} = e m_{\mu} (\bar{e} \sigma^{\mu\nu} P_{L} \mu) F_{\mu\nu},$$

$$O^{V LL}_{f} = (\bar{e} \gamma^{\mu} P_{L} \mu) (\bar{f} \gamma_{\mu} P_{L} f),$$

$$O^{V LR}_{f} = (\bar{e} \gamma^{\mu} P_{L} \mu) (\bar{f} \gamma_{\mu} P_{R} f),$$

$$O^{S LL}_{f} = (\bar{e} P_{L} \mu) (\bar{f} P_{L} f),$$

$$O^{S LR}_{f} = (\bar{e} P_{L} \mu) (\bar{f} P_{R} f),$$

$$O^{T LL}_{f} = (\bar{e} \sigma^{\mu\nu} P_{L} \mu) (\bar{f} \sigma_{\mu\nu} P_{L} f),$$

and an analogous notation is assumed for cases in which the $L \leftrightarrow R$ exchange is applied. In the previous equations, the convention $P_{L/R} = (1 \mp \gamma^{5})/2$ is understood. Apart from being multiplied by the QED coupling $e$, the operator in Eq.6 is also rearranged into a dimension-6 operator with an appropriate normalisation factor $m_{\mu}$. The reason is that this operator is directly related to a dimension-6 operator in the SMEFT.

Direct comparison of Eq. 5 and Eq. 4 reveals that the latter assumes a tree-level correlation between independent operators. This assumption is manifestly inconsistent when quantum fluctuations are considered. Notably, an analysis of LFV transitions in nuclei calls for a further dimension-7 operator relating to the leading-order muon-electron-gluon interaction, which is generated by threshold corrections induced by the heavy quark operators (see Ref. 21 for details).

3 Lepton-flavour-violating muonic observables

This section describes two of the most relevant LFV muon decay processes, $\mu^{+} \rightarrow e^{+}\gamma$ and $\mu^{+} \rightarrow e^{+}e^{-}e^{+}$. Since the following analysis does not include a study of angular distributions (as in Ref. 22 for the case of polarised $\tau$-lepton decays), the charges of the external states need not be specified. The following partial widths should be divided by the total muon decay width, i.e. $\Gamma_{\mu} \simeq (G_{F}^{2} m_{\mu}^{5}) / (192 \pi^{3})$, in order to obtain the corresponding BRs.

3.1 $\mu \rightarrow e\gamma$

The simplest and most investigated LFV muonic process is $\mu \rightarrow e\gamma$. On the one hand, the serious experimental bounds on this kinematically simple transition clearly indicate that there
is an indisputable conservation mechanism at work. On the other hand, any observation of a non-zero $\mu \to e\gamma$ in current or future experiments would indicate the existence of BSM physics. The Lagrangian in Eq. 5 results in a branching ratio

$$\Gamma (\mu \to e\gamma) = \frac{e^2 m_\mu^5}{4 \pi \Lambda^4} \left( |C_L^D|^2 + |C_R^D|^2 \right) ,$$

(12)

from which it is clear that, with the Wilson coefficients defined at the muon energy scale, the associated BR is related only to the dipole operators $C_{L/R}^D$. According to the RGEs presented in Eq. 17, these operators will receive contributions from scalar ($C_{ll}^S$ with $l = e, \mu$) and tensor ($C_{\tau\tau}^T$ and $C_{qq}^T$ with $q = u, c, d, s, b$) operators, with non-vanishing coefficients at higher scales.

3.2 $\mu \to eee$

The second representative channel for muonic LFV decays is $\mu \to eee$. Prospects for future experimental developments in this rare muon process are very promising: the current experimental limit is expected to be improved considerably by the Mu3e experiment. Again, any signal of such a rare decay would be a clear signal for BSM physics.

The partial width reads

$$\Gamma (\mu \to 3e) =$$

$$= \frac{\alpha^2 m_\mu^5}{12 \Lambda^4 \pi} \left( |C_L^D|^2 + |C_R^D|^2 \right) \left( 8 \log \left[ \frac{m_\mu}{m_e} \right] - 11 \right)$$

$$+ \frac{m_\mu^5}{3 \Lambda^4 (16 \pi)^3} \left( |C_{ee}^S LL|^2 + |C_{ee}^S RR|^2 \right) + 8 \left( 2 |C_{ee}^V LL|^2 + |C_{ee}^V LR|^2 + |C_{ee}^V RL|^2 + 2 |C_{ee}^V RR|^2 \right)$$

$$- \frac{\alpha m_\mu^5}{3 \Lambda^4 (4 \pi)^2} \left( \Re[C_L^D \left( C_{ee}^V RL + 2 C_{ee}^V RR \right)^*] + \Re[C_R^D \left( 2 C_{ee}^V LL + C_{ee}^V LR \right)^*] \right) ,$$

(13)

where a more complicated interplay between operators occurs. The next section provides an explicit example of a correlation between the coefficients in Eqs. 12 and 13 with respect to the two experimental bounds on LFV transitions.

4 Limits on Wilson coefficients and correlations

In this section, the present experimental limits together with anticipated updates are applied to the observables of Eqs. 12 and 13 defined at a UV-completion energy scale.

Closer examination of Eqs. 12 and 13 together with the RGE equations in the appendix reveals that only two classes of operators – the dipole ($O^D$) and the scalar ($O^S_{ll}$) – are manifestly correlated at the one-loop level in two self-consistent systems (separate by chirality) of ordinary differential equations (ODE). In principle, more complicated relations occur if non-zero tensorial quark or $\tau$-lepton operators are considered. In addition, at the two-loop level, even the vectorial operators mix with the dipole. However, a complete quantitative treatment of all possible correlations is beyond the scope of this analysis.

For illustrative purposes, in the following discussion, we consider a scenario where an underlying UV-complete theory produces non-vanishing SMEFT coefficients. We assume that matching this SMEFT to the low-energy Lagrangian of Eq. 5, only two categories of non-vanishing coefficients are produced, namely $C^D$ and $C^S_{ee}$.

According to the RGE described by Eqs. 17 and 18, if the RGE effects are neglected for the
EM coupling and fermion masses, then the running of these two operators can be described by a relatively simple system of two ODE. The solutions are

\[
C_{L/R}^D (\mu) \simeq \left( \frac{\mu}{m_Z} \right)^4 \alpha \left( \frac{C_{L/R}^D (m_Z)}{16 \alpha m_\mu} \right)^{3 \alpha} \left( \frac{m_\mu^2 - \mu^2}{m_Z^2} \right) \alpha \left( m_Z - \alpha \right) C_{LL/RR}^S (m_Z),
\]

(14)

\[
C_{ee}^{LL/RR} (\mu) \simeq \left( \frac{\mu}{m_Z} \right)^{3 \alpha} \alpha \left( \frac{C_{LL/RR}^S (m_Z)}{16 \alpha m_\mu} \right)^{3 \alpha} \left( \frac{m_\mu^2 - \mu^2}{m_Z^2} \right) \alpha \left( m_Z - \alpha \right) C_{ee}^{LL/RR} (m_Z),
\]

(15)

where \( \mu \) is the phenomenological energy scale at which the coefficients should be evaluated, and \( \tilde{\alpha} = \alpha / \pi \) is the normalised EM coupling.

By combining these results with the BRs of Section 3 and applying the experimental limits, at the muon mass scale \( \mu = m_\mu \), we obtain the constraints on the coefficients \( C_{L/R}^D (m_Z) \) and \( C_{ee}^S (m_Z) \) shown in Figure 1 (right-chirality ones give the same result). Note that the evolution of the EM coupling and fermion masses is taken into account in these numerical results.

First, it must be appreciated that the limits originating from the non-observation of LFV muon decays in different experiments are manifestly complementary. In particular, for \( \mu \to e\gamma \) there is a region of the parameter space in which an explicit cancellation occurs between the contributions of the two operators. This effect is due to the relative sign in the evolution equation, which implies that \( C_{L/R}^D (m_\mu) \) is small if

\[
C_{L/R}^D (m_Z) \simeq \left( \frac{m_\mu}{16 \alpha m_\mu} \right)^{3 \alpha} \left( \frac{m_\mu^2 - \mu^2}{m_Z^2} \right) \alpha \left( m_Z - \alpha \right) C_{ee}^{LL/RR} (m_Z).
\]

(16)

Thus for MEG there is a blind direction in parameter space. In contrast, the \( \mu \to 3e \) decay mode is not subject to any cancellation among effective couplings, meaning that only the future Mu3e experiment will be able to explore this corner of the parameter space, as the SINDRUM experiment did in the past.

A second important aspect is that the last stage of the Mu3e experiment will cover a wider region of the parameter space than the MEG II experiment (in the absence of other correlations between operators), producing better limits for both the dipole and four-fermion effective couplings.

A much more involved scenario might arise if other operators are taken into account. For example, if \( C_{bb}^T \) is generated at the EWSB energy scale, the evolution of the dipole operator changes dramatically. However, salient aspects of the complementarity of the two experimental searches will remain qualitatively unaltered.

5 Conclusion

In this note, LFV muon decays have been analysed within the framework of an effective field theory with higher-dimensional operators at low energy scales.

The processes \( \mu \to e\gamma \) and \( \mu \to 3e \) have been investigated below the EWSB energy scale, down to the natural energy regime at which such processes occur, i.e. the muon mass scale. The complete class of contributing dimension-5 and dimension-6 operators allowed by QED and QCD have been systematically studied at the tree level, and one-loop contributions to the RGE have been taken into account.

The current experimental limits from the MEG and SINDRUM experiments have been used to extract bounds on some of the Wilson coefficients of the effective theory and, ultimately, on the Wilson coefficients at any energy level below the EWSB scale.

If the running of the electromagnetic (EM) coupling and the fermion masses is taken into account, then the evolution of the couplings is more involved, but at the same time the qualitative conclusion of this note will remain unchanged.
Figure 1 – Allowed parameter space for the two coefficients $\mathbf{C}_L^D$ and $\mathbf{C}_{ee}^{SLL}$ (non-vanishing at the $\Lambda = m_Z$ energy scale) by the $\mu \rightarrow e\gamma$ (red regions) and $\mu \rightarrow 3e$ experiments (yellow/green regions). Present (solid lines) and anticipated bounds (dashed/dashed-dotted lines) are plotted on a linear (upper frame) and pseudo-logarithmic scale (lower frame). In evaluating of the RGE, the running of the gauge coupling and fermion masses are included.
This note has also presented an explicit example of a correlation between dipole and four-fermion scalar effective couplings, under the assumption that they are the only two non-vanishing couplings generated at the EWSB energy scale by an underlying BSM theory, illustrating the complementarity of the searches planned for the MEG II and Mu3e experiments. In particular, it has been shown that the $\mu \to 3e$ channel allows for exploration of a region of the parameter space which $\mu \to e\gamma$ experiments are unable to investigate. Furthermore, in the absence of any other correlation it was shown that the last experimental phase of Mu3e will provide the best bound on the parameter space for both considered operators. However, this assertion might be invalid in the presence of other operators that mix in some way with the tree-level Wilson coefficients.

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Appendix - Anomalous dimensions

This appendix presents the anomalous dimensions of the operators exploited in the phenomenological analysis of Section 4. The corresponding equations for the chirality-flipped operators are obtained by the label interchange $R \leftrightarrow L$.

The dipole operator runs according to

$$16\pi^2 \frac{\partial C^D_L}{\partial (\log \mu)} = 16e^2 Q_l^2 C^D_L \left( - Q_l \frac{m_e}{m_\mu} C^{\mu\mu}_{ee} + Q_l \frac{m_\tau}{m_\mu} C^{\tau\tau}_{\tau\tau} \right) \Theta(\mu - m_\tau) + 8N_c \sum_q \frac{m_q}{m_\mu} Q_q C^T_{qq} \Theta(\mu - m_q). \tag{17}$$

where $N_c$ is the number of colours, and $Q_l$, $Q_u$ and $Q_d$ are the charges associated with leptons, $u$-type and $d$-type quarks, respectively.

The running of the leptonic scalar and tensorial operators is summarised by the following equations:

$$16\pi^2 \frac{\partial C^{S RR}_{ee/\mu \mu}}{\partial (\log \mu)} = 12e^2 Q_l^2 C^{S RR}_{ee/\mu \mu}, \tag{18}$$

$$16\pi^2 \frac{\partial C^{S RR}_{\tau \tau}}{\partial (\log \mu)} = -12e^2 Q_l^2 \left( C^{S RR}_{\tau \tau} + 8C^T_{\tau \tau} \right), \tag{19}$$

$$16\pi^2 \frac{\partial C^{S RL}_{\tau \tau}}{\partial (\log \mu)} = -12e^2 Q_l^2 C^{S RL}_{\tau \tau}, \tag{20}$$

$$16\pi^2 \frac{\partial C^T_{\tau \tau}}{\partial (\log \mu)} = -2e^2 Q_l^2 \left( C^{S RR}_{\tau \tau} - 2C^T_{\tau \tau} \right). \tag{21}$$
The running of the scalar and tensorial quark operators is given by

\[ 16\pi^2 \frac{\partial C_{qq}^{SR}}{\partial (\log \mu)} = (-6 \left(Q_l^2 + Q_q^2\right) e^2 + (1 - N_c^2) g_S^2) C_{qq}^{SR} - 96 e^2 Q_l Q_q C_{qq}^{TR}, \]  

and

\[ 16\pi^2 \frac{\partial C_{qq}^{TR}}{\partial (\log \mu)} = -2e^2 Q_l Q_q C_{qq}^{SR} + \left(2 \left(Q_l^2 + Q_q^2\right) e^2 + \left(\frac{N_c^2 - 1}{N_c}\right) g_S^2\right) C_{qq}^{TR}. \]

The running of vector operators is decoupled from the dipole operator \( C^D \) at the one-loop level. Nevertheless, it is well known that a non-vanishing mixing occurs at the two-loop level \(^{23,24}\). However, inclusion of these effects is beyond the scope of the present analysis and will be provided in a future publication \(^{25}\).

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