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Exploring the flavour mystery with Roberto

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Summary. — In this contribution we review our research activity with Roberto which focused mainly on the study of New Physics (NP) effects in Lepton Flavour Universality Violating (LFUV) observables such as $R_K = \Gamma(K \to e\nu)/\Gamma(K \to \mu\nu)$. After reviewing our results, we discuss also the present status of LFUV in semileptonic B decays which is currently hinting to significant NP contributions.

1. – Introduction

If relentless curiosity, explorations outside the mainstream, high-risk high-gain theoretical adventures have constantly characterized Roberto's work, it is certainly true that they have reached their vertex in the final period of his career. This became quite apparent during his supervision of Paride's PhD thesis work (2003-2006) and in the subsequent years when the three of us had a "strong interaction" on the fascinating front of the search of new physics beyond the Standard Model (SM) through its effects on electroweak precision tests and flavour physics.

We shall provide later on in this contribution some details of the specific issue that we tackled in two papers we wrote together with Roberto. However, we wish to make clear that these two papers were the fruit of only a (quantitatively minor) part of the huge spectrum of topics and ideas that we covered in our discussions and work with Roberto. The point is that discussions with Roberto were more kind of wild brainstorming than the fruit of a planned work. Or better, such preliminary brainstorming without a well-defined target could suddenly converge to this or that new suggestion often a wild, original idea. Then Roberto without any apparent effort could dig into his huge and deep mine of knowledge and expertise hastily producing quick estimates or even more refined computations that would have required the two of us much more time and thought to reach a comparable level.

If we had to describe in a couple of words our interaction with Roberto, we would first use the expressions "excitement" and "fun". At that time Roberto was INFN President so, obviously, his days were already quite crowded with the duties connected to such position. Yet, Roberto used to repeat to us that teaching and performing research work could not be entirely eliminated from his agenda. We still vividly remember when he was arranging for "secret" discussion meetings with us at Tor Vergata or even at the INFN headquarters. Most of the times no agenda was prepared in advance. Rather, Roberto was starting by suggesting some idea and from that moment on it was an endless series of hypotheses, objections to them, new proposals and so on in a dazzling circle of arguments and counter-arguments.

There is no doubt that the SM cannot account for remarkable observational facts, for instance in the SM there is no room for non-vanishing neutrino masses or for the existence of dark matter. Hence, the issue is not whether new physics beyond the SM exists; rather, the issue is what it is made of and where, *i.e.* in which physical phenomena, we may have some hope to spot its presence. New physics means new particles not included in the SM. In quantum field theory, there are two ways to manifest the presence of a particle: either you produce and observe it as a real, physical particle or you see it through kind of "quantum glasses", *i.e.* through its effects as a virtual particle contributing to physical processes and, hence, producing effects on them which are not included in the SM prediction.

While keeping faithful to his confidence that some day high-energy physics will be able to produce such new particles, undoubtedly the last years of Roberto's activity were vigorously (and enthusiastically) devoted to explore the implications of the high-intensity frontier, *i.e.* of the high-precision physics where virtual effects of what lies beyond the SM could be manifested even without reaching energies high enough to physically produce the particles of the new physics.

Obviously, to better disentangle such deviations from the SM expectations, one should make very precise tests of SM predicted electroweak quantities and/or look for rare, suppressed (or even forbidden) processes in the SM. Discussions with Roberto were wildly covering both classes of processes. Curiously enough, the two papers we produced together represent a mix of the two mentioned investigation fronts. Purely leptonic decays of the kaons are not rare phenomena, but one can make a detailed study of the single decay channels comparing their rates. A deviation from what is called lepton flavour universality (LFU), *i.e.* the SM prediction that an electron or a muon couple to the W boson with the same strength, would be a clear manifestation of new physics. It is interesting that to account for a possible hint of deviation from LFU, together with Roberto we invoked new physics in the form of supersymmetric contributions to flavour changing neutral current (FCNC) effects. The latter phenomena are suppressed in the SM and, hence, FCNC processes constitute a wonderful laboratory where to pin down the (virtual) effects of new physics.

In the case of kaon physics the issue of LFU has been thoroughly pursued experimentally (and, indeed, as it was recognized, our work was instrumental in prompting such vigorous experimental effort). Finally, no significant deviation from the SM prediction of exact LFU was discovered. However, as we are going to mention later on, just recently, the whole issue of LFU has been revisited because of puzzling results in semileptonic B decays possibly entailing a violation of LFU.

We regret so much that for this alleged anomaly we shall not hear the sudden phone calls from Roberto (typically on Saturdays or Sundays) asking to urgently meet because he has some new promising idea to debate together.

2. – Lepton Flavour Universality circa 2005

High-precision electroweak tests represent a powerful tool to probe the SM and, hence, to constrain or obtain indirect hints of NP beyond it. Kaon and pion physics are natural grounds where to perform such tests, for instance in the purely leptonic dacays $\pi \to \ell\nu_\ell$ and $K \to \ell\nu_\ell$, where $\ell = e$ or μ. Since the relevance of these single decay channels in probing the SM is severely hindered by our theoretical hadronic uncertainties related to the decay constants f_π and f_K, it is customary to consider the ratios $R_\pi = \Gamma(\pi \to e\nu)/\Gamma(\pi \to \mu\nu)$ and $R_K = \Gamma(K \to e\nu)/\Gamma(K \to \mu\nu)$, in which the hadronic uncertainties cancel to a very large extent.

The SM prediction R_K was known with excellent accuracy already in the nineties [1]:

$$R_K^{\rm SM} = (2.472 \pm 0.001) \cdot 10^{-5}, \tag{1}$$

and it was well consistent with the 2005 PDG value [2]

$$R_K^{\rm exp} = (2.44 \pm 0.11) \cdot 10^{-5}. \tag{2}$$

However, at ICHEP 2005, L. Fiorini —for the NA48/2 Collaboration— presented a new result on R_K [3]

$$R_K^{\rm exp} = (2.416 \pm 0.043_{\rm stat} \pm 0.024_{\rm syst}) \cdot 10^{-5}. \tag{3}$$

Although the new experimental measurement was just 1σ below the SM prediction, it was noticed with interest by Roberto who promptly asked us whether there was a plausible NP scenario where to accommodate this small tension. This signed the beginning of our amusing and fruitful Collaboration [4]. It was natural to us to consider low-energy minimal SUSY extensions of the SM (MSSM) as the source of NP to be tested by R_K. The question we intended to address was whether SUSY could cause deviations from μ-e universality in R_K at the percent level, roughly corresponding to the 2005 experimental sensitivity on R_K.

We showed that i) it was indeed possible for regions of the MSSM to obtain contributions at the level of $\mathcal{O}(10^{-2})$ and ii) such large contributions to $K \to \ell\nu$ did not arise from SUSY lepton flavor conserving (LFC) effects, but, rather, from LFV ones.

At first sight, the latter statement may seem rather surprising. Indeed, the $K \to e\nu_e$ and $K \to \mu\nu_\mu$ decays are LFC and one could expect that it is through LFC SUSY contributions affecting differently the two decays that one obtains the dominant source of lepton flavor non-universality in SUSY.

However, one can easily guess that, whenever NP intervenes in $K \to e\nu_e$ and $K \to \mu\nu_\mu$ to create a departure from the strict SM μ-e universality, these new contributions will be proportional to the lepton masses. As a result, it may happen that LFC contributions are suppressed with respect to the LFV ones by higher powers of the first two generations lepton masses. Another important reason for such result is that among the LFV contributions to R_K one can select those which involve flavor changes from the first two lepton generations to the third one with the possibility of picking up terms proportional to the tau-Yukawa coupling which can be large in the large $\tan\beta$ regime (the parameter $\tan\beta$ denotes the ratio of Higgs vacuum expectation values responsible for the up- and down-quark masses, respectively). Moreover, the relevant one-loop induced LFV Yukawa interactions were known [5] to acquire an additional $\tan\beta$ factor with respect to the tree level LFC Yukawa terms. Thus, the loop suppression factor can be (partially) compensated in the large $\tan\beta$ regime.

For future convenience, we denote by $\Delta r_{\rm NP}^{e\text{-}\mu}$ the deviation from μ-e universality in R_K due to NP, *i.e.*:

$$R_K = \frac{R_K^{\rm SM}}{R_K^{\rm exp}} = 1 + \Delta r_{NP}^{e\text{-}\mu}. \tag{4}$$

Imposing the NA48/2 result at 2σ level one can find the following allowed range for $\Delta r_{\rm NP}^{e\text{-}\mu}$:

$$-0.063 \leq \Delta r_{NP}^{e\text{-}\mu} \leq 0.017. \tag{5}$$

Since the SM contributions to $\pi \to \ell\nu$ and $K \to \ell\nu$ are helicity suppressed, these processes are very sensitive to non-SM effects (such as multi-Higgs effects) which might induce an effective pseudoscalar hadronic weak current. In particular, charged Higgs bosons ($H^\pm$) appearing in any model with two Higgs doublets (including the SUSY case) contribute at tree level to the above processes as follow [6]:

$$\frac{\Gamma(M\to\ell\nu)}{\Gamma_{\rm SM}(M\to\ell\nu)} = \left[1 - \tan^2\beta \left(\frac{m_{s,d}}{m_u + m_{s,d}}\right) \frac{m_M^2}{m_H^2}\right]^2 , \tag{6}$$

where m_u is the mass of the up-quark while $m_{s,d}$ stands for the down-type quark mass of the M meson ($M = K, \pi$). From eq. (6) it is evident that such tree level contributions do not introduce any lepton flavour dependent correction. The first SUSY contributions violating the μ-e universality in $\pi \to \ell\nu$ and $K \to \ell\nu$ decays arise at the one-loop level with various diagrams involving exchanges of (charged and neutral) Higgs scalars, charginos, neutralinos and sleptons. For our purpose, it is relevant to divide all such contributions into two classes: i) LFC contributions where the charged meson M decays without FCNC in the leptonic sector, *i.e.* $M \to \ell\nu_\ell$; ii) LFV contributions $M \to \ell_i\nu_k$, with i and k referring to different generations (in particular, the interesting case will be for $i = e, \mu$, and $k = \tau$).

One-loop corrections to R_π and R_K include box, wave function renormalization and vertex contributions from SUSY particle exchange. The complete calculation of the μ decay in the MSSM [7] can be easily applied to the meson decays. It turns out that all these LFC contributions yield values of $\Delta r_K^{e\text{-}\mu}$ which are much smaller than the percent level required by the achieved experimental sensitivity.

A typical $\Delta r_K^{e\text{-}\mu}$ induced by charginos/neutralinos sleptons ($\tilde{\ell}_{e,\mu}$) exchanges is of order

$$\Delta r_K^{e\text{-}\mu} \sim \frac{\alpha_2}{4\pi}\left(\frac{\tilde{m}_\mu^2 - \tilde{m}_e^2}{\tilde{m}_\mu^2 + \tilde{m}_e^2}\right)\frac{m_W^2}{M_{\rm SUSY}^2}. \tag{7}$$

Even if we assume a quite large mass splitting among slepton masses of order one we end up with $\Delta r_K^{e\text{-}\mu} \leq 10^{-4}$.

However, as discussed in ref. [4], purely leptonic $\pi^\pm$ and $K^\pm$ decays provide a unique way to detect LFV SUSY effects through a deviation from the μ-e universality. One could naively think that SUSY effects in the LFV channels $M \to \ell_i\nu_k$ are further suppressed with respect to the LFC ones. Instead, charged Higgs mediated SUSY LFV contributions, in particular in the kaon decays into an electron or a muon and a tau neutrino, can be strongly enhanced. It is well known that models containing at least two Higgs doublets

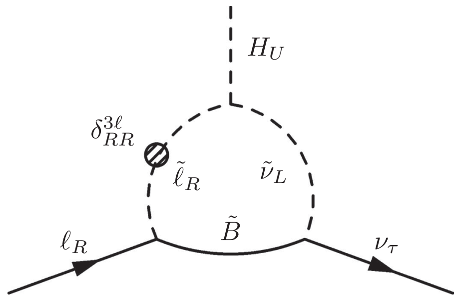

Fig. 1. – Contribution to the effective $\bar{\nu}_\tau \ell_R H^+$ coupling with $\ell = e, \mu$.

generally allow flavour-violating couplings of the Higgs bosons with the fermions [8]. In the MSSM such LFV couplings are absent at tree level. However, once non-holomorphic terms are generated by loop effects (so-called HRS corrections [9]) and given a source of LFV among the sleptons, Higgs-mediated (radiatively induced) $H\ell_i\ell_j$ LFV couplings are unavoidable [5].

The quantity which now accounts for the deviation from the μ-e universality reads:

$$R^{\rm LFV}_{\pi,K} = \frac{\sum_i \Gamma(\pi(K) \to e\nu_i)}{\sum_i \Gamma(\pi(K) \to \mu\nu_i)}, \qquad i = e, \mu, \tau,$$

with the sum extended over all (anti)neutrino flavors (experimentally one determines only the charged lepton flavor in the decay products).

The dominant SUSY contributions to $R^{LFV}_{\pi,K}$ arise from the charged Higgs exchange. The effective LFV Yukawa couplings we consider are (see fig. 1)

$$\ell H^\pm \nu_\tau \to \frac{g_2}{\sqrt{2}} \frac{m_\tau}{M_W} \Delta^{3l}_R \tan^2\!\beta, \qquad \ell = e, \mu. \tag{8}$$

Crucial to our result is the quadratic dependence on tanβ in the above coupling: one power of tanβ comes from the trilinear scalar coupling in fig. 1, while the second one is a specific feature of the above HRS mechanism. The $\Delta^{3\ell}_R$ terms are induced at one loop level by the exchange of Bino (see fig. 1) or Bino-Higgsino and sleptons. Since the Yukawa operator is of dimension four, the quantities $\Delta^{3\ell}_R$ depend only on ratios of SUSY masses, hence avoiding SUSY decoupling. Numerically, it turns out that $\Delta^{3\ell}_R \le 10^{-3}$.

Making use of the LFV Yukawa coupling in eq. (8), it turns out that the dominant contribution to $\Delta r^{e\text{-}\mu}_{NP}$ reads

$$R^{\rm LFV}_K \simeq R^{\rm SM}_K \left[1 + \left(\frac{m^4_K}{M^4_H}\right)\left(\frac{m^2_\tau}{m^2_e}\right) |\Delta^{31}_R|^2 \tan^6\!\beta\right]. \tag{9}$$

In eq. (9) terms proportional to Δ^{32}_R are neglected given that they are suppressed by a factor m^2_e/m^2_μ with respect to the term proportional to Δ^{31}_R. Taking $\Delta^{31}_R \simeq 5 \cdot 10^{-4}$, $\tan\beta = 40$ and $M_H = 500\,\text{GeV}$ we end up with $\Delta r^{e\text{-}\mu}_K \sim 0.01$. We see that in the large (but not extreme) $\tan\beta$ regime and with a relatively heavy $H^\pm$, it is possible to reach contributions to $\Delta r^{e\text{-}\mu}_K$ at the percent level thanks to the possible LFV enhancements arising in SUSY models.

Turning to pion physics, one could wonder whether the analogous quantity $\Delta r_\pi^{e\text{-}\mu}$ is able to constrain SUSY LFV. However, the correlation between $\Delta r_\pi^{e\text{-}\mu}$ and $\Delta r_K^{e\text{-}\mu}$,

$$\Delta r_\pi^{e\text{-}\mu} \simeq \left(\frac{m_d}{m_u + m_d}\right)^2 \left(\frac{m_\pi^4}{m_k^4}\right) \Delta r_K^{e\text{-}\mu}, \tag{10}$$

clearly shows that the constraints on $\Delta r_K^{e\text{-}\mu}$ force $\Delta r_\pi^{e\text{-}\mu}$ to be much below its actual experimental upper bound.

Obviously, a legitimate worry when witnessing such a huge SUSY contribution through LFV terms is whether the bounds on LFV tau decays, like $\tau \to eX$ (with $X = \gamma, \eta, \mu\mu$), are satisfied. Higgs mediated $Br(\tau \to \ell_j X)$ and $\Delta r_K^{e\text{-}\mu}$ have exactly the same SUSY dependence; hence, we can compute the upper bounds of the relevant LFV tau decays which are obtained for those values of the SUSY parameters yielding $\Delta r_K^{e\text{-}\mu}$ at the percent level. We obtain $Br(\tau \to eX) \leq 10^{-10}$, much below the current and expected future experimental bounds.

Our promising results triggered the attention of both the theoretical and experimental communities. In particular, the SM value of R_K was recomputed with higher accuracy leading to $R_K^{SM} = (2.477 \pm 0.001) \times 10^{-5}$ [10]. On the other hand, recent in-flight decay experiments, such as KLOE [11] and NA62 [12], have measured the R_K ratio leading to a current world average of $R_K = (2.488 \pm 0.010) \times 10^{-5}$, which is one order of magnitude more accurate than the corresponding 2005 world average (see eq. (2)).

Although the current experimental result is remarkably consistent with the SM prediction, the NA62 Collaboration as well as the TREK/E36 Collaboration at J-PARC aim to further improve the resolution on R_K in the upcoming years.

3. – Lepton Flavour Universality circa 2017

The search for LFUV still represents one of the most powerful tool to unveil NP phenomena. Interestingly enough, in the last few years, hints of large LFUV in semileptonic B decays were observed by various experimental collaborations both in charged-current as well as neutral-current transitions. In particular, the statistically most significant results are accounted for by the following observables:

$$R_{D^*}^{\tau/\ell} = \frac{\mathcal{B}(B \to D^* \tau\overline{\nu})_{\rm exp}/\mathcal{B}(B \to D^* \tau\overline{\nu})_{\rm SM}}{\mathcal{B}(B \to D^* \ell\overline{\nu})_{\rm exp}/\mathcal{B}(B \to D^* \ell\overline{\nu})_{\rm SM}} = 1.23 \pm 0.07, \tag{11}$$

$$R_{D}^{\tau/\ell} = \frac{\mathcal{B}(B \to D \tau\overline{\nu})_{\rm exp}/\mathcal{B}(B \to D \tau\overline{\nu})_{\rm SM}}{\mathcal{B}(B \to D \ell\overline{\nu})_{\rm exp}/\mathcal{B}(B \to D \ell\overline{\nu})_{\rm SM}} = 1.34 \pm 0.17, \tag{12}$$

where $\ell = e, \mu$, which follow from the HFAG averages [13] of Babar [14], Belle [15], and LHCb data [16], combined with the corresponding theory predictions [17, 18], and

$$R_{K^*}^{\mu/e} = \left.\frac{\mathcal{B}(B \to K^* \mu\bar{\mu})_{\rm exp}}{\mathcal{B}(B \to K^* e\bar{e})_{\rm exp}}\right|_{q^2 \in [1.1, 6]{\rm GeV}} = 0.685^{+0.113}_{-0.069} \pm 0.047, \tag{13}$$

$$R_{K}^{\mu/e} = \left.\frac{\mathcal{B}(B \to K \mu\bar{\mu})_{\rm exp}}{\mathcal{B}(B \to K e\bar{e})_{\rm exp}}\right|_{q^2 \in [1, 6]{\rm GeV}} = 0.745^{+0.090}_{-0.074} \pm 0.036, \tag{14}$$

based on combination of LHCb data [19, 20] with the SM expectation $R^{\mu/e}_{K^{(*)}} = 1.00 \pm 0.01$ [21]. Moreover, there are additional tensions between the SM predictions and experimental data in $b \to s\ell\bar{\ell}$ differential observables, though large non-perturbative effects can be invoked to explain the observed anomaly [22]. Yet, it is interesting that the whole set of $b \to s\ell\bar{\ell}$ data could be reconciled with the theory predictions assuming some NP contributions exclusively in the muonic channels, see, *e.g.*, ref. [23].

These anomalies have triggered many theoretical speculations about the possible NP scenarios at work. Of particular interest are those attempting to a simultaneous explanation of both charged- and neutral-current anomalies. Such a task can be most naturally achieved assuming that NP intervenes through effective 4-fermion operators involving left-handed currents, $(\bar{s}_L\gamma_\mu b_L)(\bar{\mu}_L\gamma_\mu\mu_L)$ and $(\bar{c}_L\gamma_\mu b_L)(\bar{\tau}_L\gamma_\mu\nu_L)$, which are related by the $SU(2)_L$ gauge symmetry [24]. In this setup, a necessary requirement is that NP couples much more strongly to the third generation than to the first two, since $(\bar{c}_L\gamma_\mu b_L)(\bar{\tau}_L\gamma_\mu\nu_L)$ is already generated at the tree level in the SM while $(\bar{s}_L\gamma_\mu b_L)(\bar{\mu}_L\gamma_\mu\mu_L)$ is loop-induced. Such a requirement is automatically accomplished if NP is coupled, in the interaction basis, only to the third fermion generation, couplings to lighter generations being generated by the misalignment between the mass and the interaction bases through small flavour mixing angles [25]. In this case LFUV is expected to be associated with lepton flavour violating (LFV) phenomena.

It is interesting to observe that the main idea we put forward with Roberto —the possibility of LFU violation from LFV effects— is still largely used nowdays to explain the current anomalies in B-physics.

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