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### Progress in Physics (62)

**Lepton Flavor Universality violations: a new challenge in fundamental physics.**

*Gino Isidori, Uni Zürich*

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## Progress in Physics (62)

### Lepton Flavor Universality violations: a new challenge in fundamental physics.

*Gino Isidori, Uni Zürich*

Recent measurements question one of the pillars of the Standard Model: the universality of the forces acting on the different families of elementary particles. If confirmed, this phenomenon could lead to a significant change of paradigm in our understanding of elementary interactions.

The nature and the fundamental interactions of the basic constituents of matter are well described by the so-called *Standard Model* (SM). This theory, which is called “Model” only for historical reasons, describes microscopic interactions in agreement with the principles of Quantum Mechanics and Special Relativity. It describes not only the microscopic forces, but also the nature of the basic constituents of matter, which turn out to be three “families” of elementary particles called quarks and leptons. Each family contains four types of particles, two quarks and two leptons, with different quantum numbers. These quantum numbers, and the symmetry structure of the theory, determine completely the properties of these particles under the three fundamental forces relevant at the microscopic level, namely strong, weak and electromagnetic interactions. Ordinary matter consists essentially of particles of the first family, namely the up and down quarks (the constituents of atomic nuclei), the electrons, and the electron neutrinos (abundantly produced by the fusion reactions occurring inside the stars). According to the SM, quarks and leptons of the second and third families are identical copies of those in the first family except for their different, heavier, masses. These heavier copies are unstable particles that can be produced in high-energy collisions and that decay very fast, via weak interactions, into lighter particles. Why we have three almost identical replicas of quarks and leptons (referred also as three “flavors” of quarks and leptons) and what is the origin of their different masses, are among the big open questions in particle physics.

Within the SM, the masses of quarks and leptons are the result of a peculiar short-range force, namely the interaction of these matter constituents (described by fermion fields) and the Higgs field (the only scalar field of the theory). The Higgs field has a non-trivial ground-state configuration, interacting with which quarks and leptons acquire an effective mass term. The observation of the excitation of the Higgs field, namely the Higgs boson, reported in 2012 by the ATLAS and CMS experiments at CERN, provides a remarkable confirmation of this mechanism and, more generally, of the SM. Still, this description of quark and lepton masses is rather unsatisfactory: contrary to the other fundamental forces, the interaction between quarks, leptons and the Higgs field is not controlled by symmetry principles. Each mass is the result of a specific (ad-hoc) coupling. Altogether, we are forced to introduce a large number of unexplained parameters that spans several orders of magnitude (an issue often referred to as the “flavor problem”).

One of the key predictions of the SM is that quarks and leptons of the different families behave in the same way, but for their different mass (or, more precisely, their different interaction with the Higgs field). Surprisingly enough, a series of precision measurements performed recently by the LHCb experiment at CERN are challenging this prediction [1,2]. The LHCb experiment has analyzed a series of processes where a b quark (namely a quark of the third family) decays into a strange quark (belonging to the second family) and a lepton-antilepton pair. In a nutshell, data seem to indicate a significant difference between processes that are identi-

cal but for the type of leptons involved, which can be either electrons (first family) or muons (second family). This is why this phenomenon is denoted “violation of Lepton Flavor Universality” (LFU). More precisely, since the lepton-antilepton pair is electrically neutral, we denote this effect a violation of LFU in neutral-current processes. Present data indicate a deviation from the SM prediction with high statistical significance (see Figure 1), but is too early to draw definite conclusions. The comparison of the various decay rates is indeed rather difficult: these processes are quite rare and the deviation from the SM predictions is a relatively small effect (of the order of 20%).

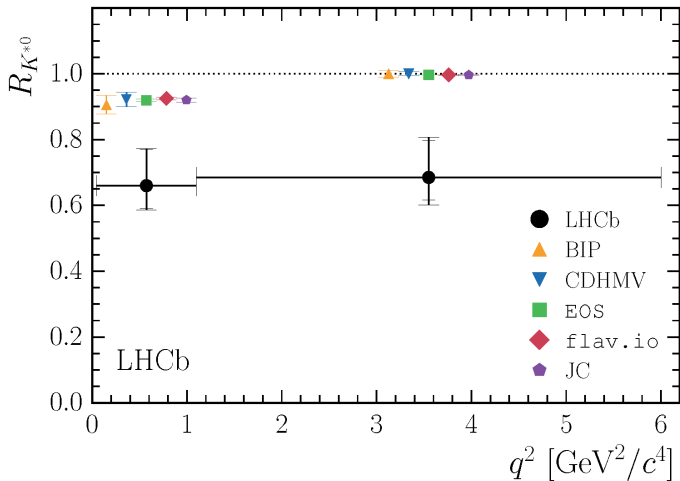


Figure 1: Evidence of violation of LFU in neutral currents obtained by the LHCb experiments at CERN [2]. The vertical axis denotes the LFU ratio  $\Gamma(B \rightarrow K^* \mu^+ \mu^-) / \Gamma(B \rightarrow K^* e^+ e^-)$  measured on different intervals of the lepton-antilepton invariant mass, reported on the horizontal axis. The black points are the experimental data, the colored points are the SM predictions obtained by different theory groups.

What is particularly interesting of these “anomalies” is that they do not appear in a single decay channel, but in several processes and observables. Another set of processes showing significant deviations from the SM predictions, and indicating a possible violation of Lepton Flavor Universality, are the decays of b quarks into final states containing a single charged lepton and a neutrino. In this case we are dealing with charged-current processes, and the comparison is between processes with tau leptons (third family) and processes with muons (second family). Also in this case the deviation relative the SM prediction is of the order of 10 - 20%, but the SM rate itself is larger, hence the strength of the effect (if due to a new interaction) is larger in absolute terms compared to the deviation observed in neutral currents. Interestingly enough, in this case the anomaly is observed not only in the LHCb experiment [3]. The first evidence of an anomalous behavior was reported by the Babar experiment in 2012 [4], and later on by Belle in 2015 [5] (Babar and Belle are the experiments that were running at the  $e^+e^-$  accelerators in US and Japan, respectively). None of these experiments has a result that, if taken alone, has a high statistical significance; however, all the results are coherent and, once combined, they indicate deviations from the SM predictions with high statistical significance [6] (see Figure 2).

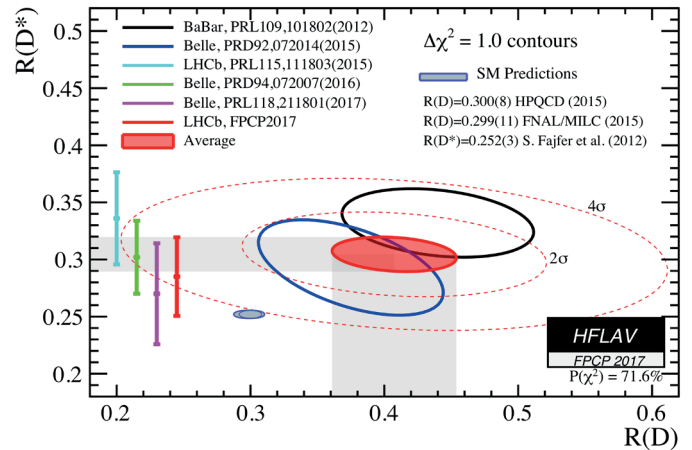


Figure 2: Evidence of violation of LFU in charged currents obtained by various experiments [6]. The vertical axis denotes the LFU ratio  $\Gamma(B \rightarrow D^* \tau \nu) / \Gamma(B \rightarrow D^* \mu \nu)$ , the horizontal axis denotes the LFU ratio  $\Gamma(B \rightarrow D \tau \nu) / \Gamma(B \rightarrow D \mu \nu)$ . The red ellipse is the average of the present experimental results, as obtained by the HFLAV working group. The small blue ellipse denotes the SM prediction.

These surprising results have raised a strong interest in the particle-physics community and have stimulated a lot of theoretical investigations. A first natural question to be addressed is the consistency of these anomalies with the tight bounds on possible extensions of the SM derived by many past experiments. In particular, past experiments analyzing other flavor-changing processes, such as rare decays involving quarks and leptons of the second generation, have set limits on possible deviations from the SM predictions in these processes at the per-mil level. Similar strong bounds have been derived on possible deviations from universality in the couplings of the different fermion families to the SM gauge bosons (or the force mediators of strong, weak and electromagnetic interactions). A recent theoretical study of the UZH theory group [7] has clarified that there is no inconsistency between the recent b-physics anomalies and these tight bounds, provided the hypothetical “new force” responsible for the anomalies is not universal not only as far as the lepton flavor is concerned, but also on the quark side. More precisely, the strength of the new interaction should be maximal for quarks and leptons of the third generation, should become weaker for particles of the second generation, and must be super-weak for those of the first generation (this is why we do not experience on ordinary matter). Interestingly enough, this hypothesis also explains the different strength of neutral- and charged-current anomalies, and provides a strong hint that this new interaction maybe the key toward a solution of the flavor problem.

Another relevant question that recent studies tried to address is consistency of these anomalies with the bounds from the so-called direct searches of physics beyond the SM. Which is the energy scale of this hypothetical new interaction? Is it consistent that no trace of the corresponding mediator has been seen yet in high-energy proton-proton collisions at the LHC? Also in this case the answer is yes [7]: the mediator of this peculiar new interaction could have escaped all direct searches performed so far. However, it cannot be arbitrarily heavy: it could well be within the reach of the next high-luminosity runs of the LHC. More generally, it has become clear that if these anomalies are confirmed, they cannot remain isolated. Many other violations of LFU

should appear in other rare decay channels currently under investigation at the LHCb experiment. A key confirmation of this phenomenon could also be obtained in a few years by the Belle-II experiment at Super-KEK (the successor of the Japanese B-factory, that is expected to start within less than two years). Last but not least, other manifestations of the same force could occur in rare flavor-violating decays involving leptons only, such as the rare muon to electron transitions searched for at PSI and in other laboratories around the world. Altogether, there are very good chances of learning much more about this hypothetical new interaction in the near future.

One the most fascinating aspect of this phenomenon is the significant shift of paradigm that it could imply in the theoretical attempts to build an extension of the SM. So far, most of the proposed extensions of the SM were focused on addressing the so-called “hierarchy problem”, or the large hierarchy between the energy scale of weak interactions (which is related to the Higgs mass) and that of gravitational interactions. The attempts to solve this problem have given rise to several interesting proposals, such as supersymmetric models, models with extra space-time dimensions, or models where the Higgs boson is a composite particle. All of them predict the existence of new particles at the TeV scale (not much heavier than the Higgs boson), hence within the reach of the LHC. However, none of these particles has been found yet, shedding serious doubts on the validity of all these ideas, at least in their simplest implementation. On

the other hand, less attention has been devoted so far on the flavor problem and its possible solution. This is because the solution to the flavor problem can in principle occur at very high energies. Actually this is what has been assumed (explicitly or implicitly) in most of the proposed SM extensions formulated so far, mainly for reasons of simplicity. The recent b-physics anomalies seem to indicate we need to move from this simple paradigm: we should not “postpone” the solution of the flavor problem to high energies. Its solution, or at least some key ingredient for its solution, may be accessible around the TeV scale [8]. It could well be that only addressing the flavor problem we will gain a deeper insight on other open issues of the SM, such as the hierarchy problem and the unification of fundamental forces. As already mentioned, the good news is that we should not wait much before knowing if these tempting speculations have anything to do with what Nature has in store for us.

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### The return of Leptoquarks

Among the models recently proposed to explain the b-physics anomalies, a particularly interesting class is the one based on the gauge group  $SU(4) \times SU(2)_L \times SU(2)_R$ . This gauge group was proposed long ago by Pati and Salam [1] in order to unify the interactions acting on quarks and leptons. Within the Standard Model (SM), strong interactions are ruled by the  $SU(N_c)$  gauge group: here  $N_c = 3$  stands for the three degrees of freedom (denoted “colors”) that each quark species possesses. Leptons carry no color and therefore do not feel the strong interaction. In the Pati-Salam extended gauge group, color is part of a larger symmetry group,  $SU(4)$ , whose fourth degree of freedom is the lepton number. This model predicts the existence of a new type of interactions mediated by “leptoquarks” gauge bosons, namely force carriers transforming quarks into leptons and viceversa. The model explains the quantum numbers of quarks and leptons in terms of a reduced number of free parameters and provides an (a posteriori) explanation for the quantization of the electric charge. However, till recently the Pati-Salam model was not very popular given the absence of any direct or indirect evidence of leptoquark-mediated interactions. Actually the bounds on leptoquarks coupled to the first two families of quarks and leptons are extremely tight, such that the masses of these mediators, if any, must lie above 100 TeV. The phenomenological interest on this class of model was therefore not particularly high.

The situation has drastically changed during the last two years, when analyses of b-physics have demonstrated that “light” leptoquark fields (with masses around 1 TeV), coupled mainly to quarks and leptons of the third family, are very good candidates for the explanation of the anomalies. This has led to a revival of the original proposal by Pati and Salam, with a key modification: a non-trivial flavor structure for the leptoquark fields, such that only those coupled to third-family fermions are light enough to induce sizable effects at low energies [2,3]. This fact also explains why the hypothetical leptoquarks with mass around 1 TeV have not been seen yet at the LHC: their production via quarks of the third family (mainly b quarks), and subsequent decay into leptons of the third family (i.e. tau leptons) is a difficult signature, that could have escaped the direct searches performed so far. While it is premature to draw definite conclusions about the existence of leptoquarks, it is interesting to note that a large fraction of the parameter space of this class of models will be probed in the near future during the high-luminosity phase of the LHC. Moreover, a striking indirect evidence could be obtained by observing a large enhancement over the SM predictions for rare b decays into a tau-anti-tau pair (currently searched for by LHCb and other experiments).

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