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LFV in Meson and Baryon Decays—Theory Overview[#]

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Abstract—A summary and outlook of the theory motivations and status of searches for lepton flavour violation (LFV) in meson and baryon (semi-)leptonic decays is provided. The contribution is structured as follows: (i) A short overview of $b \to s$ as well as $b \to c$ data; (ii) general arguments for pursuing LFV in b-hadron decays; (iii) additional arguments for possible LFV signatures in other meson decays, in particular, of kaons. Emphasis is on a presentation accessible to a wider public, describing the underlying motivation and physics arguments with a minimum of equations.

Keywords: BSM physics, lepton flavor violation, baryon decays

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INTRODUCTION

This talk is meant to cover the theory motivation for pursuing lepton flavour violation (LFV) in decays of mesons and baryons. In doing so, the talk also discusses specific directions that are particularly promising at present.

Some words of context are in order. We have no evidence of beyond-Standard Model (BSM) physics from direct searches at colliders. We have, however, several hints from flavour observables, forming an actually coherent pattern. These observables roughly fall into the following categories: (1) branching-ratio (BR) data for $b \to s\mu\mu$ modes below the respective Standard-Model (SM) predictions. Here, the challenge are form factors, whose theory prediction brings in the largest uncertainties. Importantly, a large subset of such predictions are steadily improving through non-perturbative, first-principle approaches such as lattice QCD (LQCD)—this holds notably in the Λ_b channel. (2) $B \to K^*\mu\mu$ angular data in poor agreement with the SM prediction in well-defined bins of the di-lepton invariant mass squared q^2. Here, the challenge are charm loops. This is a rapidly evolving subject in its own right, and I will not dwell more on it here. (3) $b \to s\mu\mu$ over $b \to see$ ratio data below the SM prediction. These ratios include R_K and R_{K^*}, whose experimental error is mostly statistical.

All of items (1) to (3) concern loop processes, on which new dynamics of some sort has been anticipated for decades. Finally, there is a persistent, although somewhat fading, discrepancy in $b \to c\tau\nu/b \to c\ell\nu$ data, which are tree processes.

Note that the data in each of the concerned categories is affected by different challenges from a theory as well as experimental standpoint. Hence the errors attached to each of these datasets bear little correlation with each other.

Next, I would like to make a few basic theory considerations. The very first one is that data follow well-defined patterns, that are suggestive of a certain number of theory ideas. It is this basic fact that makes these data alluring. These ideas emerge before doing any fit and can be shortly summarized as follows.

First, and quite remarkably, of all the wealth of $b \to s$ semileptonic decays, most data hint at shifts in just two effective couplings. The full $b \to s\ell\ell$ effective Hamiltonian includes, besides the $(V-A)\times V$ as well as $(V-A)\times A$ di-quark di-lepton structures (called $\mathcal{O}_9$, $\mathcal{O}_{10}$), also right-handed quark counterparts, dipole operators, as well as scalar and tensor ones. Interestingly, effects are mostly in the Wilson coefficients $C_{9,10}$ of the muonic $\mathcal{O}_{9,10}$. In particular, two scenarios stand out, namely, either a δC_9 shift alone or a shift in the combination $\delta C_9 \simeq -\delta C_{10}$ (see, e.g., [1]). The renormalization scale is understood to be around the b-quark mass scale, yet the above condition does not imply fine-tuning for well-known

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reasons. Also remarkably, the second of the two mentioned scenarios amounts to a $(V-A)\times(V-A)$ current [2]. This is theoretically appealing, because it corresponds to operator combinations that can be written in terms of $SU(2)_L$ invariants—well suited for UV completions.

The preference for δC_9 vs. $\delta C_9 \simeq -\delta C_{10}$ will ultimately be resolved by well-defined measurements, in particular, an accurate, $\mathcal{O}(10\%)$ determination of $BR(B_s \to \mu\mu)$. Present error is at about 16% as we know, but the experimental combination of Atlas, CMS and LHCb measurements may quite soon be able to confirm or disprove deviations of C_{10} of $\mathcal{O}(10\%)$.

A further theory consideration concerns the patterns of observed lepton universality violation in $b\to s$, with effects in ee much smaller than in $\mu\mu$, in turn much smaller than those allowed in $\tau\tau$. As first pointed out in [3], this observed pattern is suggestive of new physics coupled dominantly to the third generation of SM fermions. This idea, by way of $SU(2)_L$ invariance, offers in turn a natural way to link $b\to s$ and $b\to c$ data [4]. Starting from these and other ideas, the theoretical picture has greatly evolved over the last years. Present data allow for a more accurate picture, and this will be even more so with upcoming data—from LHCb and Belle II as well.

These considerations can be matched to the quantitative picture emerging from global fits of data to couplings of the weak effective theory (WET), e.g., [1, 5]. The simplest case is to consider the shift to one single Wilson coefficient at a time. By factoring out the SM weak phase, an even simpler ansatz is to consider the real part of such shifts only. To first approximation, such case delivers already the most popular picture of the new physics hinted at by the data: the two scenarios mentioned above, with the leptonic index understood to be in the muon direction. Also C_{10} alone works, but the lower performance is due to the fact that it does not account for the anomaly in $B\to K^*\mu\mu$ angular data.

LFV IN $b \to s$ DECAYS

With this introduction, I would like to now discuss LFV decays. A basic motivation is the fact that, if we observe LUV, then, in general, we should also expect observable LFV. A caveat is in order. "We should expect" implies that exceptions are logically possible within models existing in the literature. For an exception to be convincing, the dynamics that explains LUV should have a built-in mechanism that prevents LFV. This is the case for minimal flavour violation [6].

In the absence of such mechanisms, one expects new LUV and LFV to go hand in hand, in the same way as one in general expects that the CKM matrix is non-diagonal. One may argue that this alleged LUV–LFV connection has a counterexample precisely in the SM, e.g., in the Higgs-induced couplings to fermions. The lack of LFV in this case—due to the small neutrino masses—is intimately connected with the peculiar SM pattern of flavour violation, generalized by the hypothesis of MFV. The point is that there is no reason to assume that the new physics responsible for the "B anomalies" should fulfil MFV.

We can make a simple example of this LUV—LFV connection. Recall that all $b\to s$ data are explained at one stroke if one considers a $(V-A)_q\times(V-A)_\ell$ bilinear, with a Wilson coefficient larger for $\mu\mu$ than for ee. Such pattern suggests a purely 3rd-generation interaction of this kind, generated at a scale larger than the EWSB scale. Therefore, fermionic fields are not in the mass eigenbasis. The transformations leading to this basis will in general misalign the initial interaction across generations, and yield LFV along with LUV.

Crucially, one can parametrically relate the measured LUV (measured through R_K and siblings) to measurable LFV decays such as $B\to K\tau\mu$. In fact, the BR for an LFV decay is proportional to a factor depending on the departure of R_K from unity, times a function of ratios of the charged-lepton unitary transformations (the quark ones on the other hand cancel), times this measured BR. Plugging numbers, one sees that LFV BRs are generically expected in the ballpark of 10^{-8}. This point was made in [2].

Certain well measured LFV decays constrain this picture [7, 8]. To see this, one may start from an effective 3rd-generation interaction like the one mentioned before, but properly $SU(2)_L$-symmetrized, close the quark loop, and attach a gauge boson decaying to two final-state leptons. One thereby obtains also LFV in the decays of leptons, e.g., $\tau\to 3\mu$. This example allows relating and comparing B-decay LFV with purely leptonic LFV, here $\tau\to 3\mu$. Till very recently, searches of leptonic LFV used to be more advanced than searches of LFV in B decays. Accordingly, existing limits on some leptonic LFV decays are already very close—or even partly exclude—their allowed parameter space.

It is interesting to turn from EFTs to UV-complete and calculable models, such as ones involving the so-called U_1 leptoquark. Such models are clearly more predictive than EFTs. One can see that leptonic LFV constraints can be fulfilled and still the model gives interesting signals for b-hadron LFV. A well-known and well-studied example are so-called PS_3 models (where PS stands for Pati–Salam) [9]. One includes a $U(2)^5$ symmetry for the light generations

[10], and this symmetry implies a well-defined range of values for the $\tau \to \mu$ effective coupling. Then, LFV is calculable and one finds signals not far from, but below, current experimental limits [11].

CONNECTIONS WITH KAON DECAYS?

Finally, an interesting question is whether LUV effects in B physics may have any observable implications in Kaon decays. Quite a few studies have actually appeared on the subject of correlations between B- and K-physics LUV and/or LFV. It turns out that especially interesting examples include $K \to \pi\nu\nu$ modes and $K \to \mu e$ as well as $K \to \pi\mu e$ modes [12, 13]. It turns out that these modes may be accessed not only at dedicated kaon machines the likes of NA62, KOTO, etc., but also at B-physics machines like LHCb and BelleII. Even if most kaons decay well outside the detector, they are so copiously produced that many will decay close enough to the primary vertex that reconstruction is actually possible.

We now turn to the question why correlated effects with B anomalies may be expected. As said before, the NP introduced for B decays is usually written in the form of WCs times effective operators, $\mathcal{L}_{\text{eff}} \supset C^{(a)}_{ijkl}/\Lambda^2 \mathcal{O}^{(a)}_{ijkl}$, where the operators $\mathcal{O}^{(a)}_{ijkl}$ involve two quarks and two leptons, with flavor indices ij and kl, respectively. The scale Λ is fixed from the size of observed discrepancies. Typical ranges are in the few to few tens of TeV. Then, the Wilson couplings encode the flavour structure. If dynamics is tree level, then the couplings may either factorize between a quark vertex with coupling $\lambda^{(q)}_{ij}$ and a lepton vertex with coupling $\lambda^{(\ell)}_{kl}$. This is the case for Z'-like NP. Otherwise, one can have a quark-lepton coupling $\lambda^{(q\ell)}_{il}$ times another quark-lepton coupling $\lambda^{(q\ell)*}_{jk}$, as is the case for LQ-like NP. In either case, with well motivated flavour-structure ansaetze, the λ's entering B decays and those entering K decays are highly correlated.

An example is provided by [12], which states that LHCb may well improve existing limits on $K_L \to \mu e$ and $K^+ \to \pi\mu e$. This study starts from the $(V-A)_q \times (V-A)_\ell$ effective Hamiltonian advocated to explain the B anomalies, whose Wilson coefficients can be matched to the mentioned λ couplings. For the latter, one can make a CKM ansatz for the $\lambda^{(q)}$'s, and stay agnostic on the $\lambda^{(\ell)}$'s. Ensuing signals in both of the above mentioned channels may be 1 to 2 o.o.m. below current limits.

Finally, I would like to spend a few words on existing searches. After [3], many searches of LFV decays have been performed and more are underway (for an executive summary and references, see [14]). All modes involve leptons with different flavours; since muons are an ideal handle, the most favourable searches involve a muon and a different lepton, hence μe and $\mu\tau$. Sensitivity depends crucially on background rejection. Here there are several sources, including combinatorial; semi-leptonic or resonant decays (especially $c\bar{c}$ resonances) with mis-ID of the final states—resonant decays are important of course because of their large rates. One would argue that $B \to K\mu e$ has the advantage that one can close the kinematics. However, electrons introduces a challenge, because they copiously radiate, and the momentum measured is the momentum after radiation. Besides, the accompanying τ decay necessarily involves missing energy. Nonetheless, many searches are already public, and they are quite stringent already. There are limits that bite the 10^{-9} BR region for the semileptonic case, which makes these limits severe, even in the light of the generic argument made before.

CONCLUSIONS

As of Moriond 2021, B anomalies endure, with one clear message: there is a hint of non-standard LUV. In general, LUV and LFV are two sides of the same broken symmetry; i.e., in order to prevent LFV in the presence of LUV, one needs an additional assumption, often ad hoc. By general arguments, the several-percent level of the measured LUV, implies BRs around 10^{-8} for LFV. This figure starts to be challenged by real data. Using EFT-driven arguments one can even relate LFV in B decays with LFV in K decays.

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CONFLICT OF INTEREST

The author declares that he has no conflicts of interest.

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