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A comprehensive EFT global fit to semi-leptonic charged-current transitions of the light quarks

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Abstract

This Letter of Interest (LOI) proposes to systematically study the physics beyond the standard model (BSM) in the (charged-current) semi-leptonic light-quark transitions. Our proposal encompasses the exploration, within the framework of the SMEFT, of the precise data resulting from ongoing experiments measuring nuclear, neutron, kaon, hyperon and tau decays, together with LHC data on mono-lepton and di-lepton searches at high-p_T. This should spearhead the development of a global fit including also heavy-quark decay data and considering also CP-violation.

Semileptonic decays of nuclei and hadrons play an important role in the field of precision physics. Thanks to the continuous advancement of numerical simulations of lattice QCD (LQCD) and the arrival of more and more precise experimental data, these processes are precious probes of small nonstandard effects generated by hypothetical heavy particles beyond the standard model (SM). On the other hand, the large and rich data that is being collected at the LHC and other experiments together with the lack of direct evidence of new physics (NP) at the TeV scale has prompted a surge in the application of effective field theories (EFT), in particular the SMEFT, to systematically test the SM and search for nonstandard effects in the data.

The application of the EFT approach to NP searches in semileptonic quark decays is the subject of this note. Such application will make possible to properly analyze the coming experimental data, to assess which theory calculations need to be prioritized and to understand the implications of these difficult measurements and calculations for the search of new phenomena.

Semileptonic quark decays comprise many different processes. In the following we focus mainly on light quarks (up, down, strange) and discuss some examples to give an overview of the exciting times ahead and the need for a theory effort in this front.

Nuclear and neutron β-decay: This field has witnessed important developments in the last few years that will continue in the coming ones. Experiments with cold and ultracold neutrons keep improving and (sub)permille level measurements have been carried out recently [1,2]. In the coming years they are expected to provide a competitive extraction of V_{ud} after half a century of nuclear-based extractions [3, 4]. Old inconsistencies regarding e.g. the neutron lifetime should also be completely clarified with the arrival of new experiments.

On the theory front, new methods are being applied (or proposed) to the calculation of radiative corrections [5–8]. These works have questioned the previously accepted values and have a promising potential for further improvement. Advances in numerical simulations are also very impressive, with e.g. percent-level LQCD calculations of the nucleon axial charge [9–11], which are expected to further improve in the near future [12].

These new results will have direct implications for the V_{ud} extraction, but also for the searches of new phenomena, which should be carefully and systematically explored. The EFT setup has proven to be a solid framework to carry out this analysis.

(Semi)leptonic kaon decays: Measurements of leptonic $K \to \ell\bar{\nu}$ (or $K_{\ell 2}$) and semileptonic $K \to \pi\ell\bar{\nu}$ (or $K_{\ell 3}$) kaon decays, with $\ell = e$, μ, carried out over the past $\sim$ 60 years have collected a very precise data set, which has been recently matched by theoretical calculations of hadronic form factors and radiative corrections [13,14]. The $K_{\ell 3}$ decays, together with LQCD calculations of the form factor $f_+(0)$, give access directly to $|V_{us}|$, while the ratio of the rates of $K_{\ell 2}$ and $\pi_{\ell 2}$ decays, with the corresponding calculation of the ratio f_K/f_π, allows one to determine $|V_{us}|/|V_{ud}|$. This has enabled a simultaneous determination of $|V_{us}|$ and $|V_{ud}|$ with permille precision and to stringent tests of the SM through e.g. the "first-row CKM unitarity". Interestingly, there is currently a tension with unitarity that reaches a significance of $\sim 2.7\sigma$ using $N_f = 2+1+1$ LQCD calculations [11]. This could point to the effect of uncontrolled experimental or theoretical systematics appearing at this level of precision or to a manifestation of BSM physics [15].

Clarifying this discrepancy should be one of the targets of this field in the decade to come. Improvements on the experimental kaon data set and on the precision of the LQCD calculations are expected to be modest, of the order of $\sim 30\% - 50\%$ from each source of uncertainty in the determination of $|V_{us}|$ [14,16]. Besides unitarity tests, the kaon decays offer very powerful probes of NP [15]. In particular, scalar and tensor contributions could significantly change the spectrum of $K_{\mu 3}$ and more accurate bounds are expected from using LQCD calculations of the q^2 dependence of the form factors [17].

Semileptonic hyperon decays: They provide an independent source of information for the $s \to u\ell\bar{\nu}$ transitions. Except for the measurements performed by the KTeV and NA-48 Collaborations in the $\Xi_0 \to \Sigma^+\ell\bar{\nu}$ decay channel, most of the data is more than 40 years old [18]. Theoretical calculations, on the other hand, are still far from the level of maturity that have been reached in the kaon sector [19–21]. This is very likely to change over the next decade. LHCb and BESIII turned out to be hyperon factories and a hyperon physics program is starting to emerge in these collaborations [22,23] (see also Ref. [24]). LQCD calculations in the baryon sector are finally ramping up and determination of baryon properties down to sub-percent precision is starting to become feasible [9,11,12]. This will lead to an alternative determination of $|V_{us}|$ [25] and to constraints on NP complementary to those stemming from kaon decays [26].

Hadronic tau decays: They have been extensively used in the last decades to extract chiral parameters and fundamental SM quantities such as α_s or V_{us} [27]. Recently, EFT analyses of nonstandard effects in tau decays were carried out for the first time [28, 29]. Such EFT approach makes possible to understand the implications for ultraviolet physics of the (dis)agreement between the very precise measurements and SM calculations, and to extract competitive NP bounds.

There are multiple aspects in which this programme should be refined and extended in the coming years: (i) inclusion of CP-violating observables and operators; (ii) analysis of the impact of new data, e.g. Belle-2 [30], and new lattice calculations, e.g. [31]; (iii) addition of strange tau decays, which will make possible to understand the NP contributions affecting the associated V_{us} extraction; (iv) comparison of the spectrum of the 2-pion decay with $e^+e^- \to \pi^+\pi^-$ data, taking into account isospin-breaking and radiative corrections; (v) study of the potential of additional CP-conserving channels such as the 3-pion mode, for which a large amount of data will be obtained by Belle-2; (vi) study of the interplay with new LHC measurements in the tau sector, such as Ref [32].

CP-violation with the light(est) quarks: Another direction we propose to focus on is the studies of CP violation in the semileptonic processes. CP violation has been observed in the decays of kaons, B-mesons, and D-mesons, and the data so far are well described by the CKM paradigm of the SM. On the other hand, for semileptonic processes in the up and down quark sectors, where SM predicts negligible CP violation, experimental and theoretical analyses are currently less developed. From the theoretical viewpoint, such decay processes can be sensitive to phases in contact interactions between up/down quarks and leptons. However, state-of-the-art global EFT fits typically operate under the assumption of real Wilson coefficients, and ignore the input from CP-violating observables, see e.g. [3]. We propose to generalize these fits so as to provide model-independent and robust constraints on the CP phases of 4-fermion $(u\Gamma d)(l\Gamma\nu)$ operators with various Lorentz structures Γ. This can be done thanks to the experimental input from the measurements of the so-called D and R parameters [33] of the neutron and nuclei. The progress in this case relies on future more precise experimental measurements, but also on improving existing theoretical calculations of the final-state interactions, which may mimic CP-violating effects [34]. Finally, an interplay between these probes and the electric dipole moments (which are sensitive to the same EFT operators at a higher-loop level [35]) must be investigated.

Complementarity with high-p_T: One should stress that high-energy colliders, including the LHC, can also play an important part in this program. Various high-p_T processes, such as the Drell-Yan production $q\bar{q} \to \ell^+\ell^-$, provide complementary information to what can be extracted from low-energy experiments, see e.g. [36, 37]. A strength of the LHC is that it can access the $q\bar{q}\ell^+\ell^-$ 4-fermion operators for *all* quark flavors [38]. However, a complete and model-independent characterization of the LHC constraints on the semileptonic operators is not available in the literature. We propose to construct a global likelihood for the $q\bar{q}\ell^+\ell^-$ operators based on the available LHC data, and integrate it with the likelihood derived from low-energy studies of semi-leptonic processes.

Global fit to flavor data: Global fits to flavor observables in the (SM)EFT are normally restricted to a particular type of quark-flavor transition. Each of these flavor sectors involve typically many processes requiring an extensive and careful assessment of uncertainties. Furthermore, in the SM all flavor-violation is parametrized within the CKM paradigm by 3 angles and a complex phase and extending this to a generic BSM framework can prove to a be non trivial task. However this can be achieved systematically and in all generality within the SMEFT [39], allowing us to distil the wealth of experimental and theoretical information on flavor transitions into the correlated values of the most general set of Wilson coefficients. Setting up and developing such BSM frameworks for global fits to an increasingly diverse and larger flavor data set should be one of the *ultimate* goals of the flavor physics community. This is particularly timely given the tensions in the $|V_{ud}| - |V_{us}|$ plane, in the determinations of $|V_{cb}|$ and $|V_{ub}|$ or in light of the recent anomalies in semileptonic B-decays.

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