Topical Groups:

■ (RF1) Weak Decays of b and c Quarks
■ (EF05) QCD and Strong Interactions: Precision QCD
■ (CompF2) Theoretical Calculations and Simulation
■ (TF05) Lattice Gauge Theory

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Snowmass 2021 Letter of Interest
Precision Lattice QCD in Support of BSM Searches

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In the search for new physics, high-precision experimental measurement and high-precision theoretical prediction work together. New physics at energy scales exceeding those of present accelerators will first reveal itself via virtual processes that produce tensions between predictions of the Standard Model and experimental measurement. A substantial experimental effort is currently focused on B-meson decays, motivated by several such tantalizing, long-standing tensions [1, 2]. The experimental effort will certainly extend into the next decade. High-precision lattice QCD provides crucial nonperturbative information about the strong-interaction environment of heavy-quark processes. Indeed, it is now the nonperturbative tool of choice. New methods in lattice QCD under current development will allow theory to keep up with expected reductions in measurement uncertainties.

The Belle II experiment began full physics running in Spring 2019 and expects to collect data sets that are 50–100 times larger than what was obtained by the Belle experiment [3]. For example, Belle II measurements of the semileptonic $B \to \pi\ell\nu$ differential distributions could yield a determination of $|V_{ub}|$ at close to 1% uncertainty [4], provided that there are commensurate improvements in the accuracy of the corresponding lattice QCD form factors. The Belle II physics program will, of course, feature a broad range of measurements, including a large number of semileptonic B- and D-meson decay observables, for which we can expect similar improvements in the measurements. Similarly, it is expected that the LHC luminosity and detector upgrades will yield improved measurements at LHCb [5] with, again, significant reductions in the experimental uncertainties. Over the next decade, these and similar experiments will continue to refine their measurements. These anticipated experimental improvements motivate the need for improved lattice-QCD calculations with commensurate precision.

Recent years have brought enormous progress in lattice QCD, establishing it as an essential tool in high energy phenomenology, especially for quark-flavor physics [6]. In particular, we have very precise results for a number of hadronic matrix elements relevant for weak kaon, D- and B-meson processes, with significant reductions in uncertainties compared with previous results. There are now simply no other methods that can match the ability of lattice QCD to provide crucial, precise nonperturbative information about the hadronic environment of both leptonic decays, such as $B \to \ell\nu_\ell$ and semileptonic decays such as $B \to \pi\ell\nu$. As an *ab-initio* method, lattice QCD excels in the control of systematic errors that could distort the final result. The QCD contributions to leptonic decays are characterized by a decay constant, while those to semileptonic decays are characterized by form factors, which are functions of the momentum transferred to the outgoing leptons. Recent results for the leptonic B, B_s, D, and D_s decay constants have sub-percent errors. Results for the semileptonic B-meson form factors at both zero and nonzero recoil, when combined with experimental measurements of the corresponding decay rates, yield precise determinations of the associated CKM matrix elements, $|V_{cb}|$ and $|V_{ub}|$. Other recent highlights are precise calculations of the semileptonic kaon form factor at zero q^2, which improves upon our knowledge of the CKM matrix element $|V_{us}|$, a complete set of semileptonic form factors for tree-level and rare B-meson decays to pions, and kaons, yielding new, interesting constraints on models of new physics, and the complete set of the neutral B and B_s meson mixing matrix elements, yielding the tight constraints on $|V_{td}|$, $|V_{ts}|$, and their ratio.

Over the next decade, we would like to participate in both ongoing and new efforts that will yield lattice results at the permille level for a range of B- and D-meson quantities. This includes the semileptonic form factors and other hadronic matrix elements, that are already part of our collaboration's program. In addition, there are exciting opportunities for broadening precision lattice calculations relevant for heavy-flavor physics to include multi-hadron states, inclusive decays, and nonlocal matrix elements. The following developments will help pave the way:

- **Exascale computing, algorithms, and software** The era of exascale computing has begun. In 2021 the Argonne and Oak Ridge Leadership Computing Facilities will deploy exascale computers that will greatly enhance lattice-QCD calculations. In particular, they are essential for enabling permille-level precision as well as extending the reach of lattice calculations to more challenging quantities.

  It is important to recognize that improvements in software and algorithms over the past decades have played and will continue to play a role equal to hardware in this enhancement. The increasing complexity of computer architectures requires a continued workforce investment in computational physicists to assure that we will continue to make the most of these facilities.

- **QED and strong isospin breaking effects:** To reach permille level precision in the hadronic amplitudes for B- and D-meson processes, effects of quantum electrodynamics and strong isospin breaking must be included in the lattice computations. There is already a large effort underway to include these effects in the hadronic corrections to the muon $g-2$ (and related quantities) [7], which will have direct benefits to these efforts here. In addition, first lattice results for isospin corrections of leptonic decay rates, which include radiative QED corrections, are already available [8] and extensions to radiative leptonic decays are also being developed [9, 10].

- **Multi-hadron states** Because of final-state interactions, calculations of decays to resonant final states, such as K^* and ρ mesons, are more challenging than calculations of decays to longer-lived states, such as pions and kaons. Nonetheless, there is an abundance of experimental data for these processes. Precise lattice calculations with fully quantified uncertainties require a careful treatment. The theoretical framework treating two interacting hadrons in a finite volume was developed long ago (see, for example, Refs. [11, 12]). Fortunately, within the lattice community there has been continuing work to develop further the framework and the methodologies for handling intermediate and final multi-state hadronic systems (see, for example, Refs. [13–15]), which enable computations of new, challenging quantities, including weak decay processes involving multiple hadrons. New computing power is essential to push such calculations to the needed level of precision.

- **Inclusive decays (and related quantities)** New methodologies are also extending the phenomenological coverage of lattice QCD. Until recently, lattice methods have been limited to exclusive decays. However, a number of recent proposals [16–19] show promise of providing, for the first time, a well-posed, first-principles lattice calculation of rates for inclusive decays. For further details, please see the companion LOI "Lattice studies of inclusive B-meson decays". Thus, over the next few years we can hope to have new results from lattice QCD that will clarify the notorious discrepancy in the exclusive and inclusive determinations of the CKM matrix element $|V_{cb}|$.

  Finally, we note that it would also be interesting to explore similar methods for long-distance contributions to D-meson mixing or for nonfactorizable contributions to rare semileptonic B-meson decays, as, for example in $B \to K^{(*)}\ell\ell$.

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