The Future Quark Flavor Physics Program

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I. JUSTIFICATIONS

Complimentary to the high-p_T physics program Over the past decade, heavy flavor factories been pouring out data needed to pin down the values of the CKM matrix elements and CP-violating phase and to measure decay rates for rare processes. This program to measure Standard Model parameters with ever more exacting precision and look for inconsistencies with Standard Model predictions is complimentary to the search for new physics via direct production of new particles at colliders. Once ATLAS and CMS discover new particles, they will measure the spectrum. Precision flavor measurements will still be needed, however, to extract the couplings and determine the underlying structure of the theory.

Probes higher energy scales than the high-p_T program Because new particles will typically appear in loop-level processes such as neutral kaon mixing, the flavor sector is sensitive to physics at very high scales (~ 1000 TeV). Therefore if new physics is above the TeV scale, indirect searches in the flavor sector will be our only probe.

New physics is often seen first at the "intensity" frontier Many surprises and insights have come from rare processes, starting with strangeness-changing decays. Other examples include the discovery of CP violation in the kaon system, and the need for a charm quark in a theory with sufficiently small flavor-changing neutral currents. Fits to intensity-frontier data have also anticipated the masses of the W and Z bosons and the top quark.

II. MOTIVATIONS

Expect new physics in the flavor sector Most Standard Model extensions contain new CP-violating phases and new quark-flavor changing interactions that would lead to deviations from Standard Model predictions in the flavor sector.

"$|V_{ub}|$ puzzle" For several years, there has been a persistent tension between determinations of $|V_{ub}|$ from exclusive B-meson semileptonic decays and inclusive $B \to X_u \ell \nu$ decays. More recently, the situation has been further muddled by the experimental measurement of $\mathcal{B}(B \to \tau\nu)$, which leads to a determination of $|V_{ub}|$ that disagrees with both the inclusive and exclusive values. This tension may be due to new physics effects such as right-handed currents that contribute differently to each of the three B-meson decay processes.

Tension in the global UT fit Improved experimental flavor-physics measurements and lattice QCD weak matrix element calculations have shrunk substantially the allowed region of parameter space in the ρ-η plane and revealed a $\sim 3\sigma$ tension in the CKM unitarity triangle. This tension may be due to a non-Standard Model source of CP-violation.

III. KEY INGREDIENTS

Lattice QCD weak matrix element calculations In the past decade, experimental measurements at the flavor factories, in conjunction with lattice QCD calculations of hadronic weak matrix elements, have established that the CKM paradigm of CP-violation describes experimental observations at the $\sim 10\%$ percent level. Lattice QCD calculations will continue to play a key role in interpreting the results of heavy-flavor (such as NA62, KOTO, and Belle II) and other intensity frontier experiments (such as muon $g-2$) in the future.

Improved lattice precision We may now be seeing the first cracks in the Standard Model CKM framework. In the future, even more precise lattice weak matrix element calculations will be needed to establish the presence of new physics in the flavor sector with 5σ significance. This includes better calculations of neutral B-meson mixing matrix elements, B-meson decay constants, and B-meson semileptonic form factors.

For example, the error in the CKM matrix element $|V_{cb}|$ is now the limiting uncertainty in the constraint on the apex of the CKM unitarity triangle from neutral kaon mixing (ε_K). The predictions for the Standard Model $K \to \pi\nu\bar{\nu}$ branching ratios are also limited by the error in $|V_{cb}|$. Spectacular deviations from the Standard Model predictions for $K \to \pi\nu\bar{\nu}$ are possible in many new physics scenarios. Given current lattice QCD methods, we can expect a reduction in the error on $|V_{cb}|$ to below $\sim 1.5\%$ from improved calculations of $B \to D^{(*)}\ell\nu$ decays, leading to an error in the SM branching fraction of below $\sim 6\%$. With this precision, even a $\sim 30\%$ deviation from the Standard Model prediction for $K \to \pi\nu\bar{\nu}$ would be 5σ evidence for new physics. Further reduction in the errors on inclusive $|V_{cb}|$ will require (not yet thought-of) improved lattice QCD methods.

For some hadronic quantities, obtaining percent-level precision will require including effects in numerical lattice simulations that until now have been neglected, such as dynamical charm effects, EM effects, and disconnected diagrams. This work is in progress.

New lattice observables The discovery of new physics in the flavor sector may require studying quark flavor-changing processes that have not yet been addressed with precise three-flavor lattice QCD calculations. For example, rare B semileptonic and radiative decays (*e.g.* $B \to K^{(*)}\ell^+\ell^-$ and $B \to K^*\gamma$) and direct CP-violation in the neutral kaon system (ε'_K) are both mediated by QCD and EW penguin diagrams, and may be particularly sensitive to new physics effects. Once new physics signals in the flavor sector are sufficiently substantiated, precise lattice calculations of beyond-the-Standard Model hadronic matrix elements (such as those that contribute to neutral kaon or B mixing) will be needed to distinguish between new-physics scenarios. Lattice calculations of $B \to \rho\ell\nu$ are needed to test the right-handed current resolution to the "$|V_{ub}|$ puzzle". Further, lattice QCD calculations of non flavor-changing observables, *e.g.* the hadronic light-by-light contribution to muon $g-2$, will also be needed to interpret the results of upcoming intensity-frontier experiments.