Snowmass 2021 Letter of Interest:
Decays of Heavy Flavors Beauty, Charm, and Tau

The Heavy Flavor Averaging Group

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Thematic Area(s):

Rare Processes and Precision Measurement Frontier
■ (RF01) Weak Decays of b and c
■ (RF04) Baryon & Lepton Number Violation
■ (RF05) Charged Lepton Flavor Violation (e, μ, and τ)

Abstract:

The Heavy Flavor Averaging Group provides this Letter of Interest (LOI) as input to the Snowmass 2021 Particle Physics Community Planning Exercise organized by the Division of Particles and Fields of the American Physical Society. Research in heavy flavor physics is an essential component of particle physics, both within and beyond the Standard Model. To fully realize the potential of this field, we advocate strong support within the U.S. high energy physics program for ongoing and future experimental and theory research in heavy flavor physics.

The Heavy Flavor Averaging Group (HFLAV) is an international collaboration responsible for calculating world averages of b-hadron, c-hadron and τ-lepton properties from relevant experimental measurements. All results are documented in an extensive collection of web pages[1] and compiled into a biannual review article. The most recent compilation will appear in *Eur. J. Phys. C*.[2] Many of our world averages are used by the Particle Data Group.[3] With this perspective we comment on the importance of heavy flavor physics as input to the Snowmass 2021 Particle Physics Community Planning Exercise.

Flavor physics is one of the cornerstones of the Standard Model (SM). Indeed, many advances in the construction of the SM resulted from flavor physics research. This includes the three-generation prediction of the Kobayashi-Maskawa mechanism, the universality of the gauge interactions, the high masses of the top quark and the weak gauge bosons, and the presence of large charge-parity (CP) violation in beauty hadrons. Similarly, flavor physics can give insights into physics beyond the SM, referred to here as new physics (NP). Some specific examples are:

- The baryon asymmetry of the universe necessitates CP violation well beyond that provided by the SM. Precise measurements of CP violation in heavy flavor (b, c, and τ) decays may uncover new sources of CP violation. Processes in which the SM predicts zero or very small CP violation are particularly sensitive to NP amplitudes.
- The origin of the three generations of fermions and their Yukawa couplings are not explained by the SM; this shortcoming hints that there might exist additional physics. These couplings are probed by precision measurements of the Cabibbo-Kobayashi-Maskawa (CKM) matrix, which test the three-generation picture and the prediction that quark-flavor non-universality depends on only three real parameters and one complex phase in the CKM matrix.
- The SM gauge couplings depend only on weak isospin. This can be tested to high precision in weak decays of D and B mesons, and of τ leptons; any deviation would be a sign of NP. Thus, measurements of lepton-flavor non-universality, lepton-flavor violation, and lepton-number violation are important probes of NP. Similarly, flavor-changing neutral currents, which necessarily proceed via internal loop diagrams, are sensitive to the presence of new intermediate states and couplings.

The sensitivity of heavy flavor measurements leads to tight constraints on NP, in many cases at energy scales far above those accessible at an energy-frontier machine. Some flavor physics measurements have shown deviations from SM predictions and in fact might indicate NP, e.g., measurements of the lepton-universality ratios $R(D)$, $R(D^*)$, and R_K. In these cases, more data and confirmation among different experiments are needed to firmly establish these discrepancies. If these deviations were due to NP, additional deviations should arise in other measurements of $B_{(s)}$ and τ decays.[4] Some flavor physics measurements have motivated searches for new mediators at the LHC;[5] in this case heavy flavor physics played a role at an energy-frontier machine.

In addition to elucidating the structure of weak interactions, heavy flavor physics provides a unique laboratory for studying strong interactions. In particular, beginning in 2003 a number of hadronic states containing c or b quarks with unexpected quantum numbers and properties have been discovered, e.g., the D^+_{sJ}, $X(3872)$, $Z^+_c(4430)$, and P^+_c (pentaquark) states. These discoveries opened up a new research area by revealing new ways in which QCD forms bound states.

Heavy flavor physics has been, and continues to be, a major effort in the US high energy physics (HEP) program. Flavor physics was the main thrust of the CLEO, Belle, and BaBar experiments, and a significant thrust of the CDF, DØ, and SLD experiments. It was a main thrust of the Fermilab fixed target program. US groups played a leading role in studying B and D physics at Belle, and also at LEP experiments. Today, the leading flavor physics experiments are Belle II, LHCb, and BES-III, and the number of US groups working on these are 18, 6, and 5, respectively. Flavor physics is also studied at the energy-frontier experiments CMS and ATLAS. In addition, US theory groups play leadership roles in flavor physics phenomenology and lattice QCD calculations. As in other areas of HEP, data analysis and theory calculations are often performed by small groups at universities and laboratories and can take years to complete. Thus, long-term support of such groups is essential for advancing the field and training the next generation of particle physicists.

The majority of heavy flavor physics measurements for the next ten years will be made by Belle II, an e^+e^- experiment, and LHCb, which runs at the CERN LHC. The physics programs of both experiments are well-documented.[6;7] BES-III will also make many measurements.[8] Belle II builds upon the extremely successful physics programs of the "B-factory" experiments Belle and BaBar, while LHCb continues its very successful physics program achieved with LHC Runs I and II data. Belle II excels at reconstructing B, D, and τ decays with undectected neutrinos, photons, and neutral mesons in the final state, while LHCb benefits from large production cross sections for both mesons and baryons, and (due to a large Lorentz boost) excellent decay-time resolution. The two experiments can be viewed as complementary, e.g., LHCb will make high-statistics measurements of B_s^0 decays, while Belle II will study τ decays. Both experiments will study B and D electroweak penguin decays, one typically with high statistics (LHCb) and one typically with low backgrounds (Belle II). The resulting systematic uncertainties will be quite different. In addition to complementarity, there is also notable symbiosis among flavor physics experiments. For example, BES-III produces D^0-$\overline{D}^0$ pairs in a quantum-correlated state and uses such correlations to measure strong phase differences between $D^0 \to K_S\pi^+\pi^-$ and $\overline{D}^0 \to K_S\pi^+\pi^-$ decays. These strong phase differences will subsequently be used by Belle II and LHCb to precisely measure the CKM unitarity triangle angle ϕ_3 (or γ).

Finally, we point out that each generation of flavor-physics experiments involves significant advances in detector design and performance. The Belle II detector includes a state-of-the-art pixel detector and an innovative particle identification detector that extends the concept of BaBar's DIRC detector by adding focusing and precision timing. The LHCb detector for the upcoming Run III uses a new state-of-the-art vertex detector and the next generation of triggering architecture and hardware. Belle II has recently begun taking data and plans to collect 50 times more data than Belle did by the end of the decade.[6] On the same time scale, LHCb will collect five times more data than its current sample. Beyond Run 4 of the LHC, LHCb proposes an upgrade to collect an order of magnitude more data.[9] Similarly, Belle II and the SuperKEKB accelerator have begun exploring how to extend the data sample beyond the planned 50 ab^{-1}, and possibly polarize the electron beam to expand the physics program further.

In summary, heavy flavor physics has played a crucial role in understanding the SM and in searching for NP. This will continue to be the case in the future. To fully realize the potential of heavy flavor physics, we advocate that the US continue to play a leading role in the field, and for US funding agencies to strongly support this physics.

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