HFLAV input to the update of the European Strategy for Particle Physics

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Abstract

The Heavy Flavor Averaging Group provides with this document input to the European Strategy for Particle Physics. Research in heavy-flavor physics is an essential component of the particle-physics program, both within and beyond the Standard Model. To fully realize the potential of the field, we believe the strategy should include strong support for the ongoing experimental and theoretical heavy-flavor research, future upgrades of existing facilities, and significant heavy-flavor capabilities at future colliders, including dedicated experiments.

The Heavy Flavor Averaging Group (HFLAV) [1] was formed in 2002 to continue the activities of the LEP Heavy Flavor Steering Group [2]. HFLAV is responsible for calculating world averages of measurements of beauty-hadron, charm-hadron and tau-lepton properties from current and past experiments, and provides a comprehensive resource for the field in terms of web pages and full documentation of results. The most recent compilation of our results appears in Ref. [3]. Many of our world averages are used by the Particle Data Group. With this perspective, we take the opportunity to comment on the importance of future heavy-flavor physics research. **In this document, we make the argument for support of heavy-flavor physics in both the near term and the far future.**

Flavor physics is among the central foundations of the Standard Model (SM). Indeed, many advances in the construction of the SM originated from research into flavor physics. This included 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, heavy-flavor physics is closely tied to questions that aim to unravel the physics beyond the SM (BSM). Some of these questions, and the ways in which current research in heavy-flavor physics studies them, are as follows:

- The baryon asymmetry of the universe necessitates CP violation far beyond that provided by the SM. Precise measurements of CP violation provide unique access to CP violation in BSM physics. Processes in which the SM predicts zero or very small CP violation can be particularly sensitive to BSM amplitudes. These include decays of the tau lepton and specific charm- and beauty-hadron decays.
- The origins of the three generations of fermions and of the Yukawa couplings that distinguish between them lie in BSM physics. This is probed by precision studies of

the Cabibbo-Kobayashi-Maskawa (CKM) matrix, which test the three-generation picture and the SM hypothesis that quark-flavor nonuniversality depends on only the four parameters of the CKM matrix.

- The SM gauge interactions are independent of flavor. However, the flavor-nondiagonal Yukawa couplings motivate searching for flavor-nonuniversal BSM interactions, which may arise from new gauge bosons or scalars, and may also be related to the dark-matter puzzle. Thus, it is important to test universality in heavy-flavor decays. In particular, lepton-flavor nonuniversality, lepton-flavor violation and lepton-number violation are unambiguous and sensitive probes of BSM physics. Similarly, flavor-changing neutral currents (FCNCs), which in the SM occur only at loop level, are very sensitive to the presence of heavy new states.

The sensitivity of heavy-flavor measurements leads to tight constraints on BSM physics, in many cases at energy scales that are far beyond those accessible at energy-frontier facilities. Examples of recent heavy-flavor results that have received a great deal of attention in the phenomenology and model-building literature include measurements of lepton-flavor universality and the observation of rare bottom-meson decays into $\mu^+\mu^-$. In turn, some of these measurements have motivated searches for new heavy mediators at the LHC [4]. In at least some of the channels, studies show that only a 100 TeV collider will be able to cover most of the model-parameter space allowed by the heavy-flavor constraints [5]. Thus, **heavy-flavor physics has far-reaching BSM sensitivity, as well as an important role in informing research at current and future energy-frontier facilities.**

Heavy-flavor physics provides a unique laboratory for studying the strong interaction. In particular, a number of hadrons with nonstandard quantum numbers that contain charm or beauty quarks, such as the $X(3872)$ and the $Z_c^{\pm}(4430)$, have been discovered in the past 15 years. Revealing new ways in which QCD forms bound states, these discoveries have opened up a very active area of hadronic-physics research.

Heavy-flavor research is a major effort in Europe. Across the continent, there are 61 groups on the LHCb experiment, 36 on the Belle II experiment, and 17 on the BESIII experiment. In addition, a significant number of groups work on heavy-flavor physics within ATLAS and CMS, and many European groups are leaders in the related theory. As in other areas of particle physics, data analysis in heavy-flavor physics is often performed in small groups at universities and laboratories, involves detailed and specific collaboration with phenomenologists, and can take several years to complete due to its high complexity. For these reasons, the long-term support of the experimental and theoretical groups that are involved in heavy-flavor research and train the students and postdocs is essential for the success of the field and for the efficient exploitation of the investment in the facilities. **A healthy research program requires support for CERN and other global laboratories, as well as the individual experimental and theoretical research groups throughout European universities and institutes.**

In the past, successful heavy-flavor programs were carried out at the LEP experiments and SLD, the Tevatron experiments, and ARGUS and CLEO. BABAR and Belle dominated the field in the first decade of this century, and are still producing unique results. Currently, almost half the publications in heavy-flavor physics originate from research at LHCb, followed closely by BESIII and Belle, with fewer contributions from BABAR, ATLAS and CMS. By far, the majority of beauty-hadron measurements in the next decade will come from LHCb and Belle II. LHCb benefits from large cross-sections for production of all types of beauty and charm hadrons and from precise timing that arises from the high boost of the produced particles. Belle II will exploit production of B-meson pairs with well known kinematics in a clean environment, allowing better reconstruction of photons, particularly from π^0 and η decays. To give an example of their complementarity in one case of interest, LHCb will provide the most accurate measurements of angular distributions in exclusive electroweak-penguin decays with charged leptons and hadrons, while Belle II will study the corresponding inclusive decays and exclusive decays with soft photons, and will measure the branching fractions of the related decays $B \to K^{(*)}\nu\bar{\nu}$. The combination of these results will constitute a stringent test of BSM physics involving new couplings to leptons and the b quark. Similarly, in charm physics, LHCb and Belle II will produce the majority of high-statistics results, while BESIII, and possibly future charm-tau factories that are being studied in Russia and China, will exploit the $e^+e^- \to D^0\bar{D}^0$ process to perform quantum-correlation measurements. By contrast, the physics of τ leptons will be dominated by Belle II, and will offer unique probes of BSM physics. As an example, Belle II will be sensitive to lepton-flavor violation in τ decays down to branching fractions of order 10^{-10}. **The dual approach of conducting heavy-flavor physics in both the controlled e^+e^- environment and in the higher statistics hadronic environment should be supported both in the short term and into the future.**

Each generation of flavor-physics experiments involves significant technological advances and large luminosity increases. BABAR, Belle, and LHCb have pushed the boundaries of the heavy-flavor physics that could be performed at e^+e^- colliders and in a hadron collider environment, respectively. Furthermore, Belle II, which has just started, will collect 50 times more data than Belle by the middle of the next decade [6]. On the same time scale, LHCb will collect 5 times more data than its current sample. Beyond Run-4 of the LHC, the LHCb Upgrade II [7] is proposing to collect yet an order of magnitude more data, increasing the explored BSM mass scale by close to a factor two relative to that of the Upgrade I program. The theoretical uncertainties related to the measurements are under control in most areas, while others require parallel developments in lattice QCD. The Belle II experiment and SuperKEKB accelerator have also begun discussion of upgrade opportunities to extend the data sample beyond the currently planned 50 ab^{-1}, and possibly to introduce polarization on the electron beam. **Support for the construction and full exploitation of LHCb Upgrade II and upgrades of Belle II is important for probing the flavor structure of BSM physics at significantly higher mass scales.**

Heavy-flavor physics will continue to play this important role in the post-LHC era. Experiments at a future high-luminosity e^+e^- collider operating at the Z resonance would perform unique heavy-flavor studies in specific channels. Maximising the detector's ability in this area would probably require charged-hadron identification capability. At a circular, high-energy pp collider, heavy-flavor physics would be best studied with a dedicated experiment, along the lines of LHCb, where the advantages of optimized detector and trigger have been demonstrated. **It is imperative that planning of new facilities include consideration of the ways in which heavy-flavor physics can be further explored.**

Heavy-flavor physics helps drive the search for BSM physics and the understanding of the SM. This will continue to be the case in the foreseeable future. To fully realize the potential of heavy-flavor physics, we believe the European Strategy for Particle Physics should include strong support for the experimental and theoretical research in this area, as well as the development of future facilities.

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