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Theoretical challenges for flavor physics

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Abstract. We discuss some highlights of the FCC-*ee* flavor physics program. It will help to explore various aspects of flavor physics: to test precision calculations, to probe nonperturbative QCD methods, and to increase the sensitivity to physics beyond the standard model. In some areas, FCC-*ee* will do much better than current and near-future experiments. We briefly discuss several probes that can be relevant for maximizing the gain from the FCC-*ee* flavor program.

1 Introduction

The goal of the FCC-*ee* program in its tera-Z phase is to produce about 5×10^{12} Z decays (per experiment), which will greatly improve precision electroweak tests of the standard model (SM). These decays will yield about 10^{12} $b\bar{b}$ and $c\bar{c}$ pairs, as well as a large and clean sample of $\tau^+\tau^-$ pairs. Using these data, the FCC-*ee* can shed light on open issues in flavor physics. The flavor physics capabilities of circular e^+e^- colliders were recently reviewed in Refs. [1,2].

There are several ways the FCC-*ee* can probe flavor physics: by directly producing heavy particles (Z, W, and t) and studying their properties, or by making highly sensitive measurements of decays of hadrons. Using the production of the gauge bosons, we can directly probe the flavor structure of their couplings. For example, by measuring Z decays we can test flavor universality to very high precision both in the lepton and the quark sectors. Moreover, collecting 10^8 WW pairs would yield a qualitatively new determination of $|V_{cb}|$ from $W \to b\bar{c}$ decays, with 0.3%–0.4% uncertainty [3,4]. Such a determination will be independent of $|V_{cb}|$ measurements in B decays. (The statistical uncertainty of extracting $|V_{ub}|$ from $W \to b\bar{u}$ is estimated around 5% [4], and would need to improve to be competitive with anticipated prior results.) Also, collecting $1.5\,\mathrm{ab}^{-1}$ data near the $t\bar{t}$ threshold yields a clean sample of 10^6 $t\bar{t}$ events [1]. For some flavor-changing neutral-current (FCNC) top decays, $t \to \{H, Z, \gamma\}\,q$, the sensitivity improves compared to the HL-LHC.

In this brief essay we focus on other ways the FCC-*ee* can probe the flavor sector of the SM. We concentrate on the tera-Z phase of the FCC-*ee*, and discuss its capability to shed light on open issues in flavor physics, especially on bottom and charm quark physics. In particular, we aim to minimize the overlap with Refs. [1,2], and focus on less often discussed physics topics, to show that the FCC-*ee* could be useful in many ways that are not yet fully developed.

In the next few years, the two main experiments in flavor physics will be LHCb and Belle II. (By LHCb we refer throughout this article to all LHC experiments, as LHCb is expected to dominate most flavor physics measurements, though in some modes ATLAS and CMS will also contribute significantly.) Each of them can teach us new things about flavor physics, that are partly overlapping and partly complementary. The FCC-*ee* program will take place later, and therefore it has to be viewed in light of earlier findings.

We do not know what the status of particle physics will be when the FCC-*ee* starts operating. If a deviation from the SM is established before the FCC-*ee* starts, the physics program will be tuned to explore in detail that direction of beyond standard model (BSM) physics. We assume in this review that no conclusive deviations from the SM will be found before the FCC-*ee*. Under that assumption, besides the fact that the FCC-*ee* will provide a huge amount of data, the point is to exploit the unique capabilities of the FCC-*ee* compared to LHCb [5] and Belle II [6].

The FCC-*ee* and Belle II share the clean environment provided by e^+e^- colliders. Compared to Belle II (with 50/ab), much more data is anticipated at the FCC-*ee*, by roughly a factor of 10 (see Table 7.1 in Ref. [1]). Moreover, the FCC-*ee* also produces b-baryons and B_s mesons (Belle II can also produce B_s at the $\Upsilon(5S)$ resonance, but much fewer than the FCC-*ee*, and cannot resolve B_s oscillations.) Concerning CP violation (CPV) in B decays, at the FCC-*ee* the b and $\bar{b}$ quarks hadronize independently (like at the LHC), while Belle II is an asymmetric collider in order to study the time-dependence of the decays of correlated B mesons from $\Upsilon(4S)$ decays.

Compared to LHCb, there are important differences due to triggering. At the LHC, complex triggers make the data sets manageable, while the FCC-*ee* (and also Belle II) can have a much more open trigger. For fully reconstructed decays to charged particles, the FCC-ee sensitivities will not be much better than at LHCb, so we focus on channels which are hard for LHCb. Since efficiencies at LHCb depend hugely on the decay channels, one cannot make simple comparisons based only on luminosity. The clean environment of the FCC-ee will result in much better sensitivities, for example, for final states involving neutrinos or neutral mesons, that are not easily accessible at LHCb. Moreover, since the initial state is CP symmetric at the FCC-ee, there are no production asymmetries. This eliminates a systematic uncertainty at the LHC experiments, which may become important for some CP asymmetry measurements as their sensitivities approach the per mille level.

Another important difference between the FCC-ee compared to both Belle II and the LHC is that quarks from Z decays are highly polarized. In particular, the b and c quarks polarizations are very large. These large values make studies that require polarization ideal for the FCC-ee.

2 Specific probes

2.1 CP violation and BSM physics in $B_{d,s}$ meson mixing

Among the three types of CP violation, CPV in decay and CPV in the interference of decay with and without mixing have been well established in many b hadron decays. However, CPV in mixing has only been observed in K^0 mesons so far. Due to the many more decay channels available in $B^0_{d,s}$ mesons, CPV in B mixing provides a complementary probe of BSM [7]. It can be measured via the CP asymmetry in semileptonic B decays, $A_{\rm SL}$.

The current world averages for the B_d and B_s mesons are $A^d_{\rm SL} = -(2.1 \pm 1.7) \times 10^{-3}$ and $A^s_{\rm SL} = -(0.6 \pm 2.8) \times 10^{-3}$ [8], respectively. These uncertainties are well above the SM expectations, $A^d_{\rm SL} = -(4.7 \pm 0.6) \times 10^{-4}$ and $A^s_{\rm SL} = (2.22 \pm 0.27) \times 10^{-5}$ [9]. (The theory uncertainties are subject to some recent discussions [10].) At the FCC-ee, the achievable experimental uncertainty has been estimated to be about 2.5×10^{-5} for both quantities [11,12], which would allow a measurement of $A^d_{\rm SL}$ even at the SM level. These measurements would help probe BSM physics, as well as help discriminate between models, should BSM physics be discovered in other processes.

In a large class of models, the dominant BSM physics effects in the flavor sector may be those that modify neutral meson mixing amplitudes, while impacts on decay rates may be smaller. In addition to exploring specific models, this is justified, or maybe even expected, from an effective field theory viewpoint. The scale of dimension-6 operators contributing to neutral meson mixing is typically constrained to be higher by the data than the scales of operators affecting decays. A recent analysis of future sensitivities observed that beyond the Belle II and LHCb data taking in this decade, future improvements are hindered by the expected uncertainty of $|V_{cb}|$ [12]. To go beyond current expectations and reach the per mille level, not yet known theoretical progress would be needed.

2.2 CP violation in hadronic b decays

Measurements of CP asymmetries in b decays shaped our understanding that the breaking of CP symmetry observed in hadron decays is due to a single complex parameter of the CKM matrix. Currently, there is a lot of effort at the LHC and Belle II to test the CKM picture of CPV to much higher precision. The drive for this program is the fact that some observables are theoretically extremely clean, and thus any experimental progress will improve the sensitivity to BSM physics. At the same time, measurements of observables which can currently only be computed with large theoretical uncertainties due to hadronic physics, provide us with information about QCD.

The FCC-ee is expected to deliver a very large and clean sample of b hadrons. It is anticipated that the uncertainties of the CKM angle γ will reach about 0.004 rad, of β about 0.005, and of ϕ_s about 0.002 (see Table 7.3 of Ref. [1]). While these are only modest improvements over what is expected from LHCb (with 300/fb), these observables relate to measurements which can be done well at the LHC. To interpret measurements of β and ϕ_s with such precisions, improvements in the theory are also needed to relate the results to parameters in the Lagrangian. The FCC-ee should have greater advantages in modes containing neutrals, but few dedicated sensitivity studies exist so far. It will also allow combining results from experiments in different environments, and thus with different systematic uncertainties.

While most probes of CPV use rate asymmetries (with or without time-dependence) one other way to probe CP violation is to use angular distribution asymmetries. They are usually called “triple products”, which is an idea that can be applied to many different angular distributions [13]. The FCC-ee can be used to measure many such modes. A theoretical question is how clean information can be extracted from them. The result is sensitive to hadronic matrix elements in a way similar to rate asymmetries. While it is interesting to measure them as a way to get insights into QCD, it would be even more significant to find a way to cleanly probe also the underlying weak interactions in such cases. The hope is that some progress in this direction will take place by the time the FCC-ee starts collecting data.

2.3 Very rare decays

The FCC-*ee* will have unique capabilities to measure decay modes with large missing energy. These include decays with neutrinos (or τ leptons) in the final state. The FCC-*ee* should also be able to measure electrons better than LHCb. Both exclusive and inclusive measurements are interesting, as the experimental and theoretical uncertainties are distinct, so they provide complementary probes of the underlying physics.

Prime examples are decays mediated by $b \to s\nu\bar{\nu}$ or $b \to s\tau^+\tau^-$ transitions, as well as their $b \to d$ counterparts. While LHCb is well suited to measure $B \to K^{(*0)}\mu^+\mu^-$ with high precision, its $b \to d$ analogs, $B \to \rho\mu^+\mu^-$ or $B_s \to K^{(*0)}\mu^+\mu^-$ are much more challenging [14,15]. The FCC-*ee* is expected to be able to tackle these, as well as $B \to K^{(*0)}\tau^+\tau^-$, $\Lambda_b \to \Lambda\tau^+\tau^-$ [1], $B \to K^{(*)}\nu\bar{\nu}$, $B_s \to \phi\nu\bar{\nu}$, and $\Lambda_b \to \Lambda\nu\bar{\nu}$ decays, and maybe even $B \to \pi(\rho)\nu\bar{\nu}$.

The two-body decays $B \to \ell^+\ell^-$ are sensitive to particularly high scales among B decays, especially if BSM physics alleviates the helicity suppression in the SM. From an effective theory point of view, these decays have some of the highest mass-scale sensitivities, comparable to $K \to \pi\nu\bar{\nu}$. The FCC-*ee* is expected to be comparably sensitive to the HL-LHC for the decays $B_{s,d} \to \mu^+\mu^-$, but should be a lot more sensitive for $B_{s,d} \to e^+e^-$, and measure $B_s \to \tau^+\tau^-$ even at the SM level, $\mathcal{B}(B_s \to \tau^+\tau^-) = (7.7 \pm 0.5) \times 10^{-7}$ [16] (with 80 events/exp/year [17]).

In many models inspired by the $R_{K^{(*)}}$ and $R(D^{(*)})$ anomalies hinting at lepton universality violation, there are correlated deviations from the SM predictions in transitions mediated by operators with flavor structures $b\bar{s}\ell^+\ell^-$ and $b\bar{s}\nu\bar{\nu}$, which makes these modes particularly interesting. If any of the anomalies become established, then searches for $b \to s\tau\mu$, $b \to s\tau e$, and similar modes would gain a lot in importance, since lepton universality violation in most models also leads to lepton flavor violation. The not yet observed $B_c \to \tau\bar{\nu}$ decay, which the FCC-*ee* should be able to measure [18], is impacted by many models that attempt to explain the $R(D^{(*)})$ anomaly. The challenge to precision physics using B_c decays may be the knowledge of production rates. These decay modes are important even if the current anomalies become less significant, as they are generic probes of many BSM scenarios [19] which treat the 3rd generation differently from the 1st and 2nd.

In order to fully benefit from these measurements, precise SM calculations of these rates are needed. Regarding the inclusive calculations, the operator product expansion will probably remain the main tool. The calculations for exclusive decays will likely rely on lattice QCD, and new developments are needed to extend the calculations for the full ranges of q^2. Another significant challenge for lattice QCD calculations is to account for QED corrections and isospin violation. These have been started to be addressed in limited contexts, and they will have to be included more comprehensively [20]. Fully addressing electromagnetic corrections will necessitate dedicated interactions between theorists and experimentalists, for example to refine Monte Carlo tools. The hope is that by the time data from FCC-*ee* is available, the theoretical uncertainties may be below the anticipated experimental ones.

2.4 Polarized baryons and quarks

Many probes of flavor that can be done with mesons can also be done with baryons. In many cases, adding baryons provide more statistics as well as a different set of systematics. There are, however, some ways baryons can probe short-distance physics that cannot be done with mesons. In particular, baryons can be polarized, which is not the case for the pseudoscalar mesons that are most often used to probe the weak interaction. The fact that b and c quarks in Z decays are highly polarized, make polarization related physics well suited for the FCC-*ee*.

There are two aspects of polarization that can be exploited. First, by determining the polarization of the baryons, we can learn about the polarization of the underlying quark, which can teach us about the production mechanism [21, 22]. In particular, it can teach us about the Dirac structure of the operator that creates them. That information is washed out by hadronization into pseuduscalar mesons. (For example, if squarks are discovered, we would like to know if they are the left- or the right-handed ones. One way to probe this is to measure the polarization of the quarks that emerge from their decays.) In order to be able to use baryon polarization as a measure of the quark polarization, we need to know how much of the quark polarizations is retained by the baryons. It was shown that this can be obtained using top decays [22]. A generalization of that idea to Z decay is needed in order to fully exploit this method at the FCC-*ee*. Moreover, comparing the two determinations is another interesting check of the SM.

Polarization is also required in order to explore the full structure of the weak decays of the quarks. The point is that Λ_b baryons produced at the FCC-*ee* are highly polarized. The reason is that in $Z \to b\bar{b}$ the quarks are highly polarized and based on data from LEP [23,24,25] and theoretical estimates [21,22], we expect an $\mathcal{O}(1)$ fraction of that polarization to be retained by the Λ_b. Thus, we can have a very large sample of polarized Λ_b decays. For example, looking for semileptonic $\Lambda_b \to \Lambda_c\ell\nu$ decays with polarized Λ_b can test the handedness of the weak interaction in similar ways that it is done with the Michel parameters in muon decays [26]. It can also be used to test the structure of FCNC decays, like $\Lambda_b \to \Lambda\ell^+\ell^-$ [27]. Similar studied can be done for Λ_c decays [28].

2.5 Exclusive hadronic Z decays

One way to learn about some nonperturbative aspects of QCD is to study meson productions in exclusive Z decays. For example, the rate of $Z \to X\gamma$ is sensitive to the light-cone distribution amplitude of the meson X [29]. This avenue to probe these amplitudes is very promising theoretically, as the expansion parameter is $1/Q$, where Q is the energy carried by the hadron. Thus, using Z decays, we can get theoretical sensitivity that is absent in B decays. A promising candidate for such decay is $Z \to J/\psi\gamma$, where the branching ratio is expected to be of $\mathcal{O}(10^{-7})$. Thus, at the FCC-*ee*, we can hope to measure the rate with high precision.

The interest in these decays goes beyond QCD as they are closely related to decays of the form $H \to X\gamma$. Such decays can probe the couplings of the Higgs to light quarks [30]. These couplings are very hard to measure, and exclusive decays may be the best option. Thus, Z decays provide important calibration for these calculations.

Another unique opportunity of the FCC-*ee* is to look for FCNC Z decays, e.g., $Z \to B_s\gamma$ or $Z \to B_s\mu^+\mu^-$. In the SM such decay rates are expected to be suppressed compared to $Z \to J/\psi\gamma$ by roughly $[|V_{cb}|/(16\pi^2)]^2 \sim 10^{-7}$, resulting in branching ratios smaller than about 10^{-14}, and thus too small to measure. Yet, one can envision a situation where such rates are enhanced by some BSM physics. In many cases, such an enhancement is ruled out by rare B_s and B decays. Yet, there could be cancellations between several contributions in B decays that is absent in Z decays. While we are not aware of any model that predicts such an enhancement, the FCC-*ee* is unique in its ability to probe directly such FCNC couplings of the Z boson that is not available from B decays. Theoretically, it would be interesting to study decays like $Z \to B^+K^-$ or $Z \to B^+K^-\gamma$ to check if they can provide sensitivity to FCNC Z couplings.

2.6 Charm physics

CP violation in both charm mixing and decay are probes of QCD dynamics and BSM physics. In 2011, the LHCb hint of a nearly 1% CP violation in D decays generated intense attention, since the central value was larger than what was previously considered to be allowed in the SM [31,32,33,34]. In 2019 a smaller central value was established with more than 5σ significance, $A_{CP}(K^-K^+) - A_{CP}(\pi^-\pi^+) = -(1.54 \pm 0.29) \times 10^{-3}$ [35]. It is possible to accommodate this result in the SM, but it requires hadronic enhancements compared to the available (model dependent) calculations. It is expected that the FCC-*ee* will be able to measure many individual CP asymmetries with good precision, without having to construct differences, like the one recently measured by LHCb.

The FCC-*ee* can probe many more observables that can teach us about CPV in the charm system. In particular, we should be able to have many tests of the SM, as we briefly explain below. These tests can either confirm the picture that there are large hadronic enhancements in certain channels, or will show that there is some BSM physics that is significant in the D system.

The FCC-*ee* can provide many such measurements. In particular, the anticipated superb time resolution can make them more precise than we can hope to get at the LHC and Belle II. Moreover, one problem for the LHC when it attempts to probe very small CP asymmetries has to do with the production asymmetry between c and $\bar{c}$, which can only be controlled using other measurements. This issue is not there in the FCC-*ee*, as the production is symmetric.

While we cannot make precision calculations for charm CPV because of hadronic uncertainties, we are still able to make rough predictions that can be tested. In particular, one can explore consequences of flavor $SU(3)$ symmetry. The point is that different observables arise at different orders of $SU(3)$ breaking, and while we cannot calculate how large this breaking is in specific matrix elements, it is typically of order 20%. Thus, by exploiting relations that hold to higher order in $SU(3)$ breaking, we can derive a pattern that can be used to probe the SM [36,37].

In particular, the SM predicts that to leading order in $SU(3)$ breaking all the time-dependent CP asymmetries are identical. Moreover, there are subsets of them that are identical to second order in the breaking. To test these predictions, we need to have many different measurements, with uncertainties that are at the level of the anticipated $SU(3)$ symmetry breaking effects.

The situation can dramatically change if there is a theoretical breakthrough that enables the calculation of some of the hadronic input needed for these observables. The prime candidate is lattice QCD, and while some preliminary studies for the matrix elements relevant for $A_{CP}(K^-K^+) - A_{CP}(\pi^-\pi^+)$ have started, it is yet unknown what can be achieved for these observables.

3 Conclusions

Flavor physics is a mature field, with a lot of promising directions to probe BSM physics and QCD dynamics. It has played critical roles in developing the SM, and provides some of the strongest constraints on BSM physics. The data from the FCC-*ee* will be important in moving this program forward. The field of particle physics when the FCC-*ee* starts may be rather different from where we are today, but it is clear that there are many ways FCC-*ee* can shed light on open questions in flavor physics after the end of the LHC and Belle II. In this short paper we tried to touch upon some less frequently discussed areas, to show the breadth of topics where the FCC-*ee* can make a significant impact.

Some advances are needed in theoretical particle physics in order to take full advantage of the FCC-*ee* data. Improvements are expected in lattice QCD, which will enable better control over hadronic uncertainties in certain processes. We also anticipate new calculations of higher-order corrections to precision measurements. Theoretical advances are also needed in understanding hadronic physics in some areas where we do not yet know how to make progress using current effective field theory or lattice QCD methods. While we cannot guess how breakthroughs will arise and what their scope may be (in terms of matrix elements that the novel methods can better calculate), large new data sets in the past have always resulted in unexpected developments. Whatever the situation will be when data from the FCC-*ee* is analyzed, we are going to learn significant new information about flavor physics from them.

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