Heavy-quark physics at FCC-ee: CP-violation case study

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Thematic Areas: Rare Processes and Precision Measurement Frontier

- Weak Decays of b and c

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Abstract

The FCC-ee is a frontier Higgs, Top, Electroweak, and Flavour factory. It will be operated in a 100-km circular tunnel built in the CERN area, and will serve as the first step of the FCC integrated programme towards ≥ 100 TeV proton-proton collisions exploiting the same infrastructure [2]. With its huge luminosity at the Z-pole, $\sim 10^{12}$ $Z \to b\bar{b}$ decays will be collected at the currently foreseen two interaction points, which is a sample of b hadrons an order of magnitude larger than anticipated at the Belle II experiment. This enormous data set, the clean environment, the high boost of the b hadrons, and the production of the full spectrum of heavy-flavoured particles provides unique opportunities for Heavy Flavour physics at FCC-ee.

Current measurements of CP-conserving and CP-violating flavour observables so far give a picture of the CKM matrix that is consistent with the Standard Model hypothesis, which in turn constitutes one pillar of our understanding of the electroweak interaction. LHCb upgrades and the Belle II experiment are expected to significantly improve precision. FCC-ee experiments can complement and extend this measurement programme if the following detector performance requirements are met: high reconstruction efficiency and good invariant-mass resolution for final-states containing K_S^0 and π^0 mesons; good identification efficiency for K_L^0 mesons; charged hadron identification (PID) over a wide momentum range; excellent proper-time resolution. Several benchmark b-hadron decays and CP-violation measurements will be used to determine the key detector requirements in the areas of photon energy and angular resolution, in particular for π^0 reconstruction, tracking efficiency for long-lived particles, the necessary kinematical range of the PID performance, and vertexing capabilities, focusing on hit-point resolution and alignment specifications.

The flavour structure observed in nature can be accommodated within the Standard Model (SM), but has many unexplained and seemingly arbitrary features that demand a deeper explanation from a beyond-the-SM (BSM) theory.

- The flavour structure of the SM is dictated by the strong hierarchy between the couplings of the fermions to the scalar Brout-Englert-Higgs field (vacuum expectation value), referred to as the Yukawa couplings. No known underlying dynamics fixes these couplings, which have to be determined experimentally. The spontaneous electroweak-symmetry breaking leads to quark mass-mixing in weak-charged current processes, expressed through the so-called Cabibbo-Kobayashi-Maskawa (CKM), which also generates a set of strongly hierarchised flavour-violating transitions between the quark generations. The strength of the quark-transition couplings are also free parameters in the SM and must also be determined experimentally. The origin of these hierarchies is still to be understood, but it must be acknowledged that the KM paradigm matches all measurements to date with a remarkable consistency [5].

- Speculating on possible BSM explanations for the origin of these hierarchies leads inevitably to the second flavour problem. Mixing ins neutral down-type quark mesons systems (*i.e.* $K^0 - \overline{K}^0$, $B^0 - \overline{B}^0$, and $B_s^0 - \overline{B}_s^0$) is well established experimentally and satisfactorily described by box diagrams involving the heavier degrees-of-freedom of the SM (ı.e. W boson and top quark). These phenomena will also be sensitive to any heavy degrees-of-freedom that arise in BSM theories, and the current agreement between measurement at the SM in general points to a mass scale for these theories that is far higher than expected from other considerations.

These questions can be addressed experimentally by measuring observables that are predicted with small or well-controlled theoretical uncertainties. These are, namely, the CP-violating phases α, β and γ, the neutral B-meson oscillation frequencies, and the magnitude of the CKM matrix elements governing the strength of the quark transitions $b \to u$ and $b \to c$. Other clean CP observables include the very small asymmetries expected in B^0 and B_s^0 mixing, as well as the CP phase characterising the interference in between mixing and decay phenomena in the B_s^0 system, ϕ_s. Complementing these observables are a wide range of suppressed flavour-changing-neutral-current (FCNC) processes, and other decays, where the SM predictions are reliable, and BSM effects could be pronounced.

The abundant production of all b-flavoured particle species at FCC-ee is summarised in Table 1. The FCC-ee data set will be an order-of-magnitude larger than that expected at Belle II [3]. The foreseen event yields for hadronic decays of b hadrons will be comparable to those that are anticipated with LHCb Upgrade II [1] The physics opportunities generated by this abundant production are further augmented by the clean experimental environment, the production of all b-hadron species and the high relativistic boost that comes from Z^0 decays..

Table 1: Yields of heavy flavour particles produced at FCC-ee. The charge conjugate states have the same production yields. They are calculated using the branching fractions and hadronisation rate reported in [4, 6] . † B_c hadronisation fraction assumed to be $f_{B_c} = 2.10^{-3}$.

Particle species at FCC-ee	B^0	B^+	B_s^0	Λ_b	B_c^+	$c\bar{c}$	$\tau^- \tau^+$
Yield $(\times 10^9)$ [for $5.10^{12}\ Z$]	310	310	75	65	$1.5^\dagger$	600	180

The FCC-ee therefore presents an exciting opportunity for flavour physics, and the precise study of the observables summarised above. Achieving this goal and taking full advantage of the statistical precision that will be available, requires designing a detector with the necessary attributes. Case studies can be devised to define these requirements in more detail:

- Charged particle identification (PID) is necessary in order to reconstruct the final state of interest under the correct mass hypotheses, and suppress background contamination. First studies have been performed of the hadronic decay $B_s \to D_s^\pm K^\pm$, important for the measurement of the CKM angle γ, as a benchmark mode. Here many companion decays with different final-state contents cross-feed into the signal region of the mass spectrum. This background can, in principle, be suppressed or eliminated by PID. This initial mark should be extended to understand the PID performance that is required for the study of $B^- \to DK^-$ decays, also important for the γ measurement, multi-body hadronic decays of b-baryons, which represent a largely unexplored domain, and for flavour-tagging in time-dependent CP violation measurments with 'same-side' and 'opposite-side' kaons. These studies will define the momentum range over which PID is necessary, and also the required level of π-K separation.

- As demonstrated by the B-factories, many important CP-violation measurements can be performed by reconstructing modes with neutral pions in the final state $e.g.$) $B^0 \to \pi^+\pi^-\pi^0\pi^0$. Successfully realising this goal requires an electromagnetic calorimeter with excellent resolution at rather low energies. It will also be important to assess the demands on the calorimeter for radiative FCNC processes, not only in the b system, but also in charm decays, and how the calorimeter can contribute when imposing isolation criteria, $e.g.$ for the reconstruction of decays with taus.

- CP-violation in B^0 and B_s^0-meson mixing remains unobserved to date. Precise studies of this phenomenon will be invaluable for constraining the contribution of BSM amplitudes in neutral-meson mixing. The anticipated statistical precision at the FCC-ee will allow sensitivity to the very small mixing CP asymmetries that are expected in the SM, provided that the level of systematic control is at the same level or better. The detection asymmetry for the charged particles in the final states is likely the limiting systematic uncertainty. Measurement methods and an overall detector

design must be devised to ensure that this source of bias is kept sufficiently small, and is well understood.

- Precise vertex reconstruction is a prerequisite for the majority of flavour studies, for example in time-dependent B_s^0 measurements where excellent proper-time resolution is essential. This attribute is also very important in the study of FCNC decays and other interesting modes involving tau mesons, $e.g.$ $B^0 \to K^{*0}\tau^+\tau^-$ and $B_c^+ \to \tau^+\nu_\tau$, where the analysis must rely on partial-reconstruction techniques. These techniques are among the most demanding for the veretx detector design. Simulation studies are necessary to determine the dependence of the reconstruction efficiency on the vertex resolution, and how the resolution varies with hit point precision, detector material and geometry, the beampipe design.

Most of these detector requirements are entangled and thus the detector optimisation is a global problem. For example, the implementation of a dedicated PID detector has implications for the calorimeter performance, and also the tracking volume. The case study will evaluate the individual detector requirements discussed above, together with the constraints that come from the other sub-detectors to arrive at an integrated detector design which is optimised for exploiting the flavour potential of FCC-ee.

References

[1] Roel Aaij et al. Physics case for an LHCb Upgrade II - Opportunities in flavour physics, and beyond, in the HL-LHC era. Other thesis, 2016.

[2] A. Abada et al. FCC-ee: The Lepton Collider: Future Circular Collider Conceptual Design Report Volume 2. *Eur. Phys. J. ST*, 228(2):261–623, 2019.

[3] W. Altmannshofer et al. The Belle II Physics Book. *PTEP*, 2019(12):123C01, 2019. [Erratum: PTEP 2020, 029201 (2020)].

[4] Yasmine Sara Amhis et al. Averages of b-hadron, c-hadron, and τ-lepton properties as of 2018. 9 2019.

[5] J. Charles et al. Current status of the Standard Model CKM fit and constraints on $\Delta F = 2$ New Physics. *Phys. Rev. D*, 91(7):073007, 2015.

[6] P.A. Zyla et al. Review of Particle Physics. *PTEP*, 2020(8):083C01, 2020.