PROCEEDINGS OF SCIENCE

Flavour prospects at the FCC-ee

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In recent years the attention of the particle physics community with respect to future experiments has become increasingly focused on the prospects of a circular electron-positron collider based at CERN, the FCC-ee. Much progress has recently been made to evaluate the potential of flavour physics measurements at this facility. Studies are now developing beyond just understanding the baseline feasibility of measurements to also quantify the dependence of these measurements on detector performance. The most recent of these developments are discussed.

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1. Introduction

The FCC-ee is a collider envisioned to be constructed at CERN [1]. This will be the first stage of the FCC project, where, similar to the LEP and LHC colliders, CERN will initially operate an electron-positron collider to eventually be replaced by a proton-proton collider. The FCC tunnel will be about 91 km long, and the FCC-ee will be configured to allow for four collision points. The collider will operate for 16 years in four energy modes, namely the Z pole, the WW threshold, the Higgs factory ZH threshold, and the $t\bar{t}$ pair threshold.

The Z pole and WW threshold runs have garnered the most interest from the flavour community in recent years. The Z pole run will produce an unprecedented number of $b\bar{b}$ and $c\bar{c}$ pairs, allowing significant improvements in statistical sensitivity beyond what is feasible in current experiments. The WW threshold run will provide unique access to knowledge of the Cabibbo-Kobayashi-Maskawa (CKM) matrix. In the current baseline FCC-ee design, these runs will yield 6×10^{12} Z bosons and 2.4×10^{8} WW pairs, respectively. Note that in some of the sensitivity estimates discussed in section 2, different quantities of Z/W bosons were assumed. As illustrated in table 1, in the context of the Z pole run, the FCC-ee can be viewed as a best of both worlds scenario when compared to the current flagship flavour experiments, namely Belle II and LHCb [2, 3].

Attribute	$\Upsilon(4S)$	pp	Z^0
All hadron species		✓	✓
High boost		✓	✓
Enormous production cross-section		✓	
Negligible trigger losses	✓		✓
Low backgrounds	✓		✓
Initial energy constraint	✓		(✓)

Table 1: Advantageous properties of Belle II ($\Upsilon(4S)$), the LHC (pp), and the FCC-ee (Z^0) [4].

Although the FCC-ee will lack the high production cross section of collisions at the LHC, this can be compensated by having a much larger instantaneous luminosity. The initial energy constraint is also not quite as simple as at Belle II because the momenta of the b and c hadrons produced by the Z decay is not known a priori, but the distribution is very well understood, so this is only a minor concern.

To facilitate studies of detector requirements, Monte-Carlo (MC) event samples are generated to model the response of the IDEA detector [5]. The inner detector consists of a silicon vertex detector close to the interaction point and a drift chamber tracker surrounded by a silicon wrapper. The drift chamber also performs particle identification (PID) using a cluster counting method. This is enclosed by a thin solenoid providing a 2T magnetic field. A dual-readout calorimeter is positioned in between the solenoid and the return yoke and μ chambers.

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2. Topics of interest

2.1 $|V_{cb}|$ and $|V_{ub}|$

The elements of the CKM matrix are crucial inputs for constraining new physics (NP) from rare meson decays and meson mixing; currently, they are the largest source of uncertainty. Furthermore, there is now some tension between inclusive and exclusive measurements of $|V_{cb}|$ and $|V_{ub}|$ as shown in fig. 1; increased sensitivity is required to understand the cause of this [6].

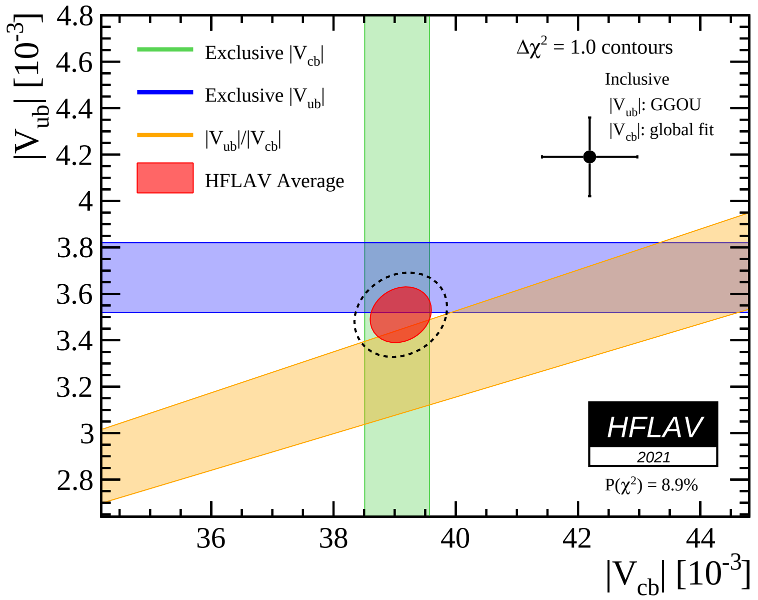

Figure 1: Combination of exclusive measurements of $|V_{ub}|/|V_{cb}|$, $|V_{cb}|$ and $|V_{ub}|$ compared to the values obtained from inclusive extractions of the CKM elements [7].

It is estimated that with the full LHCb and Belle II datasets, the relative uncertainties of $|V_{cb}|$ and $|V_{ub}|$ will be O (1%) and will be systematically dominated. The FCC-ee will provide an avenue for new measurements. One method is the measurement from on-shell W decays in the WW run of the FCC-ee. Assuming 10^8 WW pairs, it is expected that a relative statistical uncertainty of 0.14% could be obtained from a measurement of $|V_{cb}|$. If the efficiency of jet flavour tagging is incorporated, the sensitivity decreases to 0.4% [8]. Another method is to use branching fraction (BF) measurements of $B^+ \to \tau^+ \nu_\tau$ and $B_c^+ \to \tau^+ \nu_\tau$ decays, as considered in two recent FCC-ee feasibility studies [9, 10]. These can be measured by reconstructing the τ in the "3-prong" final state, $\tau^+ \to \pi^+\pi^-\pi^+\bar{\nu}_\tau$. Assuming perfect detector performance and 5×10^{12} Z bosons, it is estimated that the BF of $B^+ \to \tau^+ \nu_\tau$ can be measured with a statistical uncertainty of 2%. This would result in a considerable increase to the sensitivity of extractions of $|V_{ub}|$ as shown in fig. 2.

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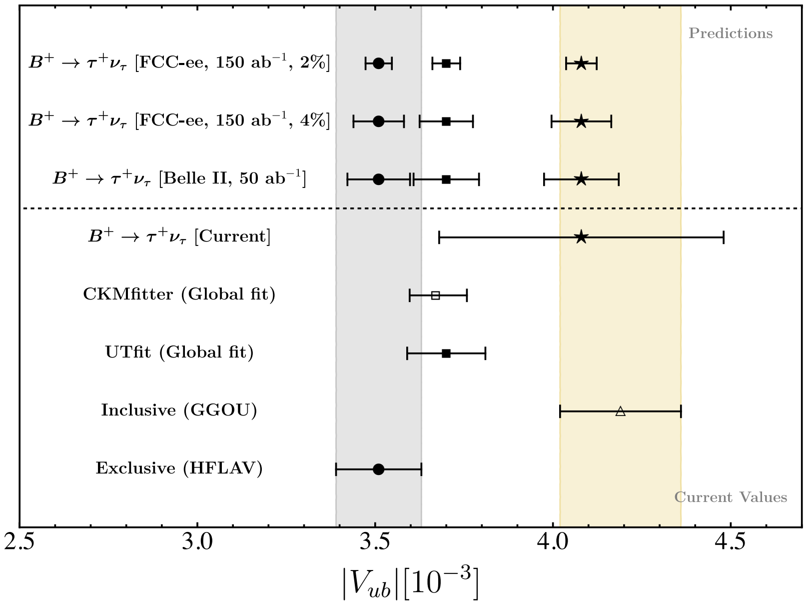

Figure 2: Comparison between current determinations of $|V_{\rm ub}|$ and predicted determinations from Belle II and the FCC-ee, where the FCC-ee values correspond to 2% and 4% uncertainty on the BF. Different central values are taken from the current Exclusive, Global, and $B^+ \to \tau^+\nu_\tau$ values.

2.2 $\mathbf{b \to s\nu\bar{\nu}}$ and $\mathbf{b \to s\tau^+\tau^-}$

The measurement of $\mathrm{b} \to \mathrm{s}\nu\bar{\nu}$ decays is impossible at LHCb, and while possible at Belle II, there are limitations. The most significant of which is the kinds of B decays that are accessible at Belle II. Collisions at the $\Upsilon(4S)$ resonance produce a high number of B^+ and B^0 decays, however, they are unable to produce B^0_s and Λ^0_b hadrons, this is not the case at the Z pole. Therefore as well as providing a significantly larger dataset for all B species, the FCC-ee will enable measurements of decays that are impossible at current experiments. Belle II has recently determined the BF of $\mathrm{B}^+ \to \mathrm{K}^+\nu\bar{\nu}$ decays to be $(2.3 \pm 0.5^{+0.5}_{-0.4}) \times 10^{-5}$, with a significance of 3.5σ [11]. This is in tension with the Standard Model (SM) prediction of $(5.58 \pm 0.37) \times 10^{-6}$ with a significance of 2.7σ. In addition to this interesting result, these decays are theoretically valuable. For instance, in contrast to their $\mathrm{b} \to \mathrm{s}\ell^+\ell^-$ partners, they are immune to long-distance charm loop effects which simplifies theoretical predictions. They can be used to extract the CKM matrix elements, hadronic form factors and constrain Wilson coefficients. With enough data, they can also be used as novel probes of CP violation (CPV) effects from (NP) [12]. It is expected that with the full Belle II dataset, the BFs of B^+ and B^0 decays could be measured with relative uncertainties of $O(10\%)$ [13]. In a recent feasibility study, it was shown that the FCC-ee will achieve measurements of $\mathrm{b} \to \mathrm{s}\nu\bar{\nu}$ BFs with relative uncertainties of $O(1\%)$ for $\mathrm{B}^0 \to \mathrm{K}^{*0}\nu\bar{\nu}$ and $\mathrm{B}^0_\mathrm{s} \to \phi\nu\bar{\nu}$ decays [14]. For $\mathrm{B}^0 \to \mathrm{K}^0_\mathrm{S}\nu\bar{\nu}$ and $\Lambda^0_\mathrm{b} \to \Lambda\nu\bar{\nu}$ decays, measurements will achieve $O(3\%)$ and $O(10\%)$ relative statistical uncertainty, respectively.

Similar probes of NP are $\mathrm{b} \to \mathrm{s}\tau^+\tau^-$ decays. With an expected BF of $O(10^{-7})$, they are yet to be observed with current limits $> O(10^{-4})$. Many models expect NP to couple primarily to the Higgs boson and the third generation of fermions; therefore, these measurements are a high priority for future experiments [15]. A study is currently in progress to explore the feasibility of observing $B^0 \to K^{*0}\tau^+\tau^-$ decays at the FCC-ee using the 3-prong τ decay final state [16].

2.3 Measurements of τ properties

The mass of the τ, m_τ, is an SM parameter and therefore requires precise measurement. It is required for predictions of τ BFs and enters lepton flavour universality (LFU) tests at the fifth power. The current most precise measurement, $m_\tau = 1777.09 \pm 0.08 \pm 0.11\ \mathrm{MeV}/c^2$, was performed at Belle II [17]. This measurement is systematics limited due to limitations of the beam energy corrections and charged particle momentum corrections. In contrast, it is expected that the FCC-ee will have greater knowledge of the initial beam energy and a superior momentum scale calibration. With the baseline IDEA detector, it should be possible to obtain a measurement of m_τ with an uncertainty $\sim 0.02\mathrm{MeV}/c^2$. As shown in fig. 3, FCC-ee will also provide updated measurements of the τ lifetime and BFs orders of magnitude more precise than prior measurements [18].

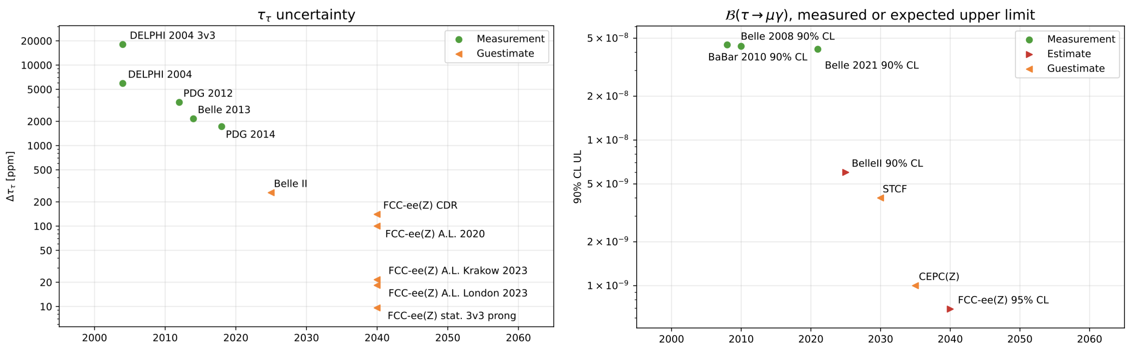

Figure 3: Estimates for expected sensitivity of the τ lifetime (left) and lepton flavour violating decay $\tau \to \mu\gamma$ BF (right) at the FCC-ee compared to other experiments.

3. Detector requirements

In the study of $B^+ \to \tau^+\nu$ decays it was determined that the PID performance will have a negligible effect on sensitivity as long as a minimum of 3σ π-K separation is attainable across the full kinematic phase-space. Imperfect vertexing could lead to greater combinatorial backgrounds, which may result in a non-negligible decrease in sensitivity [10].

As shown in fig. 4, the PID performance and vertex resolution will have little effect on the sensitivity of $b \to s\nu\bar{\nu}$ BF measurements, assuming 2σ K-π separation and 0.2mm vertex resolution can be achieved, a realistic expectation.

In the case of τ property measurements, it is currently expected that the baseline IDEA detector design is sufficient; however, dedicated studies are required to investigate this fully [18].

On the contrary, it has been shown that this is not the case for $B^0 \to K^{*0}\tau^+\tau^-$ measurements. As shown in fig. 5 greater transverse vertex resolution is required to allow for evidence of this decay to be reached, and a significant improvement is required for an observation at the 5σ level. Further studies will be required to understand how this can be overcome. There are several solutions with varying degrees of difficulty. Currently, the most prudent solution is to investigate other final states in addition to the 3-prong τ decay to fully utilise the dataset that would be available.

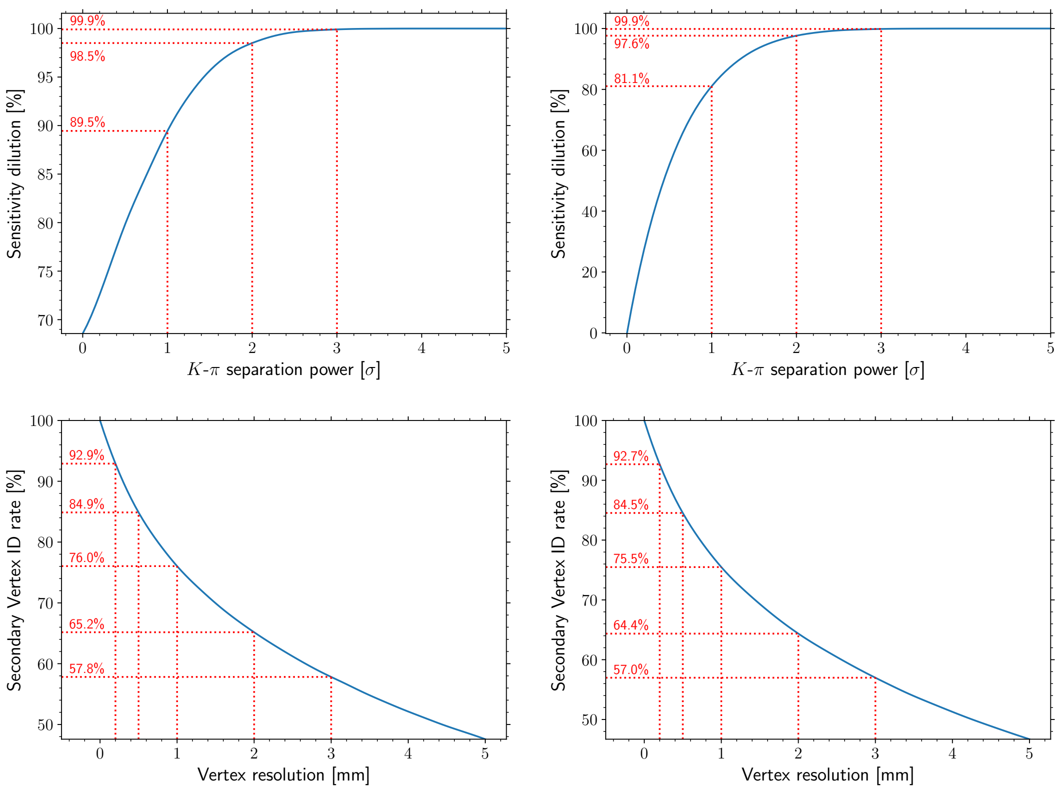

Figure 4: BF sensitivity dependence on PID performance for $\mathrm{B}^0 \to \mathrm{K}^{*0}\nu\overline{\nu}$ (top left) and $\mathrm{B}_s^0 \to \phi\nu\overline{\nu}$ (top right), and secondary vertex identification in terms of the vertex resolution for $\mathrm{B}^0 \to \mathrm{K}^{*0}\nu\overline{\nu}$ (bottom left) and $\mathrm{B}_s^0 \to \phi\nu\overline{\nu}$ (bottom right) [14]

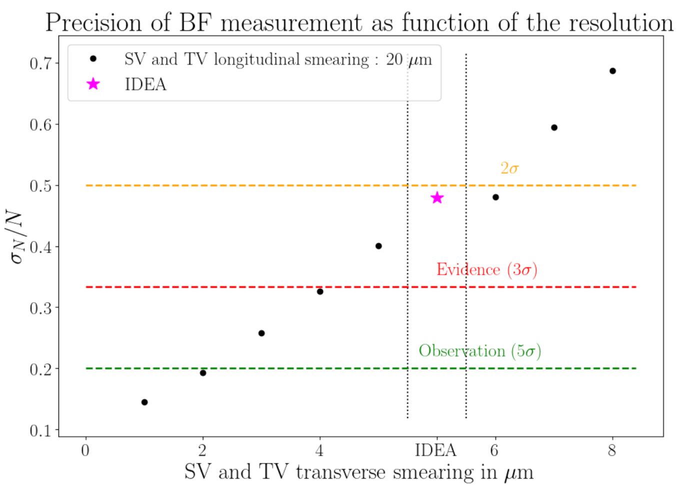

Figure 5: Dependence of sensitivity of a BF measurement of $B^0 \to K^{*0}\tau^+\tau^-$ decays at the FCC-ee on the secondary and tertiary vertex transverse resolution [16].

4. Conclusions

A number of recent studies across a breadth of flavour physics topics have been discussed. All of the results indicate that the FCC-ee would provide a unique (besides CEPC) opportunity for flavour physics, with many world-leading measurements possible with the baseline design of the IDEA detector. The required detector performance is starting to be clarified, which will provide us guidance towards the development of a detector prototype. Given that four collision points are planned for the FCC-ee, it is sensible to consider designing a detector specifically optimised to provide the best possible performance for flavour measurements.

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