# Prospects in flavour physics at the FCC

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**Abstract**

The sample of $6 \times 10^{12}$ Z decays that will be produced by FCC-ee offers immense opportunities for flavour physics. The low background environment, and high acceptance and reconstruction efficiencies of the detectors will allow this dataset to be fully exploited for a wide range of studies in the beauty, charm and tau sectors. In many cases, it is expected that these measurements will be world-leading in precision, and thereby be powerful in probing for the effects of New Physics. Interesting possibilities also exist for the measurement of the magnitude of CKM elements from W-boson and top decays. Discussion and numerical estimates are provided for the prospects of FCC-ee in a set of benchmark measurements, as requested by the Physics Preparatory Group of the European Strategy for Particle Physics Update 2025-26. Additional discussion is included on some other studies of interest. Finally, brief consideration is given to the prospects for flavour-physics studies at FCC-hh.

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## 1 Flavour physics landscape in the post HL-LHC era

The flavour sector contains most of the free parameters of the Standard Model (SM), and is associated with many questions that the SM does not answer. What is the mechanism that led to exactly three families of quarks and leptons? What explains the hierarchy of fermion masses and the particular structure of the Cabibbo-Kobayashi-Maskawa (CKM) matrix? What is the origin of CP violation, and what is the explanation for the dominance of matter over antimatter in the universe? Moreover, precise measurements of flavour transitions can provide indirect sensitivity to new particles at the highest mass scales. For these reasons, flavour physics is a key field of investigations at current experiments, most notably LHCb and Belle II, and is expected to remain so in the coming decades.

A second upgrade is planned for LHCb during LS4 (2034-35) [1], and the upgraded ATLAS and CMS experiments will also be capable of exciting flavour measurements during the HL-LHC era. The Belle II experiment in Japan aims to collect a sample of $50\,\mathrm{ab}^{-1}$ over the coming decade [2]. It is therefore very likely there will be significant progress in CP-violation measurements and in the study of Flavour-Changing Neutral Current (FCNC) processes by the 2040s. Nonetheless, there are many categories of interesting decays that will be poorly explored, either due to the limited sample sizes at Belle II or the high backgrounds at the HL-LHC. Furthermore, many important measurements in flavour physics are theoretically very clean, and therefore should be pursued with the highest possible experimental precision. All these considerations motivate an extensive programme of flavour studies at FCC.

This document is submission to the 2025-26 update of the European Strategy for Particle Physics (ESPP). The discussion focuses on the exciting opportunities that exist in flavour physics at FCC-ee, firstly summarising the advantages that this facility offers for such studies, and then presenting the prospects in a set of benchmark measurements, which have been selected by the Physics Preparatory Group (PPG) of the ESPP. Consideration is also given to the physics reach of FCC-ee in other flavour-physics topics. Finally, some remarks are made on the prospects for flavour physics at FCC-hh.

## 2 FCC-ee as an ideal laboratory for flavour physics

Table 1 compares the advantages for flavour-physics studies at an $\mathrm{e^+e^-} \to \Upsilon(4\mathrm{S}) \to \mathrm{b\bar{b}}$ experiment, such as Belle II, a $\mathrm{pp} \to \mathrm{b\bar{b}X}$ experiment, such as LHCb, and an experiment that relies on $\mathrm{e^+e^-} \to \mathrm{Z} \to \mathrm{b\bar{b}}$ production, such as would be the case at FCC-ee. It can be seen that the Z environment combines most of the advantages of Belle II and LHCb. For the former these are the high signal-to-noise, fully efficient trigger and very high geometrical acceptance; for the latter they are the production of the full spectrum of hadrons, and the high boost. Another differentiating feature concerns the flavour tagging of the initial state of neutral b-mesons, which is essential information for time-dependent CP-violation measurements. The flavour-tagging performance, expressed as a *tagging power*, which gives the effective efficiency after dilution effects are accounted for, can be much larger at the Z pole on account of the clean environment, as demonstrated at LEP, which achieved tagging powers of $\sim$25% [3], to be compared to values of $\sim$5% at the LHC [4, 5]. The momenta of b and c hadrons produced at the Z are not known a priori, in contrast to the $\Upsilon(4\mathrm{S})$, although their distribution is very well understood. The momentum of the produced taus is of course perfectly known in both $\mathrm{e^+e^-}$ environments.

The one disadvantage that the Z has in comparison with the LHC is the production cross section, but this is partially mitigated at FCC-ee by the enormous luminosity that is foreseen. Table 2 gives the yields for each b-hadron species that will be produced in the so-called Tera-Z run, where $6 \times 10^{12}$ Z decays will be collected. The number of $\mathrm{b\bar{b}}$ pairs from which these yields arise is around fifteen times larger than that expected at Belle II. There will also be great opportunities in charm and tau physics, for which yields are also listed in Table 2.

We also note that the proposed running strategy of FCC-ee, with the intention to collect data at several collision energies, will open up flavour possibilities that are not restricted to the Z pole. The decays of on-shell W bosons will provide a particularly rich laboratory for studies of the CKM matrix, as is described in more detail below.

Table 1: Advantageous attributes for flavour-physics studies at Belle II ($\Upsilon(4S)$), the LHC (pp) and FCC-ee (Z).

| Attribute | $\Upsilon(4S)$ | pp | Z |
|---|---|---|---|
| All hadron species | | ✓ | ✓ |
| High boost | | ✓ | ✓ |
| Enormous production cross-section | | ✓ | |
| Negligible trigger losses | ✓ | | ✓ |
| High geometrical acceptance | ✓ | | ✓ |
| Low backgrounds | ✓ | | ✓ |
| Flavour-tagging power | ✓ | | ✓ |
| Initial-energy constraint | ✓ | | (✓) |

Table 2: Yields of heavy-flavoured particles produced at FCC-ee for $6 \times 10^{12}$ Z decays (the charge-conjugated hadrons have the same yields). These sample sizes assume the branching fractions and hadronisation rates reported in Refs. [6,7]. The $B_c^+$ hadronisation fraction is assumed to be $f_{B_c} = 2 \times 10^{-3}$ [8].

| Particle species | $B^0$ | $B^+$ | $B_s^0$ | $\Lambda_b$ | $B_c^+$ | $c\bar{c}$ | $\tau^-\tau^+$ |
|---|---|---|---|---|---|---|---|
| Yield ($10^9$) | 370 | 370 | 90 | 80 | 2 | 720 | 200 |

The detector concepts under consideration for FCC-ee are evolving with the requirements of flavour-physics measurements very much in mind. The detector capabilities that are essential for Higgs physics are also, in general, beneficial for flavour studies, for example excellent momentum resolution. However, in some cases flavour physics demands even higher levels of performance, such as in secondary and tertiary vertex resolution, and in electromagnetic-calorimeter resolution for the reconstruction of single $\pi^0$ mesons and photons. Here, therefore, it is flavour that is acting as one of the main drivers for detector design. Hadron identification from around 1 GeV to several 10s of GeV is essential for a comprehensive programme of flavour measurements, and various solutions are being pursued that will enable this, from cluster counting in a wire chamber to a compact Ring Imaging Cherenkov detector. The availability of four interaction points will ensure that at least one experiment can be fully optimised for flavour physics.

## 3 Performance in selected measurements: PPG benchmarks

Brief prospects are provided for the measurements in selected topics requested by the PPG of the ESPP. In several cases, the numerical projections need to be consolidated by full simulation studies.

### 3.1 Rare B decays with neutrinos and taus

Studies of FCNC processes involving the third generation of leptons are of great interest, as these transitions may be perturbed in different ways by New Physics than the more well-studied decays involving muons and electrons. For example, large effects are predicted by models that seek to explain the $R(D^{(*)})$ anomalies [9, 10]. Currently, these decays are poorly constrained by experiment, with the best limits being $\mathcal{B}(B^+ \to K^+\tau^+\tau^-) < 2.25 \times 10^{-3}$ at the 90% CL from BaBar [11] and $\mathcal{B}(B_s^0 \to \tau^+\tau^-) < 6.8 \times 10^{-3}$ at the 95% CL from LHCb [12]. These limits will improve over the full HL-LHC and Belle II running periods, but still remain far above the SM prediction, which is at the $\sim 10^{-7}$ level for $B \to K^{(*)}\tau^+\tau^-$ [13]. The Tera-Z programme of FCC-ee provides an outstanding opportunity to probe this regime.

The search for the transition $B^0 \to K^{*0}(892)\tau^+\tau^-$ is challenging because of the two undetected neutrinos emitted from $\tau$ decays. However, sufficiently good knowledge of the $B^0$ decay vertex from the $K^{*0}(892) \to K^+\pi^-$ decay and that of the taus from the three-prong $\tau^+ \to \pi^+\pi^-\pi^+$ decay, together with mass constraints, allows for an exclusive reconstruction of the decay [13]. A sample of FCC-ee events simulated with the IDEA tracking detector is used to evaluate how the signal significance depends on the performance of the vertex reconstruction. A comprehensive set of background processes is considered

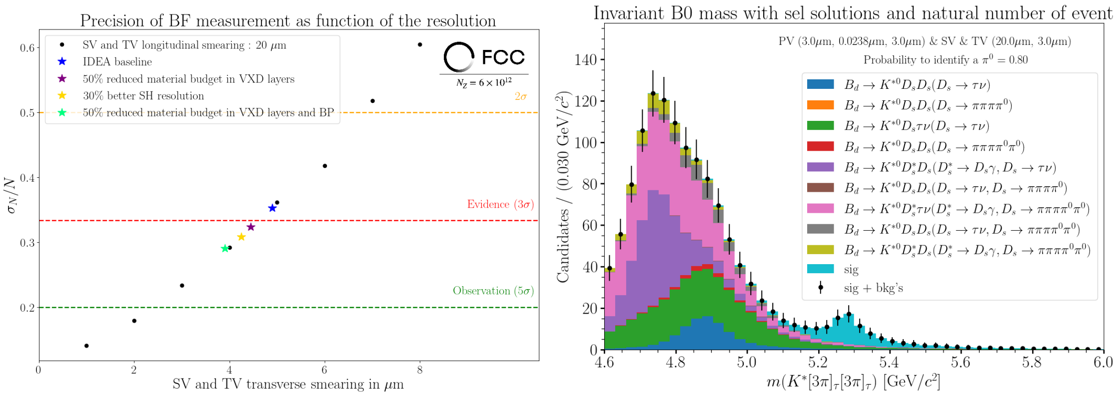


Fig. 1: (Left) Sensitivity of the $\mathcal{B}(\mathrm{B}^0 \to \mathrm{K}^{*0}\tau^+\tau^-)$ measurement for different values of the transverse resolution for the secondary and tertiary vertices, for a fixed longitudinal resolution. Various detector configurations are superimposed. (Right) Invariant-mass distribution of candidates for 3 $\mu$m transverse vertex resolution.

and a selection based on the topology of the decays is performed. Different values of vertex resolution, in both the longitudinal and transverse directions, are emulated and the precision on the measured branching fraction is determined for each set of values, as shown in Fig. 1, which also displays the invariant-mass spectrum for one working point. Superimposed on these points is the performance obtained from a simulation of the IDEA detector, and other configurations where the resolution and the material budget of the beam pipe is varied. The number of signal and background events are determined in the range of invariant masses [5.0,6.0] GeV from a maximum likelihood fit. The significance of the signal in this range is used as a conservative figure of merit for the sensitivity. It is concluded that with the current assumption for the IDEA performance and an accurate knowledge of the distribution of the background processes, it will be possible to observe the signal for the SM expectation with $6 \times 10^{12}$ Z decays. Detector solutions are being actively considered with improved resolution and reduced material, which will allow for a measurement of even higher sensitivity. Such improvements would as well open up the possibility of studying the angular observables associated with this decay.

Interesting FCNCs involving third generation leptons can also be probed through loop-level decays involving $\nu\bar{\nu}$ pairs, as these involve the transition $\mathrm{b} \to \mathrm{s}\nu_\tau\bar{\nu}_\tau$. The Belle II collaboration has recently reported first evidence for the decay $\mathrm{B}^+ \to \mathrm{K}^+\nu\bar{\nu}$, and determined the branching fraction to be $(2.3 \pm 0.5^{+0.5}_{-0.4}) \times 10^{-5}$ [14], which is intriguingly $2.7\sigma$ above the SM prediction.

A recent analysis has been performed to give a first estimate for the sensitivity achievable at FCC-ee in $\mathrm{b} \to \mathrm{s}\nu\bar{\nu}$ transitions, including an assessment of the particle-identification and vertex-resolution requirements [15]. The most suitable modes are those that involve the decay of a neutral b-hadron, where the daughter hadron accompanying the $\nu\bar{\nu}$ pair then decays into a pair of charged particles. This approach allows for study of $\mathrm{B}^0_\mathrm{s}$ and $\Lambda^0_\mathrm{b}$ decays, which are not accessible at Belle II. Assuming decay rates at the SM expectation, it is determined that the branching fractions of $\mathrm{B}^0 \to \mathrm{K}^*\nu\bar{\nu}$, $\mathrm{B}^0_\mathrm{s} \to \phi\nu\bar{\nu}$, $\mathrm{B}^0 \to \mathrm{K}^0_\mathrm{S}\nu\bar{\nu}$ and $\Lambda^0_\mathrm{b} \to \Lambda^0\nu\bar{\nu}$ can be measured with statistical precision of $0.53\%$, $1.20\%$, $3.37\%$ and $9.86\%$, respectively, and with systematic uncertainties that should be controllable at a similar level. It will also be possible to make differential measurements, by making an approximate reconstruction of the $\mathrm{q}^2$ of the $\nu\bar{\nu}$ pair. In Ref. [15] it is demonstrated how the measurements for the ensemble of decay channels considered can be used to set stringent and complementary constraints on short distance Wilson coefficients.

Although a tree-level decay, rather than a FCNC, the mode $\mathrm{B}^+_\mathrm{c} \to \tau^+\nu_\tau$ is of great interest because of its sensitivity to, for example, charged Higgs or leptoquarks, but is inaccessible at both the (HL-)LHC and Belle II. It can, however, be observed at FCC-ee and its relative branching fraction (normalised to that of $\mathrm{B}^+_\mathrm{c} \to \mathrm{J}/\psi\mu^+\nu_\mu$) measured with an experimental precision of better than 5% [16]. Even higher precision will be a achievable for a measurement of the branching fraction of $B^+ \to \tau^+\nu_\tau$. Such a measurement will allow for $|V_{ub}|$ to be determined with a relative uncertainty of 1% [16], which is significantly more precise than current extractions based on semileptonic b-decays [7].

### 3.2 Rare leptonic B decays

The ultra-suppressed decay modes $B^0_s \to \mu^+\mu^-$ and $B^0 \to \mu^+\mu^-$ have been the subject of extensive experimental effort at the LHC [17–19]. The branching fraction of $B^0_s \to \mu^+\mu^-$ is now known to a precision of almost 10%, and with a value in agreement with the prediction of the SM. The rarer mode $B^0 \to \mu^+\mu^-$ has not yet been observed. The current picture is broadly in accordance with the expectations of the SM [20, 21]. Nonetheless, more precise measurements of the branching fractions are desirable, as are measurements of other observables, such as the effective lifetime and CP asymmetry of $B^0_s \to \mu^+\mu^-$. Recently, first measurements of the effective lifetime have emerged [18, 19, 22], but the sample sizes are currently too small to allow for CP-violation studies.

An analysis has been performed to investigate the prospects for studying these two modes at FCC-ee. Both decays are generated with a DELPHES fast simulation of the IDEA detector. Candidates are reconstructed from oppositely charged particle tracks with a momentum greater than 3 GeV, which are well contained within the acceptance of the detector ($|\cos\theta| < 0.98$). The pairs of tracks are fitted to a vertex, which is required to have good quality and to be significantly displaced from the luminous region. These criteria have an overall selection efficiency of 77%. This performance leads to the expectation of 500 $B^0_s \to \mu^+\mu^-$ and 60 $B^0 \to \mu^+\mu^-$ decays (including the charge-conjugate initial states), integrated over the entire Tera-Z run. The excellent momentum resolution of the IDEA detector provides a wide separation between the two mass peaks, as illustrated in Fig. 2.

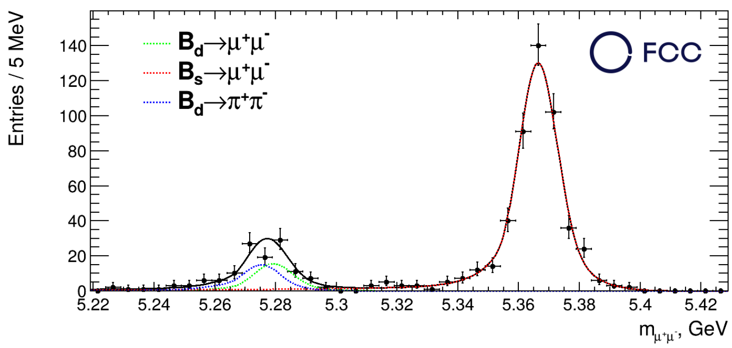


Fig. 2: Invariant-mass distribution of $B^0 \to \mu^+\mu^-$ and $B^0_s \to \mu^+\mu^-$ candidates (including charge-conjugate decays) for $6 \times 10^{12}$ Z decays, also showing the contribution from misidentified $B^0 \to \pi^+\pi^-$ decays.

A potential source of peaking background arises from the charmless decay $B^0 \to \pi^+\pi^-$, where both pions are misidentified as muons. The detector designs at FCC-ee are still to be optimised, but it is hoped that improved performance can be attained with respect to the LEP experiments, which had a typical misidentification efficiency of 0.8% [23], to be contrasted with the 0.2% achieved at CMS [24]. The current study assumes a misidentification efficiency of 0.4%. The background from $B^0 \to \pi^+\pi^-$ with such a performance is included in Fig. 2. No studies have yet been performed to estimate the level of combinatoric background, but this contamination is expected to be at a lower level than at the LHC, because of the lower multiplicity and also the back-to-back production of the two b hadrons.

With this performance and, for now, assuming the other background contributions to be negligible, it follows that the branching fractions of $B^0 \to \mu^+\mu^-$ and $B^0_s \to \mu^+\mu^-$ can be measured with precisions of about 15% and 5%, respectively. The expected uncertainties on the effective lifetime and time-dependent CP asymmetry of the $B^0_s$ mode $S_{\mu\mu}$ are 75 fs and 0.17, respectively, where a tagging power of 25% is assumed and a proper-time resolution of 45 fs, which is conservative given the expected performance of the FCC-ee vertex detectors. These indicative numbers suggest that FCC-ee can make an

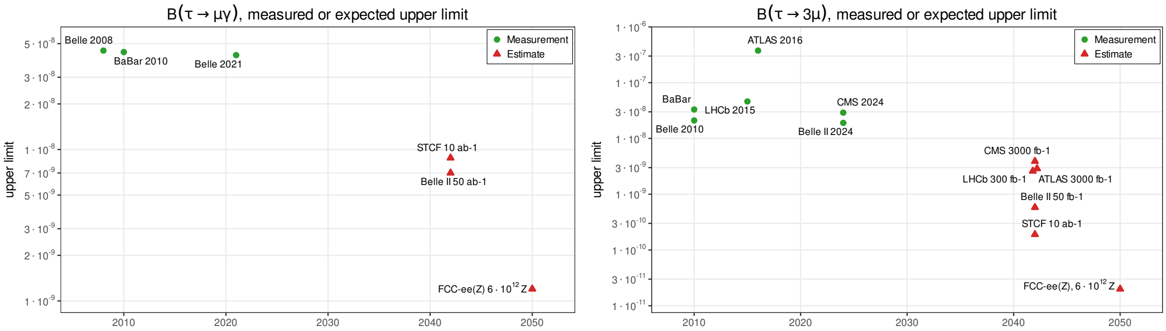


Fig. 3: Current and future experimental upper limits at 90% confidence level for $\mathcal{B}(\tau^- \to \mu^-\gamma)$ (left) and $\mathcal{B}(\tau^- \to \mu^+\mu^-\mu^+)$ (right). The future estimates for LHC and Belle II are extrapolated from published results, and taken from Ref. [31] for STCF. The dates of the future measurements are indicative.

important contribution to the investigation of these decays. Future studies will also establish FCC-ee's potential in related unobserved modes such as $\mathrm{B}^0_{(\mathrm{s})} \to \mu^+\mu^-\gamma$, $\mathrm{B}^0_{(\mathrm{s})} \to \tau^+\tau^-$ and $\mathrm{B}^0_{(\mathrm{s})} \to \mathrm{e}^+\mathrm{e}^-$, where high sensitivity is expected in all cases.

### 3.3 Lepton-flavour violation in $\tau$ decays: $\mathcal{B}(\tau^- \to \mu^-\mu^+\mu^-)$ and $\mathcal{B}(\tau^- \to \mu^-\gamma)$

The Tera-Z programme offers excellent prospects for searches for lepton-flavour violating (LFV) tau decays, with $2 \times 10^{11}$ $\tau^+\tau^-$ pairs produced in a very low background environment. Here the prospects for two benchmark modes, $\tau^- \to \mu^-\gamma$ and $\tau^- \to \mu^+\mu^-\mu^+$ are discussed, with more information available in Ref. [25]. The current status and FCC-ee outlook for both decays is summarised in Fig. 3, together with unofficial estimates of the future capabilities of the HL-LHC and lower-energy facilities. It is expected that FCC-ee will reach the best sensitivity for both modes.

The current upper limit on the decay $\tau^- \to \mu^-\gamma$ is $4.2 \times 10^{-8}$ at the 90% CL, from Belle [26]. At both the $\Upsilon(4\mathrm{S})$ and the Z pole, searches for this mode must contend with background from $\mathrm{e}^+\mathrm{e}^- \to \tau^+\tau^-\gamma$ radiative events, and therefore both the spatial and energy resolution of the calorimeter are critical factors, as these determine the resolution on the invariant mass of the $\mu^-\gamma$ pair. The results of the studies reported in Refs. [27] are here scaled to the expected Tera-Z sample size. A selection efficiency of 8% is assumed, together with a calorimeter energy resolution of $3\%/\sqrt{E\,[\mathrm{GeV}]}$ and $\sim$1 mm spatial resolution, which leads to an upper limit of $1.2 \times 10^{-9}$, at the 90% CL.

Belle II has reported an upper limit at the 90% CL of $1.9 \times 10^{-8}$ on $\tau^- \to \mu^+\mu^-\mu^+$, obtained from a sample of $3.9 \times 10^8$ $\tau^+\tau^-$ pairs [28]. The LHCb and CMS collaborations have also obtained limits of the same order of magnitude [29, 30]. The search at FCC-ee is not foreseen to be background limited, and so the expected performance can be estimated by scaling the Belle II result to the Tera-Z sample size, with a reconstruction efficiency of 35%, which gives a limit of $2.0 \times 10^{-11}$.

### 3.4 Lepton universality tests with tau decays

The enormous sample of tau decays available at Tera-Z will allow for precise lepton-universality tests, comparing the couplings of the third generation with those of the first and second. An important set of measurements for these tests comprises the leptonic branching fractions $\mathcal{B}(\tau^- \to \ell^-\nu_\tau\bar{\nu}_\ell)$ ($\ell = \mathrm{e}, \mu$) and the tau lifetime. The visualisation of one such test is shown in Fig. 4, displaying the current status and the anticipated impact of FCC-ee, which is seen to be extremely significant. The tau mass is another important input to these tests. The prospects for improving each of these measurements are now discussed in turn. More information may be found in Ref. [25].

***Tau mass***

Belle II have reported the most precise current measurement of the tau mass, which is $1777.09 \pm 0.08 \pm 0.11\,\mathrm{MeV/c^2}$ [32]. The expected statistical precision at FCC-ee is 0.9 ppm, which is estimated by taking that obtained by the OPAL experiment at LEP [33] and scaling to the larger sample size. The two

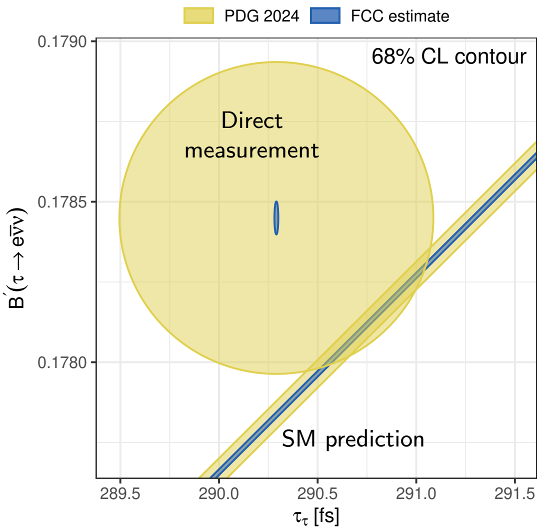


Fig. 4: Comparison of the measured tau leptonic branching fraction and lifetime with the SM prediction, showing the current status and FCC-ee expectation. Here $\mathcal{B}'(\tau^- \to \mathrm{e}^-\bar{\nu}_\mathrm{e}\nu_\tau)$ is the average of the measured value of $\mathcal{B}(\tau^- \to \mathrm{e}^-\bar{\nu}_\mathrm{e}\nu_\tau)$ and the SM prediction based on the measured value of $\mathcal{B}(\tau^- \to \mu^-\bar{\nu}_\mu\nu_\tau)$.

leading systematic uncertainties in the Belle II measurement arise from the knowledge of the collision energy and momentum scale of the tracks. At FCC-ee the collision energy will be known to 1 ppm and it will be possible to calibrate the momentum scale to a precision approaching 2 ppm from $\mathrm{J}/\psi$ decays. The dominant systematic uncertainty is expected to come from sources such as the choice of fit function to the pseudo-mass distribution, knowledge of the detector material, and modelling of the initial and final-state radiation, and the tau decay. At Belle II the uncertainties from such components contribute a total of 29 ppm. It is assumed that at FCC-ee it will be possible to reduce these uncertainties by a factor of around three, to give an overall precision on the tau mass of 10 ppm, or 0.02 MeV.

### *Tau lifetime*

The most precise single measurement of the tau lifetime is $290.17 \pm 0.53 \pm 0.13$ ps, which was performed by Belle using events in which both taus decay into three charged prongs [34]. In these events, the vertex position and the constraint of the very small luminous region allow the flight direction to be well determined. The FCC-ee performance can be estimated by taking the DELPHI measurement performed at LEP [35] with the same topology, and scaling the FCC-ee sample size. It is also important to account for the better single-event uncertainty that FCC-ee detectors will have on account of improved impact-parameter resolution and the smaller beamspot. These considerations lead to an expected statistical precision of 15 ppm from the full Tera-Z sample.

In surveying how the systematic uncertainties in the DELPHI measurement will evolve at FCC-ee, those components related to background subtraction, reconstruction bias and vertex alignment can be controlled with data, and are expected to become subdominant. Optical interferometry techniques will allow the length scale of the vertex detector to be controlled to a level where it will contribute a possible bias of 5 ppm or less to the measurement [36]. The knowledge of the tau mass, improved by FCC-ee itself, will contribute an uncertainty of 10 ppm. The largest uncertainty will most likely arise from the estimation of the average radiated energy in the initial state before the production of the tau pair, which is assigned to be 11.5 ppm. This value assumes a large (factor 30) improvement on the DELPHI assignment, but there the uncertainty was very sub-dominant and so did not warrant close attention. When adding these contributions in quadrature with the statistical component, it is estimated that the tau lifetime can be measured at FCC-ee with a precision of 21.5 ppm, or 3 as.

*Tau leptonic branching fractions*

The ALEPH collaboration measured the tau leptonic branching fractions $\mathcal{B}(\tau \to \mu\nu\bar{\nu})$ and $\mathcal{B}(\tau \to \mathrm{e}\nu\bar{\nu})$ with a relative statistical uncertainty of 0.40% and a relative systematic uncertainty of 0.19% [37]. At FCC-ee the extrapolated statistical precision is 4.0 ppm and the challenge will be in suppressing the sources of systematic bias. If the systematic uncertainty can be improved by an order of magnitude with respect to LEP, it will be possible to measure the leptonic branching fractions at FCC-ee with a relative precision of 0.019%.

### 3.5 CP violation in neutral D-meson mixing

CP violation in the charm system is predicted to be very small in the SM [38], an expectation which is confirmed by the small value of direct CP violation observed by LHCb in two-body decays [39], and existing limits for mixing-related CP violation [40]. It is important that these studies are pursued with increased precision, which will occur at LHCb and its second upgrade [1]. The Tera-Z run at FCC-ee offers the opportunity to make a significant contribution to this programme.

At FCC-ee it will be possible to perform charm measurements across a wide range of topologies, but when considering the complementarity with LHCb it is instructive to focus on multibody decays, and those that involve $\mathrm{K^0_S}$ and $\pi^0$ mesons. Such decays, when analysed as a function of decay time and with the flavour of the initial state tagged by the charge of the 'slow pion' from a $\mathrm{D}^{*+} \to \mathrm{D}^0\pi^+$ decay, allow for studies of mixing and searches for CP violation in mixing-related observables, as demonstrated by measurements with the mode $\mathrm{D}^{*+} \to \mathrm{D}^0(\mathrm{K^0_S}\pi^+\pi^-)\pi^+$ [41]. An example set of promising decay channels in this category is listed in Table 3, together with the expected events yields from the Tera-Z run from $\mathrm{c\bar{c}}$ events alone. The following acceptance and reconstruction efficiencies are assumed: 90% for the slow pion from the $\mathrm{D}^{*+}$ decay, 91% (83%) for a charged two-body (four-body) decay, with a further 80% efficiency for vertex-reconstruction requirements, and 50% and 80% for each $\mathrm{K^0_S}$ and $\pi^0$, respectively. The fragmentation fraction of $\mathrm{D}^{*+}$ mesons in a charm jet is taken to be 23% [42].

Table 3: Estimated yields in the Tera-Z run for selected $\mathrm{D}^0$ decay modes produced through $\mathrm{D}^{*+}$ decays in $\mathrm{c\bar{c}}$ events (the charge-conjugated processes are included). See main text for assumptions made.

| Mode | Estimated yield [$\times 10^6$] |
|---|---|
| $\mathrm{D}^{*+} \to \mathrm{D}^0(\mathrm{K}^+\pi^-\pi^-\pi^+)\pi^+$ | 33 |
| $\mathrm{D}^{*+} \to \mathrm{D}^0(\mathrm{K^0_S}\pi^0)\pi^+$ | 1000 |
| $\mathrm{D}^{*+} \to \mathrm{D}^0(\mathrm{K^0_S}\pi^+\pi^-)\pi^+$ | 2400 |
| $\mathrm{D}^{*+} \to \mathrm{D}^0(\mathrm{K^0_S}\pi^+\pi^-\pi^0)\pi^+$ | 4400 |

The expected sample sizes listed in Table 3 are all large, and in the flagship mode of $\mathrm{D}^{*+} \to \mathrm{D}^0(\mathrm{K^0_S}\pi^+\pi^-)\pi^+$ is much bigger than would be accumulated by Belle II with 50 ab$^{-1}$ and is comparable with that expected at LHCb Upgrade II [38]. In the modes with $\pi^0$ mesons in the final state it is reasonable to expect FCC-ee will be world-leading. All these samples can be augmented significantly by including $\mathrm{D}^{*+} \to \mathrm{D}^0\pi^+$ decays from secondary charm in $\mathrm{b\bar{b}}$ events, and also $\mathrm{D}^0$ decays that are flavour-tagged without relying on $\mathrm{D}^{*+}$ production, as has been successfully demonstrated by Belle II [43]. It is concluded, therefore, that there are excellent prospects for improving the knowledge of CP violation in the charm system at FCC-ee.

### 3.6 Time-dependent CP violation in $\mathrm{B^0_s} \to \phi\phi$

Measurements of CP violation arising from the interference between mixing and decay in the $\mathrm{B^0_s}$-$\mathrm{\bar{B}^0_s}$ system are of great interest, as the CP-violating phase, commonly denoted as $\phi_s^{\mathrm{f}}$, where the f superscript labels the composition of the final state from the quark decay, is precisely predicted in the SM and known to be very small. Hence, any observed enhancement or deviation from the SM prediction would indicate the possible effects of New Physics. The decay mode $\mathrm{B^0_s} \to \phi\phi$ is of particular note since in the SM there is a near-perfect cancellation between the phase of the mixing diagram and that in the loop-diagram mediating the direct decay. Hence, the measurement of CP violation in $B^0_s \to \phi\phi$ is essentially a null test of the SM. The LHCb collaboration has studied this mode with the full Run-1 and 2 dataset [44, 45]. An angular analysis is performed that fully exploits the kinematical information of the decay, and determines the weak phase to be $\phi_s^{s\bar{s}s} = -74 \pm 69$, on the assumption that it is polarisation-state independent.

Prospects for studying $B^0_s \to \phi\phi$ at FCC-ee have been presented in Ref. [46]. This analysis is performed with a parametrised Monte Carlo simulation, which finds a geometric acceptance of 86%. No losses are included from reconstruction, particle identification or selection requirements, but these are expected to be small. The expected event yield is $9.4 \times 10^5$ $B^0_s \to \phi\phi$ (and charge-conjugate) decays, integrated over the full Tera-Z sample. The impact of background is assumed to be negligible, which will be approximately the case, given the FCC-ee environment and expected detector performance. An effective tagging efficiency of 25% is assumed, similar to that achieved by ALEPH [3], which is a conservative estimate given the expected improvement in detector performance and advances in analysis techniques. Simulated samples are fit to determine the expected sensitivity to the weak phase $\phi_s^{s\bar{s}s}$, assuming it to be polarisation-state independent. The study makes no use of angular information, which means that the sensitivity is reduced with respect to an analysis that incorporates this information. It is found that $\phi_s^{s\bar{s}s}$ can be determined with a precision of 9 mrad. Including a dilution factor from a finite proper-time resolution, and conservatively assuming this resolution to be 45 fs, would degrade this precision to around 12 mrad. It is estimated that performing an angular analysis would allow the sensitivity to be improved by around a factor of two, providing an order of magnitude improvement on the current knowledge of this parameter. Similar precision will be achievable in the study of related decays, including those that involve neutrals in the final state, such as $B^0_s \to \eta'\eta'$.

### 3.7 CKM elements from W decays

The very large sample of $2.4 \times 10^8$ $W^+W^-$ events that will be collected at FCC-ee offers the opportunity to measure the magnitude of specific CKM elements, such as $|V_{cb}|$ and $|V_{cs}|$, in on-shell W decays, and with a precision significantly better than current knowledge [47–49]. Improved measurements of $|V_{cb}|$ are of particular interest, given the longstanding tension between inclusive and exclusive measurements in semileptonic B-meson decays [7], and the possibility that the uncertainty on this parameter may ultimately prove a limiting factor in attempts to probe for New Physics in $B^0_{(s)}$-$\bar{B}^0_{(s)}$ mixing [50].

From the unitarity of the CKM matrix it follows that the branching fraction of $W^+ \to u_i\bar{d}_j$, for up-type quark $u_i$ and down-type quark $d_j$, is $\mathcal{B}_{ij} = (|V_{ij}|^2/2)\,\mathcal{B}_{had}$, where small quark-mass effects are neglected and $\mathcal{B}_{had}$ is the hadronic branching fraction. Therefore, the magnitude of the element $V_{cb}$, for example, may be measured by counting the fraction of hadronic W decays in which one jet is tagged as containing a b quark and the other a c quark (alternatively, the sum $|V_{ub}|^2 + |V_{cb}|^2$ may be measured by b-tagging only one jet).

Aside from the size of the $W^+W^-$ sample, the precision of the measurement depends on the performance and understanding of the jet-flavour tagging. In recent years, machine learning-based flavour-tagging algorithms have been developed that promise excellent discrimination. A summary of the tagging efficiencies provided by one such algorithm when applied within a fast simulation of the IDEA detector is provided in Table 4 [51–53]. Although this performance must be confirmed with full simulation studies, it serves as a baseline to estimate the expected physics sensitivity. It is also noted that improvements in the material budget, considered desirable for other measurements in flavour physics, may further benefit the performance.

With the expected sample size, and the performance given in Table 4, it will be possible to reach a statistical precision of about 0.15% on $|V_{cb}|$ and 0.01% on $|V_{cs}|$, to be compared with the current uncertainties of 2.9% and 0.6%. To ensure that the $|V_{cb}|$ measurement does not become systematics limited, it will be necessary to know the tagging efficiencies with a relative uncertainty of 0.1%, as shown in Fig. 5 (better control is required for the $|V_{cs}|$ measurement). This control will be achievable by measuring the efficiencies in data, making use of frequent samples of $\sim 10^8$ events from Z calibration

Table 4: Identification and misidentification efficiencies for jet-flavour tagging at selected working points [51].

| | b | c | s | u | d | g |
|---|---|---|---|---|---|---|
| b tag | 0.8 | 0.003 | 0.0001 | 0.0005 | 0.0005 | 0.007 |
| c tag | 0.02 | 0.8 | 0.008 | 0.01 | 0.01 | 0.01 |
| s tag | 0.01 | 0.1 | 0.9 | 0.3 | 0.3 | 0.2 |

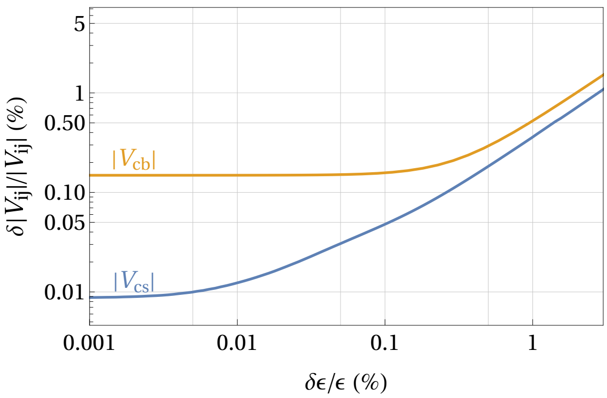


Fig. 5: Sensitivity reach on $|V_{cs}|$ (blue) and $|V_{cb}|$ (orange) from $\mathrm{e^+e^-} \to \mathrm{WW} \to 4\mathrm{j}$ as a function of the systematic uncertainty on the tagging efficiencies [48].

runs, which could be accumulated very rapidly. Attention will need to be paid to possible sources of residual biases when transporting the results from Z to W decays, and overlapping jets.

Top decays provide another opportunity to measure CKM elements, either from the decay itself, or using the top decay as a clean sample of on-shell W bosons [54]. The FCC-ee will produce $2 \times 10^6$ $\mathrm{t\bar{t}}$ pairs. A study has investigated the possibility of making a direct measurement of $|\mathrm{V_{ts}}|$ with this sample, complementary to the indirect determination from B-oscillations and lattice QCD. It is concluded that a precision of 3.1% will be achievable [55].

## 4 Other flavour-physics studies

From the discussion above, it is clear that FCC-ee can have a high impact across a very wide range of CP-violation measurements, FCNC studies and tau physics. A few additional examples can be mentioned where investigations are ongoing.

– Decays involving the transition $\mathrm{b} \to \mathrm{s}\ell^+\ell^-$ have attracted great attention at the B-factories and LHCb, on account of the rich range of observables that can be measured. These modes will remain of great interest in the FCC-ee era. Reference [56] assesses the impact of FCC-ee measurements of these FCNCs, while Ref. [57] presents a time-dependent study of the mode $B_s^0 \to \phi\mu^+\mu^-$. The FCC-ee experiments will be particularly well suited to reconstructing dielectron decays, which are challenging at the LHC, and will be able to perform precise lepton-universality tests. For example, fast simulation studies performed with the IDEA detector indicate that it will be possible to collect a high purity sample of $\sim 250 \times 10^3$ $\mathrm{B^\pm \to K^\pm e^+e^-}$ decays, which would enable a sub-percent measurement of the lepton-universality ratio $\mathrm{R_K}$ in a central bin (e.g. [1.1,6] $\mathrm{GeV}^2$) of dilepton invariant-mass squared.

– The discussion in Sec. 3.5 has made clear the potential of FCC-ee for studies of CP violation in the charm system. There are similarly good prospects for FCNC studies with charm. An example is given by the transition $\mathrm{c} \to \mathrm{u}\nu\overline{\nu}$, which is highly suppressed in the SM, but can be enhanced by BSM contributions up to branching fractions of $\mathcal{O}(10^{-6})$ [58,59]. Preliminary studies have been performed for the challenging decay mode $\mathrm{D}^0 \to \pi^+\pi^-\nu\overline{\nu}$, which indicate that the BSM range of interest is reachable with the Tera-Z $\mathrm{c\bar{c}}$ sample [60].

– The opportunities at FCC-ee for searching for LFV in tau decays was discussed in Sec. 3.3. There are equally exciting possibilities in $b$-hadrons decays, such as $B^{\pm} \to K^{\pm}\mu^{+}\tau^{-}$, and similarly in Higgs and Z decays. Reference [27] assesses the physics reach of FCC-ee in LFV Z decays and concludes that sensitivities of $10^{-8}$ to $10^{-10}$ will be attainable for $\mathrm{Z} \to \mu^{\pm}\mathrm{e}^{\mp}$, depending on the capabilities of the particle-identification system, and down to $10^{-9}$ for $\mathrm{Z} \to \tau^{\pm}\mu^{\mp}$ and $\mathrm{Z} \to \tau^{\pm}\mathrm{e}^{\mp}$.

There are many other topics in heavy-flavour physics where the potential of FCC is yet to be investigated, but is certain to be high. For example, high-impact studies of $\mathrm{b} \to \mathrm{c}\ell\bar{\nu}_{\ell}$ and $\mathrm{b} \to \mathrm{u}\ell\bar{\nu}_{\ell}$ transitions will be possible, thanks to the good hermiticity of the detectors and high boost. The large sample of b-hadron decays will also make FCC-ee an ideal laboratory for spectroscopy studies, in which the good reconstruction efficiency for soft photons will allow for complementary searches to those performed at the HL-LHC.

## 5 Flavour physics at FCC-hh

There will be exciting opportunities for flavour-physics measurements at FCC-hh. The cross-section for $\mathrm{b\bar{b}}$ production at $\sim$100 TeV is expected to be around 3 mb, which is five times higher than at the LHC. High-$\mathrm{p_T}$ production, in particular, receives a large boost in going from LHC to FCC-hh energies, growing by a factor of 30-40 above a $\mathrm{p_T}$ cut of 100 GeV [61]. However, preliminary studies indicate that a forward detector, with similar layout to LHCb, would also be a suitable geometry for exploiting the increased flux of heavy-flavour hadrons at these energies [62]. As well as the increased production cross-section, it is expected that improvements in computing and detector technology will allow the decays to be selected with much higher efficiency and inclusivity than has been traditionally the case at hadron machines, and at the highest operating luminosity of the collider.

At FCC-hh it will also be possible to collect very large samples of b-hadrons from top decays, which will be very clean and, if triggered by a lepton, carry a high-purity flavour tag. This approach has been proposed for the LHC [54, 63], where proof-of-principle measurements have been conducted [64], but will be more powerful at FCC-hh.

## 6 Conclusions

The FCC-ee holds immensely exciting prospects for flavour physics. The enormous sample of heavy-flavour hadrons and taus produced in the Tera-Z run can be exploited for transformative studies of FCNCs, CP violation, lepton universality and lepton-flavour violation. This programme of measurements will have excellent sensitivity to New Physics at energies significantly above the electroweak scale [65]. The example modes considered in this document illustrate that in many analyses involving fully charged final states, the intrinsic advantages of FCC-ee, including very high luminosity, high acceptance, excellent flavour tagging and low backgrounds, will largely offset the difference in production cross-sections between $\mathrm{pp}$ and $\mathrm{e^{+}e^{-}}$ collisions, and open the possibility for measurements of similar or higher sensitivity to those that will be performed at the HL-LHC. This capability will be invaluable in confirming or refuting any potential anomaly seen at the HL-LHC or by Belle II, and increasing precision for most key observables. In modes involving electrons, $\pi^{0}$ and $\eta$ mesons, photons, and neutrinos, FCC-ee will have unmatchable reach. All projections presented in this document assume the baseline plan for Tera-Z data taking, but the sample sizes could be increased substantially by adjusting the balance of data-taking between 'on peak' and 'off peak' at the Z pole, and/or extending Z-pole operation by one or a few years. It would therefore be relatively straightforward to increase the precision on any measurement of interest without greatly perturbing the overall FCC schedule. Promising opportunities also exist for measuring the magnitude of CKM matrix elements from W-boson and top decays. Looking beyond FCC-ee, it is already clear that this high precision programme of measurements can be further advanced at FCC-hh, although detailed studies are yet to be performed. In summary, the FCC will be an outstanding laboratory for the study of flavour physics, and is the only proposed facility for CERN that will allow for significant progress in the study of heavy quarks and leptons in the post HL-LHC era.

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