PROCEEDINGS OF SCIENCE

Quark and lepton flavor physics opportunities at FCC-ee

Xunwu Zuo[a,1,*]

[a] *Karlsruhe Institute of Technology, D-76131 Karlsruhe, Germany*

E-mail: xunwu.zuo@cern.ch

The Future Circular Collider (FCC) is a post-LHC project aiming at direct and indirect searches for physics beyond the SM in a new 91 km tunnel at CERN. The abundant production of beauty and charm hadrons in the 6×10^{12} Z boson decays expected in e+e- collisions at FCC-ee offers outstanding opportunities in flavour physics with b and c hadron samples that exceed those available at Belle II by a factor of 20, and are complementary to the LHC heavy-flavour programme. A wide range of measurements will be possible in heavy-flavour spectroscopy, rare decays of heavy-flavoured particles and CP-violation studies, which will benefit from the low-background experimental environment, the high Lorentz boost, and the availability of the full spectrum of hadron species. The tau pairs production in the Tera-Z phase will be 3 times larger than at Belle II, and thanks to more favorable experimental conditions (better tau - hadrons separation, better tau hemispheres separation, higher momentum tracks) it will be possible to significantly improve the determinations of the tau-lepton properties – lifetime, leptonic and hadronic widths, and mass – allowing for important tests of lepton universality. Furthermore, it will be possible to extend the searches for Lepton-Flavour-Violating tau decays, and, via the measurement of the tau polarisation, FCC-ee can access a precise determination of the neutral-current couplings of electrons and taus. These measurements present strong experimental challenges to exploit as far as possible statistical uncertainties $O(10^{-5})$, raising strict detector requirements. This contribution will present an overview of the broad potential of the FCC-ee flavour physics program and also some preliminary results from recent analyses.

The European Physical Society Conference on High Energy Physics (EPS-HEP2023)
21-25 August 2023
Hamburg, Germany

[1] On behalf of the FCC-ee flavor group
[*] Speaker

https://pos.sissa.it/

PoS(EPS-HEP2023)331

1. FCC-ee dataset for flavor physics

The Future Circular Collider (FCC) [1, 2] project is a design for a post-LHC collider complex near CERN, Geneva. The first stage of FCC focuses on electron-positron collisions (FCC-ee) and features operations at four different center-of-mass energy windows: around the Z-pole, the W^+W^- pair production, the ZH production, and the $t\bar{t}$ pair production. The integrated luminosity and the corresponding number of events for the accumulated dataset (assuming four total experiment sites) at each collision energy are summarized in Table 1.

Dataset	Operation time (yrs)	Int. lumi. (ab^{-1})	Number of events
Z	4	180	6×10^{12}
WW	2	12	2.4×10^{8}
ZH	3	7	1.5×10^{6}
$t\bar{t}$	5	2.5	2×10^{6}

Table 1: Summary of the expected total luminosity and the corresponding event yield for each operation energy at FCC-ee.

Such datasets provide unprecedented opportunities for a plethora of physics topics, including electroweak measurements, QCD measurements, flavor physics, and new physics searches. In particular, the Z-pole dataset features a total of 6×10^{12} Z bosons, which decay into all types of lighter fermions, serving as a clean and prolific "flavor factory". This leads to a more abundant production of heavy flavor particles than the existing flavor factory, the Belle-II experiment [3], as summarized in Table 2. In particular, the FCC-ee is highly advantageous in the production of heavy hadrons like $B_s^0(\bar{B}_s^0)$, $B_c^\pm$, and $\Lambda_b(\bar{\Lambda}_b)$, whose yields are limited at Belle-II by its energy threshold.

Particle count (10^9)	$B^0(\bar{B}^0)$	$B^\pm$	$B_s^0(\bar{B}_s^0)$	$B_c^\pm$	$\Lambda_b(\bar{\Lambda}_b)$	$c(\bar{c})$	$\tau^\pm$
Belle-II	55	55	0.6	N.A.	N.A.	130	90
FCC-ee	770	770	170	7	150	1400	400

Table 2: Expected yields of heavy-flavor products in the full Belle-II dataset (50 ab^{-1}) and the FCC-ee Z-pole dataset (180 ab^{-1}). The Belle-II yields are calculated from the production cross sections given in Ref. [3], while the FCC-ee yields are calculated from the Z branching ratios and the hadronization fractions given in Ref. [4].

Future electron-positron colliders like the FCC-ee also exhibit unique advantages when compared to flavor experiments at hadron colliders. The clean environment of electron-positron collisions makes it free from the vast QCD backgrounds and pileup effects at hadron machines. The precise knowledge of the center-of-mass energy of the system allows for the full reconstruction of the missing energy. The back-to-back $Z \to q\bar{q}$ decay provides a way for unbiased flavor tagging through the tag-and-probe approach. For these reasons, many measurements faced with fundamental difficulties at hadron colliders and become straightforward and precise at FCC-ee.

The main goal for the current FCC-ee flavor program is to explore the unique physics cases at FCC-ee and understand their impacts on the landscape of flavor physics, as well as the corresponding requirements on detectors. The findings from such studies are constantly evolving. At the time of the conference, recent studies had led to exciting prospects on various topics.

PoS(EPS-HEP2023)331

2. Case studies for b physics

2.1 $b \to q\ell\nu$ transition

Traditionally, the best way to extract CKM matrix elements $|V_{ub}|$ and $|V_{cb}|$ is through the semileptonic $b \to u\ell\nu$ and $b \to c\ell\nu$ decays. However, a long-standing discrepancy exists between the results from the exclusive and inclusive methods [5, 6], at more than 3σ level for both $|V_{ub}|$ and $|V_{cb}|$. The $b \to c\ell\nu$ transition is also a powerful tool to probe lepton flavor universality, for which the ratio $\mathcal{R}(D^{(*)})$ from recent measurements [7] shows a 3.3σ deviation from the SM prediction.

The purely leptonic $B^+/B_c^+ \to \tau^+\nu_\tau$ decays are counterparts to the $b \to q/c\ell\nu$ transitions that are theoretically clean while highly sensitive to New Physics (NP) possibilities. Recent FCC-ee studies [8] on the $B^+/B_c^+ \to \tau^+\nu_\tau$ processes, with a focus on the hadronic $\tau^+ \to \pi^+\pi^+\pi^-\bar{\nu_\tau}$ decay, has demonstrated the possibility to measure both processes at the precision about 2%. Such result is interpreted in both SM and BSM cases, as a measurement on $|V_{ub}|$ and as constraints on certain EFT operators. Examples of the results are given in Fig. 1.

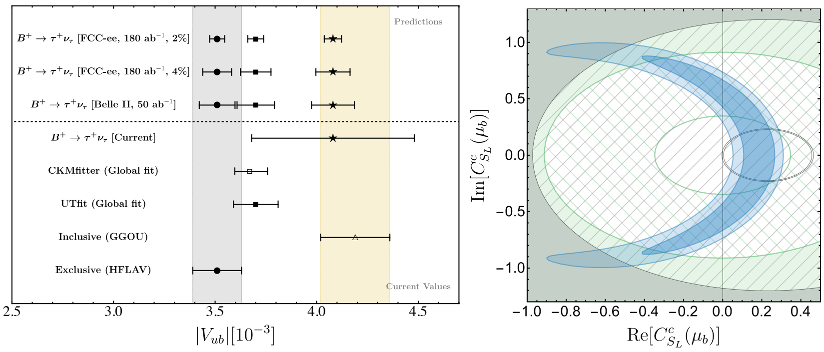

Figure 1: Plots from Ref. [8]. Left: comparison of $|V_{ub}|$ determinations from various current sources as well as future predictions. Right: an example of the phenomenological interpretation of the $B_c^+ \to \tau^+\nu_\tau$ measurement at FCC-ee, in the context of a scalar leptoquark model. The blue shaded region are inferred from the current $b \to c$ anomalies, the green shade (hash) is the exclusion limit from direct searches for leptoquarks with the current LHC (expected HL-LHC) results, and the grey shade (hash) is the constraint based on current searches for (future FCC-ee measurement of) the $B_c^+ \to \tau^+\nu_\tau$ decay.

2.2 $b \to s\ell\ell$ transition

The $b \to s$ transition is prohibited at tree level in SM. The different box or penguin diagrams that mediate the $b \to s\ell\ell$ transition are highly sensitive to a wide range of possible beyond SM (BSM) modifications. In particular, the FCC-ee presents unique advantages in the search for the $B^0 \to K^{*0}\tau^+\tau^-$ process and may provide the first chance to see this process at the SM strength.

Benefiting from the high boost of the B meson and the exquisite vertex resolution, all three vertices of the $B^0 \to K^{*0}\tau^+\tau^-$, $\tau^+ \to \pi^+\pi^+\pi^-\bar{\nu_\tau}$ decay chain can be reconstructed, depicted in the left plot of Fig. 2. Consequently, the direction of flight of the τ leptons can be extracted from vertex positions, allowing for the event kinematics to be fully solved, albeit the missing information of the neutrinos. A preliminary study from the FCC-ee demonstrates the possibility to reconstruct the invariant mass of the B meson and separate this process from various backgrounds, shown in the right plot of Fig. 2.

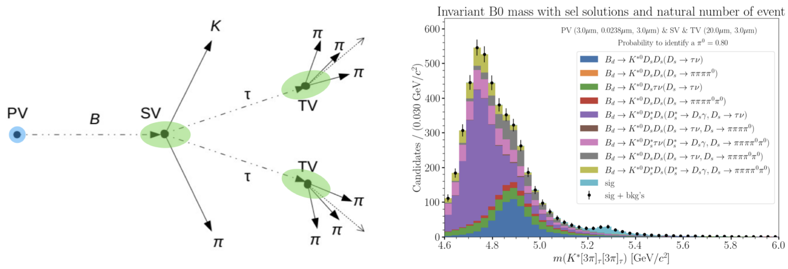

Figure 2: Plots from Ref. [9]. Left: sketch of the $B^0 \to K^{*0}\tau^+\tau^-$, $\tau^+ \to \pi^+\pi^+\pi^-\bar{\nu_\tau}$ decay chain. Right: distribution of the reconstructed invariant mass of the $B^0 \to K^{*0}\tau^+\tau^-$ candidates.

Apart from the semileptonic decays, the purely leptonic $B_s \to \ell\ell$ decays are independent clean probe for the same physics. The SM expectation for the $\mathcal{B}(B_s \to \tau^+\tau^-)$ is about 200 times that for $\mathcal{B}(B_s \to \mu^+\mu^-)$ due to the relaxation of helicity suppression. However, the current experimental precision for the $B_s \to \tau^+\tau^-$ is limited by reconstruction difficulties at LHCb and production yields at Belle-II. The FCC-ee would be the ideal place for precision measurements of $B_s \to \tau^+\tau^-$. Moreover, searches for charged lepton flavor violating (CLFV) decays like $B_s \to \tau\mu$ and $B_s \to \tau e$ can also be conducted at extreme precisions at FCC-ee, probing a broad range of NP.

2.3 $b \to s\nu\nu$ transition

The $b \to s\nu\nu$ transition is deeply connected to $b \to s\ell\ell$ transitions in flavor phenomenology, sharing complementarity in their physics impacts [10]. A recent study [11] from the FCC-ee on the $B \to K^{(*)}$ and $B_s \to \phi$ has demonstrated the potential to measure the $b \to s\nu\nu$ transition at high precision. Figure 3 shows estimates of the expected sensitivity for $B^0 \to K^{*0}\nu\nu$ and $B_s \to \phi\nu\nu$ decays, in which the B meson decay vertex can be reconstructed from the consequent $K^{*0} \to K^+\pi^-$ and $\phi \to K^+K^-$ decays.

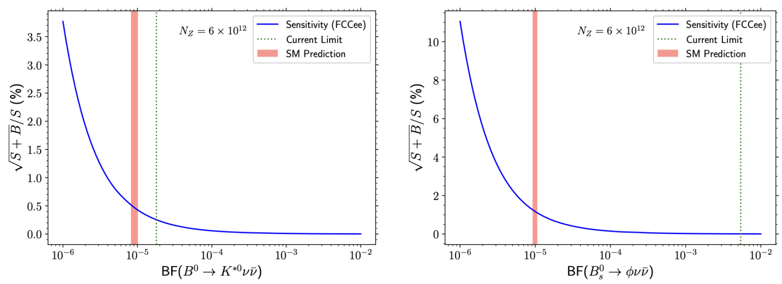

Figure 3: Plots from Ref. [11]. The sensitivity estimates of the $B^0 \to K^{*0}\nu\nu$ (left) and $B_s \to \phi\nu\nu$ (right) decays.

Similar projections are also performed on other decay modes involving long-lived neutral particles, such as $B^0 \to K_S\nu\nu$ and $\Lambda_b \to \Lambda\nu\nu$. From preliminary studies, we believe it is possible to observe such processes at the SM strength, given efficient reconstruction of the highly displaced $K_S \to \pi^+\pi^-$ and $\Lambda \to p\pi^-$ vertices. The combination of all these decay modes is expected to provide tight constraints on the $bs\nu\nu$ effective coupling.

3. Case studies for other flavor physics

3.1 Tau physics

As there is no hadronic shower activities in the $Z \to \tau^+\tau^-$ decay, the τ leptons in the FCC-ee environment always come with a significant and well-determined boost, bringing advantages to the vertex reconstruction and time-of-flight measurement. The τ branching ratio measurements, in both SM and BSM cases, also benefit from the abundant production. The CLFV τ decays is of particular interest at FCC-ee, as in many NP cases the amplitude for $\tau \leftrightarrow \mu/e$ conversion, comparing to that for $\mu \leftrightarrow e$, is enhanced by the higher lepton mass.

The left plot of Fig. 4 summarizes the expected precision for the SM properties of the τ lepton, in which the FCC-ee provides the most precise branching ratio and lifetime measurements [12], while the mass measurement benefits mostly from the Super Tau Charm Factory (STCF) [13]. The right plot of Fig. 4 shows the expected limit for the CLFV $\tau \to 3\mu$ decay in different experiments in the next few decades.

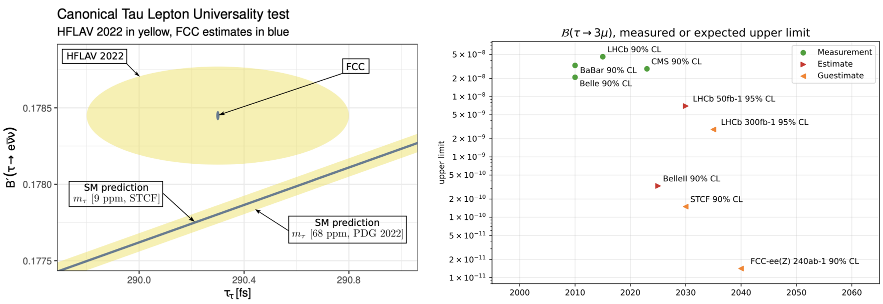

Figure 4: Plots from Ref. [14]. Left: expected precision on the SM properties of the τ lepton in the FCC-ee era. Right: current and future upper limits on the CLFV $\tau \to 3\mu$ decay.

3.2 Flavor changing neutral current in Z, Higgs, and top decays

Flavor changing neutral currents (FCNC) is forbidden at tree level in SM and is a powerful tool to probe NP. The CLFV decays of the Z or Higgs bosons, $Z/H \to \ell\ell'$, are extremely suppressed in SM and are excellent null tests. The sensitivity of $Z \to e\mu, e\tau, \mu\tau$ searches at FCC-ee is expected to reach $10^{-8} - 10^{-10}$ level at the FCC-ee [12]. In addition, the clean samples of Z and Higgs bosons in the FCC-ee dataset also opens up possibilities to measure quark flavor changing decays $Z/H \to qq'$ at high precision. Figure 5 shows the potential range of the upper limits on $Z/H \to bs$ decays, under different benchmarks of flavor tagging performance.

References

[1] A. Abada et al., *FCC Physics Opportunities: Future Circular Collider Conceptual Design Report Volume 1*, Eur. Phys. J. C 79, 474 (2019).

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

PoS(EPS-HEP2023)331

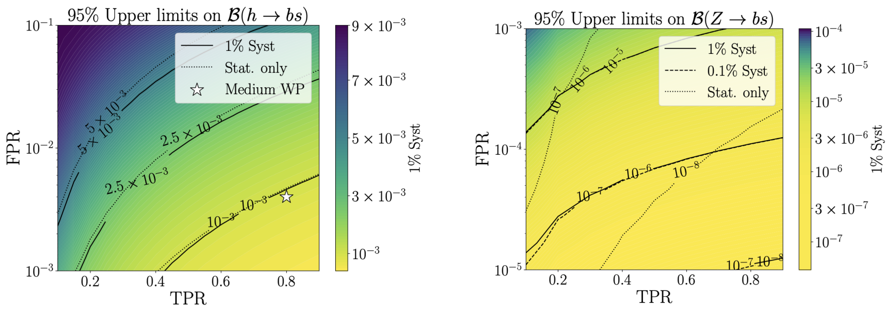

Figure 5: Plots from Ref. [15]. Projected limits on the FCNC $H \to bs$ (left) and $Z \to bs$ (right) decays.

[3] E. Kou et al., *The Belle II Physics Book* Prog. Theor. Exp. Phys. 2019, 123C01

[4] P. A. Zyla et al., *Review of particle physics* Prog. Theor. Exp. Phys. 2020, 083C01

[5] UTfit, M. Bona et al., *New UTfit Analysis of the Unitarity Triangle in the Cabibbo-Kobayashi-Maskawa scheme*, Rend. Lincei Sci. Fis. Nat. 34 (2023) 37

[6] CKMfitter group, *Recent ckmfitter updates on global fits of the ckm matrix*, https://indico.cern.ch/event/891123/contributions/4601722/attachments/2351890/ 4013122/CKM-fitter2021.pdf

[7] HFLAV group, *Preliminary average of R(D) and R(D*) for Summer 2023*, https://hflav-eos.web.cern.ch/hflav-eos/semi/summer23/html/RDsDsstar/RDRDs.html

[8] M. Fedele, C. Helsens, D. Hill, S. Iguro, M. Klute, and X. Zuo, *Prospects for B_c^+ and $B^+ \to \tau^+\nu_\tau$ at FCC-ee*, arXiv 2305.02998

[9] T. Miralles, *Detector requirements from B to K* tau tau, FCC Week 2023*, slides

[10] W. Buchmüller and D. Wyler, *Effective lagrangian analysis of new interactions and flavour conservation*, Nucl. Phys. B 268 (1986) 621

[11] Y. Amhis, M. Kenzie, M. Reboud, A. R. Wiederhold, *Prospects for searches of $b \to s\nu\bar{\nu}$ decays at FCC-ee*, arXiv 2309.11353

[12] M. Dam, *Tau-lepton Physics at the FCC-ee circular e+e- Collider*, SciPost Phys. Proc. 1, 041 (2019)

[13] M. Achasov et al., *STCF Conceptual Design Report: Volume 1 – Physics and Detector* arXiv 2303.15790

[14] A. Lusiani, *LFV/CLFV at e+e- Colliders, CLFV 2023*, https://indico.desy.de/event/37920/contributions/139559/

[15] J. F. Kamenik et al., *Flavor violating Higgs and Z decays at FCC-ee*, arXiv 2306.17520