Electroweak Heavy Flavour (bottom, charm,tau) at the FCC-ee

Letter of Interest submitted to Snowmass 2021

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Abstract

The FCC-ee is a frontier Higgs, Top, Electroweak, and Flavour factory. It will be operated in a $100\,\mathrm{km}$ circular tunnel built in the CERN area, and will serve as the first step of the FCC integrated programme towards $\geq 100\,\mathrm{TeV}$ proton-proton collisions in the same infrastructure [1]. In addition to an essential and unique Higgs program, it offers powerful opportunities for discovery of direct or indirect evidence for BSM physics, via a combination of high precision measurements and searches for forbidden or rare processes, and feebly coupled particles.

A key element of the FCC-ee physics program is, thanks to the huge Z statistics, the ability to provide a complete determination of the chiral couplings of the Z to fermions via a combination of total widths, decay rates and forward-backward or polarization asymmetries, with a leap in precision of up to two orders of magnitude. In this LOI we focus on some of the heavy flavour observables (b, c, τ). The ultimate goal, that experimental and theory systematic errors match the statistical accuracy, leads to highly demanding requirements on detector design and on theoretical calculations. This letter of interest describes some of the many challenges presented by these benchmark measurements.

Thematic Areas:
■ (EF03) EW Physics: Heavy flavor and top quark physics
■ (EF04) EW Physics: EW Precision Physics and constraining new physics
■ (EF05) QCD and strong interactions: Precision QCD

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The FCC-ee program foresees an extended run at and around the Z pole, producing a total of five trillion (10^{12}) Z bosons. This provides a unique opportunity to measure the electroweak properties of heavy fermions like the tau lepton, bottom and charm quarks with unprecedented precision. In addition to an unbeatable statistical precision of $\mathcal{O}(10^{-6})$, at the FCC-ee one expects a significant reduction of systematic uncertainties compared with previous experiments at LEP and SLC. Better detectors (tracking, granularity, energy sampling, ...), improved configurations for lifetime tagging (smaller beam pipe radius) and outstanding particle flow identification techniques should help in reducing significantly the experimental component of these uncertainties.

The Z partial decay widths to b and c quarks normalized to the Z hadronic width, R_b and R_c, are electroweak observables that test $Zb\bar{b}$ and $Zc\bar{c}$ vertex corrections, which are particularly sensitive to new physics. One order of magnitude improvement in precision is expected at the FCC-ee compared with the present world average [2]. The two-hemisphere multi-tagging strategies developed at LEP and SLD experiments [3] should still be optimal for the high-statistics samples expected at the new future facility. Beside already existing improvements in the knowledge of heavy flavor inputs to the measurement (fragmentation, decay branching fractions, lifetimes, ...), better secondary vertex tagging capabilities should contribute to considerably reduce background contamination, both in the R_b and R_c cases. Large gluon-splitting samples $g \to b\bar{b}/c\bar{c}$, excellent granularity for particle-flow reconstruction and recent jet substructure techniques will be available to study and eventually reduce the impact of QCD correlation uncertainties between the two hemispheres of the event. The small transverse size of the beam spot ($< 10~\mu$m) will ensure a negligible correlation between the measured vertices in those hemispheres. Last but not least, the huge recorded statistics should allow precision measurements of R_c using purer, exclusive decays like $D^* \to D^\circ \pi_{\mathrm{slow}}$ in both hemispheres.

The forward-backward asymmetry of b quarks at the Z pole, $A_{FB}^{0,b}$, is the electroweak observable that currently presents the largest deviation with respect to standard model expectations [3] (2.8σ pull). An order of magnitude improved measurement at the FCC-ee could thus become a clean signal of new physics if the deviation in the central value stays. The world average measurement is still dominated by statistical uncertainties ($\Delta A_{FB}^{0,b} = 0.0016$), but is also affected by non-negligible systematic uncertainties ($\Delta A_{FB}^{0,b}(syst.) = 0.0007$). A fraction of it can be reduced at FCC-ee through dedicated studies on high-statistics control samples selected with well understood charge/flavor tagging techniques. A detailed analysis of the detector requirements to maximize heavy-flavor identification capabilities is also mandatory. Exclusive B decays should also be exploited. For instance, $\approx 10^8$ B^+ decays, not affected by charm contamination or B-mixing effects - will be available at the FCC-ee [2]. Similar approaches, using both inclusive and exclusive tagging capabilities should be followed for the measurement of the forward-backward asymmetry of charm quarks, $A_{FB}^{0,c}$.

An irreducible source of uncertainty in the current estimate of $A_{FB}^{0,b}$, fully correlated among experiments, is the use of a theoretical QCD factor, or order $1 - \alpha_S/\pi$, that corrects the experimentally observed asymmetry [4, 5, 6]. This correction takes into account the unavoidable angular distortions due to QCD radiation in the Z $\to b\bar{b}(g)$ decay. Recent re-evaluations of that uncertainty [7] using modern parton shower tunes seem to be consistent with the initial estimates. New strategies to reduce or constrain experimentally the size of these uncertainties should be developed in order to keep am overall uncertainty target of $\Delta A_{FB}^{0,b} \approx 0.0001$.

The tau polarization in Z decay is one of the most sensitive electroweak observables [3], giving direct access to Z polarization generated in the e^+e^- collision, $-\mathcal{A}_e$. It is the analysis of the τ polarization dependence on the scattering angle θ what gives access to both the tau and electron asymmetries $\mathcal{A}_\tau$ and $\mathcal{A}_e$ independently:

$$P(\cos\theta) = \frac{\mathcal{A}_\tau(1 + \cos^2\theta) + 2\mathcal{A}_e \cos\theta}{(1 + \cos^2\theta) + 2\mathcal{A}_e\mathcal{A}_\tau \cos\theta}, \tag{1}$$

and serves as a crucial ingredient for a full lepton-by-lepton extraction of the left and right (or vector and axial-vector) neutral weak couplings. A closely related outcome is a precise determination of the vector and axial vector spectral functions [8], which provide important information for the extraction of $\alpha_s(m_\tau^2)$ and $\alpha_{\mathrm{QED}}(q^2)$.

The tau polarization is measured from the energy distribution and relative kinematics of the visible decay products. Both leptonic ($\tau \to e\nu_e\nu_\tau$, $\mu\nu_\mu\nu_\tau$) and hadronic decays $\tau \to h\nu_\tau$ where

h can be π, K, ρ, K*, a$_1$, ... can be used for this purpose. Each channel having its own analysis power, a clean separation between them is essential. In addition, a proper identification and measurement of the individual particles in the decay is important to maximize the sensitivity in the hadronic channels. Together with a substantial reduction of statistical uncertainties, the FCC-ee detectors should provide a reduction of systematic uncertainties in the identification and separation of charged kaons, charged kaons and photons in collimated tau decays, which should be studied and quantified in detail.

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