Snowmass2021 - Letter of Interest

Tau lepton properties and lepton universality measurements at the FCC-ee

Thematic Areas:
■ EF04: EW Physics: EW Precision Physics and constraining new physics
■ EF03: EW Physics: Heavy flavor and top quark physics

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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 $\geq$ 100-TeV proton-proton collisions in the same infrastructure [1]. With its huge luminosity at Z-pole energies, unrivalled samples of 5×10^{12} Z decays will be produced at multiple interaction points. The five orders of magnitude larger statistics than at LEP opens the possibility of much improved measurements of τ-lepton properties—lifetime, (leptonic) branching fractions, and mass—in $\tau^+\tau^-$ final states. Such measurements provides interesting tests of lepton universality, in effect probing whether the Fermi coupling constant is the same in τ decays as in μ decays. The ultimate goal, that experimental errors match the statistical accuracy, leads to highly demanding requirements on detector design. This Letter of Interest describes some of the many challenges presented by this benchmark measurement.

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Precision measurements of τ lepton properties, its mass, lifetime, and leptonic branching fractions, provide interesting tests of lepton universality. Firstly, the ratio of the weak-charged-current couplings, g_μ/g_e, between muons and electrons can be readily derived from the ratio of the branching fractions for the two decay modes, $\tau \to \mu\bar{\nu}\nu$ and $\tau \to e\bar{\nu}\nu$. Secondly, the coupling ratio, g_τ/g_ℓ, between τ and light lepton $\ell = e, \mu$ can be derived from the relation

$$\left(\frac{g_\tau}{g_\ell}\right)^2 = \frac{\mathcal{B}(\tau \to \ell\bar{\nu}\nu)}{\mathcal{B}(\mu \to \ell\bar{\nu}\nu)} \cdot \frac{\tau_\mu}{\tau_\tau} \cdot \left(\frac{m_\mu}{m_\tau}\right)^5,$$

where (small and known) effects due to phase space and radiative and electroweak corrections have been omitted. In both cases, data support lepton universality at the $\mathcal{O}(10^{-3})$ level [2].

Historically, lepton universality tests took a giant leap with the precise LEP measurements based on about 10^6 $Z \to \tau^+\tau^-$ events. Whereas precise τ-mass measurements (currently $\mathcal{O}(10^{-4})$ precision) have been dominated by threshold scans, LEP provided important measurements of both the lifetime and the leptonic branching fractions. In fact, the LEP branching fraction measurements ($\mathcal{O}(10^{-3})$) still stand unchallenged, whereas the world-average life-time measurement ($\mathcal{O}(10^{-3})$), since LEP, has seen an improvement of about a factor two from a high-statistics Belle measurement [3].

At FCC-ee, with about 10^{11} $Z \to \tau^+\tau^-$ events, statistical precisions will improve by more than two orders of magnitude down to the 10^{-5} level. The experimental challenge will then be to follow down as far as possible with the systematic uncertainties. Studies will be devised aiming to derive the key detector requirements in order to exploit maximally the event statistics. A list of initial observations are:

i. At Z-pole energies, the τ lifetime is determined via measurement of the 2.2-mm average flight distance. A lifetime measurement matching the 10^{-5} statistical precision would then correspond to a flight-distance measurement to a few tens of nanometers accuracy. Approaching as far as possible towards this limit imposes formidable requirements on the accuracy of the construction and the alignment of the vertex detector. With a 10–15-mm beam pipe radius, the first vertex detector layer will be very close to the beam line and an impact parameter resolution of about 3 μm looks feasible.

ii. With the very large statistics, an important improvement of the τ mass measurement may be possible via the so-called pseudomass method pioneered by ARGUS [4] and later exploited by OPAL [5] at LEP and by BaBar [6] and Belle [7] at the b-factories. In three-prong τ decays, the pseudomass variable depends on the measured mass and momentum of the 3π system and on the beam-energy. At FCC-ee, the beam energy is controlled to 10^{-6} via resonant spin depolarisation [8], and only the measurement of the 3π system contributes to the uncertainty on the pseudomass. As a reference process, in order to control the mass and momentum scale, it is suggested to exploit the very large sample of J/ψs from Z decays ($\mathcal{B}(Z \to J/\psi X) = 3.5 \times 10^{-3}$), and the fact that the J/ψ mass is known to the ppm level due a very precise measurement from KEDR [9] at the VEPP-4M collider likewise based on resonant spin depolarisation. It could be also considered to make use of τ decays with higher charged-particle multiplicities that will provide a larger fraction of events close to the end-point of the pseudomass distribution. An excellent measurement of tracks in collimated multi-track final states is a key experimental requirement.

iii. At Z-pole energies, where the separation of a clean and relatively unbiased sample of $\tau^+\tau^-$ events has been proven possible, accurate measurements of the τ leptonic branching fractions rely primarily on the ability to separate precisely the two leptonic decay modes, on the one hand, from the single-prong hadronic modes, on the other. The separation relies critically on a fine-grained calorimeter system combined with a dedicated muon system. The electron/pion separation can potentially be improved by the addition of a powerful $\mathrm{d}E/\mathrm{d}x$ measurement providing a welcome experimental redundancy.

A lesson from LEP is that the most precise leptonic branching fraction measurement (provided by

ALEPH [10]) was obtained via an global procedure where all τ decays were classified concurrently into the the various modes.

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