# Snowmass2021 - Letter of Interest

# Tau exclusive branching fractions and tau polarisation observables at the FCC-ee

**Thematic Areas:**

■ EF04: EW Physics: EW Precision Physics and constraining new physics
■ EF05: QCD and strong interactions:Precision QCD


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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 $5 \times 10^{12}$ Z-decays will be produced at multiple interaction points. This opens the possibility for very precise measurements of $\tau$ leptons including their exclusive branching fractions and their polarisation in Z decays, one of the most precise electroweak observables. This letter of interest concentrates on some of the main experimental challenges in $\tau$-lepton measurements, namely the inter-channel separation and the precise measurement of the final state kinematics. This relies critically on the precise measurement of photons and $\pi^0$s (and other neutral particles) in the calorimeter system, on the precise tracking of high-multiplicity collimated topologies, and—at least for the exclusive branching fractions—on the ability to separate pions from kaons over the full momentum range.



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The tau polarization in Z decays is one of the most sensitive electroweak observables [2]. The analysis of the polarization's dependence on the scattering angle $\theta$ gives access to both the tau and electron chiral coupling asymmetries $\mathcal{A}_\tau$ and $\mathcal{A}_\mathrm{e}$ independently,

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

and serves as a crucial ingredient of a full lepton-by-lepton extraction of the neutral-current chiral couplings. In the leptonic decays $\tau \to \mathrm{e}\nu_\mathrm{e}\nu_\tau$, $\mu\nu_\mu\nu_\tau$ and in decays with a single final-state hadron, $\tau \to h\nu_\tau$, $h = \pi$, K, the polarization is derived from the charged-particle momentum distribution. For decays with multiple final-state hadrons, more variables are exploited. As an important example, for the dominant $\tau$-decay mode, $\tau \to \rho \to \pi\pi^0$, the two sensitive variables are the $\pi\pi^0$-system total energy and the asymmetry between the $\pi$ and $\pi^0$ energies. Each channel having its own set of variables with different dependence on the polarization, a clean separation between channels, e.g. between $\tau \to \pi\nu_\tau$ and $\tau \to \pi\pi^0\nu_\tau$, is essential.

An experimentally related measurement is that of the $\tau$-decay branching fractions. Experience from LEP [3] shows that the branching fractions are most precisely determined via a global analysis method, where in a preselected $\tau^+\tau^-$ sample, all decays are categorised concurrently according to a set of predefined decay modes. An important outcome of this analysis is a precise determination of the vector and axial-vector spectral functions, which provide important information for the extraction of $\alpha_\mathrm{s}(m_\tau^2)$ and $\alpha_\mathrm{QED}(q^2)$.

A limiting systematic error is associated with cross-channel contamination, implying tight detector requirements on reconstruction of photons, $\pi^0$s and other neutral particles, as well as K/$\pi$ separation.

Key to the analyses is a precise measurement of photons and $\pi^0$s in the electromagnetic calorimeter. The high collimation of $\tau$ decays at Z-pole energies tends to complicate photon reconstruction, since photons are close to one another or close to the showers generated by charged hadrons. Of particular relevance is the rejection of fake photons which may occur because of hadronic interactions, fluctuations of electromagnetic showers, or the overlapping of several showers. A main outcome of the study will be the understanding of the requirements on the electromagnetic calorimeter for an optimal separation and measurement of the $\tau$ decay modes. Different calorimeter designs have been proposed each with different performance charateristics in terms of transverse and longitudinal granularity and resolution. The study will allow a comparison and optimisation of these designs.

For a complete determination of the $\tau$-decay branching fractions, K/$\pi$ separation over the full momentum range $[0; E_\mathrm{beam}]$ is needed. Whether this is also the case for a very precise $\tau$ polarization measurement has to be understood. Obviously, $\pi\nu$ and $\rho\nu$ final states, on the one hand, have different kinematics from K$\nu$ and K$^*\nu$, on the other. To which extend a statistical correction based on known branching fractions may be sufficient to account for this should be understood.

With the current limit on the still unobserved seven-prong $\tau$ decay mode, up to $\mathcal{O}(10^5)$ such decays could be produced at FCC-ee. Kinematically, up to 11 charged pions (plus one $\pi^0$) are allowed. For the design of the tracking detectors it is worthy exercise to make sure that such strongly collimated high-multipicity topologies are correctly reconstructed. The precise, high-statistics measurement of multiprong $\tau$ decays will certainly bring a much improved determination of the $\tau$ neutrino mass, where the current 18.2 MeV limit stems from LEP [4].

## References

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