Tau lifetime measurement at FCC-ee(Z)

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We estimate the uncertainty on the experimental measurement of the tau lepton lifetime at FCC-ee at the Z peak. This measurement can be used to test the Standard Model lepton universality.

This work has been performed within the FCC collaboration.

1 Tau lepton lifetime measurement at FCC-ee(Z)

We summarize the estimate of the FCC-ee experimental precision on the measurement of the tau lifetime, which has been documented in an FCC internal note [1][1]. This measurement can be used to test the Standard Model lepton universality. We assume that FCC-ee will observe at the Z peak $N_{\mathrm{Z}}^{\mathrm{FCC}} = 6{\cdot}10^{12}$ Z decays [2], corresponding to $2.0{\cdot}10^{11}$ tau pairs, and to an integrated luminosity of $\mathscr{L}_{\mathrm{int}}^{\mathrm{FCC}} = 210\,\mathrm{ab}^{-1}$.

With a sample of $6{\cdot}10^{12}$ Z decays, it is convenient to measure the tau lifetime on the relatively small sub-sample of tau pairs where both tau leptons decay into a 3-prong topology, like Belle did [3]. For these events, the two 3-prong vertices and the constraint of the very small luminous region precisely define the tau leptons' flight directions, significantly reducing systematics from Monte Carlo simulation of the effects of the undetected neutrinos on the reconstruction of the tau flight directions.

We consider as the baseline for extrapolating to the FCC sample the DELPHI tau lifetime measurement [4], which includes a measurement done on tau pairs both decaying to 3 charged tracks (3-3-prongs topology). The DELPHI measurement is performed on the 1991-1995 sample, corresponding to about $4.0{\cdot}10^{6}$ hadronic Z decays [5], hence about $N_{\mathrm{Z}}^{\mathrm{DELPHI\ 2004}} = 4.0{\cdot}10^{6}/70\% = 5.7{\cdot}10^{6}$ Z decays. The relative statistical uncertainty of the measurement restricted to the 3-3 prongs events is $\sigma(\tau_\tau, 3-3)/\tau_\tau \cdot 1{\cdot}10^{6}\,\mathrm{ppm} \simeq 18000\,\mathrm{ppm}$, where τ_τ is the tau lifetime 2024 world average. For the DELPHI measurement using 3-3 prongs tau decays, the relative statistical single-event uncertainty on the tau lifetime is determined to a good approximation by the sum in quadrature of two contributions with comparable size: 100% for the exponential decay time distribution, and the ratio between the vertex resolution in the transverse plane, mainly determined by the uncertainty on the reconstructed tracks' d_0 helix parameter, and the average signed tau impact parameter with respect to the beams axis, $\langle \hat{d}_0 \rangle \simeq 70\,\mu\mathrm{m}$, proportional to the tau mean lifetime. At FCC-ee(Z) we expect that the track d_0 resolution (and also the beam spot size in the transverse plane, which matters for other tau lifetime measurement methods) will be negligible with respect to $\langle \hat{d}_0 \rangle$. Accounting for that, and scaling the number of Z decays from DELPHI to FCC-ee, we estimate that the relative statistical uncertainty on the tau lifetime will be $\sigma(\tau_\tau, 3{-}3, \mathrm{FCC})/\tau_\tau \simeq 15.0\,\mathrm{ppm}$.

Three of the DELPHI 2004 quoted systematics contributions can be optimistically expected to scale down according to statistics (i.e., with the square root of the number of events): background subtraction (for which the simulation can be tuned with data control samples), reconstruction bias (which can be studied with data prompt events), and vertex alignment (done with data events). Regarding alignment, past studies [6] indicate that the measurement of the tau lifetime is unaffected at first order by the vertex detector alignment, and in particular from the length scale of the radial positions of the vertex detector sensitive elements, provided that the lifetime measurement relies on decay length measurements on the plane transverse to the beams, and there is uniform and complete azimuthal acceptance. Uniform azimuthal acceptance can also be obtained by weighting events. Assuming that the systematic uncertainties that can be studied with data samples will scale down according to the luminosity, their size will be reduced from 4500 ppm to 3.9 ppm for an FCC measurement. The remaining uncertainty related to the knowledge of the overall average absolute scale of the vertex detector sensitive elements can plausibly be improved from about 100 ppm at LEP to 5 ppm at FCC-ee using optical interferometry techniques [7, 8].

The center-of-mass energy will be known with a 1 ppm precision at FCC [9], contributing to an uncertainty of the same size. Also the tau mass relative uncertainty will contribute with a systematic contribution of the same size. We assume that the tau mass uncertainty will be reduced to 9 ppm by either a measurement at the tau pair production threshold by a Super Charm Tau factory. A tau mass measurement to 10 ppm appears to be possible also at FCC-ee(Z) by fitting the tau pseudo-mass distribution [1], further improving the techniques that have been recently used by Belle II [10].

The tau lifetime measurement also requires the estimation of the average radiated energy in the initial state before the tau pair production. The DELPHI measurement relies on a $\mathrm{e}^+\mathrm{e}^- \to \mathrm{Z} \to \tau^+\tau^-$ Monte Carlo simulation, whose estimated uncertainty contributes a 350 ppm systematic uncertainty. We optimistically speculate that an improvement of a factor 30 may be achieved, reducing the related uncertainty on the tau lifetime to 11.5 ppm at FCC.

Table 1 summarizes the expected FCC tau lifetime measurement uncertainty contributions, which sum up

[1] Document in development, content restricted as of 20 October 2024, will eventually become public.

Table 1: Tau lifetime uncertainties for a measurement using 3-prong tau vertices on a sample of tau pairs where both tau leptons decay with 3-prong topology, for the DELPHI 2004 measurement and as expected for a measurement at FCC-ee(Z) with $6{\cdot}10^{12}$ Z decays.

	DELPHI 2004 [fs]	DELPHI 2004 [ppm]	FCC-ee(Z) $6{\cdot}10^{12}$ Z [ppm]
statistical uncertainty	5.2	18000	15.0
luminosity-dependent systematics	1.3	4500	3.9
- background	0.2		
- reconstruction bias	0.8		
- vertex detector alignment	1.0		
luminosity-independent systematics			
- detector length scale	-	100	5.0
- average tau energy	-	-	1.0
- radiative energy loss	0.1	350	11.5
- tau mass	-	68	9.0
total systematics			15.9
total uncertainty			21.5

to 21.5 ppm.

2 References

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