Towards a measurement of the tau polarization at FCC-ee

Juan Alcaraz Maestre*, María Cepeda*, Dolores García†

* *CIEMAT,* † *CERN*

PLACEHOLDER: ECFA submission uploaded for now as the FCCNote is still in progress.

The FCC-ee promises to be a powerful platform for tau physics. The huge sample of Z $\rightarrow \tau\tau$ decays (10^{11} events) to be collected will enable precise measurements of the properties of the tau lepton and stringent tests of the Standard Model. Amongst them there is the measurement of the tau polarization. With negligible statistical uncertainty and a potentially very reduced systematic compared to LEP, the measurement of $\mathscr{A}_\tau$ and $\mathscr{A}_e$ are expected to reach uncertainties below 0.02%, and yield fantastic precision in the measurement of the couplings of the Z and fundamental SM parameters such as $\sin^2\theta_{eff}$. A full study of these properties requires the development of analyses with full simulation that exploit the potential of the future detectors. Tau measurements pose demanding detector requirements on momentum resolution, on the knowledge of the vertex detector dimensions, on e/μ/π separation over the whole momentum range, and require fine granularity and high efficiency in the tracker and electromagnetic calorimeter. A first implementation of tau reconstruction for FCC-ee using the CLD detector has been developed to be used as an example in the tau polarization measurement and serve as a basis for future detailed systematic studies for detector optimization.

The tau lepton is a particularly interesting particle for testing the electroweak sector of the Standard Model, thanks to its heavy mass and rich decay phenomenology. In high-energy e^+e^- colliders, tau pairs are produced through the process $e^+e^- \to Z/\gamma^* \to \tau^+\tau^-$. In the proposed Future Circular Collider (FCC-ee) Z pole run, the production cross-section of $\sigma(e^+e^- \to Z \to \tau^+\tau^-) = 1476.58\,\text{pb}^{-1}$ at $\sqrt{s} = 91.188\,\text{GeV}$ will yield an unprecedented $\tau^+\tau^-$ sample of approximately 10^{11} events, with the added bonus of precise momentum reconstruction capabilities and very low-background environment. Tau measurements pose demanding detector requirements on momentum resolution, on the knowledge of the vertex detector dimensions, on e/μ/π separation over the whole momentum range, and require fine granularity and high efficiency in the tracker and electromagnetic calorimeter. A comprehensive program of tau studies will be performed on this tau pair sample, aimed at achieving high-precision measurements including the measurement of the tau polarization and the extraction of fundamental electroweak properties through its study.

The tau polarization, $\mathscr{P}_\tau$, provides a sensitive probe of the couplings of the Z and the weak interaction. It can be measured through the angular distributions and energy spectra of the tau decay products. It can be expressed as $\mathscr{P}_\tau \equiv \frac{\sigma_+ - \sigma_-}{\sigma_+ + \sigma_-}$, where σ_+ and σ_- are the cross-sections for the production of left-handed and right-handed tau leptons, respectively. The polarization can be further expressed as a function of the two neutral current asymmetry parameters ($\mathscr{A}_e$ and $\mathscr{A}_\tau$), taking into account as well its dependence on the direction of the tau expressed as the angle between the tau momentum and the electron beam (θ) [1, 2]

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

Measuring $\mathscr{P}_\tau(cos\theta)$ yields nearly independent determinations of $\mathscr{A}_\tau$ and $\mathscr{A}_e$. Consequently, τ polarisation measurements provide not only a determination of $\sin^2\theta_{eff}$ but also test the hypothesis of the universality of the couplings of the Z to the electron and τ lepton. Integrating over $cos\theta$ we obtain $\mathscr{P}_\tau(total) = -\mathscr{A}_\tau$.

At LEP, $\mathscr{A}_\tau$ and $\mathscr{A}_e$ were measured to be $\mathscr{A}_\tau(\text{LEP}) = 14.39 \pm 0.35\,(\text{stat}) \pm 0.26\,(\text{syst})\%$ and $\mathscr{A}_e(\text{LEP}) = 14.98 \pm 0.48\,(\text{stat}) \pm 0.09\,(\text{syst})\%$ [1], dominated by the statistical uncertainties. The systematic uncertainty for $\mathscr{A}_\tau$ is found to be significantly larger than the $\mathscr{A}_e$ one: this is due to a cancellation of charge and $\cos\theta$-independent systematic uncertainties in the latter case, leading to a extremely precise measurement. The most sensitive results are obtained in the decay modes to pions ($\tau \to \pi\nu$) and rho ($\tau \to \rho\nu \to \pi\pi^0\nu$). Uncertainties varied largely between LEP experiments. This underlines the importance of the detector concept. A key aspect is having excellent performance in the reconstruction and identification of both charged particles and photons. At FCC-ee, the large data samples and the excellent performance in charged particle and photon identification promised by the future detectors will lead to much smaller uncertainties overall. Assuming a 10 improvement in systematics over the LEP measurements leads to an estimated systematic uncertainty for $\mathscr{A}_\tau$ that could be as good as 0.02%, and even lower for $\mathscr{A}_e$.

To go beyond this estimation, a full simulation study that starts by developing a tau reconstruction is necessary. We will focus on the reconstruction of τ leptons with full simulation of the CLD detector [3]. The results documented in this note should be understood as a proof of concept, that will be refined in the future. Tau identification relies on reconstructing charged hadrons and photons with precise energy resolution. Around 65% of tau decays are hadronic, primarily manifesting as one or three charged hadrons accompanied by photons coming from the decay of π^0. Effective identification of π^0s is key. For rare decays, discrimination between pions and kaons will also be relevant. A first algorithm for reconstructing hadronic tau decays at the FCC-ee has been developed based on PandoraPFA [4] candidates as input. This approach involves identifying tau candidates by clustering charged candidates (assumed pions) and nearby photons into tau lepton candidates. The identification process focuses on reconstructing the main decay modes of the tau: $\tau \to \pi\nu_\tau$: a single charged pion; $\tau \to \rho\nu_\tau$: involving $\pi^\pm$ and a π^0; $\tau \to a_1\nu_\tau$: with a_1 decaying into either $\pi^\pm 2\pi^0$ or $\pi^\pm\pi^\mp\pi^\pm$. The first two decay modes (π and ρ) are expected to provide the most sensitive measurements for the polarization study. Decays of the taus to light leptons are considered in the algorithm and removed, based on the identification of said light leptons by PandoraPFA. To address limitations in the PandoraPFA approach, a Graph Neural Network (GNN) method is being developed in parallel. The GNN takes as inputs the tracks and calorimeter clusters. This method aims to improve separation between similar decay modes, for example aiding in the distinction between merged photons and resolved diphotons.

A first study of tau polarization including optimal variables has been done with the PandoraPFA method. This first analysis is limited to Z $\to \tau\tau$ events in which one of the taus decays leptonically in one hemisphere and the other tau hadronically. This will be expanded in future iterations of the analysis to improve the coverage of the phase-space and to benefit from the determination of the tau direction possible in the case in which both taus decay hadronically [5]. Only tau backgrounds coming from category migration are considered in the analysis for now. The Monte Carlo samples used in the analysis have been generated in Pythia8.3 [6, 7]. In order to model the behaviour of samples with anomalous polarization a reweighting technique [8], based on the dependence of the polarization on the kinematics of the tau and in particular on the theta of the outgoing meson, is used. This approach can be validated with additional samples with specific settings for $\mathscr{P}_\tau = \pm 1$ generated in Pythia8.

Figure 1 shows the optimal variables for the study of the polarization after this very simple selection, for the three main configurations considered in the analysis: a single charged pion, a charged pion and a single (merged) photon, and a single pion and two resolved photons. The first mode is designed to select $\tau \to \pi\nu$ decays. In this case the optimal variable is directly the energy fraction $x_\pi = \frac{E_\pi}{E_{\text{beam}}}$. The later two categories correspond to the $\tau \to \rho\nu \to \pi\pi^0\nu$ channel with either one or both of the photons resulting from the π^0 decay reconstructed. Here the optimal observable in LEP was defined to be $\omega_\rho = \frac{W_+(\theta^*,\psi) - W_-(\theta^*,\psi)}{W_+(\theta^*,\psi) + W_-(\theta^*,\psi)}$, where W_+ and W_- represent the angular distributions of the ρ decay products for different helicity states, and θ^* and ψ are angles describing the decay products in the τ rest frame[9]. The reweighted $\mathscr{P}_\tau = \pm 1$ signal templates are shown in comparison to the SM prediction. Additionally, the backgrounds coming from tau misidentification are also shown. No other backgrounds are considered at this stage. Further studies of the full simulation samples and optimization of the reconstruction algorithm are in progress.

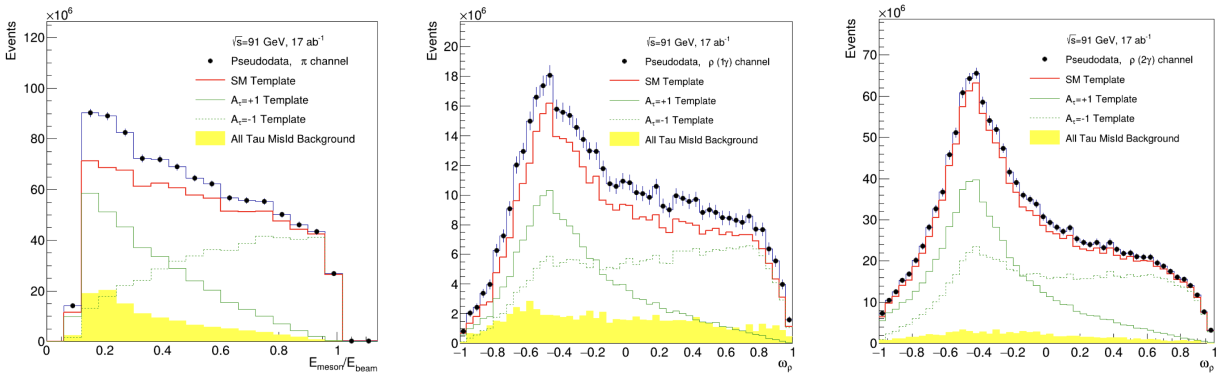

Figure 1: Optimal variables in the π (right), ρ with one identified photon, (middle) and ρ with two identified photons (right) decay modes

A comprehensive extraction of the polarization parameters requires an analysis of the data in multiple bins of $\cos\theta$. This binned analysis allows for a simultaneous determination of $\mathscr{A}_\tau$ and $\mathscr{A}_e$ and goes beyond this preliminar study. As a first step to gauge the potential uncertainties, we have performed a limited analysis that aims for $\mathscr{A}_\tau$, which can be extracted independently of $\cos\theta$. This has been done through a log-likelihood fit of the optimal variable in the ρ channel with two resolved photons. For a dataset corresponding to an integrated luminosity of $17\,\text{ab}^{-1}$, which corresponds to the data collected by only one FCC-ee experiment during a single year, the statistical uncertainty of the polarization asymmetry extracted with this very simple approach is found to be $\Delta\mathscr{A}_\tau \approx 0.007\%$. This corresponds to very small fraction of the full dataset available at FCC-ee: the final statistical uncertainty can be considered negligible even for the final analysis binned in terms of $\cos\theta$.

Future steps in the analysis will assess the impact of systematic variables on the optimal observables based on the performance of different detector configurations. Backgrounds will be expanded to include Bhabha scattering, particularly important for the $\mathscr{A}_e$ measurement.

1 References

[1] S. Schael et al., ALEPH, DELPHI, L3, OPAL, SLD, LEP Electroweak Working Group, SLD Electroweak Group, SLD Heavy Flavour Group, *Precision electroweak measurements on the Z resonance*,

Phys. Rept. **427** (2006) 257, DOI: 10.1016/j.physrep.2005.12.006, arXiv: hep-ex/0509008.

[2] P. H. Eberhard et al., *The tau polarization measurement at LEP* (1989), DOI: 10.5170/CERN-1989-008-V-1.235, URL: https://cds.cern.ch/record/201688.

[3] N. Bacchetta et al., *CLD – A Detector Concept for the FCC-ee* (2019), arXiv: 1911.12230 [physics.ins-det].

[4] M. Thomson, *Particle flow calorimetry and the PandoraPFA algorithm*, Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment **611** (2009) 25, ISSN: 0168-9002, DOI: https://doi.org/10.1016/j.nima.2009.09.009, URL: https://www.sciencedirect.com/science/article/pii/S0168900209017264.

[5] A. Heister et al., ALEPH, *Measurement of the tau polarization at LEP*, Eur. Phys. J. C **20** (2001) 401, DOI: 10.1007/s100520100689, arXiv: hep-ex/0104038.

[6] C. Bierlich et al., *A comprehensive guide to the physics and usage of PYTHIA 8.3*, SciPost Phys. Codeb. **2022** (2022) 8, DOI: 10.21468/SciPostPhysCodeb.8, arXiv: 2203.11601 [hep-ph].

[7] P. Ilten, *Tau Decays in Pythia 8*, Nucl. Phys. B Proc. Suppl. **253-255** (2014), ed. by K. Hayasaka, T. Iijima 77, DOI: 10.1016/j.nuclphysbps.2014.09.019, arXiv: 1211.6730 [hep-ph].

[8] J. Alcaraz, *Tau physics at LEP*, Proceedings of the 22nd International Winter Meeting on Fundamental Interactions (1994), URL: https://cds.cern.ch/record/293383.

[9] I. Nikolic, *La mesure de la polarisation du lepton τ dans l'expérience ALEPH en utilisant la direction du τ*, PhD thesis, Paris 11, 1996.