Tau Polarization Study

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Abstract

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 $\mathcal{A}_\tau$ and $\mathcal{A}_e$ 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.

1 Introduction

The tau lepton is an essential particle for testing the electroweak sector of the Standard Model due to its heavy mass and rich decay phenomenology. One of the most important experimental measurements of its properties to be performed in future $e+e-$ machines will be its polarization as it provides a sensitive probe of the weak interaction.

In high-energy e^+e^- colliders, tau pairs are produced through the process $e^+e^- \rightarrow Z/\gamma^* \rightarrow \tau^+\tau^-$. The proposed Future Circular Collider (FCC-ee) has the potential to act as a tau factory. In the Z pole run, given the production cross-section of $\sigma(e^+e^- \rightarrow Z \rightarrow \tau^+\tau^-) = 1476.58$ pb at $\sqrt{s} = 91.188$ GeV, we can expect to obtain 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, $\mathcal{P}_\tau$, 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: $\mathcal{P}_\tau \equiv \frac{\sigma_+ - \sigma_-}{\sigma_+ + \sigma_-}$, 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 ($\mathcal{A}_e$ and $\mathcal{A}_\tau$), 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_τ) [1, 2],

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

Measuring $\mathcal{P}_\tau(cos\theta_\tau)$ yields nearly independent determinations of $\mathcal{A}_\tau$ and $\mathcal{A}_e$. Consequently, τ polarization 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.

At LEP, $\mathcal{A}_\tau$ and $\mathcal{A}_e$ were measured to be $\mathcal{A}_\tau(\mathrm{LEP}) = 14.39 \pm 0.35\,(\mathrm{stat}) \pm 0.26\,(\mathrm{syst})\%$ and $\mathcal{A}_e(\mathrm{LEP}) = 14.98 \pm 0.48\,(\mathrm{stat}) \pm 0.09\,(\mathrm{syst})\%$ [1], dominated by the statistical uncertainties. The systematic uncertainty for $\mathcal{A}_\tau$ is found to be significantly larger than the $\mathcal{A}_e$ 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 factor of 10 improvement in systematics over the LEP measurements leads to an estimated absolute systematic uncertainty for $\mathcal{A}_\tau$ of less than 2×10^{-4}, and even lower for $\mathcal{A}_e$.

To go beyond this estimation, a full simulation study that starts by developing a tau reconstruction is necessary. In this note we explore the measurement of $\mathcal{A}_\tau$ using the FCCee detector and full simulation of the CLD detector [3]. We discuss reconstruction algorithms for τ leptons, starting by a simple approach based on clustering of particle flow candidates identified using the PandoraPFA algorithm [4]. The Monte Carlo samples used have been generated in Pythia 8.3 [5, 6]. This is a first exploration of the measurement. The results documented in this note should be understood as a proof of concept, that will be refined in the future.

2 Reconstruction of tau leptons

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. Hadronic tau decays can be effectively distinguished from other hadronic processes thanks to their low charge multiplicity and the fact that the jet invariant mass is smaller than the tau mass. Identification primarily depends on the precise reconstruction of charged hadrons and photons, along with accurate momentum resolution and efficiency to minimize misidentification. A particularly important aspect is the identification of neutral pions (π^0) from pairs of photons. This requires efficient photon identification and reconstruction, both for 'resolved' (two identified reconstructed photons) and for 'merged' (a single reconstructed photon resulting from two very close by true photons) cases. Several kinematic variables aid in background reduction, including missing mass, acollinearity, lepton momentum, and lepton vetoes for suppressing dilepton and diphoton events, as well as missing transverse momentum (p_T) considerations in diphoton backgrounds. Finally, though not addressed in this first reconstruction attempt, distinguishing pions from kaons will be essential for identifying rare decays.

Several strategies are currently being explored for reconstructing hadronic tau decays at the FCC-ee. The study presented in this note is based on a traditional approach that relies on particle flow techniques and exclusive identification of main decay modes by analyzing charged pion and photon multiplicities within a narrow cone. In parallel, machine learning-based methods are also under development, including Particle Transformer models built on top of particle flow (PandoraPFA) inputs and also a Graph Neural Network (GNN) approach designed to address the limitations of PandoraPFA [7]. The GNN method uses tracks and calorimeter clusters as inputs, offering improved separation between similar decay modes, particularly in distinguishing merged photons from resolved diphotons.

Each approach has its own strengths and weaknesses, making them complementary and providing a flexible foundation to support the needs of any future FCC-ee tau analysis, from precision measurements in the Z pole to more statistically-challenged measurements and searches. For polarization studies, the primary focus is on identifying specific decay modes while maintaining control over systematic uncertainties. In this context, the traditional method provides a robust foundation for a first analysis, which should lead to an easier understanding of how different detector-related uncertainties impact the measurement. Future iterations of this work will perform a comprehensive comparison between these different reconstruction techniques, to incorporate the improved efficiency and decay mode discrimination of the ML techniques.

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.

The reconstruction targets different hadronic tau decay modes based on the sum of four-momenta of charged particles and photons present in a cone of $\Delta R = \sqrt{\Delta\phi^2 + \Delta\theta}$ around a tau seed. The momentum of the candidates and the angle can be configured to obtain optimal efficiency and background rejection. The algorithm only allows combinations of candidates compatible with a tau decay, by charge (± 1) and decay configuration.

The different decay modes considered are labeled using an identification flag which accounts for the number of pions and photons in the tau candidate:

- $\tau \to \pi\nu_\tau$ (π channel). Characterized by the presence of a single identified pion in the cone.
- $\tau \to \rho\nu_\tau$, with $\rho \to \pi\pi^0$ (ρ channel). Characterized by the presence of a charged pion and one or two photons, which yields two distinct categories.
- $\tau \to \pi\pi^0\pi^0\nu_\tau$ (a_1 channel with one charged track). Characterized by the presence of a charged pion and more than two photons.
- $\tau \to a_1\nu_\tau$ with $a_1 \to \pi^\pm\pi^\mp\pi^\pm$ (a_1 channel with three charged tracks). Characterized by the presence of three charged pions.
- $\tau \to \pi^\pm\pi^\mp\pi^\pm\pi^0\nu_\tau$. (Three charged tracks plus π^0). Characterized by the presence of three charged pions accompanied by photons.

In a preliminary tuning of the reconstruction parameters, the tau cone is chosen to be $\Delta R = 0.4$, the minimum momentum for pf candidates in the clustering is set to be $p > 1$ for charged particles and $p > 0.1$ for photons, and the minimum reconstructed tau momentum is set to be 5 . A protection is added against additional neutral hadrons that could result from misidentification in PandoraPFA. Events with a single charged pion and additional neutral hadrons with $p > 1$ in the tau cone are excluded from the analysis.

In order to study the performance of the reconstruction technique, a similar categorization is done at generator level, identifying the tau decay mode and reconstructing the visible tau decay information from the generator level products of the tau, excluding the neutrinos. The polarization study will focus mainly on the first two cases: $\tau \to \pi\nu_\tau$ (π channel) and $\tau \to \rho\nu_\tau$, with $\rho \to \pi\pi^0$ (ρ channel).

Figure 1 shows the reconstruction efficiency as a function of the visible tau momentum at generator level and the tau θ for the main decay modes. An overall reconstruction efficiency of 80% is observed. This efficiency is higher for decay modes with only one track (π, ρ) and decreases for the decay modes with multiple tracks. This loss of efficiency is driven by the performance in the PandoraPFA identification workflow for this version of CLD full simulation for FCC-ee, which has a preliminary tuning. The lower-than-expected charged pion identification efficiency, 90%, is paired with a 10% misidentification rate of charged pions as neutral hadrons. A similar effect also with PandoraPFA was reported in Ref. [8]. In the $a_1 \to \pi^\pm\pi^\mp\pi^\pm$ case, this leads to a significant fraction of reconstructed candidates with only one or two charged hadrons accompanied by neutral hadrons.

Figure 2 shows the reconstructed mass of the tau candidate at reconstructed level, which corresponds to the masses of the intermediate meson in the decay. The masses of the ρ, a_1 are clearly reconstructed. Note that no distinction is made between kaons and pions in this version of the algorithm: decay modes with kaons are assimilated to their pion counterparts. The classification for this plot is done at the generator level, based on the true decay of the tau lepton. This explains the presence of a peak at the pion mass, corresponding to misidentification (migration) of ρ and a_1 as pions when no photons are identified.

Table 1 shows the probability of identifying the correct hadronic decay mode once the tau is reconstructed in the form of a migration matrix. In the case of the ρ note the split between events with a single reconstructed photon and events with two reconstructed photons, and the presence of events with three photons. Further identification criteria on the mass of the π^0 could be applied to reduce the migration from a_1 decays to ρ. The impact of the presence of neutral hadrons and the loss of charged hadrons in the identification of a_1 ($\pi^\pm\pi^\mp\pi^\pm$) is also shown in dedicated columns. Migration from decays with three charged pions to decays with only one charged pion are highly suppressed by the mentioned neutral hadron veto. It is important to stress that this performance results reflect the current status of reconstruction achievable with out-of-the-box CLD reconstruction and with this very simple reconstruction algorithm, and will improve in the future.

	h	h+γ	h+2γ	h+3γ	h+>4γ	3h	3h+> 1γ	h+n	2h	2h+n
$\pi^\pm$	0.78	0.05	0.01	0.00	0.02	0.00	0.00	0.15	0.00	0.00
ρ ($\pi^\pm\pi^0$)	0.01	0.13	0.65	0.09	0.03	0.00	0.00	0.08	0.01	0.00
a_1 ($\pi^\pm 2\pi^0$)	0.00	0.01	0.04	0.22	0.60	0.00	0.00	0.09	0.02	0.00
a_1 ($\pi^\pm\pi^\mp\pi^\pm$)	0.01	0.00	0.00	0.00	0.00	0.50	0.08	0.12	0.11	0.18
a_1 ($\pi^\pm\pi^\mp\pi^\pm\pi^0$)	0.00	0.00	0.01	0.00	0.00	0.00	0.54	0.14	0.12	0.18

Table 1: Migration matrix. Each row corresponds to a generator-level tau decay, and each column to a reconstructed mode at the detector level. 'h' stands for 'charged hadron'. Cases with one track and at least four photons are combined in one column, as are cases with at three tracks and at least one photons. Tau candidates in which clusters of neutral hadrons is found alongside the charged pions are distinguished in columns 'h+n' and '2h+n'.

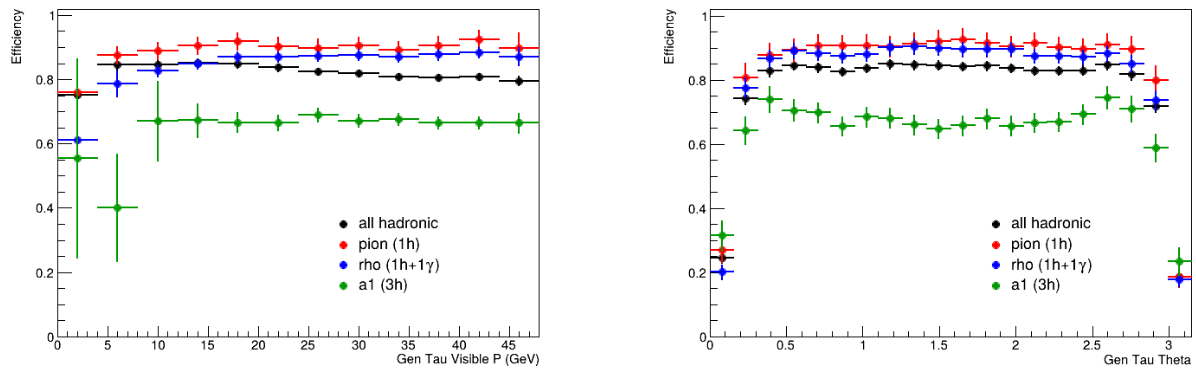

Figure 1: Reconstruction efficiency as a function of the visible tau momentum and the tau direction θ_τ for the different tau decay modes.

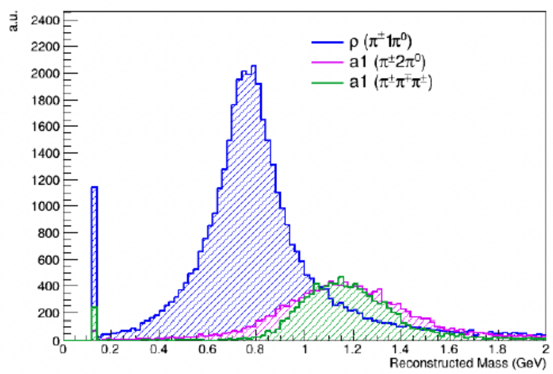

Figure 2: Reconstructed meson mass distribution for different true generator-level tau decay modes. The ρ resonance ($\pi^{\pm}\pi^{0}$) is shown in blue, the a_1 resonance with one charged pion and two neutral pions ($\pi^{\pm}2\pi^{0}$) in magenta, and the a_1 resonance with three charged pions ($\pi^{\pm}\pi^{\mp}\pi^{\pm}$) in green. In the lower end of the distribution a narrow peak at the π mass corresponds to migration from ρ and a_1 to a single pion when no photons or additional charged pions are identified.

Overall, while the performance is still not optimal, the results for the pion and rho channels are sufficient to be exercised in an analysis. We find good energy resolution and reasonable decay mode identification. In this consideration it is important to remark that polarization study will not be limited by statistics: the key challenge lies in the accurate identification of photons. For this reason, we have carried on with this reconstruction for this first version of the analysis.

3 Analysis Strategy

3.1 Selection of $\mathrm{Z} \to \tau\tau$ events

This study aims to exercise the tau reconstruction algorithms developed in the previous section in an analysis, using a Monte Carlo sample generated with Pythia 8.3 [5] using the CLD detector. The analysis therefore employs the PandoraPFA-based exclusive decay mode finding algorithm, with future comparisons planned against machine-learning-based approaches. The Monte Carlo dataset utilized consists of 7.7 million $Z \to \tau\tau$ events, or an approximated equivalent luminosity of $5.20\,\mathrm{fb}^{-1}$. This is significantly smaller than the expected real data sample. The lack of Monte Carlo statistics is the major limitation of the current analysis, and will be addressed in future iterations. Further improvements also contemplate using more specialized generators like KKMC [9].

For this first iteration of the analysis, we focus on $Z \to \tau\tau$ events where one tau decays leptonically (yielding a muon or electron) and the other hadronically. This approach allows the polarization study to be conducted using a single reconstructed tau. 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 [10].

A simple selection requiring one light lepton (muon or electron) with $p > 10$ GeV is done. The hadronic tau candidate is required to have a momentum $p > 5$ (2) GeV in the pion (rho) channel and $|\cos\theta| < 0.90$. At this stage no further $Z \to \tau\tau$ selection criteria are required, since only true tau backgrounds coming from category migration within true tau decays are considered in the analysis. Further refinements and background suppression techniques will be explored in future iterations.

The analysis targets the two main decay modes: pion and rho channels. In the rho channel, special attention is given to the reconstruction of π^0, with categories split between merged photons and two resolved photons. The backgrounds are mainly driven by photon and pion misidentification, with potential contamination of the pion channel from rho decays and vice versa in the rho channel with two resolved leptons.

3.2 Modeling of polarization samples

The MC samples used in the analysis have been generated in Pythia 8.3 [5], which implements a 'Sophisticated Tau Decay' [6] method that allows to describe the decay of tau leptons. The main MC sample used is a Standard Model sample.

In order to model the behavior of samples with anomalous polarization two approaches can be used: the generation of additional samples with specific settings for $\mathcal{P} = \pm 1$ or the reweighting of the original Pythia sample [11], based on the dependence of the polarization on the kinematics of the tau and in particular on the theta of the outgoing meson. This approach can be validated with additional samples with specific settings for $\mathcal{P}_\tau = \pm 1$.

The simplest implementation of this event-by-event reweighting is $w = \frac{1+\alpha_R \mathcal{P}_{new} z}{1+\alpha_R \mathcal{P}_\tau z}$, where $z = \cos\theta_{\mathrm{meson}}$ and α_R is a constant that depends on the decay. This is sufficient for the pion case, with $\alpha_R = 1$. In the case of ρ decays a more complicated reweighting that also takes into account the kinematics and angular variables described above is used, as described in Ref. [2].

3.3 Optimal observables

An important part of the polarization analysis is the choice of optimal observable or polarimeter. The simplest observable that can be used for this polarization analysis is the fraction of the total tau energy energy carried by the visible tau, or $x = E_{\tau_{vis}}/E_\tau = E_{Meson}/E_{beam}$. For the simplest case, the decay to a single charged pion and a neutrino, this observable gives already good separation between polarization modes.

For more complicated decays involving intermediate mesons more complex variables should be used, as done in LEP [1, 10, 12, 13]. See also [14, 8] for an ILC study. The optimal observable for ρ 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.

For a proper reconstruction of this polarization observables an estimation of the true tau direction is needed. As a first approach the meson direction is used as a proxy. We have used the implementation of the variable in terms of masses and angles described in Ref.[13]:

$$\omega_\rho = \frac{\left(-2+\frac{m_\tau^2}{Q^2}+2\left(1+\frac{m_\tau^2}{Q^2}\right)\frac{3\cos\psi-1}{2}\frac{3\cos^2\beta-1}{2}\right)\cos\theta+3\sqrt{\frac{m_\tau^2}{Q^2}}\frac{3\cos^2\beta-1}{2}\sin 2\psi\sin\theta}{2+\frac{m_\tau^2}{Q^2}-2\left(1-\frac{m_\tau^2}{Q^2}\right)\frac{3\cos\psi-1}{2}\frac{3\cos^2\beta-1}{2}}. \qquad (2)$$

Here $x = 2\frac{E_h}{\sqrt{s}}$, $s = 4E_{beam}^2$, Q is the meson resonance, β is the disintegration angle for the ρ in the ρ rest frame, and the expressions of the θ and ψ angles can be approximated in the case in which the tau direction is not known [13] :

$$\cos\theta = \frac{2xm_\tau^2 - m_\tau^2 - m_h^2}{(m_\tau^2 - m_h^2)\left(\sqrt{1-4m_\tau^2/s}\right)} \quad \text{and} \quad \cos\psi = \frac{x(m_\tau^2+Q^2)-2Q^2}{(m_\tau^2-Q^2)\sqrt{x^2-4Q^2/s}}$$

Figure 3 compares generator level variables for the ρ channel (with the true tau direction) and their corresponding reconstructed variables (with approximated tau direction). Reasonable agreement is found in all cases, with the worst performance seen for cosθ.

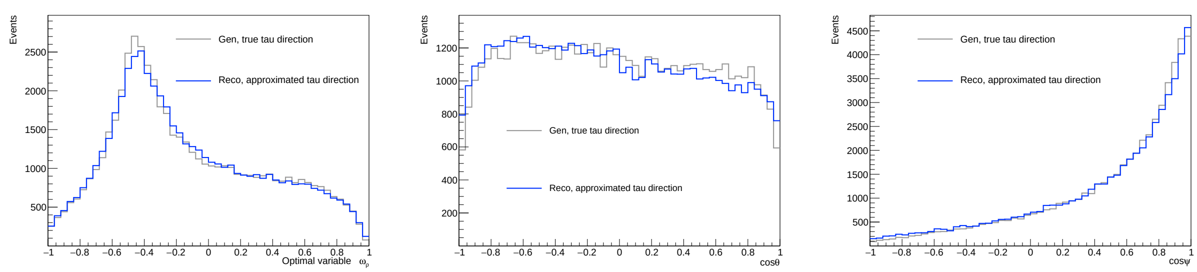

Figure 3: Comparison between generator and reconstructed observables for the ρ decay channel. Generator-level observables use the true tau direction, while reconstructed observables approximate the direction of the tau based on the meson direction. See text for details.

3.4 Backgrounds

Figure 4 shows the optimal variables for the study of the polarization after this very simple selection and for the very reduced dataset (5.20 fb^{-1}, 7675000 Z $\rightarrow \tau\tau$ events) used in analysis. for the three main configurations considered in the analysis: a single charged pion, a charged pion and a single photon, and a single pion and two resolved photons. The first mode is designed to select $\tau \rightarrow \pi\nu$ decays. In this case the optimal variable is directly the energy fraction $x_\pi = \frac{E_\pi}{E_{\text{beam}}}$, and tau candidates are required to have a minimum momentum of $p_\pi > 5$ GeV. The later cases correspond to the $\tau \rightarrow \rho\nu \rightarrow \pi\pi^0\nu$ channel with either one or both of the photons resulting from the π^0 decay reconstructed, and the optimal variable depicted is ω_ρ. This yields two distinct categories, for which tau candidates are reconstructed down to of $p_\rho > 2$ GeV. The reweighted $\mathcal{P}_\tau = \pm 1$ signal templates are shown in comparison to the SM prediction. Backgrounds coming from tau misidentification in this $Z \rightarrow \tau\tau$ sample, from migration between categories, are also shown in the figure.

The main background background contribution in the pion channel are decays to ρ in which the photons are not identified. This background could be reduced with further studies on the photon

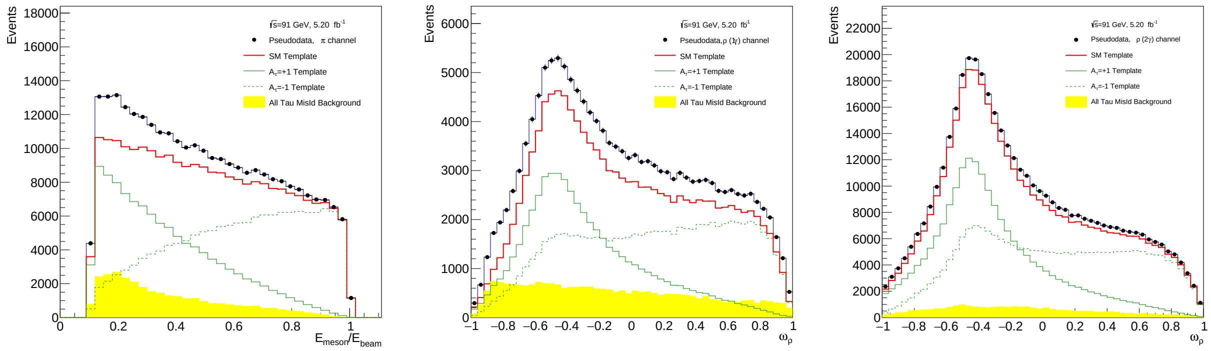

Figure 4: Optimal variables in the π (left), ρ with one identified photon, (middle) and ρ with two identified photons (right) decay modes

veto. In the case of the ρ channel, the main backgrounds are coming from $\tau \to \pi\nu$ decays in which a photon not corresponding to the decay, for example arising from FSR, is found, or from $\tau \to \pi^{\pm}\pi^0\pi^0$ decays in which some of the photons are not identified. This underlines the importance of photon and π^0 identification and the need for a dedicated systematic uncertainty study, which has been left for future work. Cases in which tau decays to electrons are misidentified as pions are also observed. Further backgrounds coming from other tau decays are also present at a smaller rate than the mentioned π, ρ and electron cross-contamination.

The cleanest category is the ρ decay with two identified photons, which boasts an excellent signal/background ratio when we consider only tau decays as contamination. Efforts are ongoing to incorporate other backgrounds, in particular bhabha scattering.

4 Extraction of $\mathcal{A}_\tau$ and $\mathcal{A}_e$

A simple log-likelihood fit to the optimal variable polarization templates can be performed to simulate the extraction of the polarization assymetries The ρ channel with two resolved photons, described by the optimal variable shown in Fig. 4 (right) for the full $\cos\theta_\tau$ phase-space, has been used as an example for this fit procedure.

As a first step, we performed a first version of this fit that aimed only at $\mathcal{A}_\tau$, since it can be extracted independently of $\cos\theta$. The analysis has been performed on a very limited MC dataset, corresponding to 5.20 fb^{-1}. Extrapolating to a dataset corresponding to an integrated luminosity of 17 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 $\Delta\mathcal{A}_\tau \approx 7 \times 10^{-5}$. This still corresponds to very small fraction of the full dataset available at FCC-ee, and of the phase-space ($\text{Z} \to \tau_l\tau_h$, $\tau_h \to \rho\nu$). The final statistical uncertainty can be considered negligible.

A comprehensive extraction of the polarization parameters requires an analysis of the data in multiple bins of $\cos\theta_\tau$. The direction of the tau can be approximated to the direction of the reconstructed messon, shown in Fig. 5 (left). The phase-space can be divided in bins of $\cos\theta_\tau$, so that log-likelihood fits to the optimal variable ω_ρ as the one described above can be performed in each bin. This yields a measurement of $\mathcal{P}_\tau\,(cos\theta_\tau)$ that can be used to simultaneously extract $\mathcal{A}_\tau$ and $\mathcal{A}_e$ in a subsequent likelihood fit (see equation (1)).

Figure 5 (right) shows this dependence of the polarization on the direction of the tau expressed as θ_{meson}, for the very reduced MC statistics available (5.20 fb^{-1}). The asymmetry values extracted in this fit correspond to $\mathcal{A}_\tau = 14.96 \pm 0.40\%$ and $\mathcal{A}_e = 14.94 \pm 0.54\%$, showing good closure with the theoretical prediction used as input to model the templates (14.955%). Extrapolating to a 17 ab^{-1} dataset, $\mathcal{A}_\tau$ and $\mathcal{A}_e$ can be extracted in this ρ channel with statistical uncertainties lower than $\Delta\mathcal{A}_\tau \approx 7 \times 10^{-5}$ and $\Delta\mathcal{A}_e \approx 9 \times 10^{-5}$. As a reminder, even this larger dataset is a small fraction of the expected FCC-ee Z statistics.

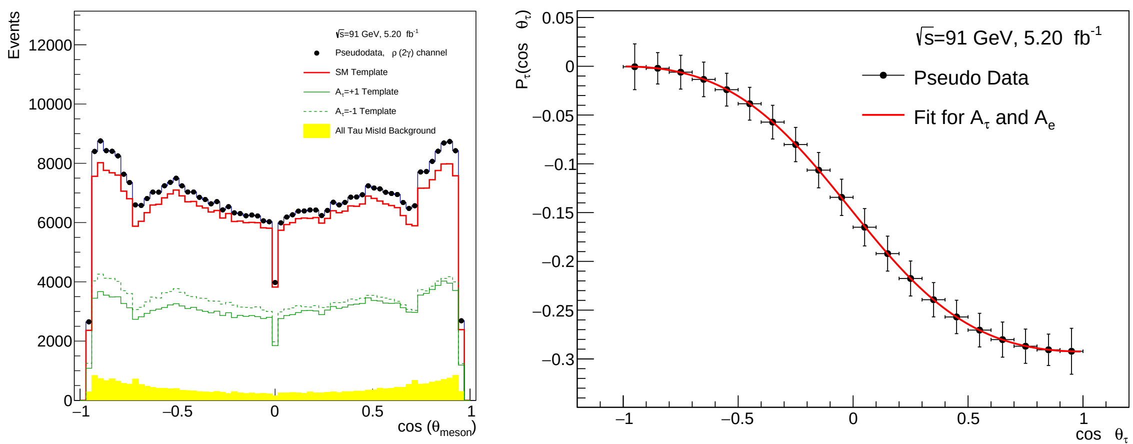

Figure 5: Left: Distribution of the $\cos\theta_\tau$ variable in the ρ channel with two resolved photons. The direction of the tau is approximated to the direction of the observed meson. Right: Dependence of the tau polarization $\mathcal{P}_\tau$ on the $\cos\theta_\tau$ in the ρ channel with two resolved photons. The direction of the tau is approximated to the direction of the observed meson. The distribution is fitted to extract the values of $\mathcal{A}_\tau$ and $\mathcal{A}_e$.

5 Systematic uncertainties

The next step in this prospective study will be an evaluation of the systematic uncertainties. Looking once again at the LEP results as reference [1], we see that systematic uncertainties in tau polarization measurements varied significantly across experiments. This emphasizes the role of detector performance, and the usefulness of tau studies in future detector design. Using the results from ALEPH [10] as a base, we see that the dominant systematic contributions come from π^0 and photon reconstruction, misidentification of leptons as hadrons, and modeling of non-tau backgrounds. Excellent photon identification and low-momentum charged track reconstruction are necessary.

The systematic uncertainty breakdown is different for the measurements of $\mathcal{A}_\tau$ and $\mathcal{A}_e$. For $\mathcal{A}_\tau$ the systematic uncertainties are larger, particularly in the dominant pion and ρ decay channels ($\Delta\mathcal{A}_\tau = 2.6 \times 10^{-3}$ in the experiment combination [1]). These are driven by contributions including hadron identification, lepton misidentification, π^0 and photon reconstruction, and non-tau backgrounds. In contrast, the total systematic uncertainties for $\mathcal{A}_e$ in the same channels are significantly smaller ($\Delta\mathcal{A}_e = 9 \times 10^{-4}$ in the combination [1]), due to a cancellation of detector-related effects in the calculation (see equation (1)). Only the effect of non-tau backgrounds remains relevant. The study of these backgrounds is currently underway, and will be taken into account in future versions of this work, along with improvements in the identification of photons and π^0.

Overall, the FCC-ee offers the opportunity to reduce these uncertainties significantly thanks to the much larger data samples and advanced detector technologies. Even under conservative assumptions, systematic uncertainties on $\mathcal{A}_\tau$ and $\mathcal{A}_e$ could be reduced by a factor of four compared to LEP, reaching levels below 1×10^{-3} and 2×10^{-4}, respectively. In a more optimistic scenario an order of magnitude improvement can potentially be achieved. This would bring even the $\mathcal{A}_\tau$ absolute systematic uncertainty below 2×10^{-4}.

6 Conclusions

We have presented a first step toward measuring the tau lepton polarization at the FCC-ee using a full detector simulation for the CLD detector. The study focuses on the two most sensitive tau hadronic decay modes, $\tau \to \pi\nu$ and $\tau \to \rho\nu \to \pi\pi^0\nu$, which offer excellent potential for precise polarization measurements due to their simple final-state topologies and clean angular correlations.

A simple tau reconstruction algorithm based on PandoraPFA was developed. The decay mode classification performance, while not yet optimal, demonstrates sufficient quality for initial studies in the two decay modes. Using these reconstruction tools, we applied a basic $\mathrm{Z} \to \tau\tau$ selection and extracted polarization-sensitive variables: the energy fraction $x = E_{\tau_{vis}}/E_{beam}$ for the pion channel, and an optimal variable based on LEP studies for the rho channel.

A first extraction of the polarization asymmetries $\mathcal{A}_\tau$ and $\mathcal{A}_e$ was performed using a template fit approach to the angular dependence of the polarization $\mathcal{P}_\tau(\cos\theta_\tau)$. The analysis was exercised in the ρ channel yields, and yields a projected statistical uncertainty at the order of $\Delta\mathcal{A}_\tau \approx 7 \times 10^{-5}$ and $\Delta\mathcal{A}_\tau \approx 9 \times 10^{-5}$ when extrapolated to 17 ab^{-1}. Note that this is a much smaller sample than the full FCCee Z pole statistics. Only tau backgrounds coming from misassignation of decay categories, particularly due to π^0 identification from reconstructed photons, have been considered at this stage.

The large data samples and excellent performance in charged particle and photon identification promised by the future FCC-ee detectors will lead to a significant reduction of systematic uncertainties with respect to the LEP measurements, which could be as large as an order of magnitude. This implies absolute systematic uncertainties for $\mathcal{A}_\tau$ below 2×10^{-4}, and even lower for $\mathcal{A}_e$.

The current study is limited by the small Monte Carlo dataset used, the simple approach to tau identification, and the preliminary stage of the full simulation of the future detector. These results need to be understood as a proof of concept. Future work will focus on assessing systematic uncertainties, improving π^0 identification, and extending the analysis to cover the full range of $\mathrm{Z} \to \tau\tau$ final states. Further tau reconstruction studies, including both traditional and machine learning-based algorithms, will be pursued, with the goal of using tau reconstruction as a benchmark in the comparison of different detector configurations. Backgrounds will be expanded to include Bhabha scattering, particularly important for the $\mathcal{A}_e$ measurement. These developments will be essential for fully exploiting the unprecedented tau dataset expected at the FCC-ee and achieving permil-level or better precision in electroweak coupling measurements.

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