Study of CP Violation in $h \to \tau^+\tau^-$ at Future Lepton Collider

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We evaluate the prospects for a measurement of the CP phase in $h \to \tau^+\tau^-$ at a future e^+e^- collider. Previous studies have not considered detector effects and deemed them as negligible. We investigate how these effects affect the feasibility such a measurement. They are found to have important repercussions, and the accuracy of this measurement is severely limited.

Contents

I. INTRODUCTION

Since the discovery of the Higgs boson in summer of 2012 by part of the CMS and ATLAS collaborations at CERN [2], it has been a topic of interest to check whether the discovered Higgs boson agrees in every aspect with the predictions made by the Standard Model (SM) of particle physics. Of particular importance, is the study of the couplings of the Higgs to other SM particles. The strengths of the couplings have been found to agree with predictions, as measured branching ratios agree with theory. A stronger test for the SM is the measurement of the CP phase in the couplings of the Higgs. It is predicted to have purely scalar couplings to all bosons and fermions. In fact, the purely pseudo-scalar coupling to electroweak gauge bosons has been excluded at 99.9% confidence level at ATLAS [3] and at 99.84% (need to check this number) at CMS [4]. The CP-mixing parameter $\tilde{d}$ was also constrained to the interval $[-0.11, 0.05]$ at 68% confidence level by ATLAS [5].

In this study we focus on a possible measurement of the CP phase in the coupling of the Higgs to taus. The most general form of the Lagrangian density from this coupling is

$$\mathcal{L}_{h-\tau\tau} = -\frac{y_\tau}{\sqrt{2}} h\bar{\tau}(\cos\Delta + i\gamma_5 \sin\Delta)\tau, \tag{1.1}$$

where y_τ is a parameter fixing the strength of the coupling, and Δ is the mixing angle of scalar and pseudo-scalar contributions, with $\Delta = 0$ corresponding to a purely scalar coupling and $\Delta = \pi/2$ to a purely pseudo-scalar one. Although current measurements disfavor a purely pseudo-scalar coupling, new physics in the TeV scale could result in a small pseudo-scalar contribution that is larger than in couplings to gauge bosons[6]. In this study we focus on the Θ-variable proposed by Harnik et al. in Ref. [6]. This variable makes use of the spin correlations of the taus in the $h \to \tau^+\tau^-$ decays to extract information about the CP phase of the coupling. It has been shown that this variable offers far greater discrimination power from other previously proposed variables, such as those in Refs. [7, 8]. Thus, this variable lets us probe for a smaller pseudo-scalar component in the coupling. This method, however, is not optimal for use in a hadron collider. Due to the lack of precise information about the collision and the information loss due to neutrinos escaping the detector one must resort to using collinear approximations, which highly degrade the performance of this observable. Hence, we will focus on future lepton colliders such as the International Linear Collider (ILC) [9] and FCC-ee (formerly known as TLEP), the proposed successor to the LHC [10].

In this paper we examine how this observable would work in a realistic detector environment considering detector resolution and inefficiencies not considered in previous studies. We first present how we generated our Monte Carlo samples and how we simulated detector effects. We then proceed to explain the event selection used and the statistical method used to determine the CP-phase value. Finally, we present our results and conclusions.

II. EVENT GENERATION AND SIMULATION

The generation of signal and background events and the calculation of leading order (LO) cross sections were done using MadGraph 5 [11]. The parton showering and hadronization was done using Pythia 8 [12]. And the detector simulation was done using Delphes 3 [13]. We used the Delphes card for the International Linear Detector (ILD), which is based on the expected performance presented in the Technical proposal for the ILD [9]. Although the performance of the detector is not carefully modeled, this is used to investigate how an imperfect detector impacts the usefulness of the observable. In the previous study [6], the detector effects were deemed negligible and it was assumed that charged and neutral pions could easily be identified. Here we check whether this is the case.

We produce Zh samples with a CP-phase of $n\pi/12$ with $n = 0, 1, 2, \cdots, 11$. We also consider the main backgrounds, which are ZZ, Zll, jj and Drell-Yan.

III. CANDIDATE SELECTION

We begin by looking for jets with $p_T > 20$ GeV reconstructed using the anti-k_T algorithm [14] with a distance parameter of 0.4. For each jet we take the leading track lying within a distance of 0.2 of the jet axis. We require this track to have $p_T > 0.5$ GeV and the remaining tracks in the jet to have in total $|\vec{p}_{\text{total}}| < 5$ GeV. This ensures that the jet is consistent with a 1-prong decay from a τ. We then pick the two leading photons in the jet. We require each of them to have $p_T > 0.5$ GeV. The remaining photons in the jet are required to have a total of $|\vec{p}_{\text{total}}| < 5$ GeV. This ensures that there was only one neutral pion in the tau decay. The jets that pass these requirement are taken as τ-candidates. Events are then required to have two τ-candidates with their corresponding selected tracks having opposite charges. If there are more than two candidates we take the ones with the highest track p_T.

Since we must also reconstruct the associated Z boson, we require the events to have either two isolated leptons with $p_T > 10$ GeV, or two additional jets with $p_T > 20$ GeV. Since the reconstruction using leptons is far superior than using jets, we divide the events into those with leptonically and hadronically decaying Z's. As we will show below, the observable of interest is highly sensitive on the reconstruction of the Higgs, and therefore of the Z, which renders the hadronic Z events impractical. For this reason, here we only consider leptonic Z events. As a last check, we require that the reconstructed mass of the Z and its recoil mass satisfy $|m_{ll} - M_Z| < 5$ GeV and $|m_{\text{Recoil}} - M_h| < 5$ GeV.

IV. STATISTICAL METHOD

The observable of interest is described in detail in Ref. [6], here we recall the main features. An "electric field" is defined as

$$\vec{E}_\pm = p^0_{\tau^\pm} \vec{k}_\pm - k^0_\pm \vec{p}_{\tau_\pm}, \tag{4.1}$$

where $p^\mu_{\tau^\pm} = (p^0_{\tau^\pm}, \vec{p}_{\tau^\pm})$ is the 4-momentum of $\tau^\pm$, and $k^\mu_\pm$ is given by

$$k^\mu_\pm \equiv y_\pm q^\mu_\pm + r p^\mu_{\nu^\pm}, \qquad \text{with} \qquad y_\pm \equiv \frac{2(p_{\pi^\pm} - p_{\pi^0\pm}) \cdot p_{\tau^\pm}}{(p_{\pi^\pm} + p_{\pi^0\pm}) \cdot p_{\tau^\pm}}, \qquad r \equiv \frac{m^2_\rho - 4m^2_\pi}{m^2_\tau + m^2_\rho} \approx 0.14, \tag{4.2}$$

and where $p^\mu_{\nu^\pm}$ is the 4-momentum of the neutrino from $\tau^\pm$. In the Higgs frame, for a boosted $\tau^\pm$ the magnitude of the component of this field that is perpendicular to the $\tau^\pm$ velocity is much greater than the magnitude of the parallel component. Hence, one can approximate this field as

$$\vec{E}_\pm \approx \frac{m_h}{2} \left[(y_\pm - r)\, \vec{p}_{\pi^\pm}\big|_0 - (y_\pm + r)\, \vec{p}_{\pi^0\pm}\big|_0 \right]^\perp, \tag{4.3}$$

where $\vec{p}_{\pi^\pm}$ is the 3-momentum of $\pi^\pm$, $\vec{p}_{\pi^0\pm}$ is the 3-momentum of the neutral pion from $\tau^\pm$, $|_0$ denotes evaluation in the Higgs frame, and $\perp$ denotes the perpendicular component to the $\tau^\pm$ velocity.

The Θ-variable, which is the observable of interest, is thus defined as

$$\Theta = \text{sgn}\left[\vec{v}_{\tau^+} \cdot (\vec{E}_- \times \vec{E}_+) \right] \arccos\left(\frac{\vec{E}_+ \cdot \vec{E}_-}{|\vec{E}_+||\vec{E}_-|} \right). \tag{4.4}$$

The distribution followed by this variable is given approximately by

$$P(\Theta) = A\cos(\Theta - 2\Delta) + B, \tag{4.5}$$

for some constants A and B. As we will show below, the overall shape of this distribution is unchanged by when considering detector effects and using the proposed event selection. However, the amplitude A of the oscillation is reduced, which results in a decrease in the accuracy of the measurement. As it was mentioned before, this distribution is highly sensitive to the reconstruction of the Higgs momentum. In hadronic Z events, the reconstruction is not ideal and the distribution of this variable becomes severely distorted.

To determine the uncertainty this measurement we first fitted the resulting distributions of the Θ variable with a function of the form 4.5. From them we averaged the values of A and B and interpolated to all other CP-phase angles Δ. We then used a maximum likelihood method to estimate the uncertainty of the measurement.

V. RESULTS

The results from applying the proposed selection are shown in Table I. It can be seen that there is only a small portion of both signal and background left at the end. This is mainly due to the reconstruction of the associated Z boson. The main theoretical advantage of using a lepton collider is that one can use this associated boson to reconstruct the 4-momentum of the Higgs. However, as we have mentioned before, the reconstruction from jets is not ideal and results in a severe distortion to the Θ variable distribution. Thus, one can only use the leptonic Z events for this measurement. Ironically, it seems that it would instead be better to use collinear approximations to do this measurement, as with a hadron collider. In this case both signal and background yields would be much higher, but one could use additional cuts to obtain a better signal to background ratio. Furthermore, since backgrounds have been shown to have a flat θ distribution, one could still perform the measurement with high background levels.

Table I: Cut-flow for Zh events and main backgrounds using selection described in III with a dataset of 1 ab^{-1}.

Requirement	Signal	Backgrounds			
	$Zh \to Z\tau^+\tau^-$	ZZ	Zll^a	jj	Drell-Yan
None	15033	1163000	1497000	10270000	2954000
Two τ-candidates	775	8860	1142	7075	142688
Opposite τ charge	657	5652	2078	4005	142496
Two leptons	26	0	4.5	0	0
Mass cuts	26	0	4.5	0	0

[a]ZZ and Zh events are excluded here.

The distribution of the Θ variable obtained with this selection is shown in Fig. 1. It can be seen that although the amplitude of the oscillation is reduced compared to the Monte Carlo truth, the overall shape of the distribution is unchanged. Hence, we can fit these distributions with functions of the form 4.5 and estimate the uncertainty of the measurement as it was mentioned earlier.

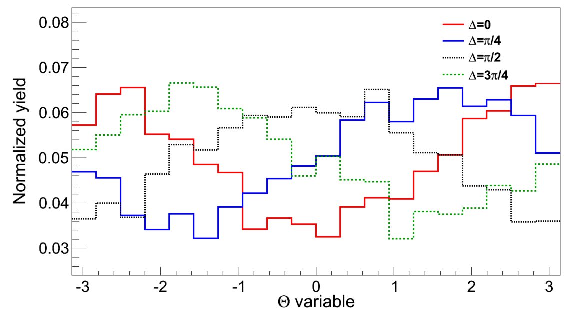
From the maximum likelihood method we obtain an uncertainty on the measurement of 59° for a dataset of 1 ab^{-1}. This is much worse than the 4.4° uncertainty obtained by Ref. [6]. Thus, we see that detector effects play an important role in this measurement and cannot be neglected.

VI. CONCLUSION

We have shown that detector effects, which were neglected by previous studies, play an important role in this measurement. The main obstacle is to accurately reconstruct the Z 4-momentum. This can only be done for leptonic Z decays, which results in a very decreased signal yield culminating in a very limited accuracy of the measurement.

(placeholder)

(a)Monte Carlo truth



(b)Reconstructed

Figure 1: Comparison of Θ variable distribution between generated and reconstructed information for various values of the phase Δ. Although the amplitude of the oscillation is decreased, the overall shape is preserved.

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