Study of the Higgs couplings to leptons and Higgs CP measurement at the ILC

Shin-ichi Kawada [a]

DESY, Notkestraße 85, 22607 Hamburg, Germany

The International Linear Collider (ILC) is a planned electron-positron collider. The initial stage of the ILC will provide data at the center-of-mass energy of 250 GeV to be able to study electroweak sector and perform precise measurements of Higgs boson. In this contribution, the prospects of measuring the Higgs boson decaying into tau pair $H \to \tau^+\tau^-$ and muon pair $H \to \mu^+\mu^-$ are described. The measurement of CP properties of Higgs boson using $H \to \tau^+\tau^-$ decay process is also discussed. All studies in this contribution are based on the full detector simulation of ILD concept. We have found that the cross section times branching ratio can be measured with the precision of 1.2% for $H \to \tau^+\tau^-$ and of 21% for $H \to \mu^+\mu^-$. The mixing angle between CP-even and CP-odd components of the Higgs boson can be determined with the precision of 75 mrad.

1 Introduction

A Standard Model (SM)-like Higgs boson has been found at the LHC. Currently all measurements are consistent with the SM Higgs boson. However, we still have many open questions like the existence of dark matter which cannot be explained by the SM. A precise measurement of the Higgs boson would be a key to explore new physics beyond the SM, especially the couplings between particles and Higgs boson. In the SM, the Yukawa coupling between matter fermions and Higgs boson is proportional to the fermions' mass. If we observe any deviations from this prediction, it is an indication of new physics beyond the SM.

The International Linear Collider (ILC) [1] is a planned electron-positron collider, which provides collision data of center-of-mass energy ($\sqrt{s}$) of 250 GeV at the initial stage. The electron(positron) beams are longitudinally polarized by 80%(30%). Around half million Higgs bosons will be produced via $e^+e^- \to ZH$ process in the initial running period of $\sim$ 11 years. The main purposes of the ILC at $\sqrt{s} = 250$ GeV are the investigation of electroweak sector and model-independent measurements of Higgs boson with very high precision. In this contribution, we will describe the prospects for the measurements of Higgs boson decays to leptonic final states, $H \to \tau^+\tau^-$ and $H \to \mu^+\mu^-$, and the measurement of CP state of the Higgs boson using $H \to \tau^+\tau^-$ decay process.

[a] on behalf of the International Large Detector (ILD) Concept Group

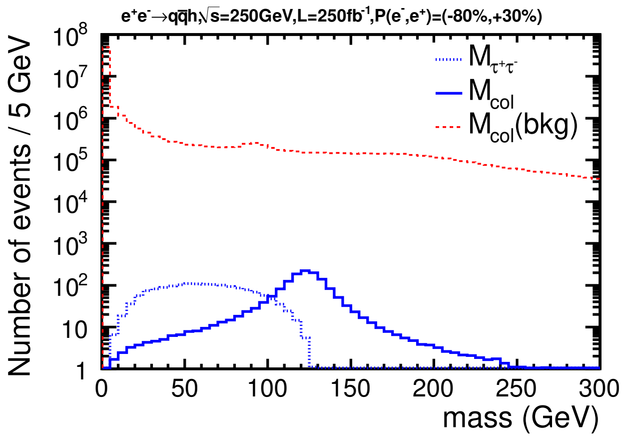

Figure 1 – Reconstructed τ-pair mass in $H \to \tau^+\tau^-$ analysis [3]. Dotted blue is the invariant mass of τ-pair only using visible τ decay products in the signal process, solid blue (dotted red) is the invariant mass of τ-pair with using collinear approximation in the signal (background) process, respectively.

2 International Large Detector

The International Large Detector (ILD) is one of the detector concepts for the ILC [2]. It is designed as a high-precision detector for Particle Flow Algorithm (PFA). It consists of a vertex detector, a time projection chamber, silicon tracking detectors, an electromagnetic calorimeter, a hadronic calorimeter, a forward detector system, all these are placed inside of a solenoidal coil which provide 3.5 T magnetic field, and an iron yoke is placed outside of the coil. The calorimeters are highly segmented to be able to apply PFA techniques. The ILD will provide an impact parameter resolution of $\sigma_{d_0} \sim 5$ μm, a transverse momentum resolution of $\sigma_{p_T}/p_T \sim 2 \times 10^{-5} p_T$, and a jet energy resolution of $\sim 3-4\%$ over a wide range of jet energies.

The full detector simulation is performed using Geant4-based detector geometry with ILD model and the reconstruction is performed using PFA techniques. In this contribution, all analyzes use Monte-Carlo (MC) event samples subjected to such full simulation and reconstruction.

3 Measurement of Higgs Couplings

As explained before, the Yukawa coupling between fermions and Higgs boson is proportional to the fermions' mass. Many BSM models predict different types of deviations in this relation. It typically predicts a few % level deviations from the SM. Thus, measurements of couplings at a few % level or better will allow these BSM models to be tested. In this section, we will describe the prospects of the measurement of μ and τ-leptons' Yukawa coupling at the ILC.

3.1 Higgs to τ

At $\sqrt{s} = 250$ GeV, the processes of $e^+e^- \to ZH$ with $Z \to q\bar{q}/e^+e^-/\mu^+\mu^-$, $H \to \tau^+\tau^-$ are investigated [3, 4]. The τ lepton candidates are identified by searching isolated narrow jets which contain one or three charged particles with the sum of charge equal to ± 1, and the invariant mass should be lower than 2 GeV/c^2. To reconstruct the invariant mass of τ-pair, the collinear approximation method is applied which assumes the neutrinos from τ decay are collinear with the visible products of τ lepton. Figure 1 shows the distribution of τ-pair invariant mass using collinear approximation.

Various preselection cuts are applied to suppress background processes. A boosted decision tree technique is applied as the final step to distinguish signal and background efficiently. The estimated precision on the cross section times branching ratio $\sigma \times \mathrm{BR}(H \to \tau^+\tau^-)$ is 1.2% when

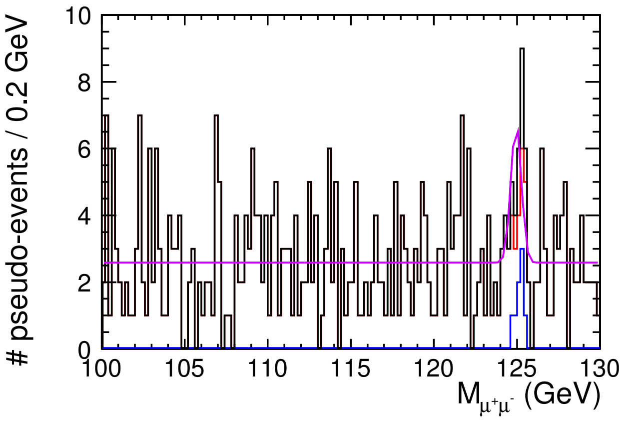

Figure 2 – One example of pseudo-experiment in $H \to \mu^+\mu^-$ analysis [5]. Blue(red) is pseudo-signal(-background) data, black is the sum of blue and red, purple curve is the fitting result using a Gaussian and constant function, respectively.

using 2 ab^{-1} of data at $\sqrt{s} = 250$ GeV. This result improves to 1.0% when we add 4 ab^{-1} collision data at $\sqrt{s} = 500$ GeV.

3.2 Higgs to μ

This channel gives an opportunity of direct access to the Yukawa coupling between Higgs boson and second generation fermions. However, this analysis is very challenging because the branching ratio of $H \to \mu^+\mu^-$ is tiny: estimated to be $\sim 2.2 \times 10^{-4}$ in the SM when the mass of Higgs boson is 125 GeV/c^2. The study has been carried out at $\sqrt{s} = 250$ GeV, with considering the processes of $e^+e^- \to ZH$ with $Z \to q\overline{q}/\nu\overline{\nu}$, $H \to \mu^+\mu^-$ [5].

In all processes, the analysis strategy is structured in a same way. First, a pair of well-measured, prompt, oppositely charged muons is selected as the candidate of $H \to \mu^+\mu^-$. Then, the remaining particles are subjected to a channel-specific analysis, like applying jet clustering. A series of preselection cuts is applied to suppress background processes. A boosted decision tree technique is used for further background rejection. Finally, a toy MC technique is applied to estimate the precision. Figure 2 shows one example of pseudo-experiment in the toy MC.

Using 2 ab^{-1} data at $\sqrt{s} = 250$ GeV, the precision on the cross section times branching ratio $\sigma \times \mathrm{BR}(H \to \mu^+\mu^-)$ is estimated to be $\sim 21\%$. This improves to $\sim 15\%$ when we add 4 ab^{-1} collision data at $\sqrt{s} = 500$ GeV.

4 Higgs CP Measurement in $H \to \tau^+\tau^-$

The decay process of $H \to \tau^+\tau^-$ gives an opportunity to access the CP nature of the Higgs boson and of its couplings. The CP state of the τ-pair affects transverse spin correlations between two τs, as shown in Figure 3 (left). The distribution of τ decay products are sensitive to the polarization of the τ lepton, allowing these correlations to be measured. The high precision detectors envisaged for the ILC, and the clean experimental environment of leptons colliders, enable such a measurement.

The processes of $e^+e^- \to ZH$ with $Z \to q\overline{q}/e^+e^-/\mu^+\mu^-$, $H \to \tau^+\tau^-$ are investigated at $\sqrt{s} = 250$ GeV [6]. The impact parameters of τ decay products are used to reconstruct the momenta of τ [7]. The polarimeters, powerful estimators of the spin direction of τ, are extracted in the decay processes of $\tau^\pm \to \pi^\pm\nu$ and $\tau^\pm \to \pi^\pm\pi^0\nu$. After applying several selection cuts, a neural network technique is applied to separate signal and background. The remaining events are classified according to their sensitivity to CP effects. One example distribution is shown in Figure 3 (right). Pseudo-experiments are performed to estimate the experimental sensitivity.

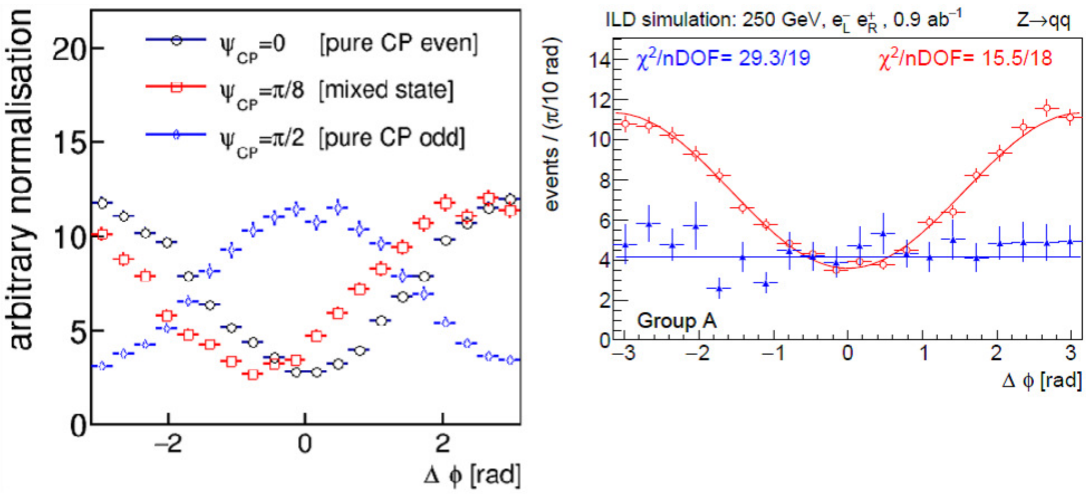

Figure 3 – Left: distribution of the CP-sensitive correlation angle for different CP mixing cases at the generator-level. Right: reconstructed angular distribution in the case of the SM, for a sub-sample of selected events; signal is shown in red and background is blue.

The mixing angle of CP-even and CP-odd components of the τ-pair system can be measured to a precision of 75 mrad when using 2 ab^{-1} of data at $\sqrt{s} = 250$ GeV.

Acknowledgments

We would like to thank the LCC generator working group and the ILD software working group for providing the simulation and reconstruction tools and producing the Monte-Carlo samples used in this study. We would like to thank Daniel Jeans (KEK) for providing lots of materials for this contribution. This work has benefited from computing services provided by the ILC Virtual Organization, supported by the national resource providers of the EGI Federation and the Open Source GRID. We thankfully acknowledge the support by the Deutsche Forschungsgeinschaft (DFG) through the Collaborative Research Centre SFB 676 Particles, Strings and the Early Universe, project B1.

References

1. C. Adolphsen *et al.* The International Linear Collider Technical Design Report - Volume 3.II: Accelerator Baseline Design. 2013.
2. T. Behnke *et al.* The International Linear Collider Technical Design Report - Volume 4: Detectors. 2013.
3. Shin-ichi Kawada, Keisuke Fujii, Taikan Suehara, Tohru Takahashi, and Tomohiko Tanabe. A study of the measurement precision of the Higgs boson decaying into tau pairs at the ILC. *Eur. Phys. J.*, C**75**:617, 2015.
4. Shin-ichi Kawada. *Study of Higgs boson decays to tau pairs at the International Linear Collider*. PhD thesis, Hiroshima University, 2016.
5. Shin-ichi Kawada, Jenny List, and Mikael Berggren. Branching ratio measurement of $h \to \mu^+\mu^-$ at the ILC. In *International Workshop on Future Linear Collider (LCWS2017) Strasbourg, France, October 23-27, 2017*, 2018.
6. D. Jeans and G. W. Wilson. Measuring the CP state of tau lepton pairs from Higgs decay at the ILC. *Phys. Rev.*, D**98**:013007, 2018.
7. D. Jeans. Tau lepton reconstruction at collider experiments using impact parameters. *Nucl. Instrum. Meth.*, A**810**:51–58, 2016.