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Full Text

Study of Higgsstrahlung Cross Section and Higgs Mass Measurement Precisions with ZH ($Z \rightarrow \mu^+ \mu^-$) Events at CEPC

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Abstract

The Circular Electron Positron Collider (CEPC) is a future Higgs factory proposed by the Chinese high energy physics community. Using Monte Carlo samples corresponding to 5 ab^{-1} at 250 GeV center-of-mass energy—the benchmark luminosity of CEPC Higgs runs—model-independent (MI) analyses of the Higgsstrahlung (ZH) cross section σ_{ZH} and Higgs mass m_{H} are performed with ZH events where the Z boson decays into a pair of muons. The relative precision of σ_{ZH} could reach 0.92% and the Higgs mass can be measured with an accuracy of 6.5 MeV. Using information from Higgs decay final states, the backgrounds can be further reduced, leading to a mass precision of 5.4 MeV. The impacts of tracker size are investigated and parameterized for these measurements. Using similar analysis technology, we also evaluate the capability of CEPC in measuring Higgs invisible decays. With ZH ($Z \rightarrow \mu^+\mu^-$) events at 5 ab^{-1} , the upper limit of the invisible decay cross section beyond the Standard Model (SM) $\sigma_{\text{ZH,H}\rightarrow\text{inv}}$ can be determined to be 2.0 fb at 95% confidence level.

Keywords: CEPC, Higgs mass, cross section

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1 Introduction

The LHC has been playing an important role in Higgs physics. It not only discovered the Higgs boson [1-3], but also demonstrated that the discovered new particle is highly consistent with the one predicted by the Standard Model [4-8]. Compared to the dataset that led to the Higgs discovery, the LHC will acquire much higher integrated luminosity in its Run-2 and future operations at higher center-of-mass energies. These data will greatly enhance our understanding of the Higgs boson [9]. However, as a hadron collider, Higgs measurement precision at the LHC is limited by huge QCD backgrounds, underlying events, and pile-up effects. At the LHC, only a small fraction of produced Higgs bosons can be identified, and the measurement of the Higgs total width is also limited.

Compared to the LHC, an electron-positron collider offers distinct advantages for measuring Higgs boson properties. First, it is free of QCD backgrounds, allowing nearly every Higgs boson to be recorded and reconstructed. Second, the beam energy and polarization of the initial states are precisely known and adjustable. Most importantly, the electron-positron collider provides absolute measurements for Higgs couplings [10, 11]. Therefore, an electron-positron Higgs factory is an essential step toward understanding the nature of the Higgs boson.

The Circular Electron Positron Collider (CEPC) is a Higgs factory proposed by the Chinese high energy physics community [10]. The CEPC will operate at a center-of-mass energy of 240–250 GeV with an instantaneous luminosity of $2 \times 10^3 \text{ cm}^{-2}\text{s}^{-1}$ at each interaction point. With two detectors operating over 10 years, CEPC will accumulate 5 ab^{-1} of integrated luminosity and 10 Higgs boson events.

A series of simulation studies have been performed for future Higgs factories. The International Linear Collider (ILC) community explored Higgs inclusive cross section measurement using full detector simulation. With an integrated luminosity of 250 fb^{-1} at 250 GeV collisions, ILC achieves an accuracy of 2.5% [11]. Compared to the ILC, the collision environment of CEPC has changed significantly. First, ILC uses polarized beams (30% right-handed polarized positron beam and 80% left-handed polarized electron beam) while CEPC has no beam polarization, thus changing the cross sections for both signal and backgrounds. Second, the beam spot size of CEPC at the interaction point is much larger than that of ILC [10], resulting in much weaker beamstrahlung effects and a much narrower beam energy spread. CEPC also has much higher integrated luminosity at 240–250 GeV collisions. Therefore, it is necessary to perform full detector simulation analysis with adequate CEPC collision conditions.

The production processes for the SM Higgs boson [12–17] at CEPC are $e e \rightarrow \text{ZH}$ (Higgsstrahlung), $e e \rightarrow \gamma\text{H}$ (WW fusion), and $e e \rightarrow e e \text{H}$ (ZZ fusion), as shown in Fig. 1 [Figure 1: see original paper]. The corresponding total and individual production cross sections for a 125 GeV SM Higgs boson, as functions of center-of-mass energy, are plotted in Fig. 2 [Figure 2: see original paper]. At 250 GeV center-of-mass energy, Higgs bosons are dominantly produced through the ZH process, where the Higgs is produced in association with a Z boson.

The Z boson has a branching ratio of 3.3% to decay into $\mu \mu$. Muons can be easily identified and their momentum can be precisely measured at CEPC. By tagging ZH, $Z \rightarrow \mu \mu$ events, the Higgsstrahlung events can be reconstructed using the recoil mass method:

$$M_{\text{recoil}} = \sqrt{s - 2\sqrt{s}(E_{\mu^+} + E_{\mu^-}) + M_{\mu^+\mu^-}^2}$$

where E_{μ^+} , E_{μ^-} are the energies of the two leptons in the center-of-mass system, $M_{\mu^+\mu^-}$ is the invariant mass of the $\mu \mu$ pair, and s is the square of the center-of-mass energy. Therefore, the ZH ($Z \rightarrow \mu \mu$) events form a clear peak in the M_{recoil} distribution at the Higgs boson mass. A typical M_{recoil} distribution of the Higgs signal is shown in Fig. 3 [Figure 3: see original paper]. The high-mass tail is induced by radiation effects, including beamstrahlung, ISR, FSR, and bremsstrahlung.

In the recoil mass method, the Higgs boson in the ZH event is selected without using its decay information. By counting the total number of ZH events, the inclusive ZH cross section σ_{ZH} and thus the coupling g_{HZZ} can be determined model-independently. The measured g_{HZZ} , combined with other event rate measurements, could be used to determine the absolute value of the Higgs boson width and absolute values of couplings between the Higgs boson and its decay final states [10]. Meanwhile, the Higgs mass m_{H} can be extracted from the peak position. The m_{H} measurement is also very important since it is the only free parameter in the SM Higgs potential and it determines all Higgs decay

branching ratios in the SM. Higgs decay information can be used to further suppress potential backgrounds, leading to better m_H precision. Many new physics models predict a significant branching ratio for invisible Higgs decays [18-21]. At the LHC, the current upper limit on the Higgs invisible decay branching ratio is about 40% [22, 23], much larger than the value predicted in the SM ($B(H \rightarrow \text{inv}) = B(H \rightarrow ZZ \rightarrow \gamma\gamma) = 1.06 \times 10^{-3}$). At CEPC, using the recoil mass method, the measurement precision of Higgs to invisible final states can be significantly improved. In this paper, the measurement capability of CEPC for Higgs invisible decays is investigated.

This paper is organized as follows. Section 2 describes the MC simulation and samples used in the studies. The details of the analyses are presented in Section 3. This section covers the MI and model-dependent (MD) analysis of Higgsstrahlung, and precision investigation of Higgs to invisible decays. The MI analysis also shows the effects of TPC radius, thus providing important reference for CEPC detector design. The conclusion is summarized in Section 4.

2 Monte Carlo Simulation

A GEANT4-based full simulation is performed on the CEPC conceptual detector, which is developed from the International Large Detector (ILD) [24, 25] at the ILC [11]. With respect to the ILD, the CEPC conceptual detector has a much shorter L^* (the distance between the interaction point and QD0, the final focusing magnet) and a less thick return yoke. A set of generator samples at 250 GeV center-of-mass energy, corresponding to 5 ab^{-1} integrated luminosity, is produced by Whizard [26, 27]. It consists of SM Higgs signal and the major SM backgrounds, including all the 2-fermion processes ($e e \rightarrow f \bar{f}$ with ISR correction, where $f \bar{f}$ refers to $e e$, $\mu \mu$, $\tau \tau$ and quark pairs) and 4-fermion processes (ZZ, WW, ZZ or WW, single Z, single W). The interference effects are taken into account in the sample dataset. For example, if the final states consist of two mutually charge-conjugated fermion pairs that could decay from both WW and ZZ intermediate states, such as $e e \rightarrow \mu \mu$, this process is classified as a “ZZ or WW” process. If there are $e \pm$ together with its partner neutrino and an on-shell W boson in the final state, this type is named as “single W”. In our analysis, the “single W” background vanishes after requiring a pair of muons in the final states. Similarly, if the final state is an electron-positron pair and an on-shell Z boson, this case is called “single Z”. More details about the CEPC sample set can be found in reference [28]. The Higgs mass is set to be 125 GeV for the SM Higgs signal. A 0.16% beam energy spread has been included in this analysis. Limited by computing resources, the SM backgrounds are processed with a fast simulation tool, where the differential momentum resolution and detection efficiency for different types of particles are parameterized. The fast simulation tool is validated by comparison to full simulation, as shown in Fig. 3 [Figure 3: see original paper].

3 The Analyses

As mentioned in Section 1, the cross section σ_{ZH} can be obtained by counting ZH events in the recoil mass spectrum. The observed number of ZH events N_{ZH} is proportional to the sum of a series of Higgs exclusive decay cross sections, which can be expressed as:

$$N_{ZH} \propto \sum \sigma_{ZH} \cdot \epsilon(H \rightarrow X) \cdot \mathcal{B}(H \rightarrow X)$$

where $H \rightarrow X$ represents an exclusive Higgs decay channel (Higgs decaying to X), $\mathcal{B}(H \rightarrow X)$ is its branching fraction, and $\epsilon(H \rightarrow X)$ corresponds to the event selection efficiency. If the Higgs signal is selected without using its decay information, the selection efficiency is global for different Higgs decay channels. Therefore, we have $N_{ZH} \propto \sigma_{ZH} \cdot \epsilon \cdot \sum \mathcal{B}(H \rightarrow X) = \sigma_{ZH} \cdot \epsilon$ and thus σ_{ZH} can be determined model-independently.

Higgs decay information can be used to further suppress the SM background, leading to better precision on the Higgs boson mass and N_{ZH} measurement. This technique is also known as MD analysis. In this case, the selection efficiency $\epsilon(H \rightarrow X)$ depends on the Higgs decay modes, and σ_{ZH} cannot be factorized directly from the N_{ZH} measurement.

3.1 Model-Independent Analysis of ZH and m_H Measurement

In the MI analysis, the event selection consists of a pre-selection with loose criteria and a multivariate analysis (MVA). In the pre-selection, the selection criteria are as follows: (1) At least one pair of muons with opposite charge are reconstructed. For events with more than one combination, the one with the minimum $|M_{\mu^+\mu^-} - M_Z|$ is selected, where $M_{\mu^+\mu^-}$ is the invariant mass of the reconstructed Z boson and M_Z is 91.2 GeV [31]. (2) The invariant mass of $\mu^+\mu^-$ is required to satisfy $80 \text{ GeV} < M_{\mu^+\mu^-} < 100 \text{ GeV}$, while the recoil mass is in the region of $120 \text{ GeV} < M_{\text{recoil}} < 160 \text{ GeV}$. (3) The transverse momentum $p_T^{\mu^+\mu^-}$ is required to be larger than 20 GeV. In addition, it is required that $|\phi_{\mu^+} - \phi_{\mu^-}| < 175^\circ$, where ϕ_{μ^\pm} is the azimuthal angle of μ^+ or μ^- .

The Toolkit for Multivariate Analysis (TMVA) [32] provided by ROOT is used for further background rejection. In this paper, the method of Boosted Decision Trees (BDT) is adopted and the selected variables for TMVA inputs are $M_{\mu^+\mu^-}$, $p_T^{\mu^+\mu^-}$, the polar angle of the Z boson, and the acollinearity, which is defined as $\text{acol} = \cos^{-1} \left(\frac{\vec{p}_{\mu^+} \cdot \vec{p}_{\mu^-}}{|\vec{p}_{\mu^+}| |\vec{p}_{\mu^-}|} \right)$ where \vec{p}_{μ^\pm} is the momentum vector of μ^\pm . After the MVA, the cutflow is summarized in Table 1. The signal event selection efficiency is 65.33%.

In the MI analysis, the event selection efficiencies for different Higgs boson decay modes are expected to be the same. Fig. 4 [Figure 4: see original paper] shows the selection efficiencies of different Higgs decay channels; no significant bias

toward any specific Higgs decay channel is observed. The selected muons may also come from Higgs boson decays or Z boson hadronic decays. About 200 ZH events of this type survive after event selection and their recoil mass distributes flatly in the signal mass window.

The final recoil mass spectrum of $\mu\mu$ is shown in Fig. 5 [Figure 5: see original paper]. An unbinned maximum likelihood fit of the M_{recoil} distribution is performed in the region of 120 GeV to 140 GeV, extracting the yield of signal events and Higgs mass simultaneously. The background is represented by a third-order Chebyshev polynomial function, whose parameters are fixed to values extracted from background samples. The Higgs signal shape is described by a Crystal Ball function. Using this method, ZH is measured to a relative precision of 0.92% and mH is measured to a precision of 6.5 MeV simultaneously.

3.2 Dependency of ZH and mH Measurement Accuracy on TPC Radius

From the detector perspective, the precisions of ZH and mH in these analyses are mainly determined by the performance of muon identification and muon momentum resolution. The latter strongly depends on the tracker design, especially the tracker radius. The tracking system in the CEPC conceptual detector is composed of a silicon tracking system and a main tracker TPC. A larger TPC radius provides better momentum resolution at higher detector construction cost. A series of fast simulation studies have been performed, parameterizing the tracker performance at different TPC radii. Using the same fast simulation method described in Section 3.1, the relationship between the precision of ZH and TPC radius is extracted and described by an exponential function:

$$\delta\sigma_{ZH} = 0.485 \times (1 + e^{-0.094 \cdot R_{TPC}})$$

where $\delta\sigma_{ZH}$ (%) is the relative precision of cross-section measurement and R_{TPC} (m) is the TPC radius. Similarly, the mH accuracies δm_H at different TPC radii are obtained. Its dependence on the TPC radius can be expressed as:

$$\delta m_H = 36.286 \times (1 + 0.092 \times e^{-1.820 \cdot R_{TPC}}) \text{ MeV}$$

Fig. 6 [Figure 6: see original paper] shows that when the TPC radius is changed by 25%, the precisions of ZH and mH change by 1% and 22%, respectively. In the explored range of TPC radius, the accuracies of both ZH and mH measurements vary more slowly than the TPC radius. This is not surprising as the tracker momentum is determined not only from the TPC but also from the silicon tracking system. The mH measurement is much more sensitive to the TPC radius since the mass measurement highly depends on the recoil mass peak position measurement.

3.3 Model-Dependent Analysis of mH Measurement

In the MD analysis, further background suppression can be achieved by using Higgs decay information, and the mH measurement precision can then be improved. Similar to the MI analysis described in Section 3.1, the event selection in the MD analysis also consists of a pre-selection and an MVA stage. On top of the event selection criteria of the MI analysis, we require more than two reconstructed charged tracks at the pre-selection stage. In the MVA stage, the energy of all reconstructed final states E_{vis} is also taken as an input variable. After the final selection, the event selection efficiency is 71.65%.

The final recoil mass spectrum is shown in Fig. 7 [Figure 7: see original paper], and the precision of mH is improved to 5.4 MeV. The selection efficiencies of Higgs decays in the MD analysis are checked as in the MI analysis. The efficiencies of the major SM Higgs decay channels are roughly the same, except $\epsilon(H \rightarrow \gamma\gamma)$ is significantly lower than the others. This is caused by the requirement of more than two charged tracks in signal candidates, as the extra tracks in $H \rightarrow \gamma\gamma$ can only come from photon conversion.

3.4 Measurement of Higgs Invisible Decay

The Higgs invisible decay is a well-motivated signature of physics beyond the SM [18-21]. At CEPC, the Higgs invisible decay branching ratio can be determined precisely using the recoil mass method. On top of the SM Higgs generation and decay, we assume extra BSM Higgs signal decays inclusively into invisible final states: $\sigma_{ZH} = \sigma_{ZH}^{\text{SM}} + \sigma_{ZH,H \rightarrow \text{inv}}^{\text{BSM}}$. As the SM Higgs has a tiny fraction decaying invisibly, the total cross section of Higgs invisible decay from ZH events can be expressed as:

$$\sigma_{ZH} \times \mathcal{B}(H \rightarrow \text{inv}) = \sigma_{ZH}^{\text{SM}} \times 1.06 \times 10^{-3} + \sigma_{ZH,H \rightarrow \text{inv}}^{\text{BSM}}$$

The potential for Higgs invisible measurement at CEPC is investigated at different values of $\sigma_{ZH,H \rightarrow \text{inv}}^{\text{BSM}}$. The Higgs invisible signal events are identified using the same pre-selection as in the MI analysis; in addition, we require no visible energy except the $\mu\mu$ pair from Z boson decay and E_{vis} to be within 105 GeV and 125 GeV. The MVA cut values are optimized at different values of $\sigma_{ZH,H \rightarrow \text{inv}}^{\text{BSM}}$. Fig. 8 [Figure 8: see original paper] shows the $\mu\mu$ recoil mass spectrum of candidate Higgs invisible decay events at $\sigma_{ZH,H \rightarrow \text{inv}}^{\text{BSM}} = 200$ fb. In this scenario, the final event selection efficiency is 63.87% and the relative precision of $\sigma_{ZH,H \rightarrow \text{inv}}^{\text{BSM}}$ reaches 0.76%.

At different values of $\sigma_{ZH,H \rightarrow \text{inv}}^{\text{BSM}}$, the relative precision of $\sigma_{ZH} \times \mathcal{B}(H \rightarrow \text{inv})$ measurement is given in Fig. 9 [Figure 9: see original paper]. The point at $\sigma_{ZH,H \rightarrow \text{inv}}^{\text{BSM}} = 0$ corresponds to the SM Higgs. Using the likelihood ratio test method [33], the upper limit of $\sigma_{ZH,H \rightarrow \text{inv}}^{\text{BSM}}$ at 95% confidence level can be determined to be 2.0 fb.

4 Summary

The CEPC is expected to play a crucial role in understanding Higgs properties. In this paper, the measurement precisions of the Higgs production cross section σ_{ZH} and mass m_H are investigated with fully simulated Higgsstrahlung signal at 5 ab^{-1} integrated luminosity at 250 GeV center-of-mass energy, where the Z boson decays to $\mu\mu$. In a model-independent analysis without tagging Higgs decays, the relative precision of σ_{ZH} is determined to be 0.92% and the accuracy of m_H is 6.5 MeV using the recoil mass method. By using information from Higgs decays, the m_H accuracy is improved to 5.4 MeV. The dependence of performance on TPC radius is investigated and parameterized. Reducing the TPC radius by 25% changes the precisions of σ_{ZH} and m_H to 0.93% and 7.9 MeV, respectively.

The σ_{ZH} measurement is the core of the Higgs program at $e e$ colliders. It determines the absolute value of g_{HZZ} and therefore serves as a sensitive probe for new physics beyond the SM. It is also an essential input for determining the absolute Higgs width and all couplings between the Higgs boson and its decay final states. In this paper, the absolute value of g_{HZZ} is determined to a relative accuracy of 0.46% at CEPC. This accuracy is one order of magnitude better than that at HL-LHC [9]. The result is also statistically consistent with those at other proposed Higgs factories TLEP(FCC-ee) [34] and ILC [11]. In addition, we explored the potential of Higgs invisible decay measurements at CEPC. The upper limit of $\sigma_{ZH, H \rightarrow \text{inv}}$ corresponding to the 95% confidence level is determined to be 2.0 fb. All results above are incorporated into the CEPC-SPPC Preliminary Conceptual Design Report [10].

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