$H \rightarrow e^+e^-$ at CEPC: ISR effect with MadGraph

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ABSTRACT: The Circular Electron Positron Collider (CEPC) is a future Higgs factory proposed by the Chinese high energy physics community. It will operate at a center-of-mass energy of 240-250 GeV. The CEPC will accumulate an integrated luminosity of 5 ab⁻¹ in ten years' operation. With GEANT4-based full simulation samples for CEPC, Higgs boson decaying into electron pair is studied at the CEPC. The upper limit of $\mathcal{B}(H \to e^+e^-)$ could reach 0.024% at 95% confidence level. The signal process is generated by MADGRAPH, with Initial State Radiation (ISR) implemented ¹, as a first step to adjust MADGRAPH for a electron positron Collider.

KEYWORDS: CEPC, Higgs Coupling, ISR, MadGraph

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1 Introduction

The amazing discovery of Higgs boson [1, 2] in 2012 by the ATLAS and CMS experiments at the CERN LHC has made a considerable step in particle physics, opening doors to new physics search through Higgs portal. The up-to-date results indicate that it is highly Standard Model (SM) like [3–8]. However, many new physics models predict the Higgs couplings deviate from the SM at the percent level. Thus the percent or even sub-percent level precision becomes necessary for the future Higgs measurement program. With this consideration, a Higgs factory at e^+e^- collider with high luminosity is best suited for this goal, due to its clean environment and relative lower cost.

The Circular Electron-Positron Collider (CEPC) [9] is such a nice example, which is a proposed circular collider, designed to run around $240 \sim 250$ GeV with an instantaneous luminosity of 2×10^{34} cm⁻² s⁻¹, and will deliver 5 ab⁻¹ of integrated luminosity during 10 years of operation. About 10^6 Higgs events will be produced in a clean environment, which allows the measurement of the cross section of the Higgs production as well as its mass, decay width and branching ratios with precision much beyond those of hadron colliders.

At CEPC with the center-of-mass energy of 250 GeV, the Higgs bosons are dominantly produced from ZH process, where the Higgs boson is produced in association with a Z boson. Major deay modes of the Higgs boson have been extensively studied in Refs [9, 10], such as the channel of $H \to ZZ$, and $H \to \gamma\gamma$ etc. In this study we are interested in a rare decay $H \to e^+e^-$. The Feynman diagram of $H \to e^+e^-$ is shown in Figure. 1.

The SM prediction for the branching fraction $\mathcal{B}(H \to e^+e^-)$ is as tiny as approximately 5×10^{-9} . However, in new physics scenario (see e.g. [11]), it can be enhanced significantly. Moreover, searching or measurement for $H \to e^+e^-$ together with $\mu^+\mu^-$ and $\tau^+\tau^-$, can be used to test the lepton universality of Higgs boson couplings.

The two electrons from Higgs decay can be easily identified and their momentum can be precisely measured in the detector. The Higgsstrahlung events can then be reconstructed with the recoil mass method:

$$m_{recoil}^2 = s + m_H^2 - 2 \cdot E_H \cdot \sqrt{s} ,$$
 (1.1)

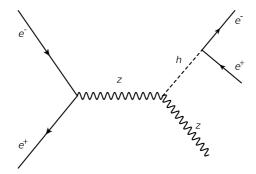


Figure 1. Example Feynman diagram.

where \sqrt{s} is the center of mass energy, m_H and E_H are the mass and energy of the Higgs boson reconstructed by the two lepton four momentum. Therefore, the ZH ($H \to e^+e^-$) events form a peak in the M_{recoil} distribution at the Z boson mass. With the recoil mass method, the ZH events are selected without using the decay information of the Z boson.

A search has already been performed at CMS with RunI data [12], with an upper limit of 0.19% placed on the branching fraction $\mathcal{B}(H \to e^+e^-)$. Studies through resonant s-channel $e^+e^- \to H$ have also been proposed at FCC-ee [13] operating at a collison energy of 125 GeV, with sensitivies being able to reach down to 2 times SM prediction with 10 ab⁻¹ of integrated luminosity, depending, however, on good controls on beam spread.

This paper is organized as follows. Section 2 shows the ISR implementation in MAD-GRAPH. Section 3 describes the detector model, Monte Carlo (MC) simulation and samples used in the studies. Section 4 presents the measurements of $H \to e^+e^-$. The conclusion is summarized in Section 5.

2 ISR implementation in MadGraph

The Initial State Radiation (ISR) is an important issue in high energy processes, especially for lepton colliders. ISR affects cross section significantly, for example, reduces the ZH cross section by more than 10%. Following Whizard [14], we have implemented in Madgraph the lepton ISR structure function that includes all orders of soft and soft-collinear photons as well as up to the third order in hard-collinear photons. Comparisons can be seen in Fig. 2 for $e^+e^- \to ZH$, from which one can see the good agreement between Whizardam Madgraph with ISR included, on distributions of center-of-mass energy and Higgs transverse momentum. Similar checks have also been passed for other processes including for the process $e^+e^- \to W^+W^-$ and W^+W^-Z .

One should note that besides ISR, another macro effect at high luminosity electronpositron collider, beamstrahlung, also affects the cross section. In the storage ring the beamstrahlung effect makes the beam energy spread larger and reduces the center of mass energy [15]. The effect, however, are found to be small at CEPC.

Based on above progress, we are now able to generate signal samples in MADGRAPH with ISR effect included, for $e^+e^- \to ZH$, together with the decay of $H \to e^+e^-$ at matrix element level, thanks to the convinience of MADGRAPH.

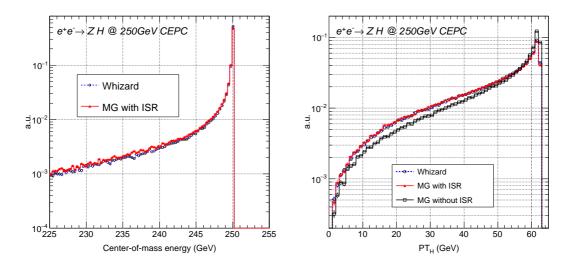


Figure 2. Comparisons plots on center-of-mass energy and Higgs transverse momentum, between WHIZARD and MADGRAPH with or without ISR effect included, for the process $e^+e^- \to ZH$.

3 Detector and Simulation

The analysis is performed on the MC samples simulated on the CEPC conceptual detector, which is based on the International Large Detector (ILD) [16, 17] at the ILC [18]. At CEPC, electron identification efficiency is expected to be over 99.5% for $p_{\rm T}$ larger than 10 GeV, and with excellent $p_{\rm T}$ resolution of $\sigma_{1/p_{\rm T}} = 2 \times 10^{-5} \oplus 1 \times 10^{-3}/(p_{\rm T}\sin\theta)$. More details can be checked in [9, 10].

For the signal process, $e^+e^- \to ZH$ with $H \to e^+e^-$, 50K events are generated by MADGRAPH V2.3.3 with ISR effect included, with Higgs mass set to be 125 GeV. For the backgrounds, WHIZARD V2.2.8 [14], are exploited as the event generator. All these samples are produced at the center-of-mass energy of 250 GeV.

The major SM backgrounds, including all the 2-fermion processes $(e^+e^- \to f\bar{f})$, where $f\bar{f}$ refers to all lepton and quark pairs except $t\bar{t}$) and 4-fermion processes (ZZ, WW, ZZ) or WW, single Z, single W). The initial states radiation (ISR) and all possible interference effects are taken into account in the generation automatically. The classification for four fermions production, is referred to LEP [19], depending crucially on the final state. For example, if the final states consist of two mutually charge conjugated fermion pairs that could decay from both WW and ZZ intermediate state, such as $e^+e^-\nu_e\bar{\nu}_e$, this process is classified as "ZZ or WW" process. If there are e^\pm together with its parter neutrino and an on-shell W boson in the final state, this type is named as "single W". Meanwhile, if there are a electron-positron pair and a on-shell Z boson in the final state, this case is named as "single Z". More details about the CEPC samples set can be found in reference [20].

Signal and background samples are further interfaced with PYTHIA 6 [21] for parton shower and hadronization, and then fully simulated with Mokka [22] and reconstructed with ArborPFA [23].

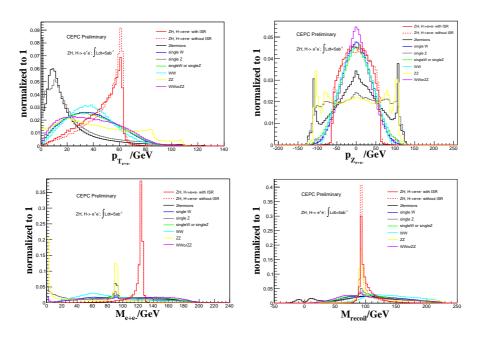


Figure 3. Distributions of $p_{\text{Te}^+e^-}$, $p_{\text{Ze}^+e^-}$, $M_{e^+e^-}$ and M_{recoil} for signals and backgrounds. Signals without ISR effect included are also superimposed for comparison.

4 Results

As mentioned in Section 1, signal events can be extracted with recoil mass method without using the decay information of the Z boson decay. The detailed event selections are listed as following: at least one pair of electrons with opposite charge is required, with final state radiation photon in included in the electron momenta. The pair with invaraiant mass $M_{e^+e^-}$ closer to Higgs mass is selected in case of multi-combinations, and required then to satisfy $120 < M_{e^+e^-} < 130 \,\text{GeV}$. The recoil mass M_{recoil} of e^+e^- is required to be greater than 90 GeV and less than 93 GeV, to be consistent with the Z-boson hypothesis. Fig. 3 shows signal and backgrounds distributions on various kinematic variables, where signal without ISR effect included are also superimposed for comparison.

To suppress 2-fermions background, it is required that the difference between the two electrons' azimuth angles should satisfy $\Delta\phi < 166^\circ$. In addition, to suppress background from 4-fermions background, the transverse momentum of electron pair and the scalar sum over Z-direction momentum, are required to $46 < p_{\text{Te}^+e^-} < 93\,\text{GeV}$ and $-42 < p_{\text{Ze}^+e^-} < 41\,\text{GeV}$, which can efficiently cut away ZZ and single Z backgrounds, as shown in Fig. 3. Finally, requirements are set on polar angle of each lepton particle, $\cos_{e^+} \geq -0.07$ and $\cos_{e^-} \leq 0.14$, as the electrons from Higgs boson are more uniformly distributed as it is a scalar particle. The selections of each variable as mentioned above are determined by maximazing the significance S/\sqrt{B} , where S is the number of signal events passing all the selection criteria, and B is the number of the corresponding background events number.

The cut chain table is shown in Table 1. The background yields are scaled to $5000fb^{-1}$. The signal yields starts from 50K before any selection, and the final efficiency is about 7.1%.

Category	signal	2fermions	single ZorW	single Z	single W
total	50000	418194802	1259165	7913405	17190655
$N_{e^+} \ge 1, N_{e^-} \ge 1$	47418	36822471	978594	3480494	2260761
$120 \text{ GeV} < M_{e^+e^-} < 130 \text{ GeV}$	34463	1954192	71193	126094	151950
$90 \text{ GeV} < M_{recoil} < 93 \text{ GeV}$	12362	61089	3564	6954	7255
$46 \text{ GeV} < p_{\text{Te}^+e^-} < 63 \text{ GeV}$	8582	6816	1863	1861	3652
$-42~{\rm GeV} < ~p_{{\rm Ze^+e^-}} ~ < 41~{\rm GeV}$	8511	6372	1783	1750	3468
$\Delta \phi < 166^{\circ}$	7404	5131	1696	1651	3233
$cos_{e^+} \ge -0.07, cos_{e^-} \le 0.14$	3564	241	86	48	161

Category	WW	ZZ	WWorZZ	total background
total	49115769	4967152	21902983	520543931
$N_{e^+} \ge 1, N_{e^-} \ge 1$	640839	758732	814608	45756499
$120 \text{ GeV} < M_{e^+e^-} < 130 \text{ GeV}$	26731	7593	55196	2392949
$90~{\rm GeV} < ~M_{recoil} ~< 93~{\rm GeV}$	1783	1464	2434	84543
$46~{\rm GeV} < ~p_{{\rm Te^+e^-}} ~< 63~{\rm GeV}$	868	682	1297	17039
$-42~{\rm GeV} < ~p_{{\rm Ze^+e^-}} < 41~{\rm GeV}$	837	647	1247	16104
$\Delta \phi > 166^{\circ}$	702	566	1182	14161
$cos_{e^+} \ge -0.07, cos_{e^-} \le 0.14$	20	178	70	804

Table 1. Yields for backgrounds and signals at the CEPC with $\sqrt{s} = 250$ GeV and integrated luminosity of 5000 fb⁻¹.

We have also exploited the Toolkit for Multivariate Analysis (TMVA) [24] for further background rejection, where the method of Boosted Decision Trees (BDT) is adopted and the selected variables for TMVA input are those as mentioned above. No significant improvement is found compared with the cut-based results, thus in this study, we provide only the latter.

After the event selections as mentioned above, we perform a $\mu S + B$ fit (with μ as the signal strength) on CEPC simulated data which is essential purely background as the SM predicted $H \to e^+e^-$ branch ratio is too low. As shown in Fig. 4, an unbinned maximum likelihood fit is performed on $M_{e^+e^-}$ spectrum, in the region of 120 GeV to 130 GeV. The Higgs signal shape is described by a Crystal Ball function, while the background is represented by a second order Chebychev polynomial function, whose parameters are fixed to the values extracted from the background samples. By scanning over signal strength in the $\mu S + B$ fit, one can extract the dependence of negative log likelihood on it. The 95% confidence level upper limit on $H \to e^+e^-$ branch ratio can then be decided to be 0.024%. This corresponds to a signal yield of around 20, while from Figure 4, the background yield under the Higgs peak is near 200, and thus by naively couting, $S/\sqrt{B} \sim 1.4$ which supports the above result from the shape analysis. Finally we mention that checks with different background modelling have also been done. With e.g. third order Chebychev polynomial function, the result improves a bit while the fit goodness gets worse.

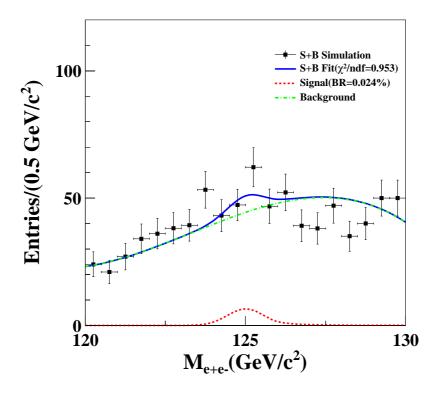


Figure 4. The invariant mass spectrum of e^+e^- in the inclusive analysis. The dots with error bars represent data from CEPC simulation. The solid (blue) line indicates the fit. The dashed (red) shows the signal (assuming $\mathcal{B}(H \to e^+e^-)=0.024\%$) and the long-dashed (green) line is the background.

5 Summary and Conclusions

The CEPC is expected to play a crucial role in understanding Higgs boson properties. In this paper, a probe on $H \to e^+e^-$ at CEPC is investigated with full simulated Higgsstrahlung signal at 5 ab⁻¹ integrated luminosity at 250 GeV center-of-mass energy. The upper limit at 95% confidence level on the production cross section times branching fraction for $e^+e^- \to ZH$ with $H \to e^+e^-$ are found to be 0.051 fb. This corresponds to an upper limit on the branching fraction of 0.024%. As a by-product, ISR effect has been implemented in Madgraph to generate the signal process. Finally, we mention that with similar framework, measurements for $H \to \mu^+\mu^-$ together with $\tau^+\tau^-$ at CEPC are being finalized [25], which show similar or even improved accuracy compared with the results for HL-LHC [26, 27].

Acknowledgments

This work is supported in part by the National Natural Science Foundation of China, under Grants No. 11475190 and No. 11575005, by the CAS Center for Excellence in Particle Physics (CCEPP), and by CAS Hundred Talent Program (Y3515540U1).

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