

Fast simulation of the CEPC detector with Delphes and its validation ^{*}

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Abstract: In this paper, the DELPHES is used to simulate the detector at the Circular Electron-Positron Collider (CEPC). The geometry and performance of the CEPC detector are presented and validated with a series of benchmark processes. The comparisons between DELPHES and the full simulation, which is based on Geant4 & Marlin, show that DELPHES simulates the CEPC detector well. The differences of physics analysis between hadron and lepton collider are also stressed.

Key words: CEPC, DELPHES, fast simulation

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1 Introduction

CEPC[1, 2] is a next generation electron-positron collider proposed by Chinese scientists. The machine is expected to collide electron and positron beams at the center-of-mass energy of 240 - 250 GeV to maximize the Higgs production cross section of the $e^+e^- \rightarrow ZH$ process, with an instantaneous luminosity of $2 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$. CEPC is designed to deliver a total of 5 ab^{-1} integrated luminosity with two detectors in 10 years, which means that over 10^6 Higgs events will be produced. The large statistics with clean backgrounds can enable CEPC to perform Higgs precision measurements, Standard Model (SM) tests, and searches for potential new physical phenomena. Theorists would get involved to test various new models to investigate the precisions and sensitivities of the CEPC. In order to save computing time and to simplify the procedure of full detector simulation and reconstruction, a dedicated fast simulation tool is highly demanded.

DELPHES [3] is a fast simulation framework developed in 2009, and the latest prime version was released in 2013, which is widely used for phenomenological studies on the simulation of various detector designs. The DELPHES framework simulates the response of a general purpose collider detector, whose components are organized concentrically with a cylindrical symmetry around the beam axis. The energy and momentum are simulated according to the detector resolutions and efficiencies re-

quired by users. Eventually, all kinds of particles are reconstructed with algorithm based on PFA[4] philosophy, then clustering into jets with FastJet [16].

This paper is organized as following. In Sect. 2, the CEPC detector geometry are briefly introduced. Then in Sect. 3, the MC generation, full simulation, and reconstruction chain are presented in detail, the data analysis of e^+e^- experiment is also discussed as well. In Sect. 4, a series of benchmark processes are chosen to validate the fast simulation on CEPC by comparing it with full simulation. In Sect. 5, the improvement of flavor tagging according to full simulation and its usage are introduced. In the end the conclusion remarks are presented.

2 The CEPC detector concept

The CEPC detector concept design[1] takes the ILC detector, ILD[5, 6], as a reference and adopts the philosophy of PFA, which benefits from its precision tracking system and high granularity calorimetry system.

The CEPC detector consists of three main sub-detectors and a superconducting solenoid of 3.5 T. The three sub-detectors are, from inner to outer, a hybrid tracking system composed of several silicon based devices and a Time Projection Chamber (TPC), a high granularity calorimetry system, and a Muon detector.

The hybrid tracking system has five parts. A vertex detector (VTX), constructed with high spatial resolution pixel sensor, is placed very close to the interaction point

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(IP) and the inner radius is only 16 mm. The VTX¹²⁰ provides very precision measurements of the impact parameters of tracks, which is used for the b -/ c -jet flavor¹²¹ tagging and τ -tagging. A Silicon Inner Tracker (SIT)¹²³ is just outside and cooperating with the VTX for vertex¹²⁴ reconstruction and flavor tagging. A set of Forward¹²⁵ Tracking Disks (FTDs) are placed in the forward region¹²⁶ to increase the geometric acceptance of tracking system¹²⁷ with coverage up to $|\cos\theta| = 0.99$. A Silicon External¹²⁸ Tracker (SET) and End-cap Tracking Disks (ETD) are¹²⁹ taken as the outermost layer of whole tracker system,¹³⁰ which provide precision position measurements of tracks¹³¹ entering the calorimetry system. The TPC, with a 2.35m¹³² half-length and 1.8m outer radius, provides over 200 hits¹³³ per track and 100 μm resolution in $r\phi$ plane, which al-¹³⁴lows for excellent pattern recognition, track reconstruc-¹³⁵tion efficiency, and potential dE/dx -based particle iden-¹³⁶tification. ¹³⁷

A calorimetry system consisting of Electromagnetic¹³⁸ Calorimeter (ECAL) and Hadron Calorimeter (HCAL)¹³⁹ with very fine granularity is placed inside the solenoid.¹⁴⁰ The system plays an essential role in the Particle-¹⁴¹Flow Algorithm (PFA), providing excellent separation of¹⁴² showers from different particles and jet energy resolution¹⁴³ of 3-4%. ¹⁴⁴

A superconducting solenoid of 3.5 T is surround-¹⁴⁵ing the calorimetry system. The return yoke is placed¹⁴⁶ outside the solenoid. The CEPC muon system acts as¹⁴⁷ the muon identifier, the solenoid flux return yoke and¹⁴⁸ the support structure for the whole spectrometer. High¹⁴⁹ muon detection efficiency, low hadron mis-identification¹⁵⁰ rate, modest position resolution and large coverage are¹⁵¹ the main concerns of the design. ¹⁵²

3 Monte Carlo samples, detector simulation, reconstruction, and analysis ¹⁵⁴

For the CEPC detector design and optimization, a¹⁵⁸ whole set of $e^+e^- \rightarrow ZH$ signal process and Standard¹⁵⁹ Model (SM) backgrounds have been generated [7] with¹⁶⁰ the generic Monte-Carlo generator Whizard 1.95 [8]. To¹⁶¹ simulate the detector response, a full simulation package,¹⁶² Mokka [9], based on Geant4 [10] and a fast simulation¹⁶³ framework of the DELPHES [3] are used. The Particle¹⁶⁴Flow Algorithm (PFA) philosophy is utilized in the re-¹⁶⁵construction of both the full and fast simulation. ¹⁶⁶

After full simulation, hits in different sub-detectors¹⁶⁷ are digitized properly and reconstructed with reconstruc-¹⁶⁸tion software Marlin [11]. A dedicated PFA, Arbor[12]¹⁶⁹ is used for particle reconstruction, and Pandora [13], an¹⁷⁰ alternative one, is taken as reference. All jets are recon-¹⁷¹structed with LCFIPlus package[14], where a $e^+e^- k_t$ al-¹⁷²gorithm [15], often referred to also as Durham algorithm,¹⁷³ is used for jet-clustering. ¹⁷⁴

The detector model implemented in the DELPHES is same as the one in full simulation with necessary simplifi-¹⁷⁵cations. For the charged tracks simulated with DELPHES,¹⁷⁶ there is a common strategy to smear their momentum.¹⁷⁷ The angular resolution is assumed to be perfect, so that¹⁷⁸ the smearing only applied to the transversal momen-¹⁷⁹tum. In practice, the resolution of their momentum is¹⁸⁰ described as a Gaussian and $\Delta(1/p_t) = a \oplus (bp_t)$, where¹⁸¹ a and b are taken same as CEPC pre-CDR. The recon-¹⁸²struction efficiency is 100% in the detector coverage since¹⁸³ the it is greater than 99% for $p_t > 0.1$ GeV. ¹⁸⁴

For neutral objects which mainly rely on the¹⁸⁵ calorimetry system, some points should be clarified. The¹⁸⁶ first, the fake rate for electrons, muons and photons is¹⁸⁷ not implemented in the current version of DELPHES ;¹⁸⁸ The second, photon conversions into electron-positron¹⁸⁹ pairs are ignored neither. Both the true photons and¹⁹⁰ electrons reaching calorimeter without a reconstructed¹⁹¹ track are considered as photon in DELPHES . The res-¹⁹²olutions of photon and neutral hadrons are taken from¹⁹³ pre-CDR, which are consistent those of full simulation. ¹⁹⁴

The overall reconstruction of particles implemented¹⁹⁵ in DELPHES is mainly based on a perfect PFA. For¹⁹⁶ the charged tracks, the reconstruction involves both the¹⁹⁷ tracker system and the calorimetry system. Since the res-¹⁹⁸olution of tracking system is better than this of calorime-¹⁹⁹ter in the CEPC energy region, it can be convenient to²⁰⁰ use the tracking information within the tracker accep-²⁰¹tance for estimating the charged particle momenta. The²⁰² efficiencies could be parameterized as a function of the²⁰³ energy and pseudo-rapidity. But it should be borne in²⁰⁴ mind that the detection efficiencies of fast simulation is²⁰⁵ higher than full simulation by about 5% per photon since²⁰⁶ the photon conversions is not simulated. ²⁰⁷

In order to get same performance of jet-clustering,²⁰⁸ $e^+e^- k_t$ algorithm is also used in fast simulation. The²⁰⁹ exclusive mode of fast jet is used and the input particles²¹⁰ are forced into fixed number of jets without any y_{ij} or²¹¹ P_t requirements, which can be applied at analysis stage. ²¹²

It is worthy to note that the analysis strategy at e^+e^- ²¹³ collider is different from the one of hadron colliders, such²¹⁴ as the Atlas and the CMS. The e^+e^- experiments have²¹⁵ much less backgrounds than hadron ones and almost pile-²¹⁶up free, and usually almost all final states particles of a²¹⁷ event are detected and used in analysis. For instance,²¹⁸ all the final physics objects will be used in the analysis²¹⁹ of $e^+e^- \rightarrow ZH$, with $Z \rightarrow \mu^+\mu^-$ and $H \rightarrow 2\text{Jets}$. As a²²⁰ consequence, the muon pair should be identified firstly²²¹ with both Pid and kinematic constrains. Then, the re-²²²main particles are forced into 2 jets with exclusive mode²²³ of $e^+e^- k_t$ jet-clustering algorithm. And any background²²⁴ contaminations of mis-combination can be suppressed in²²⁵ the final event selection with additional requirements. ²²⁶

4 Validation with full simulation

On the CEPC, the full simulation is achieved with Geant4 and several toolkits based on the LCIO framework[17]. Geant4[10] is a general simulation package suitable from single particle phenomena study to full scale detector simulation. In the current study, the geometric structure and material information of the CEPC have been encoded as CEPC_v1 configuration card, which is essentially for simulating the detector responds with Geant4. After the digitization, the detector responds are stored in the form of LCIO format. A user interface of LCIO, named as Marlin, is provided to read all the data from simulation and reconstruct them as hits, tracks, and clusters.

Tracks and clusters then will be interpreted as the reconstructed particles with Arbor algorithm[12]. The basic idea of Arbor algorithm is inspired by the fact that the shower spatial development in the calorimeter follows the topology of a tree. In calorimeter, if the distance of a pair of hits is less than a predefined threshold, a connector will be established for the pair. To avoid loop connectors or multiple connectors to a single hit, a cleaning procedure is implemented to ensure that at each hit there is at most one connector which with minimum angle to a well selected direction. After all tree structure of shower completed, the shower would be merged with a track if it is charged or not.

The fast simulation and its reconstruction in DELPHES must be validated by comparing the relative distributions of all types of physics objects to those of full simulation, as well as the efficiencies. Several benchmark processes are selected, which cover all the physics objects of CEPC experiments, such as leptons, photons, and jets.

4.1 $e^+e^- \rightarrow \mu^+\mu^-H$

The $e^+e^- \rightarrow \mu^+\mu^-H$ process is one of the most important analysis on at e^+e^- Higgs factory, which enables the model-independent measurement of Higgs mass and production rate. The di-muons come from Z boson decay and Higgs is tagged from the recoiling side, since the initial four-momentum is precisely defined. So the study on the recoil mass distribution produces important properties of the Higgs but without detecting any Higgs decay products. Fig. 1 shows the comparisons of invariant mass of and recoil mass against $\mu^+\mu^-$ pair between fast and full simulations. It can be found that these two are consistent very well.

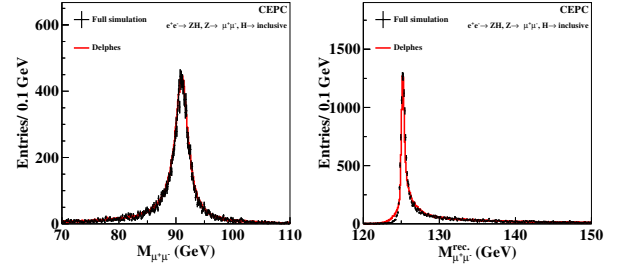


Fig. 1. The invariant mass (left) of and recoil mass (right) against $\mu^+\mu^-$ distributions in $e^+e^- \rightarrow ZH, Z \rightarrow \mu^+\mu^-, H \rightarrow \text{inclusive}$. The dot with error bar and red histogram represent full and fast simulation, respectively (same in the following plots).

4.2 $e^+e^- \rightarrow \nu\bar{\nu}H, H \rightarrow \gamma\gamma$

To validate the detection of photon in the CEPC detector conceptual design, the $e^+e^- \rightarrow \nu\bar{\nu}H, H \rightarrow \gamma\gamma$ is taken as an example. There are only two isolated photon in the final state if the initial state radiation (ISR) photons are neglected. Fig. 2 shows the comparison between fast and full simulation, it can be seen that the energy resolution of photon is well modeled by fast simulation. But it should be noted that the photon conversion effect is not taken into account in the fast simulation and its photon detection efficiency is higher than full simulation.

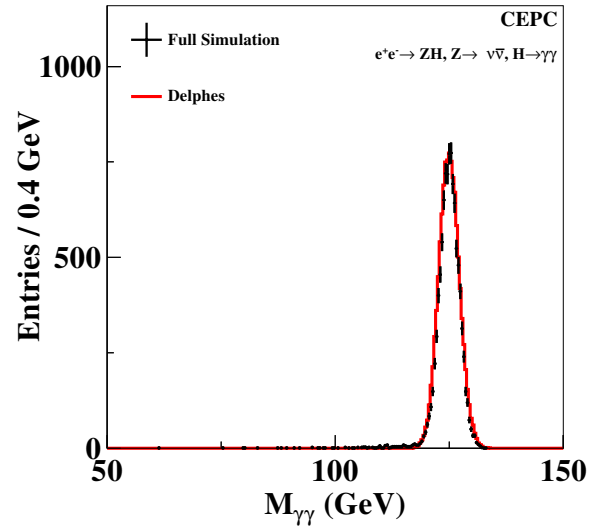


Fig. 2. The invariant mass distribution of di-photon system.

4.3 $e^+e^- \rightarrow \nu\bar{\nu}H, H \rightarrow WW^*$

The $e^+e^- \rightarrow \nu\bar{\nu}H, H \rightarrow WW^*$ process includes the Higgs-strahlung and WW fusion contributions. All the visible final state particles come from WW^* system except the ISR photon(s) and eventually from Higgs, which

contains all types of physics objects at the CEPC, such as jets, leptons, and photons and is very useful to validate the performance of fast simulation. The plots in Fig. 3 show distributions of the invariant masses of and recoil mass against all visible decay products of the process, which represent Higgs and Z (here it includes the WW fusion contribution), respectively.

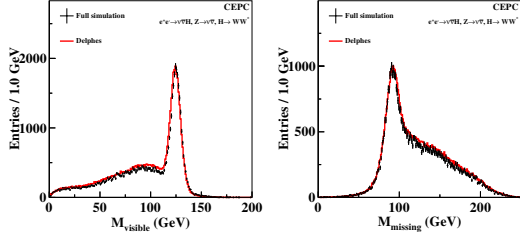


Fig. 3. The distributions of invariant mass(left) of and recoil mass (right) against WW^* system in $e^+e^- \rightarrow \nu\bar{\nu}H$, $H \rightarrow WW^*$.

4.4 $e^+e^- \rightarrow ZH \rightarrow 2(q\bar{q})$

The $e^+e^- \rightarrow ZH \rightarrow 2(q\bar{q})$ process contains four jets in the final states, which is very useful to validate the performances related jets, such as jet-clustering, jet energy resolution, and jet pairing, etc. In both full and fast simulation, all the final states particles are forced into four jets with ee_{kt} algorithm. The four jets are paired by minimize $\chi^2 = (M_{j_1,j_2} - M_Z)^2 + (M_{j_3,j_4} - M_H)^2$, where M_Z and M_H are the world averages of Z and Higgs boson masses. The invariant mass distribution of jet pairs are shown in Fig.4. From Fig. 4, it can be seen that both of the distributions are well consistent. In Fig. 5, the scattering plots of M_{j_1,j_2} vs. M_{j_3,j_4} demonstrate similar patterns in the available kinematic region.

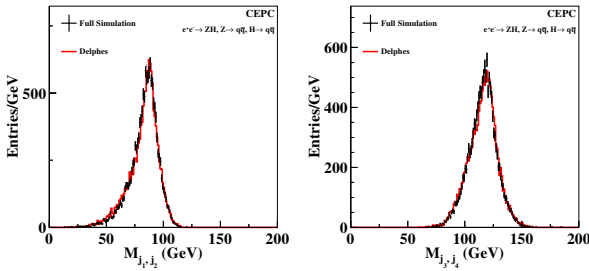


Fig. 4. The invariant mass distributions of the jet pairs, which are peaking at Z and Higgs masses.

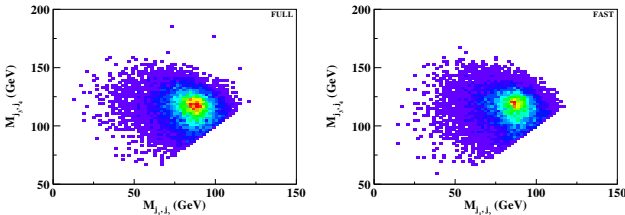


Fig. 5. The Scattering plots of M_{j_1,j_2} vs. M_{j_3,j_4} for full (the left) and fast (the right) simulations, respectively.

5 Flavor tagging based machine learning

In the original Delphes, the b -tagging is proceeding as following: the jet becomes a potential b jet candidate if a generated b is found within some distance $\Delta R = \sqrt{(\eta^{\text{jet}} - \eta^b)^2 + (\phi^{\text{jet}} - \phi^b)^2}$ of the jet axis. The probability to be identified as b depends on user-defined parameterizations of the b efficiency. The user can also specify a mis-tagging efficiency parameterization. But in the CEPC full simulation, the package LCFIPlus [14], which is based on machine learning (BDT) approach, is used for b/c -tagging. In this approach, jet flavor is identified based on a series of variables, up to 60, such as secondary vertex, jet shape and energy, etc. LCFIPlus attaches two real numbers, $btag$ and $ctag$, to each jet, which represent the probabilities of a jet to be a b/c and light jet ($1 - btag - ctag$).

In order to make a unified analysis procedure for fast and full simulations, each jet in fast simulation is also attached the same two real numbers according to the flavor of the corresponding generated jet and two dimensional distributions of b/c -tag of the full simulation.

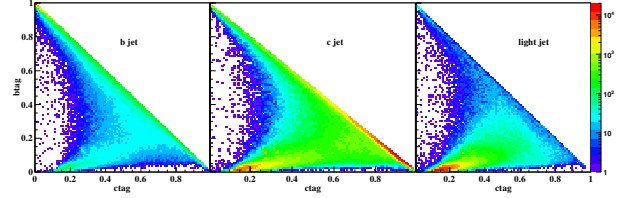


Fig. 6. Two dimensional distributions of b -tag versus c -tag for b , c and light jets, which are from full simulation and taken as input to fast simulation.

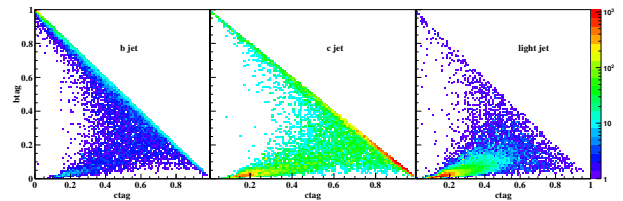


Fig. 7. Two dimensional distributions of b -tag versus c -tag for b , c and light jets, which are the output of fast simulation based on the full simulation input.

Fig. 6 and 7 demonstrate the input b -tag versus c -tag of various jet flavors of input distribution and the output fast simulation results, which can be seen that the fast simulation can reproduce the full simulation very well.

6 Conclusion

A dedicated fast simulation tool is essential for the CEPC phenomenological study. The fast simulation frame work of the CEPC detector based Delphes is introduced. To validate the performance, comprehensive comparisons between DELPHES fast and full simulation are performed. The results show well agreement between fast and full simulations on the CEPC.

On the analyses in high energy e^+e^- experiments, it is worthy to note that exclusive jet-clustering algorithm is favored in most cases, since it uses all final state particles and doesn't lose any available information. It also should be noted that the flavor tagging module are improved based on the machine learning results of full simulation, which is very useful since it provides a possibility to use the unified analysis procedure as full simulation.

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