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Precise simulation of drift chamber in the CEPC experiment

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Abstract. The Circular Electron Positron Collider (CEPC) is one of the future experiments which aims to precisely study the properties of the Higgs boson and to search for new physics beyond the Standard Model. To achieve that, it puts strict requirements on the particle reconstruction and identification ability of the CEPC detector. In order to obtain better particle identification performance, the drift chamber is chosen for the outer tracking detector which can provide information used by the cluster counting method for getting excellent particle identification performance. To evaluate the performance of the cluster counting method, it is necessary to develop a simulation tool that can be used to precisely simulate the response of the gaseous particle detector. This work proposes a new way to combine Geant4 and Garfield++ at the Geant4 step level for the drift chamber simulation. Due to the extreme time consumption of simulating the avalanche process in Garfield++, a fast signal response simulation method based on a neural network has been developed to replace detailed simulation. It shows the fast simulation can give consistent results with Garfield++ simulation and achieve the speedup by a factor of 200.

1. Introduction

The Circular Electron Positron Collider (CEPC) [1] is a large international scientific facility proposed by the Chinese particle physics community. The main goal of the CEPC experiment is to strictly test the Standard Model and search for new physics. It will focus on the Higgs physics and precise measurements of the properties of Higgs boson. To achieve that, the CEPC detector is required to have very good particle reconstruction and identification ability. An innovative detector design has been proposed which can be seen in Figure 1. The innermost detector is a silicon vertex detector which is surrounded by a silicon tracker (SIT). A drift chamber is placed between the second layer of SIT and the third layer of SIT which is used for obtaining better particle identification (PID) performance as well as it can work at high luminosity Z pole runs. The electromagnetic calorimeter consists of crystal bars which can give better π^0 and γ reconstruction with low cost. The scintillator glass is used for hadron calorimeter which has low cost and high density. A solenoid is put between the electromagnetic calorimeter and hadron calorimeter which makes the absorbers of the hadron calorimeter act as part of the magnet return yoke. Finally, the outermost part is the muon detector and yoke.

As explained in previous paragraph, the purpose of adding a drift chamber into the CEPC

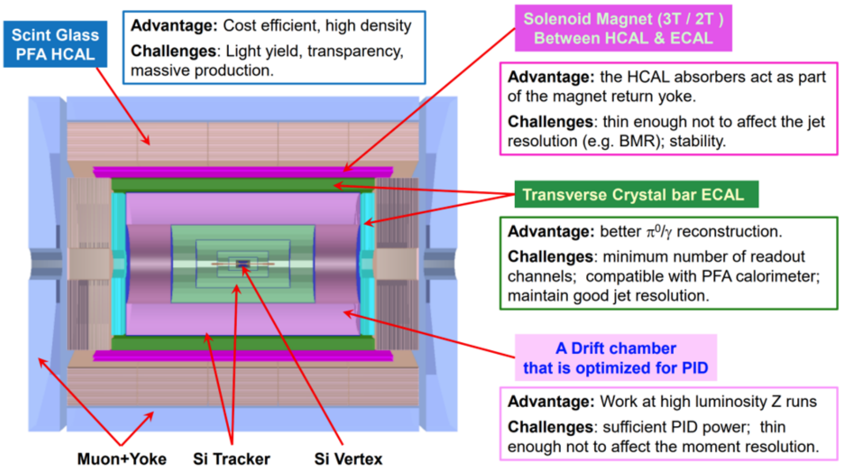

Figure 1. An innovative detector design of CEPC experiment.

detector is to improve the PID performance. Traditionally, the measurement of energy deposition per unit length (so-called dE/dx) is used for charged particle identification. Due to the delta-ray production and the gas gain effect, the dE/dx follows the Landau distribution. In order to get the expected dE/dx value, a truncated mean method is usually used, therefore reducing the measurement precision. Typically, the resolution for dE/dx is $\sim 6\%$.

With the development of electronics, another method called the cluster counting method [2] (so-called dN/dx) seems to become feasible. The number of clusters of avalanching electrons from primary ionization follow the Poisson distribution. By counting the number of clusters precisely, the resolution for dN/dx method could be better than 3% [3] which is extremely attractive. Therefore, to study the cluster counting method in detail in the CEPC experiment, a higher precision simulation for the CEPC drift chamber is necessary.

2. Integration of Geant4 and Garfield++

The software for the CEPC experiment is CEPCSW [4]. It consists of core software, external libraries (ROOT, Python, ...), and applications including simulation, reconstruction, and analysis. The Gaudi is used for the framework which defines interfaces to all software components and controls their execution. The CEPC-specific framework software includes generator, Geant4 [5] simulation, beam background mixing, fast simulation, machine learning interface, and so on. EDM4hep [6] is used for the generic event data model. DD4hep [7] is used for geometry and non-uniform magnetic field description.

For the drift chamber simulation, Geant4 is used to transport particles in the detector and simulate the interaction between particles and detector material. However, for the simulation of ionization in the gas, Geant4 can not do it precisely. Usually, Garfield++ [8] is used for precise ionization simulation in gas detectors with simple geometry (it does not simulate multiple scattering process). Therefore, it is necessary to combine Geant4 and Garfield++ to obtain a precise simulation of the drift chamber. The implementation of the combination will be described in Section 2.2. Due to the extremely time-consuming signal simulation for each cell using Garfield++, a fast simulation method based on machine learning has been developed which will be explained in Section 3.

2.1. Related work

This paper [9] has already described studies about how to combine Geant4 and Garfield++ for the simulation. The method it proposed is that the Geant4 PAI model is used to simulate primary or secondary ionization for charged particles. And when the kinetic energy of an ionized electron is lower than a threshold, it will be killed by Geant4. Then Garfield++ will take over the simulation of the killed electron to the end. We checked this simulation method in our study using π^- particle with different energy. Figure 2 shows the calculated energy of the gas ($50\%\mathrm{He}+50\%\mathrm{C_4H_{10}}$) versus the production cut which can be tuned in Geant4 simulation. From that plot, one can see once the production cut is tuned to be between 18 and 19 eV, the mean ionization energy of the gas is consistent with Garfield++ calculation. However, from Figure 3 which shows the ratio of the expected number of primary ionization between this method and Garfield++ standalone simulation versus the production cut, one can see that the number of primary ionizations produced by this method is much smaller than the one from Garfield++ standalone simulation. As the number of primary ionizations is vital for cluster counting method study, it is necessary to develop a new method for obtaining a more precise simulation of the drift chamber.

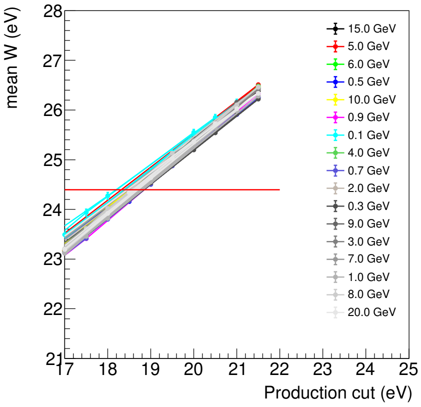

Figure 2. The calculated gas ($50\%\mathrm{He} + 50\%\mathrm{C_4H_{10}}$) mean ionization energy versus production cut from Geant4 simulation for different energy of π^-. Red horizontal line gives the value from Garfield++.

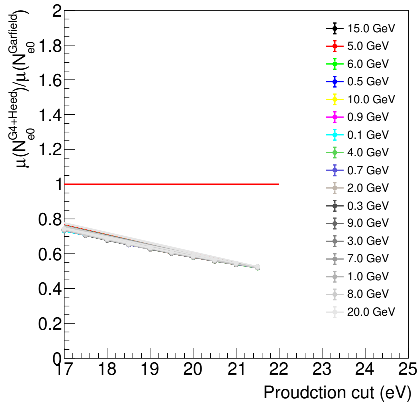

Figure 3. The ratio of expected number of primary ionization between Garfield++ simulation and Geant4 simulation for different energy of π^-.

2.2. Proposed methodology

In this study we introduced a new way to combine Geant4 and Garfield++ at the step level. We believe Garfield++ can give a more precise simulation of the ionization process. Therefore, Garfield++ is responsible for the ionization simulation. Geant4 is responsible for simulating the transition of particles in the detector and the interaction between the particle and detector material except for ionization simulation. For each step, Geant4 provides information which is needed for Garfield++ simulation, such as the type and momenta of charged particles. After ionization simulation, energy of the particle should be updated according to the energy loss in the ionization simulation. More specifically, in CEPCSW, a Gaudi tool is created for Garfield++

simulation task. The input of the tool is the G4Step information (including particle type, initial position, momentum, ionization path length). As we want to simulate the ionization with desired path length, a new Application Programming Interface (API) is added in Garfield++ for this purpose. This tool uses class TrackHeed (from Garfield++) to simulate one ionization. Information about produced primary ionization and total ionization (including position, time, cell id of the ionization) is saved in the event data model. Finally, total energy loss during the ionization simulation is returned by the tool and the kinetic energy of G4Track is updated according to the energy loss.

3. Machine Learning based signal simulation algorithm

In order to do a cluster counting study, one needs to simulate the signal waveform for each drift chamber cell. Garfield++ can do signal simulation precisely. However, it is extremely time-consuming due to simulation of the avalanche process. For example, it takes about $\mathcal{O}(1)$ to $\mathcal{O}(10)$ seconds just to simulate one electron signal and a few hours for one track. Therefore, it is necessary to develop a faster signal simulation method. A study of single-electron signals shows that single-electron signal differs only in the beginning time and in the amplitude, which depends on the local position of the electron in the cell. If the beginning time and the amplitude are normalized, all single-electron signals are almost the same. Therefore, we can simulate the single-electron signal by simulating its beginning time and amplitude according to the local position of the ionized electron in the drift chamber cell. Then, as done by Garfield++, we can pile up all single-electron signals which come from the same drift chamber cell and it gives the final signal waveform for this drift chamber cell. To simulate the relationship between the local position of an ionized electron and the signal's beginning time and amplitude, a machine learning method is used.

3.1. Data sample and neural network model

The data used for training is from Garfield++ standalone simulation. The size of the drift chamber cell is set to be 1×1 cm^2. A signal wire with 2000 V is placed at the center of the cell. Eight field wires with 0 V are placed in the edge of the cell (four at the middle of each side, four at four corners). The gas is 50%He + 50%C_4H_{10}. Total of 500k single-electron events are simulated with their position uniformly distributed in the cell, 350k events are used for training, 150k events are used for testing.

The model is a fully connected neural network. It consists of input, hidden, and output layers. The input layer contains 3 inputs which are local x and y positions of ionized electron, and a random number sampling from standard normal distribution. There are 2 hidden layers and each layer has 814 neurons. ReLU is used as activation function after each hidden layer. The output layer has 2 outputs, one for predicting the beginning time of the signal and another for predicting the amplitude of the signal, respectively. The loss function used is a differentiable two-sample test statistics [10] between the prediction and the label. The Adam is used as optimizer.

3.2. Performance

Performance of the neural network is shown in Figure 4. It is the single-electron signal amplitude versus the local x position of the electron for Garfield++ simulation and neural network simulation. One can see that result from neural network simulation is very close to the one from Garfield++ simulation which means the model performs well. Similarly, the beginning time of single-electron signal versus the local x position of the electron for Garfield++ simulation and neural network simulation is shown in Figure 5. Again, these two results are almost the same. As for cluster counting study, it will use the final waveform information from each drift chamber cell to reconstruct the cluster size. Therefore, the quality of final waveform should be

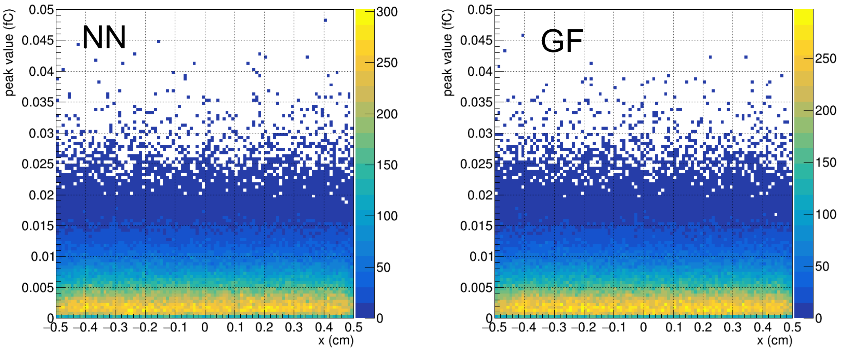

Figure 4. The amplitude of the signal versus local x position of electron simulated by neural network (left) and Garfield++ (right).

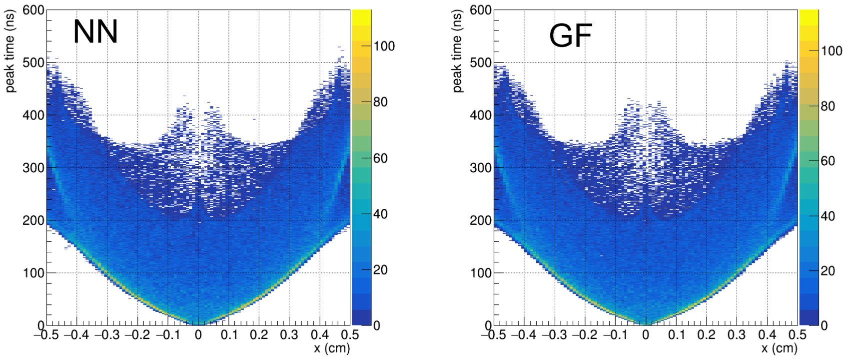

Figure 5. The begin time of the signal versus local x position of electron simulated by neural network (left) and Garfield++ (right).

checked for this neural network based signal simulation method. Figure 6 shows the number of found peaks (by using find_peaks algorithm from scipy python package) of the waveform by simulating 1 GeV electrons passing through a drift chamber cell. It can be seen that the results from neural network simulation is consistent with Garfield++ simulation. This means the final waveform simulated by neural network based method can be used to replace the Garfield++ simulation.

For the simulation time, Garfield++ needs ∼250 s for 1 GeV π^- passing through the cell for one event. For the same event, the neural network based simulation takes only ∼1 s. Therefore, it gives more than 200 speed-up. Moreover, by using the neural network simulation method, the signal simulation is not related to Geant4 and it is independent between each ionized electron which means the GPU or multi-threading techniques can be easily applied if we want to further speed up the simulation.

4. Summary

A precise simulation of the drift chamber is vital for the CEPC experiment. This article introduced a new way to combine Geant4 and Garfield++ for this purpose. For each Geant4 step simulation, the class TrackHeed from Garfield++ is used to simulate the ionization process, then the kinetic energy of the primary particle is updated according to the energy deposition in the ionization simulation. Due to the extremely time-consuming signal simulation in Garfield++, a

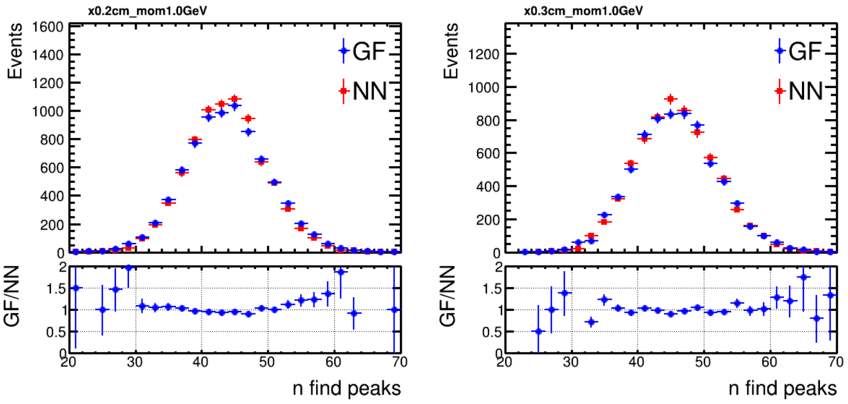

Figure 6. The number of found peaks for the cell signal waveform when 1 GeV electron pass through different place (x position equal 0.2 cm for left plot and x position equal 0.3 cm for right plot) of the drift chamber cell. Blue histogram is from Garfield++ simulation, red is for neutral network simulation.

fast simulation method based on the neural network has been developed to overcome the speed bottleneck. Results from the fast simulation are consistent with Garfield++ simulation and speed up of more than 200 times can be achieved. Last but not least, methods from this article could benefit other future collider experiments such as Future Circular Collider (FCC) [11] and Super Tau Charm Factory (STCF) [12] which are also working on exploring the cluster counting method by using the drift chamber.

Acknowledgments

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References

[1] Group T C S 2018 CEPC Conceptual Design Report: Volume 2 - Physics & Detector (*Preprint* `1811.10545`)
[2] Caron J F *et al.* 2014 *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment* **735** 169–183 ISSN 0168-9002
[3] Cuna F *et al.* 2021 Simulation of particle identification with the cluster counting technique (*Preprint* `2105.07064`)
[4] CEPCSW `https://github.com/cepc/CEPCSW`
[5] Geant4, a simulation toolkit `https://geant4.web.cern.ch/node/1`
[6] EDM4HEP `https://github.com/key4hep/EDM4hep`
[7] DD4HEP `https://github.com/AIDASoft/DD4hep/releases/tag/v01-18`
[8] Garfield++ `https://garfieldpp.web.cern.ch/garfieldpp/`
[9] Pfeiffer D *et al.* 2019 *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment* **935** 121–134 ISSN 0168-9002
[10] Djolonga J and Krause A 2017 Learning Implicit Generative Models Using Differentiable Graph Tests (*Preprint* `1709.01006`)
[11] Abada A *et al.* 2019 FCC-ee The Lepton Collider : Future Circular Collider Conceptual Design, report Volume 2 Eur. Phys. J. Spec. Top.228 (2019) 261-623
[12] Peng H 2018 High Intensity Electron Positron Accelerator (HIEPA), Super-Tau-Charm-Facility (STCF) in China, talk at Charm2018, Novosibirsk, Russia, 21–25 May (2018), pg. 501