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Development of CEPC Drift Chamber Software

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on behalf of the CEPC DC software working group

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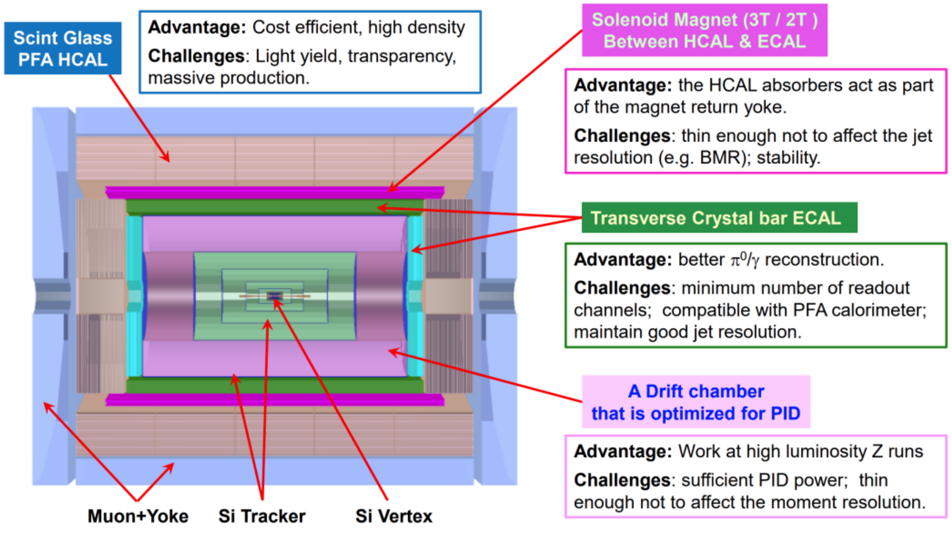
Detector Design

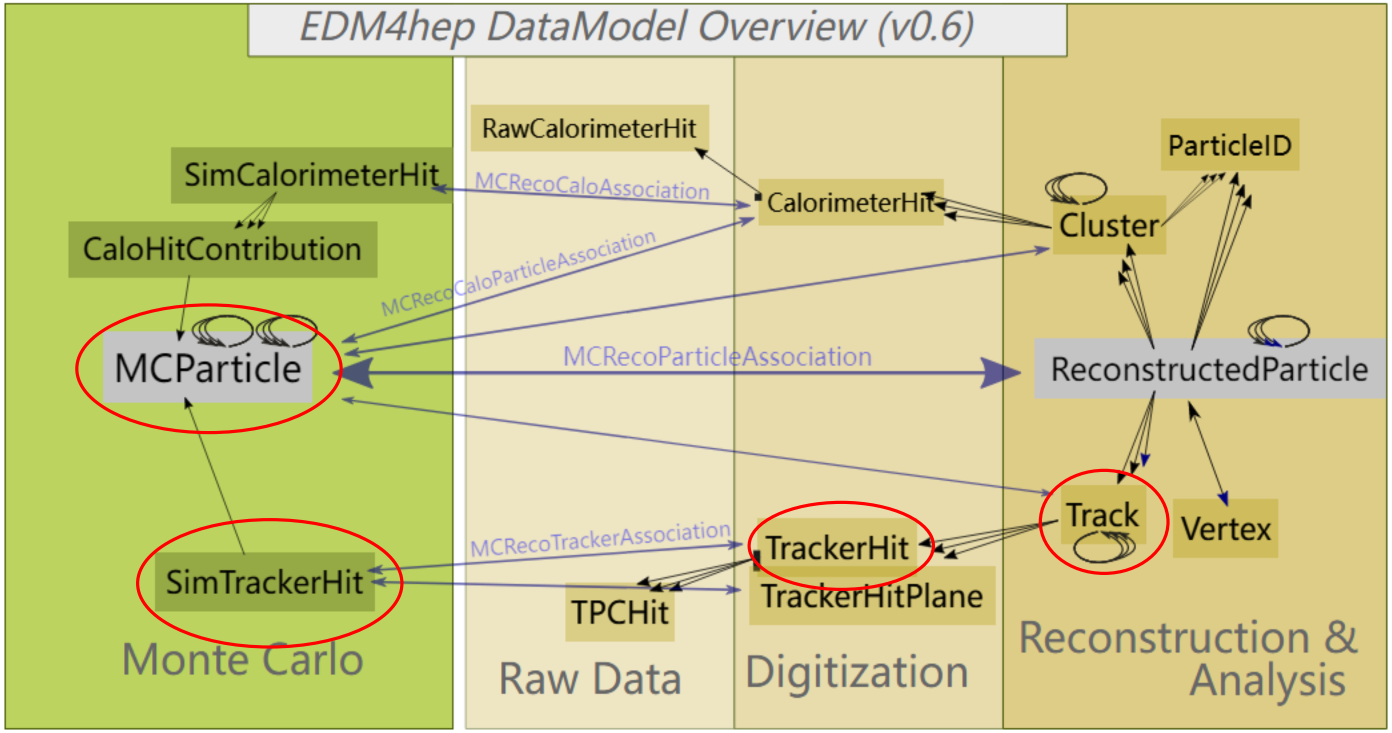
- The CEPC experiment mainly aims to precisely measure the property of the Higgs boson.
- Physics requirements: high track efficiency (~100%), momentum resolution (<0.1%), PID (2σ p/K separation at P < ~ 20 GeV/c), etc.
- For the 4th conceptual detector, silicon detector and drift chamber (DC) are designed to provide both tracking and PID for charged particles.
- Both detector design and physics potential studies needs strong support of simulation and reconstruction software.



Half length	2980 *mm*
Inner and outer radius	800 to 1800 *mm*
# of Layers	100/55
Cell size	~10x10mm/18x18mm
Gas	He:C_4H_{10}=90:10
Single cell resolution	0.11 *mm*
Sense to field wire ratio	1:3
Total # of sense wire	81631/24931
Stereo angle	1.64~3.64 *deg*
Sense wire	Gold plated Tungsten ϕ=0.02*mm*
Field wire	Silver plated Aluminum ϕ=0.04*mm*
Walls	Carbon fiber 0.2 *mm*(inner) and 2.8 *mm*(outer)

Event Data Model (1)

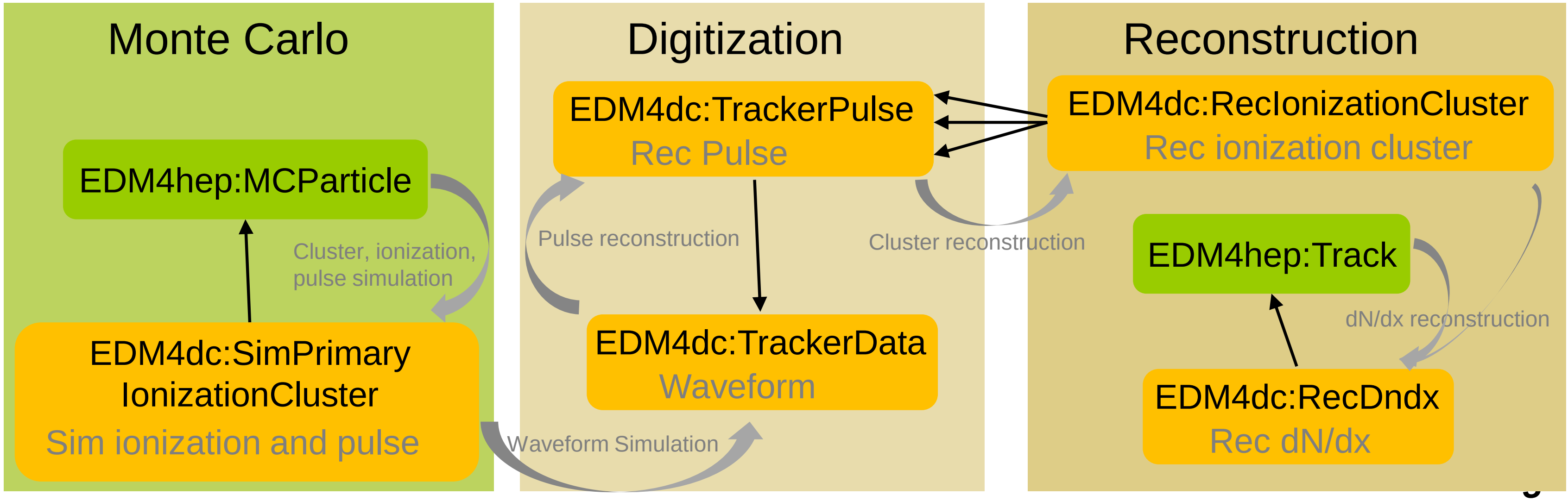
- EDM4hep is the common event data model (EDM) being developed for the future experiments like CEPC, CLIC, FCC, ILC, etc.



- EDM4hep describes event objects created at different data processing stages and also reflects the relationship between them.
- For the drift chamber, MCParticle, SimTrackerHit, TrackHit, Track have been used since the begin of the software project.

Event Data Model (2)

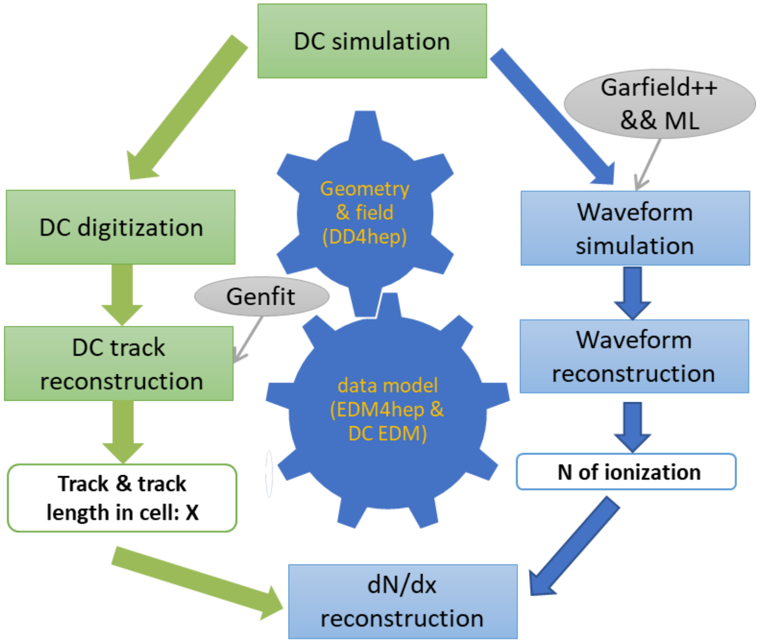
- As the development progressed, the previous versions of EDM appeared not able to fit all the requirements brought by newly added detector like the CEPC' s drift chamber.
- Due to the strong flexibility of EDM4hep, TPCHit was extended to accommodate the new needs:
  - Discussions inside EDM4hep group and also with the IDEA-CEPC drift chamber working group
  - By using the upstream mechanism of PODIO, a common EDM was implemented for both TPC and drift chamber



Data Processing Flow

❖ Detector simulation

- Geant4 is employed to simulate particle's propagation (including particle decay) in the detector, interaction with detector material, etc.
- TrackerHeed (from Garfield++) is used to simulate ionization process of charged particles (e, μ, π, K, p, ...) when they pass through the drift chamber.
- Garfield++ was integrated with the CEPCSW to simulate but its extreme computation intensiveness makes it impossible



Drift chamber simulation and reconstruction flow

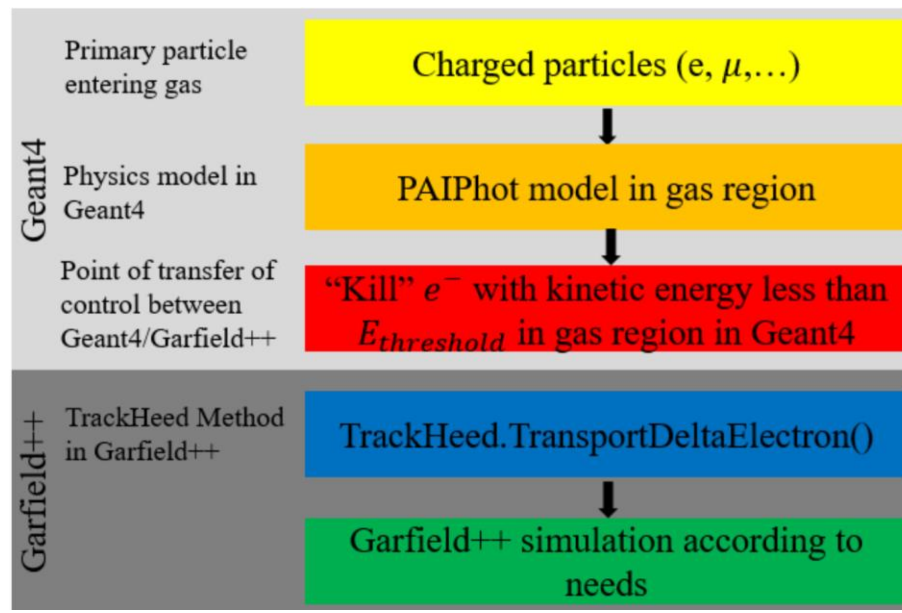
- Machine learning (ML) based simulation: training data is created by Garfield++ and ML model is be executed to replace Garfield++ in the detector simulation.

❖ Reconstruction

- Extrapolating the track segment found in the inner silicon detector to drift chamber, collecting the hits on the path, and applying a Kalman Fit to the found track .
- dN/dx reconstruction: waveform reconstruction + path length calculation

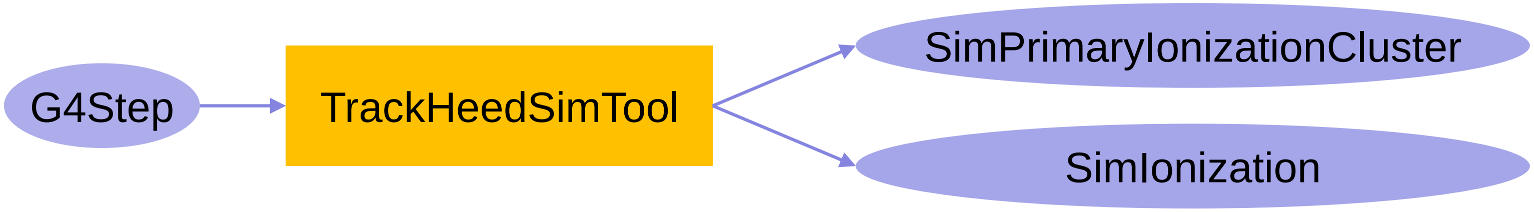
Simulation of Gaseous Detector (1)

- Since Geant4 can not be used to simulate the ionization process properly (arXiv:2105.07064), Garfield++ becomes a common tool for precise ionization simulation.
- “Interfacing Geant4, Garfield++ and Degrad for the Simulation of Gaseous Detectors” studied how to combine Geant4 and Garfield++ to get correct energy deposition or total number of ionized electrons (adopted by COMET experiment)
- Method:
  - Geant4 PAI (Photo Absorption Ionization) model to simulate primary or secondary ionization
  - TrackHeed (from Garfield++) to simulate ionization from residual delta electron



Simulation of Gaseous Detector (2)

- TrackHeedSimTool (Gaudi tool) was implemented for using TrackHeed to do ionization simulation
  - Input: G4Step information (particle type, initial position and momenta, ionization path length)
  - Use TrackHeed (used by Garfield++) to simulate one step length (or multi-step length for speed up) ionization (new API contributed to Garfield++ PR)
  - Output: primary and total ionization information (contains position, time, cell id), saved in EDM
  - The kinetic energy of G4Track will be updated according to the energy loss in the ionization
  - Non-uniform magnetic field can be handled easily

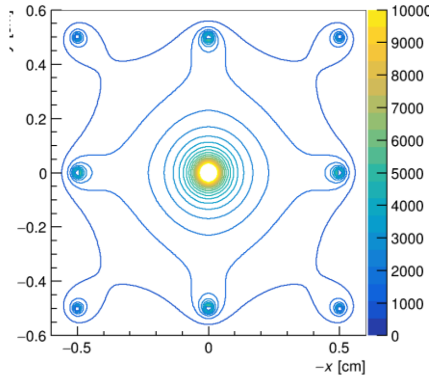


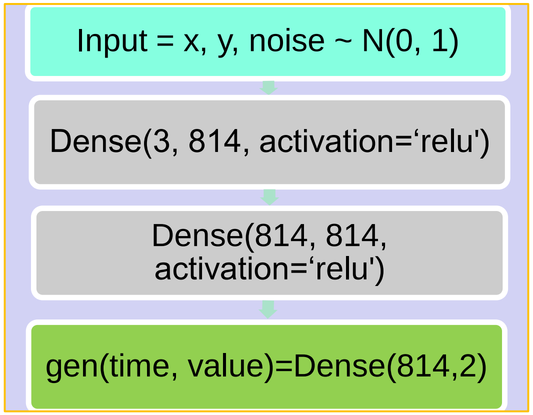
- Garfield++ is precise but extremely time consuming, it takes $\mathcal{O}(1)$ to $\mathcal{O}(10)$ seconds to simulate an electron (a few hours for one track)

ML-based dN/dx Simulation

- Garfield++ simulation events:
  - 350k single electron event with electron position uniformly distributed $1 \times 1\ \mathrm{cm}^2$ drift chamber cell
  - Gas: 50% He + 50 % C_4H_{10}
  - Center signal wire (2000 V), eight field wires (0 V)
- Model: fully connected neural network
  - Consist of input, hidden, and output layers
  - Input: Local x and y positions of ionized electron, N(0,1) distribution noise
  - Output: peak time and value of the single-electron signal
- Loss: a differentiable two-sample test statistics based on smoothed k-nearest neighbor tests (arXiv:1709.01006) between real data and generated data

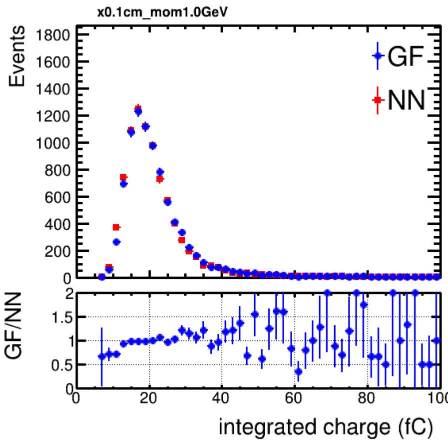
Electric field contour plot

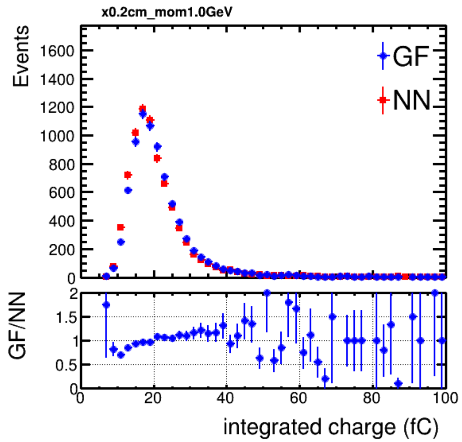


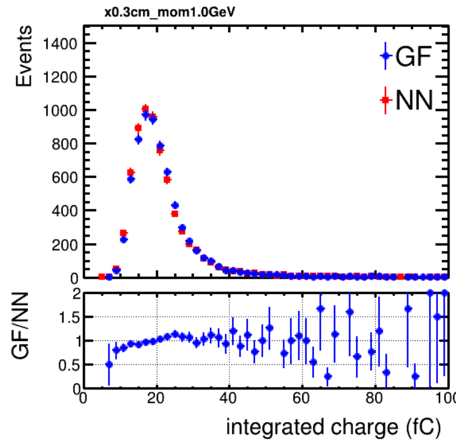


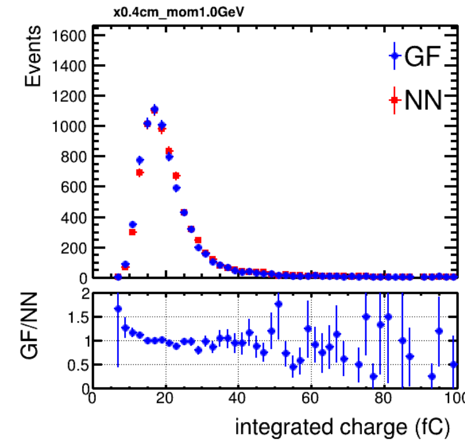
Mini-batch training: using Faiss (fast similar search) to get a batch (1024) of closet data (L2 distance)

dN/dx Simulation Performance (1 GeV e-)







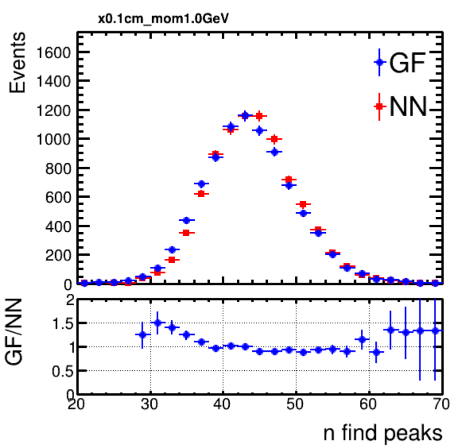


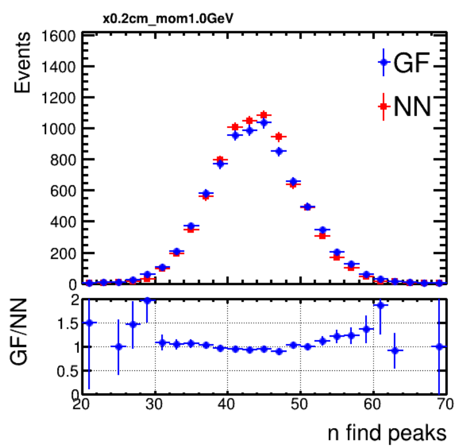
x=0.1 cm

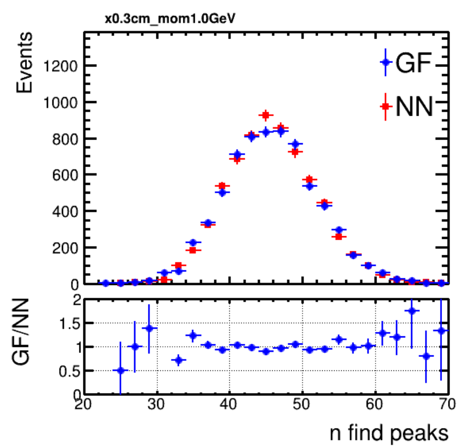
x=0.2 cm

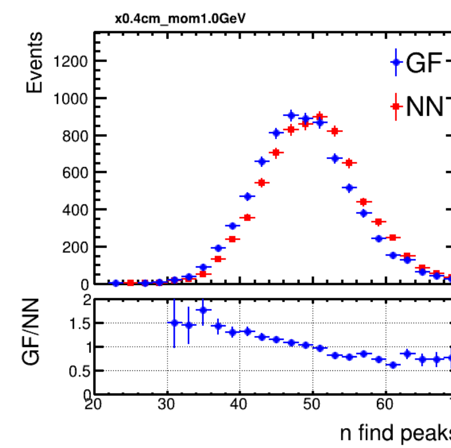
x=0.3 cm

x=0.4 cm



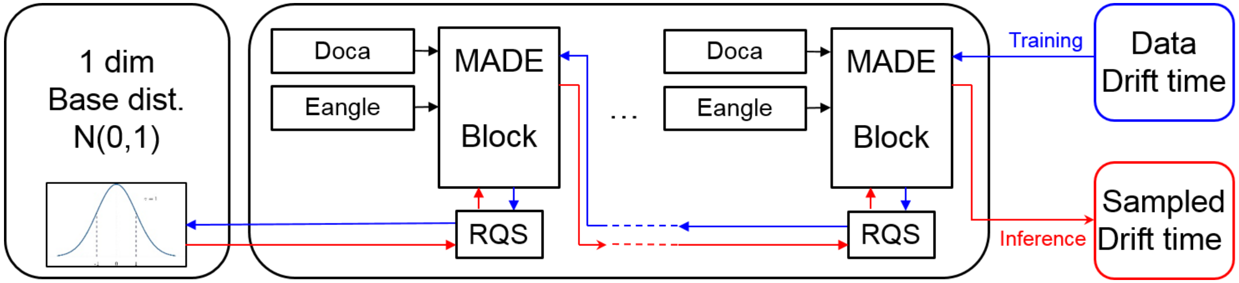




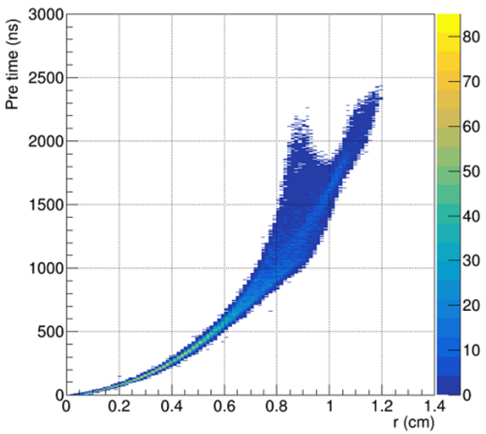


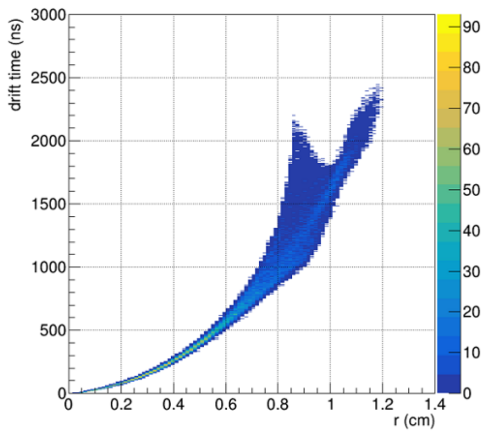
- Checked total integrated charge and number of found peaks(using scipy.signal.find_peaks)
- Good agreement in general (a little bias for the number of found peaks for x=0.4 cm. Could be improved in future), Similar results for other energy points (0.5, 5, and 10 GeV)

Simulation of Drift Time (3)



- Normalizing Flow network was adopted
  - A similar model to CaloFlow is used, RQS (for transformation)+MADE block (for the parameters of RQS)





- By using the NN model, the drift time can be simulated as well:
  - Drift time versus distance of closest approach (Doca) between a track and the signal wire

Performance Validation with BESIII Data (1)

- To investigate the possibility of applying ML to simulation, the real data from the BESIII experiment was used evaluate the performance of the chosen neural network.
- Radiative bhabha events were selected to study the simulation of drift time in the chamber cell
  - X-T relation: the Doca versus drift time

Prepare experimental data for training

↓

Learn drift time distribution: $D_{drift\ time} = f(doca, eangle, layer)$

↓

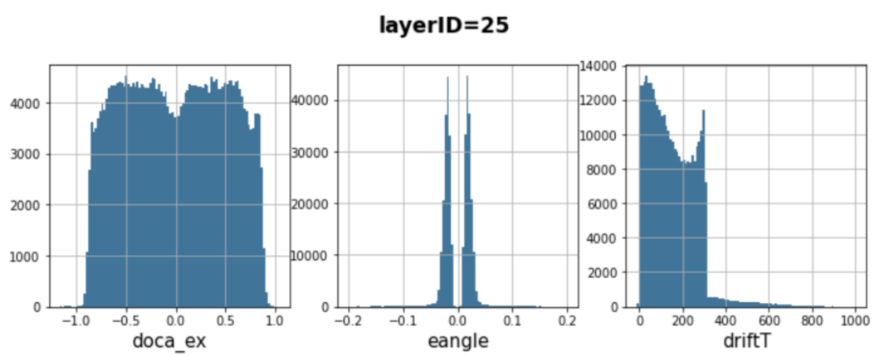
Check $D^{data}_{drift\ time}$, $D^{NN\ sim.}_{drift\ time}$

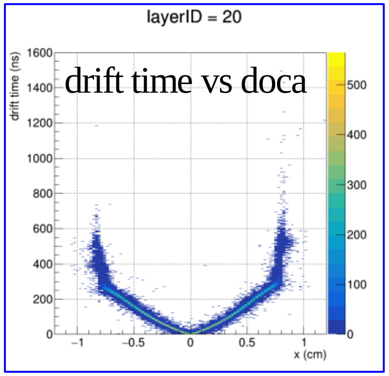
↓

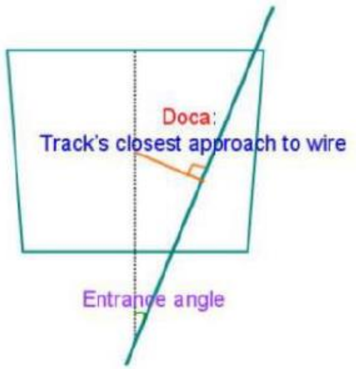
check the X-T cure: C^{data}_{X-T} , $C^{NN\ sim.}_{X-T}$

↓

check spatial resolution: using C^{data}_{X-T} , $C^{NN\ sim.}_{X-T}$

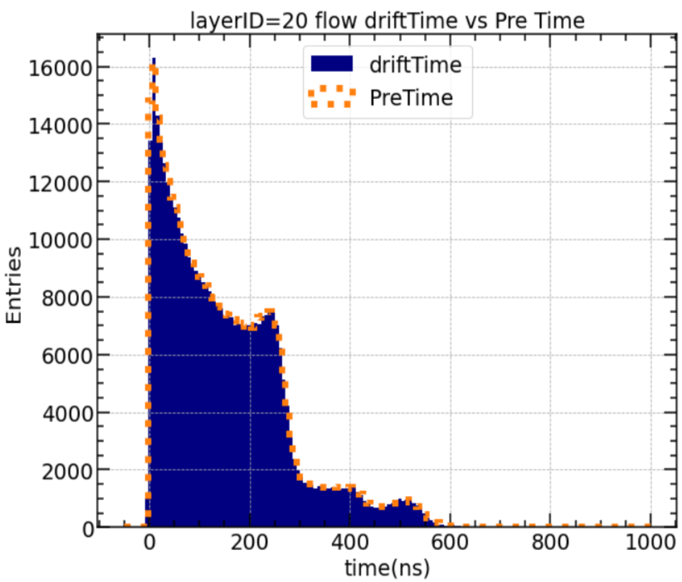


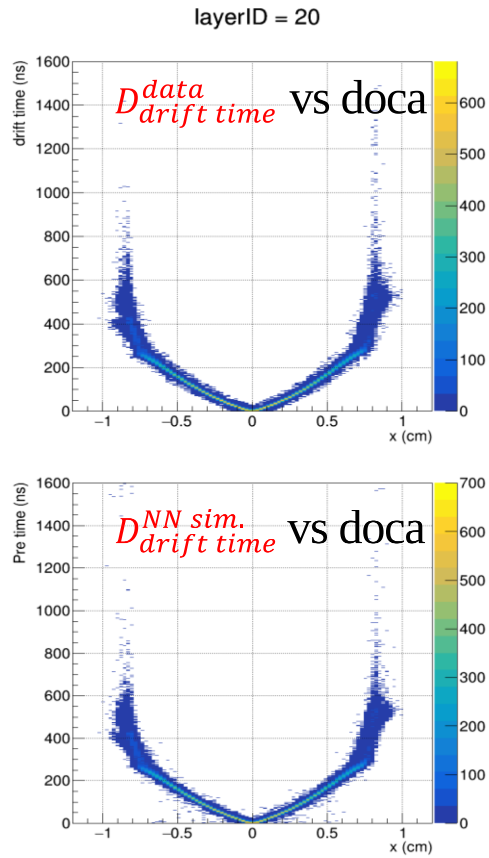




Performance Validation with BESIII Data (2)

- Comparison of drift time distributions between real data and ML-based simulation



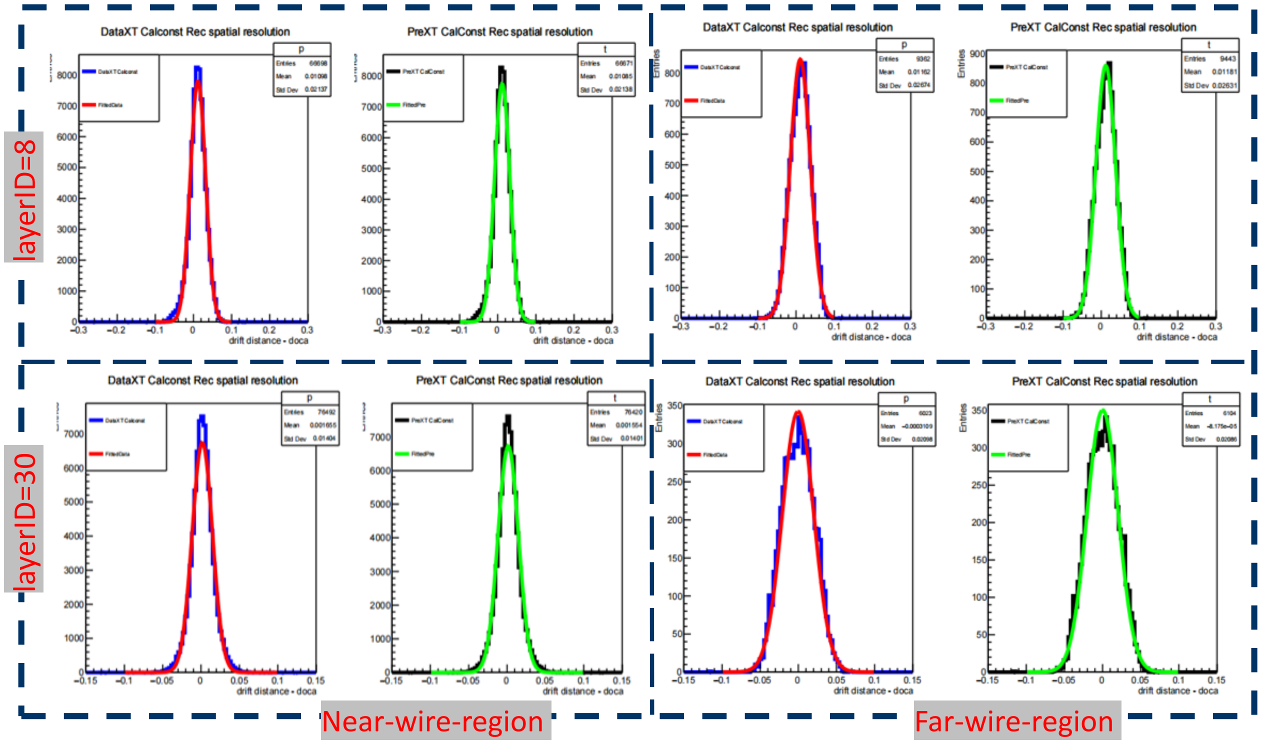


- Prepare experimental data for training
- Learn drift time distribution: $D_{drift\ time} = f(doca, eangle, layer)$
- Check $D^{data}_{drift\ time}$, $D^{NN\ sim.}_{drift\ time}$
- check the X-T cure: C^{data}_{X-T} , $C^{NN\ sim.}_{X-T}$
- check spatial resolution: using C^{data}_{X-T} , $C^{NN\ sim.}_{X-T}$

- Good agreement was found

Performance Validation with BESIII Data (3)

- Checked the spatial resolution of reconstructed tracks, using C_{X-T}^{data} and $C_{X-T}^{NN\,sim.}$ (calibration constants)



layerID	Near-wire-region (C_{X-T}^{data} v.s. $C_{X-T}^{NN\,sim.}$)		Far-wire-region (C_{X-T}^{data} v.s. $C_{X-T}^{NN\,sim.}$)	
	mean	sigma	mean	sigma
8	0.01096/0.01085	0.02137/0.02138	0.01162/0.01181	0.02674/0.02631
30	0.001055/0.001564	0.01404/0.01401	-3.1e-4/-5.1e-5	0.02060/0.02086

Prepare experimental data for training

↓

Learn drift time distribution: $D_{drift\ time} = f(doca, eangle, layer)$

↓

Check $D_{drift\ time}^{data}$, $D_{drift\ time}^{NN\,sim.}$

↓

check the X-T cure: C_{X-T}^{data}, $C_{X-T}^{NN\,sim.}$

↓

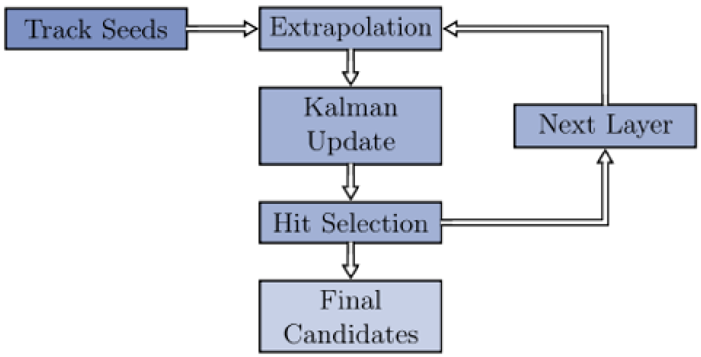
check spatial resolution: using C_{X-T}^{data}, $C_{X-T}^{NN\,sim.}$

- Consistent spatial resolution results obtained for C_{X-T}^{data} and $C_{X-T}^{NN\,sim.}$
- The NN can learn the drift time from the data

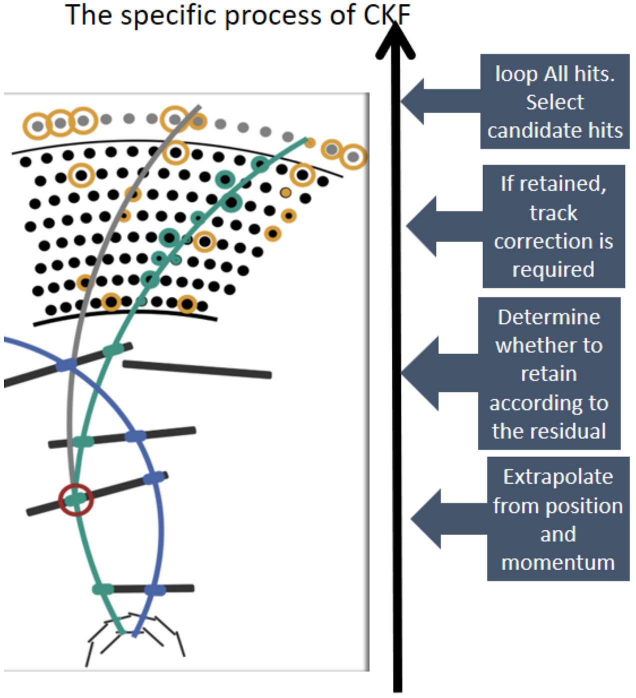
Track Reconstruction

- Tracking with Combinatorial Kalman Filter (CKF) method
  - Combining track recognition and track fitting
  - Used by many high energy physics experiments
- Track finding with CKF in the drift chamber
  - Implementation: track segments reconstructed in the silicon dectctor, called seeds, are extrapolated to the DC and all the DC hits belonging to the track are collected
- Current progress:
  - Managed to port the Belle II code to the CEPCSW
  - Performance validation is ongoing

Basic procedure behind the CKF

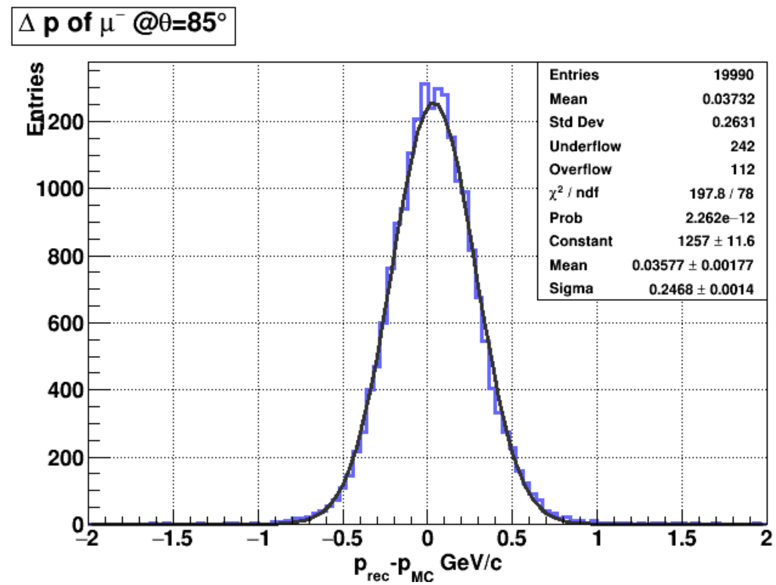


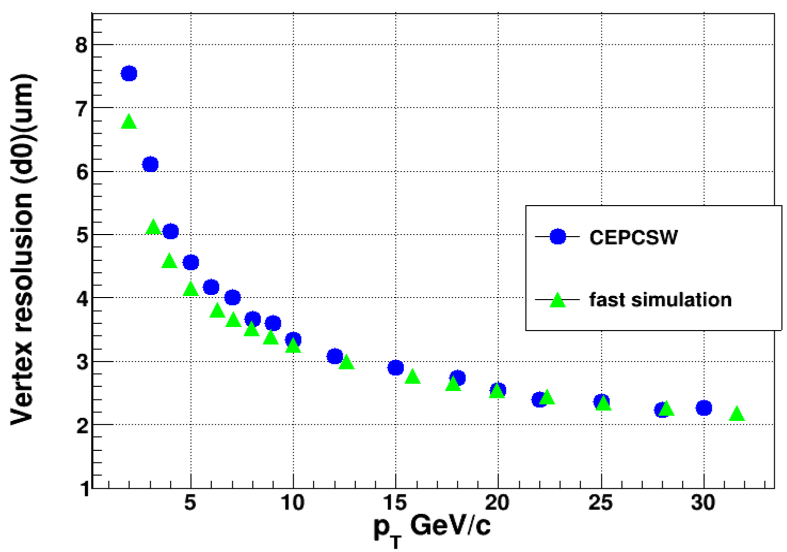
The specific process of CKF

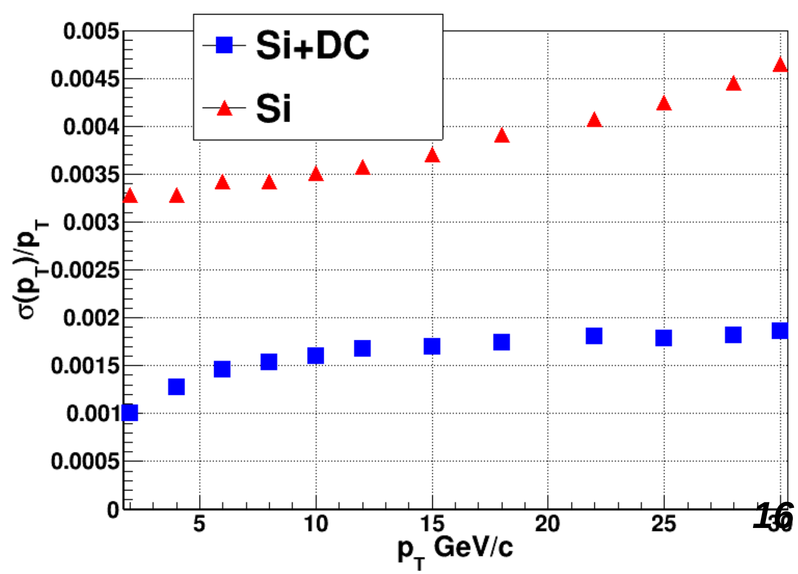


Tracking Performance (1)

- Tack recognition using the MC truth information was also implemented
- Genfit is adopted as the track fitter
  - using kalman filter method
  - non-uniform magnetic field field and material effects are taken into account
- Momentum/vertex resolution
  - Particle gun : mu- , 100 GeV@85°

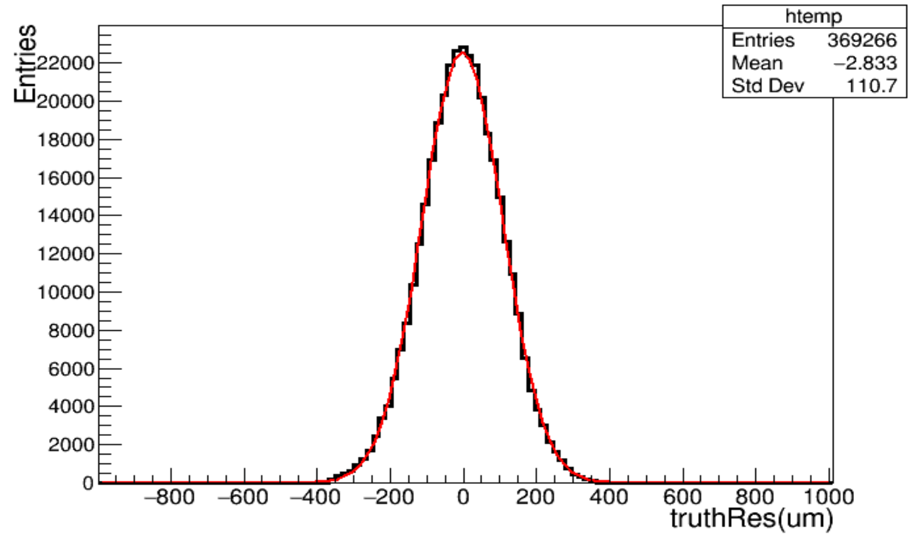


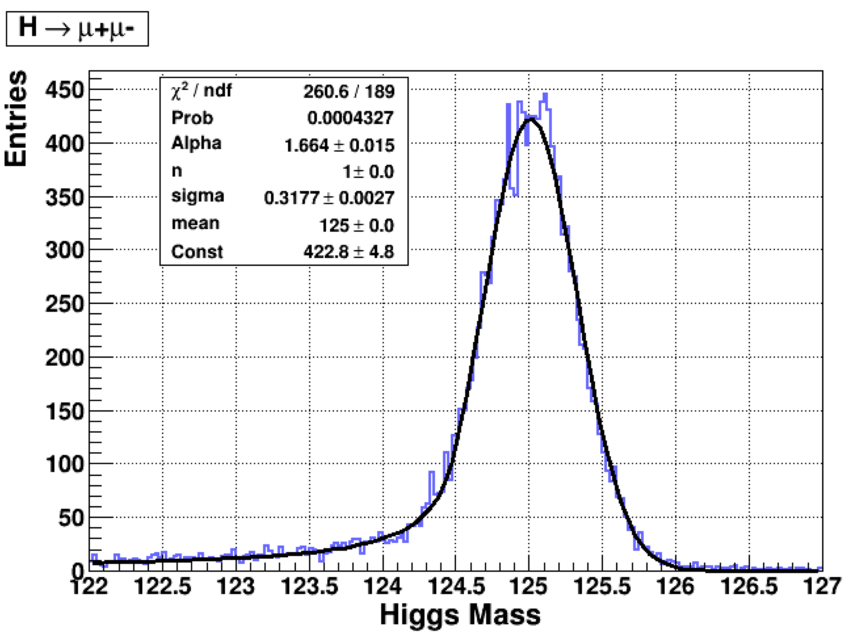


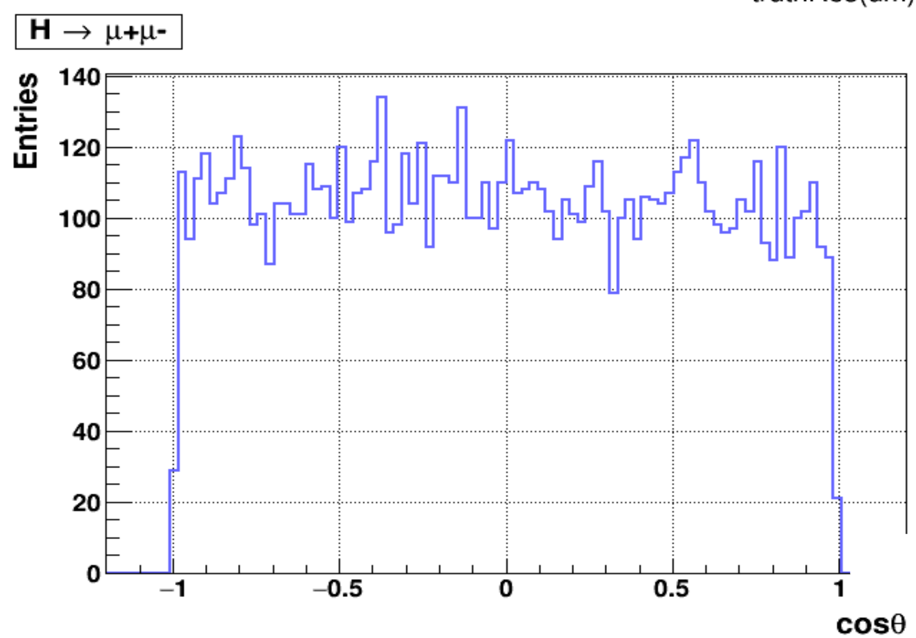


Tracking Performance (2)

- Spatial resolution
  - Spatial resolution: 110 um
  - Consistent with the value set in the simulation
- Events with two muons :
  - $e^+e^- \rightarrow ZH\,, H \rightarrow \mu^+\mu^+$







Summary

- As part of the Key4hep project, event data model of TPC detector was extended to accommodate the requirements from cluster counting studies.
- In CEPCSW, Garfield++ was integrated with the Geant4 to perform a precise simulation for the drift chamber.
- Machine learning based simulation was developed to model the response of the chamber cell.
- Tracking algorithm was implemented by reusing the code of Belle II and performance validation is still in progress.

Thank You！

谢谢