中国科学院高能物理研究所
Institute of High Energy Physics
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Progress in Drift Chamber Software

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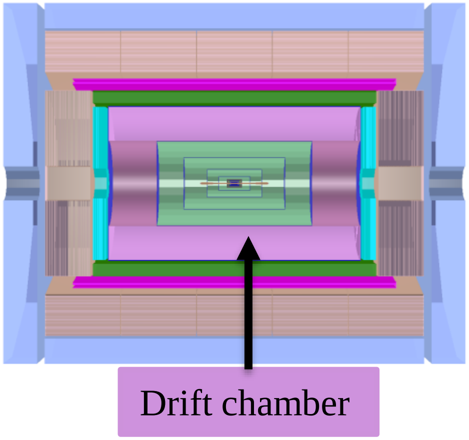
on behalf of the CEPC DC software working group

The CEPC day (2022.12.19)

Introduction

- The CEPC experiment aims to measure the property of the Higgs boson precisely
  - Requirements: high track efficiency (~100%), momentum resolution (<0.1%), PID (2σ p/K separation at P < ~ 20 GeV/c), …
  - Precise simulation is needed as it gives precise results

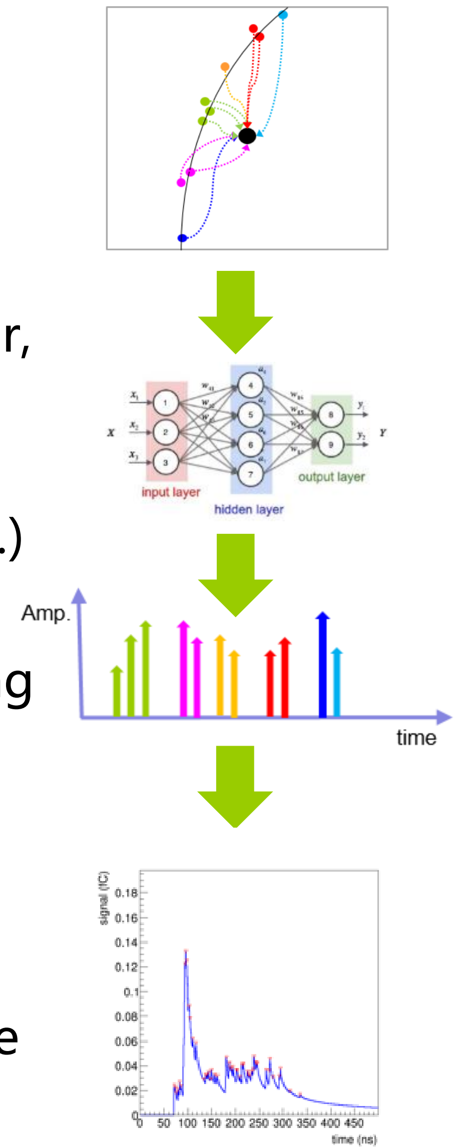
- The 4th conceptual detector design adopts silicon + drift chamber (DC) for tracking system
  - The DC: track reconstruction and PID (dN/dx+dE/dx)



- Performance of the DC needs to be studied with precise simulation

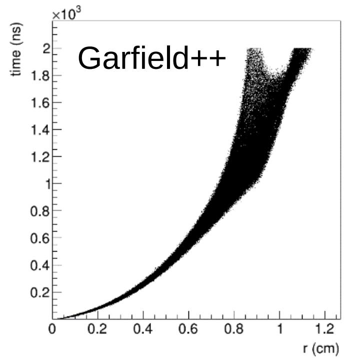
Towards precise DC simulation

- Originally driven by the dN/dx study:
  - Needs precise ionization simulation, waveform simulation
  - Geant4 + TrackerHeed + NN model is adopted
  - Geant4: for particle propagation (decay) in the detector, interaction with detector material, …
  - TrackerHeed (from Garfield++): used for ionization process simulation for charged particles (e, μ, π, K, p, …)
  - NN model: is used for fast pulse simulation for each ionized electron (primary particle independent), training data is from Garfield++
  - More details in this [talk]
  - Shortcoming, the space charge effect can not be simulated
    - arXiv:2211.06361, RPC simulation with space charge effect (dynamic update of the electric field)



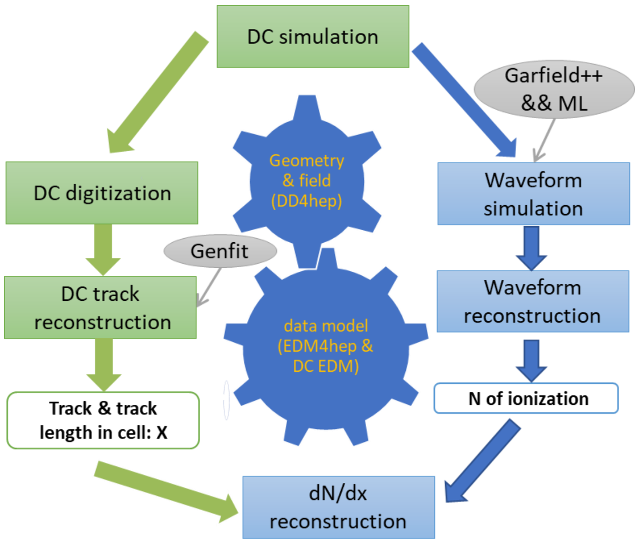
Towards precise drift time simulation

- The measurement of the earliest drift time for a fired DC cell is important for track reconstruction, as it will be converted to closet distance (between track and signal wire, via X-T relationship) and be input for tracking
- In previous: constant drift velocity V_{drift}=40μm/ns & fixed spatial resolution: σ=110μm
- Although the Garfield++ has some difficulties in space charge effect simulation, the earliest drift time simulation is almost independent of the space charge effect and can be simulated precisely
- Idea: learn drift time distribution from Garfield++ and apply it in the simulation



Overview of the DC software

- The drift chamber software has been developed from scratch
- The CEPCSW
  - Gaudi-based framework
  - External libraries and tools (Geant4, ROOT, …)
- Geometry and field map
  - DD4hep, supports a non-uniform magnetic field
- Data model
  - EDM4hep and FWCore
  - dN/dx event model extension

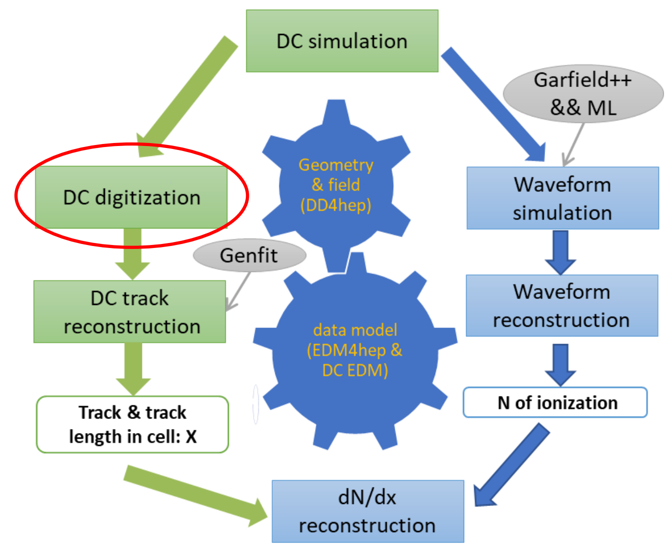


Drift chamber simulation and reconstruction flow

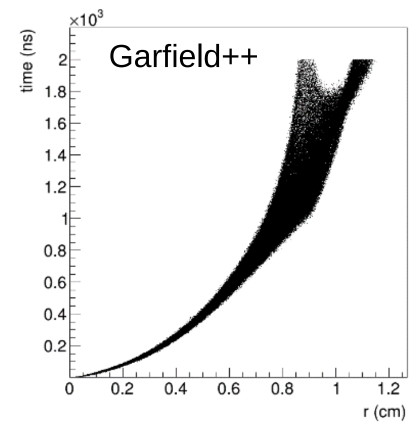
Half length	2980 *mm*
Inner and outer radius	800mm to 1800 *mm*
# of Layers	100/55
Cell size	~10mmx10mm/18mmx18mm
Gas	He:iC_4H_{10}=90:10
Single cell resolution	0.11 *mm*
Sense to field wire ratio	1:3
Total # of sense wire	81631/24931
Stereo angle	1.64~3.64 *deg*
Sense wire	Gold plated Tungsten ϕ=0.02*mm*
Field wire	Silver plated Aluminum ϕ=0.04*mm*
Walls	Carbon fiber 0.2 *mm*(inner) and 2.8 *mm*(outer)

The DC digitization

- In DC digitization
  - Time and charge measurements will be given for fired DC cells
  - The earliest drift time will be assigned to the measured time of this DC cell
  - Drift time simulation plays a role
- In DC track reconstruction:
  - Calibrated X-T relationship is used, which converts measured time to closet distance (between track and signal wire) which will be used for track reconstruction
- Full working flow:
  - 1, learn drift time from Garfield++ (NN) (this talk)
  - 2, do X-T calibration
  - 3, check the track reconstruction performance



Drift chamber simulation and reconstruction flow



Proof of the feasibility

- To proof of the feasibility of NN can learn complex drift time distribution, real data from the BESIII experiment is used
- Dataset: radiative Bhabha event
  - Detailed event selection [link]

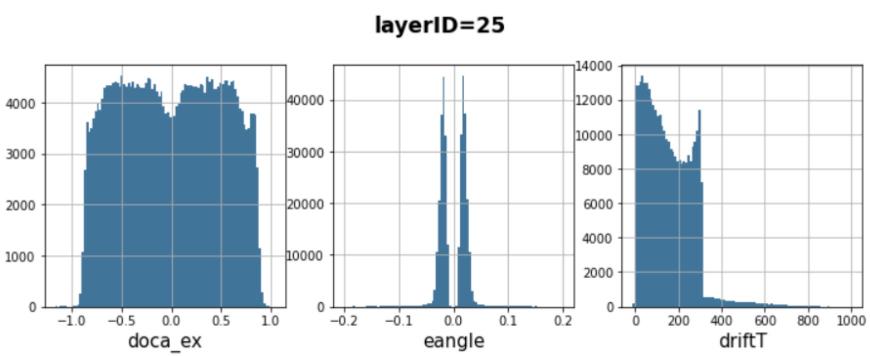
Prepare experimental data for training

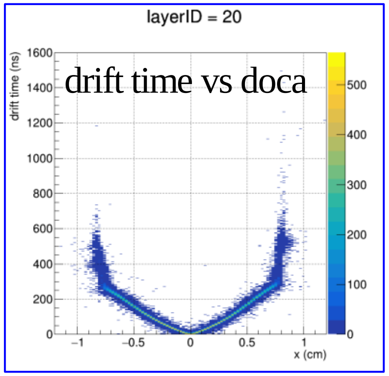
Learn drift time distribution: $D_{drift\ time} = f(doca, eangle, layer)$

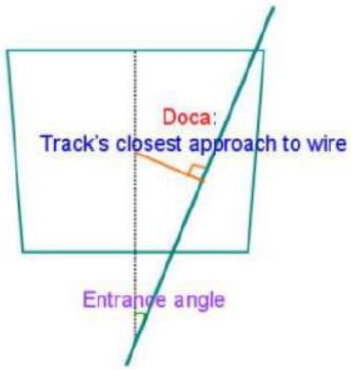
Check $D^{data}_{drift\ time}$, $D^{NN\ sim.}_{drift\ time}$

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

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

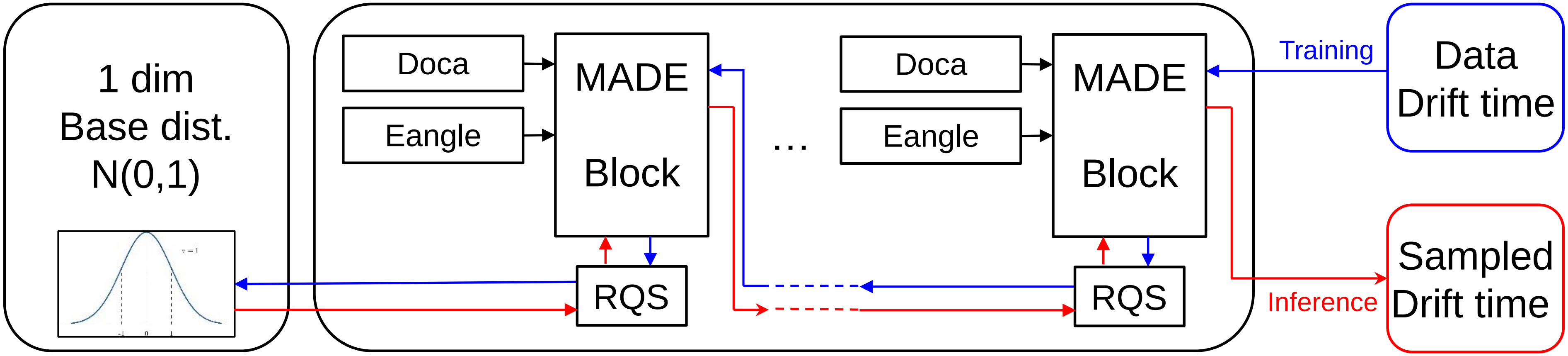




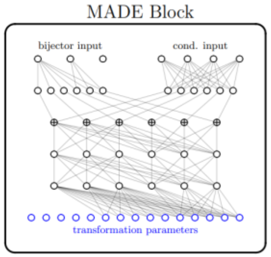


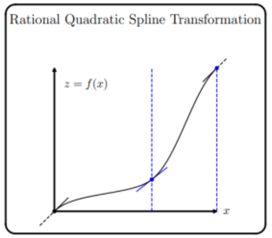
The NN model

- The Normalizing Flow is adopted:
  - Learning bijective transformation between two distributions(e.g. drift time ~ N(0,1))
  - Compared to GAN, it is much easier to train (stable and convergent)
  - Reference to the CaloFlow, a similar model is used, RQS (for transformation)+MADE block (for the parameters of RQS)



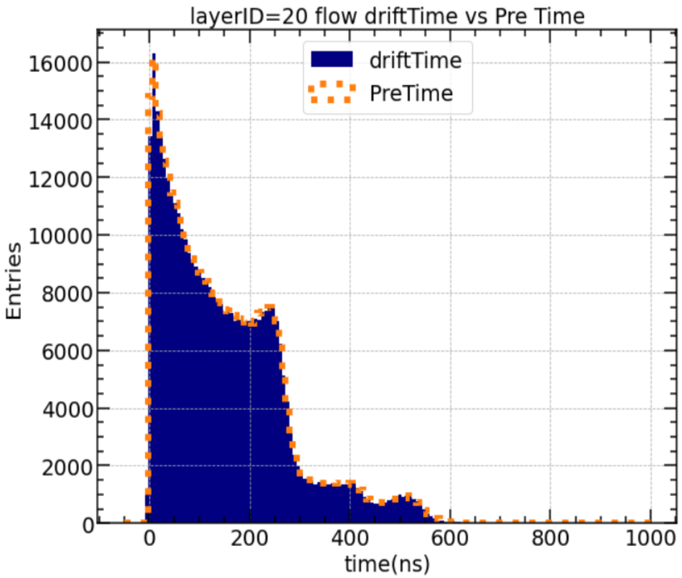
Base distribution	Number of MADE blocks	Layer sizes			Number of RQS bins
		input	hidden	output	
1-dim Standard Normal	6	64	3×64	23	8

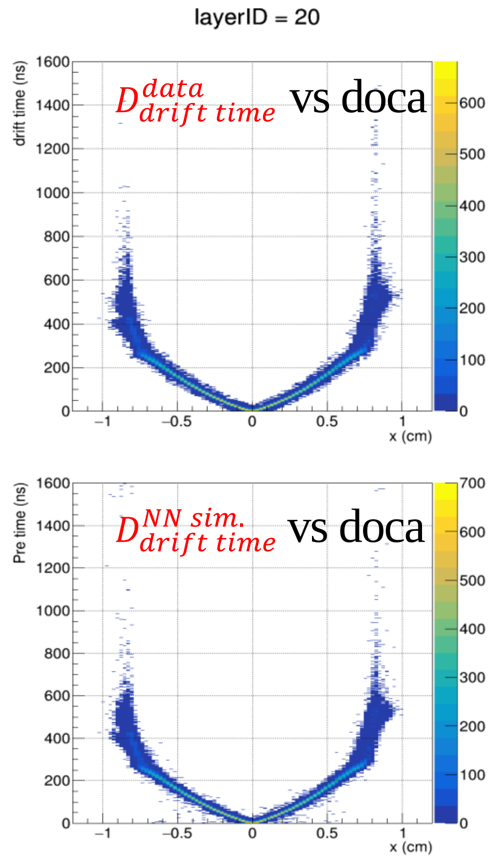




NN simulation performance

- Compared the drift time distribution between data and NN simulation





Prepare experimental data for training

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

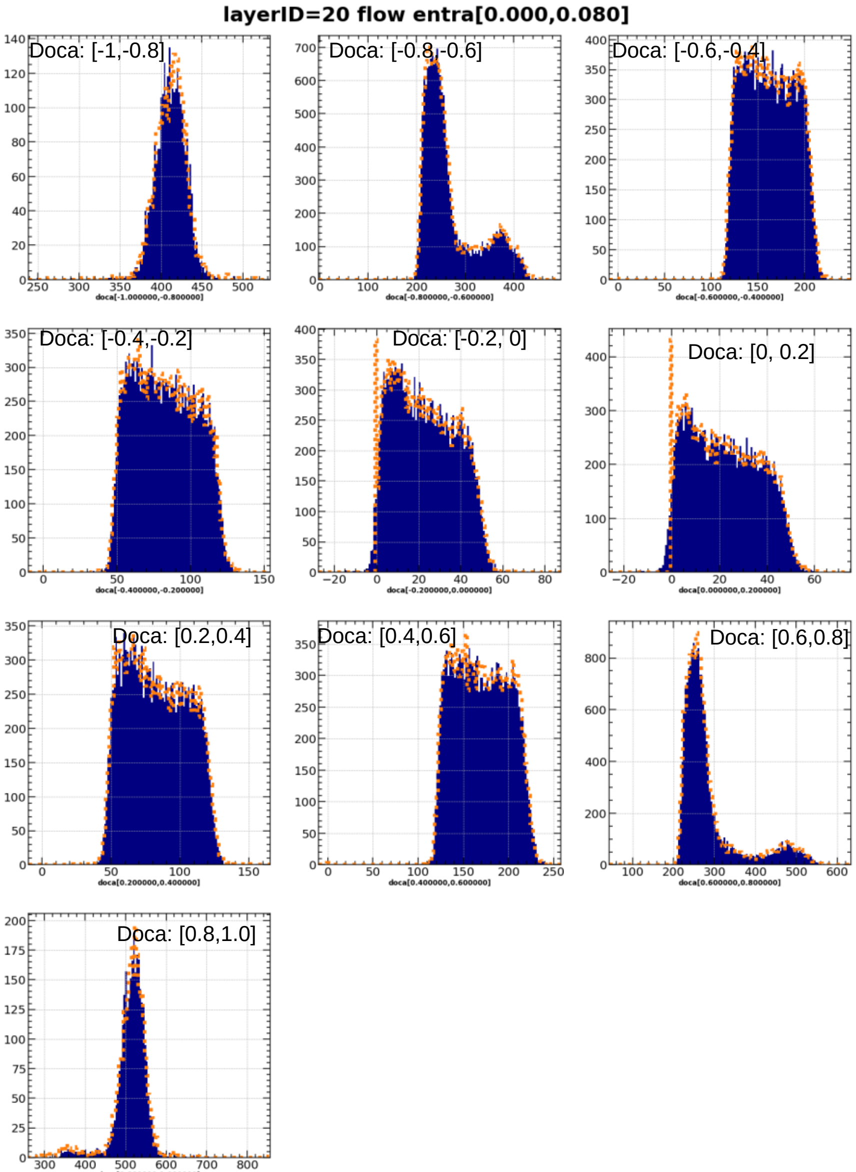
Check $D_{drift\ time}^{data}$, $D_{drift\ time}^{NN\ sim.}$

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 between data and NN simulation

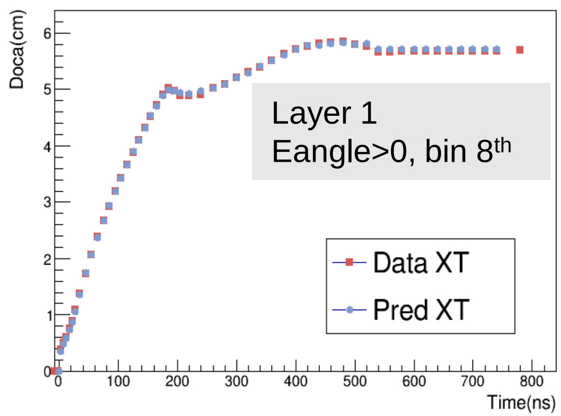
NN simulation performance

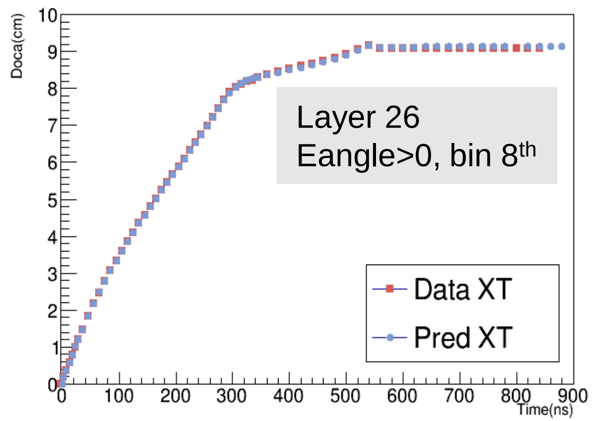


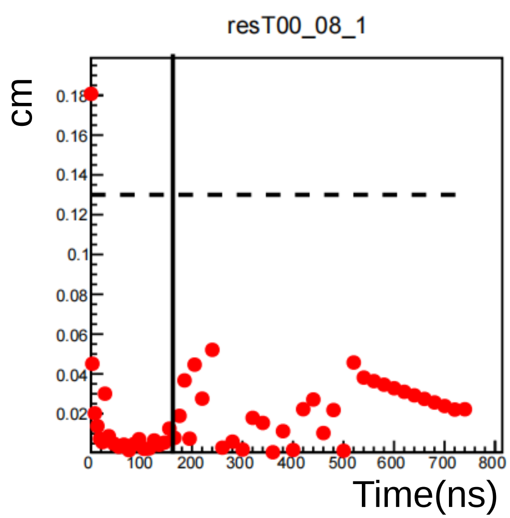
- A detailed check, in different entrance angles and Doca region.
- In general, good agreement between data and NN simulation
- Drift time distributions are flatter in small Doca regions (|Doca|<0.6) , complex for the large Doca regions (close to cell edge)

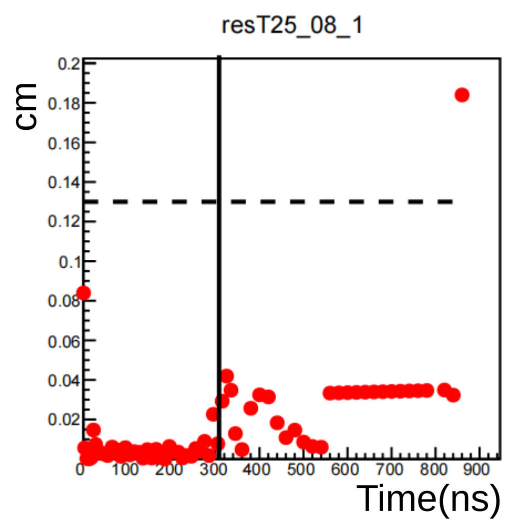
X-T relationship curve

- Check the X-T curve from the experimental data and NN simulation









Prepare experimental data for training

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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} , $C^{NN\ sim.}_{X-T}$

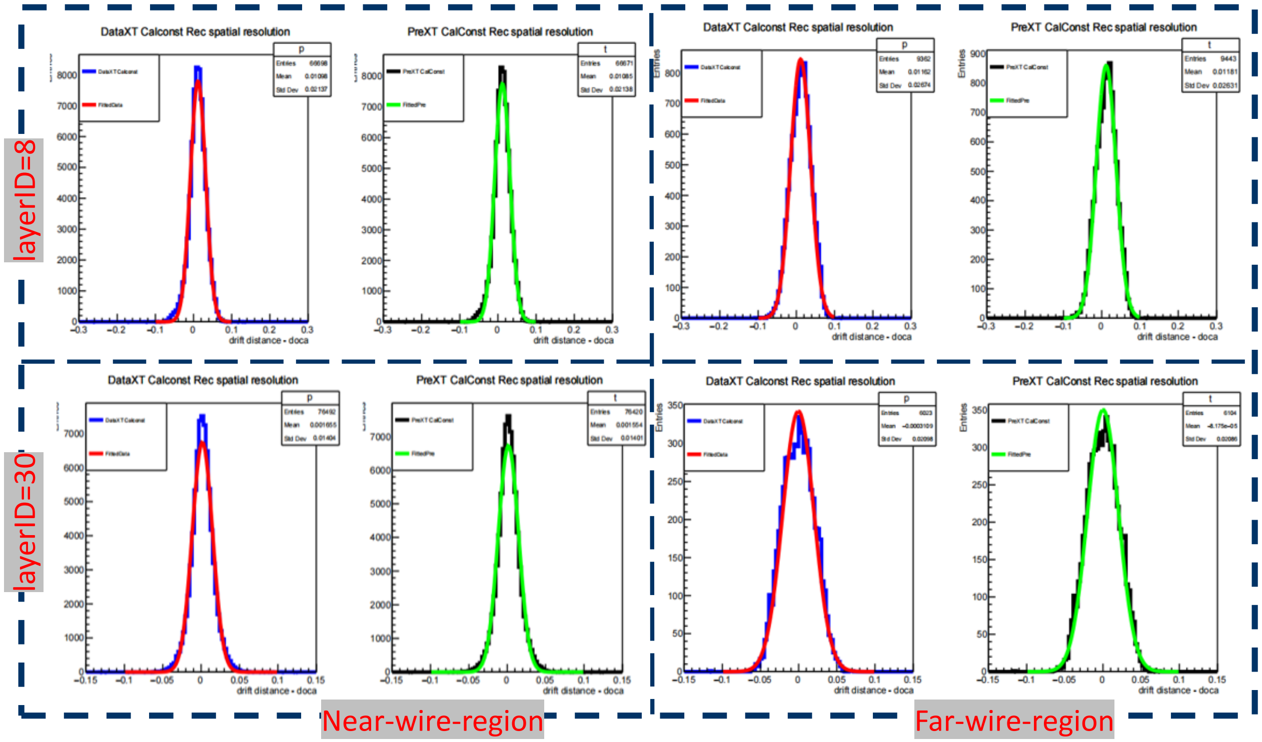
↓

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

- The mean Docas versus time are obtained for different layers and entrance angle
- red for C^{data}_{X-T}, blue for $C^{NN\ sim.}_{X-T}$
- Difference is < 40 μm

Spatial resolution check

- Checked the spatial resolution of reconstructed track, using C_{X-T}^{data} and $C_{X-T}^{NN\ sim.}$



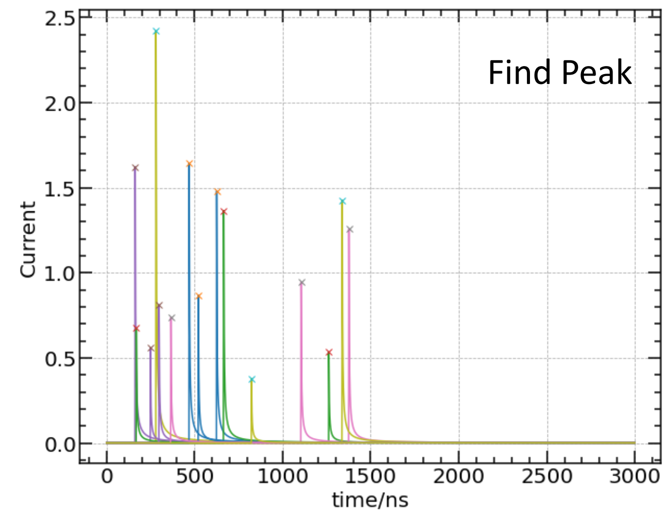
Prepare experimental data for training
↓
Learn drift time distribution: $D_{drift\ time} = f(doca, eangle, layer)$
↓
Check $D_{drift\ time}^{data}$, $D_{drift\ time}^{NN\ sim.}$
↓
check the X-T cure: C_{X-T}^{data} , $C_{X-T}^{NN\ sim.}$
↓
check spatial resolution: using C_{X-T}^{data} , $C_{X-T}^{NN\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

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

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

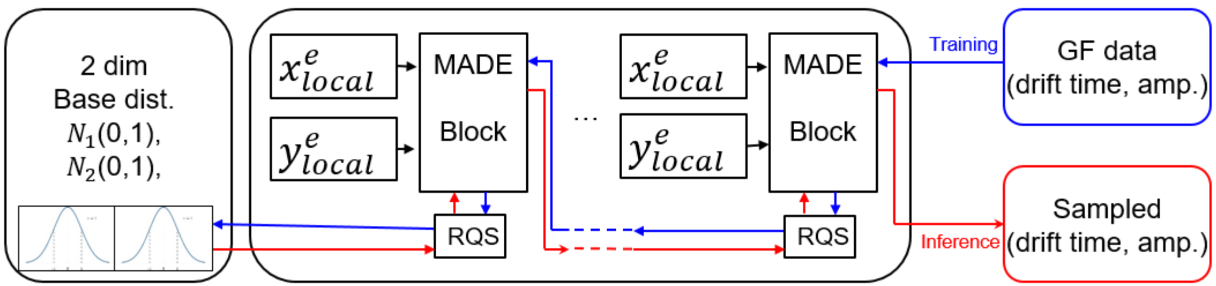
Drift time simulation in CEPC

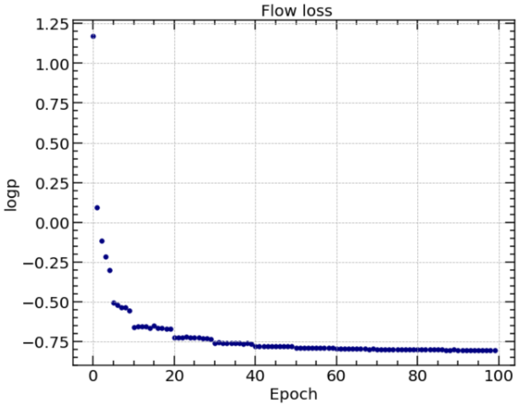
- Using a similar method for the CEPC drift time simulation
- Produce Garfield++ simulation data for training:
  - DC Cell size is 18 mm* 18 mm
  - Gas: 90%He+10%C_4H_{10}
  - Signal wire voltage: 1630 V
  - For each event, an ionized electron is uniformly generated in the cell (x,y) and the pulse is simulated
  - Then peak finding algorithm (scipy.signal.find_peaks()) is used to get pulse time (drift time) and amplitude (used for threshold cut)

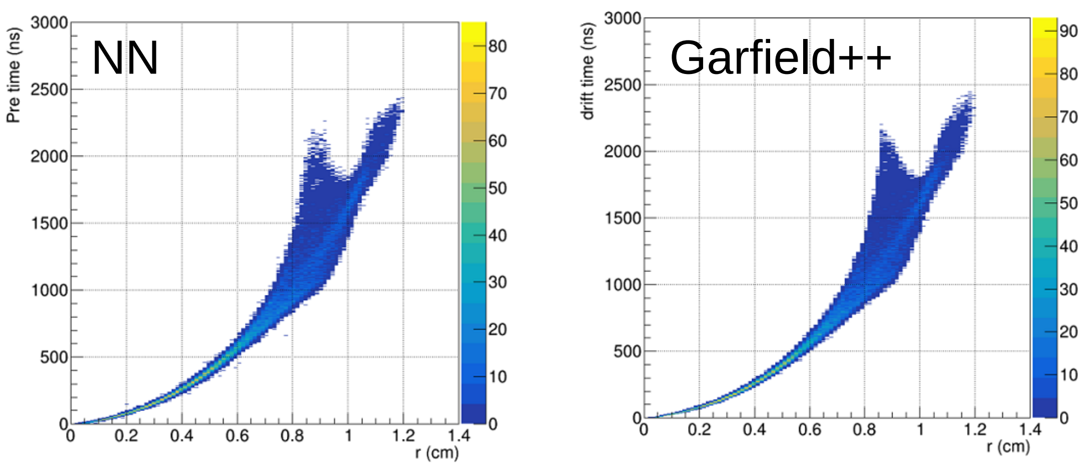


Drift time simulation in CEPC

- Similar NF model is used for training







- By using the NN model, one can simulate the drift time and pulse amplitude according to the cell local x,y position of the ionized electron

Summary and plan

- Precise simulation is important for the CEPC, the DC software is now moving on precise simulation
- Similar to dN/dx simulation, a precise drift time simulation is performed by learning Garfield++ data sample
- To prove the feasibility of the method, real data from the BESIII experiment is used. The results show the NN is able to learn the drift time precisely
- Next step:
  - the X-T calibration should be performed. An iterative process between track reconstruction and X-T calibration
  - Using cell local positions of ionized electrons (simulated by TrackerHeed) as input of the NN

Thanks for your attention!

Back up

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} , $C^{NN\ sim.}_{X-T}$

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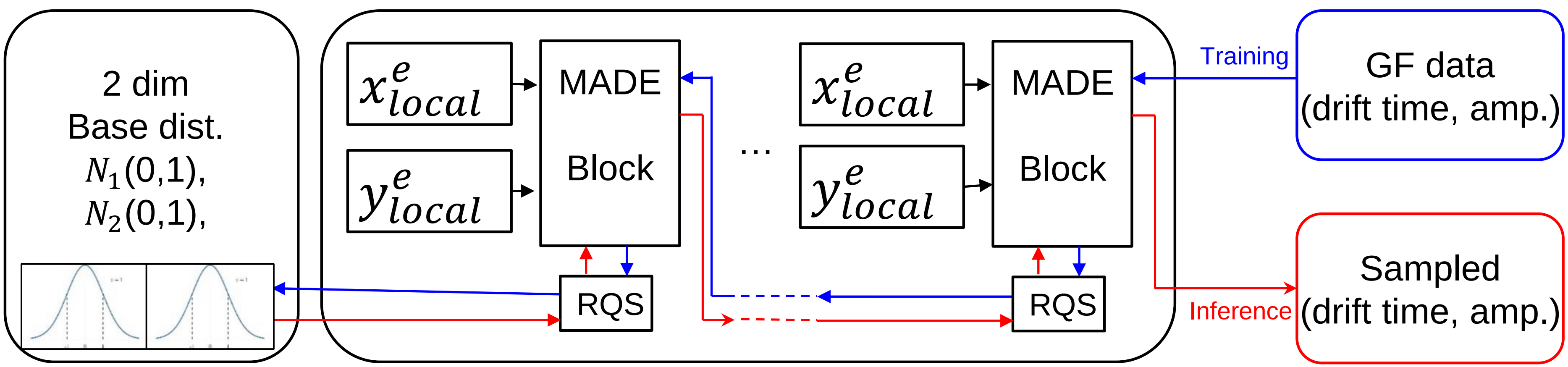
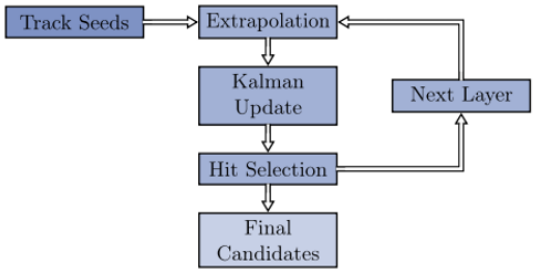
check spatial resolution: using C^{data}_{X-T} , $C^{NN\ sim.}_{X-T}$



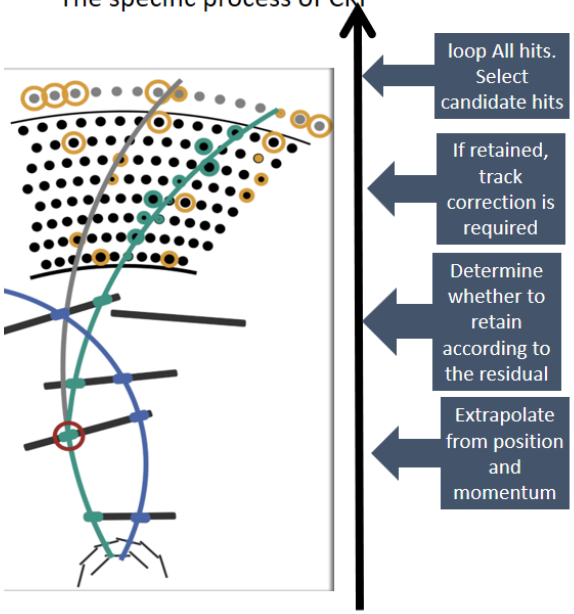
Track Finding by CKF

- Combinatorial Kalman Filter (CKF)
  - A tracking concept that combines track finding and track fitting in a search-tree-based algorithm.
  - Used by many high energy physics experiments
- Track finding using CKF in Drift chamber
  - Methods: The reconstructed SiTrack is selected as seed to select DC hits belonging to the same track
- Current progress:
  - Reusing CKF from Belle II and running it in CEPCSW

Basic procedure behind the CKF

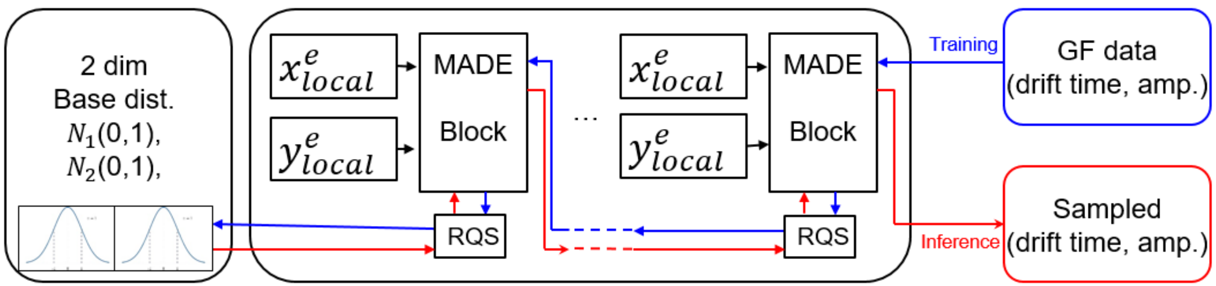


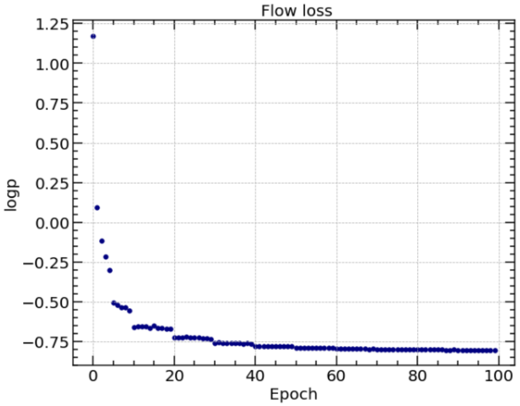
The specific process of CKF



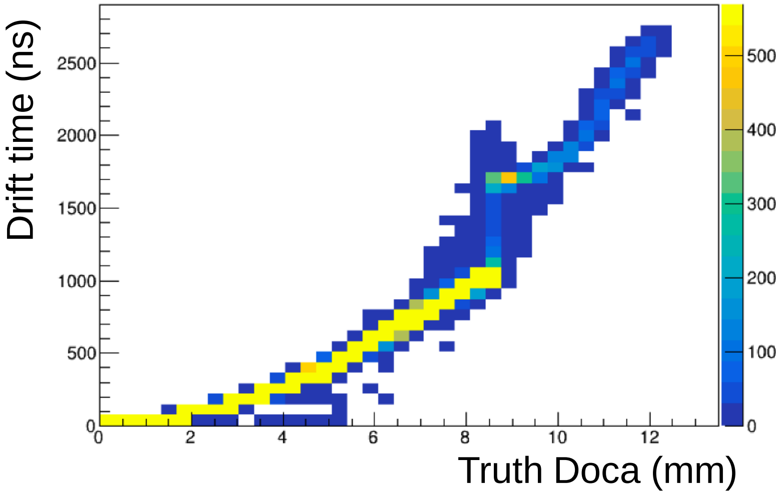
Drift time simulation in CEPC

- Similar NF model is used for training



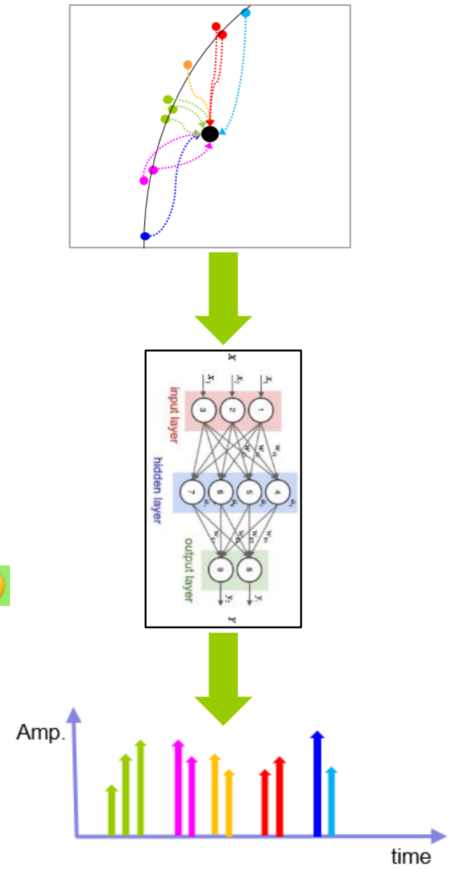


- After obtaining the NN model, one can simulate the drift time and pulse amplitude according to the local x,y position of the ionized electron



Ionization simulation

- The ionization simulation is done by combining Geant4 and TrackerHeed
  - TrackerHeed (from Garfield++) used for ionization process simulation
  - Geant4 for particle propagation (decay) in the detector, interaction with detector material, …
- Pulse simulation for each ionized electron
  - The Garfield++ simulation takes a long time 😟
  - NN is used for fast simulation, simulating the time and amplitude of each pulse, more details in this talk 😊



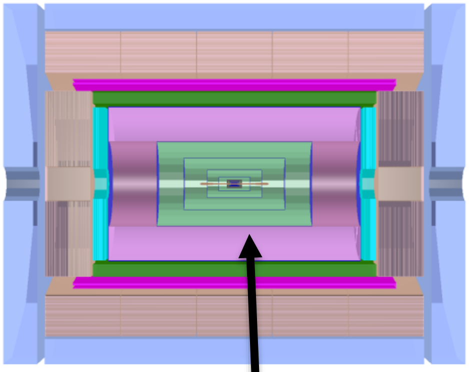
Summary

- The DC simulation and track reconstruction in the CEPCSW is presented
- The multi-track fitting has been developed with Si+DC measurements and the performance is reasonable
- The chain of dN/dx study in CEPCSW is presented
- The preliminary results for dN/dx PID performance in CEPCSW are checked, they are in good agreement with the results from the standalone Garfield++ simulation
- Future plan:
    - Continue working on track finding
    - Track reconstruction with background mixing and using more realistic X-T relation
    - More detailed dN/dx performance check

Thank you for your attention!

Drift Chamber(DC) Software

- Drift chamber is the key detector in the 4th conceptual detector design to provide PID
  - Good PID ability (2σ p/K separation at P < ~ 20 GeV/c)
  - Precise momentum measurement (eff. ~100%, σ_p<=0.1%)
- Motivation of DC software project
  - Development of simulation and reconstruction for DC
  - Support the detector design, optimization and performance study
  - Support physics sensitivity study
- Requirements for DC software
  - Modular design and friendly interfaces
  - Easily integrated with common tools (ACTS, Genfit etc.)
  - Reuse existing algorithms from other experiments
  - Application of advanced technic (ML) to simulation and reconstruction
- Manpower
  - IHEP: Yao Zhang, Tao Lin, Wenxing Fang, Chengdong Fu, Ye Yuan, Weidong Li
  - SDU: Mengyao Liu, Xueyao Zhang, Xingtao Huang



A PID drift chamber

Physics process	Measurands	Detector subsystem	Performance requirement
$ZH, Z \to e^+e^-, \mu^+\mu^-$ $H \to \mu^+\mu^-$	$m_H, \sigma(ZH)$ $\mathrm{BR}(H \to \mu^+\mu^-)$	Tracker	$\Delta(1/p_T) = 2 \times 10^{-5} \oplus \frac{0.001}{p(\mathrm{GeV}) \sin^{3/2}\theta}$

Drift Chamber Parameters in CEPCSW

- The baseline configuration of DC in CEPCSW

Half length	2980 *mm*
Inner and outer radius	800mm to 1800 *mm*
# of Layers	100/55
Cell size	~10mmx10mm/18mmx18mm
Gas	He:iC_4H_{10}=90:10
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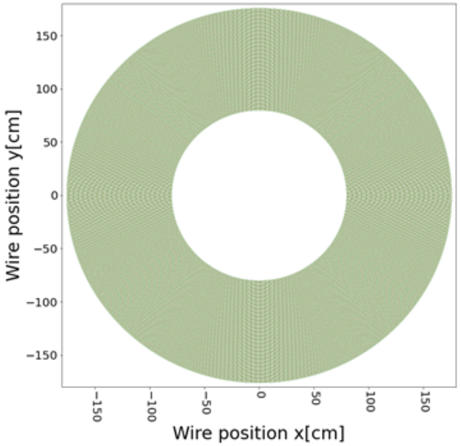
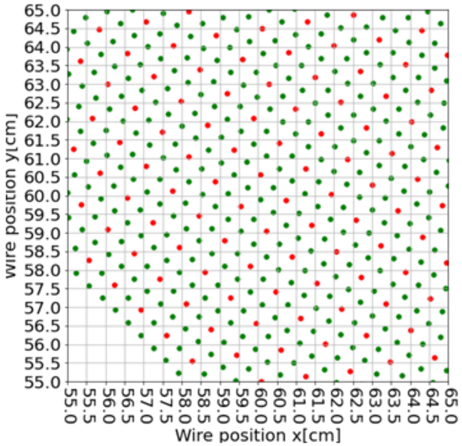
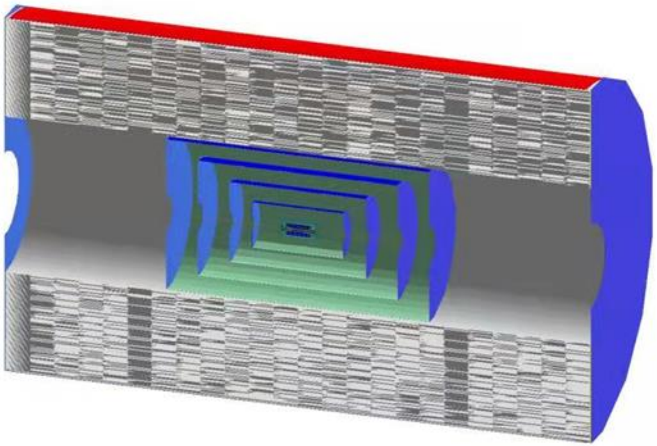




Cell structure

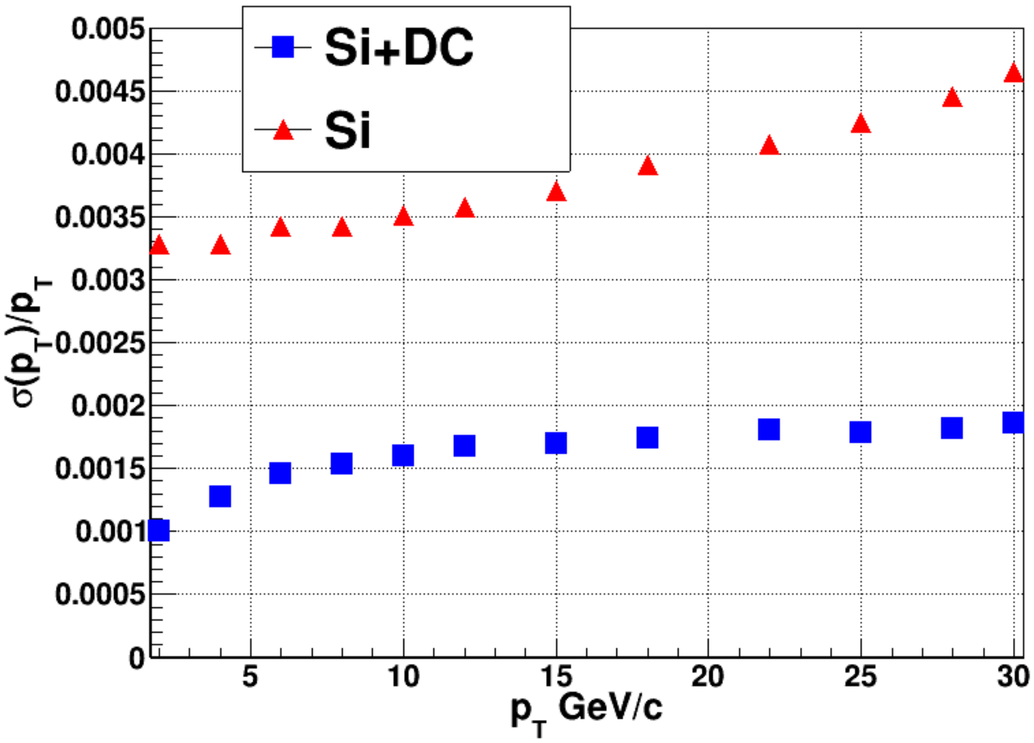
Silicon detectors Parameters in CEPCSW

Silicon tracker	*Number of layer*	*Radius(mm)*	$\sigma_U\,(\mu m)$	$\sigma_V(\mu m)$
VXD	3 double layers	16-58	2.8/6/4/4/4/4	2.8/6/4/4/4/4
SIT	4 layers	230-770	7.2	86
SOT(SET)	1 layer	1815	7.2	86



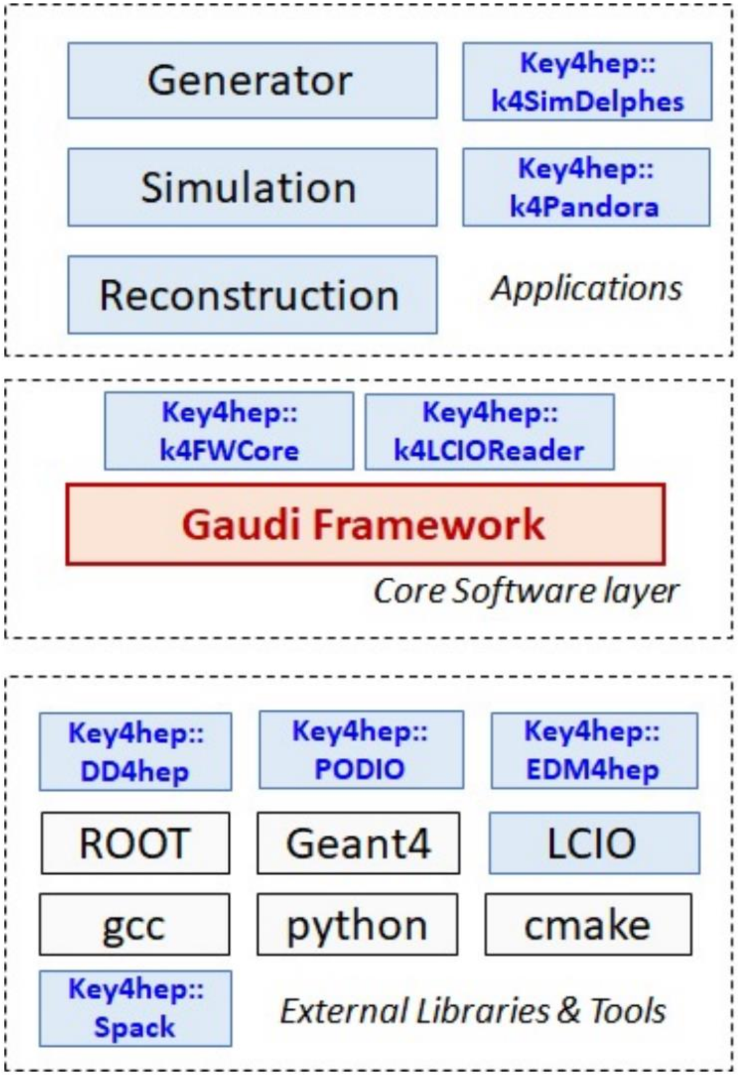
Silicon+DC vs Silicons

- Got better momentum measurement with the drift chamber



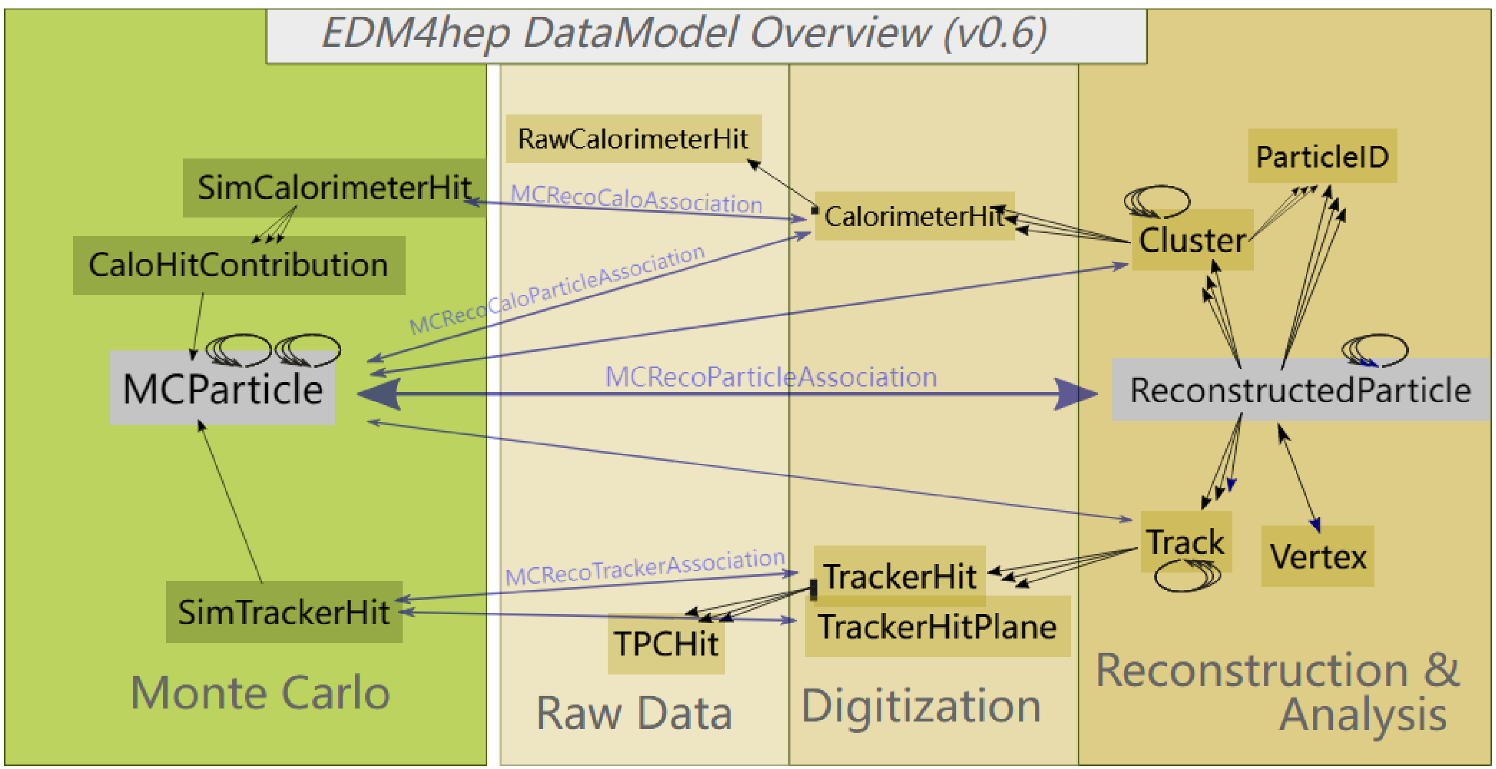
CEPCSW Software

- CEPCSW software structure
  - External libraries:
    - DD4hep: complete detector description (geometry, B field, Material, …). Consistent description (simulation, reconstruction, analysis)
    - EDM4hep: the generic event data model for HEP experiments (see next slide)
    - …
  - Core software:
    - Gaudi framework: defines interfaces to all software components and controls their execution
    - K4FWCore: data service for EDM4hep
  - Applications:
    - CEPC-specific software: generator, Gean4 simulation, reconstruction, and analysis



EDM4hep

- Common EDM: ILC, FCC, CEPC, CLIC, …
- Efficiently implemented (fast data access, efficient memory usage)
- Support multi-threading
- Potentially heterogeneous computing
- Easy to generate the C++ code from a high-level description of the desired EDM (YAML file) using the podio



EDM4hep Extension

- Currently, the EDM4hep does not include the EDM for dN/dx study, we extended it by using the extension mechanism of podio (very convenient)
- Following EDMs are extended (more details in following slides):
  - SimPrimaryIonizationCluster
  - TrackerData
  - TrackerPulse
  - RecIonizationCluster
  - RecDndx
- The extended EDM is supposed to be used both for the drift chambers and the TPC