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Precise simulation of drift chamber in the CEPC experiment

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On behalf of CEPC drift chamber working group

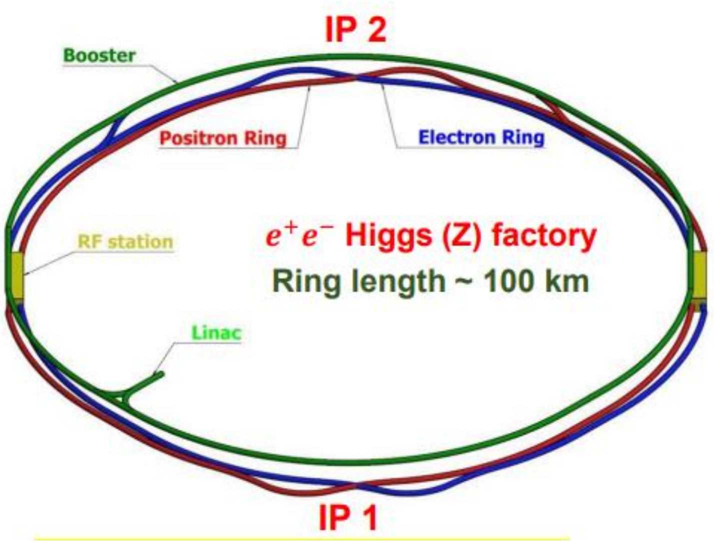
20th International Workshop on Advanced Computing and Analysis Techniques in Physics Research

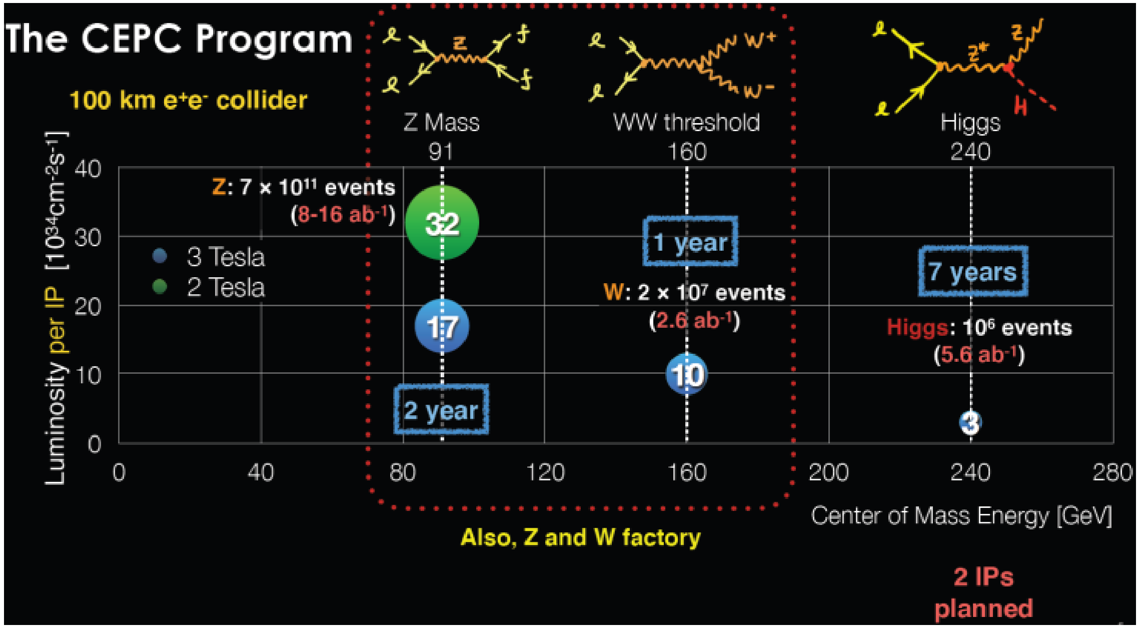
Outline

- Introduction:
  - CEPC experiment
  - CEPC 4^{th} concept detector design
  - Cluster-counting technique
  - CEPC software
- Geant4 combined Garfield++ simulation
- Fast signal response simulation using ML
- Summary

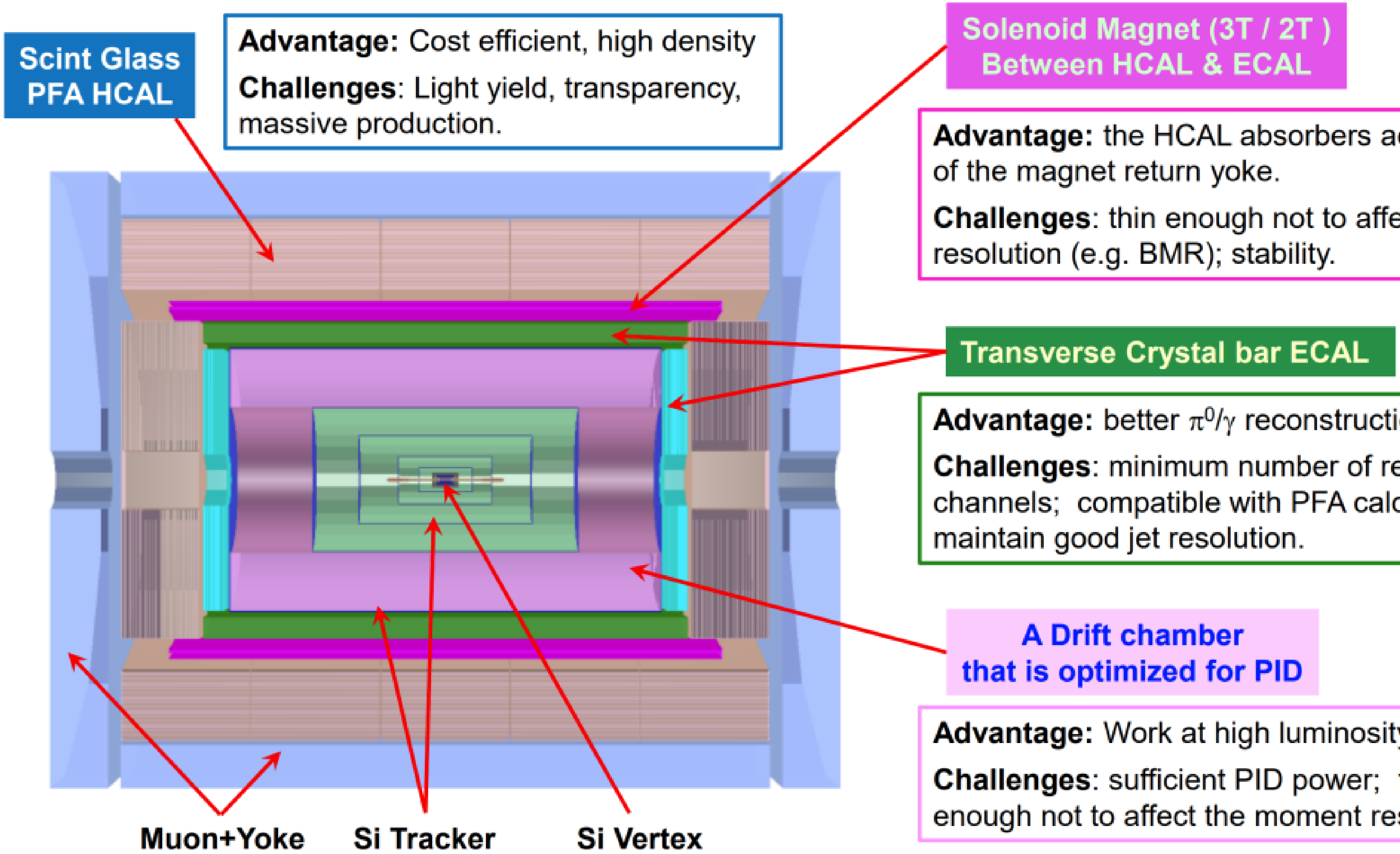
Circular Electron Positron Collider (CEPC)

- The CEPC is a Higgs(Z/W) factory in China
- ~1M Higgs at $\sqrt{s} = 240\ \mathrm{GeV}\ (\mathrm{ZH})$, ~Tera Z at Z pole and ~10M $\mathrm{W^+W^-}$ pair and possible $\mathrm{t\bar{t}}$ pair production
- Higgs, EW, flavor physics, BSM
- Possible Super pp Collider (SppC) of $\sqrt{s}$~100 TeV in the future





The 4th Conceptual Detector Design



Advantage: Cost efficient, high density

Challenges: Light yield, transparency, massive production.

Advantage: the HCAL absorbers act as part of the magnet return yoke.

Challenges: thin enough not to affect the jet resolution (e.g. BMR); stability.

Advantage: better π^0/γ reconstruction.

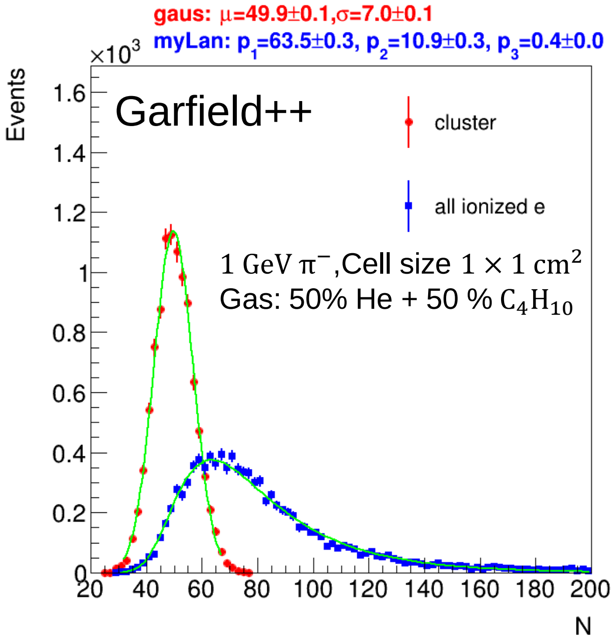
Challenges: minimum number of readout channels; compatible with PFA calorimeter; maintain good jet resolution.

Advantage: Work at high luminosity Z runs

Challenges: sufficient PID power; thin enough not to affect the moment resolution.

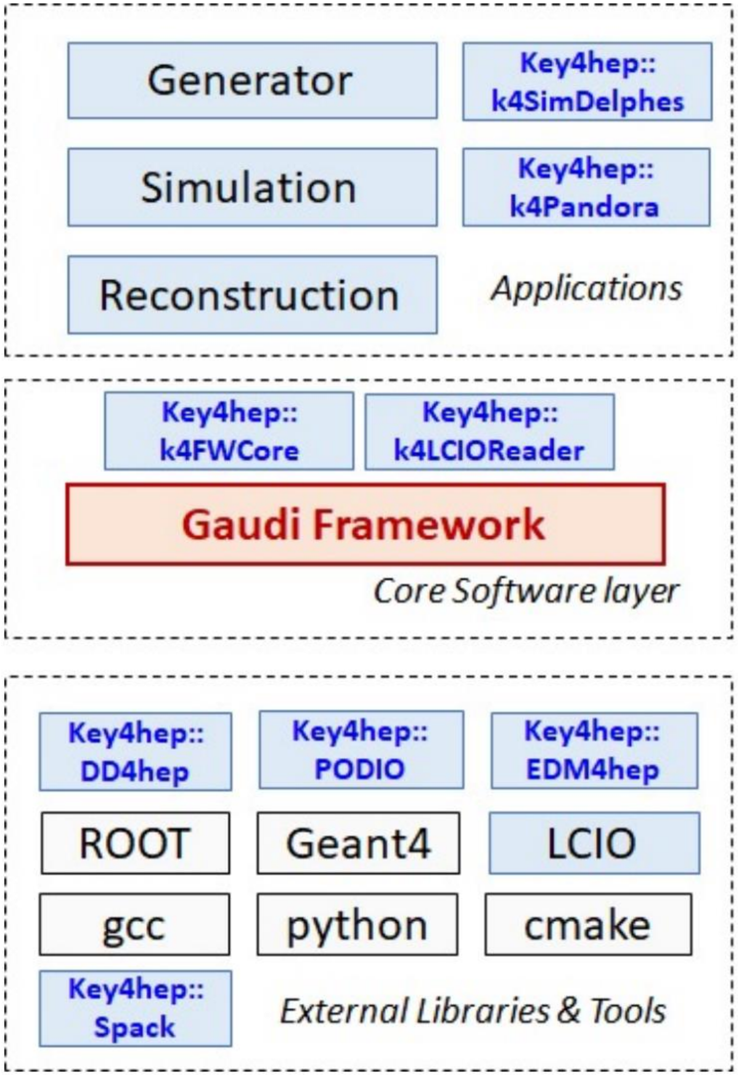
Particle Identification with dE/dx and dN/dx

- Traditionally: using dE/dx
  - The distribution follows Landau distribution (due to the delta-ray production, the gas gain)
  - Using truncated mean to get the expected dE/dx will lose some measured information
  - Resolution is ~6%
- New technique: using Cluster-counting (dN/dx) method
  - The number of clusters of avalanching electrons from primary ionization follows the Poisson distribution
  - Resolution could reach <3%(arXiv:2105.07064)
  - Will be studied in detail in CEPC drift chamber

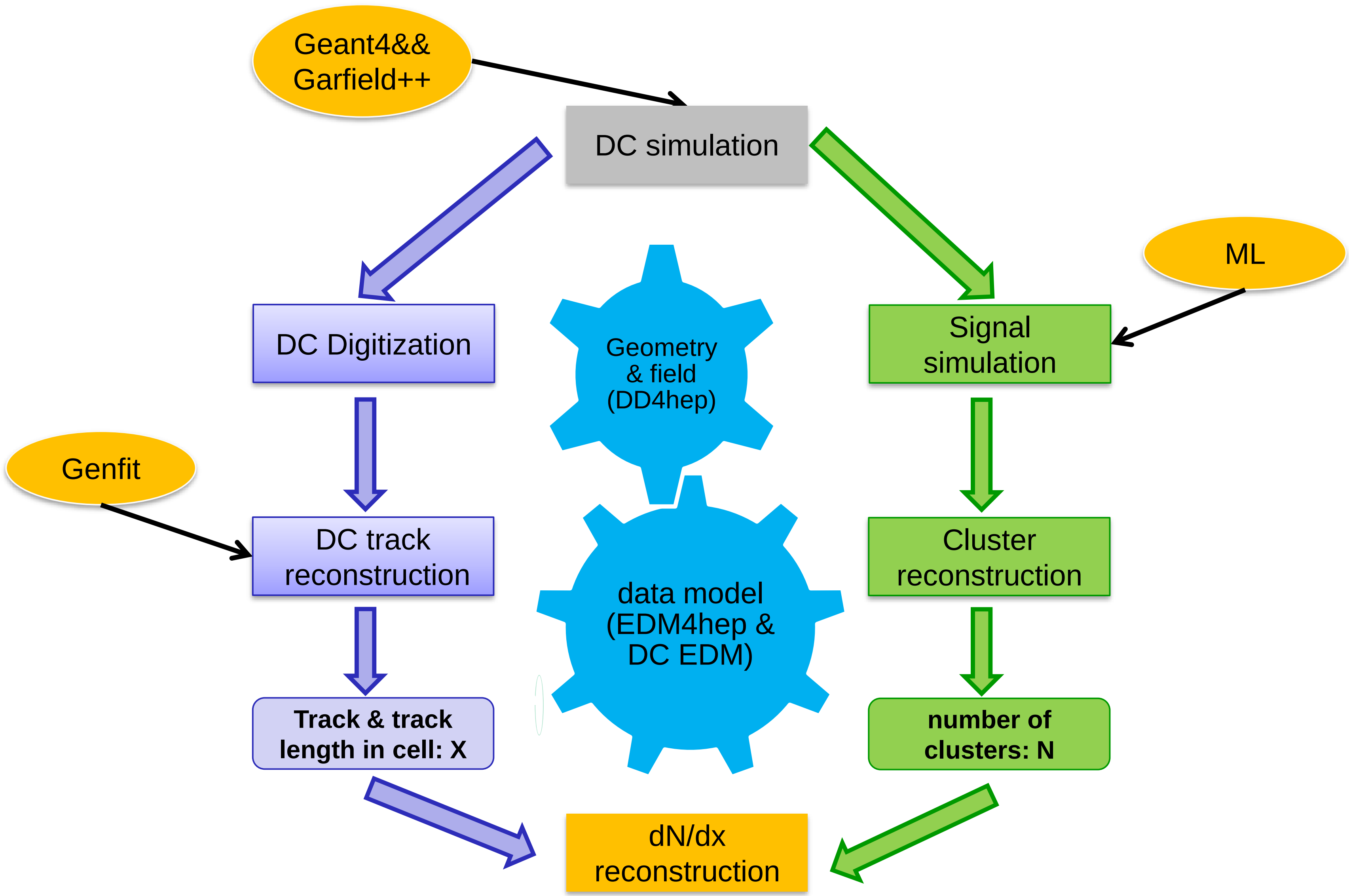


CEPCSW Core Software

- CEPCSW software structure
  - Core software
  - Applications: simulation, reconstruction and analysis
  - External libraries
- Core software
  - Gaudi/Gaudi Hive: defines interfaces to all software components and controls their execution
  - CEPC-specific framework software: generator, Gean4 simulation, beam background mixing, fast simulation, machine learning interface, etc.
  - EDM4hep:generic event data model for HEP experiments (see poster)
  - K4FWCore: manages the event data
  - DD4hep: geometry description, non-uniform B field



Drift Chamber Simulation and Reconstruction Flow

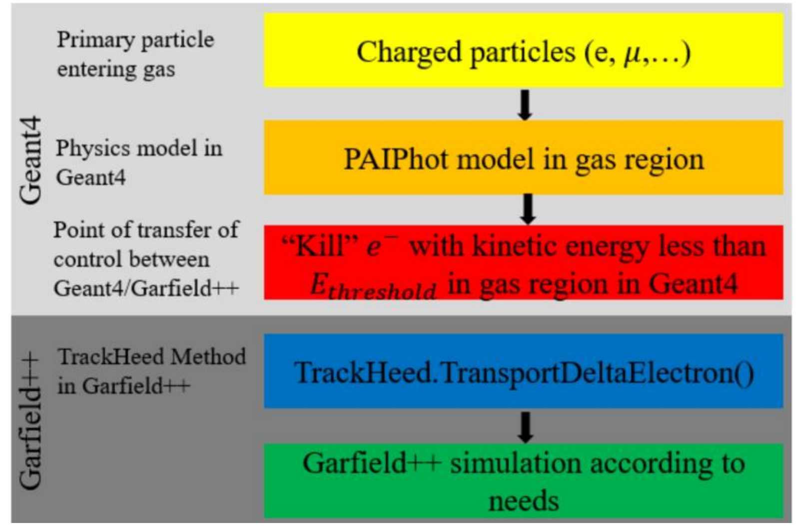


Drift Chamber Ionization Simulation

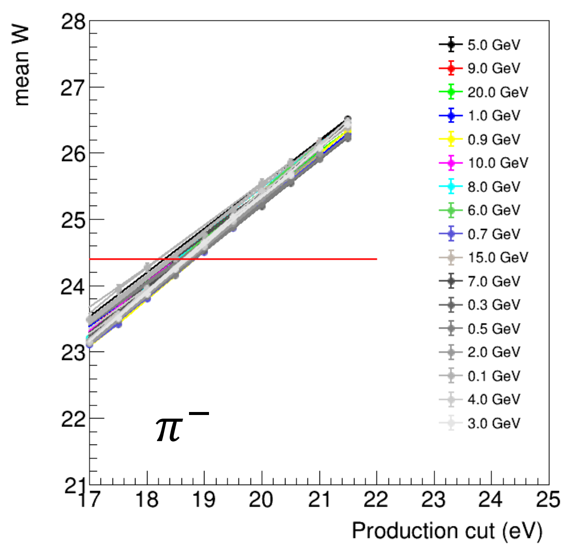
- As we know Geant4 can not simulate the ionization process properly (arXiv:2105.07064)
- Garfield++ is commonly used for precise ionization simulation for simple geometry
- In order to do a detailed drift chamber simulation, including particle interaction with detector materials, ionization in gas, drift and avalanche processes in drift chamber cell, combining Geant4 and Garfield++ is needed
- This paper "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)

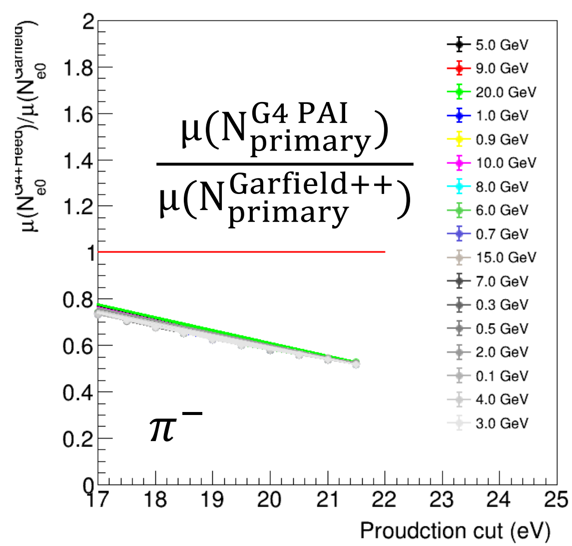
Drift Chamber Ionization Simulation by G4 PAI

- Method:
  - Geant4 PAI(Photo Absorption Ionization) model to simulate primary or secondary ionization
  - TrackHeed (from Garfield++) to simulate ionization from residual delta electron



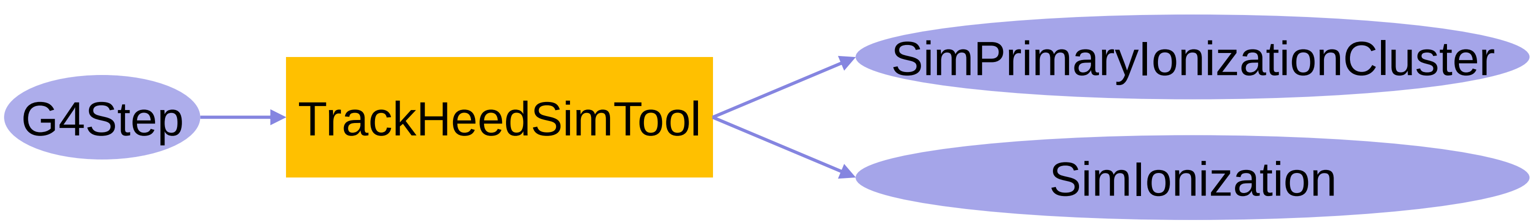
- It was found that the primary ionization produced by this method is much less than the one from Garfield++ standalone simulation
- Confirmed with authors





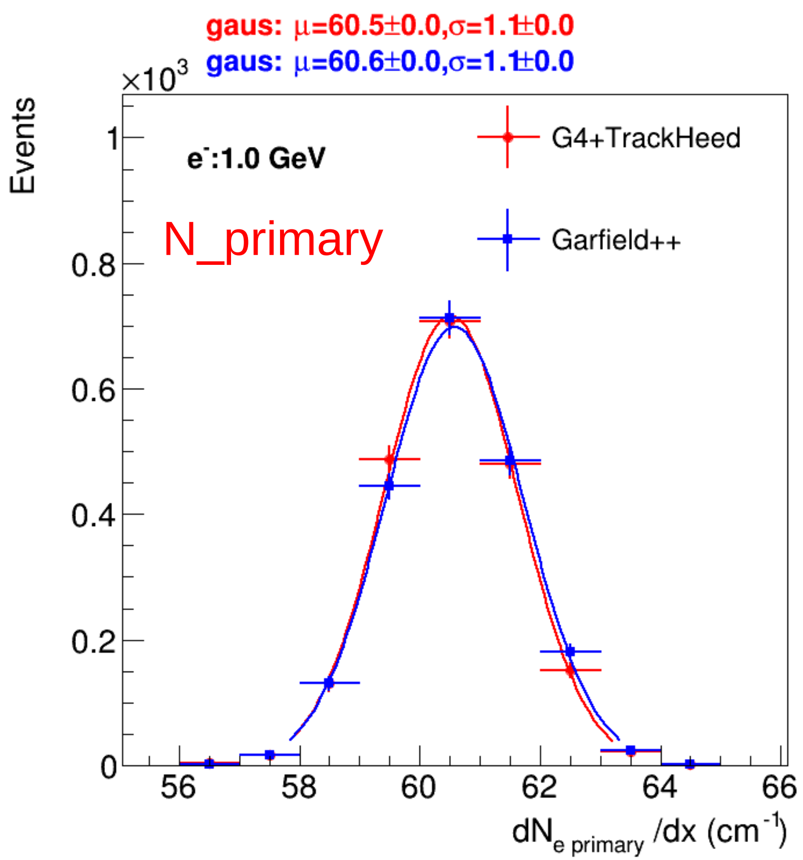
Proposed Drift Chamber Ionization Simulation

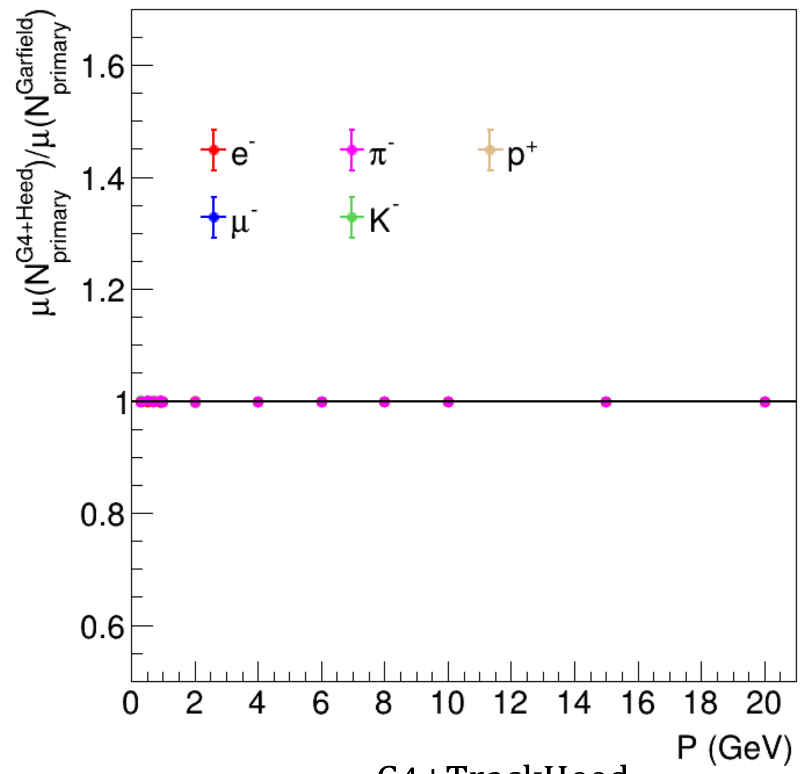
- Combining Geant4 and Garfield++ at G4Step level
- TrackHeedSimTool (Gaudi tool) is created for this task
  - Input: G4Step information (particle type, initial position and momenta, ionization path length)
  - Use TrackHeed (used by Garfield++) to simulate one step length (or multi-step length for speed 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



Ionization Simulation Performance Check

- Gas: 50% He + 50 % C_4H_{10}





$$\frac{\mu(N_{\text{primary}}^{\text{G4+TrackHeed}})}{\mu(N_{\text{primary}}^{\text{Garfield++}})}$$

Consistent with Garfield++ standalone simulation results, see backup for more details

Ionization Simulation Performance Check

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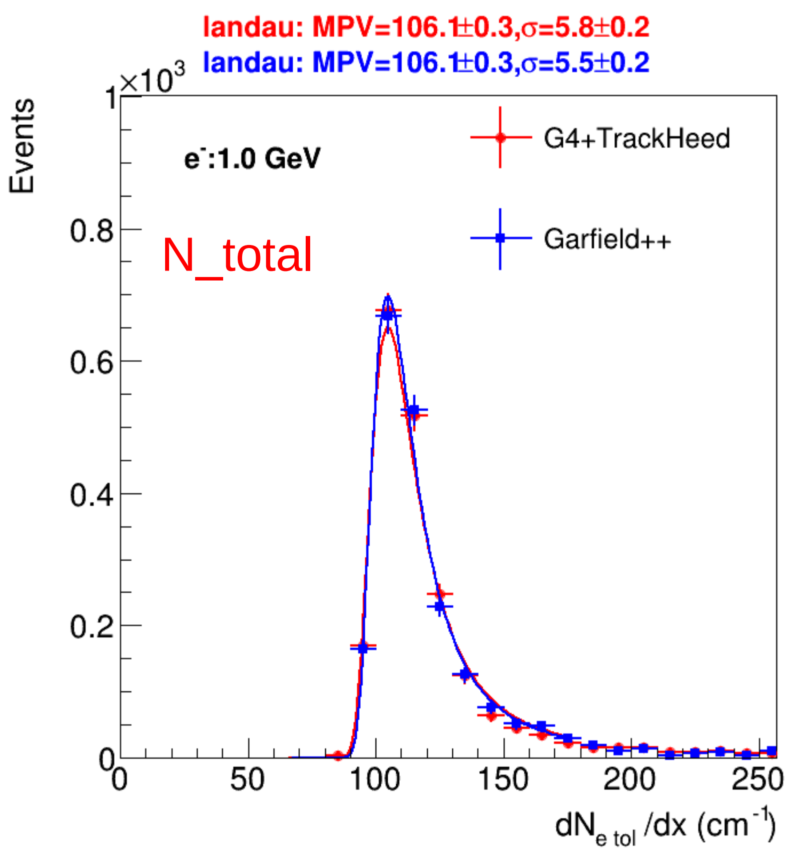
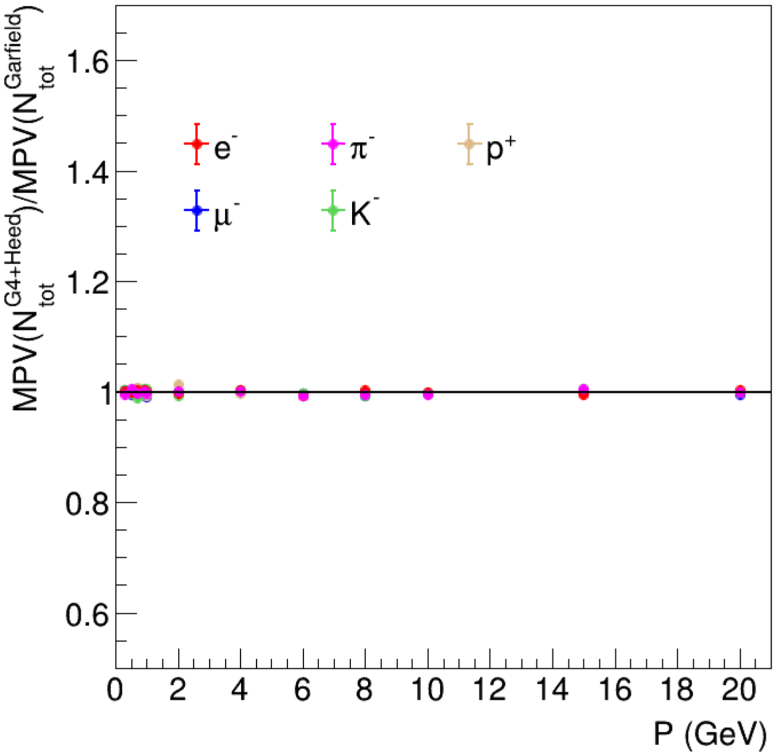


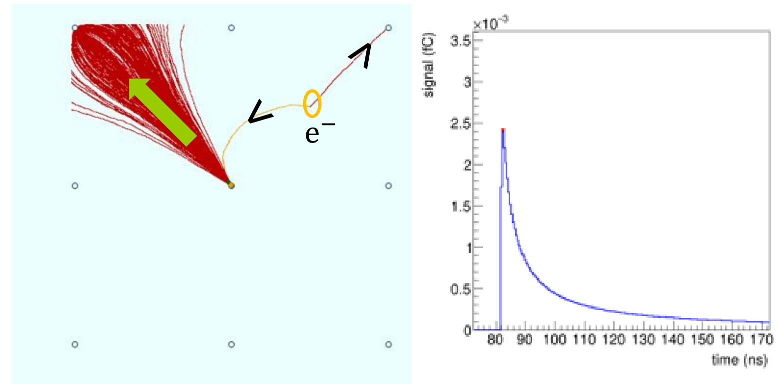


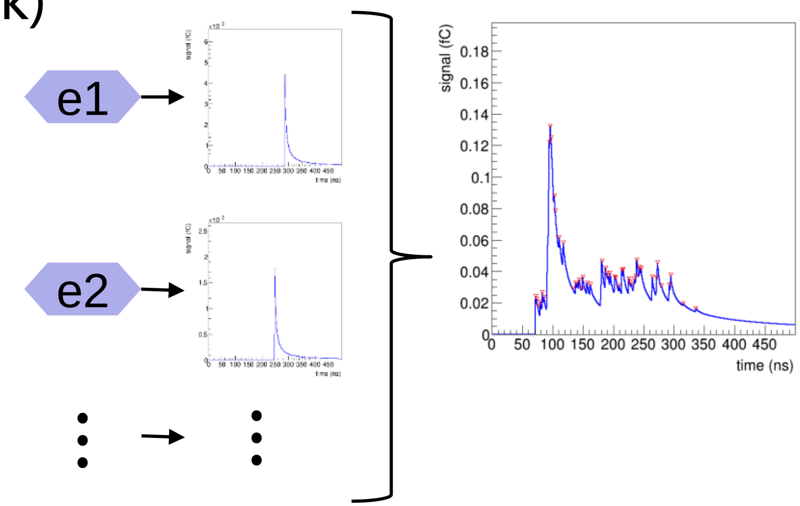
$$\frac{\mathrm{MPV}(\mathrm{N}_{\mathrm{tot}}^{\mathrm{G4+TrackHeed}})}{\mathrm{MPV}(\mathrm{N}_{\mathrm{tot}}^{\mathrm{Garfield++}})}$$

Consistent with Garfield++ standalone simulation results, see backup for more details

Signal response simulation

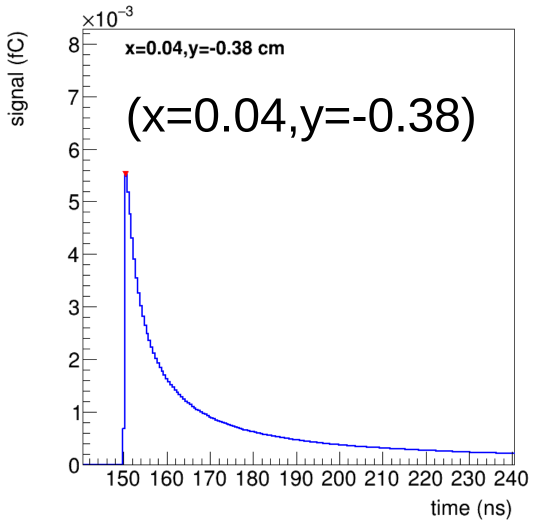
- ❑ Simulating the drift and avalanche processes of ionized electron and ions
- ❖ Using Garfield++: very precise but extremely time consuming, could take $\mathcal{O}(1)$ to $\mathcal{O}(10)$ seconds just for one electron (few hours for one track)
- ❖ Going to use parameterization (fast simulation) method, parameters are based on Garfield++ simulation results
  - For each electron, simulate its own signal
  - As done by Garfield++, piling up all signals from the same drift chamber cell gives the final signal response

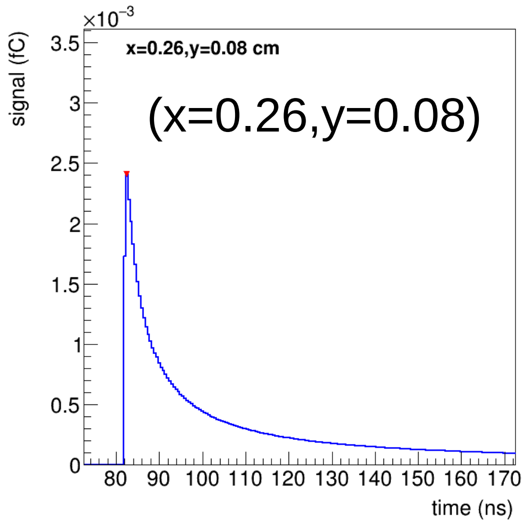


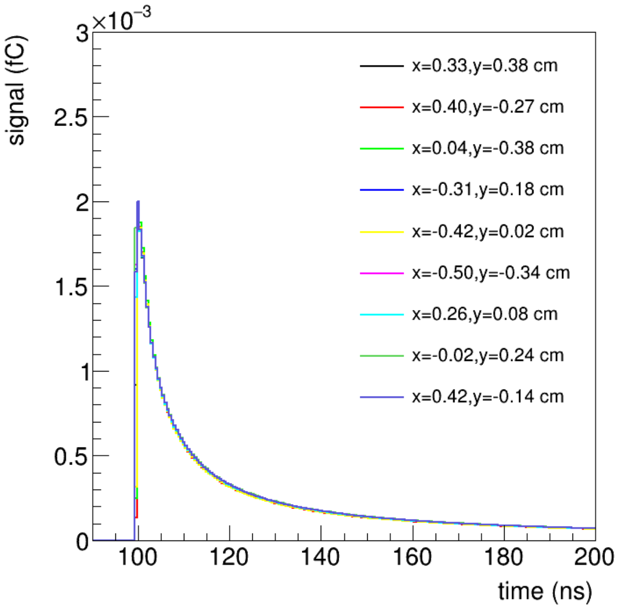


Single-electron signal study

- Performed single-electron simulations using Garfield++
- single-electron signals are similar after normalization. For example, if its peak position is shifted to some value (e.g. 100 ns) and its peak value is scaled to some value (e.g. 2×10^{-3})

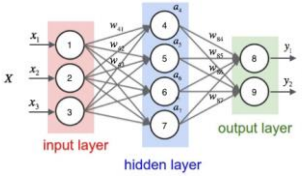






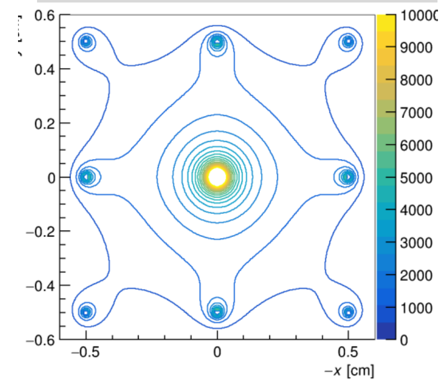
- Simulating single-electron signal ≈ simulating peak_time and peak_value of the signal + using signal template

Dataset and Generative Model



- 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



Input = x, y, noise ~ N(0, 1)

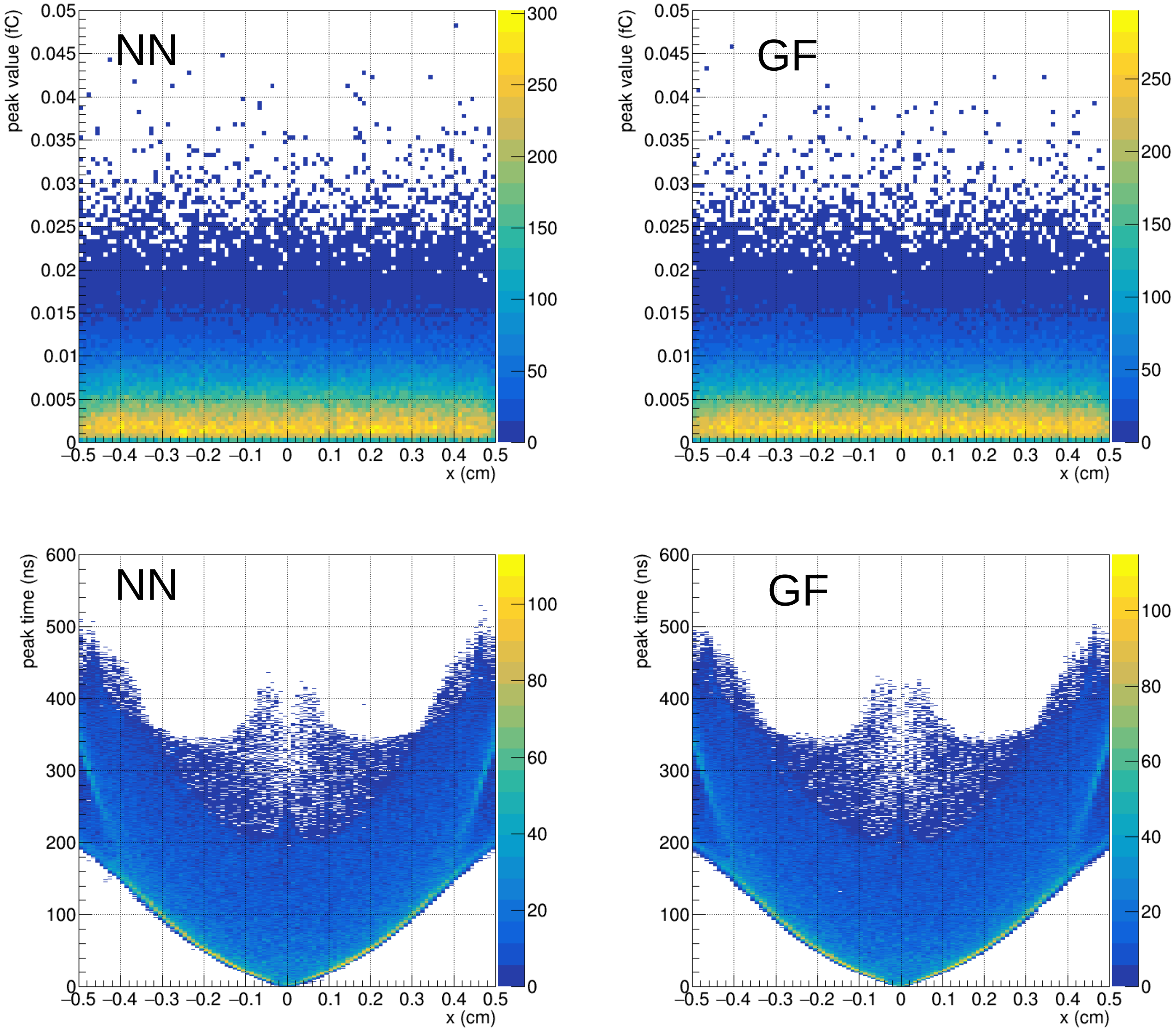
Dense(3, 814, activation='relu')

Dense(814, 814, activation='relu')

gen(time, value)=Dense(814,2)

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

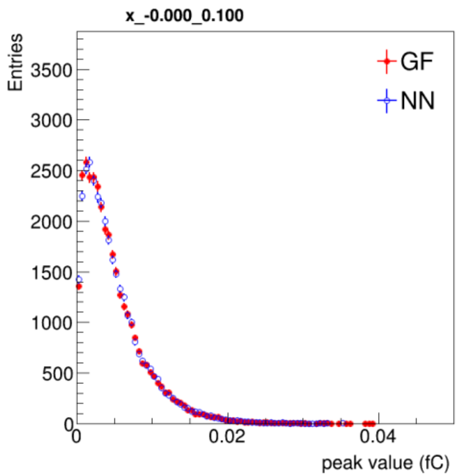
Simulation performance (2D distribution)

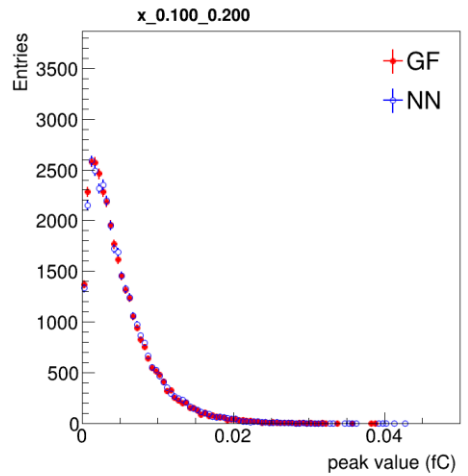


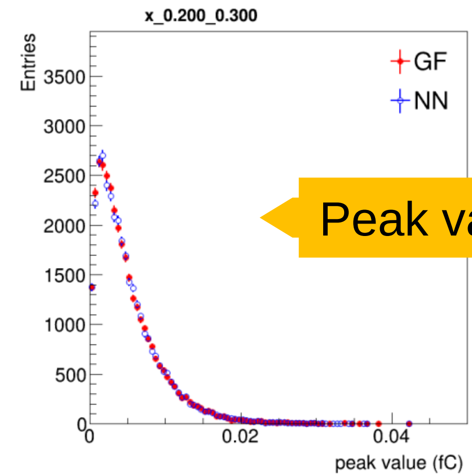
Peak value vs x

Peak time vs x

One Dimension Check





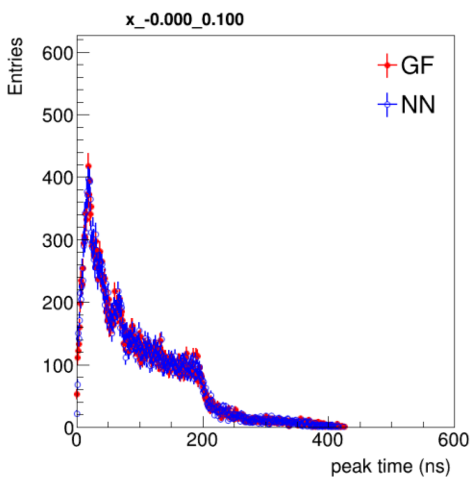


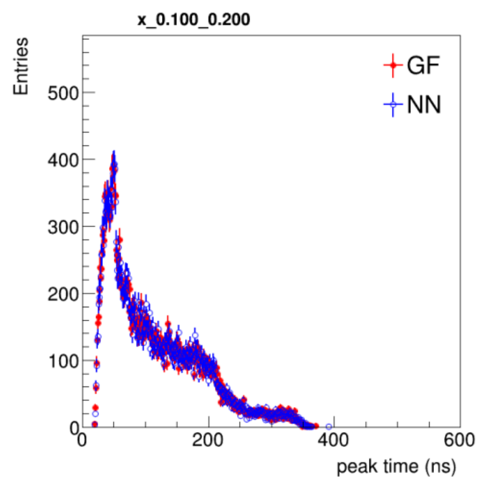
Peak value

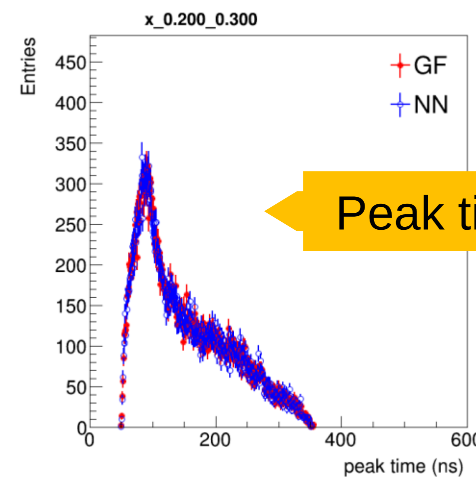
x(0,0.1) cm

x(0.1,0.2) cm

x(0.2,0.3) cm



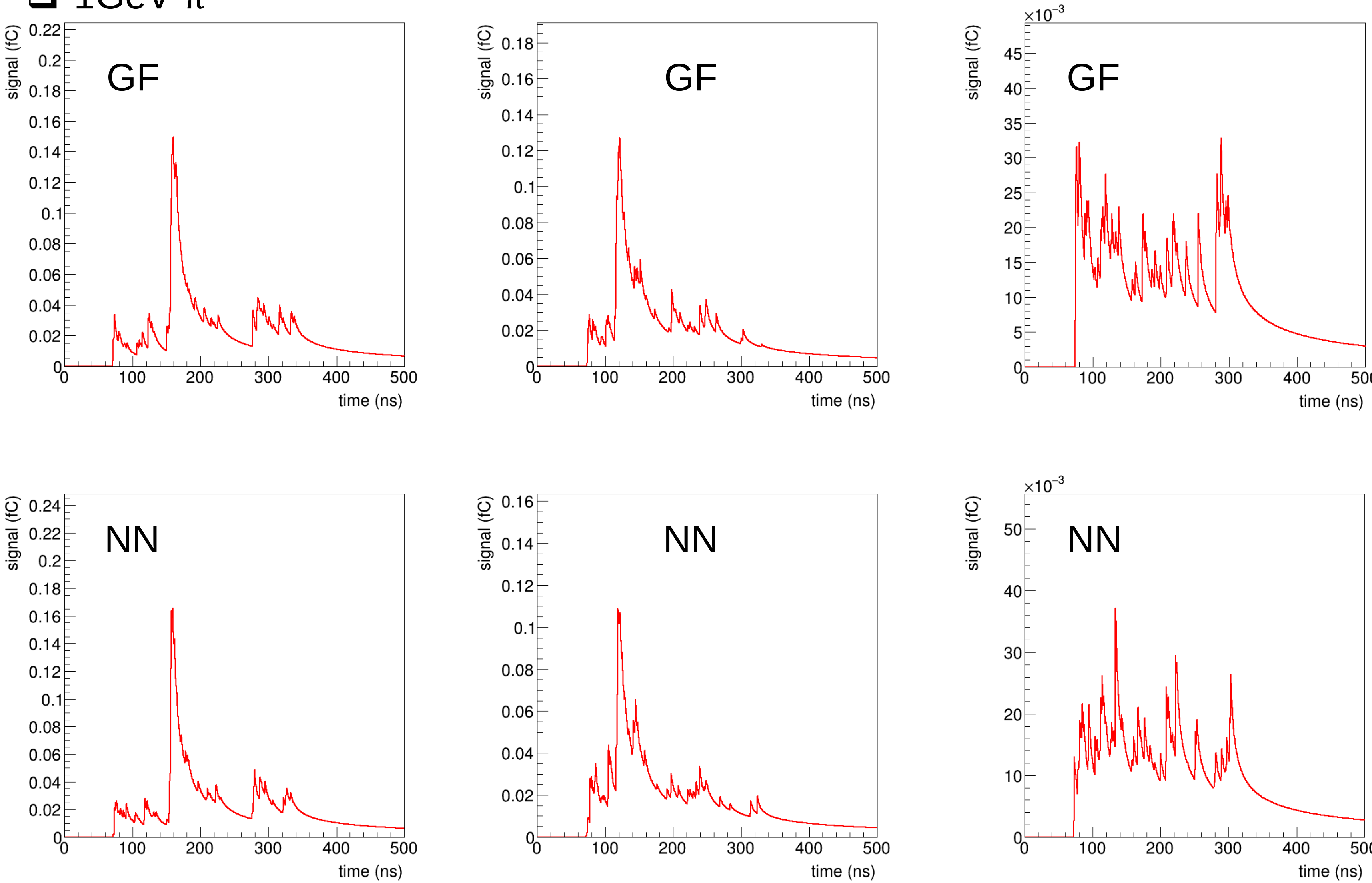




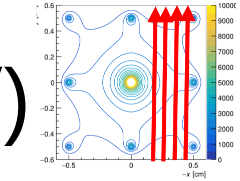
Peak time

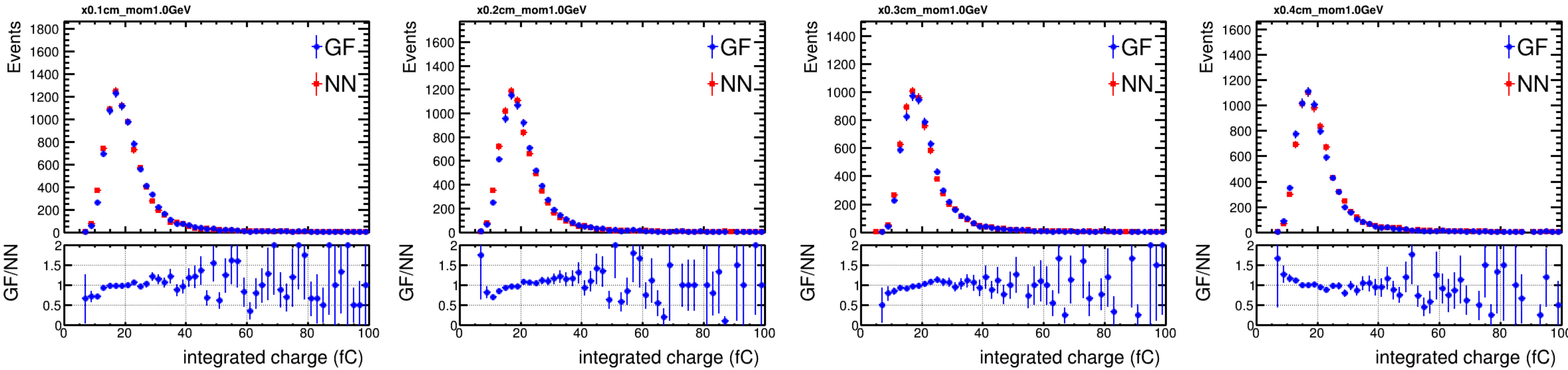
Display of signal response for one cell

❑ 1GeV π^-

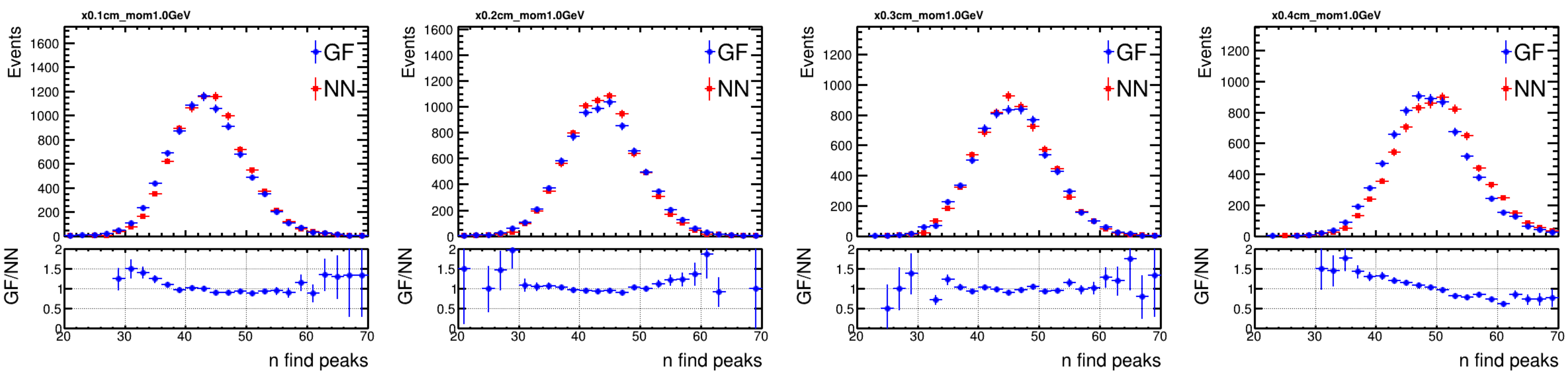


Performance check: electron (1 GeV)





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)

Benefits of the new method

- Average time for one cell ($1 \times 1\mathrm{cm}^2$) simulation for 1 GeV π^- (gas: $50\%\mathrm{He} + 50\%\mathrm{C_4H_{10}}$) :
  - Garfield++: ~250 s
  - NN: ~1 s
- This simulation algorithm is general and applicable for different particles. As for different particles, only the ionization part is different, the signal response simulation keeps the same
- By this way, signal simulation is not related to Geant4 and it is independent between each electron. To further speed up the signal response simulation, GPU or multithreading techniques can be easily used

Summary

- The Garfield++ was integrated with the Geant4-based simulation in the CEPCSW to simulate detector response inside the cell of the drift chamber
- With TrackHeed PAI simulating ionization of primary particles, results from CEPCSW are consistent with those from the standalone simulation with Garfield++
- Fast simulation using machine learning method has been developed and testing shows consistent physics performance, as well as ~200 times speedup can be achieved

Acknowledgement

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- CAS Center for Excellence in Particle Physics
- Ministry of Science and Technology of the People’s Republic of China

AIDA innova

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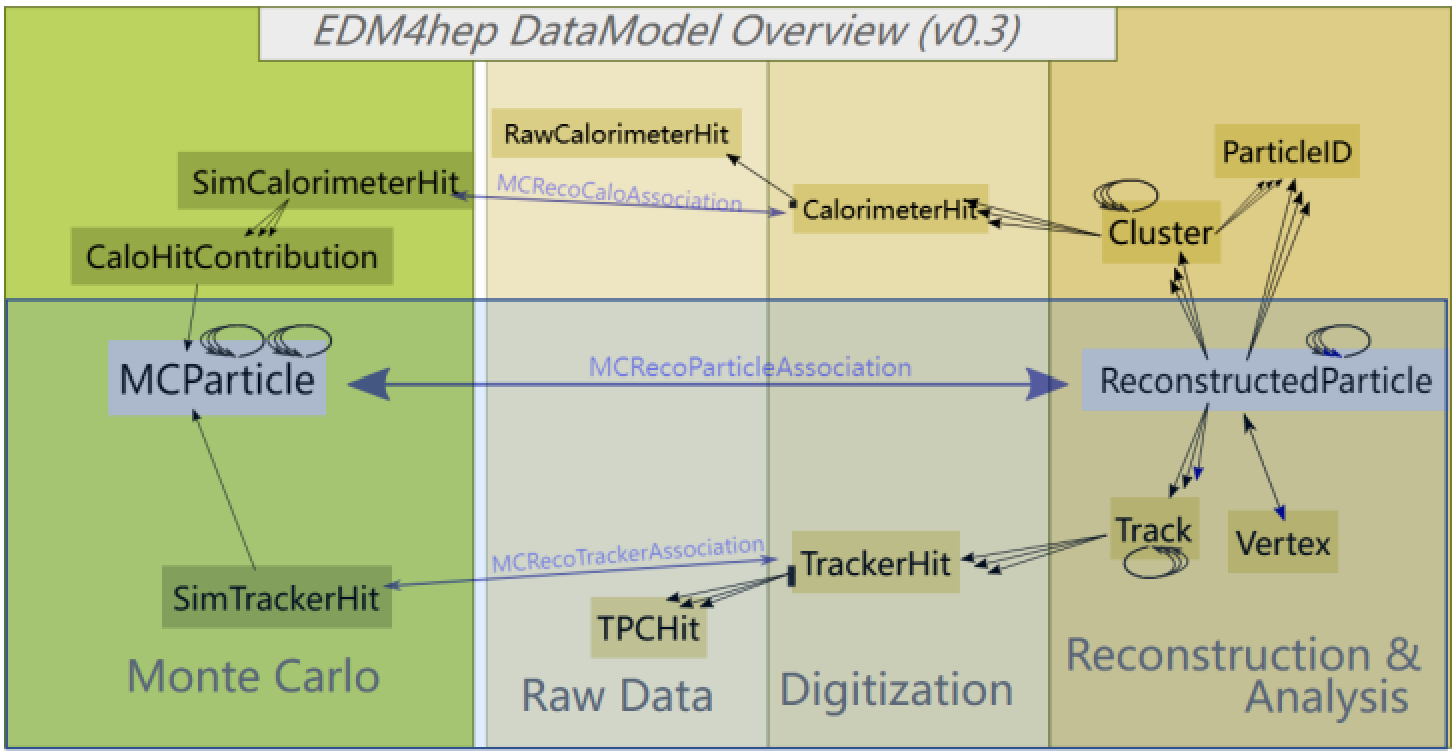
Thanks for your attention !

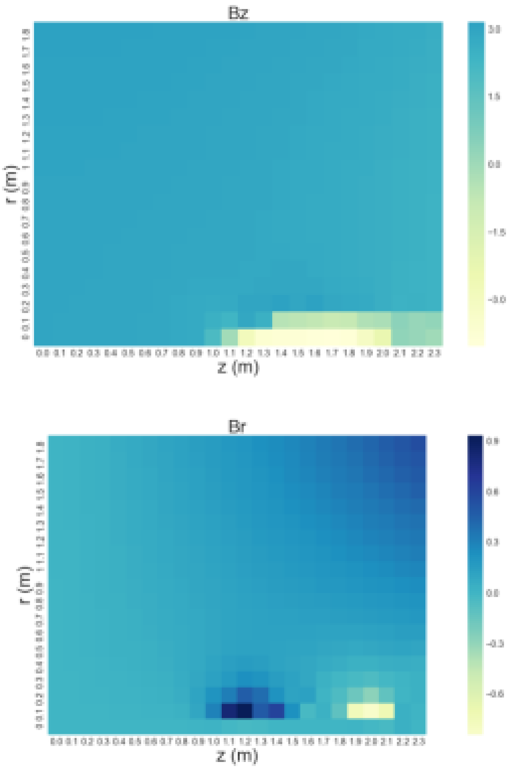
Back up

Event Data Model

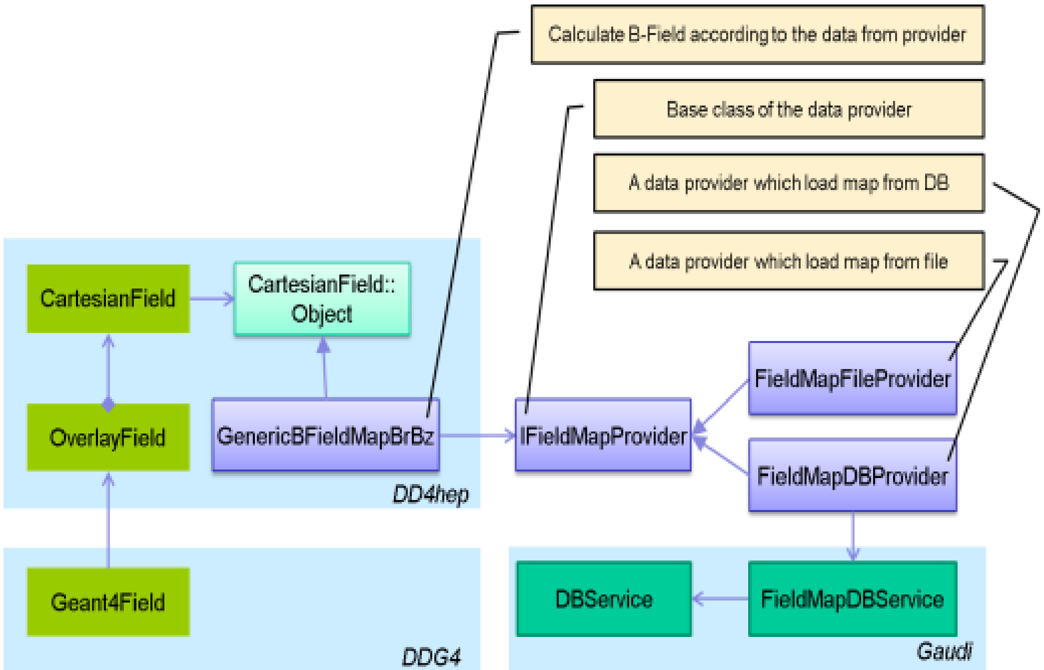


Non-uniform B-Field

- A generic B-field service is developed and integrated with DD4hep
  - CSV-like format data from magnetic group
  - Bz=3Tesla, in DC region non-uniformity<5% in z direction and <55% in radial



Filed map

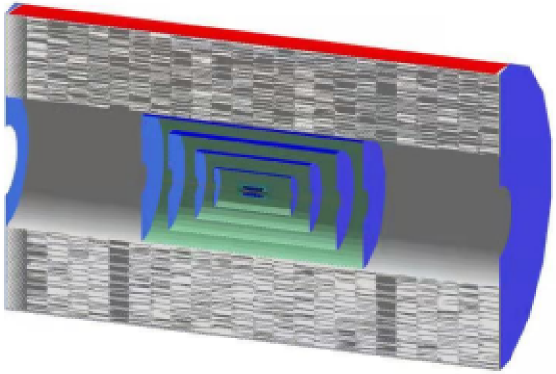


B-field service in CEPCSW

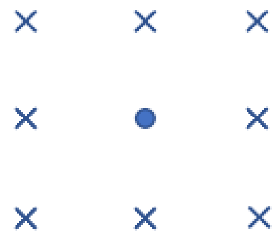
Drift Chamber Parameters in CEPCSW

- The base line configuration of DC in CEPCSW

Half length	2980 *mm*
Inner and outer radius	800 to 1800 *mm*
# of Layers	100
Cell size	~9.6 *mm x 9.6 mm*
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
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)



CRD tracker o1 v01



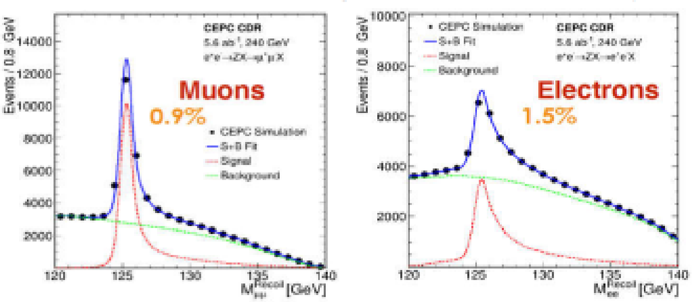
field wire: x, sense wire: o
Cell structure

Physics requirement

Detector performance requirements in CDR

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	$\Delta(1/p_T) = 2 \times 10^{-5} \oplus \frac{0.001}{p(\mathrm{GeV}) \sin^{3/2}\theta}$
$H \to b\bar{b}/c\bar{c}/gg$	$\mathrm{BR}(H \to b\bar{b}/c\bar{c}/gg)$	Vertex	$\sigma_{r\phi} = 5 \oplus \frac{10}{p(\mathrm{GeV}) \times \sin^{3/2}\theta} (\mu\mathrm{m})$
$H \to q\bar{q}, WW^*, ZZ^*$	$\mathrm{BR}(H \to q\bar{q}, WW^*, ZZ^*)$	ECAL HCAL	$\sigma_E^{\mathrm{jet}}/E = 3 \sim 4\%$ at 100 GeV
$H \to \gamma\gamma$	$\mathrm{BR}(H \to \gamma\gamma)$	ECAL	$\Delta E/E = \frac{0.20}{\sqrt{E(\mathrm{GeV})}} \oplus 0.01$

Good EM energy resolution is required for bremsstrahlung radiation recovery



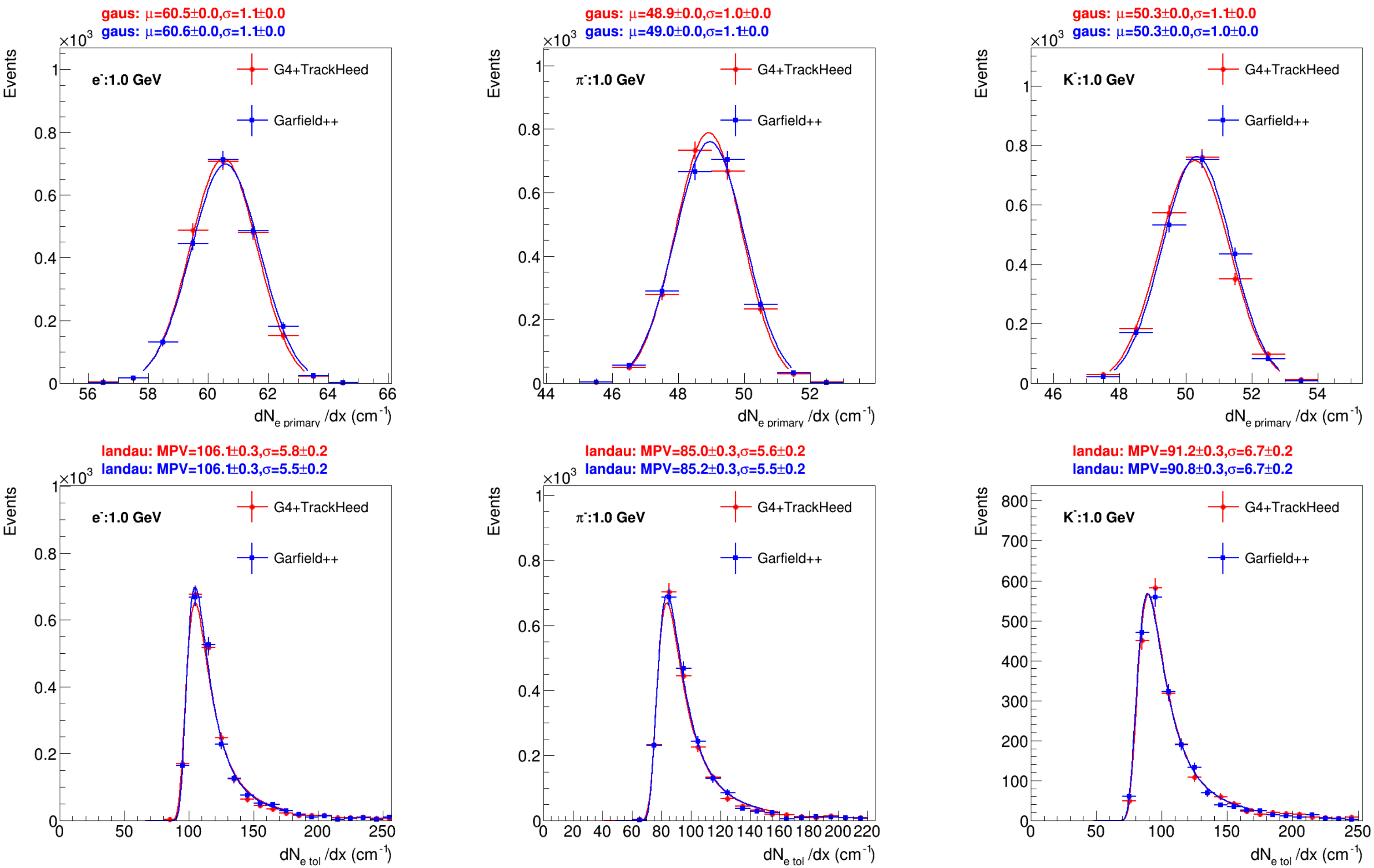
ee → HZ(→ee/μμ), recoil mass against Z boson

EWK physics:
Precise EM measurement

Flavor physics:
Precise EM measurement
Dedicated hadron identification

Ionization simulation performance

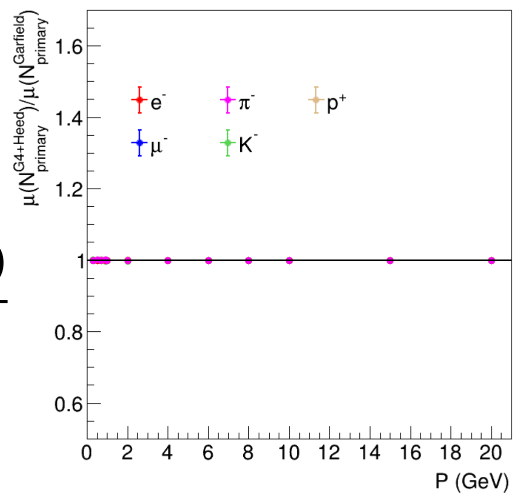
- Gas: 50% He + 50 % C_4H_{10}

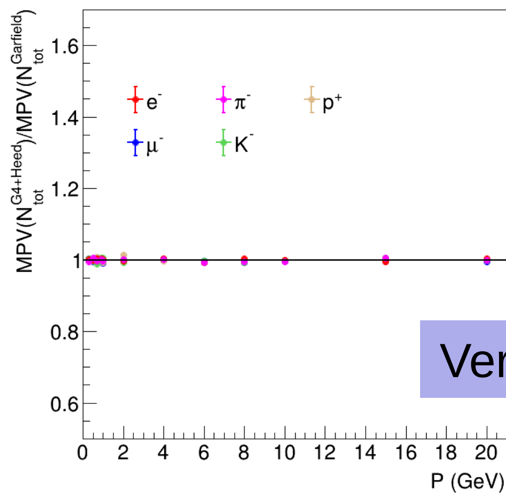


Ionization simulation performance

- Gas: 50% He + 50 % C_4H_{10}

$$\frac{\mu(N_{primary}^{G4+TrackHeed})}{\mu(N_{primary}^{Garfield++})}$$

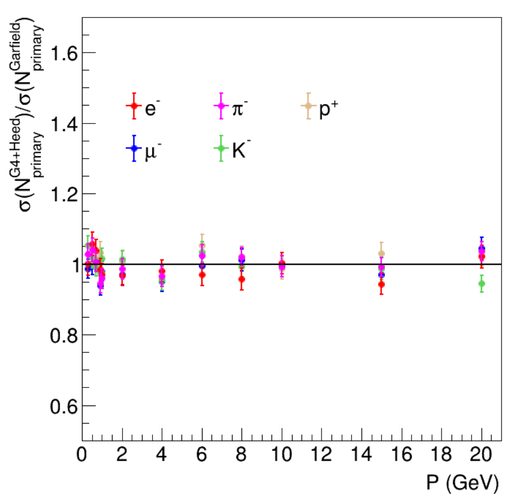


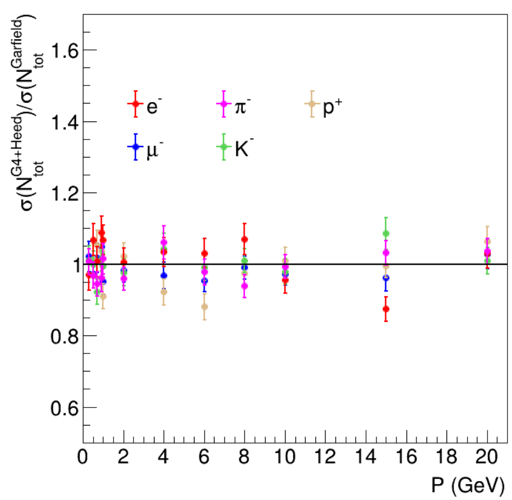


$$\frac{MPV(N_{tot}^{G4+TrackHeed})}{MPV(N_{tot}^{Garfield++})}$$

Very good agreement

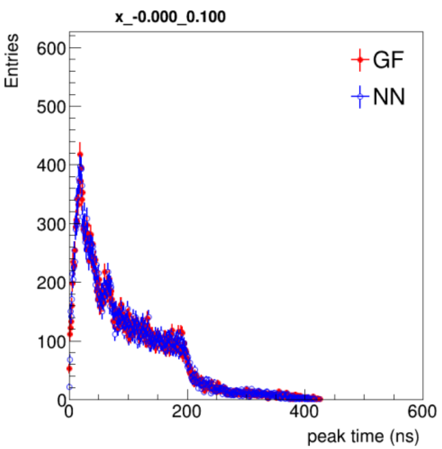
$$\frac{\sigma(N_{primary}^{G4+TrackHeed})}{\sigma(N_{primary}^{Garfield++})}$$

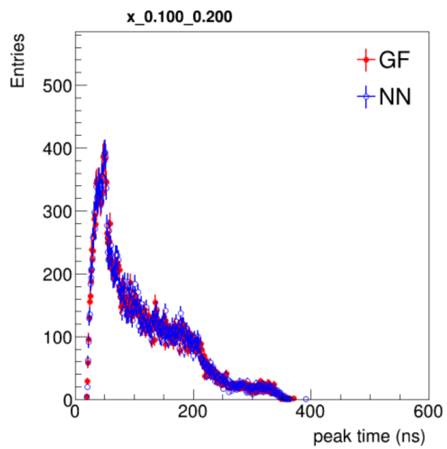


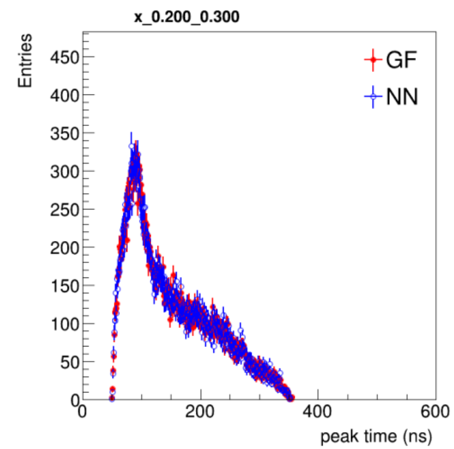


$$\frac{\sigma(N_{tot}^{G4+TrackHeed})}{\sigma(N_{tot}^{Garfield++})}$$

1 dimension check



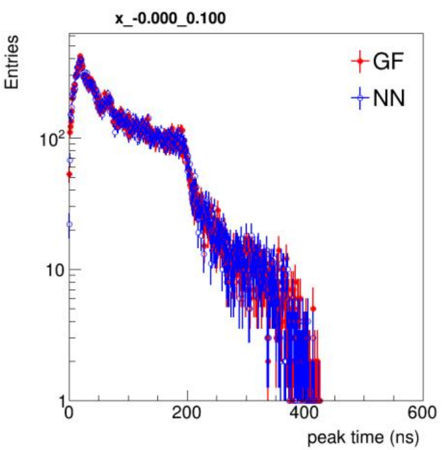


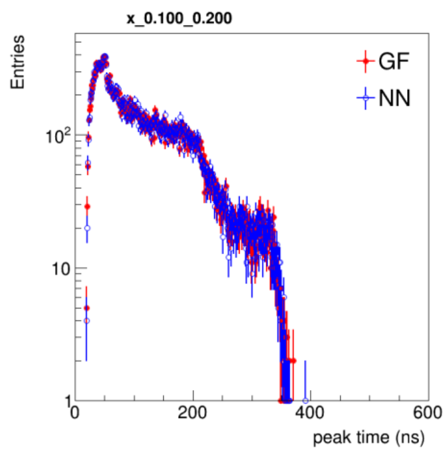


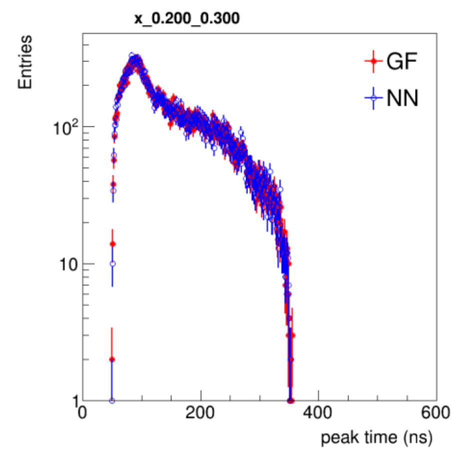
x(0,0.1) cm

x(0.1,0.2) cm

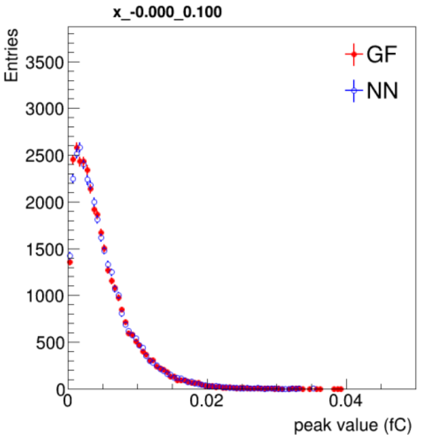
x(0.2,0.3) cm

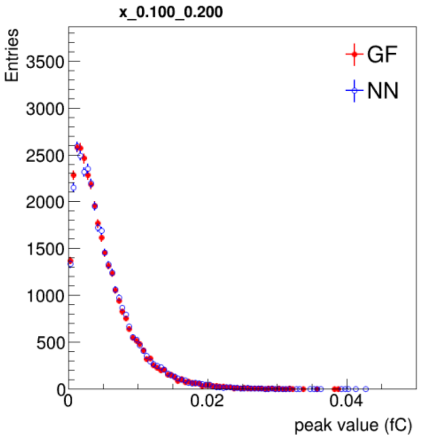


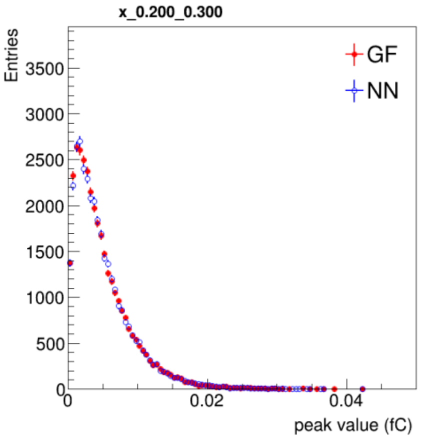




Peak value simulation



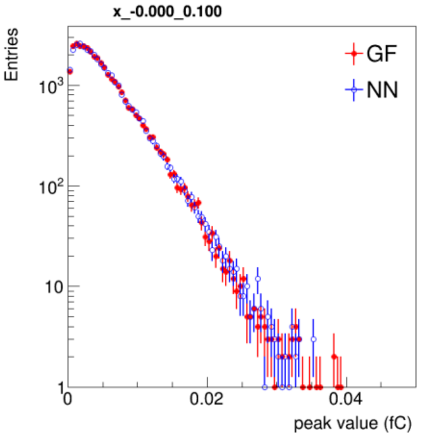


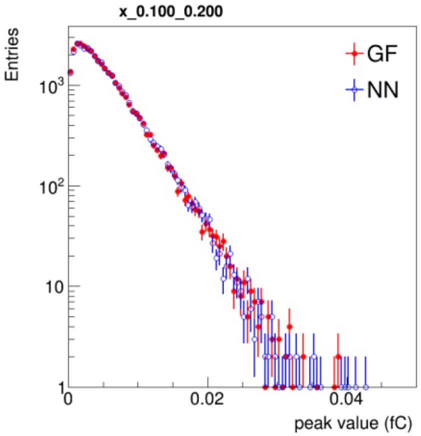


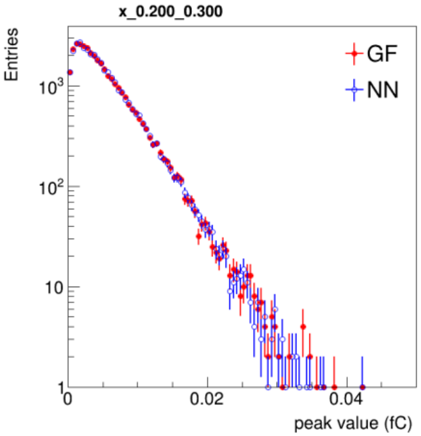
x(0,0.1) cm

x(0.1,0.2) cm

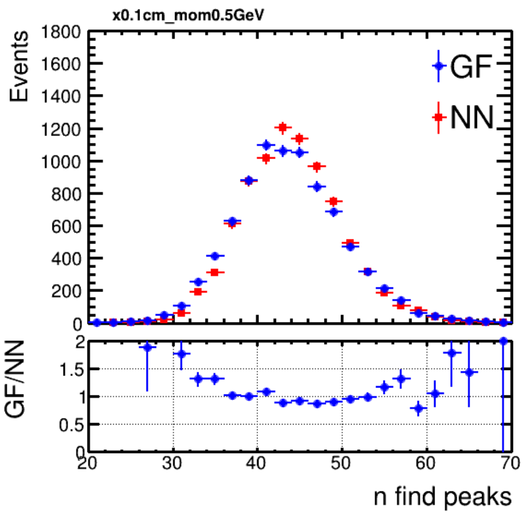
x(0.2,0.3) cm

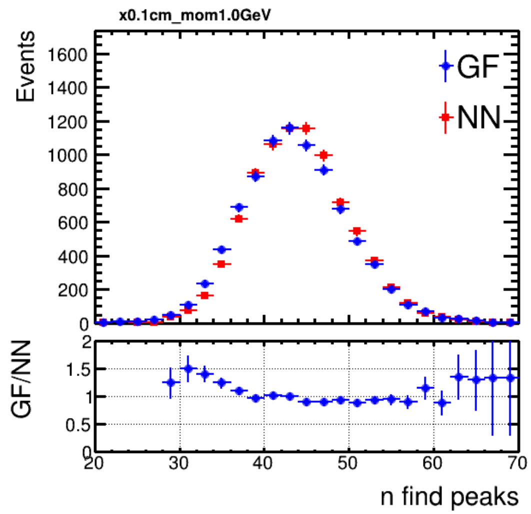


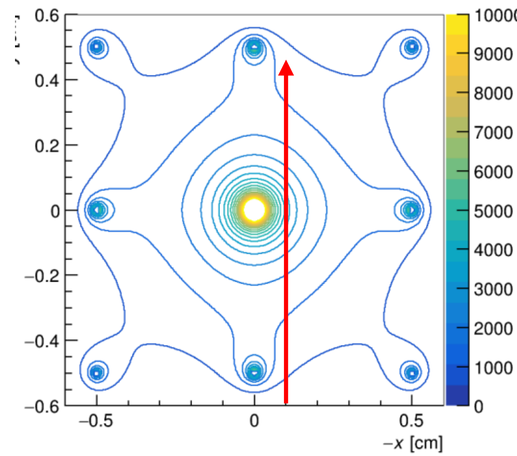




Performance check: electron (x=0.1 cm)

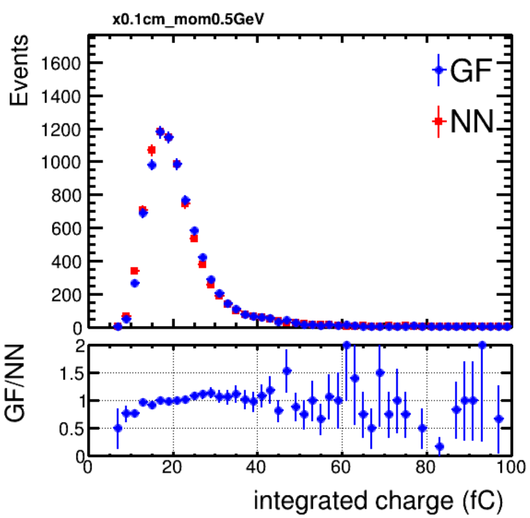


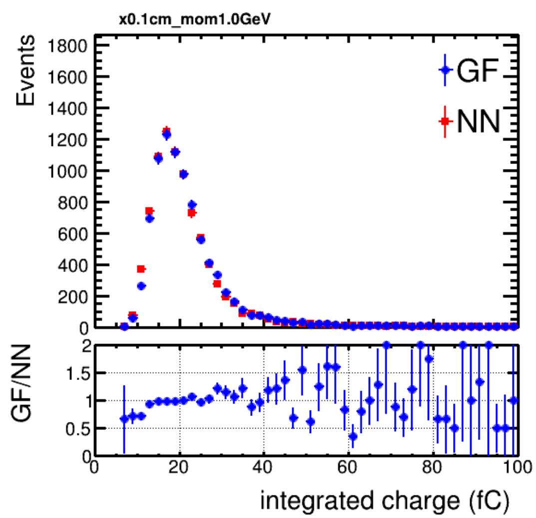




0.5 GeV

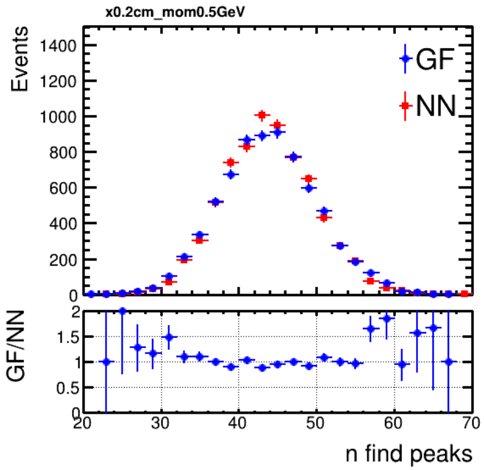
1 GeV

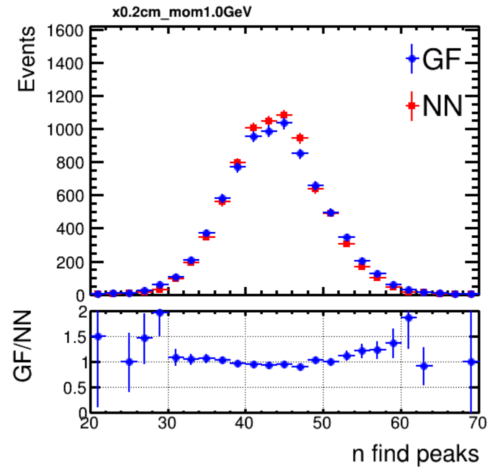


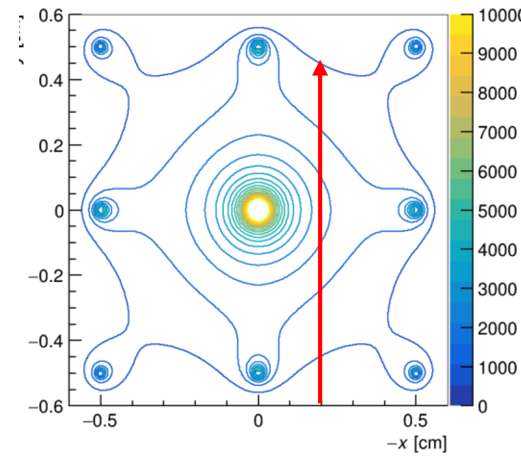


- Checked the number of found peaks(scipy.signal.find_peaks) and total charge
- Good agreement in general
- Similar results for 5 and 10 GeV

Performance check: electron (x=0.2 cm)

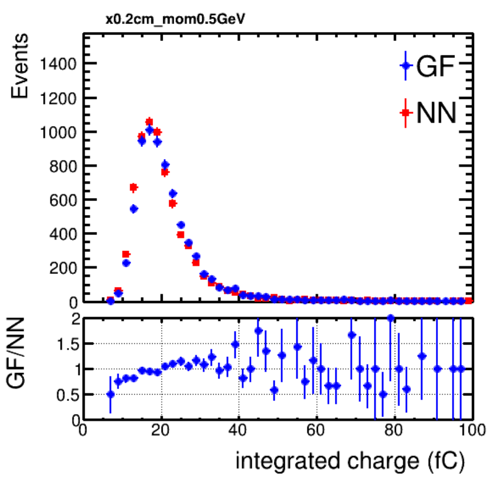


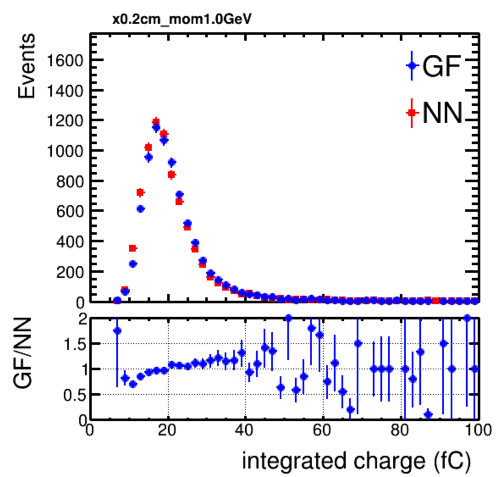




0.5 GeV

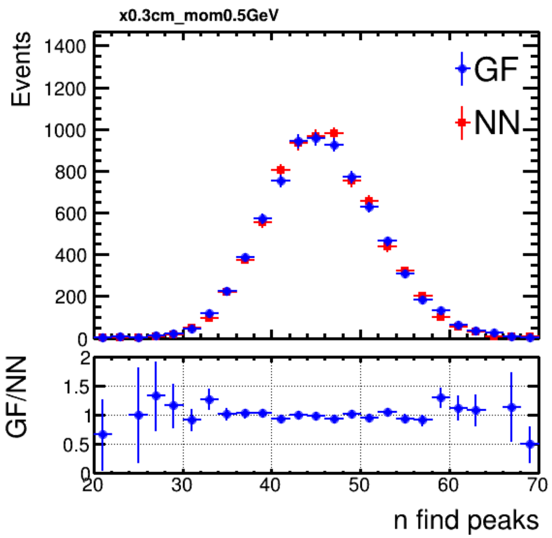
1 GeV

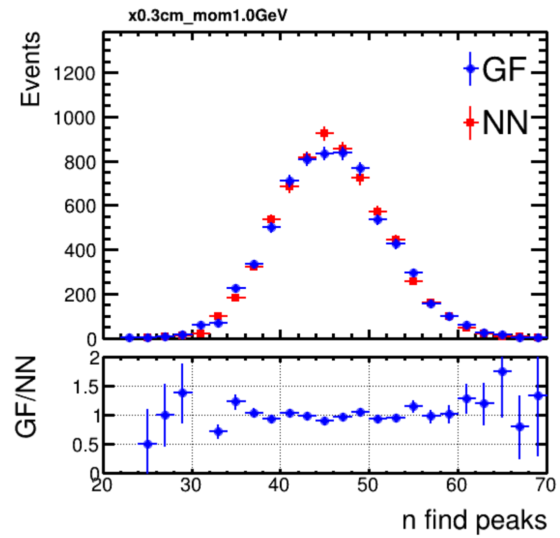


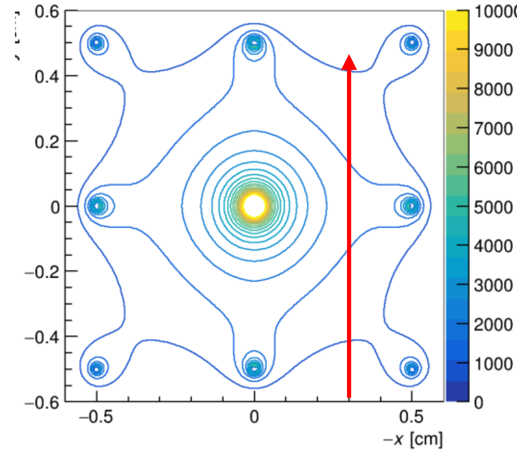


- Good agreement in general
- Similar results for 5 and 10 GeV

Performance check: electron (x=0.3 cm)

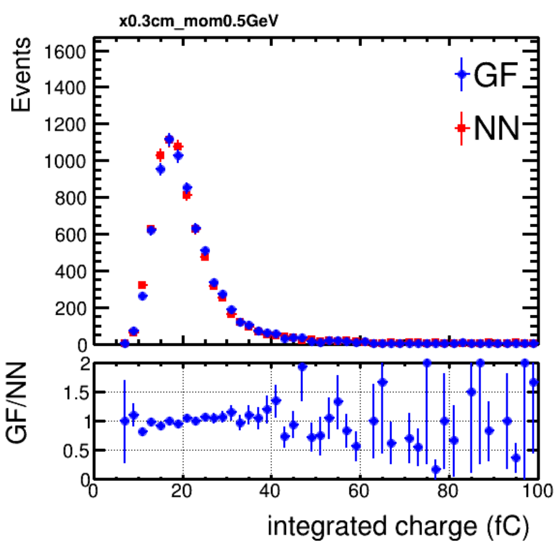


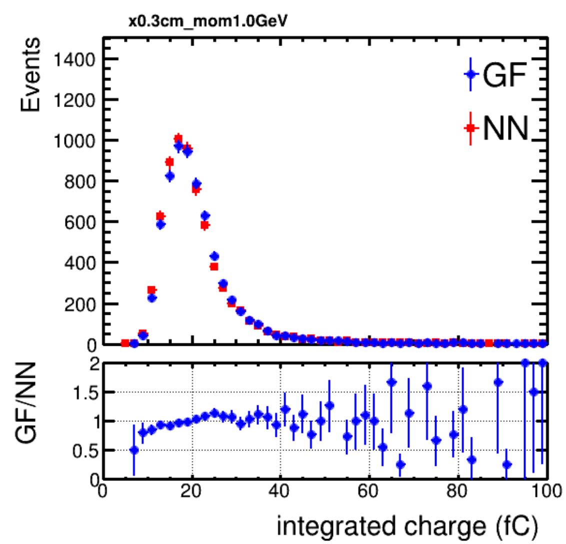




0.5 GeV

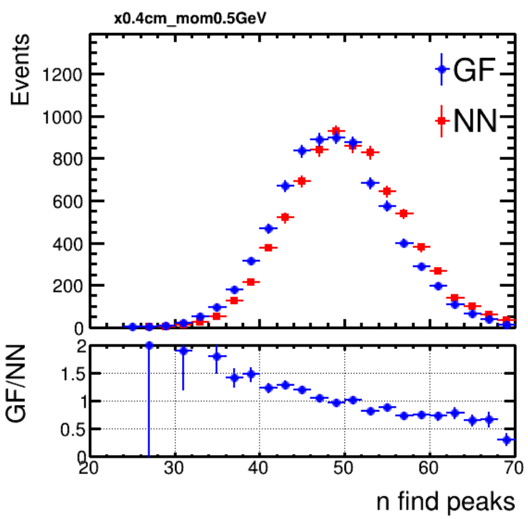
1 GeV

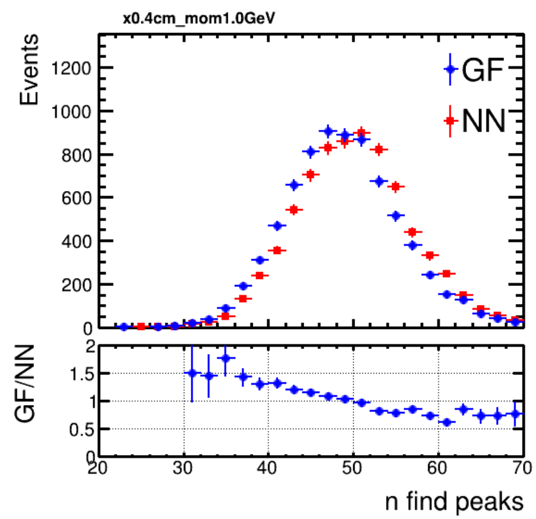


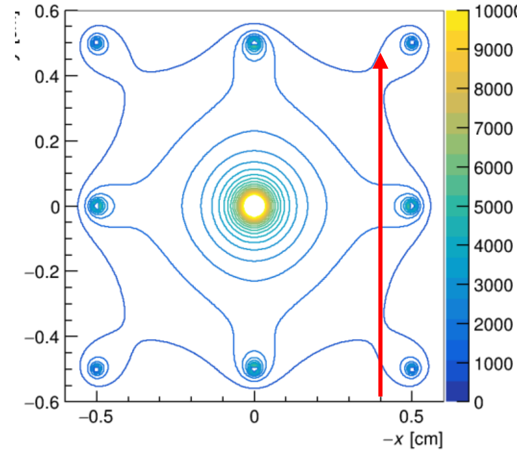


- Good agreement in general
- Similar results for 5 and 10 GeV

Performance check: electron (x=0.4 cm)

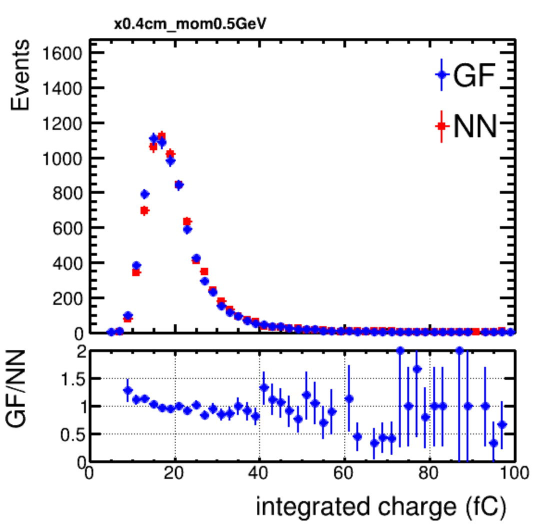


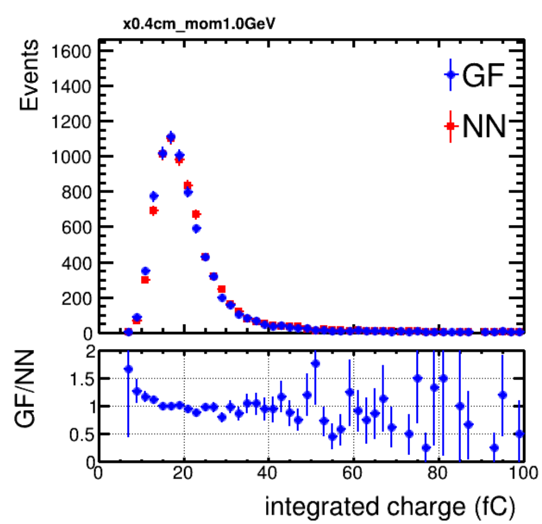




0.5 GeV

1 GeV





- A little bias for number of found peaks. Could be improved in future
- Similar results for 5 and 10 GeV

Ionization simulation in gas

- Garfield++
  - Using Heed PAI model to simulate the ionization in gas precisely
  - Can simulate the drift and avalanche of electrons in gas
  - The drift of ions to cathode can be simulated
  - The induced current can be given
  - It is useful to study and characterize the properties of gas detector with simple geometry but not for full drift chamber detector
- Geant4
  - Can simulate collider events and the interaction between particles and materials in full detector
  - It does not simulate the ionization process properly, neither the drift and avalanche processes
- In order to simulate including particle interaction will detector materials, ionization in gas, drift and avalanche processes in full detector, we try to combined Geant4 and Garfield++ in CEPCSW