中国科学院高能物理研究所
Institute of High Energy Physics
Chinese Academy of Sciences

Simulation of Calorimeter with GAN

Wenxing Fang (IHEP), Prof. Weidong Li (IHEP)

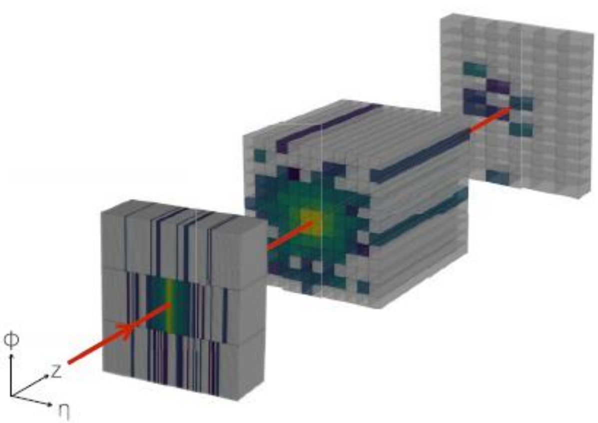
The 2019 international workshop on the high energy Circular Electron-Positron Collider (CEPC) (18th November 2019, Beijing)

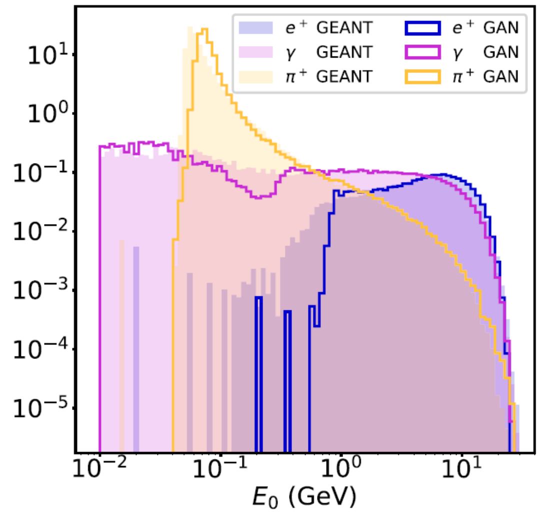
Outline

- Introduction.
- Generative Adversarial Networks (GAN).
- GAN in BESIII.
- GAN in CEPC.
- Summary and outlook.

Introduction

- As we known, in high energy physics the traditional way to do the mc simulation is using Geant4. Usually, the simulation result agrees with data in very good precision. However, it requires a tremendous amount of computation resources and it will be difficult to meet a demand resulting from large quantities of data.
- Therefore, it is attractive to develop a faster and efficient algorithm to do the particle detector simulation. Recently, some studies proved the Generative Adversarial Networks (GAN) could be used for particle detector fast simulation.

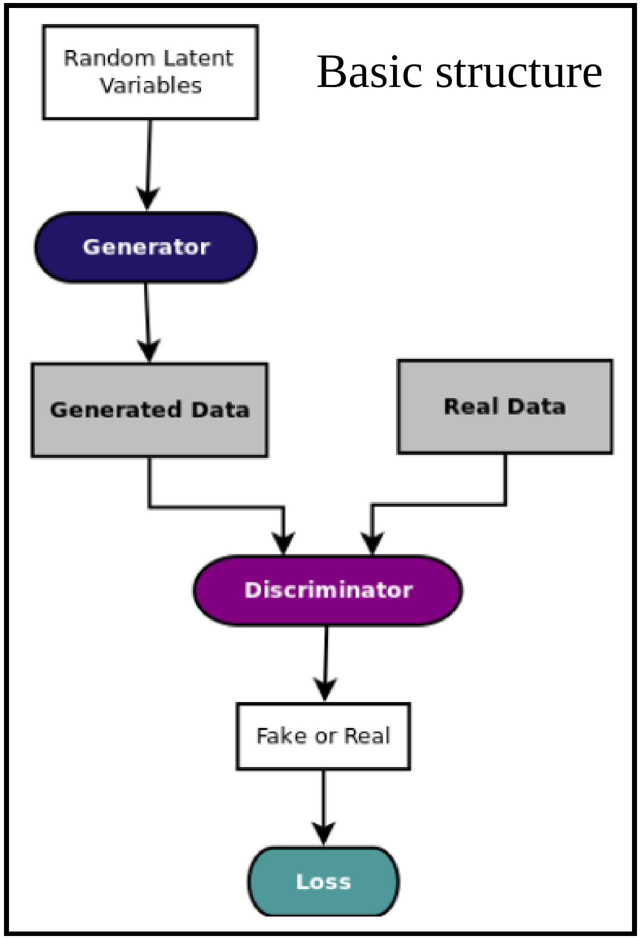




Simulator	Hardware	Batch size	ms/shower
GEANT4	CPU	N/A	1772
CALOGAN	CPU	1	13.1
		10	5.11
		128	2.19
		1024	2.03
	GPU	1	14.5
		4	3.68
		128	0.021
		512	0.014
		1024	0.012

PRL 120, 042003 (2018)

Generative Adversarial Networks (GAN)



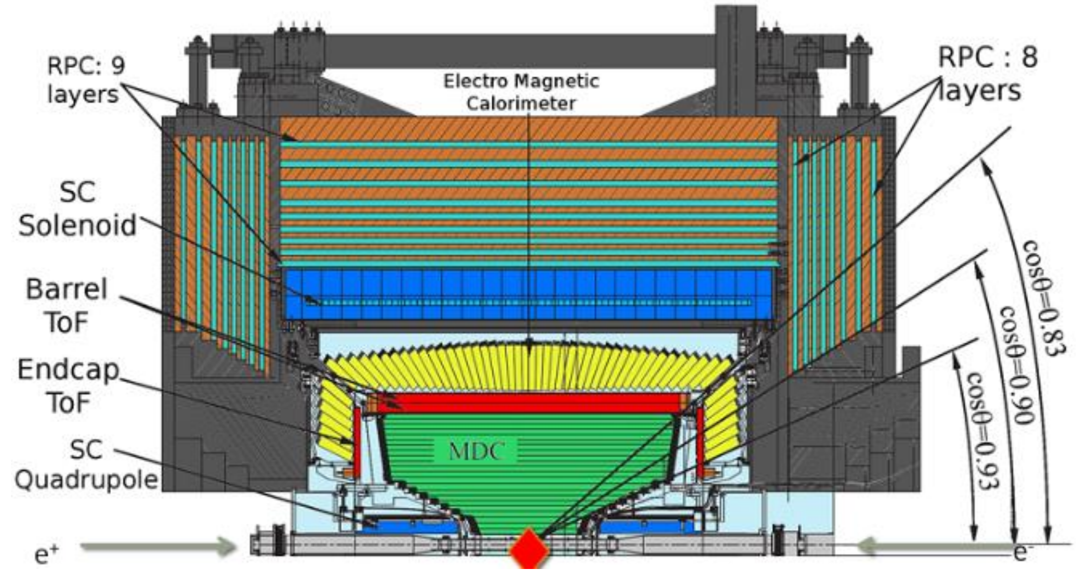
- Discriminator tries to discriminate the real data and generated data.
- Generator tries to produce generated data which can confuse the discriminator.
- In the end, the discriminator can not discriminate the real or generated data. And the generator learns the true underlaying data distribution.

vanilla loss formulation

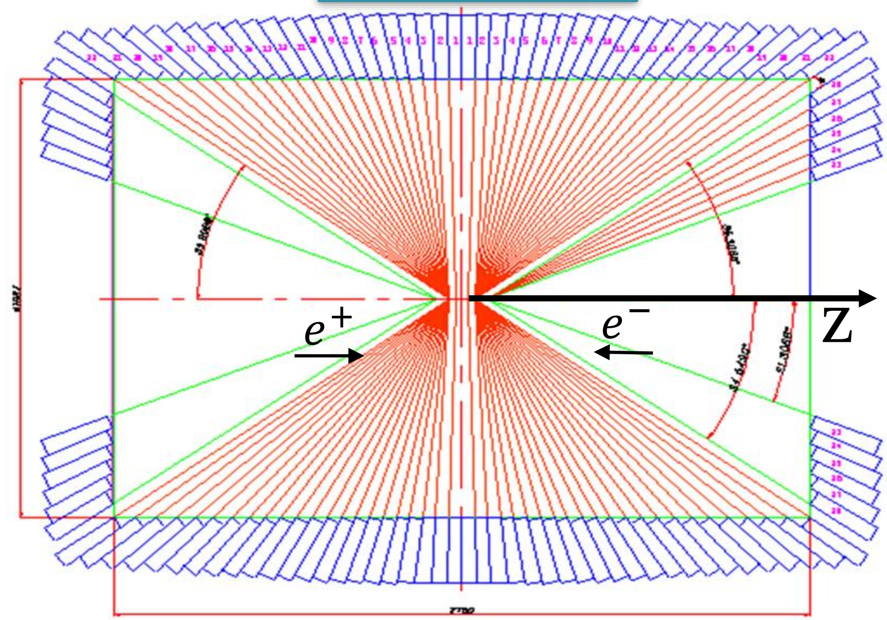
$$\min_G \max_D V(D,G) = E_{x\sim p_{data}(x)}[logD(x)] + E_{z\sim p_z(z)}[log(1-D(G(z)))]$$

Here, x is real data, G(z) is fake data

- ❑ The BESIII detector is designed to study physics in the τ-charm energy region utilizing the high luminosity BEPCII double ring e^+e^- collider which has peak luminosity $10^{33}cm^{-2}s^{-1}$ at center-of-mass energy 3.78 GeV.



Zoomed EMC

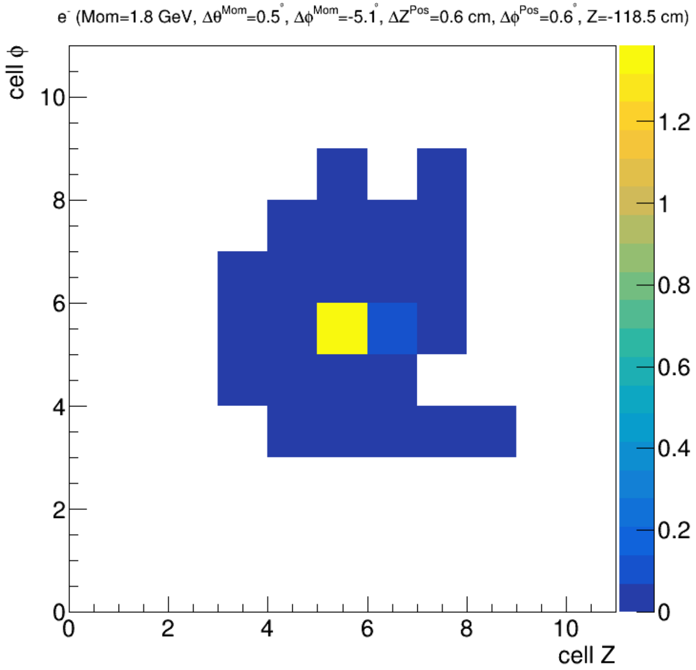


- 44 rings of crystal in barrel and 120 crystals in each ring. The front size of each crystals is 5×5 cm^2, the crystal length is 28 cm .
- 6 rings of crystal in each endcap.

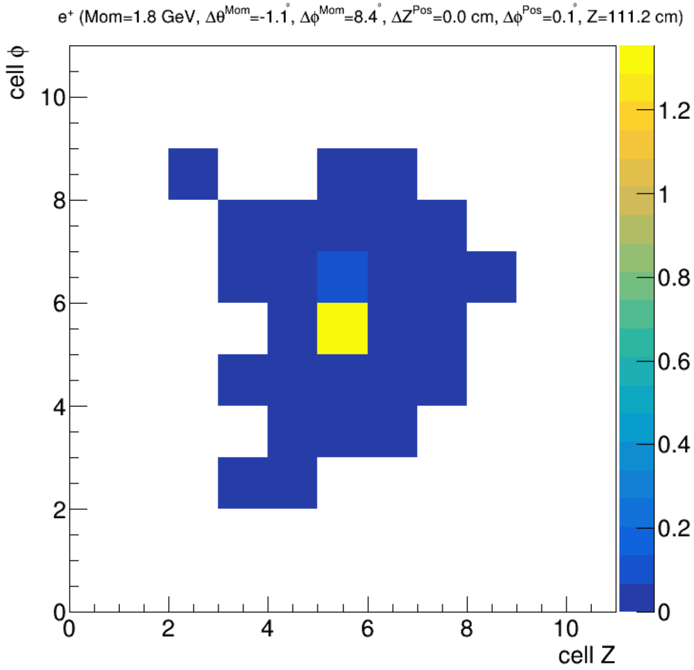
Dataset

- Using MC Bhabha events for training.
  - Selecting $e^{\pm}$ at barrel region.
  - The position of $e^{\pm}$ MDC track extends to EMC is chose as the center. Hit energy in 11×11 calorimeter cells are considered.
  - ~ 450000 training events.

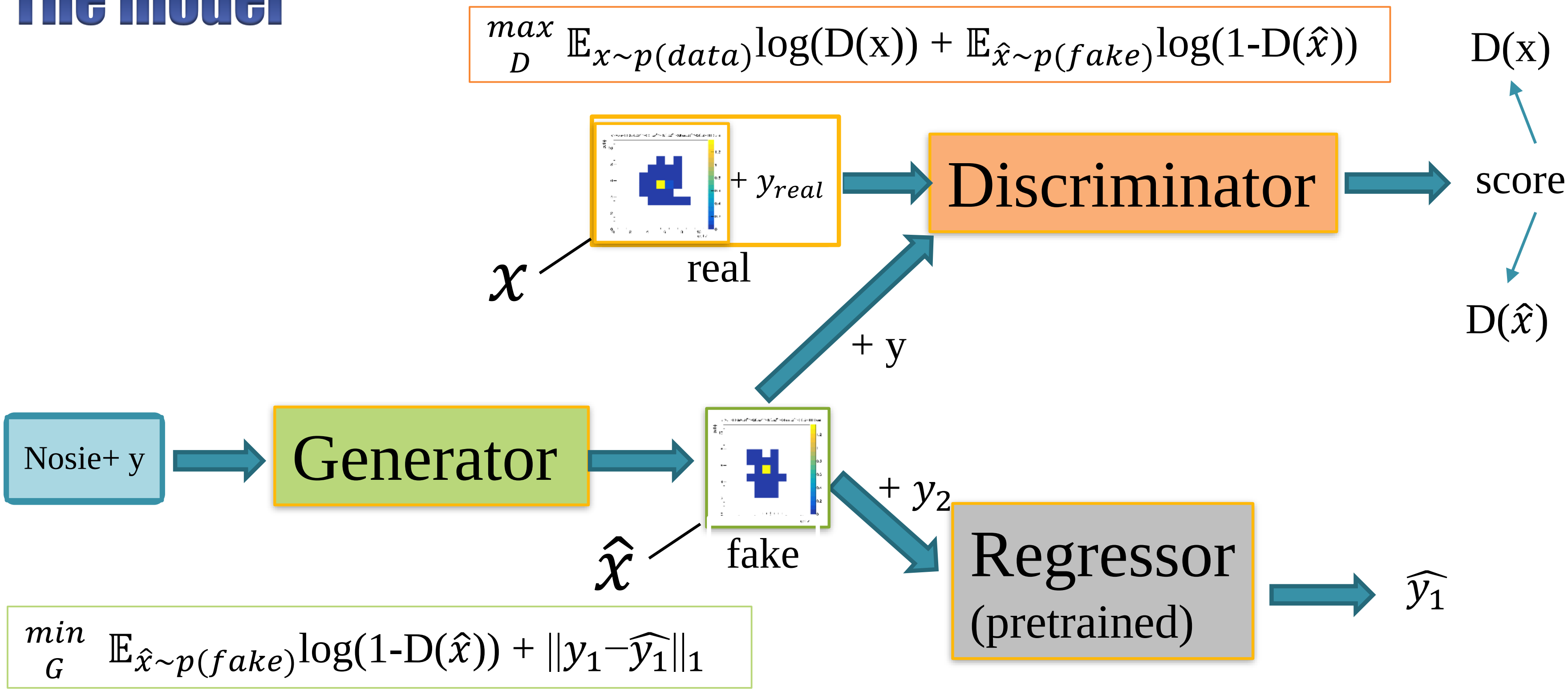
$e^{-}(\mathrm{Mom} = 1.8\ \mathrm{GeV}, \Delta\theta^{\mathrm{Mom}} = 0.5^{\circ}, \Delta\phi^{\mathrm{Mom}} = -5.1^{\circ}, \Delta Z^{\mathrm{Pos}} = 0.6\ \mathrm{cm}, \Delta\phi^{\mathrm{Pos}} = 0.6^{\circ}, Z = -118.5\ \mathrm{cm})$



$e^{+}(\mathrm{Mom} = 1.8\ \mathrm{GeV}, \Delta\theta^{\mathrm{Mom}} = -1.1^{\circ}, \Delta\phi^{\mathrm{Mom}} = 8.4^{\circ}, \Delta Z^{\mathrm{Pos}} = 0.0\ \mathrm{cm}, \Delta\phi^{\mathrm{Pos}} = 0.1^{\circ}, Z = 111.2\ \mathrm{cm})$

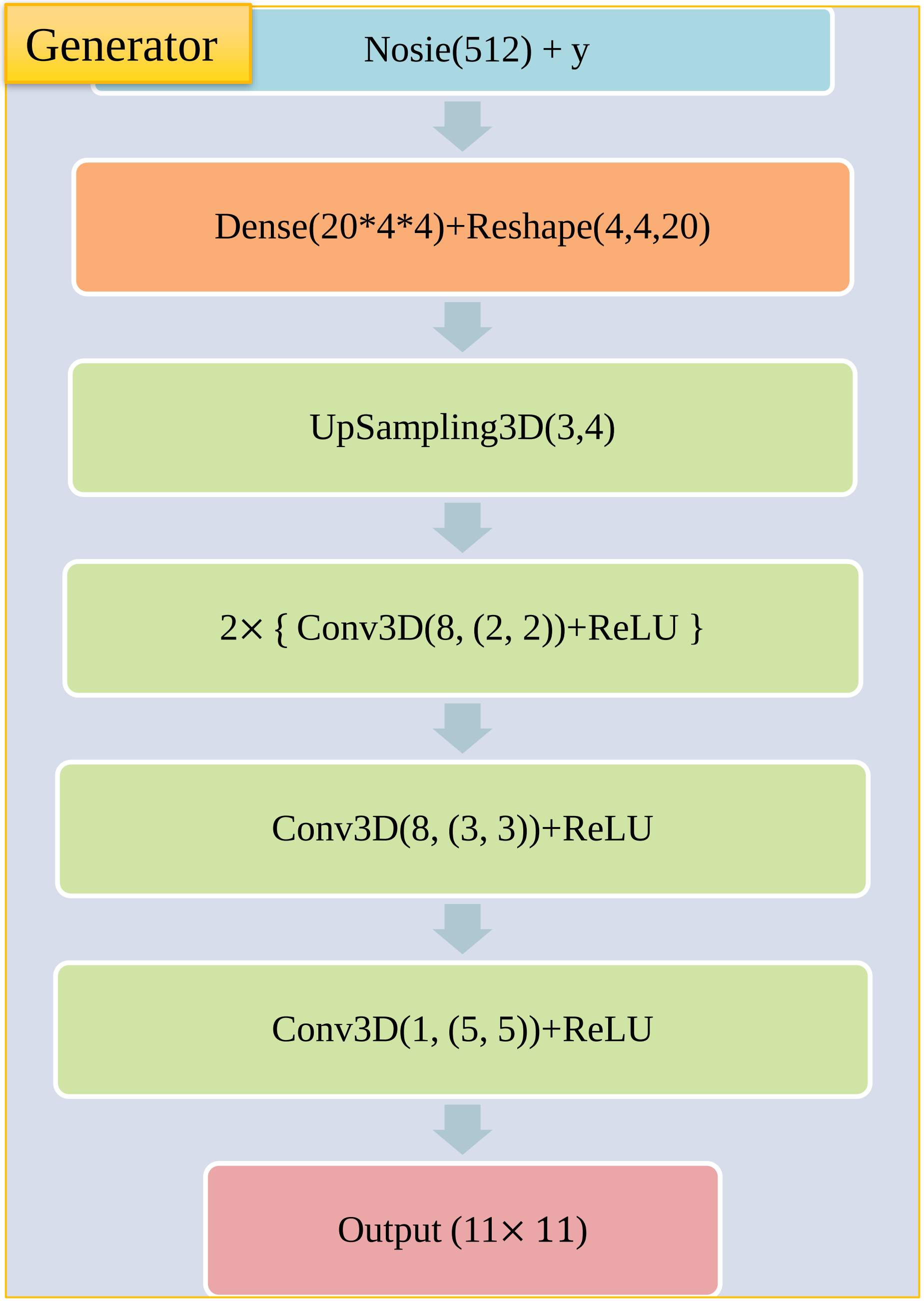


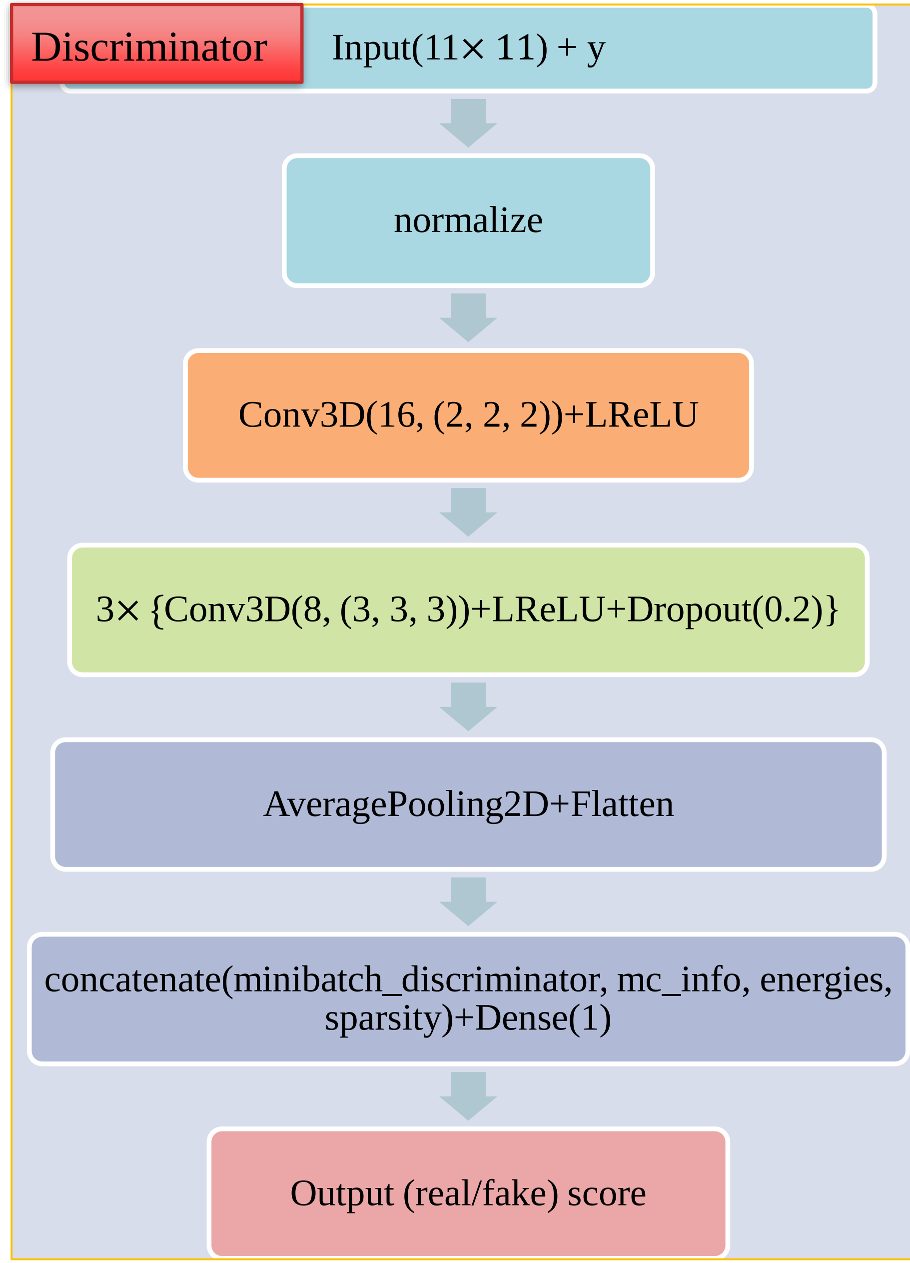
The model



- The y ($y_1 + y_2$) contains the momentum of particle and the relative position and angular between the particle and the calorimeter.
  - y_1
    - Momentum: the momentum of the particle.
    - $\Delta\phi^{Mom}$: the ϕ difference between the momentum of incoming particle and the direction of the crystal.
    - $\Delta\theta^{Mom}$: the θ difference between the momentum of incoming particle and the direction of the crystal.
  - y_2
    - ΔZ^{Pos}: the Z difference between the hit point of incoming particle and the z of front center of the crystal.
    - $\Delta\phi^{Pos}$: the ϕ difference between the hit point of incoming particle and the ϕ of front center of the crystal.
    - Z: the Z value of hit point.
- Pre-trained regressor for the particle parameters prediction makes our model conditional.

The model


Generator
Nosie(512) + y
Dense(20*4*4)+Reshape(4,4,20)
UpSampling3D(3,4)
2× { Conv3D(8, (2, 2))+ReLU }
Conv3D(8, (3, 3))+ReLU
Conv3D(1, (5, 5))+ReLU
Output (11× 11)

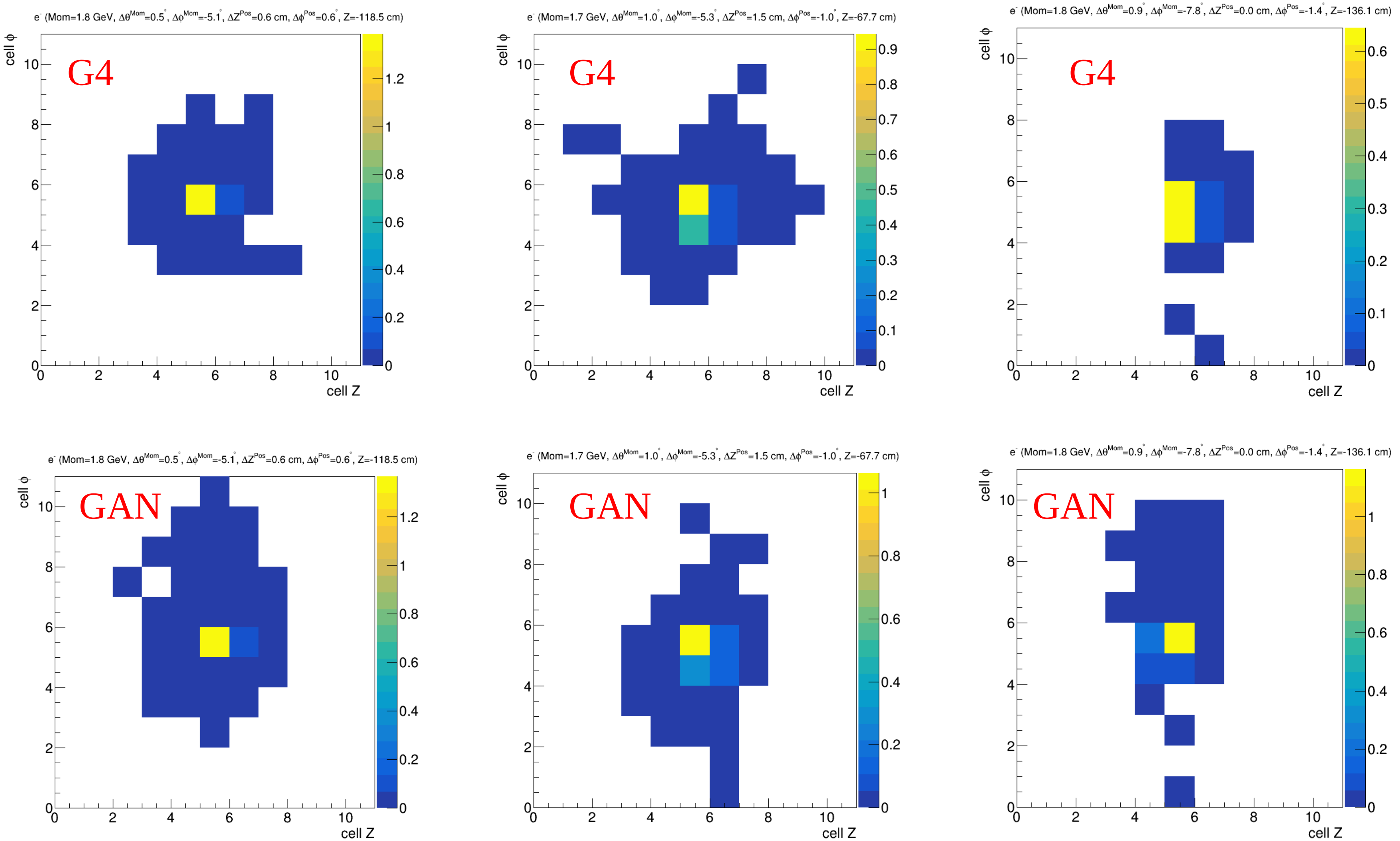

Discriminator
Input(11× 11) + y
normalize
Conv3D(16, (2, 2, 2))+LReLU
3× {Conv3D(8, (3, 3, 3))+LReLU+Dropout(0.2)}
AveragePooling2D+Flatten
concatenate(minibatch_discriminator, mc_info, energies, sparsity)+Dense(1)
Output (real/fake) score

Some generated events (e^-)

e^-(Mom = 1.8 GeV, $\Delta\theta^{Mom}$ = 0.5°, $\Delta\phi^{Mom}$ = −5.1°, ΔZ^{Pos} = 0.6 cm, $\Delta\phi^{Pos}$ = 0.6°, Z = −118.5 cm)

e^-(Mom = 1.7 GeV, $\Delta\theta^{Mom}$ = 1.0°, $\Delta\phi^{Mom}$ = −5.3°, ΔZ^{Pos} = 1.5 cm, $\Delta\phi^{Pos}$ = −1.0°, Z = −67.7 cm)

e^-(Mom = 1.8 GeV, $\Delta\theta^{Mom}$ = 0.9°, $\Delta\phi^{Mom}$ = −7.8°, ΔZ^{Pos} = 0. cm, $\Delta\phi^{Pos}$ = −1.4°, Z = −136.1 cm)



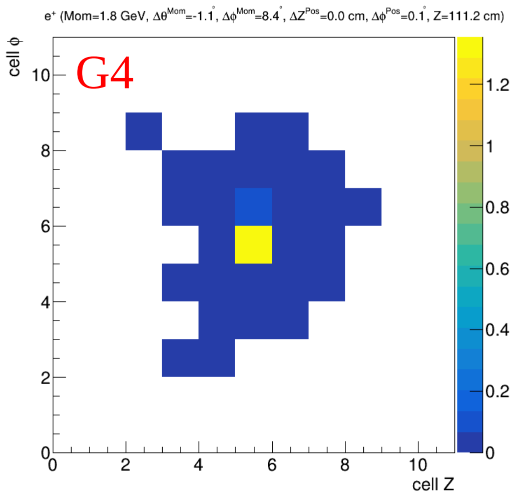
It looks fine for the events from GAN.

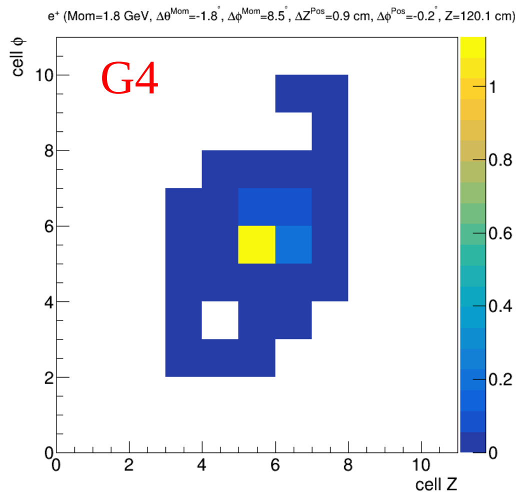
Some generated events (e^+)

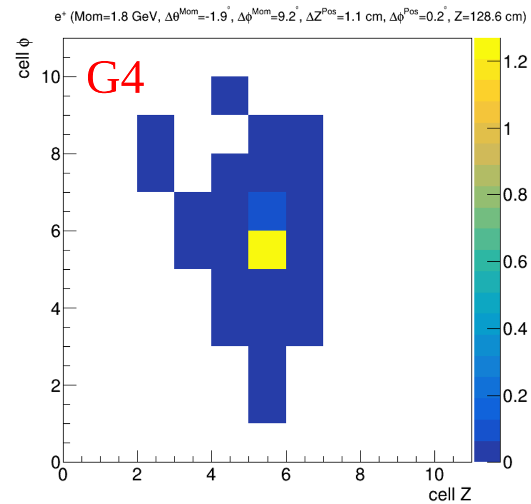
e^+(Mom = 1.8 GeV, $\Delta\theta^{Mom} = -1.1^\circ$, $\Delta\phi^{Mom} = 8.4^\circ$, $\Delta Z^{Pos} = 0.0$ cm, $\Delta\phi^{Pos} = 0.1^\circ$, Z = 111.2 cm)

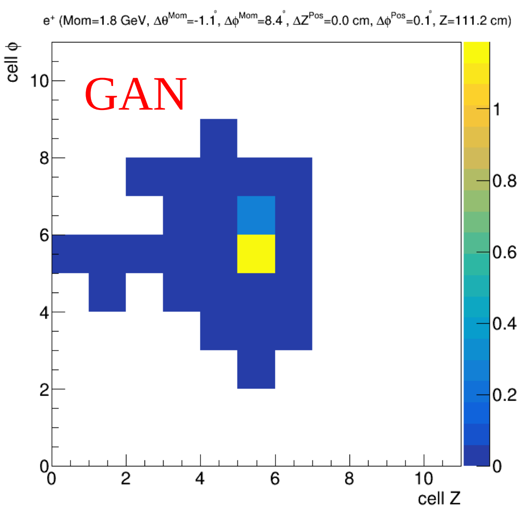
e^+(Mom = 1.8 GeV, $\Delta\theta^{Mom} = -1.8^\circ$, $\Delta\phi^{Mom} = 8.5^\circ$, $\Delta Z^{Pos} = 0.9$ cm, $\Delta\phi^{Pos} = -0.2^\circ$, Z = 120.1 cm)

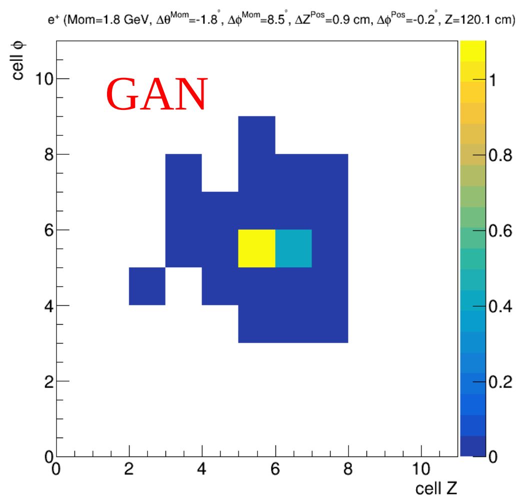
e^+(Mom = 1.8 GeV, $\Delta\theta^{Mom} = -1.9^\circ$, $\Delta\phi^{Mom} = 9.2^\circ$, $\Delta Z^{Pos} = 1.1$ cm, $\Delta\phi^{Pos} = 0.2^\circ$, Z = 128.6 cm)

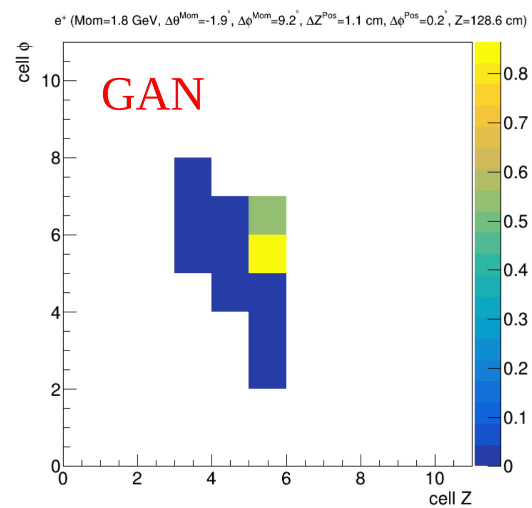






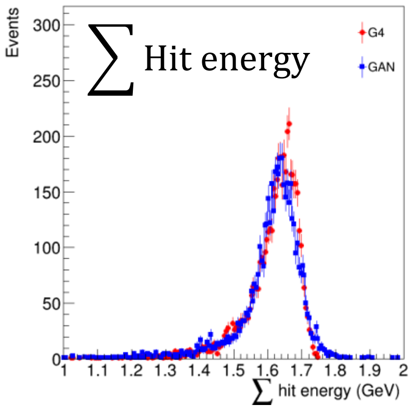


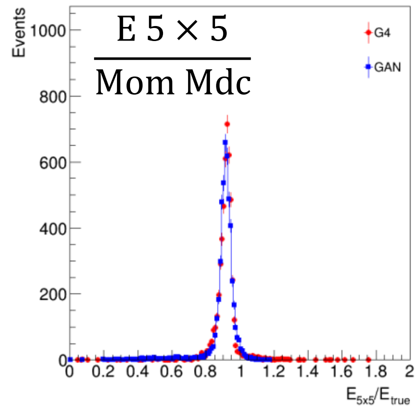


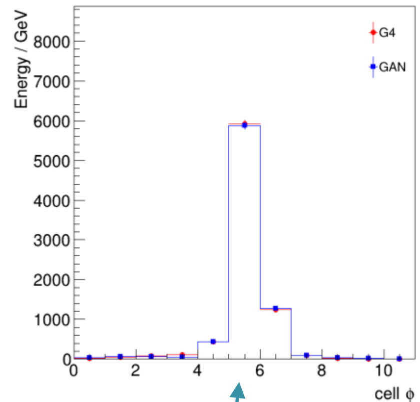


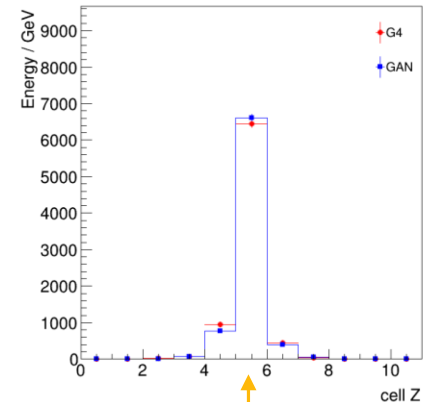
It looks fine for the events from GAN.

Some distributions (e^-)





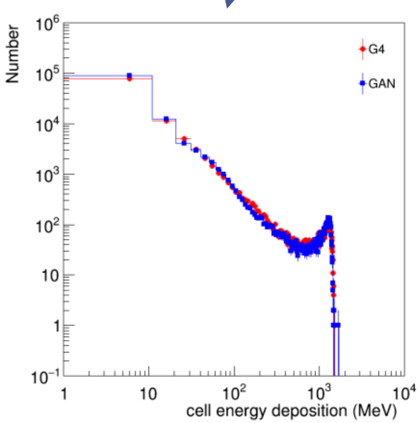


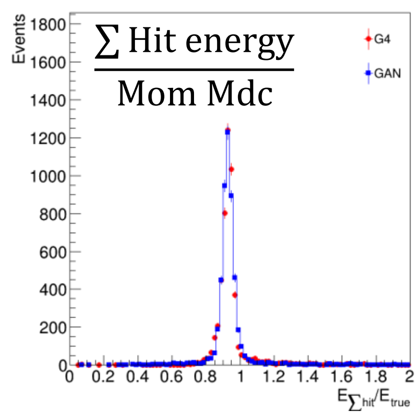


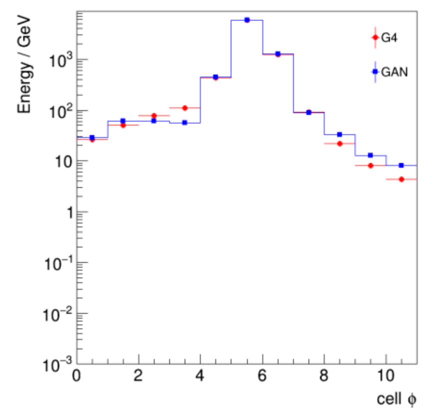
Energy deposited in ϕ direction

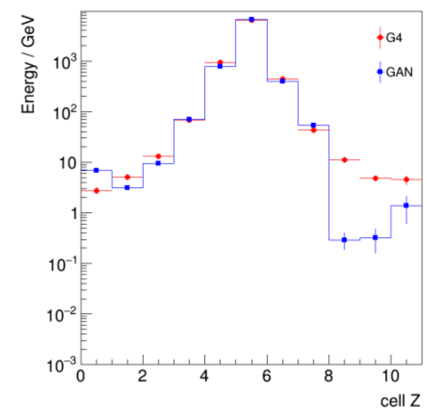
Energy deposited in Z direction

Energy of calorimeter cells

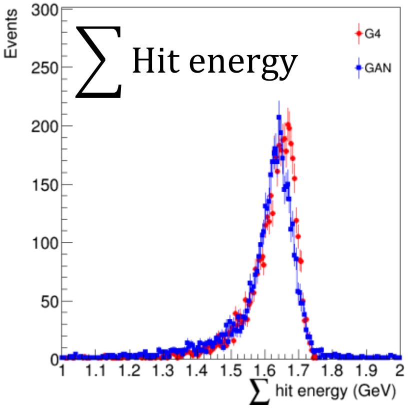


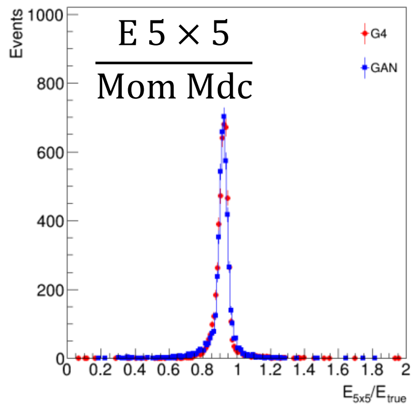


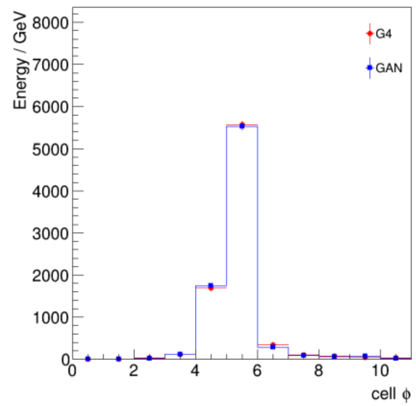


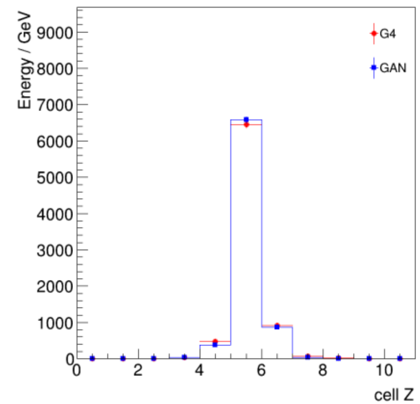


Some distributions (e^+)





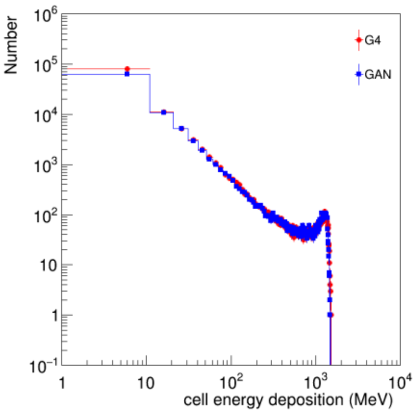


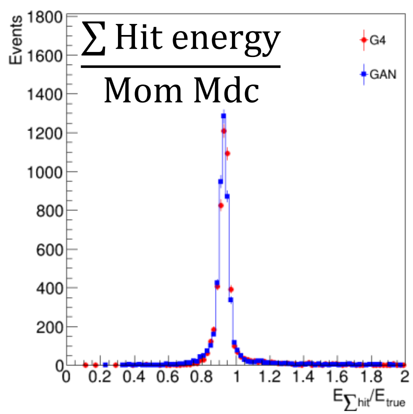


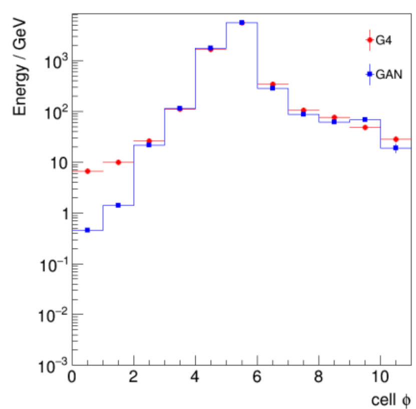
Energy deposited in ϕ direction

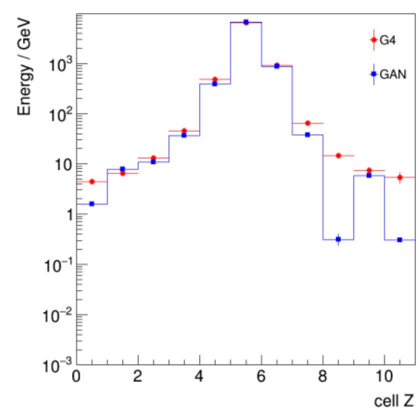
Energy deposited in Z direction

Energy of calorimeter cells

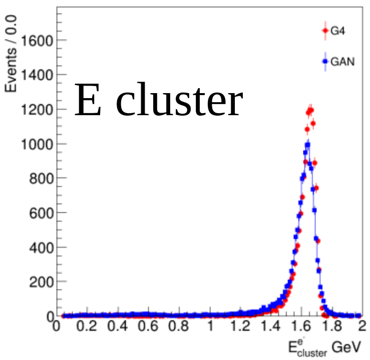


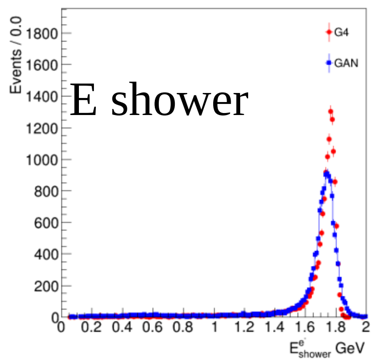


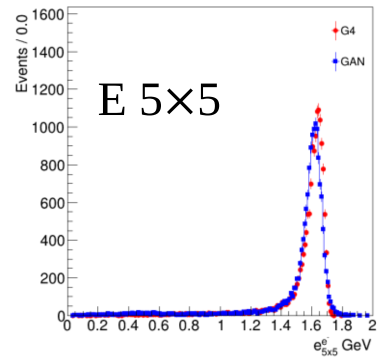


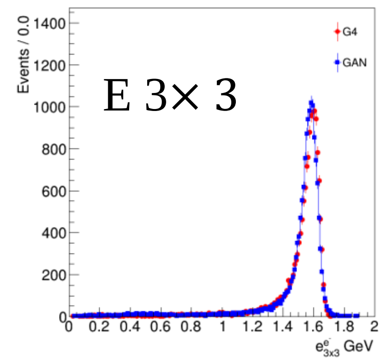


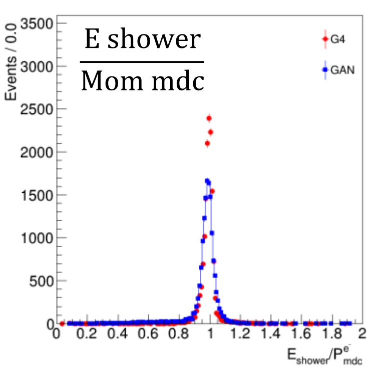
Some distributions for reconstruced particle (e^-)

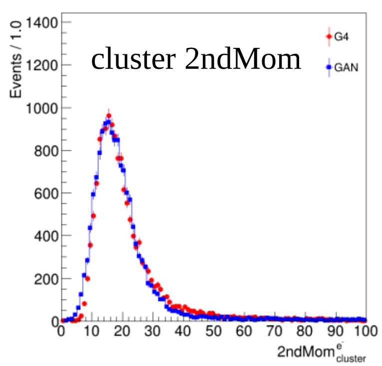


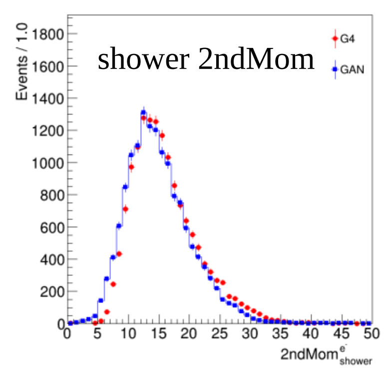


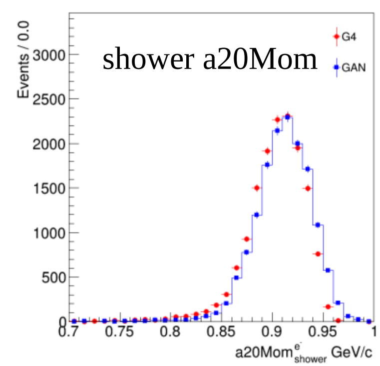


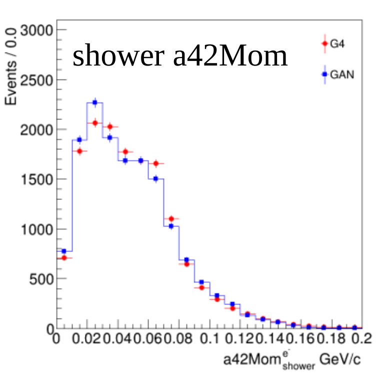


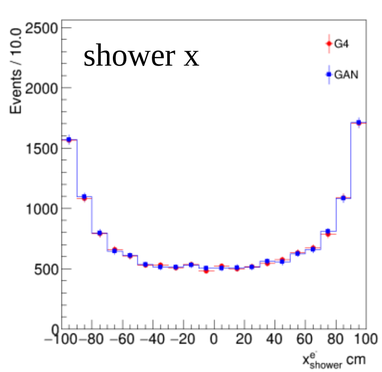


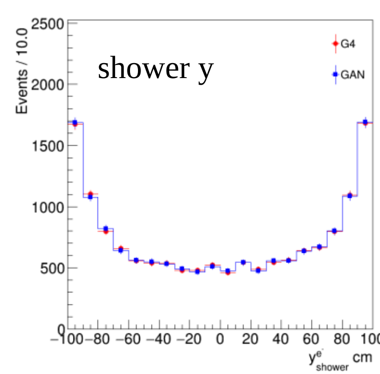


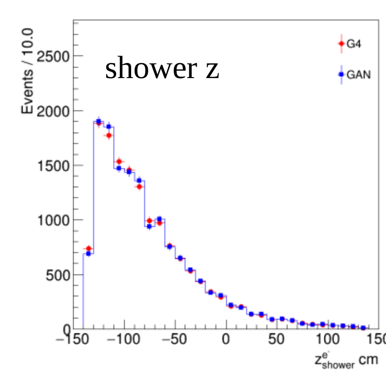




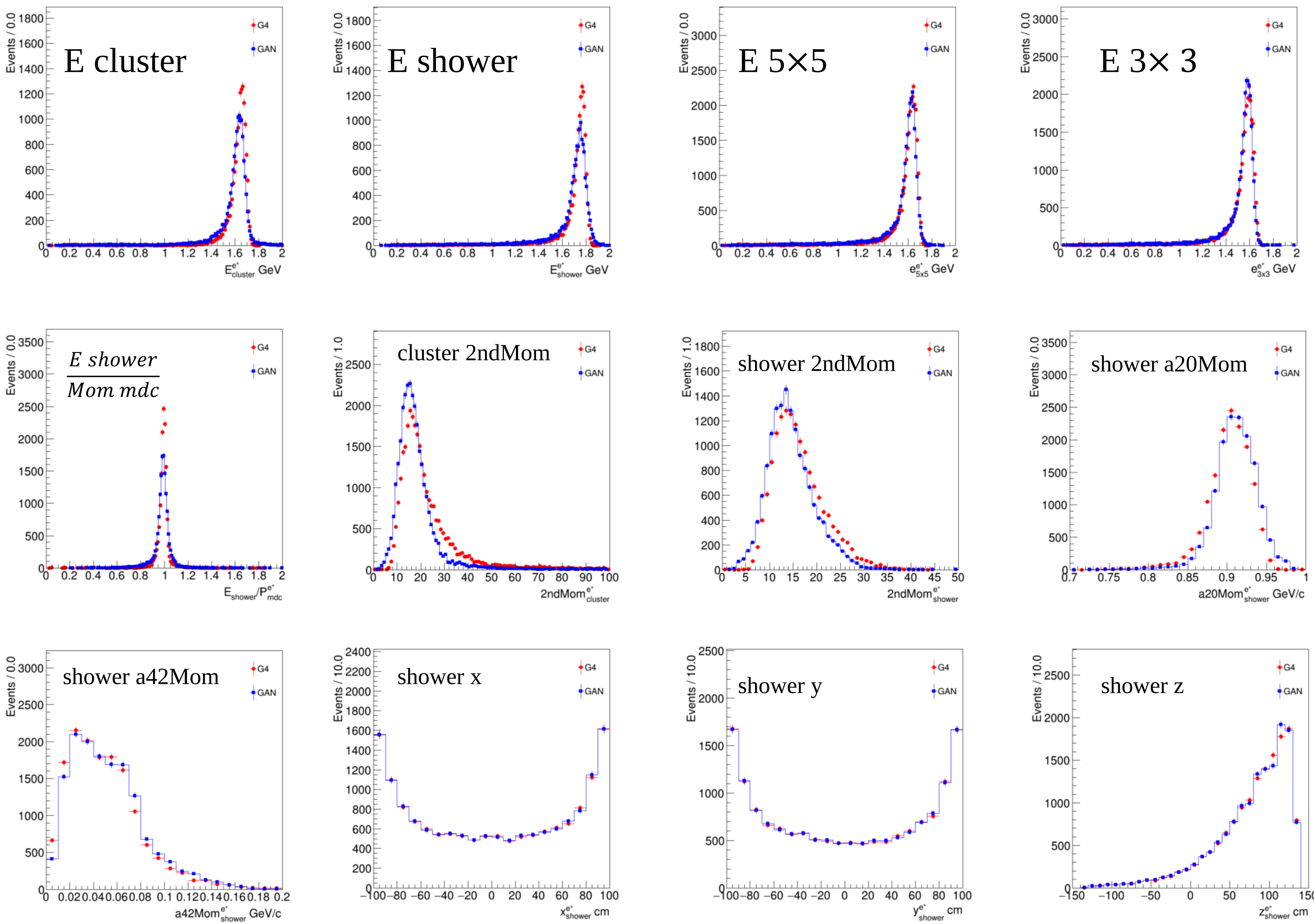








Some variables for reconstruced particle (e^+)

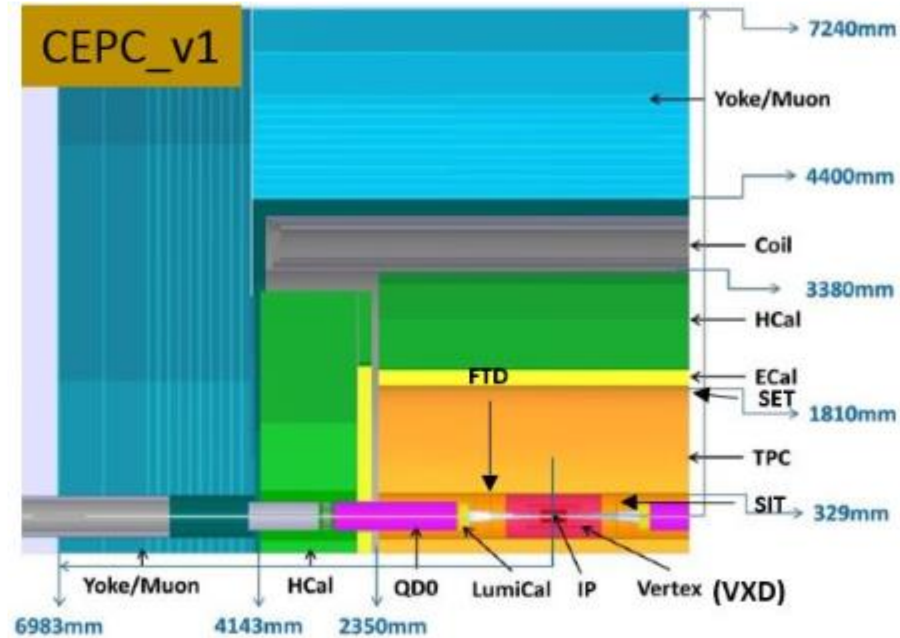


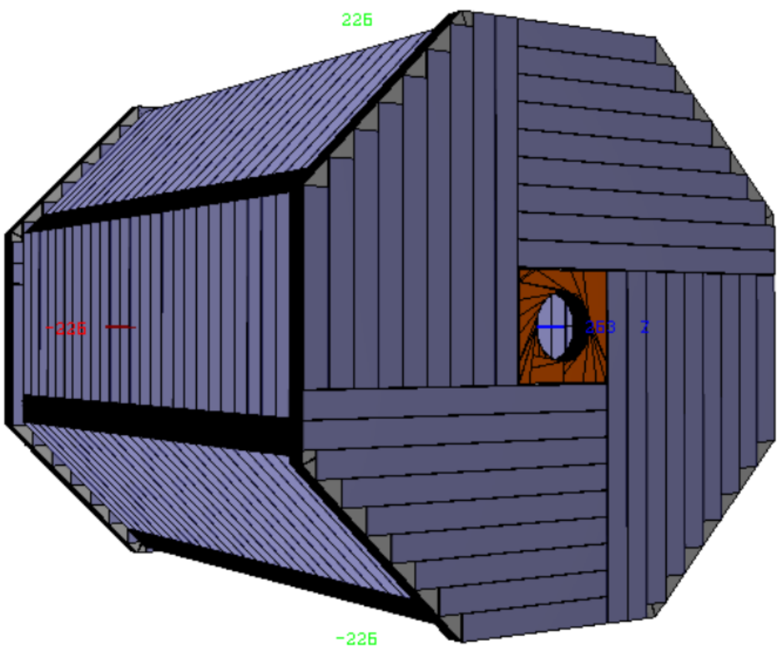
Short summary

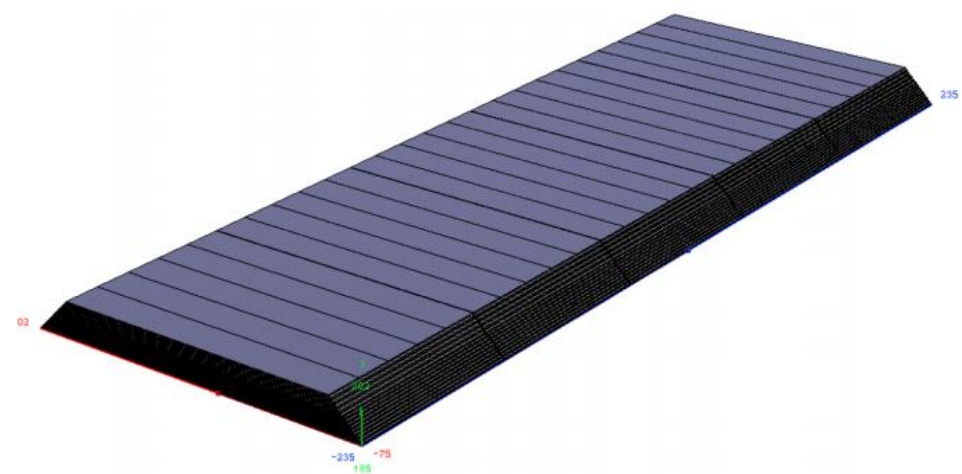
- In general, the results from GAN looks good, although the agreement between Geant4 and GAN still need to be improved.
- It is shown that GAN may be a solution for the fast calorimeter simulation in BESIII.

- Now lets do the GAN study in CEPC !

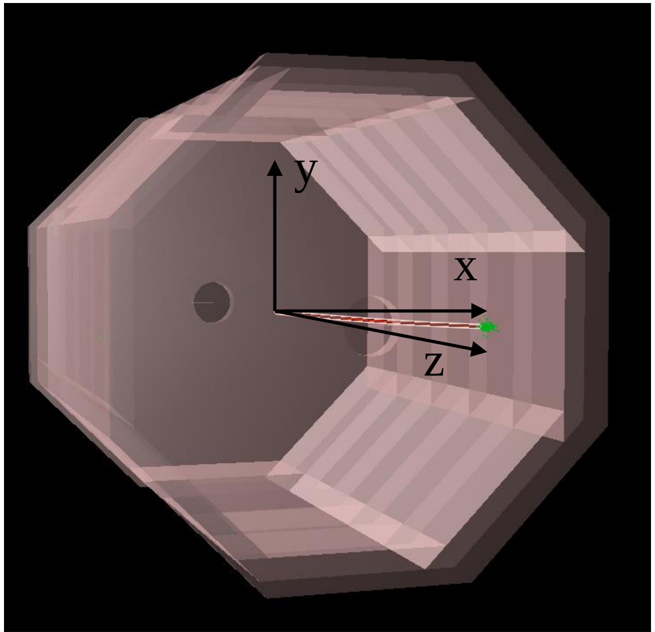
- The Circular Electron Positron Collider (CEPC) is a large international scientific facility proposed by the Chinese particle physics community.
- The CEPC will be hosted in China in a circular underground tunnel of approximately 100 km in circumference.
- It is designed to operate at around 91.2 GeV as a Z factory, at around 160 GeV of the WW production threshold, and at 240 GeV as a Higgs factory.





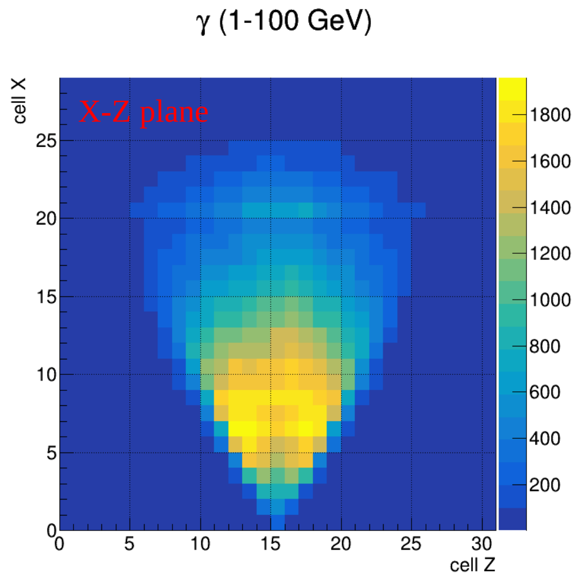


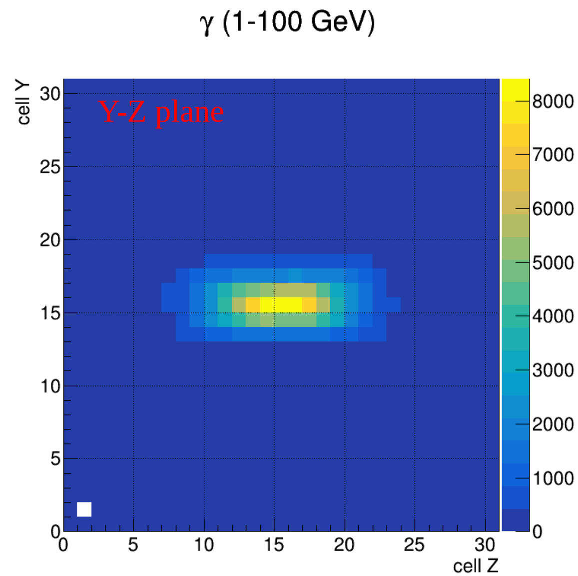
Using particle gun to hit ECAL barrel (CEPC_v4)



- The single photon (electron) particle gun samples are used for training.
  - Energy in [1, 100] GeV uniformly
  - θ in [50, 140] degree uniformly
  - ϕ in [-15, +15] degree uniformly
- Only hits from Ecal barrel are used and they are within 15 calorimeter cells range with respect to the first hit cell.

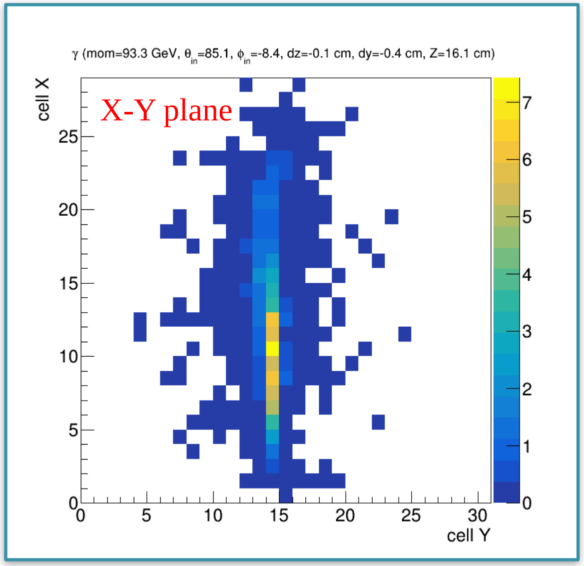
```
/generator/generator particleGun
/gun/position 0 0 0 mm
/gun/direction 1.0 0.0 0.0
/gun/momentum 55 GeV
/gun/momentumSmearing 45 GeV
/gun/phiSmearing 15 deg
/gun/thetaSmearing 50 deg
/gun/directionSmearingMode
uniform
/gun/momentumSmearingMode
uniform
/gun/particle e-/gamma
/run/beamOn 100000
```

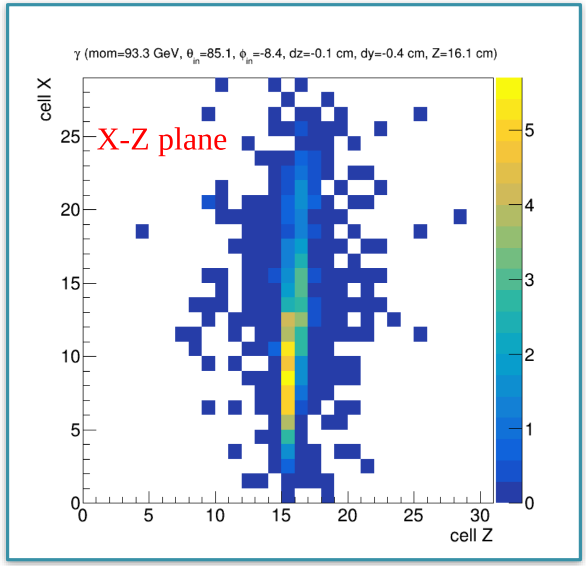


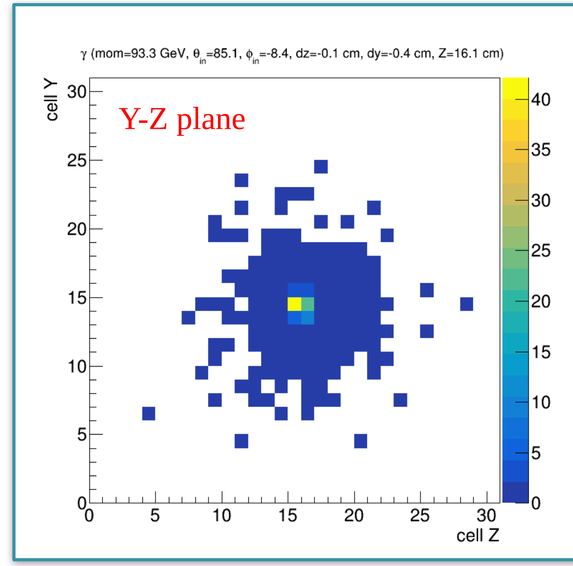


Energy shower of γ in Ecal

γ (Mom = 93.3 GeV, $\theta_{in} = 85.1^{\circ}$, $\phi_{in} = -8.4^{\circ}$, $\Delta Z^{Pos} = -0.1$ cm, $\Delta Y^{Pos} = -0.4$ cm, Z = 16.1 cm)



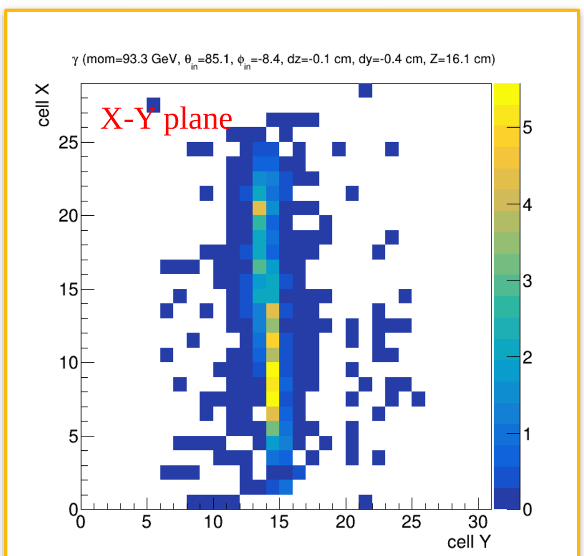


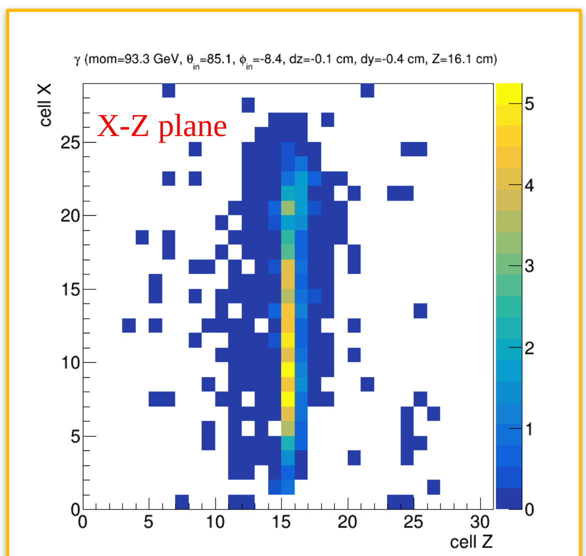


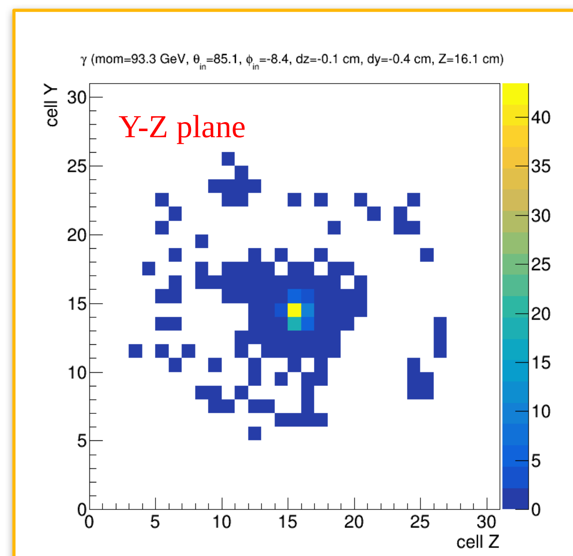
Geant4

See the detailed GAN network in backup

GAN

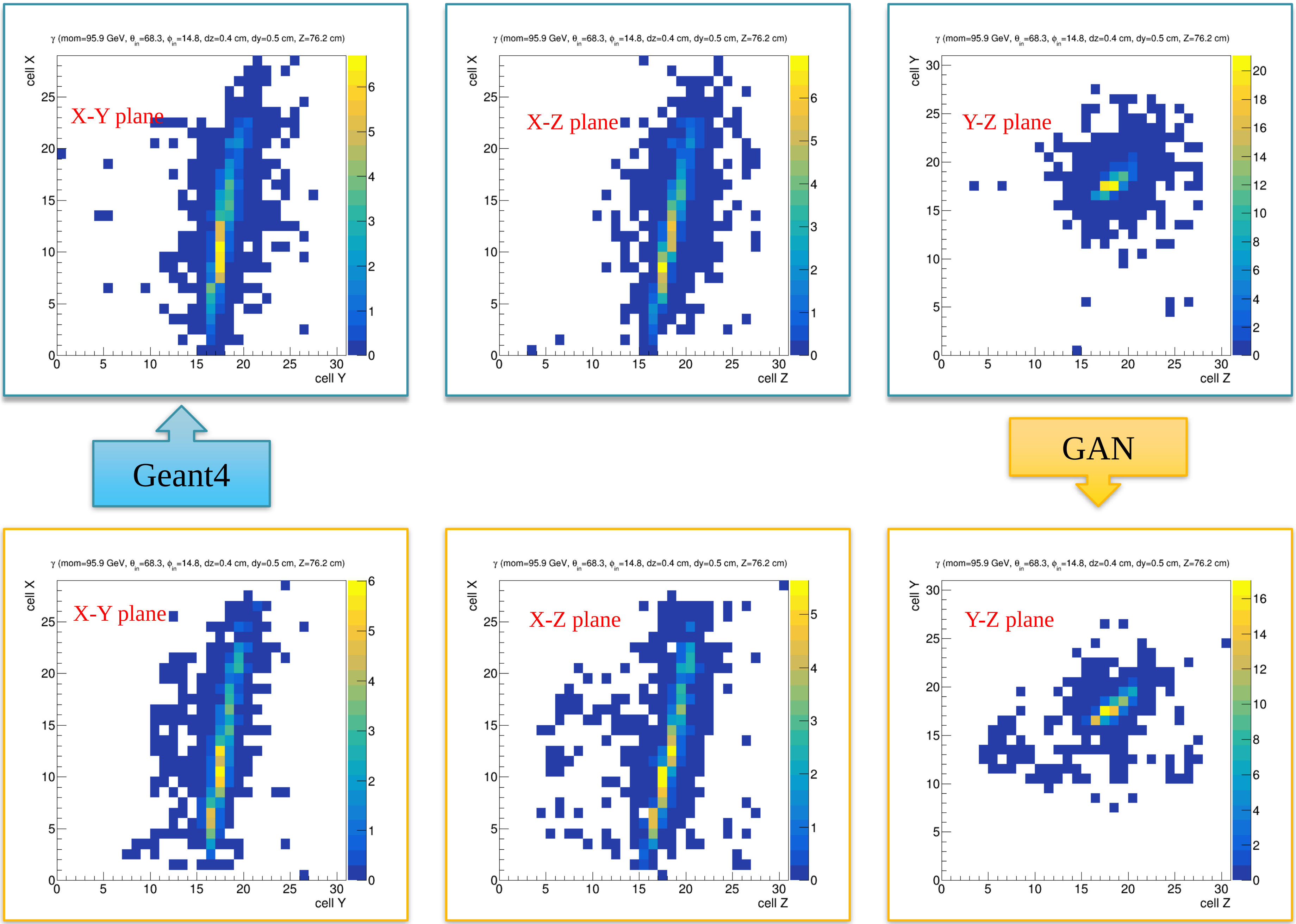






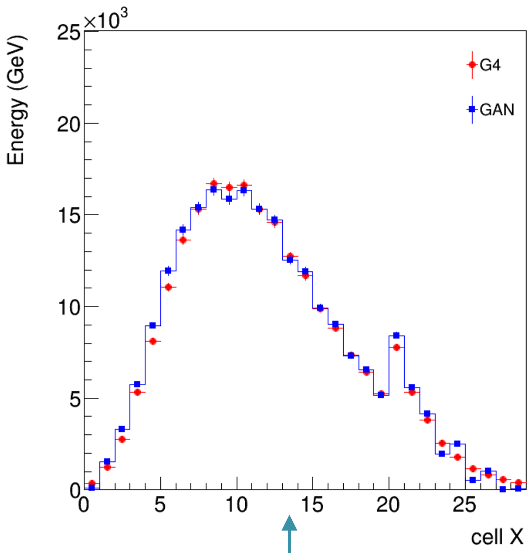
Energy shower of γ in Ecal

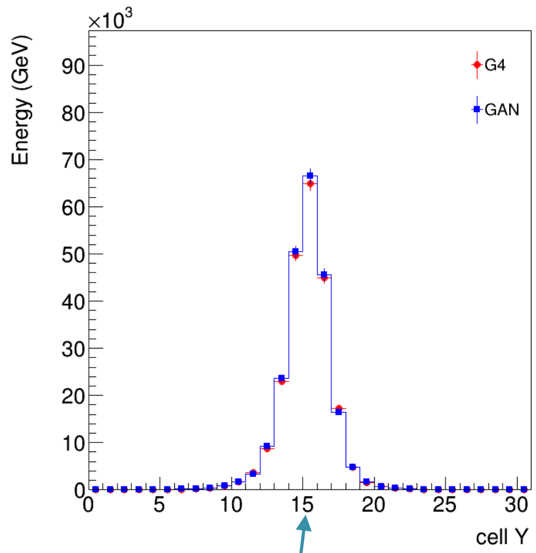
γ (Mom $= 95.9$ GeV, $\theta_{in} = 63.8^{\circ}$, $\phi_{in} = 14.8^{\circ}$, $\Delta Z^{Pos} = 0.4$ cm, $\Delta Y^{Pos} = 0.5$ cm, $Z = 76.2$ cm)

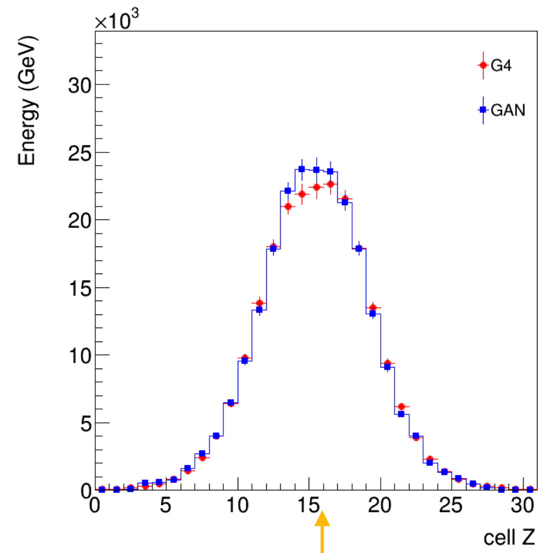


Some distributions for γ

See similar results for electron in backup







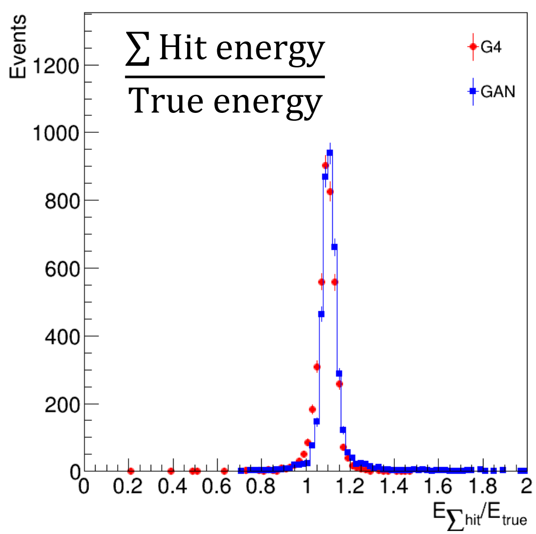
Energy deposited in X(layer) direction

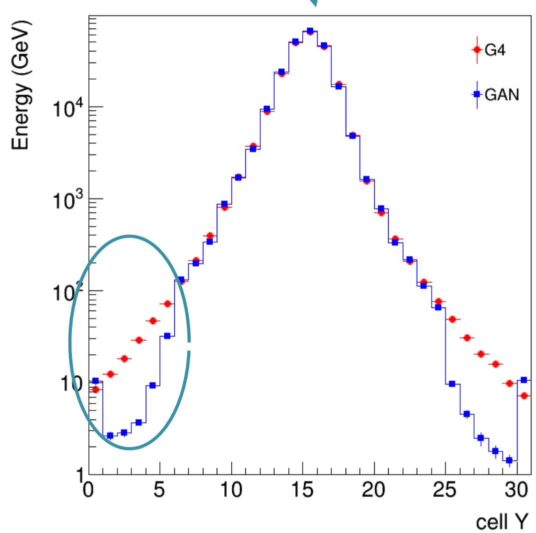
Energy deposited in Y direction

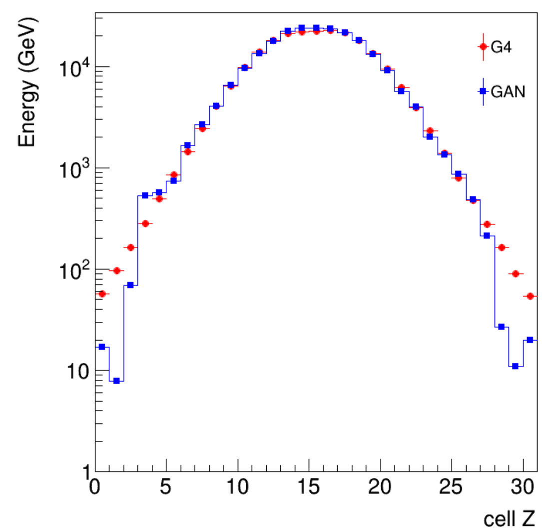
Energy deposited in Z direction

log scale

log scale

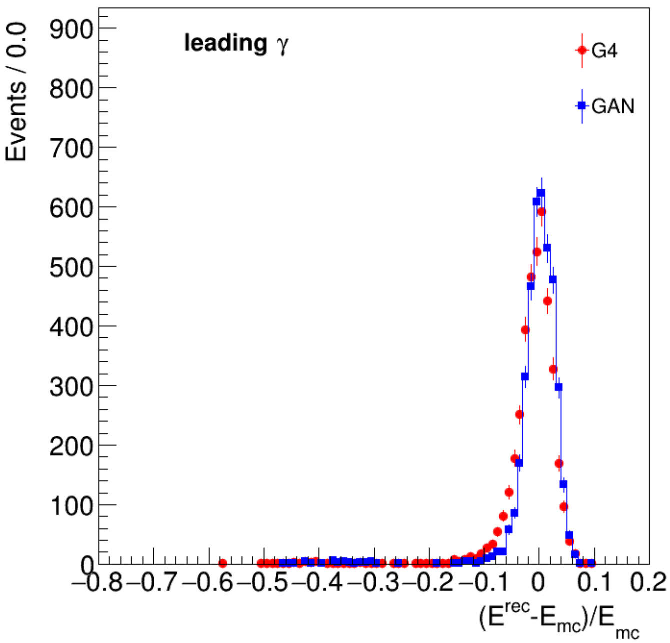


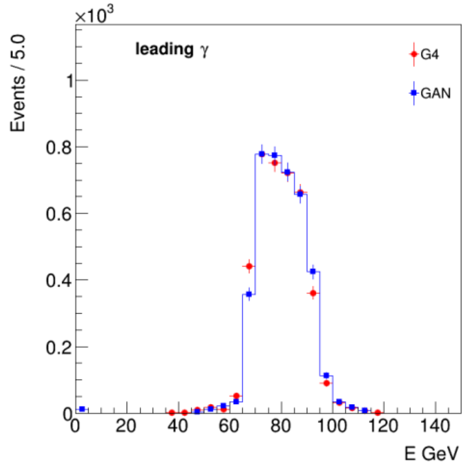


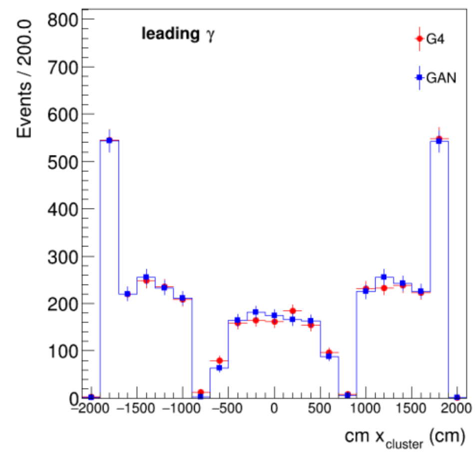


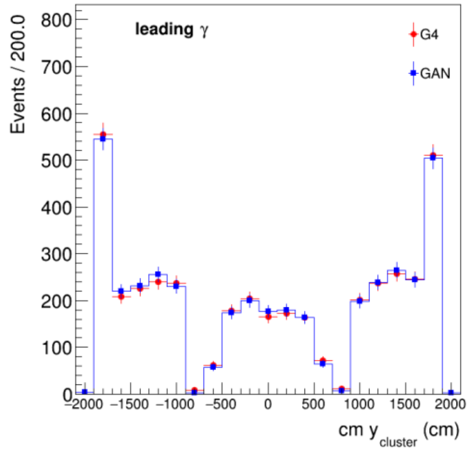
Apply GAN and do event reconstruction using mc samples

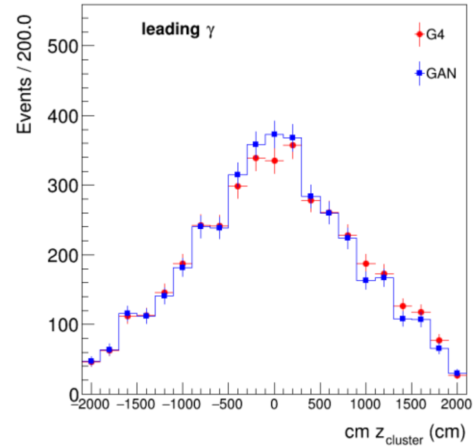
Using $e^{+}e^{-} \rightarrow Z(\nu\nu)H(\gamma\gamma)$ mc samples and comparing the properties of reconstructed gamma.











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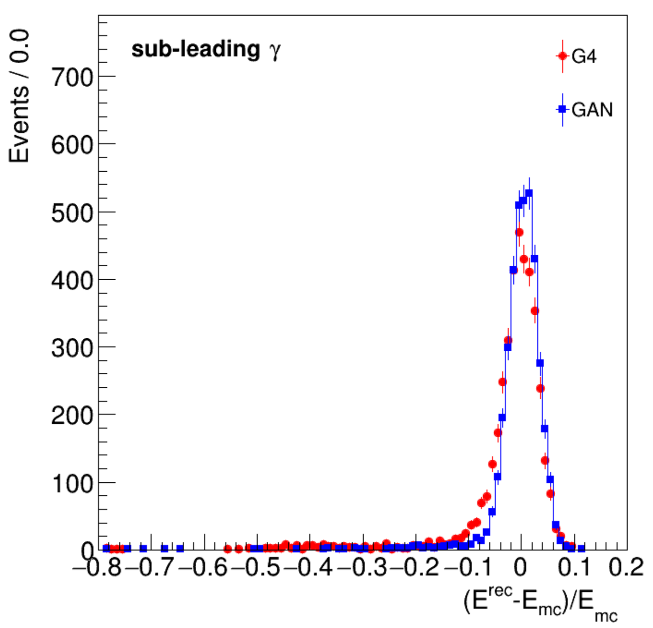
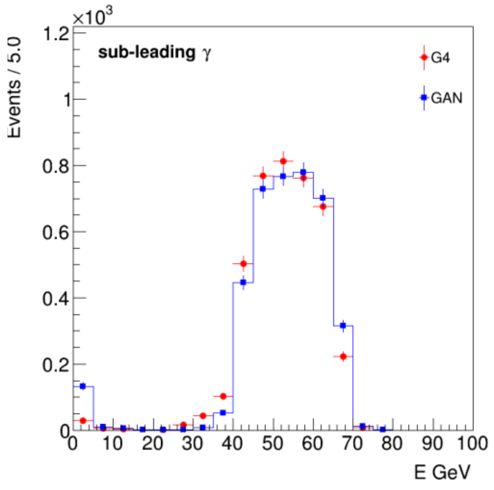
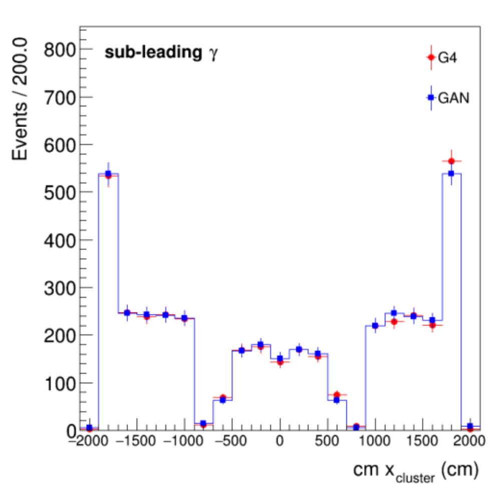
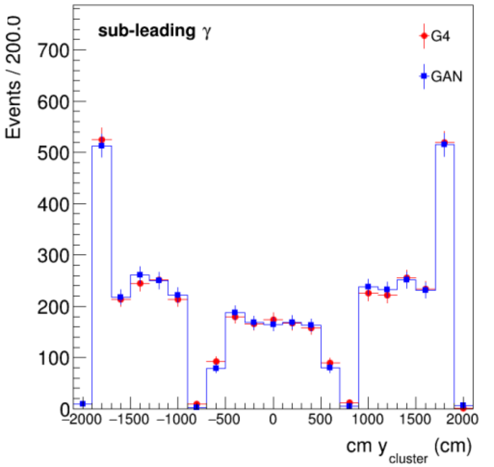
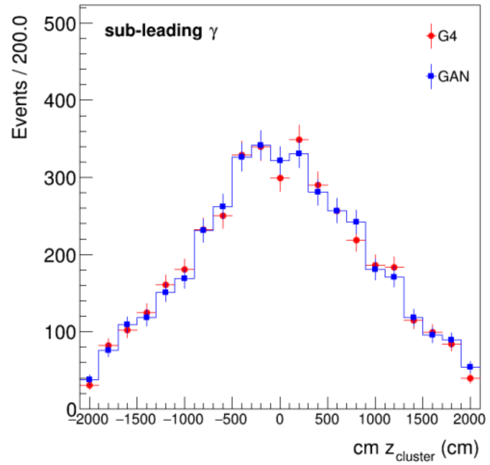
Using $e^+e^- \to Z(\nu\nu)H(\gamma\gamma)$ mc samples and comparing the properties of reconstructed gamma.





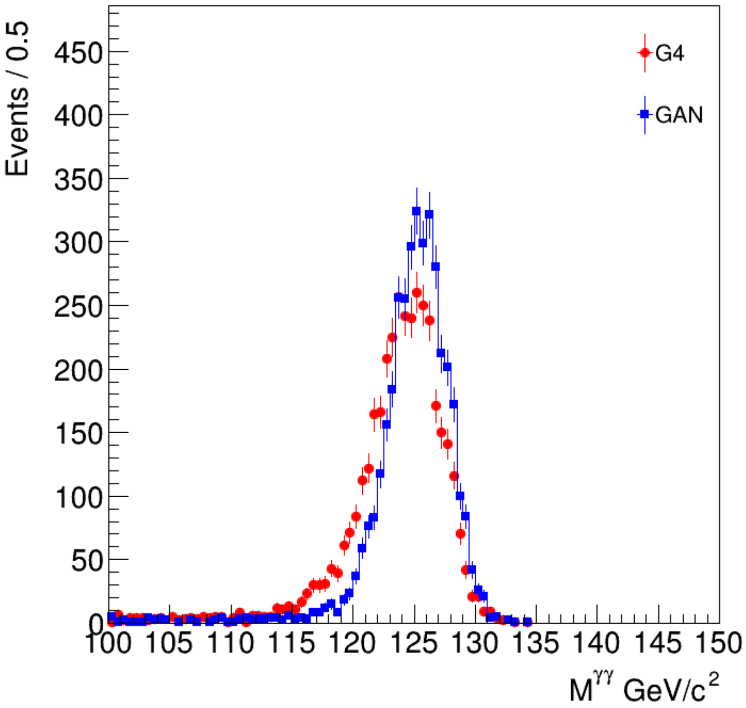


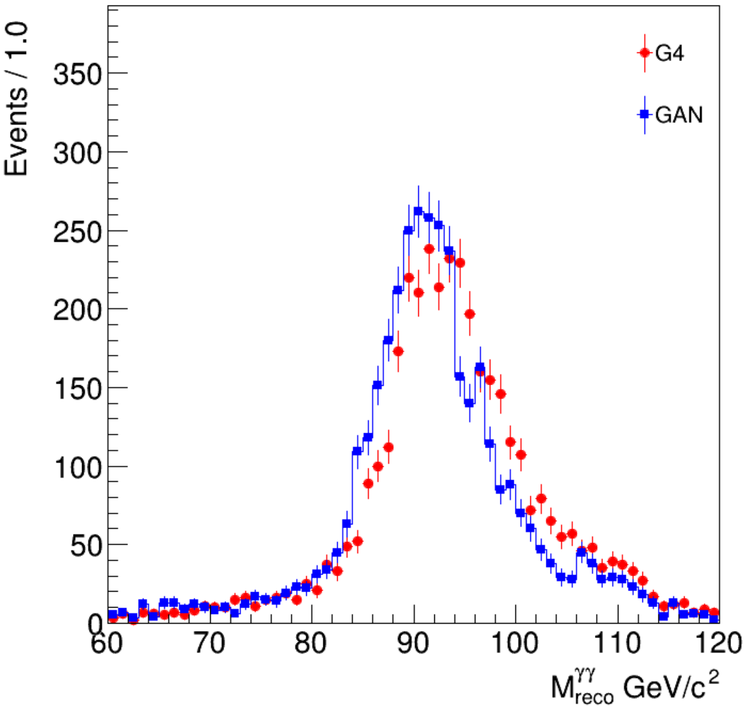




Apply GAN and do event reconstruction using mc samples

Using $e^+e^- \to Z(\nu\nu)H(\gamma\gamma)$ mc samples and comparing the properties of reconstructed gamma.





Looks fine, but still need to be improved.

Summary and Outlook

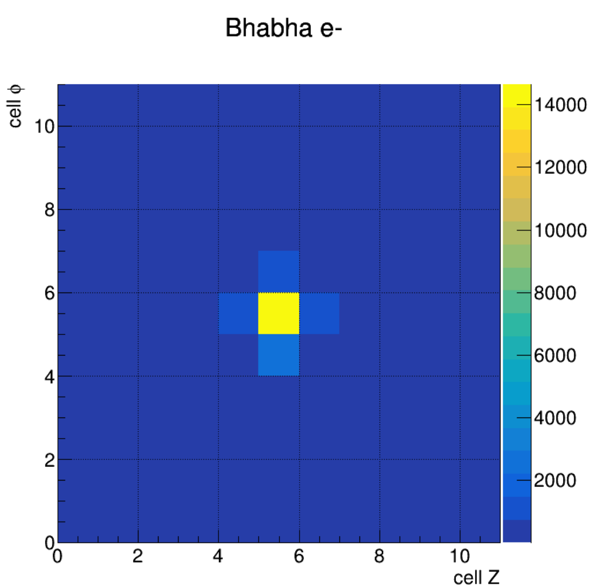
- We performed the simulation of calorimeter with GAN in BESIII and CEPC. In general, the results from GAN looks good which shows the potential of GAN for fast calorimeter simulation.
- However, there are still some discrepancies between GAN and Geant4, especially for marginal region.
- Next to do:
  - Try to improve the performance of GAN. In the study we found the GAN is unstable which is well- known. We are going to try with Wasserstein GAN with gradient penalty which seems more stable in the training.
  - As we have huge BESIII real data, so we can training the GAN using real data and apply it for simulation and check the agreement between data and simulation.

Thanks for your attention

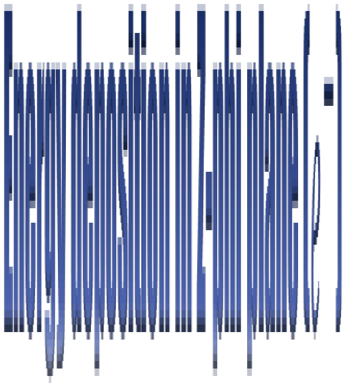
Back up

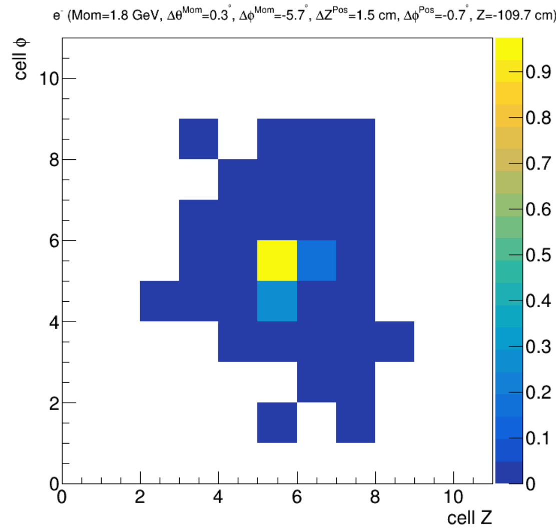
Dataset

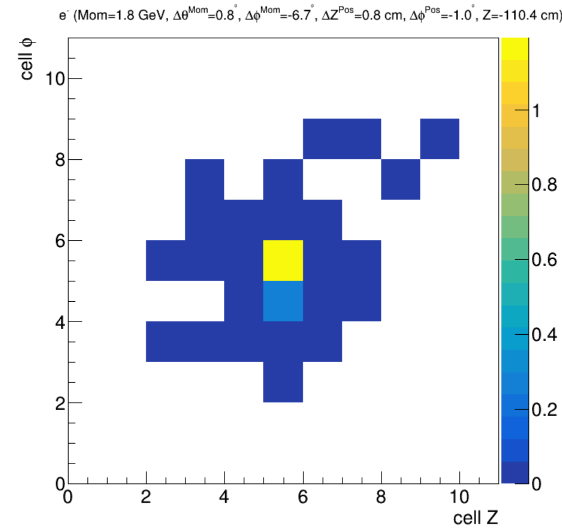
- /besfs/groups/cal/emc/liucx/BhabhaCalib/mcdata/bb703/bb1776_703_2017*
- Select $e^{\pm}$:
  - EvtRecTrack. isMdcTrackValid && EvtRecTrack. isExtTrackValid .
  - EvtRecTrack. isEmcShowerValid && RecEmcShower .energy > 40 MeV .
  - RecEmcShower. getCluster != 0 .
  - RecMdcTrack. Charge > 0 for e^{+} and < 0 for e^{-} .
  - Select one e^{+} and one e^{-} with highest momentum according to RecMdcTrack. P .
  - Finally the $|\cos\theta| < 0.83$ is asked for selected $e^{\pm}$.
- ~ 450000 training events.
- The position of MDC track extends to EMC is chose as the center. Hit energy in 11×11 calorimeter cells are considered.



Energy deposition in Z-phi plane (e^-)

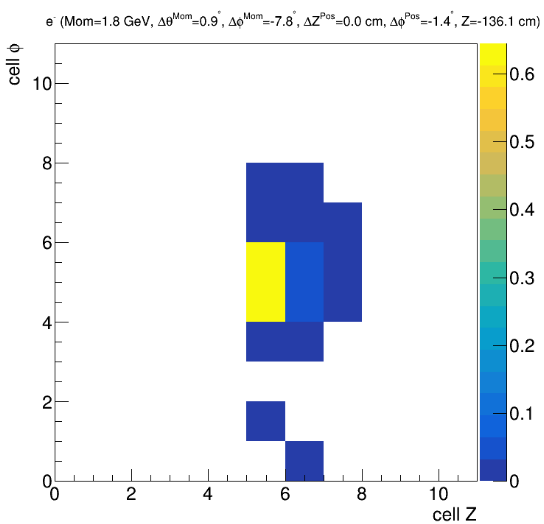


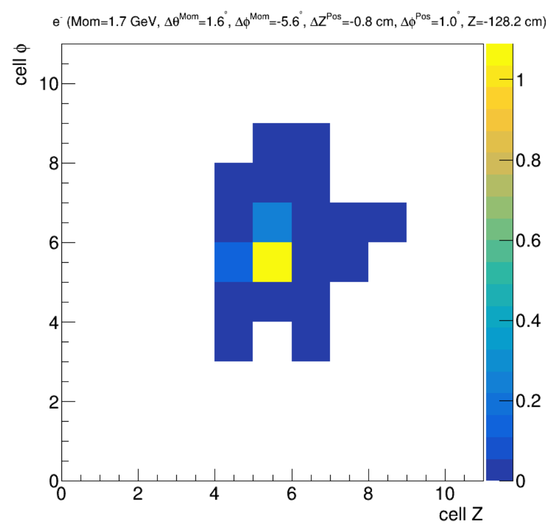


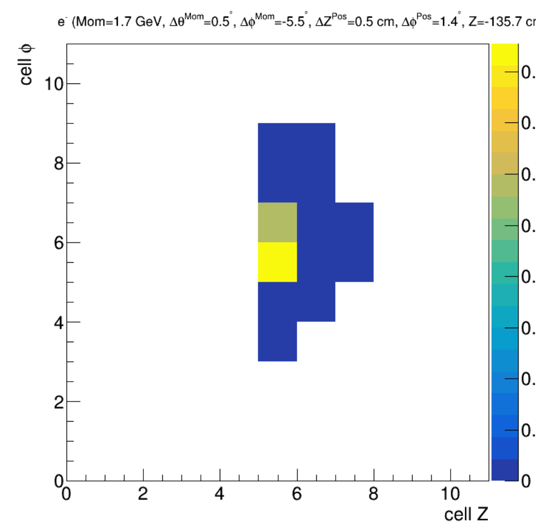


|Z|<125cm

|Z|>125cm



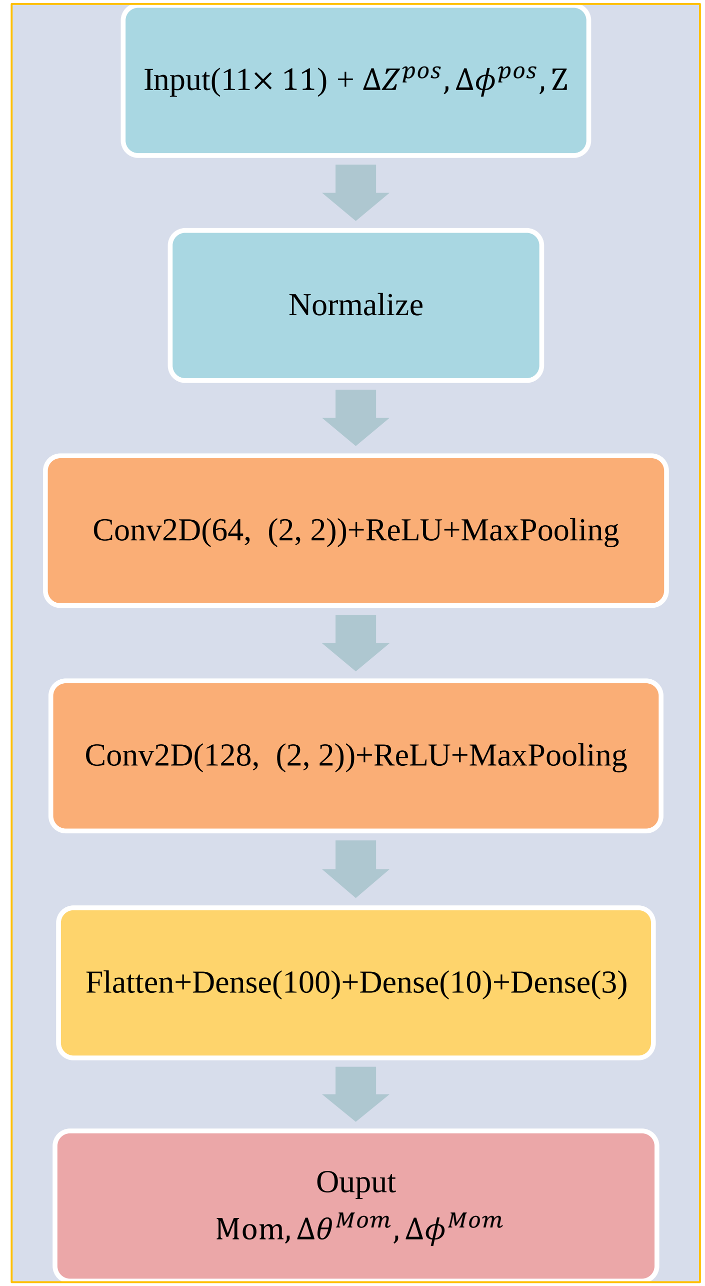




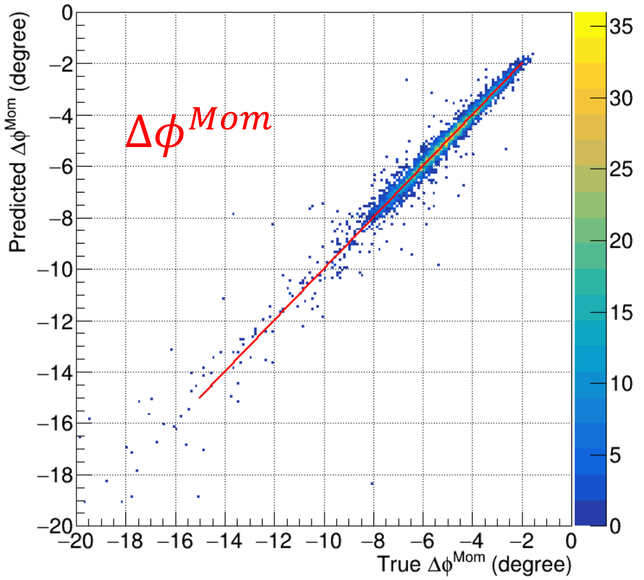
Regressor

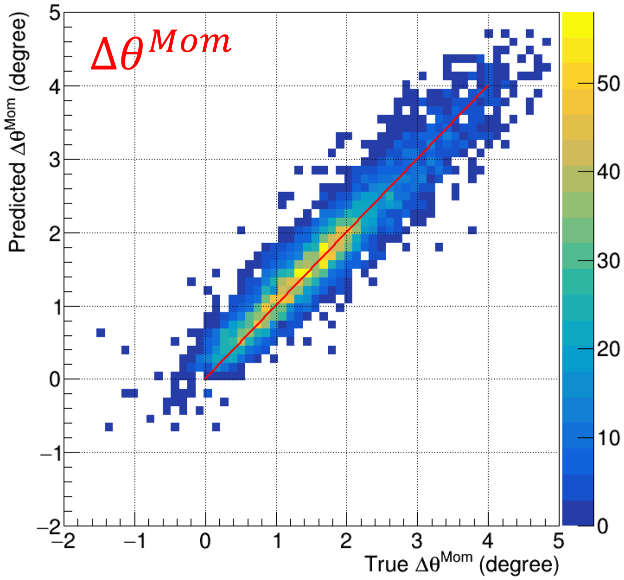
- $\Delta\phi^{Mom}$: the ϕ difference between the momentum of incoming particle and the direction of the crystal.
- $\Delta\theta^{Mom}$: the θ difference between the momentum of incoming particle and the direction of the crystal.
- ΔZ^{Pos}: the Z difference between the hit point of incoming particle and the z of front center of the crystal.
- $\Delta\phi^{Pos}$: the ϕ difference between the hit point of incoming particle and the ϕ of front center of the crystal.
- Momentum: the momentum of the particle.
- Z

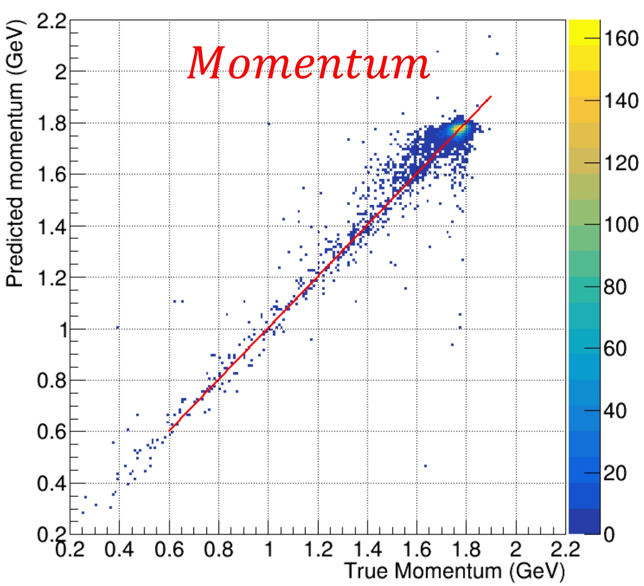
❖ Due to the e^- (e^+) is mostly at negative (positive) Z region, the e^- (e^+) at positive (negative) is not used.



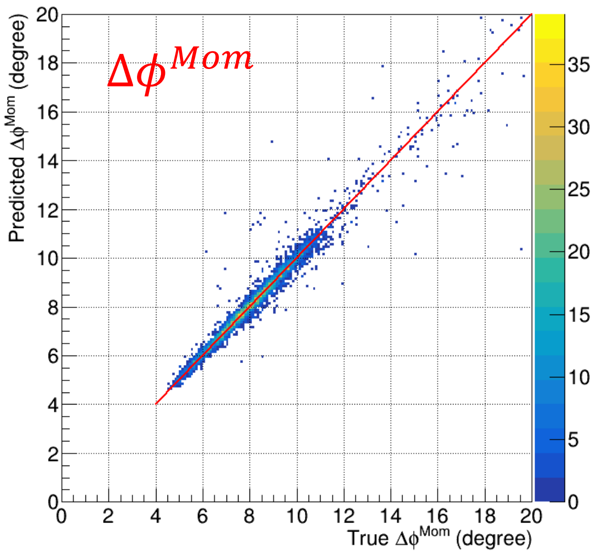
Regressor performance (e^-)

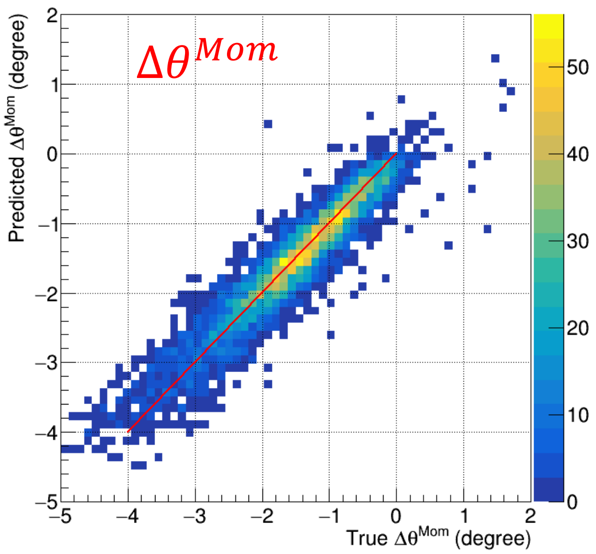


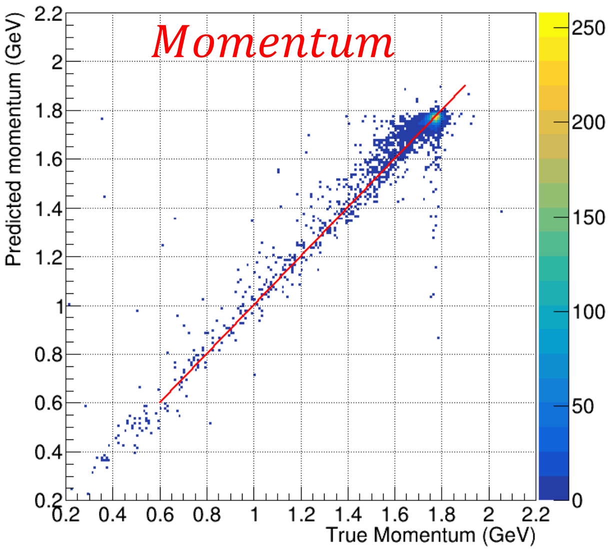




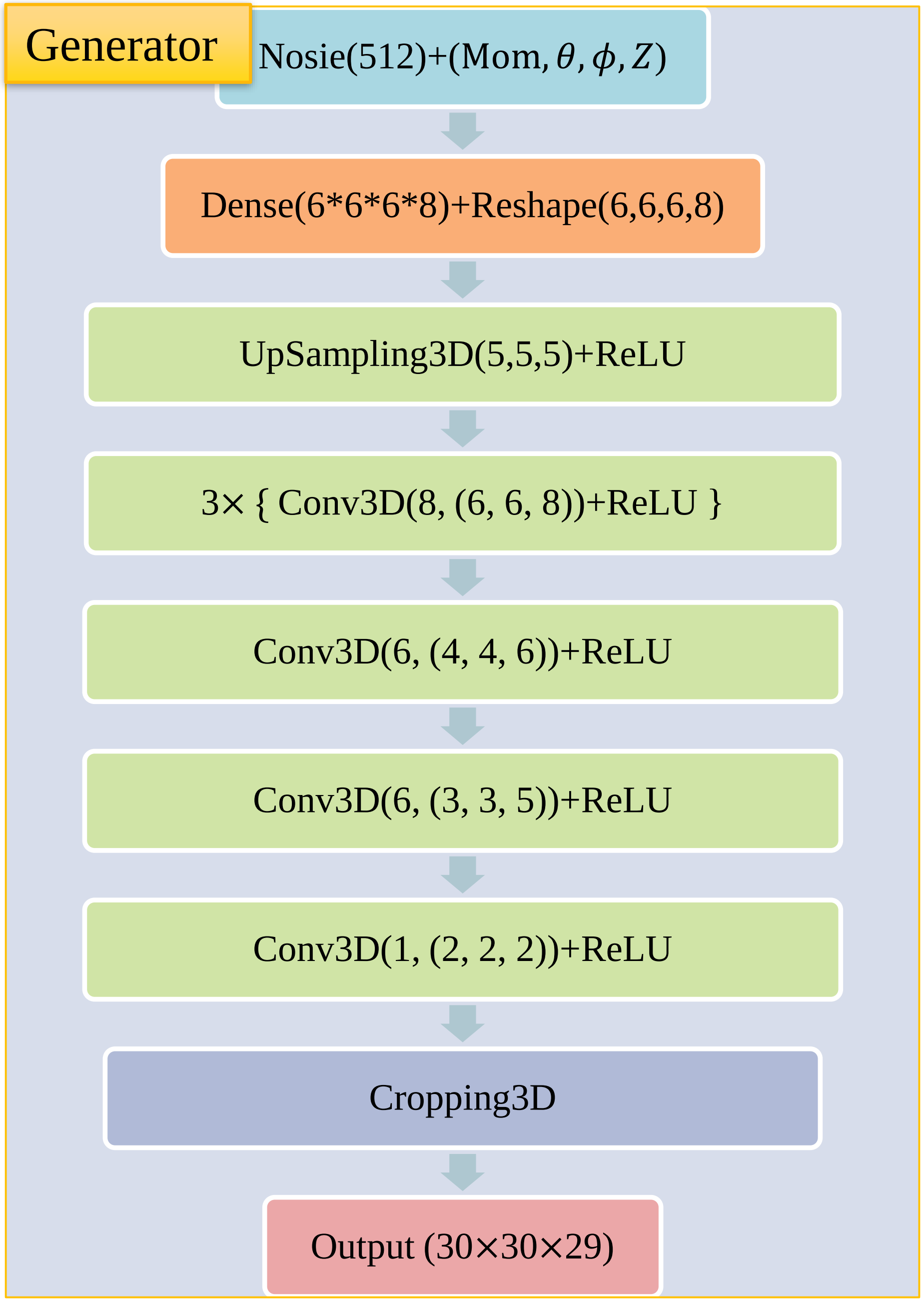
Regressor performance (e^+)

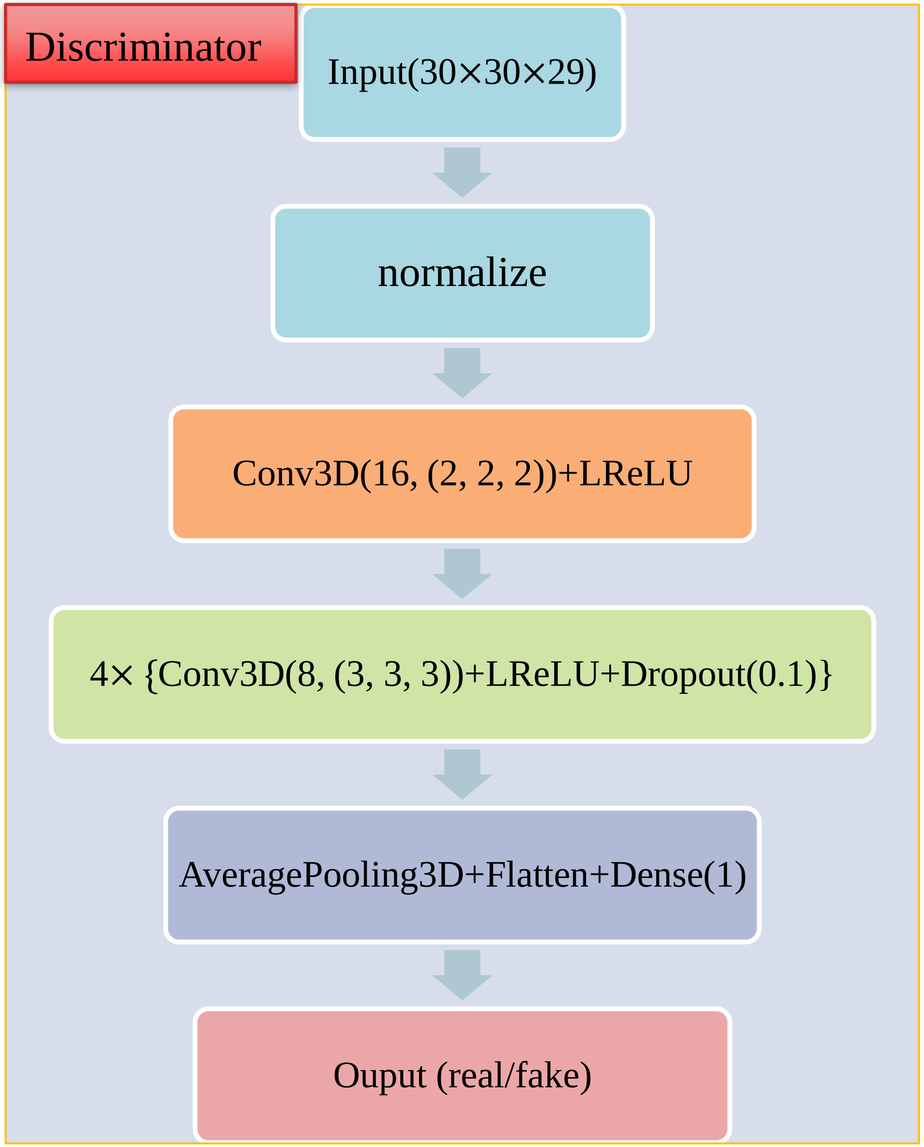




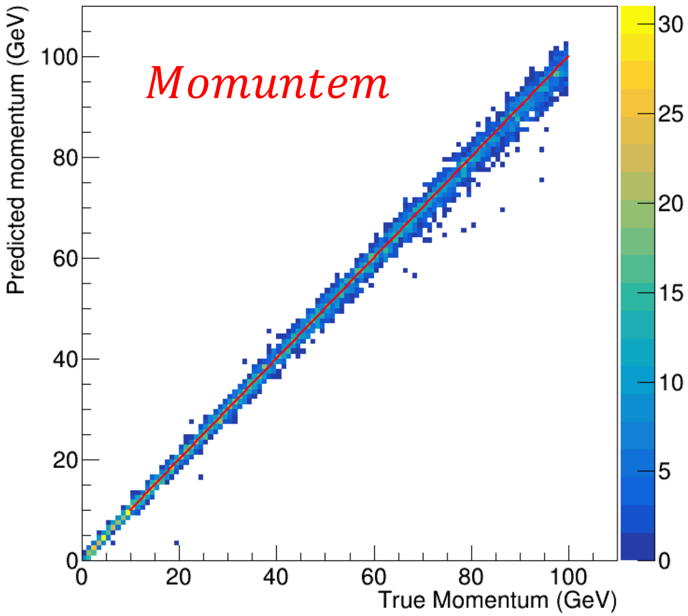


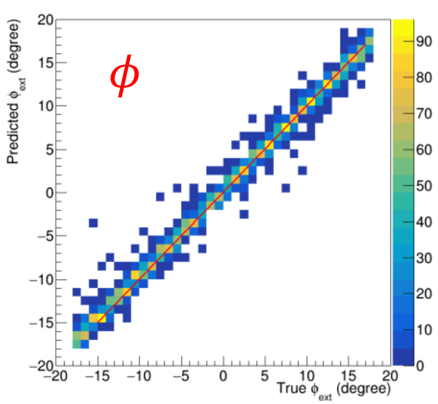
Generator and discriminator architecture (CEPC)

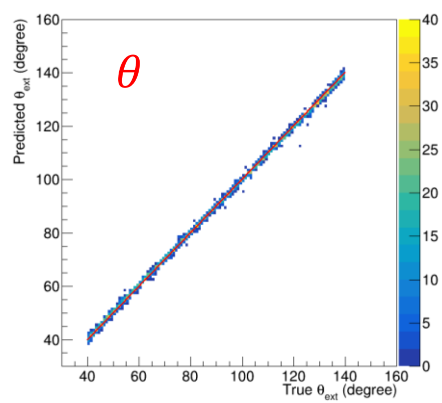


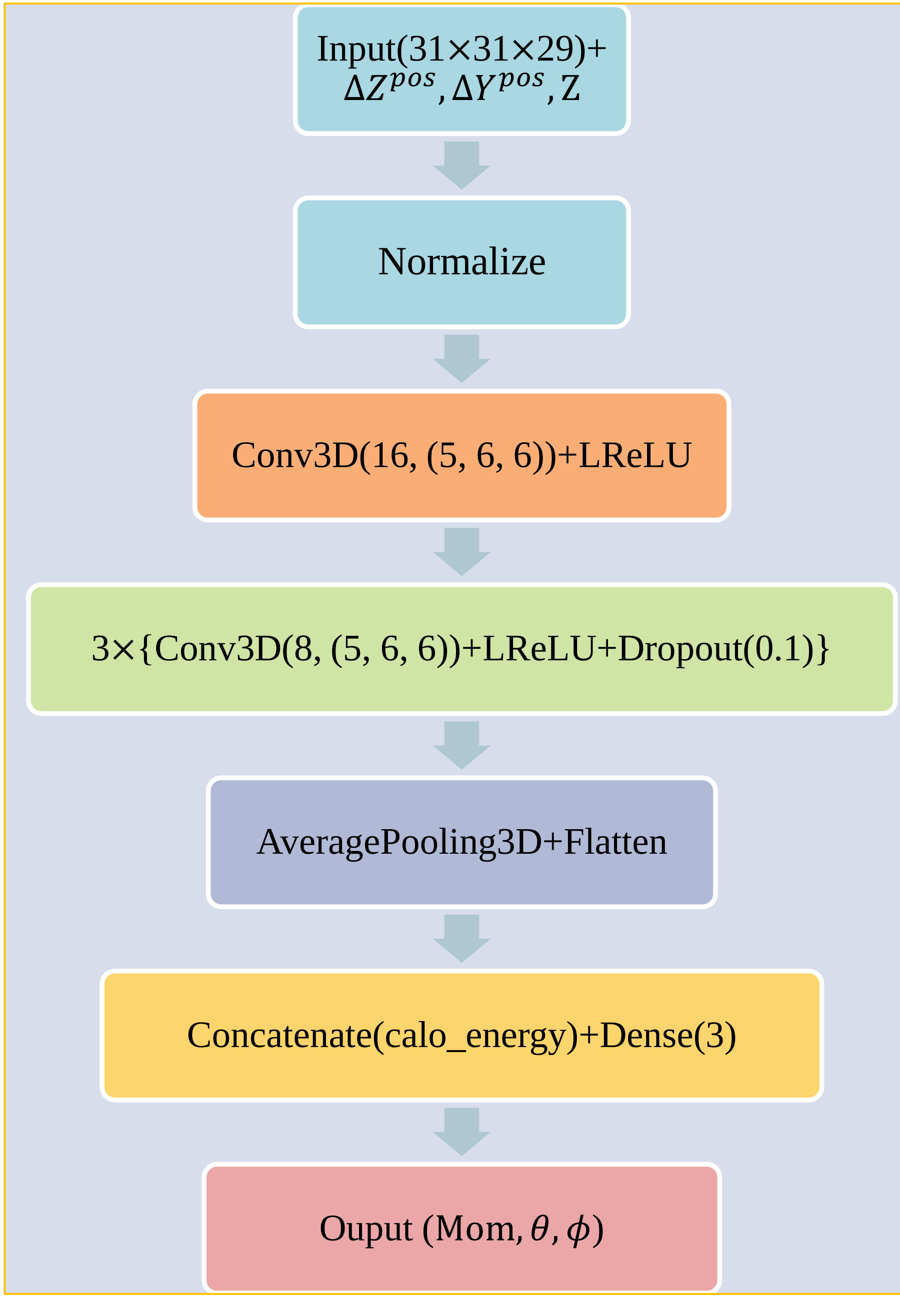


Regressor architecture and performance (γ)

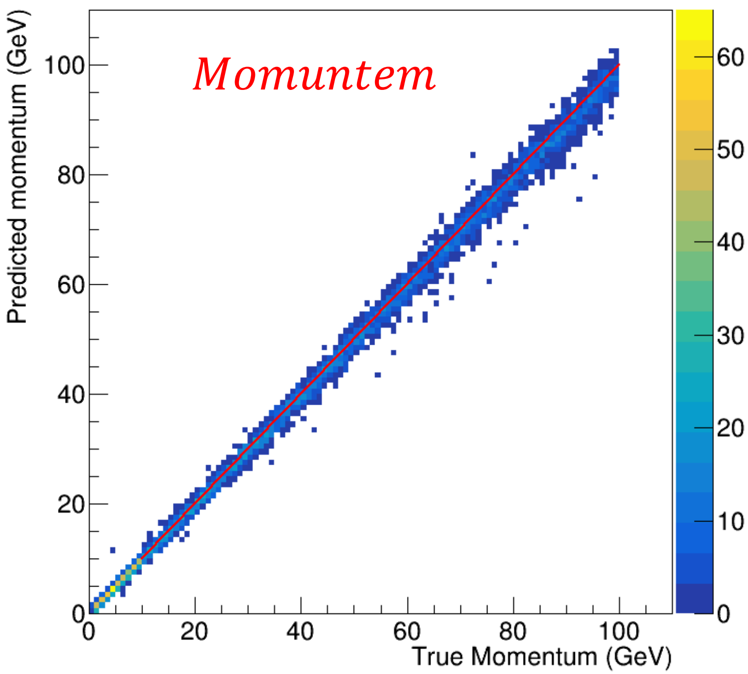


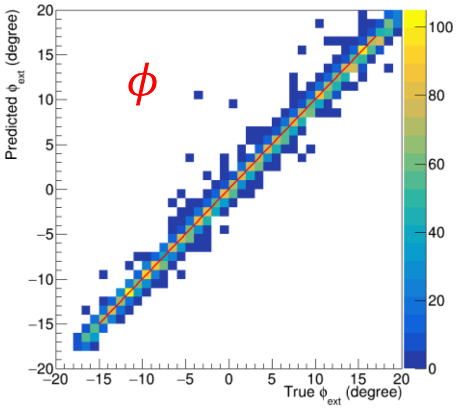


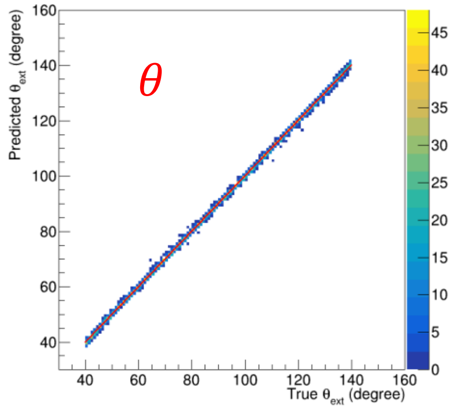


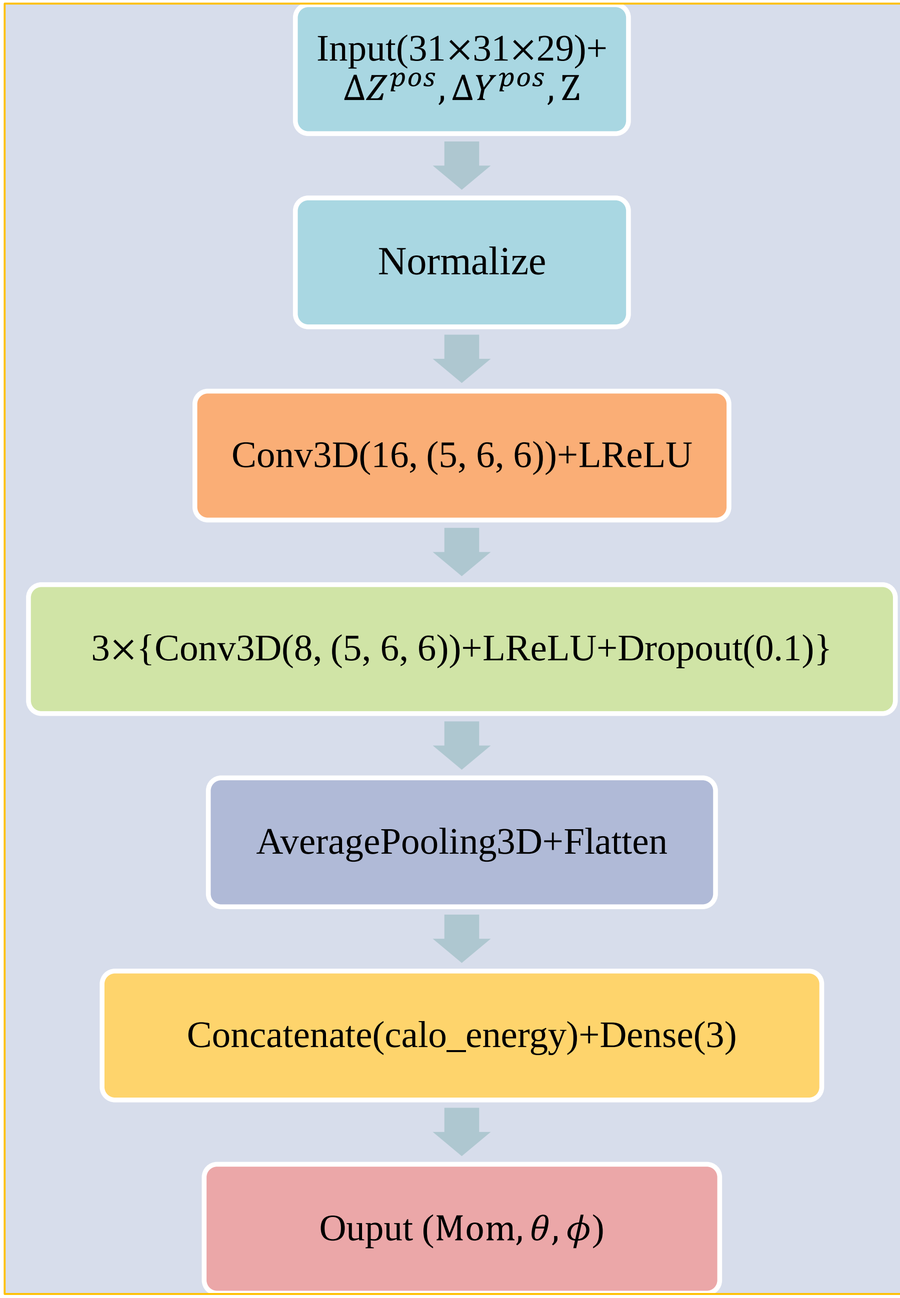


Regressor architecture and performance (e^-)



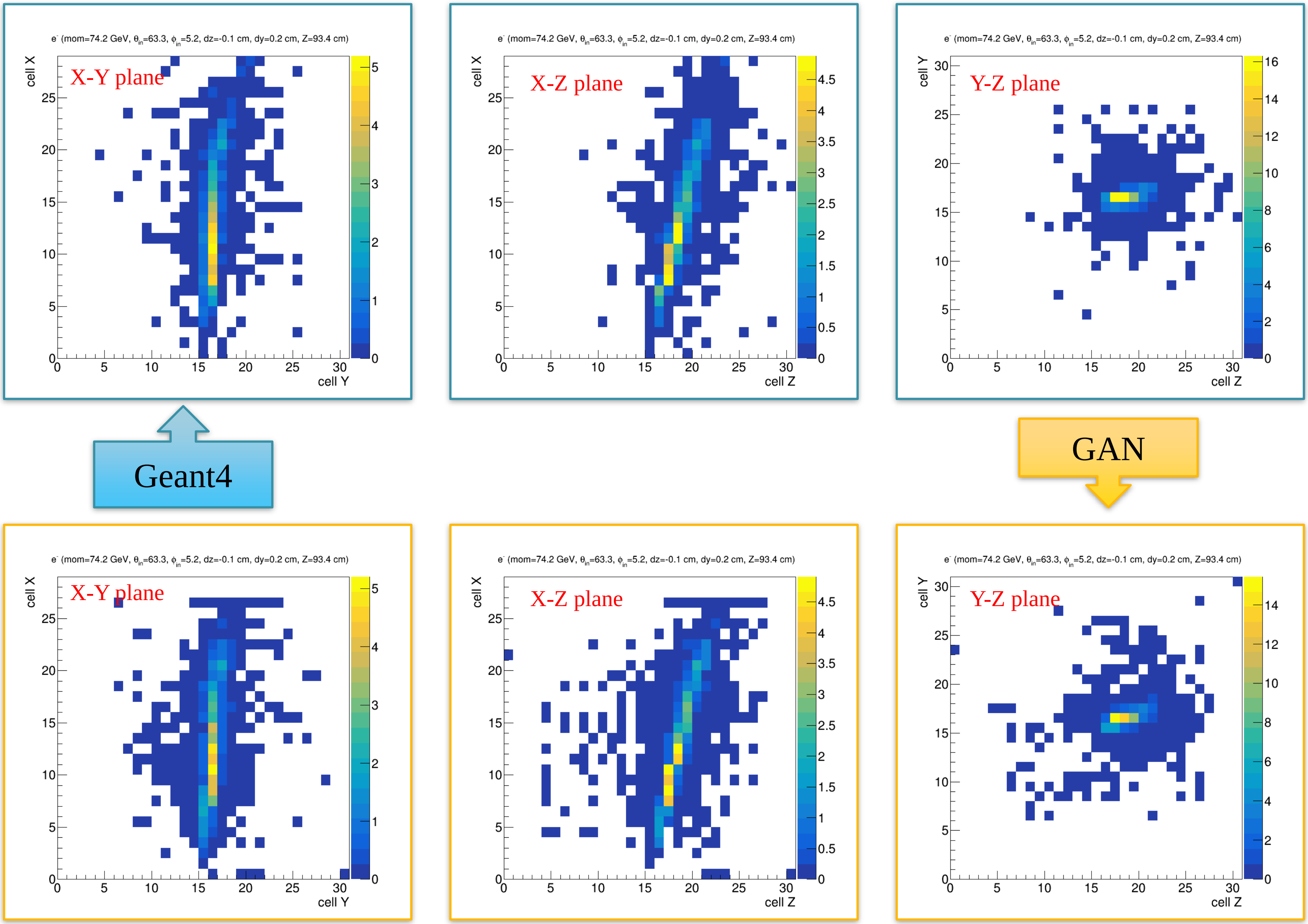




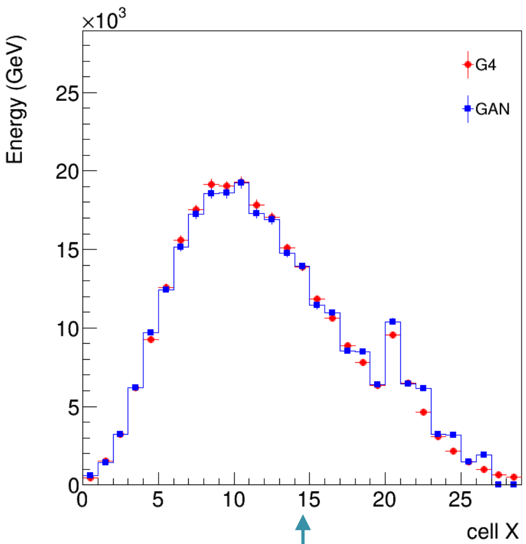


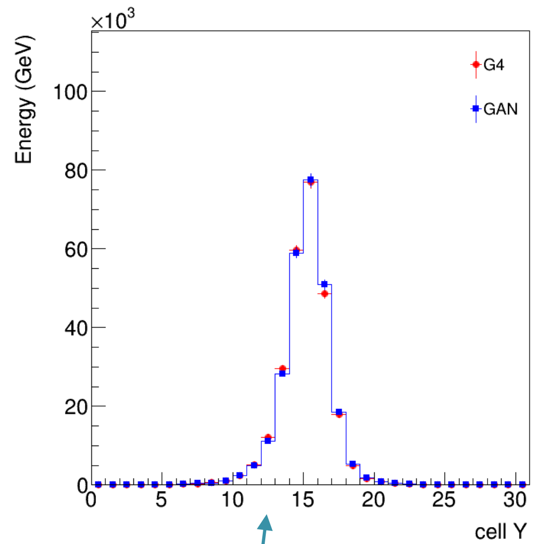
Energy shower of e^- in Ecal (cepc v4)

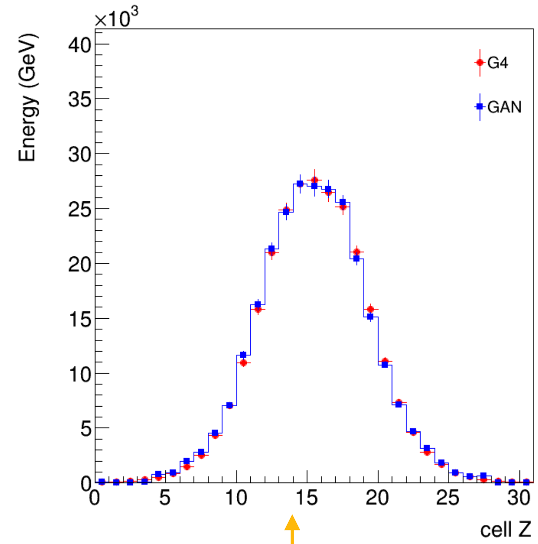
γ (Mom = 74.2 GeV, θ_{in} = 63.3°, ϕ_{in} = 5.2°, ΔZ^{Pos} = −0.1 cm, ΔY^{Pos} = 0.2 cm, Z = 93.4 cm)



Some variables for e^- (cepc v4)







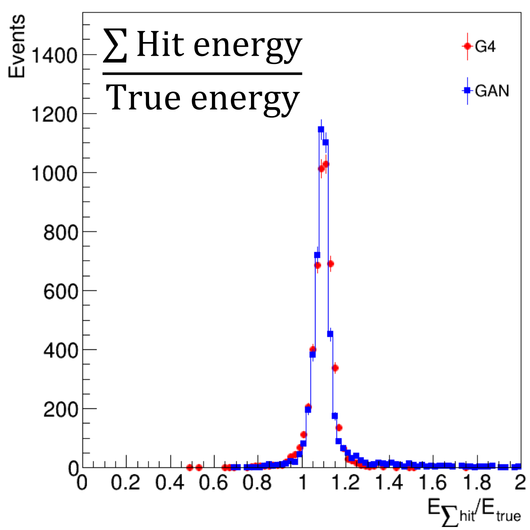
Energy deposited in X(layer) direction

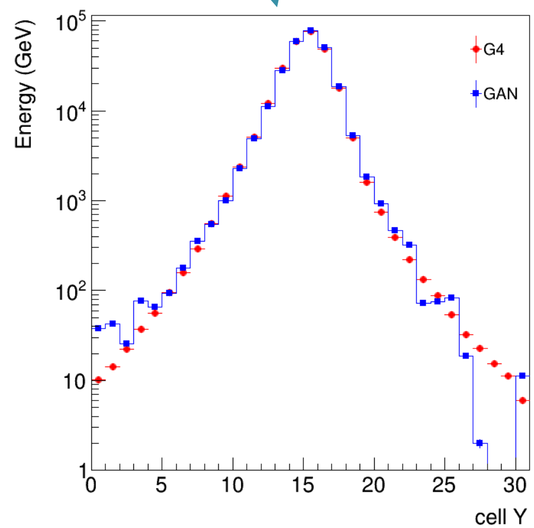
Energy deposited in Y direction

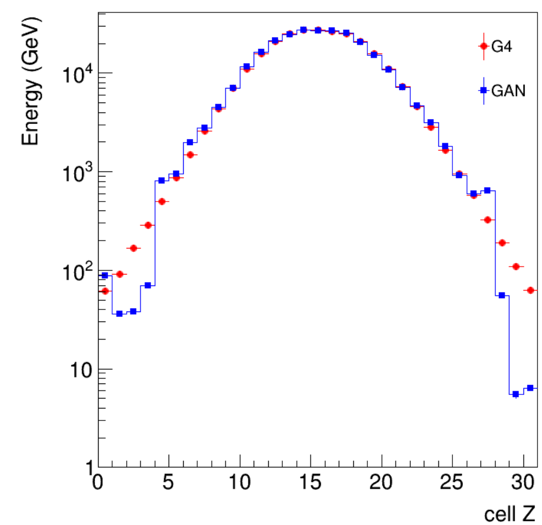
Energy deposited in Z direction

log scale

log scale





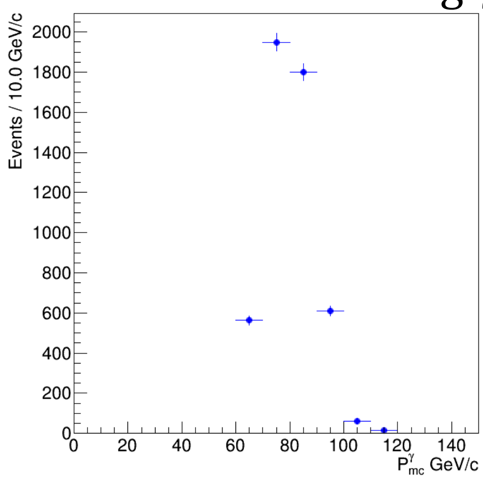


using mc samples

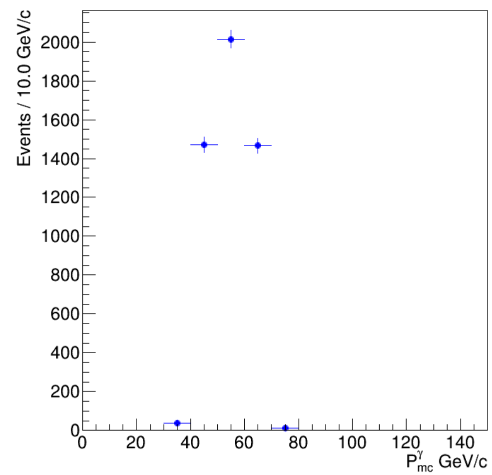
➢ Dataset: $e^+e^- \rightarrow Z(\nu\nu)H(\gamma\gamma)$

/cefs/data/FullSim/CEPC240/CEPC_v4/higgs/E240.Pnnh_aa.e0.p0.whizard195/nnh_aa.e0.p0.0000*_sim.slcio

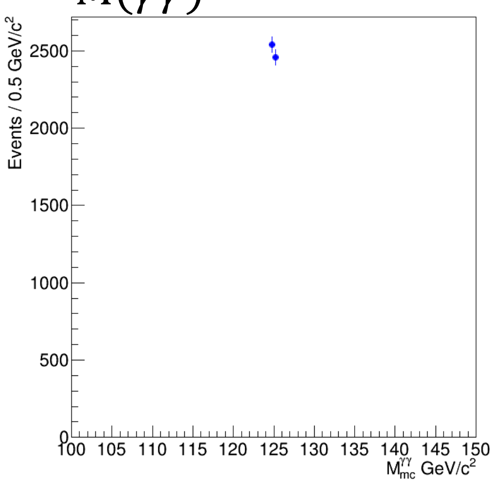
Momentum leading γ



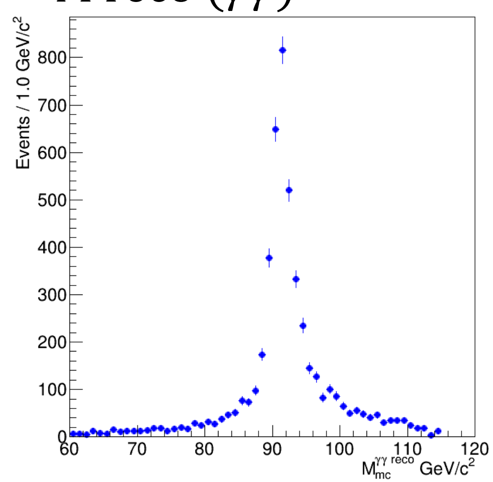
Momentum sub − leading γ



$M(\gamma\gamma)$



M reco $(\gamma\gamma)$

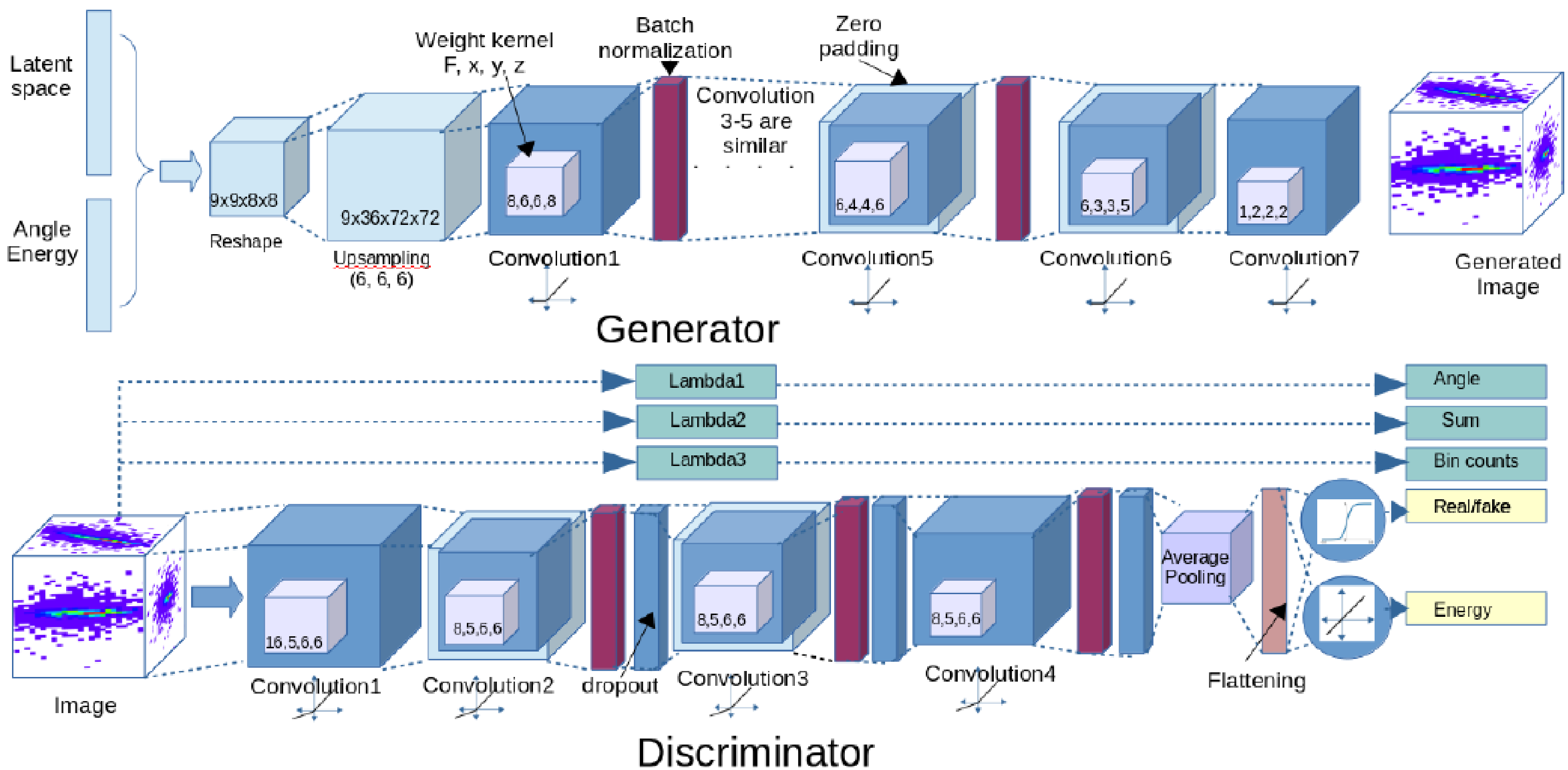


The model

3D convolutional Generative Adversarial Networks

Condition training on input variables, **Custom losses**

Auxiliary regression tasks assigned to the discriminator



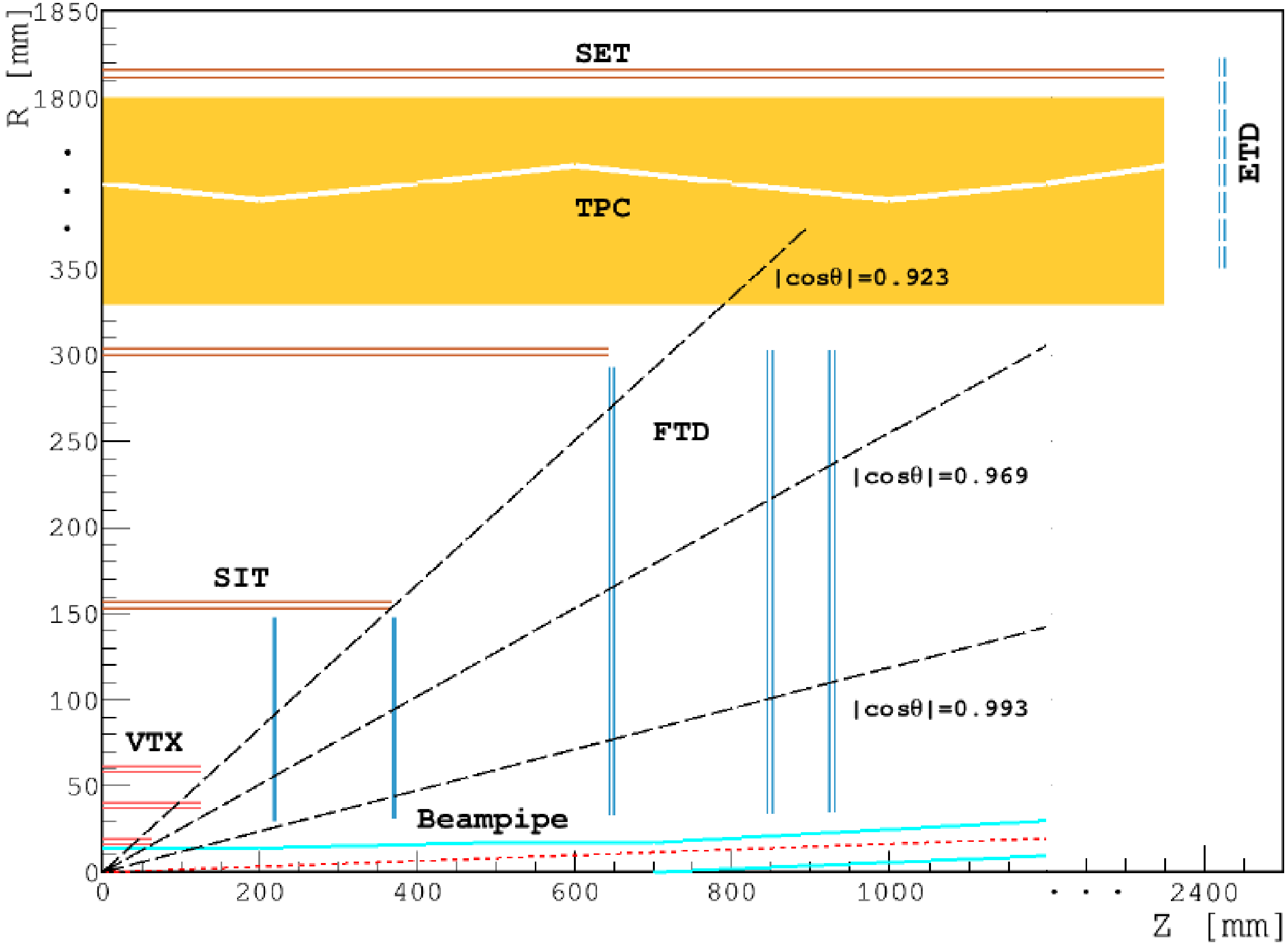
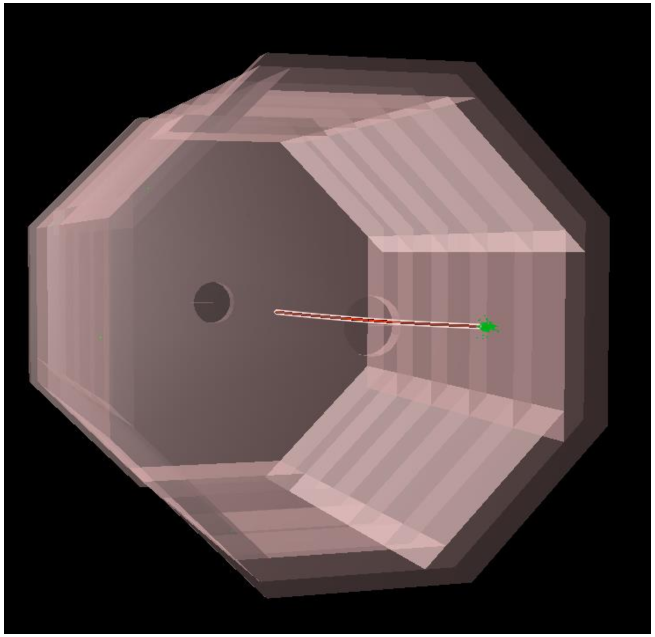
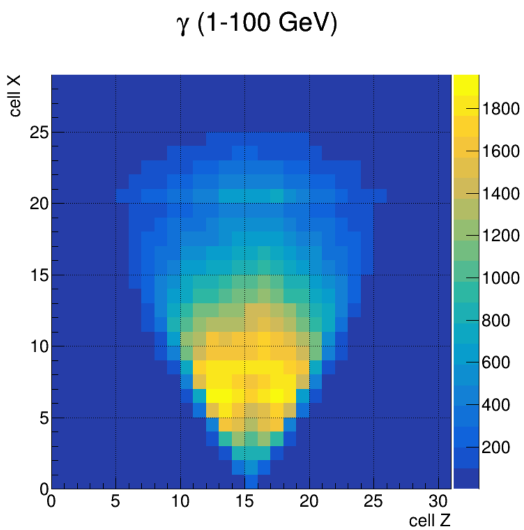


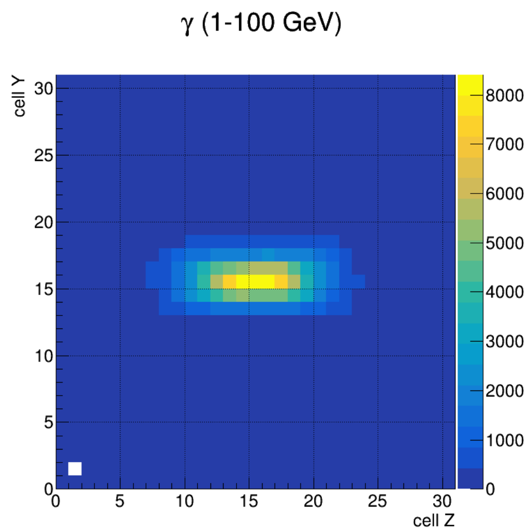
Figure 4.1: Preliminary layout of the tracking system of the CEPC baseline detector concept. The Time Projection Chamber (TPC) is embedded in a Silicon Tracker. Colored lines represent the positions of the silicon detector layers: red lines for the Vertex Detector (VTX) layers; orange lines for the Silicon Inner Tracker (SIT) and Silicon External Tracker (SET) components of the silicon tracker; gray-blue lines for the Forward Tracking Detector (FTD) and Endcap Tracking Detector (ETD) components of the silicon tracker. The cyan lines represent the beam pipe, and the dashed red line shows the beam line position with the beam crossing angle of 16.5 mrad. The ETD line is a dashed line because it is not currently in the full simulation. The radial dimension scale is broken above 350 mm for display convenience.

Using particle gun to hit ECAL barrel (CEPC_v4)



```
/generator/generator particleGun
/gun/position 0 0 0 mm
/gun/direction 1.0 0.0 0.0
/gun/momentum 55 GeV
/gun/momentumSmearing 45 GeV
/gun/phiSmearing 15 deg
/gun/thetaSmearing 50 deg
/gun/directionSmearingMode uniform
/gun/momentumSmearingMode uniform
/gun/particle e-/gamma
/run/beamOn 100000
```





- Using ECAL only.
- Use magnetic field.
- The digitalization is applied.
- The hit point of incoming particle at first layer (x=1.85m) is chose as the center of Z-Y plane. Besides, |hit_point_y|<0.5 m and |hit_point_z|<2m is required.
- Only consider the hits within radius of 150 mm.