中国科学院高能物理研究所
Institute of High Energy Physics
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Simulation of Calorimeter with GAN

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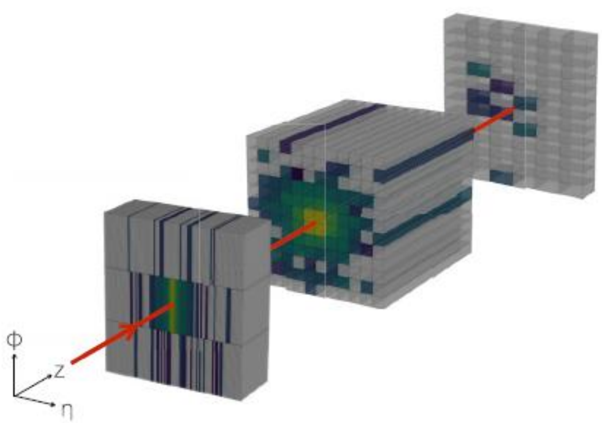
The 2019 international workshop on the high energy Circular Electron-Positron Collider (CEPC) (18th November 2019, Beijing)

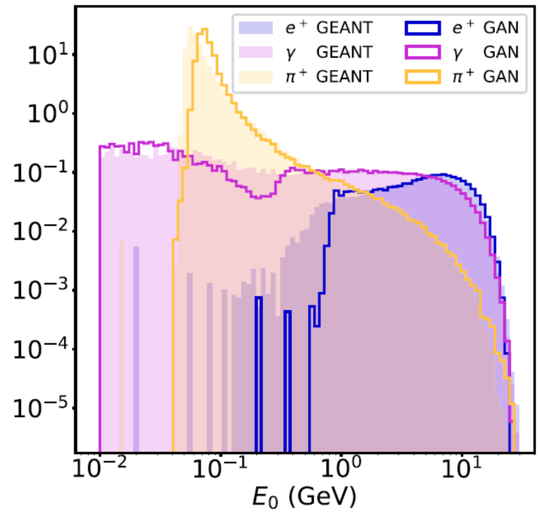
Outline

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

Introduction

- In HEP, Geant4 simulation:
  - Pro: very precise
  - Con: requires large computing resources
- Calorimeter simulation is one of bottlenecks.
- The Generative Adversarial Networks (GAN) could be used for calorimeter 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

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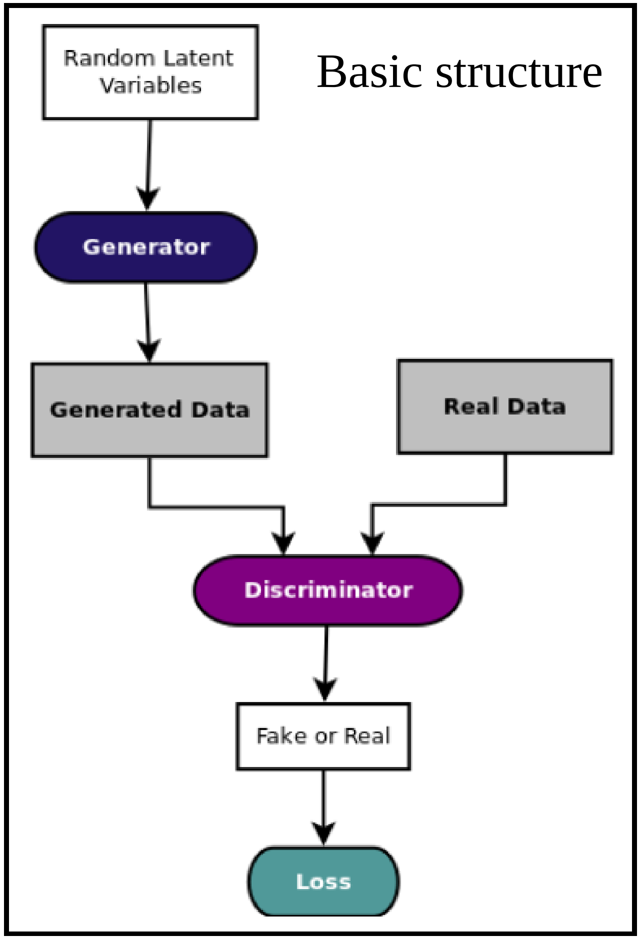
Generative Adversarial Networks (GAN)



- 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

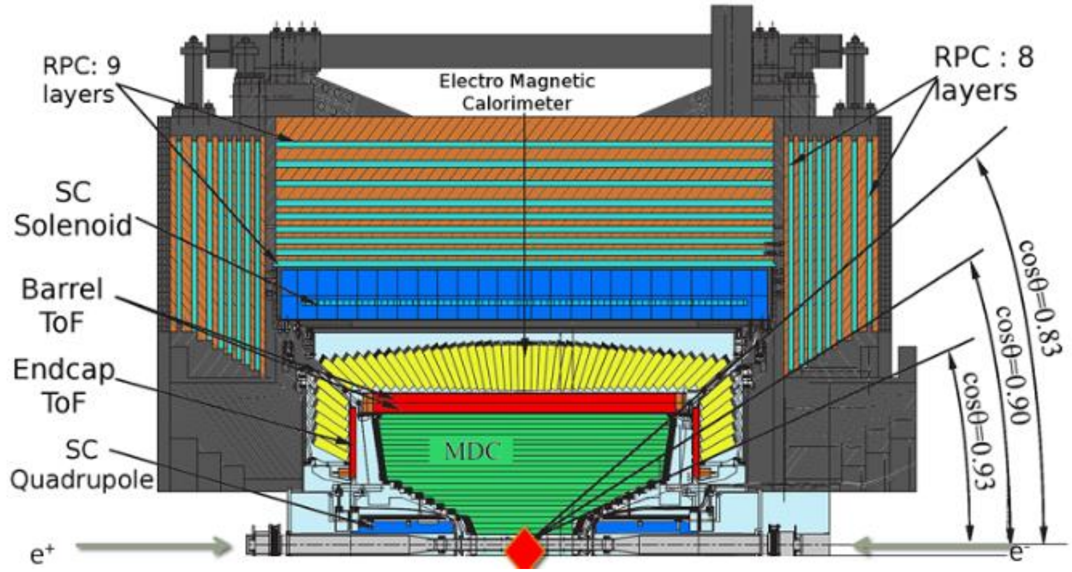
GAN from BESIII to CEPC

- Because there are huge mount of real data from BESIII experiment, we can do GAN study in BESIII firstly to prove the principle of GAN that can be used.

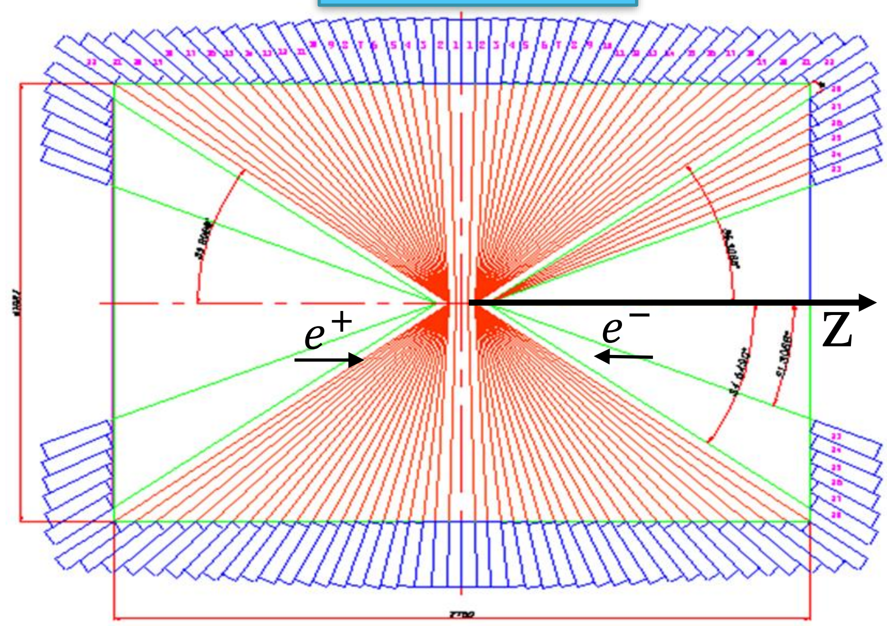
- Then we do the GAN study for CEPC experiment.

BESIII experiment

- 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

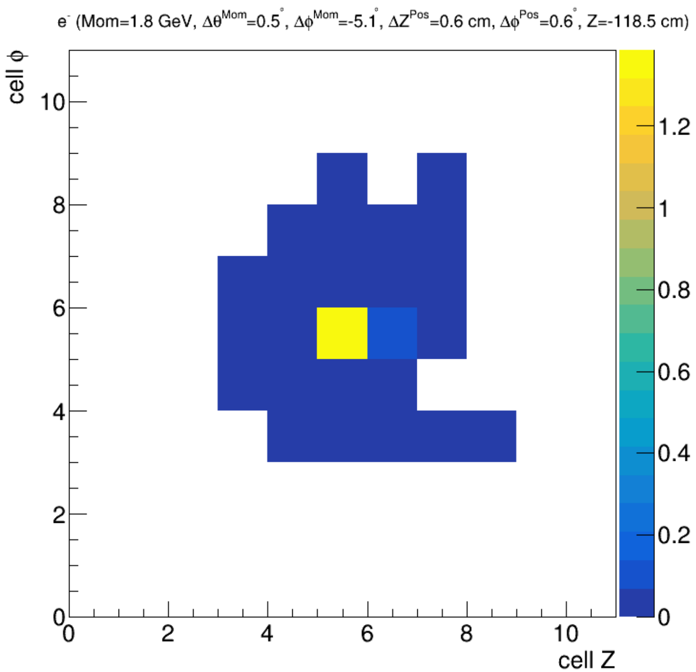


- 44 rings of crystal in barrel and 120 crystals in each ring. The front size of each crystals is 5×5 cm^2.
- 6 rings of crystal in each endcap.

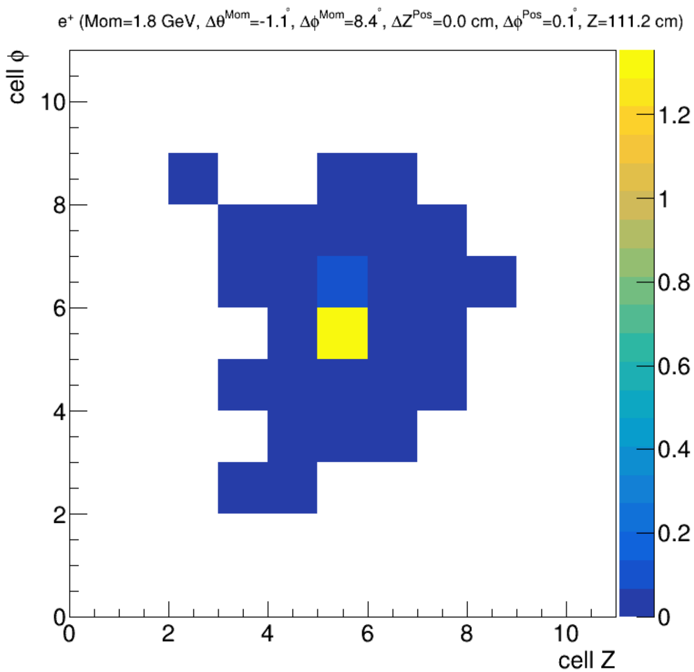
Dataset for training

- 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.

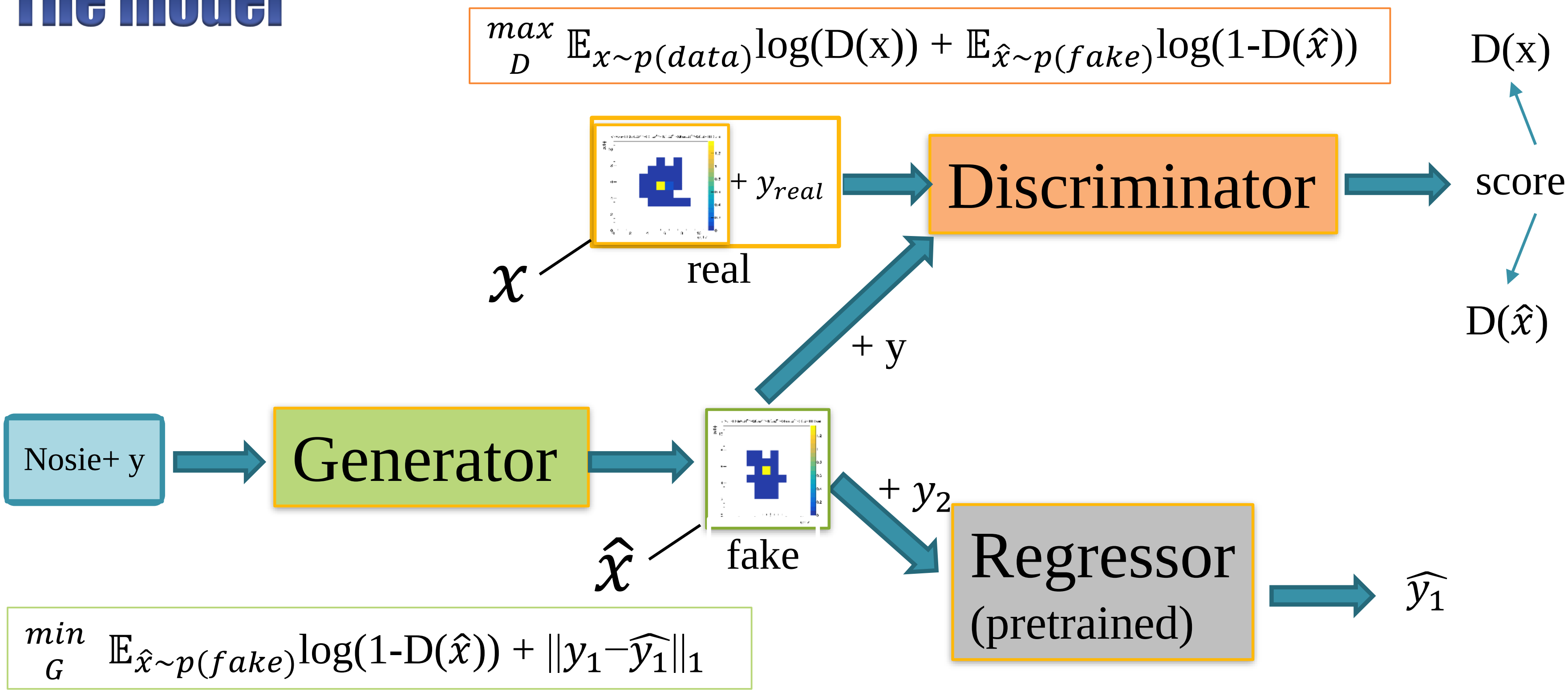
$e^{-}(\text{Mom} = 1.8\ \text{GeV}, \Delta\theta^{\text{Mom}} = 0.5^{\circ}, \Delta\phi^{\text{Mom}} = -5.1^{\circ},$
$\Delta Z^{\text{Pos}} = 0.6\ \text{cm}, \Delta\phi^{\text{Pos}} = 0.6^{\circ}, Z = -118.5\ \text{cm})$



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



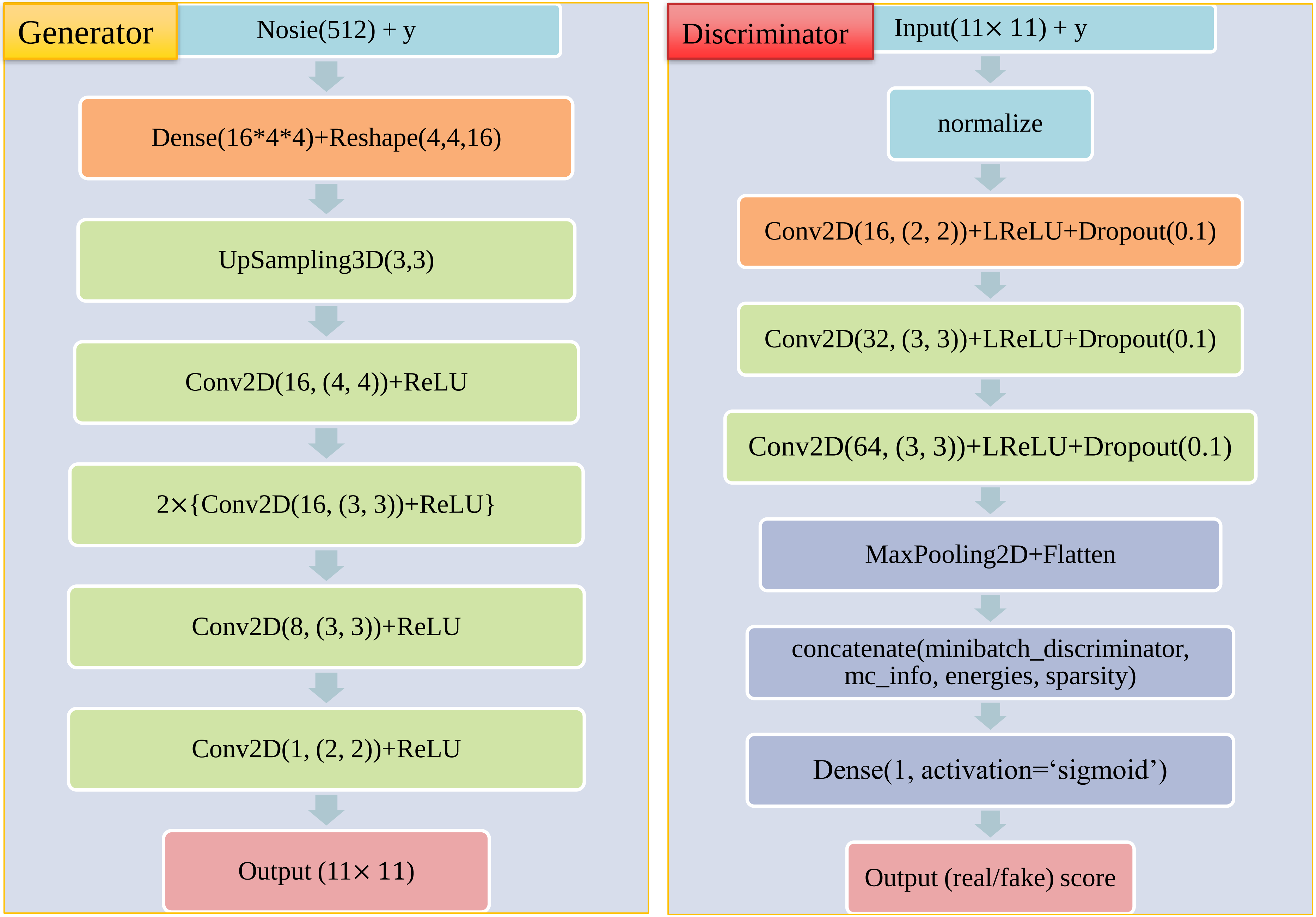
The model



- 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 helps the generator.

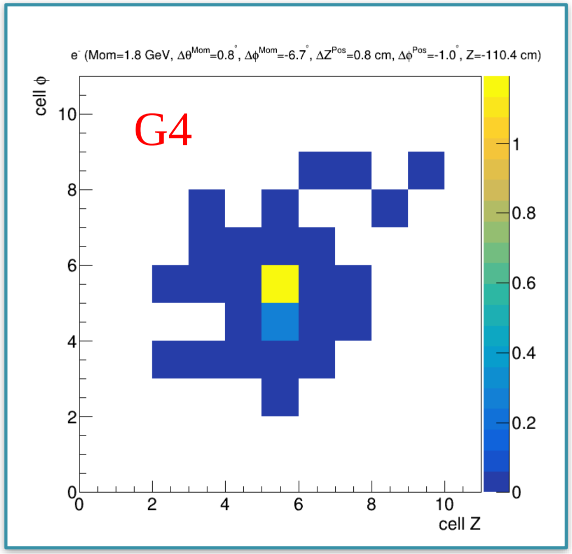
Reference

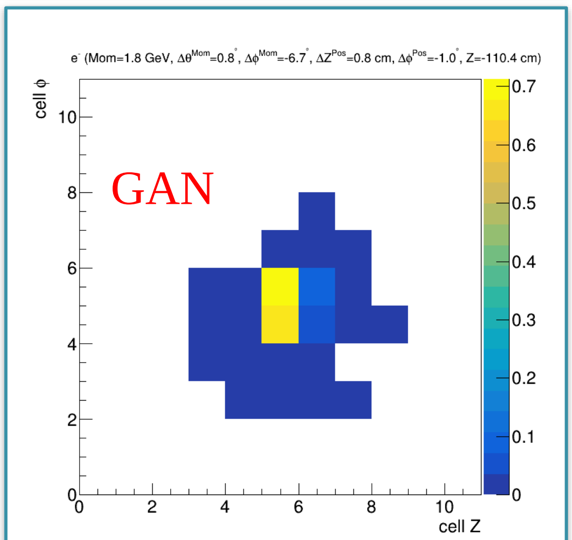
The model


Generator
Nosie(512) + y
Dense(16*4*4)+Reshape(4,4,16)
UpSampling3D(3,3)
Conv2D(16, (4, 4))+ReLU
2×{Conv2D(16, (3, 3))+ReLU}
Conv2D(8, (3, 3))+ReLU
Conv2D(1, (2, 2))+ReLU
Output (11× 11)
Discriminator
Input(11× 11) + y
normalize
Conv2D(16, (2, 2))+LReLU+Dropout(0.1)
Conv2D(32, (3, 3))+LReLU+Dropout(0.1)
Conv2D(64, (3, 3))+LReLU+Dropout(0.1)
MaxPooling2D+Flatten
concatenate(minibatch_discriminator,
mc_info, energies, sparsity)
Dense(1, activation=‘sigmoid’)
Output (real/fake) score

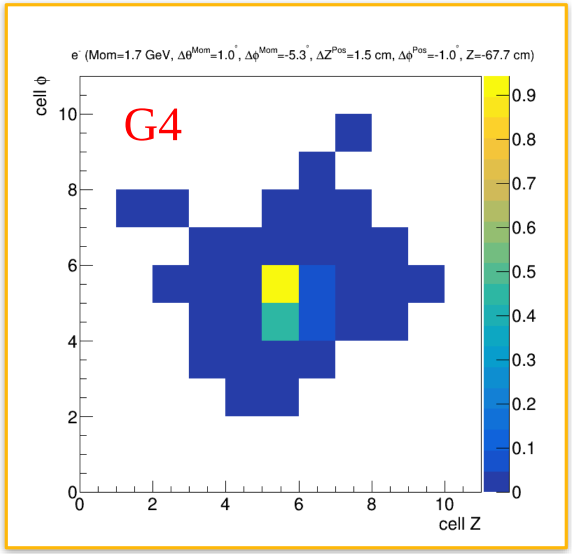
Event display (e^-)

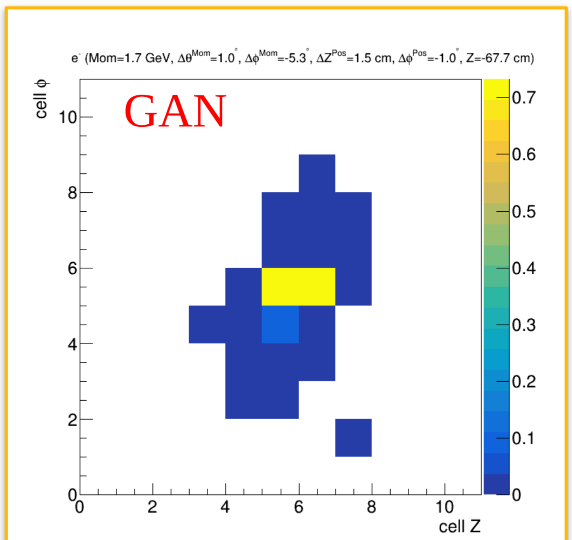
$e^-(\mathrm{Mom} = 1.8\ \mathrm{GeV}, \Delta\theta^{\mathrm{Mom}} = 0.8^\circ, \Delta\phi^{\mathrm{Mom}} = -6.7^\circ, \Delta Z^{\mathrm{Pos}} = 0.8\ \mathrm{cm}, \Delta\phi^{\mathrm{Pos}} = -1.0^\circ, Z = -110.4\ \mathrm{cm})$



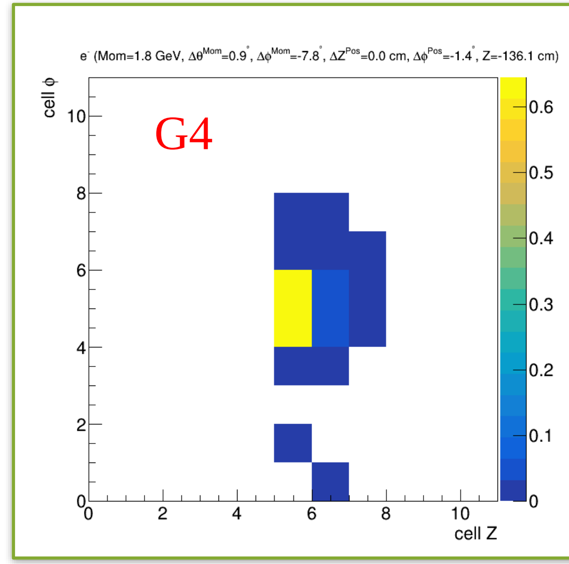


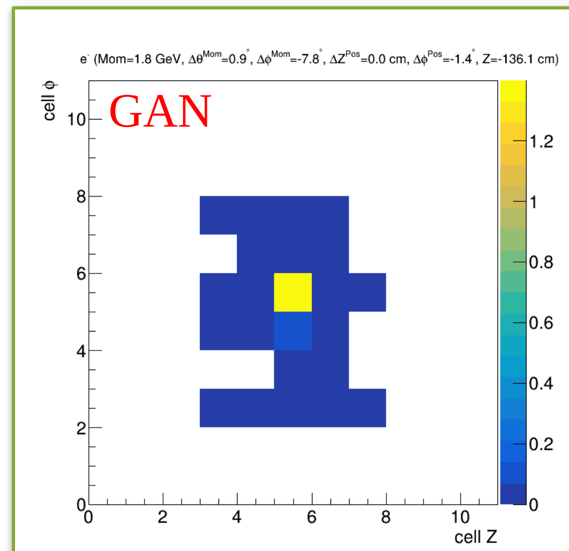
$e^-(\mathrm{Mom} = 1.7\ \mathrm{GeV}, \Delta\theta^{\mathrm{Mom}} = 1.0^\circ, \Delta\phi^{\mathrm{Mom}} = -5.3^\circ, \Delta Z^{\mathrm{Pos}} = 1.5\ \mathrm{cm}, \Delta\phi^{\mathrm{Pos}} = -1.0^\circ, Z = -67.7\ \mathrm{cm})$





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



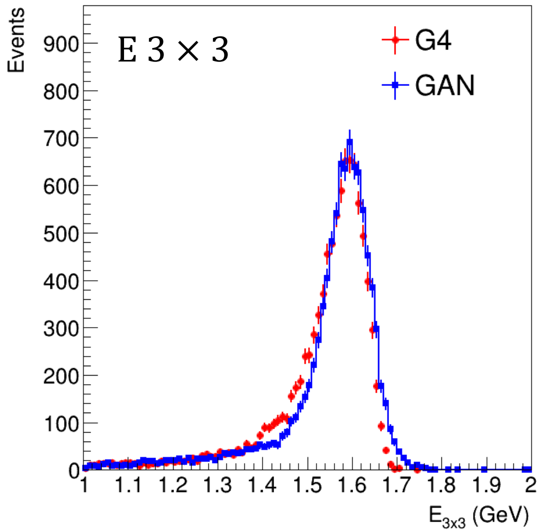


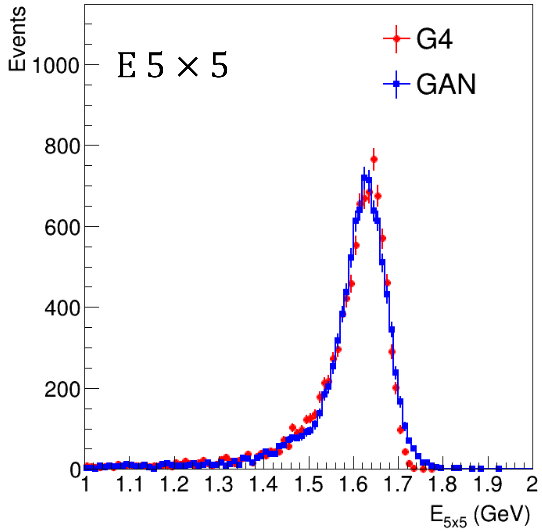
See distributions in following.

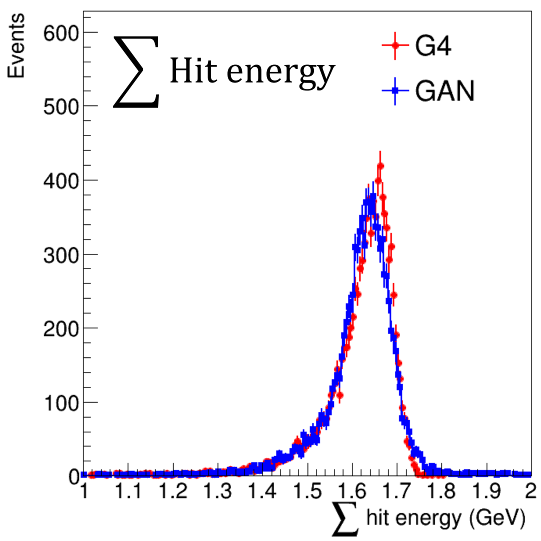
See results for e^+ in backup

Some distributions (e^-)

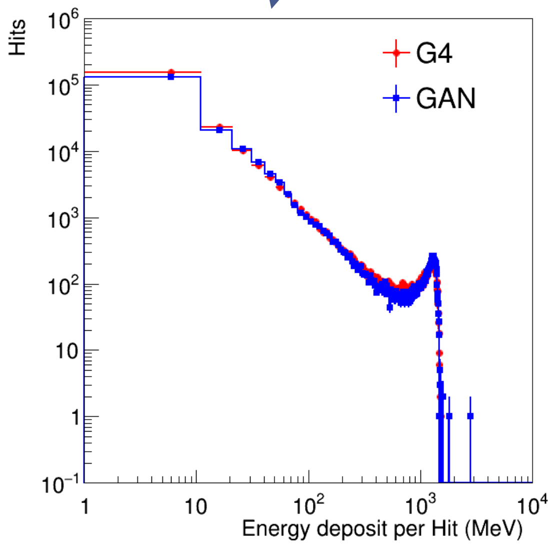
See similar results for e^+ in backup





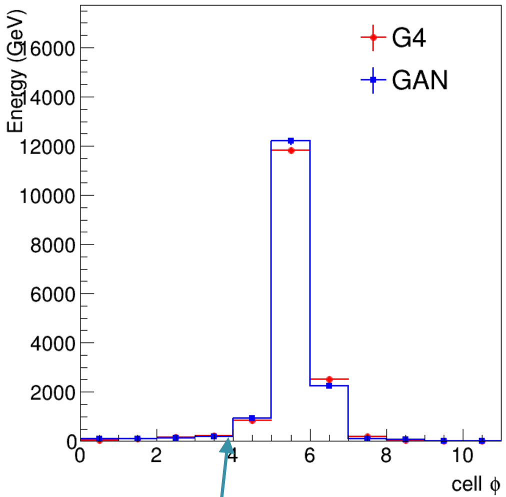


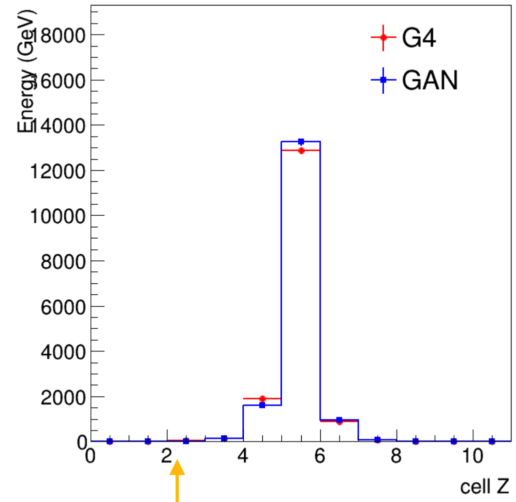
Energy of calorimeter cells



Some distributions (e^-)

See similar results for e^+ in backup



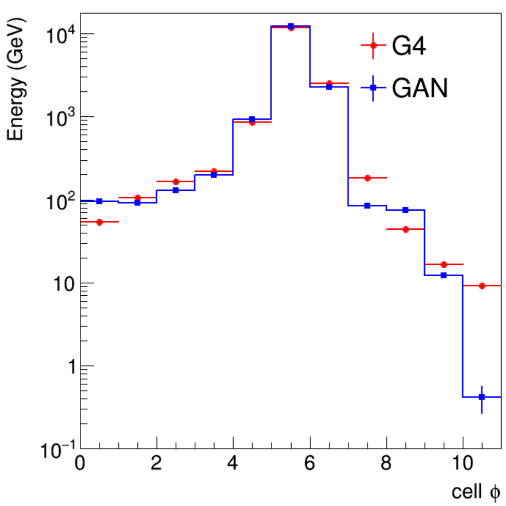


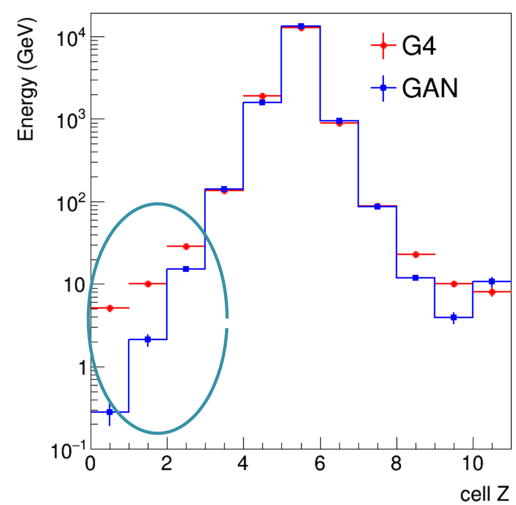
Energy deposited in ϕ direction

log scale

Energy deposited in Z direction

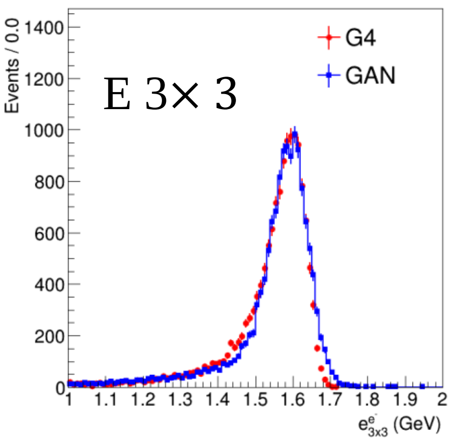
log scale

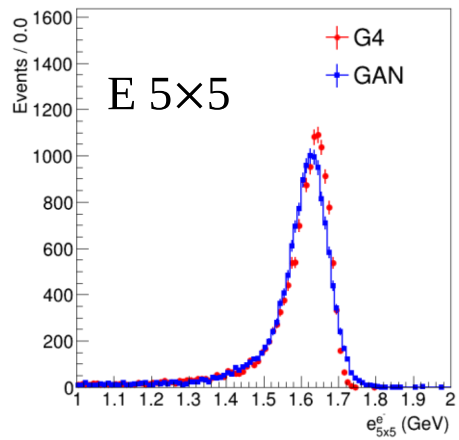


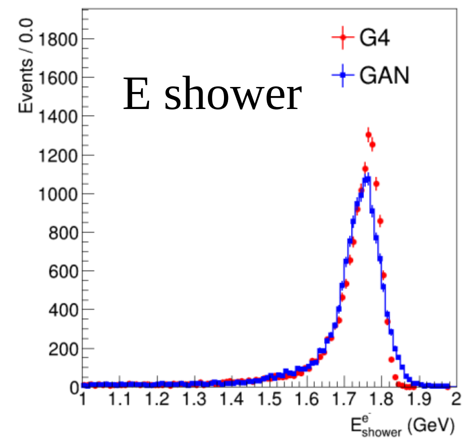


Some distributions for reconstruced particle (e^-)

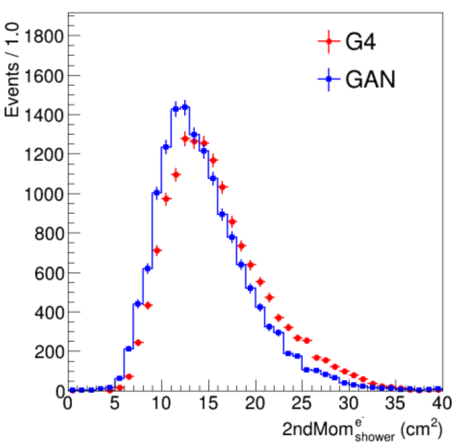
Apply the GAN simulation in BESIII.

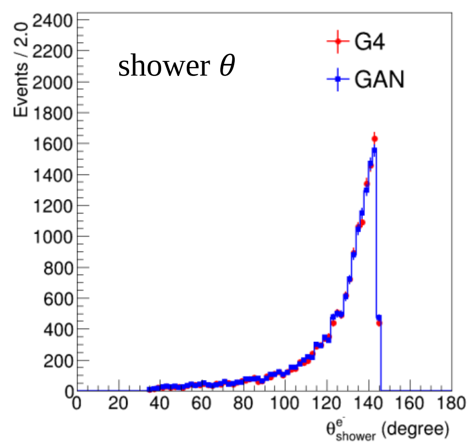


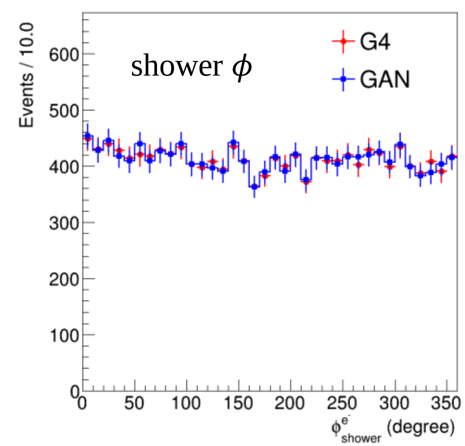




Shower 2nd mom







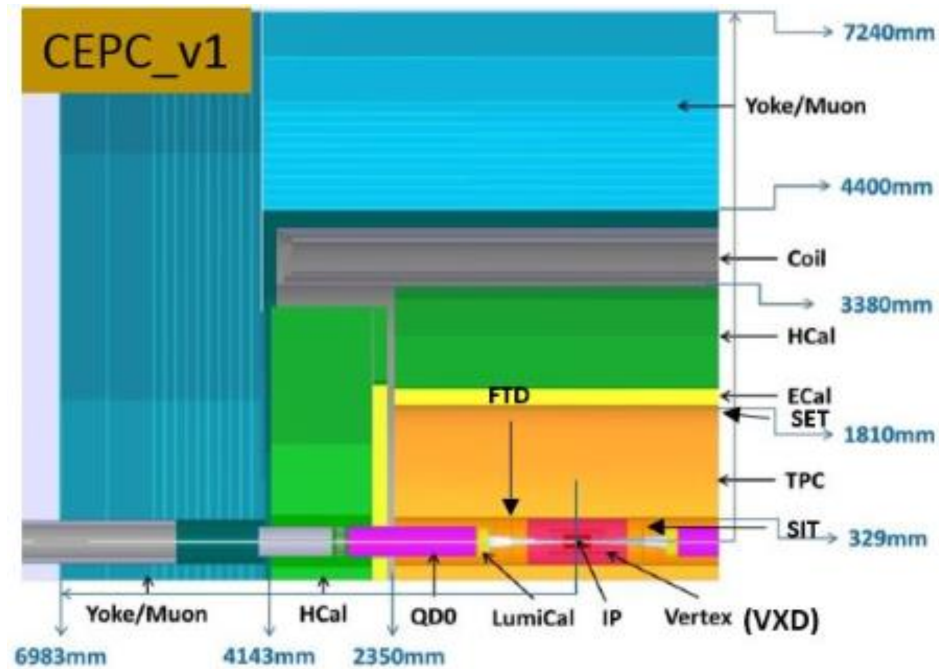
Short summary

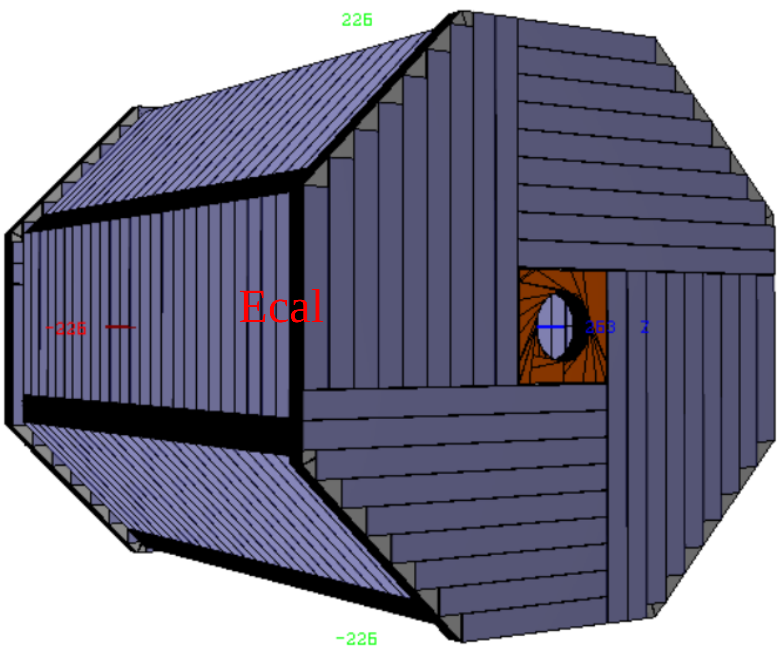
- In general, the results from GAN looks good, although the agreement between Geant4 and GAN still need to be improved.
- It is shown that GAN may be a solution for the fast calorimeter simulation in BESIII.
- Next plan for BESIII:
  - Training the GAN using real data and apply it for simulation and check the agreement between data and simulation.

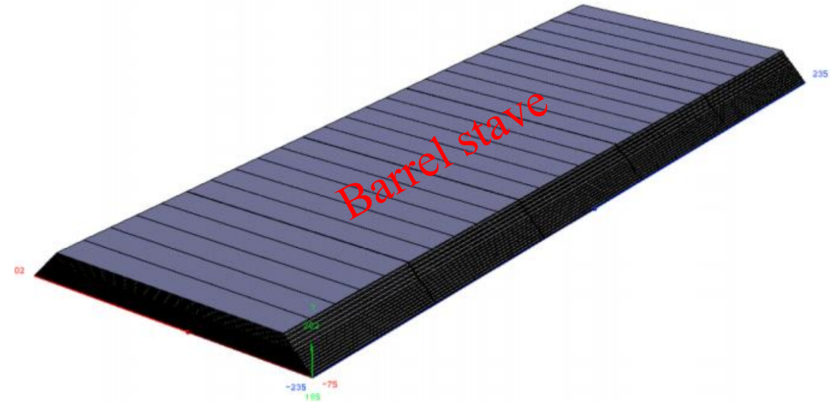
- Now lets do the GAN study in CEPC !

Circular Electron Positron Collider (CEPC)

- The CEPC is a proposed future circular electron positron collider.
- 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.

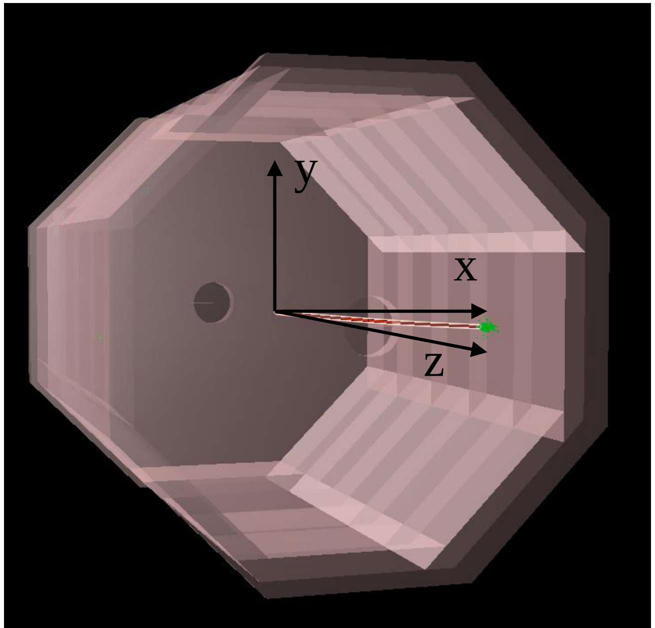






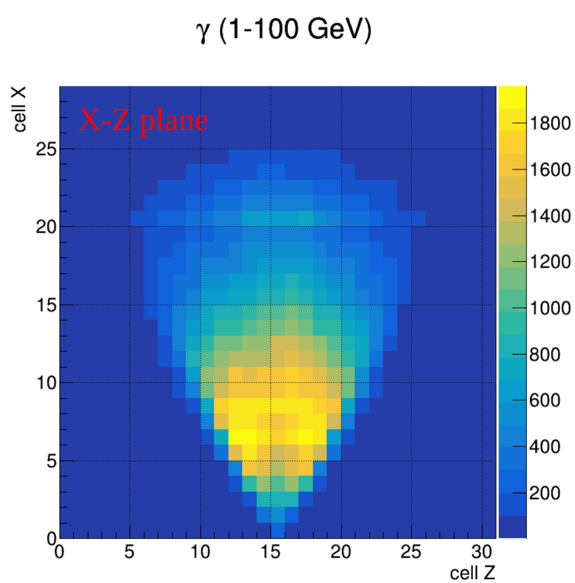
Ecal in Barrel	Cell size	Layer	Particle energy
BESIII	5 cm × 5 cm	1	$\mathcal{O}(1)$ GeV
CEPC	1 cm × 1 cm	29	$\mathcal{O}(10)$ GeV

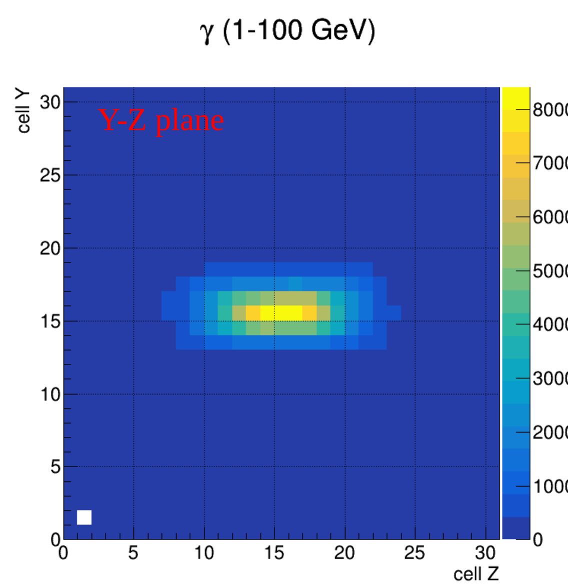
Dataset for training



/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 gamma
/run/beamOn 100000

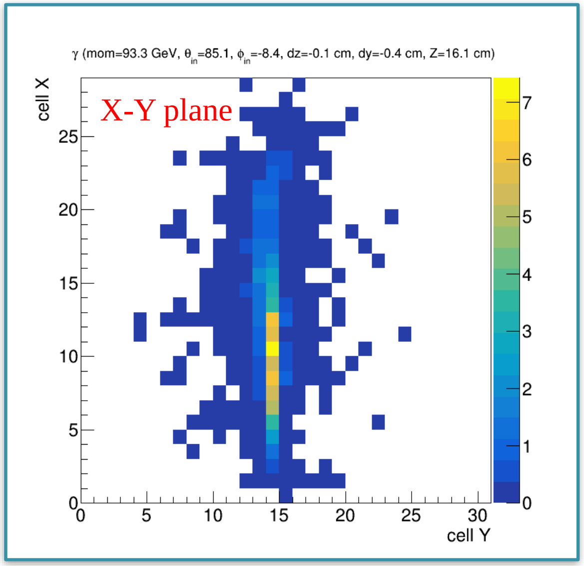
- ❖ The single photon particle gun samples are used for training.
  - Energy in [1, 100] GeV uniformly.
  - θ in [50, 140] degree uniformly.
  - ϕ in [-15, +15] degree uniformly.
- ❑ Only hits from Ecal barrel are used.
- ❑ The concatenate regions between different staves are excluded.
- ❑ Hit energy in 31× 31×29 calorimeter cells are considered.

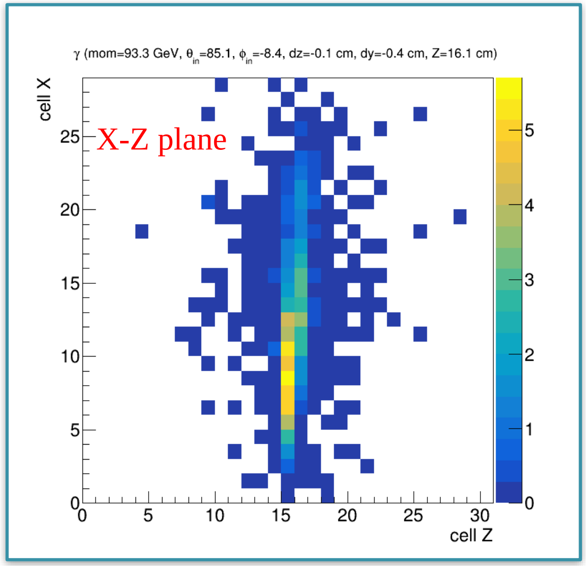


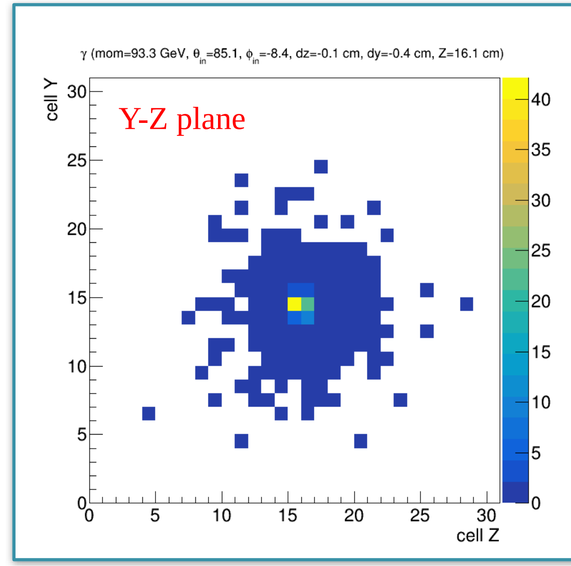


Event display

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)



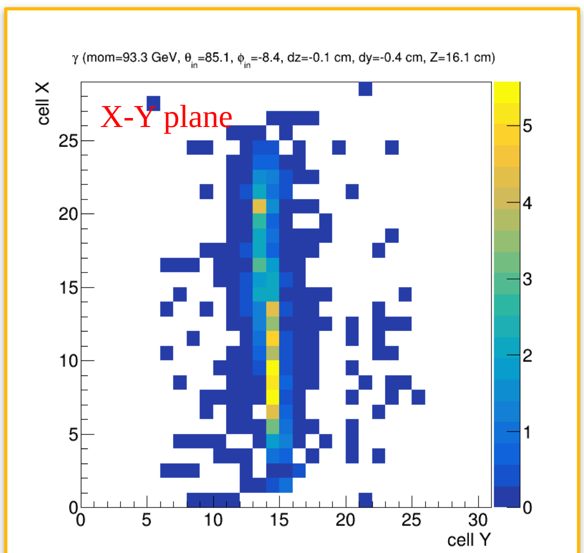


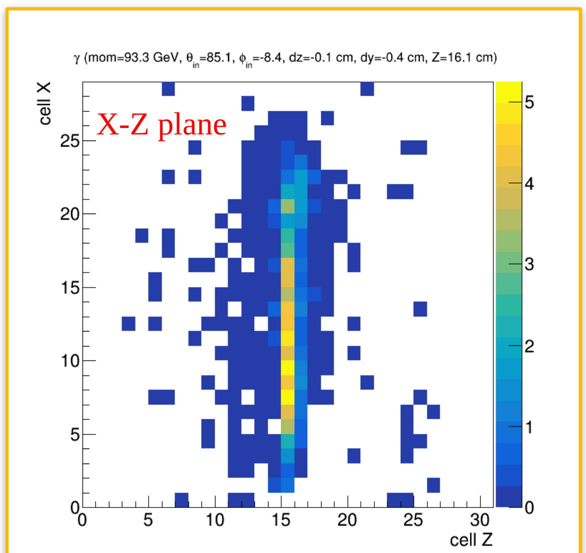


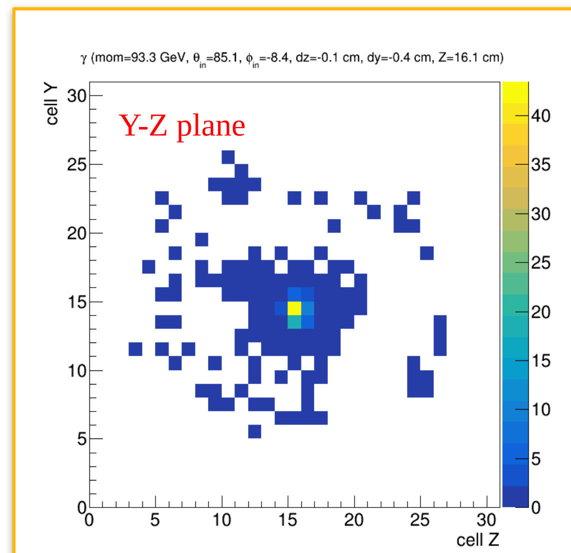
Geant4

See the detailed GAN network in backup

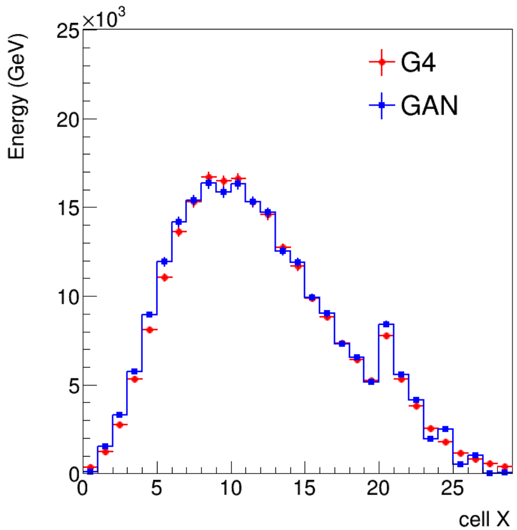
GAN

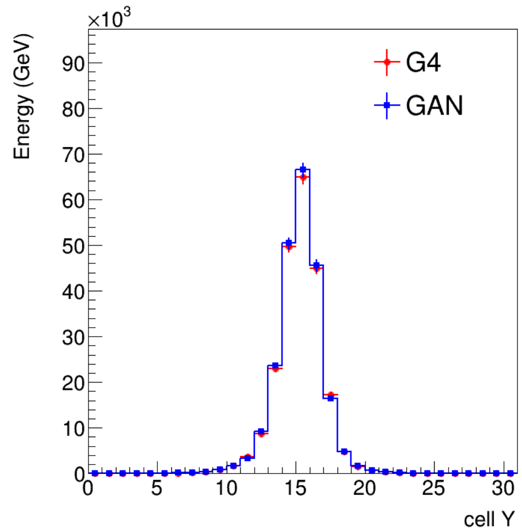


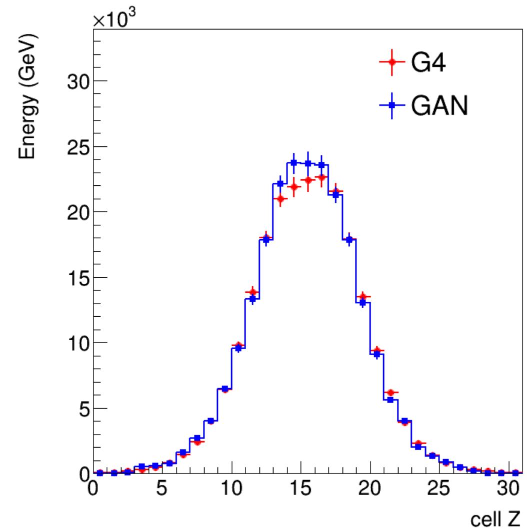




Some distributions for γ







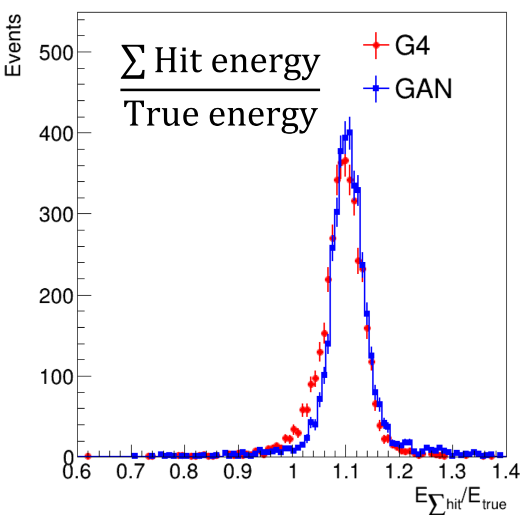
Energy deposited in X(layer) direction

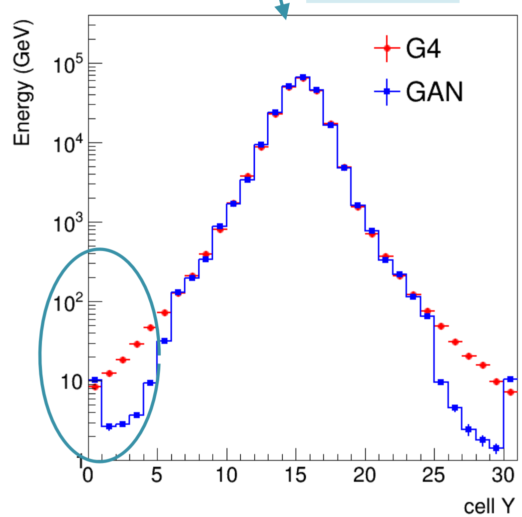
Energy deposited in Y direction

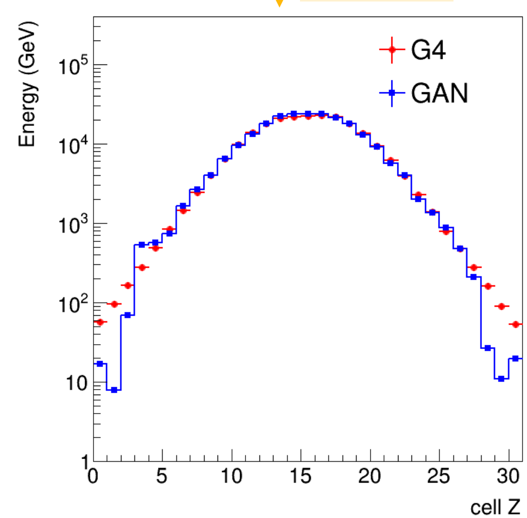
log scale

Energy deposited in Z direction

log scale



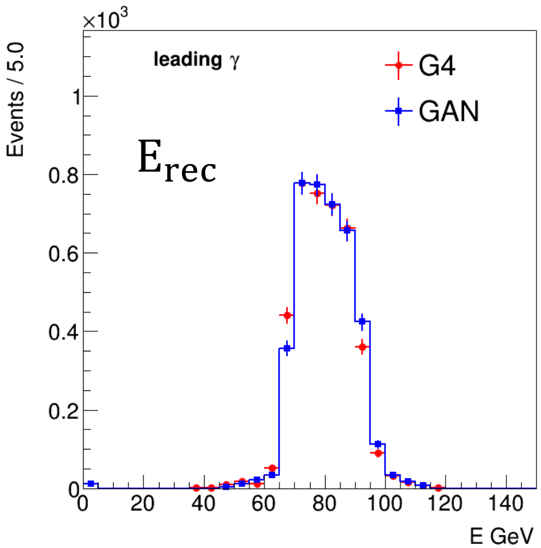


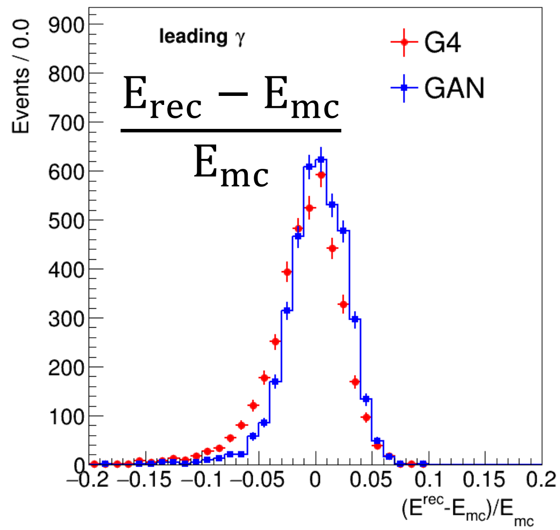


Apply GAN and do event reconstruction using mc samples

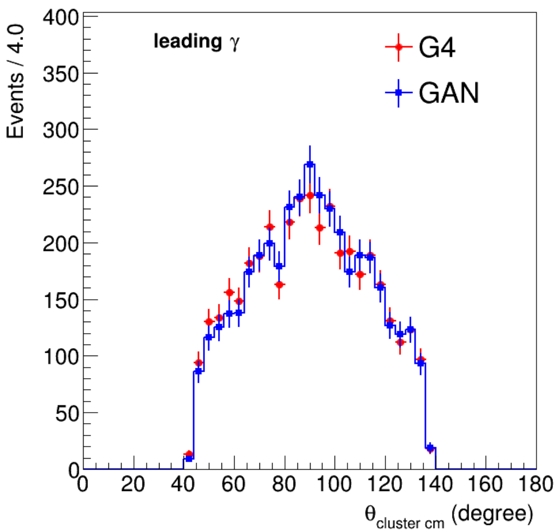
- Using $e^+e^- \rightarrow Z(\nu\nu)H(\gamma\gamma)$ mc samples.
- Comparing the properties of reconstructed leading gamma.

The concatenate regions between different staves are excluded.

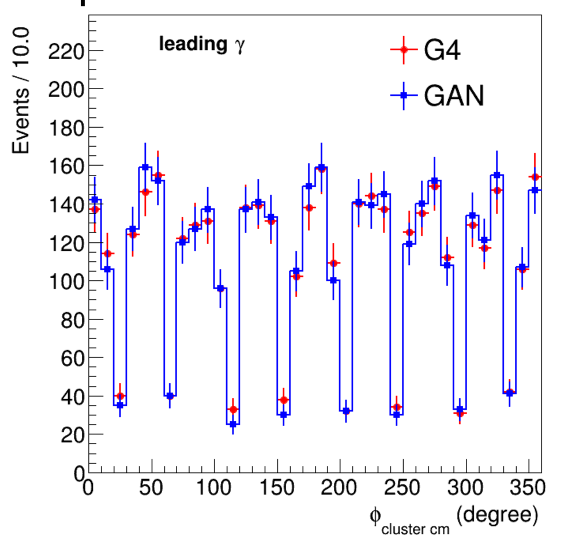




θ of center of mass cluster



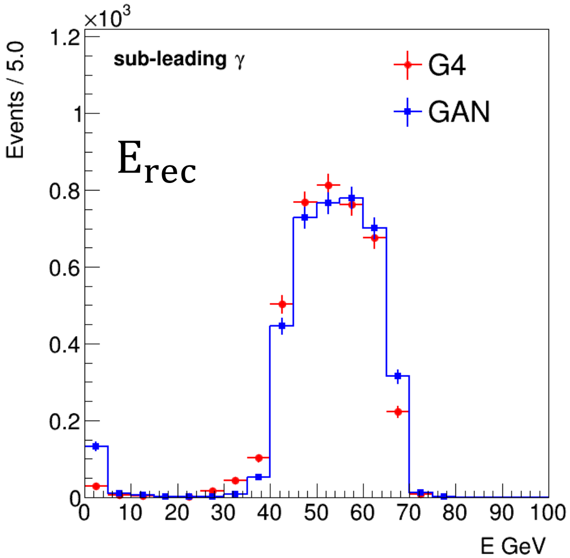
ϕ of center of mass cluster

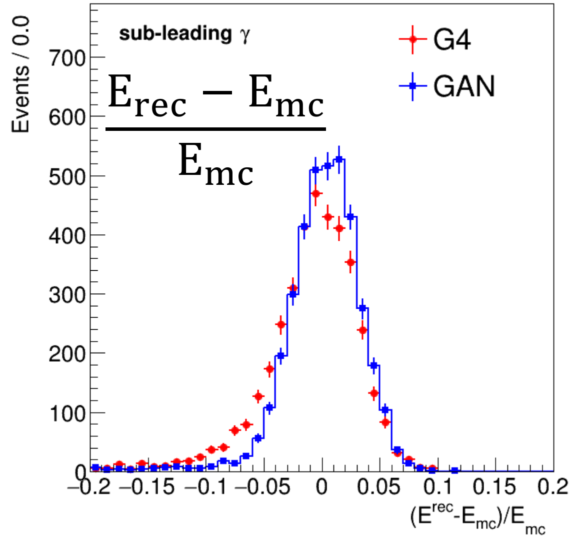


Apply GAN and do event reconstruction using mc samples

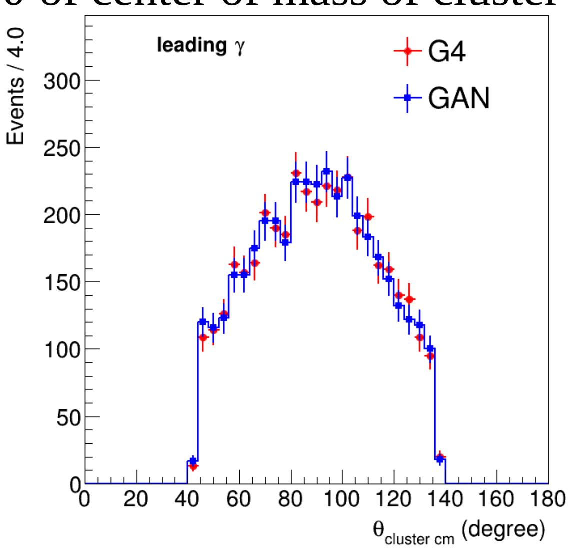
- Using $e^+e^- \to Z(\nu\nu)H(\gamma\gamma)$ mc samples.
- Comparing the properties of reconstructed sub-leading gamma.

The concatenate regions between different staves are excluded.

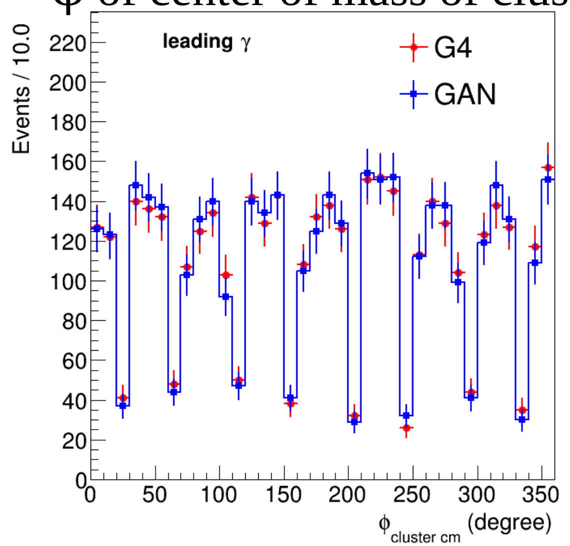




θ of center of mass of cluster

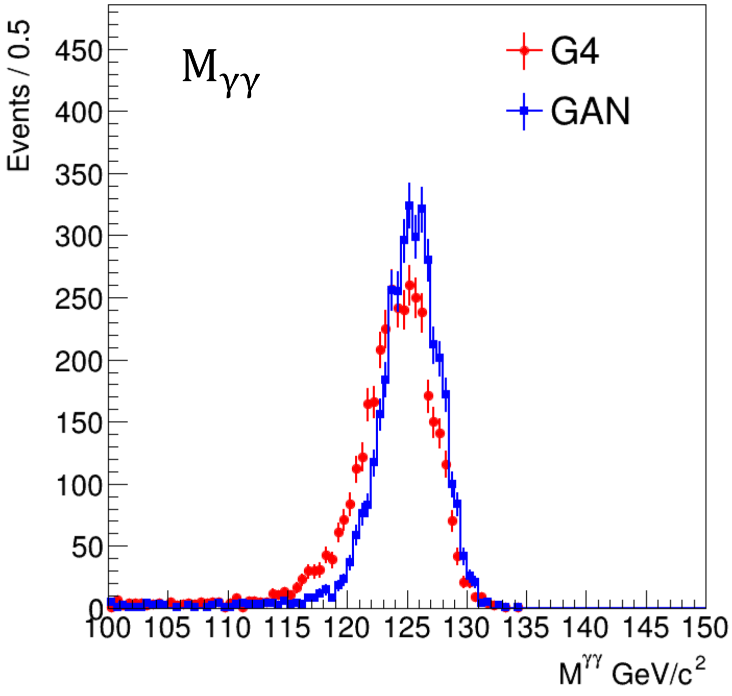


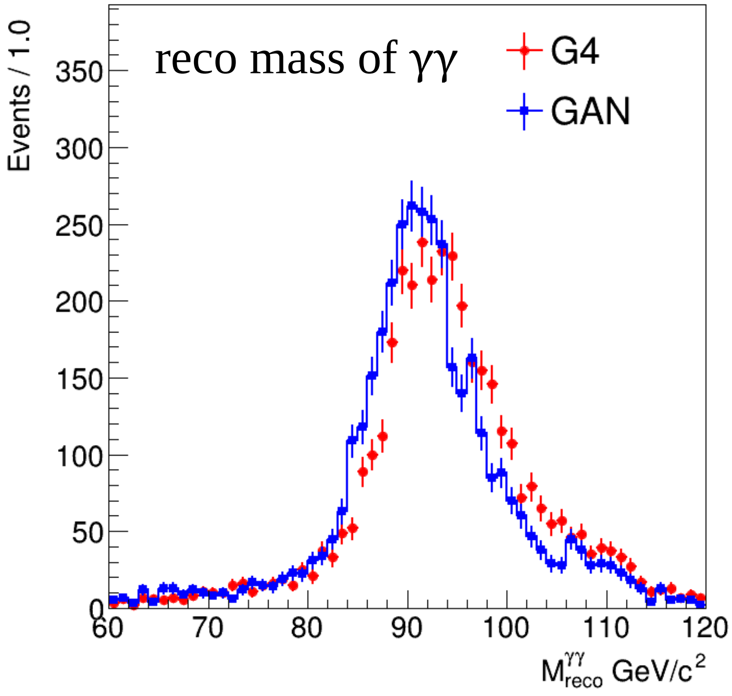
ϕ of center of mass of cluster



Apply GAN and do event reconstruction using mc samples

- Using $e^+e^- \rightarrow Z(\nu\nu)H(\gamma\gamma)$ mc samples.
- Comparing the $M_{\gamma\gamma}$ from reconstructed gamma and reco mass of $\gamma\gamma$.





Looks fine, but still need to be improved.

The concatenate regions between different staves are excluded.

- 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.
- There are still some discrepancies between GAN and Geant4 which need to be improved.

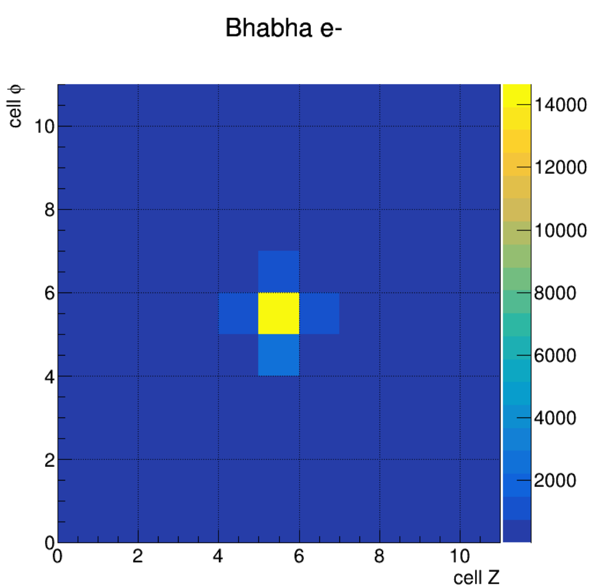
- Next to do:
  - Improve the performance of GAN.
  - Try with Wasserstein GAN with gradient penalty which seems more stable in the training.
  - Integrating the GAN into CEPC framework.

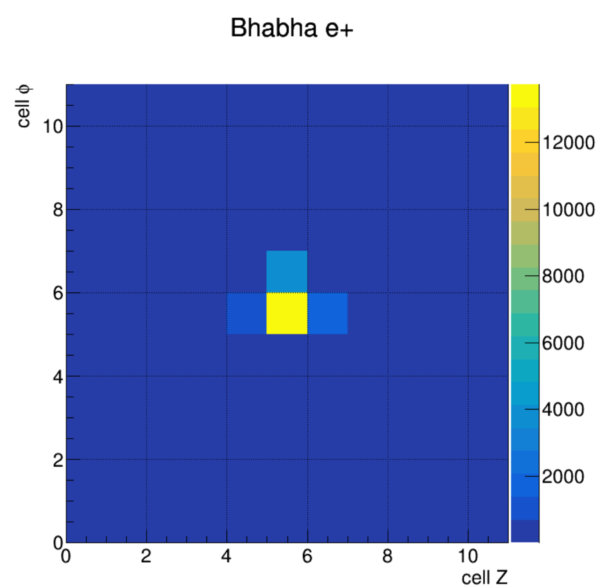
Thanks for your attention

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.



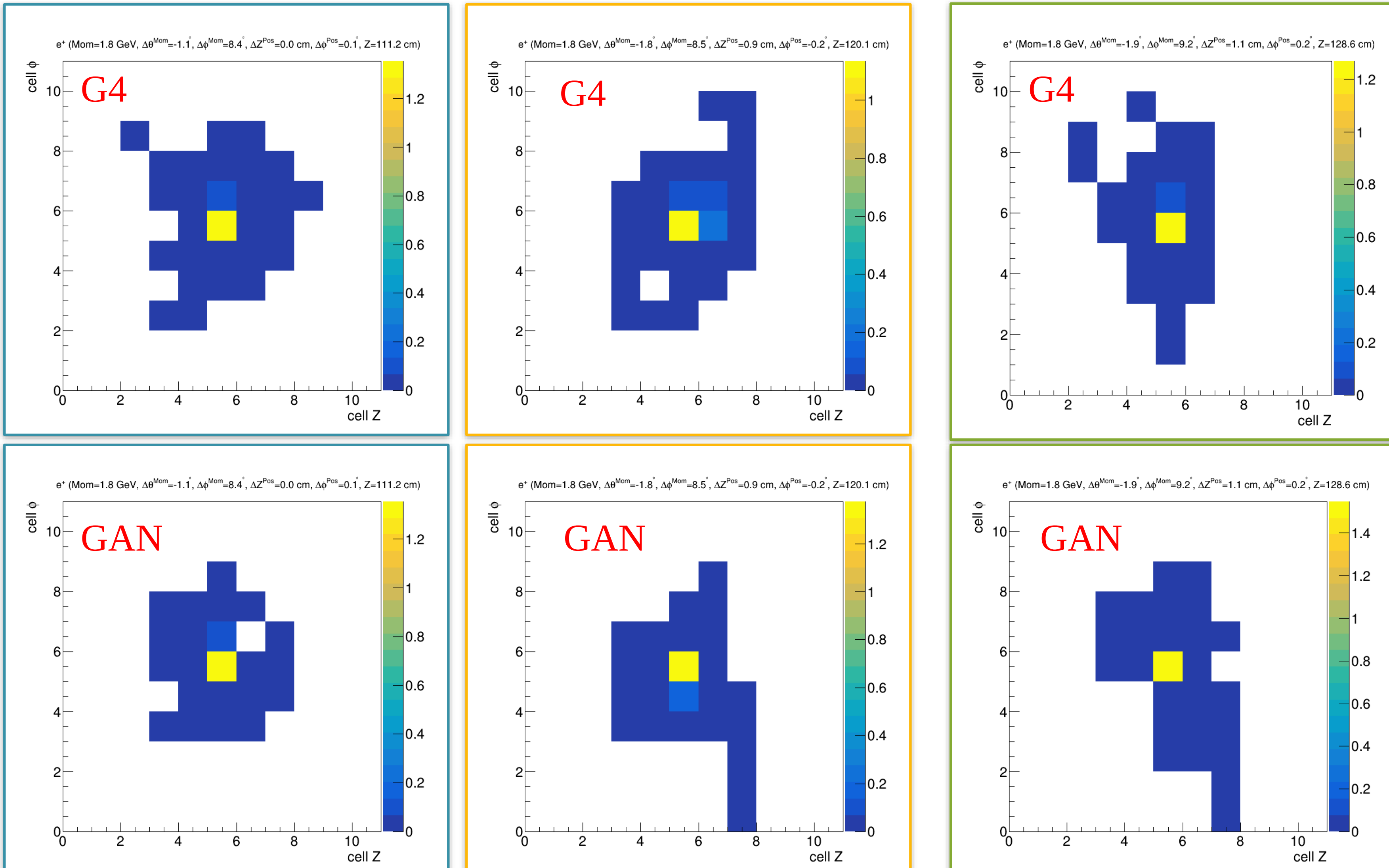


Event display (e^+)

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

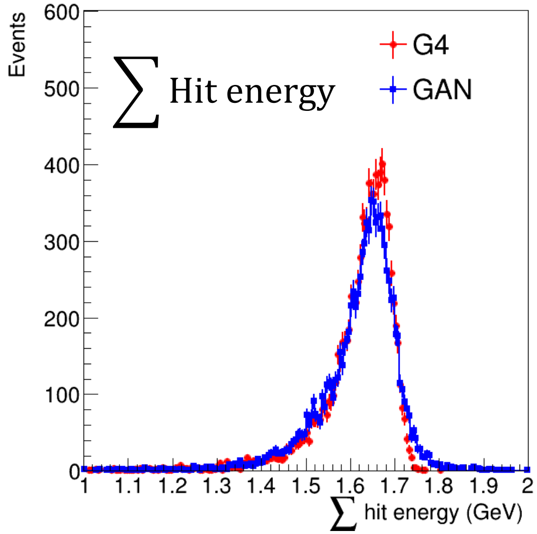
e^+(Mom $= 1.8$ GeV, $\Delta\theta^{\mathrm{Mom}} = -1.8^\circ$, $\Delta\phi^{\mathrm{Mom}} = 8.5^\circ$, $\Delta Z^{\mathrm{Pos}} = 0.9$ cm, $\Delta\phi^{\mathrm{Pos}} = -0.2^\circ$, $Z = 120.1$ cm)

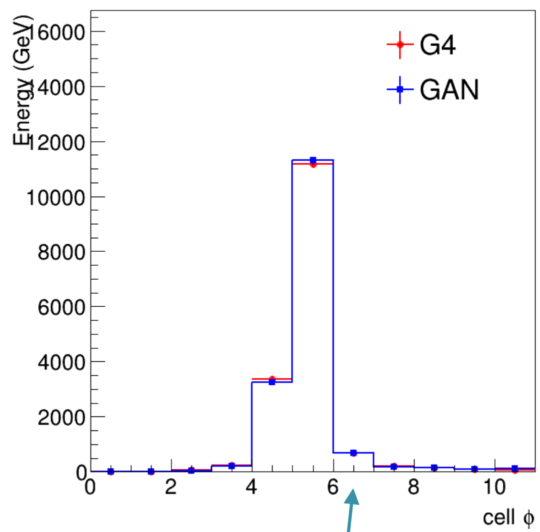
e^+(Mom $= 1.8$ GeV, $\Delta\theta^{\mathrm{Mom}} = -1.9^\circ$, $\Delta\phi^{\mathrm{Mom}} = 9.2^\circ$, $\Delta Z^{\mathrm{Pos}} = 1.1$ cm, $\Delta\phi^{\mathrm{Pos}} = 0.2^\circ$, $Z = 128.6$ cm)

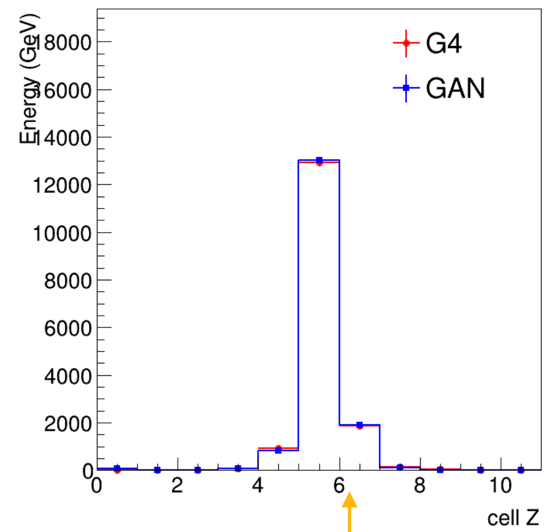


See distributions in following.

Some distributions (e^+)



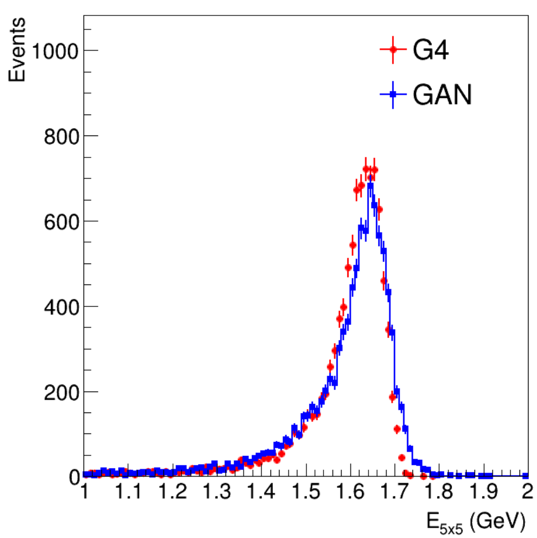


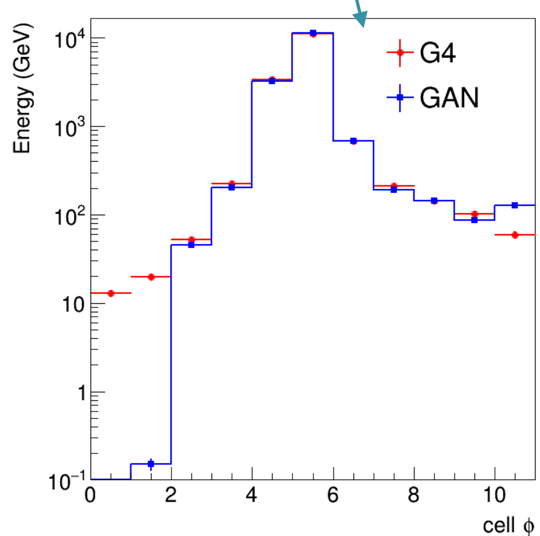


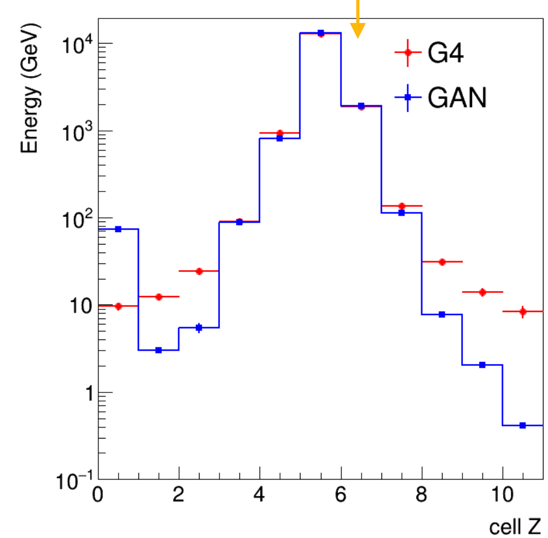
Energy of calorimeter cells

Energy deposited in ϕ direction

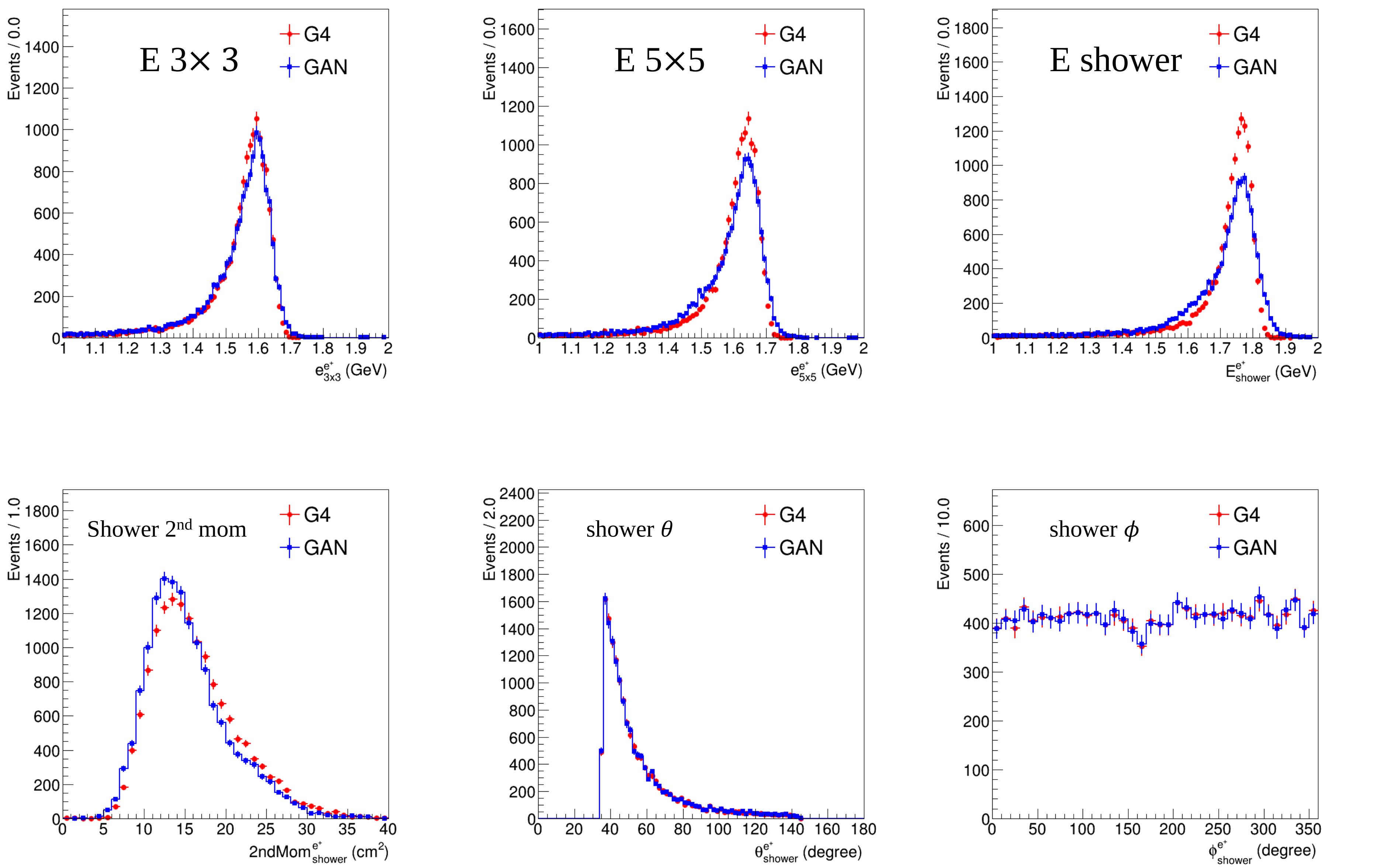
Energy deposited in Z direction







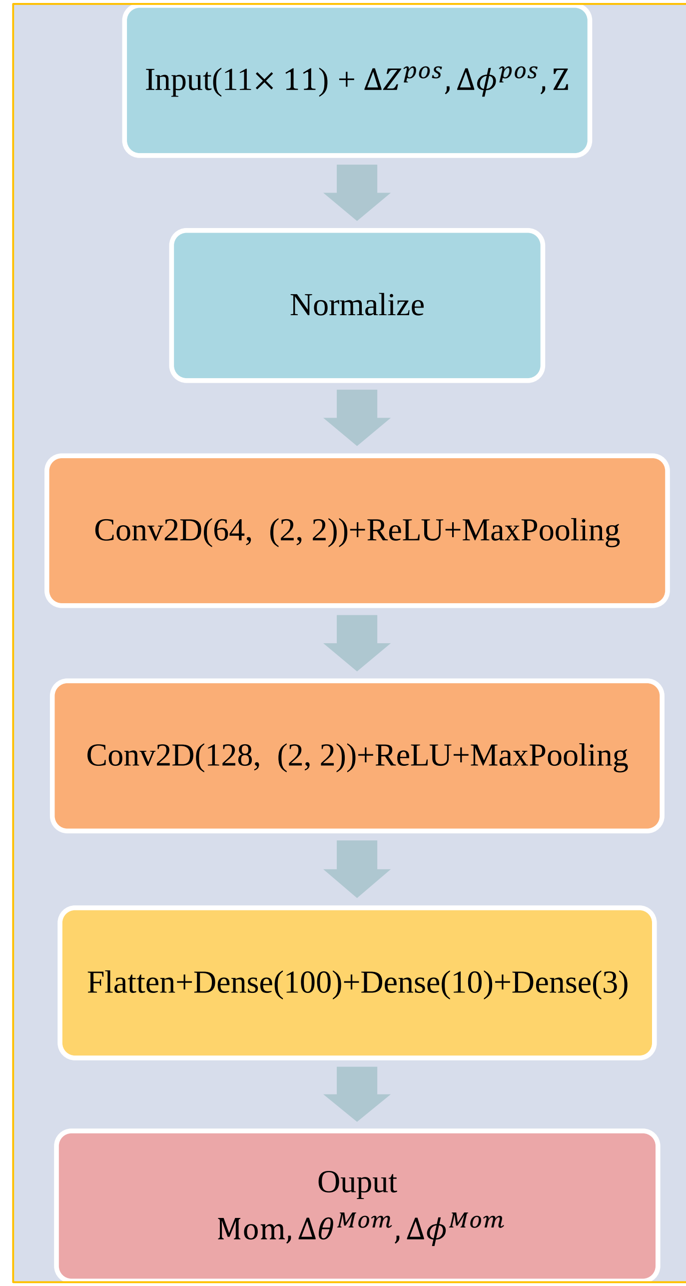
Some variables for reconstruced particle (e^+)



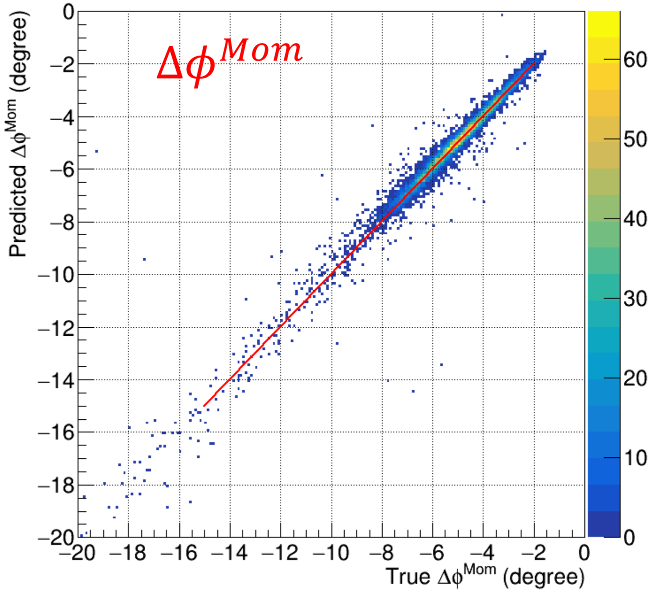
Regressor

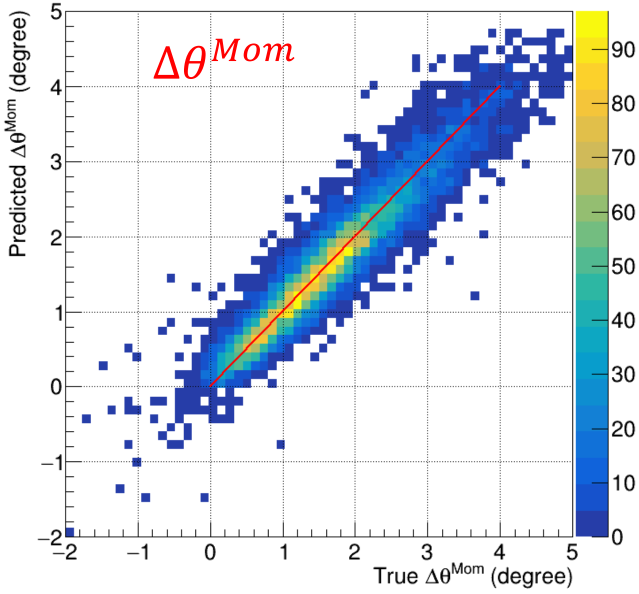
- $\Delta\phi^{Mom}$: the ϕ difference between the momentum of incoming particle and the direction of the crystal.
- $\Delta\theta^{Mom}$: the θ difference between the momentum of incoming particle and the direction of the crystal.
- ΔZ^{Pos}: the Z difference between the hit point of incoming particle 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 ($P_{MDC} - E_{TOF}$).
- Z

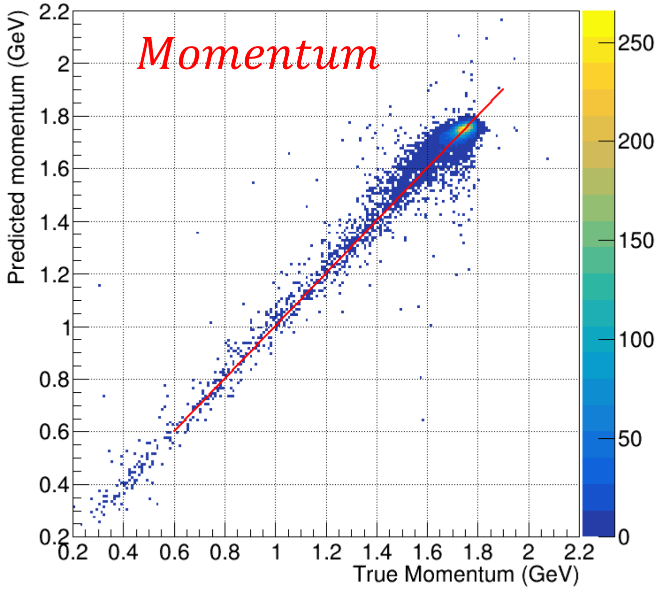
❖ Due to the e^- (e^+) is mostly at negative (positive) Z region, the e^- (e^+) at positive (negative) is not used.



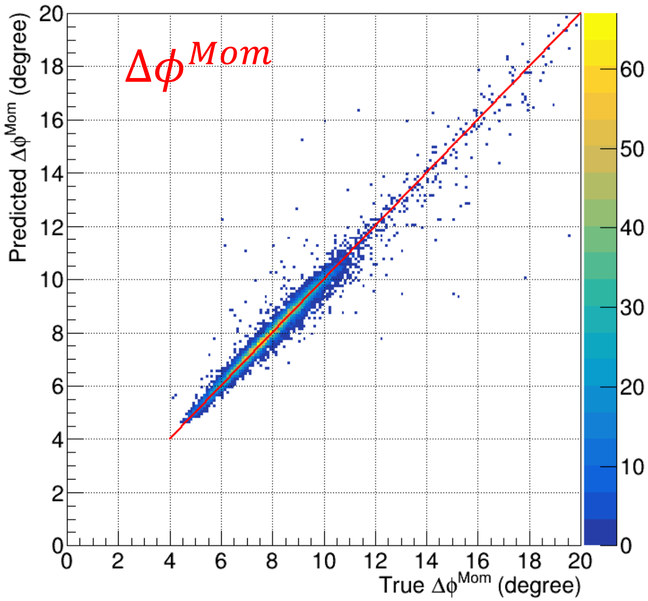
Regressor performance (e^-)

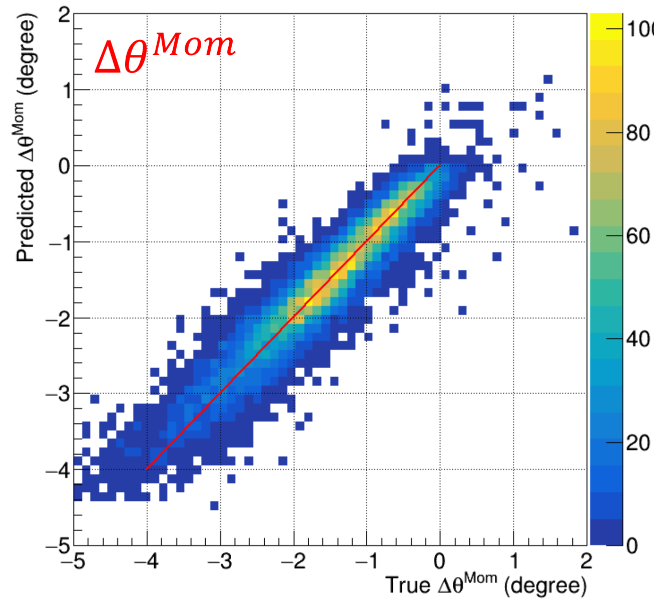


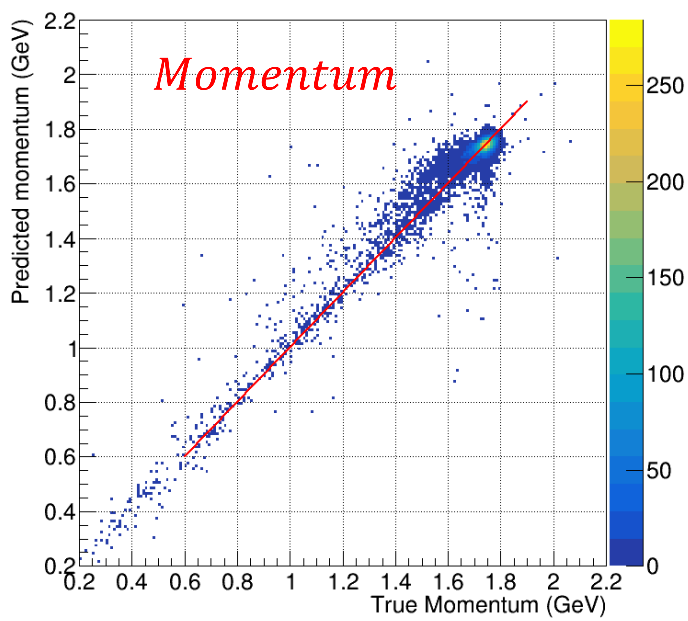




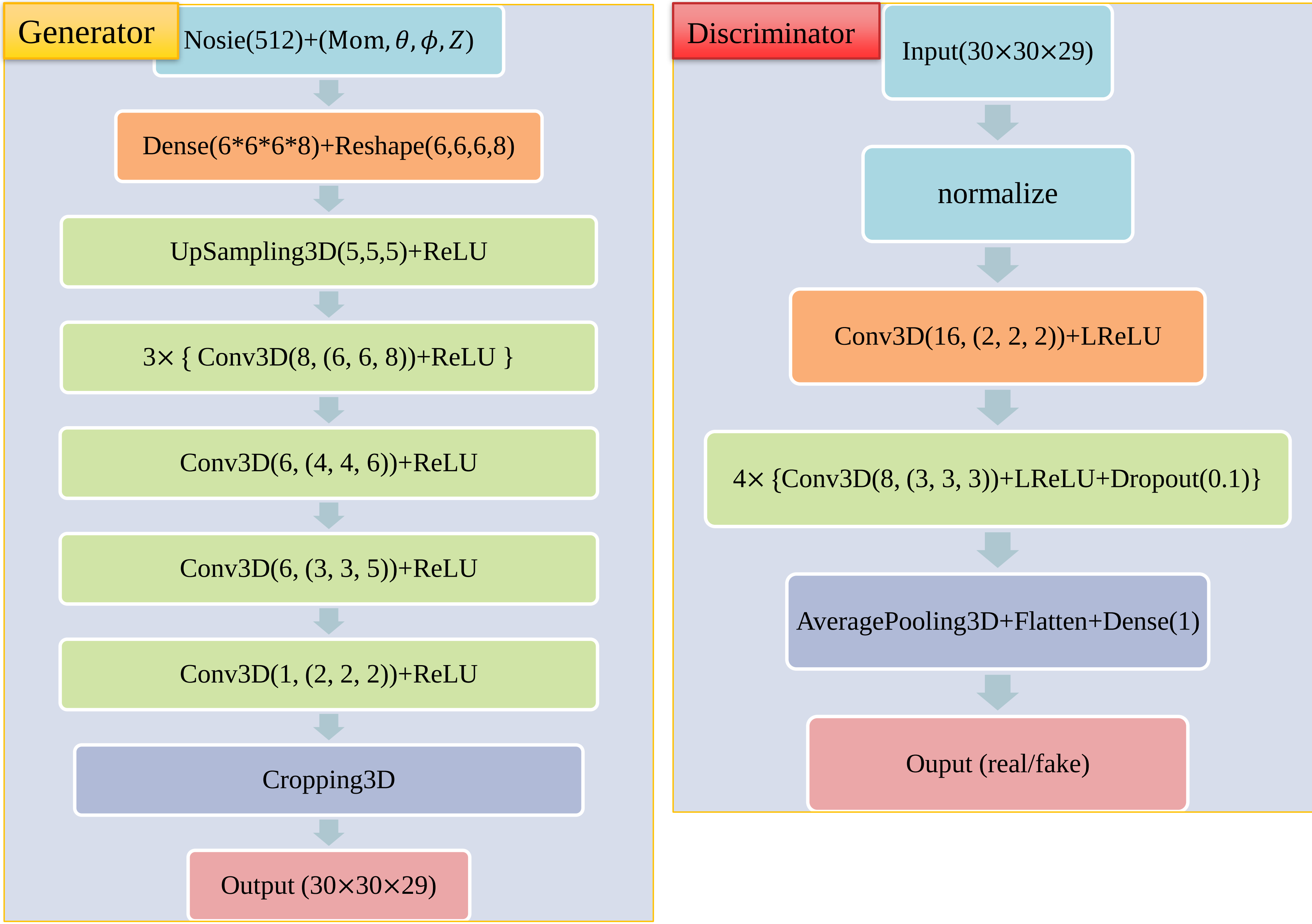
Regressor performance (e^+)



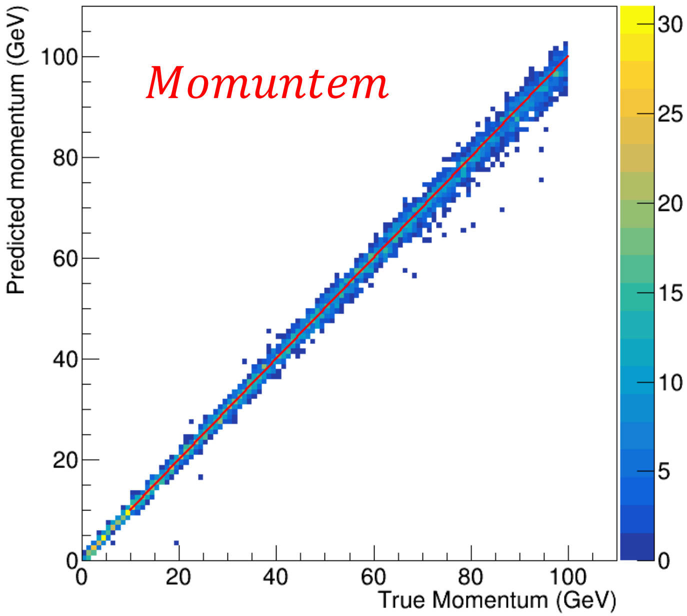


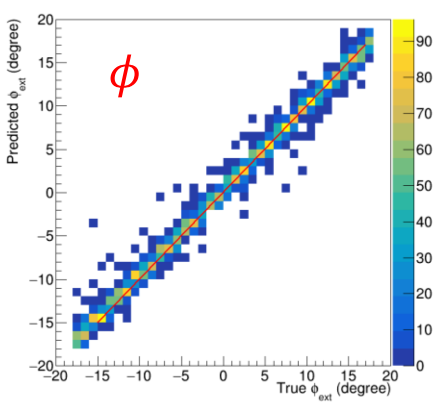


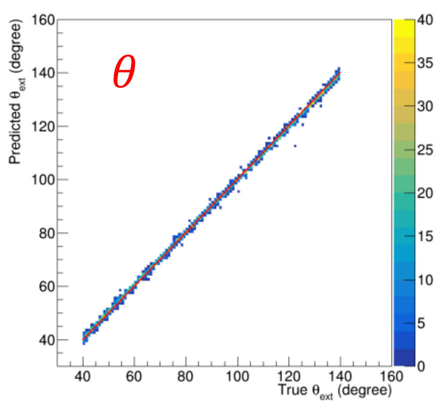
Generator and discriminator architecture (CEPC)



Regressor architecture and performance (γ)







Input(31×31×29)+ $\Delta Z^{pos}, \Delta Y^{pos}$, Z

↓

Normalize

↓

Conv3D(16, (5, 6, 6))+LReLU

↓

3×{Conv3D(8, (5, 6, 6))+LReLU+Dropout(0.1)}

↓

AveragePooling3D+Flatten

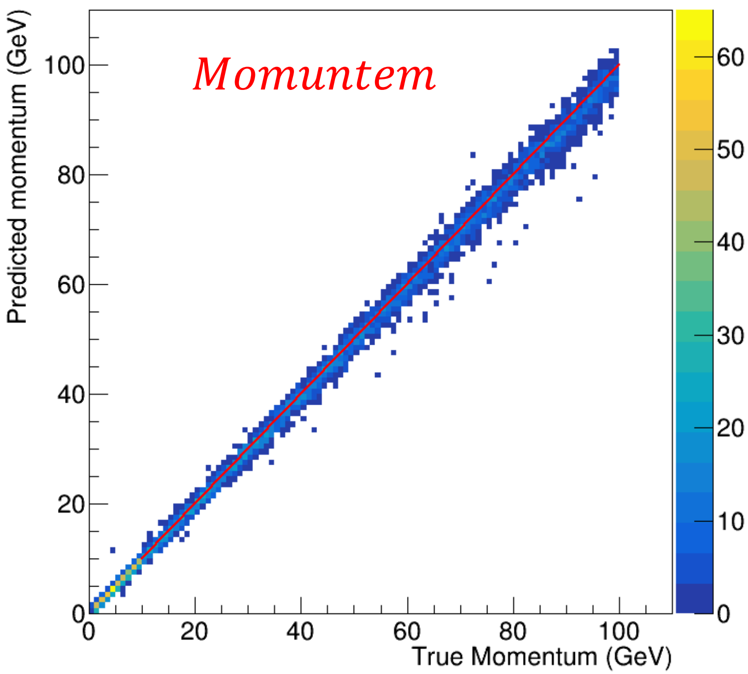
↓

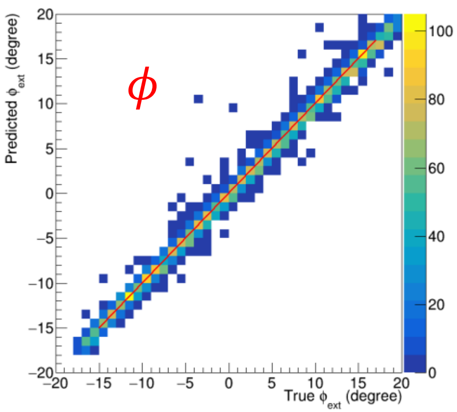
Concatenate(calo_energy)+Dense(3)

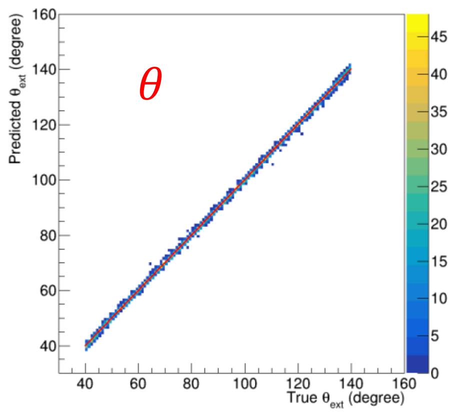
↓

Ouput (Mom, θ, ϕ)

Regressor architecture and performance (e^-)







Input(31×31×29)+ $\Delta Z^{pos}, \Delta Y^{pos}$, Z

Normalize

Conv3D(16, (5, 6, 6))+LReLU

3×{Conv3D(8, (5, 6, 6))+LReLU+Dropout(0.1)}

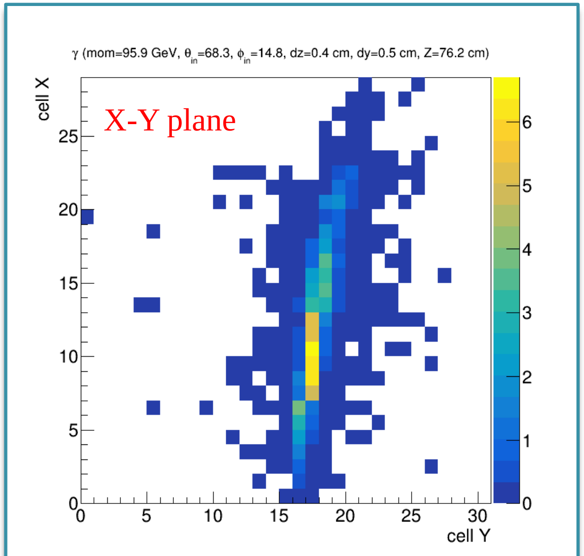
AveragePooling3D+Flatten

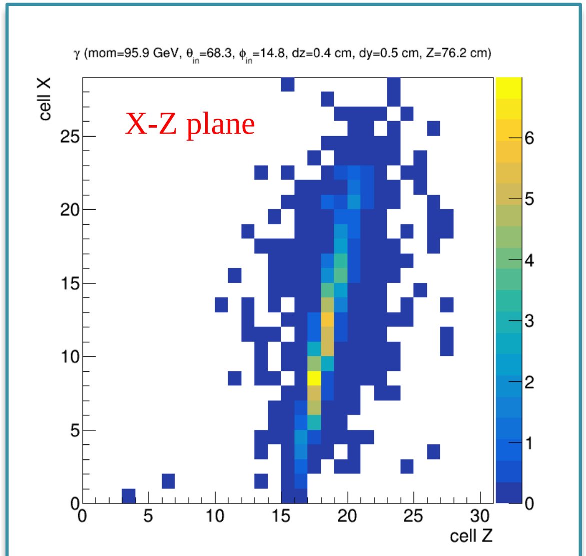
Concatenate(calo_energy)+Dense(3)

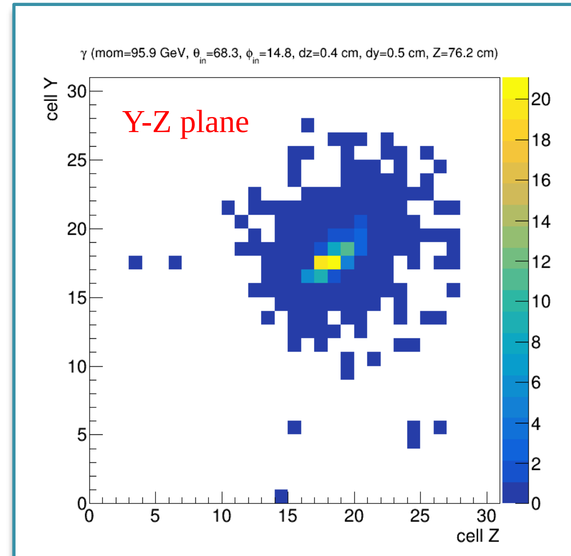
Ouput (Mom, θ, ϕ)

Event display

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

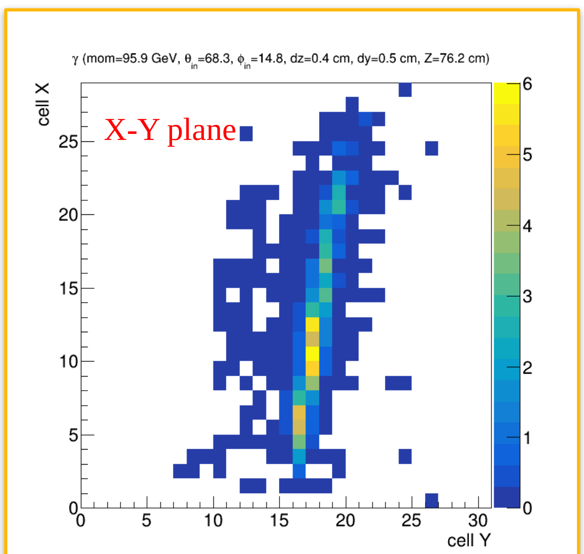


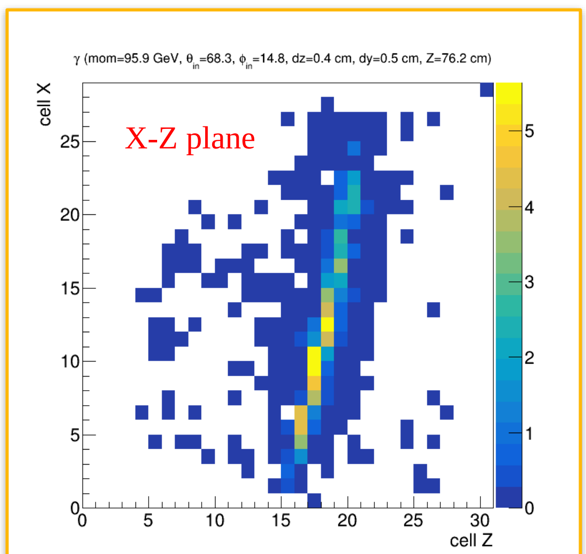


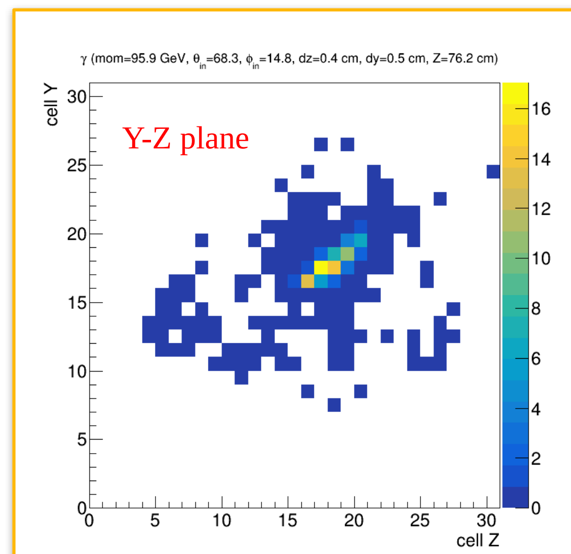


Geant4

GAN

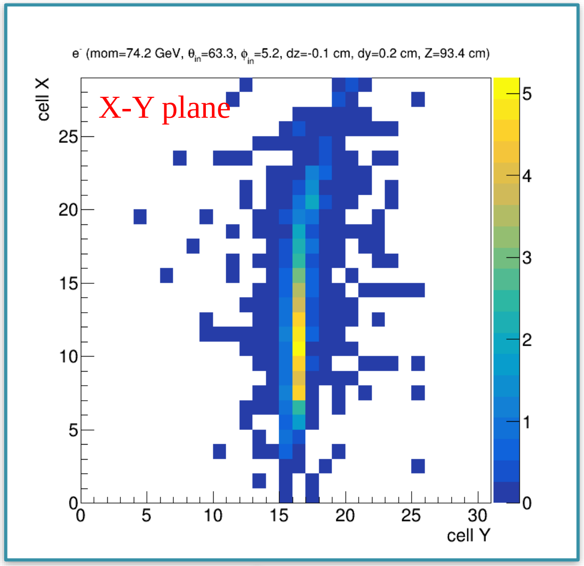


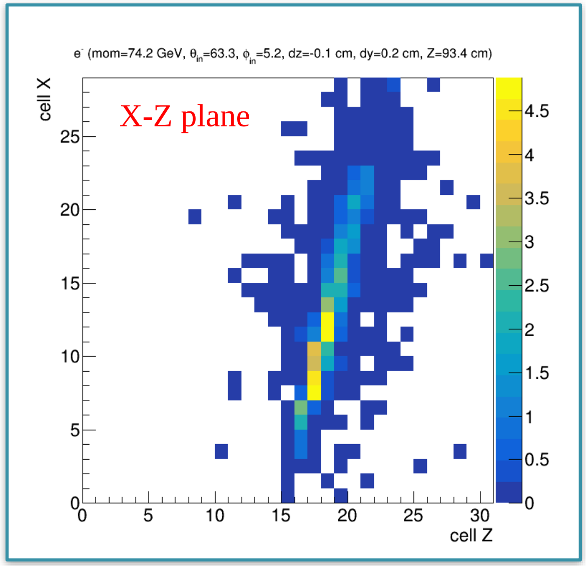


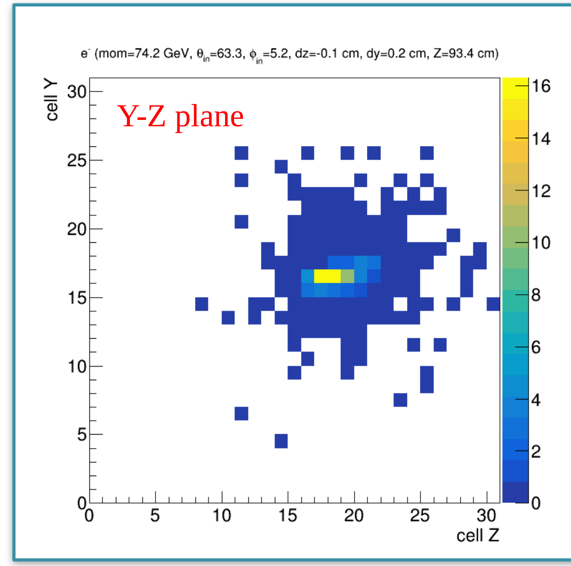


Event display of e^-

$e^-(\mathrm{Mom} = 74.2\ \mathrm{GeV}, \theta_{\mathrm{in}} = 63.3^{\circ}, \phi_{\mathrm{in}} = 5.2^{\circ},$
$\Delta Z^{\mathrm{Pos}} = -0.1\ \mathrm{cm}, \Delta Y^{\mathrm{Pos}} = 0.2\ \mathrm{cm}, Z = 93.4\ \mathrm{cm})$

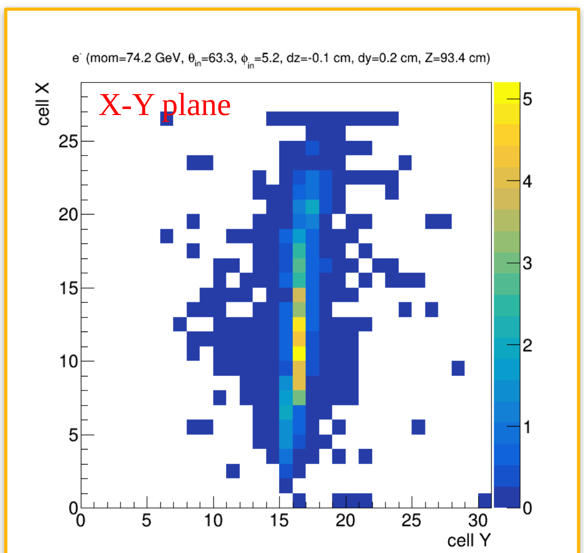


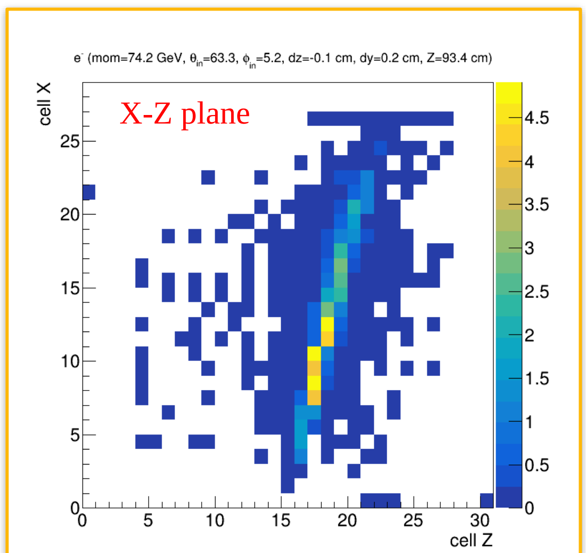


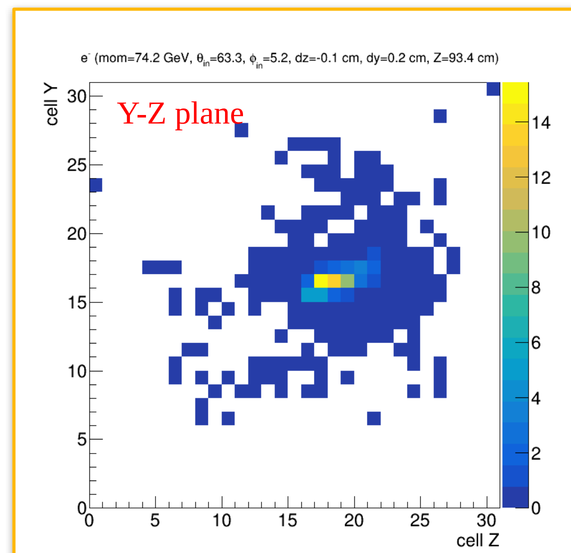


Geant4

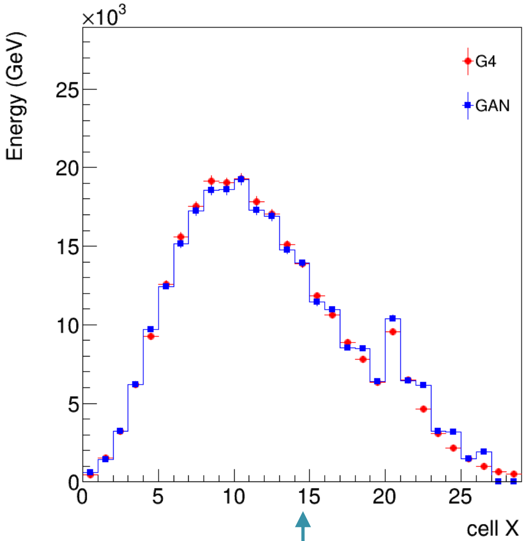
GAN

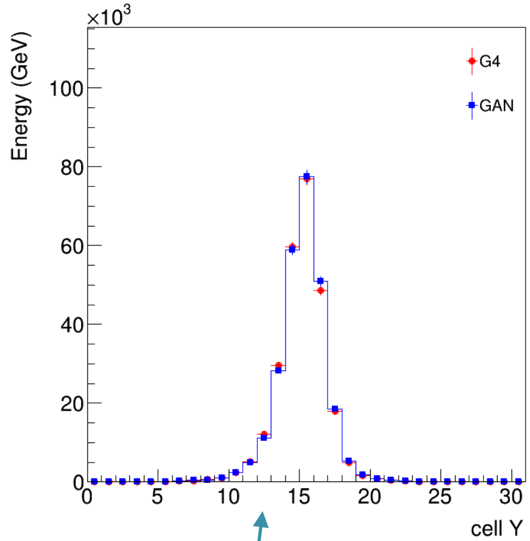


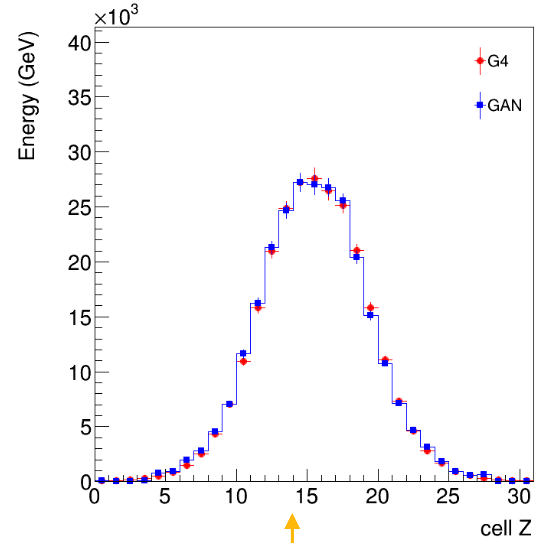




Some variables for e^- (cepc)







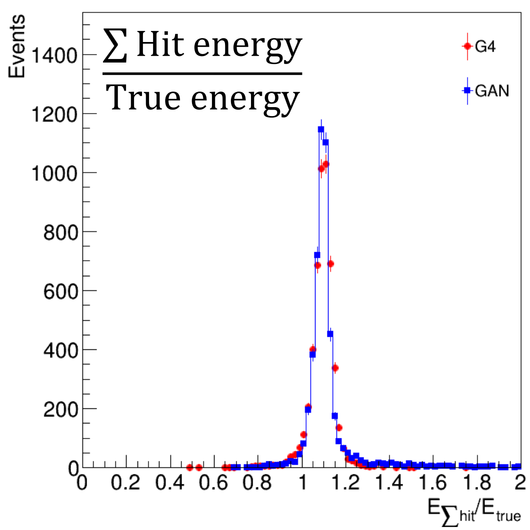
Energy deposited in X(layer) direction

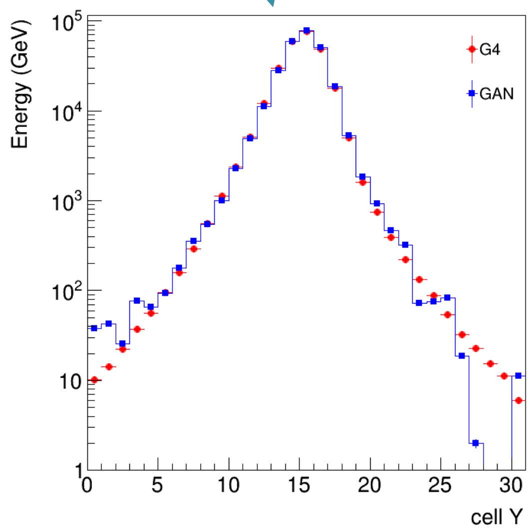
Energy deposited in Y direction

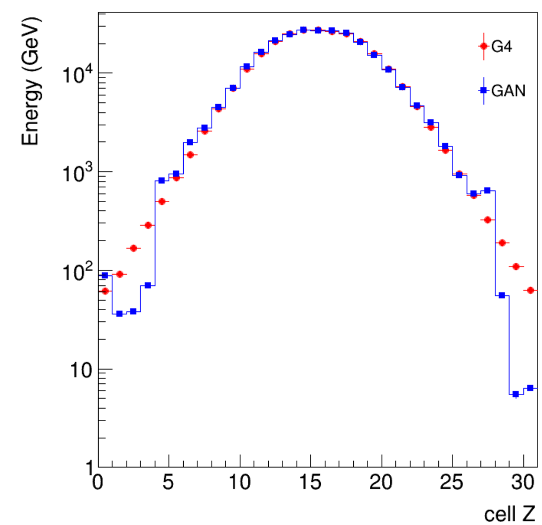
log scale

Energy deposited in Z direction

log scale





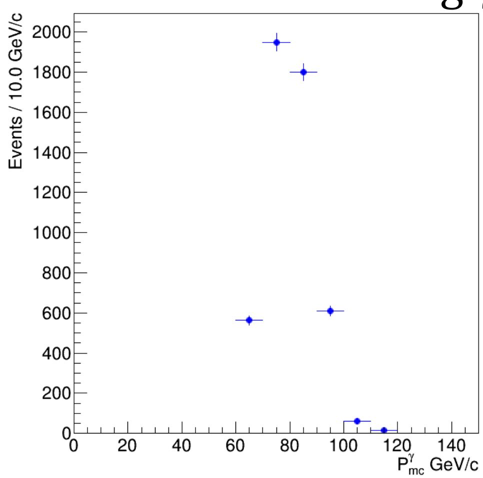


using mc samples

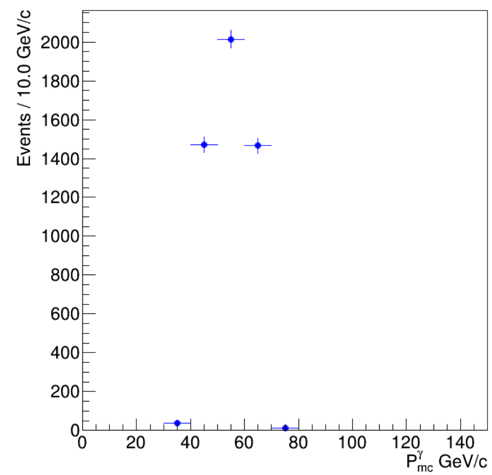
$e^+e^- \to Z(\nu\nu)H(\gamma\gamma)$

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

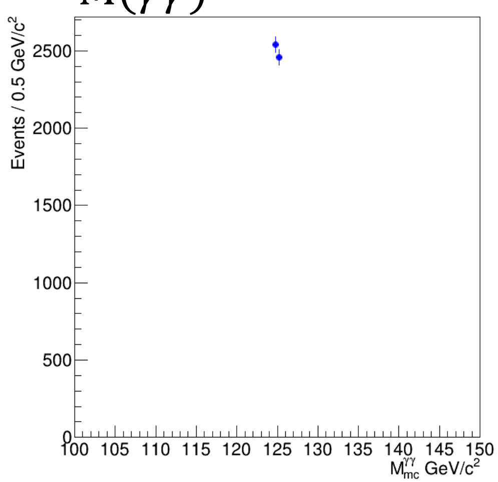
Momentum leading γ



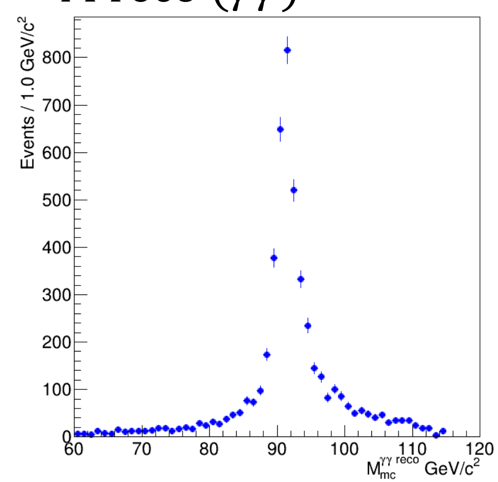
Momentum sub − leading γ



$M(\gamma\gamma)$



M reco $(\gamma\gamma)$

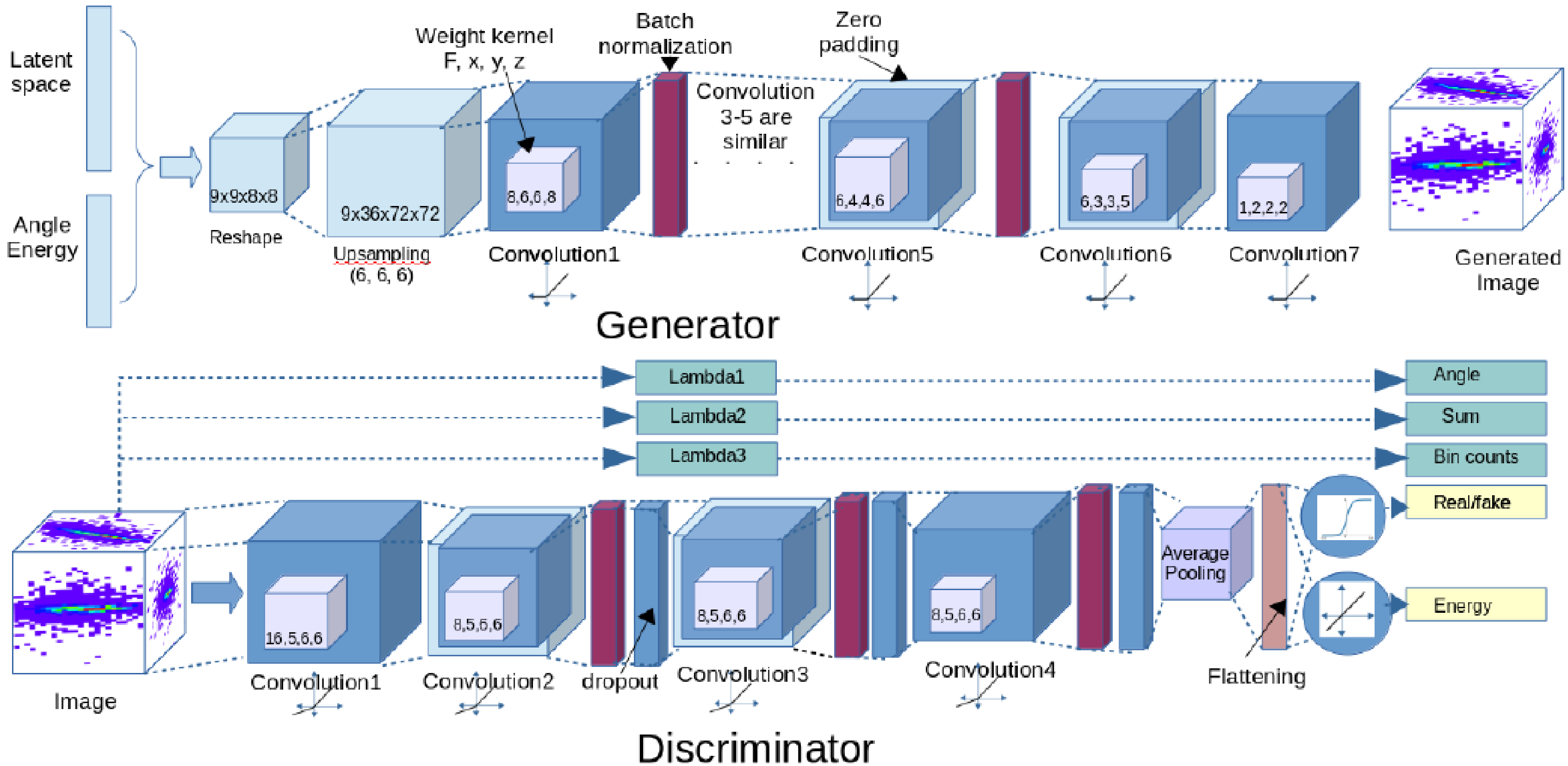


The model

3D convolutional Generative Adversarial Networks

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

Auxiliary regression tasks assigned to the discriminator



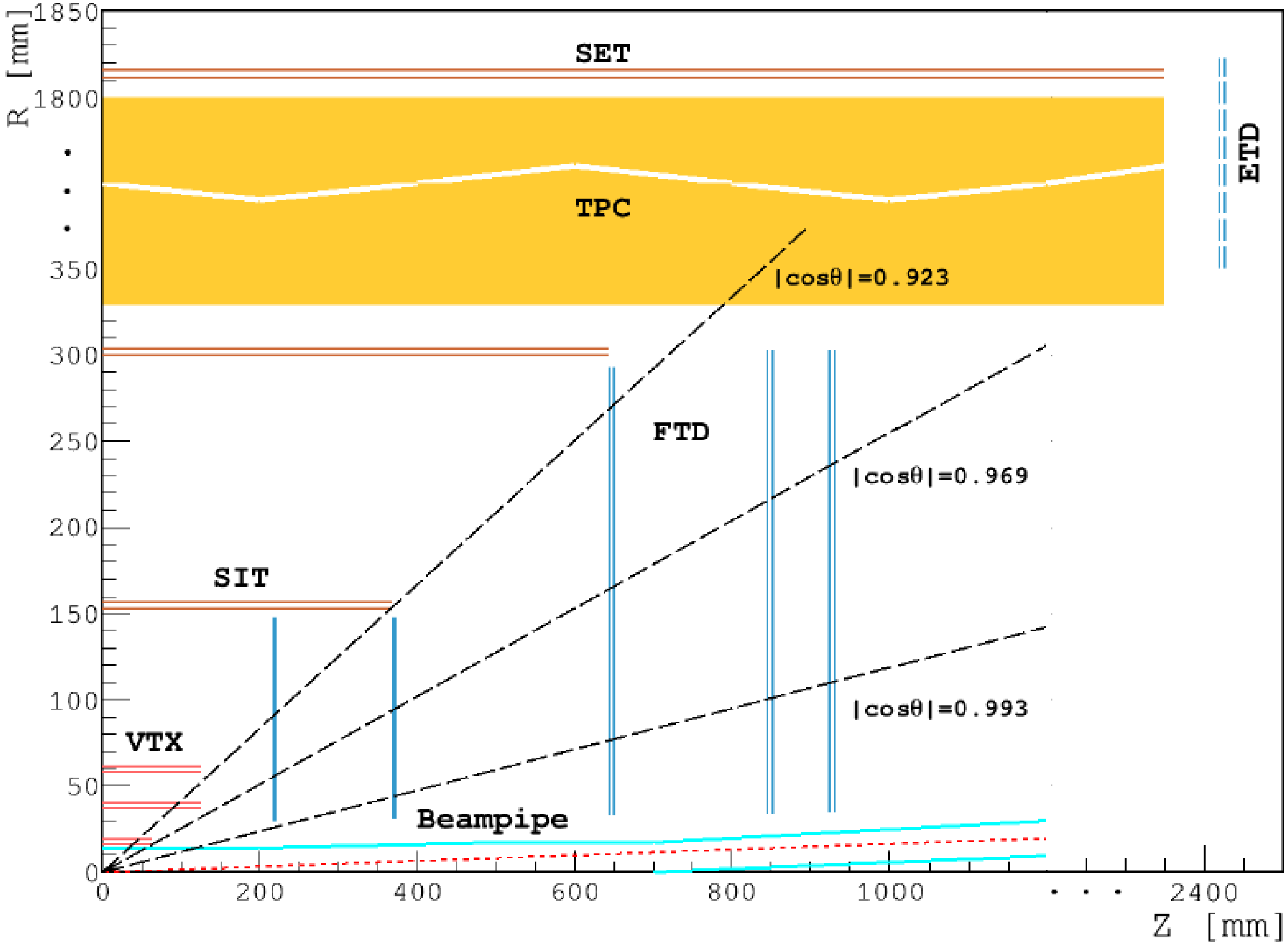
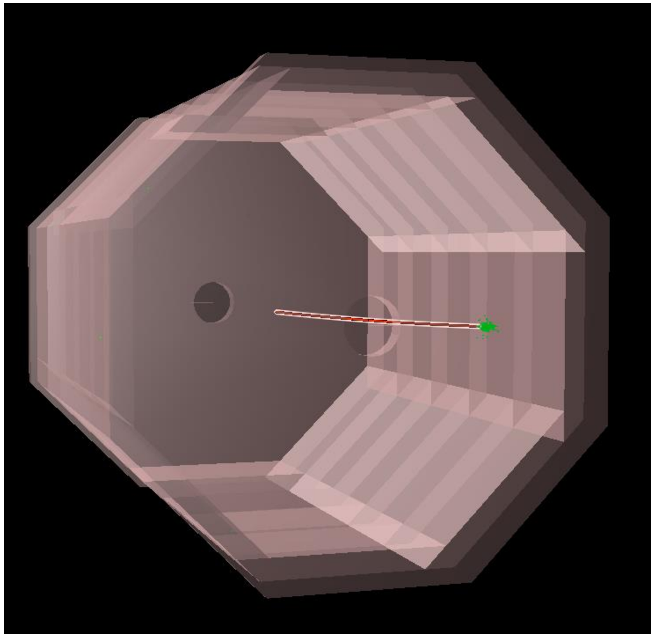
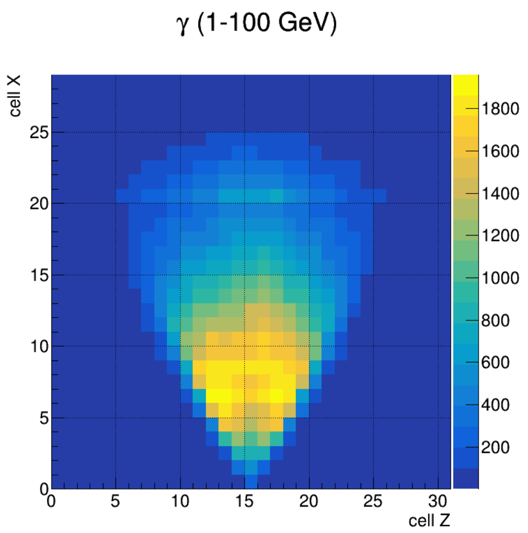


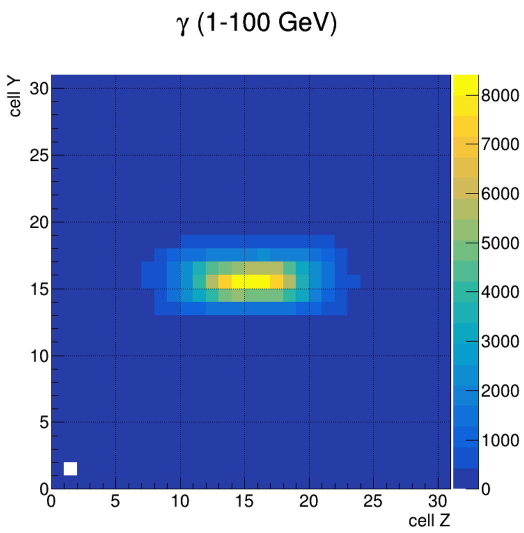
Figure 4.1: Preliminary layout of the tracking system of the CEPC baseline detector concept. The Time Projection Chamber (TPC) is embedded in a Silicon Tracker. Colored lines represent the positions of the silicon detector layers: red lines for the Vertex Detector (VTX) layers; orange lines for the Silicon 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.

Time estimation

- Simulation 10000 gamma with 50 GeV.

User time (seconds): 55422.35
System time (seconds): 96.96
Percent of CPU this job got: 98%
Elapsed (wall clock) time (h:mm:ss or m:ss): 15:36:11
Average shared text size (kbytes): 0
Average unshared data size (kbytes): 0
Average stack size (kbytes): 0
Average total size (kbytes): 0
Maximum resident set size (kbytes): 100688
Average resident set size (kbytes): 0
Major (requiring I/O) page faults: 2815
Minor (reclaiming a frame) page faults: 100938
Voluntary context switches: 56581
Involuntary context switches: 7696399
Swaps: 0
File system inputs: 661200
File system outputs: 4812024
Socket messages sent: 0
Socket messages received: 0
Signals delivered: 0
Page size (bytes): 4096
Exit status: 0

User time (seconds): 8711.46
System time (seconds): 8468.84
Percent of CPU this job got: 184%
Elapsed (wall clock) time (h:mm:ss or m:ss): 2:35:36
Average shared text size (kbytes): 0
Average unshared data size (kbytes): 0
Average stack size (kbytes): 0
Average total size (kbytes): 0
Maximum resident set size (kbytes): 4091284
Average resident set size (kbytes): 0
Major (requiring I/O) page faults: 10137
Minor (reclaiming a frame) page faults: 91926716
Voluntary context switches: 9498903
Involuntary context switches: 2390225
Swaps: 0
File system inputs: 24576
File system outputs: 4874656
Socket messages sent: 0
Socket messages received: 0
Signals delivered: 0
Page size (bytes): 4096
Exit status: 0