Performance of the negative Hadronic Calorimeter (nHCal) based on Simulations

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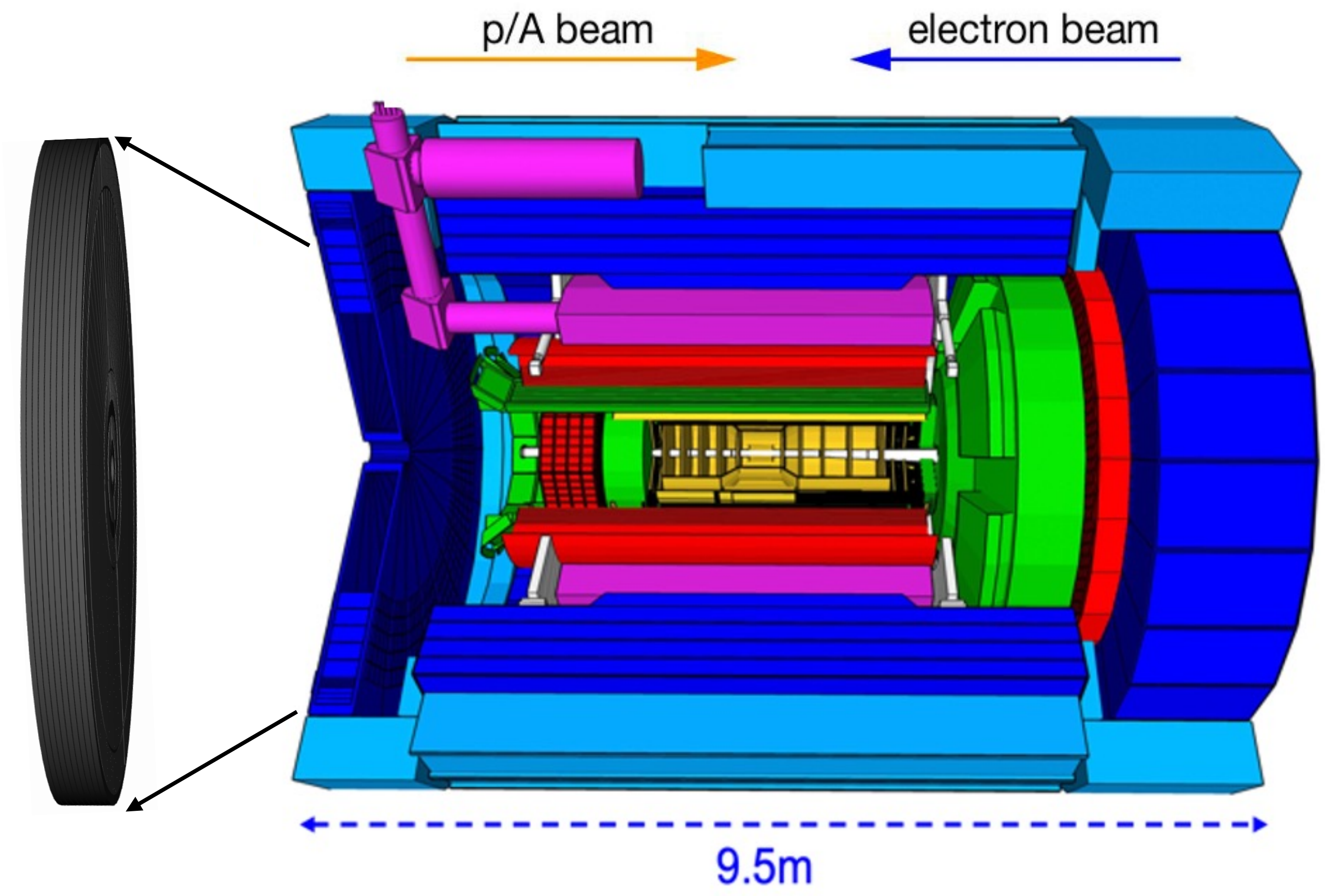
Outline

1. Design and requirements of negative hadronic calorimeter
2. Calibration
3. Clustering and Position Resolution
4. e/h response

The Negative (backward) Hadronic Calorimeter

- ❑ Sampling calorimeter with 10 alternating layers of
  - stainless steel 4 cm.
  - plastic scintillator 4 mm. (Kuraray SCSN-81)
- ❑ Total of 44 cm. (~ 2.4 λ_0)
- ❑ Tail catcher for the high-resolution electromagnetic calorimeter in electron identification.
- ❑ Characterize the jet kinematics at small Bjorken *x*.

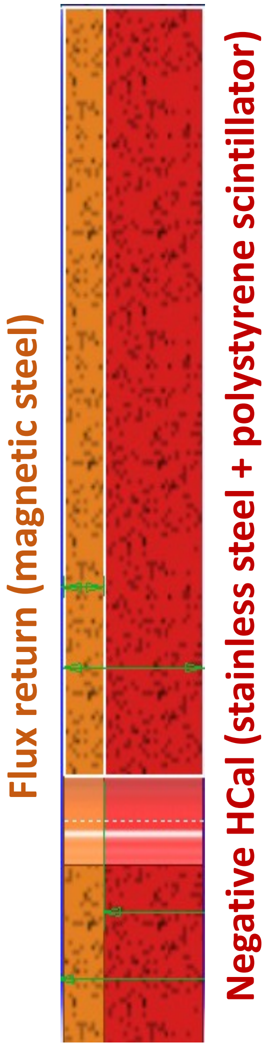


negative $\eta (or\ z)$
<u>backward</u>

positive $\eta (or\ z)$
<u>forward</u>

$$\eta \equiv -\ln\left[\tan\left(\frac{\theta}{2}\right)\right],$$

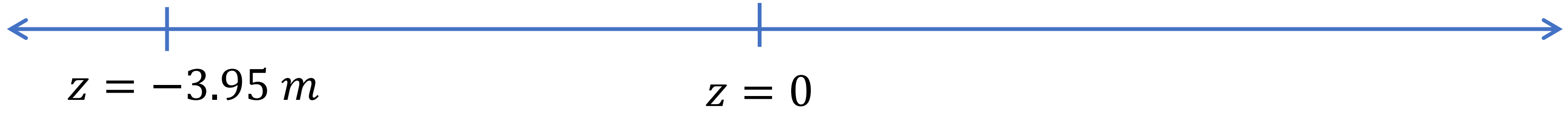
The Negative Hadronic Calorimeter - Design

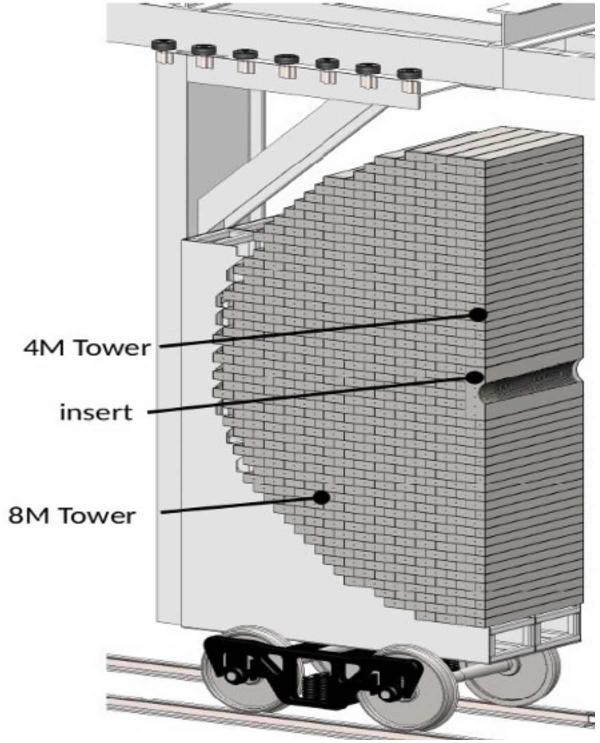


- Absorber : non-Magnetic Stainless Steel
  (no interference with the solenoid flux return)

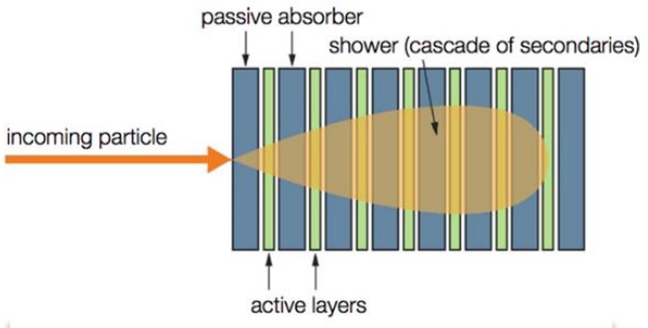
- Sampling : Plastic scintillator tiles
  (10 cm×10cm segmentation: following LFHCAL design)

- Signal readout:
  - Scintillator light guided by WLS fibers.
  - SiPM used for light collection.





LFHCAL schematic

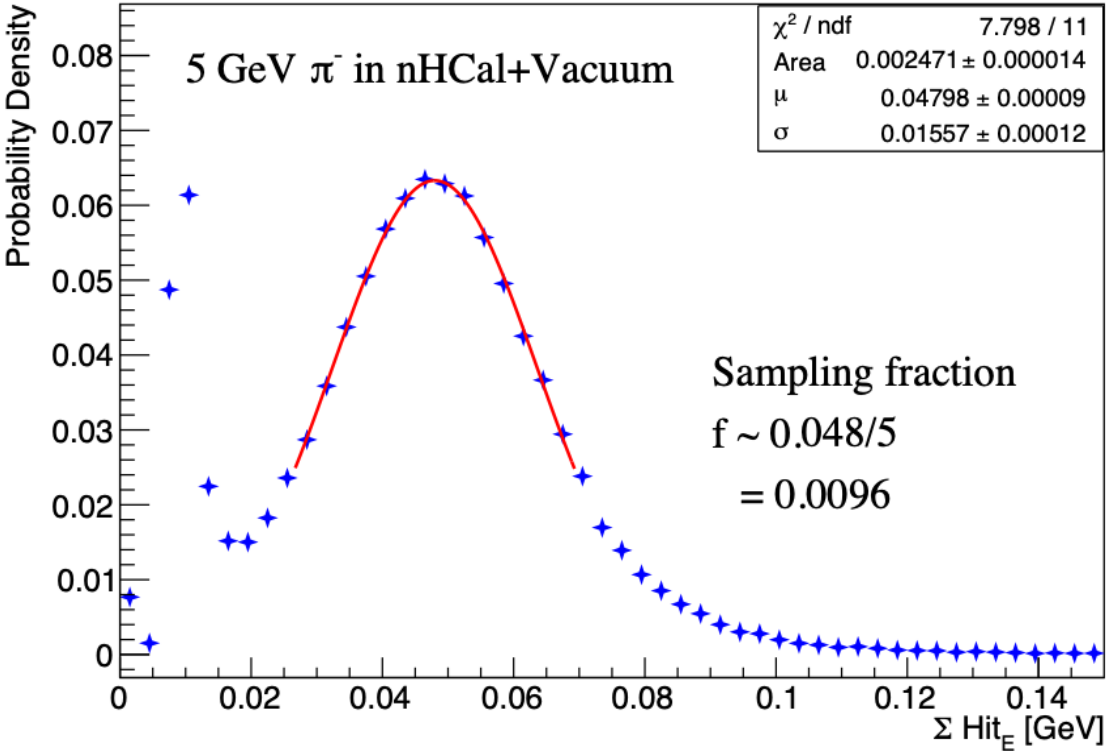


Calibration – Sampling Fraction

- ☐ nHCal is calibrated using π^-
- ☐ 1 π^- /event, 100k events
  and p = 5 GeV/c in nHCal+Vacuum

Simulations performed using DD4hep.
Sampling fraction: $f = \langle \Sigma\, \mathrm{Hit}_{\mathrm{Energy}} \rangle / \pi^-_{\mathrm{Energy}}$

$f = 0.04798/5.00196$
$= 0.009592$
$\sim$ 0.0096 +/- 0.0031



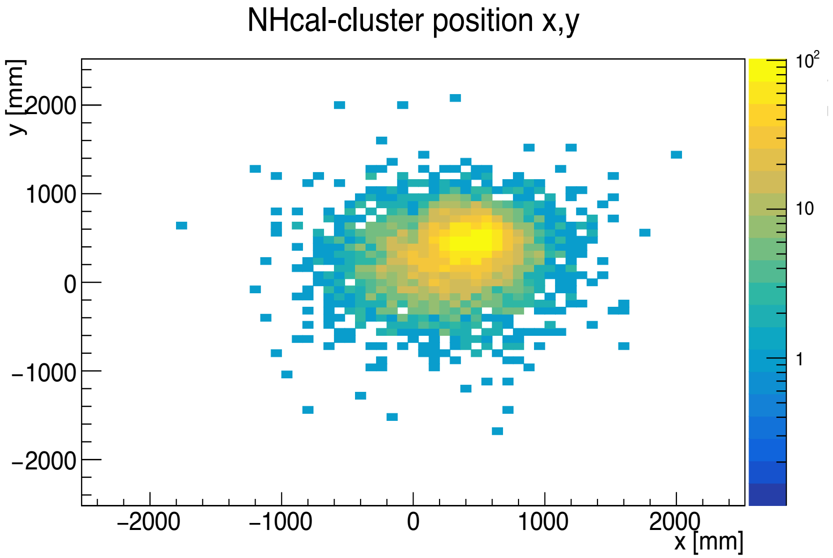
NAME	VALUE	ERROR
Area	0.002471	0.000014
Mean	0.04798	0.00009
Sigma	0.01557	0.00012

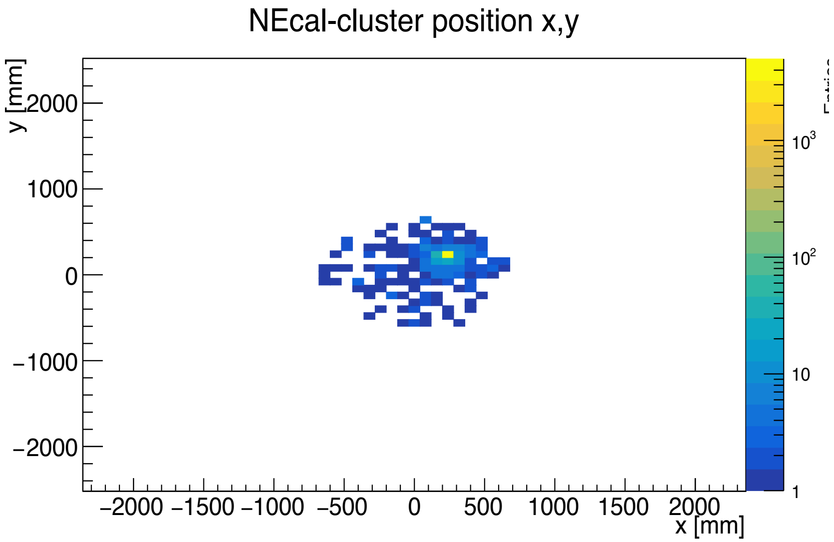
Distribution of hit energy sum fitted with gaussian distribution

Position Resolution Study

Objective **:** *Use clusters to investigate the angular resolution for neutron shower reconstruction.*

- ☐ 1 neutron/event and p = 5 GeV
- ☐ $\theta = 170^\circ$ (**2.967 rad)** and $\phi = 45^\circ$ **(0.785 rad)**

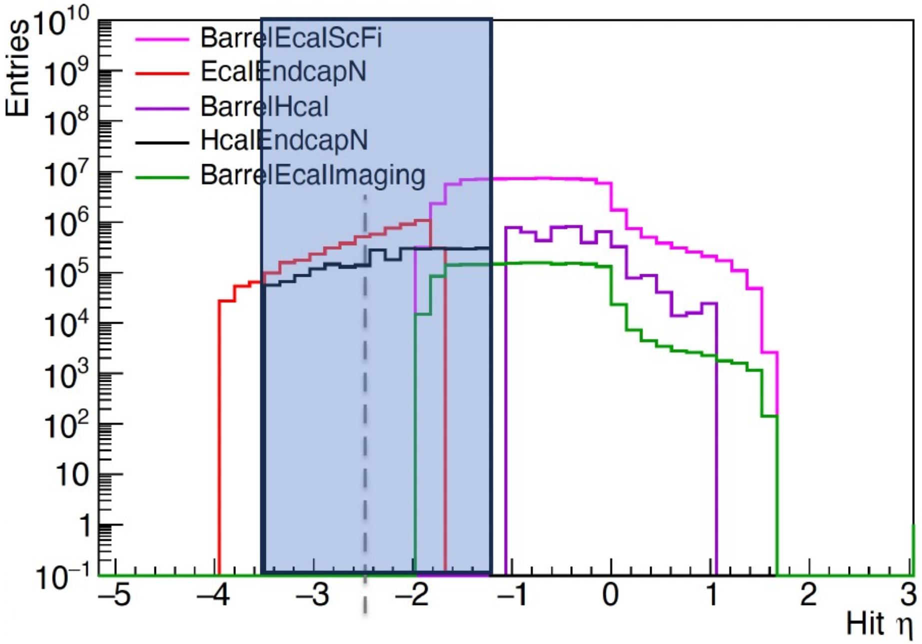

NHcal-cluster position x,y

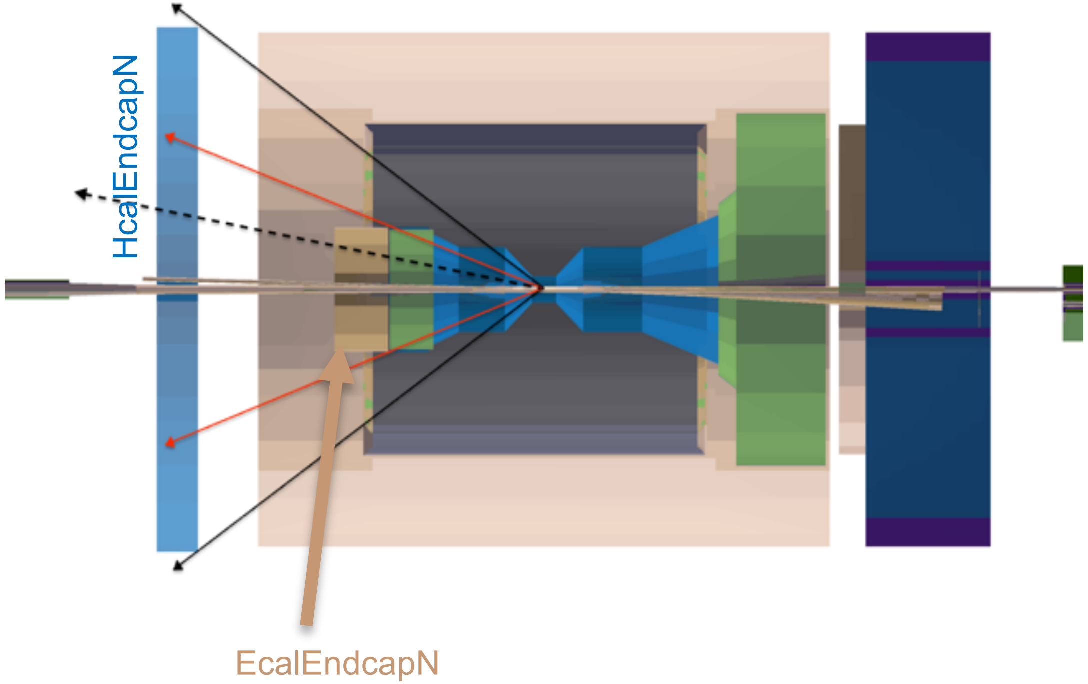

NEcal-cluster position x,y

Will perform a combined measurement with nHCal and nEMCal.

Energy Sharing

❑ nEMCal + nHCal response to π^-



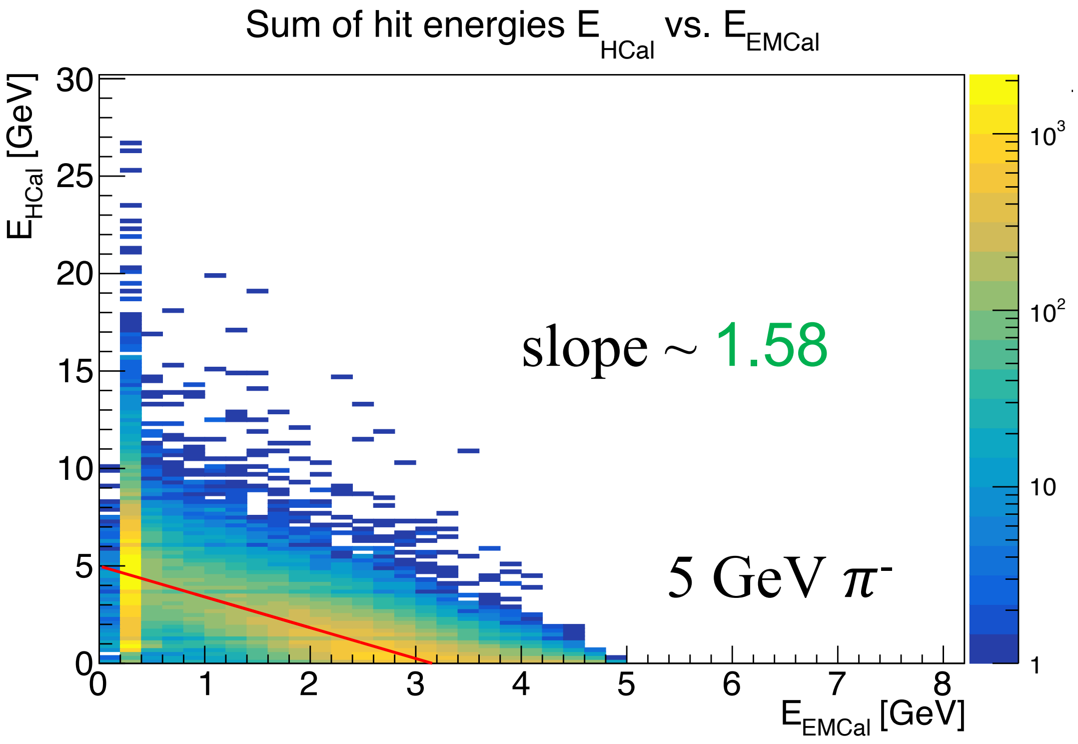


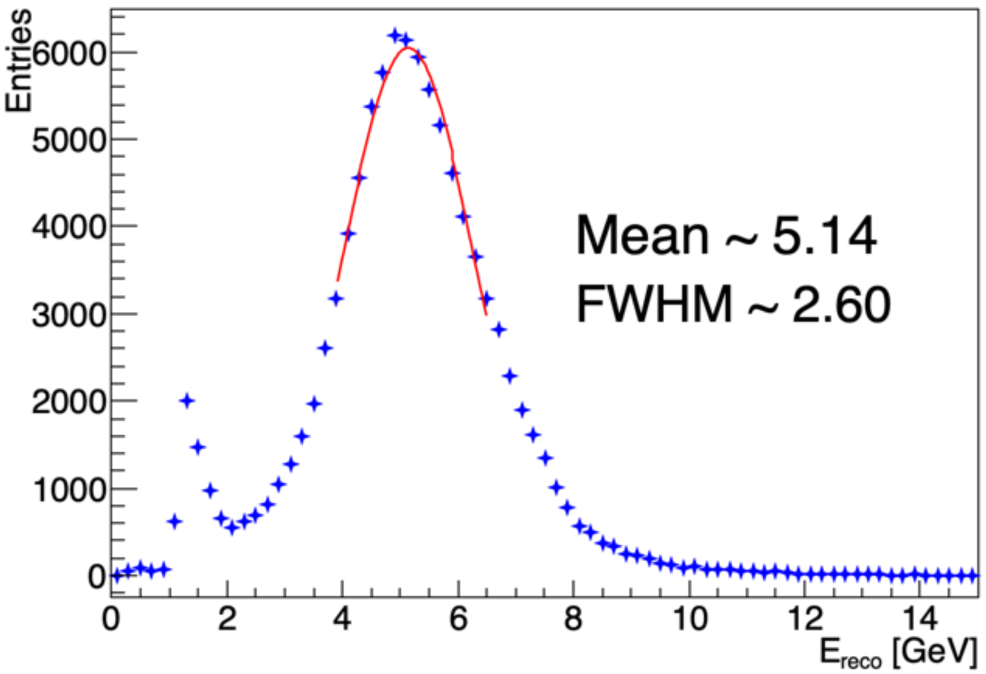
- ❑ Acceptance of nHCal: **$-3.5 < \eta < -1.25$**

Significant overlap in acceptance with the backward (or negative) Endcap EMCal

Energy Sharing

- ☐ 1 π^- /event and p = 5 GeV
- ☐ Fitted a linear function to E_{HCal} (corrected with sampling fraction f) vs. E_{EMCal} histogram to extract the energy sharing parameters.



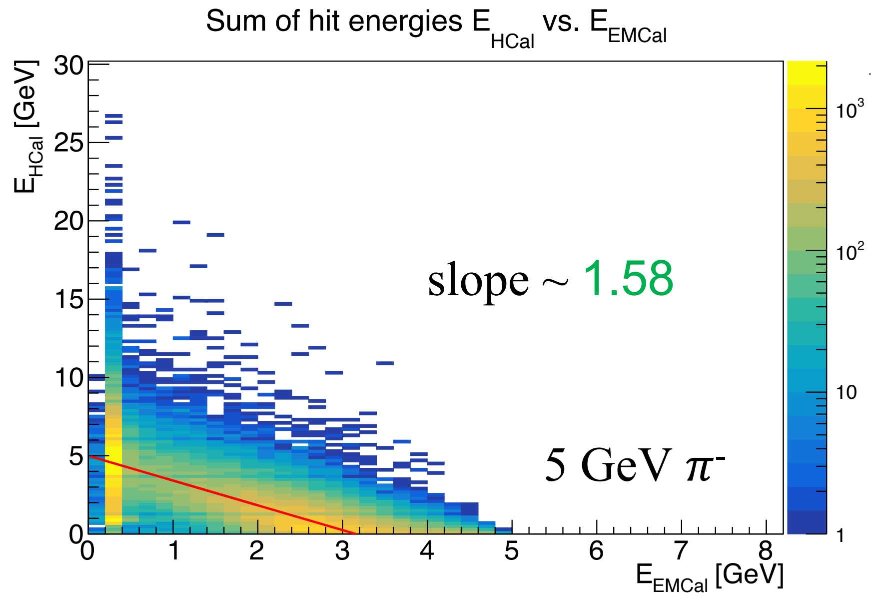


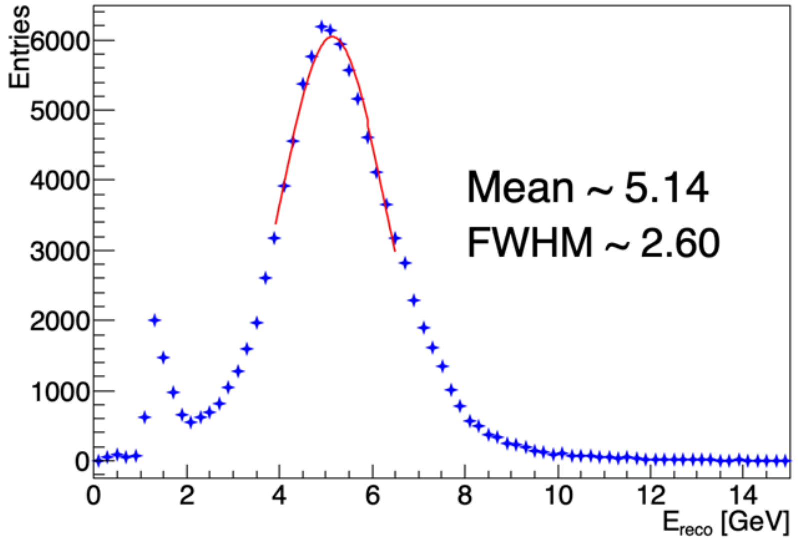
$$\boxed{E_{reco} = mE_{EMCal} + E_{HCal}} \quad ; m = 1.58$$

Position Resolution Study – Recombining Clusters

Energy Reconstruction

$$E_{reco} = mE_{EMCal} + E_{HCal}$$



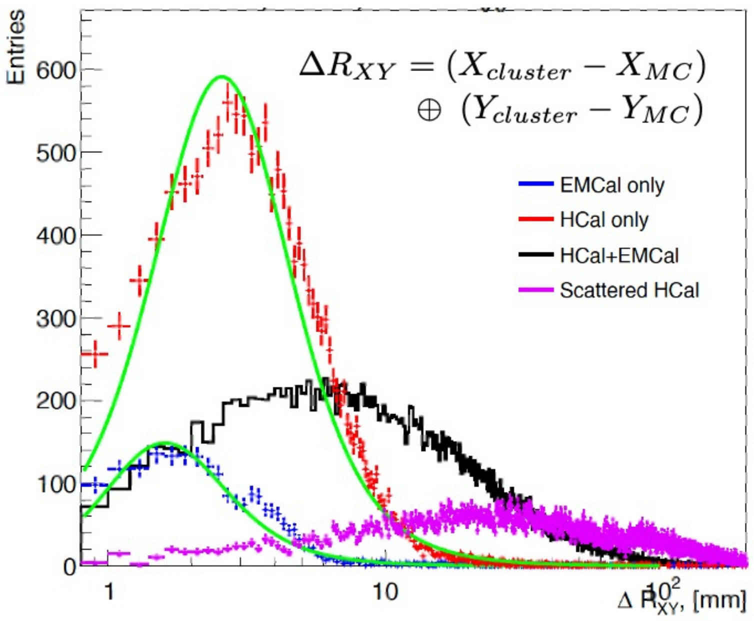


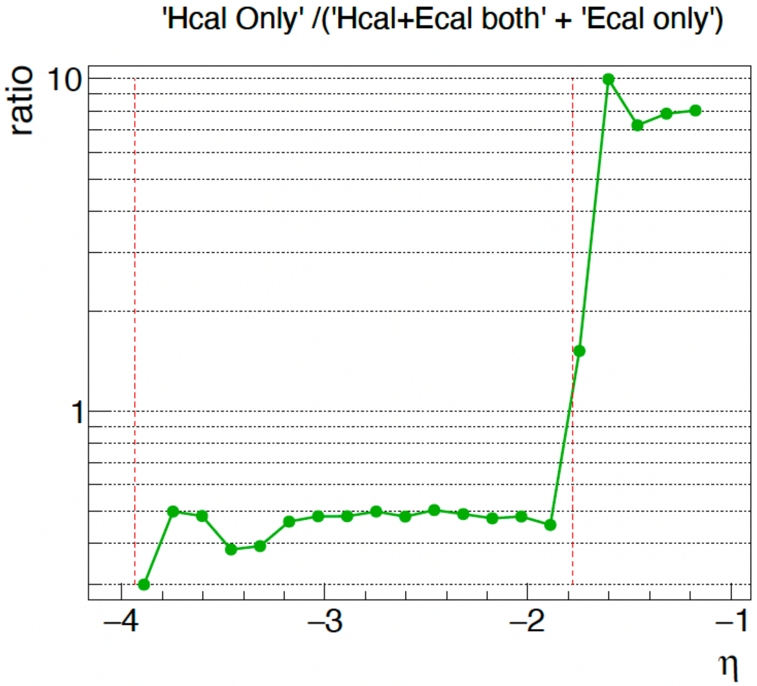
EMCal and HCal clusters are combined with energy weights to have a combined angular coordinate measurement.

$$\Theta_{reco} = (w_{EMCal} * \Theta_{EMCal}) + (w_{HCal} * \Theta_{HCal})$$
$$\phi_{reco} = (w_{EMCal} * \phi_{EMCal}) + (w_{HCal} * \phi_{HCal})$$

$$w_{EMCal} = \frac{m*EEMC_{al}}{E_{reco}} \; ; \; w_{HCal} = \frac{E_{Hcal}}{E_{reco}}$$

Position Resolution Study - Resolution

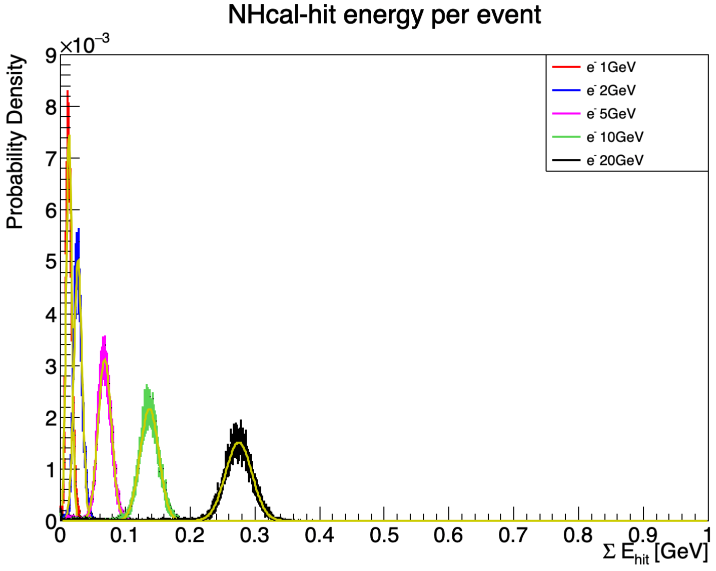


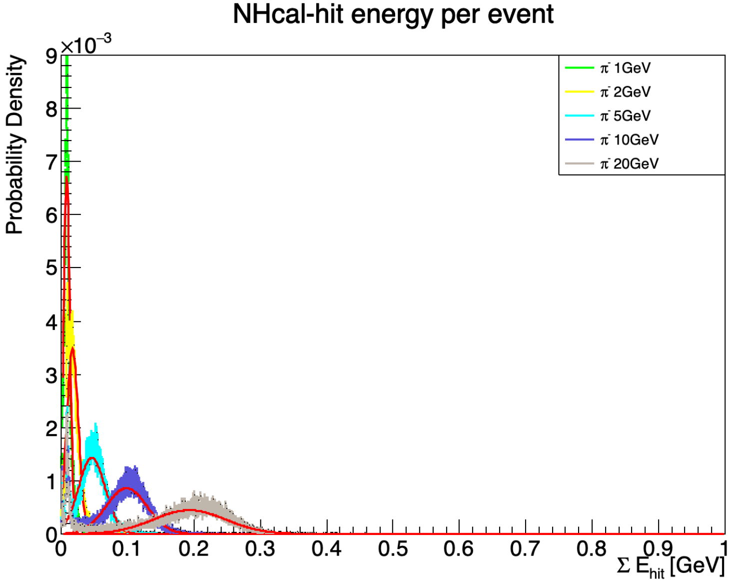


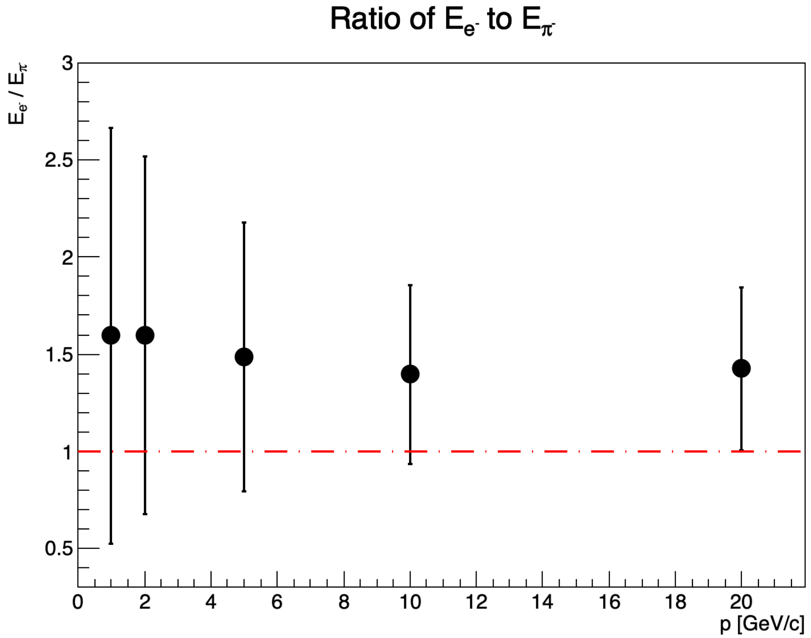
❑ ~ 68% of neutrons scatter in EEEMCal which might fall out of a jet reconstruction cone. This might be an issue for jet energy reconstruction.

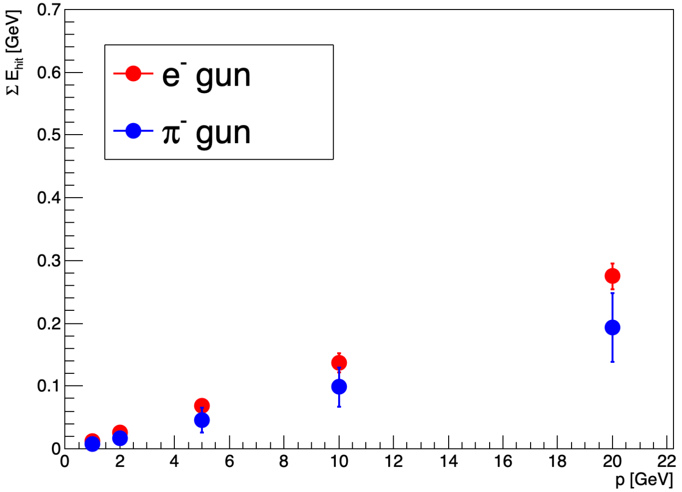
❑ Scattering in EEMCal affects the ΔR_{XY} resolution.

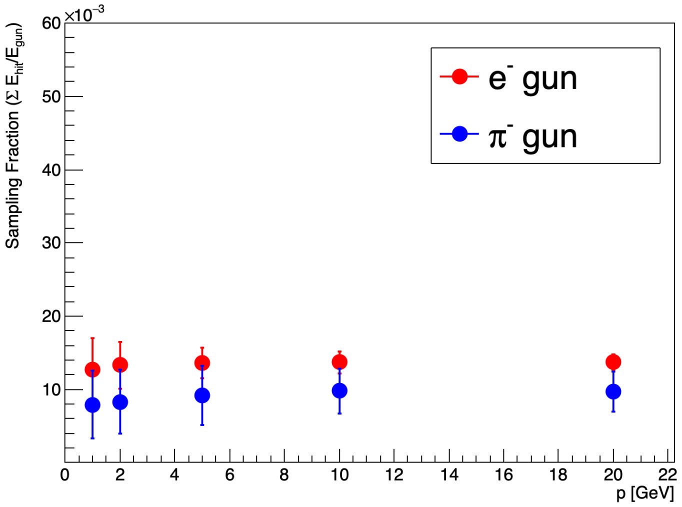
e/h response study







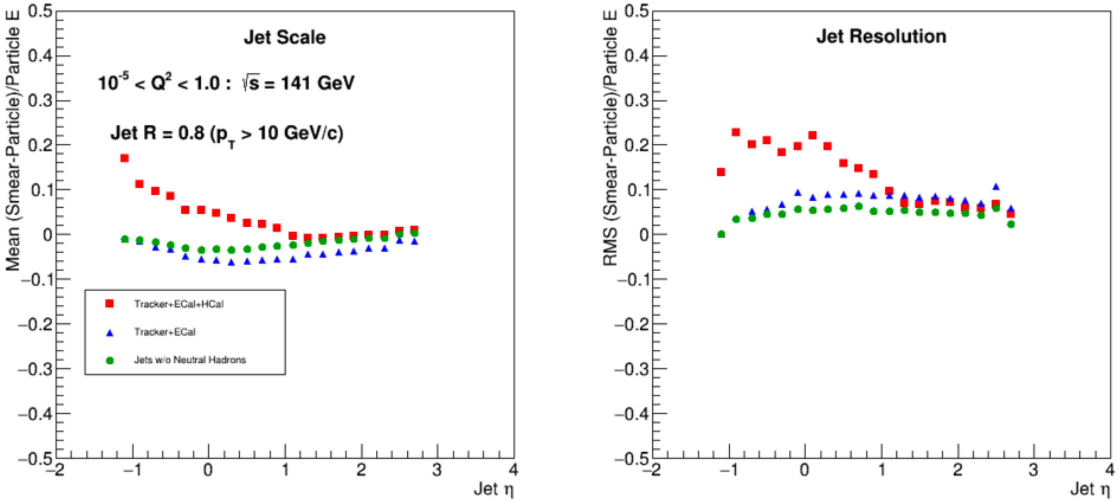




Two-Particle Position Resolution Study

Objective *: Use clusters to physically isolate neutron/pion shower reconstruction.*

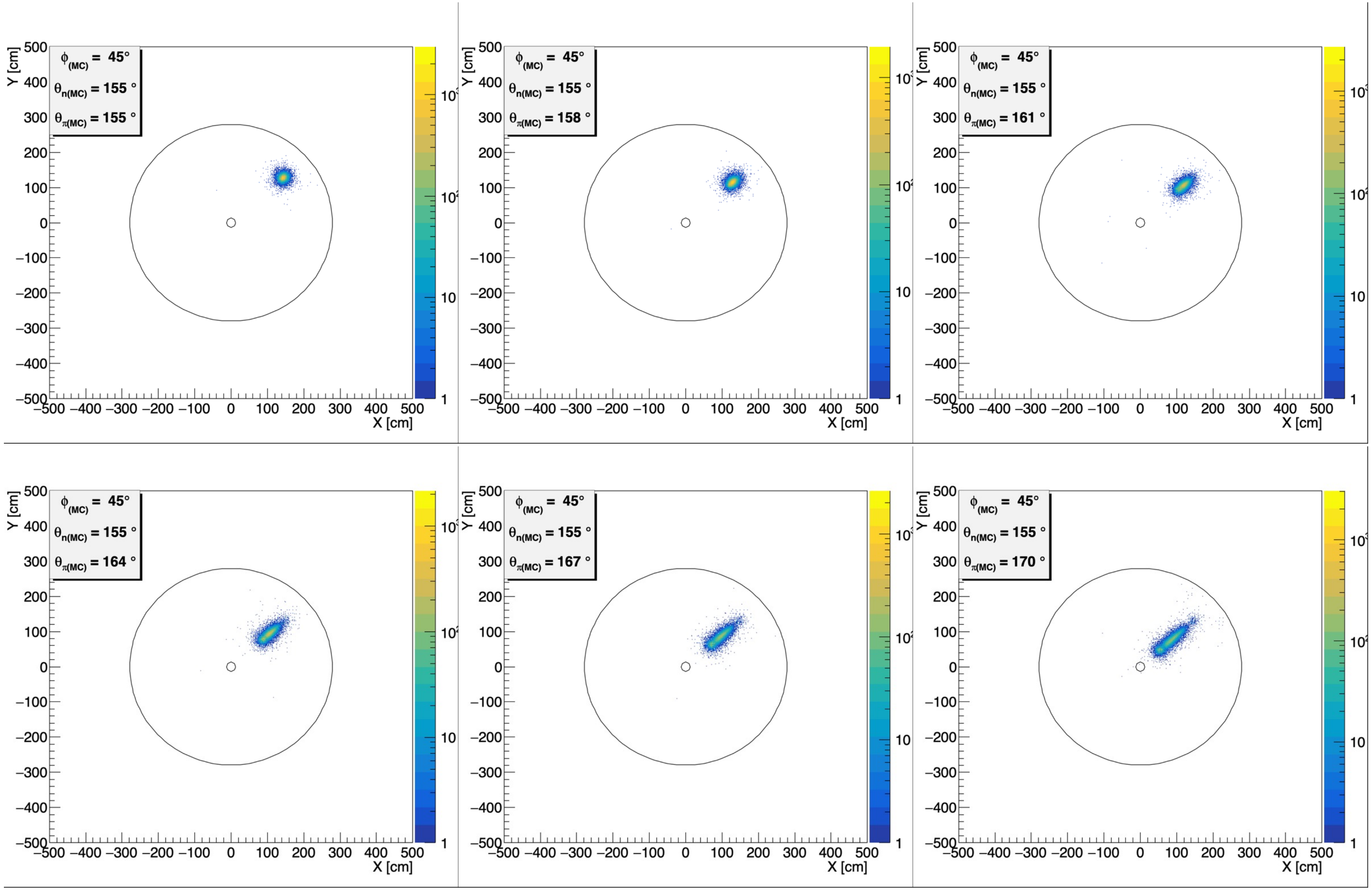
- ☐ $(1\,n + 1\,\pi^-)$ / event. ---- *Standalone ddsim*
- ☐ $\varphi = 45^\circ$
  - $\theta_n = 155^\circ$ ($\eta = -1.51$) ------ *fixed*
  - $\theta_\pi = 155^\circ$ ($\eta = -1.51$), 158° ($\eta = -1.64$), 161° ($\eta = -1.79$), 164° ($\eta = -1.96$), 167° ($\eta = -2.17$), 170° ($\eta = -2.44$)



- ☐ Select jets without a neutral hadron.
- ☐ Use HCal as a neutral hadron veto.
- ☐ <u>This neutral hadron veto capability depends critically on the ability to physically isolate individual showers within the calorimeter</u> and match them to a charged particle track to select clusters arising from long-lived neutral hadrons.

EIC Yellow Report

Cluster Positions (local xy)



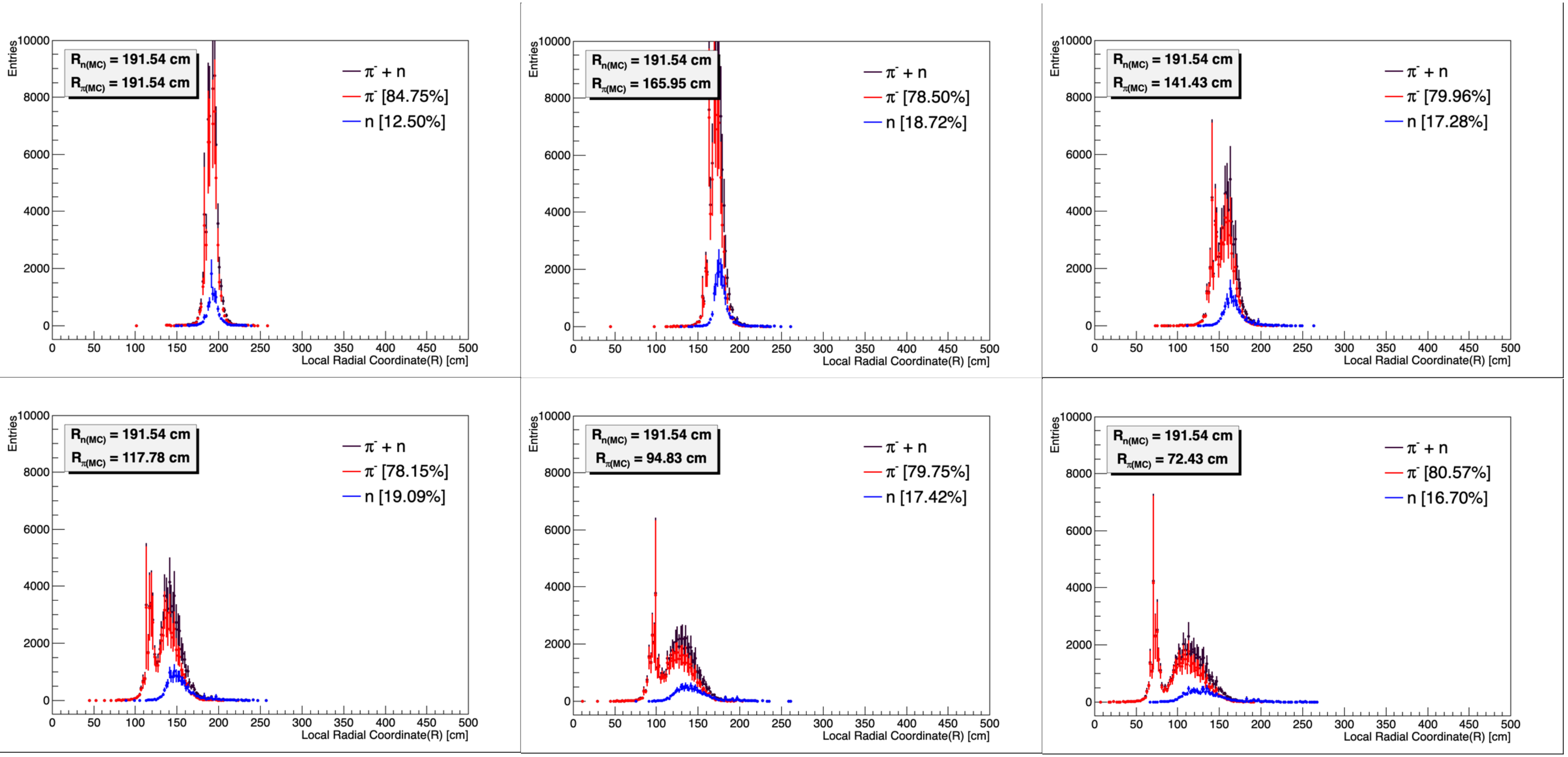
Cluster (x,y) are shown along with simulated angular coordinates

p = 1 GeV/c

[neutron showers in outer region; pion showers in inner region]

Distributions are becoming more smeared as (θ_π - θ_n) increases…

Cluster Radial Coordinates



Percentages are based on ClusterMCParticle associations

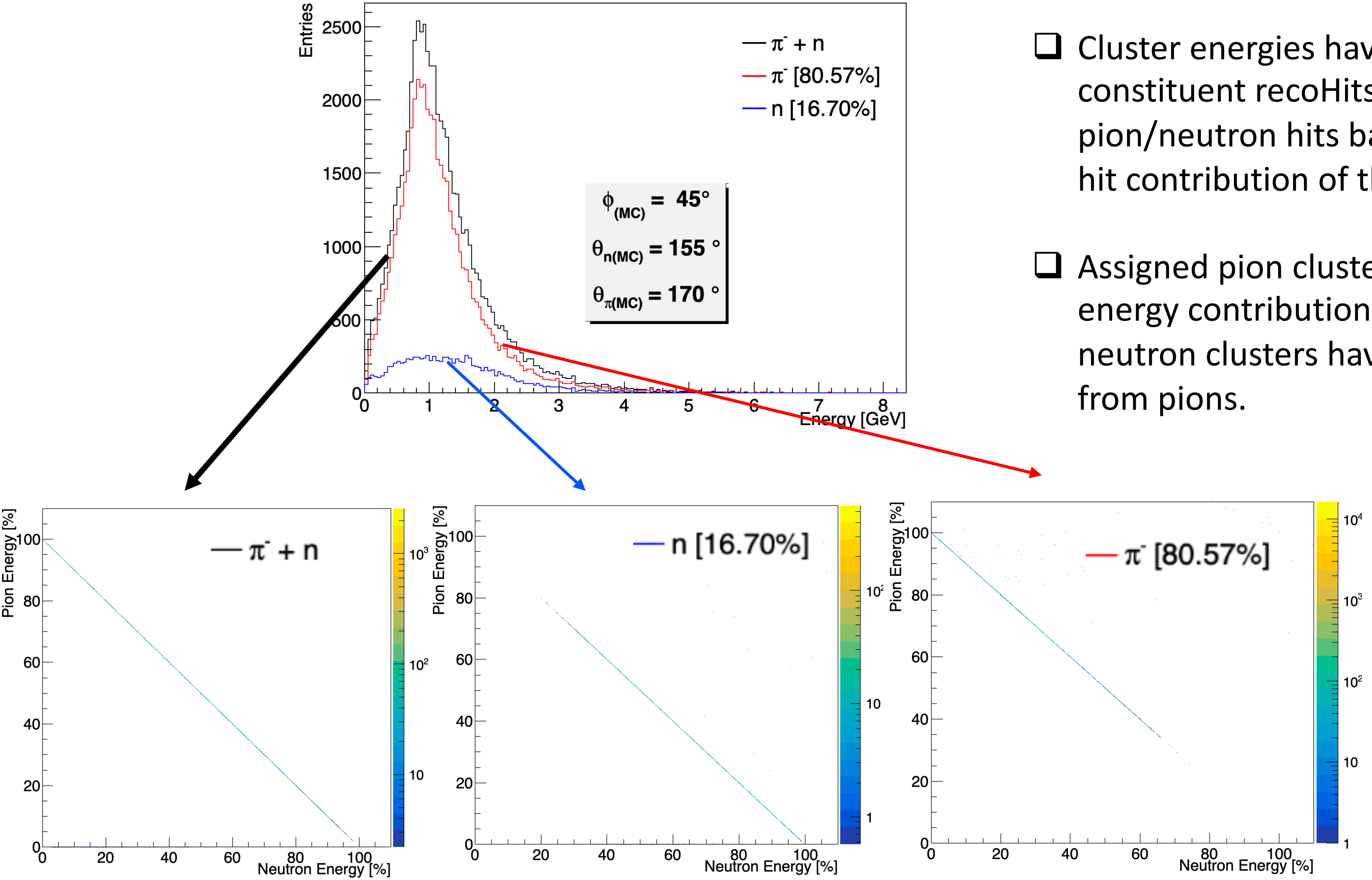
Neutron Clusters start to shift inwards as $(R_n - R_\pi)$ increases

~ 80% of the clusters associated with pions

~ 20% of the clusters associated with neutrons

p = 1 GeV/c

Cluster Reconstruction



- Cluster energies have been traced back to the constituent recoHits which were tagged as pion/neutron hits based on the most energetic hit contribution of the mapped simHit.
- Assigned pion clusters have on an average 14% energy contribution from neutron recoHits and neutron clusters have 36% energy contribution from pions.

Summary

- Work in progress.
- Sampling fraction of the detector has been determined.
- Energy reconstruction from a combined measurement from EEEMCal and nHCal has been done.
- Position resolution was tested with neutrons using backward HCal and EMcal as a combined system.
- Scattering in EEEMCal affects the position resolution.
- A first-look study at n-π position resolution study has been done. Further studies include energy dependence and charged cluster correction

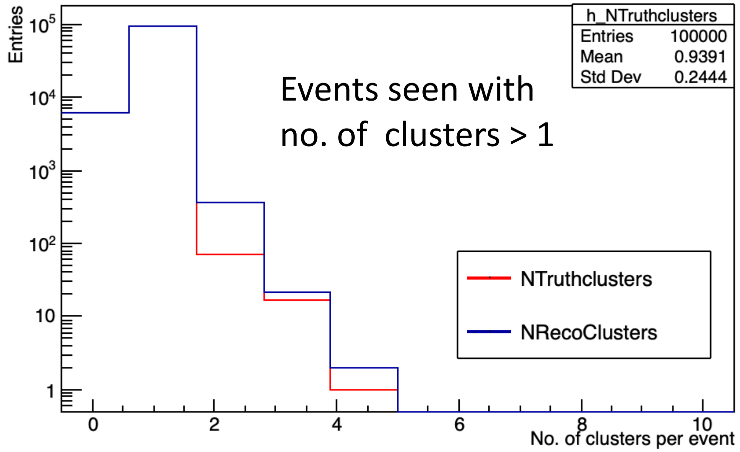
Thank You

Backup

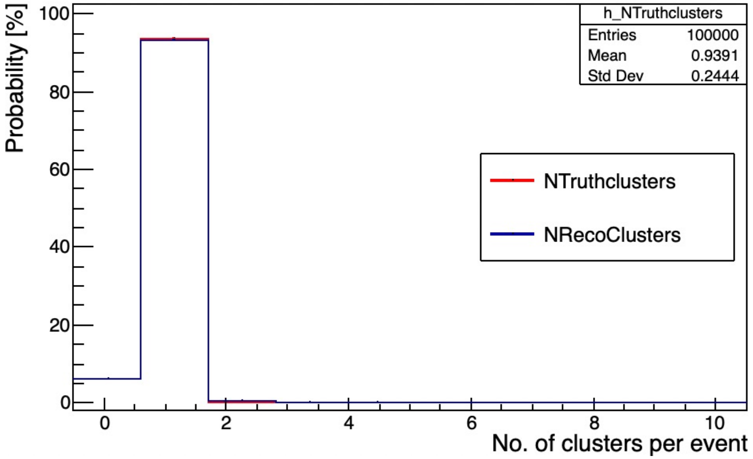
Hit and Cluster Positions

☐ 1 neutron/event, 100k events and p = 5 GeV

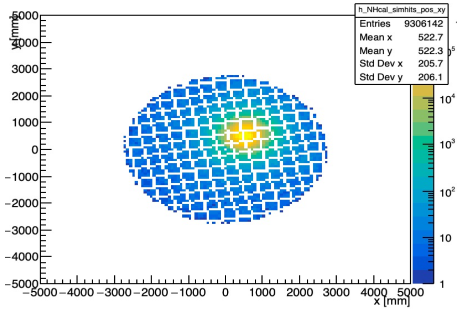
☐ θ = 170◦ and φ = 45◦



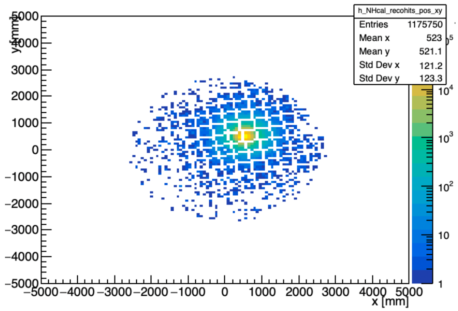
Events seen with no. of clusters > 1



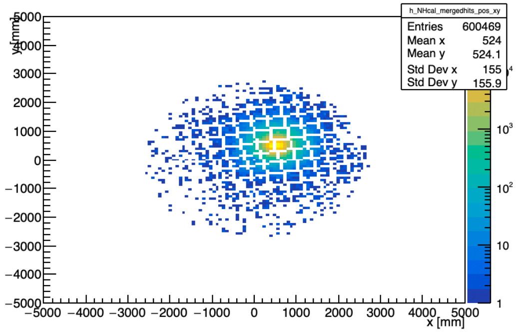
Simulated Hits



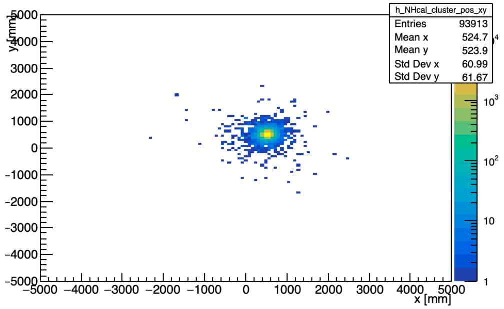
Reconstructed Hits



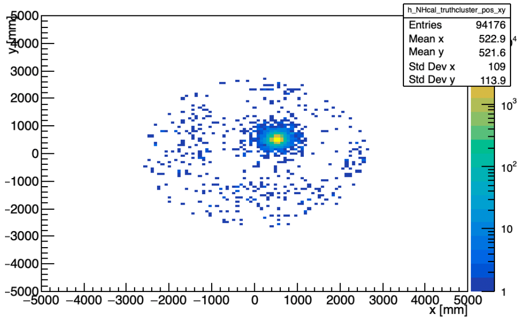
Merged Hits



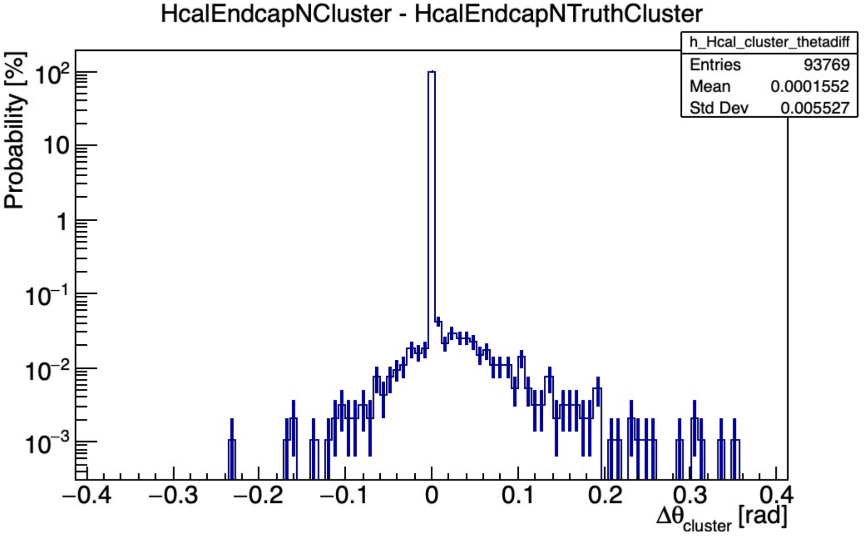
Reconstructed Clusters (Island Clustering)

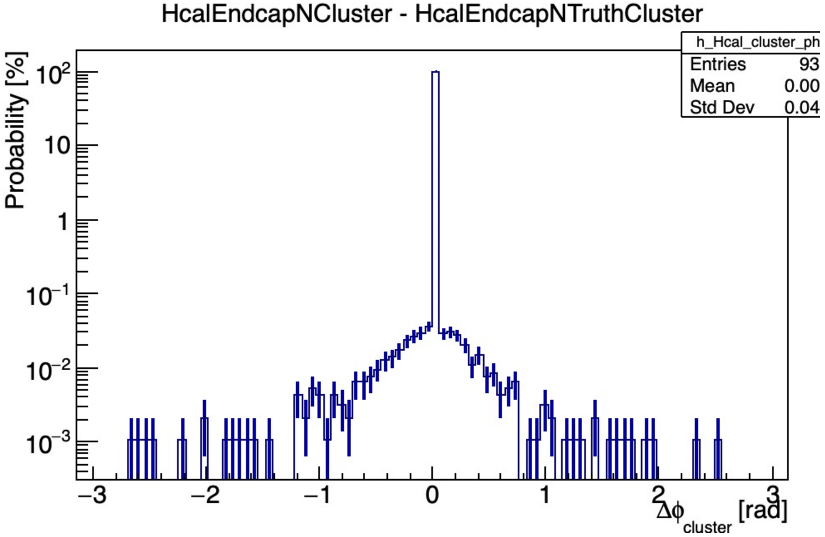


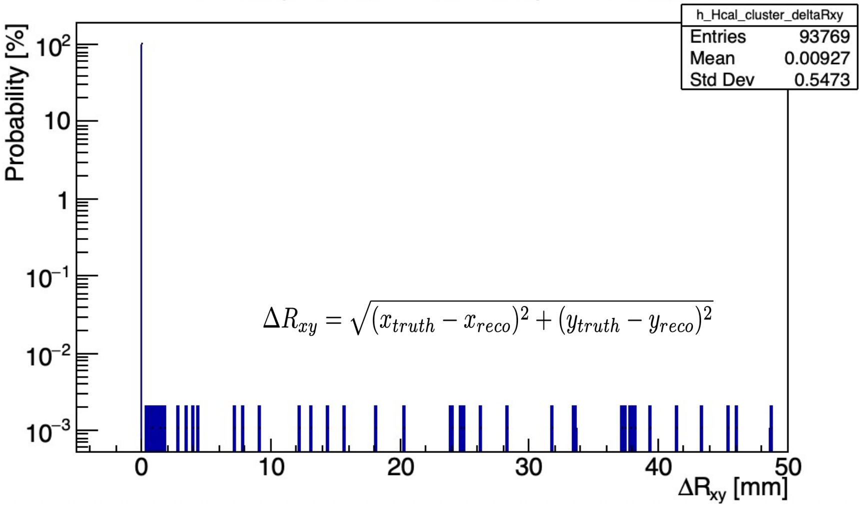
Truth Clusters

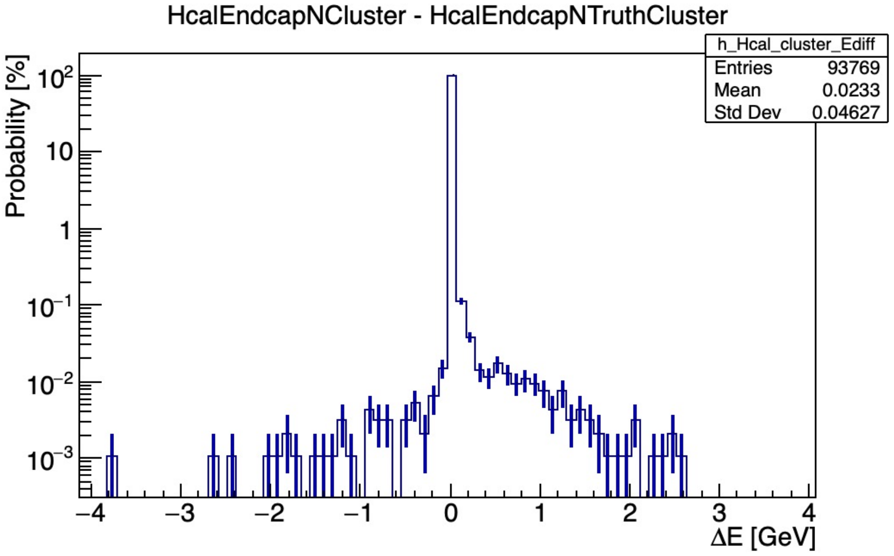


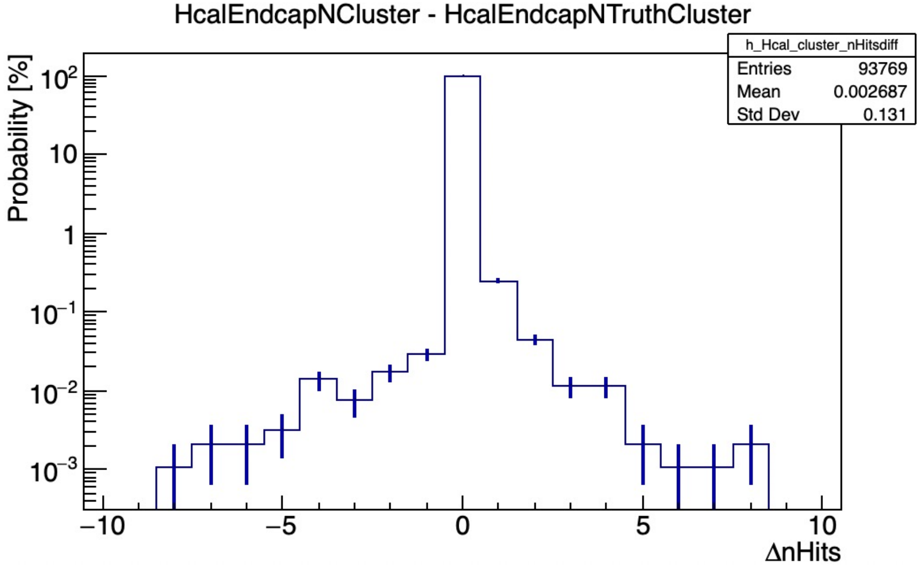
Comparison between Truth and Reco clusters











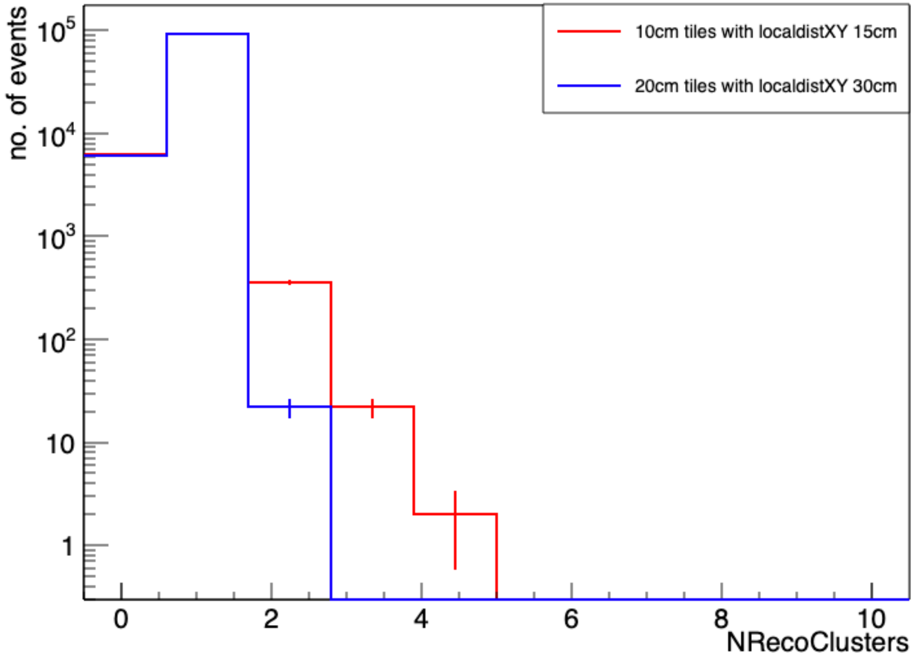
Highest energy truth and reco clusters are compared for an Event

Scaling of the algorithm with segmentation

- 10cm tiles with localdistXY 15cm
- 20cm tiles with localdistXY 30cm

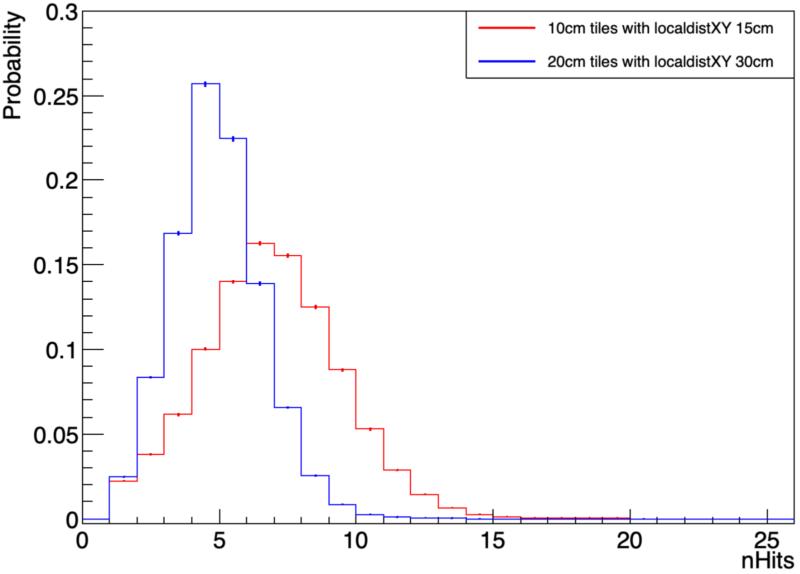
neighbourhood parameter
to cluster merged hits
[Island clustering]

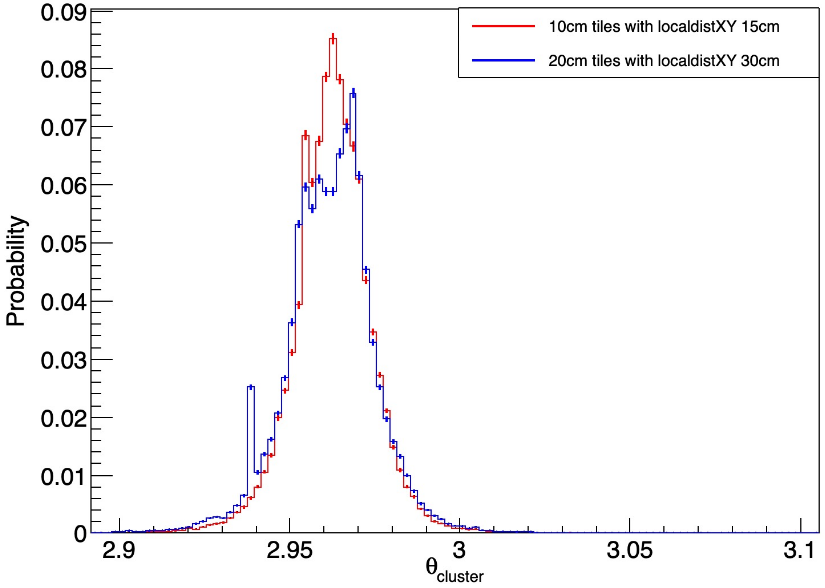
```
❑ static edm4hep::Vector2f localDistXY(const CaloHit
  &h1, const CaloHit &h2) {
  const auto delta =h1.getLocal() - h2.getLocal();
  return {delta.x, delta.y};
  }
```

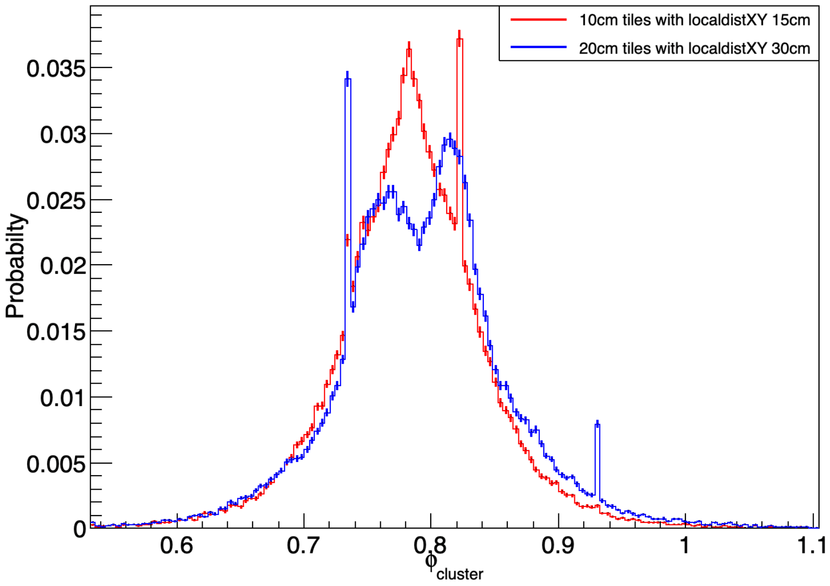


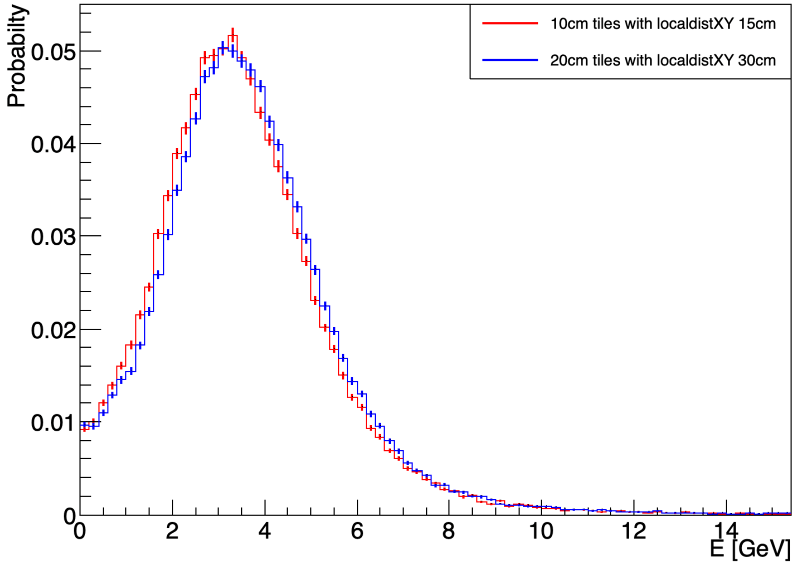
Less split clusters in case of
20cm tiles with localdistXY
30cm

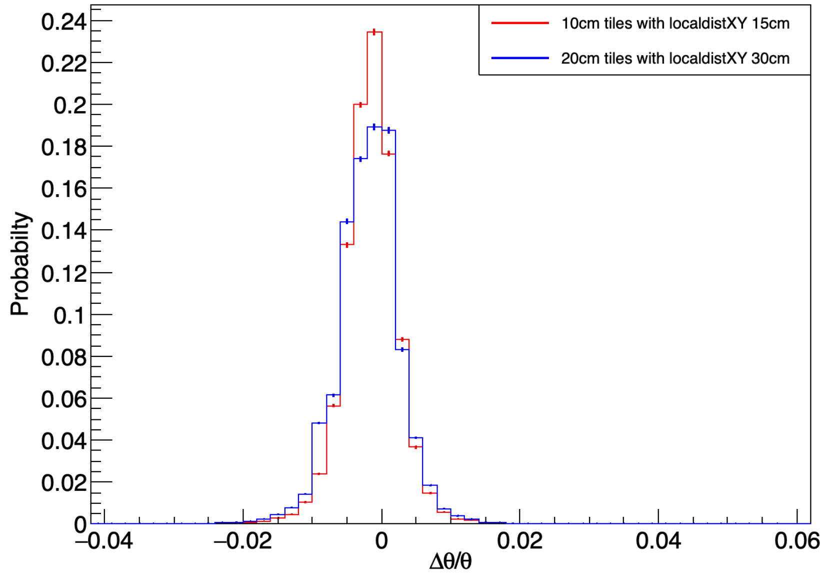
Scaling of the algorithm with segmentation

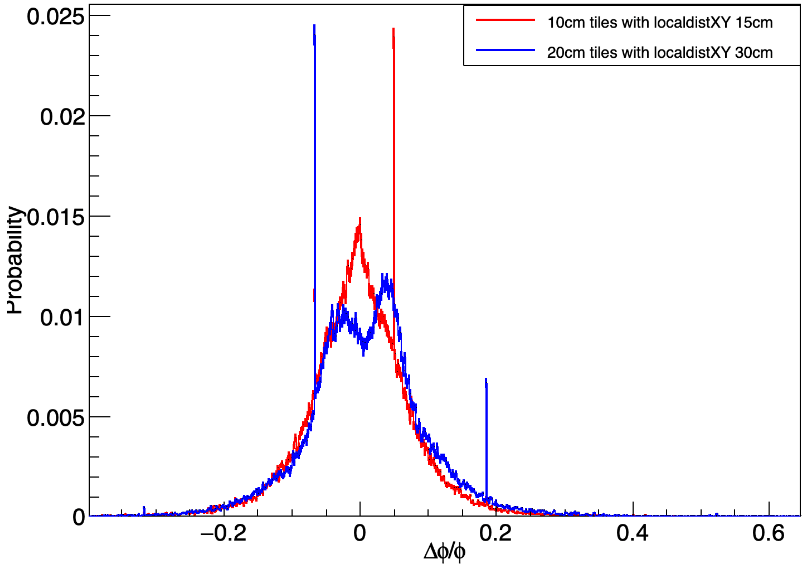




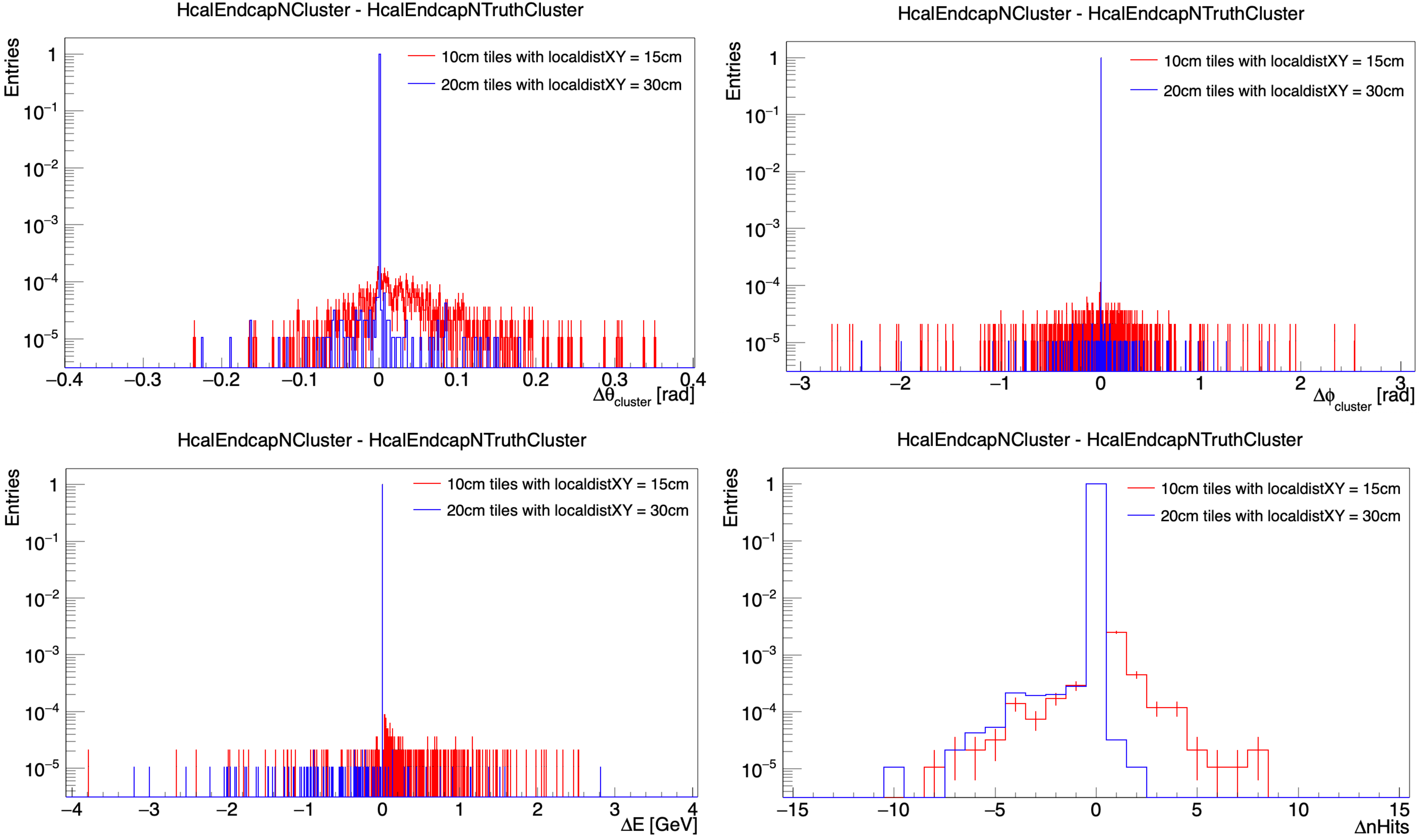






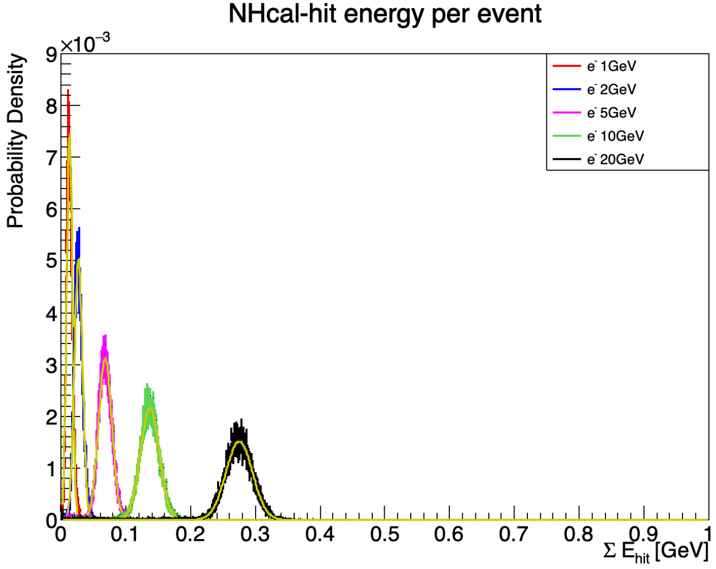


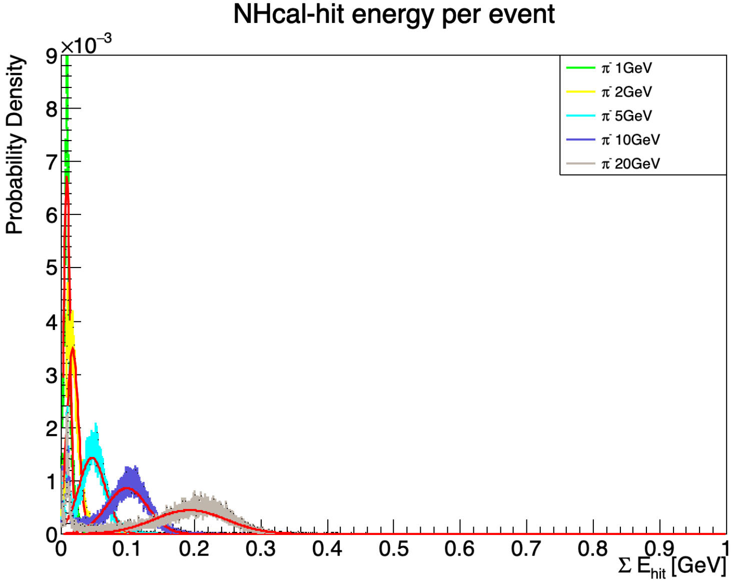
Scaling of the algorithm with segmentation

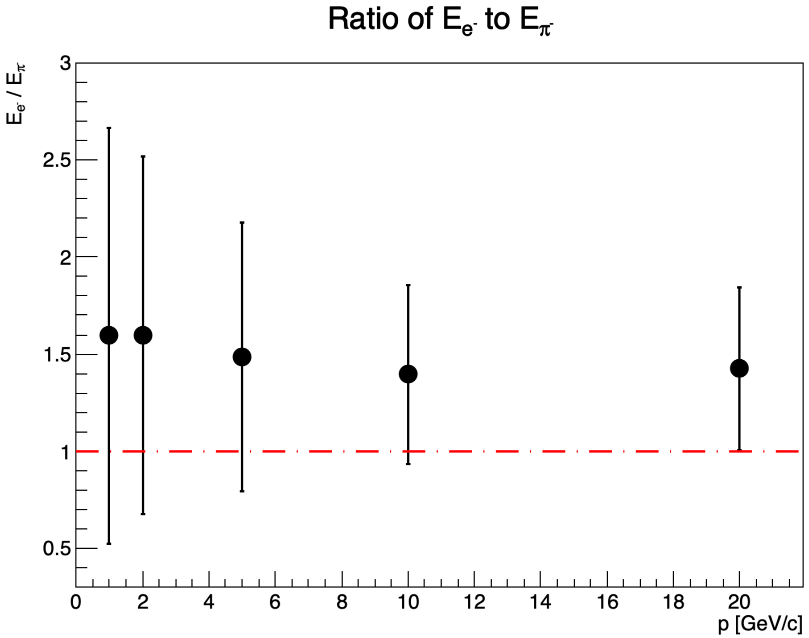


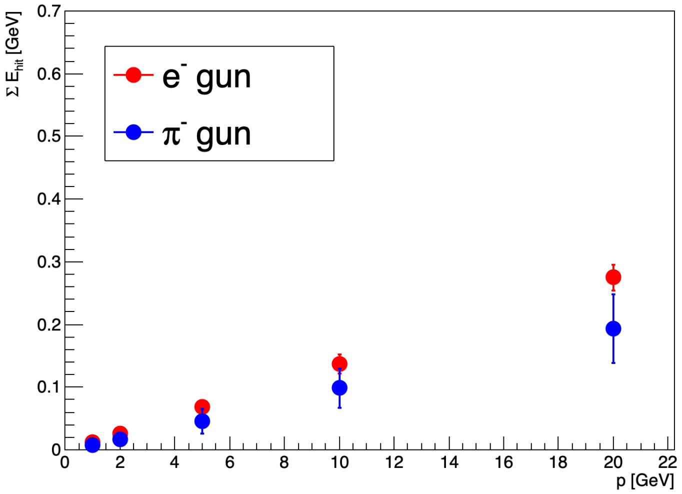
Less discrepancy in case of
20cm tiles with localdistXY 30cm

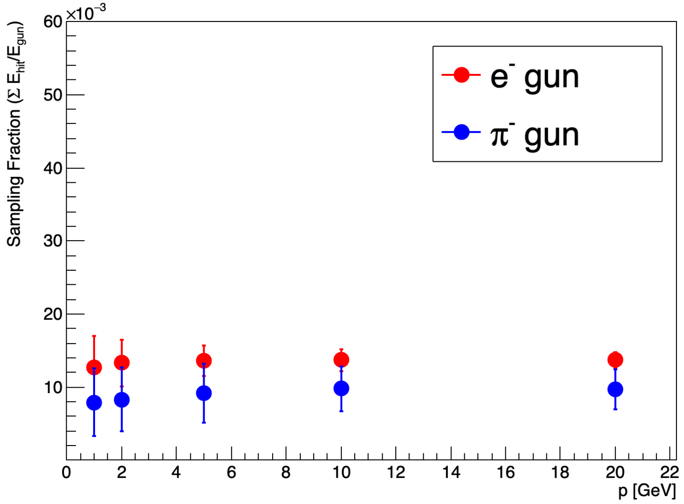
Steel/Scint = 10:1; 10 layers [40 mm Steel + 4 mm Scint]





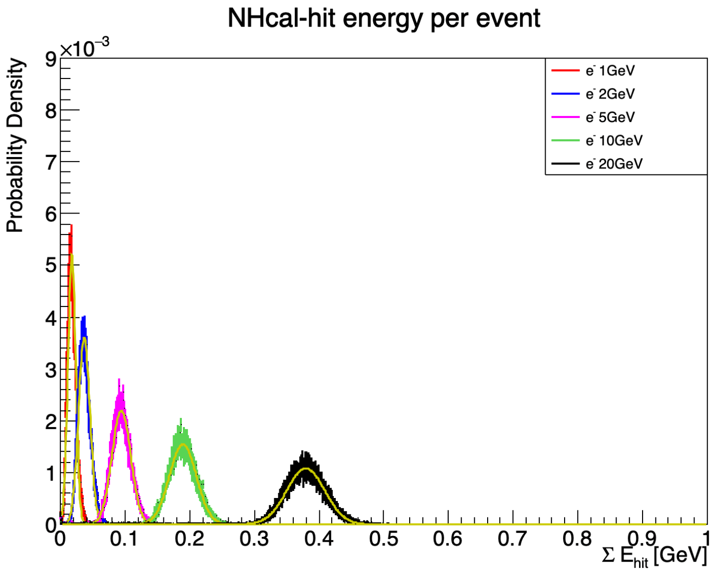


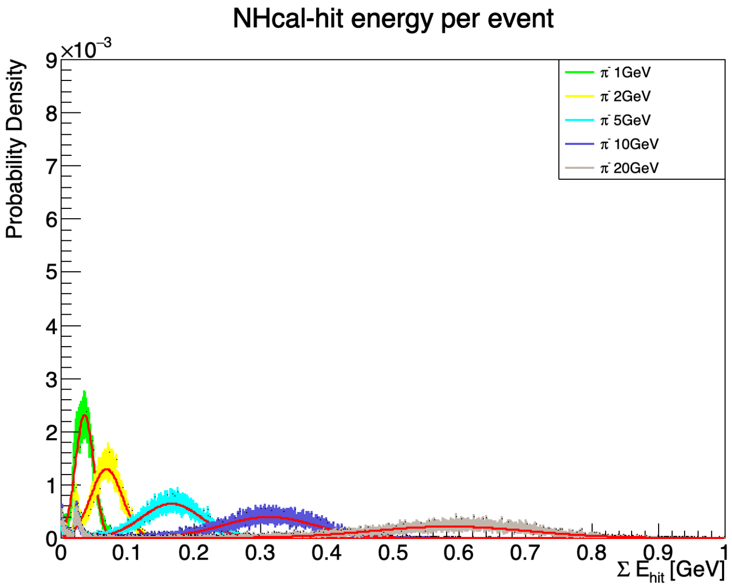


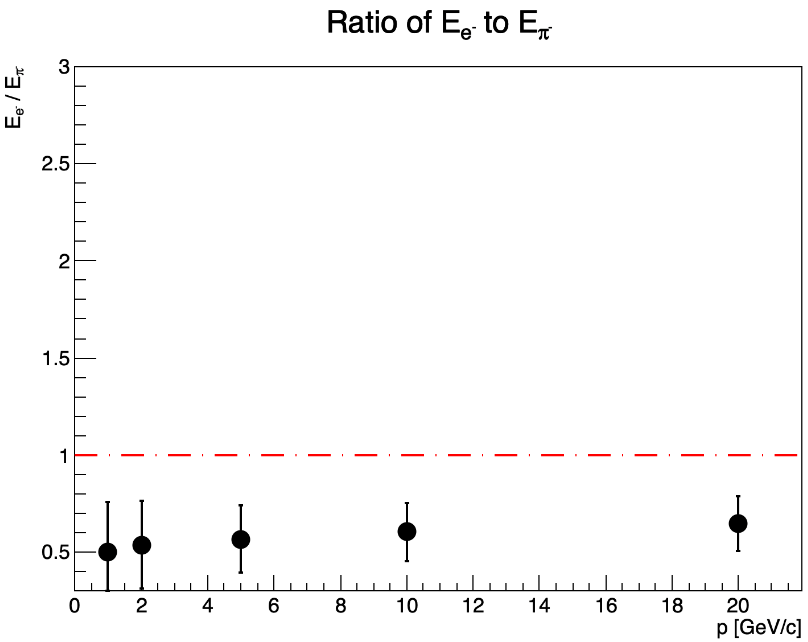


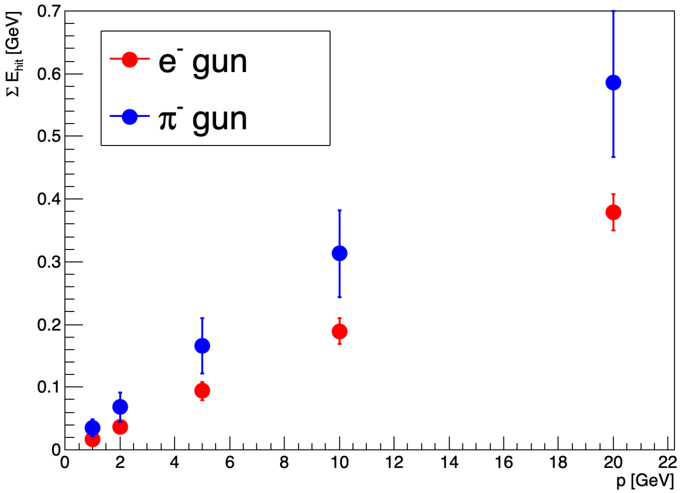
Undercompensating

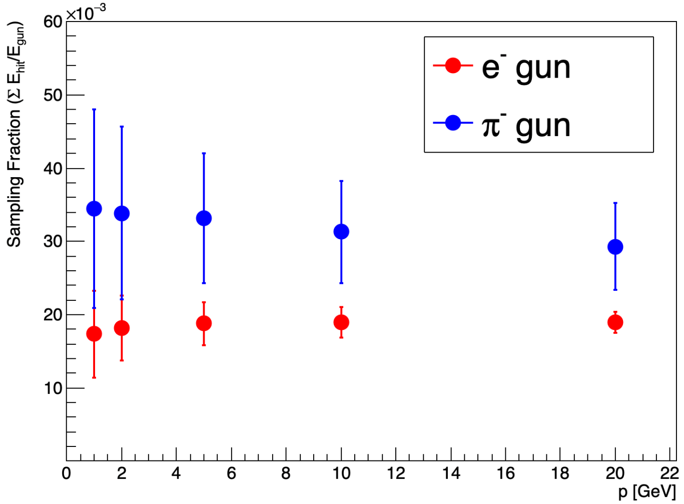
U/Scint = 3:1; 26 layers [12 mm U + 4 mm Scint]





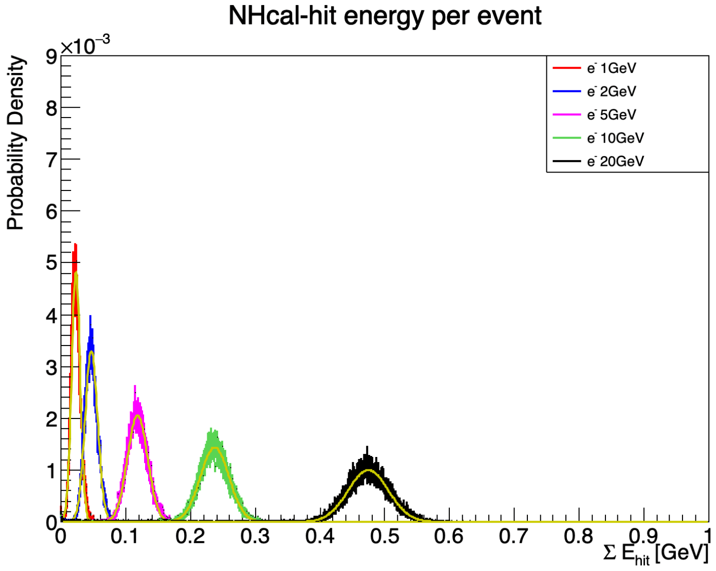


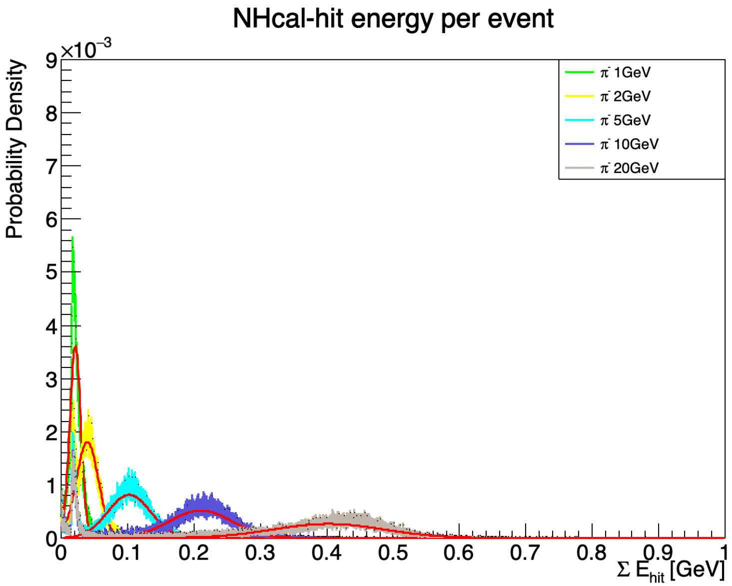


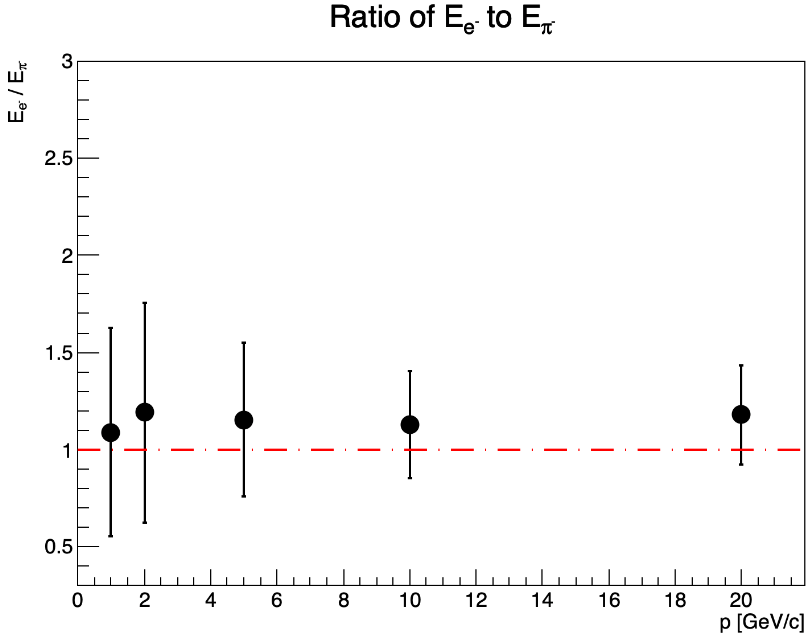


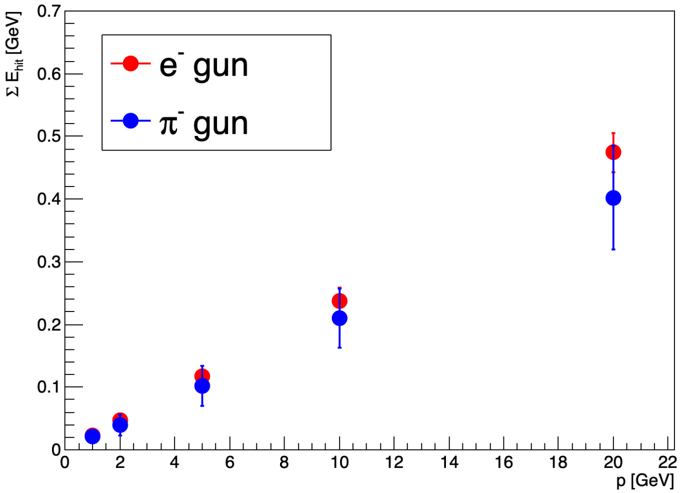
Overcompensating

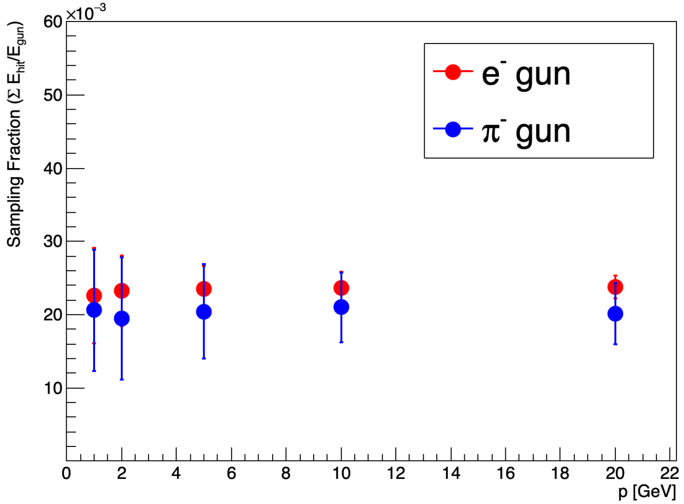
Pb/Scint = 4:1; 21 layers [16 mm Pb + 4 mm Scint]



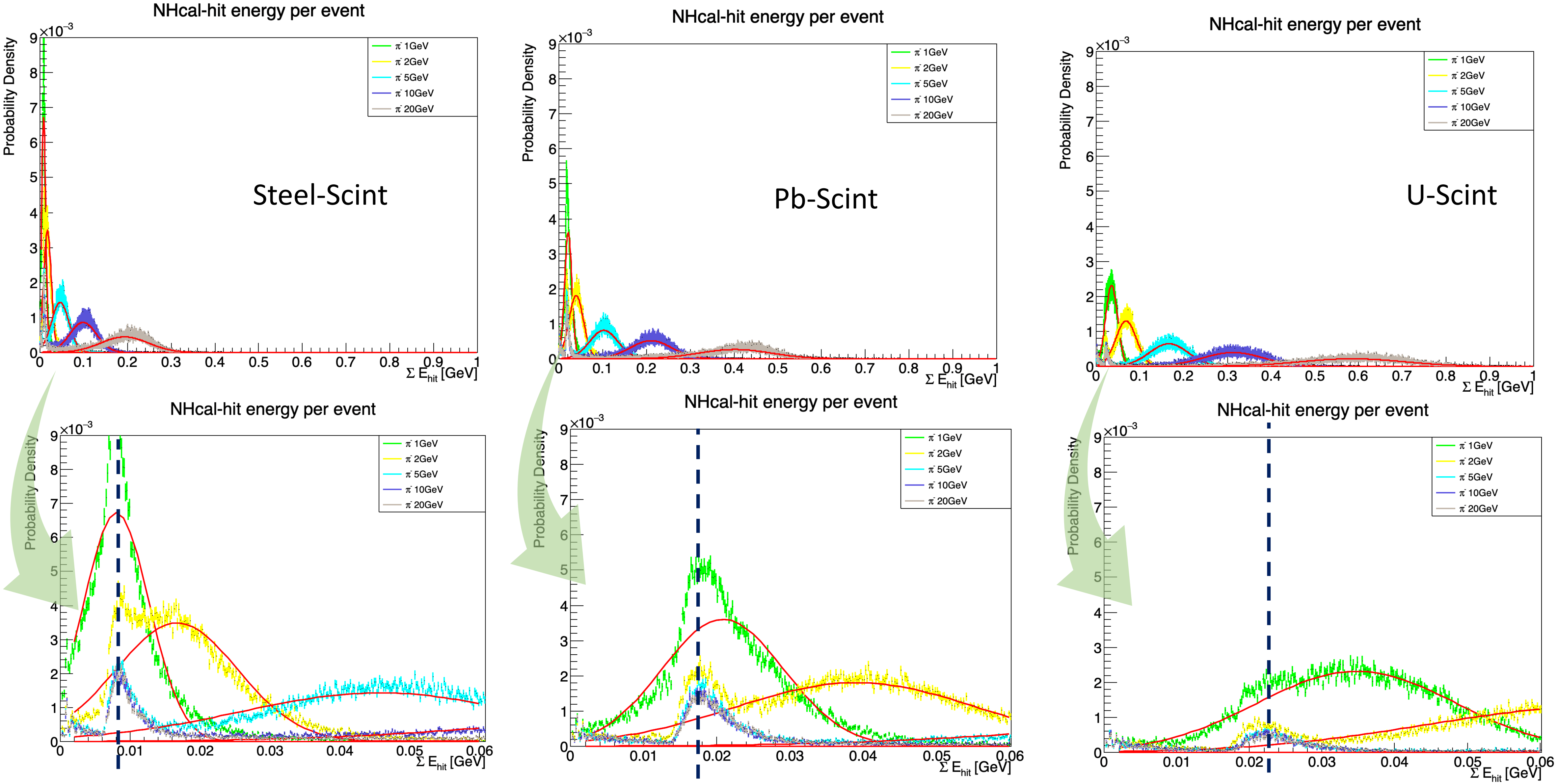








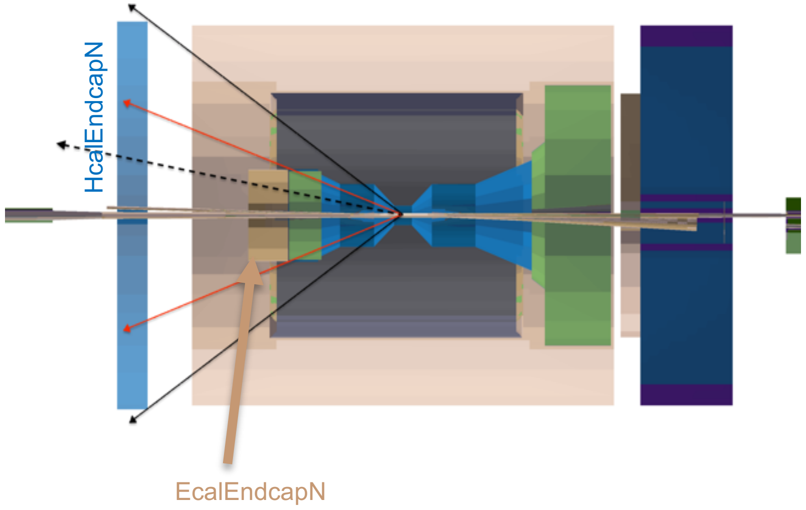
≃ Compensating

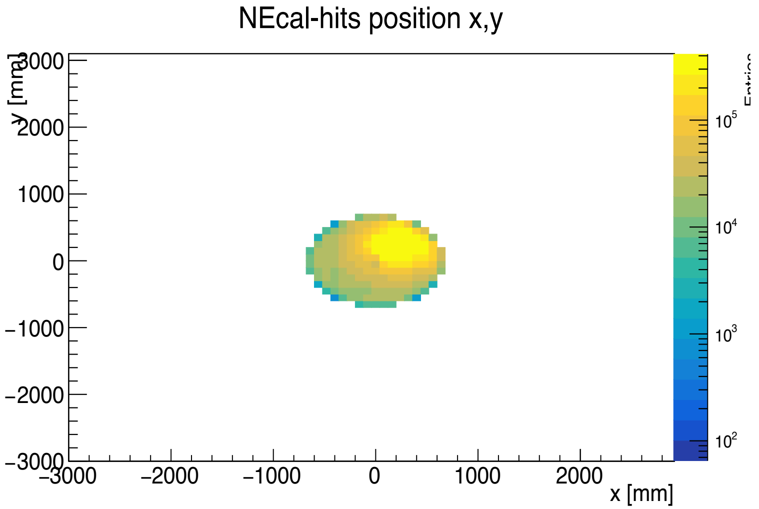


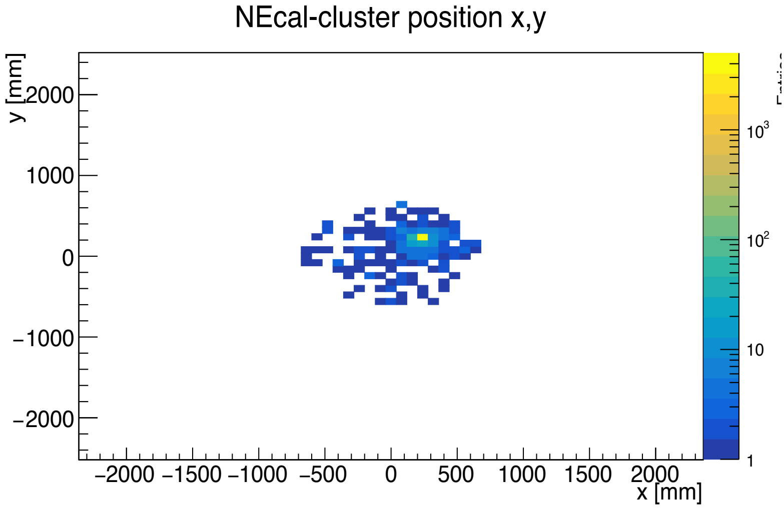
Common MIP peaks in different energies

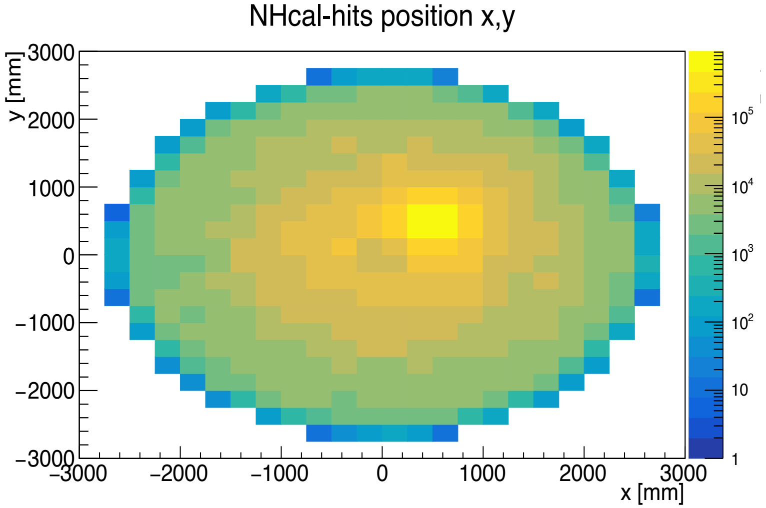
Hit and Cluster Positions

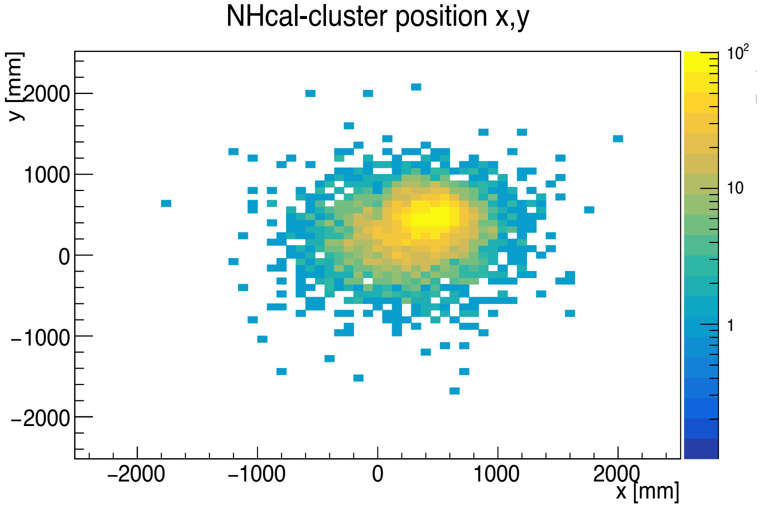
- ☐ 1 neutron/event, 100k events and p = 5 GeV
- ☐ $\theta = 170^\circ$ and $\varphi = 45^\circ$





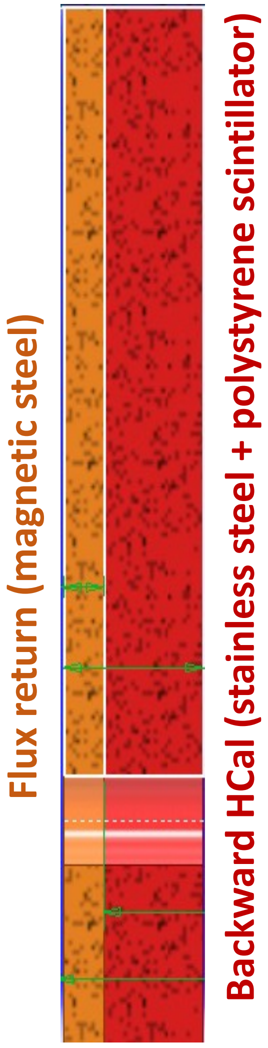






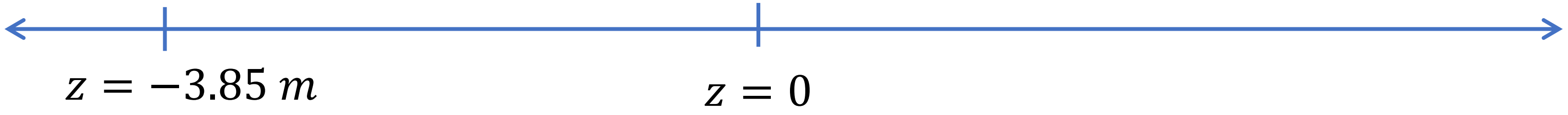
- nHCal hits (clusters) are more spread out than nECal hits (clusters).
- wide Ecal showers come in front of nHcal

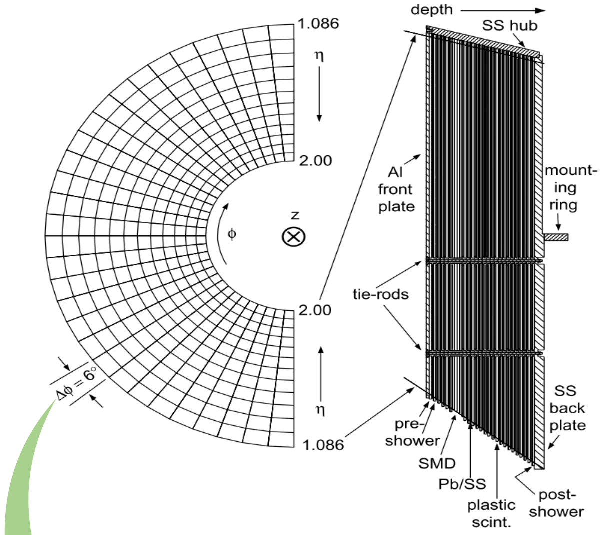
The Backward (or Negative) Hadronic Calorimeter - Design



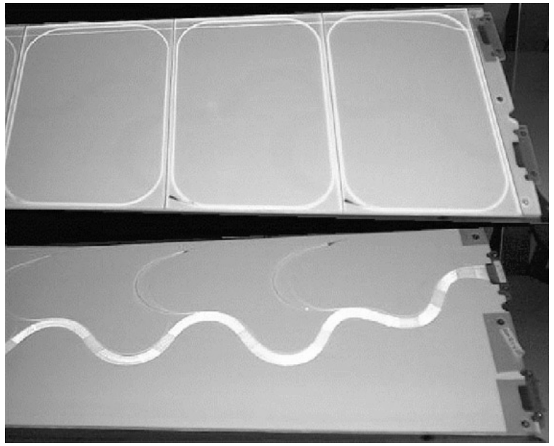
Based on STAR Endcap ElectroMagnetic Calorimeter:

- Absorber : non-Magnetic Stainless Steel
  (no interference with the solenoid flux return)
- Sampling : Plastic scintillator tiles
  (STAR EEMC scintillator megatiles will be reused)
- Signal readout:
  - Scintillator light guided by WLS fibers.
  - SiPM used for light collection.





STAR EEMC tower structure

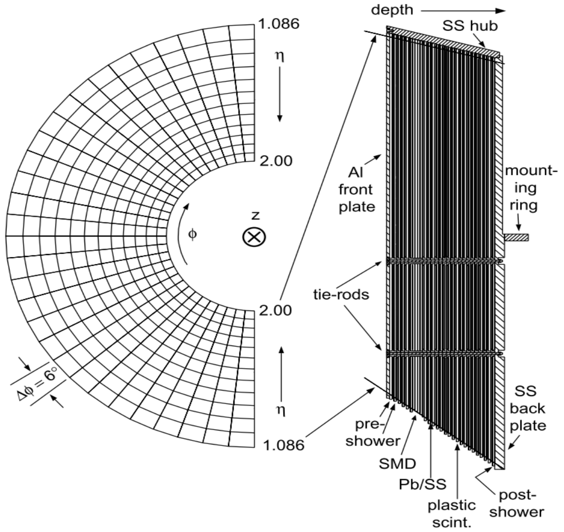


STAR EEMC 6° megatile : 12 tiles in η direction (radial) each

The Backward (or Negative) Hadronic Calorimeter - Design

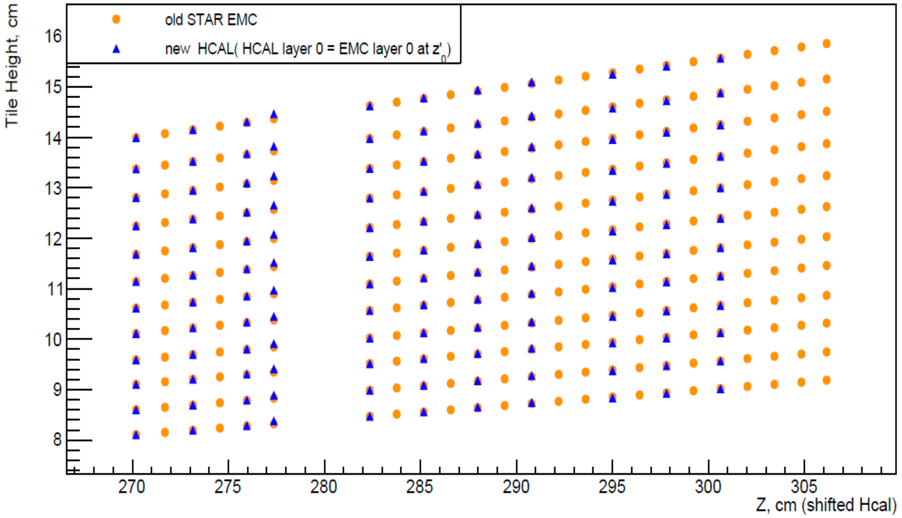
Scintillator Megatiles:

- STAR EEMC scintillator megatiles will be reused.
- 24 layers of plastic scintillator.
- $-2.0 < \eta < -1.086$; $\Delta\phi = 6^\circ$ placed at $z_{STAR} = -2.7$m.
- ePIC nHCal will have 10 layers placed at $z_{ePIC} = -3.5$ m.



Choice of Megatiles from STAR EEMC:

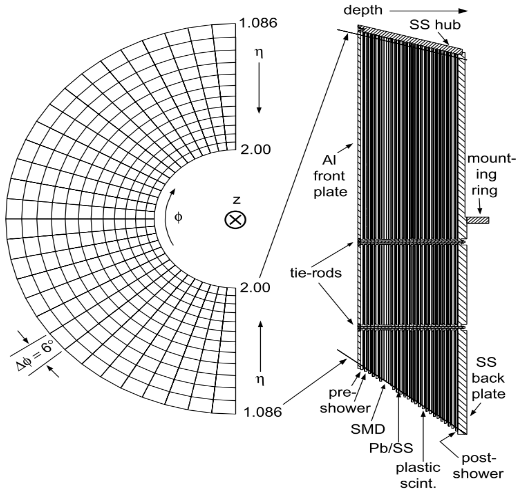
1. η bins for ePIC - calculated by shifting the z position.
2. 1st EEMC layer ($z_{STAR} = -2.7$ m) placed at $z_{ePIC} = -3.5$ m.
3. nHCal tile sizes calculated across 10 layers ($\Delta z = 4.4$ cm.)
4. Tile sizes compared with STAR EEMC.
5. Matched layers were taken.



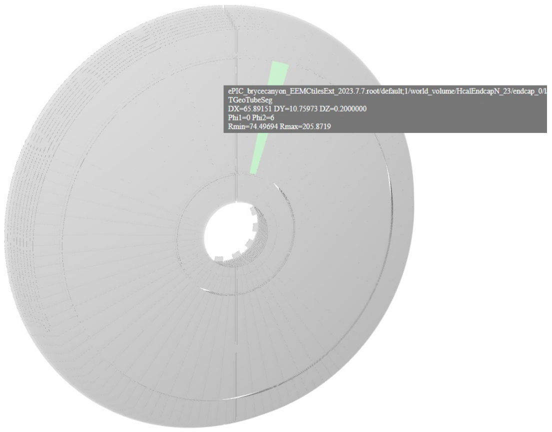
z_{ePIC} is shifted for demonstration purposes

Acceptance

- ❑ STAR EEMC tiles cover $-1.39 < \eta < -2.195$ when placed in the correct position.
- ❑ New tiles added by extrapolation
  - Sizes kept around ~10 cm.
  - Tiles are merged in ϕ as those approach the beampipe.
- ❑ Total acceptance: **$-3.5 < \eta < -1.25$**

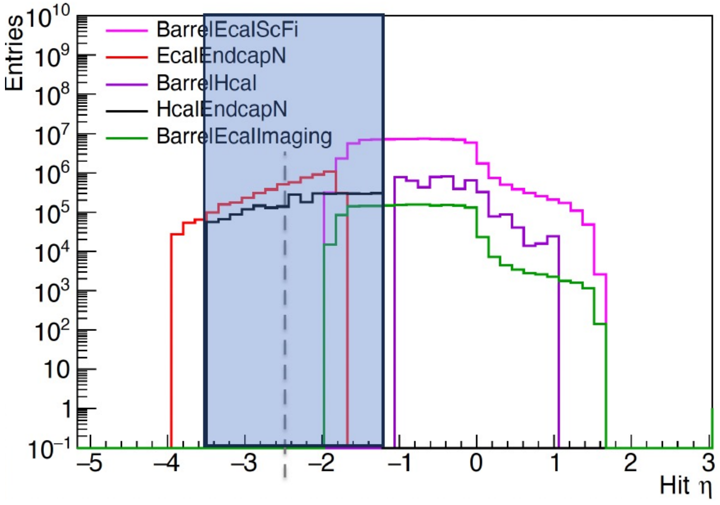


STAR EEMC



ePIC_brycecanyon_EEMCtilesExt_2023.7.7.root/default;1/world_volume/HcalEndcapN_23/endcap_0/
TGeoTubeSeg
DX=65.89151 DY=10.75973 DZ=0.2000000
Phi1=0 Phi2=6
Rmin=74.49694 Rmax=205.8719

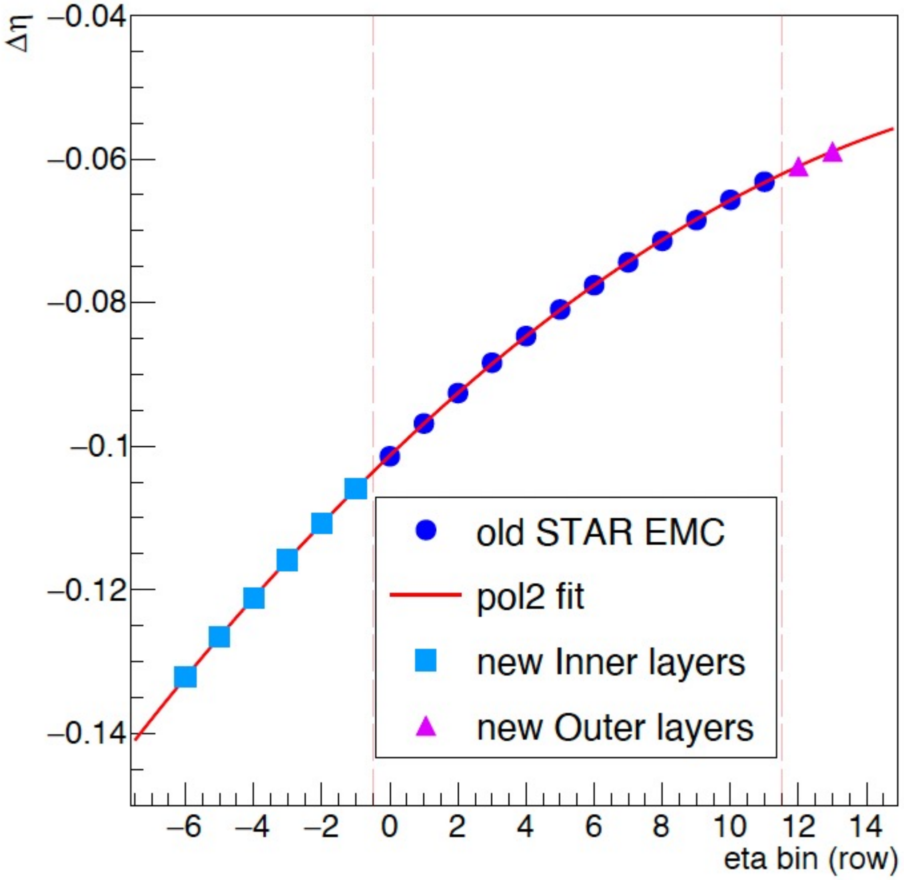
ePIC nHCal



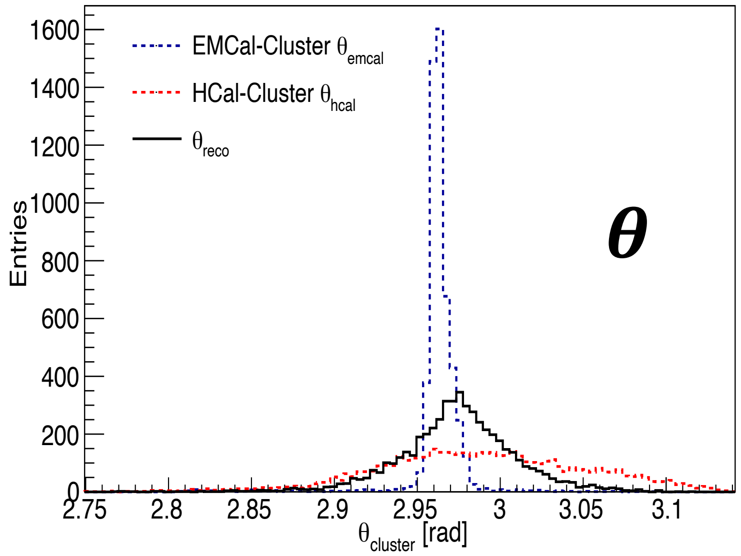
Significant overlap in acceptance with the backward (or negative) Endcap EMCal

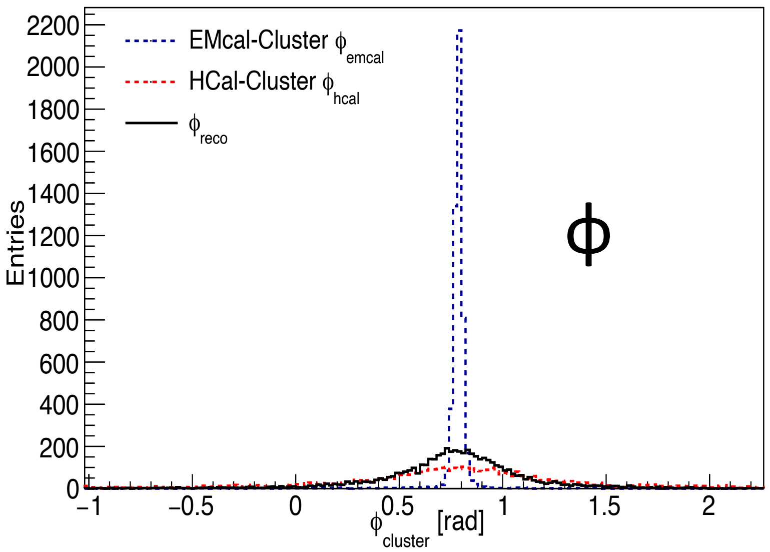
- ➢ Design considerations
  - High efficiency for neutron detection.
  - Good spatial resolution to distinguish between neutral/charged hadrons.

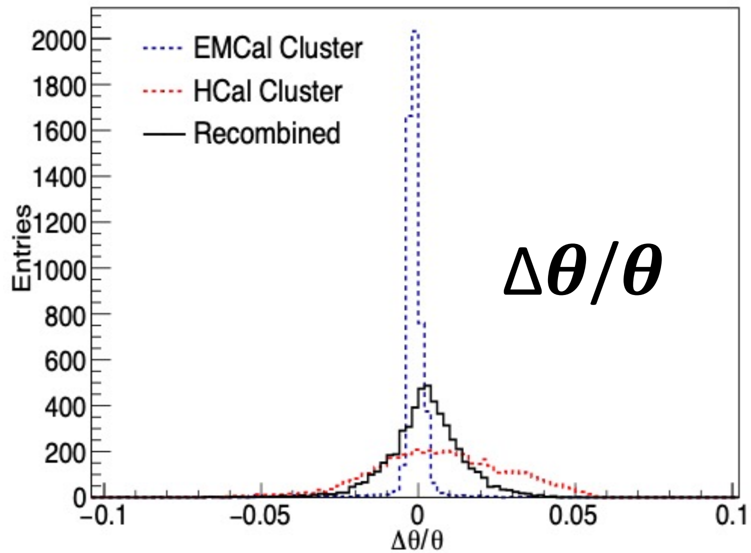
Backup

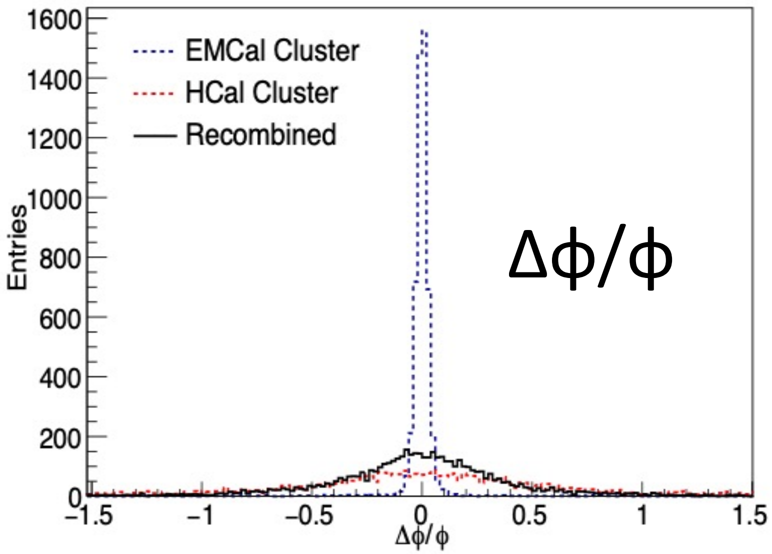

Δη
−0.04
−0.06
−0.08
−0.1
−0.12
−0.14
−6
−4
−2
0
2
4
6
8
10
12
14
eta bin (row)
● old STAR EMC
pol2 fit
■ new Inner layers
▲ new Outer layers

Position Resolution Study – Recombining Clusters

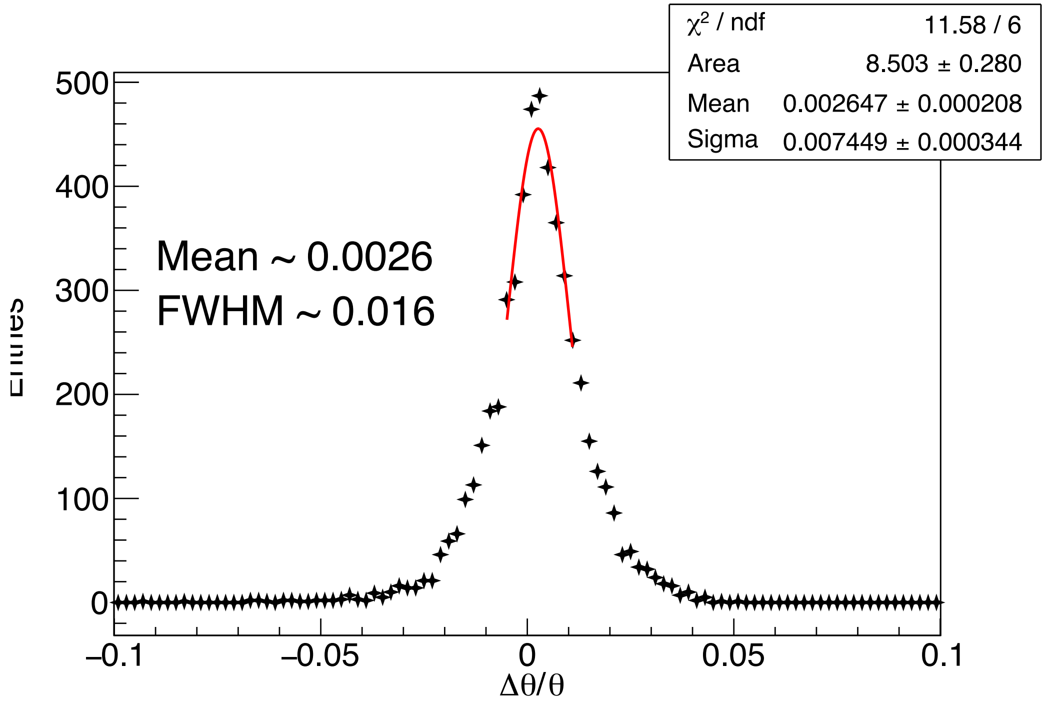


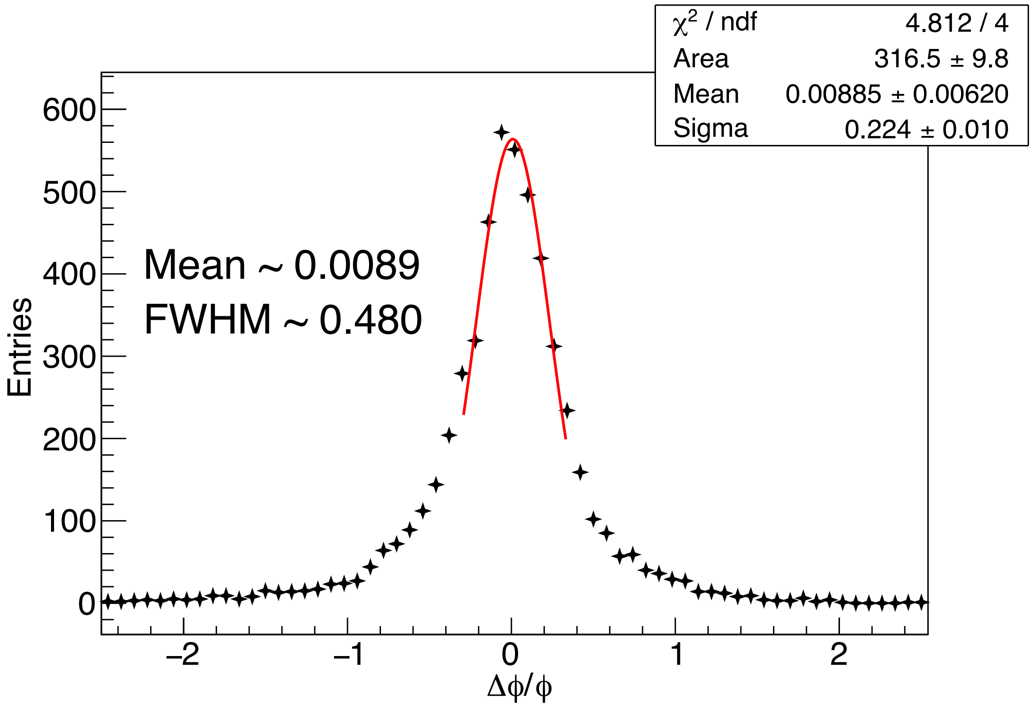






Resolutions (nHCal + nEMCal)



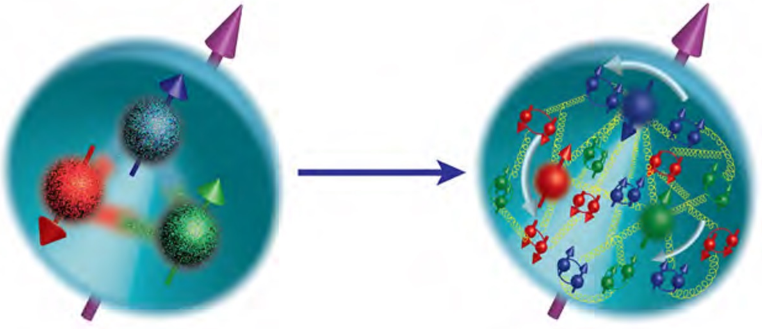


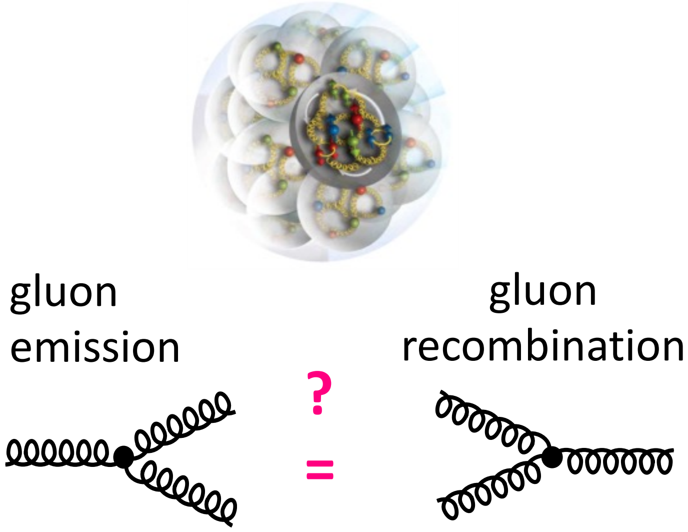
- Gaussian fits work only in a narrow range.
- Much worse resolution in the ϕ direction - may be due to proximity to beam.

A Quick Look into EIC Physics

- How are the sea quarks and gluons, and their spins, distributed in space and momentum inside the nucleon?

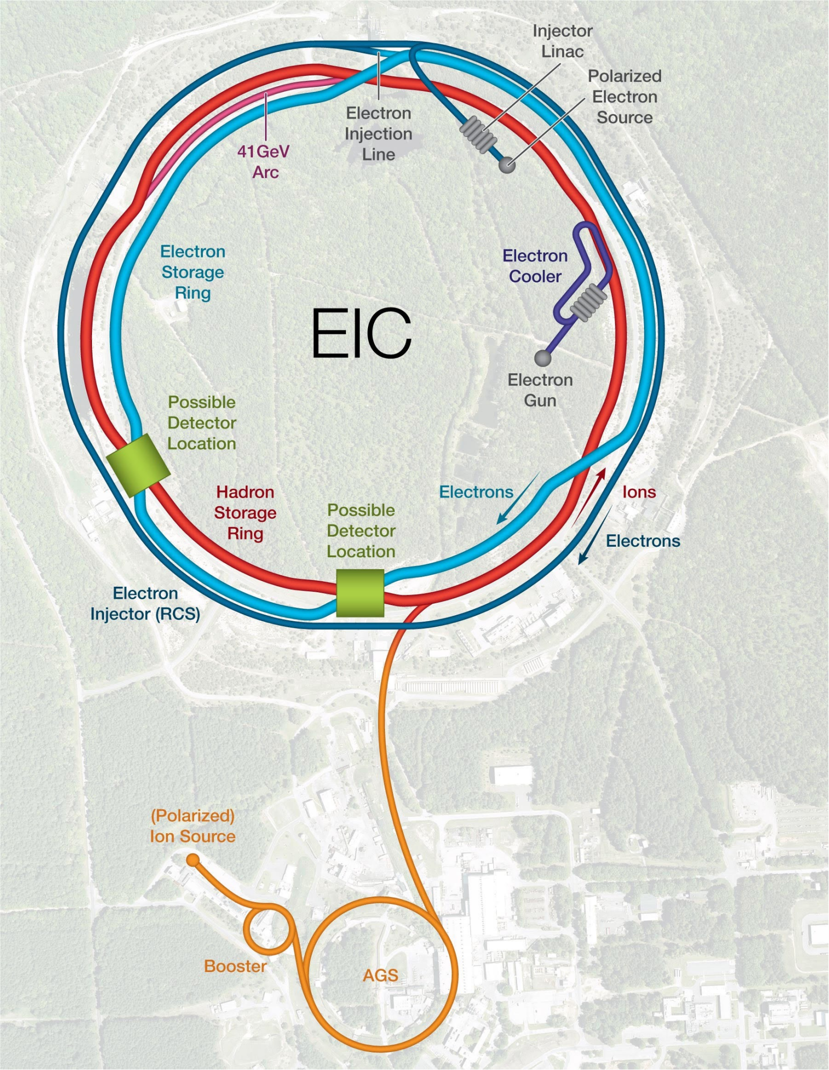
- How do the nucleon properties (mass & spin) emerge from their interactions?





- What happens to the gluon density in nuclei? Does it saturate at high energy (low x), giving rise to a gluonic matter with universal properties in all nuclei (and perhaps even in nucleons)?

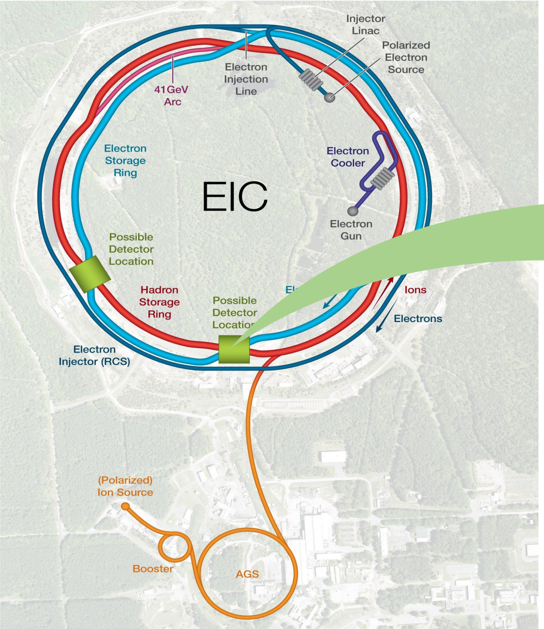
The Electron-Ion Collider (EIC)

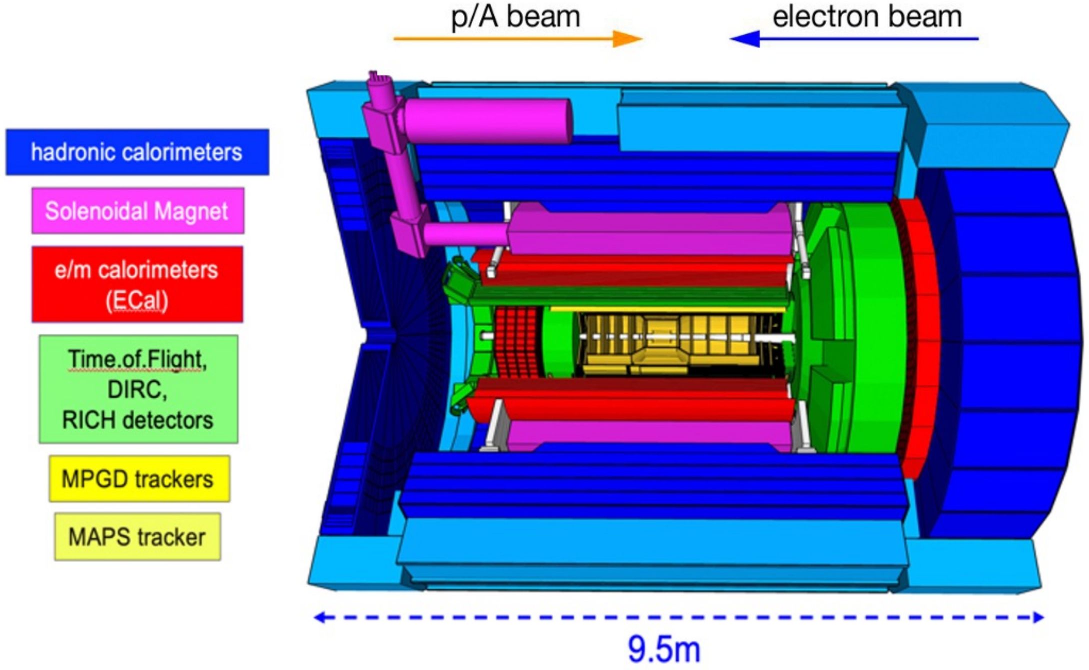


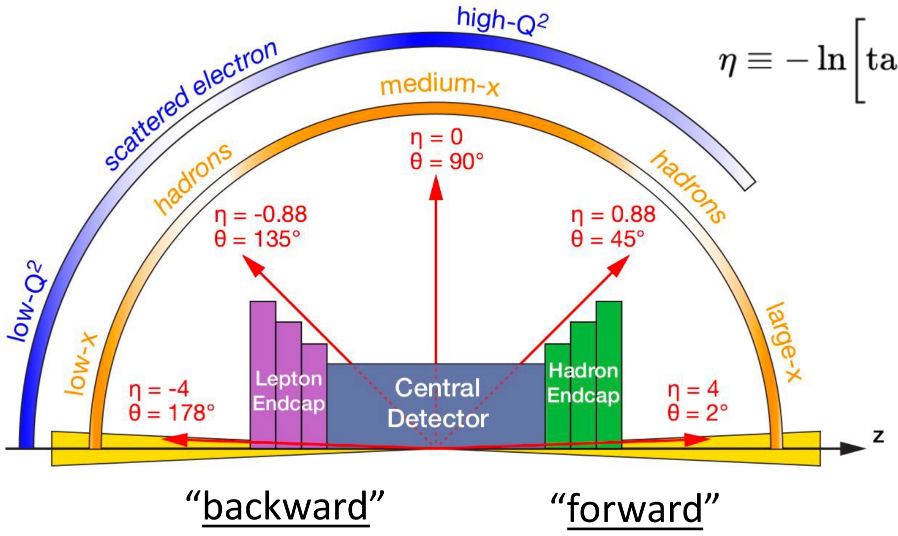
- Accelerator to be built on the current site of RHIC, BNL to yield e+p/nuclei collision.
- Variable e+p center-of-mass energies from 29−140 GeV.
- Ion beams from deuterons to heavy nuclei such as gold, lead, or uranium.
- High collision electron-nucleon luminosity 10^{33}–10^{34} $\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$.
- The possibility to have more than one interaction region.

[EIC White Report]

The ePIC detector







$$\eta \equiv -\ln\left[\tan\left(\frac{\theta}{2}\right)\right],$$

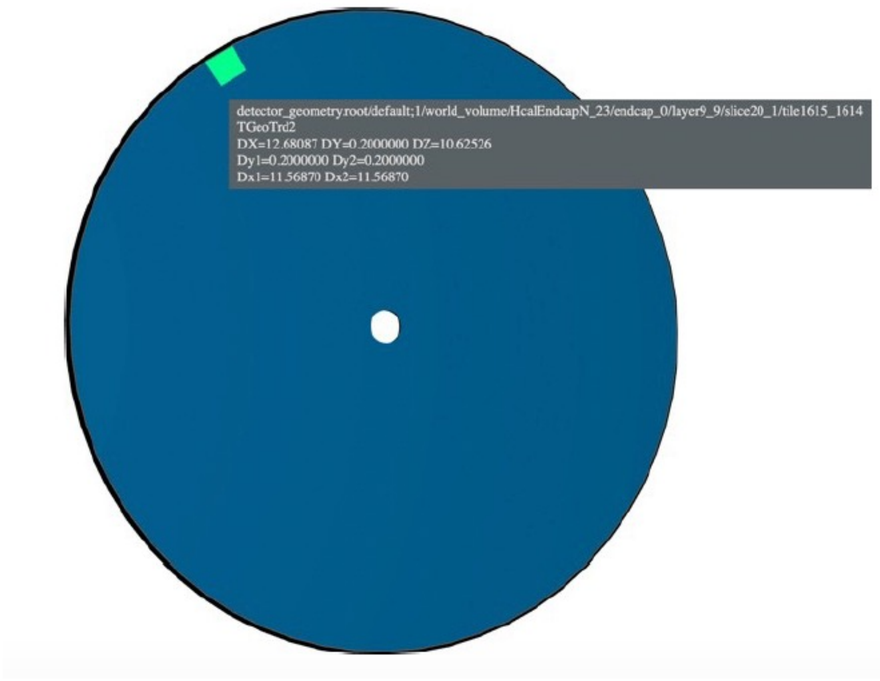
- Primary general-purpose detector to be sited at IP6.
- 1.7 T (extending up to 2.0 T) solenoidal superconducting magnet.

https://wiki.bnl.gov/EPIC

DD4hep – detector description toolkit

- ❑ Works with Geant4 for particle transport
- ❑ Uses ROOT for visualization

- ➢ Separate detector descriptions from their interpretation
  - • The compact detector description is contained in a .xml file
  - • Interpretation is done by detector Constructors (.cpp file)
    - ○ Can create one detector element with a given shape.
    - ○ Make multiple placements to replicate it.

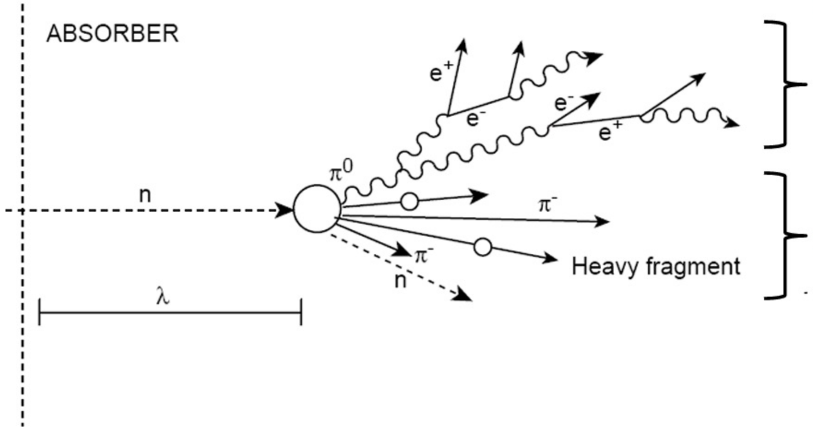


```
detector_geometry.root/default;1/world_volume/HcalEndcapN_23/endcap_0/layer9_9/slice20_1/tile1615_1614
TGeoTrd2
DX=12.68087 DY=0.2000000 DZ=10.62526
Dy1=0.2000000 Dy2=0.2000000
Dx1=11.56870 Dx2=11.56870
```

https://dd4hep.web.cern.ch/dd4hep

Hadronic Showers

A hadronic shower is a cascade of secondary particles initiated by the interaction with matter (i.e, energy loss) of an incoming of hadron.

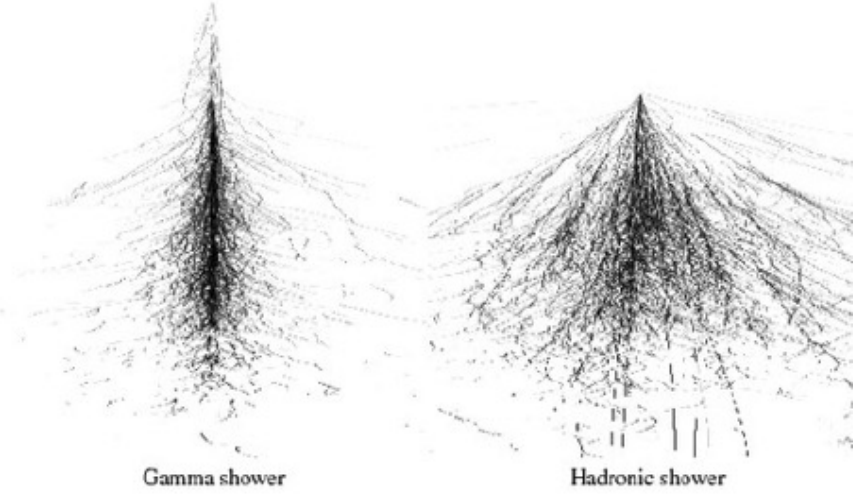


Electromagnetic component:

- Electrons, photons (from excitation, radiation, decay of hadrons, photo-effect, …)
- Neutral pions (eg, $\pi^0 \to \gamma\gamma$, $\eta \to \gamma\gamma$)

Hadronic component:

- Charged hadrons $\pi^\pm$, $K^\pm$, p, …
  - ionization, excitation, nuclei interaction (spallation p/n production, evaporation n, spallation products)
- Neutrons,
  - Elastic collisions, thermalization+capture (=>γ's)
- Break-up of nuclei



- Part of the energy is lost in breaking nuclei (nuclear binding energy)
  - Invisible part of the shower! Only part of the shower energy is sampled!