

# Study of EIC Calorimeters Using Fun4All

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# Introduction

# Aim of the analysis

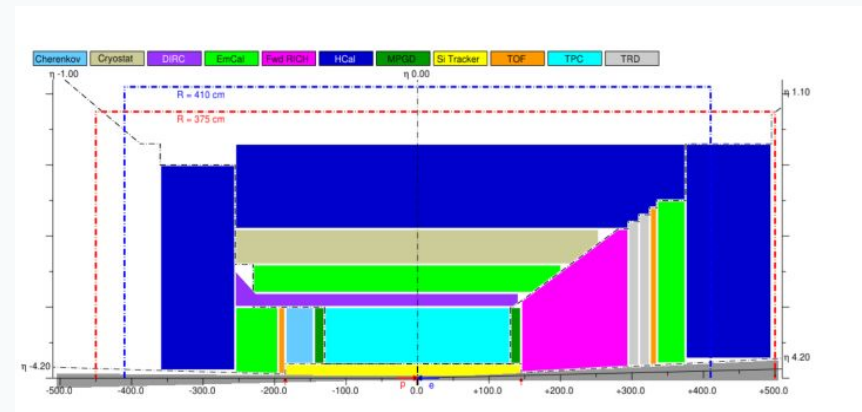
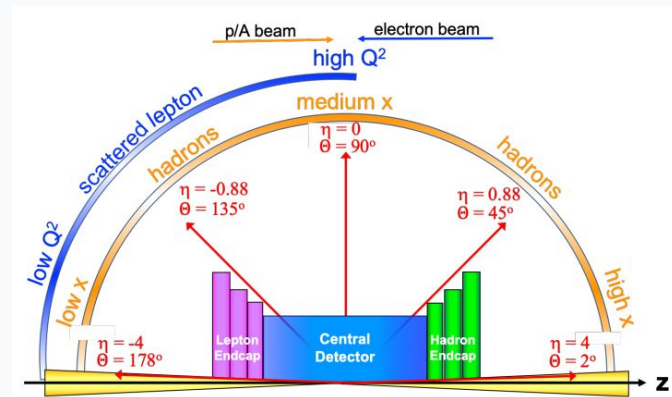
- To perform parameterization of the energy resolution of various Fun4All calorimeters
  - Simplest case:
    - ➡ A simple **circular clustering** method is employed that clusters the neighbouring towers together based on their **theta** and **phi** values.
    - ➡ **Noise** from readout channels is **not simulated**.



# Details for EIC Calorimeters

Calorimeters in Fun4All layout :

- Backward Region:
  - EEMC (Electron EMCal) - PWO crystals
- Barrel Region:
  - CEMC (Central EMCal) - Mixture of tungsten powder and epoxy + scintillating fibers
  - HCALIN (Inner HCal) - Aluminium absorber + plastic scintillator
  - HCALOUT (Outer HCal) - Steel absorber + plastic scintillator
- Forward Region:
  - FEMC (Forward EMCal) - Lead Scintillator sampling calorimeter
  - FHCAL (Forward HCal) - Steel absorber + plastic scintillator



Reference: [EIC Yellow Report](#)

# Simulation Parameters

- Particles:  $e^-$ ,  $\pi^-$
- Pseudorapidity range ( $\eta$ ): -4 to 4
- Azimuth range ( $\Phi$ ):  $-\pi$  to  $+\pi$

- Cuts employed:

- Detector-wise geta cuts
- Manual Clustering cuts: Circular cuts on dphi (tphi - gphi) and dtheta (ttheta - theta)
- Energy cut on the **aggregated tower energy\*** : **100 MeV**
  - Aggregate tower energy refers to the sum of the energies recorded by all the towers hit by the incident particle's shower in one event.

- Photon digitization: turned off

## Statistics

Group 1	Group 2
100000 (0-30 GeV)	100000 (0-30 GeV)
50000 (0-10 GeV)	50000 (0-2 GeV)

tphi : tower  $\phi$   
gphi : generated  $\phi$

ttheta : tower  $\theta$   
gtheta : generated  $\theta$

te/  $te_{agg}$  : aggregate tower energy  
ge : generated energy

# Electron

CEMC, FEMC, EEMC

# Calibration methods

## Group 1

- Obtain Tprofile plots for the calorimeters' te/ge vs ge plots.
- **Fitting the TProfile plots with a fit function**
- Use this fit function to calibrate the tower energy of the respective calorimeters.

$$\text{te(calibrated)} = \text{te(raw)}/\text{FitFunction}$$

## Group 2

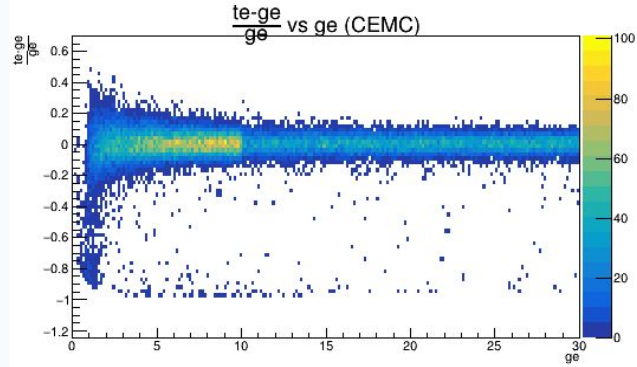
- Obtain Tprofile plots for the calorimeters' te/ge plots.
- **Use bin-wise mean values of the TProfile of te/ge as the calibration factor. (The first slice is manually calibrated for electrons)**
- Use this calibration factor to calibrate the tower energies of the respective calorimeters.

$$\text{te(calibrated)} = \text{te(raw)}/\text{CalibrationFactor}$$

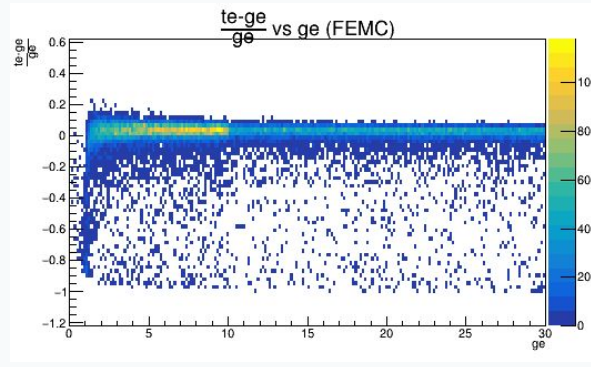
# Electron After Calibration

Group 1

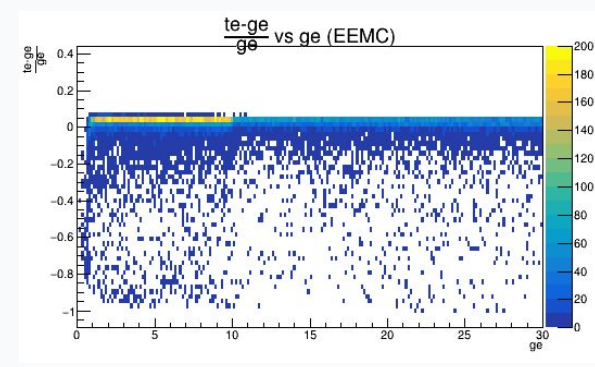
CEMC



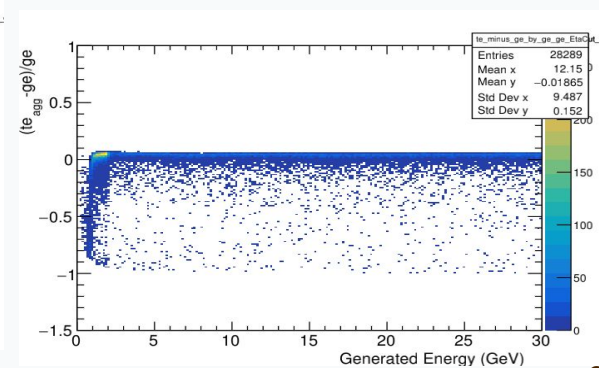
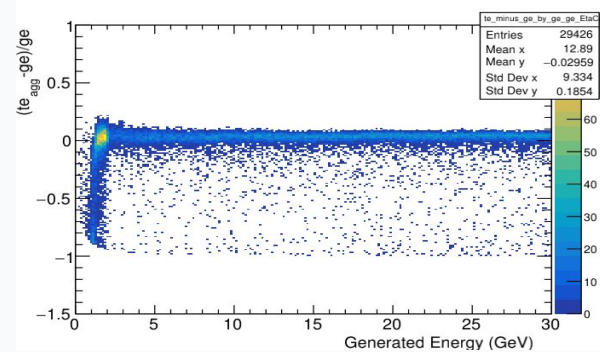
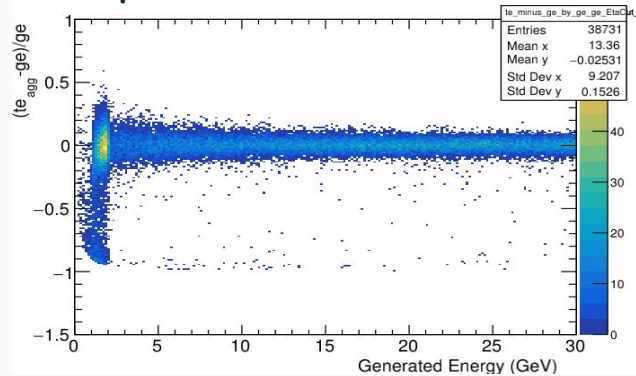
FEMC



EEMC



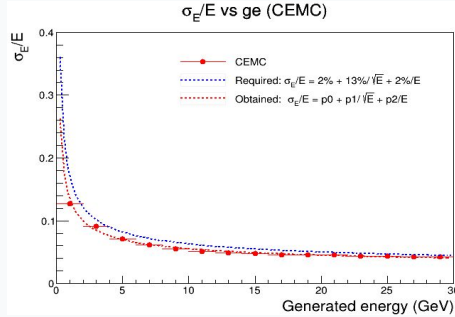
Group 2



# Electron After Calibration FEMC

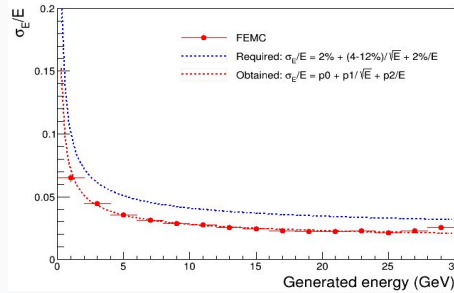
## Group 1

### CEMC



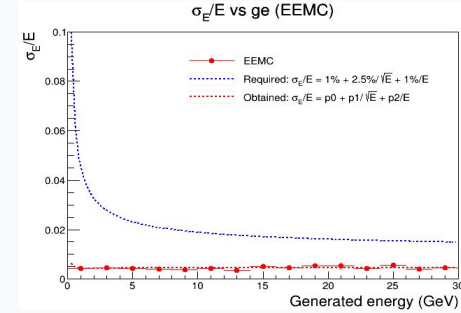
$$\sigma_E/E = 2.05\% + 10.53\%/\sqrt{E} + 2\%/E$$

### FEMC



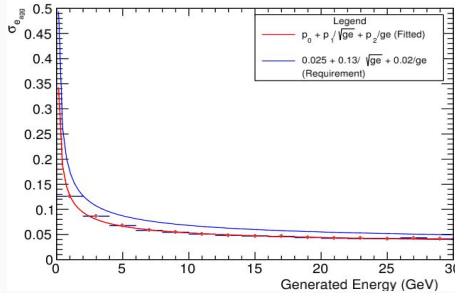
$$\sigma_E/E = 1.16\% + 4.85\%/\sqrt{E} + 1.08\%/E$$

### EEMC

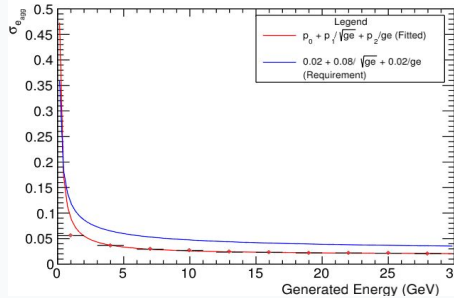


$$\sigma_E/E = 0.49\% - 0.16\%/\sqrt{E} + 0.12\%/E$$

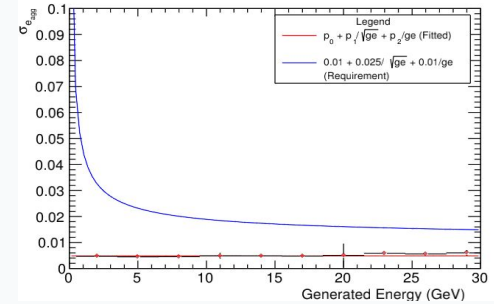
## Group 2



$$\sigma_E/E = 2.28\% + 9.19\%/\sqrt{E} + 1.23\%/E$$



$$\sigma_E/E = 1.71\% + 0.5\%/\sqrt{E} + 6.56\%/E$$



$$\sigma_E/E = 0.48\%$$

- The energy resolution values obtained **exceed** the minimum requirements stipulated by the JLab Detector Matrix.
- Overly optimistic (Plausible explanations - noise not included yet; EEMC is made out of crystals)



# Pion

CEMC + HCALIN + HCALOUT

FEMC + FHCAL

# Calibration methods

## Group 1

- Obtain Tprofile plots for the individual calorimeters' te/ge vs ge plots.
- **Fitting the TProfile plots with a fit function.**
- Use this fit function to calibrate the tower energy of the respective calorimeter.
- Multiplying the Mean value of te/ge (as a weight) for each calorimeter to these calibrated energies.

**te(scaled) =**

**$(\text{te}(\text{raw})/\text{FitFunction}) * (\text{Mean of te/ge})$**

- Add the corresponding scaled tower energies of each individual calorimeter.
- Obtain TProfile plot for these summed up scaled te/ge vs ge plots.
- **Find the fit function for the same.**
- Calculate the final calibrated tower energy  
**te(calibrated) = te(summed)/FitFunction**

## Group 2

- Obtain Tprofile plots for the individual calorimeters' te/ge vs ge plots.
- **Use bin-wise mean values of the TProfile of te/ge as the calibration factor for respective calorimeters.**
- Multiply the Mean value of te/ge (as a weight) for each calorimeter with these calibrated energies.

**te(scaled) =**

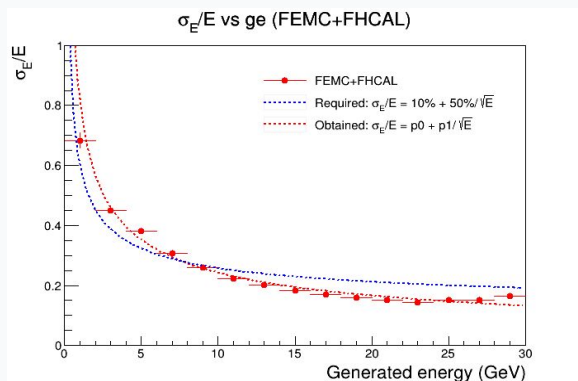
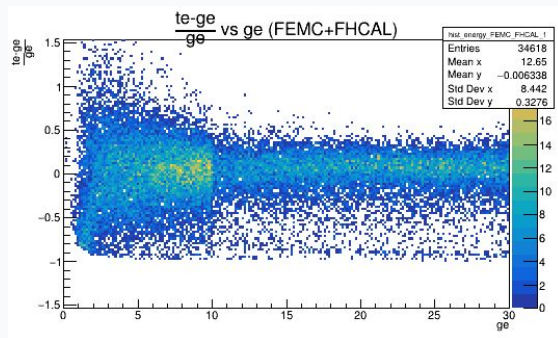
**$(\text{te}(\text{raw})/\text{CalibrationFactor}) * (\text{Mean of te/ge})$**

- Add the corresponding scaled tower energies of each individual calorimeter.
- Obtain TProfile plot for these summed up and scaled te/ge vs ge plots.
- **Use bin-wise mean values of the above Tprofile plot as the calibration factor.**
- Calculate the final calibrated tower energy  
**te(calibrated) =**  
**te(summed)/CalibrationFactor2**

# Pion: FEMC + FHCAL

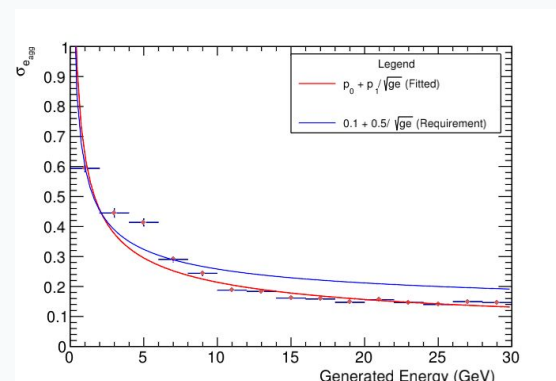
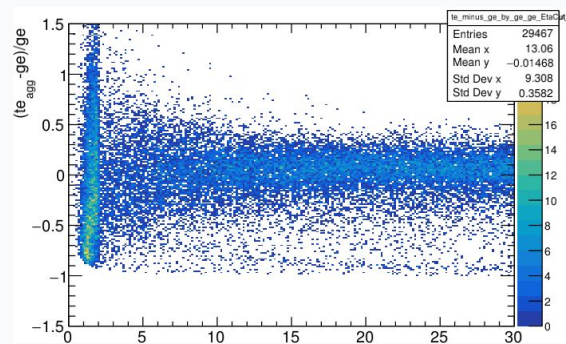
After Calibration

Group 1



$$\sigma_E/E = -2.06\% + 83.4\%/ \sqrt{E}$$

Group 2

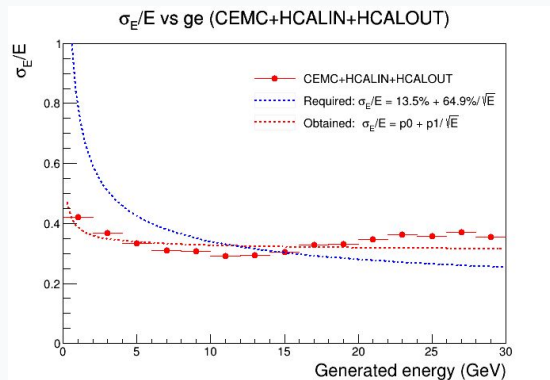
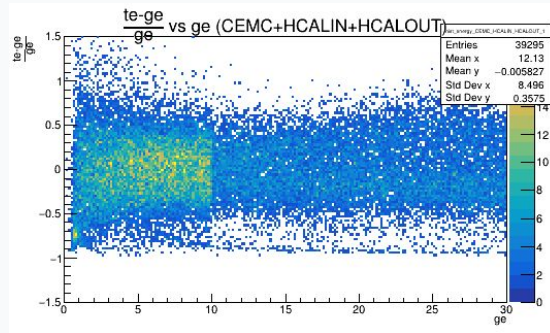


$$\sigma_E/E = 1.83\% + 61.9\%/ \sqrt{E}$$

- The obtained hadron energy resolution seems to match the minimum requirements for forward calorimeters.

# Pion: CEMC + HCALIN + HCALOUT

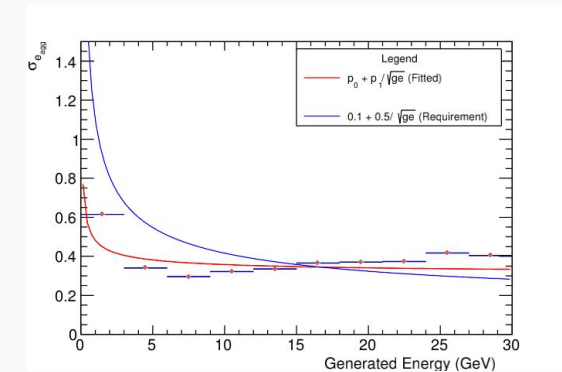
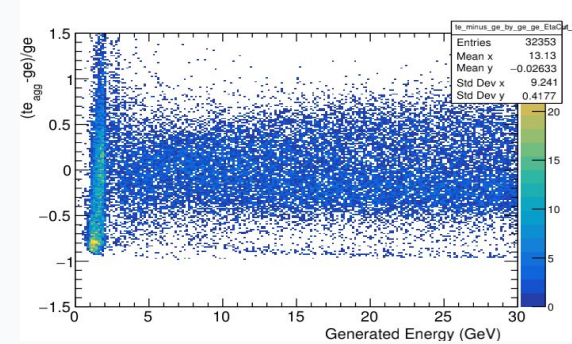
Group 1



$$\sigma_E/E = 29.95\% + 8.62\%/\sqrt{E}$$

After Calibration

Group 2



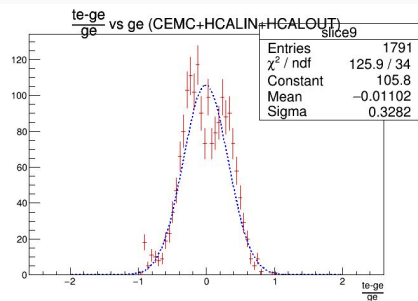
$$\sigma_E/E = 30.0277\% + 18.1573\%/\sqrt{E}$$

- The spread in energy distribution at high energies (>10 GeV) worsens the hadron energy resolution in the case of barrel calorimeters.

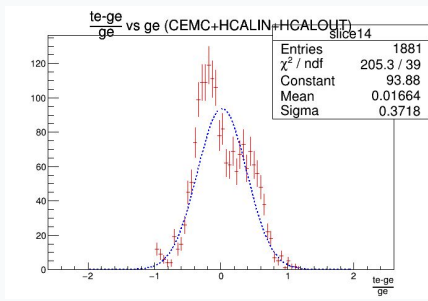
# Problem in Hadron Energy Resolution

## Group 1

### Barrel Calorimeters:

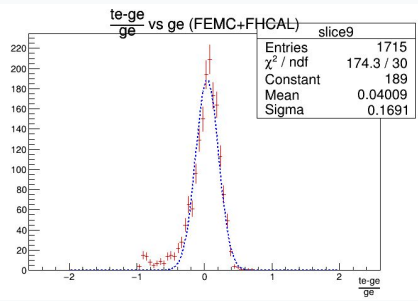


16-18 GeV

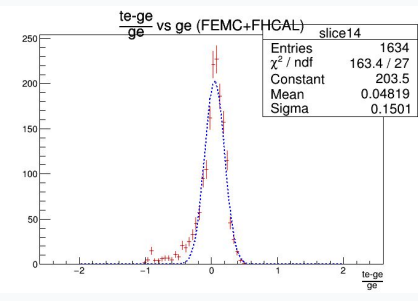


26-28 GeV

### Forward Calorimeters:



16-18 GeV

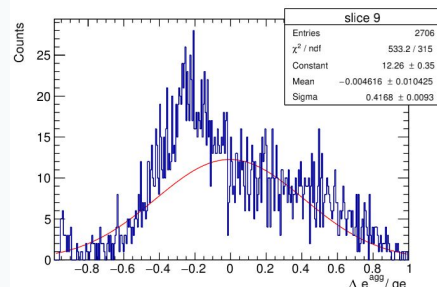


26-28 GeV

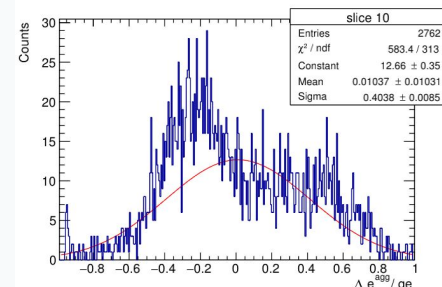
- The spreading of energies widens the gaussian fitting in case of barrel calorimeters while the calibration seems to work reasonably in the case of forward calorimeters. This spreading could be attributed to the calibration procedure used.

## Group 2

### Barrel Calorimeters:

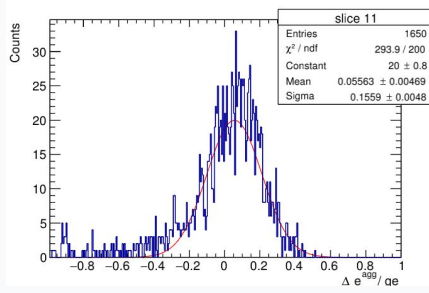


16-18 GeV

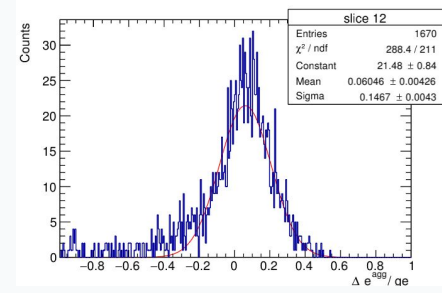


26-28 GeV

### Forward Calorimeters:



16-18 GeV

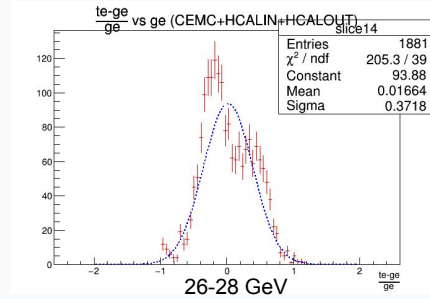
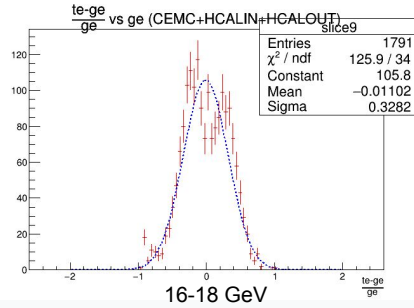


26-28 GeV

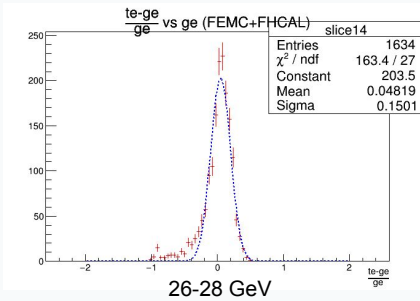
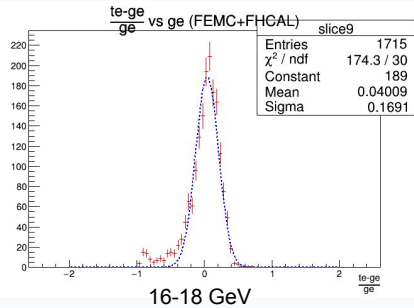
# Individual Slices for Barrel Calorimeters

## Group 1

### Barrel Calorimeters:

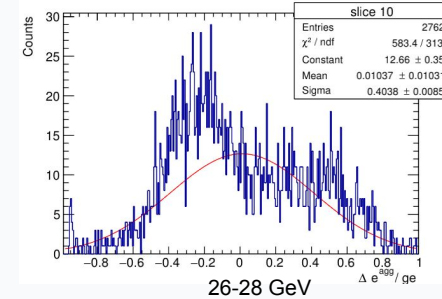
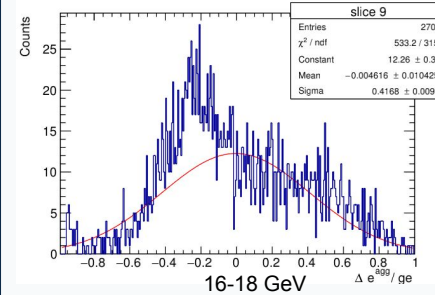


### Forward Calorimeters:

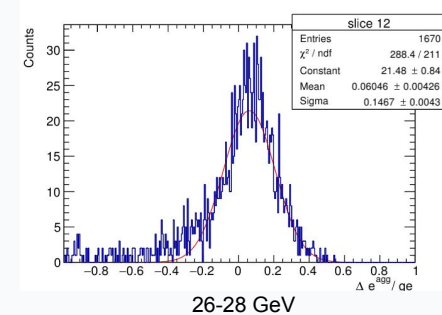
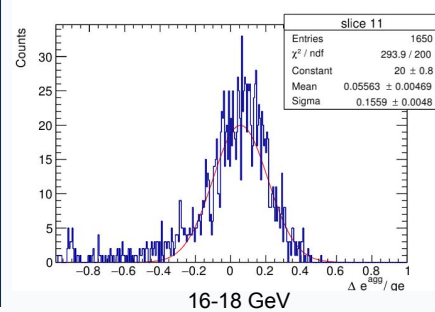


## Group 2

### Barrel Calorimeters:



### Forward Calorimeters:



- The spreading of energies widens the gaussian fitting in case of barrel calorimeters while the calibration seems to work reasonably in the case of forward calorimeters. This spreading could be attributed to the calibration procedure used.



# Summary

- The obtained electron energy resolution for EMCals seems to be reasonable.
- The obtained hadron energy resolution for the Forward Calorimeters seems to match the minimum requirements for incident energies higher than 6 GeV.
- The 'shouldering'\* in the case of Barrel Calorimeters detecting pions worsens the energy resolution at high energies.

\*Shouldering is the occurrence of a less pronounced second peak in the energy distribution slice, due to which the fitted gaussian widens.

# Next Steps

- Include Noise in the simulations to get a more realistic estimate of the energy resolution of the detectors

Need your expert feedback regarding

- ▶ Improvement of the clustering method employed on the towers
- ▶ Calibration of the calorimeters

What are your comments/suggestions?

# Backup Slides

Pion : CEMC + HCALIN + HCALOUT

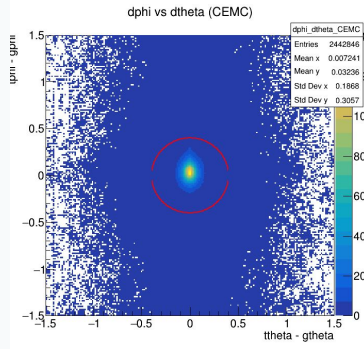
# Pion: CEMC + HCALIN + HCALOUT

Group 1

Manual Clustering

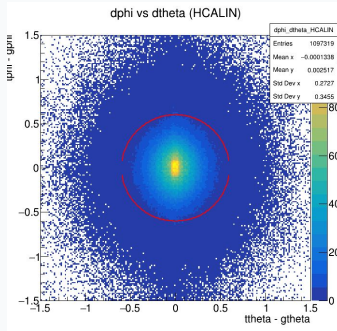
Group 2

CEMC:

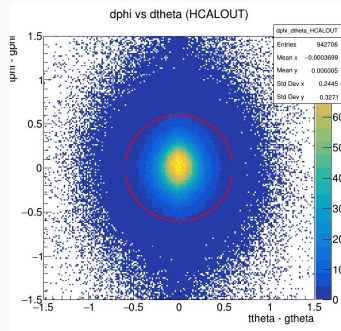


Radius = 0.40 units

HCAL:

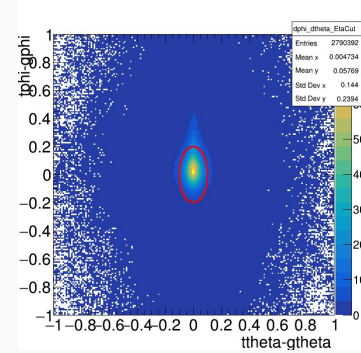


Radius = 0.60 units



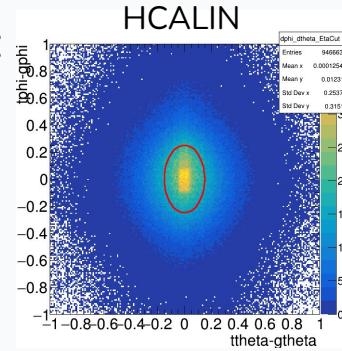
Radius = 0.60 units

CEMC:

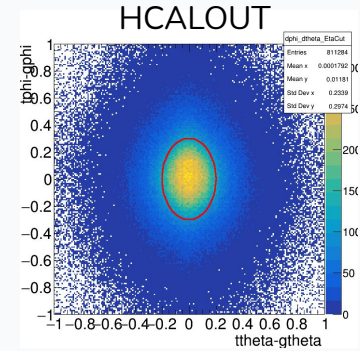


semi-minor axis = 0.10 units  
semi-major axis = 0.20 units

HCAL:



semi-minor axis = 0.15 units  
semi-major axis = 0.25 units

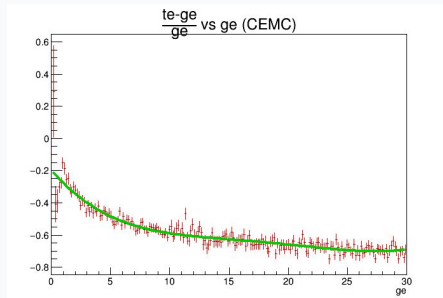
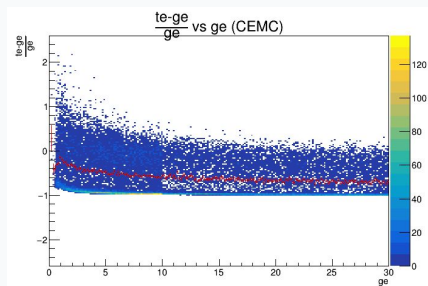


semi-minor axis = 0.20 units  
semi-major axis = 0.30 units

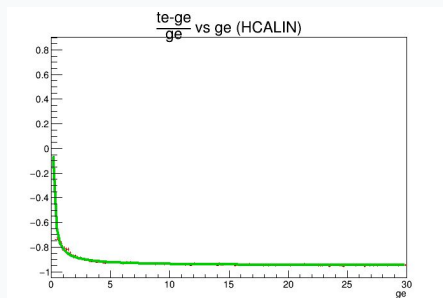
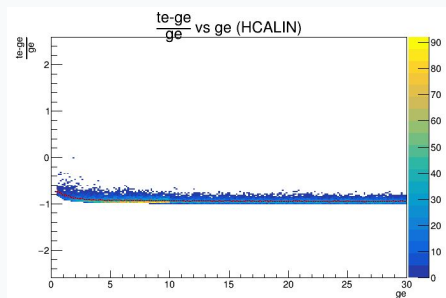
# Pion: CEMC + HCALIN + HCALOUT

## Steps involved in calibration

### Group 1

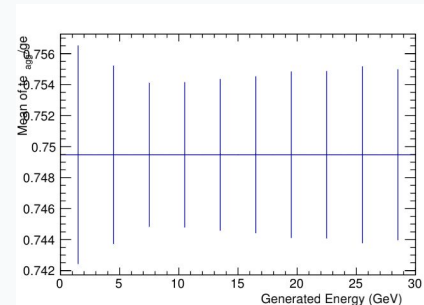
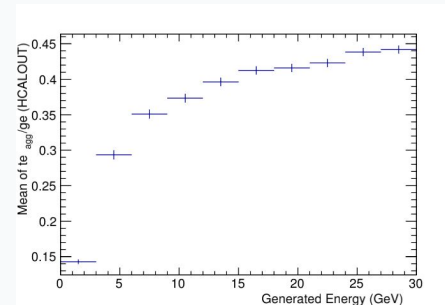
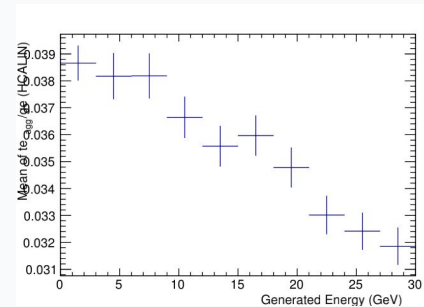
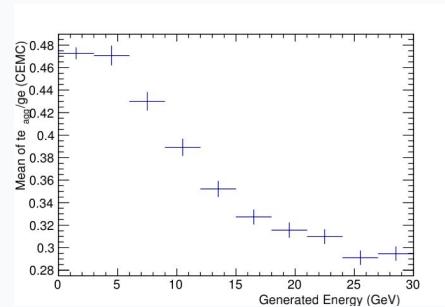


Weight for CEMC = 0.444424



Weight for HCalIN = 0.0679849

### Group 2

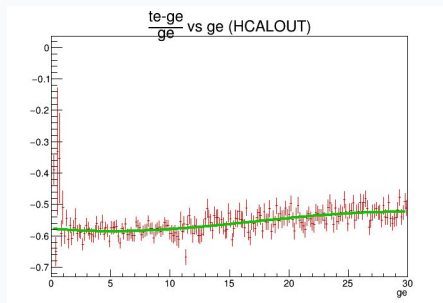
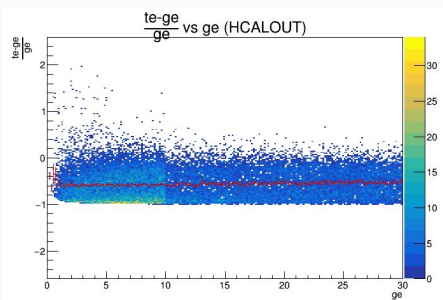




# Pion: CEMC + HCALIN + HCALOUT

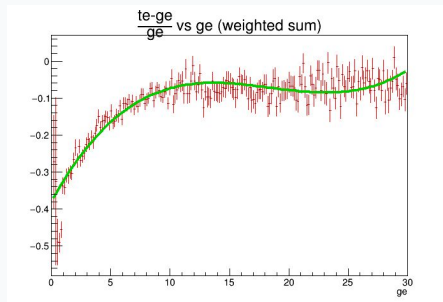
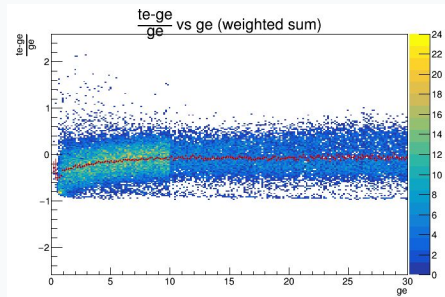
## Steps involved in calibration

### Group 1



Weight for HCALOUT = 0.436801

Sum of weights is  $0.444424 + 0.0679849 + 0.436801 = 0.94921$



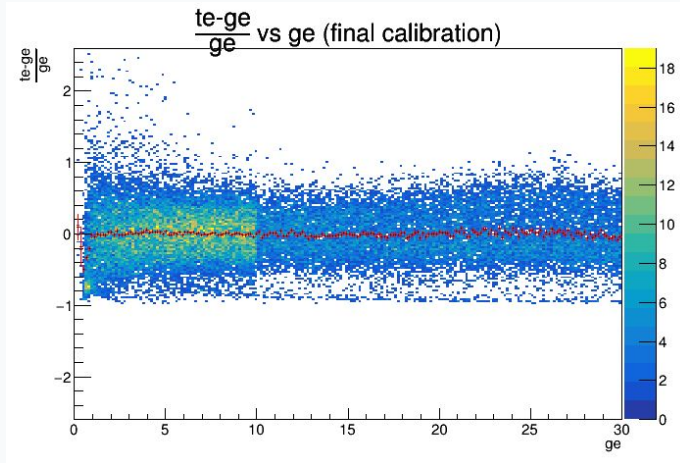
### Group 2

# Pion: CEMC + HCALIN + HCALOUT

## Steps involved in calibration

Group 1

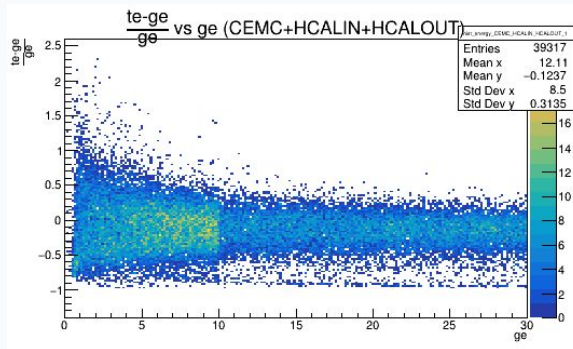
Group 2



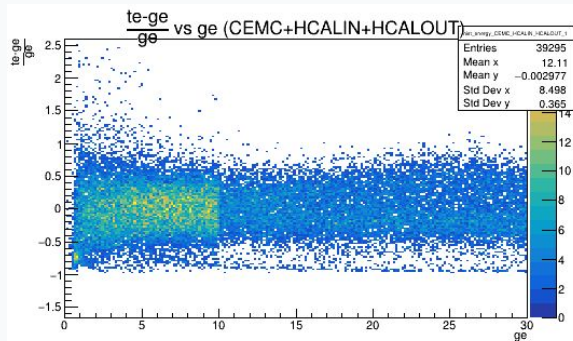
# Pion: CEMC + HCALIN + HCALOUT

## Group 1

Before Calibration

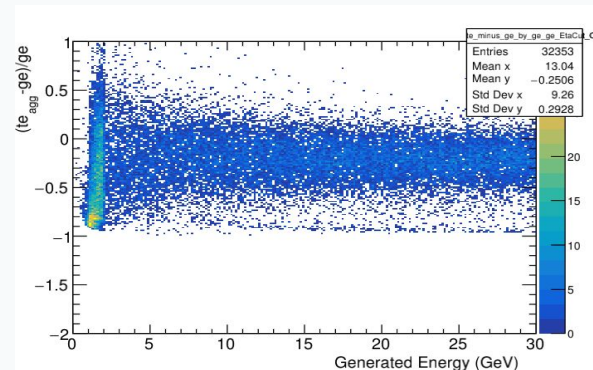


After Calibration

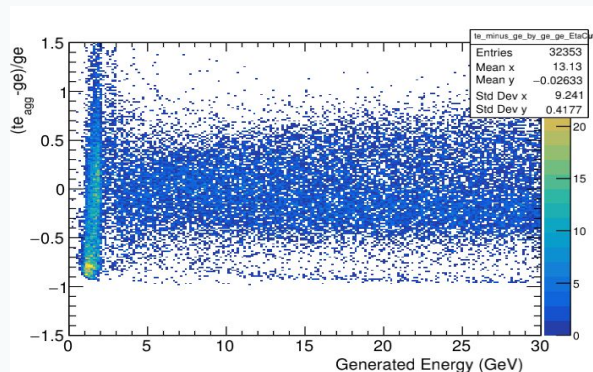


## Group 2

Before Calibration



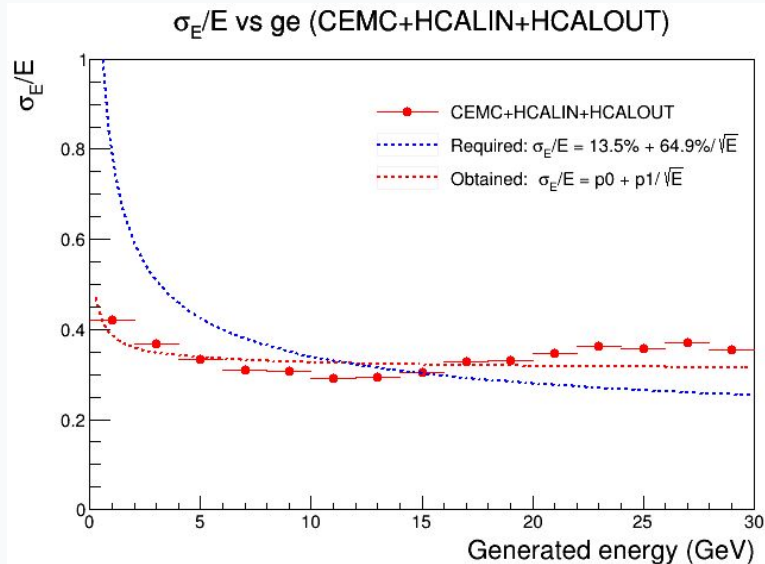
After Calibration



# Pion: CEMC + HCALIN + HCALOUT

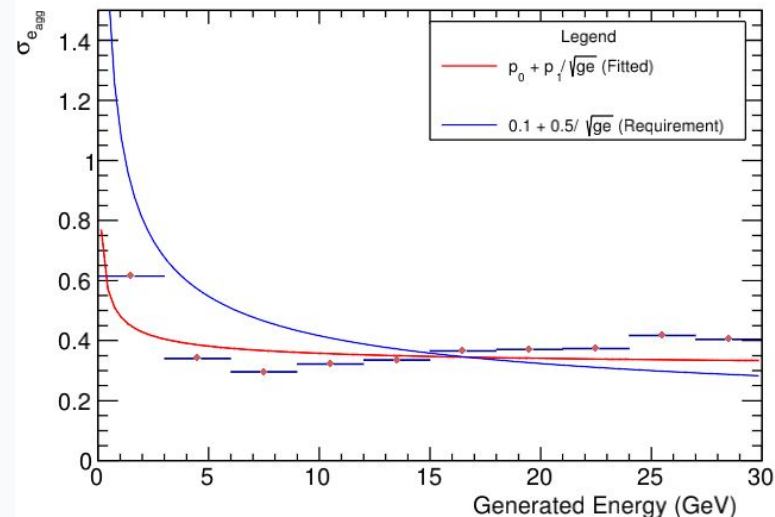
## After Calibration

Group 1



$$\sigma_E/E = 29.9479\% + 8.62227\%/ \sqrt{E}$$

Group 2



$$\sigma_E/E = 30.0277\% + 18.1573\%/ \sqrt{E}$$

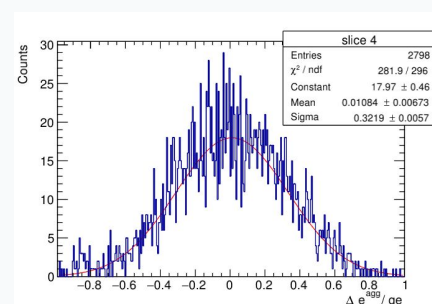
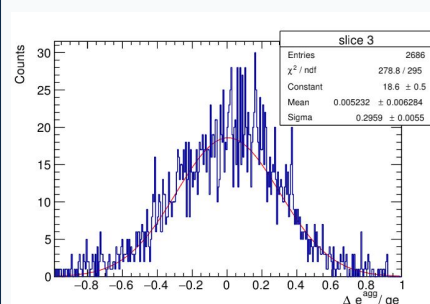
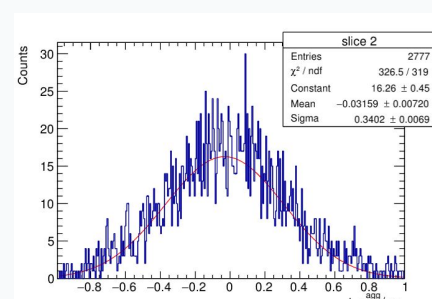
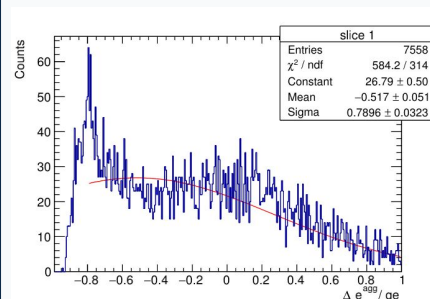
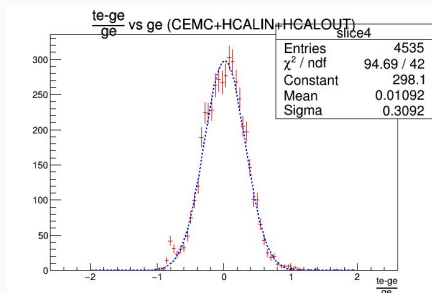
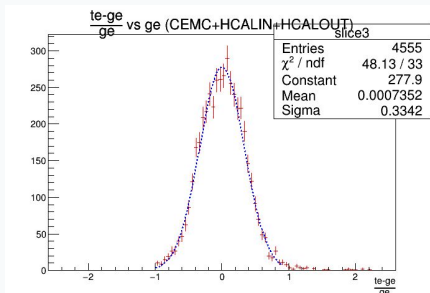
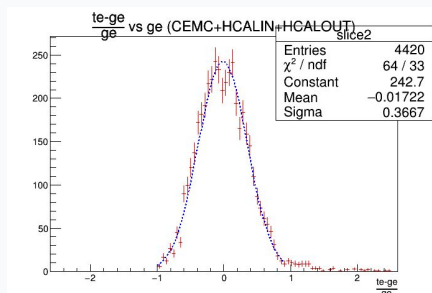
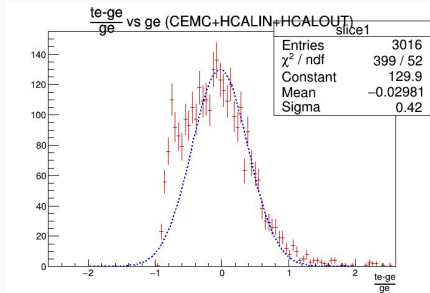
# Pion: CEMC + HCALIN + HCALOUT

After Calibration

Fit Slices

Group 1

Group 2



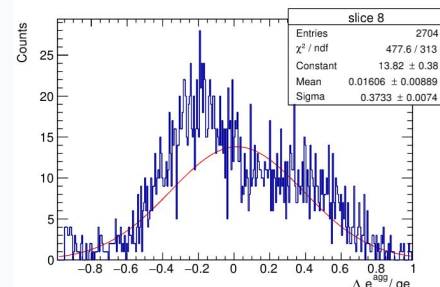
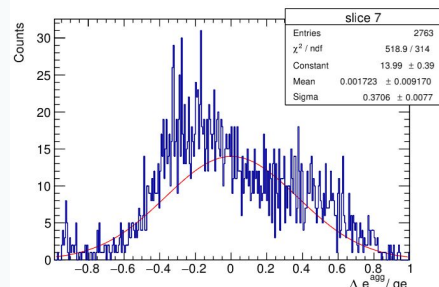
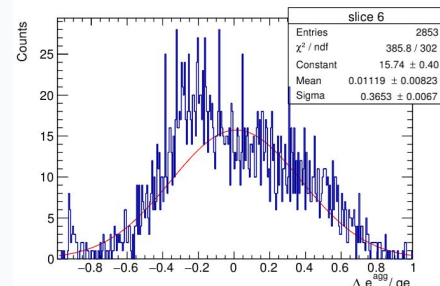
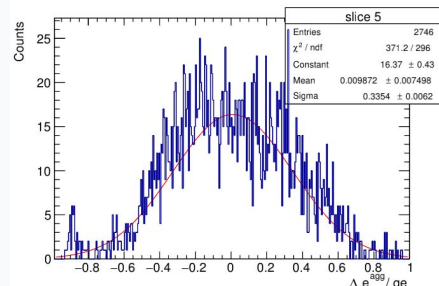
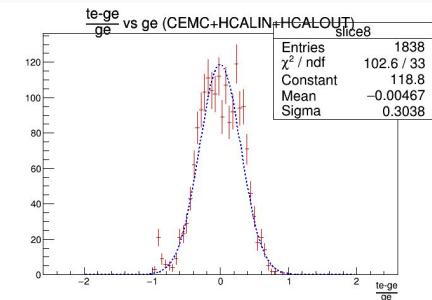
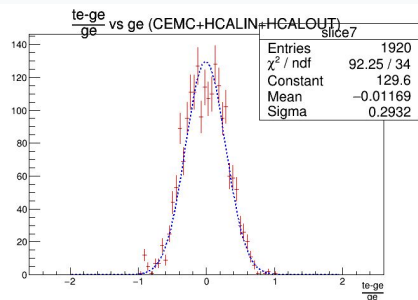
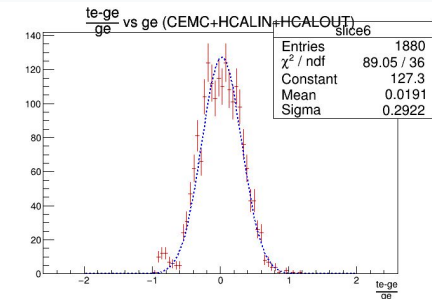
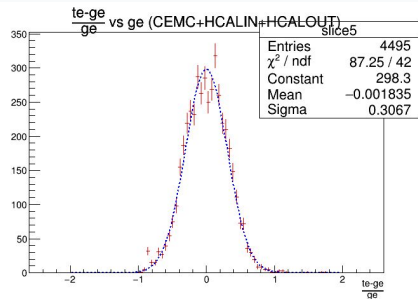
# Pion: CEMC + HCALIN + HCALOUT

After Calibration

Group 1

Fit Slices

Group 2





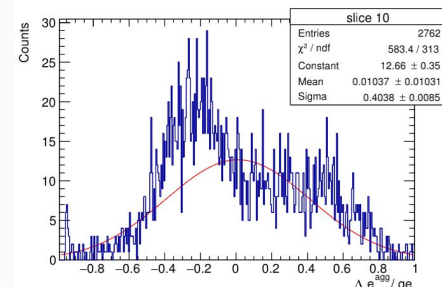
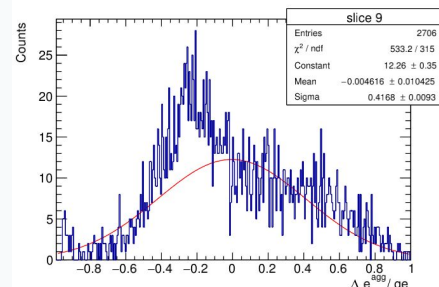
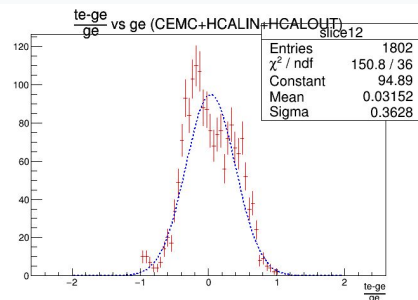
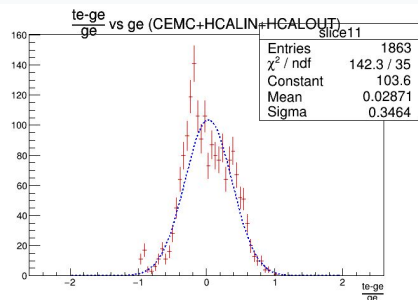
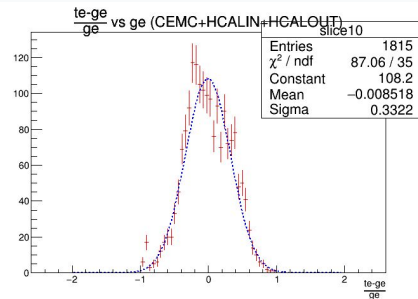
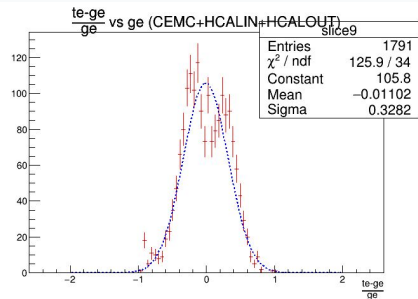
# Pion: CEMC + HCALIN + HCALOUT

After Calibration

Group 1

Fit Slices

Group 2

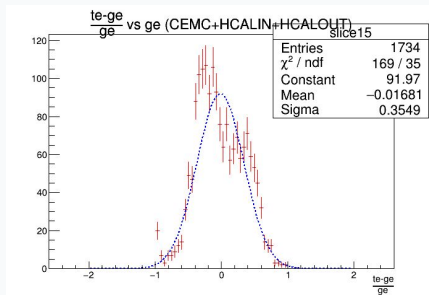
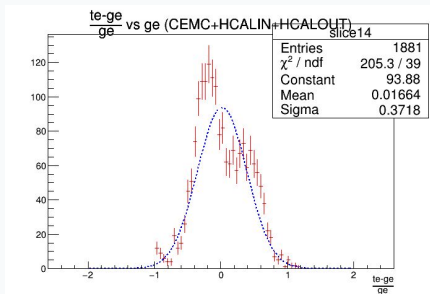
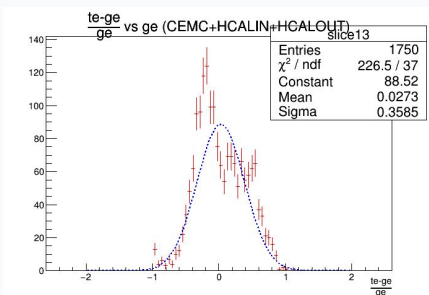


# Pion: CEMC + HCALIN + HCALOUT

## After Calibration

### Fit Slices

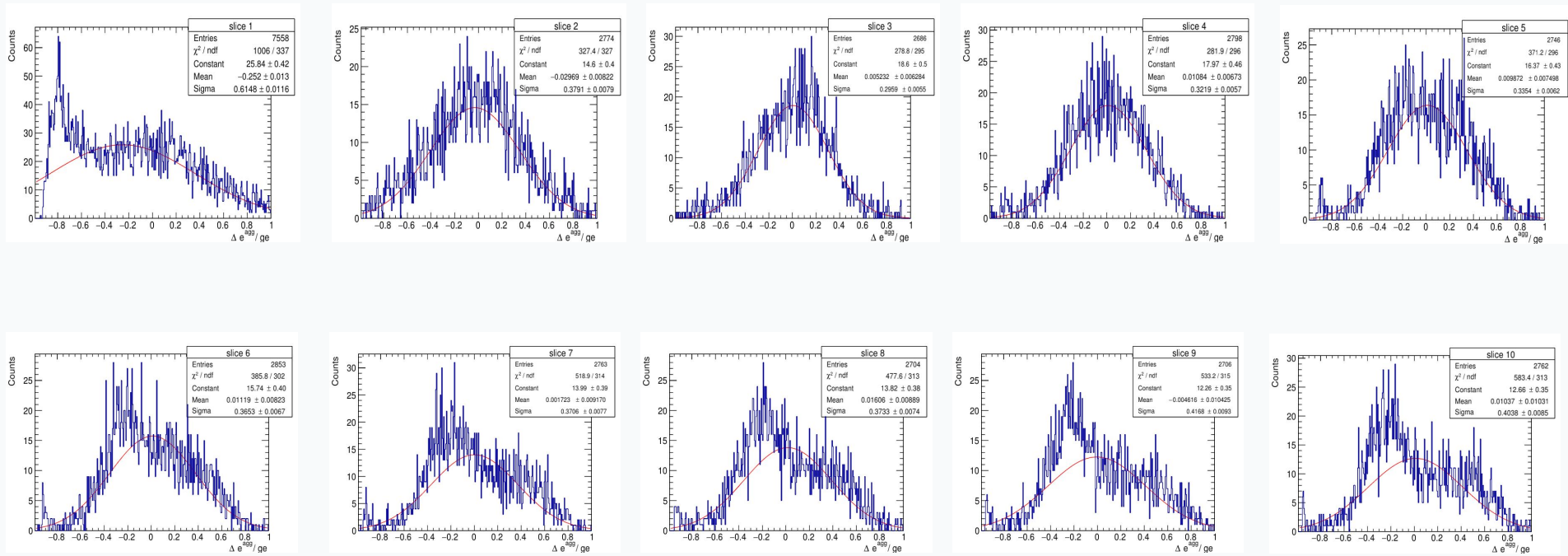
Group 1



# Pion: CEMC + HCALIN + HCALOUT

## After Calibration

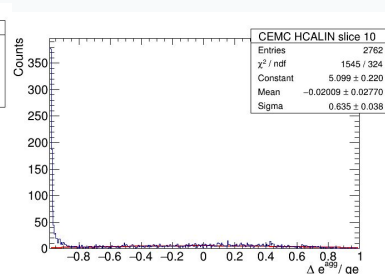
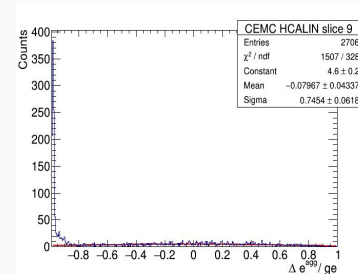
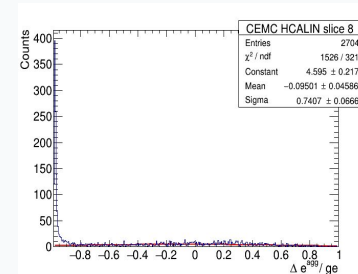
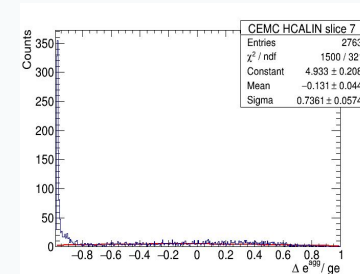
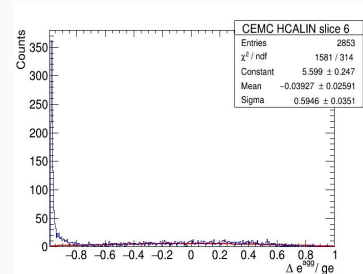
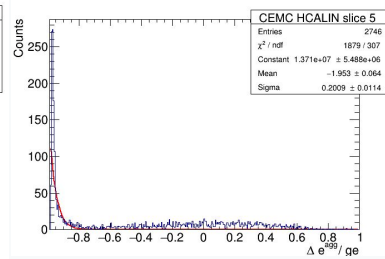
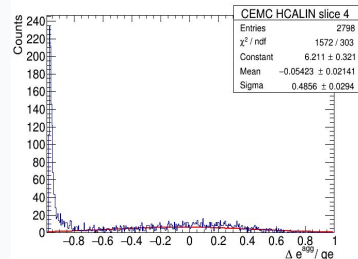
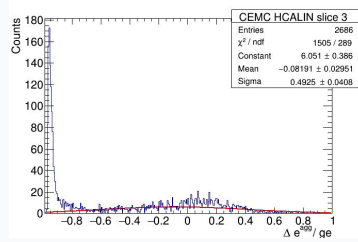
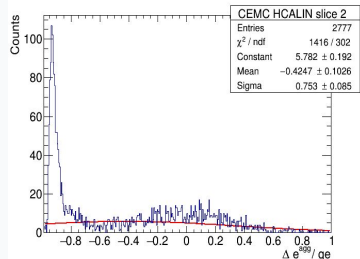
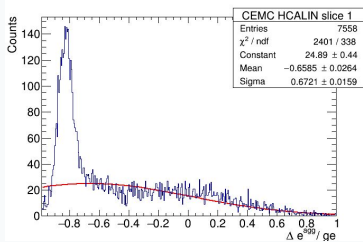
### Fit Slices



# Pion: CEMC + HCALIN

## After Calibration

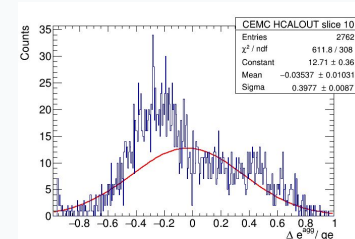
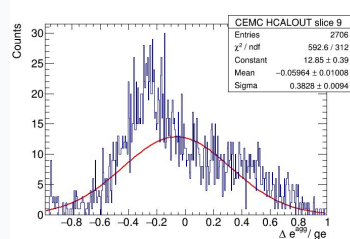
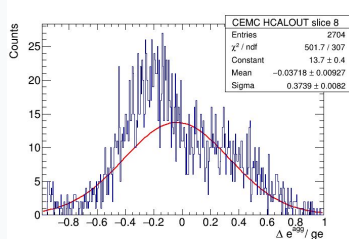
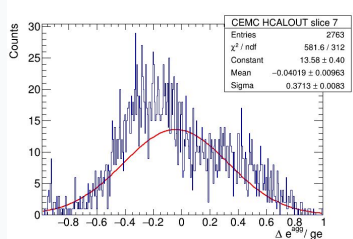
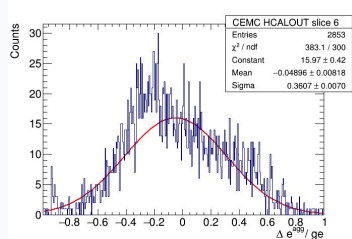
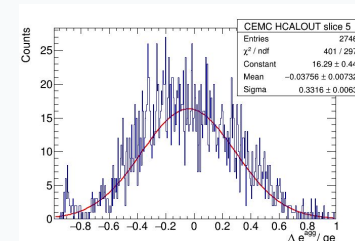
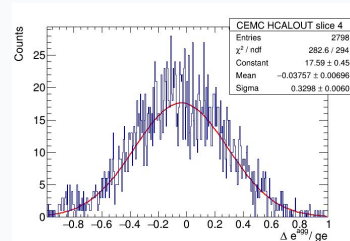
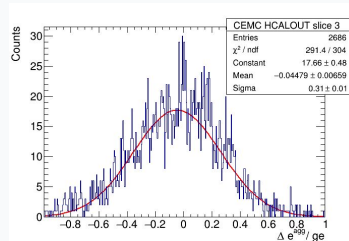
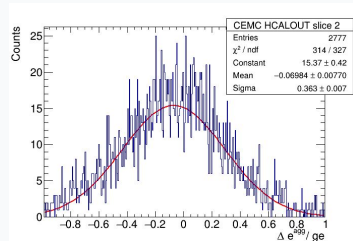
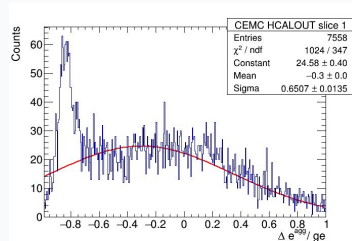
### Fit Slices



# Pion: CEMC + HCALOUT

## After Calibration

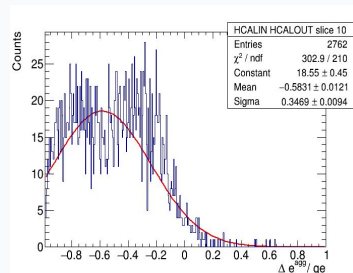
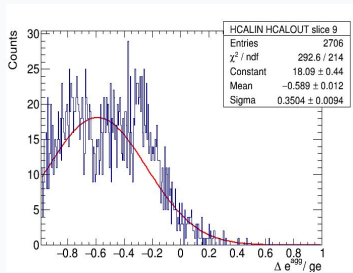
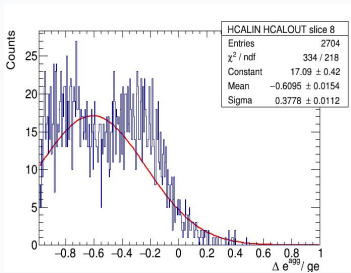
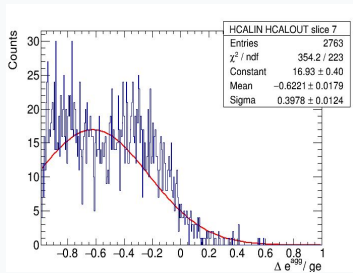
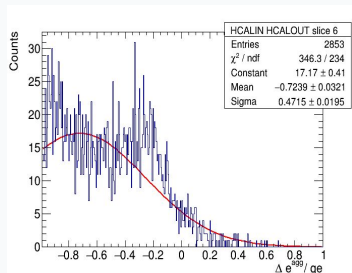
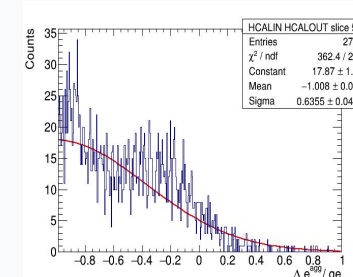
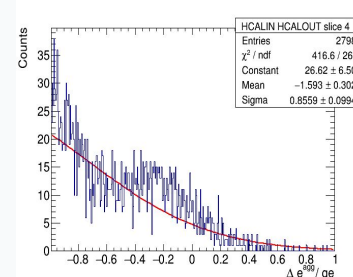
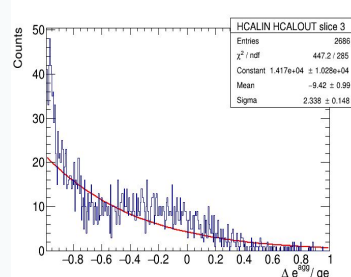
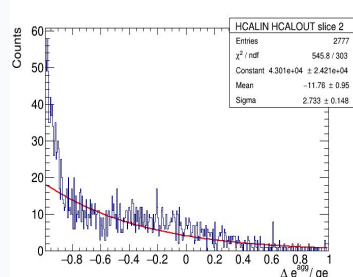
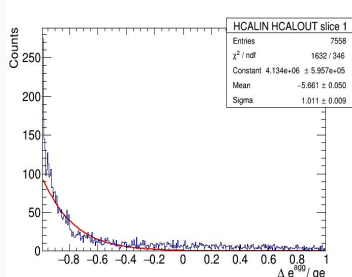
### Fit Slices



# Pion: HCALIN + HCALOUT

## After Calibration

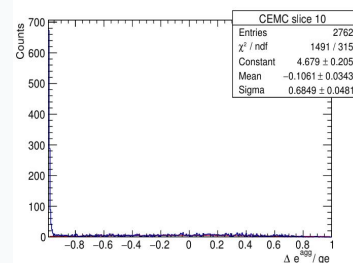
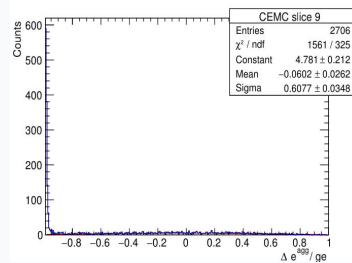
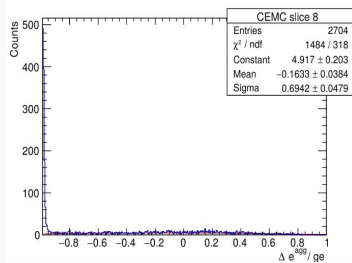
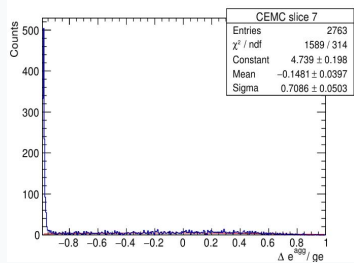
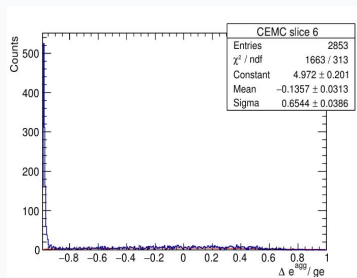
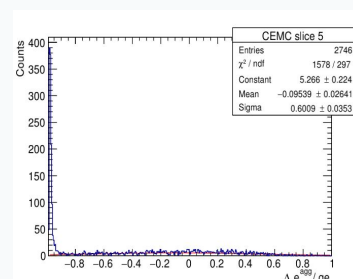
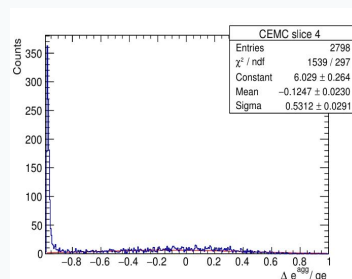
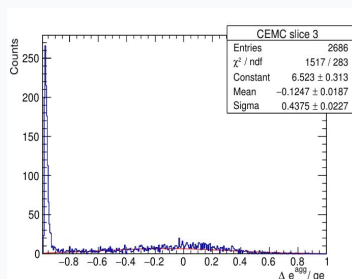
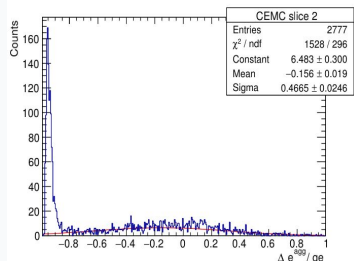
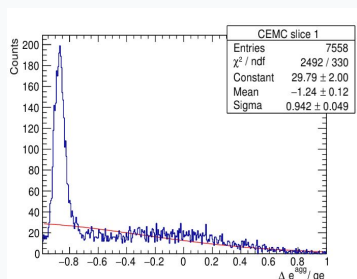
### Fit Slices



# Pion: CEMC

## After Calibration

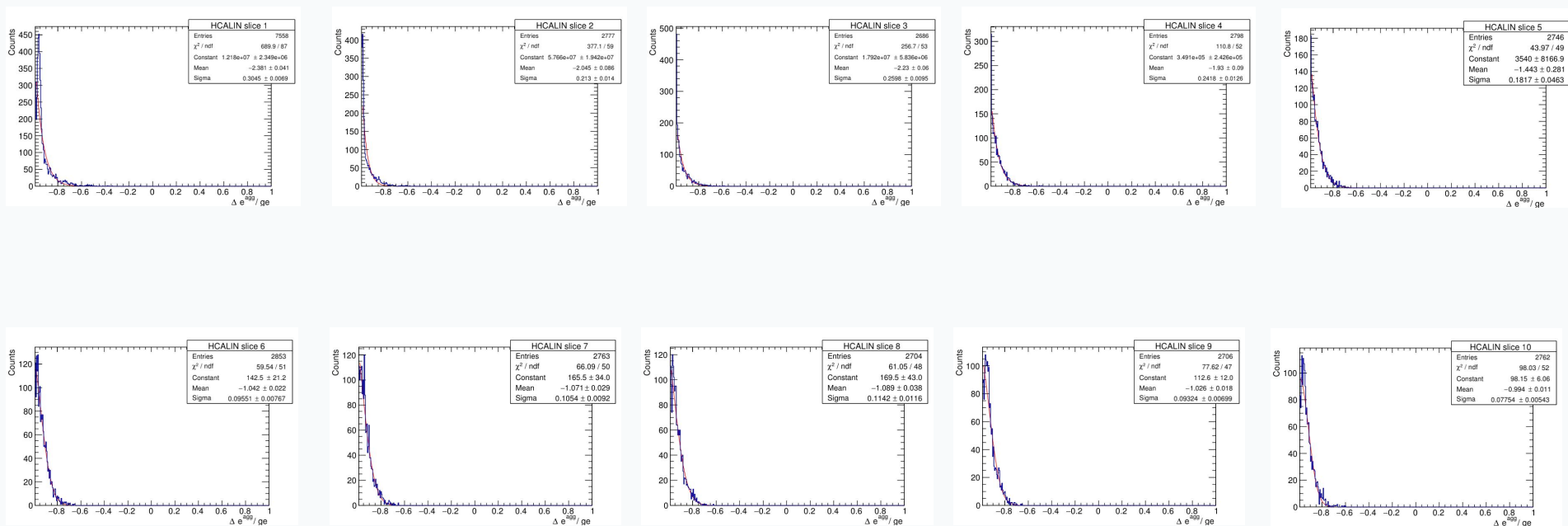
### Fit Slices



# Pion: HCALIN

## After Calibration

### Fit Slices

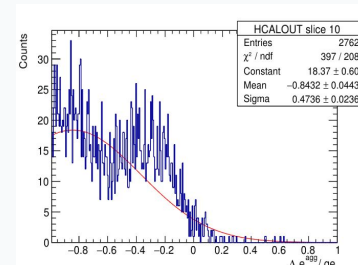
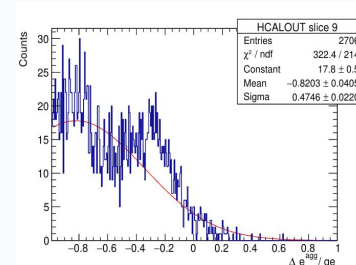
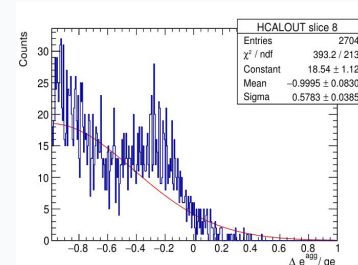
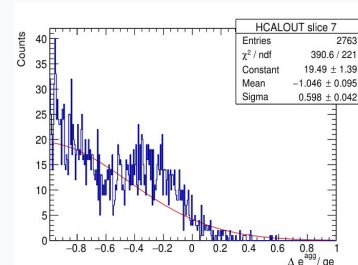
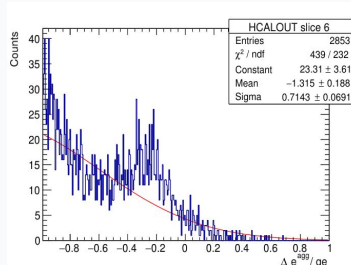
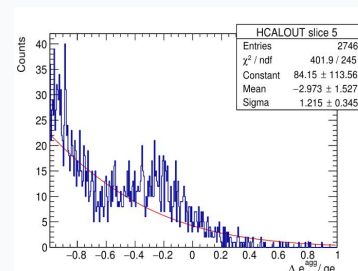
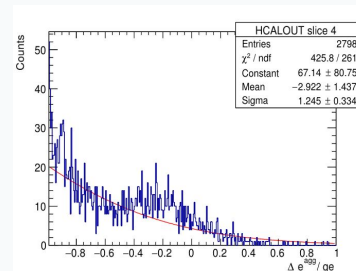
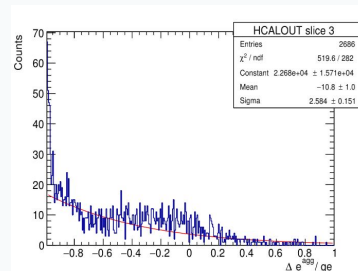
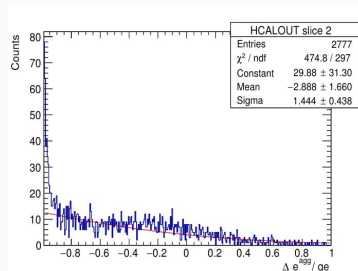
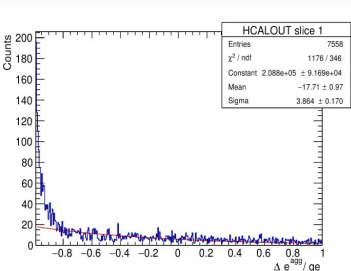




# Pion: HCALOUT

## After Calibration

### Fit Slices



Pion : FEMC + FHCAL

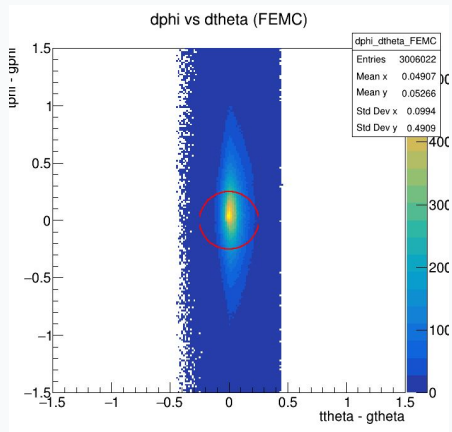
# Pion: FEMC + FHCAL

Group 1

Manual Clustering

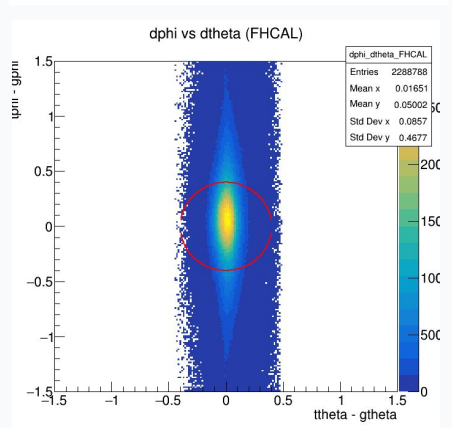
Group 2

FEMC:



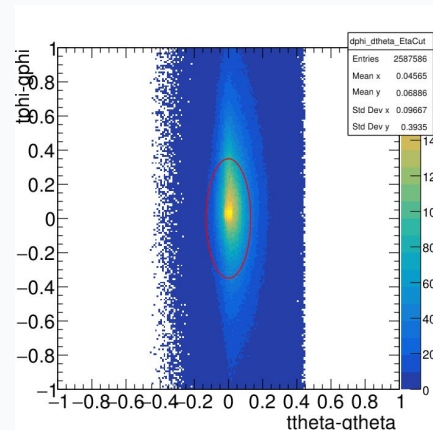
Radius = 0.25 units

FHCAL:



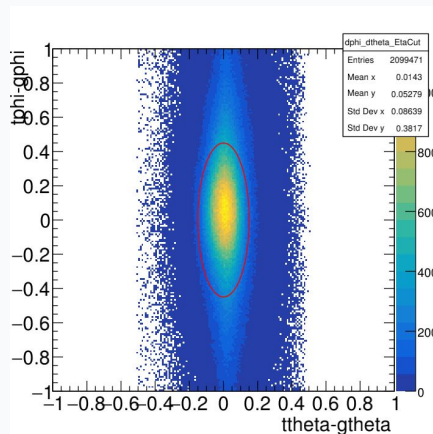
Radius = 0.40 units

FEMC:



semi-minor axis = 0.13 units  
semi-major axis = 0.35 units

FHCAL:

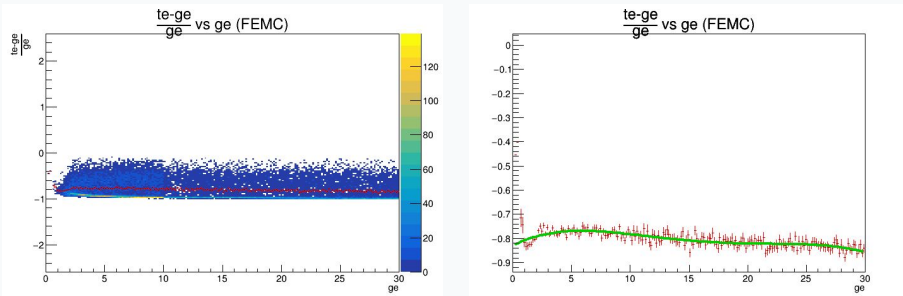


semi-minor axis = 0.13 units  
semi-major axis = 0.35 units

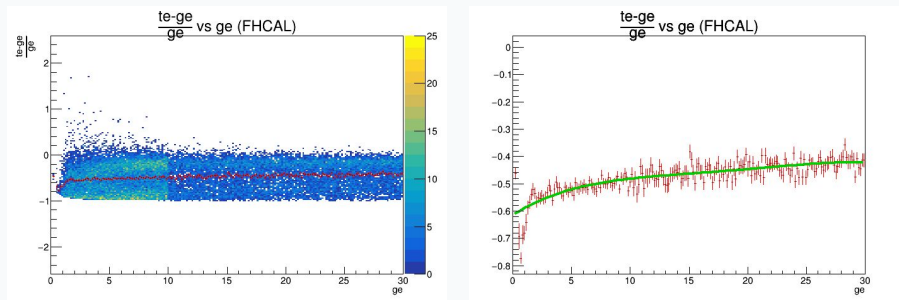
# Pion: FEMC + FHCAL

## Steps involved in calibration

### Group 1



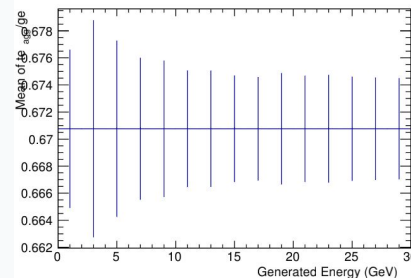
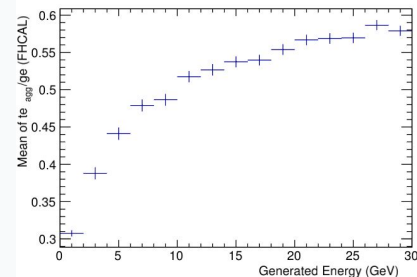
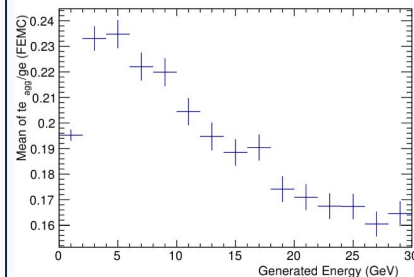
Weight for FEMC = 0.205014



Weight for FHCAL = 0.519019

Sum of weights is  $0.205014 + 0.519019 = 0.724032$

### Group 2

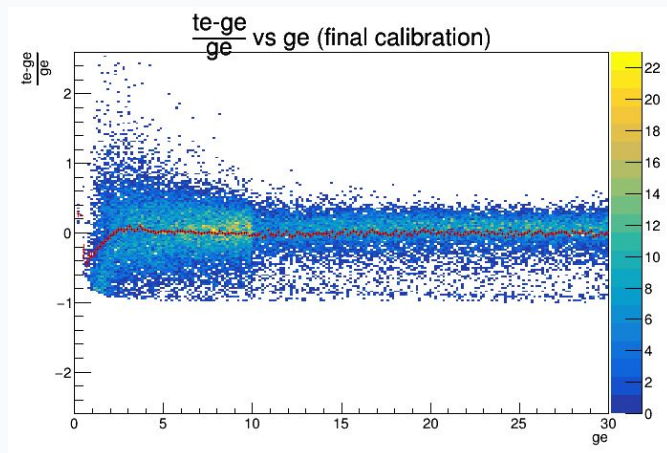
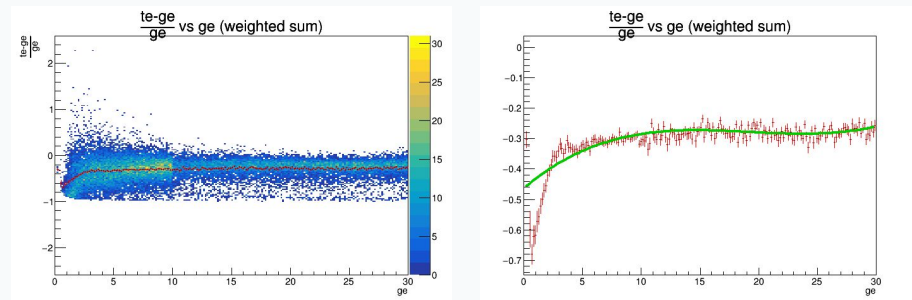


# Pion: FEMC + FHCAL

## Steps involved in calibration

Group 1

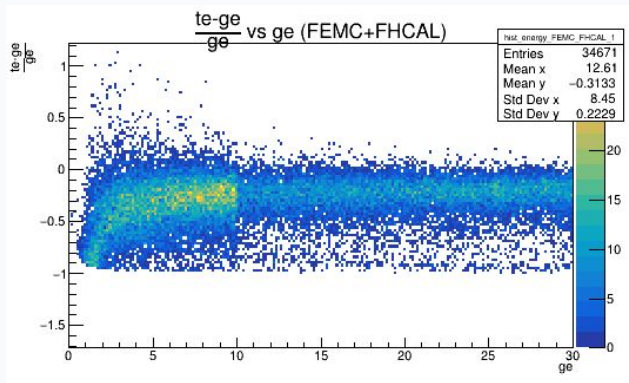
Group 2



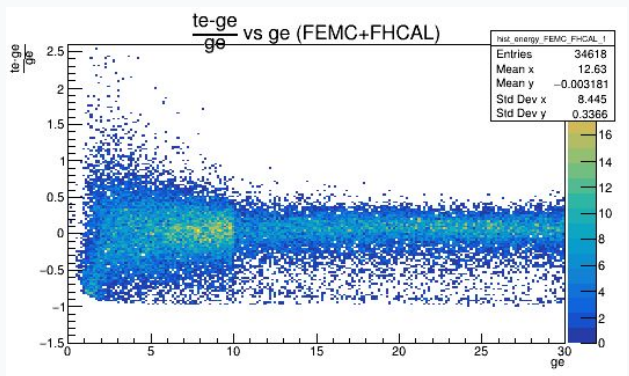
# Pion: FEMC + FHCAL

## Group 1

Before Calibration

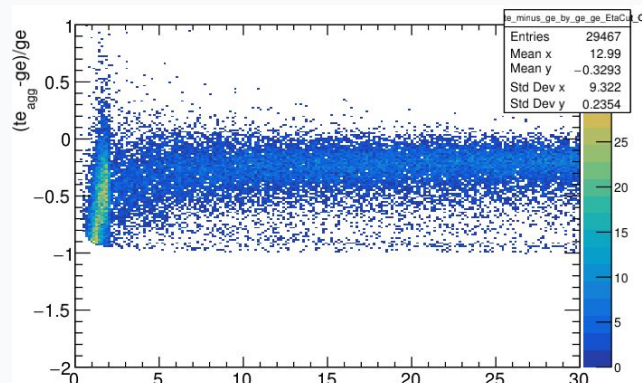


After Calibration

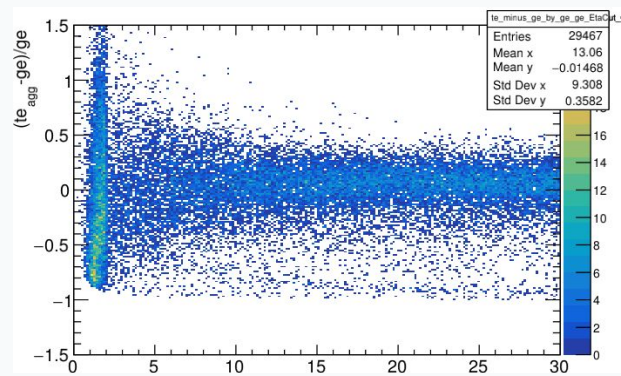


## Group 2

Before Calibration



After Calibration

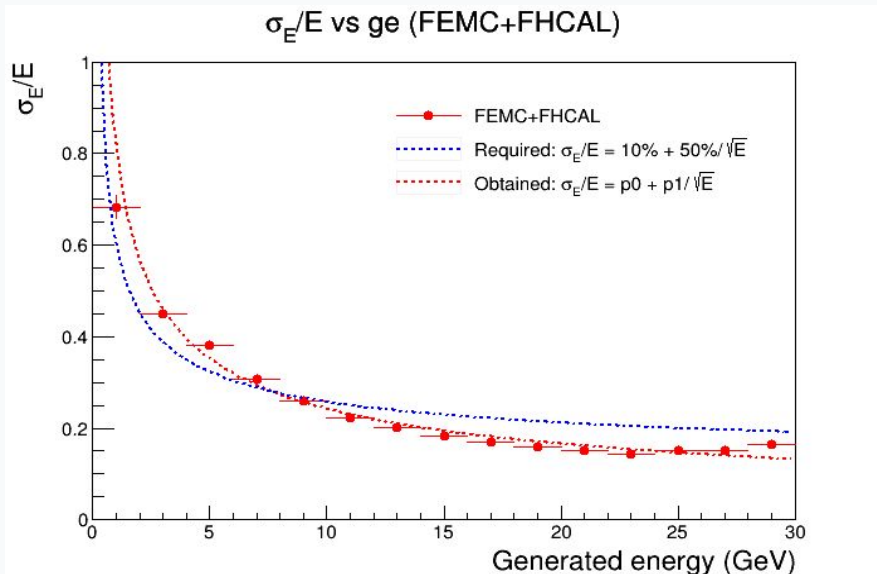


# Pion: FEMC + FHCAL

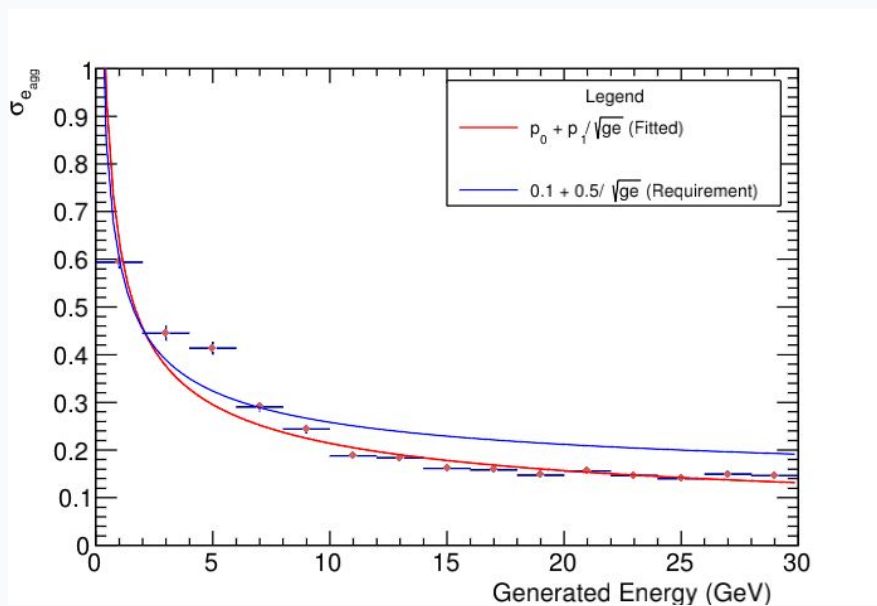
Group 1

After Calibration

Group 2



$$\sigma_E/E = -2.06291\% + 83.4022\%/\sqrt{E}$$



$$\sigma_E/E = 1.83350\% + 61.9024\%/\sqrt{E}$$

- The obtained hadron energy resolution seems to match the minimum requirements for forward calorimeters.

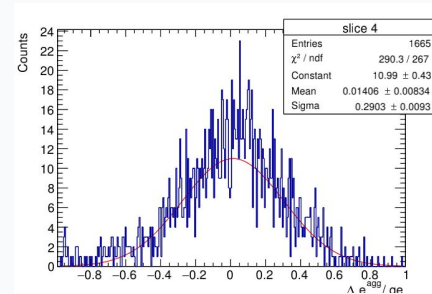
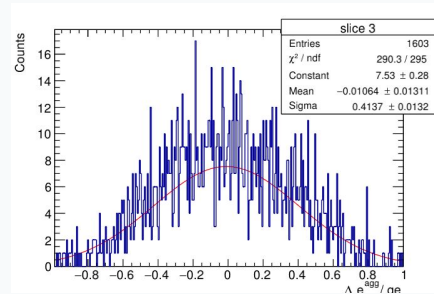
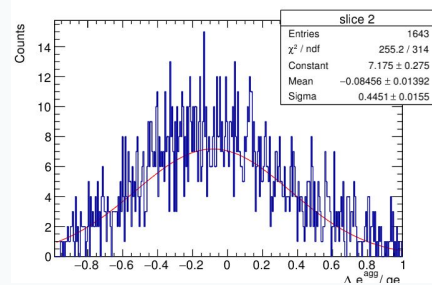
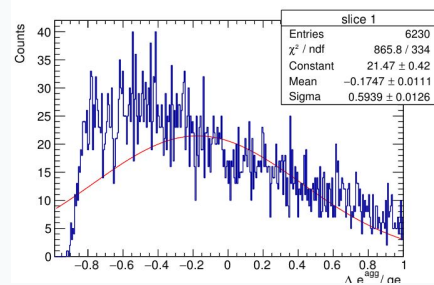
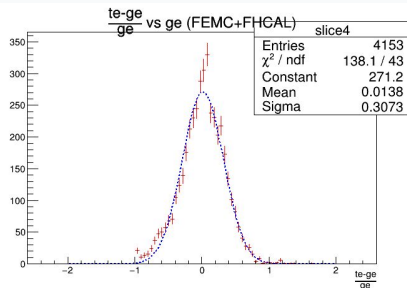
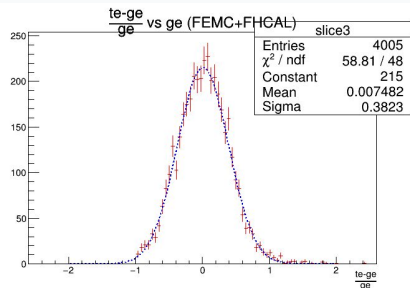
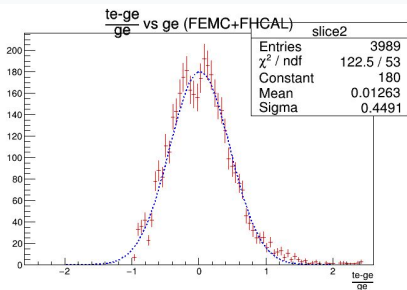
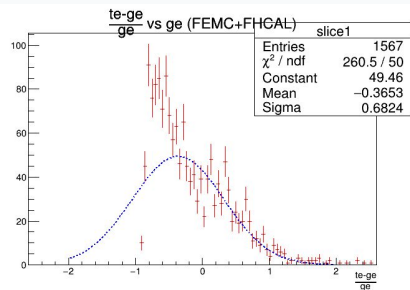
# Pion: FEMC + FHCAL

After Calibration

Group 1

Fit Slices

Group 2





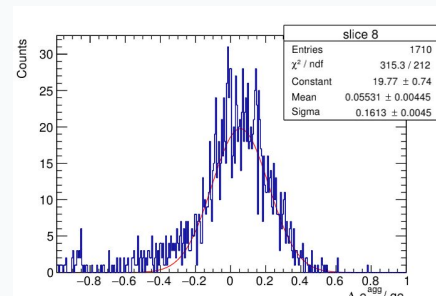
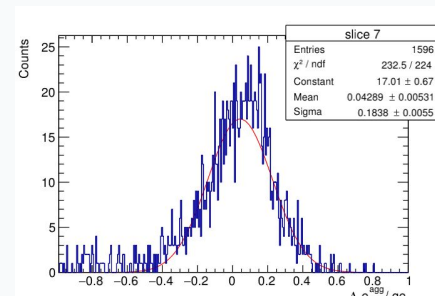
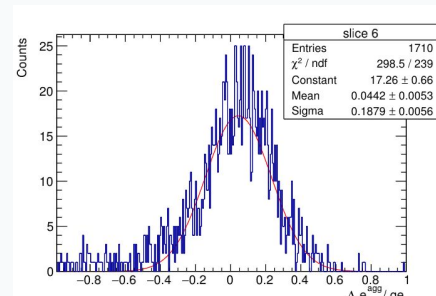
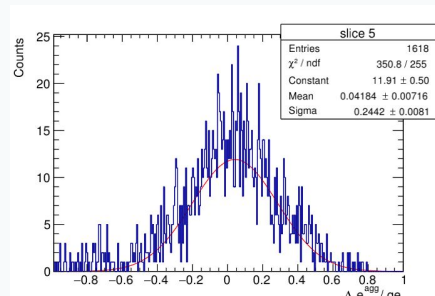
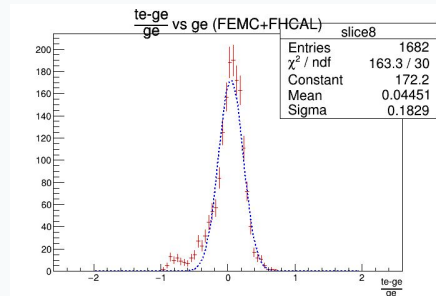
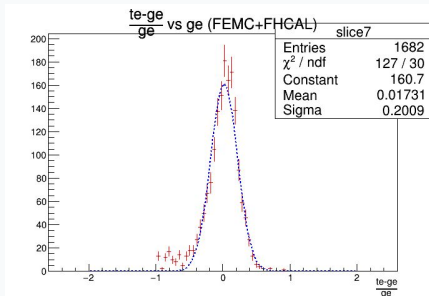
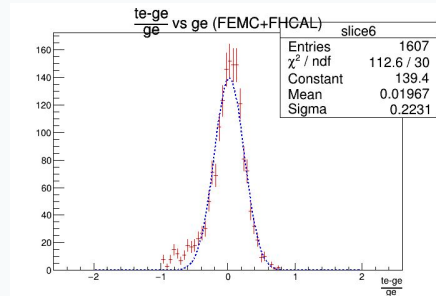
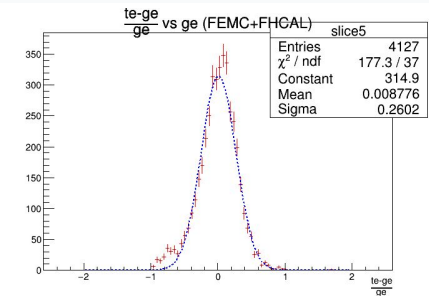
# Pion: FEMC + FHCAL

After Calibration

Fit Slices

Group 1

Group 2



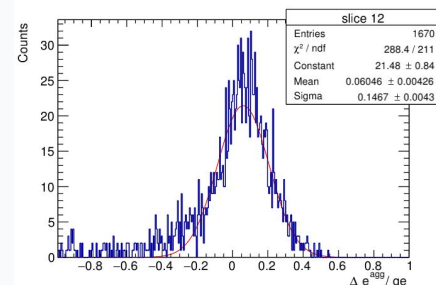
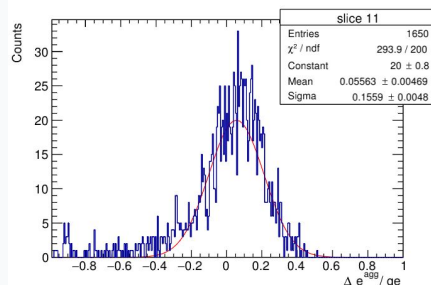
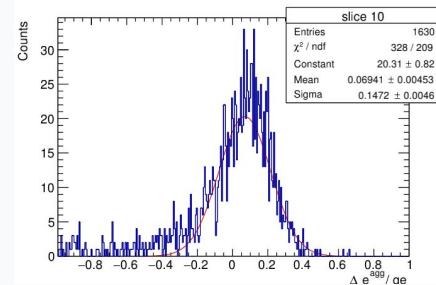
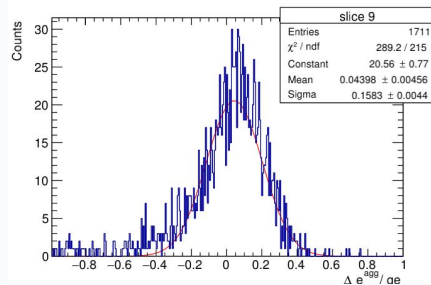
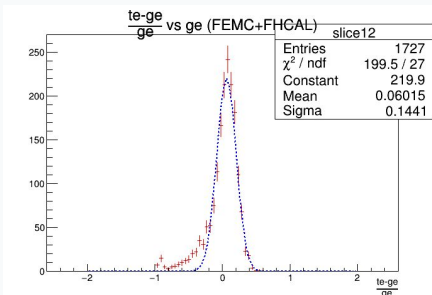
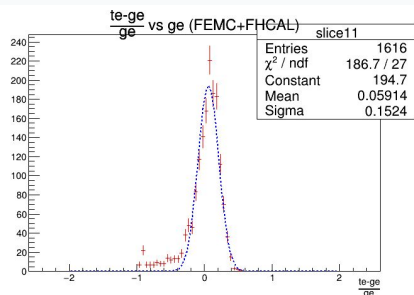
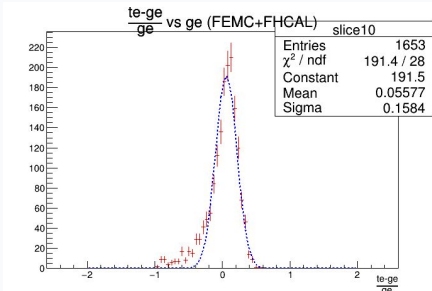
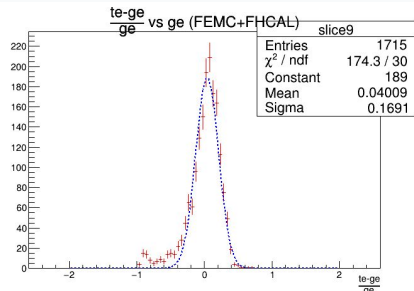
# Pion: FEMC + FHCAL

After Calibration

Group 1

Fit Slices

Group 2



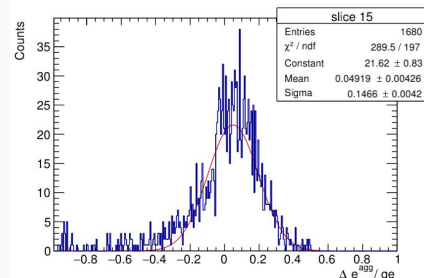
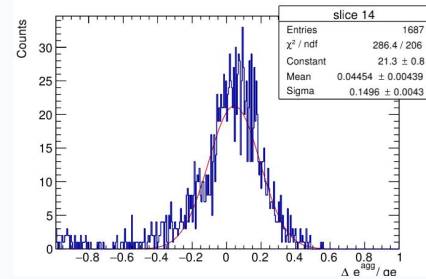
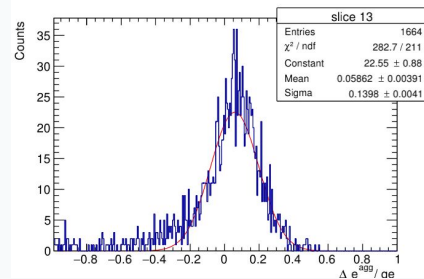
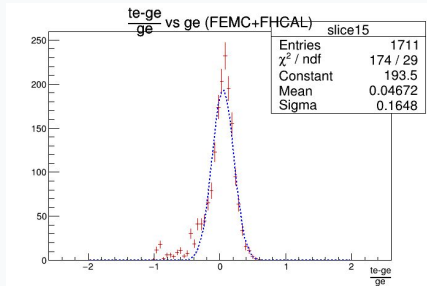
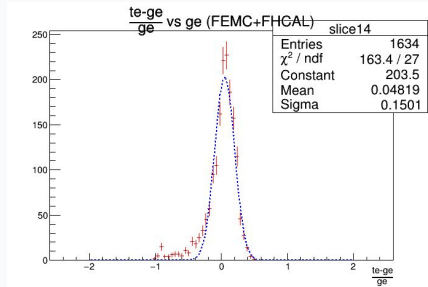
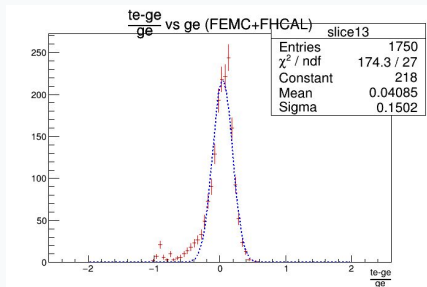
# Pion: FEMC + FHCAL

After Calibration

Fit Slices

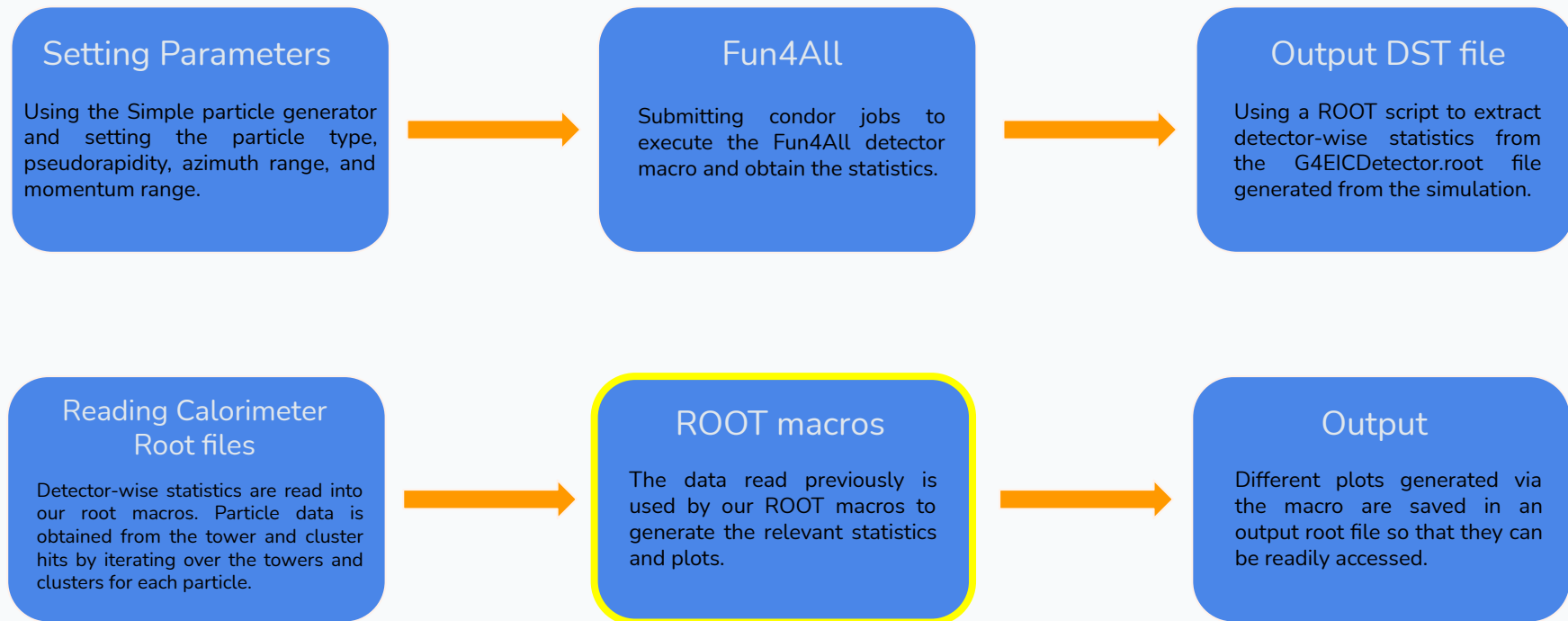
Group 1

Group 2



# Workflow

Fun4all is a C++ based framework steered by ROOT macros, that runs GEANT4 based full detector simulations, raw data reconstruction, and analysis.



# Eta Cuts Employed

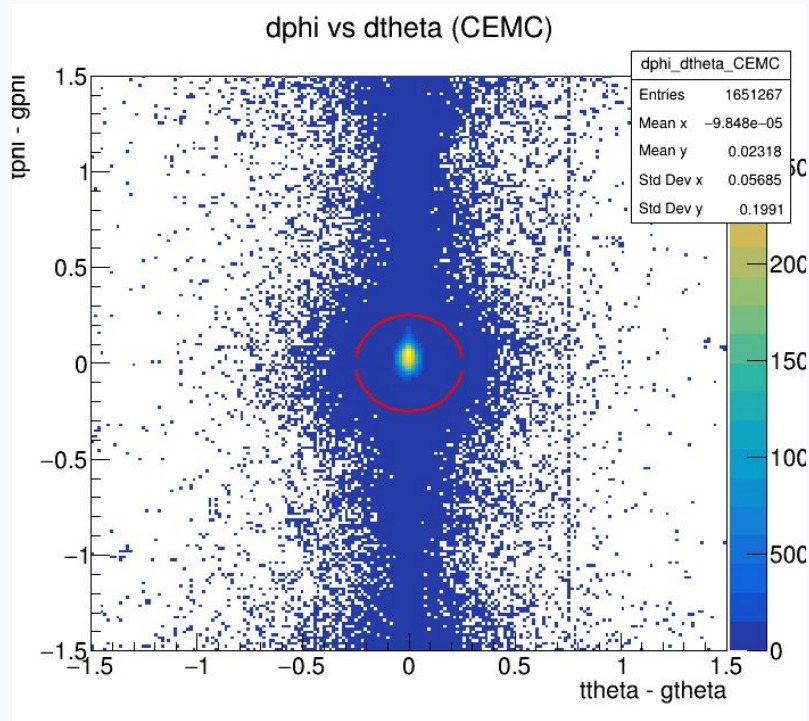
- Detector-wise eta cuts
  - Electron:
    - CEMC:  $\eta = -1.5$  to  $1.2$
    - FEMC:  $\eta = 1.3$  to  $3.3$
    - EEMC:  $\eta = -3.5$  to  $-1.7$
  - Pion:
    - CEMC, HCALIN, HCALOUT:  $\eta = -1.1$  to  $1.1$
    - FEMC, FHCAL:  $\eta = 1.3$  to  $3.3$

Electron : CEMC

# Electron: CEMC

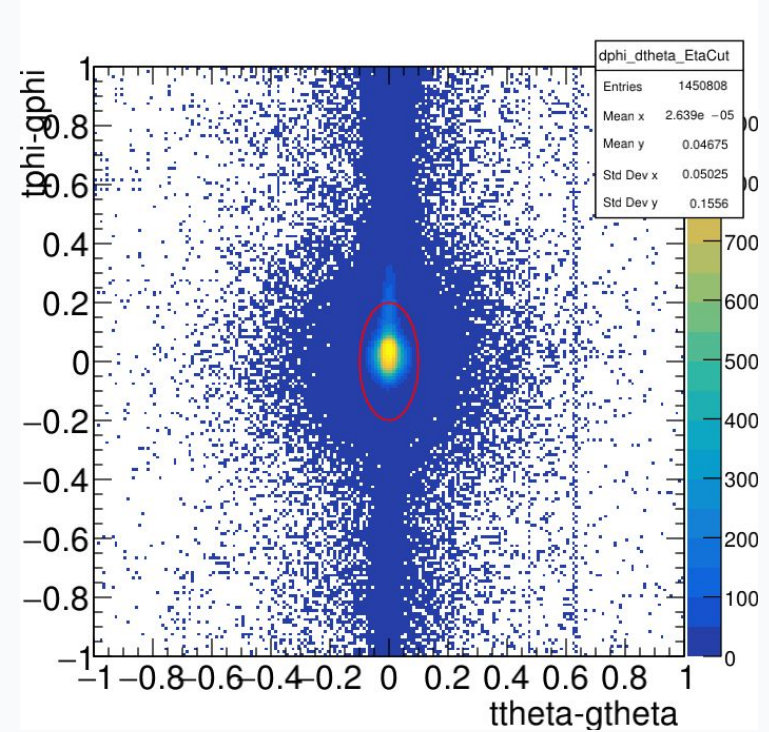
## Manual Clustering

Group 1



Radius = 0.25 units

Group 2



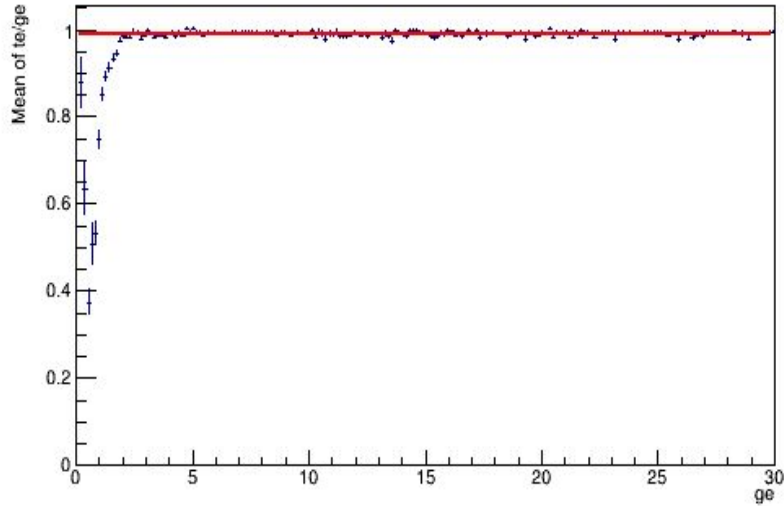
semi-minor axis = 0.10 units  
semi-major axis = 0.20 units

# Electron: CEMC

## TProfile plots for calibration

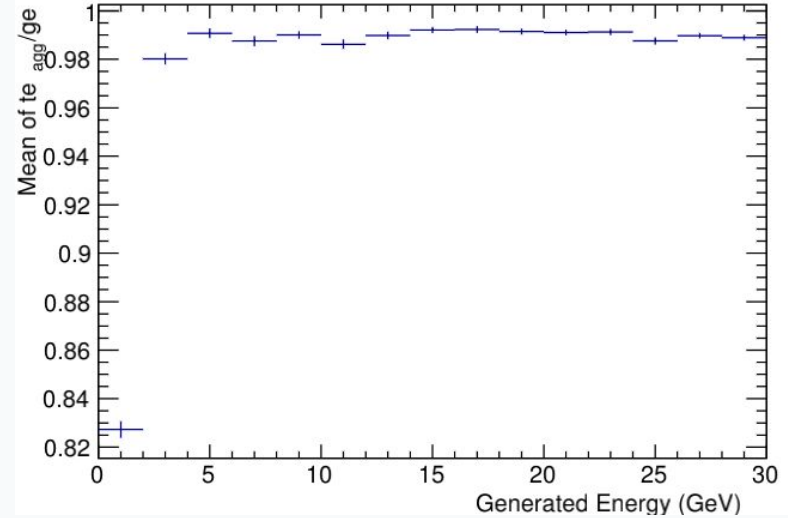
Group 1

CEMC



Calibration Factor = Fit Function for the above plot

Group 2



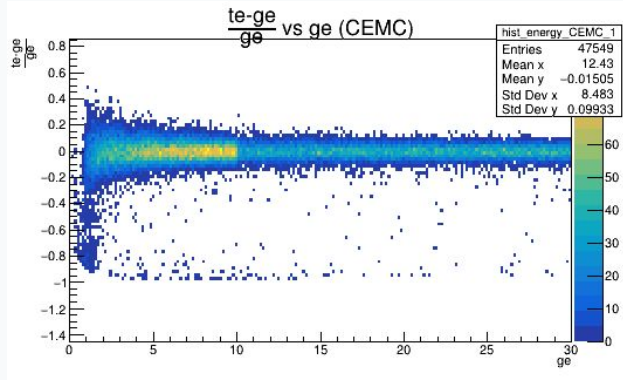
Calibration Factor of first slice = 0.96



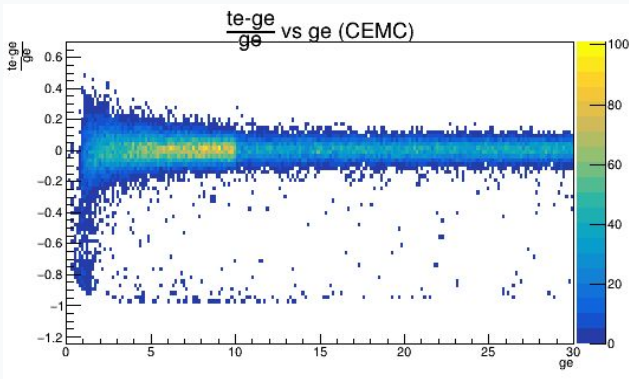
# Electron: CEMC

100 MeV on aggregated tower energy for each event

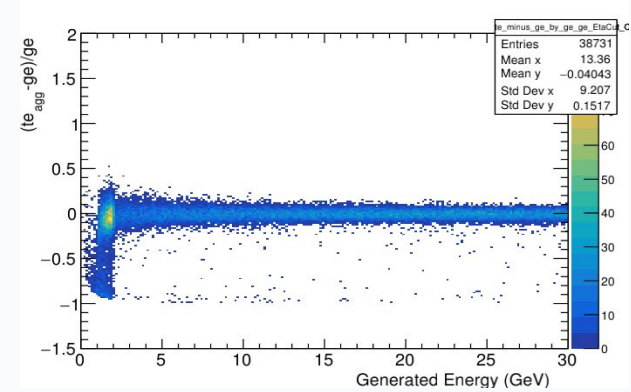
Before Calibration



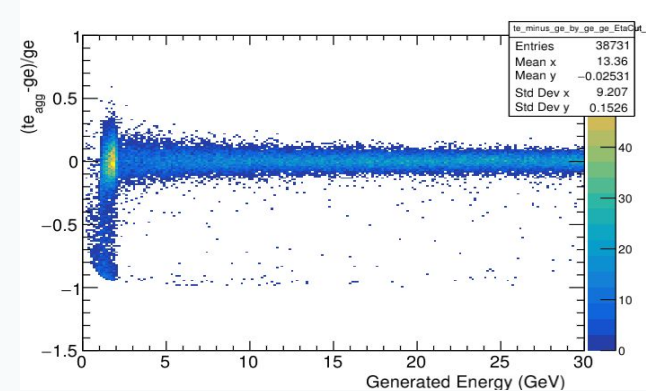
After Calibration



Before Calibration



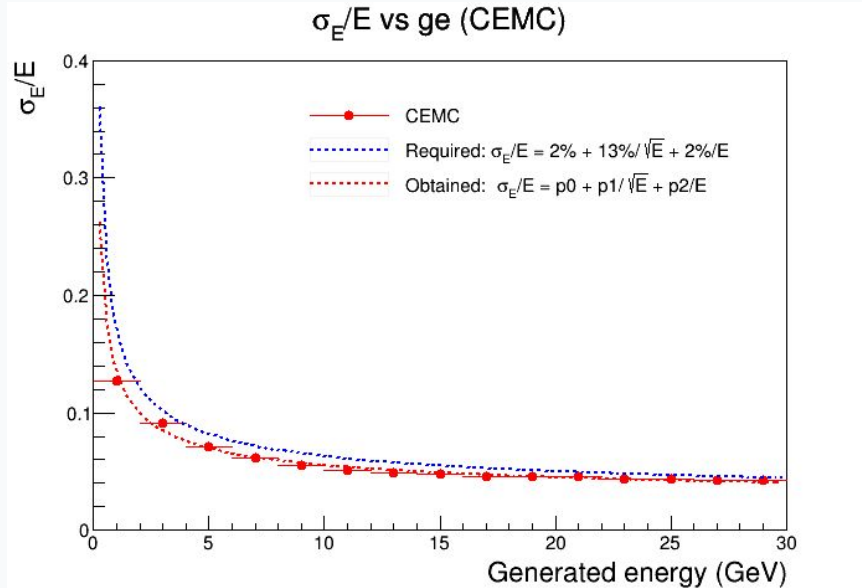
After Calibration



# Electron: CEMC

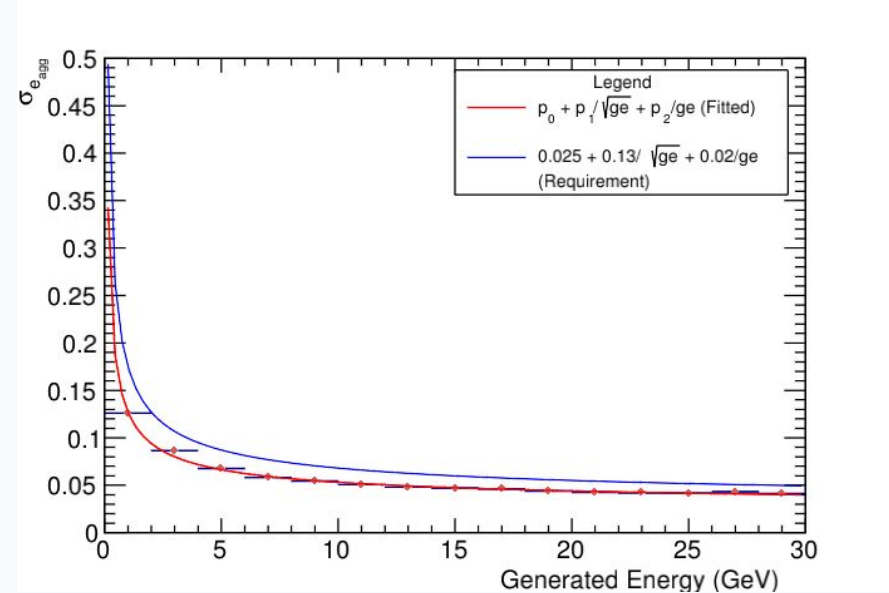
100 MeV on aggregated tower energy for each event  
After Calibration

Group 1



$$\sigma_E/E = 2.0520\% + 10.534\%/\sqrt{E} + 2\%/E$$

Group 2



$$\sigma_E/E = 2.28119\% + 9.19356\%/\sqrt{E} + 1.23408\%/E$$

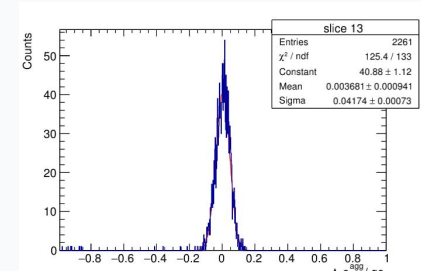
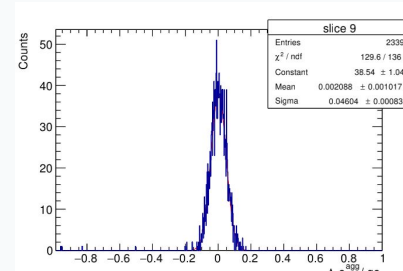
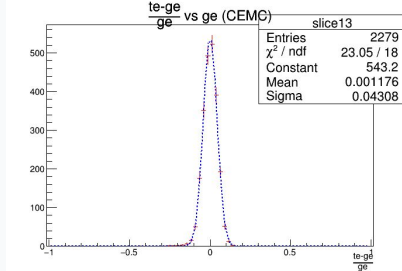
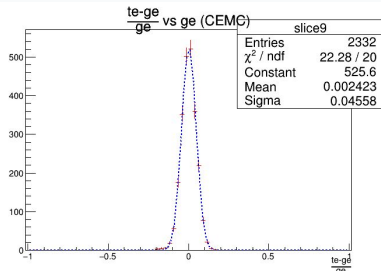
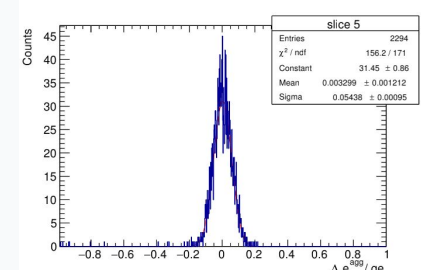
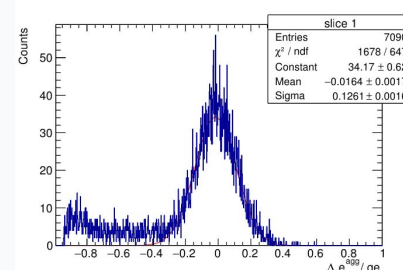
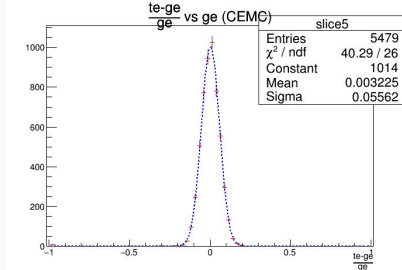
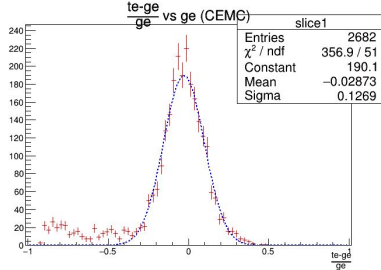
# Electron: CEMC

100 MeV on aggregated tower energy for each event  
After Calibration

Group 1

Fit Slices

Group 2



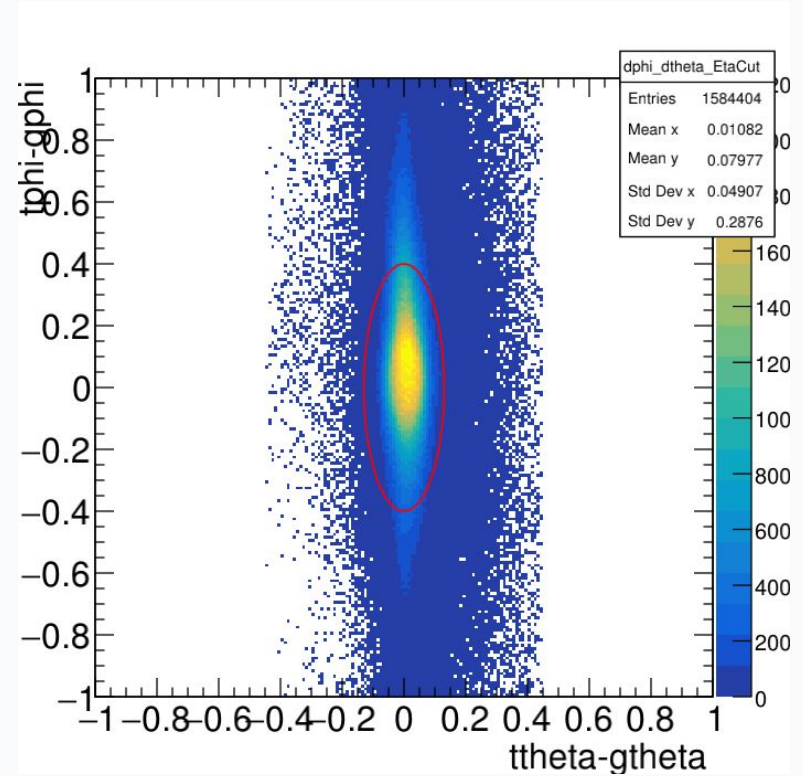
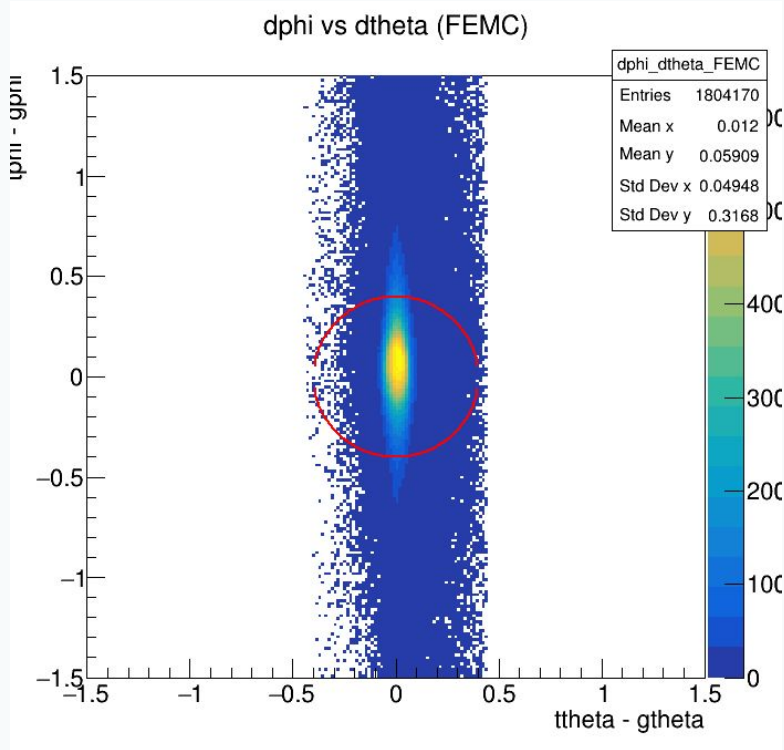
Electron : FEMC

# Electron: FEMC

Group 1

Manual Clustering

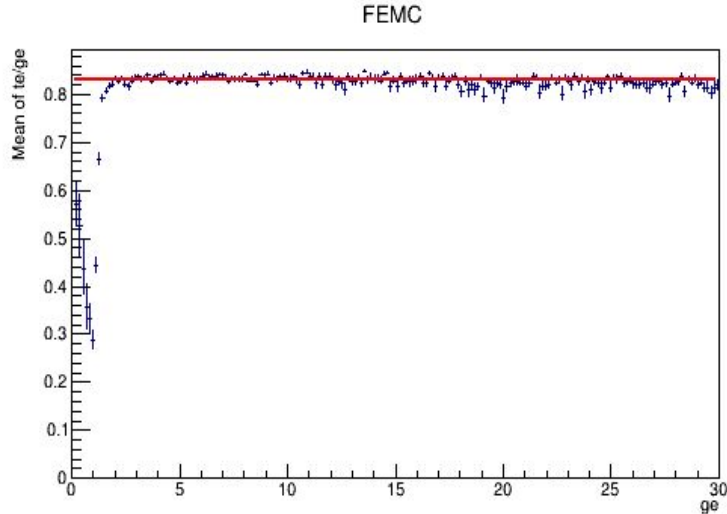
Group 2



# Electron: FEMC

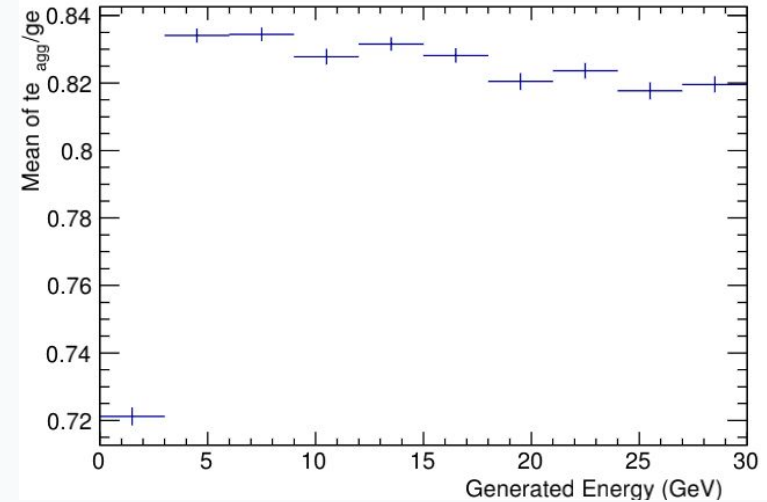
100 MeV on aggregated tower energy for each event  
TProfile plots for calibration

Group 1



Calibration Factor = Fit Function for the  
above plot

Group 2



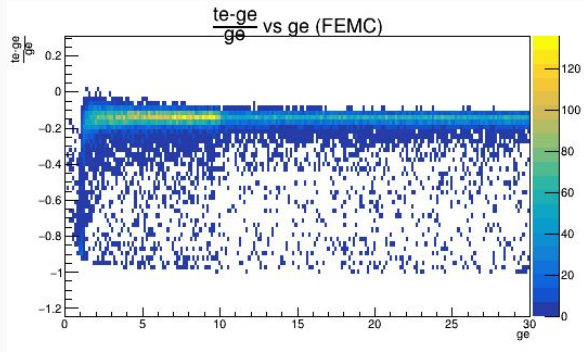
Calibration Factor of first slice = 0.82

# Electron: FEMC

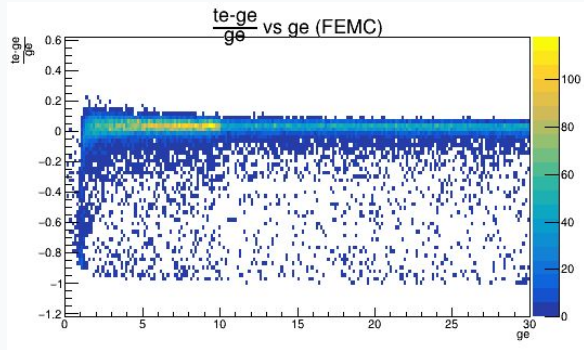
100 MeV on aggregated tower energy for each event

Group 1

Before Calibration

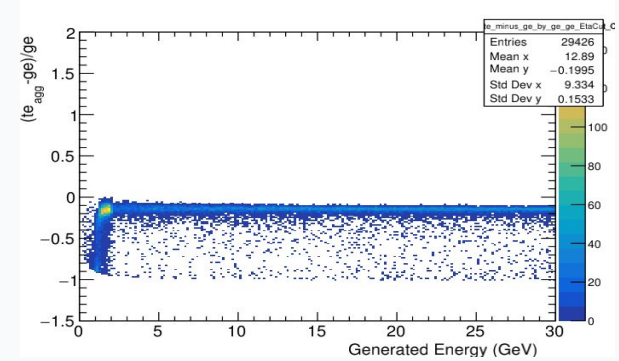


After Calibration

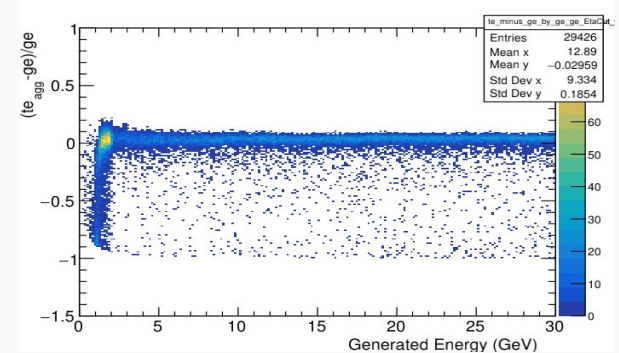


Group 2

Before Calibration



After Calibration

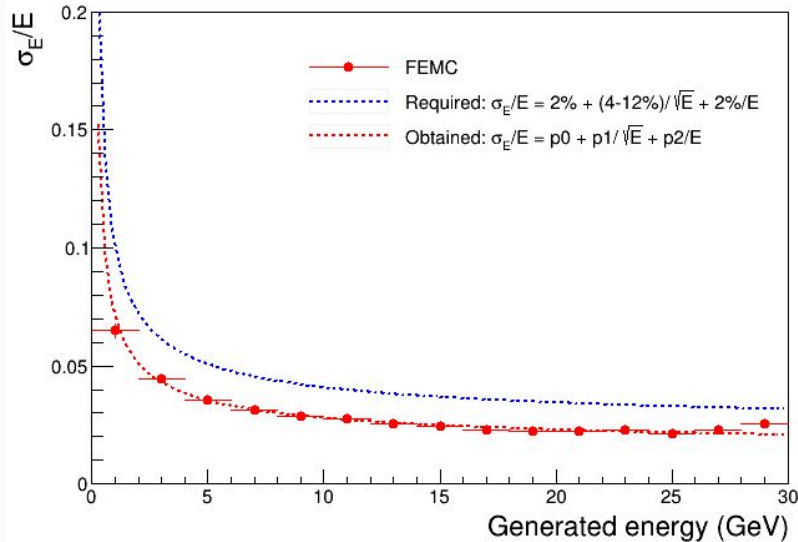


# Electron: FEMC

100 MeV on aggregated tower energy for each event  
After Calibration

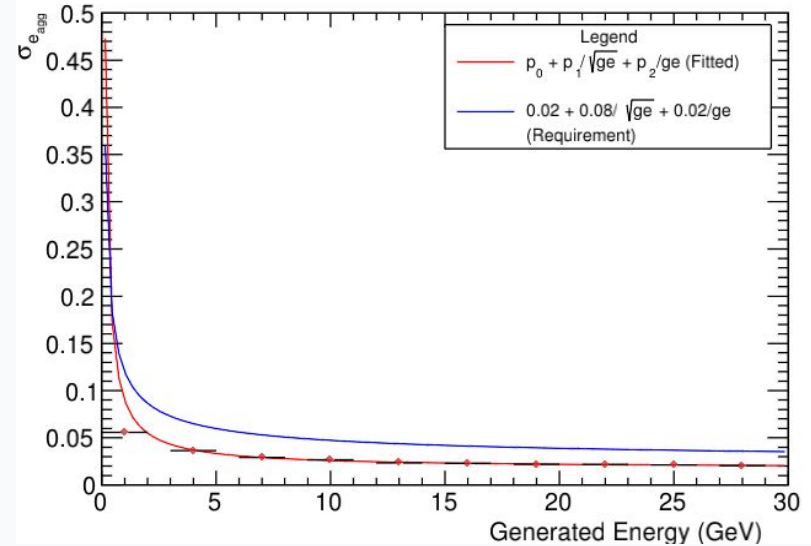
Group 1

$\sigma_E/E$  vs  $ge$  (FEMC)



$$\sigma_E/E = 1.15892\% + 4.84642\%/\sqrt{E} + 1.08484\%/E$$

Group 2



$$\sigma_E/E = 1.70581\% + 0.502211\%/\sqrt{E} + 6.56204\%/E$$



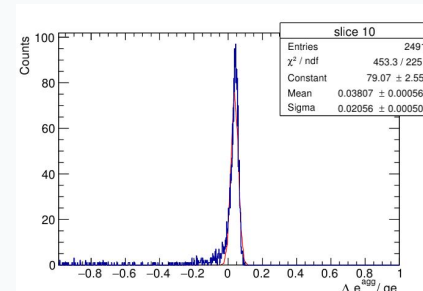
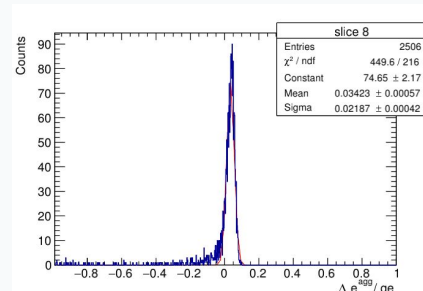
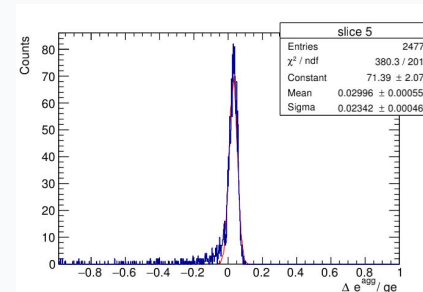
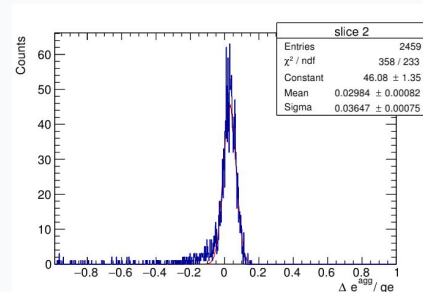
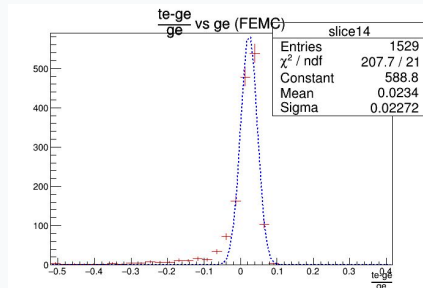
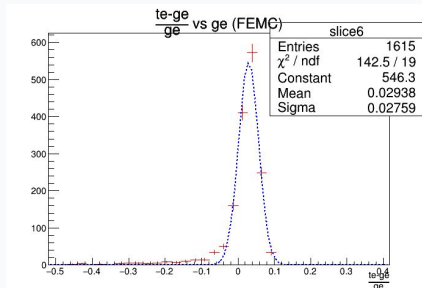
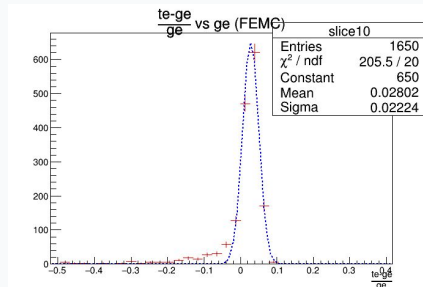
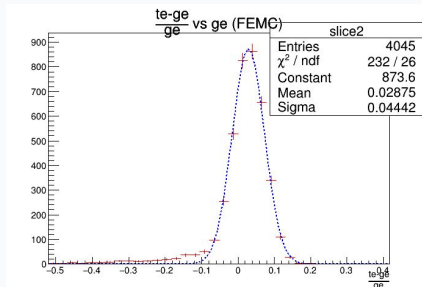
# Electron: FEMC

100 MeV on aggregated tower energy for each event  
After Calibration

Fit Slices

Group 1

Group 2

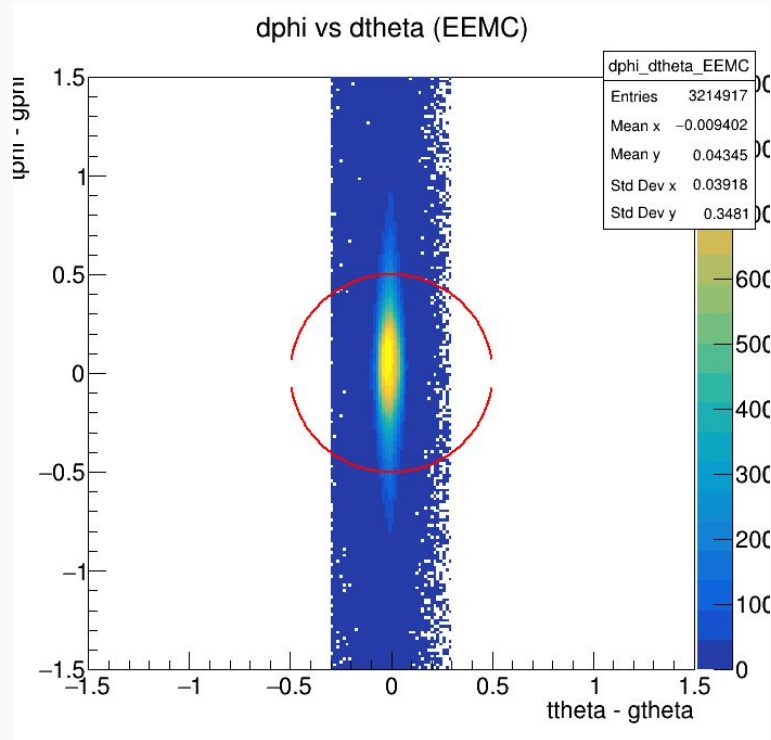


Electron : EEMC

# Electron: EEMC

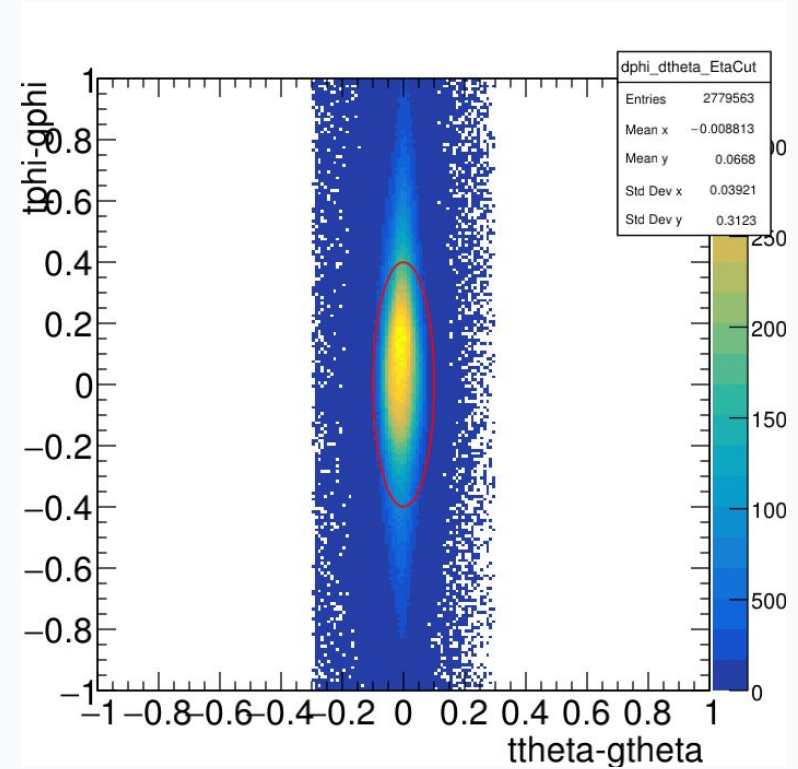
## Manual Clustering

Group 1



Radius = 0.50 units

Group 2



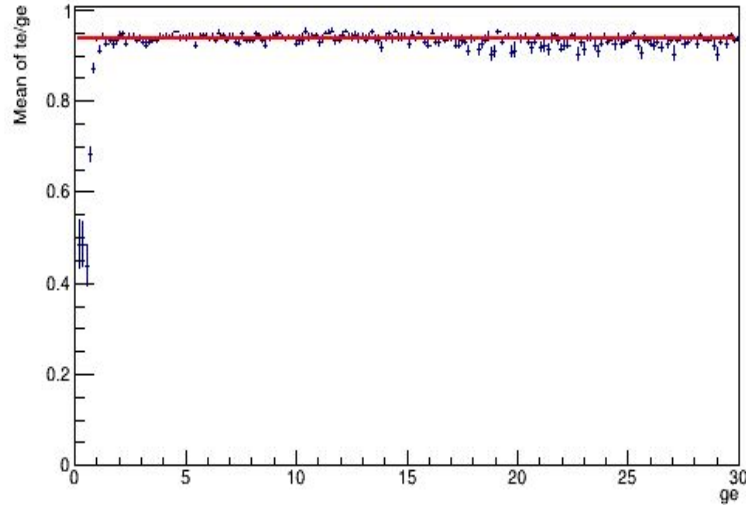
semi-minor axis = 0.10 units  
semi-major axis = 0.40 units

# Electron: EEMC

100 MeV on aggregated tower energy for each event  
TProfile plots for calibration

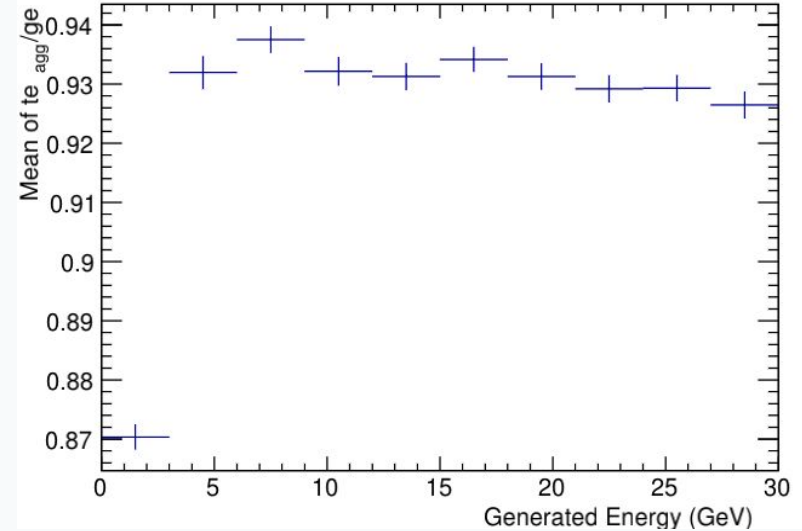
Group 1

EEMC



Calibration Factor = Fit Function for the  
above plot

Group 2



Calibration Factor of first slice = 0.93

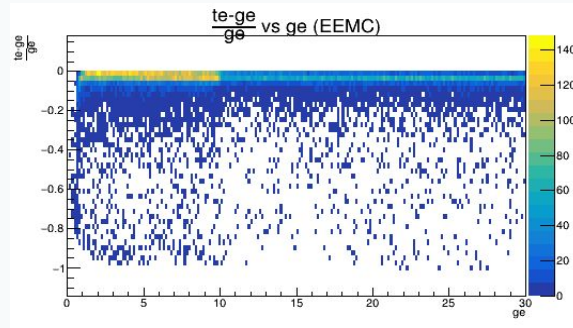
# Electron: EEMC

100 MeV on aggregated tower energy for each event

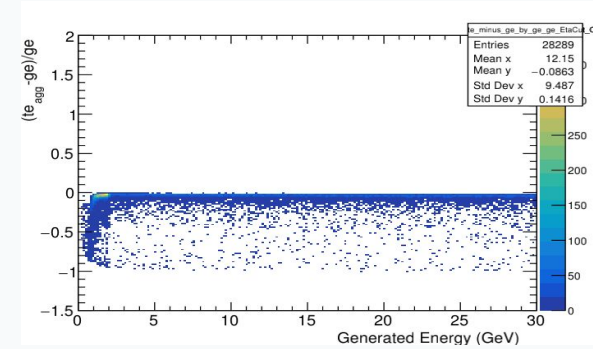
Group 1

Group 2

Before Calibration

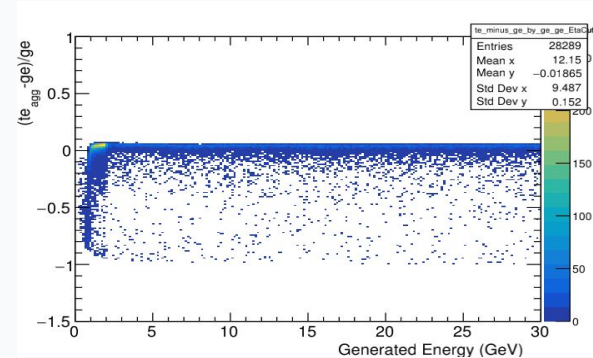
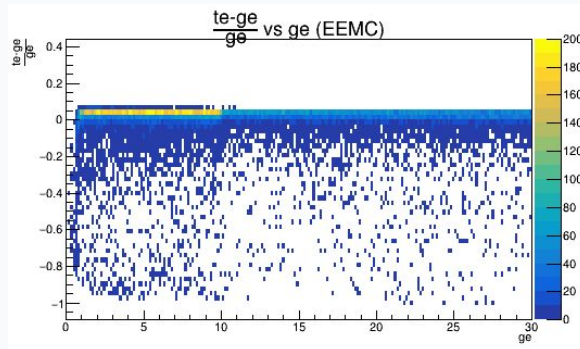


Before Calibration



After Calibration

After Calibration



# Electron: EEMC

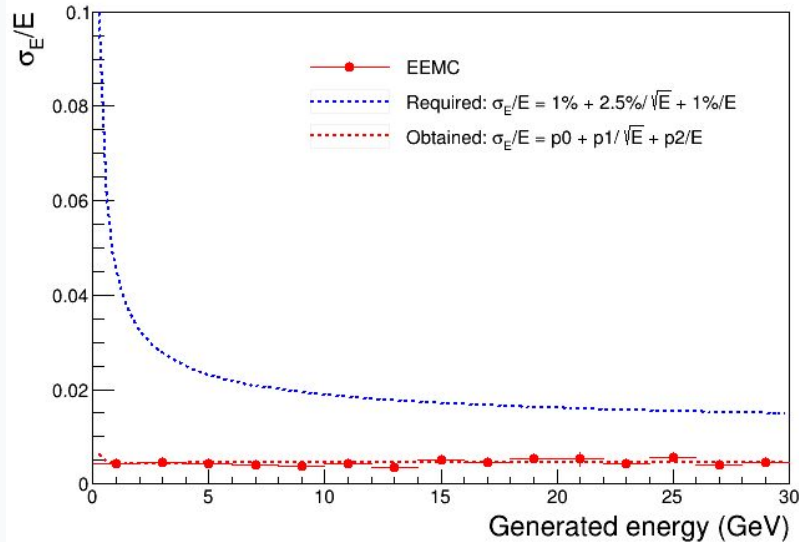
100 MeV on aggregated tower energy for each event

After Calibration

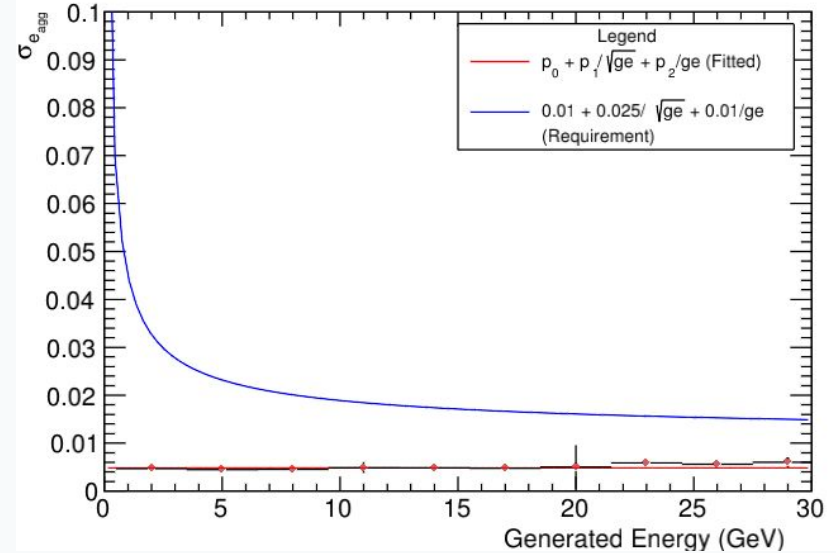
Group 1

Group 2

$\sigma_E/E$  vs  $ge$  (EEMC)



$$\sigma_E/E = 0.493094\% - 0.162239\%/\sqrt{E} + 0.117333\%/E$$



$$\sigma_E/E = 0.483728\%$$

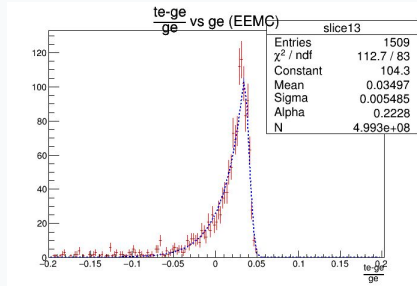
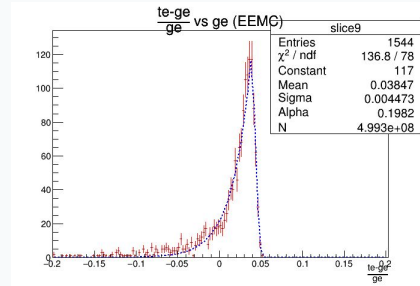
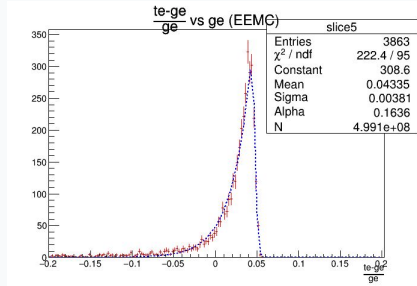
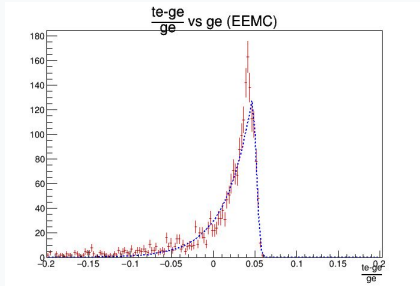
# Electron: EEMC

100 MeV on aggregated tower energy for each event

After Calibration

Fit Slices

Group 1



Group 2

