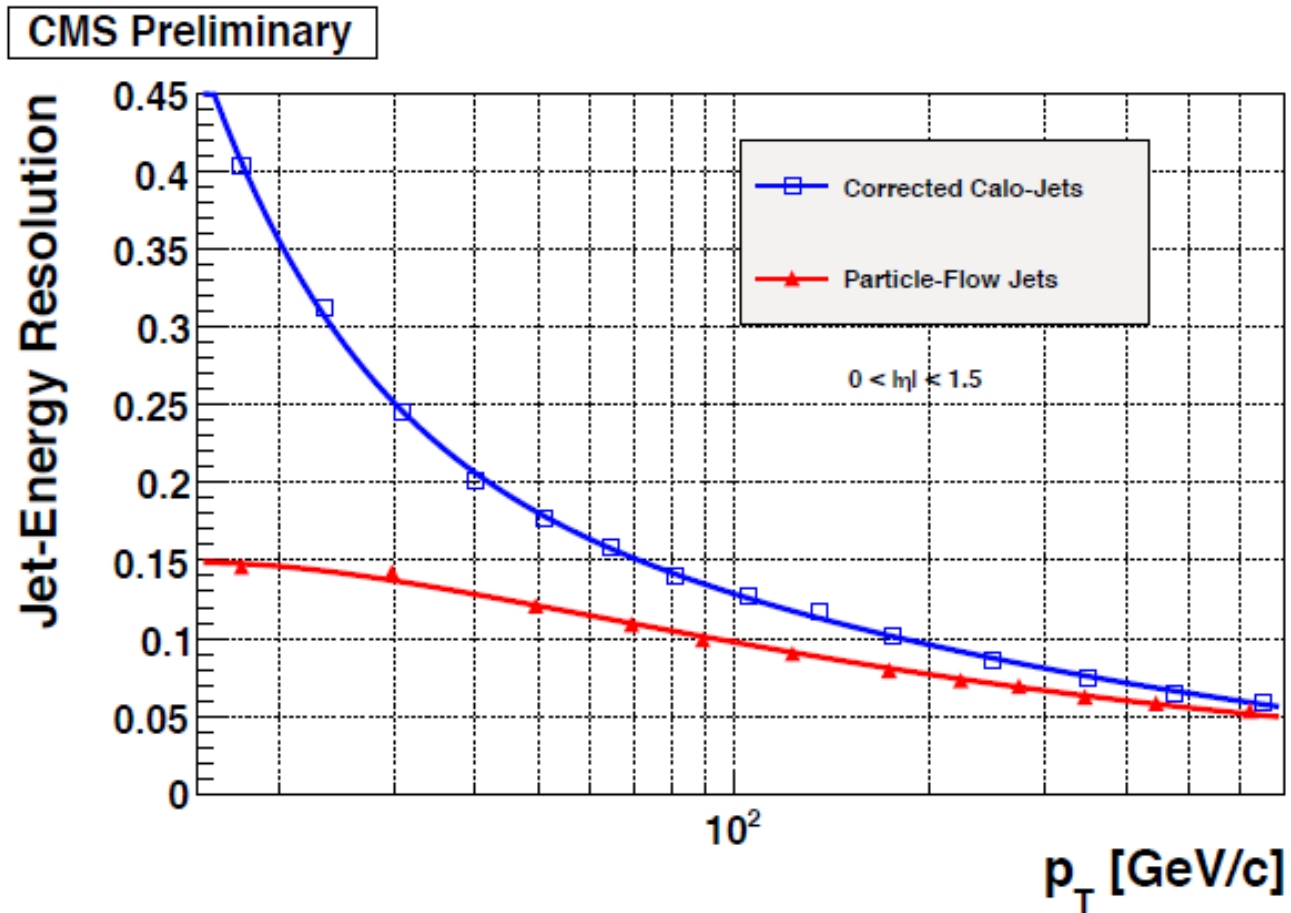# Improving Jet Energy Resolution via Particle Flow

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(Colorado)

Goal

To improve jet energy resolution, as CMS has done

Algorithm

E_{HCO}

E_{HCI}

E_{EMC}

E_{Track}

1. Is the E_{Track} $=$ E_{Clus}?

We're better off using just track for jet reconstruction instead of clusters.
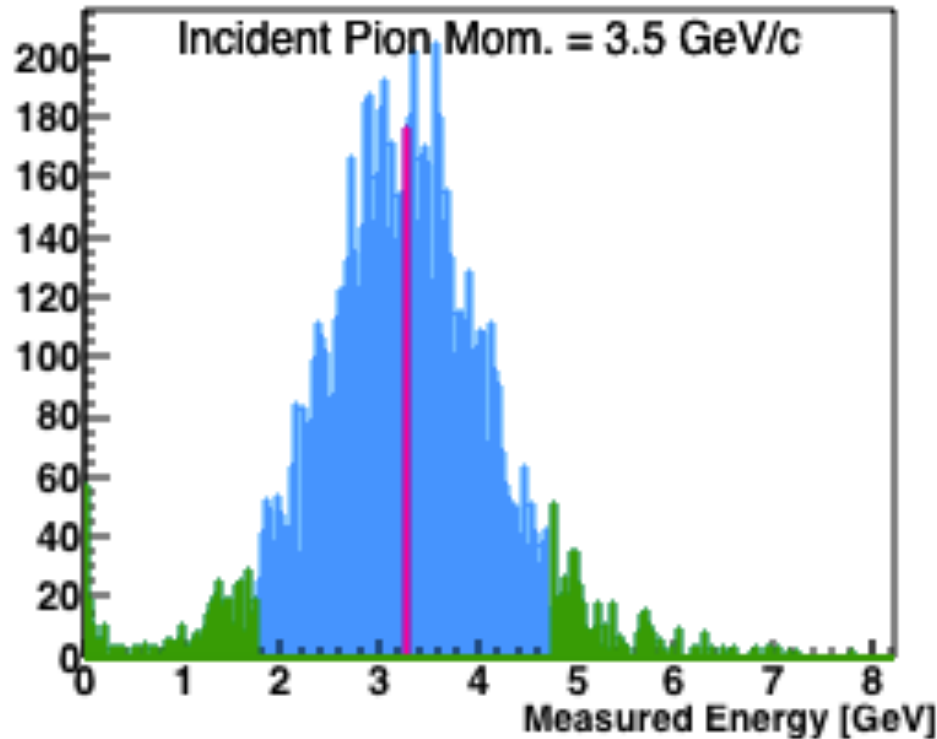
2. Is E_{Track} $>$ E_{Clus}?

This doesn't make sense. Discard track.

3. Is E_{Track} $<$ E_{Clus}?

Most likely the cluster is contaminated. Subtract track energy and look for other matching tracks.

What does it mean for the $E_{Track} = E_{Clus}$?

Summed cluster energy distributions for incident single pions at various energies.

Find energy interval so as to enclose 90% of the distribution (blue).

For a given track energy, this provides a "matching" criterion between track and clusters.

Interpolate if needed!

Simulation

We use 140k PYTHIA dijet events forcing the hard scale.

Once the algorithm has been applied, we end up with a set of clean particles that are given to FastJet for jet reconstruction. We use the anti-kT algorithm with R=0.3

For a given reconstructed flow jet, its energy can lie in either

- *Tracks whose energy was perfectly matched to clusters*
- *Tracks whose energy was only partially matched to clusters*
- *Clusters with leftover energy after matching them to tracks*
- *Clusters that were not matched to any track*

Examining the fraction of the jet energy in each of these categories can provide an indication of how effective the jet flow algorithm is. The ideal scenario would be to have 2/3 of the energy in (charged) tracks and 1/3 in (neutral) unmatched calorimeter clusters, minimizing the energy in contaminated clusters.

The figure in the following slide shows the fraction of jet energy in each of these categories for our simulation.
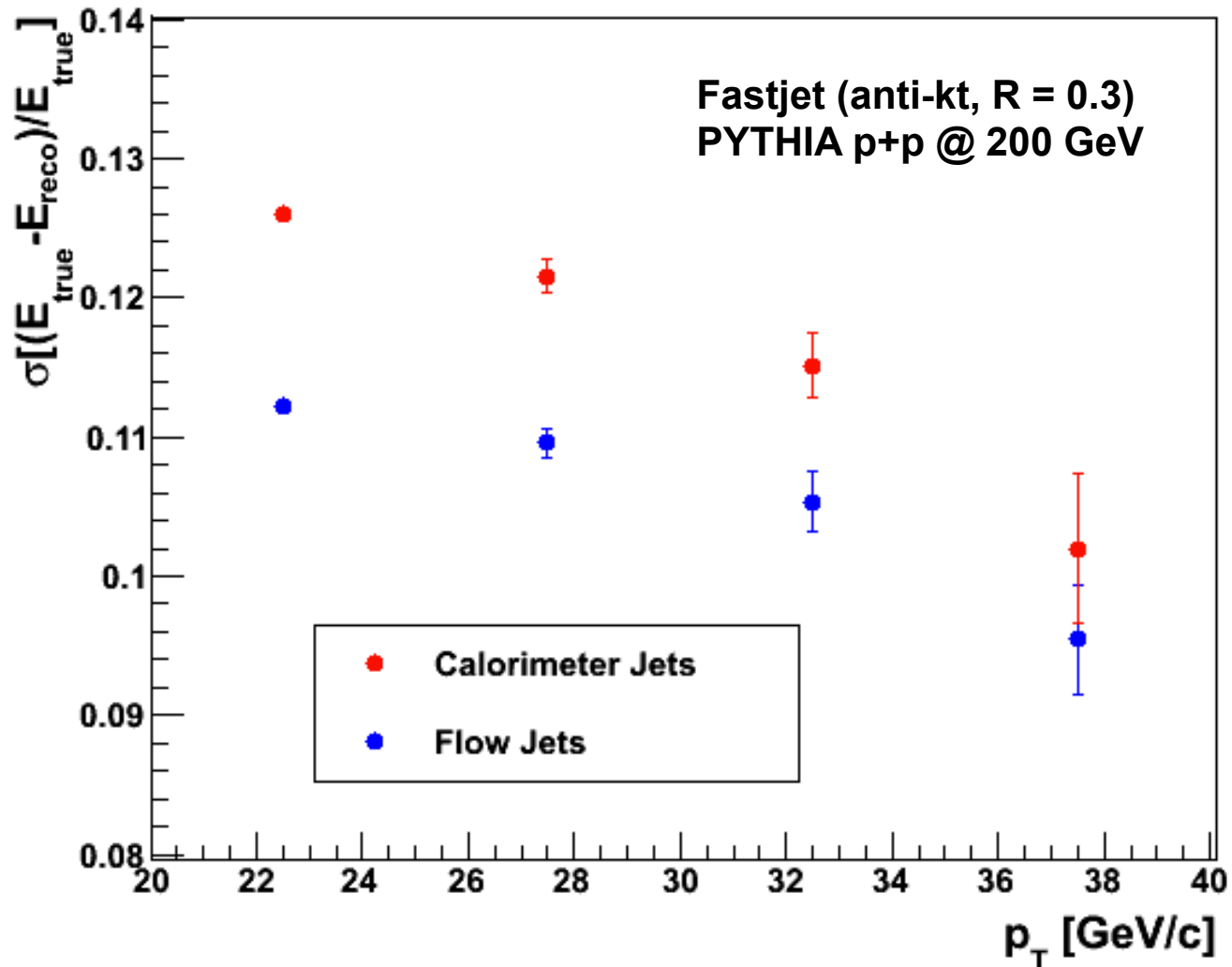
Results

Fraction of Jet Energy in Various Categories for Inclusive Particle Flow Jets
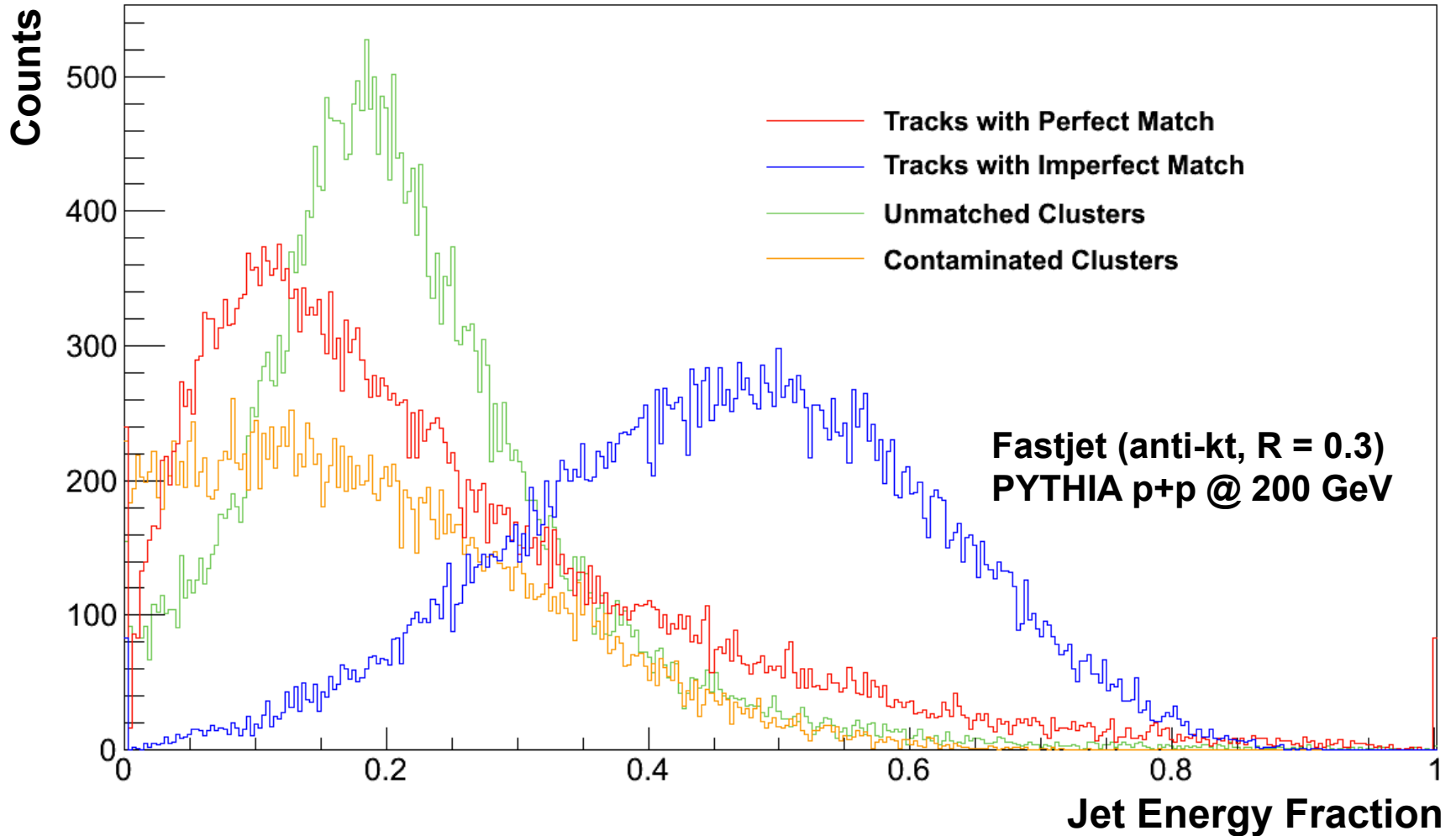
Results

We can match flow jets and calorimeter jets to true PYTHIA jets in order to compute the energy resolution. We see a ~10% improvement with flow jets.

Conclusions

The particle flow algorithm leads to modest improvement in jet energy resolution, much smaller than in CMS.

There are several reasons why this might be the case. Firstly, we would need a stronger magnetic field to separate the jets into distinct clusters left by its constituent particles that could be matched to individual tracks. In our case, we just match all tracks to (mostly) one big cluster per jet. This fact limits the resolution we can achieve (see appendix).

There are also refinements to the algorithm that could be implemented with finer granularity in the calorimeters. For instance, we could use improved cluster finders.

APPENDIX

A typical dijet event looks like this. Each panel corresponds to a calorimeter. Pink circles represent tracks; white circles represent clusters. The area is proportional to their energy. We distinctly observe the two jets, with their associated tracks and clusters.
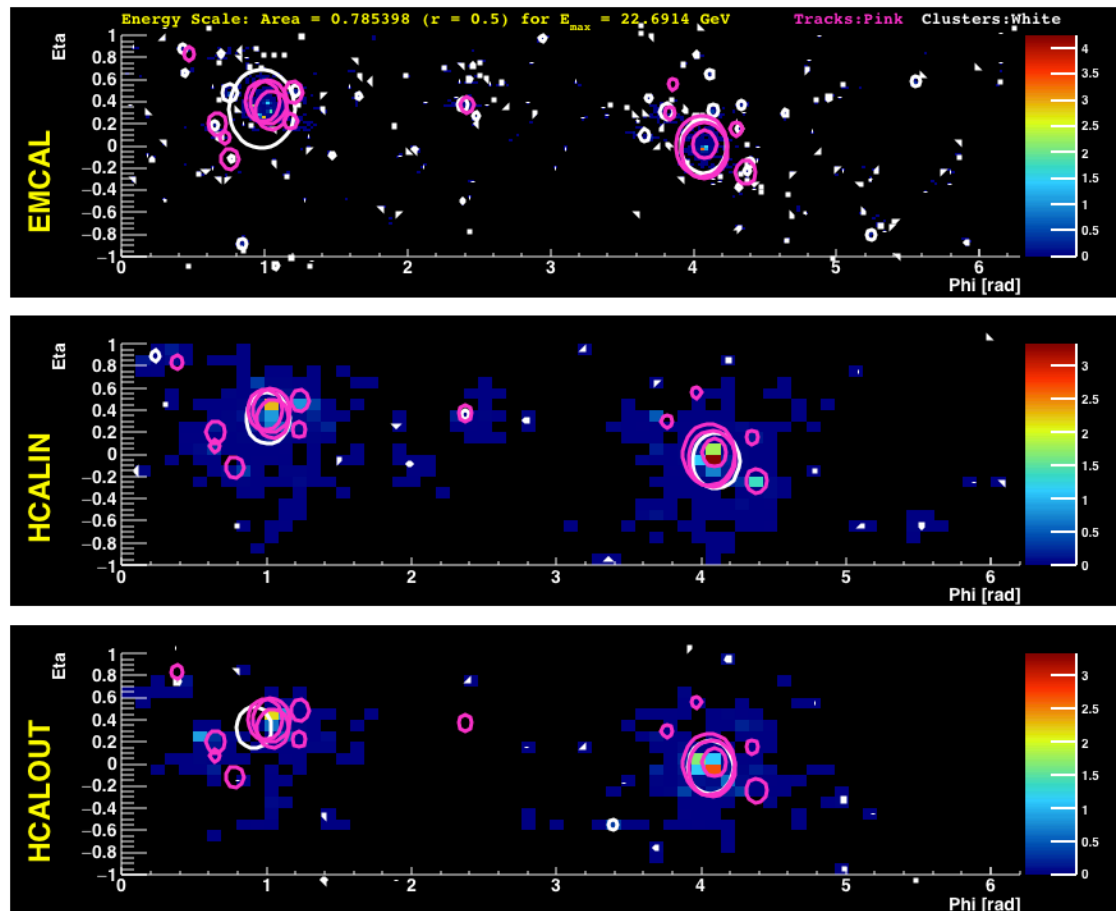
Let's walk through the event, track by track, to understand what the flow jets algorithm does. In particular, we will see how tracks are matched to clusters and their energy gets subtracted until only residual energy is left in the calorimeter.

Energy Scale: Area = 0.785398 (r = 0.5) for E_{max} = 22.6914 GeV   Tracks:Pink Clusters:White
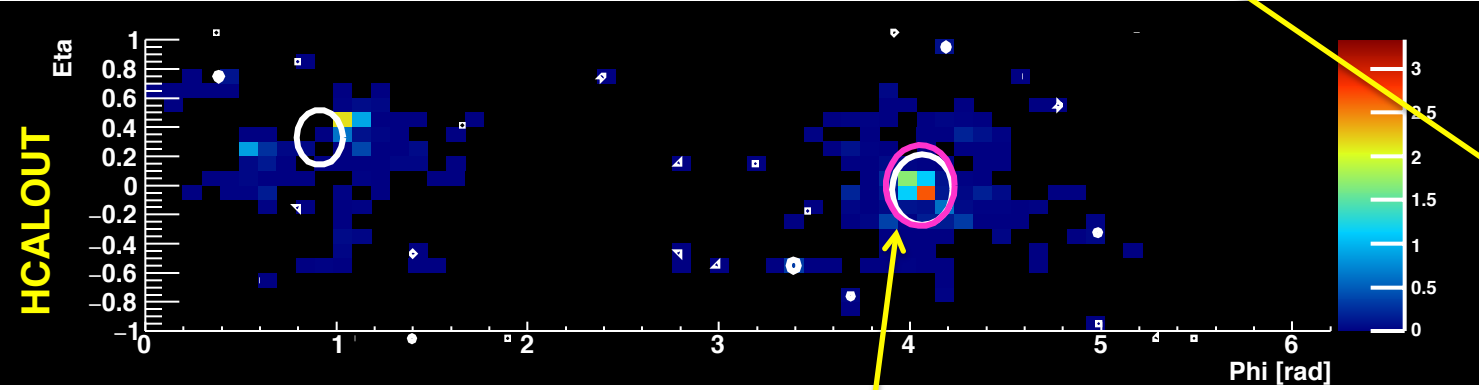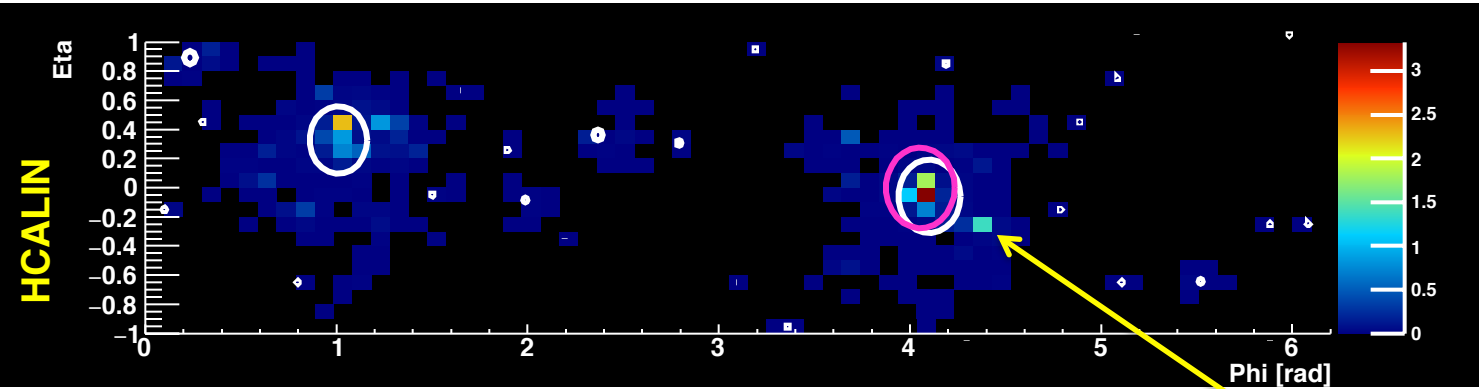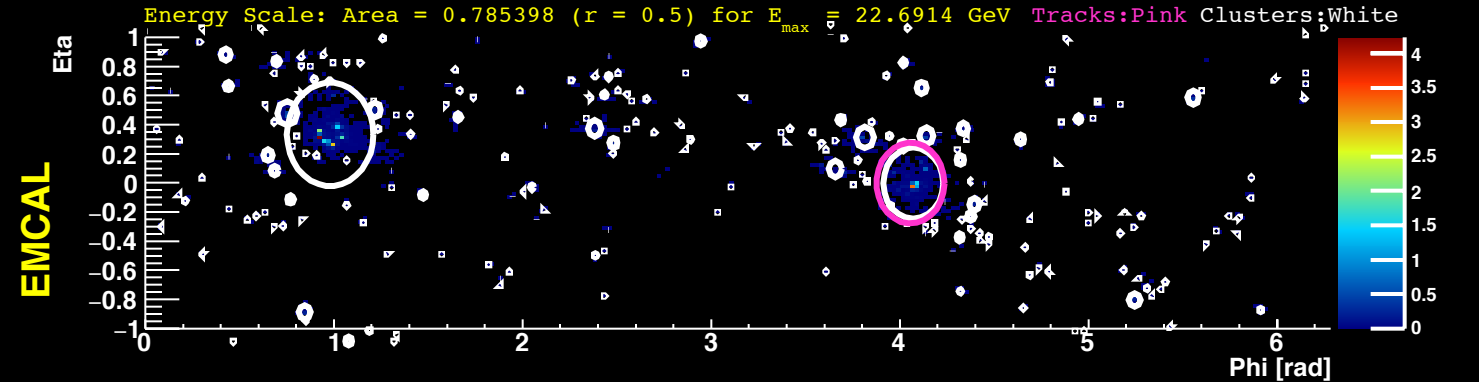
TRACK 0
Track Energy   = 13.9 GeV
Track Eta   = -0.000897
Track Phi   = 4.07
Range   : 7.36 - 16.1
Track Matched   = 1
 -EMC Energy   = 10.8
 -HCI Energy   = 11.4
 -HCO Energy   = 10.7
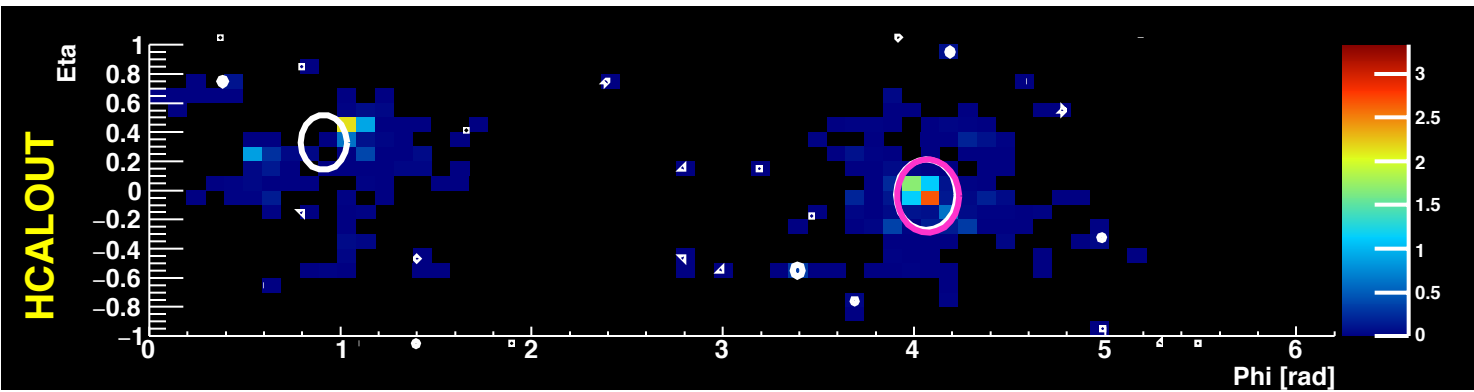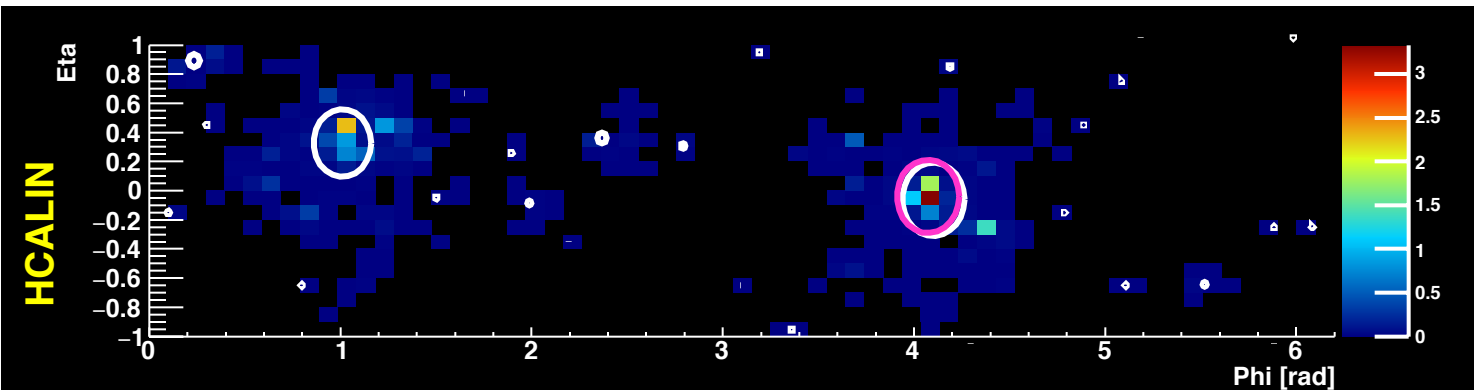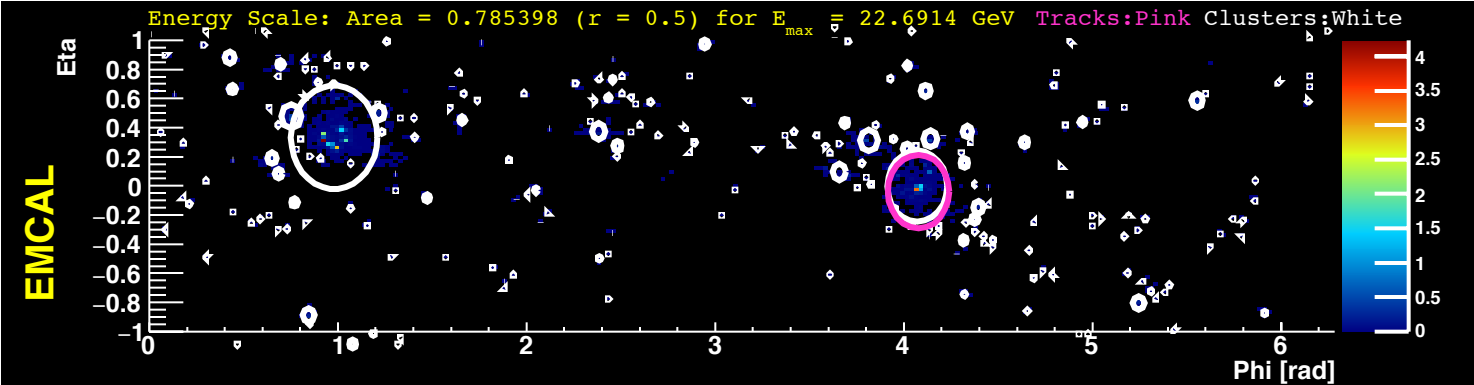 -Summed Energy = 32.9 GeV

 -EMC ID: 62
 -HIN ID: 3
 -HOU ID: 7

 -dPhi EMC   = 0.0144
 -dPhi HCI   = 0.0481
 -dPhi HCO   = 0.0219

 -dEta EMC   = 0.00107
 -dEta HCI   = 0.0585
 -dEta HCO   = 0.0278

This tower was not identified as a cluster!

There is more energy summed in the clusters than that provided by the track

11

Energy Scale: Area = 0.785398 (r = 0.5) for E_{max} = 22.6914 GeV   Tracks:Pink Clusters:White
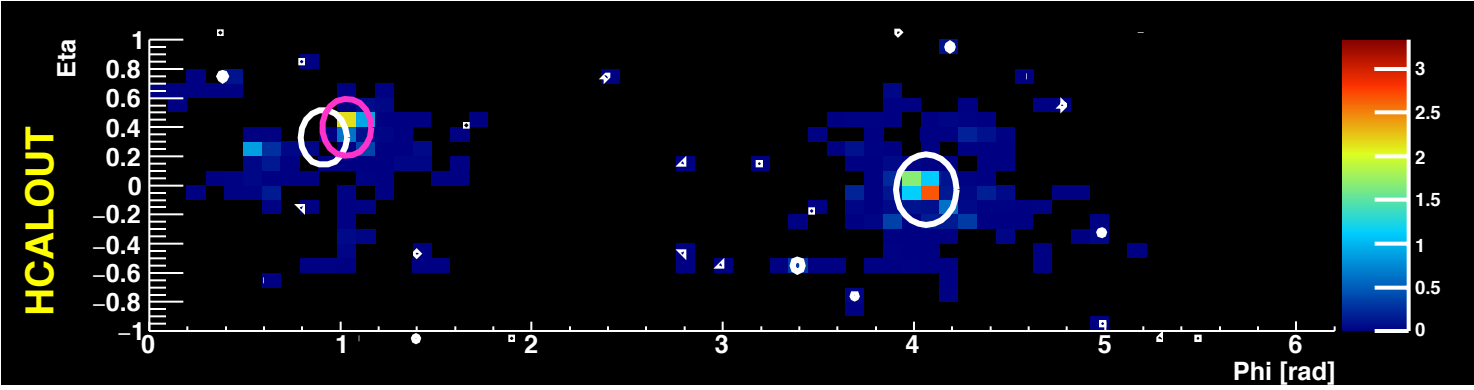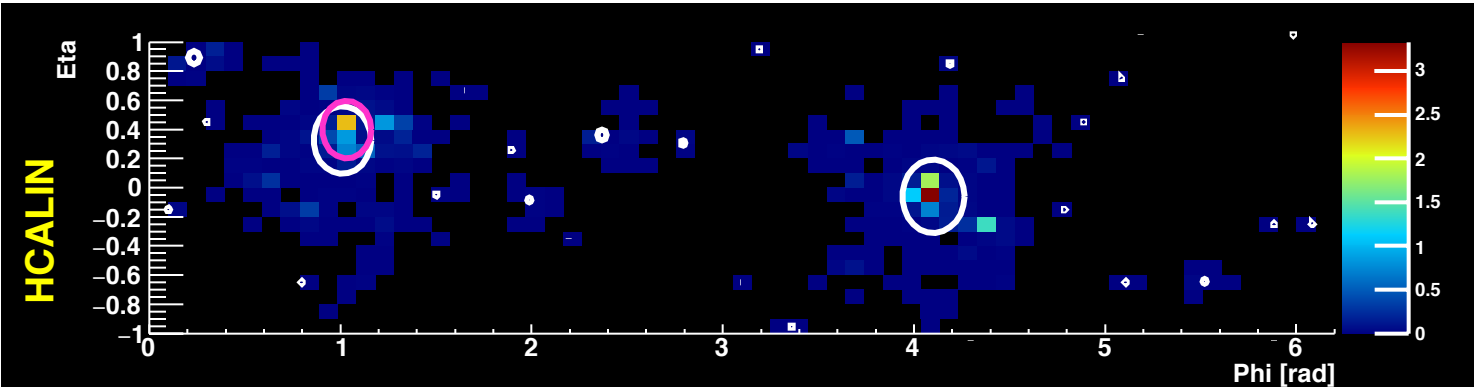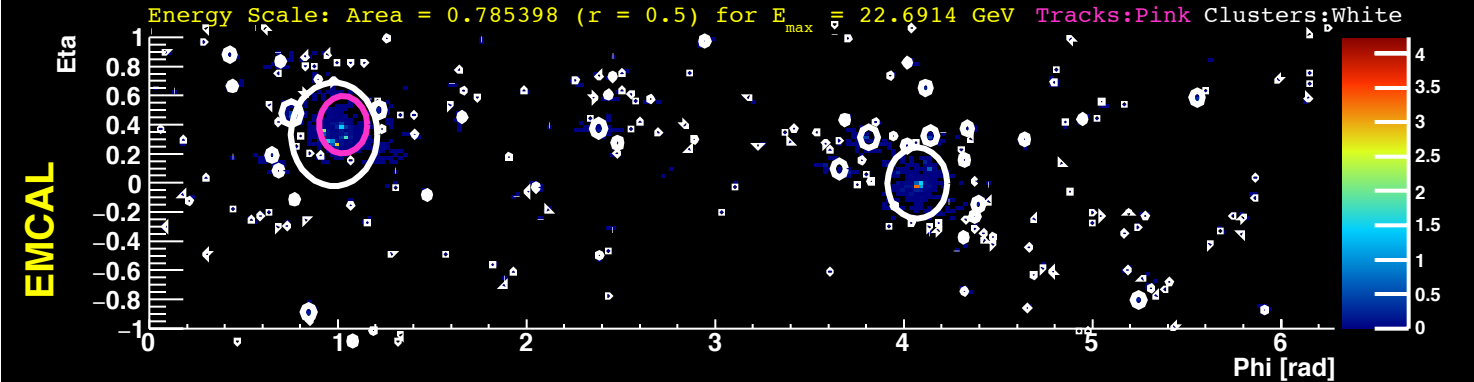
EMCAL

HCALIN

HCALOUT

TRACK 1
Track Energy   = 11.4 GeV
Track Eta   = -0.039
Track Phi   = 4.1
Range   : 5.76 - 13.6
Track Matched   = 1
 -EMC Energy   = 6.23
 -HCI Energy   = 6.62
 -HCO Energy   = 6.2
 -Summed Energy = 19 GeV

 -EMC ID: 62
 -HIN ID: 3
 -HOU ID: 7

 -dPhi EMC   = 0.00558
 -dPhi HCI   = 0.0287
 -dPhi HCO   = 0.00493

 -dEta EMC   = 0.037
 -dEta HCI   = 0.0205
 -dEta HCO   = 0.0103

Energy Scale: Area = 0.785398 (r = 0.5) for E_{max} = 22.6914 GeV **Tracks:Pink** Clusters:White
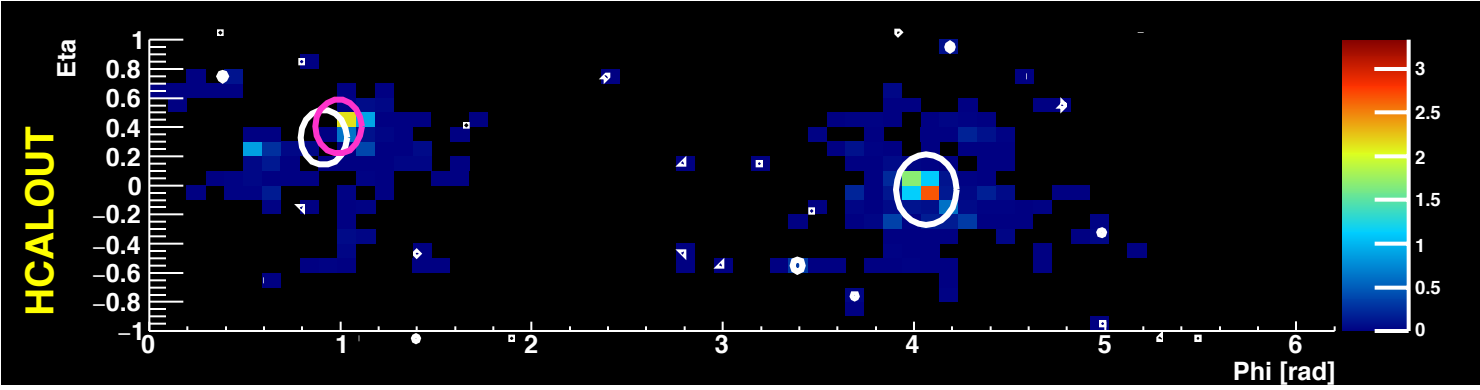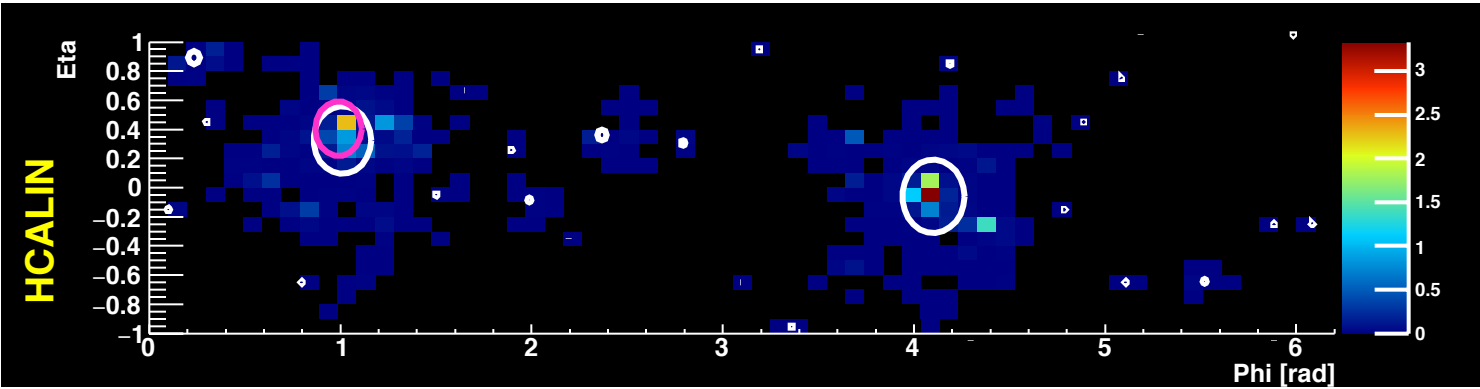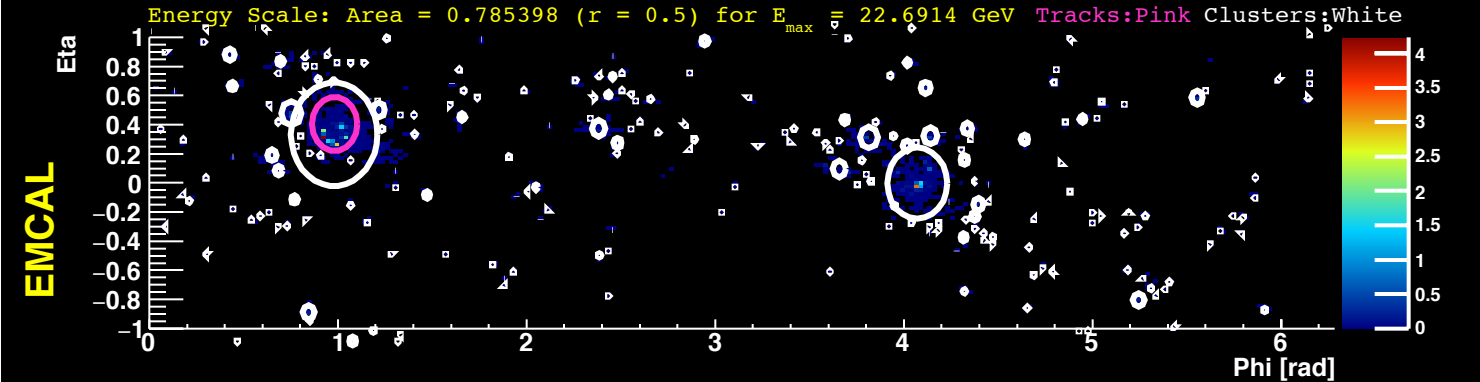
TRACK 2
Track Energy = 7.02 GeV
Track Eta = 0.399
Track Phi = 0.994
Range : 3.48 - 8.8
Track Matched = 1
-EMC Energy = 22.7
-HCI Energy = 9.76
-HCO Energy = 6.42
-Summed Energy = 38.9 GeV

-EMC ID: 112
-HIN ID: 4
-HOU ID: 11

-dPhi EMC = 0.0469
-dPhi HCI = 0.0237
-dPhi HCO = 0.145

-dEta EMC = 0.0657
-dEta HCI = 0.0718
-dEta HCO = 0.0704

13

Energy Scale: Area = 0.785398 (r = 0.5) for E_{max} = 22.6914 GeV   Tracks:Pink Clusters:White
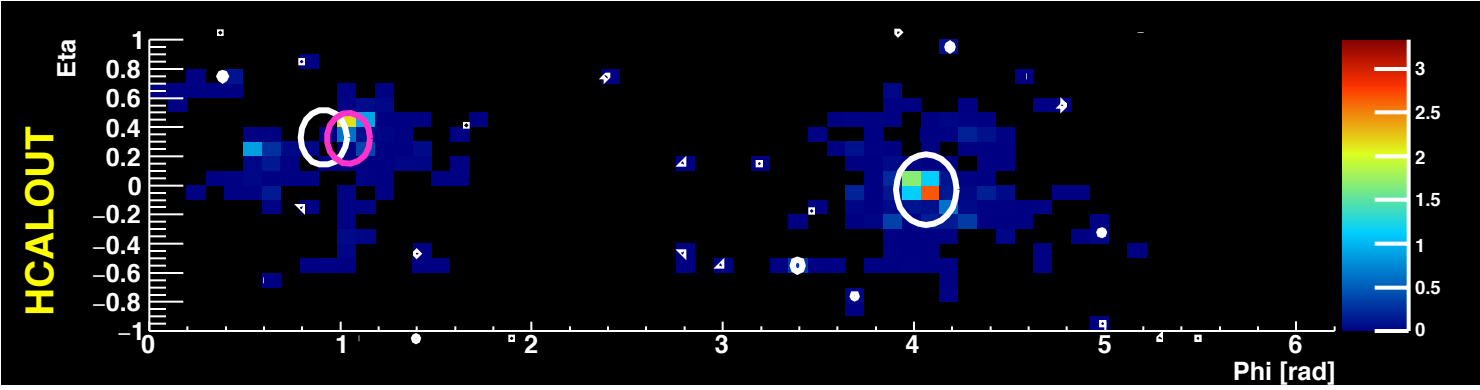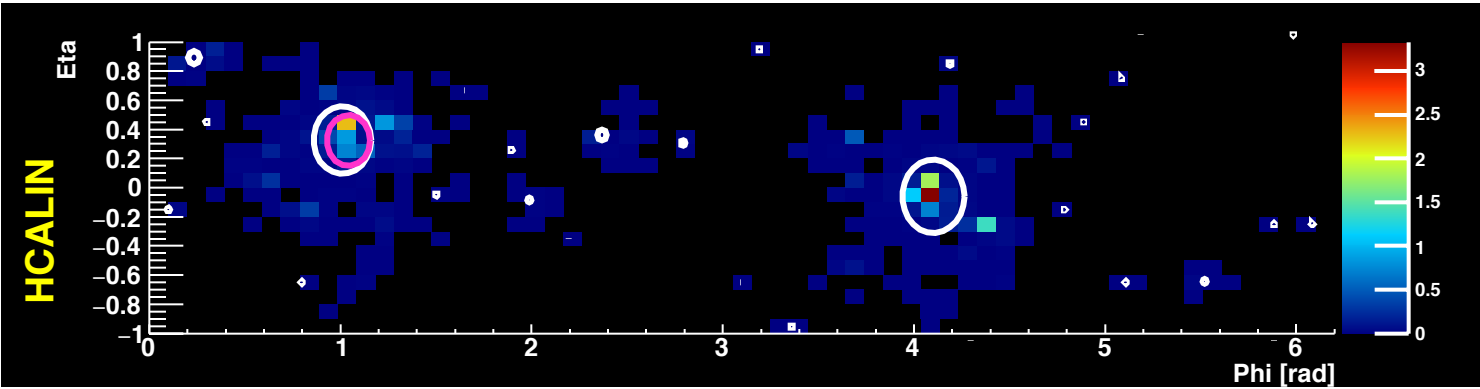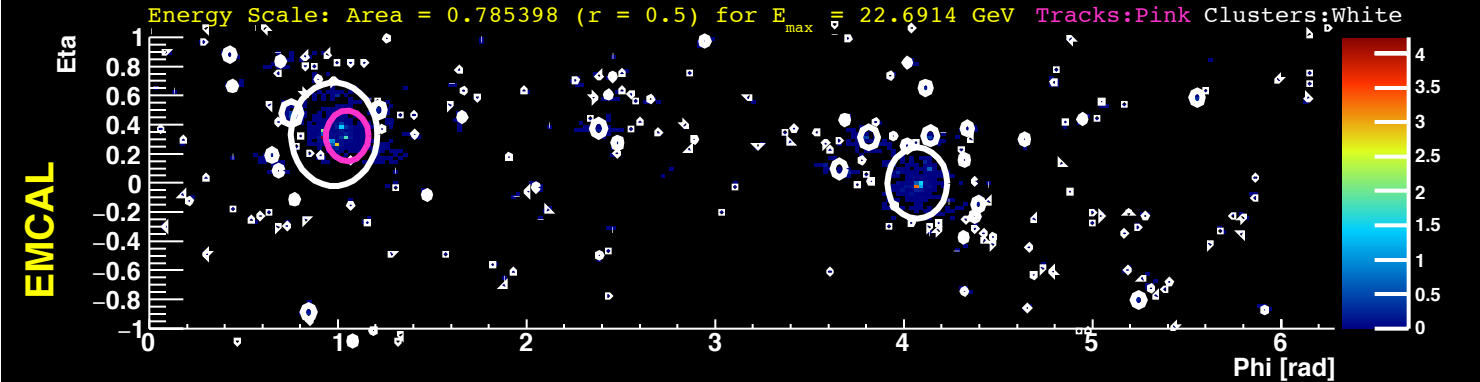
TRACK 3
Track Energy   = 6.29 GeV
Track Eta   = 0.405
Track Phi   = 0.947
Range   : 3.16 - 7.97
Track Matched   = 1
 -EMC Energy   = 18.6
 -HCI Energy   = 8
 -HCO Energy   = 5.26
 -Summed Energy = 31.9 GeV

 -EMC ID: 112
 -HIN ID: 4
 -HOU ID: 11

 -dPhi EMC   = 0.00413
 -dPhi HCI   = 0.0183
 -dPhi HCO   = 0.106

 -dEta EMC   = 0.0713
 -dEta HCI   = 0.0775
 -dEta HCO   = 0.0762

14

Energy Scale: Area = 0.785398 (r = 0.5) for E_max = 22.6914 GeV   Tracks:Pink Clusters:White
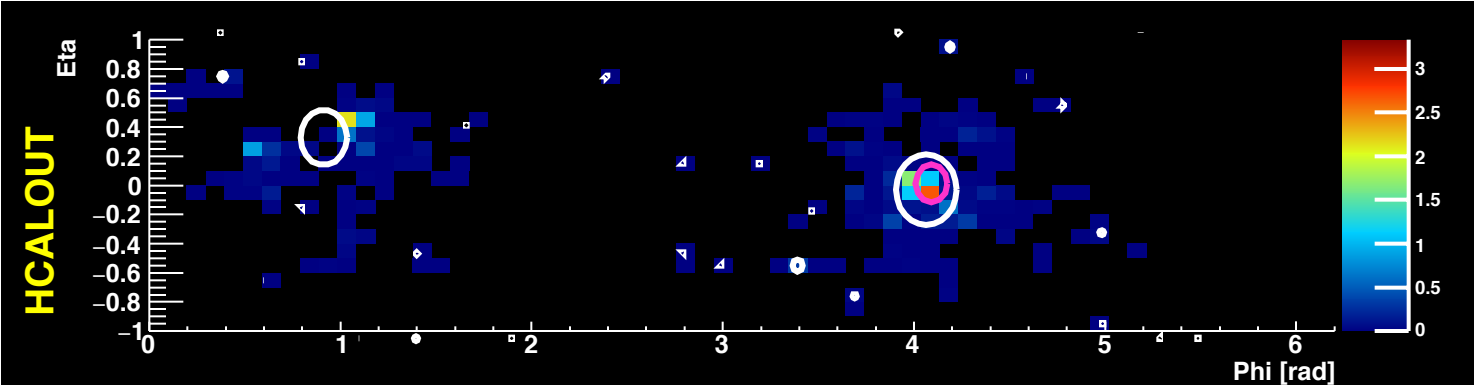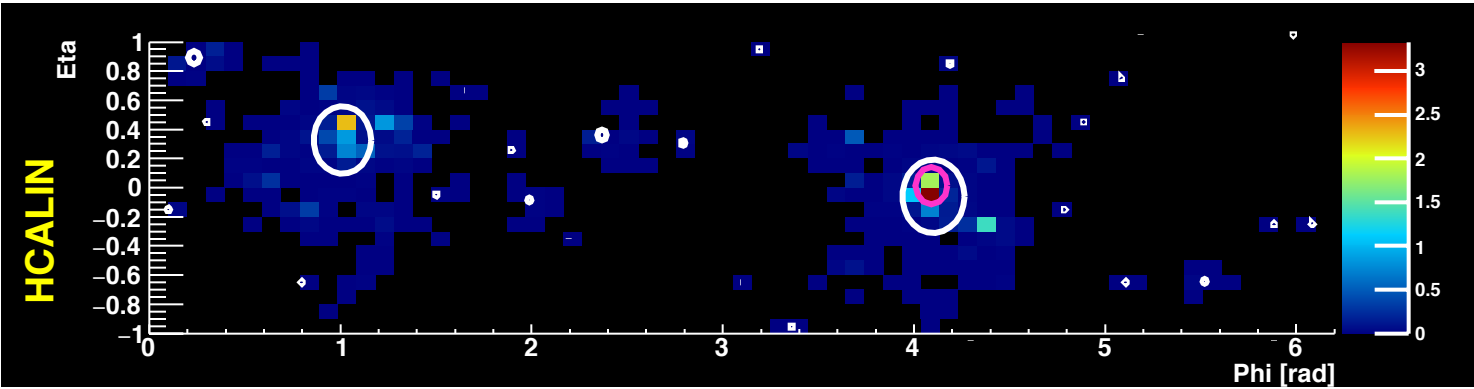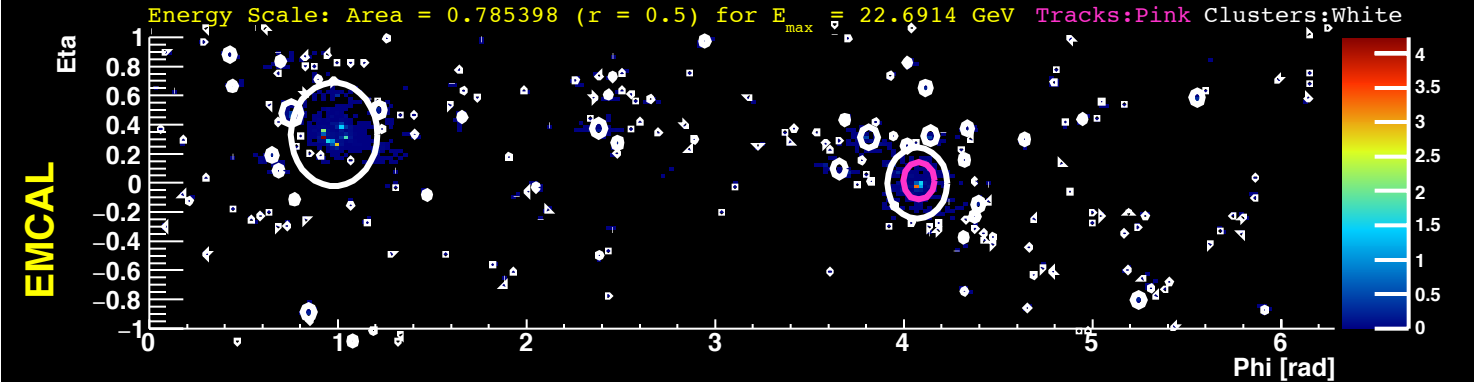
TRACK 4
Track Energy   = 5.48 GeV
Track Eta   = 0.324
Track Phi   = 1.09
Range   : 2.81 - 7.05
Track Matched   = 1
 -EMC Energy   = 14.9
 -HCI Energy   = 6.42
 -HCO Energy   = 4.22
 -Summed Energy = 25.6 GeV

 -EMC ID: 112
 -HIN ID: 4
 -HOU ID: 11

 -dPhi EMC   = 0.0683
 -dPhi HCI   = 0.0318
 -dPhi HCO   = 0.099

 -dEta EMC   = 0.00964
 -dEta HCI   = 0.00344
 -dEta HCO   = 0.00479

Energy Scale: Area = 0.785398 (r = 0.5) for E_max = 22.6914 GeV   Tracks:Pink Clusters:White

TRACK 5
Track Energy   = 3 GeV
Track Eta   = 0.014
Track Phi   = 4.01
Range   : 1.64 - 4.13
Track Matched = 1
 -EMC Energy   = 2.49
 -HCI Energy   = 2.65
 -HCO Energy   = 2.48
 -Summed Energy = 7.62 GeV

 -EMC ID: 62
 -HIN ID: 3
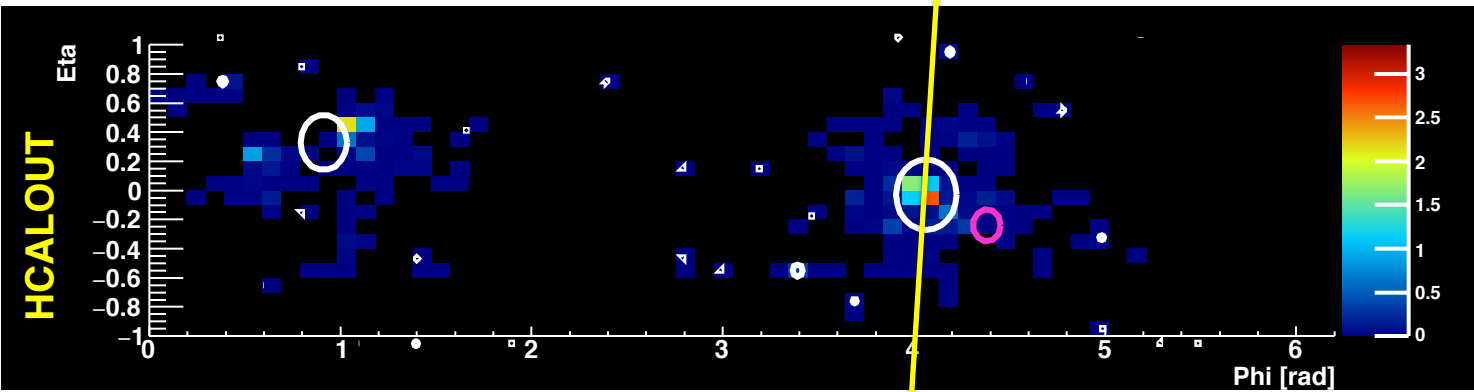 -HOU ID: 7

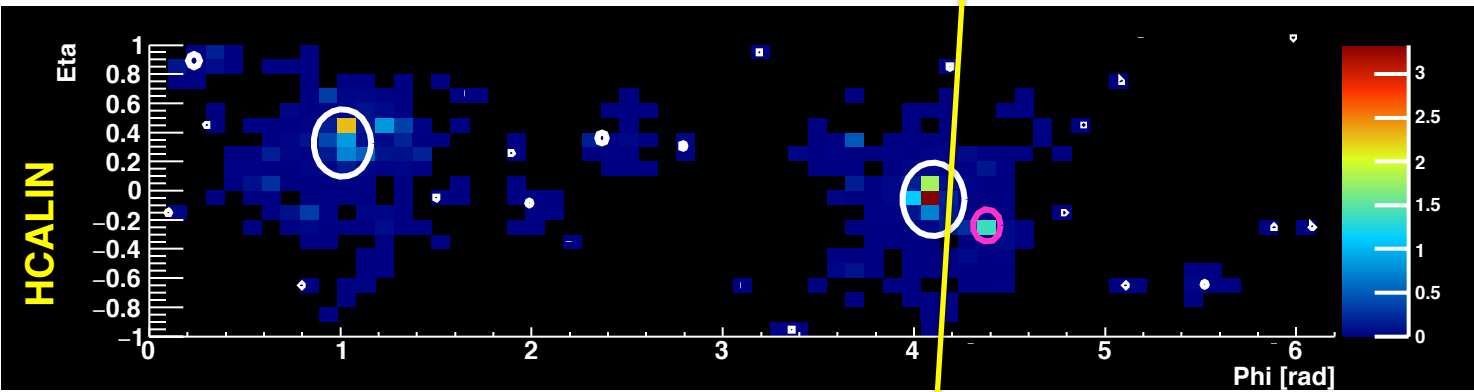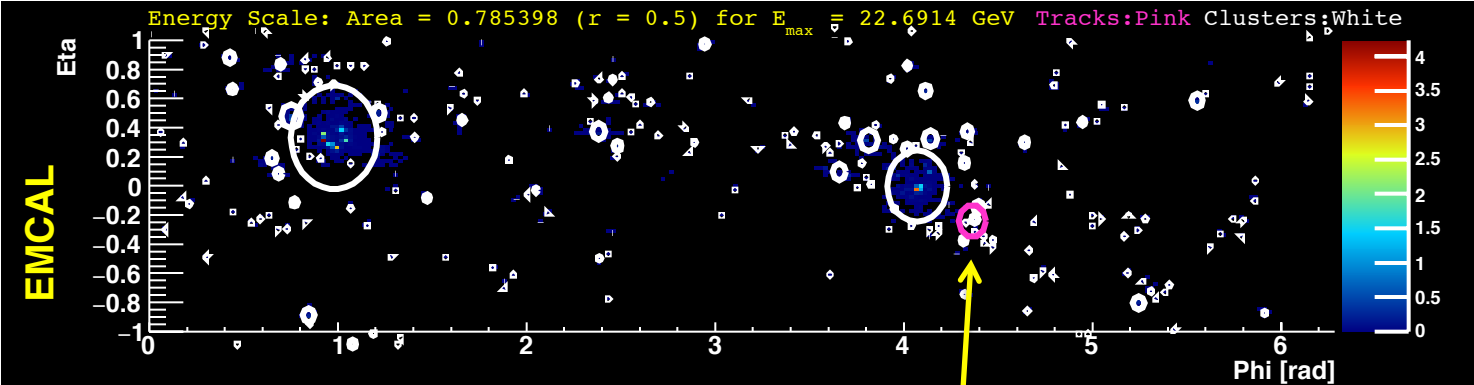 -dPhi EMC   = 0.00896
 -dPhi HCI   = 0.00894
 -dPhi HCO   = 0.0806

 -dEta EMC   = 0.016
 -dEta HCI   = 0.0734
 -dEta HCO   = 0.0427

16

Energy Scale: Area = 0.785398 (r = 0.5) for E$_{max}$ = 22.6914 GeV   Tracks:Pink Clusters:White
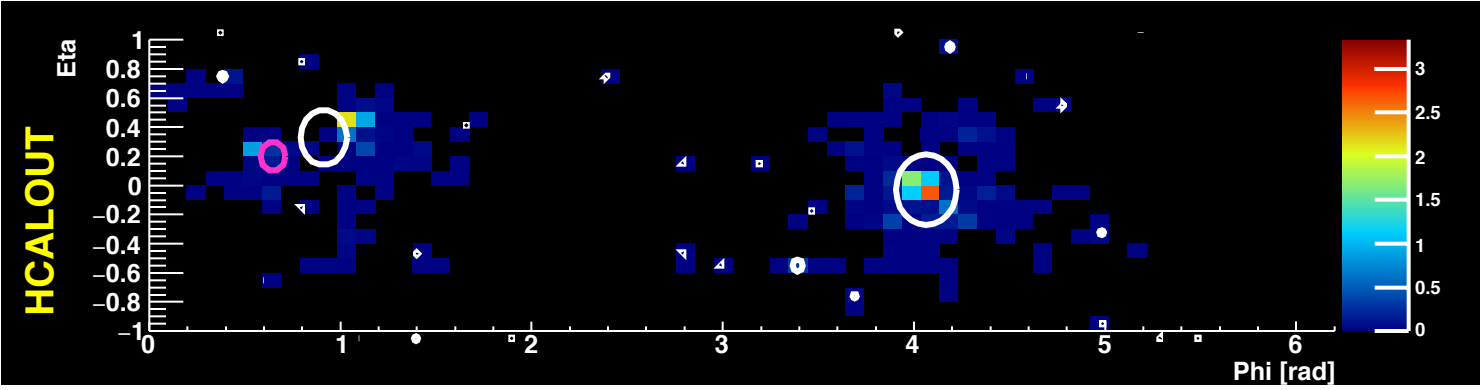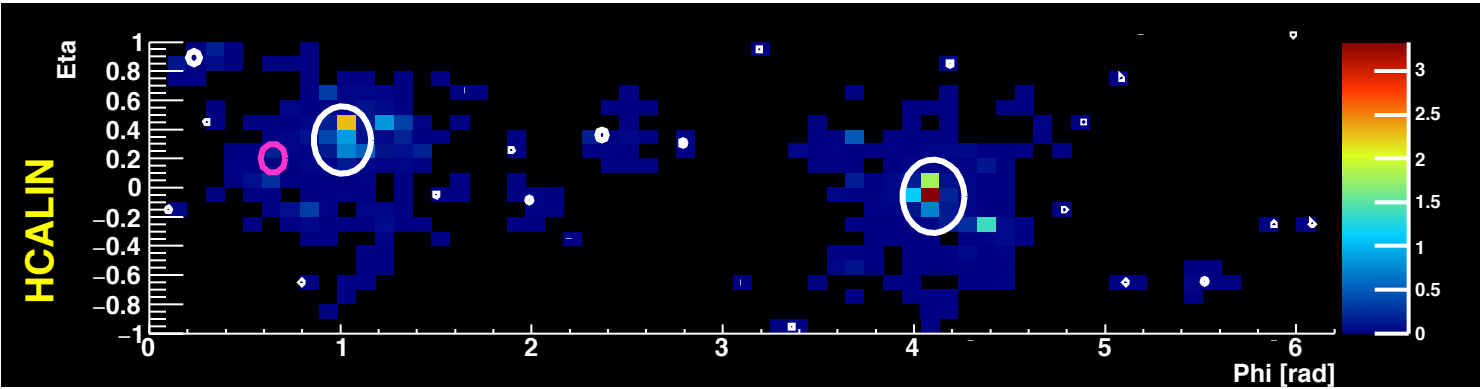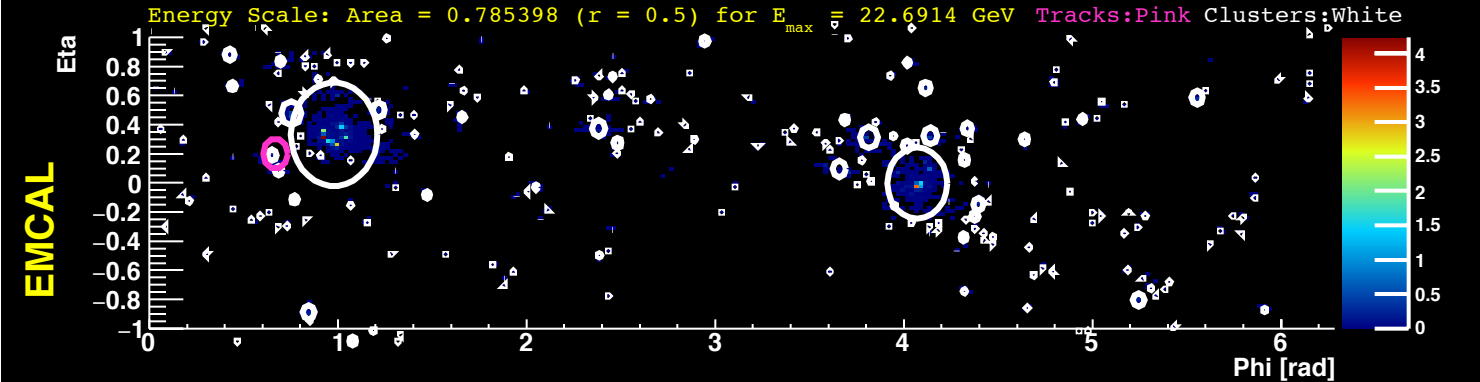
TRACK 6
Track Energy = 2.24 GeV
Track Eta   = -0.24
Track Phi   = 4.26
Range   : 1.21 - 3.21
Track Matched = 0
 -EMC Energy   = 0.174
 -HCI Energy   = 0
 -HCO Energy   = 0
 -Summed Energy = 0.174 GeV

 -EMC ID: 65
 -HIN ID: 3
 -HOU ID: 10

 -dPhi EMC   = 0.012
 -dPhi HCI   = 0.281
 -dPhi HCO   = 0.232

 -dEta EMC   = 0.0101
 -dEta HCI   = 0.181
 -dEta HCO   = 0.286

There is more energy in this track than in the clusters it matches to. Hence, it is most likely a fake.

17

Energy Scale: Area = 0.785398 (r = 0.5) for E_{max} = 22.6914 GeV   Tracks:Pink Clusters:White
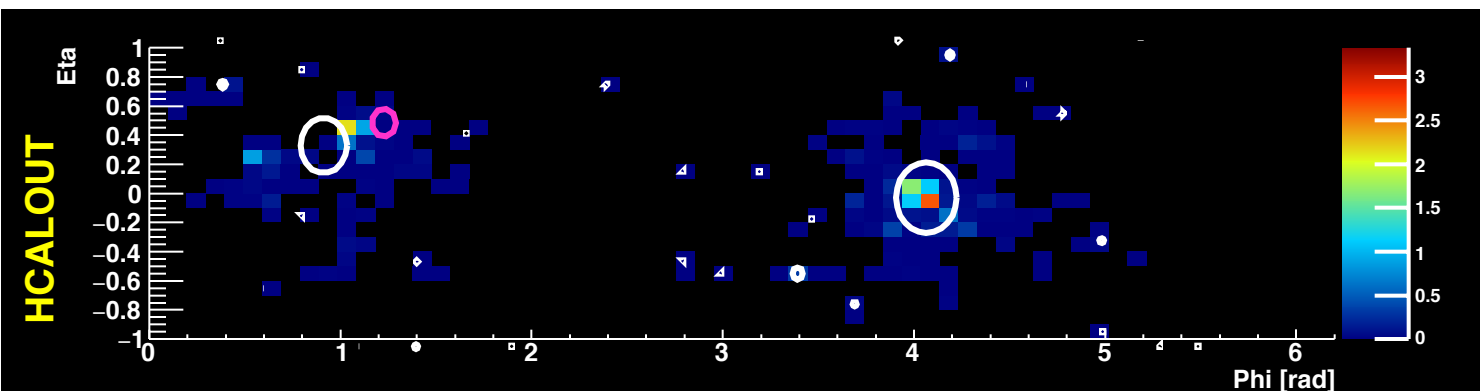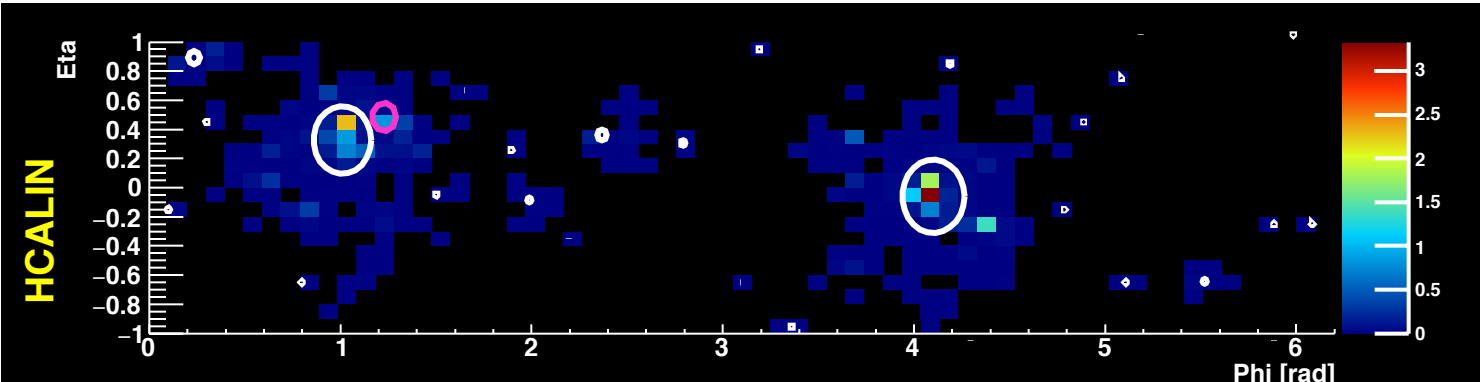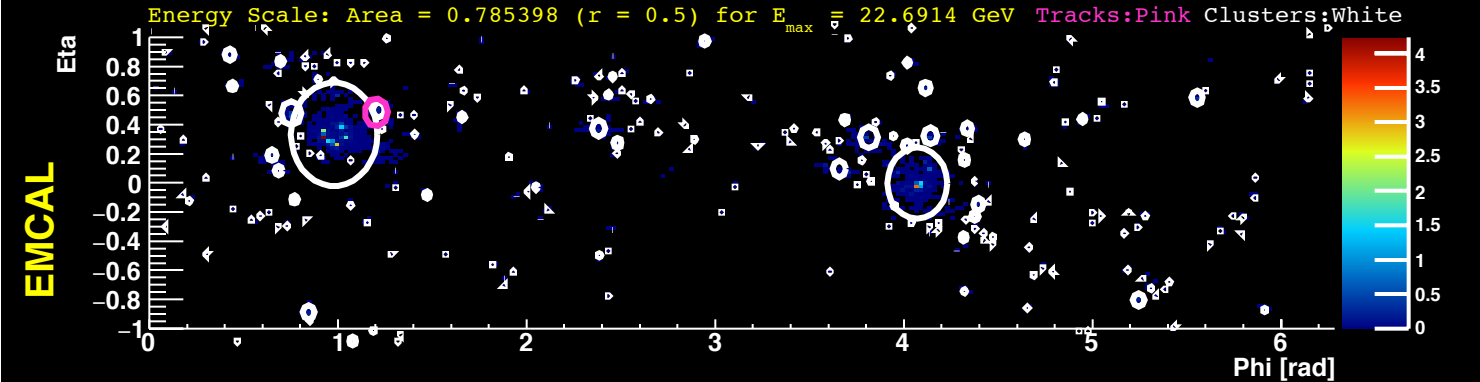
TRACK 7
Track Energy   = 1.87 GeV
Track Eta   = 0.201
Track Phi   = 0.786
Range   : 0.98 - 2.77
Track Matched = 0
 -EMC Energy   = 0.283
 -HCI Energy   = 0
 -HCO Energy   = 0
 -Summed Energy = 0.283 GeV

 -EMC ID: 111
 -HIN ID: 4
 -HOU ID: 11

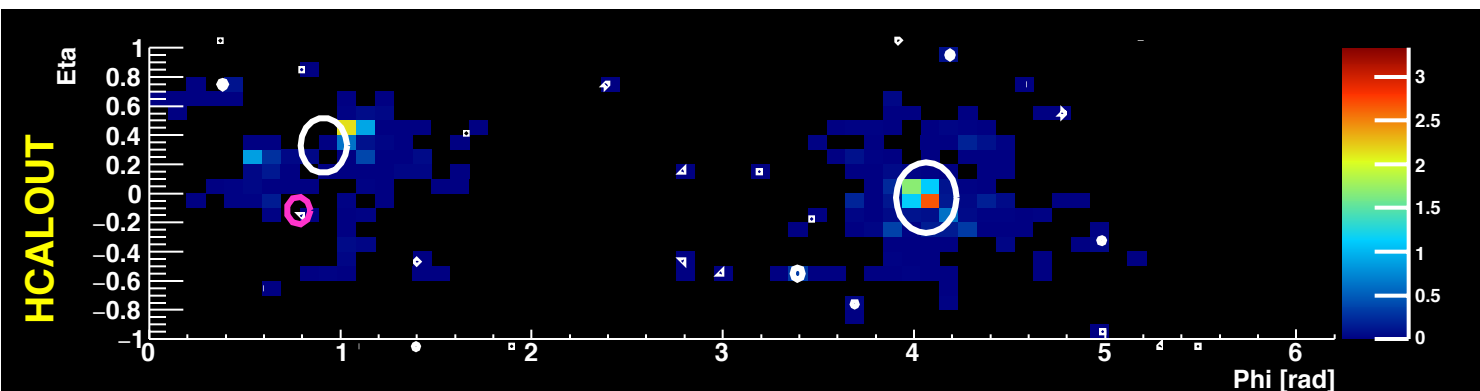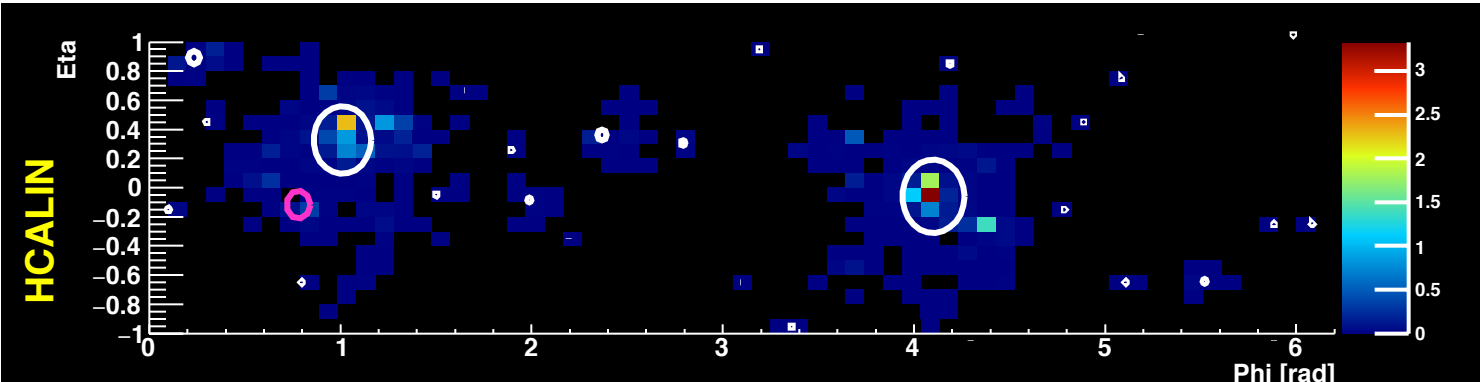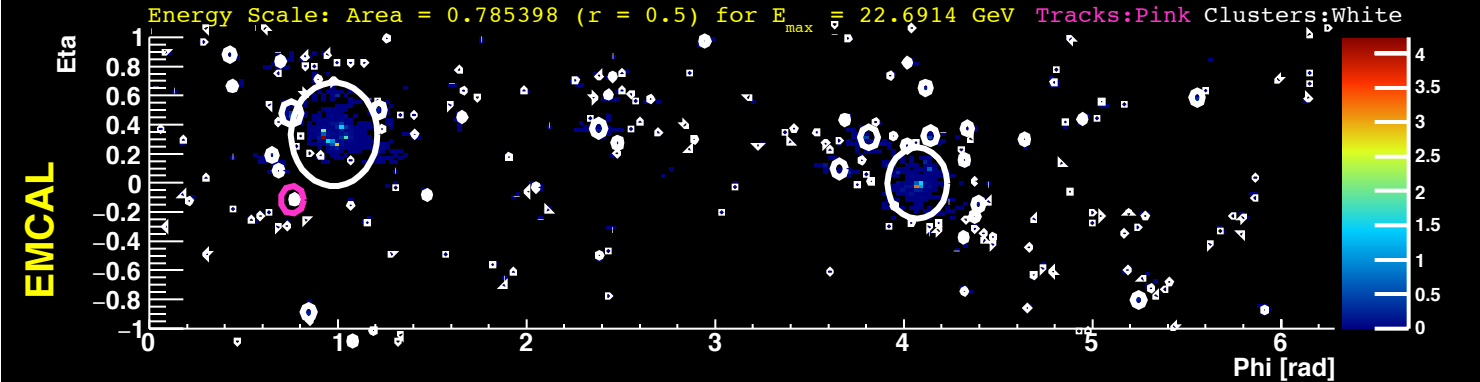 -dPhi EMC   = 0.0169
 -dPhi HCI   = 0.364
 -dPhi HCO   = 0.353

 -dEta EMC   = 0.0107
 -dEta HCI   = 0.126
 -dEta HCO   = 0.126

18

Energy Scale: Area = 0.785398 (r = 0.5) for E_max = 22.6914 GeV   Tracks:Pink Clusters:White
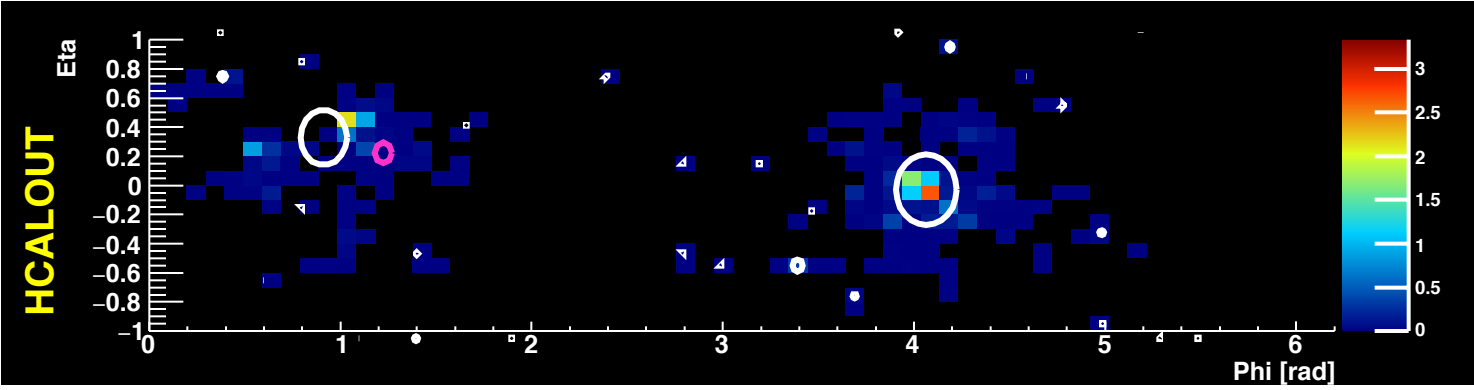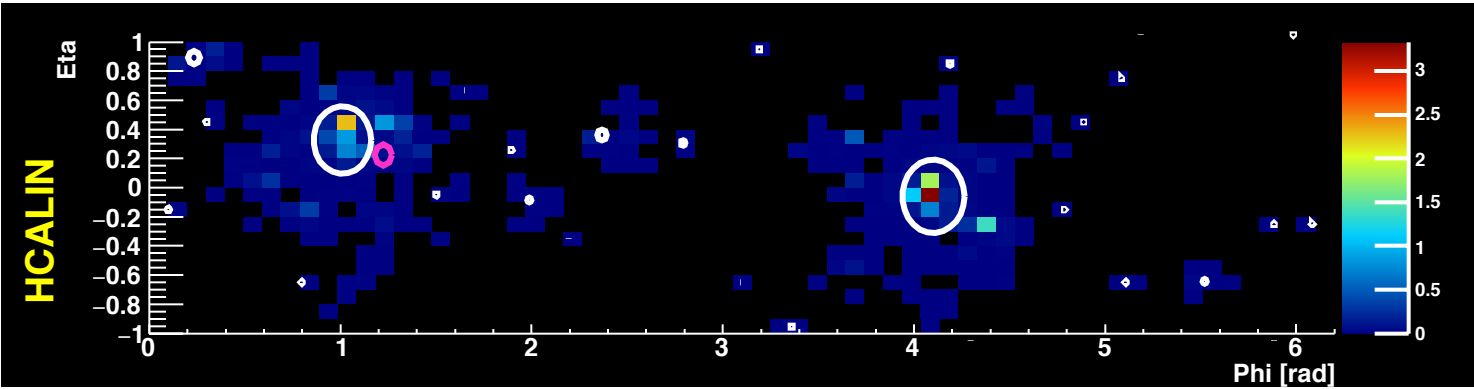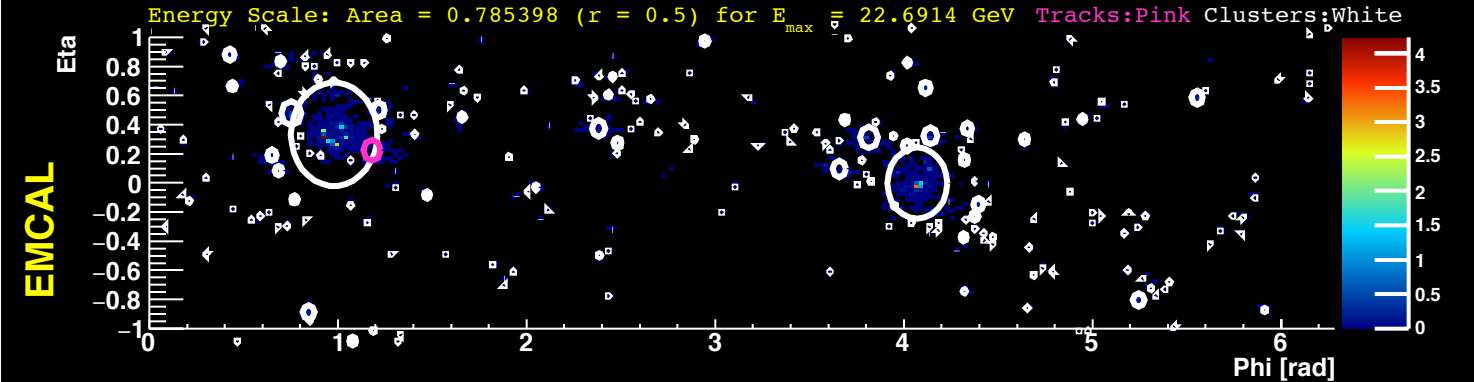
TRACK 8
Track Energy   = 1.69 GeV
Track Eta   = 0.486
Track Phi   = 1.06
Range   : 0.861 - 2.54
Track Matched = 0
 -EMC Energy   = 0.443
 -HCl Energy   = 0
 -HCO Energy   = 0
 -Summed Energy = 0.443
GeV

 -EMC ID: 155
 -HIN ID: 4
 -HOU ID: 21

 -dPhi EMC   = 0.0117
 -dPhi HCl   = 0.222
 -dPhi HCO   = 0.321

 -dEta EMC   = 0.0133
 -dEta HCl   = 0.161
 -dEta HCO   = 0.0787

19

Energy Scale: Area = 0.785398 (r = 0.5) for E_{max} = 22.6914 GeV   Tracks:Pink Clusters:White

TRACK 9
Track Energy   = 1.65 GeV
Track Eta   = -0.117
Track Phi   = 0.626
Range   : 0.834 - 2.49
Track Matched = 0
 -EMC Energy   = 0.136
 -HCI Energy   = 0
 -HCO Energy   = 0.000308
 -Summed Energy = 0.136
GeV

 -EMC ID: 86
 -HIN ID: 4
 -HOU ID: 18

 -dPhi EMC   = 0.0111
 -dPhi HCI   = 0.226
 -dPhi HCO   = 0.0824

 -dEta EMC   = 0.00302
 -dEta HCI   = 0.445
 -dEta HCO   = 0.0319

20

Energy Scale: Area = 0.785398 (r = 0.5) for E_{max} = 22.6914 GeV   Tracks:Pink Clusters:White
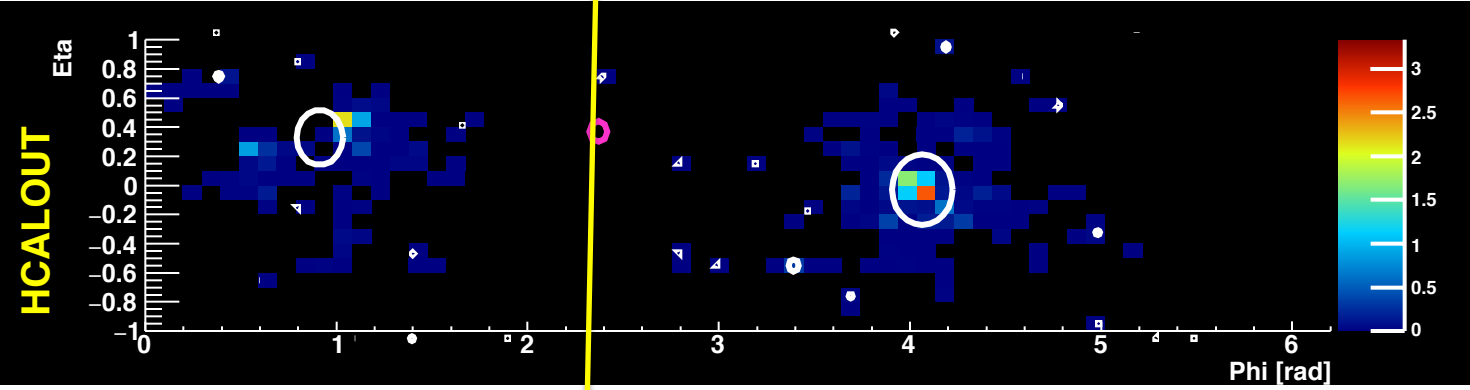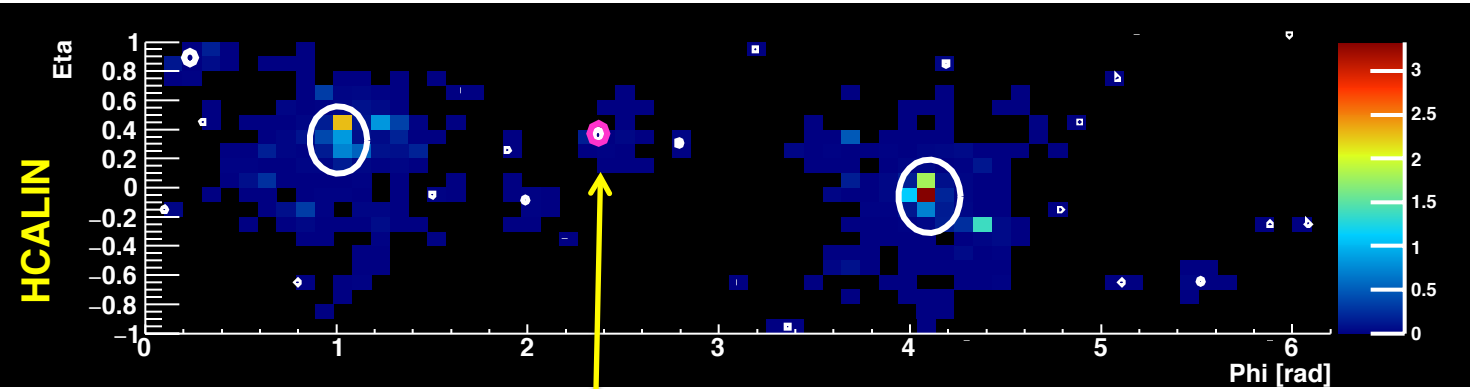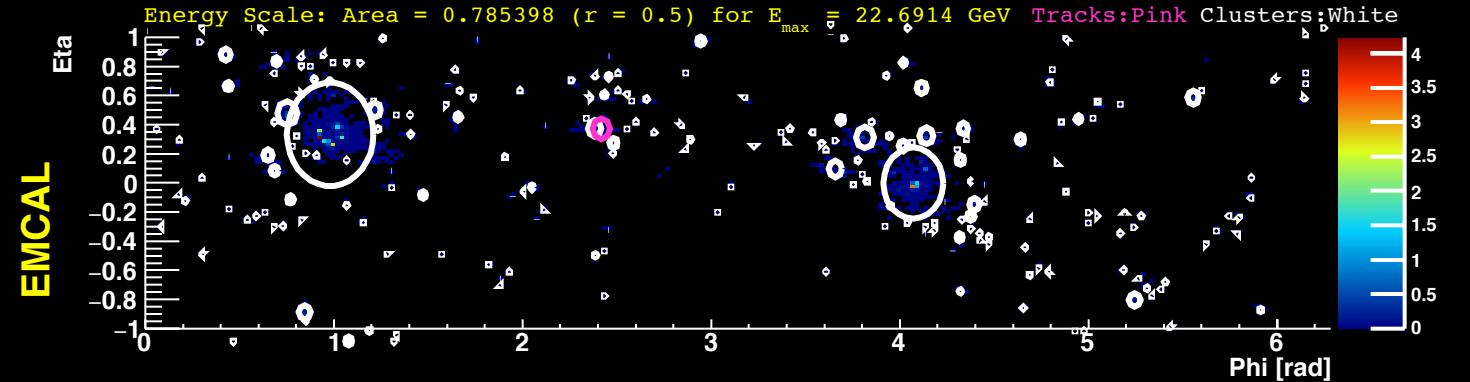
TRACK 10
Track Energy = 0.944 GeV
Track Eta   = 0.224
Track Phi   = 0.944
Range   : 0.327 - 1.63
Track Matched = 0
 -EMC Energy   = 0.00601
 -HCI Energy   = 0
 -HCO Energy   = 0
 -Summed Energy = 0.00601 GeV

 -EMC ID: 116
 -HIN ID: 4
 -HOU ID: 21

 -dPhi EMC   = 0.117
 -dPhi HCI   = 0.219
 -dPhi HCO   = 0.246

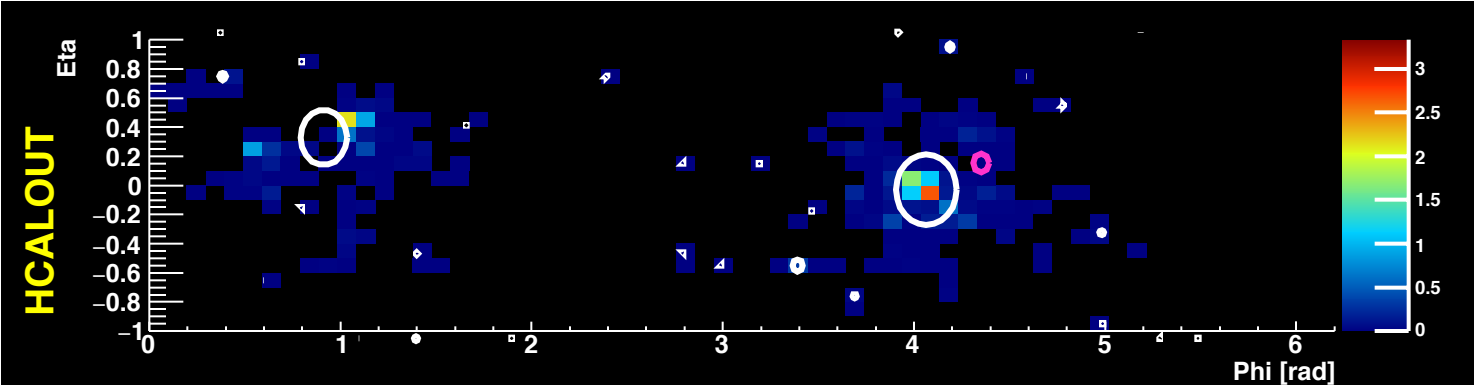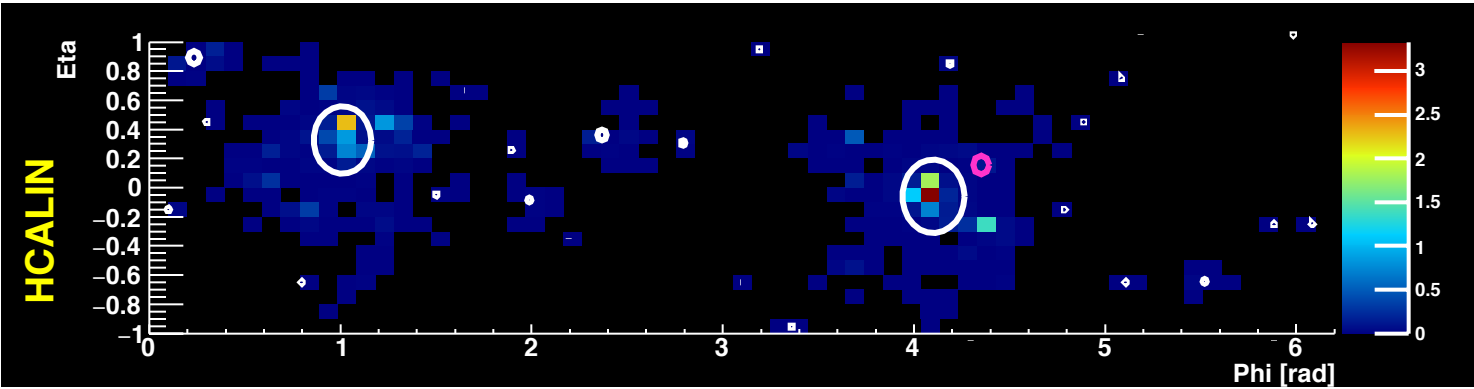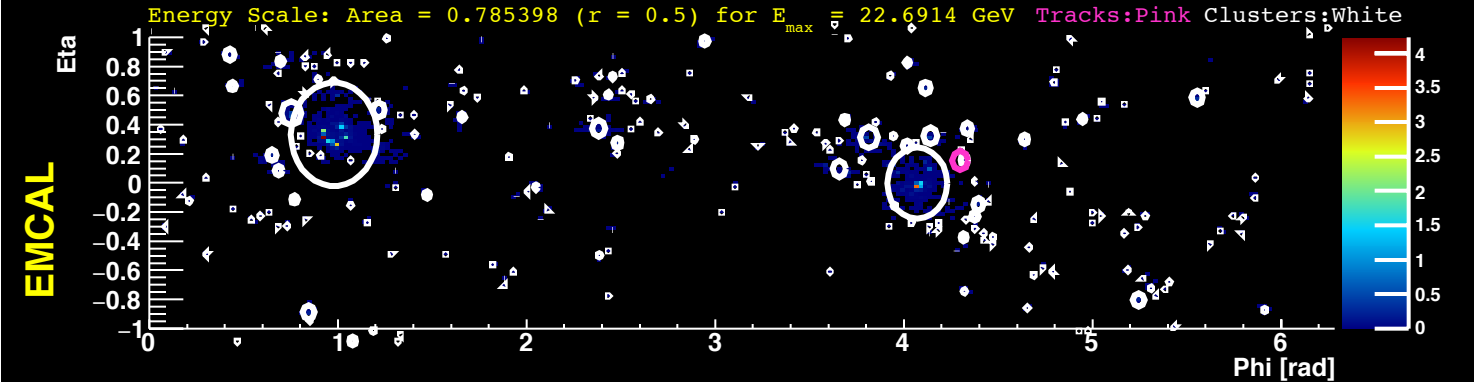 -dEta EMC   = 0.0703
 -dEta HCI   = 0.101
 -dEta HCO   = 0.181

21

Energy Scale: Area = 0.785398 (r = 0.5) for E$_{max}$ = 22.6914 GeV   Tracks:Pink Clusters:White

TRACK 11
Track Energy   = 0.925 GeV
Track Eta   = 0.371
Track Phi   = 2.67
Range   : 0.312 - 1.6
Track Matched = 2
 -EMC Energy   = 0.567
 -HCl Energy   = 0.26
 -HCO Energy   = 0
 -Summed Energy = 0.827 GeV

 -EMC ID: 143
 -HIN ID: 17
 -HOU ID: 25

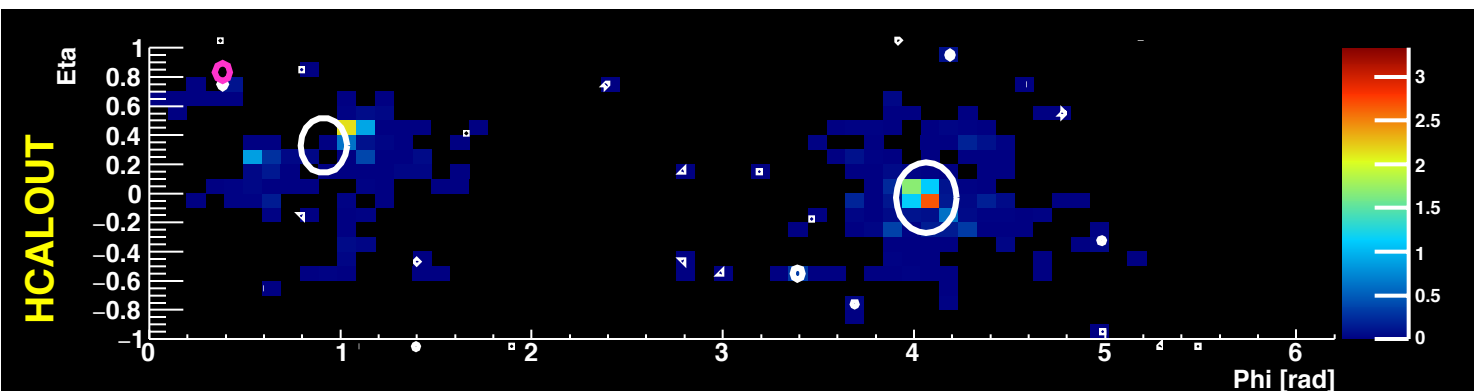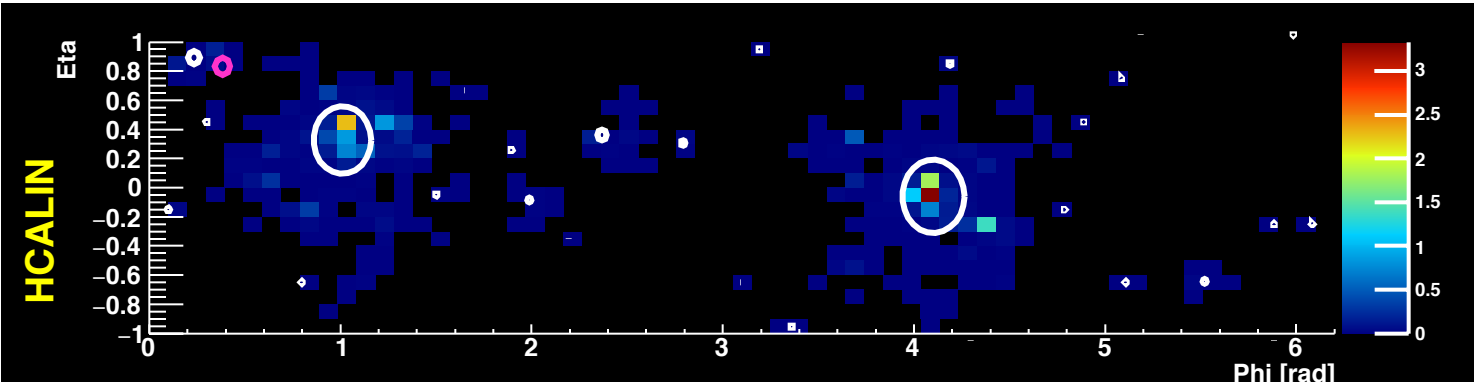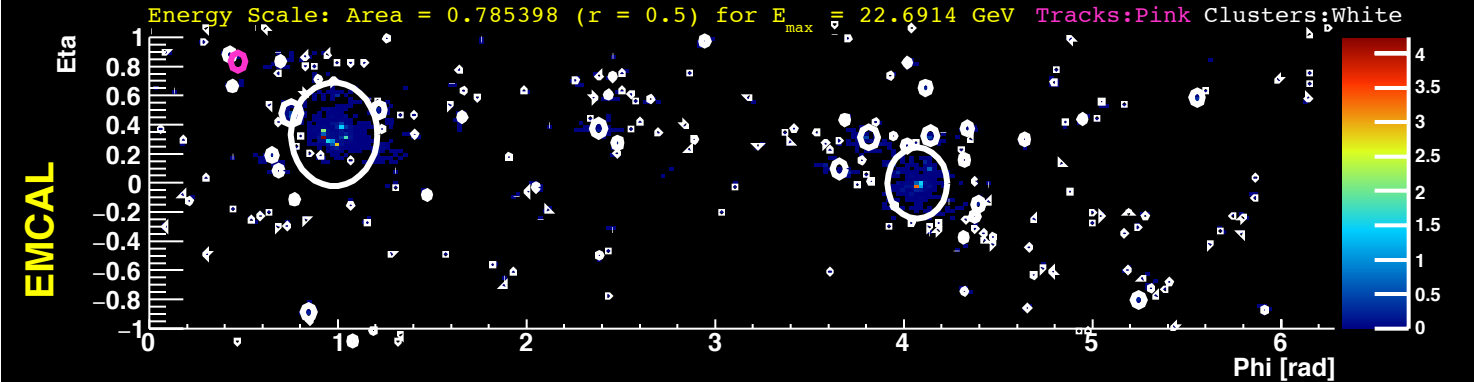 -dPhi EMC   = 0.03
 -dPhi HCl   = 0.00414
 -dPhi HCO   = 0.226

 -dEta EMC   = 0.00139
 -dEta HCl   = 0.0143
 -dEta HCO   = 0.363

The energy of this track matches the cluster energy exactly

Energy Scale: Area = 0.785398 (r = 0.5) for E_{max} = 22.6914 GeV   Tracks:Pink Clusters:White

EMCAL

HCALIN
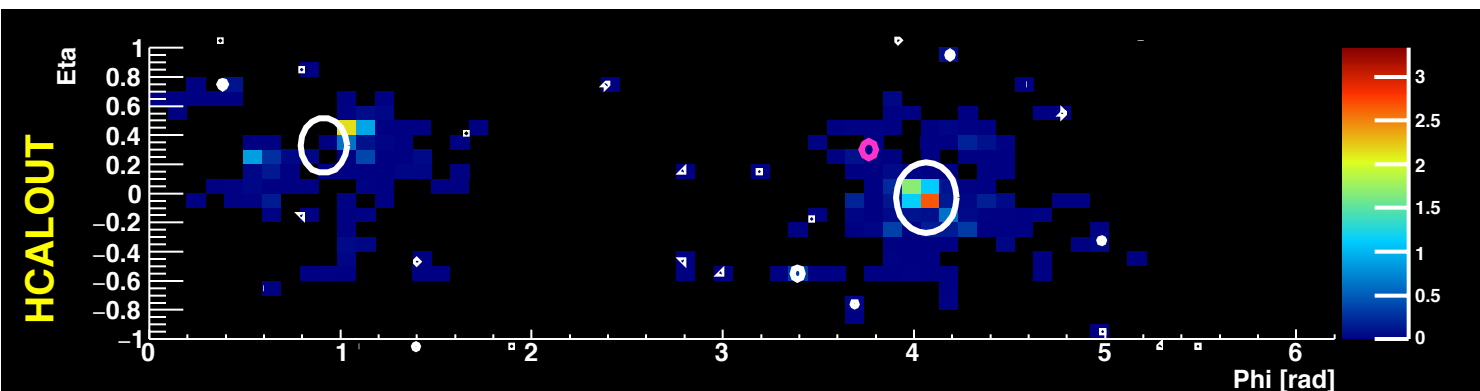
HCALOUT

TRACK 12
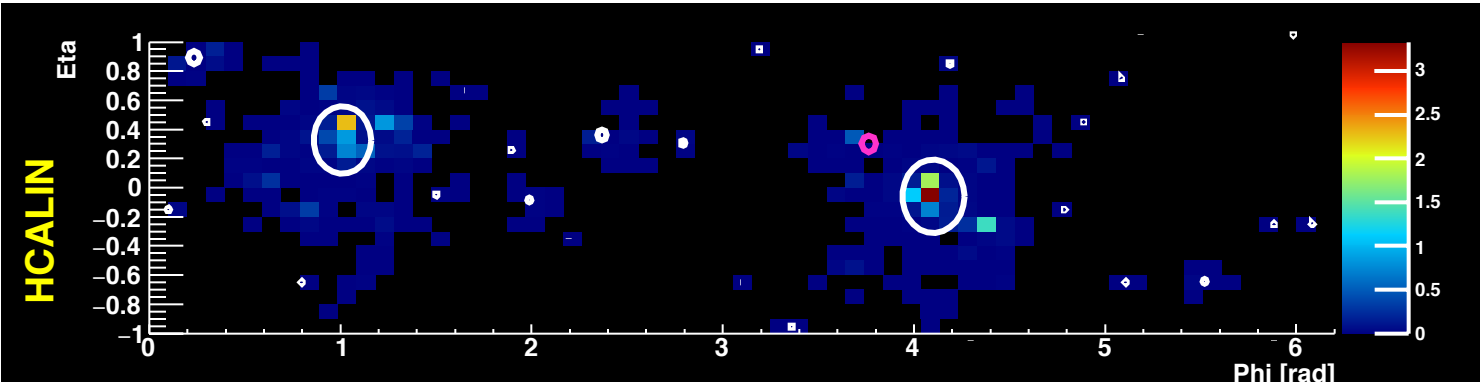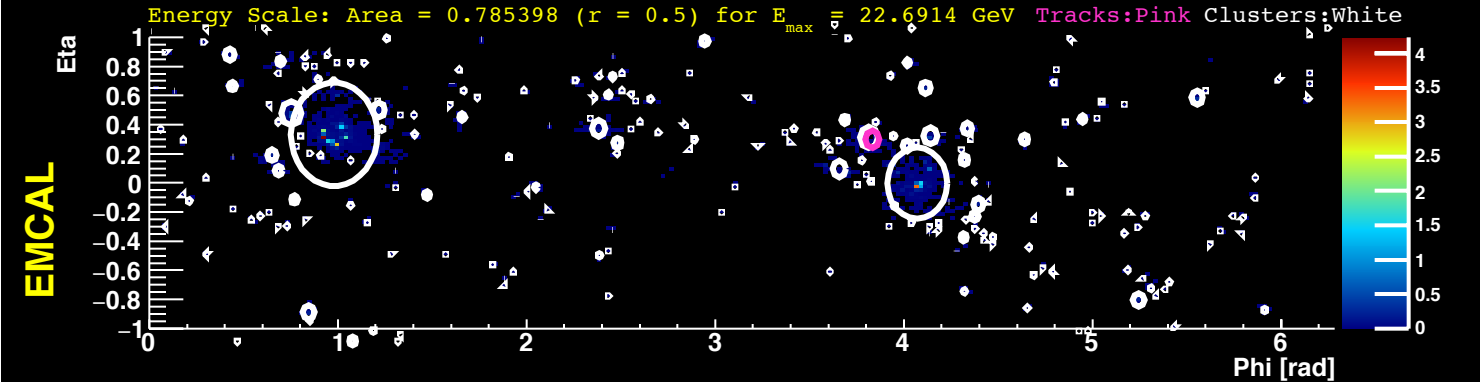Track Energy   = 0.773 GeV
Track Eta   = 0.155
Track Phi   = 4.01
Range   : 0.194 - 1.42
Track Matched = 0
 -EMC Energy   = 0.177
 -HCI Energy   = 0
 -HCO Energy   = 0
 -Summed Energy = 0.177
GeV

 -EMC ID: 114
 -HIN ID: 3
 -HOU ID: 22

 -dPhi EMC   = 0.0179
 -dPhi HCI   = 0.255
 -dPhi HCO   = 0.194

 -dEta EMC   = 3.13e-05
 -dEta HCI   = 0.217
 -dEta HCO   = 0.386

23

Energy Scale: Area = 0.785398 (r = 0.5) for E_{max} = 22.6914 GeV   Tracks:Pink Clusters:White

TRACK 13
Track Energy   = 0.687 GeV
Track Eta   = 0.833
Track Phi   = 0.921
Range   : 0.125 - 1.31
Track Matched = 2
 -EMC Energy   = 0.296
 -HCI Energy   = 0.395
 -HCO Energy   = 0
 -Summed Energy = 0.691 GeV

 -EMC ID: 221
 -HIN ID: 25
 -HOU ID: 30

 -dPhi EMC   = 0.0373
 -dPhi HCI   = 0.14
 -dPhi HCO   = 0.441

 -dEta EMC   = 0.0236
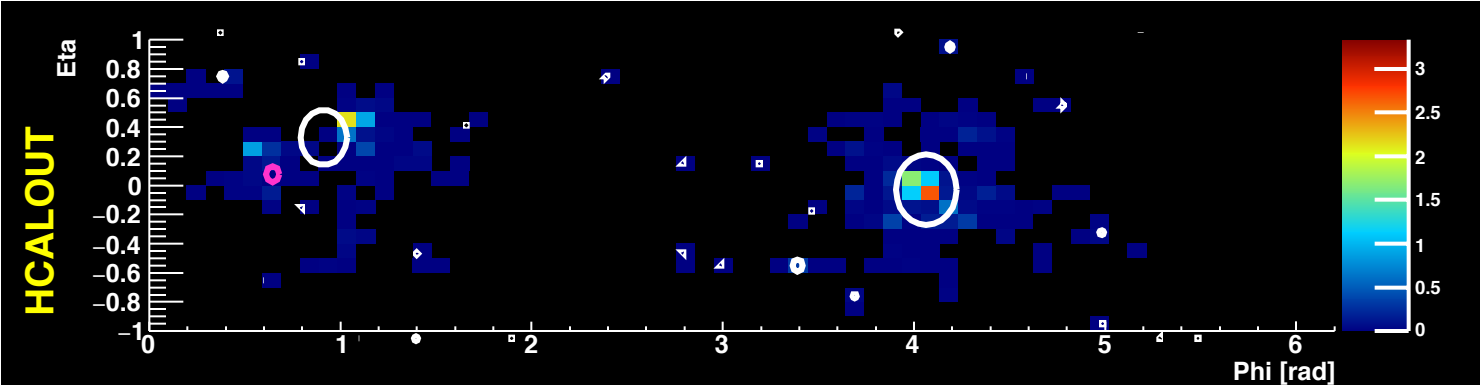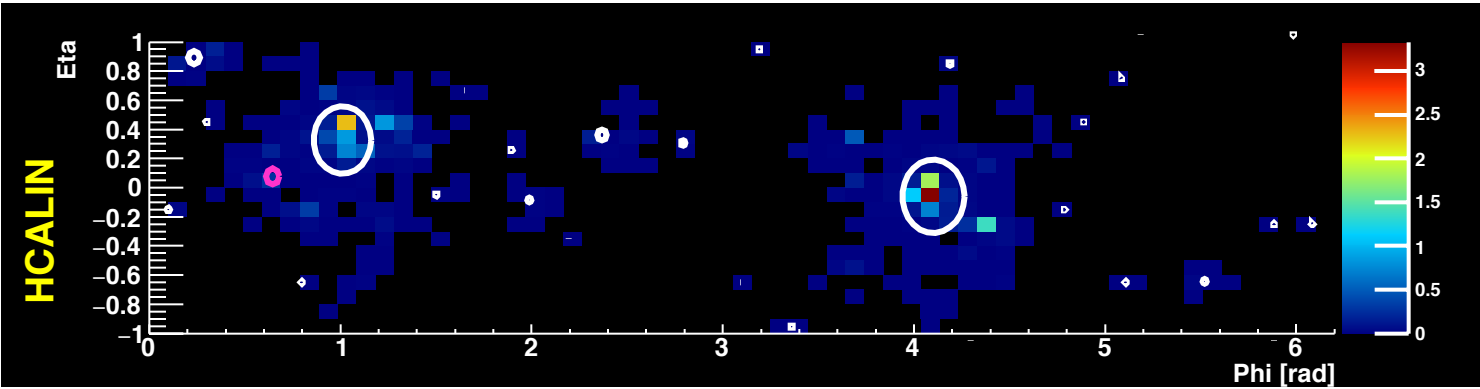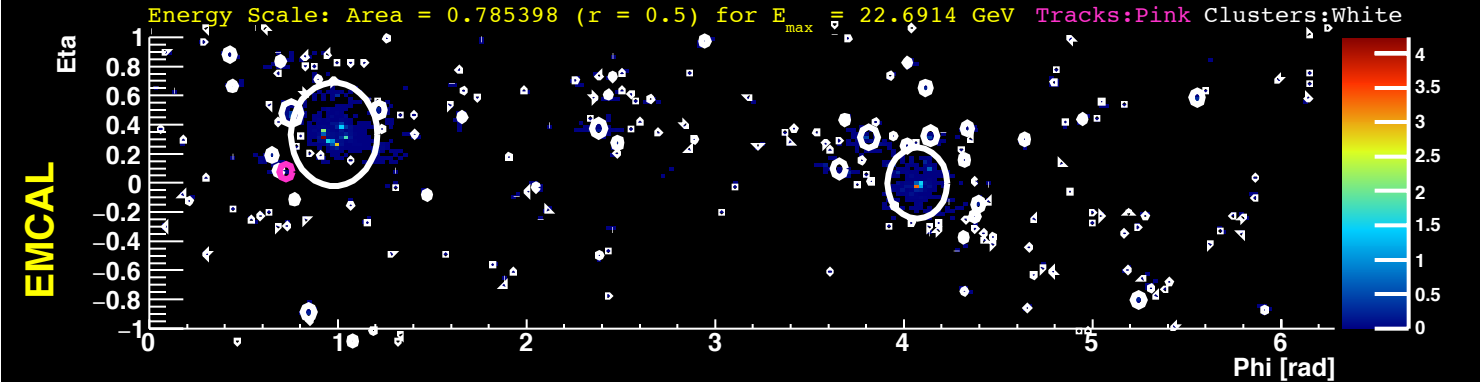 -dEta HCI   = 0.0242
 -dEta HCO   = 0.0967

Energy Scale: Area = 0.785398 (r = 0.5) for E_max = 22.6914 GeV Tracks:Pink Clusters:White

TRACK 14
Track Energy   = 0.638 GeV
Track Eta   = 0.3
Track Phi   = 4.2
Range   : 0.0853 - 1.25
Track Matched = 2
 -EMC Energy   = 0.987
 -HCl Energy   = 0
 -HCO Energy   = 0
 -Summed Energy = 0.987
GeV

 -EMC ID: 120
 -HIN ID: 22
 -HOU ID: 19

 -dPhi EMC   = 0.0142
 -dPhi HCl   = 0.067
 -dPhi HCO   = 0.248

 -dEta EMC   = 0.00404
 -dEta HCl   = 0.34
 -dEta HCO   = 0.181

Energy Scale: Area = 0.785398 (r = 0.5) for E_max = 22.6914 GeV   Tracks:Pink Clusters:White
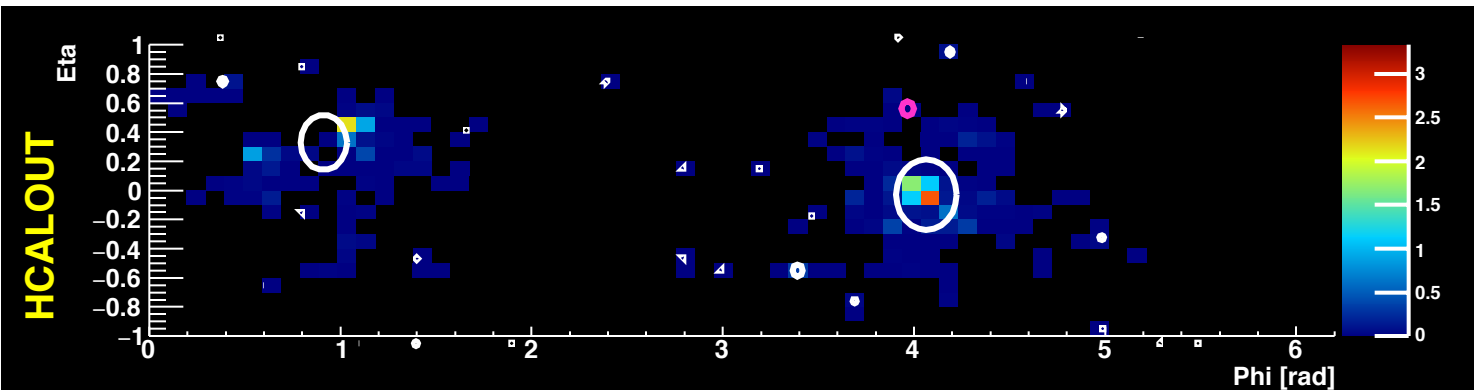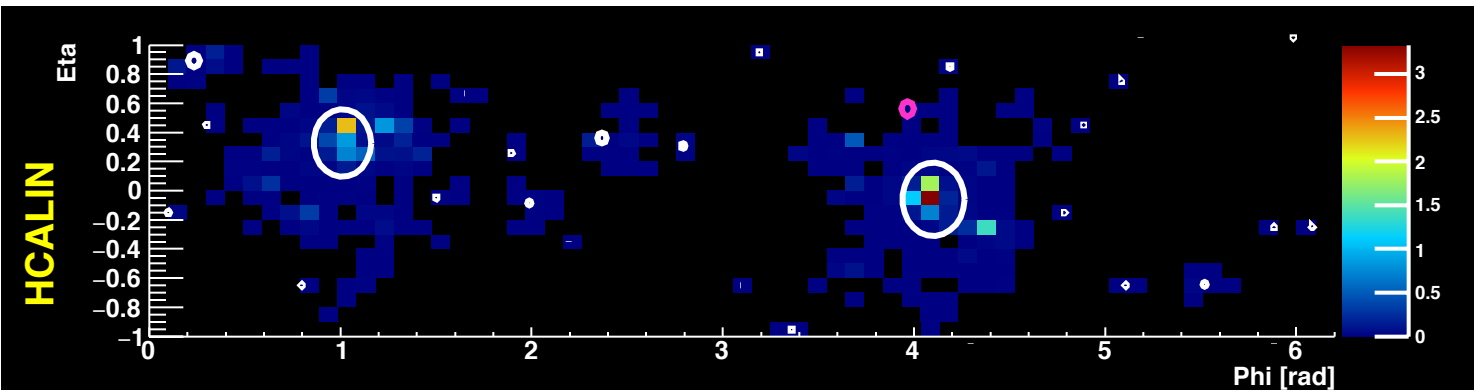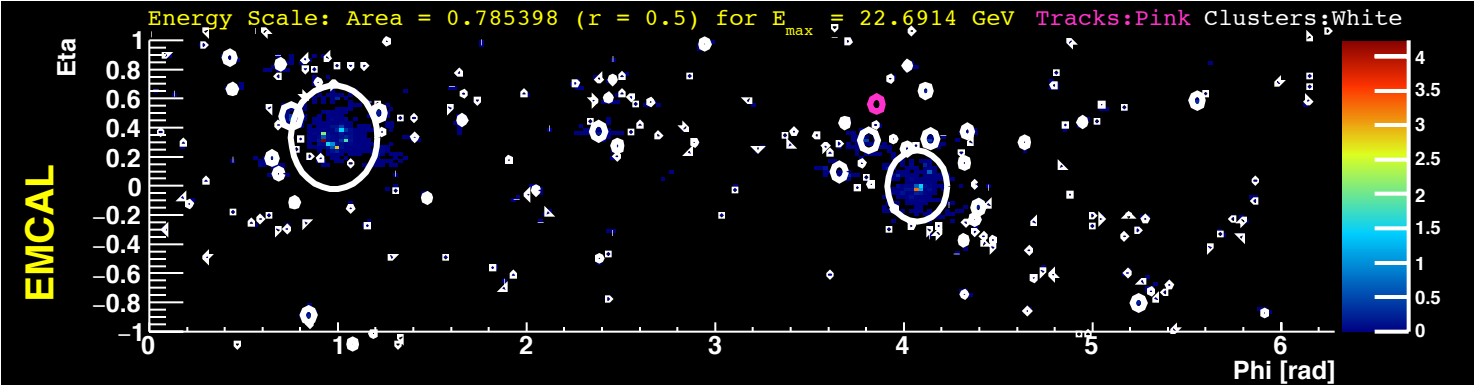
TRACK 15
Track Energy   = 0.558 GeV
Track Eta   = 0.0771
Track Phi   = 1.13
Range   : 0.0196 - 1.15
Track Matched = 2
 -EMC Energy   = 0.183
 -HCI Energy   = 0
 -HCO Energy   = 0
 -Summed Energy = 0.183 GeV

 -EMC ID: 107
 -HIN ID: 4
 -HOU ID: 18

 -dPhi EMC   = 0.0312
 -dPhi HCI   = 0.373
 -dPhi HCO   = 0.534

 -dEta EMC   = 0.00446
 -dEta HCI   = 0.247
 -dEta HCO   = 0.238

Energy Scale: Area = 0.785398 (r = 0.5) for E_{max} = 22.6914 GeV   Tracks:Pink Clusters:White

TRACK 16
Track Energy   = 0.502 GeV
Track Eta   = 0.561
Track Phi   = 3.31
Range   : -0.0273 - 1.08
Track Matched = 2
 -EMC Energy   = 0.0183
 -HCI Energy   = 0
 -HCO Energy   = 0
 -Summed Energy = 0.0183
GeV

 -EMC ID: 202
 -HIN ID: 22
 -HOU ID: 24

 -dPhi EMC   = 0.0646
 -dPhi HCI   = 0.288
 -dPhi HCO   = 0.154

 -dEta EMC   = 0.15
 -dEta HCI   = 0.0501
 -dEta HCO   = 0.023

Thank You!