Application of layer-by-layer clustering to a generalised calorimeter

Chris Ainsley

University of Cambridge

<ainsley@hep.phy.cam.ac.uk>

LCWS 05: simulation & reconstruction session
18-22 March 2005, Stanford, CA, USA

Motivation

- Desire for excellent jet energy resolution at ILC

  ⇒ highly granular calorimeter, capable of resolving individual particles within jets.

- Calorimeter will have a pixelated, layered structure

  ⇒ require a novel approach to clustering.

- Existing calorimeter clustering algorithms tied to specific geometries, but want to make objective comparisons between different detector designs

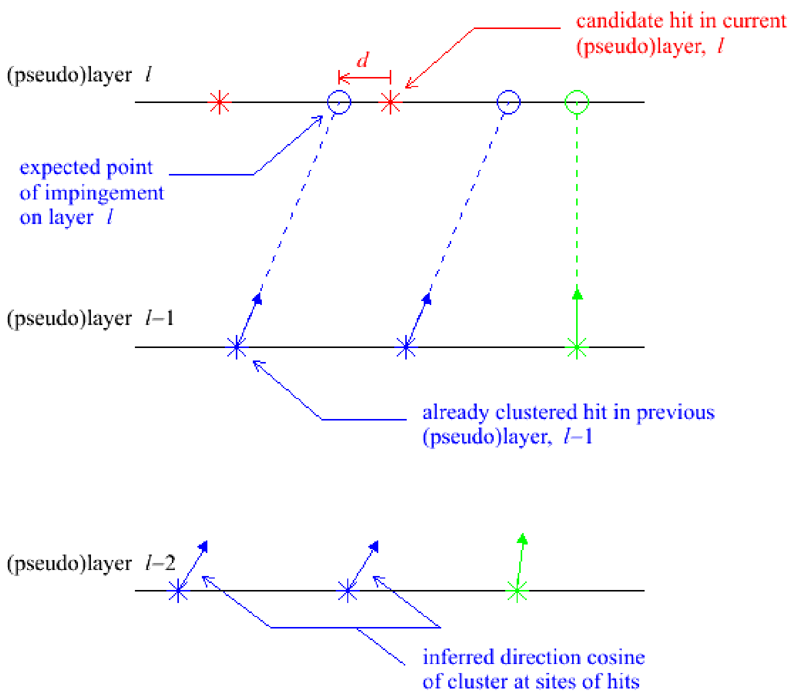
  ⇒ need a clustering algorithm flexible w.r.t. geometry.

Order of service

- Layer-by-layer clustering algorithm in outline.
- Performance in two-particle separation.
- Putting the calorimeter geometry into a generalised form for layer-by-layer clustering.
- How it's coded.
- Summary.

Layer-by-layer clustering: stage 1

- Form coarse clusters by ***tracking*** closely-related hits ***layer-by-layer*** through calorimeter:
  - for a candidate hit in a given layer, ***l***, minimize the distance, ***d***, w.r.t all (already clustered) hits in layer ***l***–1;
  - if ***d*** < **distMax** for minimum ***d***, assign candidate hit to same cluster as hit in layer ***l***–1 which yields minimum;
  - if not, repeat with all hits in layer ***l***–2, then, if necessary, layer ***l***–3, *etc*., right through to layer ***l***–**layersToTrackBack**;
  - after iterating over all hits in layer ***l***, seed new clusters with those still unassigned, grouping those within **proxSeedMax** of highest weighted remaining hit into same seed;
  - assign a direction cosine to each layer ***l*** hit:
    - if in Ecal, calculate weighted centre of each cluster's hits in layer ***l*** (weight by energy (analogue) or density (digital)); assign a direction cosine to each hit along the line joining its cluster's centre in the seed layer (or (0,0,0) if it's a seed) to its cluster's centre in layer ***l***;
    - if in Hcal, assign a direction cosine to each hit along the line from the hit to which each is linked (or (0,0,0) if it's a seed) to the hit itself;
  - iterate outwards through layers.

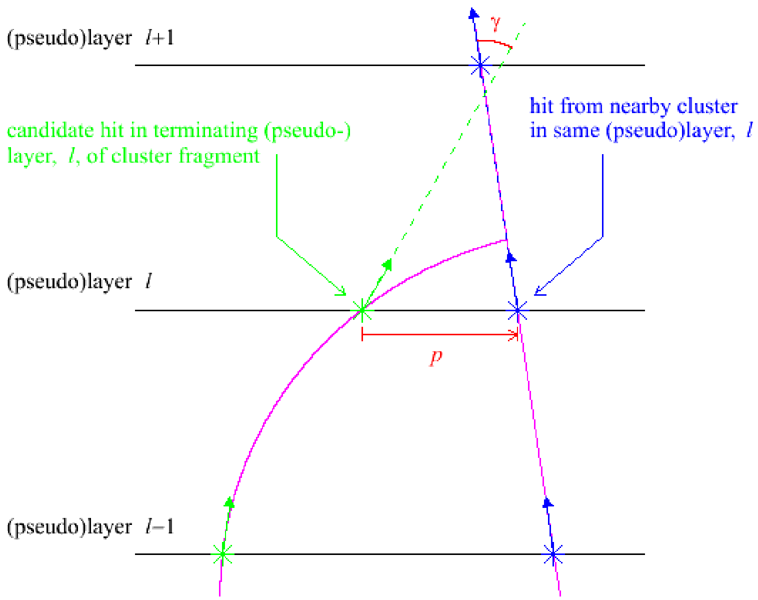


Chris Ainsley
<ainsley@hep.phy.cam.ac.uk>

Layer-by-layer clustering: stage 2

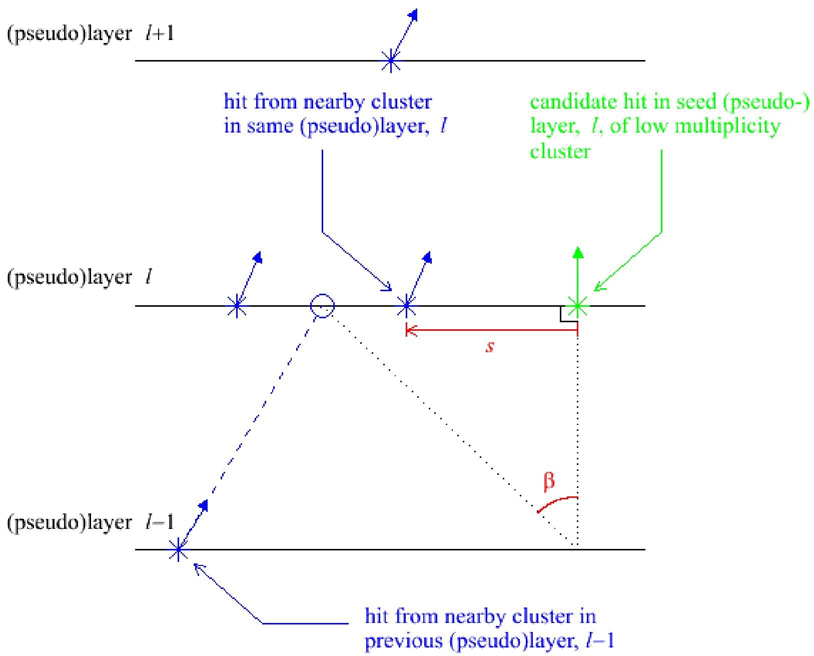
- Try to merge backward-spiralling track-like cluster-fragments with the forward propagating clusters to which they belong:
  - for each hit in the terminating layer, ***l***, of a candidate cluster fragment, calculate the distance, ***p***, to each hit in nearby clusters in the same layer, and the angle, γ, between their direction cosines;
  - loop over all pairs of hits;
  - if, for any pair, both:
    - ***p*** < **`proxMergeMax`** *and*
    - **cos** γ < **`cosGammaMax`**

    are satisfied, merge clusters together into one;
  - iterate over clusters.



Layer-by-layer clustering: stage 3

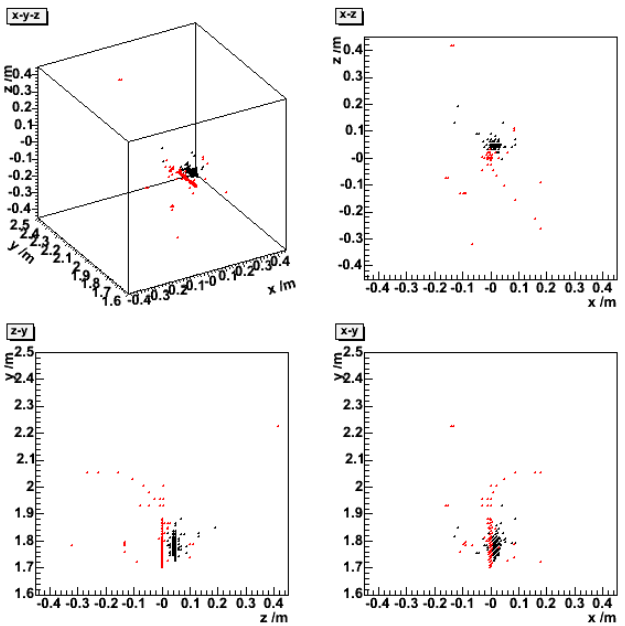
- Try to merge low multiplicity cluster “halos” (hit multiplicity < **`clusterSizeMin`**) which just fail the stage 1 cluster-continuation cuts:
  - for the highest weighted candidate hit in the seed layer, ***l***, of a low multiplicity cluster, minimize the angle, β, w.r.t all hits in layer ***l***–1;
  - if **tan** β < **`tanBetaMax`** for minimum β, merge the clusters containing the repsective hits into one;
  - if not, repeat with all hits in layer ***l***–2, then, if necessary, layer ***l***–3, *etc*., right through to layer ***l***–**`layersToTrackBack`**;
  - if still not, repeat above steps with the next highest weighted candidate hit of the low multiplicity cluster in the seed layer, *etc*. .
  - if still not, merge the low multiplicity cluster into the nearest cluster in the same layer, provided the two clusters contain hits separated by ***s*** < **`proxMergeMax`**;
  - iterate over clusters.

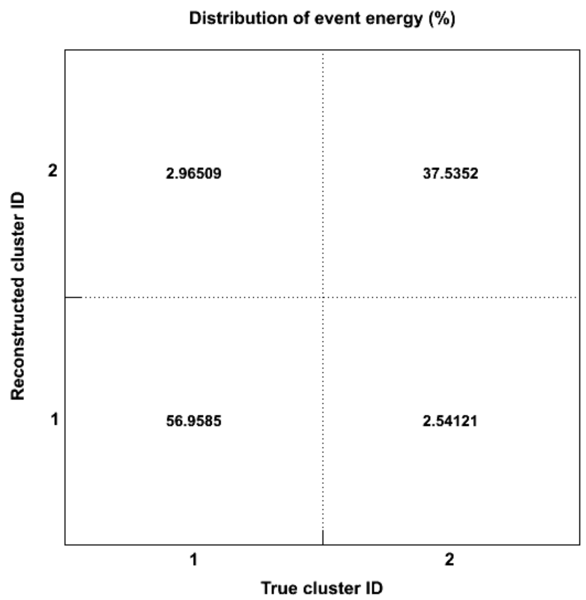


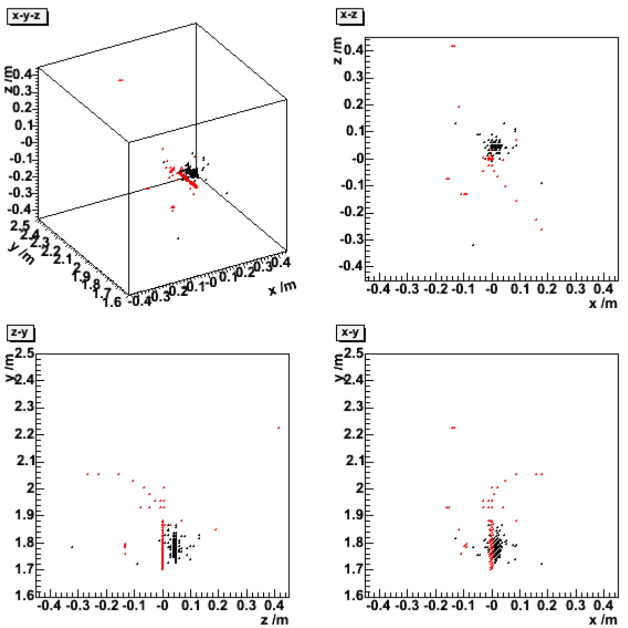
5 GeV $\pi^+\gamma$ event at 5 cm separation

Reconstructed clusters

True particle clusters



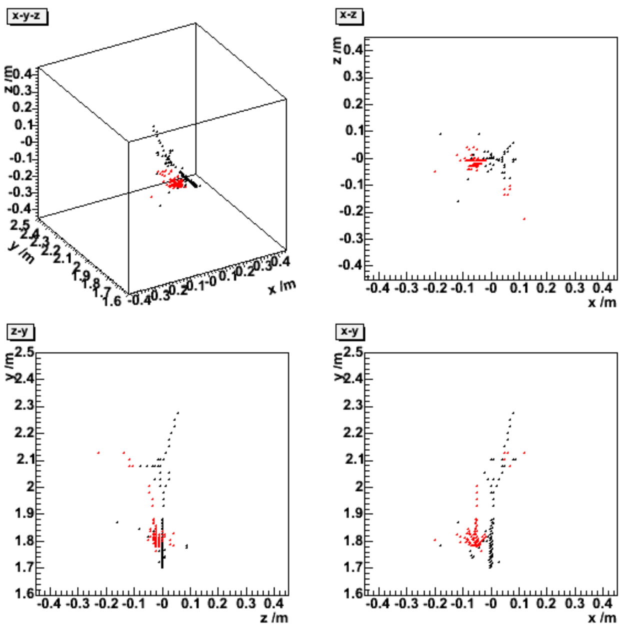


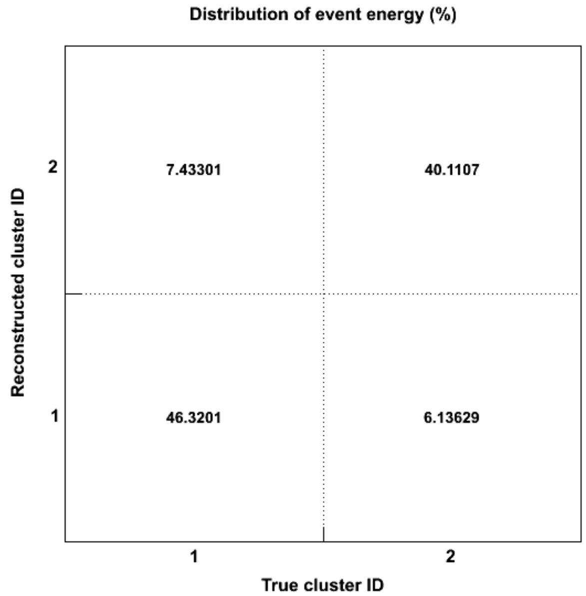


- Energy calibrated (CALICE detector – D09 model) according to:
  $E = \alpha[(E_{\mathrm{Ecal;\ 1\text{-}30}} + 3E_{\mathrm{Ecal;\ 31\text{-}40}})/E_{\mathrm{mip}} + 20N_{\mathrm{Hcal}}]$ GeV.
- Hits map mostly ***black*** $\leftrightarrow$ ***black*** **(γ)** and ***red*** $\leftrightarrow$ ***red*** **(π^+)** between reconstructed and true clusters.
- Fraction of event energy in 1:1 correspondence = **57.0 + 37.5 = 94 %**.

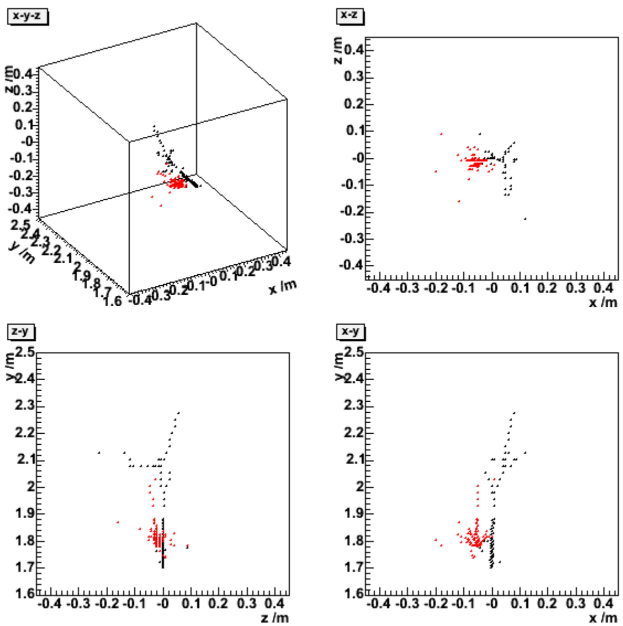
5 GeV $\pi^+ n$ event at 5 cm separation

Reconstructed clusters





True particle clusters



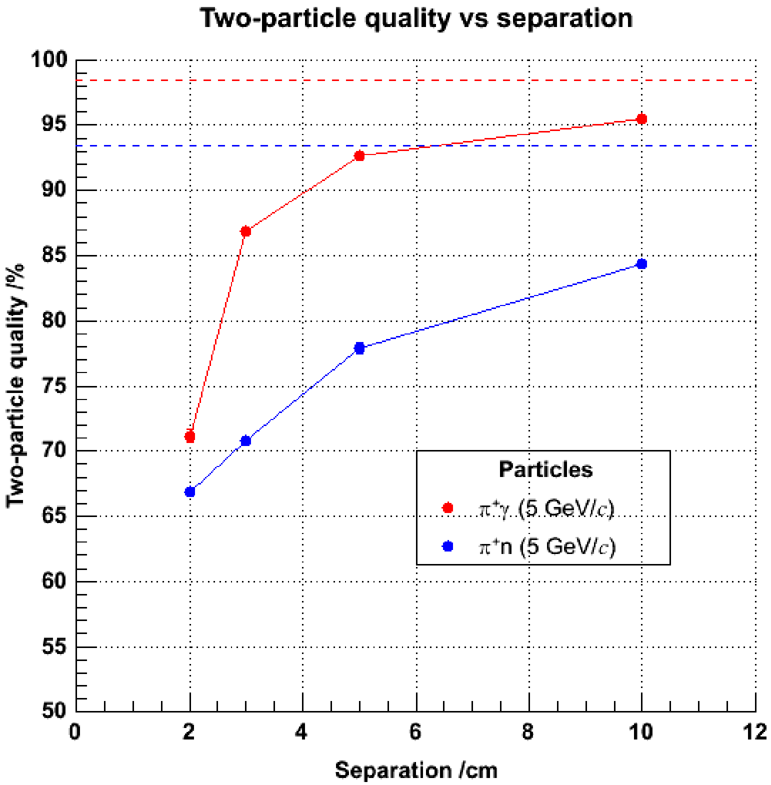
- Energy calibrated (CALICE detector – D09 model) according to:

  $E = \alpha[(E_{\mathrm{Ecal;\ 1\text{-}30}} + 3E_{\mathrm{Ecal;\ 31\text{-}40}})/E_{\mathrm{mip}} + 20N_{\mathrm{Hcal}}]$ GeV.
- Hits map mostly ***black*** $\leftrightarrow$ ***black*** **(π^+)** and ***red*** $\leftrightarrow$ ***red*** **(n)** between reconstructed and true clusters.
- Fraction of event energy in 1:1 correspondence = **46.3 + 40.1 = 86 %**.

5 GeV two-particle quality vs separation

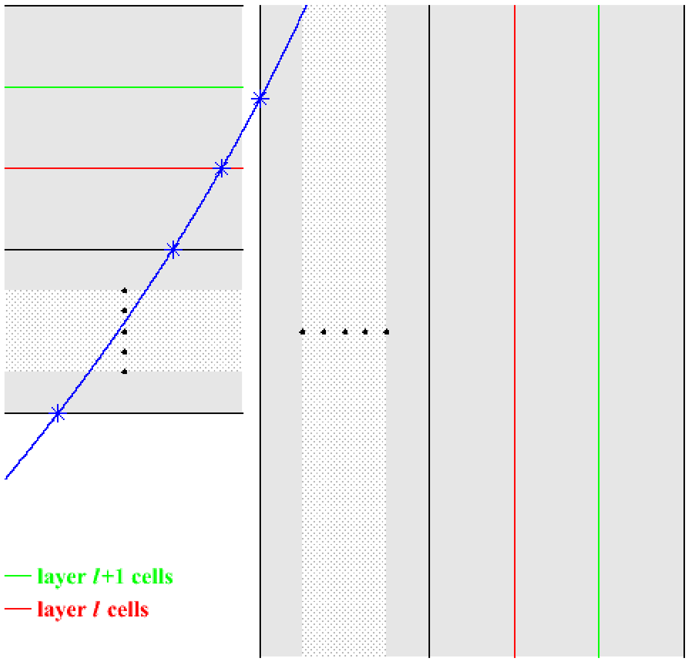
- Goal: to distinguish charged clusters from neutral clusters in calorimeters.
- Propose a figure of merit to gauge performance of algorithm:

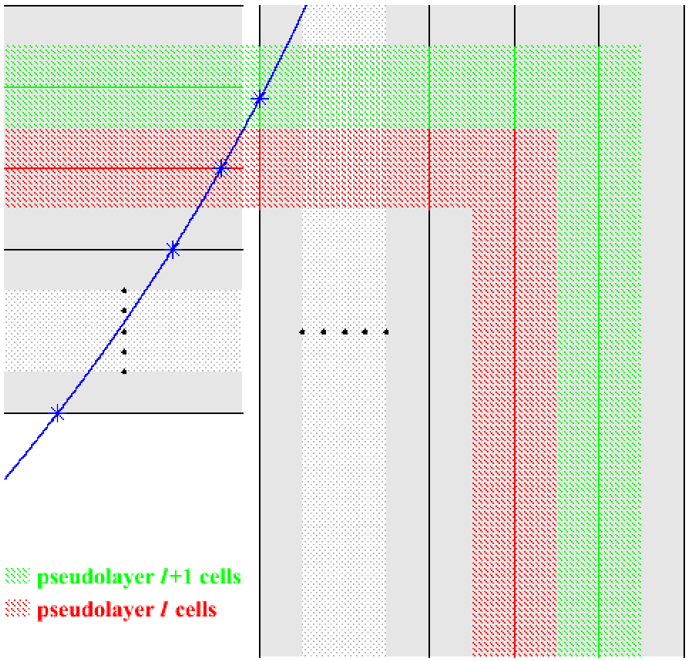
  Quality = fraction of event energy that maps in a 1:1 ratio between reconstructed and true clusters.
- Higher quality ⇔ less “confusion”.
- Quality improves with separation (naturally).
- $\pi^+\gamma$ separation at 5 GeV pretty good; π^+**n** somewhat tougher (**n** showers typically not well connected geometrically).



Chris Ainsley
<ainsley@hep.phy.cam.ac.uk>

Generalising the calorimeter (1)

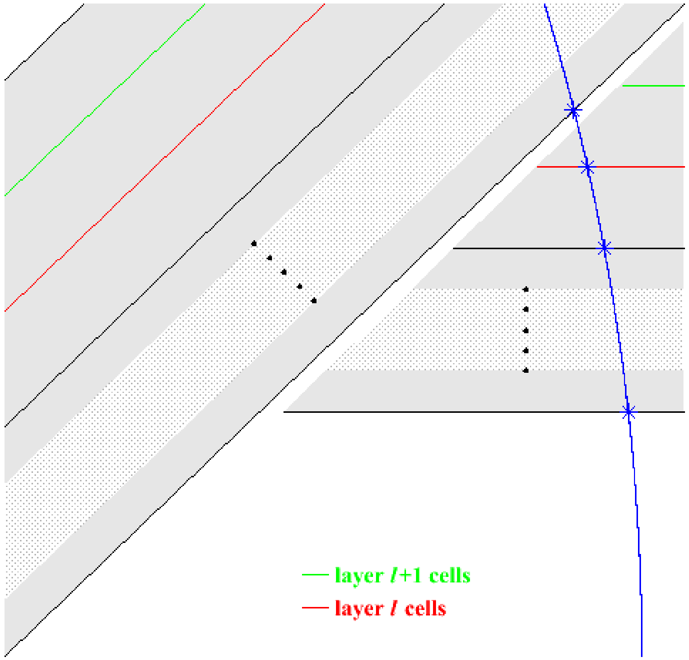


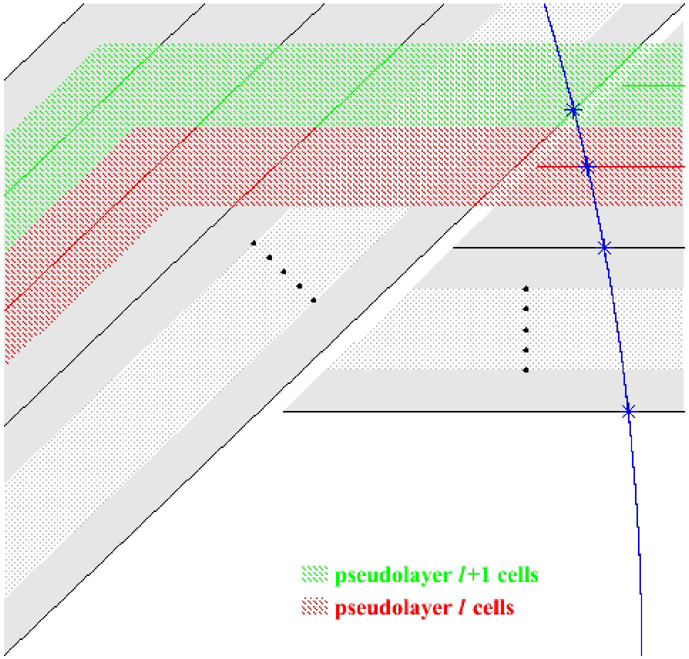


- Layer index changes discontinuously at barrel/endcap boundary.
- On crossing, jumps from ***l*** to 1 (first Ecal layer).

- Define a ***"pseudolayer"*** index based on projected intersections of physical layers.
- Index varies smoothly across boundary.
- Pseudolayer index = layer index, *except* in overlap region.

Generalising the calorimeter (2)





- Layer index changes discontinuously at boundary between overlapping barrel staves.
- On crossing, jumps from ***l*** to 1 (first Ecal layer.

- Again, define ***"pseudolayer"*** index from projected intersections of physical layers.
- Again, index varies smoothly across boundary.
- Again, pseudolayer index = layer index, *except* in overlap region.

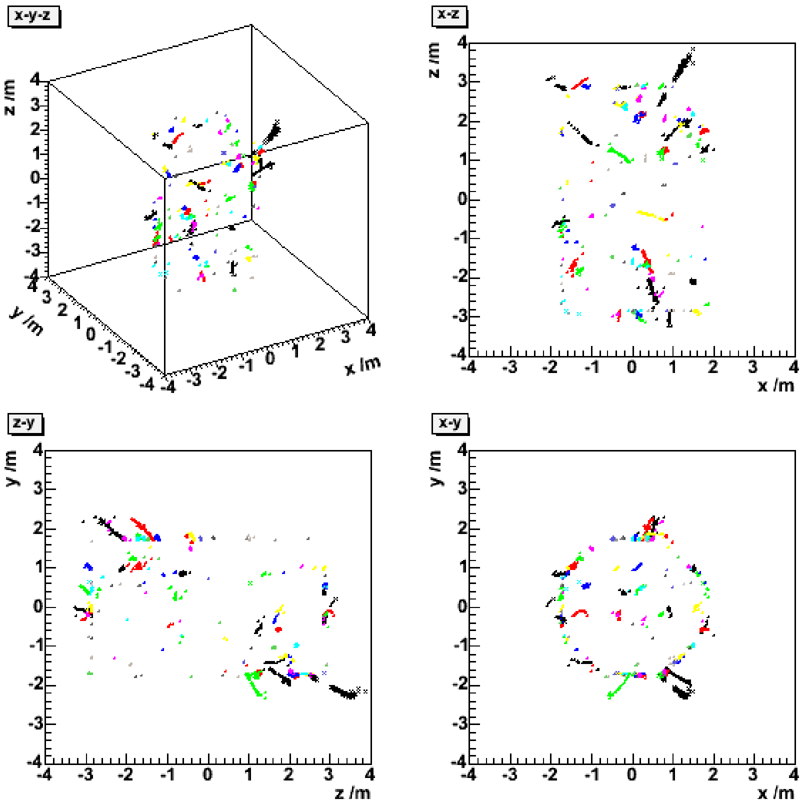
Generalising the calorimeter (3)

- Code automatically recasts any calorimeter geometry into this standard, generalised form comprising layered shells of rotationally-symmetric ***n***-polygonal prisms, coaxial with *z*-axis.
- Only required inputs as far as algorithm is concerned are:
  - **`barrelSymmetry`** = rotational symmetry of barrel;
  - **`phi_1`** = orientation of barrel w.r.t. *x*-axis;
  - **`distanceToBarrelLayers[ecalLayers+hcalLayers+2]`**
    = layer positions in barrel layers ("+2" to constrain inside edge of first pseudolayer and outside edge of last pseudolayer); and
  - **`distanceToEndcapLayers[ecalLayers+hcalLayers+2]`**
    = layer positions in endcap layers;

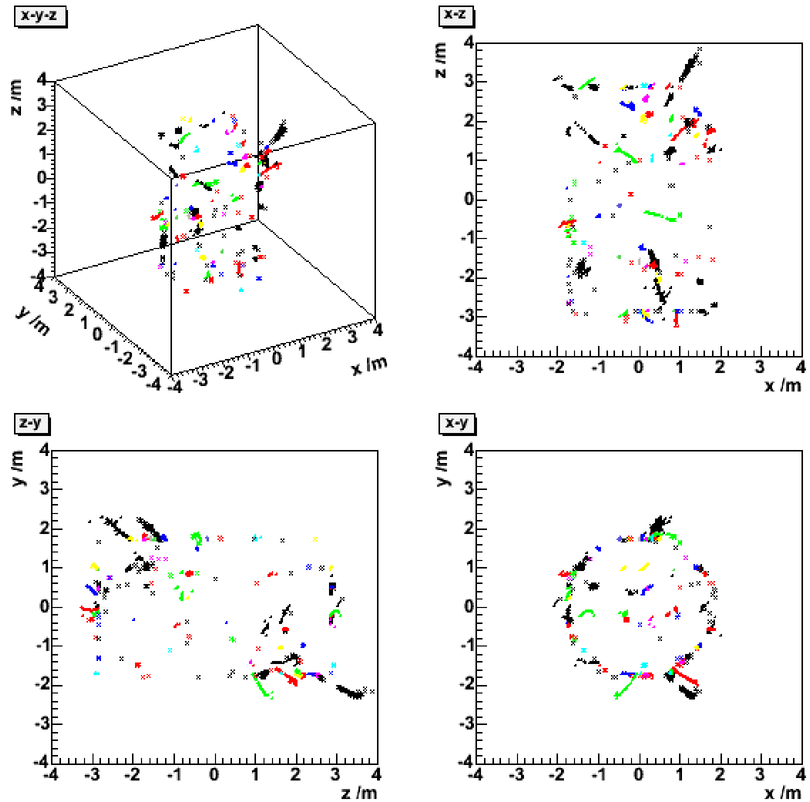
→ as geometry-independent as it's likely to get!

91 GeV $Z \rightarrow u,d,s$ jets event

Reconstructed clusters



True particle clusters



- Reconstruction now works successfully not only for ***intra***-stave, but also for ***inter***-stave clusters.

How it's coded in LCIO with MARLIN

- Code structured as a series of **MARLIN** ***"processors"***, together with a steering file: `my.steer` (read at ***run-time***).
- Takes **LCIO** hit objects as input; outputs cluster objects with pointers back to component hits.
- Detector parameters and clustering cuts set in `my.steer` (*e.g.* based on CALICE design):

```
ProcessorType CalorimeterConfig
      ecalLayers          40        # number of Ecal layers
      hcalLayers          40        # number of Hcal layers
      barrelSymmetry      8         # degree of rotational symmetry of barrel
      phi_1               90.0      # phi offset of barrel w.r.t. x-axis (in deg)
ProcessorType StoreOrderedToCluster1
      layersToTrackBack   80        # number of layers to loop back over
      distMax_ecal        20.0      # Ecal distance cut for continuation (in mm)
      distMax_hcal        30.0      # Hcal distance cut for continuation (in mm)
      proxSeedMax_ecal    20.0      # Ecal seed radius cut (in mm)
      proxSeedMax_hcal    20.0      # Hcal seed radius cut (in mm)
ProcessorType Cluster1ToCluster2
      proxMergeMax_ecal   20.0      # Ecal proximity cut for merging (in mm)
      proxMergeMax_hcal   20.0      # Hcal proximity cut for merging (in mm)
      cosGammaMax         0.25      # angular cut for merging
ProcessorType Cluster2ToCluster3
      clusterSizeMin      10        # minimum cluster size to avert merging
      layersToTrackBack   80        # number of layers to loop back over for merging
      tanBetaMax          6.0       # angular cut for merging
      proxSeedMax_ecal    400.0     # Ecal proximity cut for merging (in mm)
      proxSeedMax_hcal    400.0     # Hcal proximity cut for merging (in mm)
```

Summary & outlook

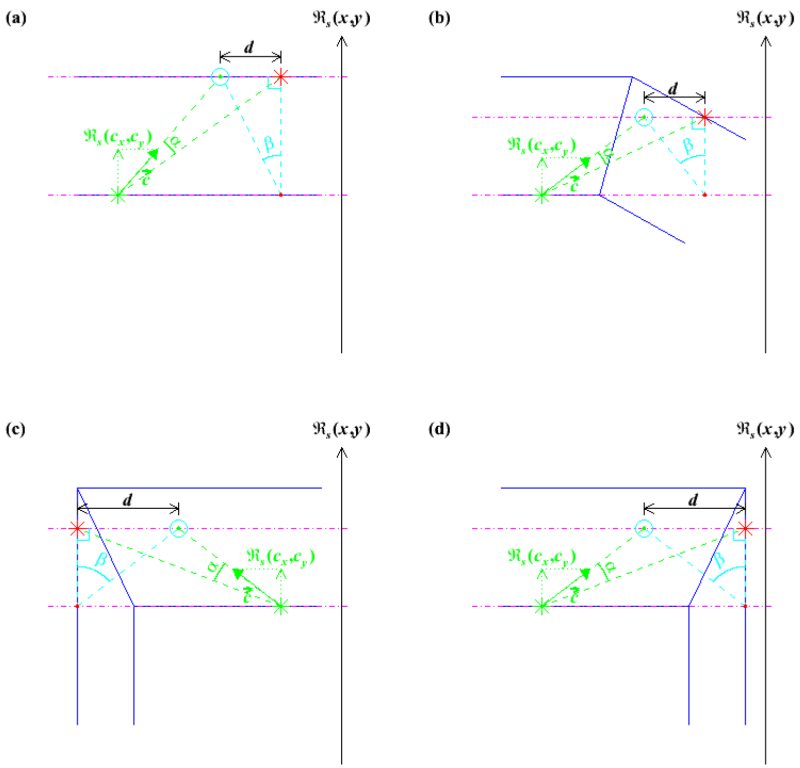
- **Developed a clustering algorithm** that utilizes the high granularity of the calorimeter cells to track clusters (pseudo)layer-by-(pseudo)layer.
- Straightforwardly **applicable to *any* detector design** comprising an ***n***-fold rotationally symmetric barrel closed by endcaps → just need to specify ***n***, barrel orientation, and layer positions.
- Coded in C++; **LCIO** (v1.3) fully compliant.
- Modularised thanks to **MARLIN** ⇒ input parameters (set at run-time) kept distinct from reconstruction (pre-compiled).
- Will be publicly available very soon.

The end

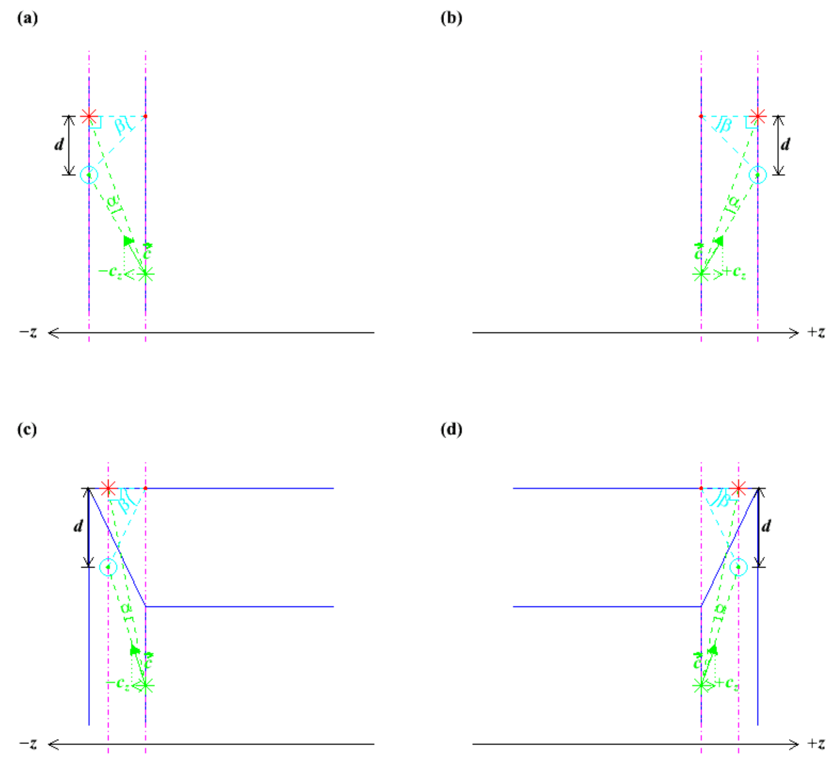
That's all folks…

Cluster-tracking between pseudolayers

From the pseudobarrel

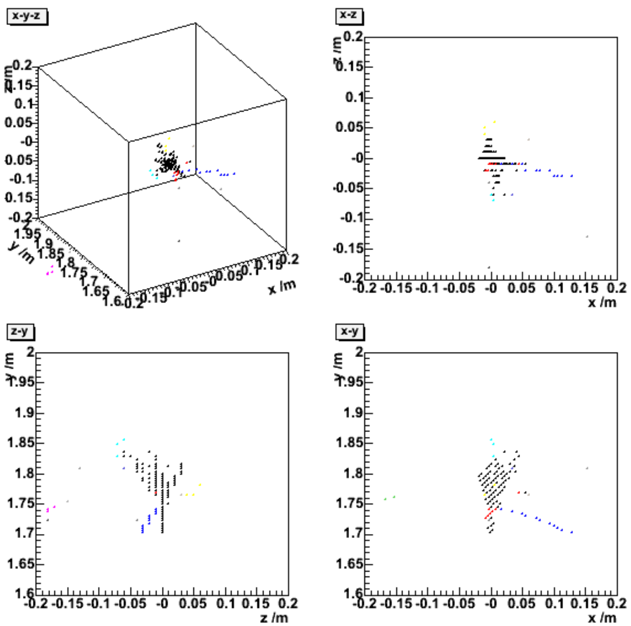


From the pseudoendcap



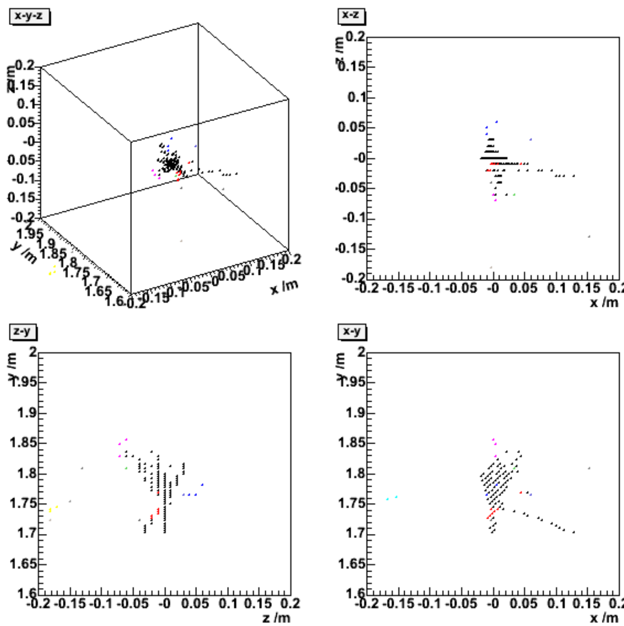
5 GeV π^+ event: 3 stages of clustering

Clusters: stage 1



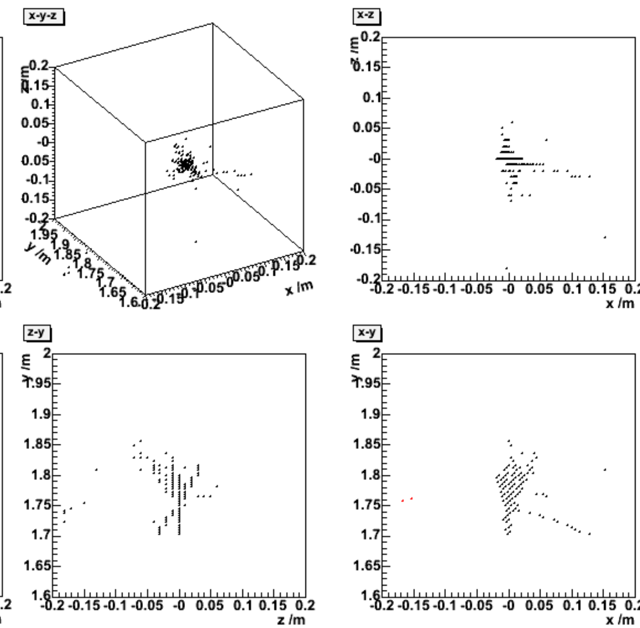
- One **backward-spiralling track** and several **halo** clusters surround principal cluster.

Clusters: stage 2



- **Backward-spiralling track** merged with principal cluster.

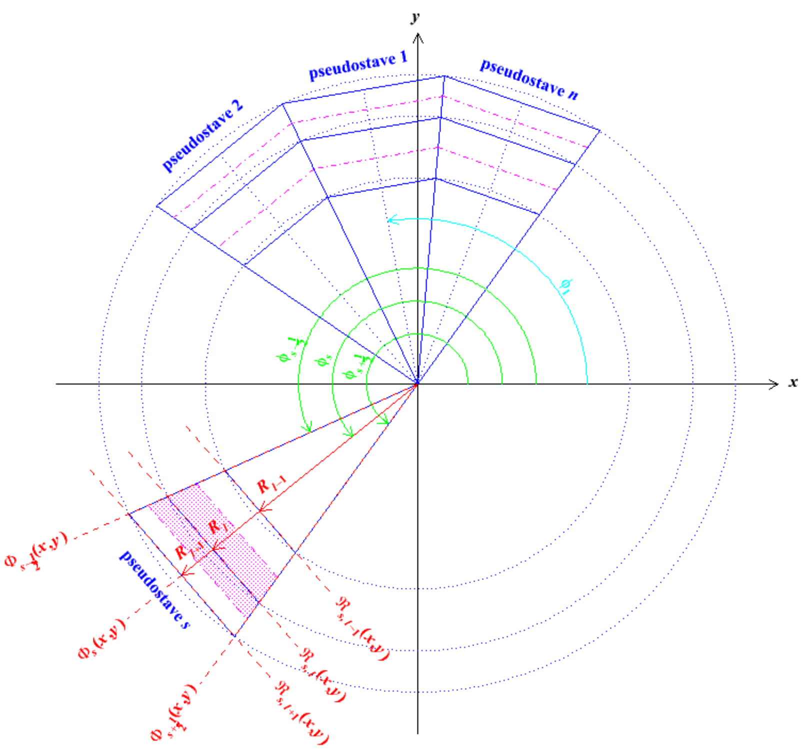
Clusters: stage 3



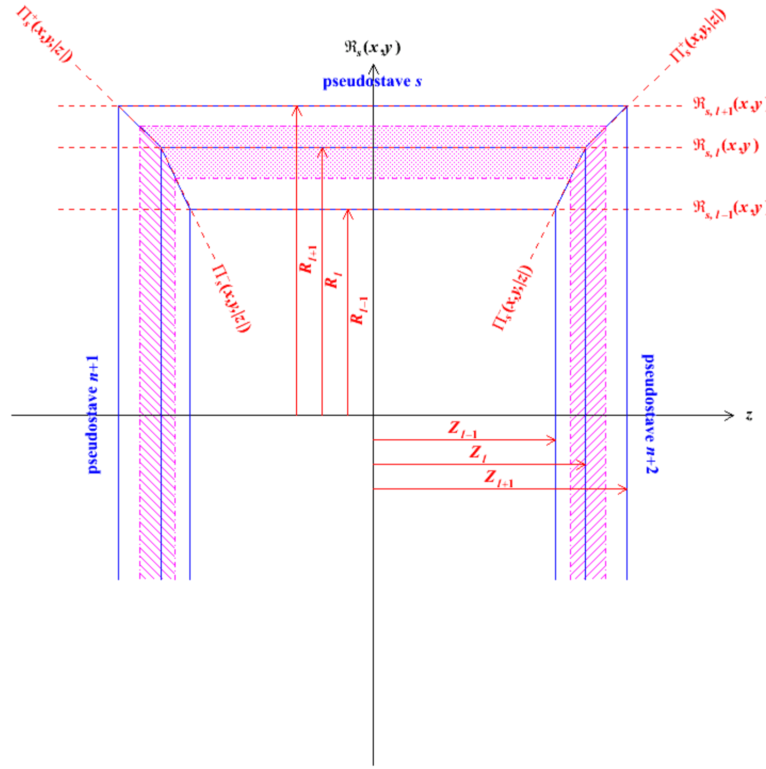
- **Halo** clusters merged with principal cluster.

How the generalised detector shapes up

Transverse section



Longitudinal section



- Solid blue lines aligned along real, physical, sensitive layers.
- Dot-dashed magenta lines bound shell containing hits with same ***pseudolayer*** index, ***l***.
- ***Pseudostaves*** automatically encoded by specifying $\boldsymbol{n}$, ϕ_1 and $\boldsymbol{R_l}$ and $\boldsymbol{Z_l}$ ($\forall$ $\boldsymbol{l}$).

How it's coded in LCIO with MARLIN (1)

- Code structured as a series of *"processors"*, (requiring compilation) together with a steering file: `my.steer` (read at *run-time*).
- Processors to do the reconstruction:
  - `CalorimeterConfig.cc`
    → (re)sets calorimeter layer positions;
  - `HitToCell.cc`
    → merges same-cell hits (MC);
  - `CellToStore.cc`
    → stores cells above energy threshold (MC);
  - `StoreToStoreOrdered.cc`
    → ranks stored cells by weight in each pseudolayer (in preparation for clustering);
  - `StoreOrderedToCluster1.cc`
    → does the coarse cluster reconstruction;
  - `Cluster1ToCluster2.cc`
    → attempts matching of backward-spiralling track-like cluster fragments onto forward-propagating parent clusters;
  - `Cluster2ToCluster3.cc`
    → attempts to reunite low multiplicity "halo' cluster fragments with parent clusters.
- Additional processor to access MC truth:
  - `StoreOrderedToTrueCluster.cc`
    → forms the true clusters.
- To apply algorithm to alternative detector designs, just need to modify parameters in `CalorimeterConfig.cc` and `my.steer`, then play → quite straightforward.
- Reconstruction code itself requires *no* modification.
- Recompilation necessary only for `CalorimeterConfig.cc`, and then only if layer positions change.
- All other detector parameters, and all clustering cuts, set at *run-time* in `my.steer`.
- Let's see how …

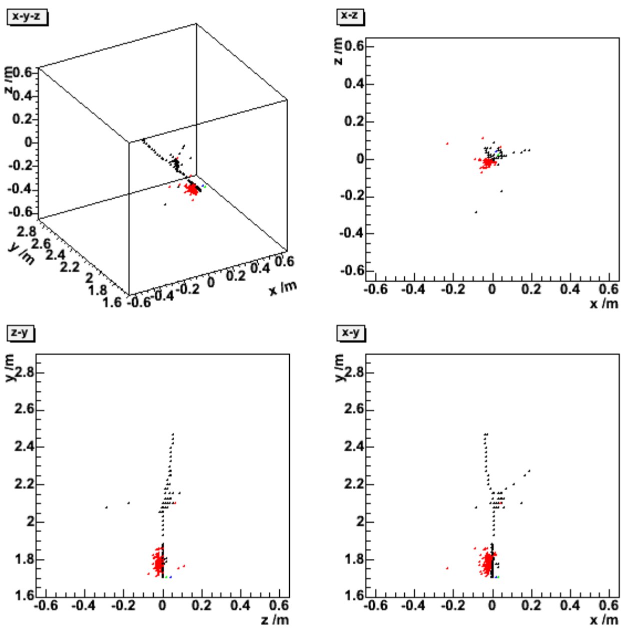
How it's coded in LCIO with MARLIN (3)

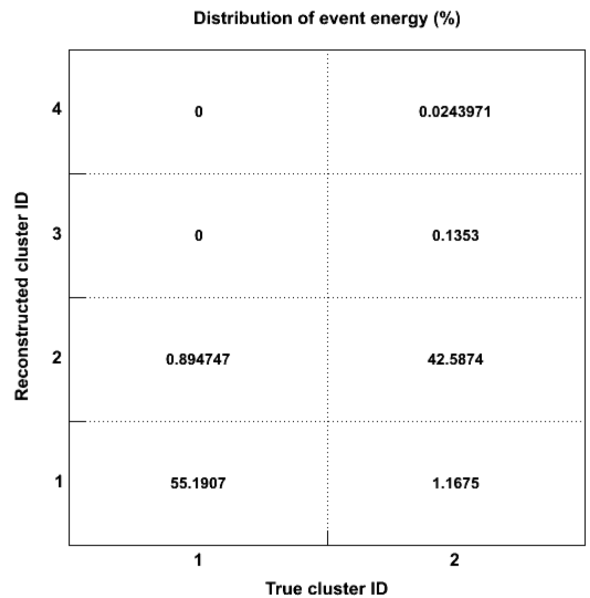
- Example (section of) code from **`CalorimeterConfig.cc`** (*e.g.* based on CALICE design):

```
// Create collections for the barrel and endcap layer positions
LCCollectionVec* distanceToBarrelLayersVec = new LCCollectionVec(LCIO::LCFLOATVEC);
LCCollectionVec* distanceToEndcapLayersVec = new LCCollectionVec(LCIO::LCFLOATVEC);

// Fill the collections with their positions (in mm)
for(int l=0; l<=ecalLayers+hcalLayers+1; l++) {
  LCFloatVec* distanceToBarrelLayers = new LCFloatVec;
  LCFloatVec* distanceToEndcapLayers = new LCFloatVec;
  if(detectorType=="full") {  // full detector
    if(l<=30) {  // first 30 Ecal layers at a pitch of 3.9 mm (+ layer 0)          ← edit
      distanceToBarrelLayers->push_back(1698.85+(3.9*l));                          ← edit
      distanceToEndcapLayers->push_back(2831.10+(3.9*l));                          ← edit
    }                                                                              ← edit
    else if(l>30 && l<=ecalLayers) {  // last 10 Ecal layers at a pitch of 6.7 mm  ← edit
      distanceToBarrelLayers->push_back(1815.85+(6.7*(l-30)));                     ← edit
      distanceToEndcapLayers->push_back(2948.10+(6.7*(l-30)));                     ← edit
    }                                                                              ← edit
    else {  // 40 Hcal layers at a pitch of 24.5 mm (+ layer 81)                  ← edit
      distanceToBarrelLayers->push_back(1931.25+(24.5*(l-41)));                    ← edit
      distanceToEndcapLayers->push_back(3039.25+(24.5*(l-41)));                    ← edit
    }                                                                              ← edit
  }
  else if(detectorType=="prototype") { ...some more code... }  // prototype detector
  distanceToBarrelLayersVec->push_back(distanceToBarrelLayers);
  distanceToEndcapLayersVec->push_back(distanceToEndcapLayers);
}

// And save the collections
evt->addCollection(distanceToBarrelLayersVec, "distance_barrellayers");
evt->addCollection(distanceToEndcapLayersVec, "distance_endcaplayers");
```

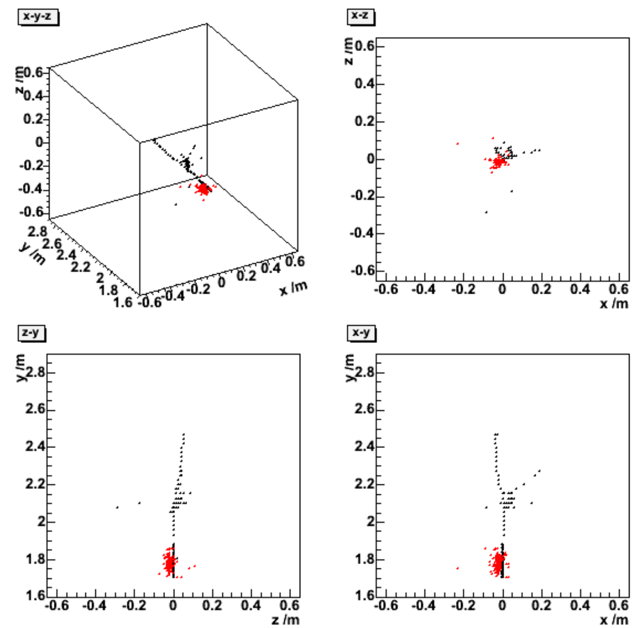
5 GeV $\pi^{+}\gamma$ event at 3 cm separation

Reconstructed clusters





True particle clusters

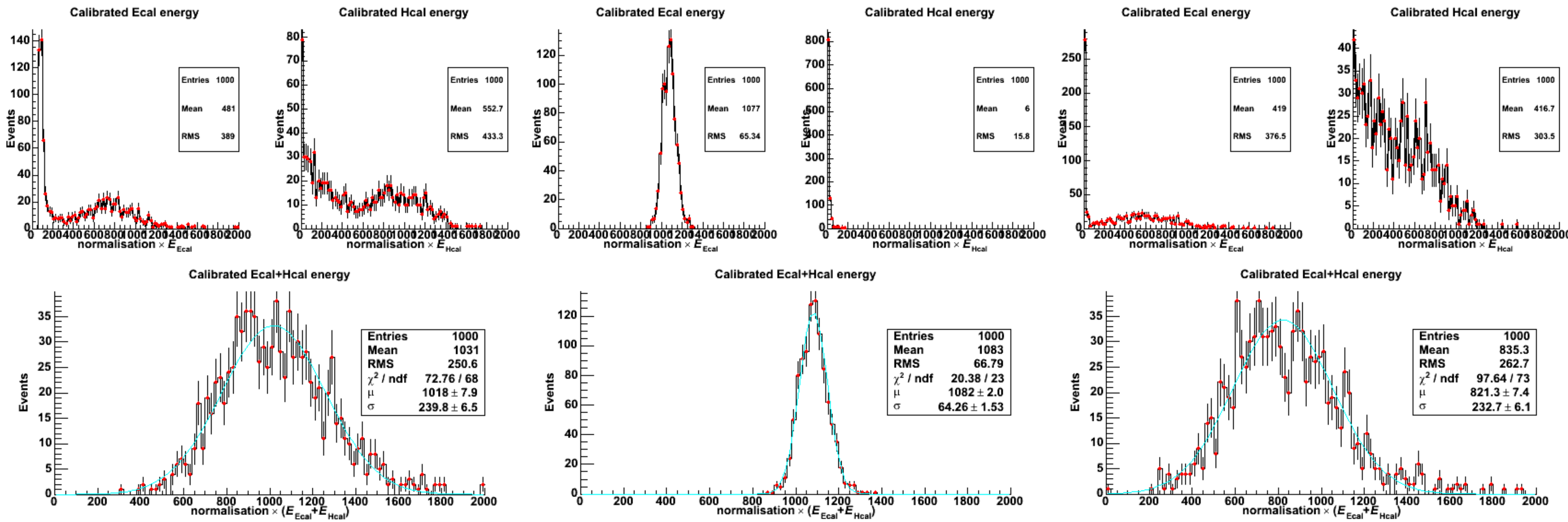


- Energy calibrated (CALICE D09 detector) according to:

  $E = \alpha[(E_{\text{Ecal; 1-30}} + 3E_{\text{Ecal; 31-40}})/E_{\text{mip}} + 20N_{\text{Hcal}}]$ GeV.
- Hits map mostly ***black*** $\leftrightarrow$ ***black*** **(π^{+})** and ***red*** $\leftrightarrow$ ***red*** **(γ)** between reconstructed and true clusters.
- Fraction of event energy in 1:1 correspondence = **55.2 + 42.6 = 98 %**.

Calibration of π^+, γ and n

π^+ **γ** **n**



- Energy calibrated (CALICE D09 detector) according to:

$$E = \alpha[(E_{\mathrm{Ecal;\,1\text{-}30}} + 3E_{\mathrm{Ecal;\,31\text{-}40}})/E_{\mathrm{mip}} + 20N_{\mathrm{Hcal}}]\ \mathrm{GeV}.$$