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

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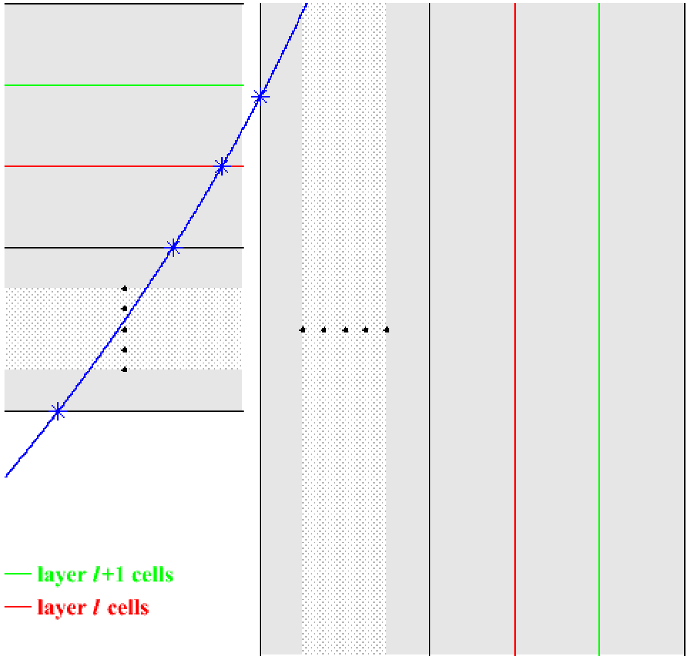
Order of service

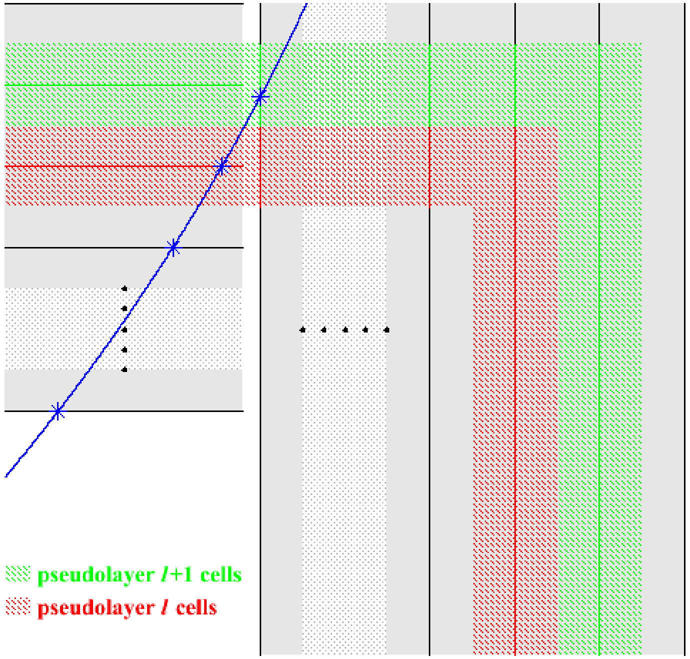
- Generalisation of any calorimeter design to cope with a layer-by-layer approach to clustering (recap):
  - Why *generalise* the calorimeter?
  - How can it be done?
- A layer-by-layer clustering algorithm for a generalised calorimeter:
  - Description in 3 parts.
  - Organisation of code.
  - Straightforward adaptation to alternative geometries.
- Summary.

Generalising the calorimeter (1)

- Algorithms for calorimeter clustering exist, but tend to be tied to specific geometries.
- To compare relative merits of different detector designs, desirable to have an algorithm which requires minimal geometrical information $\Rightarrow$ can depend only upon hit coordinates/energies.
- Could propagate clusters outwards using hit radii from IP (*i.e.* place hits on artificial spherical layers)…naturally geometry independent, but does not reflect physical detector layout $\rightarrow$ calorimeter will not be spherical!
- Moreover, space will most likely be sampled in planes of layers $\Rightarrow$ would like to preserve the natural layer-indexing in propagating clusters outwards…
- …*however*, layers have different orientations in the barrel and the endcaps, as do different barrel staves $\Rightarrow$ complications in ranking hits by layer index.
- To make use of layer indexing, need to address these in a geometry-independent way.

Generalising the calorimeter (2)

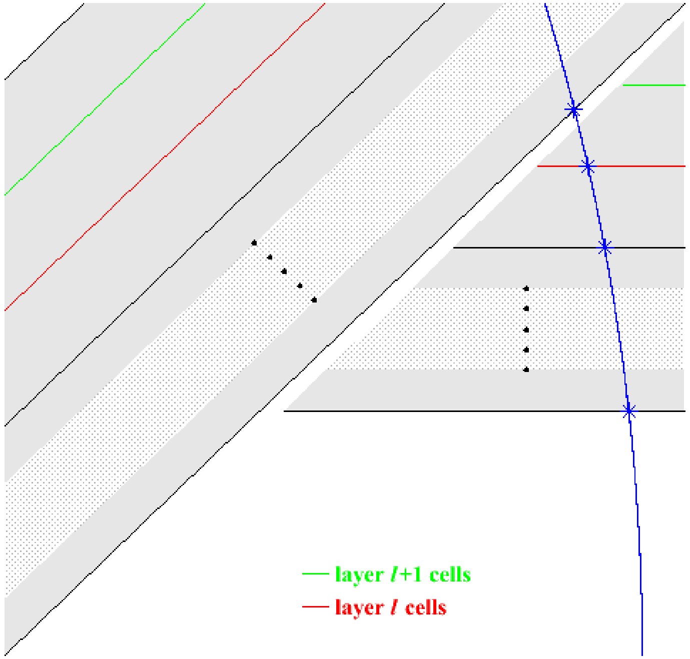


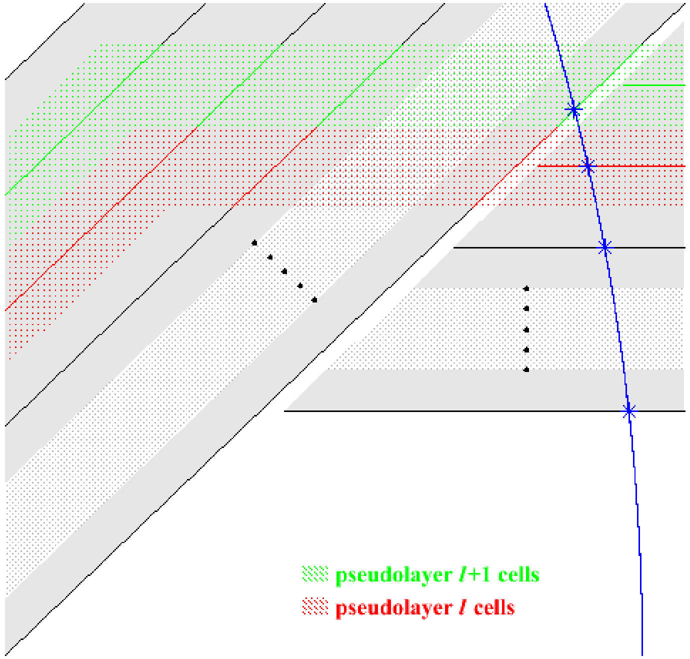


- Layer index changes discontinuously at barrel/endcap boundary.
- On crossing, jumps from l to 1 (first Ecal layer).

- 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 (3)





- 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 (4)

- For any (likely) geometry, can construct a generalised calorimeter from shells of rotationally-symmetric *n*-polygonal prisms, coaxial with *z*-axis.
- Each shell contains active cells of same pseudolayer index.
- Locations/orientations of pseudolayers *automatically* encoded from locations/orientations of physical layers (projected intersections).
- Only require as inputs:
  - `barrelSymmetry` = rotational symmetry of barrel;
  - `phi_1` = orientation of barrel w.r.t. *x*-axis;
  - `distanceToBarrelLayers[ecalLayers+hcalLayers+2]`

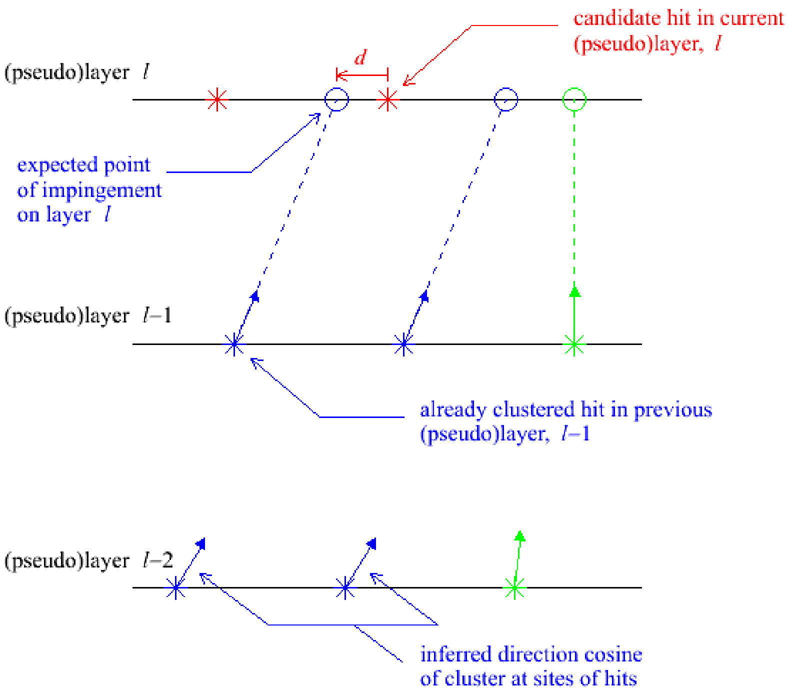
    = layer positions in barrel layers ("`+2`" to constrain inside edge of first pseudolayer and outside edge of last pseudolayer); and
  - `distanceToEndcapLayers[ecalLayers+hcalLayers+2]`

    = layer positions in endcap layers;

  → as geometry-independent as it's likely to get, while respecting the natural layer-indexing.
- Now just need a layer-by-layer clustering algorithm to exploit this…

Clustering: stage 1

- Form coarse clusters by tracking closely-related hits (> `mipThreshold`) 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.



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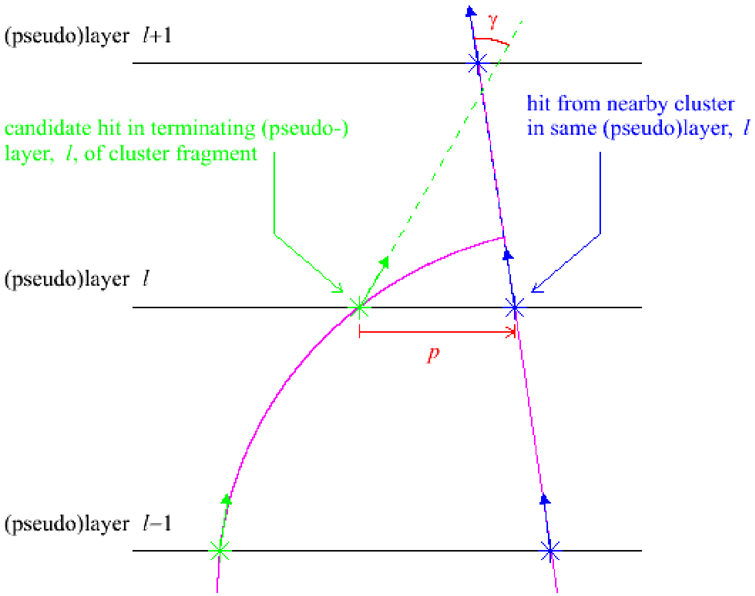
Clustering: stage 2

- 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*
    - $\cos \gamma <$ `cosGammaMax`

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



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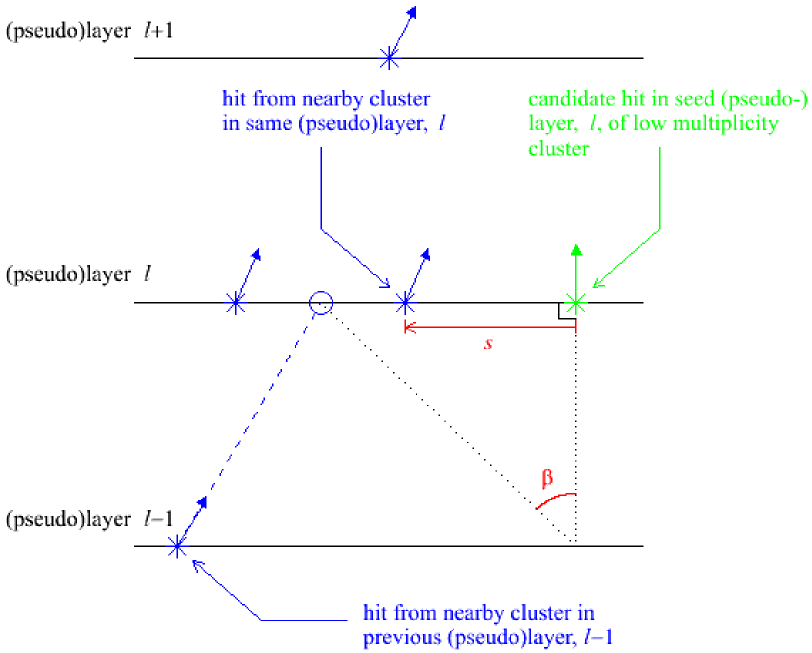
Clustering: stage 3

- 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.



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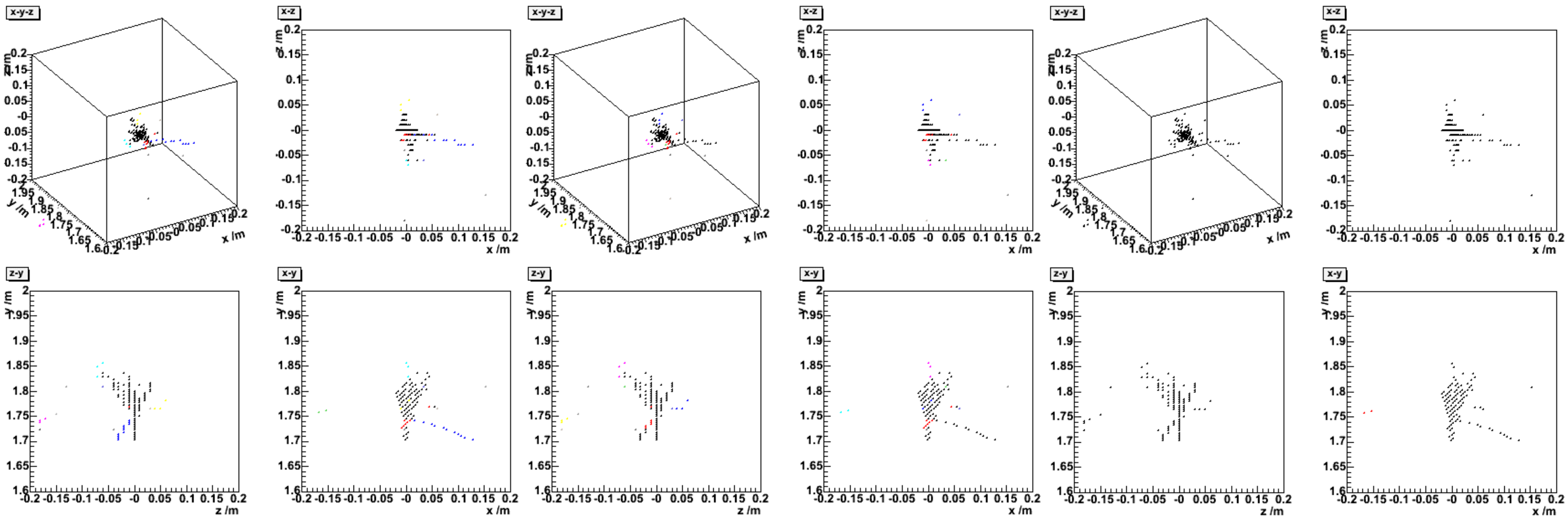
5 GeV π⁺ event: 3 stages of clustering

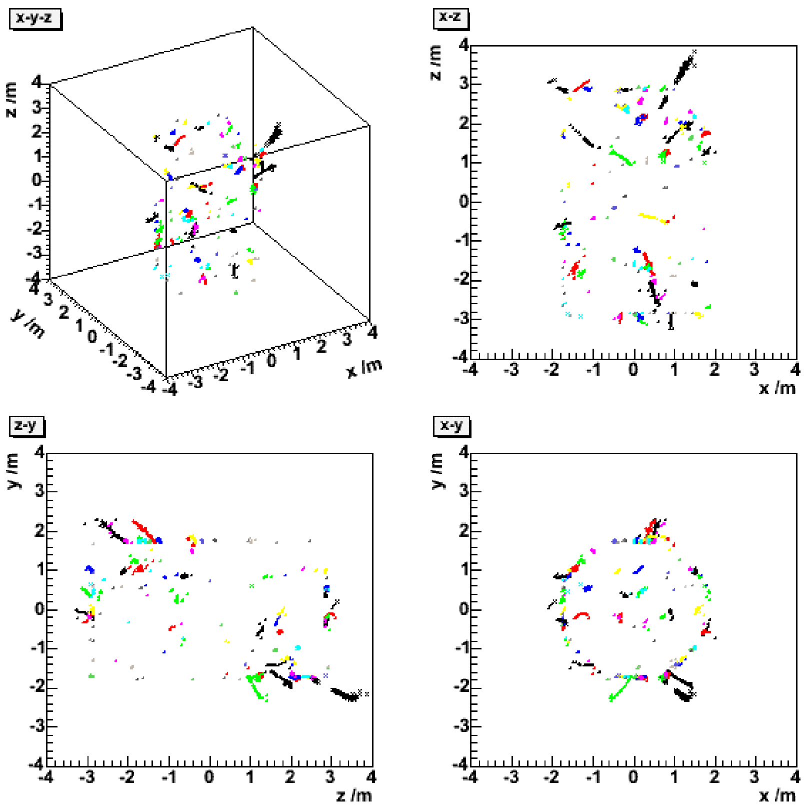
Clusters: stage 1	Clusters: stage 2	Clusters: stage 3



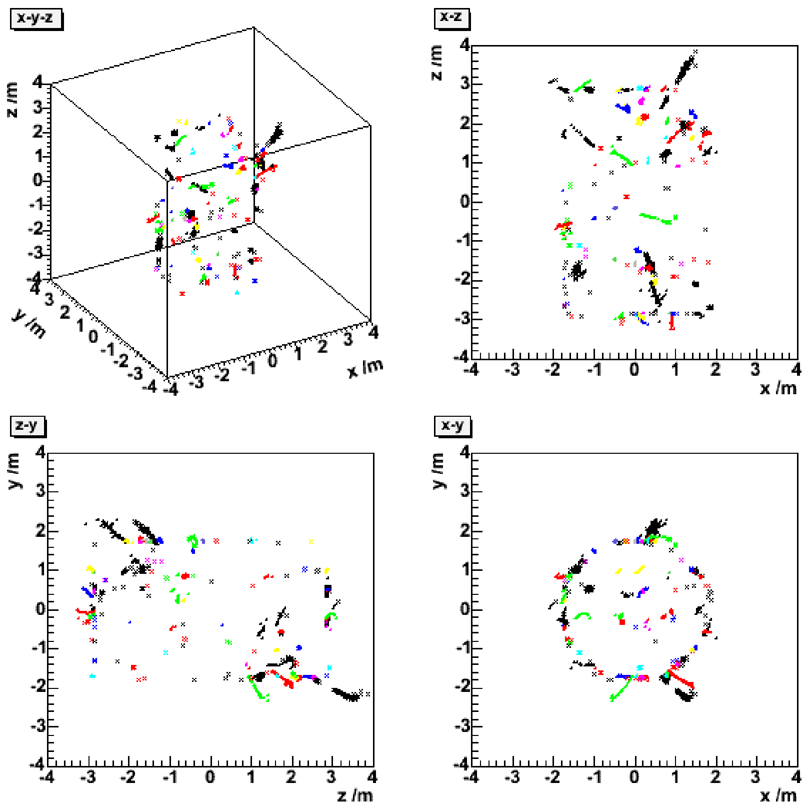
- One backward-spiralling track and several halo clusters surround principal cluster.
- Backward-spiralling track merged with principal cluster.
- Halo clusters merged with principal cluster.

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

Reconstructed clusters



True particle clusters



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 (2)

- Example (section of) code from `my.steer` (*e.g.* based on CALICE design; Si/W Ecal, Fe/RPC Hcal):

```
ProcessorType CalorimeterConfig
        detectorType            full        # detector type ("full" or "prototype")
        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 first barrel stave w.r.t. x-axis (in deg)
ProcessorType CellToStore
        mode                    a/d         # analogue mode ("a") or digital mode ("d") for Ecal/Hcal
                                            # ("a/a", "a/d", "d/a" or "d/d")
        ecalMip                 0.000150    # Ecal Mip energy (in GeV)
        hcalMip                 0.0000004   # Hcal Mip energy (in GeV)
        ecalMipThreshold        0.33333333  # Ecal Mip threshold (in Mip units)
        hcalMipThreshold        0.33333333  # Hcal Mip threshold (in Mip units)
ProcessorType StoreOrderedToCluster1
        layersToTrackBack       80          # number of layers to track back for cluster continuation
        distMax_ecal            20.0        # Ecal distance cut for cluster continuation (in mm)
        distMax_hcal            30.0        # Hcal distance cut for cluster 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 cluster merging (in mm)
        proxMergeMax_hcal       20.0        # Hcal proximity cut for cluster merging (in mm)
        cosGammaMax             0.25        # angular cut for cluster merging
ProcessorType Cluster2ToCluster3
        clusterSizeMin          10          # minimum cluster size to avert potential cluster merging
        layersToTrackBack       80          # number of layers to track back for cluster merging
        tanBetaMax              6.0         # angular cut for cluster merging
        proxSeedMax_ecal        400.0       # Ecal proximity cut for cluster merging (in mm)
        proxSeedMax_hcal        400.0       # Hcal proximity cut for cluster merging (in mm)
```

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");
```

Summary & outlook

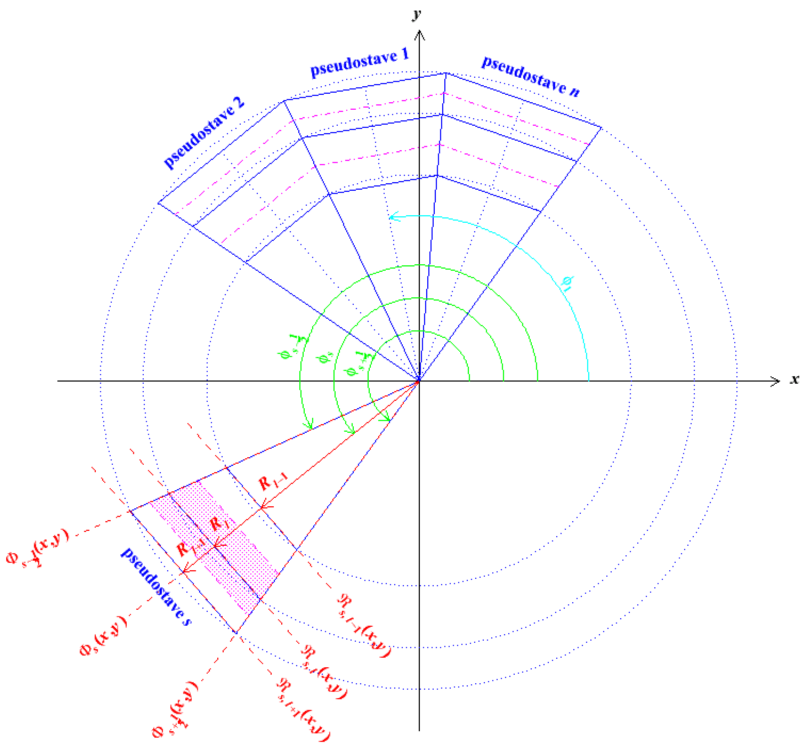
- Developed a scheme to enable a (pseudo)layer-by-(pseudo)layer clustering procedure to be applied to alternative calorimeter geometries without having to recode the algorithm itself.
- Straightforwardly applicable to any (likely) detector design comprising an n-fold rotationally symmetric barrel closed by endcaps $\rightarrow$ just need to specify n, barrel orientation, and layer positions.
- Proposed such an algorithm that utilizes the high granularity of the calorimeter cells to "*track*" clusters (pseudo)layer-by-(pseudo)layer outwards (and retrospectively deal with backward-spiralling off-shoots).
- Coded in C++; LCIO (v1.3) fully compliant $\rightarrow$ outputs cluster objects with pointers back to component hits and attributes.
- Code is modularised thanks to MARLIN $\Rightarrow$ input parameters (set at run-time) kept distinct from reconstruction (pre-compiled).
- Will be publicly releasable pretty soon.

The end

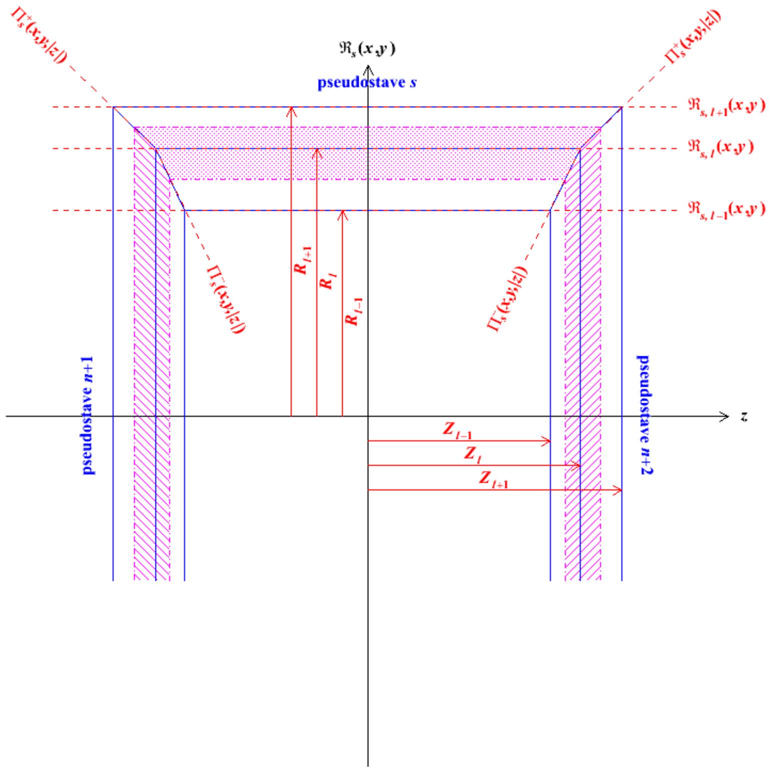
That's all folks…

How the generalised detector shapes up

Transverse section



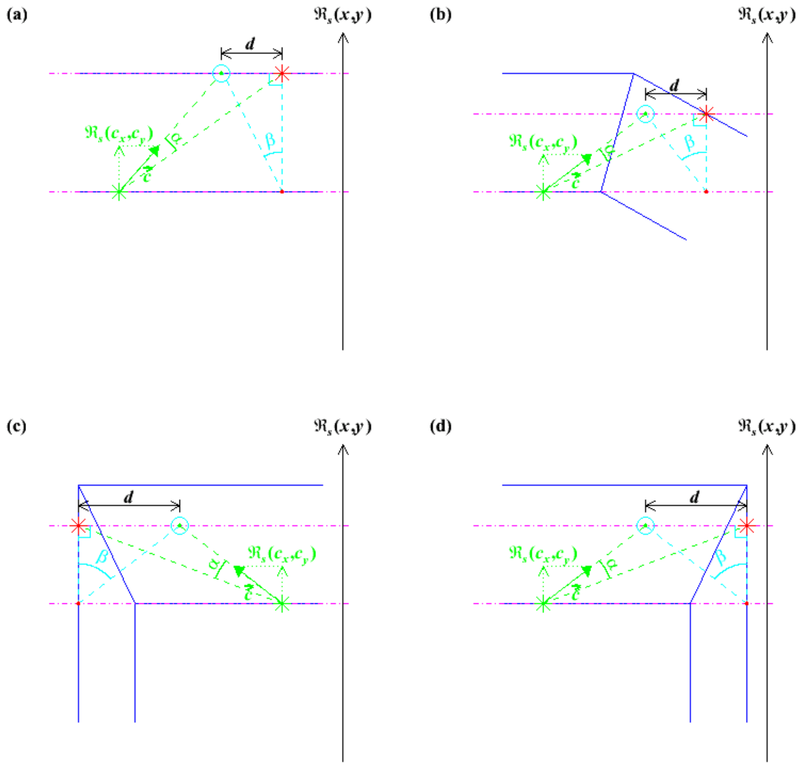
Longitudinal section



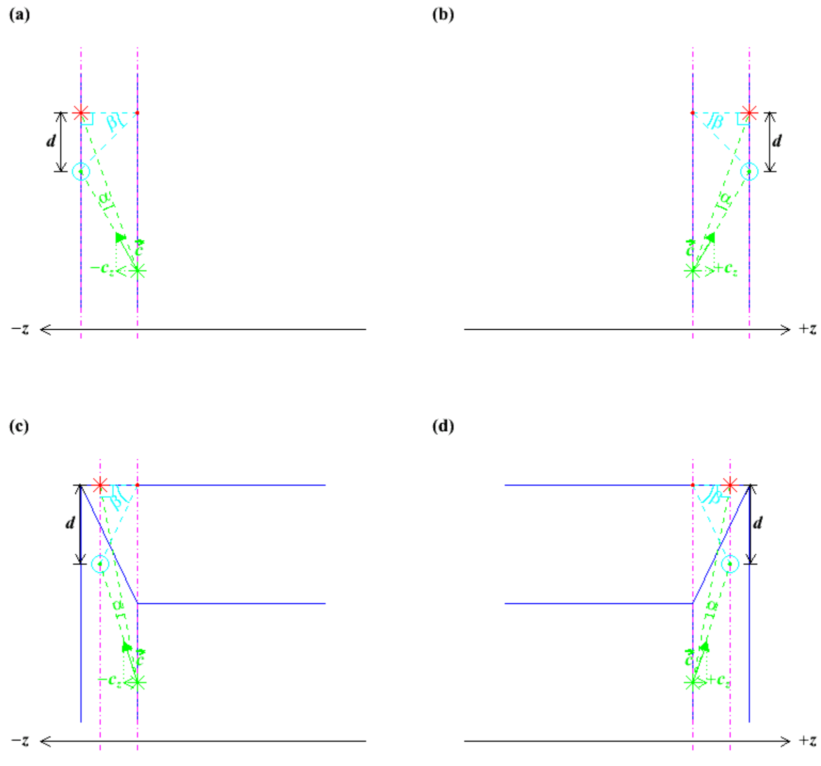
- Solid blue lines aligned along real, physical, sensitive layers.
- Dot-dashed magenta lines bound shell containing hits with same *pseudolayer* index, *l*.
- *Pseudostaves* automatically encoded by specifying n, ϕ_1 and R_l and Z_l ($\forall\, l$).

Cluster-tracking between pseudolayers

From the pseudobarrel



From the pseudoendcap



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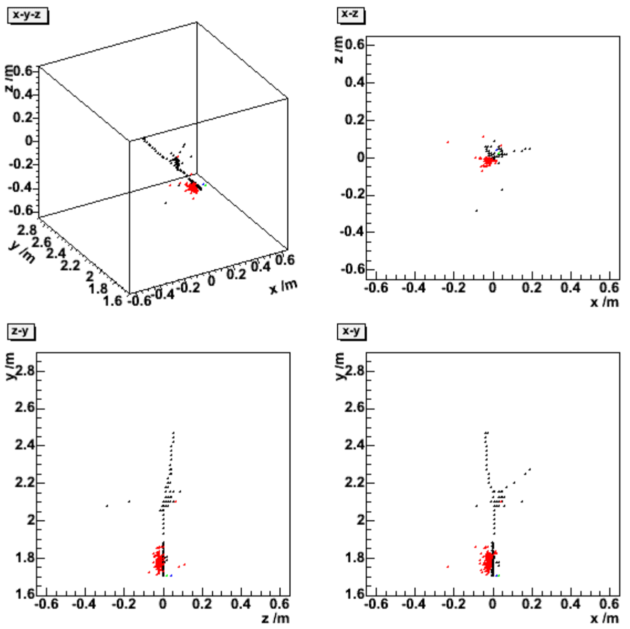
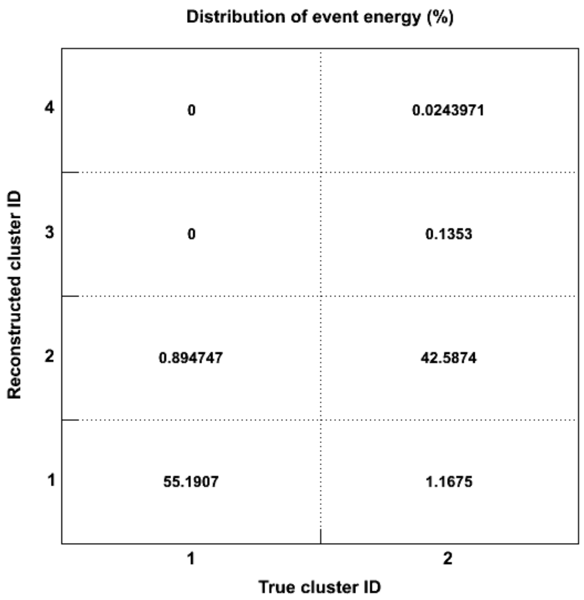
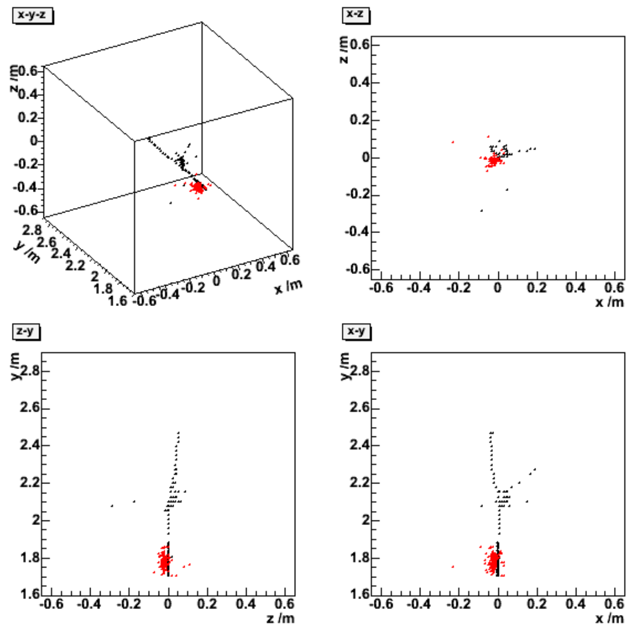
5 GeV $\pi^+\gamma$ event at 3 cm separation

Reconstructed clusters





True particle clusters

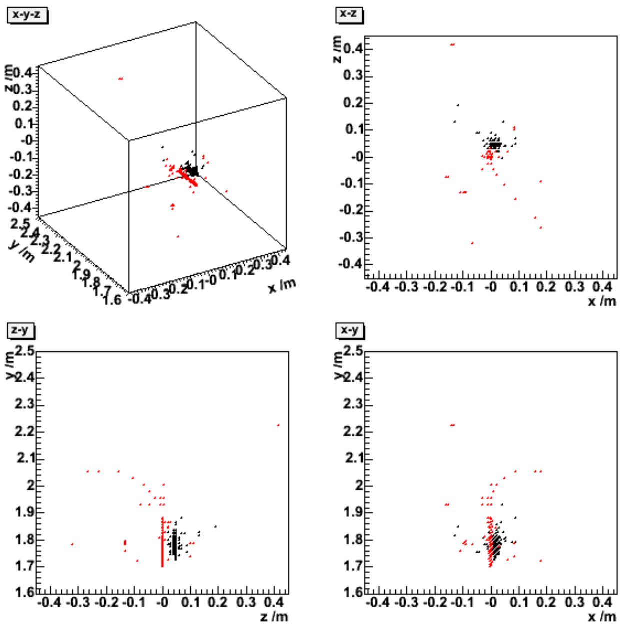


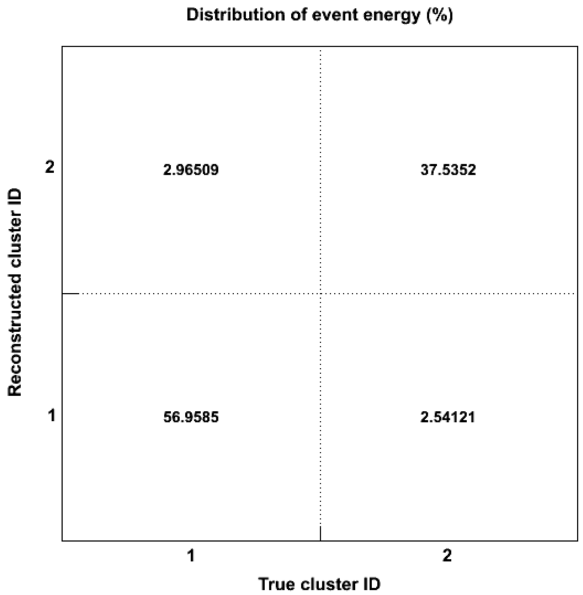
- Energy calibrated (CALICE D09 detector) according to:

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

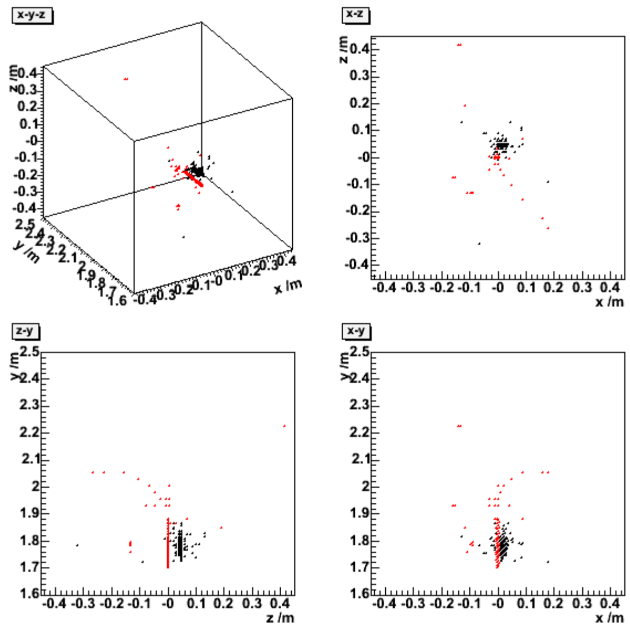
5 GeV $\pi^+\gamma$ event at 5 cm separation

Reconstructed clusters





True particle clusters



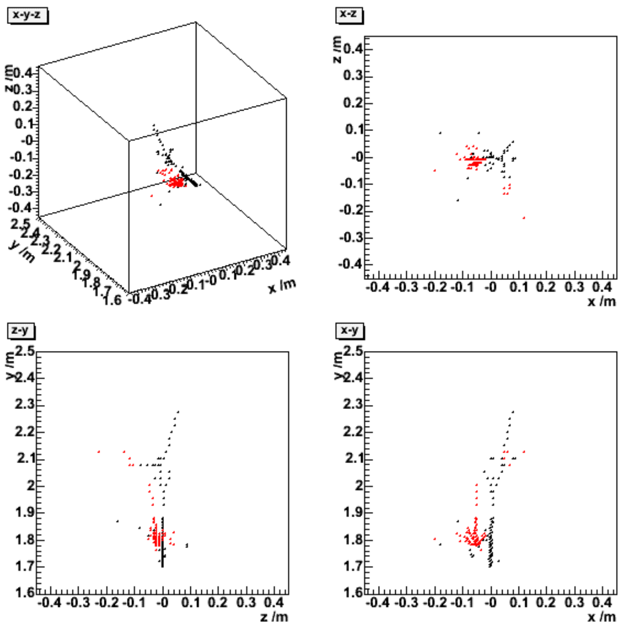
- Energy calibrated (CALICE D09 detector) according to:

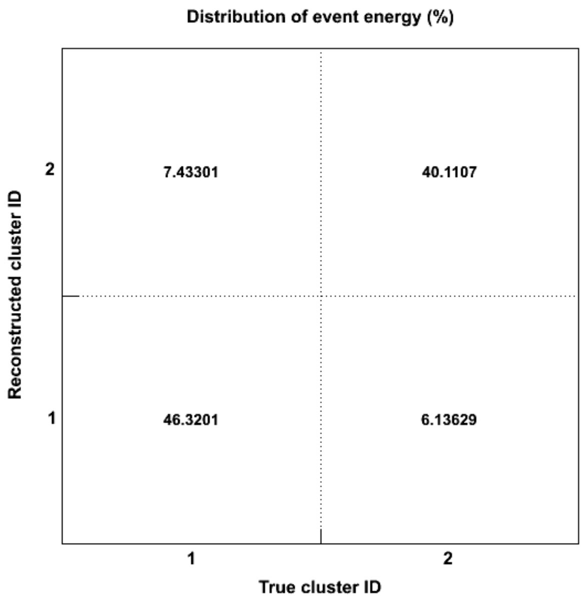
  $E = \alpha[(E_{\mathrm{Ecal;\ 1\text{-}30}} + 3E_{\mathrm{Ecal;\ 31\text{-}40}})/E_{\mathrm{mip}} + 20N_{\mathrm{Hcal}}]$ GeV.
- Hits map mostly *black* $\leftrightarrow$ *black* (γ) and *red* $\leftrightarrow$ *red* (π^+) between reconstructed and true clusters.
- Fraction of event energy in 1:1 correspondence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

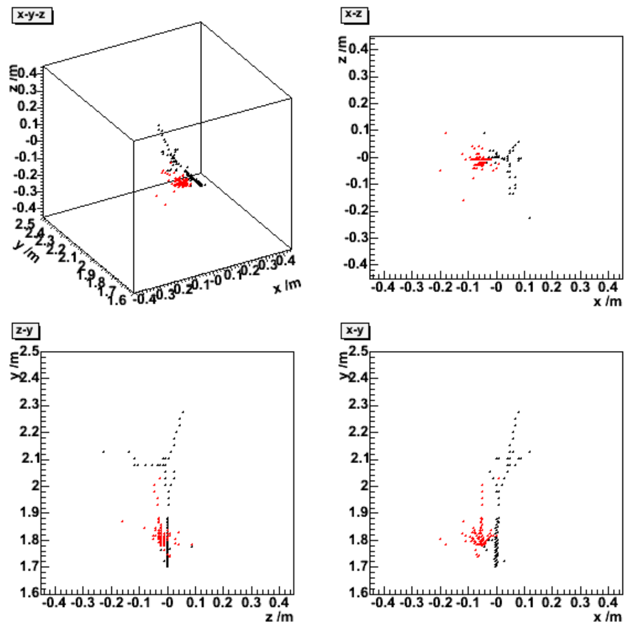
5 GeV π^+n event at 5 cm separation

Reconstructed clusters

True particle clusters







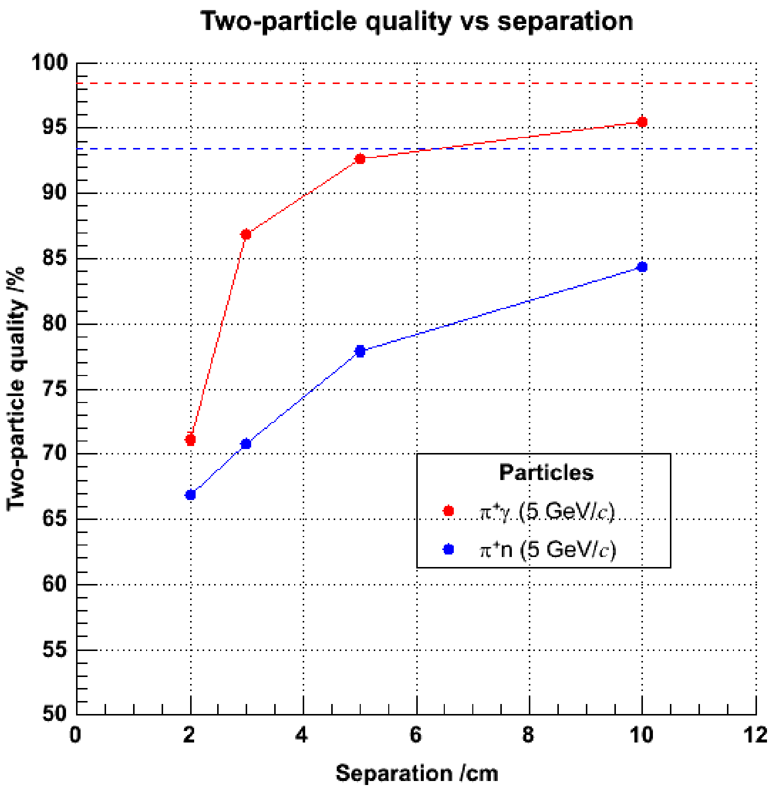
- Energy calibrated (CALICE D09 detector) according to:

  $E = \alpha[(E_{\text{Ecal; 1-30}} + 3E_{\text{Ecal; 31-40}})/E_{\text{mip}} + 20N_{\text{Hcal}}]$ GeV.
- Hits map mostly *black* ↔ *black* (π^+) and *red* ↔ *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

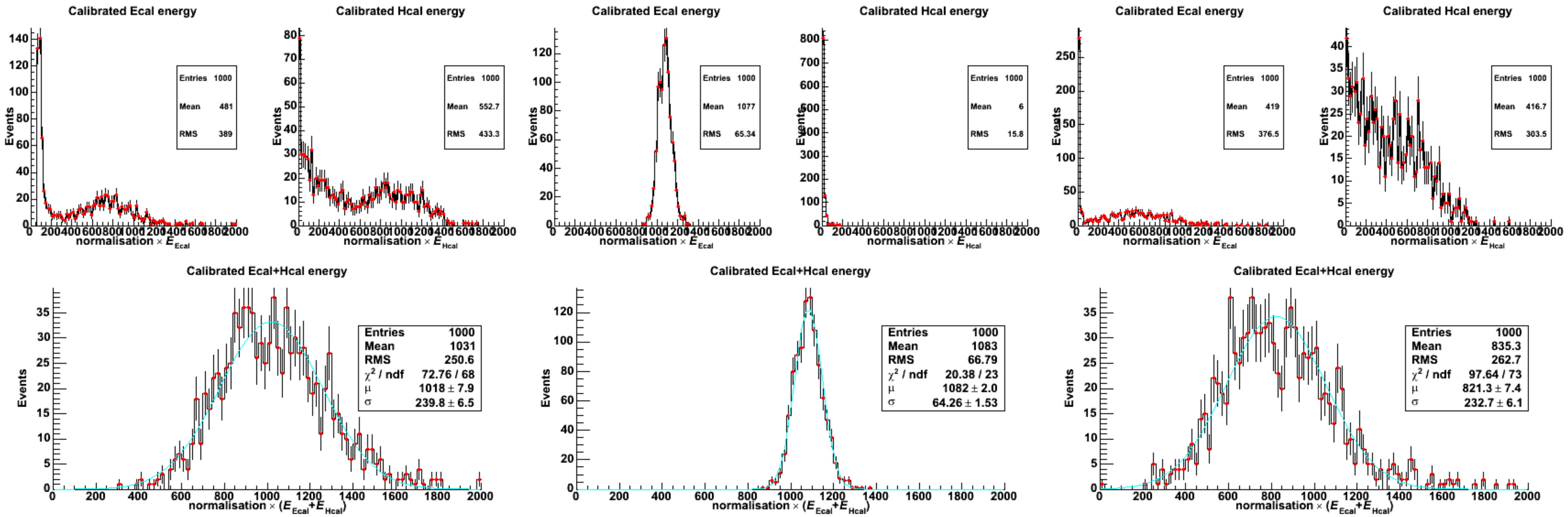
- Goal: to distinguish charged clusters from neutral clusters in calorimeters *e.g.* $\pi^+\gamma$ / π^+n.
- Propose a figure of merit:

  Quality = fraction of event energy that maps in a 1:1 ratio between reconstructed and true clusters.
- Quality improves with separation (naturally).
- $\pi^+\gamma$ separation at 5 GeV seems to be pretty good; π^+n is somewhat tougher (n showers typically have relatively ill-defined shapes).



Calibration of π^+, γ and n

π^+	γ	n



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