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Integration of Pandora to CEPCSW

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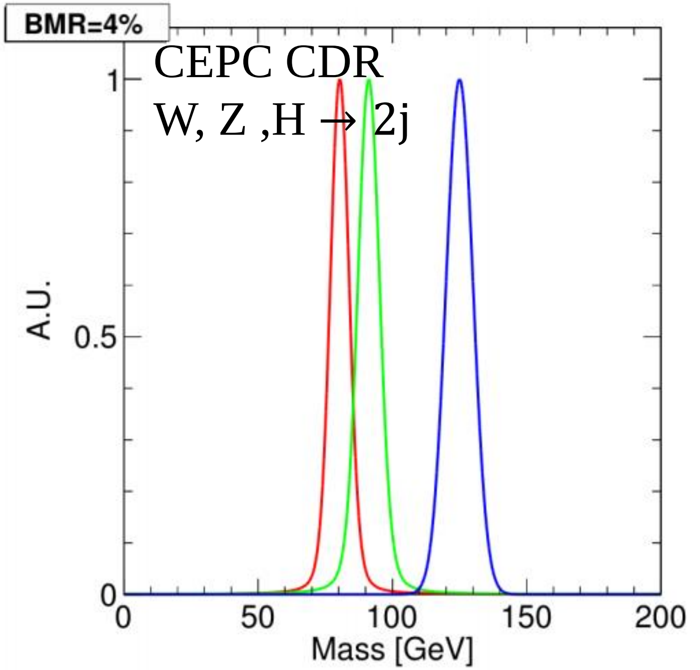
Outline

- Motivation of using Particle flow algorithms (PFAs)
- PFAs and challenge
- Pandora and Pandora in CEPCSW
- Summary

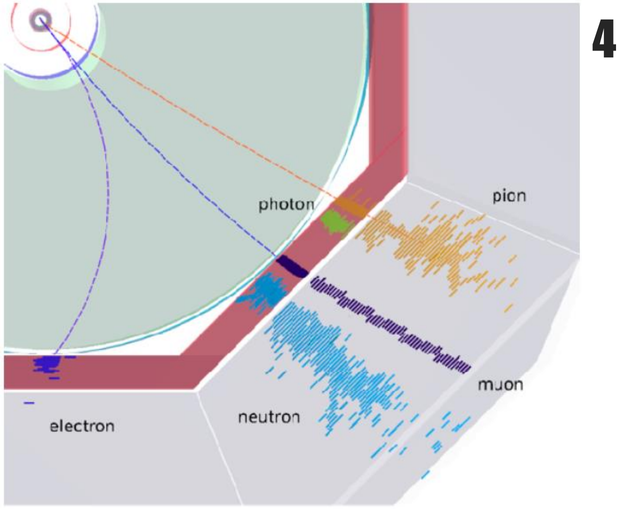
Motivation of PFAs

- The CEPC experiment aims to measure the property of Higgs, W and Z bosons precisely, and searching for new physics
- In most cases, the final states of Higgs, W and Z bosons decay include one (or multi) jets
- The concept of BMR (boson mass resolution) is useful to distinguish the events like $ZZ \to \nu\bar{\nu}q\bar{q}$ and $ZH \to \nu\bar{\nu}(q\bar{q}, gg)$ without jet reconstruction
- However, in order to distinguish events like $H \to WW^* \to 4j$ and $H \to ZZ^* \to 4j$, the jet must be reconstructed
- 2σ separation capability between W and Z boson:
  - ~4% BMR
  - ~4% jet energy resolution



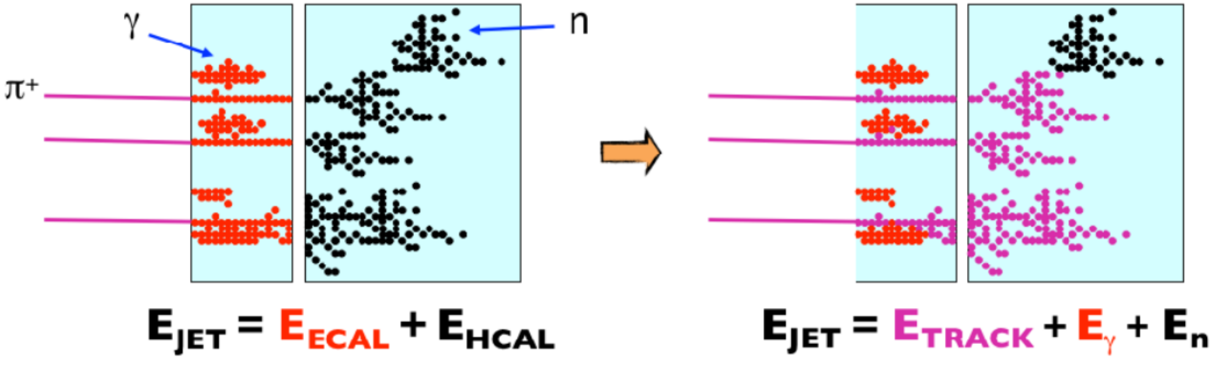
- The state-of-the-art particle flow algorithm (PFA) is adopted to achieve this requirement by reconstructing each final state particles

Particle flow algorithms



- Energy component of a typical jet:
  - 60% in charged hadrons
  - 30% in photons (mainly from $\pi^0 \to \gamma\gamma$)
  - 10% in neutral hadrons (mainly η and K_L)

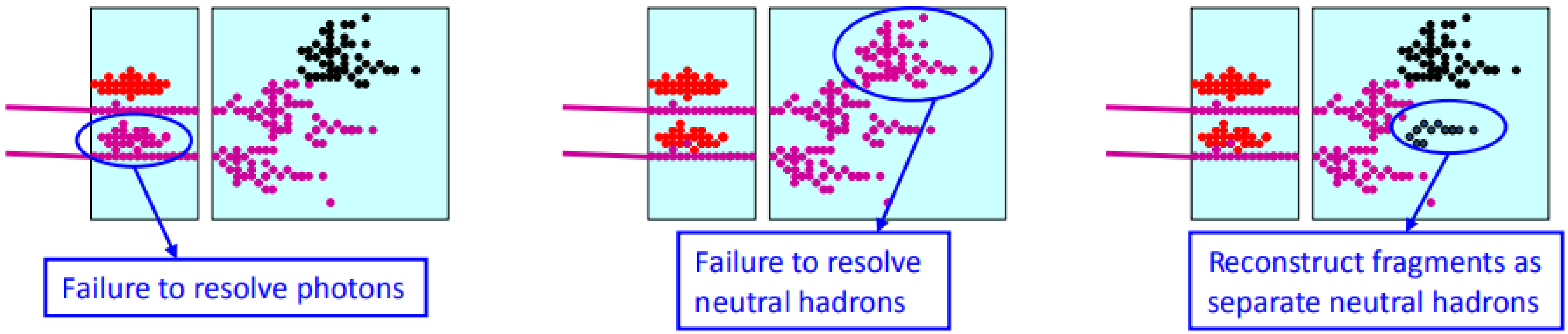
- Traditional jet energy reconstruction:
  - Measure all components of jet energy in ECAL and HCAL
  - Approximately 70% of energy measured in HCAL: $\frac{\sigma_E}{E} \approx 60\%/\sqrt{E}(GeV)$



- Particle flow algorithm: reconstruct individual particles
  - Charged particle momentum measured in tracker (essentially perfectly)
  - Photon energies measured in ECAL: $\frac{\sigma_E}{E} < 20\%/\sqrt{E}(GeV)$
  - Only neutral hadron energies (10% of jet energy) measured in HCAL
  - Much improved resolution

Challenge of PFAs

- The challenge for particle flow algorithms:
  - Avoid double counting of energy from same particle
  - Separate energy deposits from different particles
- There are three types of mistake (or "confusion") which will ruin the energy measurement of jet

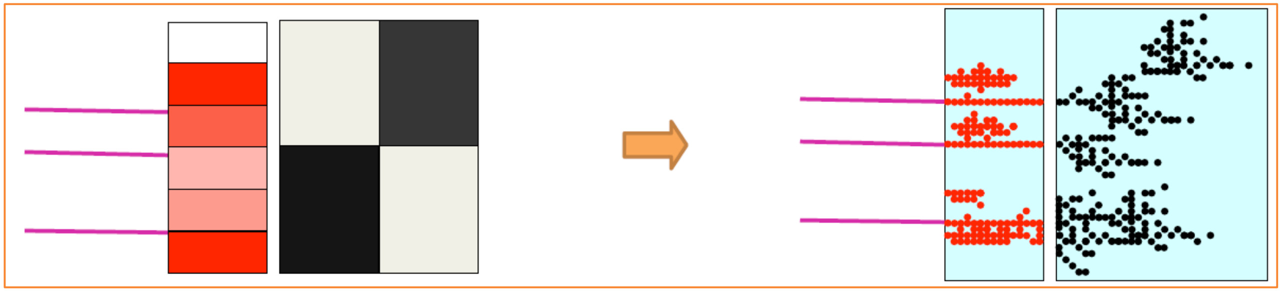


- Level of mistakes (or "confusion"), determines jet energy resolution, not intrinsic calorimetric performance

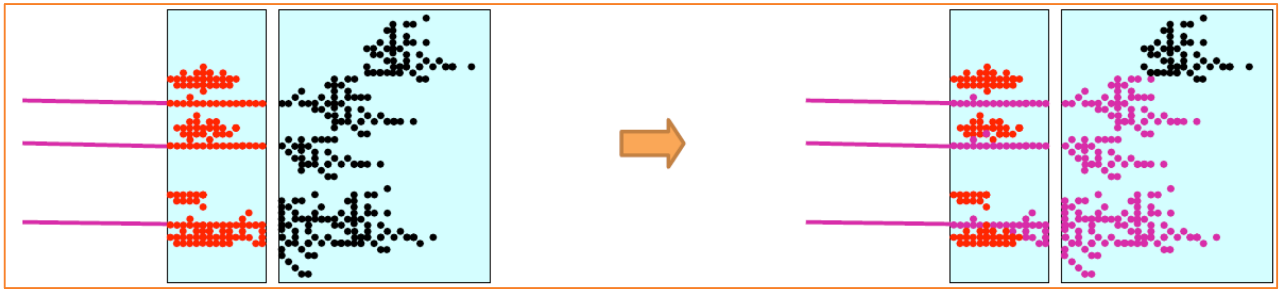
$$\sigma_{\text{jet}} = \sqrt{\sigma_{track}^2 + \sigma_{em}^2 + \sigma_{Had}^2 + \sigma_{confusion}^2}$$

Requirements

- **Hardware**: need to be able to resolve energy deposits from different particles
  - Require highly granular detectors (as the one in CEPC)



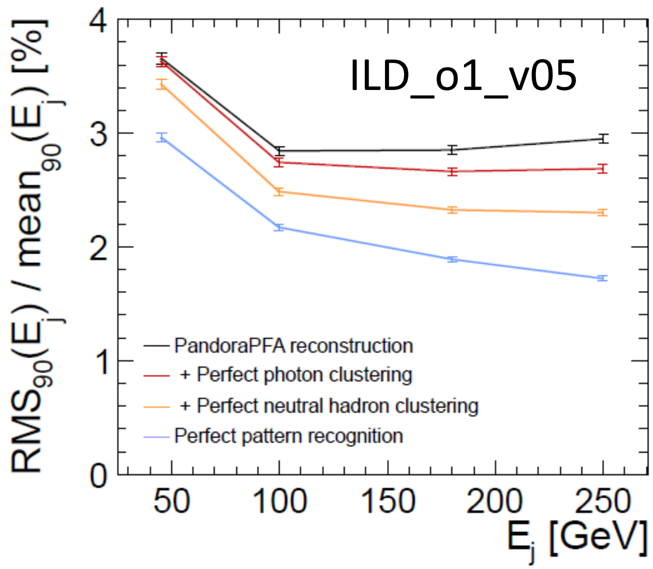
- **Software:** need to be able to identify energy deposits from each individual particle
  - Require sophisticated reconstruction software to deal with complex events, containing many hits



Particle flow algorithm = Hardware + software

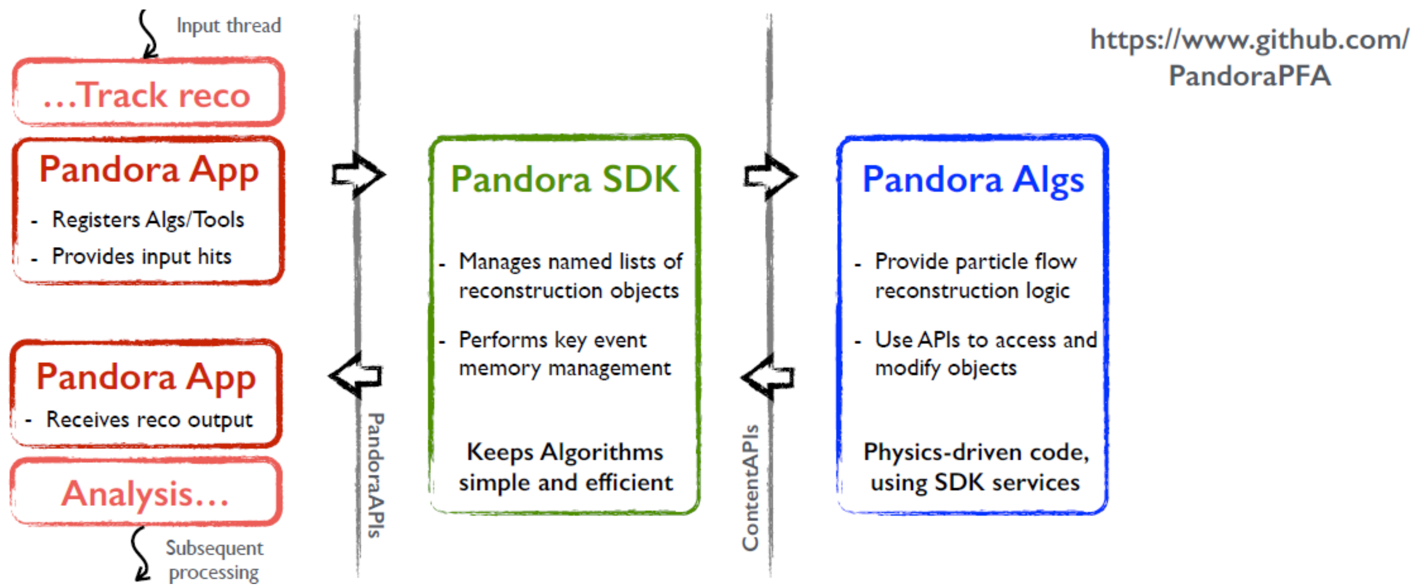
Pandora

- Pandora is a generic framework for solving pattern recognition problem (most important thing in PFA)
- In European Horizon 2020 project, the Pandora will be used for incorporating all other PFAs for easily use and do comparison
- Already used by ILC and CLIC for official PFA reconstruction, and very good jet energy resolution (< 4%) can be obtained for large energy region (> 50 GeV)



Pandora

- Integrating the Pandora into CEPCSW will facilitate the cooperation and connection between CEPC and other experiments. It will help CEPC experiment to develop its own PFAs
- The modular design of Pandora Algorithms makes some common algorithms can be easily reused, which saves time and manpower
- It consists of Pandora Client App, Pandora SDK and Pandora Algs



Pandora Client App

- Creating input Pandora objects which are used for Pandora PFA algorithms

  - CaloHit: defining a position in space with an associated energy and detector location details (e.g. layer)

  - Track: represents a continuous trajectory of well-defined space-points, with helix parameterization. Track parent-daughter and sibling relationships are supported

  - MCParticle: For development purposes, provide details of true pattern-recognition solution. Support parent-daughter links and can be associated to CaloHits and Tracks

  - The properties of input objects are defined at creation and cannot be changed

  - The usage of all input objects is monitored to ensure that no double-counting/usage occurs

Pandora Client App

- ❖ Creating Pandora geometry object ()
  - Tracker (innerR, outerR, outerZ,…)
  - Ecal (innerR, outerR, innerZ ,outerZ, nLayers,…)
  - Hcal
  - Muon, etc.

- ❖ Registering the Pandora PFAs

- ❖ Parsing XML setting file which defines the execute sequence of Pandora PFAs

- ❖ Asking Pandora to execute the PFA reconstruction

- ❖ Getting the reconstructed particle flow objects (PFOs) from Pandora and writing it to EDM

- ❖ The Pandora Client App is experiment dependent

Pandora Client App in CEPCSW

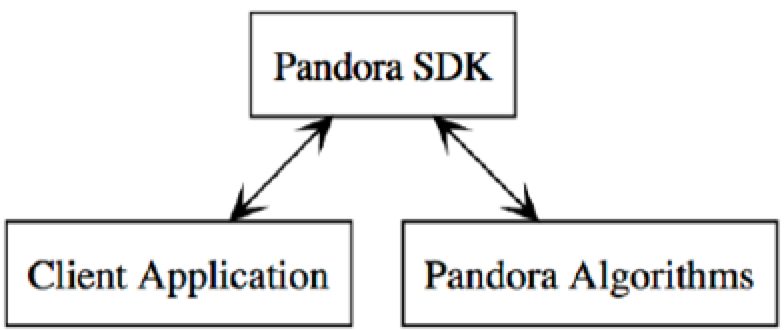
- Starting from Marlin Pandora Client App and integration it to Gaudi Pandora Client App for using it in CEPCSW
- Pseudocodes description of Pandora Client App in CEPCSW:

❖ PandoraPFAlg (Gaudi Algorithm):

- initialize()
  1. Create a Pandora instance
  2. Create Pandora geometry object (using DD4Hep Extension data or Gear file)
  3. Register Pandora PFAs
  4. Ask Pandora to parse XML setting file (which defines the execute sequence of Pandora PFAs)
- execute() (for each event)
  1. Create Pandora MCParticle instances
  2. Create Pandora CaloHit instances
  3. Specify MCPaticle-CaloHit relationships
  4. Create Pandora Tracks
  5. Specify associations between Tracks
  6. Specify MCPaticle-Track relationships
  7. Ask Pandora to process the event (to run the PFAs)
  8. Get output PFOs and translate it to EDM4HEP data
  9. Create the association between PFOs and MCParticles
  10. Write the PFOs information and association to output root file
  11. Reset Pandora for next event

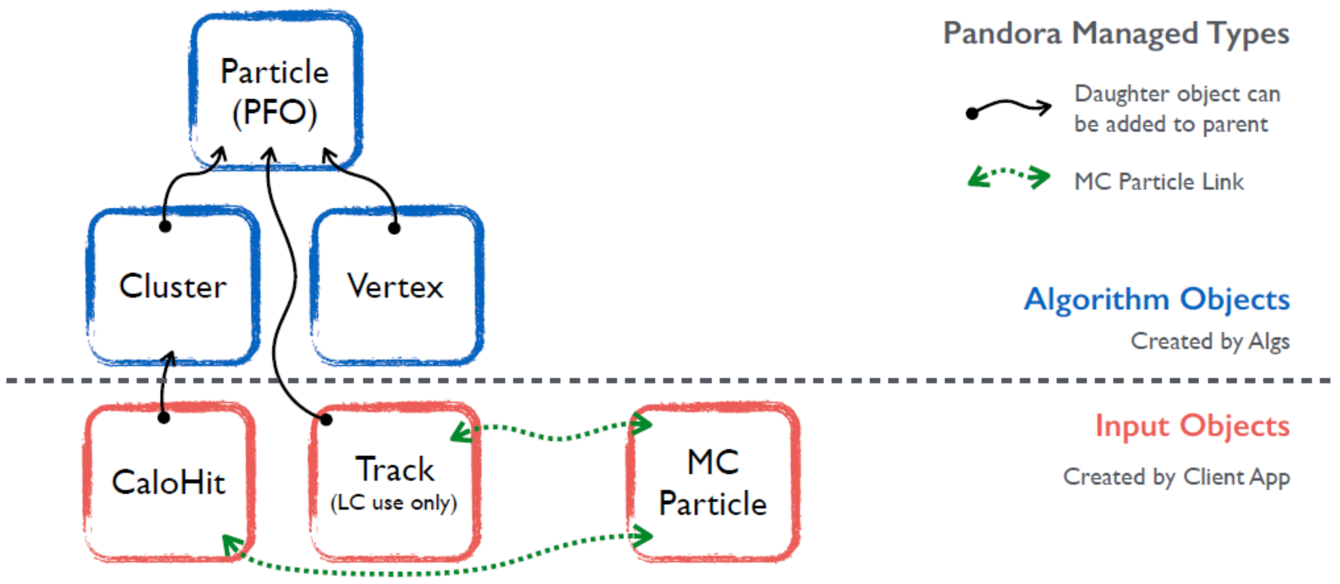
Pandora SDK

- ❑ Pandora SDK mainly contains Pandora Managers which own all instances of corresponding type of Pandora objects:
  - CaloHit Manager
  - Track Manager
  - Cluster Manager
  - PFOs Manager
  - Algorithm Manager, etc.
- ❑ This design can able to perform memory management, as Pandora objects can only be provided or accessed via APIs
- ❑ It Keeps Pandora algorithms simple and efficient



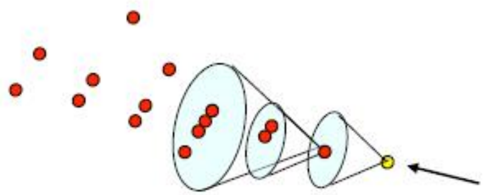
Pandora Algorithm

- Pandora algorithms contain step-by-step instructions, using Pandora APIs to perform object creation or modification
- It uses input Pandora objects to create algorithm objects:
  - Cluster: collection of Pandora CaloHits and main working-horse for algorithms (which create, merge, split Clusters).
  - Vertex: the identification and classification of a specific point in space, typically used to flag positions of particle creation or decay
  - PFO: container of Cluster, Tracks and Vertices, together with properties e.g. the particle four momenta and type. Ultimate Pandora output



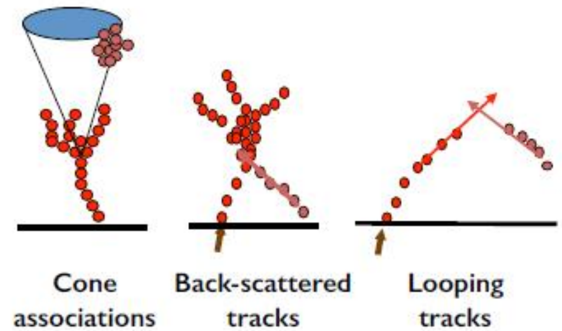
LC Pandora Algorithms

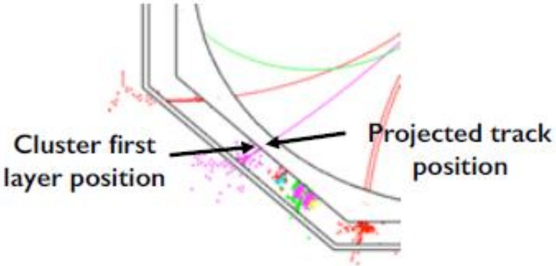
60+ algorithms for fine-granularity detectors



ConeClustering Algorithm

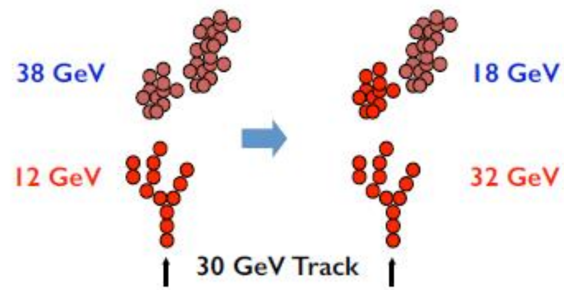
Topological Association Algorithms

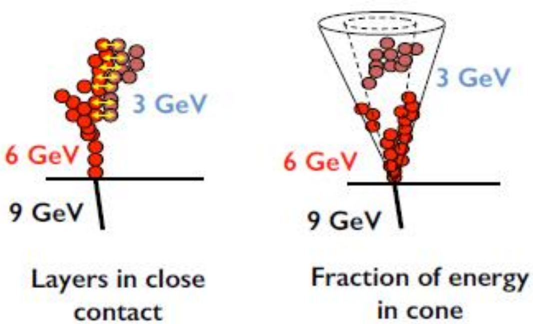




Track-Cluster Association Algorithms

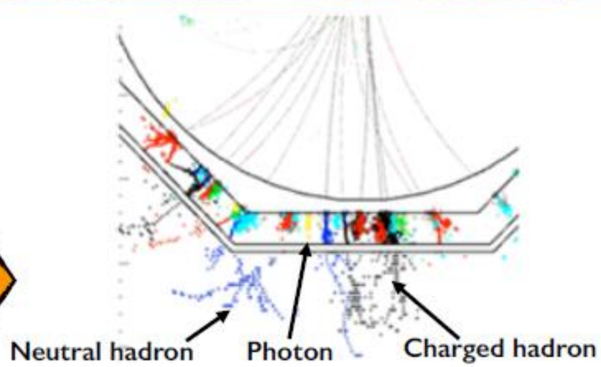
Reclustering Algorithms



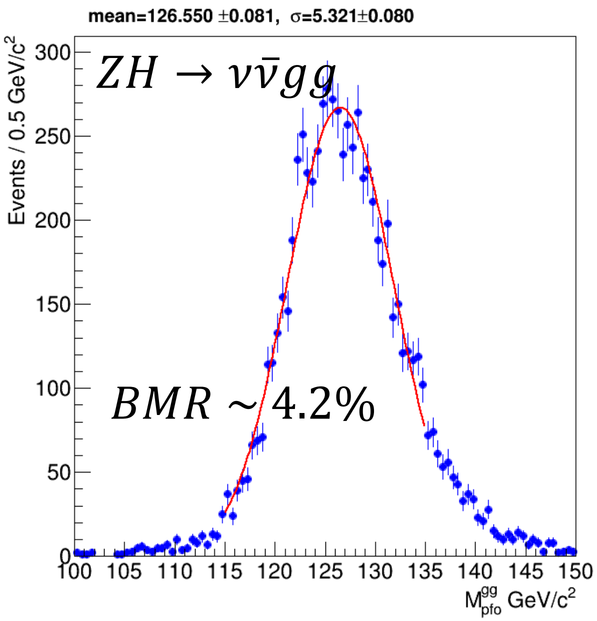


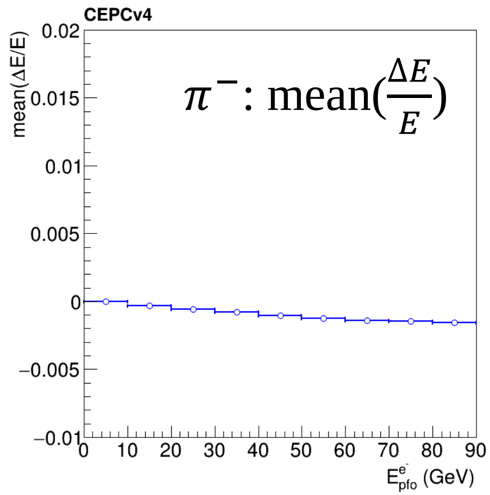
Fragment Removal Algorithms

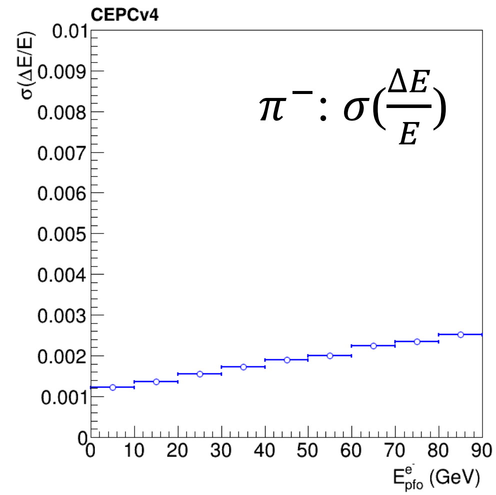
PFO Construction Algorithms

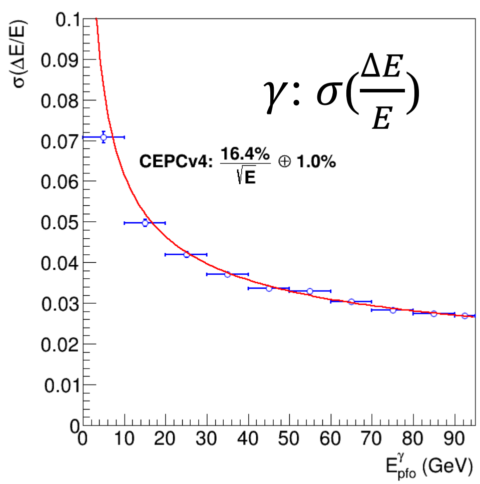


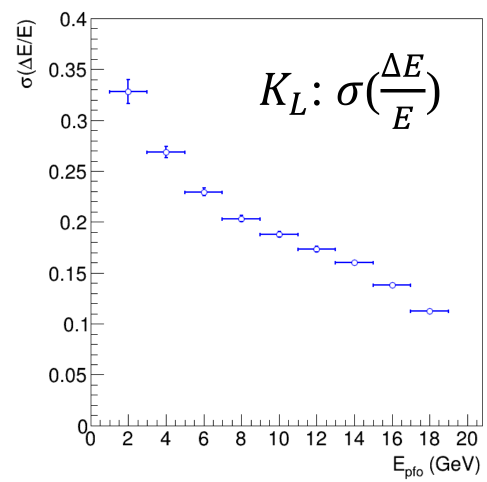
Performance of LC Pandora Algorithms











Summary

- A general pattern recognition framework, Pandora, has been introduced and has been integrated into CEPCSW
- Pandora Client App in CEPCSW transfers the EDM4hep data into Pandora input object and transfers ultimate Pandora PFOs back to the EDM4hep data
- The detector geometry information from DD4hep (or Gear) is used by Pandora
- The performance of LC Pandora algorithms for CEPCv4 have been checked which looks good
- The Pandora has become a part of key4hep project called "k4Pandora"

Thanks for your attention!

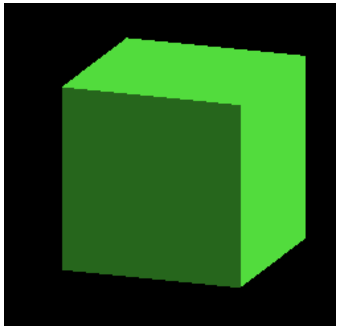
Back up

Example of using pandora in CEPCSW


```
################################################################################
from Configurables import PandoraPFAlg

pandoralg = PandoraPFAlg("PandoraPFAlg")
pandoralg.debug              = False
pandoralg.use_dd4hep_geo     = False
pandoralg.use_dd4hep_decoder = False
pandoralg.use_preshower      = False
pandoralg.WriteAna           = True
pandoralg.collections = [
        "MCParticle:MCParticle",
        "CalorimeterHit:ECALBarrel",
        "CalorimeterHit:ECALEndcap",
        "CalorimeterHit:ECALOther" ,
        "CalorimeterHit:HCALBarrel",
        "CalorimeterHit:HCALEndcap",
        "CalorimeterHit:HCALOther" ,
        "CalorimeterHit:MUON",
        "CalorimeterHit:LCAL",
        "CalorimeterHit:LHCAL",
        "CalorimeterHit:BCAL",
        "Vertex:KinkVertices",
        "Vertex:ProngVertices",
        "Vertex:SplitVertices",
        "Vertex:V0Vertices",
        "Track:MarlinTrkTracks",
        "MCRecoCaloAssociation:RecoCaloAssociation_ECALBarrel"
        ]
pandoralg.WriteClusterCollection               = "PandoraClusters"
pandoralg.WriteReconstructedParticleCollection = "PandoraPFOs"
pandoralg.WriteVertexCollection                = "PandoraPFANewStartVertices"

pandoralg.PandoraSettingsDefault_xml = "Reconstruction/PFA/Pandora/PandoraSettingsDefault.xml"
#### Do not chage the collection name, only add or delete ###############
pandoralg.TrackCollections      =  ["MarlinTrkTracks"]
pandoralg.ECalCaloHitCollections=  ["ECALBarrel", "ECALEndcap", "ECALOther"]
pandoralg.HCalCaloHitCollections=  ["HCALBarrel", "HCALEndcap", "HCALOther"]
pandoralg.LCalCaloHitCollections=  ["LCAL"]
pandoralg.LHCalCaloHitCollections= ["LHCAL"]
pandoralg.MuonCaloHitCollections=  ["MUON"]
pandoralg.MCParticleCollections =  ["MCParticle"]
pandoralg.RelCaloHitCollections =  ["RecoCaloAssociation_ECALBarrel", "RecoCaloAssociation_ECALEndcap",
pandoralg.RelTrackCollections   =  ["MarlinTrkTracksMCTruthLink"]
pandoralg.KinkVertexCollections =  ["KinkVertices"]
pandoralg.ProngVertexCollections=  ["ProngVertices"]
pandoralg.SplitVertexCollections=  ["SplitVertices"]
pandoralg.V0VertexCollections   =  ["V0Vertices"]
```

```
pandoralg.ECalToMipCalibration   = 160.0
pandoralg.HCalToMipCalibration   = 34.8
pandoralg.ECalMipThreshold       = 0.5
pandoralg.HCalMipThreshold       = 0.3
pandoralg.ECalToEMGeVCalibration= 0.9 #for G2CD Digi, 1.007 for NewLDCaloDigi
pandoralg.HCalToEMGeVCalibration= 1.007
pandoralg.ECalToHadGeVCalibrationBarrel= 1.12 #very small effect
pandoralg.ECalToHadGeVCalibrationEndCap= 1.12
pandoralg.HCalToHadGeVCalibration= 1.07
pandoralg.MuonToMipCalibration= 10.0
pandoralg.DigitalMuonHits= 0
pandoralg.MaxHCalHitHadronicEnergy    = 1.0
pandoralg.UseOldTrackStateCalculation= 0
pandoralg.AbsorberRadLengthECal= 0.2854
pandoralg.AbsorberIntLengthECal= 0.0101
pandoralg.AbsorberRadLengthHCal= 0.0569
pandoralg.AbsorberIntLengthHCal= 0.006
pandoralg.AbsorberRadLengthOther= 0.0569
pandoralg.AbsorberIntLengthOther= 0.006
```

Example



```
git clone git@github.com:cepc/CEPCSW.git (as a user)
cd CEPCSW
git checkout master
vim  Examples/options/tut_detsim_pan_matrix.py
```

```python
from Configurables import GeoSvc
geosvc = GeoSvc("GeoSvc")
#geosvc.compact = geometry_path
geosvc.compact = "./Detector/DetEcalMatrix/compact/det.xml"

##############################################################
# Physics Generator
##############################################################
from Configurables import GenAlgo
from Configurables import GtGunTool
from Configurables import StdHepRdr
from Configurables import SLCIORdr
from Configurables import HepMCRdr
from Configurables import GenPrinter

gun = GtGunTool("GtGunTool")
gun.Particles = ["gamma","gamma"]
gun.EnergyMins= [5 , 10] # GeV
gun.EnergyMaxs= [5 , 10] # GeV
gun.ThetaMins = [90, 90] # degree
gun.ThetaMaxs = [90, 90] # degree
gun.PhiMins   = [0,  4 ] # degree
gun.PhiMaxs   = [0,  4 ] # degree
```

```xml
<detectors>
  <detector id="1" name="CaloDetector" type="EcalMatrix" readout="CaloHitsCollection"
    <!-- Use cm as unit if you want to use Pandora for reconstruction -->
    <position x="200*cm"  y="0"  z="0"/>
    <dimensions dx="30*cm"  dy="30*cm"  dz="30*cm"/>
  </detector>
</detectors>

<readouts>
  <readout name="CaloHitsCollection">
    <!-- <segmentation type="NoSegmentation"/> -->

    <segmentation type="CartesianGridXYZ"
                  grid_size_x="1*cm"
                  grid_size_y="1*cm"
                  grid_size_z="1*cm"/>
    <id>system:8,x:32:-6,y:-6,z:-6</id>
  </readout>
</readouts>
```

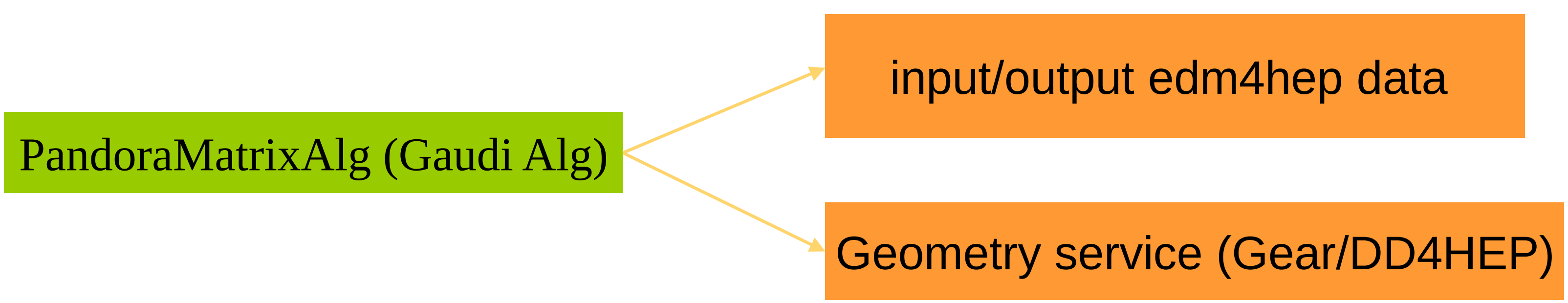
Detector/DetEcalMatrix/src/calorimeter/EcalMatrix.cpp
Construct geometry and save Extension data (e.g. layer thickness, cellSize, …) for reconstruction.

Example

```
##############################################################################
# Detector Simulation
##############################################################################
from Configurables import DetSimSvc
detsimsvc = DetSimSvc("DetSimSvc")
from Configurables import DetSimAlg
detsimalg = DetSimAlg("DetSimAlg")
# detsimalg.VisMacs = ["vis.mac"]
detsimalg.RunCmds = [
#    "/tracking/verbose 1",
]
detsimalg.AnaElems = [
    "Edm4hepWriterAnaElemTool"
]
detsimalg.RootDetElem = "WorldDetElemTool"
from Configurables import AnExampleDetElemTool
example_dettool = AnExampleDetElemTool("AnExampleDetElemTool")
##############################################################################
# Detector digitization
##############################################################################
from Configurables import CaloDigiAlg
example_CaloDigiAlg = CaloDigiAlg("CaloDigiAlg")
example_CaloDigiAlg.Scale = 1
example_CaloDigiAlg.SimCaloHitCollection = "SimCalorimeterCol"
example_CaloDigiAlg.CaloHitCollection     = "ECALBarrel"
example_CaloDigiAlg.CaloAssociationCollection     = "RecoCaloAssociation_ECALBarrel"
##############################################################################
```

```
##############################################################################
# Pandora
##############################################################################
from Configurables import PandoraMatrixAlg

pandoralg = PandoraMatrixAlg("PandoraMatrixAlg")
pandoralg.collections = [
        "MCParticle:MCParticle",
        "CalorimeterHit:ECALBarrel",
        "MCRecoCaloAssociation:RecoCaloAssociation_ECALBarrel"
        ]
pandoralg.WriteClusterCollection               = "PandoraClusters"
pandoralg.WriteReconstructedParticleCollection = "PandoraPFOs"
pandoralg.WriteVertexCollection                = "PandoraPFANewStartVertices"
pandoralg.AnaOutput = "AnaMatrix.root"
pandoralg.PandoraSettingsDefault_xml = "./Reconstruction/PFA/Pandora/PandoraSettingsDefault.xml"
pandoralg.TrackCollections      =  ["MarlinTrkTracks"]
pandoralg.ECalCaloHitCollections=  ["ECALBarrel", "ECALEndcap", "ECALOther"]
pandoralg.HCalCaloHitCollections=  ["HCALBarrel", "HCALEndcap", "HCALOther"]
pandoralg.LCalCaloHitCollections=  ["LCAL"]
pandoralg.LHCalCaloHitCollections= ["LHCAL"]
pandoralg.MuonCaloHitCollections=  ["MUON"]
pandoralg.MCParticleCollections =  ["MCParticle"]
pandoralg.RelCaloHitCollections =  ["RecoCaloAssociation_ECALBarrel"]
pandoralg.RelTrackCollections   =  ["MarlinTrkTracksMCTruthLink"]
pandoralg.KinkVertexCollections =  ["KinkVertices"]
pandoralg.ProngVertexCollections=  ["ProngVertices"]
pandoralg.SplitVertexCollections=  ["SplitVertices"]
pandoralg.V0VertexCollections   =  ["V0Vertices"]
pandoralg.ECalToMipCalibration  = 112 #1000MeV/8.918
pandoralg.HCalToMipCalibration  = 34.8
pandoralg.ECalMipThreshold      = 0.225# 8.918*0.225=2.00655
pandoralg.HCalMipThreshold      = 0.3
pandoralg.ECalToEMGeVCalibration= 1.# BGO, to be tuned
pandoralg.HCalToEMGeVCalibration= 1.007
pandoralg.ECalToHadGeVCalibrationBarrel= 1.12
pandoralg.ECalToHadGeVCalibrationEndCap= 1.12
```

```
-bash-4.2$ ls Reconstruction/PFA/Pandora/MatrixPandora/src/
CaloHitCreator.cpp   GeometryCreator.cpp   MCParticleCreator.cpp   PandoraMatrixAlg.cpp   PfoCreator.cpp   TrackCreator.cpp
```



Example

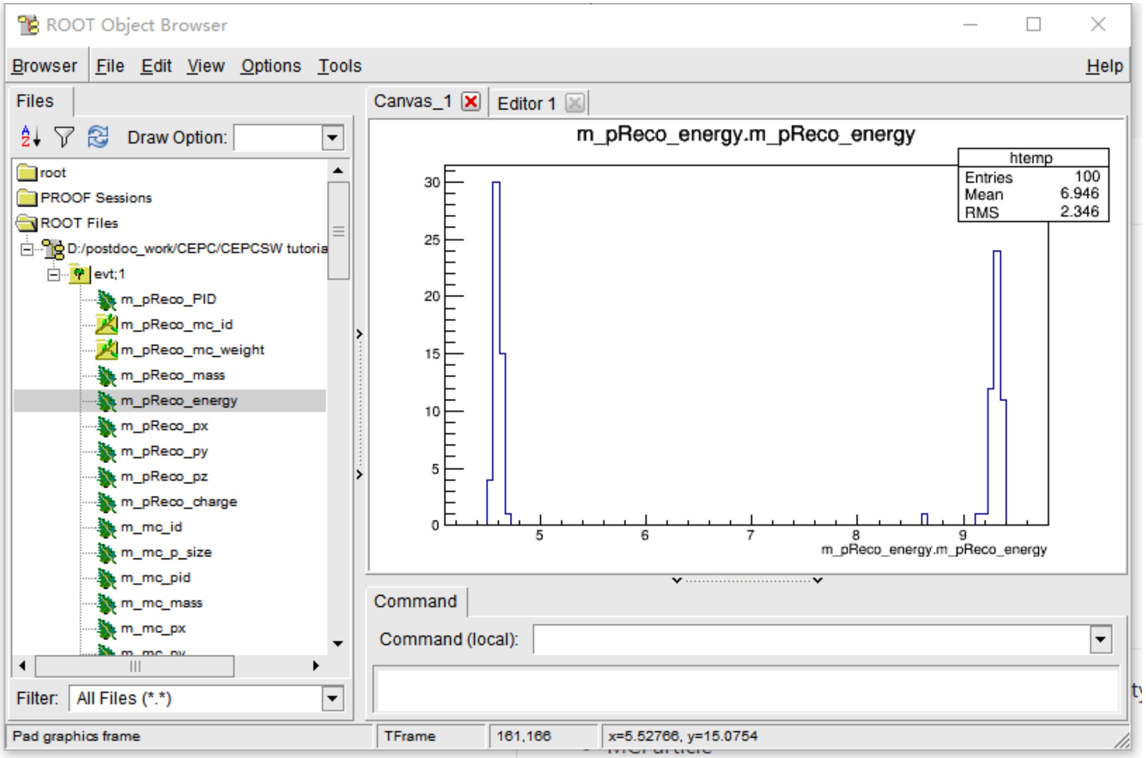
```
-bash-4.2$ ls Reconstruction/PFA/Pandora/MatrixPandora/src/
CaloHitCreator.cpp  GeometryCreator.cpp  MCParticleCreator.cpp  PandoraMatrixAlg.cpp  PfoCreator.cpp  TrackCreator.cpp
```

```
m_pPandora = new pandora::Pandora();
m_pMCParticleCreator = new MCParticleCreator(m_mcParticleCreatorSettings, m_pPandora);
m_pGeometryCreator = new GeometryCreator(m_geometryCreatorSettings, m_pPandora);
PANDORA_THROW_RESULT_IF(pandora::STATUS_CODE_SUCCESS, !=, m_pGeometryCreator->CreateGeometry(svcloc));
m_pCaloHitCreator = new CaloHitCreator(m_caloHitCreatorSettings, m_pPandora, svcloc, 0);
m_pTrackCreator = new TrackCreator(m_trackCreatorSettings, m_pPandora, svcloc);
m_pPfoCreator = new PfoCreator(m_pfoCreatorSettings, m_pPandora);
PANDORA_THROW_RESULT_IF(pandora::STATUS_CODE_SUCCESS, !=, this->RegisterUserComponents());
PANDORA_THROW_RESULT_IF(pandora::STATUS_CODE_SUCCESS, !=, PandoraApi::ReadSettings(*m_pPandora, m_settings.m_pandoraSettingsXmlFile)
```

```
StatusCode PandoraMatrixAlg::execute()
{

    try
    {
        std::cout<<"execute PandoraMatrixAlg"<<std::endl;

        updateMap();
        PANDORA_THROW_RESULT_IF(pandora::STATUS_CODE_SUCCESS, !=, m_pMCParticleCreator->CreateMCParticles(*m_CollectionMaps));
        PANDORA_THROW_RESULT_IF(pandora::STATUS_CODE_SUCCESS, !=, m_pCaloHitCreator->CreateCaloHits(*m_CollectionMaps));
        PANDORA_THROW_RESULT_IF(pandora::STATUS_CODE_SUCCESS, !=, m_pMCParticleCreator->CreateCaloHitToMCParticleRelationships(*m_Collecti
onMaps, m_pCaloHitCreator->GetCalorimeterHitVector() ));
        PANDORA_THROW_RESULT_IF(pandora::STATUS_CODE_SUCCESS, !=, m_pTrackCreator->CreateTrackAssociations(*m_CollectionMaps));
        PANDORA_THROW_RESULT_IF(pandora::STATUS_CODE_SUCCESS, !=, m_pTrackCreator->CreateTracks(*m_CollectionMaps));
        PANDORA_THROW_RESULT_IF(pandora::STATUS_CODE_SUCCESS, !=, m_pMCParticleCreator->CreateTrackToMCParticleRelationships(*m_Collection
Maps, m_pTrackCreator->GetTrackVector() ));
        PANDORA_THROW_RESULT_IF(pandora::STATUS_CODE_SUCCESS, !=, PandoraApi::ProcessEvent(*m_pPandora));
        PANDORA_THROW_RESULT_IF(pandora::STATUS_CODE_SUCCESS, !=, m_pPfoCreator->CreateParticleFlowObjects(*m_CollectionMaps, m_ClusterCol
lection_w, m_ReconstructedParticleCollection_w, m_VertexCollection_w));

        StatusCode sc0 = CreateMCRecoParticleAssociation();
        StatusCode sc = Ana();

        PANDORA_THROW_RESULT_IF(pandora::STATUS_CODE_SUCCESS, !=, PandoraApi::Reset(*m_pPandora));
        this->Reset();
```

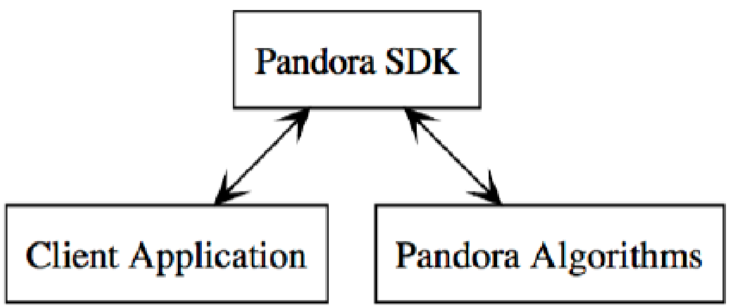
Example

```
git clone git@github.com:cepc/CEPCSW.git
cd CEPCSW
git checkout master
/cvmfs/container.ihep.ac.cn/bin/hep_container shell SL6
source setup.sh
./build.sh
./run.sh Examples/options/tut_detsim_pan_matrix.py
root -l AnaMatrix.root
```



Client Application

- **Client app is responsible for providing Input Objects that define the pattern-recognition problem and for persisting the output Particles. Experiment dependent.**
  - Responsible for creating Pandora instances and for configuring the reconstruction algorithms via the Pandora Settings XML file.



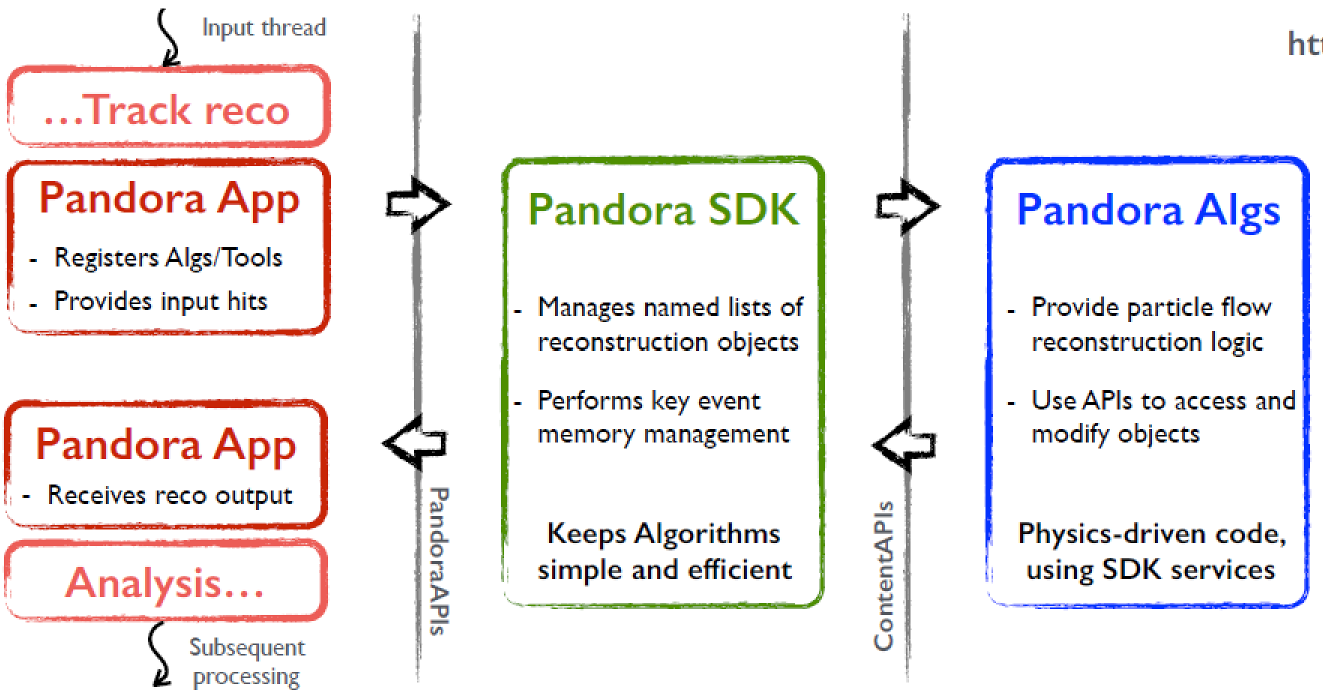
Built with client app, or in libraries of Pandora content

Algorithm Pseudocode description of a client application for LAr TPC event reconstruction in a single drift volume

```
procedure MAIN
    Create a Pandora instance
    Register Algorithms and Plugins
    Ask Pandora to parse XML settings file
    for all Events do
        Create CaloHit instances
        Create MCParticle instances
        Specify MCParticle-CaloHit relationships
        Ask Pandora to process the event
        Get output PFOs and write to file
        Reset Pandora before next event
```

PandoraSDK

- The **Pandora Software Development Kit** is engineered to provide an environment in which:
  1. It is easy for users to provide the building-blocks that define a pattern recognition problem.
  2. Logic required to solve pattern recognition problems is cleanly implemented in algorithms.
  3. Operations to access or modify building-blocks, or to create new structures, are requested by algorithms and performed by the Pandora framework.

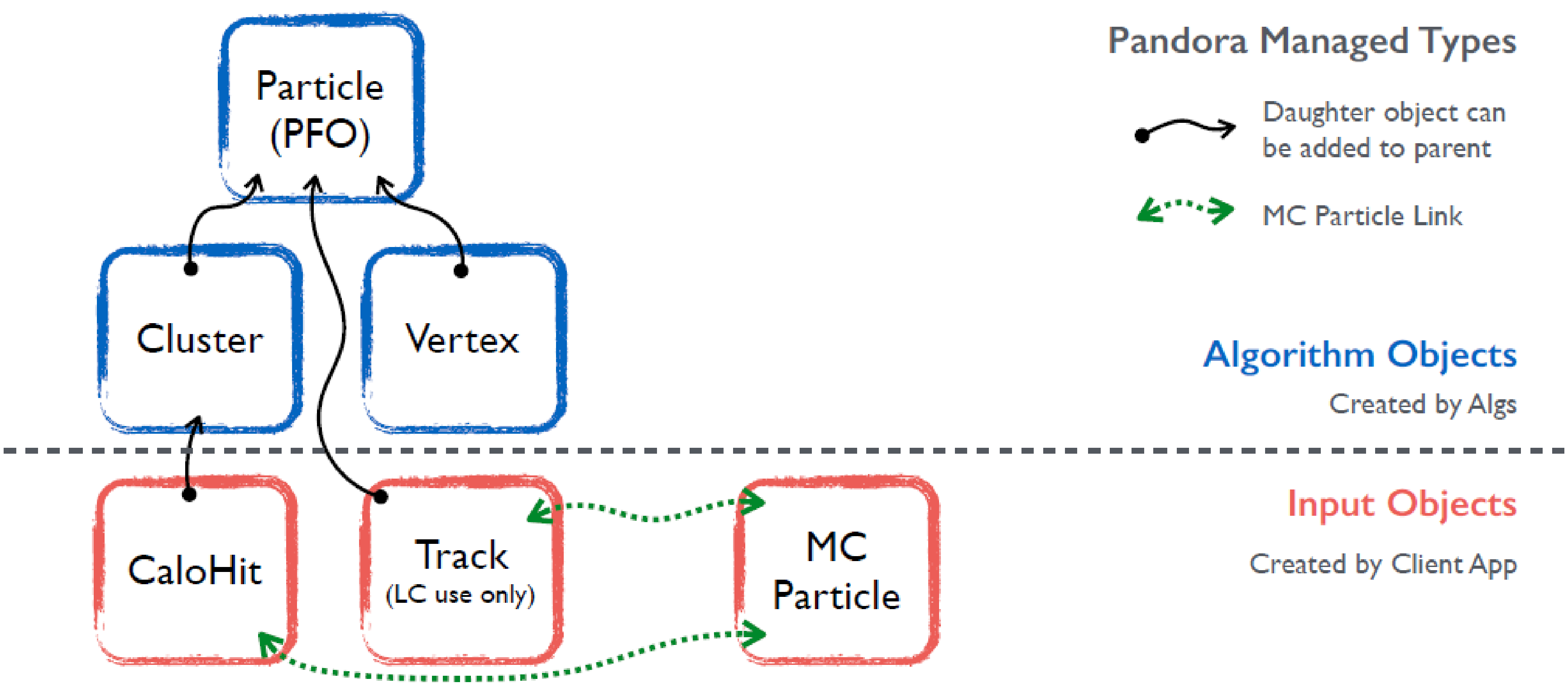


https://www.github.com/PandoraPFA

- It actively promotes use of large numbers of algorithms, each addressing specific event topologies.

Event Data Model

- **EDM consists of classes to represent the input building-blocks for pattern-recognition problems and the structures that can be created using these building-blocks.**
- Provides well-defined development environment for managing pattern-recognition problems and allows for independence of algorithms, which can only communicate via the EDM.
- EDM aims to be self-describing, with each object providing all the information required to allow investigation and processing by the pattern-recognition algorithms.



Input Objects

- **Input Objects are the building-blocks for pattern recognition, typically created by the client app before algorithm operations begin.**
- Their properties are defined at creation and cannot be changed. They are instead used to build new constructs, termed “Algorithm Objects".
- The usage of all Input Objects is monitored to ensure that no double-counting/usage occurs.

CaloHit	Primary building-block, defining a position and extent in space (or time), with an associated intensity or energy measurement and detector location details.
Track (LC use only)	Represents a continuous trajectory of well-defined space-points, with helix parameterisation. Track parent-daughter and sibling relationships supported.
MC Particle	For development purposes, provide details of true pattern-recognition solution. Support parent-daughter links and can be associated to CaloHits and Tracks.

Algorithm Objects

- **Algorithm Objects represent the higher-level structures created in order to solve pattern-recognition problems.**
- Pandora carefully manages the allocation and manipulation of these objects and all non-const operations can only be requested by algorithms via the Pandora Content APIs.
- Pandora is then able to perform the memory-management for these objects.

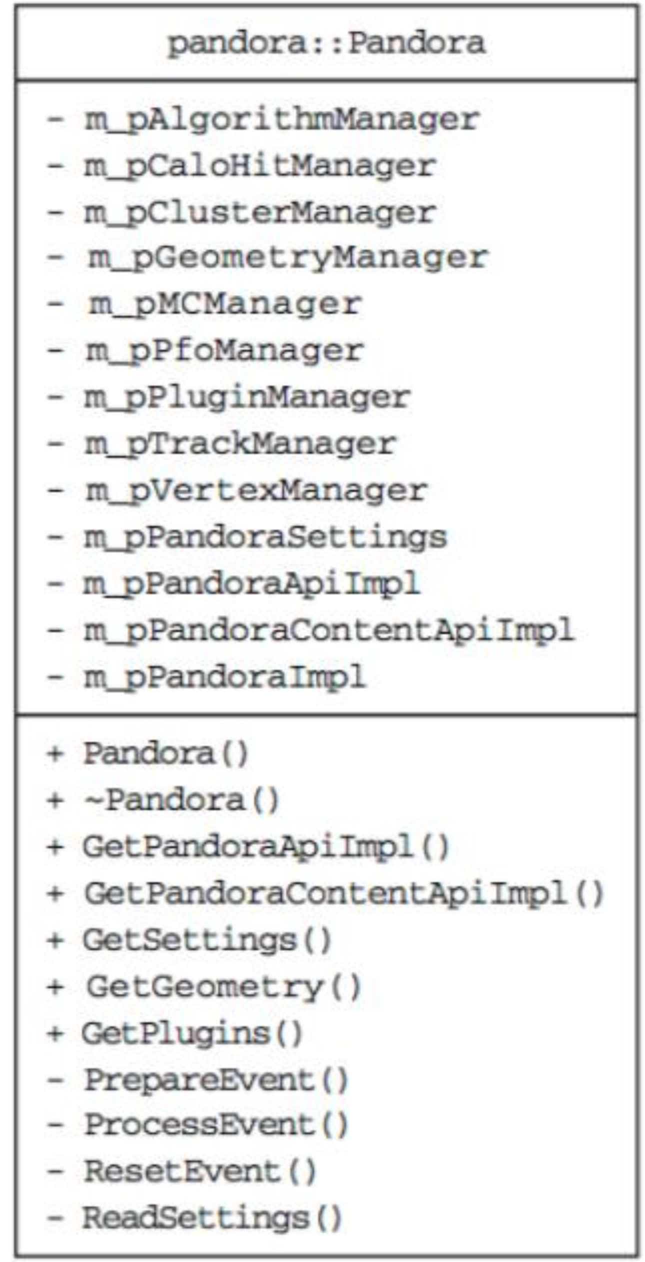
Cluster	Collection of CaloHits and main working-horse for algorithms (which create, merge, split Clusters). Provides some derived properties of CaloHit collection.
Vertex	The identification and classification of a specific point in space, typically used to flag positions of particle creation or decay.
Particle	Container of Clusters, Tracks and Vertices, together with metadata describing e.g. particle type. Ultimate Pandora output and can represent a hierarchy.

Geometry information in Pandora

- The geometry information is saved in pandora’s geometry manager in client application once.
- It includes the sub-detector type (e.g. ECAL_BARREL, ECAL_ENDCAP), R, Z, layer information and so on.
- The algorithms will use PandoraContentApi to get the geometry manager of pandora and get the needed geometry information.

Managers

- **At very heart of Pandora design are the Managers, which own all instances of objects in Pandora EDM.**
  - The Managers are designed to provide a complete set of low-level object manipulation functions.
  - Algs request high-level services (e.g. merge two Clusters), which are then satisfied when the hidden implementation calls the low-level Manager functions in the correct order.
  - Approach helps ensure that implementation is extensible, easy to maintain and rather human-readable.
  - Key part of design is that algorithms can *only* access or
  - modify managed objects via the APIs, so Managers are able to perform memory-management.

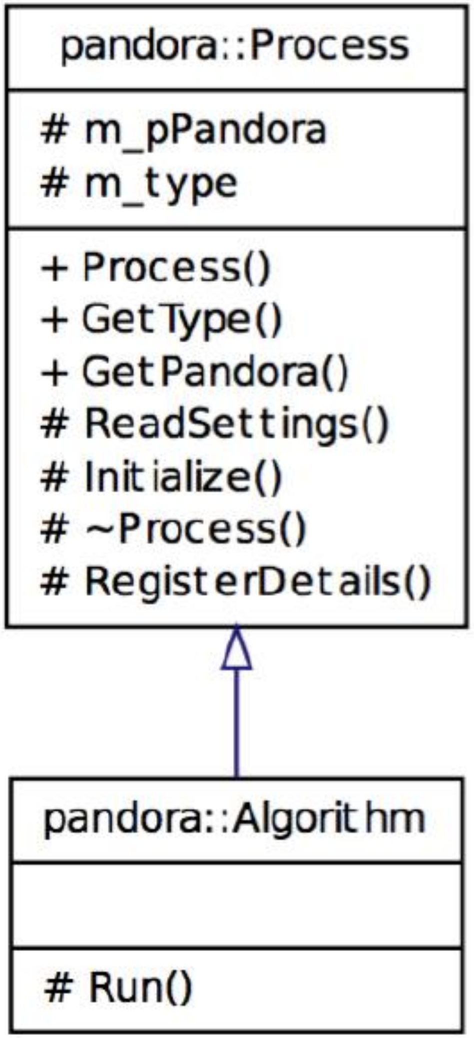


A Pandora instance is simply a container of Manager instances and API implementation instances

Algorithms

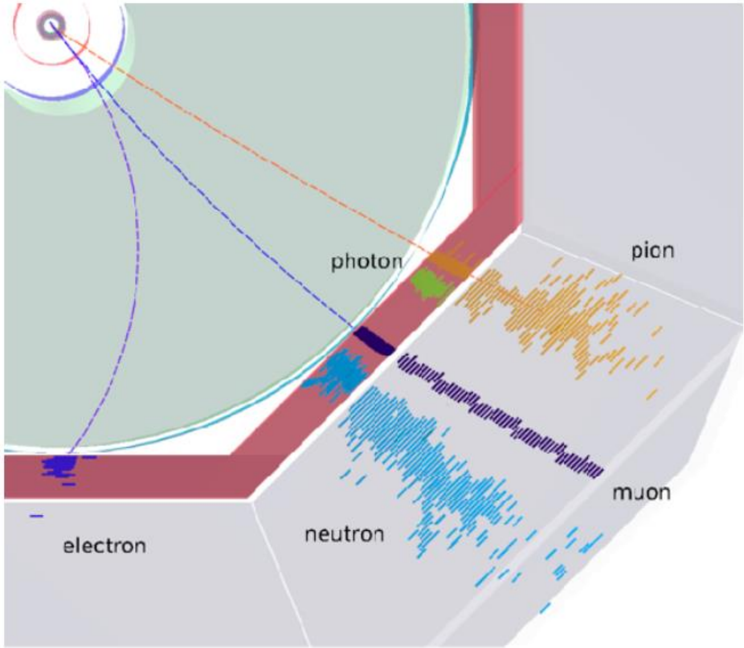
- **Algs contain step-by-step instructions, using Pandora APIs to request object creation/modification services.**
  - Algs inherit from the Pandora Process abstract base class. Inherited functionality controls handshaking between Pandora instance and algorithm instance.
  - Process provides ability to receive a ReadSettings callback with an XML handle (tiny xml) from which configurable parameters can be extracted. Also an Initialize callback.
  - The Algorithm purely abstract base class provides the interface for the Run callback, which is called each event and is the entry point for all event processing.

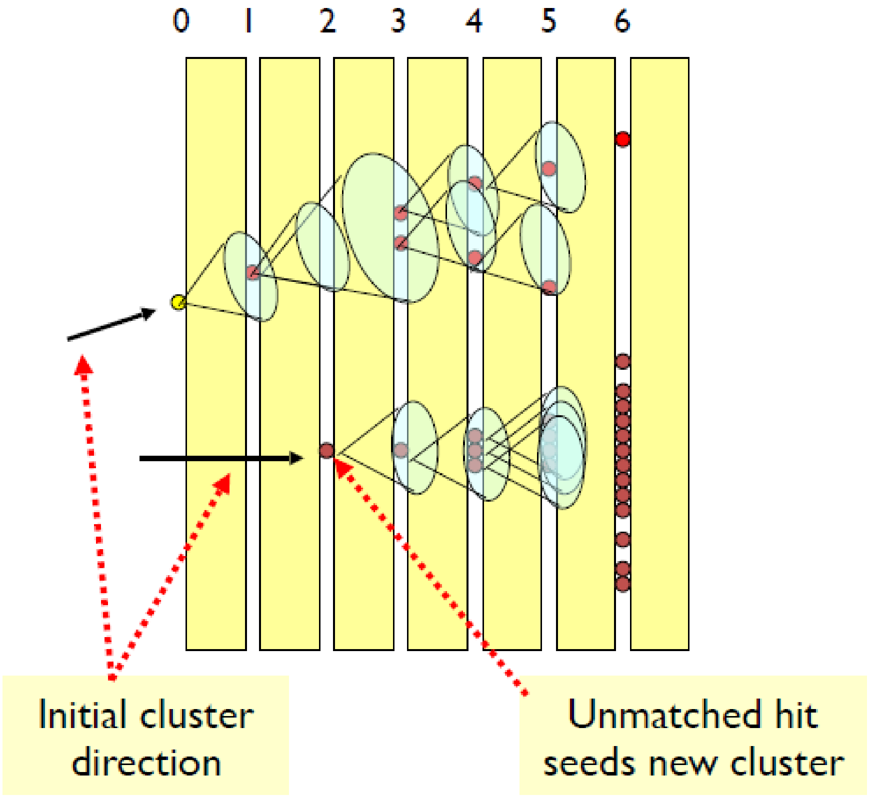
- **Algorithm Factories registered (under a specific name), by the client app are extremely simple:**
  - Must allocate instance of derived algorithm type and return pointer to Algorithm base class.



Cone Clustering

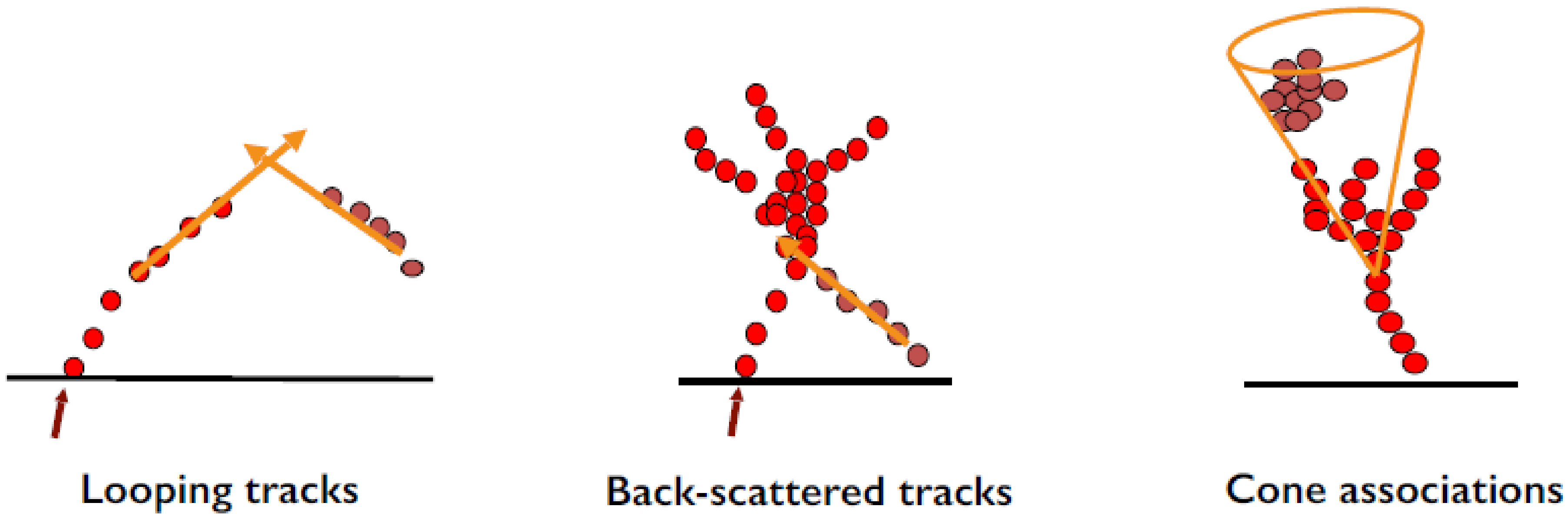
- Clusters seeded by projections of inner detector tracks to surface of calorimeter.
- Start at innermost layers and work outward, considering each calorimeter hit in turn.
  - If hit lies within cone defined by existing cluster, and is suitably close, add hit to cluster.
  - If hit is unmatched, use it to form a new cluster.





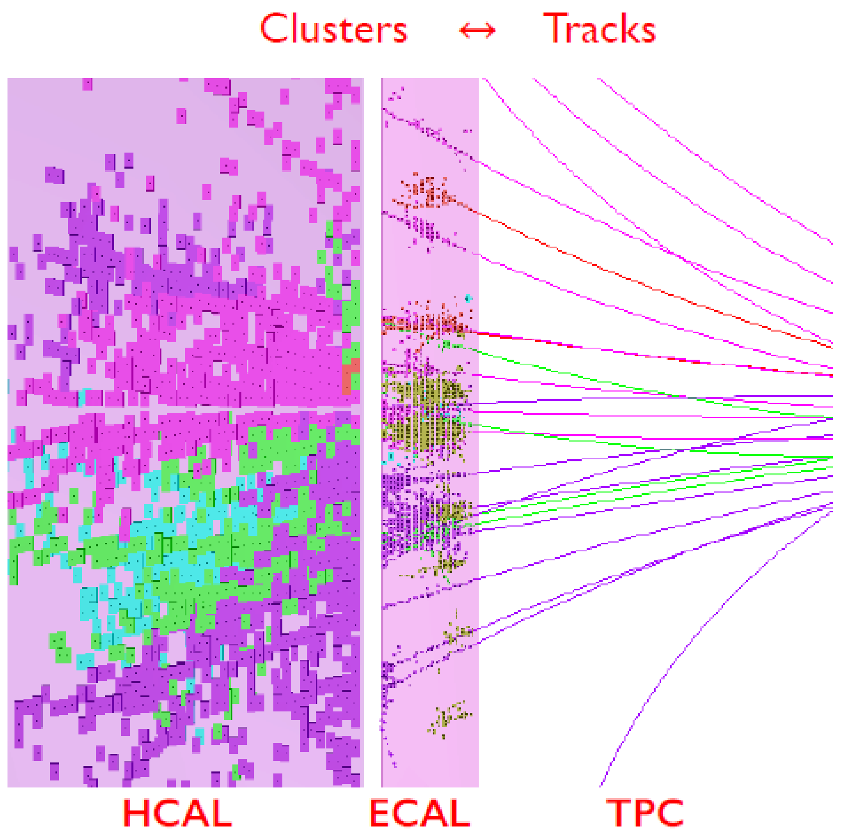
Topological Association

- Cone clustering algorithm may creates clusters that are fragments of single particles, rather than risk merging deposits from separate particles.
- Cluster fragments are then merged together by a series of algorithms, each of which follows well-defined topological rules.
- Fine granularity of the calorimeters exploited to merge cluster fragments that are clearly associated. Very few mistakes!



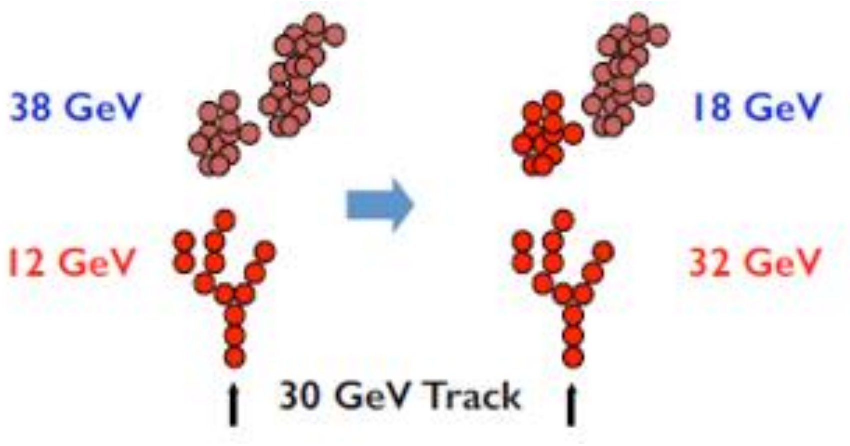
Track-Cluster Associations

- The Pandora track-cluster association algorithms look for consistency between cluster properties and the helix-projected track state at the front face of the calorimeter:
  - Close proximity between cluster and track positions.
  - Consistent track and initial cluster directions.
  - Consistent track momentum and cluster energy.



Reclustering

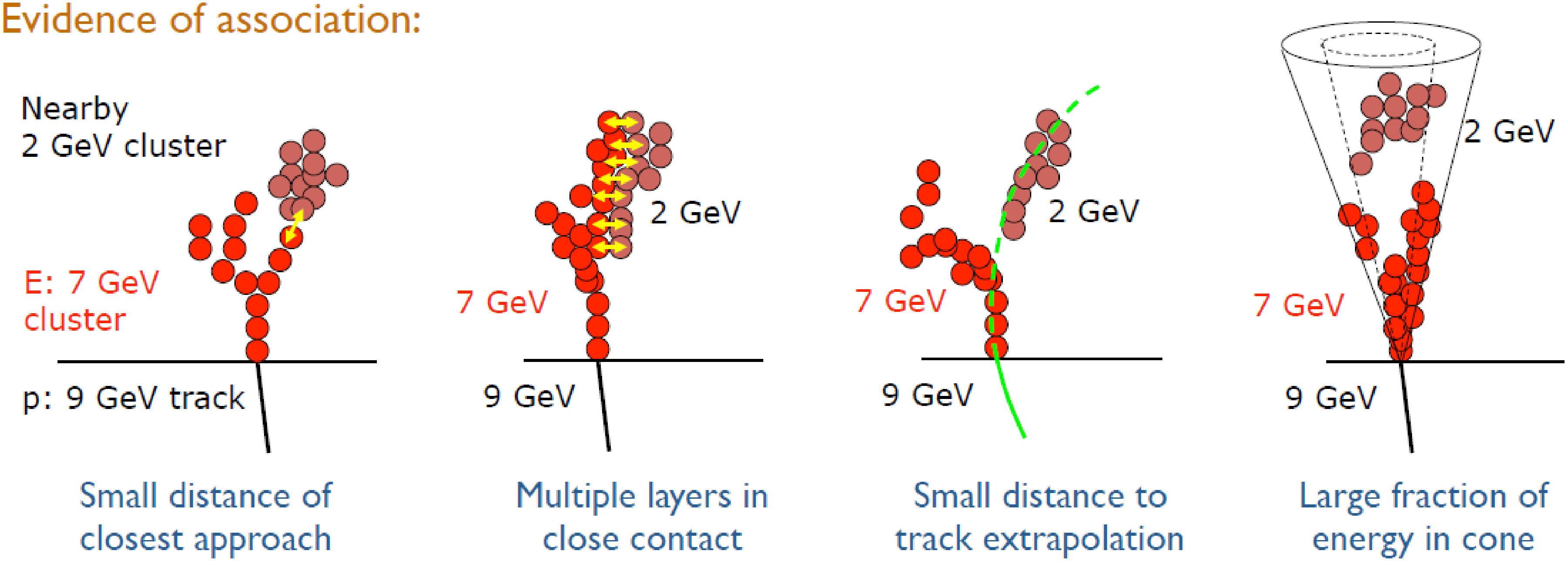
- If there are significant discrepancy between energy of a cluster and momentum of its associated track, choose to recluster.
- Alter clustering parameters, or change clustering algorithm entirely, until cluster splits in such a way that we obtain sensible track-cluster associations.



Fragment Removal

- Fragment removal algs aim to remove neutral clusters (those without track-associations) that are really fragments of charged (track-associated) clusters.
- Algs look for evidence of association between nearby clusters, merging the clusters together. In order to merge clusters, the change must bring about a satisfactory change in E/p $\chi 2$.

Evidence of association:



Particle Identification

- Particle ID is crucial for many physics analyses. Currently available: charged lepton and photon ID

e.g. dedicated muon alg.

1. Cluster hits in muon yoke
2. Associate to inner detector track
3. "Swim" through calorimeter