FUTURE CIRCULAR COLLIDER

Particle Flow at FCC

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CERN

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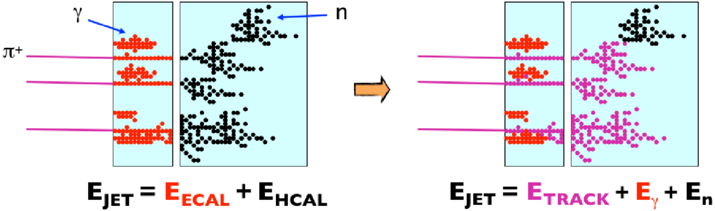
What is particle flow?

Reconstruction of **stable** particles in the event
(e, γ, μ, charged and neutral hadrons)
using the **information from all sub-detectors**.

Main idea: leverage **the most precise** sub-detector that measures a particle:

- trackers – for charged particles
- calorimetry – for neutral particles.



1308.4537

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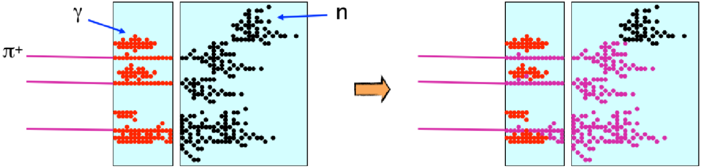
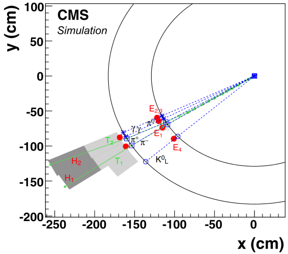
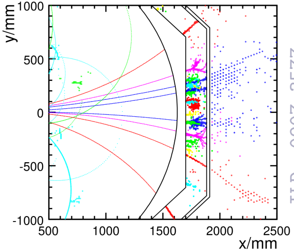


$E_{JET} = E_{ECAL} + E_{HCAL}$ $\quad\rightarrow\quad$ $E_{JET} = E_{TRACK} + E_{\gamma} + E_{n}$

1308.4537



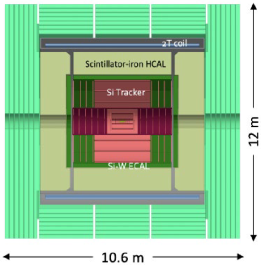
CMS, 1706.04965



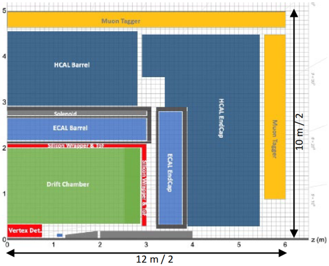
ILD, 0907.3577

Particle Flow at FCC

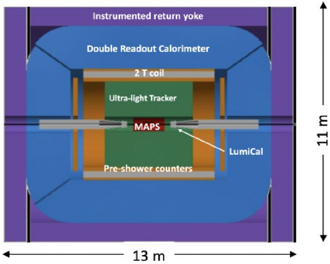
CLD



ALLEGRO



IDEA



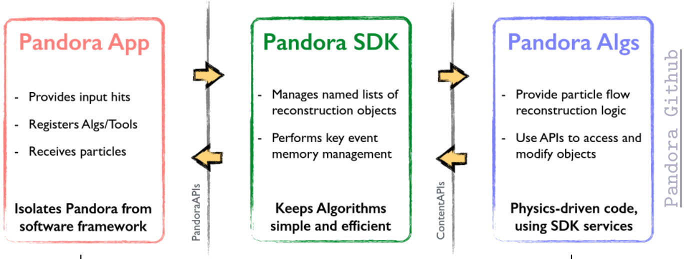
Different status for each of the detector proposals:

- CLD – Naturally most advanced, originates from CLICdp, based on Pandora.
- ALLEGRO – A study started with Pandora (for calorimeters).
- IDEA – A standalone demonstrator of the improvement when combining tracker and calorimetry (with crystals in front of fibers).

Additionally, new machine learning (ML) based method being developed, tested first on CLD to compare against Pandora → see more in the talk by Andrea de Vita.

Pandora PFA

Pandora PFA is a framework which employs several pattern recognition algorithms to **form** and **manipulate** (merge, split, delete) clusters and create particle flow objects (PFOs).



↓ CLDConfig (for CLD)

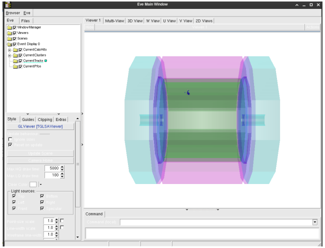
↓ LCContent

↓ via DDMarlinPandora

in future k4GaudiPandora

Each experiment must choose the algorithms, order, parameters ...

Framework should also facilitates development.



PandoraMonitoring window.

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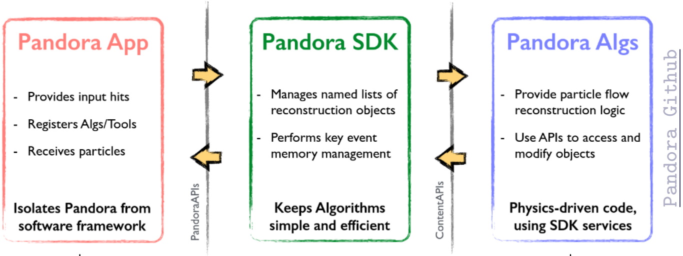

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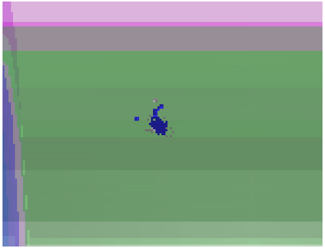

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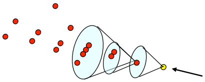
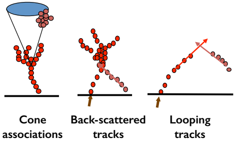
Pandora LCContent algorithms (1/2)

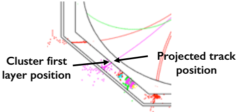
60+ algorithms for fine-granularity detectors



ConeClustering Algorithm

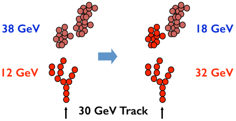
Topological Association Algorithms

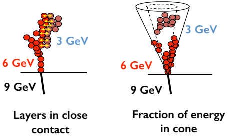




Track-Cluster Association Algorithms

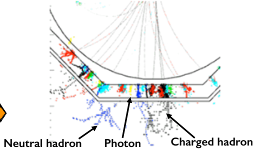
Reclustering Algorithms





Fragment Removal Algorithms

PFO Construction Algorithms



Pandora Github

Pandora LCContent algorithms (1/2)

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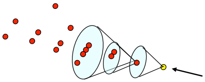
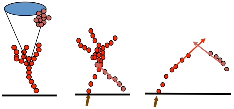


ConeClustering Algorithm

Topological Association Algorithms



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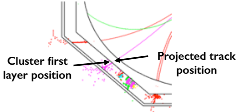

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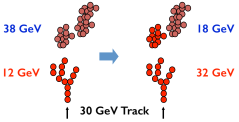

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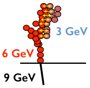

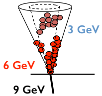

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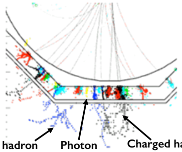

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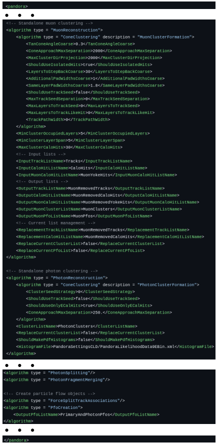

The order of execution of algorithms is steered from the XML file.
For instance for CLD: `CLDConfig/PandoraSettingsDefault.xml`

Pandora LCContent algorithms (1/2)

All algorithms come with **multiple** parameters.
Tuning of those is **vital**.

```xml
<algorithm type = "ConeClustering" description = "MuonClusterFormation">
    <TanConeAngleCoarse>0.3</TanConeAngleCoarse>
    <ConeApproachMaxSeparation>2000</ConeApproachMaxSeparation>
    <MaxClusterDirProjection>2000</MaxClusterDirProjection>
    <ShouldUseIsolatedHits>true</ShouldUseIsolatedHits>
    <LayersToStepBackCoarse>30</LayersToStepBackCoarse>
    <AdditionalPadWidthsCoarse>1</AdditionalPadWidthsCoarse>
    <SameLayerPadWidthsCoarse>1.8</SameLayerPadWidthsCoarse>
    <ShouldUseTrackSeed>false</ShouldUseTrackSeed>
    <MaxTrackSeedSeparation>0</MaxTrackSeedSeparation>
    <MaxLayersToTrackSeed>0</MaxLayersToTrackSeed>
    <MaxLayersToTrackLikeHit>0</MaxLayersToTrackLikeHit>
    <TrackPathWidth>0</TrackPathWidth>
</algorithm>
```

XML configuration

```cpp
ConeClusteringAlgorithm::ConeClusteringAlgorithm() :
    m_clusterSeedStrategy(2),
    m_shouldUseOnlyECalHits(false),
    m_shouldUseIsolatedHits(false),
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    m_layersToStepBackCoarse(3),
    m_clusterFormationStrategy(0),
    m_genericDistanceCut(1.f),
    m_minHitTrackCosAngle(0.f),
    m_minHitClusterCosAngle(0.f),
    m_shouldUseTrackSeed(true),
    m_trackSeedCutOffLayer(0),
    m_shouldFollowInitialDirection(false),
    m_sameLayerPadWidthsFine(2.8f),
    m_sameLayerPadWidthsCoarse(1.8f),
    m_coneApproachMaxSeparation2(1000.f * 1000.f),
    m_tanConeAngleFine(0.3f),
    m_tanConeAngleCoarse(0.5f),
    m_additionalPadWidthsFine(2.5f),
    m_additionalPadWidthsCoarse(2.5f),
    m_maxClusterDirProjection(200.f),
    m_minClusterDirProjection(-10.f),
    m_trackPathWidth(2.f),
    m_maxTrackSeedSeparation2(250.f * 250.f),
    m_maxLayersToTrackSeed(3),
    m_maxLayersToTrackLikeHit(3),
    m_nLayersSpannedForFit(6),
    m_nLayersSpannedForApproxFit(10),
    m_nLayersToFit(8),
    m_nLayersToFitLowMipCut(0.5f),
    m_nLayersToFitLowMipMultiplier(2),
    m_fitSuccessDotProductCut1(0.75f),
    m_fitSuccessChi2Cut1(5.0f),
    m_fitSuccessDotProductCut2(0.50f),
    m_fitSuccessChi2Cut2(2.5f),
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    m_firstLayer(1)
{
}
```

C++ implementation

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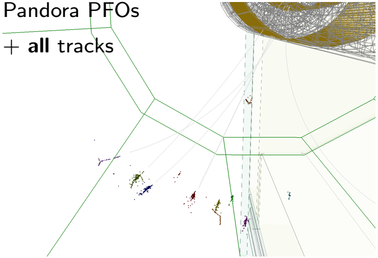
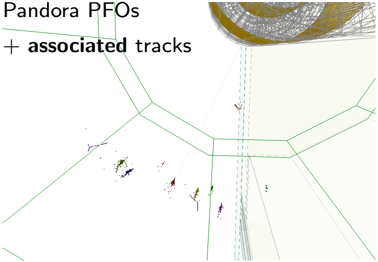
C++ implementation

CLD reconstruction (1/2)

Even though it is considered ready, some analyses encounter problems (e.g. flavour tagging).





from issue

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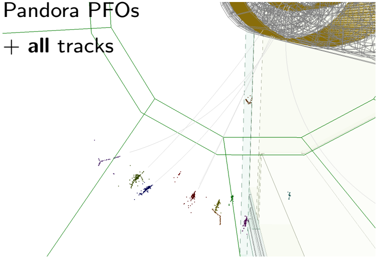

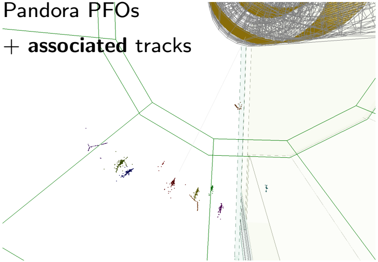

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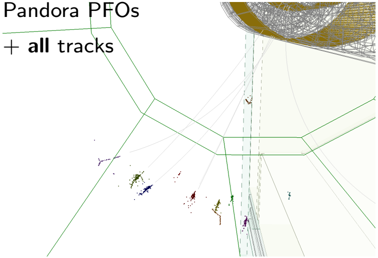
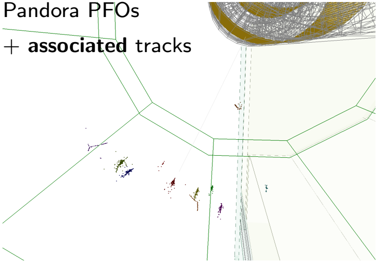
Better optimisation strategy for both should be tried out: **investigate what jet energy resolution can be obtained while maintaining good PID at the same time.**





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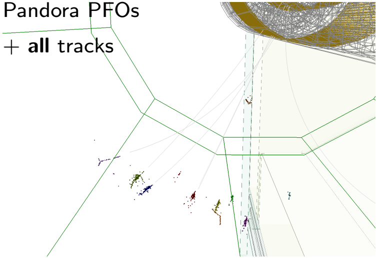
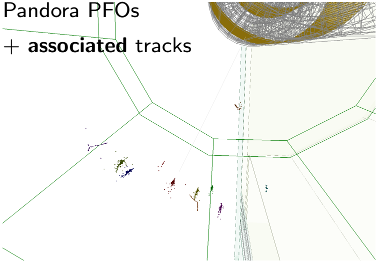
Also a potential idea – running the 'recovery' of tracks ?

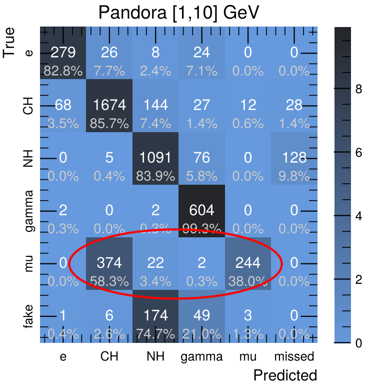




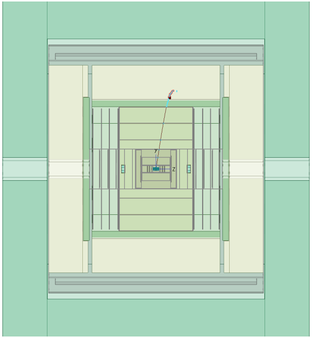
from issue

CLD reconstruction (2/2)

Muon are misidentified (for charged hadrons) if no energy is deposited in muon chambers



from the comparison of MLPF to Pandora

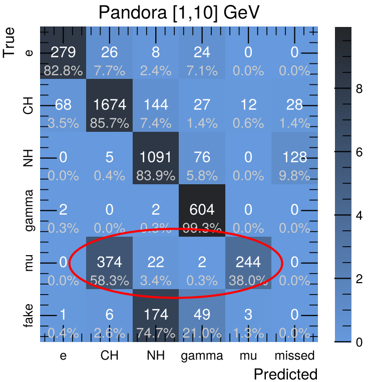


1 GeV μ^- in CLD, CED viewer

$\rightarrow$ needs to be investigated (and tuned).

CLD reconstruction (2/2)

Muon are misidentified (for charged hadrons) if no energy is deposited in muon chambers but even with clear energy deposits in muon chambers.



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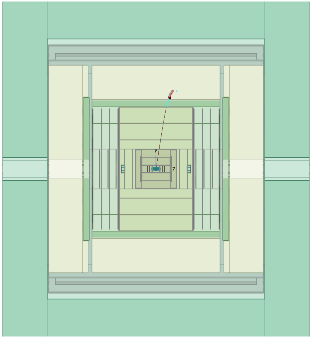
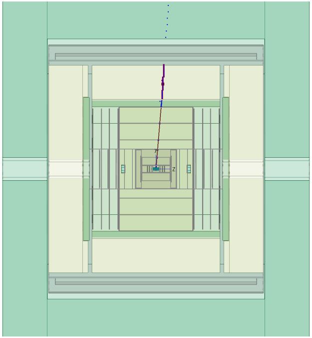


1 GeV μ^- in CLD, CED viewer



10 GeV μ^- in CLD, CED viewer

$\rightarrow$ needs to be investigated (and tuned).

Pandora Tuning and Calibration

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That must be done "by hand" looking at each algorithm and our detectors, using the available debugging tools:

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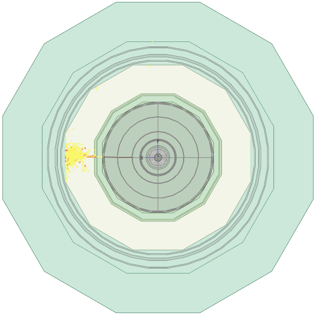
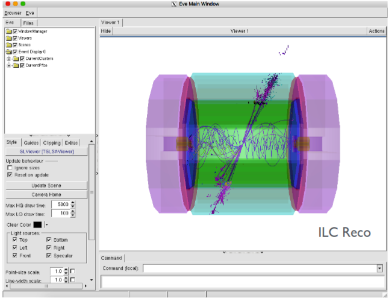
```
source /cvmfs/sw.hsf.org/key4hep/setup.sh
glced &
k4run $CLDCONFIG/share/CLDConfig/event_display.py
      --inputFiles ../../reco_piM_50GeV_REC.edm4hep.root
```



CED viewer

Pandora Monitoring




```
. . .
<algorithm type = “LoopingTracks”/>
<algorithm type = "VisualMonitoring">
    <ShowCurrentClusters>true</ShowCurrentClusters>
</algorithm>
<algorithm type = “BrokenTracks”/>
<algorithm type = "VisualMonitoring">
    <ShowCurrentClusters>true</ShowCurrentClusters>
</algorithm>
<algorithm type = "ShowerMipMerging"/>
<algorithm type = "ShowerMipMerging2"/>
<algorithm type = "BackscatteredTracks"/>
<algorithm type = "BackscatteredTracks2"/>
<algorithm type = "ShowerMipMerging3"/>
<algorithm type = "ShowerMipMerging4"/>
<algorithm type = “ProximityBasedMerging”/>
. . .
```

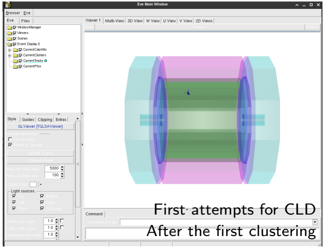
e.g. Add two event display algs to examine changes as reconstruction progresses

Advanced Particle Flow, 2017

PandoraMonitoring should be widely available in DBG Key4hep stack

```
source /cvmfs/sw-nightlies.hsf.org/key4hep/setup.sh -d
```

So far errors encountered, hopefully soon fixed (issue).



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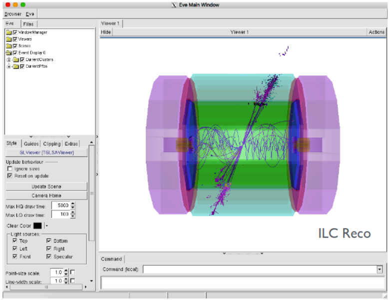


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ALLEGRO

Adaptation of Pandora to other detectors imposes certain additional implementations to the detector geometry (pseudo-layers): `DD4hep::rec::LayeredCalorimeterData` linking e.g. calorimeter depth with radiation length.
More details in S. Sasikumar, 3rd ECFA Workshop.

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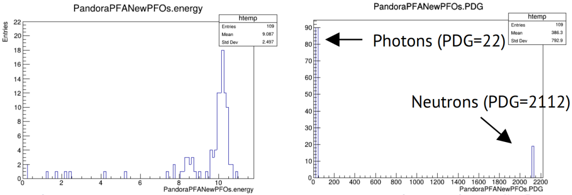
First proof-of-concept studies performed, show that (obviously) optimisation of Pandora parameters is needed.

Photon reconstruction seems to work somehow.

Needs work on track-cluster matching and possibly cluster reconstruction alternative to existing Pandora algorithm.



A. Durglishvili et al, PandoraPFA on ALLEGRO
similar results by F.Sopkova and J.Faltova

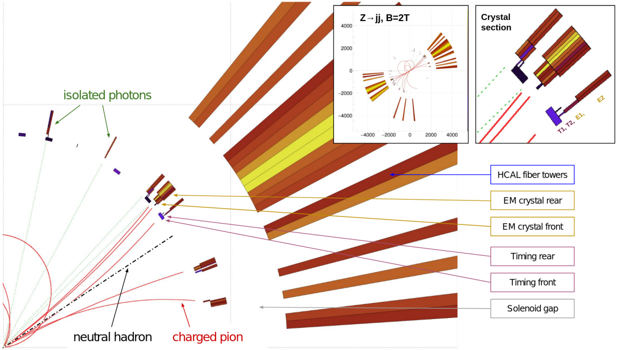
IDEA

Demonstration of the benefits of combining tracks with the calorimetry (particle flow): 2022 JINST 17 P06008 and L. Pezzotti, ECFA Higgs Factories, Feb 2022.

Crystals in front of the fibers provide good energy resolution for e, γ.

Good dual-readout jet energy resolution can be even more improved:
6.0% (calorimetry) $\rightarrow$ 4.5% (PF) for 45 GeV jets.

Implementation of the demonstrator not (yet) in the Key4hep software.



2022 JINST 17 P06008

Summary and next steps

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key4hep Pandora doc

(to be filled with detector-agnostic information that can be shared)

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As the group is growing, we will meet to catch up:
ZOOM room for weekly chats on Thursdays 15^{30} CERN time
and on Mattermost FCCSW team → High_level_reco channel.

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