Particle Flow Calorimetry

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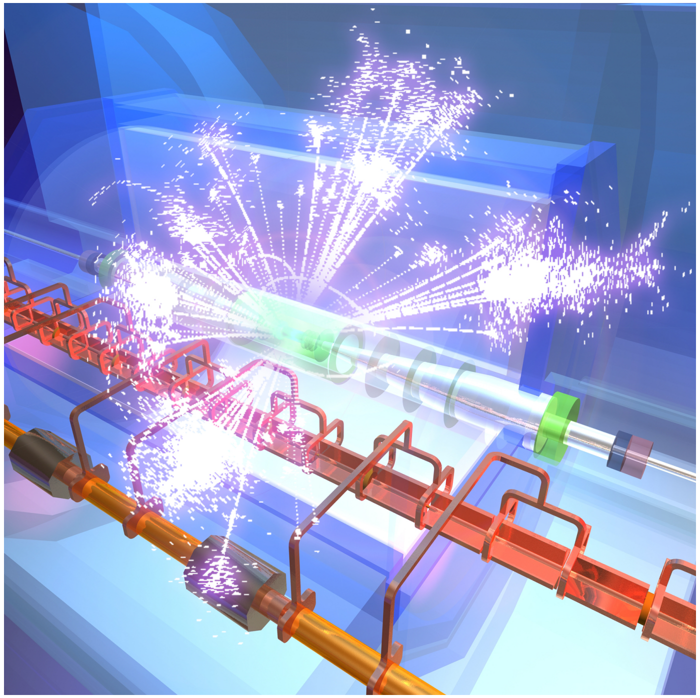


Overview

★ Task 2.3
★ Work described here from three groups
- Cambridge
  - framework
  - algorithm development/optimisation
- CERN
  - extensive validation
  - performance benchmarking
- LLR
  - algorithm development

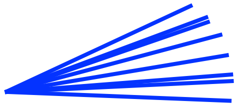
Will discuss

★ High Granularity Particle Flow Calorimetry refresher
★ Generalisation PandoraPFA as Framework/Toolkit
★ Use in CLIC and ILC
★ Applications to future neutrino physics
★ The Arbor algorithm

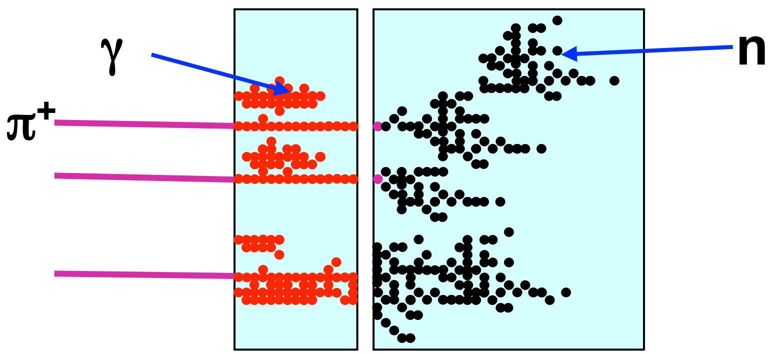
What is Particle Flow ?

Traditional Calorimetry

- **In a typical jet :**
  - 60 % of jet energy in charged hadrons
  - 30 % in photons (mainly from $\pi^0 \rightarrow \gamma\gamma$)
  - 10 % in neutral hadrons (mainly n and K_L)



- **Traditional calorimetric approach:**
  - Measure all components of jet energy in ECAL/HCAL !
  - ~70 % of energy measured in HCAL: $\sigma_{\mathrm{E}}/\mathrm{E} \approx 60\,\%/\sqrt{\mathrm{E(GeV)}}$
  - Intrinsically "poor" HCAL resolution limits jet energy resolution



$E_{JET} = E_{ECAL} + E_{HCAL}$

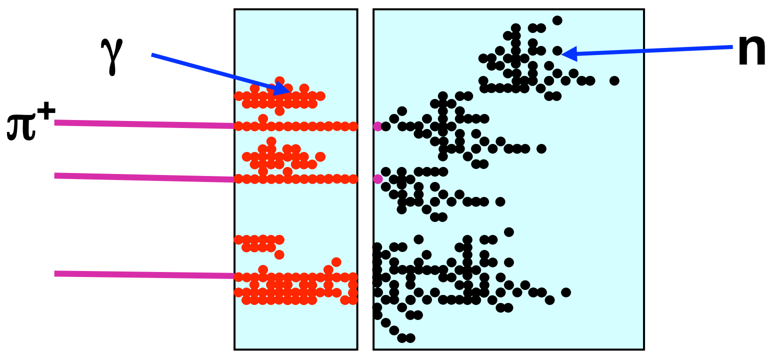
PFlow Paradigm

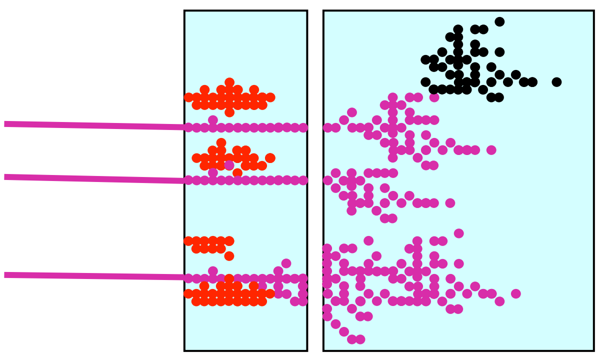
★ **Particle flow approach:**

- Try and measure energies of individual particles
- Reduce dependence on intrinsically "poor" HCAL resolution

★ **Idealised Particle Flow Calorimetry paradigm:**

- charged particles measured in tracker (essentially perfectly)
- Photons in ECAL:
- Neutral hadrons (ONLY) in HCAL
- Only 10 % of jet energy from HCAL ⇨ improved jet energy resolution

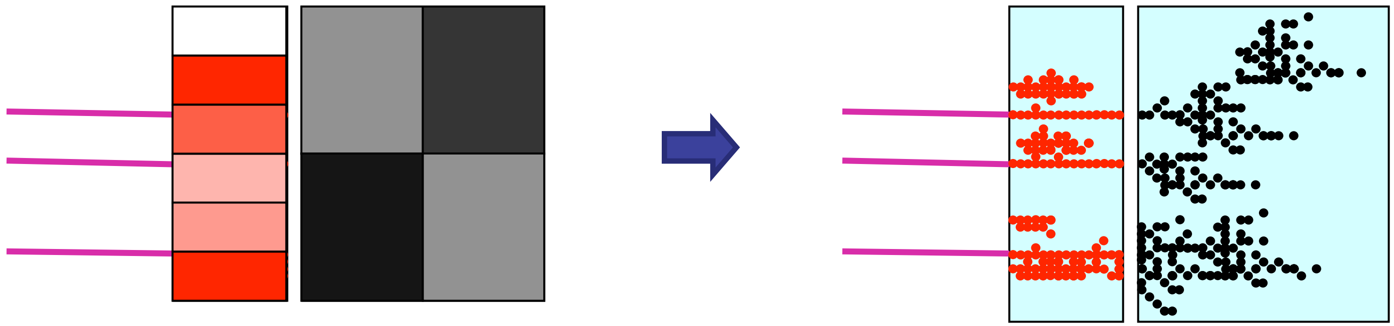




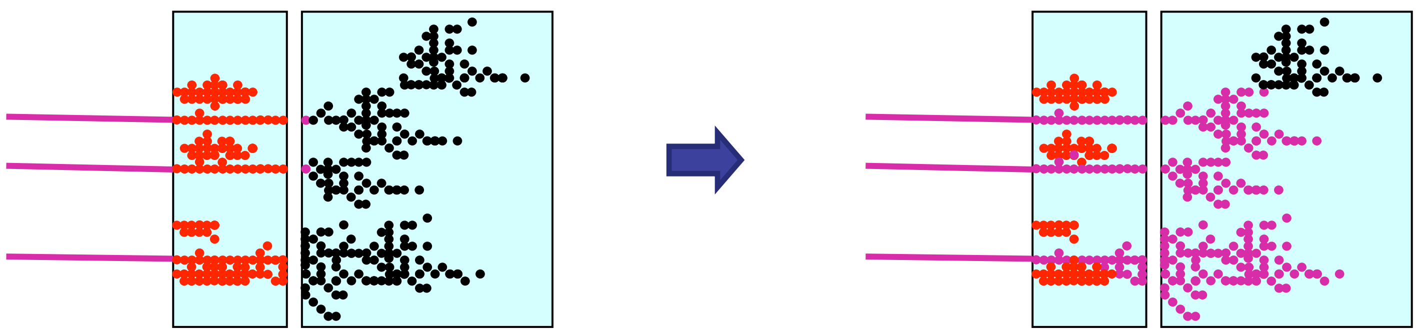
$E_{JET} = E_{ECAL} + E_{HCAL}$ ⇨ $E_{JET} = E_{TRACK} + E_{\gamma} + E_{n}$

Realising PFlow

Hardware: need to be able to resolve energy deposits from different particles
- Requires highly granular detectors (as studied by CALICE)



Software: need to be able to identify energy deposits from each individual particle
- Requires sophisticated reconstruction software



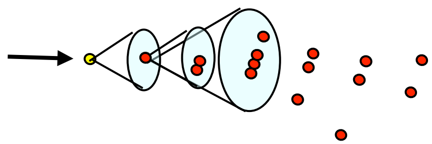
Particle Flow Calorimetry = HARDWARE + SOFTWARE

PandoraPFA

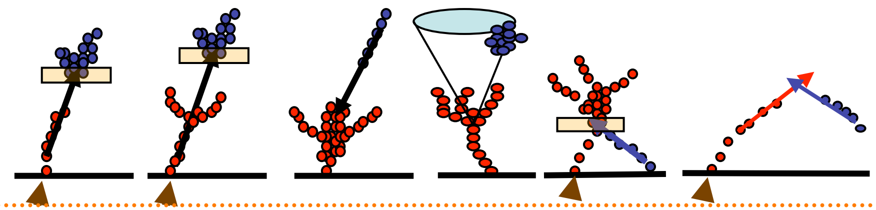
★ **High granularity Pflow reconstruction is highly non-trivial !**

PandoraPFA initially developed for the ILC detector studies

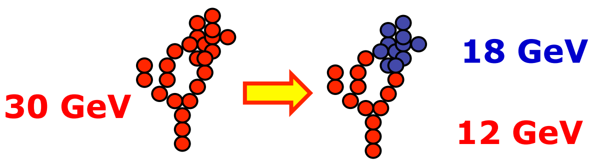
Clustering



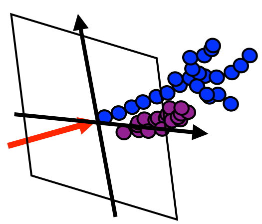
Topological Association



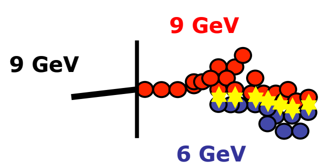
Iterative Reclustering

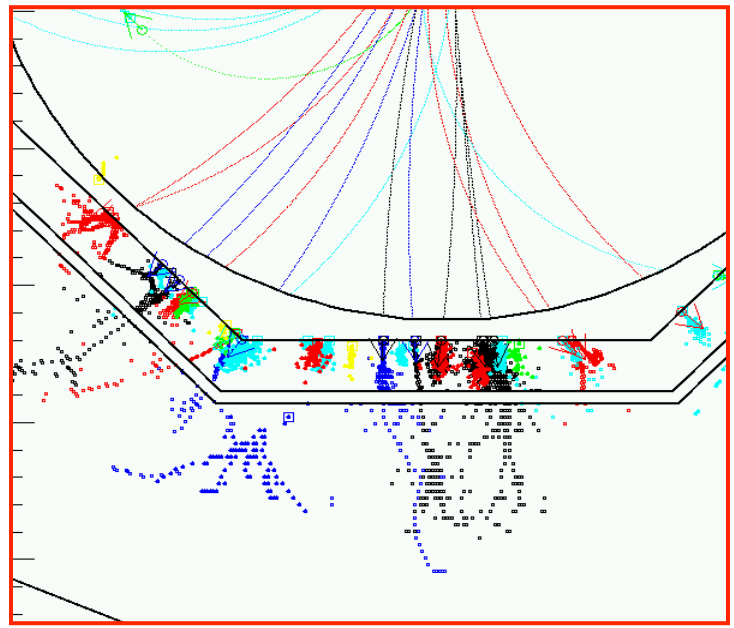


Photon ID



Fragment ID





For more details: MT, NIM 611 (2009) 24-40

The AIDA Work

PandoraPFA

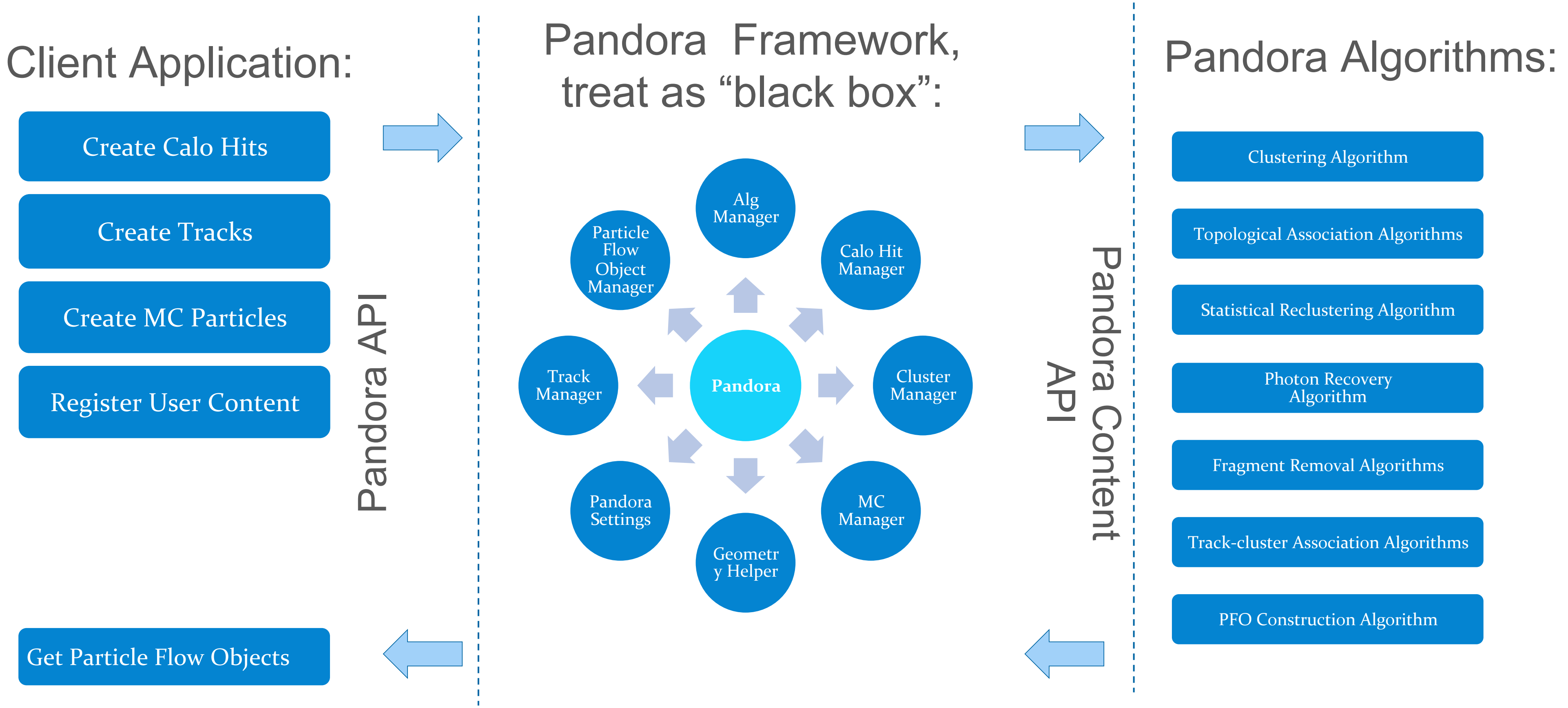
- ★ PandoraPFA initially very focussed on ILC reconstruction
- ★ Initially code developed in "physicist style"
  - resulted in single use-case unmanagable "rat's nest"
- ★ AIDA funded work has enabled this to be developed into a genuine Framework for particle flow

Redesign → **Implementation** → **Generalisation**

Software engineering | Coding | Development through multiple use cases

Framework

★ **PandoraPFA resdesigned as a framework**



★ **Highly optimised (CPU/memory footprint) framework**

★ **User code "Algorithms" separated from Framework code**

Generic Aspects

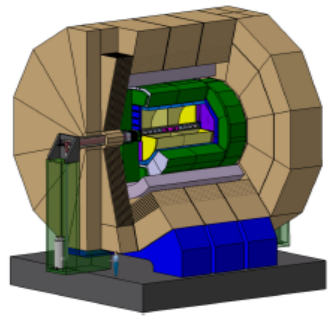
Designed to be Generic

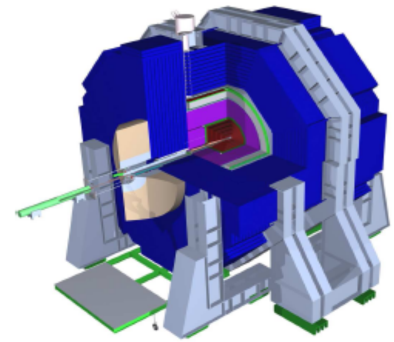
- ★ Stand-alone library accessed via APIs
  - "add calorimeter hit"
  - "add track"
  - "return particle flow objects"
- ★ Framework Aspects
  - deal with memory management
  - designed to be compact and very fast
  - runs Algorithms
  - supports external plug-ins (via APIs), e.g. algorithms, PID,…
- ★ No external dependencies !
  - 0 % root inside
- ★ No internal use of geometry information
  - e.g. hits are now self-defining (size, orientation)
  - hits know integrated material budget in front of them
- ★ Ships with separate visualisation library – internal event display

"Easily" adaptable to any detector

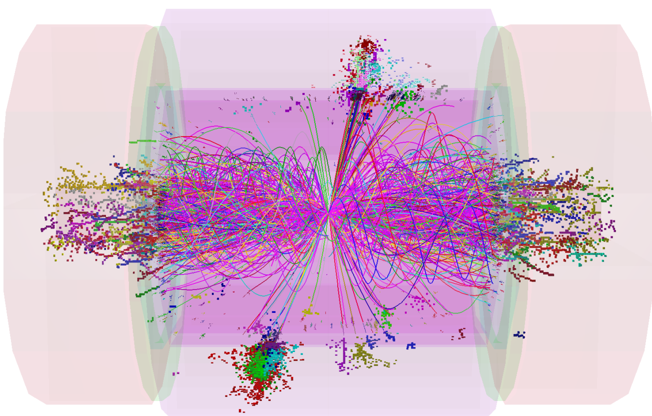
LC Usage

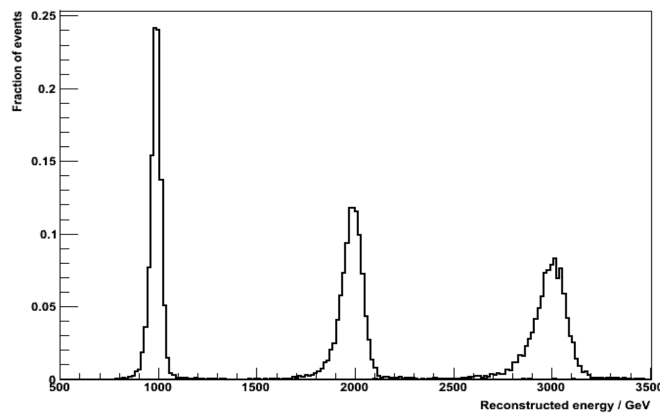
- ★ PandoraPFA used as workhorse for recent CLIC CDR and ILC TDR
- ★ All ful simulation physics studies based on PandoraPFA reconstruction !
- ★ Client applications written for two different detector concepts
  - + variants for CLIC





e.g. CLIC CDR





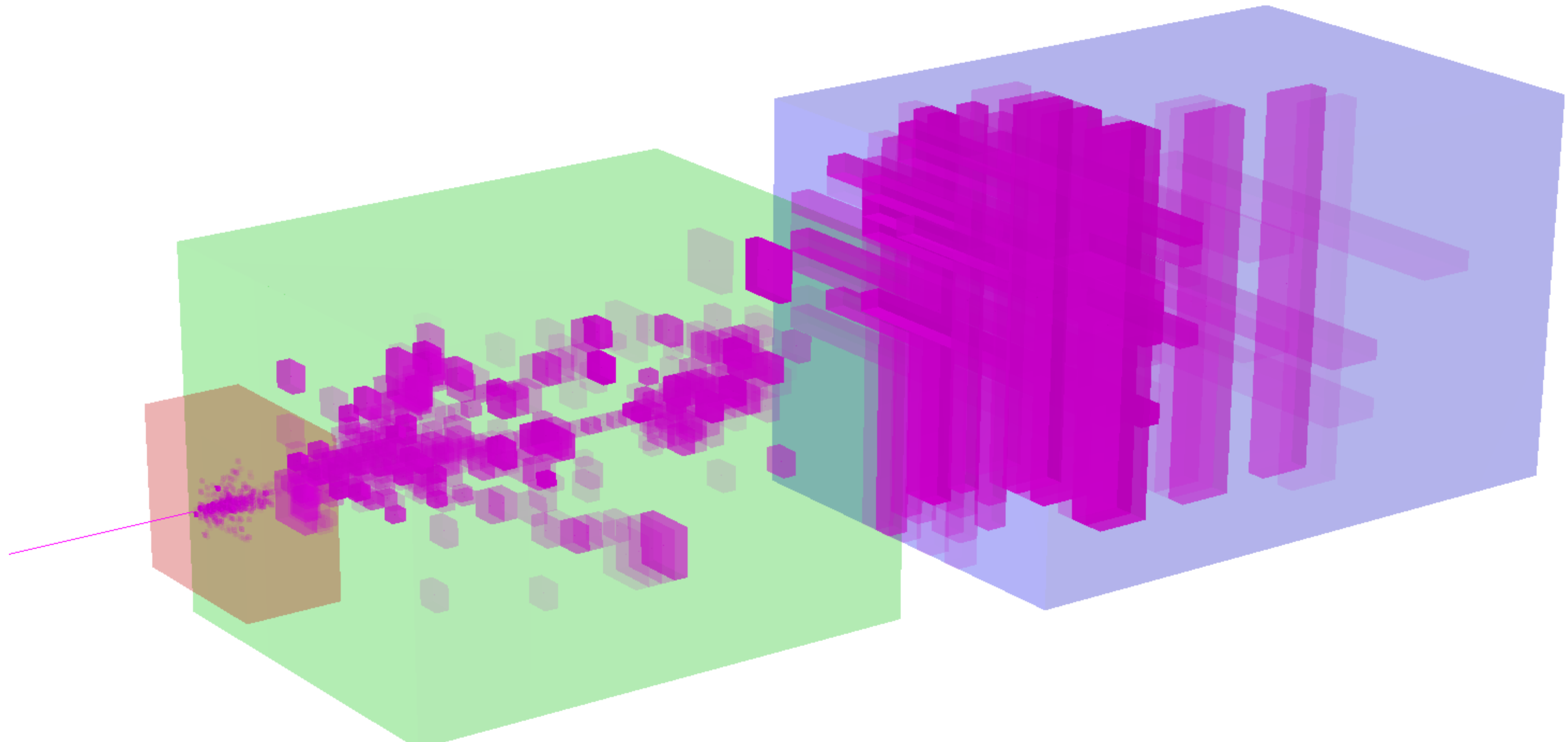
E_{JET}	RMS_{90}/E_J
45 GeV	3.6 %
100 GeV	2.9 %
250 GeV	2.8 %
500 GeV	3.0 %
1 TeV	3.2 %
1.5 TeV	3.2 %

Benchmark studies (Cambridge/CERN) published:

"Performance of particle flow calorimetry at CLIC", J.S. Marshall et al., NIM A 700, 2013, 153-162

CALICE application

★ **CERN developed client to PandoraPFA for CALICE test beam**
  e.g. 80 GeV pion test beam



★ **Worked out of the box…**

★ **"Generic" but this is an LC calorimeter prototype…**

AIDA Work Beyond the LC

Generalisation

- ★ Originally PandoraPFA tied to LC detector studies
- ★ Re implementation as a **framework** ⇒
  - greatly increased flexibility
  - part if AIDA project aims was to utilise this new flexibility
- ★ Now have 3 separate "content" libraries of algorithms
  - **Fine Granularity calorimetry** – e.g. LC detectors
  - **Coarse Granularity calorimetry** – e.g. LHC detectors
  - **Liquid Argon reconstruction** – Neutrino physics
- ★ New applications ⇒ making code more general
  - e.g. no assumptions about geometry
  - hits can be 2D or 3D (e.g. Liquid Argon TPC)
  - hits can be shared between clusters (e.g. ATLAS)

Neutrino Physics

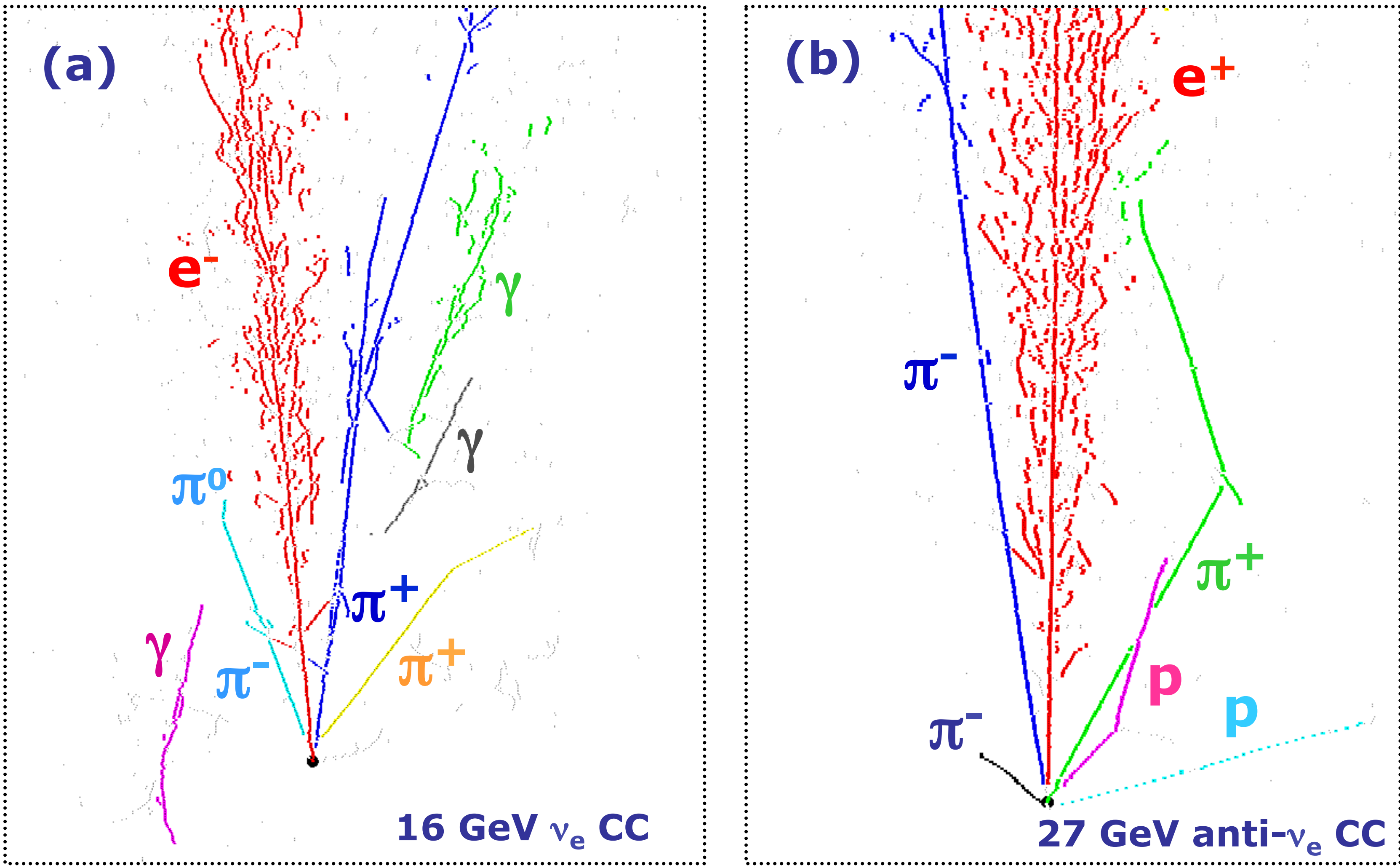
- ★ Liquid Argon TPCs likely to form basis of future neutrino oscillation experiments
- ★ Large volume detectors with ~1mm^3 granularity
  - i.e. **Fine Granularity calorimeters**
- ★ Long standing problem
  - lack of automated reconstruction software
    - non-trivial – large numbers of hits
    - applications often run into memory/CPU limitations

⇨ Optimised framework… PandoraPFA

- ★ Recently Cambridge developed initial set of Liquid Argon algorithms to plug into PandoraPFA framework
- ★ Work in progress, but generating interest in EU (**Laguna/LBNO**) and US (**LBNE**)

Eye Candy

★ No time for details… but a couple of example (well) reconstructed events…



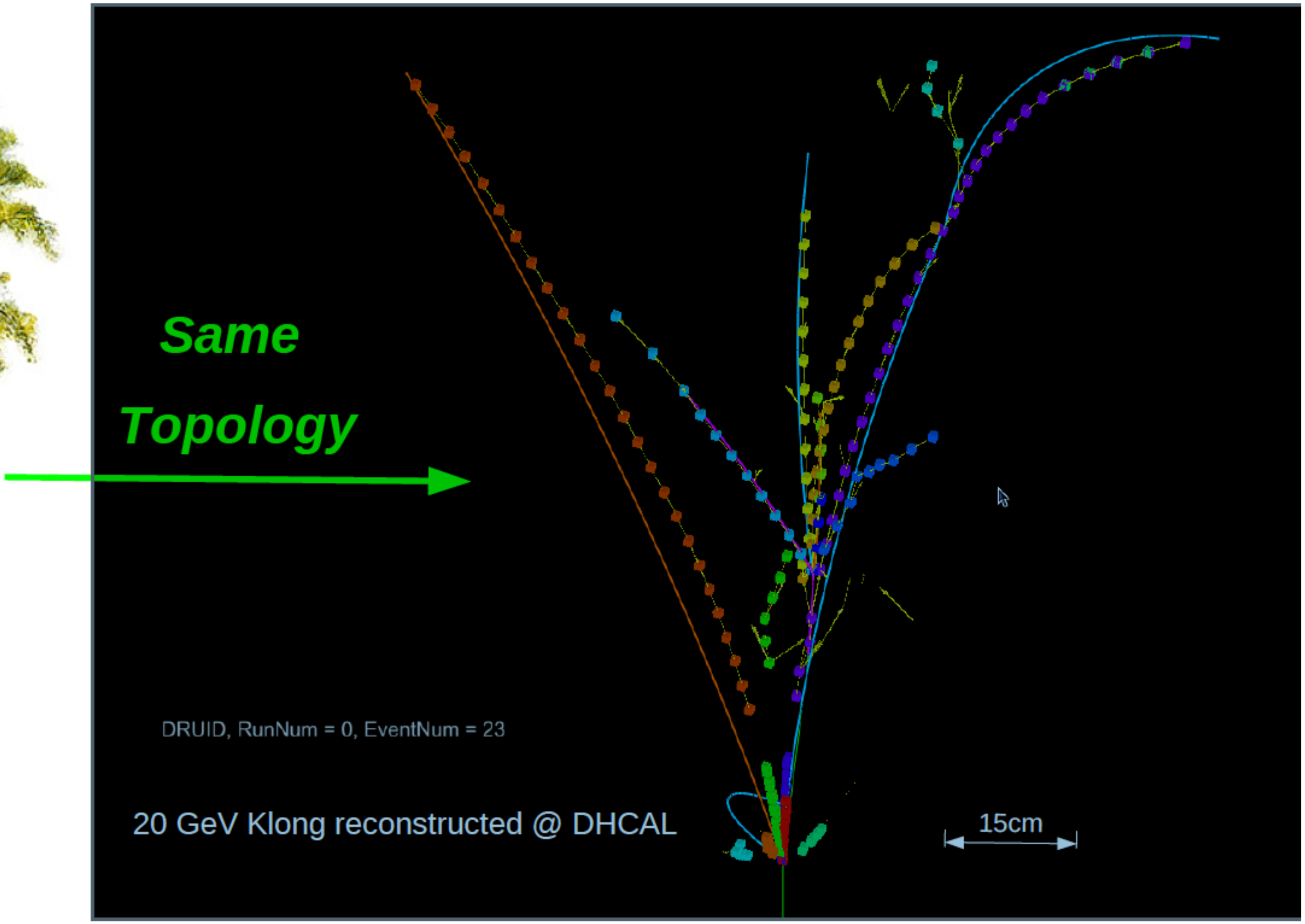
Algorithm Development at LLR

LLR Work

- ★ In parallel with PandoraPFA development/benchmarking (Cambridge/CERN)
- ★ LLR have been developing alternative Particle Flow Algorithms
  - focus on digital hadron calorimeter options for LC

⇨ **Arbor**

Arbor: shower/jet reco



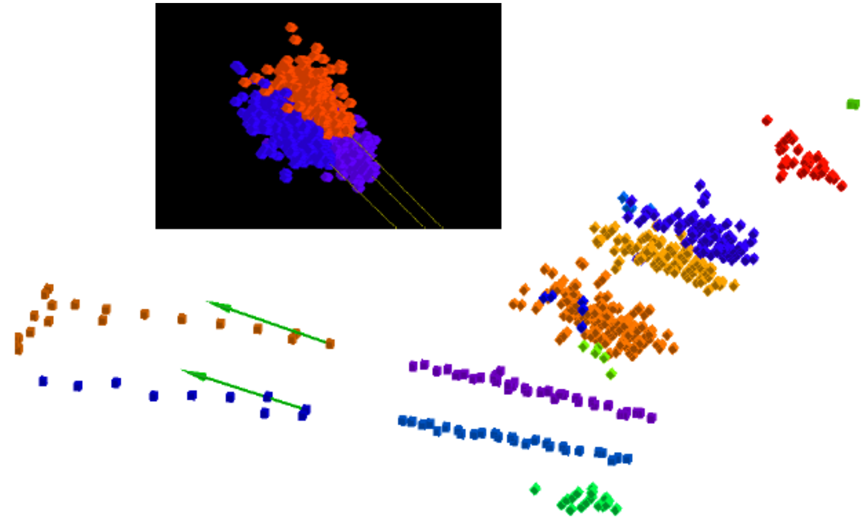
- Original idea from Henri Videau: Create local connectors, iterate until the final configuration satisfy a tree structure

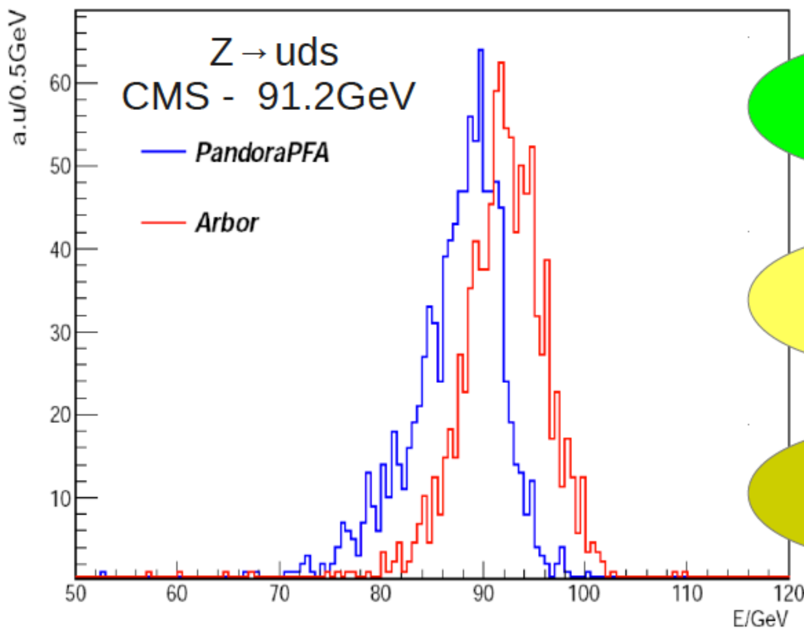
Arbor: PFA framework

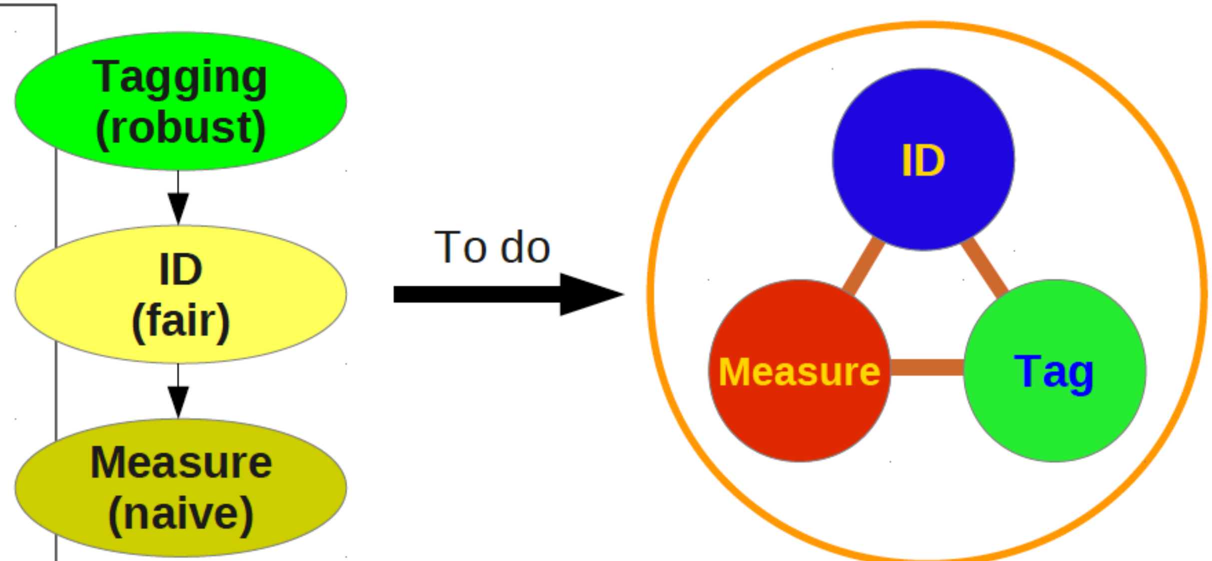
Arbor: good separation of nearby showers

Preliminary: ~ Pandora at jet energy measurement

Goal: precisely identify and measure every particle reaching calorimeter







Conclusions

Conclusions

★ **AIDA funded Particle Flow Calorimetry work is progressing well**

PandoraPFA framework, LC reimplementation, Neutrino physics, ATLAS (coming soon?)

LC benchmarking, CALICE application

Arbor algorithm

Next steps:

- ★ **Algorithm development**
  - **Full LAr reconstruction chain**
  - **Arbor development + possible integration into PandoraPFA**
  - **Application to LHC**
  - **Refinement of LC reconstruction + use in detector design/optimisation**