The Pandora Software Development Kit For Particle Flow Calorimetry

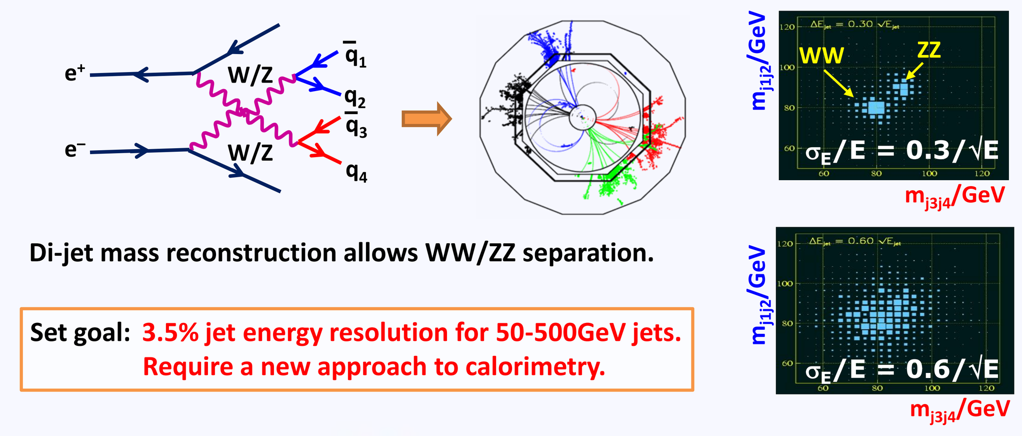
J.S. Marshall, M. A. Thomson

Cavendish Laboratory, University of Cambridge, J. J. Thomson Avenue, Cambridge, CB3 0HE, United Kingdom.

Particle Flow Calorimetry

Any future collider experiment designed for precise measurements requires very good jet energy resolution to maximise physics reach.

Oft-quoted example: $e^+e^- \to \nu\bar{\nu}W^+W^-$ vs. $e^+e^- \to \nu\bar{\nu}ZZ$

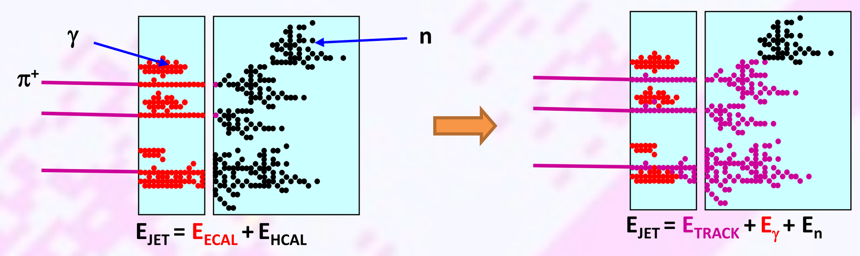


Di-jet mass reconstruction allows WW/ZZ separation.

Set goal: 3.5% jet energy resolution for 50-500GeV jets. Require a new approach to calorimetry.

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

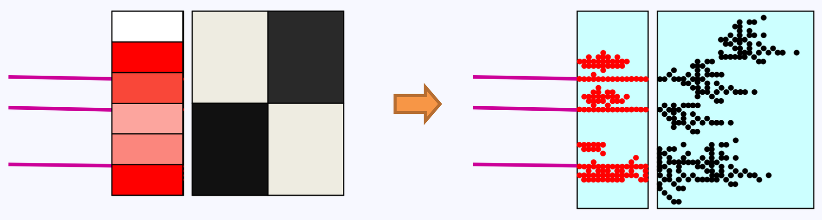
Traditional calorimetric approach:
- Measure all components of jet energy in ECAL/HCAL
- Approximately 70% of energy measured in HCAL: $\sigma_E/E \approx 60\%/\sqrt{E(GeV)}$

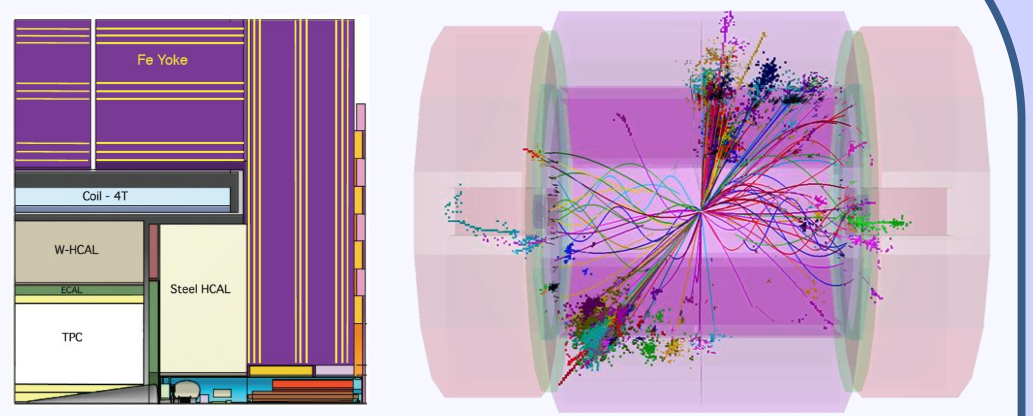


Particle Flow Calorimetry paradigm:
- Charged particle momentum measured in tracker (essentially perfectly)
- Photon energies measured in ECAL: $\sigma_E/E < 20\%/\sqrt{E(GeV)}$
- Only neutral hadron energies (10% of jet energy) measured in HCAL:
  $\Rightarrow$ Much improved jet energy resolution

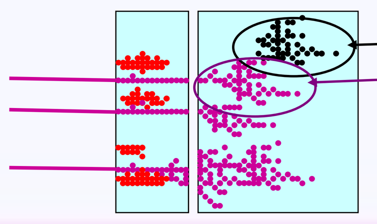
Realising Particle Flow

Particle flow calorimetry requires fine granularity detectors and sophisticated software:
- Hardware: need to be able to resolve energy deposits from different particles



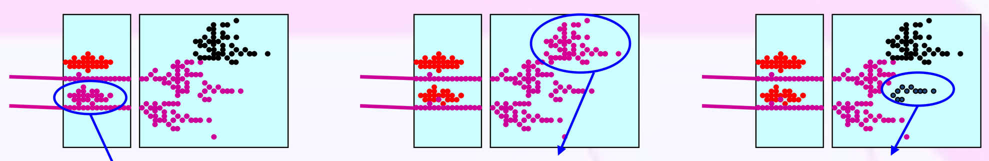


- Software: need to be able to identify energy deposits from each individual particle:
  - Avoid double counting of energy from same particle
  - Separate energy deposits from different particles



If these hits are clustered together with these, lose energy deposit from this neutral hadron (now part of track particle) and ruin energy measurement for this jet.

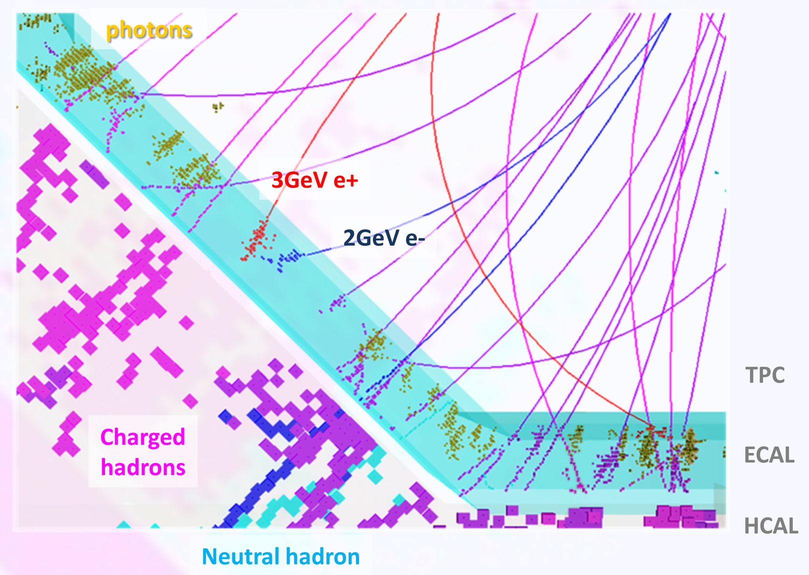
Level of mistakes, "confusion", determines jet energy resolution, not intrinsic calorimetric performance



Failure to resolve photons — Failure to resolve neutral hadrons — Reconstruct fragments as separate neutral hadrons

Detector Concept: ILD (International Large Detector)

Typical 250GeV Jet in ILD:

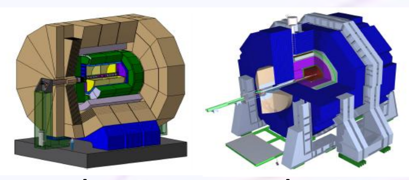


- Particle flow calorimetry demands high performance software. Need software solution allowing clean and efficient implementation of a large number of pattern recognition algorithms.
- Software framework and technology details not fixed for each detector concept, so particle flow software must be reusable, flexible and isolated from specific detector/framework details.
- Introduce Pandora C++ Software Development Kit.

Pandora SDK For Particle Flow

Non-reusable e.g. detector specific — External Content Libraries

Pandora Client Application — Isolates specific detector and software details, creating self-describing hits, tracks, etc.



ILD/Marlin — SiD/org.lcsim

Reusable, applicable to multiple detectors — Pandora Content Libraries: FineGranularity Content, CoarseGranularity Content

Register via APIs

Runs registered content and performs book-keeping

Pandora Framework: Algorithm Manager, CaloHit Manager, Cluster Manager, Tool Manager, Track Manager, PFO Manager

Calo Hit, Track, Cluster, Particle Flow Object

Structure allows for simultaneous development on multiple projects

API

Algorithms implement reconstruction strategy — Tools, used by multiple algorithms

Energy correction tools; Particle ID tools; Algorithms; Shower profile tools; Geometry and pseudolayer tools

All content registered by client and configured via xml

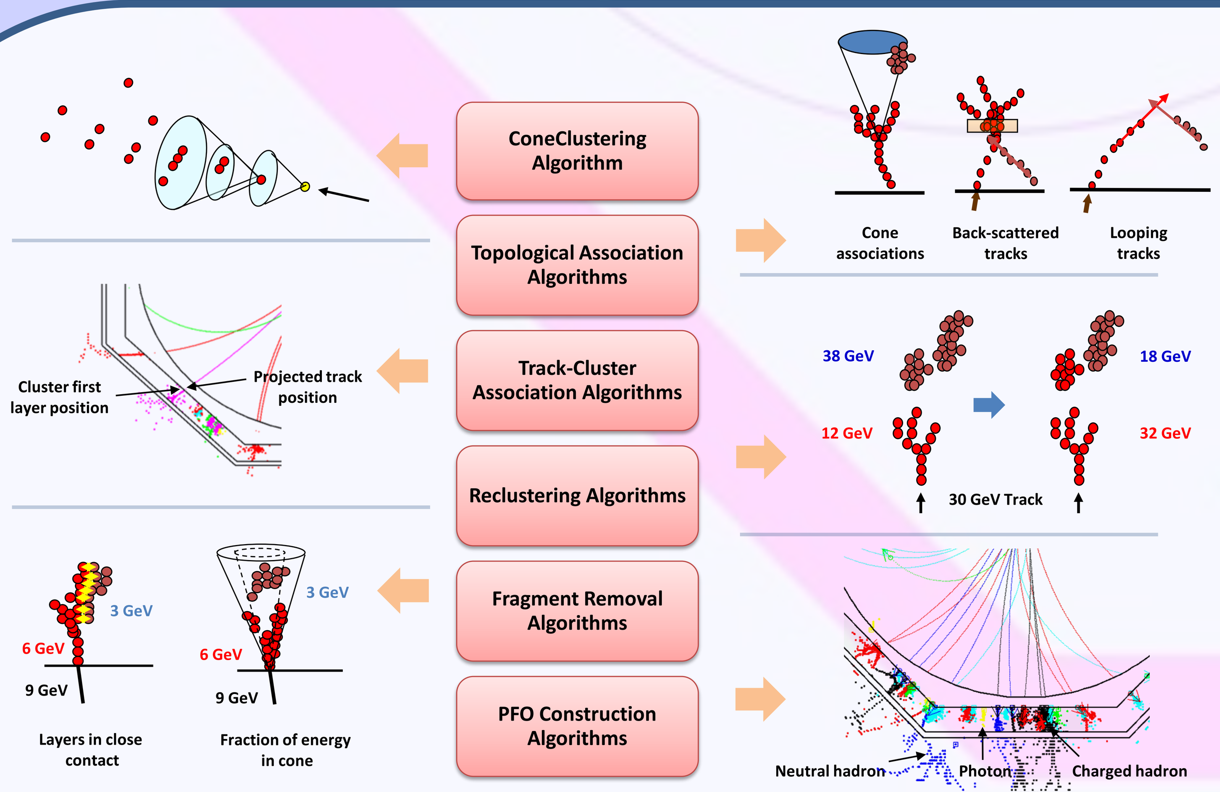
Client Application — Framework — Reconstruction Algorithms

- The Pandora C++ Software Development Kit (SDK) consists of a single framework library and a number of carefully designed Application Programming Interfaces (APIs).
- Pandora Client Applications can use the APIs to pass details of tracks and/or calo hits to the framework, which creates and manages named lists of self-describing objects.
- Pandora Algorithms then use APIs to access/manipulate the objects and perform the reconstruction. Allows algorithms to be small, physics-driven, and easy to maintain.
- The algorithms are xml-configured, reusable, and can be nested to perform complex tasks. They can also make use of Pandora Plugin Tools and Helper Functions.
- As the algorithms can only access and modify Pandora objects in a controlled manner, via APIs, the framework can perform book-keeping and memory-management.

https://svnsrv.desy.de/viewvc/PandoraPFANew

Pandora client applications are quick and easy to create, allowing rapid reuse of libraries containing over 60 pattern-recognition algorithms for application to fine-granularity detectors.

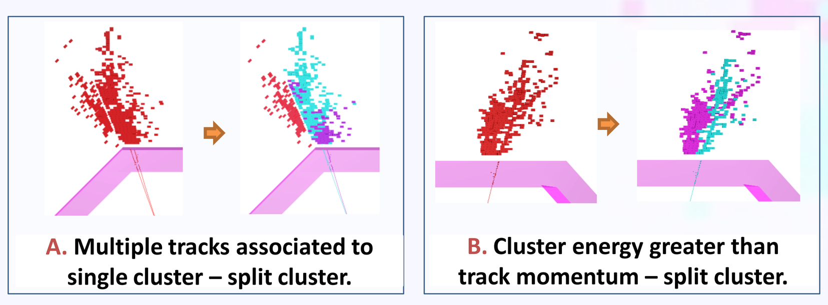
Pandora Algorithms



- Reconstruction of events in ILD uses over 60 different algorithms and tools.
- Begin with simple cone-based clustering algorithm to create seed clusters.
- Seeds intended to be fragments of single particles, rather than risk merging multiple particles.
- Fragments merged by series of algorithms, each following clear topological rules.
- Memory management and book-keeping provided by Pandora.

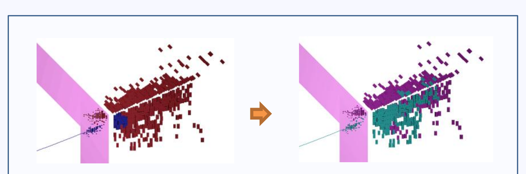
Example algorithm: Reclustering, to enforce consistency between inner detector tracks and associated calorimeter clusters. Note that algorithm simply needs to use services provided by Pandora framework, with no need to care about implementation details:

1. Ask for current lists of tracks and clusters, identify inconsistent track/cluster pairs and ask to recluster:
   - Relevant clusters moved to new temporary cluster list. Current hit/track lists changed.
2. Ask to run a clustering algorithm.
   - Creates another uniquely named temporary cluster list, filled by daughter clustering algorithm.
3. Calculate figure of merit for new track/cluster consistency.
4. Repeat stages 2. and 3. as required.
   - Can re-use original clustering algorithm, with different parameters, or try entirely new algorithms.
5. Choose most appropriate cluster(s).
   - All track/cluster lists will be updated accordingly.



A. Multiple tracks associated to single cluster – split cluster.

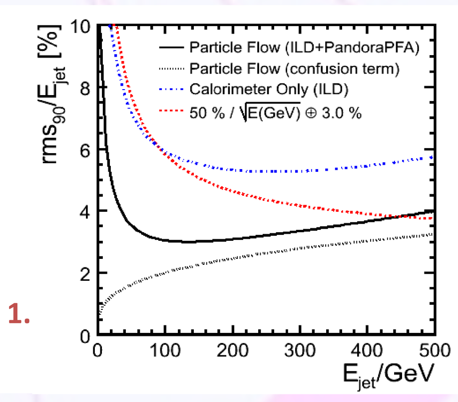
B. Cluster energy greater than track momentum – split cluster.



C. Track momentum greater than cluster energy – use nearby clusters and reconfigure.

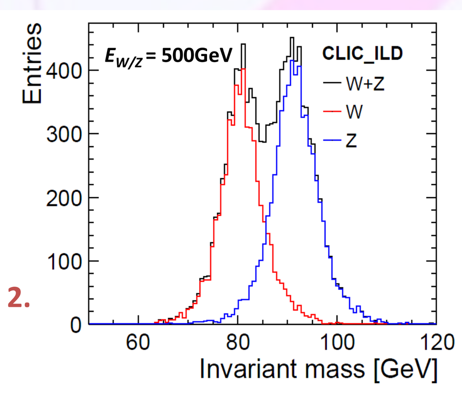
Pandora Performance

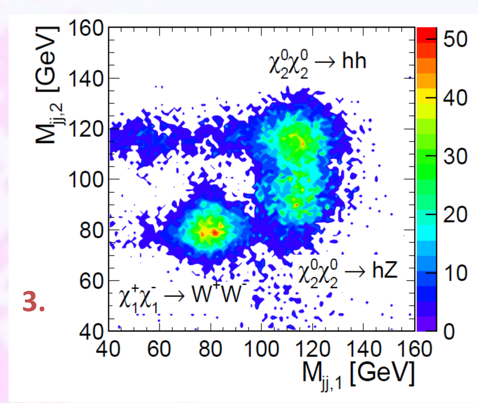
- Pandora algorithms provide the state of the art in particle flow calorimetry for the proposed International Linear Collider (ILC) and also in the challenging machine environment of the proposed Compact Linear Collider (CLIC).



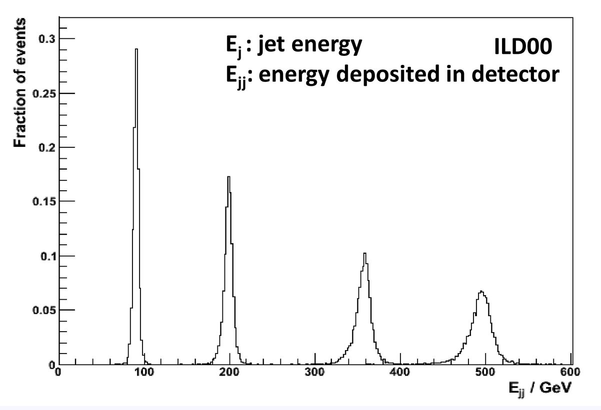
1. Pandora algorithms provide impressive jet energy resolution, always better than pure calorimetric approach.
2. Separation of W and Z bosons obtained using samples $e^+e^- \to WW \to \mu\nu qq$ and $e^+e^- \to ZZ \to \nu\nu qq$ *
3. Di-jet invariant mass allows separation of final states in study of Gaugino pair-production and decay.*

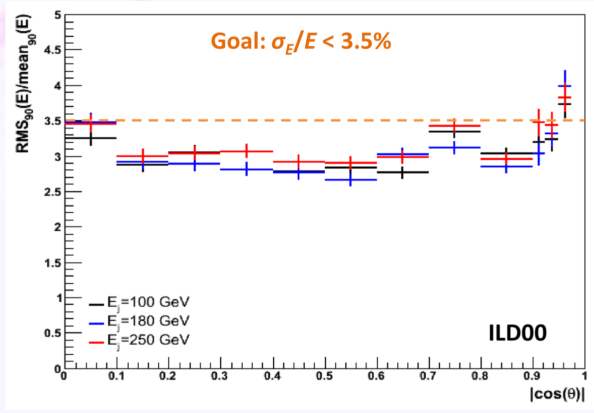
*Source: CLIC Conceptual Design Report (CDR)





- To quantify performance, use Z bosons decaying at rest into light quarks, producing back-to-back jets. Use fully reconstructed and simulated events, without backgrounds or jet finding, then analyse total reconstructed energy:





ILD00, E_j (= 2 * E_j)	91GeV	200GeV	360GeV	500GeV
$RMS_{90}(E_j)/mean_{90}(E_j)$ [%]	3.66 ± 0.05	2.86 ± 0.04	2.90 ± 0.04	3.02 ± 0.05

$$\frac{RMS_{90}(E_j)}{mean_{90}(E_j)} = \frac{RMS_{90}(E_{jj})}{mean_{90}(E_{jj})}\sqrt{2}$$