Particle Flow Calorimetry

J.S. Marshall, M.A. Thomson
University of Cambridge
Overview

1. $e^+e^-$ Physics and LC Jet Energy Requirements
2. Particle Flow Calorimetry
3. Pandora Particle Flow Reconstruction Algorithms
4. Particle Flow Performance at the ILC
5. Optimising ILC Detector Design
6. From ILC to CLIC Energies
7. Particle Flow Performance at CLIC
8. CLIC Benchmark Physics Analyses
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**e^+e^- Physics**

- Electron-positron colliders provide a clean environment for precision physics:
  - Precision studies/measurements:
    - Higgs sector, SUSY particle spectrum, SM particles (e.g. W, top) and much more.
  - Physics characterised by:
    - High Multiplicity final states, often 6/8 jets
    - Small cross-sections, e.g. $\sigma(e^+e^-\rightarrow ZHH) = 0.3\text{fb}$
  - Require high luminosity, i.e. ILC/CLIC
  - Require detector optimised for precision physics in multi-jet environment.
Comparison with LEP

**At LEP**
- Signal dominates: $e^+e^- \rightarrow Z$ and $e^+e^- \rightarrow W^+W^-$
- Backgrounds not too problematic
- Even for W mass measurement, jet energy resolution not too important

\[
\sum E_i = \sqrt{s} \\
\sum \vec{p}_i = 0
\]

**At ILC/CLIC**
- Backgrounds dominate interesting physics
- Kinematic fitting much less useful: Beamsstrahlung + many final states with $> 1$ neutrino

- Physics performance depends critically on detector performance (not true at LEP)
- Places stringent requirements on LC detectors
Any future collider experiment geared towards precise measurements requires very good jet energy resolution to maximise physics reach.

Oft-quoted example: \( e^+e^- \rightarrow \nu\bar{\nu}W^+W^- \) vs. \( e^+e^- \rightarrow \nu\bar{\nu}ZZ \)

Reconstruction of two di-jet masses discriminates between \( WW \) and \( ZZ \) final states.
LC Jet Energy Requirements

- Gauge boson width sets ‘natural’ goal for jet energy resolution:

  
  \[
  \begin{array}{|c|c|c|}
  \hline
  & LEP-like & 6\% & 3\% & 2\% & \text{Perfect} \\
  \hline
  \end{array}
  \]

  - Jet energies of interest determined by number of fermions in final states
  - At 500 GeV primarily interested in 4 and 6 fermion final states e.g. \(e^+e^- \rightarrow ZH \rightarrow q\bar{q}b\bar{b}\) and \(e^+e^- \rightarrow t\bar{t} \rightarrow b\bar{q}q\bar{b}\)
  - Fermion multiplicities will tend to increase with \(\sqrt{s}\), e.g. SUSY cascade decays

<table>
<thead>
<tr>
<th>Vs</th>
<th>#fermions</th>
<th>Jet energy</th>
</tr>
</thead>
<tbody>
<tr>
<td>250 GeV</td>
<td>4</td>
<td>~60 GeV</td>
</tr>
<tr>
<td>500 GeV</td>
<td>4 – 6</td>
<td>80 – 125 GeV</td>
</tr>
<tr>
<td>1 TeV</td>
<td>4 – 6</td>
<td>170 – 250 GeV</td>
</tr>
<tr>
<td>3 TeV</td>
<td>6 – 8</td>
<td>375 – 500 GeV</td>
</tr>
</tbody>
</table>

Goal: ~3.5 % jet energy resolution for 50 – 500 GeV jets
New approach to calorimetry needed
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 $\pi^0$ and $K_L$)

Traditional calorimetric approach:

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

Particle Flow Calorimetry paradigm:

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

$$E_{\text{JET}} = E_{\text{ECAL}} + E_{\text{HCAL}}$$
$$E_{\text{JET}} = E_{\text{TRACK}} + E_\gamma + E_n$$
Realising Particle Flow

**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
Particle Flow Algorithms

The challenge for particle flow algorithms:

- 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

Three types of confusion:

1. Failure to resolve photons
2. Failure to resolve neutral hadrons
3. Reconstruct fragments as separate neutral hadrons
ILC Detector Concepts

- Particle Flow must be studied in context of whole detector, e.g. tracking vital for reconstruction
- Need detailed GEANT 4 simulations of potential detector designs, e.g. ILC detector concepts

ILD: International Large Detector

- “Large” : tracker radius 1.8m
- B-field : 3.5 T
- Tracker : TPC
- Calorimetry : fine granularity particle flow
- ECAL + HCAL inside large solenoid

SiD: Silicon Detector

- “Small” : tracker radius 1.2m
- B-field : 5 T
- Tracker : Silicon
- Calorimetry : fine granularity particle flow
- ECAL + HCAL inside large solenoid
ECAL Considerations

- Want to minimise transverse spread of EM showers
  - Require small Molière radius
  - High transverse granularity \( \sim \) Molière radius

- Want to longitudinally separate EM and Hadronic showers
  - Require large ratio of \( \lambda_l/X_0 \)
  - Longitudinal segmentation to cleanly ID EM showers

<table>
<thead>
<tr>
<th>Material</th>
<th>( X_0/cm )</th>
<th>( \rho_M/cm )</th>
<th>( \lambda_l/cm )</th>
<th>( \lambda_l/X_0 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fe</td>
<td>1.76</td>
<td>1.69</td>
<td>16.8</td>
<td>9.5</td>
</tr>
<tr>
<td>Cu</td>
<td>1.43</td>
<td>1.52</td>
<td>15.1</td>
<td>10.6</td>
</tr>
<tr>
<td>W</td>
<td>0.35</td>
<td>0.93</td>
<td>9.6</td>
<td>27.4</td>
</tr>
<tr>
<td>Pb</td>
<td>0.56</td>
<td>1.00</td>
<td>17.1</td>
<td>30.5</td>
</tr>
</tbody>
</table>

- Favoured option: Tungsten absorber
  - Need ‘thin’ sensitive material to maintain small Molière radius
HCAL Considerations

- Want to resolve structure in hadronic showers
  ➢ Require **longitudinal** and **transverse** segmentation

- Want to fully contain hadronic showers
  ➢ Require small $\lambda_l$

- HCAL will be large, so absorber cost & structural properties will be important

<table>
<thead>
<tr>
<th>Material</th>
<th>$X_0$/cm</th>
<th>$\rho_M$/cm</th>
<th>$\lambda_l$/cm</th>
<th>$\lambda_l/X_0$</th>
</tr>
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- A number of technological options are being studied, e.g. by CALICE collaboration:
  CAlorimetry for the LLinear Collider Experiment
- Particle flow calorimetry demands **high performance software**. Need proper solution, allowing clean and efficient implementation of 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 (SDK)**. Consists of a framework library and carefully designed application programming interfaces (APIs).

- **Pandora client application** uses APIs to pass details of tracks and/or calo hits/cells to the framework, which creates and manages named lists of self-describing objects.

- The objects can be accessed by **Pandora algorithms**, which perform reconstruction. Algorithms are xml-configured, reusable, and can be nested to perform complex tasks.

- As algorithms only access Pandora objects in a controlled manner, via APIs, framework can perform book-keeping and memory-management operations: **separation of physics and C++!**

https://svnsrv.desy.de/viewvc/PandoraPFANew/
Pandora Client App

Non-reusable e.g. detector specific

- External Content Libraries
- Pandora Client Application
- Pandora Content Libraries

Runs registered content and performs book-keeping

- Pandora Framework
  - Algorithm Manager
  - CaloHit Manager
  - Cluster Manager
  - Plugin Manager, etc.

Isolates specific detector and software details, creating self-describing hits, tracks, etc.

Reusable, applicable to multiple detectors

- ILD/Marlin
- SiD/org.lcsim

Pandora content:
- algorithms, particle id functions, energy correction functions, shower profile calculators, etc...

FineGranularity Content
CoarseGranularity Content

John Marshall
Particle Flow Calorimetry
Pandora Algorithms

Pandora Framework

- Algorithm Manager
- CaloHit Manager
- Cluster Manager
- Plugin Manager, etc.

Owns named collections of Pandora objects: calo hits, tracks, clusters, PFOs.

Can perform memory management, as content can only be provided or accessed via APIs.

Pandora Algorithms

- Clustering Algorithms
- Cluster Merging Algorithms
- Track-Cluster Association Algs
- Fragment removal Algs, etc.

Use APIs to access Pandora objects and carry out particle flow reconstruction.

Physics-driven code, with nested structure promoting re-use of code to perform specific tasks.

Currently available: 56 algorithms for fine granularity detectors, including clustering, visualization, etc.
6 algorithms for reconstruction in coarse granularity detectors.
Electron, muon and photon id functions; pseudo-layer calculators, and more.
Pandora Algorithms

- ConeClustering Algorithm
- Topological Association Algorithms
- Track-Cluster Association Algorithms
- Reclustering Algorithms
- Fragment Removal Algorithms
- PFO Construction Algorithms

Layered structure and energy distribution in different particle categories.

- Neutrons
- Charged hadrons
- Photons
Cone Clustering

- Division of energy deposits into particles starts with simple cone-based clustering algorithm.
- 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.

![Diagram showing cone clustering algorithm]

**Simple cone-based clustering algorithm**

Cones based on either: initial direction or current direction
Topological Association

- **Pandora reconstruction philosophy:**
  - “It’s easier to put things together than to split them up.”

- Cone based clustering algorithm therefore errs on side of caution; 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.

- **Clear Associations:**
  - The fine granularity and tracking capabilities of the detector are exploited to join clusters that are clearly associated. Very few mistakes are made.

![Looping tracks](image1)

![Back-scattered tracks](image2)

![Cone associations](image3)
Topological Association

- **Clear Associations using cluster mip-segments:**
  - Local straight-line fits are performed to hits identified as mip-like and backwards/forward projections are used to identify associations. Tight matching criteria are applied.

  ![Diagram](image)
  - Track segment pointing to shower
  - Proximity
  - Track-like cluster points back to shower

- **Less clear associations:**
  - e.g. Small fragments removed, based on proximity to charged hadron clusters

  ![Diagram](image)
  - 7 GeV cluster
  - 6 GeV cluster
  - 4 GeV track

  Use E/p consistency to veto clear mistakes
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.

Track-track relationship information is also used:

- Kink (or Split)
  - $E = E_{\text{daughter}}$
  - $P = P_{\text{daughter}}$
  - $q = q_{\text{daughter}}$
  - $\text{PID} = \text{PID}_{\text{parent}}$

- Prong
  - $E = \sum E_{\text{good daughters}}$
  - $P = \sum P_{\text{good daughters}}$
  - $q = q_{\text{parent}}$
  - $\text{PID} = \text{PID}_{\text{parent}}$

- $V^0$
  - $E = \sum E_{\text{daughters}}$
  - $P = \sum P_{\text{daughters}}$
  - $q = \sum q_{\text{daughters}}$
  - $\text{PID}: \text{examine track PIDs}$

- $V^0$
  - $E = E_{\text{good daughter}}$
  - $P = P_{\text{good daughter}}$
  - $q = \sum q_{\text{both daughters}}$
  - $\text{PID}: \text{examine track PIDs}$

- Cluster associated with track
- Pass/fail track pfo selection cuts
Statistical Reclustering

- At some point, in high density jets (high energies), reach limit of “pure” particle flow.
- Cannot cleanly resolve neutral hadrons in hadronic showers.
- Use information from track-cluster associations to identify pattern-recognition problems:
  - Address the problem “statistically”; if we identify 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.

\[
\begin{align*}
\text{e.g. } 45 \text{ GeV track} & \quad \text{associated to } 95 \text{ GeV cluster:}
\end{align*}
\]

SOMETHING IS WRONG!

\[
\begin{align*}
\text{After topological associations} & \quad \text{Find } n \text{ absorbed into } \pi^- \text{ cluster}
\end{align*}
\]

\[
\begin{align*}
\text{Compare } E/p \text{ values to find problems}
\end{align*}
\]
Reclustering Strategies

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

2. Cluster energy much greater than track momentum – split cluster.

3. Track momentum much greater than cluster energy – bring in nearby clusters and reconfigure.
Fragment Removal

- Fragment removal algorithms aim to remove neutral clusters (no track-associations) that are really fragments of charged (track-associated) clusters. Relevant clusters are merged together.

- Look for evidence of association between nearby clusters. Evidence calculated as numerical score.
- Required evidence score also calculated, based on change in $E/p \chi^2$, location in calorimeters, etc.
- Clusters merged if collected evidence greater than required evidence. *Ad hoc*, but works well.
Particle Identification

- Identification of reconstructed particles crucial for many physics analyses. Accurate photon ID vital for accurate jet energy reconstruction in non-compensating calorimeters.
- Pandora offers a range of particle ID algorithms and reusable “fast ID functions” (registered by client application) to help identify photons and charged leptons.
- Some algorithms can perform dedicated reconstruction of specific particle types before standard reconstruction. Removal these particles from the event then helps to reduce confusion.

1. Cluster yoke hits
2. Associate to inner detector track
3. “Swim” through calorimeter

E.g. Muon reconstruction algorithm
Particle flow objects built from track and (associated) clusters using series of simple rules:

- Obtain a list of reconstructed and identified particles, with measured energies.
- Calorimeter energy resolution not critical – most energy from tracks.
- Level of mistakes in associating hits with particles dominates the jet energy resolution.

- Can now start to understand performance of a Particle Flow detector...
Jet Energy Resolution

- Assess performance of particle flow using fully simulated and reconstructed events. Use Zs at different energies decaying at rest into light quarks, producing two back-to-back jets.
- Backgrounds not included and no jet finding performed, to avoid bias. Instead, full energy deposited in the detector, $E_{jj}$, is analysed and resolution of jet energy, $E_j$, is extracted.

<table>
<thead>
<tr>
<th>ILD00, $E_z (= 2 \times E_j)$</th>
<th>91GeV</th>
<th>200GeV</th>
<th>360GeV</th>
<th>500GeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>RMS$<em>{90}(E_j)/$mean$</em>{90}(E_j)$ [%]</td>
<td>3.66 ± 0.05</td>
<td>2.86 ± 0.04</td>
<td>2.90 ± 0.04</td>
<td>3.02 ± 0.05</td>
</tr>
</tbody>
</table>

Goal: $\sigma_E/E < 3.5\%$
Understanding Particle Flow

- Implement set of algorithms that use MC information to cheat various aspects of particle flow.
- Switch some of standard reconstruction algorithms with MC versions to understand main performance drivers: resolution, confusion, ...

- **PerfectPhotonClustering**
  Hits from photons clustered using MC info and removed from main algorithm

- **PerfectNeutralHadronClustering**
  Hits from neutral hadrons clustered using MC info...

- **PerfectFragmentRemoval**
  After clustering, fragments from charged tracks identified from MC and added to correct track cluster

- **PerfectPFA**
  Perfect clustering and matching to tracks

- Also consider leakage (non-containment) of hadronic showers
Main performance driver varies with jet energy:

- Low energy jets: resolution
- High energy jets: confusion
- Cross-over at \( \sim 100 \text{ GeV} \)
- For high energies confusion dominates
- Very high energy jets: leakage important

Which kind of confusion?

1. Photons (\( \gamma \) merged into charged had. shower)
2. Neutral hadrons (\( K_L/n \) merged into charged had. shower)
3. Charged hadron fragments (reconstruct as neutral had.)

At high energies 2). is largest contributor, e.g. for 250 GeV jets:

<table>
<thead>
<tr>
<th>Component</th>
<th>Contribution</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Resolution</td>
<td>3.1 %</td>
</tr>
<tr>
<td>Confusion</td>
<td>2.3 %</td>
</tr>
<tr>
<td>1) Photons</td>
<td>1.3 %</td>
</tr>
<tr>
<td>2) Neutral hadrons</td>
<td>1.8 %</td>
</tr>
<tr>
<td>3) Charged hadrons</td>
<td>0.2 %</td>
</tr>
</tbody>
</table>

Not insignificant

Largest single contribution, but remember, enters in quadrature
PFA vs. Conventional Calorimetry

- ILD/SiD intended for PFA, but also good conventional calorimeters:
  - ECAL ~15%/\sqrt{E}
  - HCAL ~55%/\sqrt{E}

i) PandoraPFA: always wins over purely calorimetric approach

ii) PandoraPFA: effect of leakage clear at high energies

iii) PandoraPFA/ILD: Resolution better than 4 % for $E_{\text{JET}} < 500$ GeV
• Calorimeters and solenoid are the main cost drivers for a particle flow detector.

• Most important detector design considerations are:
  • B-field
  • $R$: inner radius of ECAL
  • $L$: length, equivalently aspect ratio $L/R$
  • ECAL and HCAL segmentation
  • HCAL thickness: number of interaction lengths

• Study jet energy resolution as a function of these cost critical issues

e.g. vary ECAL radius and B-field
B-field vs. Radius

\[
\frac{\sigma_E}{E} = \frac{21}{\sqrt{E/\text{GeV}}} \oplus 0.7 \oplus 0.004E \oplus 2.1 \left( \frac{R}{1825} \right)^{-1.0} \left( \frac{B}{3.5} \right)^{-0.3} \left( \frac{E}{100} \right)^{+0.3} \%
\]

- Confusion \( \propto B^{-0.3} R^{-1} \) (1/R dependence “feels right”, geometrical factor!)

Conclusions:

Detector should be fairly large

Very high B-field is less important
Consider jets in forward region:

- Performances improves with larger L, as expected
- But diminishing returns in going from 2.2 m → 2.9 m
- Conclude L = 2.2 m is reasonable for ILD
ECAL/HCAL Segmentation

HCAL tile size:
- 1x1 cm²
- 3x3 cm²
- 5x5 cm²
- 10x10 cm²

• In ILD detector model vary ECAL Si pixel size and HCAL tile size
Leakage and HCAL Depth

Leakage in coil region

<table>
<thead>
<tr>
<th>#HCAL Layers</th>
<th>$\lambda_1^{HCAL}$</th>
<th>$\lambda_1^{+ECAL}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>32</td>
<td>4.0</td>
<td>4.8</td>
</tr>
<tr>
<td>38</td>
<td>4.7</td>
<td>5.5</td>
</tr>
<tr>
<td>43</td>
<td>5.4</td>
<td>6.2</td>
</tr>
<tr>
<td>48</td>
<td>6.0</td>
<td>6.8</td>
</tr>
<tr>
<td>63</td>
<td>7.9</td>
<td>8.7</td>
</tr>
</tbody>
</table>

- Solid circles: use muon chambers as ‘tail-catcher’
- Open circles: no ‘tail-catcher’
From ILC to CLIC

- Compact Linear Collider provides potential for e^+e^- collisions up to \( \sqrt{s} = 3 \text{ TeV} \), but the machine environment is much more challenging than ILC:
  - Background levels are high
  - 0.5ns bunch structure means detectors integrate over multiple BX of background

---

Recently, significant effort made to complete CLIC Conceptual Design Report and Volume 2 “Physics and Detectors” now available:
- [https://edms.cern.ch/document/1180032](https://edms.cern.ch/document/1180032)
- Formal physics review, by a panel of experts, took place last October

- Main aim was to demonstrate possibility of precision physics measurements in CLIC environment. Second aim was to understand detector readout requirements, to guide future R&D.
- Required detailed simulation and reconstruction, including pile-up from background:
  - Build on existing work developed for ILC.
CLIC Machine Environment

<table>
<thead>
<tr>
<th></th>
<th>LEP 2</th>
<th>ILC 0.5 TeV</th>
<th>CLIC 0.5 TeV</th>
<th>CLIC 3 TeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>$L , [\text{cm}^{-2}\text{s}^{-1}]$</td>
<td>$5 \times 10^{31}$</td>
<td>$2 \times 10^{34}$</td>
<td>$2 \times 10^{34}$</td>
<td>$6 \times 10^{34}$</td>
</tr>
<tr>
<td>BX/train</td>
<td>4</td>
<td>2670</td>
<td>350</td>
<td>312</td>
</tr>
<tr>
<td>BX sep</td>
<td>247 ns</td>
<td>369 ns</td>
<td>0.5 ns</td>
<td>0.5 ns</td>
</tr>
<tr>
<td>Rep. rate</td>
<td>50 kHz</td>
<td>5 Hz</td>
<td>50 Hz</td>
<td>50 Hz</td>
</tr>
<tr>
<td>$L/BX , [\text{cm}^{-2}]$</td>
<td>$2.5 \times 10^{26}$</td>
<td>$1.5 \times 10^{30}$</td>
<td>$1.1 \times 10^{30}$</td>
<td>$3.8 \times 10^{30}$</td>
</tr>
<tr>
<td>$\gamma\gamma \rightarrow X / BX$</td>
<td>neg.</td>
<td>0.2</td>
<td>0.2</td>
<td>3.2</td>
</tr>
<tr>
<td>$\sigma_x/\sigma_y$</td>
<td>240 / 4 mm</td>
<td>600 / 6 nm</td>
<td>200 / 2 nm</td>
<td>40 / 1 nm</td>
</tr>
</tbody>
</table>

- Integrated luminosity per BX approximately same for ILC and CLIC
- Beam-related background:
  - Small beam-profile at IP leads to very high E-field
    - Beamstrahlung
    - Pair-background
    - Effects more significant at CLIC
- Bunch train structure:
  - BX separation 0.5ns
    - Integrate over multiple BXs of $\gamma\gamma \rightarrow \text{hadrons}$
    - 19TeV visible energy per 156ns bunch train

Drives timing Requirements for CLIC detector
CLIC Detector Modifications

- Detector requirements for CLIC:
  - All those for the ILC + timing
  - Optimised for CLIC backgrounds

- Starting point:
  - Validated ILC detectors, ILD and SiD
  - Fine granularity calorimetry:
    - Jet energy resolution
    - Improved background rejection

- Main modifications:
  - Location of vertex detector/beam pipe to account for increased backgrounds
  - Increased HCAL depth to contain showers; jet energy resolution studies: $7.5 \lambda_1$ HCAL
  - To maintain reasonable solenoid radius, use Tungsten as absorber in barrel
# CLIC Timing Strategy

1. **Input to reconstruction:**

<table>
<thead>
<tr>
<th>Subdetector</th>
<th>Reco Window</th>
<th>Hit Resolution</th>
</tr>
</thead>
<tbody>
<tr>
<td>ECAL</td>
<td>10 ns</td>
<td>1 ns</td>
</tr>
<tr>
<td>Fe HCAL EndCap</td>
<td>10 ns</td>
<td>1 ns</td>
</tr>
<tr>
<td>W HCAL Barrel</td>
<td>100 ns</td>
<td>1 ns</td>
</tr>
<tr>
<td>Si Detectors</td>
<td>10 ns</td>
<td>10/√12</td>
</tr>
<tr>
<td>TPC (CLIC_ILD)</td>
<td>Entire train</td>
<td>n/a</td>
</tr>
</tbody>
</table>

PandoraPFA

10ns of tracks

2. **Reconstructed particles, total energy 1.2 TeV:**

\[ e^+ e^- \rightarrow H^+ H^- \rightarrow \bar{t}b b\bar{t} \rightarrow 8 \text{ jets} \]

3. **Selected particles, total energy 85 GeV:**

Tighter timing cuts applied to cluster times (if low \(p_T\))
CLIC Benchmarks

- Performance of CLIC detectors in presence of background demonstrated in a number of benchmark analyses, plus accompanying technical studies at single physics object level.

- Benchmarks chosen to demonstrate aspects of detector performance:
  - Light Higgs (120 GeV)
  - Two SUGRA SUSY points with non-unified gaugino masses

- All studies use full simulation, full reconstruction and include $\gamma\gamma \rightarrow$ hadrons background
CLIC Resolution vs. Jet Energy

- Barrel region $|\cos \theta| < 0.7$, no background, no jet reconstruction:

- At lower energies, CLIC_ILD benefits from its larger radius.
- At higher energies, particle separation becomes more difficult; confusion term dominates energy resolution; particle flow can become energy flow. Both detectors similar performance.
One of the goals of PFA and fine granularity calorimetry is separation of $W$ and $Z$ bosons.

To study this separation, used samples $e^+e^-\rightarrow WW \rightarrow \mu\nu qq$ and $e^+e^-\rightarrow ZZ \rightarrow \nu\nu qq$

Mass distributions of reconstructed $W$ and $Z$ for CLIC_ILD at $E_{W/Z} = 500$GeV:

![Graph showing mass distributions for CLIC_ILD at $E_{W/Z} = 500$GeV for 00BX and 60BX samples.]
For the CLIC ILD detector model, consider $e^+e^- \rightarrow tt$ events at $\sqrt{s} = 3\text{TeV}$.

The simulated samples included both fully-hadronic and semi-leptonic final states: $\bar{t}t \rightarrow b(q\bar{q})\bar{b}(q\bar{q})$ (six jets) and $\bar{t}t \rightarrow b(q\bar{q})\bar{b}(l\nu)$ (four jets, lepton and missing energy).

**Mean efficiency without background:** 94% ± 1%
**Mean efficiency with background:** 94% ± 1%
CLIC Slepton Production

- Slepton production at CLIC very clean
- Use SUSY model II: slepton masses \(\sim 1\) TeV
- Channels studied include:
  - \(e^+e^- \rightarrow \tilde{\mu}_R^+\tilde{\mu}_R^- \rightarrow \mu^+\mu^- \tilde{\chi}_1^0\tilde{\chi}_1^0\)
  - \(e^+e^- \rightarrow \tilde{e}_R^+\tilde{e}_R^- \rightarrow e^+e^- \tilde{\chi}_1^0\tilde{\chi}_1^0\)
  - \(e^+e^- \rightarrow \tilde{\nu}_e\tilde{\nu}_e \rightarrow e^+e^- W^+W^- \tilde{\chi}_1^0\tilde{\chi}_1^0\)

- Acoplanar leptons and missing energy
- Masses from analysis of endpoints of energy spectra:

  - \(m(\tilde{\mu}_R) : \pm 5.6\) GeV
  - \(m(\tilde{e}_R) : \pm 2.8\) GeV
  - \(m(\tilde{\nu}_e) : \pm 3.9\) GeV
  - \(m(\tilde{\chi}_1^0) : \pm 3.0\) GeV
  - \(m(\tilde{\chi}_1^\pm) : \pm 3.7\) GeV
CLIC Gaugino Pair Production

- Test particle flow reconstruction of boosted low mass (EW scale) states in presence of background:
  \[ m(\tilde{\chi}_1^0) = 340 \text{ GeV} \quad m(\tilde{\chi}_2^0), m(\tilde{\chi}_1^+) \approx 643 \text{ GeV} \]

- Pair production and decay:
  \[ e^+e^- \rightarrow \tilde{\chi}_1^+\tilde{\chi}_1^- \rightarrow \tilde{\chi}_1^0\tilde{\chi}_1^0 W^+W^- \]
  \[ e^+e^- \rightarrow \tilde{\chi}_2^0\tilde{\chi}_2^0 \rightarrow hh \tilde{\chi}_1^0\tilde{\chi}_1^0 \quad 82 \% \]
  \[ e^+e^- \rightarrow \tilde{\chi}_2^0\tilde{\chi}_2^0 \rightarrow Zh \tilde{\chi}_1^0\tilde{\chi}_1^0 \quad 17 \% \]

- Largest BR decay has same topology for all final states:

- Separate using di-jet invariant mass.
CLIC Gaugino Pair Production

- Significant SM background, require multivariate Chargino and Neutralino event selections (BDT)
  - Invariant mass plays a central role in selections
- Chargino/Neutralino masses extracted from di-jet energy distributions

\[ m(\tilde{\chi}_1^\pm) : \pm 7 \text{ GeV} \]
\[ m(\tilde{\chi}_1^0) : \pm 10 \text{ GeV} \]

From sleptons used:
\[ m(\tilde{\chi}_1^0) : \pm 3 \text{ GeV} \]
Summary

1. Future $e^+e^-$ colliders will place unprecedented demands on calorimetry; jet energy resolutions must be 2-3 times better than achieved at LEP.

2. This requires a new approach to calorimetry, such as particle flow, which requires fine granularity detectors and sophisticated software algorithms.

3. The hardware is technologically feasible, as demonstrated by CALICE, and sophisticated (realistic?) software reconstruction tools are now available.

4. Pandora particle flow package is well established and well understood; it meets ILC jet energy goal and has played major role in optimising detector design.

5. ILC concepts are a good starting point for detectors at CLIC. Recent CDR demonstrates precision physics studies using particle flow in CLIC environment.
BACKUP
The idea behind particle flow calorimetry is not new, and a similar idea was used by ALEPH:

- **ENERGY FLOW** algorithm removes ECAL deposits from identified electrons/photons, leaving (mostly) charged and neutral hadrons.
- **Coarse HCAL granularity** means neutral hadrons can only be identified as significant excesses of energy. Neutral hadron energy obtained by subtraction: \( E_n = E_{\text{calo}} - p_{\text{track}} \)

Similar approach used by a number of other collider experiments, e.g. CMS

**PARTICLE FLOW** significantly extends this approach to a fine granularity calorimeter

- Now directly reconstruct neutral hadrons
- Potentially much better performance
- But need **fine granularity calorimeter and sophisticated** particle flow algorithms

\[ \sigma_E / E \sim 10\% \quad \text{jet E resolution for 45 GeV jets} \]

NIM A360:481-506, 1995
The Calice Collaboration is R&D group of around 280 physicists and engineers from around the world, working to develop new, high performance particle flow detectors for future high energy $e^+e^-$ experiments.

- Extensive test beam campaign:
  - 2 GeV to 80 GeV
  - Muons, $e^\pm$, $\pi^\pm$, unseparated hadrons
  - Different technologies (to date 2 ECAL, 2 HCAL, 1 TCMT)

- Opportunity to test Pandora with real data
Reclustering Implementation

Pandora framework designed to make reclustering process extremely simple and flexible:

1. Identify inconsistent pairing of track and cluster(s) and ask to recluster these.
   - 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 consistency of track and new cluster(s).

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 lists will be reorganised and tidied accordingly.

Clustering guided by track momentum; more powerful than subtraction (Energy Flow)

This is very important for higher energy jets
Particle Flow Performance

- Particle Flow Reconstruction inherently non-Gaussian, so resolution presented in terms of $\text{rms}_{90}$
  - Defined as “rms in smallest region containing 90% of events”
  - Introduced to reduce sensitivity to tails in a well-defined manner

- For a true Gaussian distribution, $\text{rms}_{90} = 0.79\sigma$

- However, this can be highly misleading:
  - Distributions almost always have tails
  - Gaussian usually means fit to some region
  - $G(\text{rms}_{90})$ larger than central peak from PFA

- MC studies to determine equivalent statistical power indicate that:

  $$\text{rms}_{90} \approx 0.9\sigma_{\text{Gaus}}$$

- Sensible convention, but does not mean PFA produces particularly large tails.
Physics Lists

• Modelling of hadronic showers far from perfect, so can we believe PFA results?
• Have tried to address this by comparing PandoraPFA/ILD performance for 5 very different Geant4 physics lists...

<table>
<thead>
<tr>
<th>Physics List</th>
<th>Jet Energy Resolution</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>45 GeV</td>
</tr>
<tr>
<td>LCPhys</td>
<td>3.74 %</td>
</tr>
<tr>
<td>QGSP_BERT</td>
<td>3.52 %</td>
</tr>
<tr>
<td>QGS_BIC</td>
<td>3.51 %</td>
</tr>
<tr>
<td>FTFP_BERT</td>
<td>3.68 %</td>
</tr>
<tr>
<td>LHEP</td>
<td>3.87 %</td>
</tr>
</tbody>
</table>

\[\chi^2\] \quad 23.3 / 4 \quad 17.8 / 4 \quad 16.0 / 4 \quad 6.3 / 4

\[\text{rms}\] \quad 4.2 % \quad 3.9 % \quad 3.5 % \quad 2.5 %

• Only a weak dependence < 5% (on the total, not just the hadronic confusion term)

Study suggests Particle Flow is rather robust to hadronic modelling
CLIC $\gamma\gamma \rightarrow$ hadrons Background

- Pair background largely affects very low angle region
- Background in calorimeters and central tracker dominated by $\gamma\gamma \rightarrow$ hadrons “mini-jets”
- At 3 TeV, average 3.2 events per BX (approximately 5 tracks per event)
- For entire bunch-train (312 BXs)
  - 5000 tracks (mean momentum 1.5 GeV) giving total track momentum : 7.3 TeV
  - Total calorimetric energy (ECAL + HCAL) : 19 TeV
- Largely low $p_T$ particles, but an irreducible background – it is physics

![20 BXs diagram]
CLIC Resolution vs. Angle

- No background, no jet reconstruction:

- Resolution for CLIC_SiD is worse in the forward region, due to reduced angular coverage. There is no HCAL coverage below $\theta = 15.5^\circ$.

- Resolution for CLIC_ILD dips in barrel/endcap overlap region, due to gap between ECAL barrel and endcap. Leakage effects due to this gap are more pronounced at higher energies.
CLIC Squark Production

• Light flavour squarks tend to be heaviest SUSY particles
  • Study in context of SUSY model I: $m_{\tilde{q}_R} = 1.123$ TeV
  • Simple topology: two high energy jets + missing energy

$$e^+ e^- \rightarrow \tilde{q}_R \tilde{q}_R \rightarrow q\bar{q} \tilde{\chi}_1^0 \tilde{\chi}_1^0$$

• Mass reconstructed from “edge” of “mass” distribution

$$M_C = (2E_1 E_2 + \mathbf{p}_1 \cdot \mathbf{p}_2)^{1/2}$$

• Main issue is large SM background, reduced using multivariate analysis: BDT

$$m_{\tilde{q}_R} : \pm 6 \text{ GeV}$$