Particle Flow Calorimetry

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These two lectures:

1. e^+e^- Collider Physics ↔ Calorimetry
2. The Particle Flow Paradigm
3. The ILD Concept
4. ILC Software
5. PandoraPFA
6. Understanding Particle Flow
7. How to design a PFlow detector
8. Potential at CLiC
9. Conclusions
**1 e^+e^- Physics ↔ Calorimetry**

★ Electron-positron colliders provide clean environment for precision physics

- **The LHC** \[ pp \rightarrow H + X \]
- **The ILC** \[ e^+e^- \rightarrow HZ \]

★ A detector at a future lepton collider (ILC/CLiC) will be designed to take full advantage of this clean environment
★ Very different detector design requirements c.f. LHC
e.g. ILC Physics

ILC PHYSICS:
Precision Studies/Measurements
★ Higgs sector
★ SUSY particle spectrum (if there)
★ SM particles (e.g. W-boson, top)
★ and much more...

Physics characterised by:
★ High Multiplicity final states
  often 6/8 jets
★ Small cross-sections, e.g.
  \[ \sigma(e^+e^- \rightarrow ZHH) = 0.3 \, fb \]

★ Require High Luminosity – i.e. the ILC/CLiC
★ Detector optimized for precision measurements in difficult multi-jet environment
**Compare with LEP**

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

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

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

★ Physics performance depends critically on the detector performance (not true at LEP)
★ Places stringent requirements on the ILC detector
ILC Calorimetry Goals

★ Aim for jet energy resolution giving di-jet mass resolution similar to Gauge boson widths

★ For a pair of jets have:

$$m^2 = m_1^2 + m_2^2 + 2E_1E_2(1 - \beta_1\beta_2 \cos \theta_{12})$$

★ For di-jet mass resolution of order $\Gamma_{W/Z}$

$$\frac{\sigma_m}{m} \approx \frac{2.5}{91.2} \approx \frac{2.1}{80.3} \approx 0.027$$

$\sigma_{E_j}/E_j < 3.8\%$

+ term due to $\theta_{12}$ uncertainty

★ Assuming a single jet energy resolution with normal stochastic term

$$\sigma_E/E = \alpha(E)/\sqrt{E(\text{GeV})}$$

$$\sigma_m/m \approx \alpha(E_j)/\sqrt{E_{jj}(\text{GeV})}$$

$$\alpha(E_j) < 0.027\sqrt{E_{jj}(\text{GeV})}$$

+ term due to $\theta_{12}$ uncertainty

★ Typical di-jet energies at ILC (100-300 GeV) suggests jet energy resolution goal of

$$\sigma_E/E < 0.30/\sqrt{E_{jj}(\text{GeV})}$$
Why is this important?

★ Direct impact on physics sensitivity, e.g. “WW-scattering”

If the Higgs mechanism is not responsible for EWSB then WW fusion processes important

\[ e^+e^- \rightarrow \nu\nu WW \rightarrow \nu\nu q\bar{q}q \]

Reconstruction of two di-jet masses allows discrimination of WW and ZZ final states

Best at LEP (ALEPH):

\[ \sigma_E/E = 0.6 (1+|\cos\theta_{\text{Jet}}|)/\sqrt{E(\text{GeV})} \]

ILC GOAL:

\[ \sigma_E/E = 0.3/\sqrt{E(\text{GeV})} \]
★ Want \[ \frac{\sigma_E}{E} < 0.30/\sqrt{E\text{(GeV)}} \] or more correctly \[ \frac{\sigma_E}{E} < 3.8\% \]

★ Very hard (may not be possible) to achieve this with a traditional approach to calorimetry

Limited by typical HCAL resolution of \( > 50\%/\sqrt{E\text{(GeV)}} \)

a new approach to calorimetry

- Particle Flow
- Dual Readout

Note: this level of performance wasn’t necessary at previous colliders
The Particle Flow Paradigm

★ 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: $\sigma_E/E \approx 60%/\sqrt{E}(\text{GeV})$
  ♦ Intrinsically “poor” HCAL resolution limits jet energy resolution

★ Particle Flow Calorimetry paradigm:
  ♦ Charged particles measured in tracker (essentially perfectly)
  ♦ Photons in ECAL: $\sigma_E/E < 20%/\sqrt{E}(\text{GeV})$
  ♦ Neutral hadrons (ONLY) in HCAL
  ♦ Only 10% of jet energy from HCAL → much improved resolution
Particle Flow Calorimetry

Hardware:
- Need to be able to resolve energy deposits from different particles
  - Highly granular detectors (as studied in CALICE)

Software:
- Need to be able to identify energy deposits from each individual particle!
  - Sophisticated reconstruction software

★ Particle Flow Calorimetry = HARDWARE + SOFTWARE
Particle Flow Algorithms (PFA)

Reconstruction of a Particle Flow Calorimeter:
★ Avoid double counting of energy from same particle
★ Separate energy deposits from different particles

e.g.

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 the intrinsic calorimetric performance of ECAL/HCAL

sounds easy….

★ PFA performance depends on detailed reconstruction
★ Relatively new, still developing ideas
★ Output of PFlow is a list of reconstructed particles
★ “Particle Flow Objects” PFOs
The ILD Detector Concept*

**NOTE:**
- Particle flow reconstruction involves “whole detector”
- To study potential performance need a detector model, tracking, calorimeters, ...

**ILC Detector Concepts:**
- Here performance of particle flow calorimetry shown in the context of the ILD detector concept for the ILC
- Detailed GEANT 4 detector model exists
- A potential design for an ILC detector
- Designed for Particle Flow calorimetry!

**ILD Main Features:**
- Large TPC central tracker (R=1.8 m)
- CMS like solenoid (B = 3.5 T)
- ECAL and HCAL inside solenoid
- ECAL/HCAL highly segmented for PFA
ILD calorimetry concept*

Very high longitudinal and transverse segmentation

ECAL:
- SiW sampling calorimeter
- Tungsten: $X_0/\lambda_{\text{had}} = 1/25$, $R_{\text{Mol.}} \sim 9\text{mm}$
  - Narrow EM showers
  - Longitudinal separation of EM/had. showers
- Longitudinal segmentation: 30 layers
- Transverse segmentation: $5 \times 5 \text{ mm}^2$ pixels

HCAL:
- Steel-Scintillator sampling calorimeter
- Longitudinal segmentation: 48 layers (6 interaction lengths)
- Transverse segmentation: $3 \times 3 \text{ cm}^2$ scintillator tiles

Comments:
★ Technologically feasible (although not cheap)
★ Ongoing test beam studies (CALICE collaboration)

*Other ILD calorimetry options being actively studied, e.g. RPC DHCAL, Scintillator strip ECAL
Calorimeter Reconstruction

- High granularity calorimeters – very different to previous detectors (except LEP lumi. calorimeters)
- "Tracking calorimeter" – requires a new approach to ECAL/HCAL reconstruction

Particle Flow Reconstruction

PFA calorimetric performance = HARDWARE + SOFTWARE

Performance will depend on the software algorithm
difficult to evaluate full potential
$\sigma_E/E = f(\text{software})$
★ There are no short cuts, fast simulation doesn’t help…

To evaluate Particle Flow Calorimetry at ILC:
need **realistic** reconstruction chain
>10 years before start of ILC !!!

★ But, as a result of a great deal of work within ILC detector community, we already have a first version…
ILD Software Framework (C++)

Everything exists – level of sophistication ~LEP experiment

G4 Simulation

Framework

Digitisation

Tracking

Vertexing

Flavour Tag

Clustering

Particle Flow

Physics Analysis

LCIO DATA

Mokka

MARLIN

Various Digitisers

Silicon Tracking

LEP TPC Tracking

FullLDCTracking

LCFI

VERTEX

PandoraPFA

...
Simulating an event

- **Physics Simulation**
  - Whizard
    - StdHep
      - Mokka
        - Icio
          - Marlin
            - Icio
              - "DstMaker"

- **Detector Simulation**
  - "Raw hits"

- **Reconstruction**
  - Tracks/Clusters
    - Tracks
    - Clusters
    - PFOs

### Existing data flow
- A lot of information carried around with final reconstructed event

### Reconstruction
- ~1 Mbyte/event
  - Tracks
  - Clusters
  - PFOs

### "DstMaker"
- ~10 kbyte/event?
  - Primary MC Particles

### Very easy to use
- Sufficient for some analyses
- Can always use detailed files
- VERY EASY TO USE
Marlin framework and reconstruction software available from web
Simple install script “IlcInstall”
Takes just a few hours to configure and then just run to get all software and associated packages

http://ilcsoft.desy.de/portal

This page serves as an entry point to common software packages developed for the International Linear Collider ILC.

The information resources needed to use the hosted projects for your ILC related study. In particular it has pointers to documentation, source code downloads and issue trackers. You can browse through existing projects on this portal by following the link to “Software Packages”.

If you want to create your own ILC related software package on this page please contact us at ilcsoft-portal@desy.de.

Every software package has a Wiki, where users can post relevant documents with documentation, howtos etc. (You also have to register to participate in the Wiki).

For questions and discussions on the various packages please use the

Linear Collider Forum

http://forum.linearcollider.org

Other resources for the ILC and simulation software

- ILC main website
- American ILC simulation homepage
- Asian ILC simulation homepage
5 PandoraPFA

Need “realistic” Particle Flow to evaluate potential of method (again no shortcuts)

New paradigm – nobody really knows how to approach this

So where are we now?

Significant effort in context of ILC detector design (~4 groups developing PFA reconstruction worldwide)

Concentrate on: PandoraPFA

This is still work-in-Progress – currently it gives the best performance

Will give an overview of the algorithm to highlight how particle flow reconstruction works
**PFA : Basic issues**

- Separate energy deposits from different particles
- Avoid double counting of energy from same particle
- Mistakes drive particle flow jet energy resolution

*e.g.*
- Need to separate “tracks” (charged hadrons) from photons

- Need to separate neutral hadrons from charged hadrons

**Hardware**
- **granularity**

**Software**
- PFlow Algorithm

![Diagram](image-url)

Isolated neutral hadron or fragment from shower?
PandoraPFA Overview

- ECAL/HCAL reconstruction and PFA performed in a single algorithm
- Fairly generic algorithm
  - applicable to multiple detector concepts
- Use tracking information to help ECAL/HCAL clustering

- This is a sophisticated algorithm: \(10^4\) lines of code

Eight Main Stages:

1. Track classification/extrapolation
2. Loose clustering in ECAL and HCAL
3. Topological linking of clearly associated clusters
4. Courser grouping of clusters
5. Iterative reclustering
6. Photon Identification/Recovery
7. Fragment removal
8. Formation of final Particle Flow Objects (reconstructed particles)
i) Tracking

- The use of optimal use of tracking information in PFA is essential
- Non trivial for looping tracks (even in a TPC)
- Matching of tracks to endcap clusters is non-trivial
- Use of track information is a major part of PandoraPFA
- Big effort to use as many tracks in the event as possible
  - helps particularly for lower energy jets
  - motivation I: better energy resolution
  - motivation II: correct measurement of direction

- TPC-oriented: take advantage of pattern recognition capability
  (the algorithm would need modification for Si tracker)

- From fully reconstructed LDC tracks identify:

  V\(^0\)s  Prongs  Kinks  Backscatters
e.g. Kinks

★ Kink finding extends to “loopers”

★ Can give a measure of missing energy
  - Consider physics hypothesis, e.g. $K^\pm \rightarrow \mu^\pm \nu$
  - Use Helix fits to start and end of tracks to reconstruct missing particle e.g. $\nu$
  - Can then reconstruct primary mass
  - If consistent with hypothesis, e.g. $m_K$ use primary track for PFO four-momentum

PandoraPFA reconstructs (some) neutrinos!
ii) ECAL/HCAL Clustering

- Start at inner layers and work outward
- Tracks can be used to “seed” clusters
- Associate hits with existing Clusters
- If no association made form new Cluster
- Simple cone based algorithm

Simple cone algorithm based on current direction + additional N pixels

Cones based on either:
- initial PC direction
- current PC direction

Parameters:
- cone angle
- additional pixels
iii) Topological Cluster Association

- By design, clustering errs on side of caution
  - i.e. clusters tend to be split
- Philosophy: easier to put things together than split them up
- Clusters are then associated together in two stages:
  - 1) Tight cluster association – clear topologies
  - 2) Loose cluster association – fix what’s been missed

★ Photon ID

- Photon ID plays important role
- Simple “cut-based” photon ID applied to all clusters
- Clusters tagged as photons are immune from association procedure – just left alone

Won’t merge

\[ \gamma \gamma \]

Won’t merge

\[ \gamma \]

Could get merged

\[ \gamma \gamma \]
Clusters associated using a number of topological rules

Clear Associations:
• Join clusters which are clearly associated making use of high granularity + tracking capability: very few mistakes

Less clear associations:

e.g. Proximity

Use E/p consistency to veto clear mistakes
Example: MIP segments

- Look at clusters which are consistent with having tracks segments and project backwards/forward (defined using local straight-line fits to hits tagged as MIP-like)

- Apply tight matching criteria on basis of projected track [NB: + track quality i.e. chi2]

- Here, association based on “tracking” in calorimeters
iv) Cluster Association Part II

- Have made very clear cluster associations
- Now try “cruder” association strategies
- BUT first associate tracks to clusters (temporary association)
- Use track/cluster energies to “veto” associations, e.g.

\[ |E_1 + E_2 - p| > 3 \sigma_E \]

This cluster association would be forbidden if \( |E_1 + E_2 - p| > 3 \sigma_E \)

Provides some protection against obvious mistakes
Proximity

Distance between hits: limited to first pseudo-layers of cluster

Shower Cone

Associated if fraction of hits in cone > some value

Shower start identified

+ Track-Driven Shower Cone

Apply looser cuts if have low E cluster associated to high E track
v) Iterative Reclustering

★ Upto this point, in most cases performance is good – but some difficult cases...

★ At some point hit the limit of “pure” particle flow
  • just can’t resolve neutral hadron in hadronic shower

The ONLY(?) way to address this is “statistically”

e.g. if have 30 GeV track pointing to 20 GeV cluster
SOMETHING IS WRONG
If track momentum and cluster energy inconsistent: RECLUSTER

e.g.

30 GeV

12 GeV

18 GeV

10 GeV Track

Change clustering parameters until cluster splits and get sensible track-cluster match

NOTE: NOT FULL PFA as clustering driven by track momentum

This is very important for higher energy jets
Iterative Reclustering Strategies

1. **Cluster splitting**
   - Reapply entire clustering algorithm to hits in “dubious” cluster. Iteratively reduce cone angle until cluster splits to give acceptable energy match to track.
   - ★ + plug in alternative clustering algorithms.

2. **Cluster merging with splitting**
   - Look for clusters to add to a track to get sensible energy association. If necessary iteratively split up clusters to get good match.

3. **Track association ambiguities**
   - In dense environment may have multiple tracks matched to same cluster. Apply above techniques to get ok energy match.

4. **“Nuclear Option”**
   - ★ If none of above works – kill track and rely on clusters alone.
vi) Photon ID/Recovery

- Use simple cut-based photon ID in the early (CPU intensive) stages of PandoraPFA
- In the final stages, use improved photon ID based on the expected EM longitudinal profile for cluster energy $E_0$

$$\Delta E = E_0 \frac{(t/2)^{a-1} e^{-t/2}}{\Gamma(a)} \Delta t$$

$$a = 1.25 + \frac{1}{2} \ln \frac{E_0}{E_c}$$

- Convert cluster into energy depositions per radiation length
  (use cluster to determine the layer spacing, i.e. geometry indep.)

- Shower Profile fixed by cluster energy
- But fit for best shower start, $s$
- Normalise areas to unity and calc.

$$f = \sum_i |o_i - e_i|$$

- Gives a measure of fractional disagreement in obs/exp profiles
- Use $f$ and $s$ to ID photons
Photon Recovery

★ With cone clustering algorithm, photons close to early showering charged hadrons can be merged into a single cluster.
★ Use longitudinal + transverse profile to recover these
★ Essentially, for each cluster associated with a track:
  • project ECAL hits onto plane perpendicular to radial vector to point where track intersects ECAL
  • search for peaks…

★ If there is an isolated peak not associated with “track peak” make new photon cluster if track energy and remaining cluster energy still statistically compatible with track momentum + cluster passes photonID
Use profiles to “dig out” photons overlapping with hadronic clusters:

- Also look for photons where only a single peak is found
- Implemented by looking at longitudinal profile of “shower”

NOTE: in PandoraPFA, photon identification is an “iterative”, rather than one-off process: different levels of sophistication applied at different stages of algorithm
viii) Fragment removal: basic idea

★ Look for “evidence” that a cluster is associated with another

- Distance of closest approach
- Layers in close contact
- Distance to track extrap.
- Fraction of energy in cone

★ Convert to a numerical evidence score $E$
★ Compare to another score “required evidence” for matching, $R$, based on change in $E/p$ chi-squared, location in ECAL/HCAL etc.
★ If $E > R$ then clusters are merged
★ Rather ad hoc but works well – but works well
Putting it all together...

- 100 GeV Jet

- Neutral hadron
- Charged hadron
- Photon

If it all works...
- Reconstruct the individual particles in the event.
- Calorimeter energy resolution not critical: most energy in form of tracks.
- Level of mistakes in associating hits with particles, dominates jet energy resolution.

End of Lecture 1
Aside: Analysing PFOs

★ Within Marlin software framework analysis is very easy:

```cpp
void ExampleDSTAnalysis::processEvent( LCEvent * evt ) {

typedef const std::vector<std::string> StringVec ;

// loop over collections in event
StringVec* strVec = evt->getCollectionNames() ;
for(StringVec::const_iterator name=strVec->begin(); name!=strVec->end(); name++){
    LCCollection* col = evt->getCollection(*name);

    // find the reconstructed particle flow object collection
    if(*name=="PandoraPFOs"){
        for(unsigned int i=0;i<nelem;i++){
            ReconstructedParticle* recoPart = dynamic_cast<ReconstructedParticle*>(col>getElementAt(i));
            // store PFOs in a vector for later analysis
            _pfovec.push_back(recoPart);
        }
    }
}

// e.g. to calculate total energy in event:
for(unsigned int i=0; i<_pfovec.size(); i++)e += _pfovec[i]->getEnergy();
```
6 Current performance

- Benchmark performance using $Z \rightarrow u\bar{u}$ and $Z \rightarrow d\bar{d}$ events (clean, no neutrinos)
- Test at for different energies with $Z$ decays at rest
- OPAL tune of Pythia fragmentation
- Full reconstruction (track + calo) using no Monte Carlo “cheat” information

NOTE:
- Quoting rms of reconstructed energy distribution is misleading
- Particle Flow occasionally goes very wrong $\Rightarrow$ tails dominate rms
- Conventional to measure performance using $\text{rms}_{90}$ which is relatively insensitive to tails
**Figures of Merit:**

- $\text{rms}_{90}$
  - Find smallest region containing 90% of events
  - Determine rms in this region

- $\sigma_{80}$
  - Fit sum of two Gaussians with same mean. The narrower one is constrained to contain 80% of events
  - Quote $\sigma$ of narrow Gaussian

It turns out that $\text{rms}_{90} \approx \sigma_{80}$

(need care when comparing to Gaussian resolution)
★ Slightlly confusing but necessary: energy distribution not Gaussian
★ To illustrate the point compare:
  - PFlow reconstructed energy distribution
  - Gaussian with raw of energy distribution
  - Gaussian with \( \text{rms}_{90} \)

★ NOTE: FWHM of distribution actually narrower than for \( \text{G}(\text{rms}_{90}) \)
Performance (ILD) \( Z \to d\bar{d}, Z \to u\bar{u} \)

| \( E_{\text{JET}} \) | \( \sigma_{E}/E = \frac{\alpha}{\sqrt{E_{jj}}} \frac{|\cos \theta|<0.7}{\sigma_{E}/E_j} \) |
|----------------|--------------------------------------------------|
| 45 GeV         | 23.8 %                                           |
| 100 GeV        | 29.1 %                                           |
| 180 GeV        | 37.7 %                                           |
| 250 GeV        | 45.6 %                                           |

- Full G4 simulation
- Full reconstruction

★ Particle flow achieves ILC goal of \( \sigma_{E}/E_j < 3.8 \% \)
★ For lower energy jets Particle Flow gives unprecedented levels of performance, e.g. @ 45 GeV : 3.5% c.f. ~10% (ALEPH)
★ “Calorimetric” performance (\( \alpha \)) degrades for higher energy jets
★ Current PFA code is not perfect – lower limit on performance

Proof of principle:

PARTICLE FLOW CALORIMETRY WORKS

At least in simulation
Understanding PFA Performance

What drives Particle Flow performance?

★ Try to use various “Perfect PFA” algorithms to pin down main performance drivers (resolution, confusion, ...)
★ Use MC to “cheat” various aspects of Particle Flow

PandoraPFA options:

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

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

- **PerfectFragmentRemoval**
  after PandoraPFA clustering “fragments” from charged tracks identified from MC and added to charged track cluster

- **PerfectPFA**
  perfect clustering and matching to tracks
<table>
<thead>
<tr>
<th>Contribution</th>
<th>45 GeV</th>
<th>100 GeV</th>
<th>180 GeV</th>
<th>250 GeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Calo. Resolution</td>
<td>3.1 %</td>
<td>2.1 %</td>
<td>1.5 %</td>
<td>1.3 %</td>
</tr>
<tr>
<td>Leakage</td>
<td>0.1 %</td>
<td>0.5 %</td>
<td>0.8 %</td>
<td>1.0 %</td>
</tr>
<tr>
<td>Tracking</td>
<td>0.7 %</td>
<td>0.7 %</td>
<td>1.0 %</td>
<td>0.7 %</td>
</tr>
<tr>
<td>Photons “missed”</td>
<td>0.4 %</td>
<td>1.2 %</td>
<td>1.4 %</td>
<td>1.8 %</td>
</tr>
<tr>
<td>Neutrals “missed”</td>
<td>1.0 %</td>
<td>1.6 %</td>
<td>1.7 %</td>
<td>1.8 %</td>
</tr>
<tr>
<td>Charged Frags.</td>
<td>1.2 %</td>
<td>0.7 %</td>
<td>0.4 %</td>
<td>0.0 %</td>
</tr>
<tr>
<td>“Other”</td>
<td>0.8 %</td>
<td>0.8 %</td>
<td>1.2 %</td>
<td>1.2 %</td>
</tr>
</tbody>
</table>

**Comments:**

- ★ For 45 GeV jets, jet energy resolution dominated by ECAL/HCAL resolution
- ★ Track reco. not a large contribution \((\text{Reco} \approx \text{CheatedTracking})\)
- ★ “Satellite” neutral fragments not a large contribution
  - efficiently identified
- ★ Leakage only becomes significant for high energies
- ★ Missed neutral hadrons dominant confusion effect
- ★ Missed photons, important at higher energies
Leakage

Two interesting questions:
★ How important is HCAL leakage?
  ▪ vary number of HCAL layers
★ What can be recovered using MUON chambers as a “Tail catcher”
  ▪ PandoraPFA now includes MUON chamber reco.
  ▪ Switched off in default version
  ▪ Simple standalone clustering (cone based)
  ▪ Fairly simple matching to CALO clusters (apply energy/momentum veto)
  ▪ Simple energy estimator (digital) + some estimate for loss in coil

e.g. 

The problem
HCAL Depth Results

- Open circles = no use of muon chambers as a “tail-catcher”
- Solid circles = including “tail-catcher”

\[ Z \rightarrow uds (|\cos\theta| < 0.7) \]

PandoraPFA v02-02

<table>
<thead>
<tr>
<th>Number of HCAL Layers</th>
<th>250 GeV Jets</th>
<th>180 GeV Jets</th>
<th>100 GeV Jets</th>
<th>45 GeV Jets</th>
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<tr>
<td>32</td>
<td>4.0</td>
<td>4.8</td>
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<td>48</td>
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<td>6.8</td>
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<td>63</td>
<td>7.9</td>
<td>8.7</td>
<td></td>
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</tbody>
</table>

ECAL: \( \lambda_i = 0.8 \)
HCAL: \( \lambda_i \) includes scintillator

- Little motivation for going beyond a 48 layer (6 \( \lambda_i \)) HCAL
- Depends on Hadron Shower simulation
- “Tail-catcher”: corrects ~50% effect of leakage, limited by thick solenoid

For 1 TeV machine “reasonable range” ~ 40 – 48 layers (5 \( \lambda_i \) - 6 \( \lambda_i \))
Optimisation of a Particle Flow detector

- Particle Flow Calorimetry lives or dies on ability to separate energy deposits from individual particles.
  - Large detector – spatially separate particles
  - High B-field – separate charged/neutrals
  - High granularity ECAL/HCAL – resolve particles

Might expect “figure-of-merit”:
\[
\frac{BR^2}{\sigma}
\]

Separation of charge/neutrals
Calorimeter granularity/R_{Moliere}

★ Argues for: large + high granularity + ↑ B
★ Cost considerations: small + lower granularity + ↓ B

Optimise detector parameters using PandoraPFA

Interpretation: observing effects of detector + imperfect software
**e.g. Radius vs. B-field**

**Cost drivers:**

- For Particle flow, ECAL and HCAL inside Solenoid
- Calorimeters and solenoid are the main cost drivers of an ILC detector optimised for particle flow
- Cost of calorimeters scales with active area
- Cost of solenoid scales with stored energy, (very approx.)

$$\$\$\$ \propto (B^2 R^2 L)^{0.66}$$

★ TPC radius and B-field play major role in total detector cost

- Study jet energy resolution as a function of B and R
PFA Optimisation: B vs Radius

★ Vary B and R

★ Empirically find

\[ \frac{\sigma_E}{E} = \frac{21}{\sqrt{E/\text{GeV}}} \pm 0.7 \pm 0.004E \pm 2.1 \left( \frac{R}{1825} \right)^{-1} \left( \frac{B}{3.5} \right)^{-0.3} \left( \frac{E}{100} \right)^{+0.3} \%
\]

★ Conclude:
  • R is more important than B for PFA performance
  • Confusion term \( \propto B^{-0.3}R^{-1} \)
  • 1/R makes sense – it’s just geometry
How important is segmentation?

- $3\times 3\, \text{cm}^2$ looks reasonable
- Hint of gain going to $1\times 1\, \text{cm}^2$
- Significant degradation for larger tile sizes, e.g. $5\times 5\, \text{cm}^2$

**Preliminary**
and ECAL Segmentation?

- Investigate 10×10mm², 20×20mm² and 30×30mm²
  - Note: retuned PandoraPFA clustering parameters

Performance is a strong function of pixel size
High ECAL segmentation is vital for PFA

Caveat:
- Remember results are algorithm dependent
- Could reflect flaw in reconstruction

Nevertheless: highly segmented HCAL/ECAL clearly essential
★ Particle Flow can deliver ILC jet energy goals
★ Whole detector concepts studied, and (partially) optimised e.g. ILD
★ What about Particle Flow for higher energy machines?
Particle Flow at CLIC

★ Particle Flow can deliver ILC jet energy goals
★ Detector concepts studied, and (partially) optimised
e.g. ILD
★ What about Particle Flow for CLIC?

STEP 1: take ILD and run...
General Considerations

★ Traditional calorimetry \( \sigma_E / E \approx 60\% / \sqrt{E/\text{GeV}} \)
★ Does not degrade significantly with energy (but leakage will be important at CLIC)
★ Particle flow gives much better performance at “low” energies
  ▪ very promising for ILC

What about at CLiC?
★ PFA perf. degrades with energy
★ For 500 GeV jets, current alg. and ILD concept:
  \( \sigma_E / E \approx 85\% / \sqrt{E/\text{GeV}} \)
★ Crank up field, HCAL depth…
  \( \sigma_E / E \approx 65\% / \sqrt{E/\text{GeV}} \)
★ Algorithm not tuned for very high energy jets, so can probably do significantly better

Conclude: for 500 GeV jets, PFA reconstruction not ruled out

<table>
<thead>
<tr>
<th>( E_{\text{JET}} )</th>
<th>rms90 ( \sigma_E / E = \alpha / \sqrt{E_{jj}} )</th>
<th>PandoraPFA v03-( \beta ) ( \sigma_E / E_j )</th>
</tr>
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<tbody>
<tr>
<td>45 GeV</td>
<td>23.8 %</td>
<td>3.5 %</td>
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<tr>
<td>100 GeV</td>
<td>29.1 %</td>
<td>2.9 %</td>
</tr>
<tr>
<td>180 GeV</td>
<td>37.7 %</td>
<td>2.8 %</td>
</tr>
<tr>
<td>250 GeV</td>
<td>45.6 %</td>
<td>2.9 %</td>
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<tr>
<td>500 GeV</td>
<td>84.1 %</td>
<td>3.7 %</td>
</tr>
<tr>
<td>500 GeV</td>
<td>64.3 %</td>
<td>3.0 %</td>
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</tbody>
</table>

63 layer HCAL (8 \( \lambda_l \))
\( B = 5.0 \text{ Tesla} \)
For 1 TeV jets, particle flow will not give $\sigma_E/E < 60%/\sqrt{E/\text{GeV}}$

This is probably not a problem for two reasons

i) Not interested in 1 TeV jets:
   - most interesting physics likely to be 6, 8, ... fermion final states
   - For 0.5 TeV jets, particle flow likely to be comparable or better than a traditional calorimetric approach

ii) A PFlow calorimeter still has good calorimetric resolution
    can design algorithm to move away from particle flow at higher energies

- Could be adapted on event, jet, locality basis
- Energy flow “trivial” to implement in PandoraPFA
- An adaptive algorithm should not be too difficult…

But, a particle flow detector is expensive: possible to justify cost?
Physics Considerations

★ Whether particle flow is appropriate for a multi-TeV e⁺e⁻ collider needs detailed study but depends on physics program, e.g.
  ◦ CLIC is unlikely to operate solely at the highest energy
  ◦ Likely to be a rich physics program below max. energy
    ▪ lower \( \sqrt{s} \) to study Higgs, SUSY threshold scans, etc.
    ▪ Here Particle Flow Calorimetry highly desirable

For high energy running what are the calorimetry goals ?
★ For ILC reasonably well defined, wish to separate W/Z
★ For CLIC, less clear and again depends on physics program
★ What is most important:
  • direct reconstruction of high mass particles
    ▪ What jet energy scale ? Not \( \sqrt{s}/2 \)
    ▪ For 6 fermion final states current PFA already competitive (ILD+)
    ▪ What mass resolution is needed ?
    ▪ For 1TeV particle, e.g. \( X \rightarrow q\bar{q} \) decaying at rest current PFA + ILD detector:
      \[ \frac{\sigma_m}{m_X} \sim 2.7\% \]
  • Missing transverse energy (i.e. \( p_T \)) resolution ?
  • W/Z separation ?
W/Z Separation at high Energies

★ On-shell W/Z decay topology depends on energy:

LEP \rightarrow ILC \rightarrow CLIC

A few comments:
- Particle multiplicity does not change
- Boost means higher particle density
- PFA could be better for “mono-jet” mass resolution

★ PandoraPFA + ILD performance studied for:

- 125 GeV Z
- 250 GeV Z
- 500 GeV Z
- 1 TeV Z
Study Z mass resolution as function of $E_Z$
with ILD detector (TPC based, B=3.5 T, 6 $\lambda_i$ HCAL)

$E_{qq} = 250$ GeV
$e^+e^-\rightarrow ZZ \rightarrow uu\bar{u}\bar{u}$
$(|\cos\theta_Z|<0.95)$
$rms_{90} = 2.8$ GeV

$E_{qq} = 500$ GeV
$e^+e^-\rightarrow ZZ \rightarrow uu\bar{u}\bar{u}$
$(|\cos\theta_Z|<0.95)$
$rms_{90} = 3.8$ GeV

$E_{qq} = 1$ TeV
$e^+e^-\rightarrow ZZ \rightarrow uu\bar{u}\bar{u}$
$(|\cos\theta_Z|<0.95)$
$rms_{90} = 5.9$ GeV

<table>
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<th>$\sigma_m/m$</th>
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<tr>
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<td>4.1 %</td>
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<tr>
<td>1 TeV</td>
<td>4.2 %</td>
<td>6.2 %</td>
</tr>
<tr>
<td>1.5 TeV</td>
<td>5.6 %</td>
<td>8.2 %</td>
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</table>
Conclusions

**Particle Flow at the ILC**

Now have a proof of principle of Particle Flow Calorimetry

Unprecedented Jet Energy Resolution

- Based on full simulation/reconstruction (gaps and all) of ILD detector concept

PFLOW drives design of ILC Detectors: ILD and SiD

**Particle Flow at CLIC**

Particle Flow Calorimetry certainly not ruled out

- Need to consider in context of the full CLIC physics programme - what drives jet energy resolution goals at CLIC?
- For Higgs + threshold studies, CLIC would be likely to run at lower energy: here there is a strong argument for PFA
- For mono-jet mass resolution, PFA may help at high energies (needs study)
- Perhaps surprisingly, ILD detector concept looks like it will give "OK" performance for 500 GeV jets and 1 TeV Zs: i.e. TPC, 3.5 T, 6 λᵢ
Thank you