Calorimetry and Particle Flow at the ILC

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This Talk:

1. ILC: Physics and Calorimetry
2. The Particle Flow Paradigm
3. ILC Detector (Calorimeter) Concepts
4. Particle Flow and ILC Detector Design
5. A Realistic(?) Particle Flow Algorithm
6. Recent Results
7. Conclusions
1 ILC Physics ↔ Calorimetry

ILC PHYSICS:
Precision Studies/Measurements
★ Higgs sector
★ SUSY particle spectrum
★ 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
★ Detector optimized for precision measurements
  in difficult multi-jet environment
Compare with LEP

- $e^+e^- \rightarrow Z$ and $e^+e^- \rightarrow W^+W^-$ dominate backgrounds not too problematic
- Kinematic fits used for mass reco.
good jet energy resolution not vital

At the ILC:
- Backgrounds dominate ‘interesting’ physics
- Kinematic fitting much less useful (Beamsstrahlung)

Physics performance depends critically on the detector performance (not true at LEP)
Stringent requirements on the ILC detector
Calorimetry at the ILC

Jet energy resolution:

Best at LEP (ALEPH):
$$\sigma_E/E = 0.6(1+|\cos\theta_{\text{Jet}}|)/\sqrt{E(\text{GeV})}$$

ILC GOAL:
$$\sigma_E/E = 0.3/\sqrt{E(\text{GeV})}$$

★ Jet energy resolution directly impacts physics sensitivity

Often-quoted Example:
If the Higgs mechanism is not responsible for EWSB then QGC processes important
$$e^+e^-\rightarrow \nu\nu WW\rightarrow \nu\nu qq qq, e^+e^-\rightarrow \nu\nu ZZ\rightarrow \nu\nu qq qq$$

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

★ EQUALLY applicable to any final states where want to separate $W\rightarrow qq$ and $Z\rightarrow qq$!
The Particle Flow Paradigm

★ Much ILC physics depends on reconstructing invariant masses from jets in hadronic final states
★ Often kinematic fits won’t help – Unobserved particles (e.g. ν) + Beamstrahlung, ISR
★ Aim for jet energy resolution ~ Γ_Z for “typical” jets - the point of diminishing return
★ Jet energy resolution is the key to calorimetry at the ILC
★ Generally (but not uniformly) accepted that PARTICLE FLOW is the only way to achieve \( \sigma_E/E \sim 0.3/\sqrt{E(\text{GeV})} \)

The Particle Flow Analysis (PFA):

• Reconstruct momenta of individual particles avoiding double counting

\[ e^\pm, \gamma, \mu^\pm, \pi^\pm \text{ etc.} \]

★ Need to separate energy deposits from different particles
★ Not calorimetry in the traditional sense
★ TESLA TDR resolution (Z→uds at rest) : \( \sim 0.30 \sqrt{E_{\text{jet}}} \)

<table>
<thead>
<tr>
<th>Component</th>
<th>Detector</th>
<th>Frac. of jet energy</th>
<th>Particle Resolution</th>
<th>Jet Energy Resolution</th>
</tr>
</thead>
<tbody>
<tr>
<td>Charged Particles((X^{\pm}))</td>
<td>Tracker</td>
<td>0.6</td>
<td>( 10^{-4} E_x )</td>
<td>neg.</td>
</tr>
<tr>
<td>Photons((\gamma))</td>
<td>ECAL</td>
<td>0.3</td>
<td>( 0.11 \sqrt{E_{\gamma}} )</td>
<td>( 0.06 \sqrt{E_{\text{jet}}} )</td>
</tr>
<tr>
<td>Neutral Hadrons((h^0))</td>
<td>HCAL</td>
<td>0.1</td>
<td>( 0.4 \sqrt{E_h} )</td>
<td>( 0.13 \sqrt{E_{\text{jet}}} )</td>
</tr>
</tbody>
</table>

★ Energy resolution gives \( 0.14 \sqrt{E_{\text{jet}}} \) (dominated by HCAL)

★ In addition, have contributions to jet energy resolution due to “confusion”, i.e. assigning energy deposits to wrong reconstructed particles (double-counting etc.)

\[
\sigma_{\text{jet}}^2 = \sigma_{x^{\pm}}^2 + \sigma_\gamma^2 + \sigma_{h^0}^2 + \sigma_{\text{confusion}}^2 + \sigma_{\text{threshold}}^2
\]

★ Single particle resolutions not the dominant contribution to jet energy resolution!

granularity more important than energy resolution
PFA : Basic issues

★ What are the main issues for PFA ?
★ Separate energy deposits + avoid double counting

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

★ Need to separate neutral hadrons from charged hadrons

Granularity helps
But less clear...
Calorimeter Requirements

- Excellent energy resolution for jets – i.e. high granularity
- Good energy/angular resolution for photons – how good?
- Hermeticity
- Reconstruction of non-pointing photons

**Particle flow drives calorimeter design:**

- Separation of energy deposits from individual particles
  - small $x_0$ and $R_{\text{Moliere}}$: compact showers
  - high lateral granularity: $O(R_{\text{Moliere}})$
- Discrimination between EM and hadronic showers
  - small $x_0/\lambda_I$
  - longitudinal segmentation
- Containment of EM showers in ECAL

**SiW:** sampling calorimeter is a good choice

- Tungsten is great: $x_0/\lambda_I = 1/25$, $R_{\text{Moliere}} \sim 9\text{mm}$
- EM showers are short/Had showers long
  + narrow EM showers
- However not cheap (very significant fraction of total detector cost)!

RAL HEP Forum 7/05/2006 Mark Thomson
The ILC Calorimeter Concepts

The 3 Main Detector Concepts:
- ILC Detector Design work centred around 3 main detector “concepts”
- Each will contribute to an ILC detector conceptual design report by end of 2006
- Ultimately may form basis for TDRs

**LDC** : Large Detector Concept (spawn of TESLA TDR)

**SiD** : Silicon Detector

**GLD** : Global Large Detector
Main Differences:

- **SIZE + B-Field**

  - Tracker
    - B = 5T
  - ECAL
    - B = 3T, B = 4T, B = 5T

Central Tracker and ECAL

<table>
<thead>
<tr>
<th></th>
<th>SiD</th>
<th>LDC</th>
<th>GLD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tracker</td>
<td>Silicon</td>
<td>TPC</td>
<td>TPC</td>
</tr>
<tr>
<td>ECAL</td>
<td>SiW</td>
<td>SiW</td>
<td>Pb/Scint</td>
</tr>
</tbody>
</table>

- **SiD + LDC + GLD** all designed for PFA Calorimetry!
- **also “4th” concept designed for “traditional” calorimetry!**
LDC/SiD Calorimetry

**ECAL** and **HCAL** inside coil

**ECAL: silicon-tungsten (SiW) calorimeter:**

- **Tungsten:** $X_0 / \lambda_{\text{had}} = 1/25$, $R_{\text{Moliere}} \sim 9\text{mm}$
  (gaps between Tungsten increase effective $R_{\text{Moliere}}$)
- **Lateral segmentation:** $\sim 1\text{cm}^2$ matched to $R_{\text{Moliere}}$
- **Longitudinal segmentation:** 40 layers ($24 X_0, 0.9\lambda_{\text{had}}$)
- **Resolution:** $\sigma_E/E = 0.11/\sqrt{E(\text{GeV})} \oplus 0.01$
  
  $\sigma_\theta = 0.063/\sqrt{E(\text{GeV})} \oplus 0.024 \text{ mrad}$
Highly Segmented – for Particle Flow

- Longitudinal: 40 samples
- $4 - 5 \lambda$ (limited by cost - coil radius)
- Would like fine (1 cm$^2$?) lateral segmentation
- For 10000 m$^2$ of 1 cm$^2$ HCAL = $10^8$ channels – cost!

Two Main Options:
- **Tile HCAL (Analogue readout)**
  - Steel/Scintillator sandwich
  - Lower lateral segmentation
  - 5x5 cm$^2$ (motivated by cost)
- **Digital HCAL**
  - High lateral segmentation
  - 1x1 cm$^2$
  - Digital readout (granularity)
  - RPCs, wire chambers, GEMS...

The Digital HCAL Paradigm

- **Sampling Calorimeter:**
  - Only sample small fraction of the total energy deposition
- **Energy depositions in active region follow highly asymmetric Landau distribution**
GLD Calorimetry

- **ECAL and HCAL inside coil**
- **W-Scintillator ECAL sampling calo.**
- **Pb-Scintillator HCAL sampling calo.**

Initial GLD ECAL concept:
- Achieve effective ~1cm x 1cm segmentation using strip/tile arrangement
- **Strips**: 1cm x 20cm x 2mm
- **Tiles**: 4cm x 4cm x 2mm

Question of pattern recognition in dense environment
Calorimeter Reconstruction

- High granularity calorimeters – very different from previous detectors
- As trad. calorimeters – not great
- “Tracking calorimeter” – requires a new approach to ECAL/HCAL reconstruction

+ PARTICLE FLOW

ILC calorimeter performance = HARDWARE + SOFTWARE

Performance will depend on the software algorithm

Nightmare from point of view of detector optimisation
PFA and ILC detector design?

PFA plays a special role in design of an ILC Detector

- **VTX**: design driven by heavy flavour tagging, machine backgrounds, technology
- **Tracker**: design driven by $\sigma_p$, track separation
- **ECAL/HCAL**: single particle $\sigma_E$ not the main factor
  - Jet energy resolution! Impact on particle flow drives calorimeter design + detector size, B field, ...

PFA is a (the?) major cost driver for the ILC Detectors

**BUT**: Don’t really know what makes a good detector from point of view of PFA (plenty of personal biases – but little hard evidence)

**How to optimise/compare ILC detector design(s) ?**

- Need to choose the key “benchmark” processes (EASY)
The rest is VERY DIFFICULT!

For example:

- Would like to compare performance of say LDC and SiD detector concepts

  e.g. tt event in LDC

  e.g. tt event in SiD

- However performance = DETECTOR + SOFTWARE
- Non-trivial to separate the two effects
- NEED REALISTIC SIMULATION/RECONSTRUCTION!
  - can’t use fast simulation etc.
A Realistic(?) Particle Flow Algorithm

Need sophisticated reconstruction before it is possible to start full detector design studies...

So where are we now?

Significant effort (~5 groups developing PFA reconstruction worldwide)

+ (opinion) to date very little hard evidence that PFA can deliver ILC goals....

For the remainder of this talk concentrate on work in UK

Work-in-Progress – but does a pretty good job
+ much better feel for what really matters....

Concentrate on general features to indicate how an ultimate particle flow reconstruction might work
An Algorithm: PandoraPFA

★ ECAL/HCAL reconstruction and PFA performed in a single algorithm
★ Keep things fairly generic algorithm
  ★ applicable to multiple detector concepts
★ Use tracking information to help ECAL/HCAL clustering

Five Main Stages:

i. Loose clustering in ECAL and HCAL
ii. Topological linking of clearly associated clusters
iii. Courser grouping of clusters
iv. Iterative reclustering
v. Formation of final Particle Flow Objects (reconstructed particles)
i) ECAL/HCAL Clustering

- Start at inner layers and work outward
- Associate Hits with existing Clusters
- Step back \( N \) layers until associated
- Then try to associate with hits in current layer
- If no association made form new Cluster
- + tracks used to seed clusters

Simple cone algorithm based on current direction + additional \( N \) pixels

Cones based on either: initial PC direction or current PC direction
ii) Cluster Association Part I

- 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 – catches what’s been missed but rather crude

**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

![Diagram](image-url)
Cluster Association Part I

Join clusters which are clearly associated
make use of high granularity + tracking capability

Only clear associations – almost no mistakes
iii) 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.

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

Provides some protection against “silly” mistakes

★ Cluster reconstruction and PFA not independent
Course Cluster Association

**Proximity**

Distance between hits - limited to first layers

**Shower Cone**

Associated if fraction of hits in cone > some value

**+Track-Driven Shower Cone**

Shower start identified

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

- Generally 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
- 18 GeV
- 12 GeV
- 10 GeV Track

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**Change clustering parameters until split cluster + get sensible track-cluster match**

**NOTE:** NOT FULL PFA as clustering driven by track momentum

★ If can’t find a sensible reclustering use the **ultimate sanction**
i.e. do not use track information
Current Performance (as of 6/5/06)

Example Reconstruction

Figure of Merit:

- Find smallest region containing 90% of events
- Determine rms in this region
PFA Results (Z → uds)

\[ \sigma_{E/E} = \alpha \sqrt{E/\text{GeV}} \]

\begin{itemize}
  \item \( |\cos \theta| \leq 0.9 \) \( - 30.9 \pm 0.3 \% \)
  \item \( |\cos \theta| \leq 0.7 \) \( - 30.3 \pm 0.3 \% \)
\end{itemize}

ILC GOAL OF 30 \% ACHIEVED!

\begin{itemize}
  \item BUT only for Z at 91.2 GeV
  \item Need to look at performance at higher energies
\end{itemize}

Have realistic (?) PFA code, can start to look at different detectors...

\( Z \to uds \) (91.2 GeV)
e.g. B-Field

LDC00 Detector (≈ TESLA TDR) – same event different B

\[ \sigma_{E}/E = \alpha \sqrt{E/\text{GeV}} \]

| B-Field | \( \sigma_{E}/E \) | \(|\cos\theta|<0.7\) |
|---------|----------------|----------------|
| 2 Tesla | 35.6±0.3%      | 32.1±0.4%      |
| 4 Tesla | 34.3±0.3%      | 30.3±0.4%      |
| 6 Tesla | 34.9±0.3%      | 30.3±0.4%      |

Only weak B-field dependence
e^+e^- \rightarrow tt \rightarrow 6 \text{ jets at } \sqrt{s}=500 \text{ GeV}

<table>
<thead>
<tr>
<th>Detector Model</th>
<th>$\sigma_E/E = \alpha \sqrt{E/\text{GeV}}$</th>
</tr>
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<tbody>
<tr>
<td>LDC01Sc $r_{\text{tpc}} = 1380\text{mm}$</td>
<td>$89 \pm 2%$ $59 \pm 1%$ $56 \pm 1%$</td>
</tr>
<tr>
<td>LDC01Sc $r_{\text{tpc}} = 1580\text{mm}$</td>
<td>$84 \pm 2%$ $56 \pm 1%$ $52 \pm 1%$</td>
</tr>
<tr>
<td>LDC00Sc $r_{\text{tpc}} = 1690\text{mm}$</td>
<td>$78 \pm 2%$ $49 \pm 1%$ $45 \pm 1%$</td>
</tr>
<tr>
<td>LDC00Sc $r_{\text{tpc}} = 1890\text{mm}$</td>
<td>$76 \pm 2%$ $45 \pm 1%$ $42 \pm 1%$</td>
</tr>
</tbody>
</table>

- Strong dependence of performance on Radius
- SIZE MATTERS
- Can start to address other design issues...
Some serious PFA-related Detector Design issues

Main questions identified at Snowmass (in some order of priority):

1) B-field : Does B help jet energy resolution
2) Size : ECAL inner radius/TPC outer radius
3) TPC length/Aspect ratio
4) Tracking efficiency – forward region
5) How much HCAL – how many interactions lengths 4, 5, 6...
6) Longitudinal segmentation – pattern recognition vs sampling frequency for calorimetric performance
7) Transverse segmentation ECAL/HCAL
   ECAL : does high/very high granularity help ?
8) Compactness/gap size
9) Impact of dead material
10) How important are conversions, $V^0$s and kinks
11) HCAL absorber : Steel vs. W, Pb, U...
12) Circular vs. Octagonal TPC (are the gaps important)
13) HCAL outside coil – probably makes no sense but worth demonstrating this (or otherwise)
14) TPC endplate thickness and distance to ECAL
15) Material in VTX – how does this impact PFA
Conclusions

- Great deal of effort (worldwide) in the design of the ILC detectors
- Centred around 4 “detector concept” groups: GLD, LDC, SiD + 4th
- Widely believed that calorimetry and, in particular, jet energy resolution drives detector design
- Also widely believed that PFA is the key to achieving the ILC goal

THIS IS HARD – BUT VERY IMPORTANT!

- Calorimetry at the ILC = HARDWARE + SOFTWARE (new paradigm)
- It is difficult to disentangle detector/algorithm....
- Can only address question with “realistic algorithms”
  - i.e. serious reconstruction 10+ years before ILC turn-on
- With PandoraPFA algorithm already getting to close to ILC goal (for \( Z \rightarrow \mu \nu s \) events)
- More importantly, getting close to being able to address real issues:
  - What is optimal detector size/B-field
  - What ECAL/HCAL granularity is needed
  - How does material budget impact performance
  - .......

FINAL COMMENT:

- GLD, LDC, SiD calorimetry “designed” for PFA
- Need to demonstrate this actually makes sense!
- not yet proven...!