Digital Calorimetry and Particle Flow Algorithms

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Outline

- Conventional Calorimetry
- International Linear Collider - ILC
- ILC physics requirements for detectors
- Particle Flow Algorithm - PFA
- Digital Calorimetry
What is a Calorimeter?

- Device to measure the energy of particles by total absorption
- Electromagnetic - ECAL
  - Measure EM objects - electrons, positrons, photons
- Hadron - HCAL
  - Measure hadrons - $\pi$, K, p, n, …
- To understand how calorimeters work, need to understand particle interactions with matter
  - See talk by Bernd Surrow, NEPPSR V, 2006
  - Particle Data Group
Conventional Calorimeters

- **Homogeneous**
  - Inorganic, high-Z, scintillating crystals - BGO, CsI, NaI,…
  - Cherenkov radiators - lead glass,…
  - Ionizing noble liquids

- **Sampling**
  - Sandwich of absorber and active medium
  - Absorbers - steel, uranium, copper,…
  - Active medium - scintillator, ionizing noble liquid, gas-filled detector, semiconductor
Energy Resolution

\[
\frac{\sigma(E)}{E} = \frac{S}{\sqrt{E}} \oplus C \oplus \frac{N}{E}
\]

- **Stochastic term**
  - Statistics-related fluctuations: shower fluctuations, PE statistics, dead material in front of the calorimeter, sampling fluctuations

- **Constant term**
  - Detector non-uniformity and calibration uncertainties

- **Noise term**
  - Electronic noise
# EM Resolution of Real Detectors

**Table 28.7:** Resolution of typical electromagnetic calorimeters. $E$ is in GeV.

<table>
<thead>
<tr>
<th>Technology (Experiment)</th>
<th>Depth</th>
<th>Energy resolution</th>
<th>Date</th>
</tr>
</thead>
<tbody>
<tr>
<td>NaI(Tl) (Crystal Ball)</td>
<td>20$X_0$</td>
<td>$2.7%/\sqrt{E}^{1/4}$</td>
<td>1983</td>
</tr>
<tr>
<td>Bi$_4$Ge$<em>3$O$</em>{12}$ (BGO) (L3)</td>
<td>22$X_0$</td>
<td>$2%/\sqrt{E} \oplus 0.7%$</td>
<td>1993</td>
</tr>
<tr>
<td>CsI (KTeV)</td>
<td>27$X_0$</td>
<td>$2%/\sqrt{E} \oplus 0.45%$</td>
<td>1996</td>
</tr>
<tr>
<td>CsI(Tl) (BaBar)</td>
<td>16–18$X_0$</td>
<td>$2.3%/E^{1/4} \oplus 1.4%$</td>
<td>1999</td>
</tr>
<tr>
<td>CsI(Tl) (BELLE)</td>
<td>16$X_0$</td>
<td>$1.7%$ for $E_\gamma &gt; 3.5$ GeV</td>
<td>1998</td>
</tr>
<tr>
<td>PbWO$_4$ (PWO) (CMS)</td>
<td>25$X_0$</td>
<td>$3%/\sqrt{E} \oplus 0.5% \oplus 0.2/E$</td>
<td>1997</td>
</tr>
<tr>
<td>Lead glass (OPAL)</td>
<td>20.5$X_0$</td>
<td>$5%/\sqrt{E}$</td>
<td>1990</td>
</tr>
<tr>
<td>Liquid Kr (NA48)</td>
<td>27$X_0$</td>
<td>$3.2%/\sqrt{E} \oplus 0.42% \oplus 0.09/E$</td>
<td>1998</td>
</tr>
<tr>
<td>Scintillator/depleted U</td>
<td>20–30$X_0$</td>
<td>$18%/\sqrt{E}$</td>
<td>1988</td>
</tr>
<tr>
<td>(ZEUS)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Scintillator/Pb (CDF)</td>
<td>18$X_0$</td>
<td>$13.5%/\sqrt{E}$</td>
<td>1988</td>
</tr>
<tr>
<td>Scintillator fiber/Pb</td>
<td>15$X_0$</td>
<td>$5.7%/\sqrt{E} \oplus 0.6%$</td>
<td>1995</td>
</tr>
<tr>
<td>spaghetti (KLOE)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Liquid Ar/Pb (NA31)</td>
<td>27$X_0$</td>
<td>$7.5%/\sqrt{E} \oplus 0.5% \oplus 0.1/E$</td>
<td>1988</td>
</tr>
<tr>
<td>Liquid Ar/Pb (SLD)</td>
<td>21$X_0$</td>
<td>$8%/\sqrt{E}$</td>
<td>1993</td>
</tr>
<tr>
<td>Liquid Ar/Pb (H1)</td>
<td>20–30$X_0$</td>
<td>$12%/\sqrt{E} \oplus 1%$</td>
<td>1998</td>
</tr>
<tr>
<td>Liquid Ar/depl. U (DØ)</td>
<td>20.5$X_0$</td>
<td>$16%/\sqrt{E} \oplus 0.3% \oplus 0.3/E$</td>
<td>1993</td>
</tr>
<tr>
<td>Liquid Ar/Pb accordion</td>
<td>25$X_0$</td>
<td>$10%/\sqrt{E} \oplus 0.4% \oplus 0.3/E$</td>
<td>1996</td>
</tr>
</tbody>
</table>

S ~ few %

S ~ 10%
Want $E(q,g,\ldots) \Rightarrow \text{Measure Jets}$
Calorimeter Segmentation

DØ calorimeter
Uranium - liquid Argon sampling calorimeter segmentation: $\Delta \eta \times \Delta \phi \sim 0.1 \times 0.1 \Rightarrow \sim 50k$ channels
~12 bit charge measurement
“Typical” 2-jet Event
Jet Energy Resolution for Real Detectors

\[ \sigma(E) \approx \alpha \sqrt{E(\text{GeV})} \]

No nice table here but a typical range for recent collider detectors is \( \alpha = (60-80)\% \)
LHC - The Next Big Accelerator
ILC - The Next Next Big Accelerator
ILC - International Linear Collider

- $e^+e^-$ collisions at 200-500 GeV
  - $E_{\text{CM}}$ tunable with 0.1% stability and precision
  - Upgrade to 1 TeV
- Peak luminosity $2 \times 10^{34} \text{ cm}^{-2} \text{s}^{-1}$
  - $\int L dt = 500 \text{ fb}^{-1}$ in 4 years
- Polarized beams allow control of initial state angular momentum
  - Electron polarization at least 80%, positrons 30–60%
- Complementary to LHC
  - LHC: run first, higher energy, broadband $q$, $\bar{q}$, $g$ beams
  - ILC: 2nd view with high precision, $E_{\text{CM}}$ fixed, initial state well defined
- When, if ever, will ILC be built?
  - Where would it be built?
    - How much will it cost?
      - These are very good questions…
ILC Physics Drives Jet Resolution

- Many of the important ILC physics topics involve multi-jet final states
- Higgs self-coupling $\lambda_{hhh}$
  - $e^+e^- \rightarrow ZHH \rightarrow q\bar{q}b\bar{b}b$  
  - Test of the Higgs mechanism
- Higgs mass in 4-jet channel
  - $e^+e^- \rightarrow ZH \rightarrow q\bar{q}bb$

\[ \frac{\Delta g_{hhh}}{g_{hhh}} \]

\[ \frac{\Delta E_{\text{jet}}}{\sqrt{E_{\text{jet}}}} \text{ (GeV}^{\frac{1}{2}}) \]

$\alpha = 60\% \rightarrow 30\%$

$\Rightarrow 40\%$ luminosity gain
ILC Physics Drives Jet Resolution

- H → WW* branching fraction
  - e^+e^- → ZH → ZWW* → qqqlν
  - Distinguish hadronic W and Z decays
- Cross section for e^+e^- → ννWW
  - Probe strong WW scattering in a Higgs-less world
  - Distinguish hadronic W and Z decays

\[ \alpha = 60\% \rightarrow 30\% \]
⇒ 40% luminosity gain
Estimate of Performance Needed for ILC

- Jet energy resolution
  \[ \sigma(E) \approx \alpha \sqrt{E} \text{(GeV)} \]
- Dijet mass resolution
  \[ \sigma(M)/M \approx \alpha / \sqrt{E}_{jj} \]
  where \( E_{jj} \) is the energy of the dijet system
- Goal: \( \sigma(M) \) for \( W \rightarrow q\bar{q} \) and \( Z \rightarrow q\bar{q} \sim W \) or \( Z \) natural widths \( \Rightarrow \sigma(M) \sim 2 \text{ GeV} \)
- At ILC, \( E_{jj} \sim 150 \text{ GeV} \) so we need
  \[ \sigma(E) \approx 30\% \sqrt{E} \text{(GeV)} \]
- About factor of 2 better than achieved to date!

Separate \( H \rightarrow WW \) and \( H \rightarrow ZZ \)

\[ \sigma(E) = 60\% \sqrt{E} \]

\[ \sigma(E) = 30\% \sqrt{E} \]
Particle Flow Algorithm

- Basic idea - use entire detector to measure jet energy
  - Must be an integral part of detector design
- Reconstruct all visible particles in the event
  - Measure charged particles’ momenta in tracker (~60% E)
  - Measure photons in the ECAL (~30% E)
  - Measure neutral hadrons in HCAL (~10% E)
- Works best when energies of particles in jets < ~100 GeV
PFA and Digital Calorimetry

- Crucial ingredients
  - Correctly assign hits in calorimeter to charged particles
  - Separate showers produced by charged and neutral particles
- Need essentially an imaging device
  - Requires fine segmentation
    ~ 1x1 cm² in the transverse direction plus ~40 layers
    ⇒ ~5x10⁷ channels!
- Analog - low channel-count and O(10-bit) measurement/channel
  ⇒ Digital - high channel-count and 1-bit measurement/channel
PFA: General Strategy

- Output is a list of reconstructed particles: “Particle Flow Objects” (PFOs)
  - Algorithms differ in detail but general strategy is same
- Reconstruct all charged particles
  - Careful to identify neutral particles that decay, e.g. $K^0 \rightarrow \pi^+\pi^-$, photon conversions, kinks, etc.
  - Pattern recognition in ECAL&HCAL
    - Associate charged particles with calorimeter clusters
    - Separate from nearby clusters
  - Charged particle PFO = track + cluster
  - If particle ID info available, assign mass to PFO
- Unassociated calorimeter clusters are neutral PFOs
  - Either photons or neutral hadrons, assignment based purely on calorimeter info

WW @ 800 GeV

MC Truth

After PFA
PFA Jet Energy Resolution

- Factors affecting the resolution
  - Resolution of subdetector systems: tracker and calorimeters
  - Unmeasured energy
    - Finite detector acceptance
    - Neutrinos - b and c quark jets
  - Clustering algorithms

\[ \sigma^2(E_{jet}) = \sigma^2(X^\pm) + \sigma^2(\gamma) + \sigma^2(h^0) + \sigma^2(miss) + \sigma^2(conf) \]
Perfect PFA Performance

- Run “perfect” PFA where all factors except confusion term are included
  - Neutrinos
  - Acceptance to 50° of beampipe
  - ECAL and HCAL resolutions
  - Wrong mass assignment, e.g. pion for a proton
- Jet energy resolution ~ 25%/\sqrt{E}

<table>
<thead>
<tr>
<th></th>
<th>$e^+e^-\rightarrow Z\rightarrow qq$ (91.2 GeV)</th>
<th>$e^+e^-\rightarrow tt$ (500 GeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sigma_\nu$/GeV</td>
<td>0.84</td>
<td>1.36</td>
</tr>
<tr>
<td>$\sigma_{FWD}$/GeV</td>
<td>1.55</td>
<td>2.68</td>
</tr>
<tr>
<td>$\sigma_{HCAL}$/GeV</td>
<td>1.40</td>
<td>3.93</td>
</tr>
<tr>
<td>$\sigma_{ECAL}$/GeV</td>
<td>0.57</td>
<td>1.40</td>
</tr>
<tr>
<td>$\sigma_{MASS}$/GeV</td>
<td>0.61</td>
<td>1.32</td>
</tr>
<tr>
<td>$\sigma_{TOTAL}$/GeV</td>
<td>2.40</td>
<td>5.31</td>
</tr>
<tr>
<td>$\sigma_{TOTAL}/\sqrt{E}$(GeV)</td>
<td>25.1 %</td>
<td>23.7 %</td>
</tr>
</tbody>
</table>
Perfect PFA Performance

Better than a factor of 2 improvement over calorimeter only measurement!
ILC Detector Concepts

- SiD
- GLD
- LDC

August 14, 2007
PFA Results From Detector Concepts

\[ e^+e^- \rightarrow Z \rightarrow uds \ (\sqrt{s} = 91.2 \text{ GeV}) \]

\( \sigma(E) \) improves with larger R and B
What could possibly go wrong?

- Monte Carlo is not real life!
- Models of showers need to be tuned to data
- Data with sufficient detail does not exist
- Motivates a program of R&D

Figure 1.1 Comparison of the shower radius in a hadron calorimeter as predicted with fifteen different MC models of hadronic showers normalized to the result with G4-FTFP.
Digital HCAL R&D

- CALICE Collaboration leads R&D
- Goal: test a physics prototype to validate/calibrate PFAs
  - “The 1 m³” - big enough to contain a shower
  - 40 layers: 2 cm steel and an active element per layer
  - 1 x 1 cm² pads with digital (single-bit) readout
- The prototype has ~400,000 channels!
- Active elements considered
  - Resistive Plate Chambers (RPCs)
  - Gas Electron Multipliers (GEMs)
  - MicroMegas
  - Scintillator
- Current Status: Vertical Slice Test
  - Argonne, BU, UC, FNAL, Iowa, UTA
  - Test at least one of everything in the detector and readout chain
  - 8-10 layers, ~2000 channels
  - RPCs are active medium
Digital HCAL R&D: RPCs

![Diagram of RPCs](image)

- **Signal Pad(s)**
- **Mylar**
- **Glass**
- **Resistive paint**
- **Channel**
- **Glue**
- **Fishing line**
- **Gas volume**
- **Signal path**

![RPCs Image](image)
Vertical Slice Beam Test at FNAL

Secondary Muon Beam

Run 999:1 Event 4031
Time: 8625726
Hits: 18 Energy: xxx mips
Vertical Slice Beam Test at FNAL

8 GeV Electron Beam

Run 999:1 Event 137
Time: 6702208
Hits: 59 Energy: xxx mips

Run 999:1 Event 1
Time: 743374
Hits: 16 Energy: xxx mips

8 GeV Pion Beam
Summary

- To meet the needs of the physics program, detectors at the ILC must achieve unprecedented jet energy resolution
- The most promising strategy is the Particle Flow Algorithm
- Requires a detector whose tracker, ECAL, and HCAL work in concert to measure jet energy
- Calorimeter must be an imaging device ⇒ 50 megachannels ⇒ digital readout
- Monte Carlo studies show that a digital HCAL will meet the performance goals
- Prototype R&D and test beam measurements are underway to demonstrate the PFA concept works in the real world
References

- “Calorimetry in Nuclear and Particle Physics”, Bernd Surrow, NEPPSR V, 2006
- Particle Data Group: [http://pdg.lbl.gov/](http://pdg.lbl.gov/)
Extra Stuff
Cluster Splitting & Merging

a) 2 photons

b) 1 photon

c) 0 photons

PandoraPFA
Jean-Claude Brient

**DHCal vs AHCal**

- **Analog**
  - $\sigma$/mean $\sim$ 22%
  - Landau Tails + path length

- **Digital**
  - $\sigma$/mean $\sim$ 19%

- **$\pi^+$ 5 GeV**

- **E (GeV)**

- **Number of Hits**

ILC – TB workshop – FNAL Jan 07
Cosmic Ray Events

Run 999042:0 Event 110

Time: Tue Feb 24 00:14:44 1970
Hits: 9  Energy: xxx mJ/s

[Diagram of cosmic ray event]
One Higgs event

After removing the 2 muons, All the rest of the event is Coming from the Higgs decay

LHC will discover (open the doors)

ILC will probe the underlying theory (turn on the light)
Scintillator HCAL

First calorimeter to use SiPMs

Physics prototype

38 steel plates with a thickness of $1 X_0$ each
Scintillator pads of $3 \times 3 \rightarrow 12 \times 12 \text{ cm}^2$
$\rightarrow \sim 8,000$ readout channels

Electronic readout

Silicon Photomultipliers (SiPMs)
Digitization with VME-based system (off detector)

Tests at DESY/CERN in 2006

23/38 readout planes
Electrons 1 – 45 GeV
Pions 6 – 50 GeV