HA HA! It took weeks and months and years of waiting, but at long last it’s here! Now I can finally get to put my new detector in the experiment!

“SOME ASSEMBLY REQUIRED. BATTERIES NOT INCLUDED.”

Olav Ullaland EP CERN 11 October 2000
The energy resolution of a calorimeter is usually parameterized as

\[ \frac{\sigma}{E} = \frac{a}{\sqrt{E}} \oplus b \oplus \frac{c}{E} \]

- \(a\) is the stochastic term
- \(b\) is the constant term
- \(c\) is the electronic noise contribution

A calorimeter is a class of detectors that measures the energy and the position of the particles through total absorption in these devices. It is a rather destructive method. For the particle.

So, how are we coming along in the understanding of how a calorimeter works?
For the class Homogeneous calorimeters the scintillating crystals are virtually free from intrinsic fluctuations.

We then get

\[
\frac{\sigma}{E} = \frac{1}{\sqrt{N_{pe}}} = \frac{1}{\sqrt{E(GeV)} \times \sqrt{N_{pe} / GeV}}
\]

\(N_{pe}/GeV\) is observed number of photons per energy unit.

To get this number the absolute light yield, the number of emitted photons for each energy unit, has to be multiplied with
- light collection efficiency
- geometrical efficiency of the photon detector
- quantum efficiency integrated over the emission spectrum
- .......

And then we have the
- Lateral leakage
- The punch through
- The material in front of the detector

which does not help.
For the moment, we will not discuss the sampling calorimeters at LEP.

They have their own features.

The L3 collaboration set out to make an electromagnetic calorimeter with
• Best obtainable E resolution for $e, \gamma$ from 50 MeV to 50 Gev
• Good angular resolution for $\gamma$ down to 50 MeV
• Hadron rejection around $10^3$ for $e > 1$ GeV
• Good separation between $e, \gamma$ showers in narrow jets

<table>
<thead>
<tr>
<th>Crystal</th>
<th>BGO</th>
<th>CsI:Tl</th>
<th>CsI</th>
<th>PWO</th>
<th>NaI:Tl</th>
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</thead>
<tbody>
<tr>
<td>Density</td>
<td>g/cm$^3$</td>
<td>7.13</td>
<td>4.53</td>
<td>4.53</td>
<td>8.26</td>
</tr>
<tr>
<td>Radiation length</td>
<td>cm</td>
<td>1.12</td>
<td>1.85</td>
<td>1.85</td>
<td>0.89</td>
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<tr>
<td>Wave length</td>
<td>nm</td>
<td>480</td>
<td>565</td>
<td>310</td>
<td>420</td>
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<tr>
<td>Light yield</td>
<td>% of Nal</td>
<td>10</td>
<td>85</td>
<td>7</td>
<td>0.2</td>
</tr>
<tr>
<td>Decay time</td>
<td>ns</td>
<td>300</td>
<td>1000</td>
<td>6+35</td>
<td>5+15+100</td>
</tr>
<tr>
<td>Temp. dependence</td>
<td>%/°C @ 18°</td>
<td>-1.6</td>
<td>0.3</td>
<td>-0.6</td>
<td>-1.9</td>
</tr>
<tr>
<td>Refr. index</td>
<td></td>
<td>2.15</td>
<td>1.8</td>
<td>1.8</td>
<td>2.29</td>
</tr>
</tbody>
</table>
The L3 detector
The L3 Electromagnetic calorimeter BGO
Bismuth Germanium Oxide \( \text{Bi}_4\text{Ge}_3\text{O}_{12} \)

24 crystals in \( \theta \) and 160 in \( \phi \) in each half barrel.

\( \heartsuit \)680 Crystals
\( \phi \) slices ranging from 48 to 128 across 17 radial segments in the End Caps

\( \clubsuit \)3054 Crystals

L3, Beijing Calorimetry Symposium, 1994
Energy resolution for some Crystal Calorimeters

CLEO II

Crystal Ball

L3

Energy (GeV)

E. Longo, Calorimetry with Crystals, submitted to World Scientific, 1999

η \rightarrow \pi^0 \pi^0 \pi^0

M=544\pm1\text{MeV}

\sigma=2.6\pm0.7\text{MeV}

N=904\pm199

L3, Beijing Calorimetry Symposium, 1994
Hey,
I just asked if you were hot

Temperature °C

Average Temperatures

L3, Beijing Calorimetry Symposium, 1994
To keep all parameters under control, a massive amount of calibration has been done
• All crystals were measured in a cosmic ray bench
• Most crystals were measured in an electron beam at 2, 10, 50 GeV
• Half the Barrel was measured in an electron beam at 180 MeV
• Each crystal was calibrated in their final support

During LEP running:

• The Xenon monitoring system
• The Radio Frequency Quadruple (RFQ) system
• Cosmic muons
• LEP data with Bhabha, MIPs and $\pi^0$

Xenon monitor

L3, CALOR99
"That's cool, man. yessssir!!!
The development of ring-imaging Cherenkov detectors is a difficult area, due to the mismatch between the Cherenkov light in the gas media and its conversion into ionization in a spatial detector. However, as we have heard at this conference [18], the problem has been solved......

However, the techniques required going from a small development to a modest size detector are very challenging, and a successful outcome will have tremendous impact in all areas of physics.....

Erwin Gabathuler,
Conclusions from the Uppsala Conference on Experimentation at LEP, June 1980
Cherenkov radiator

\[ n = f(\text{photon energy}) \]

\[ \cos \Theta = \frac{1}{\beta \cdot n(\lambda)} \]

\[ N = f(\beta) \]

\[ r = f(\beta, n) \]

\[ \Delta(r) = f(\text{resolution}) \]

\[ \text{Photon detector} \]
Hey! Did I mention TMAE to you?! Did I?!!
Particle Identification in DELPHI at LEP I and LEP II

\(-0.7 \leq p \leq 45 \text{ GeV/c}\)

\(-15^\circ \leq \theta \leq 165^\circ\)

2 radiators + 1 photodetector

Forwarad RICH

Barrel RICH

\(n = 1.28\) C\(_6\)F\(_{14}\) liquid

\(n = 1.0018\) C\(_5\)F\(_{12}\) gas
Barrel RICH
1 of 2×12 sectors

2 × 6 parabolic mirrors

2 drift tubes + 2 MWPC (= 1 bitube)
gas: 75% CH$_4$ + 25% C$_2$H$_6$
TMAE @ 28°C

2 liquid radiator
1 cm C$_6$F$_{14}$
quartz windows
p = 985 mbar

gas radiator volume
1 single vessel
c. 40 cm C$_5$F$_{12}$
p = 1030 mbar

Complete detector heated at 40 ± 0.3 °C. Pressure to ±0.5 m

Forward RICH
1 of 2×12 sectors

3 liquid radiator trays
1 cm C$_6$F$_{14}$
quartz windows
p = atm.

5 spherical mirrors

gas radiator volume
2 half vessels / side
c. 50 cm C$_4$F$_{10}$
p = atm.

T$_{vessel}$ ≈ 30°C, unregulated.

2 drift boxes + 2 MWPC’s
gas: C$_2$H$_6$ + TMAE (24°C)
Proportional Chamber with UV blinds

\[ \vec{E} \perp \vec{B} \]
\[ \alpha_L \approx 50^\circ \]

Forward RICH photon Detector

Proportional Chamber with UV blinds

Forward RICH calibration 1997 and 1998

DELPHI, NIM A 433(1999)47
Barrel RICH, $Z^0 \rightarrow \mu\mu$

Forward RICH, $Z^0 \rightarrow \mu\mu$

Barrel RICH, hadrons

Forward RICH, hadrons

DELPHI, NIM A 433(1999)47
Particle Identification with the DELPHI RICHes

From data
- p from Λ
- K from Φ
- D*
- π from K°

http://delphiwww.cern.ch/delfigs/export/pubdet4.html
DELPHI, NIM A: 378(1996)57
Yoko Ono æ1994
FRANKLIN SUMMER SERIES, ID#27
I forbindelse med utstillingen i BERGEN KUNSTMUSEUM, 1999
Particle identification through ionization losses.

Energy loss detection with MWPC started more or less at the same time as the first MWPC was operational. It was already a proven technique in the early days of the ISR.

\[ p = m\beta\gamma \]
\[ \frac{dE}{dx} \propto \frac{1}{\beta^2} \ln \left( \beta^2 \gamma^2 \right) \]

Simultaneous measurement of \( p \) and \( dE/dx \) defines \( m \).

\[ \pi/K \] separation at a 2\( \sigma \) level requires a \( dE/dx \) resolution in the range of 2 to 3\% - depending on the momentum range.

But:
Large fluctuations and Landau tails!

Average energy loss in 80/20 Ar/CH\(_4\) (NTP)
(J.N. Marx, Physics today, Oct.78)
The Use of \( \frac{dE}{dX} \) really took off with the coming of the JET chambers and the TPC like detectors. The workhorses for tracking.

The underlying physics and techniques of particle identification using the relativistic rise of the total ionization loss (\( \frac{dE}{dX} \)) in proportional counters seems to be understood in its basic limits.

............... 

Each one of them has its problems, but improved particle identification may result from a more complete understanding of the energy loss and detection mechanism.

A. H. Walenta, 
Performance and Development of \( \frac{dE}{dX} \) Counters, Uppsala 1980

Yeah, just gloat about your tail. It is still a Vavilov to me!
The **OPAL JET** Chamber

The chamber is 4 m long with an inner diameter of 0.5 m and an outer diameter of 3.7 m. The sensitive volume is divided into 24 identical sectors, each containing a plane with 159 sense wires.
Separation from pions in standard deviations for different particle types as a function of momentum.
The DELPHI Time Projection Chamber

http://pubxx.home.cern.ch/pubxx/tasks/hadident/www/dedx/#A1.5.1
L3 Time Expansion Chamber

inner radius  90 mm
outer radius  457 mm
with 62 sense wires.

Truncated mean at  80%  and  > 50 wires.
The calorimeters were built to have good position and energy resolution.

- The position resolution is needed for the precise determination of the acceptance of the calorimeter.
- The energy resolution is needed to distinguish true Bhabha events from the off-momentum beam particles which contribute to the background.

**Silicon–Tungsten calorimeters**

In sampling calorimeters the
- Particle absorption
- Shower sampling
  
is separated. This can give an optimal choice for converter material and position determination.

\[
\frac{\delta \sigma^{acc}}{\sigma^{acc}} = \frac{2 \delta R}{R_{min}} \left(1 + \frac{R_{min}^2}{R_{max}^2 - R_{min}^2}\right)
\]

\[
\leq 1 \% \quad \rightarrow \quad \leq 30 \mu m
\]

The calorimeters were built to have good position and energy resolution.

**OPAL CERN–EP–99–13**
The ultimate limit of the absolute luminosity measurement is defined by the knowledge of the absolute radial position of the silicon pads and the absolute distance between the calorimeters.

$\Delta \phi$ distribution for real and MC. Background: Off momentum and (mainly) t-channel 2/3 hard $\gamma$ in the detector frame.

These Luminometers have made a dramatic improvement of our ultimate knowledge of the $Z^0$ couplings.
Have we learnt something which should be passed over to the next generation experiments?
The years of LEP have taught us a lot about Detectors and more than what we have deserved about detector systems.

- Accessibility
- Ease of operation
- Ease of calibration
- Ease of trouble shooting

and above all

In order to have excellent and consistent data

Stability

and more Stability

If these functions are not built into the systems from the very start, it is hard to get them in afterwards.
Thanks to all who have helped me in putting together this talk.
Excuses to everybody who should have been mentioned and have not.
Special thanks to the cartoonists of this world and in particular to Edvard Munch who did, without knowing, so perfectly painted the coming of the LHC.