Calorimetry at $\text{e}^+\text{e}^-\text{C}olliders$

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Introduction
Physics Requirements
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Physics Requirements

e\pm  Identification  
[ semi-leptonic decays;  
W, Z decays;  Higgs ]

\gamma  Detection  
[ quarkonium spectroscopy;  
\pi^0, \eta, ... detection ]

Energy Flow  
[ parton kinematics, supersymmetry searches, \nu - kin. ]

Luminosity Measurements  
[ \Gamma(\pi^0 \rightarrow X), tests of SM, m_w ]

Pion - Muon Discrimination  
[ \gamma \gamma \rightarrow \pi^+ \pi^-, test of QCD ]
**e⁺e⁻ Facilities**

Have a dozen experiments at ½ dozen colliders.
CM energies 1 - 180 GeV.
All experiments have em cal.
Different techniques chosen by collaborations, even at same
CM energy:
Trade-off between tracking (magnet!) and calorimetry.

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**e⁺e⁻ Identification**

CLEO
CsI em calorimeter
7800 X-tals
projective, 50x50 mm²
18% X₀ material
4 diodes / X-tal
0.5% precision day-to-day $e^+e^- ightarrow e^+e^-$ for absolute cal.

EG&G Xenon Flasher

[Diagram of the flasher system]

a) Schematic of the flasher system

- diodes
- Schottky noise
- ADC
random trigger

E-deposit:

\[ E_{\text{req}} \geq 1 \]

\[ \text{Xtal with } E_{\text{req}} \geq 10 \text{ MeV} \]

\[ \frac{E}{p} \]

Also: lateral shower size

\[ \frac{E_9}{E_{25}} \]
Results (CLEO)

Absolute calibration maintained to ± 0.25%.

\[
\frac{\sigma_E}{E} = \frac{0.35}{E^{0.78}} + 1.9 - 0.1E \% \quad \text{(barrel)}
\]

\[
= \frac{0.26}{E} + 2.5 \% \quad \text{(endcaps)}
\]

\[
\sigma_{\phi} = \frac{2.8}{\sqrt{E}} + 1.9 \quad \text{mrad (barrel)}
\]

\[
= \frac{3.7}{\sqrt{E}} + 7.3 \quad \text{mrad (endcaps)}
\]

\[
\sigma_\phi = 0.8 \sigma_{\phi} \sin \theta \quad \text{mrad (barrel)}
\]

\[
= \frac{1.4}{\sqrt{E}} + 5.6 \quad \text{mrad (endcaps)}
\]
\( \gamma \) - Detection

CLEO: only 1/1000 B's can be reconstructed fully using charged tracks only.

Recent results on two-body B-decays require \( \pi^0, \eta, \eta' \)....
CLED

\[ \pi q, \gamma \) Reconstruction

\[ 0 < p_{\gamma \gamma} < 0.5 \]

\[ 0.5 < p_{\gamma \gamma} < 1.0 \]
\( \sigma \sim 5 \text{ MeV} \)

\[ 1.0 < p_{\gamma \gamma} < 2.0 \]

\[ p_{\gamma \gamma} > 2.0 \]

Number of Events (Thousands)

\( \gamma \gamma \) Invariant Mass (MeV)
Energy Flow

\[ m_w \rightarrow \text{jet} \, 1 + \text{jet} \, 2 \]

\[ H^\pm \rightarrow \text{jet} \, 1 + \text{jet} \, 2 \]

\[ \nu - \text{kinematics} \]

Algorithms use EM and had calorimeters

ALEPH
The ALEPH Detector
Figure 3: An event with a W pair decaying to $\mu\nu qq$. 

hadronic W mass = 81.1 GeV
leptonic W mass = 79.1 GeV
missing momentum = 39.8 GeV
EM Calorimeter

- lead absorber
- wire chamber readout:
  74,000 projective towers
  cathode pads (30 x 30 mm$^2$ or 0.9 x 0.9)
  wires readout
  3 depth segments (4, 9, 9 X$_0$)
- calibration:
  gas gain to 0.3% (Fe$^{55}$ source)
  absolute calibration:
  ee $\rightarrow$ eeee $\quad$ 1 - 10 GeV
  ee $\rightarrow$ ee $\quad$ 45 - 90 o,
got 0.3% at 45, 15% $E < 45$ GeV
- linearity: $E_{corr} = E (1 + 0.78 \times 10^{-3} E)$
- resolution: $\frac{\sigma_E}{E} = \frac{18}{\sqrt{E}} + 0.9 \%$
  [or $\frac{\sqrt{17.8}}{\sqrt{E}} \oplus 1.9 \%$]
Hadron Calorimeter

- iron absorber
- plastic streamer tube readout:
  23 layers over 7.2 int lengths
  4,788 projective towers (3.7° x 3.7°)
  capacitive readout
  wire readout (redundancy)

- calibration:
  gas gain to 0.4%
  inter tower calibration
  with \( Z \rightarrow \text{hadrons} \)
  absolute calibration with \( \mu \) from \( Z \)

- resolution:
  \[
  \frac{\Delta E}{E} = 85\%
  \]
ALEPH

"cleaning"

After cleaning \( \langle E \rangle = 15 \text{ MeV} \)

Before cleaning \( \langle E \rangle = 1 \text{ GeV} \)
Energy Flow Algorithm

- Cleaning:
  1/3 of events have fake E-dep. up to 30 GeV, $\langle E \rangle = 1$ GeV, flagged by comparing pads and wire signals

- Correlate tracks and calorimeter clusters; build "cal. objects"

- $e^{\pm}$: remove from cal.obj
  $\mu^{\pm}$: idem
  $\gamma, \pi^{0}, \eta$: idem

Remainder is hadronic energy

- Use different calibration constants for each category / detector
ALEPH
remove cuts with $E_{dep}$ "near" beam:
Calibrate method with $e^+e^- \rightarrow \gamma j_1 j_2$

$\Delta m(j_1 j_2) = 5 - 2E_j/\sqrt{s}$

![Graph showing data points and a fitted curve]

$m_{\text{VIS}} - m_r$

$\sigma(m_{\text{VIS}})$

Resolution on $M_{\text{EE}}$
Resolution on $M_{\text{M5}}$

$E_j \approx 0.39\sqrt{E+0.5} \text{ GeV}$

$\chi^2 = e^{-0.5}$ for 3 d.o.f.
Luminosity Measurement

20 physics requires best ever precision.
ALEPH's SICAL: goal = 1%

Dominating source of error:
θ_min definition requires 30μm radial position control.
24 X₀ with 12 longitudinal samples
W absorber (X₀ = 3.5 mm).
Si readout (<X₀> = 5.2 mm).
Granularity: rotate each subsequent layer up by 1/3 pad width.

Trigger: use 2 redundant triggers (odd layers and even layers).
Figure 1: Section view of one SICA1 calorimeter. The twelve sampling layers are formed from W, Si, W mininmodules which are supported internally on rods passing through G-10 and aluminum support plates.
Figure 2: Silicon detector. Sectors (2 x 11.25°) are cut from 300μm thick, 10 cm diameter, high resistivity wafers. The rounded lower radial edge is laser cut. Radial pad width is 5.225mm.
Figure 23: Distribution of the $\phi$-difference $\Delta\phi$ between the "tight-side" and "loose-side" clusters. Data are plotted as points and the Monte Carlo (without background) is shown as a line.
$\sigma_{WW}/\text{pb}$

**ALEPH**

Gentle v2

$M_W = 80.20 \pm 0.33 \text{ GeV/c}^2$
\[ d_i = \Delta z_i \sin \theta \]

\[ \Delta z_i = z_i - z_{cog} \]
\[ \pi - \mu \text{ Discrimination} \]

\[ \gamma\gamma \rightarrow \pi^+\pi^- \text{ is test of QCD at large values of } m(\pi^+\pi^-) \text{ but } \gamma\gamma \rightarrow \mu^+\mu^- \text{ is } >1000 \text{ times larger} \]

Muon detectors have small inefficiency.

CLEO: use shower shape
Bending in \((r,y)\) so use \((r,z)\).
Calibrate with \( \gamma\gamma \rightarrow \mu^+\mu^- \) and \( \pi^+ \)'s from:

\[ \pi^+ \pi^- 1\text{-prong vs } \rho^\pm \]

\[ \gamma\gamma \rightarrow \pi^+\pi^-\pi^+\pi^- \]

\[ K_S \rightarrow \pi^+\pi^- \]

Require \(\geq 1\) track to interact:
75\% efficient and factor 350 rejection of \(\mu^+\mu^-\)
Figure 12.8: Scatter plots of the total matched CsI energy versus the shower width for muons (a) and pions (b). A particle is tagged as a hadron if $E_{CC} > 400$ MeV and $R_z > 3.5$ cm.

Figure 12.9: The energy deposit distribution (a) and shower width distribution (b) for muons in the momentum interval 2 to 3 GeV/c. The arrows denote the cuts used to select pions.
Figure 12.10: The efficiency for $\pi^+$ (a) and $\pi^-$ (b) to satisfy the shower tag as a function of momentum. Data shown include pions from $\rho^\pm$ decays (solid circles), $K_S^0$ decays (empty squares), and $4\pi$ events (empty circles).

Figure 12.11: Comparison of data (solid circles) and Monte Carlo (histogram) for the efficiency for $\pi^+$ (a) and $\pi^-$ (b) to satisfy the shower tag as a function of momentum.
(Near) Future

BaBar: CsI (similar to CLEO)

KLOE: lead absorber, fiber readout

\[ \frac{e^{-}}{e^{+}} = 4.7 \% \]
Conclusions

- CsI (and BGO) em calorimeters work very well, all aspects of technology under control.
- Other techniques work too if care is taken.
- Parton kinematics in 3-dim, not just in transverse plane.
- Immediate future: KLOE \(^\varphi\)-factory
  - CLEO \(\Xi\)
  - BaBar \(B\)-factory
  - BELLE
- NLC ?!\(*\).