The Art of Calorimetry

Gabriella Gaudio, Michele Livan

Pavia University and INFN

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Main focus on the physics of calorimetric measurements, very little on calorimetric techniques

Topics:

- Introduction to calorimetry
- The development of electromagnetic and hadron showers
- Energy response and compensation
- Fluctuations
- The state of the art (towards ILC calorimetry)
- The DREAM R&D
References


- Wigmans, R. *Calorimetry.* 
  *Proceeding of the 10th ICFA School on Instrumentation in Elementary Particle Physics. Itacuruça, Brazil, December 2003.*
  *AIP Conference Proceedings - Volume 674*
Aknowlegments

These lectures are an enlarged version of lectures given by Richard Wigmans at the Pavia University in 2007.

Thanks to Richard for allowing me to use his lectures as a starting point.
Introduction to Calorimetry
The term Calorimetry finds its origin in thermodynamics.

Calorimeters are thermally isolated boxes containing a substance to study.

Modern, highly sophisticated versions, are in use in nuclear weapons Laboratories.

- $^{239}$Pu produces heat at a rate of 2 mWatts/g.

- Calorimetry can provide an accurate measurement of the amount of Plutonium in a non-invasive way.
In nuclear and particle physics, calorimetry refers to the detection of particles, and measurements of their properties, through total absorption in a block of matter, called *calorimeter*.

Common feature of all calorimeters is that the measurement process is *destructive*.

Unlike, for example, wire chambers that measure particle properties by tracking in a magnetic field, the particles are no longer available for inspection once the calorimeter is done with them.

The only exception to this rule concerns *muons*. The fact that muons can penetrate substantial amounts of matter (as a calorimeter) is an important mean for muon identification.

In the absorption process, almost all the particle’s energy is eventually converted to *heat*, hence the term calorimetry.
LHC beam: Total stored energy

\[ E = 10^{14} \text{ protons} \times 14 \times 10^{12} \text{ eV} \approx 1 \times 10^8 \text{ J} \]

Which mass of water \( M_{\text{water}} \) could one heat up (\( \Delta T = 100 \text{ K} \)) with this amount of energy (\( c_{\text{water}} = 4.18 \text{ J g}^{-1} \text{ K}^{-1} \))?

\[ M_{\text{water}} = \frac{E}{c \Delta T} = 239 \text{ kg} \]

What is the effect of a 1 GeV particle in 1 liter of water (at 20° C)?

\[ \Delta T = \frac{E}{c \cdot M_{\text{water}}} = 3.8 \times 10^{-14} \text{ K} \]

1 calorie \( \approx 10^7 \text{ TeV} \! \)

The rise in temperature of the calorimeter is thus negligible \( \Rightarrow \) More sophisticated methods are needed to determine particle properties.
Nuclear radiation Detectors

- First calorimetric measurements: late 1940’s
  - fluorescence, invention of PMT, anthracene and NaI
  - $\alpha$, $\beta$ and $\gamma$ from nuclear decays
- Semiconductor detectors developed in the ‘60s
  - Li doped Si and Ge crystals

$\gamma$-ray spectrum from Uranium nuclei measured with scintillation and semiconductor detectors. Semiconductor technology offers spectacularly improved resolution.
Calorimetry in Particle Physics

- Calorimetry is a widespread technique in Particle Physics:
  - Shower counters
  - Instrumented targets
  - Neutrino experiments
  - Proton decay/Cosmic Ray detectors
  - $4\pi$ detectors (our main topic)

- Calorimetry makes use of various detection mechanisms:
  - Scintillation
  - Ionization
  - Čerenkov radiation
  - Cryogenic phenomena
Shower counters I

- Primary use in early experiments: measure $\gamma$s from $\pi^0 \rightarrow \gamma\gamma$
  - Alternate method: use sheets of material to convert photons into $e^+e^-$ pairs $\Rightarrow$ low efficiency

- NaI(Tl) (hygroscopic), CsI and many other types of scintillating crystals
  - High light yield $\Rightarrow$ excellent energy resolution
  - Scintillation light has two components: fast and slow.
  - Decay time of slow component can be quite sizable (230 ns in NaI)

- In the 60's development of shower counters (Pb-Glass) based on Čerenkov light production.
  - High-density material but light yield several orders of magnitude smaller than for scintillating crystals $\Rightarrow$ worst energy resolution
  - Čerenkov light instantaneous $\Rightarrow$ extremely fast signals
Shower counters II

- **Homogeneous calorimeters:**
  - Scintillating crystals and Pb-Glass
  - Entire volume is sensitive to particles and may contribute to the signal

- **Sampling calorimeters:**
  - The functions of particle absorption and signal generation are exercised by different media:
    - **Passive medium:** high density material (Fe, Cu, Pb, U, ....)
    - **Active medium:** generates light or charge that produce the signal
      - Scintillator, gas, noble liquids, semiconductors,............
  - Only a small fraction of the energy is deposited in the active material ⇒ worse energy resolution (at least for electrons and γs)
  - Cheaper ⇒ used in large systems
Instrumented targets

✦ Bubble chambers: both target and detector

✦ Electronic detectors: the two functions are usually separated.
  ✦ Target
  ✦ Detector
  ✦ Determine if interesting interactions are taking place in the target (Triggering)
  ✦ Measure the properties of the reaction products

✦ Instrumented targets: combination of the functions of target and detector are maintained
  ✦ Neutrino experiments
  ✦ Proton decay experiments
  ✦ Cosmic Rays experiments
Neutrino experiments

- Cross section for neutrino induced interaction:
  \[ \sigma \sim 10^{-41} \times E[MeV] \ cm^2 \]

- \( \nu \) interaction probability in a 1 kTon detector \( \approx 10^{-9} \)
  \[ \Rightarrow \text{intense beams and very massive detectors} \]

- Example WA1 (CDHS: CERN-Dortmund-Heidelberg-Saclay Neutrino experiment)

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**Slabs of Fe (absorber) interleaved with layers of scintillator.**
In the rear: wire chambers to track muons generated in charged currents interactions and/or charmed particles production.
Cosmic Rays

- Cosmic Rays experiments deal with a number of different phenomena. Among them:
  - Atmospheric neutrinos
    - Result of the decay of $\pi$ and $K$ in the Earth atmosphere
  - Solar neutrinos
    - Produced in the nuclear fusion of H into He and some higher-order processes
  - High Energy Cosmic Rays
    - Energies up to 1 Joule ($6 \cdot 10^{18}$ eV)
  - Very large instrumented masses are needed

KASCADE Cosmic ray experiment near Karlsruhe (Germany). Large TMS (Tetramethylsilane) calorimeter located in the central building, surrounded by numerous smaller, plastic-scintillator counters to detect ionizing particles.
Proton decay

✦ In many theories Barion Number conservation breaks down ⇒ proton decay is allowed

✦ Current experimental limit on the proton lifetime based on the decay $p \rightarrow e^+ \pi^0$ is $> 10^{32}$ years

✦ Need for large instrumented mass ($300 \text{ m}^3$ of water = $10^{32}$ protons)

SuperKamiokande

Water Čerenkov calorimeter:
- Enormous volume of high purity water viewed by large number of photomultipliers: $p \rightarrow e^+ \pi^0$ decay produces 5 relativistic particles, the positron and two $e^+ e^-$ pairs from the two $\gamma$s from the $\pi^0$ decay.
- The energy carried by these particles adds up to the proton rest mass, 938.3 MeV.
4π detectors

- Onion-like structure
  - Tracking
  - (Particle ID)
  - Electromagnetic Calorimetry
  - Hadronic Calorimetry
  - Muon spectrometry

hermeticity: fraction covered by the detector (<100% always)
Why Calorimeters?

- Sensitive to both charged and neutral particles
- Differences in the shower patterns $\Rightarrow$ some particle identification is possible (h/e/µ/ν (missing $E_T$) separation)
- Calorimetry based on statistical processes
  - $\Rightarrow \sigma(E)/E \propto 1/\sqrt{E}$
  - Magnetic spectrometers $\Rightarrow \Delta p/p \propto p$
- Increasing energy $\Rightarrow$ calorimeter dimensions $\propto \log E$ to contain showers
- Fast: response times $< 100$ ns feasible
- No magnetic field needed to measure $E$
- High segmentation possible $\Rightarrow$ precise measurement of the direction of incoming particles
Particle Identification

Particle Identification

Particle Identification

Particle Identification
e/π separation
(No longitudinal segmentation !)

Exploit differences in time structure of electromagnetic and hadronic calorimeter signals
★ electron signals rather identical
★ pions signals exhibits a variety of shapes
   ★ fluctuations in shower starting point and shower development

★ Example
★ SPACAL: measurement of signal width at fixed fraction of the amplitude (e.g. 20%)
Why Calorimeters?

✦ Sensitive to both charged and neutral particles
✦ Differences in the shower patterns ⇒ some particle identification is possible (h/ e/µ/ν(missing $E_T$) separation)
✦ Calorimetry based on statistical processes
  ✦ ⇒ $\sigma(E)/E \propto 1/\sqrt{E}$
  ✦ Magnetic spectrometers ⇒ $\Delta p/p \propto p$
✦ Increasing energy ⇒ calorimeter dimensions $\propto \log E$ to contain showers
✦ Fast: response times < 100 ns feasible
✦ No magnetic field needed to measure E
✦ High segmentation possible ⇒ precise measurement of the direction of incoming particles
Why Calorimeters?

✦ Moving from fixed target to (Hadron) Colliders emphasis:

✦ from detailed reconstruction of particle four-vectors

✦ to energy flow (jets, missing $E_T$) especially when observed in combination with electrons and muons
The importance of energy resolution

a (not the only) key feature for multi-jet spectroscopy
★ jets become more collimated as energy increase
★ jets is often the preferred decay product of heavy particles

![Graphs showing two-jet invariant mass distributions from the UA2 experiment](image)

**Fig. 7.50.** Two-jet invariant mass distributions from the UA2 experiment [Alit 91]. Diagram a) shows the measured data points, together with the results of the best fits to the QCD background alone (dashed curve), or including the sum of two Gaussian functions describing $W, Z \rightarrow q\bar{q}$ decays. Diagram b) shows the same data after subtracting the QCD background. The data are compatible with peaks at $m_W = 80$ GeV and $m_Z = 90$ GeV. The measured width of the bump, or rather the standard deviation of the mass distribution, was 8 GeV, of which 5 GeV could be attributed to non-ideal calorimeter performance [Jen 88].
Partons ⇒ Particles ⇒ Jets

- Processes creating jets are very complicated, and consist of parton fragmentation, then both electromagnetic and hadronic showering in the detector.
- Reconstructing jets is, naturally, also very difficult. Jet energy scale and reconstruction is one of the largest sources of systematic errors.
In jet detection also factors other than calorimeter resolution play an important role: the jet algorithm and the contributions of underlying events to the signal. This effect becomes less important as energy increases and jets become more collimated. At high energy e+e- Colliders high resolution jet measurement will become reality.

**FIG. 45.** The hadronic energy resolution of three calorimeter systems and the contribution of a typical jet-defining cone algorithm to the jet energy resolution, as a function of energy.
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- Ionization
- Čerenkov radiation
- Cryogenic phenomena
Scintillators and Light Detectors

HPD

SiPM

Pixel size:
~25 x 25 \(\mu m^2\) to ~100 x 100 \(\mu m^2\)

Array size:
0.5 x 0.5 \(\mu m2\) to 5 x 5 \(\mu m2\)
Wavelength shifters
Scintillating fibers

- wavelength shifter (WLS) bars
  - small air gap
  - WLS
  - green Photo detector
  - blue (secondary)
  - UV (primary)
  - primary particle

WLS bars/fibres
- plastic scintillators

\[
\frac{d\Omega}{4\pi} = 0.5 (1 - \cos^2 \theta) = 3\%
\]
\[\theta \leq \arccos \frac{n_2}{n_1} \approx 69.6^\circ\]
Ionization

✦ Gas Calorimeters
  ✦ Bad resolution
  ✦ Landau fluctuations
  ✦ Pathlength fluctuations

✦ Noble liquids
  ✦ Potentially slow
  ✦ Liquid purity problems
  ✦ Stable calibration

✦ Semiconductors
  ✦ Excellent resolution
  ✦ Fast
  ✦ Expensive
Čerenkov radiation

- minor source contributing to particle energy loss
- sensitive to particle velocity
- instantaneous

**Pb-Glass**
**OPAL**
**LEP**

**Quarz Fibers**
**DREAM**
**R&D for ILC**

**BUT**
Cryogenic phenomena

- Highly specialized detectors
  - Dark matter, solar \( \nu \)s, magnetic monopoles, double \( \beta \) decay
  - Require very precise measurements of small energy deposits
  - Exploits phenomena that play a role in the 1 Kelvin to few milli-Kelvin range

- Bolometers
  - Real calorimeters: temperature increase due to E deposit is measured by a resistive thermometer

- Superconducting Tunnel Junctions
  - Use Cooper pairs excited by incident radiations that tunnel through a thin layer separating two superconductors

- Superheated Superconducting Granules
  - Use transition from superconducting to normal state induced by energy deposition
Choosing a calorimeter

- **Many factors:**
  - Choices: active, passive materials, longitudinal and lateral segmentation, readout etc.
  - Physics, radiation levels, environmental conditions, budget

- **CAVEAT: Test beam results sometimes misleading**
  - Signals large integration time or signal integration over large volume could be not possible in real experimental conditions
  - Miscellaneous materials (cables, support structures, electronics etc.) present in the real experiment can spoil resolution
  - Jet resolution not measurable in a test beam
Basic Electromagnetic Interactions
(reminder)

- Ionisation
- Bremsstrahlung
- Photoelectric effect
- Compton effect
- Pair production
Energy loss by charged particles

- **Main energy loss mechanism for charged particles traversing matter:**
  - Inelastic interaction with atomic electrons
  - If the energy is sufficient to release atomic electrons from nuclear Coulomb field ⇒ **ionization**

- **Other processes:**
  - Atomic excitation
  - Production of Čerenkov light
  - At high energy: production of δ-rays
  - At high energy: bremsstrahlung
  - At very high energy: nuclear reactions
The Bethe-Block Formula

\[
\frac{dE}{dx} = -4\pi N_A r_e^2 c^2 z^2 \frac{Z}{A} \beta^2 \left[ \frac{1}{2} \ln \frac{2m_e c^2 \gamma^2 \beta^2}{I^2} \right]^{\text{max}} - \beta^2 - \delta
\]

- \(dE/dx\) in \([\text{MeV g}^{-1}\text{cm}^2]\)
- Valid for “heavy” particles
- First approximation: medium simply characterized by \(Z/A \sim\) electron density
Interaction of charged particles

✦ Energy loss by Bremsstrahlung

✦ Radiation of real photons in the Coulomb field of the nuclei of the absorber medium

\[-\frac{dE}{dx} = 4\alpha N_A \frac{Z^2}{A} z^2 \left(\frac{1}{4\pi\varepsilon_0 mc^2}\right)^2 E \ln\frac{183}{Z^3} \propto \frac{E}{m^2}\]

✦ For electrons:

\[-\frac{dE}{dx} = 4\alpha N_A \frac{Z^2}{A} z^2 r_e^2 E \ln\frac{183}{Z^3}\]

\[-\frac{dE}{dx} = \frac{E}{X_0} \implies E = E_0^{1 - \frac{x}{X_0}}\]

\[X_0 = \frac{A}{4\alpha N_A \frac{Z^2}{A} z^2 r_e^2 E \ln\frac{183}{Z^3}}\]

radiation length \([g/cm^2]\)
Interaction of charged particles

★ Critical energy $E_c$

$$\frac{dE}{dx}|_{\text{Brems}} = \frac{dE}{dx}|_{\text{ion}}$$

★ For electrons:

$$E_c^{\text{solid+liq}} = \frac{610\text{MeV}}{Z + 1.24} \quad E_c^{\text{gas}} = \frac{710\text{MeV}}{Z + 1.24}$$

$E_c(\text{e}^-)$ in Cu ($Z=29$) = 20 MeV

★ For muons $E_c^{\mu} = E_c^{\text{elec}} \left(\frac{m_\mu}{m_e}\right)^2$

$E_c(\mu)$ in Cu = 1 TeV

★ Unlike electrons, muons in multi-GeV range can traverse thick layers of dense matter.
Energy loss by charged particles

![Graph showing energy loss by charged particles.](image)
In order to be detected a photon has to create charged particles and/or transfer energy to charged particles.
Interaction of photons

✦ Photoelectric effect

✦ Most probable process at low energy

✦ P.e. effect releases mainly electrons from the K-shell

✦ Cross section shows strong modulation if \( E_\gamma \approx E_{\text{shell}} \)

\[
\sigma^K_{\text{photo}} = \left( \frac{32}{\epsilon^7} \right)^{1/2} \alpha^4 Z^5 \sigma^e_{\text{Th}} \quad \epsilon = \frac{E_\gamma}{m_e c^2} \quad \sigma^e_{\text{Th}} = \frac{8}{3} \pi r_e^2 \quad (\text{Thomson})
\]

✦ At high energies (\( \epsilon \gg 1 \))

\[
\sigma^K_{\text{photo}} = 4\pi r_e^2 \alpha^4 Z^5 \frac{1}{\epsilon}
\]
Photoelectric effect
Interaction of photons

- Compton scattering
- Assume electrons quasi-free
- Klein-Nishina
- At high energy approximately
  \[ \sigma^e_c \propto \frac{\ln \epsilon}{\epsilon} \]
- Atomic Compton cross-section
  \[ \sigma^{\text{atomic}}_c = Z \sigma^e_c \]
  \[ \sigma_{\text{Compton}} \propto E^{-1} \]
Compton Scattering

- For all but the high Z materials: most probable process for $\gamma$s in the range between few hundred keV and 5 MeV
- Typically at least 50% of the total energy is deposited by such $\gamma$s in the absorption process of multi GeV $e^+$, $e^-$ and $\gamma$s
- Compton scattering is a very important process to understand the fine details of calorimetry
- Angular distribution of recoil electrons shows a substantial isotropic component. Many $\gamma$s in the MeV range are absorbed by a sequence of Compton scatterings $\Rightarrow$ most of the Compton electrons produced in this process are isotropically distributed
Angular distribution

1 GeV electrons in SPACAL
(Pb/scifi, $\theta = 3^\circ$)

$\gamma \rightarrow e^+e^-$

Compton, photoelectrons

Fig. 2.39. Angular distribution of the shower particles (electrons and positrons) through which the energy of a 1 GeV electron is absorbed in a lead-based calorimeter. Results of EGS4 Monte Carlo simulations. From [Aco 90].
Interaction of photons

✧ **Pair production**

✧ Only possible in the field of a nucleus (or an electron) if:

✧ \( E_\gamma > 2m_ec^2 \)

✧ Cross-section (High energy approximation)

\[
\sigma_{\text{pair}} \approx 4\alpha e^2 Z^2 \left( \frac{7}{9} \ln \left( \frac{183}{Z^4} \right) \right)
\]

\[
\approx \frac{7}{9} \frac{A}{N_A} \frac{1}{X_0}
\]

\[
\approx \frac{A}{N_A} \frac{1}{\lambda_{\text{pair}}}
\]

\[
\lambda_{\text{pair}} = \frac{9}{7} X_0
\]

\( \gamma + \text{nucleus} \rightarrow e^+ e^- + \text{nucleus} \)
Summary

\[ \mu = \gamma \text{ mass attenuation coefficient} \]

\[ I_\gamma = I_0 e^{-\mu x} \quad \mu_i = \frac{N_A}{A} \sigma_i \]

\[ \mu = \mu_{\text{photo}} + \mu_{\text{compton}} + \mu_{\text{pair}} + \ldots \]

Gammas

Electrons
Summary (Z dependence)

- Ionisation
- Bremsstrahlung
- Photoelectric effect
- Compton effect
- Pair production

\[ \frac{Z(Z+1)}{E} \]
\[ Z^\frac{4}{5} \]
Z dependence

**Gammas**

**Electrons**

- **30 MeV**
- **95 MeV**
- **28 MeV**
- **9 MeV**
- **4.6 MeV**
- **0.7 MeV**
- **0.12 MeV**

- **Energy loss by ionization**
- **Energy loss by radiation**

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Photon absorption

Energy domains in which photoelectric effect, Compton scattering and pair production are the most likely processes to occur as a function of the Z value of the absorber material.