Seventy Years of Calorimetry

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Abstract. In this opening talk of the CALOR 2016 conference, I briefly review some milestones in the history of calorimetry as a detection technique in particle physics. I also discuss common misconceptions, which are unfortunately widespread, and give you my personal outlook on the future.

1. Introduction

We are gathered here in Daegu for the 17th edition of the CALOR conference series, which started in 1990 at Fermilab. Calorimeters have become the heart and soul of practically all modern experiments in high-energy accelerator experiments. They are also playing a very important role in experiments that study natural phenomena, such as high-energy cosmic rays and neutrinos of solar, atmospheric and cosmic origin. In this opening talk, I will briefly review 70 years of calorimetry as a particle detection technique, by discussing some of the milestones in this history. The rest of my talk is devoted to a discussion of a few misconceptions that are unfortunately all too common. I’ll finish with my personal outlook on the future of this exciting field.

2. Milestones

2.1. Nuclear $\gamma$-ray detectors

The use of calorimeters as particle detectors was pioneered in nuclear physics, where crystals such as NaI(Tl) were already used as $\gamma$-ray detectors in the early 1950s. A first milestone occurred around 1965, when semiconductor detectors made their appearance. Figure 1 illustrates how the much larger number of signal quanta available in such detectors improved the energy resolution and led to a revolution in experimental nuclear physics. Nowadays, one can do even much better with certain cryogenic devices, which are based on the detection of Cooper pairs, whose binding energy is typically three orders of magnitude smaller than the energy needed to create an electron-hole pair in silicon or germanium. The resolution of all these calorimeters is dominated and limited by Poissonian signal quantum fluctuations, and thus scales like $E^{-1/2}$. This is typically not the case in calorimeters used for particle physics experiments, where the energies are measured in units of GeV, and increasingly in TeV. Sampling fluctuations, which also lead to a $E^{-1/2}$ energy dependence, typically dominate the energy resolution of electromagnetic sampling calorimeters, but especially in hadron calorimeters the energy resolution is limited by other factors.
Nuclear $\gamma$ ray detectors

Energy resolution dominated by signal quantum fluctuations (?)

Figure 1. Nuclear $\gamma$-ray spectrum of decaying uranium nuclei, measured with a BGO scintillation counter (upper curve) and with a high-purity Ge crystal (lower curve).

2.2. Shower counters

The first application of calorimeters in particle physics experiments occurred around 1970. They were called shower counters and were used in magnetic spectrometers to detect the particles that produced no signals in the tracking detectors, mainly $\gamma$s from $\pi^0$ decay. Figure 2 shows an example of such a spectrometer, used in Fermilab experiment E-70, which discovered the $\Upsilon$ family of $b\bar{b}$ resonances. The calorimeters used in this experiment were made of lead glass, a popular material in this type of application, where the calorimeters had a very limited and specific task.

Figure 2. The magnetic spectrometer of Fermilab experiment E-70 [1].
2.3. Instrumented targets

During the mid-1970s, both Fermilab and CERN started experiments with neutrino beams. The detectors used for these experiments were essentially calorimeters, but they had very different and more elaborate tasks than the shower counters mentioned above. They acted at the same time as the target for the neutrino interactions and as the detector for the reaction products. Because of the very small cross section of the $\nu$-induced interactions, these detectors had to be very massive (kilotons). They were typically sampling calorimeters, where the target and detector tasks were carried out by separate materials, e.g., iron as absorber and scintillating plastic slabs as active material. It turned out that a properly chosen readout structure could also provide very effective triggers, which separated background events (e.g., caused by cosmic rays) from the rare neutrino induced beam events.

2.4. $4\pi$ calorimeters

Because of the successful performance of these instrumented neutrino targets, calorimeters also became crucial components of detectors at colliding beam experiments. Figure 3 shows the $4\pi$ calorimeter of the UA2 experiment at CERN’s proton-antiproton collider, where the intermediate vector bosons ($W, Z$) were discovered in 1983. This calorimeter was longitudinally segmented into a $17X_0$ deep em section

![Figure 3. The calorimeter used in the UA2 experiment at the CERN Sp0p collider][1].

(lead/plastic-scintillator), followed by two hadronic sections (iron/plastic-scintillator), each $2\lambda_{int}$ deep. The central calorimeter shown in this figure was segmented into 240 independent cells, each covering $10^\circ$ in the polar angle and $15^\circ$ in azimuth, and built in a tower structure pointing toward the center of the interaction region. It served as a model for many calorimeters that would follow in years to come.

2.5. Compensation

On a fundamental level, one of the main mysterious aspects of calorimetry was the poor performance for hadronic particle detection. While sampling calorimeters could achieve energy resolutions at the 1% level without too much difficulty for detecting electrons and photons, hadronic resolutions were worse by a considerable factor in the same instruments. In addition, calorimeters were typically nonlinear for hadron detection, gave a different response to protons and pions of the same energy and had asymmetric, non-Gaussian response functions. In an attempt to solve this issue by brute force, eliminating all possible instrumental effects, Benvenuti et al. built a homogeneous calorimeter consisting of 60 tonnes of liquid scintillator (Figure 4a) and tested it with beams of hadrons. However, the energy resolution of this
detector did not get better than $\sim 10\%$, at any energy (Figure 4b) [3]. Clearly, fluctuations in the number of scintillation photons produced in the shower development did not contribute significantly to the energy resolution of this instrument.

The reasons for the mentioned problems with hadron shower detection, and the solution to these problems, were discovered/developed in the second half of the 1980s. Key to the solution was to design the calorimeter in such a way that the response (average signal per unit deposited energy) was the same for the em and non-em components of hadron showers: $e/h = 1$. One detector in which this condition was realized is shown in Figure 5, which also shows the response function for pions at three different energies. In terms of hadronic energy resolution, this detector still holds the world record. The detector was also very linear for hadron detection, and the response functions were well described by Gaussian functions.

**Figure 4.** A calorimeter consisting of 60 tonnes of liquid scintillator (a), and the hadronic energy resolution measured with this detector (b).

**Figure 5.** The Spaghetti calorimeter built at CERN (1989), and hadronic response functions measured with this detector [4].
2.6. Dual-readout calorimetry
Compensating hadron calorimeters depend crucially on the contributions of the neutrons that are abundantly produced in hadronic shower development to the signals. This implies a small sampling fraction, and a relatively large signal integration time and volume. In order to circumvent these limiting conditions, while still benefiting from the important advantages offered by compensation, dual-readout calorimetry was developed. Dual-readout calorimeters provide two signals, e.g., light produced by scintillation and Čerenkov processes. These signals provide complementary information about the shower development, and make it possible to measure the em fraction of hadron showers event by event. This in turn makes it possible to eliminate the effects of event-to-event fluctuations in that em component on the calorimeter performance. The principle is illustrated in Figure 6, and was experimentally demonstrated in [5]. Until now, no full scale calorimeters of this type have been constructed, but

Figure 6. Measurement of the em energy fraction ($f_{em}$) and the energy of showering hadrons ($E$) on the basis of the measured ratio of the Čerenkov and scintillation signals ($Q/S$) from the DREAM copper/fiber calorimeter [5].

results obtained with 1-ton detectors, combined with Monte Carlo simulations, have indicated that the performance may be at least as good as that of the best compensating calorimeters, with better energy resolution for em showers.

2.7. Imaging calorimeters
Inspired by the development of the Time Projection Chamber, which allows tracking of charged particles in a three-dimensional volume, imaging calorimeters have been developed. These detectors, in which the particles are absorbed in a large volume of liquid argon, provide information about developing showers that rivals that of the bubble chambers of several decades ago. The difference is that this information is now provided fully electronically and does not have to be obtained by laborious scanning of photographs of the events. Figure 7 shows an example of an event in the imaging calorimeter of the ICARUS experiment, which pioneered this technique [6]. It is important to realize that, since calorimeters of this type only register charged shower particles, one should not expect hadronic energy resolutions at the level of that achieved with compensating or dual-readout calorimeters, which are specifically designed with high-quality calorimetric hadron detection in mind.
3. Misconceptions

3.1. Shower particles contributing to the calorimeter signals

The most common, important and consequential misconception about calorimetry is that a shower is a collection of minimum ionizing particles (mips). Already in the early days, it was realized that the signal from a high-energy electron absorbed in a sampling calorimeter was substantially different from that of a muon that traversed this calorimeter and deposited the same energy in it as the showering electron. This is due to the fact that the composition of the em shower changes as a function of depth, or age. In the late stages, most of the energy is deposited by soft $\gamma$s which undergo Compton scattering or photoelectric effect, and the sampling fraction for this shower component (i.e., the fraction of the energy that contributes to the calorimeter signals) may be very different from that of the mips that dominate the early stages of the shower development. This causes major complications for the intercalibration of the different sections of a longitudinally segmented calorimeter, as is well known from the experiences of, for example, ATLAS [7] and AMS [8], and will also have important consequences for applications of Particle Flow Analysis (PFA), which relies on calorimeters with many longitudinal segments.

Figure 8. Arrangement of the APDs used to read the signals from the CMS ECAL (a). A “spike” event recorded by the CMS calorimeter system (b). A typical nuclear interaction in a developing hadron shower, induced by a 0.57 GeV/c proton (c).

Another aspect of this problem is the fact that a single shower particle may cause catastrophic effects for the calorimeter performance. This is particularly true for hadron showers, and may be illustrated by a recent example taken from the CMS experiment. The CMS calorimeter system consists of a crystal based em calorimeter, followed by a brass/plastic-scintillator hadronic compartment. Each PbWO$_4$ crystal is read out by two APDs (Figure 8a). When hadrons are sent into this calorimeter system, it produces sometimes events in which an anomalously large signal is recorded in one individual crystal. Such events are referred to as “spikes” (Figure 8b). Figure 8c shows an example of a nuclear interaction that is a typical feature in hadron shower development. A proton with a momentum of 0.57 GeV/c interacts with a nucleus of the absorber structure, and produces seven even lower-energy charged particles, presumably...
protons and/or nuclear aggregates such as α particles in this process. Presumably, there are also at least as many neutrons produced in this reaction, but these do not ionize the material and are thus invisible in this figure. The charged fragments are all heavily ionizing, with typical $dE/dx$ values of 100 - 1000 times that of a mip. If such an event happens close to an APD, these charged fragments may create a very large signal. The APDs are intended to detect scintillation photons produced in the PbWO$_4$ crystals, and the energy scale of the calorimeter signals is set by the production rate of such photons. However, the APDs produce much larger signals when traversed by a charged particle. The densely ionizing fragments of an event such as the one shown in Figure 8c may produce signals that are interpreted as an energy deposit of several hundred GeV inside the scintillating crystals, and this is precisely what causes these spikes. As an aside, I mention that this phenomenon should be very easily recognizable if the two APDs connected to each crystal would be read out separately, since the described phenomenon would only occur in one of them. However, in order to save money, CMS had ganged them together and treated the two APDs as one readout cell.

3.2. Scaling of the energy resolution
Another widespread misconception concerns the energy resolution. Frequently, the relative energy resolution ($\sigma/E$) of a particular calorimeter is expressed as $x\%/\sqrt{E}$. However, this is rarely a correct description of reality, since in practice other factors, which are not governed by Poisson statistics, contribute to the energy resolution, and such factors often dominate the performance, especially at the low and high ends of the energy spectrum for which the detector is intended. As an example, Figure 9 shows the hadronic energy resolutions of the ZEUS and the ATLAS calorimeters. The experimental data points are plotted on a scale that is linear in $E^{-1/2}$ and runs from right to left. Scaling with $1/\sqrt{E}$ implies that the data points should be located on a straight line through the bottom right corner in this plot. This is indeed the case for the compensating ZEUS calorimeter, for which the resolution is quoted as $35%/\sqrt{E}$. However, the resolution of ATLAS does not at all scale with $1/\sqrt{E}$. As a matter of fact, the data points are at all energies located well above the $100%/\sqrt{E}$ line in this plot, and for energies larger than 100 GeV, the resolution is more than a factor of four worse than for ZEUS. Yet, in talks about ATLAS, the hadronic energy resolution is often quoted as $0.6 - 0.7/\sqrt{E}$.

Another common mistake with regards to energy resolution has to do with its very definition. The energy resolution is the precision with which the energy of an unknown object can be determined from...
the signals it produces in the calorimeter. Typically, this resolution is determined as the relative width of the signal distribution measured for a beam of mono-energetic particles from an accelerator. However, this is only correct if the average value of that measured signal distribution corresponds indeed to the correct energy of these particles. Response non-linearities tend to invalidate that assumption.

3.3. Signal (non)linearity
Calorimeters may be non-linear for a variety of reasons. Intercalibration of longitudinal sections, signal saturation and the energy dependence of the em shower fraction (in hadron showers) are the most common causes. Many calorimeters are non-linear, even though their owners often pretend otherwise.

A common misconception is that a calorimeter is linear if the average signals plotted versus the deposited energy can be described with a straight line. **This is incorrect.** The straight line has to extrapolate through the origin of the plot. Signal linearity means that the average calorimeter signal is proportional to the deposited energy, i.e., the response is constant. Figure 10 illustrates this issue.

![Figure 10](image)

**Figure 10.** Average signal as a function of electron energy for the W/Si ECAL built by CALICE (a) [11]. Residual signals from this detector, before and after taking out a 360 MeV offset (b). Non-linearity as a result of saturation effects in a digital CALICE calorimeter [12].

Diagrams a and b concern data obtained with a W/Si em calorimeter built by CALICE [11]. The authors fit the measured signals with the following expression:

$$E_{\text{mean}} = \beta E_{\text{beam}} - 360 \text{ MeV}$$

Then, they define

$$E_{\text{meas}} = E_{\text{mean}} + 360 \text{ MeV}$$

and plot

$$(E_{\text{meas}} - E_{\text{beam}})/E_{\text{meas}}$$

as a function of the beam energy. The result is represented by the (black) squares in Figure 10b. They conclude that **“the calorimeter response is linear to within approximately 1%.”** This is highly misleading. When the calorimeter signals they actually measured are used to check the linearity, i.e., when

$$(E_{\text{meas}} - E_{\text{beam}})/E_{\text{meas}}$$

is plotted as a function of the beam energy, the results, represented by the (red) full circles in Figure 10b, look quite different. I conclude from these results that the authors measured a response non-linearity of 5% over one decade in energy.

Whereas this type of nonlinearity is the result of the intercalibration of the numerous longitudinal segments of this PFA calorimeter, Figure 10c shows non-linearity with a different origin. It concerns
data obtained with a digital hadron calorimeter built by CALICE [12]. This calorimeter contains 500,000 readout cells ($1 \times 1 \text{ cm}^2$ RPCs), which produce “digital” signals (“yes” or “no”) in response to charged particles. However, this type of cell produces the same signal, regardless whether it is caused by 1, 3 or 29 shower particles. This leads to signal non-linearity, more so in em showers which are narrower than hadronic ones and where the shower particle density is thus larger. In this calorimeter, an important source of fluctuations is suppressed, and therefore also the energy resolution measured with it is meaningless.

3.4. Other misconceptions

Other widespread misconceptions concern

- The practical importance of compensation and its consequences, which are often regarded as limited to a \textit{constant term in the hadronic energy resolution} (which is incorrect by itself, since the effects of non-compensation are \textit{not} energy independent),
- The presumed equivalence of showers induced by $\gamma$s and electrons/positrons of the same energy
- The presumed equivalence of showers induced by protons, pions and kaons of the same energy, and
- The assumption that all calorimeter problems can be solved offline

For details on these issues, the reader is referred to the new edition of my book [13].

4. Outlook

Calorimetry has come a long way in the past seventy years. Much of what has been learned about the inner workings of these somewhat mysterious detectors has been the result of dedicated generic research & development projects, although the important contributions of work carried out in the ZEUS prototype phase definitely deserve an honorary mention in this context.

Unfortunately, times have changed. There are no longer significant resources available for this type of R&D. New experiments are designed based on somebody’s concept of what the detectors should look like, and prototype work primarily concentrates on technical aspects of that concept. This approach is followed, for example, in projects carried out in the CALICE framework, which is geared towards application of PFA at future electron-positron colliders [12]. Based on my observations, calorimetry research in this new era is characterized by ignorance, misconceptions (such as the ones discussed in the previous section) and a general lack of interest in fundamental issues, combined with a strong belief that all eventual problems can be solved with technology: the use of tungsten, silicon, RPCs must of course lead to better results, because this is a more modern approach than lead + plastic.

One experiment that experiences the consequences of this modern approach is CMS. Every component of the CMS calorimeter system suffers from design flaws that were preventable:

- The PbWO$_4$ crystals composing the ECAL are each read out with two APDs, which were ganged together and treated as one readout element. If these APDs had been read out individually, spike events (Figure 8), which will become an even more serious problem than they are already now when the luminosity and collision energy are further increased, could have been avoided.
- The signals from the hadron calorimeter are read out by “Hybrid Photon Detectors”, a technology that had never before been used on a comparable scale, and which turns out to have so many problems (e.g., with noise) that this calorimeter is at the present time barely useable, and the decision has been made to completely overhaul this readout system. These problems could have been avoided in the first place with several available low-tech options.
- The Very-Forward calorimeter (HF) has such a small sampling fraction that each photoelectron produced by Čerenkov light in the quartz fibers corresponds to 5 GeV energy deposit. As a result, this calorimeter is extremely sensitive to background effects, e.g., coming from beam halo muons traversing the PMTs. These produce signals consisting of dozens of photoelectrons and are thus interpreted as sources of very large energy deposits.
In a new development, CMS has decided to replace the endcap section of its calorimeter system, where the supposedly very radiation hard PbWO\(_4\) crystals have already been seriously damaged by radiation after \(\sim 1\%\) of the total expected lifetime dose, by a W/Fe/Si PFA calorimeter. Also this decision was not based on any serious prototype studies, and there are good reasons to believe that this is a disaster waiting to happen, comparable in scope (and cost) to the “warm-liquid upgrade” that meant the end of the UA1 experiment 30 years ago. Interestingly, some of the characters involved in this decision are the same.

Because of these developments, I think the future of calorimetry is bleak. Figure 11 depicts the quality of the calorimeters used in particle physics experiments as a function of time. This curve remarkably resembles a longitudinal shower profile. We have clearly passed the peak, and I am afraid that large-scale applications of PFA, such as envisaged in CMS, will set us back half a century, to the days of the magnetic spectrometers such as the one shown in Figure 2. PFA systems will actually be \(4\pi\) versions of the magnetic spectrometers from those days (Figure 2), albeit on a scale that is an order of magnitude more compact (4 m instead of 40 m), with all the problem associated with that, since showers develop irrespective of where the absorbing calorimeters are located.

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