Concluding Remarks

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Abstract. The International Conferences on Calorimetry in High Energy Physics, or the CALOR series, have always been where the calorimeter experts come together to review the state of calorimetry and bring forth new ideas every two years. The fifteenth conference, CALOR2012, in Santa Fe was no exception. Although they were built roughly a decade ago, we are now witnessing the exceptional power of the LHC calorimeters and the crucial role they have been playing in the discovery of the 125 GeV Higgs-like boson. As we ruminate on the coming generation of experiments at the next (linear) collider and on the upgrades at the LHC, we are heartened by the substantial advances we made in calorimetry in the last decade. These advances will certainly help uncover new physics in the years to come, not only at colliders but also in astroparticle experiments that take advantage of natural elements such as air, water, and ice.

I do not dare to review all the excellent contributions to this conference in a few pages, but instead offer a heuristic perspective of where we stand and the challenges we face in calorimetry today as depicted in Figure 1.

Many calorimeters were built based on scintillation light from solids, liquids, and gasses. Similarly, when Cherenkov radiation formed the basis of signal in em calorimeters, heavy crystals and glasses were often used. These two processes are in fact complementary, and if we put them together appropriately in a single calorimeter, one of the larger sources of fluctuations that degrade performance is naturally eliminated. The ratio of the Cherenkov ($Q$) to scintillation ($S$) signal is proportional to the electromagnetic fraction ($f_{em}$) in a shower, given that $e/h$ ratios for the scintillation and the Cherenkov part of the calorimeter are known separately. Because the fluctuations in $f_{em}$ can be measured on an event-by-event basis in this way, we are now able to eliminate its contribution to the energy resolution by simply measuring $Q/S$. This so-called dual-readout technique was pioneered by the DREAM collaboration in the last decade.

The separation of scintillation and Cherenkov photons can be accomplished in different ways. One can instrument an absorber with two different types of fibers (scintillating and clear) where the separation is accomplished by design, or one can exploit the different spectral characteristics of Cherenkov and scintillation light from a single transparent medium by means of optical filters. The pulse shape may also be exploited if the temporal features of these signals are sufficiently different, e.g. since scintillation pulses are relatively slow. The directional aspect of Cherenkov light is another possibility, but it is difficult to implement in most practical calorimeters. The Cherenkov polarization, as opposed to unpolarized scintillation, may also be used but needs more research.

A large fraction of the energy is lost through nuclear interactions that do not materialize in a measurable signal in calorimeters. If an appropriate scheme is developed to turn these MeV neutrons into a signal, we will further reduce fluctuations in energy carried away by these
poorly sampled neutrons. It may require special materials in the detector and/or algorithms that exploit the (late) pulse shape. When achieved, the triple- or multiple-readout will certainly advance us towards the ultimate limit in hadronic energy resolution.

Figure 1. A snapshot of where we are today with the imminent projects in particle physics.

Particle flow algorithms (PFA) use the information from a highly segmented calorimeter and the information from a tracker system to achieve resolutions that would separate $W$s from $Z$s in future lepton colliders. Much progress has been reported in this conference and elsewhere by the CALICE collaboration. Although it is not clear, but it may be possible to employ PFA in combination with a multiple-readout calorimeter in the future. We have to contrast the advantages against technical challenges but it is worth investigating this possibility.

The LHC experiments are developing upgrade plans to better cope with higher luminosities and higher center of mass energies. Some of these plans were reported in this conference. Nearly $\sim 20 \text{ fb}^{-1}$ of LHC data per experiment taught us many lessons (see Figure 2). The radiation damage to detectors continues to plague us. Although we have developed techniques to “correct” for it, we have yet to develop fundamental understanding of radiation damage mechanisms. Similarly, we have developed clever techniques to mitigate “noise” in the calorimeters where “noise” means anything that fakes a true signal, such as low energy neutrons or charged particles hitting photosensors, photosensors misbehaving, etc. Large mismatches in the $e/h$ ratios of ECAL and HCAL combinations pose a difficulty in correct energy reconstruction because the calorimetry response depends on where the shower starts. In addition, the ECAL readout tends to be in the neighborhood of the shower maximum and thus prone to produce fake signals. The challenge is perhaps to invent a single calorimeter (CALO) that would match the performance of excellent ECAL systems but at the same time measure jets and single hadrons with precision.
The precision of calorimeter simulations has been improving over the last few years. Increasingly sophisticated “physics lists” have been introduced to get the shower physics right. A good validation test for these simulation packages is to verify if they can reproduce the experimental data from highly non-compensating calorimeters ($e/h \sim 4 - 5$), especially at low energies. As discussed in this conference, jet reconstruction algorithms have also become a crucial part of calorimetry, and they constitute an essential link between the detector and the physics.

The pulse shape from a calorimeter of any kind reveals the interaction history of an event in that detector. As higher digitization rates and logic processing become more commonplace, the front-end electronics may be able to process information such that only critical information ($f_{em}$, $f_{had}$, $\Sigma E$, etc) is transmitted to the counting room, changing our usual paradigm.

The field of high-energy calorimetry is as rich and exciting as ever. We certainly know more about calorimetry now than we did a decade ago. As we embark on developing the next generation of calorimeters, I am certain we will discover more and have the opportunity to use our creativity to uncover more physics.

![Figure 2. We have learned many things in the last decade...](image)

Acknowledgments
We all thank the participants for their hard work and excellent presentations at CALOR 2012, and for their written contributions to these proceedings. These proceedings will serve as a good source of calorimeter information, as have precious CALOR proceedings, as current calorimeters are upgraded and future calorimeters are being designed.