Available online at www.sciencedirect.com

SCIENCE DIRECT®

ELSEVIER

Nuclear Instruments and Methods in Physics Research A 518 (2004) 9–14

NUCLEAR INSTRUMENTS & METHODS IN PHYSICS RESEARCH
Section A

www.elsevier.com/locate/nima

Status and perspectives of detectors for experiments in HEP and related fields

Richard Wigmans*

Department of Physics, Texas Tech University, Box 41051, Lubbock, TX 79409-1051, USA

Abstract

Developments in the field of particle detectors are reviewed. Due to increasing physics demands, intrinsic detector limitations are becoming more and more of an issue, necessitating fundamental R&D. The example of high-resolution jet spectroscopy is chosen to illustrate this.

PACS: 02.70.Uu; 29.40.Vj

Keywords: Astroparticle physics; Calorimetry; Linear collider

---

1. Introduction

When the series of Pisa meetings on "Frontier Detectors for Frontier Physics" started, a quarter of a century ago, Frontier Physics was clearly understood to mean *accelerator-based particle physics*. The Proceedings of the 1980 meeting, for example, contain only two contributions that describe detectors intended for other purposes, and one of these two contributions, which discusses detectors for experiments in the Gran Sasso Laboratory, under construction at that time, might nowadays also be classified in the accelerator-based category. However, for this year's meeting, no less than 72 contributions (more than one-third of the total) concern detectors intended for purposes other than accelerator-based particle physics experiments. These purposes include non-accelerator particle physics experiments, cosmic ray experiments (both on Earth and outside the Earth's atmosphere) and dark matter searches, as well as a variety of spin-off applications, ranging from medical diagnostics to preservation of historic audio documents.

The R&D that was initially started to replace the bubble chamber by more convenient particle detection instruments thus has led to a variety of detectors that have found many other applications as well. In accelerator-based experiments, the ideal of developing an "electronic bubble chamber" has become reality. In several areas, e.g., neutral-particle detection and vertex detail, the quality of modern electronic detectors surpasses that of bubble chambers.

In this introductory talk, I first briefly discuss some trends that have shaped particle detectors in the past 25 years. Then, I describe in some detail one example of a challenge that will require further detector improvement for future experiments, namely the need for high-resolution jet spectroscopy at the next-generation high-energy e^+e^-

---

*Tel.: +1-806-742-3779; fax: +1-806-742-1182.
E-mail address: wigmans@ttu.edu (R. Wigmans).

0168-9002/$ - see front matter © 2003 Elsevier B.V. All rights reserved.
doi:10.1016/j.nima.2003.10.010

collider(s). I also discuss some R&D that is carried out to meet that challenge. And finally, I briefly mention some generic detector techniques which, in my opinion, hold promise for the future.

2. Trends in detector development

In the past 25 years, two developments have been crucial for the evolution of detector design:

- the availability of increasingly faster electronics,
- the increased data handling capability.

For example, in the early 1980s, a typical experiment logged data at a rate of 1 MByte/s, where this rate is envisaged to be two orders of magnitude higher in the experiments prepared for the LHC. These developments have made it possible to

(1) Obtain more precise event information. The detector can be more finely segmented, which results in improvements in position resolution and two-track separation. This in turn leads to better particle ID (based on a comparison of momentum and energy), better mass resolution, etc.
(2) Dramatically improve the triggering capability of the experiments. This capability can be used to increase the sophistication of the triggers (e.g., displaced secondary-vertex triggers as a sign of b-quark production at the Tevatron), and/or to run many triggers simultaneously, especially at hadron colliders.

These developments have also led to new approaches in detector design. As examples of detectors that benefit in crucial ways we mention:

- Pixel detectors, such as the 6 m^2 one developed for ATLAS,
- all-silicon trackers, such as the 200 m^2 CMS tracking detector system,
- jet detectors based on *energy flow measurements.*

Also in non-accelerator experiments, we have witnessed the trend to use the increased bandwidth for instrumenting the detectors such as to maximize the amount of information obtained per event. This is achieved by

- Gathering more information from each individual detector, e.g., by measuring the time structure of all signals in H_2O neutrino telescopes,
- combining the information from several independent detector systems, e.g., in KASCADE where neural network methods are used to extract the nuclear charge Z of particles that cause extensive air showers in the Earth's atmosphere,
- combining the information from detectors installed at very different locations, as in gravitational-wave experiments

or by some combination of these methods, as foreseen in the AUGER experiment.

We have also seen some ingenious alternative applications of particle physics detector technology. For example, TRDs were originally developed to help with electron identification in hadron collisions. However, several stratospheric cosmic-ray experiments, e.g., TRACER, now use TRDs also as light-weight detectors for energy measurement, in lieu of the unacceptably massive calorimeters. Since the energy carried by transition radiation photons is proportional to the Lorentz factor ($\gamma \sim E/m$) and to Z^2, the number of TR photons with energies above a certain cut-off value scales with $(\ln \gamma)^2$ and is thus a (logarithmic) measure of the particle's energy, once its mass is known.

Another example of such ingenuity comes from water Cherenkov counters. 25 years ago, these detectors were conceived to study proton decay. Later, neutrinos produced in the atmosphere by cosmic rays, in supernova explosions and in fusion processes in the Sun's core were detected with such detectors. Since these events were typically contained inside the fiducial volume of the detector, the energy calibration is straightforward, e.g., on the basis of the range-energy relationship. However, in high-energy neutrino telescopes such as ANTARES or AMANDA, the events are typically *not* contained. For example, 1 km (the typical envisaged linear size of such detectors) corresponds to the range of 800 GeV muons in water. A peculiarity of the Cherenkov mechanism makes it possible to measure the energy of muons that are orders of magnitude higher than that through the time structure of the signals. The high-energy muons lose energy through ionization and through bremsstrahlung. The Cherenkov light associated with the first process originates from a small fraction of the track, whereas the light emitted by the electrons and positrons from the electromagnetic (em) showers produced in the second process originates upstream from this segment. And since the speed of light in water is smaller than the speed of the high-energy muon, the Cherenkov light from the radiative component reaches the PMT later than that from the ionizing component. The time structure of the PMT signal thus exhibits a tail, and the tail/peak ratio is a measure of the muon energy. This is illustrated in Fig. 1.

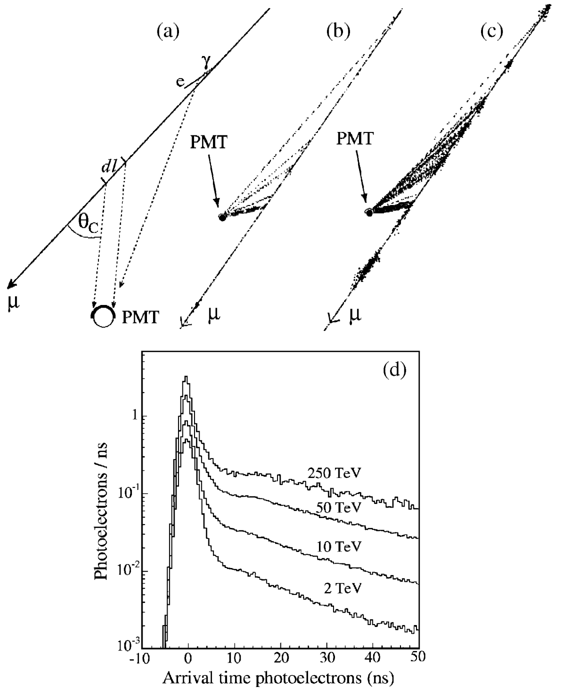

Fig. 1. Detection of Cherenkov light produced in direct ionization and in bremsstrahlung processes (a). Monte Carlo simulations of Cherenkov photons produced by a 0.1 TeV (b) and a 10 TeV (c) muon in water. Only photons reaching the sensitive surface of the PMT are drawn. Time structure of PMT signals generated by muons of different energies (d).

3. Detector limitations and physics

Detectors are designed to achieve the sensitivity required for studying the physics processes of interest. Increasing the granularity of the instrument or improving the trigger selectivity may help in this respect. However, sometimes one faces a boundary imposed by *intrinsic detector limitations*. A well-known example of a process that puts severe requirements on the detector quality is $H^0 \rightarrow \gamma\gamma$, believed to be an important discovery channel for light SM Higgs bosons. The excellent em calorimeter resolution needed to observe this process has driven the design of the ATLAS and CMS experiments.

An example from the current generation of experiments concerns the process $\bar{B}^0 \rightarrow D^0\pi^0$, studied at the *B*-factories. This color-suppressed decay, with a branching fraction of a few times 10^{-4}, experiences severe competition from the much more abundant process $B^- \rightarrow D^0\pi^0\pi^-$, with a π^- that is so soft that it escapes detection. The latter process leads to a background that limits the significance of the signal of interest, as illustrated by Fig. 2, which shows the published results of the BELLE and BaBar collaborations.

A third example of detector limitations that may affect the quality of the physics concerns jet detection at a future high-energy Linear e^+e^- Collider.

3.1. High-resolution jet spectroscopy

In a Linear e^+e^- Collider (LC) with a center-of-mass energy in the range of 1.0 TeV, the situation concerning jet measurements is quite different from that at LEP. Uncertainties stemming from the applied jet algorithms, which limit the meaningful jet energy resolutions in LEP to 5–10%, play a much smaller role at higher energies, where jets are strongly collimated. In addition, constrained fits which eliminated in some analyses the need for high-precision jet measurements in LEP, are not possible in an LC because of the uncertainties introduced by beamstrahlung effects. On the other hand, it would be a major advantage if all fundamental constituents of matter generated in the interactions could be measured with the same high precision (e.g., ~1%) and there is no fundamental reason why that would be impossible.

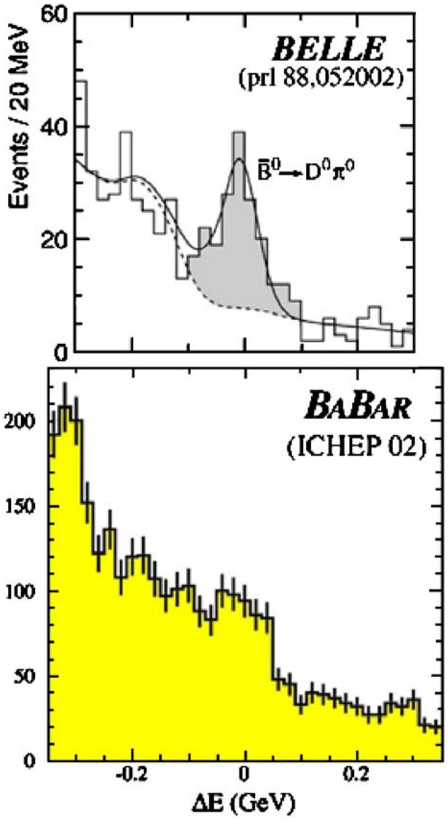

Fig. 2. Results from the BELLE and BaBar experiments on the decay $\bar{B}^0 \to D^0\pi^0$. Shown is a histogram of the quantity ΔE, the difference between the invariant mass of the $D^0\pi^0$ combination and E^*, a measure for the mass of the B meson.

There are three independent, fundamentally different, R&D efforts underway to achieve this:

The first approach is based on the use of a *compensating* detector structure. A Japanese group has performed systematic studies of a lead/plastic-scintillator combination [1] and found that when this material is used in a volume ratio of 5 to 1, the effects of event-to-event fluctuations in the em shower fraction ($f_{\rm em}$), which spoil the hadronic performance of non-compensating calorimeters [2], can be eliminated. The main drawback of this technique is the fact that the small sampling fraction limits the em energy resolution. It will be hard to do better than $10\%\sqrt{E}$ for em showers with such a detector.

The second approach is based on the *Energy Flow Method* (EFM), in which the information from the calorimeter system is combined with that from an upstream tracker system. The momenta of the charged jet fragments, measured with high precision by the tracker, serve as a first-order estimate of the jet energy. Second-order corrections, intended to account for the neutral jet component, are derived from the calorimeter signals. With methods of this type, several LEP experiments managed to improve the mass resolution for hadronically decaying W's and Z's from 12% to 9%.

The EFM exploits the fact that the charged fragments of jets can be measured much more precisely with a tracker than with a calorimeter. However, the calorimeter information is still needed to account for the contributions of neutral particles, mainly γs from π^0 decay, but also K^0s and neutrons. The proponents of this method, which is being studied in the context of the TESLA project [3], claim that the key to success is determined by the *granularity* of the detector. A high granularity would make it possible to recognize and eliminate all contributions of the charged particles to the overall calorimeter signal. The remaining calorimeter signal could then be attributed to the neutral jet components.

However, with a calorimeter located at only 1.4 m from the beam line, the 4 T magnetic field is by no means adequate to achieve sufficient separation between the showers initiated by the various jet fragments. Inevitably, there will be considerable overlap between these showers. And even the finest granularity would not make it possible to disentangle the different shower profiles in that case. A recent study showed that the relative improvement of hadronic energy resolutions that may be expected from such methods is rather modest, 30% or less compared to the typical resolutions achieved with standalone non-compensating calorimeter systems [4].

The third approach is known as *Dual Readout Calorimetry*. In this case, the em fraction of the energy deposited by the jet in the calorimeter system is measured event by event, by comparing the signals produced in the form of Cherenkov light and dE/dx (e.g., derived from scintillator signals). This method works because the Cherenkov light is, for all practical purposes, in practice almost exclusively generated by the em shower components [2,5]. Once f_{em} is known, the effects of fluctuations in this parameter can be eliminated in a straightforward way.

The beneficial effects of this technique, which offers the same advantages as compensation without the restrictions on the sampling fraction, have been demonstrated with a very thin calorimeter ($1.3\lambda_{\mathrm{int}}$), intended for measuring the energy of PeV hadronic cosmic rays outside the Earth's atmosphere [6]. In that case, the resolution is completely dominated by leakage fluctuations. This shower leakage is correlated with the production of π^0s in the first interaction, since the π^0 em showers are typically fully contained in this device. By comparing the signals from scintillating fibers and quartz fibers that served as the active elements of this detector, the authors could not only measure how much energy was detected inside the small calorimeter volume, but also how much energy leaked out. Encouraged by this success, they embarked on DREAM, a $10\lambda_{\mathrm{int}}$ deep Dual REAdout Module intended for high-resolution jet measurements. The basic detector element is a 2 m long extruded copper rod, with outer dimensions of $4 \times 4\ \mathrm{mm}^2$ and a central hole with a diameter of 2.5 mm. The detector consists of about 6000 such rods. Each hole contains seven optical fibers, three scintillating ones and four quartz ones. The detector is, for readout purposes, subdivided into 19 hexagonal cells, one central cell surrounded by two rings. The quartz and scintillator signals of each cell are read out separately by PMTs. Fig. 3 shows a picture of this detector, which is currently being prepared for beam tests at CERN.

Since hadronic shower Monte Carlo simulations are notoriously unreliable, the only way to compare the value of these different approaches is to build prototypes and test these under conditions that are as realistic as possible. The (for purposes of calorimetry) most important feature of a jet is that it represents a *collection of photons and hadrons of unknown composition and energies*. Therefore, jets can be purposefully mimicked by sending high-energy hadrons onto a thin target and measuring the particles emerging from reactions that take place in that target. In that case, the beam acts as a source of mono-energetic "jets".

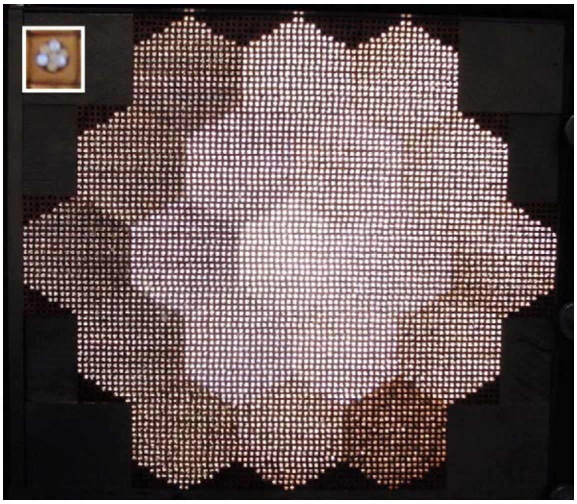

Fig. 3. Picture of the upstream face of the DREAM prototype, with the detector illuminated from the rear end. The hexagonal readout cell structure is clearly visible. The inset shows a close-up of one of the hollow copper rods that constitute the absorber structure. Each of the 6000 rods contains three scintillating fibers and four quartz ones.

4. New detector techniques

There is always a need for generic R&D in which new ideas for particle detection are investigated. Especially R&D that addresses areas of weakness of state-of-the-art detection techniques are important in this respect. Sometimes, such R&D leads to quantum jumps in the detector quality. As an example, I mention the introduction of semiconductor detectors for nuclear γ ray detection in the 1960s, which improved the energy resolution by several orders of magnitude and caused a revolution in nuclear physics. Semiconductor-based detectors have also revolutionized vertex detection and (to a lesser extent) tracking in particle physics experiments.

Among the new detection techniques that I consider promising and that are being discussed at this conference, I mention

- *CVD diamond sensors*. These devices have been studied for a number of years because they offer some specific advantages over silicon; most importantly, they are more radiation hard. Recently, this technology has led to the development of some real devices that are being used in practice, for example as radiation monitors in BaBar [7] and in dosimetry for radiotherapy [8].

- Experiments on high-energy cosmic rays have until now predominantly relied on Cherenkov light or scintillation light as the prime sources of experimental information. *Alternative signal sources* for ultrahigh-energy neutrino detection in the atmosphere, the Moon, or in water include sound (e.g., in the RICE experiment at the South Pole and NEMO in the Mediterranean [9]) and radiowaves [10].
- *New light detectors* are a recurrent theme at the Pisa conferences. It is remarkable that the good old PMT is still going strong after half a century. New improvements on the quantum efficiency and the photocathode unformity, traditionally weak points of this device, are discussed by Lorenz [11]. The HPD has become an increasingly interesting, albeit pricy, alternative to the PMT. Highly pixelized devices are presented by Joram [12]. Schyns [13] will talk about the development of very large CsI photocathode surfaces, to be used in a RICH.
- *Cryogenic detectors for cold dark matter searches*. For many years, devices developed in this context were mainly aiming for a proof of principle. Simultaneous detection of different types of signals (ionization, light, phonons) has led to a crucial reduction of the noise levels. We have now reached the stage where sizeable detectors (100 kg) are being deployed and meaningful limits on the WIMP content of the Universe are within reach [14].

5. Concluding remarks

Since the Pisa series of conferences began, 25 years ago, developments in computing and in fast electronics have revolutionized detectors for experiments in accelerator based particle physics. Other fields are taking advantage of these developments. Many experiments in astrophysics, cosmic ray physics and a variety of other fields nowadays use detector technology that was originally developed for use in an accelerator environment. This trend will undoubtedly continue.

As a result of increasing physics demands, the intrinsic limitations of detectors have become a critical issue in some experiments. As an example, I have discussed the issue of jet energy resolution for experiments at a future linear e^+e^- collider. Dedicated R&D is being carried out in an attempt to expand the intrinsic detector limitations.

The long history of scientific discovery has taught us that the evolution of our understanding of the physical world and the development of the tools available for the studies go hand in hand. Good detectors are essential for good physics, and better detectors are crucial for better physics. However, for the best physics it is also imperative that the researchers have a very good and detailed understanding of the *limitations* of their detectors. It is to achieve this understanding that we are here this week, and I am personally looking forward to learning many new things at this conference.

References

[1] T. Suzuki, et al., Nucl. Instr. and Meth. A 432 (1999) 48.
[2] R. Wigmans, Calorimetry, Energy Measurement in Particle Physics, in: International Series of Monographs on Physics, Vol. 107, Oxford University Press, Oxford, 2000.
[3] TESLA Technical Design Report, Report DESY 2001-011, DESY, Hamburg, Germany (2001).
[4] O. Lobban, A. Sriharan, R. Wigmans, Nucl. Instr. and Meth. A 495 (2002) 107.
[5] N. Akchurin, et al., Nucl. Instr. and Meth. A 399 (1997) 202.
[6] V.P. Nagaslaev, A.F. Sill, R. Wigmans, Nucl. Instr. and Meth. A 462 (2000) 411.
[7] B.A. Petersen, Nucl. Instr. and Meth. A (2004), these proceedings.
[8] M. Bruzzi, Nucl. Instr. and Meth. A (2004), these proceedings.
[9] G. Riccobene, Nucl. Instr. and Meth. A (2004), these proceedings.
[10] O. Ravel, Nucl. Instr. and Meth. A (2004), these proceedings.
[11] E. Lorenz, Nucl. Instr. and Meth. A (2004), these proceedings.
[12] C. Joram, Nucl. Instr. and Meth. A (2004), these proceedings.
[13] E. Schyns, Nucl. Instr. and Meth. A (2004), these proceedings.
[14] E. Previtali, Nucl. Instr. and Meth. A (2004), these proceedings.