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AVANCÉES EN PHYSIQUE DES PARTICULES : LA CONTRIBUTION DU LEP

ADVANCES IN PARTICLE PHYSICS: THE LEP CONTRIBUTION

The LEP detectors

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Abstract This article describes the four detectors which took data at LEP from 1989 to 2000. After a review of the design requirements and of the various answers, a more detailed description is given of some of the important detector components. Electronics, readout and computing are also described. ***To cite this article: O. Callot, P. Charpentier, C. R. Physique 3 (2002) 1131–1141.***

LEP detectors / ALEPH / DELPHI / L3 / OPAL

Les grands détecteurs sur LEP

Résumé Cet article décrit les quatre détecteurs qui ont pris des données au LEP entre 1989 et 2000. Après une revue des contraintes, et des réponses qui y ont été apportées, les plus importantes composantes seront décrites en détail. L'électronique, l'acquisition et le traitement des données sont aussi décrits. ***Pour citer cet article : O. Callot, P. Charpentier, C. R. Physique 3 (2002) 1131–1141.***

détecteurs sur LEP / ALEPH / DELPHI / L3 / OPAL

1. Design constraints

At the LEP collider, the beams are colliding at 4 points equally distributed over the 27 km of the ring. A large detector has been installed at each collision point, in huge underground caverns, between 80 m and 140 m deep. The same beams cross in the various points, so the four experiments take data at the same energy and with approximately the same rate of events, and are then in strong competition. Their size is quite impressive: around 10 m in length and 8 m in diameter! The LEP detectors were designed in the early 1980s, and even if the physics goals are the same, different choices were made by the various collaborations, putting the emphasis on one or another type of measurement.

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1.1. Basic principles

The region where the electrons and positrons collide, so called luminous region, is 1 mm long, 10 microns by 100 microns in the transverse plane. Particles produced in the interaction are emitted in all directions, and one wants to measure their properties. The basic design is similar for all 4 detectors, as it is for almost all collider detectors: several concentric layers employing different detection techniques are dedicated to measure various physical properties of the particles. Firstly one measures the charged particle trajectory with as little material as possible, inside a magnetic field, to get the initial direction and momentum. Particle identification is also performed, using either difference in ionisation or in velocity (Cherenkov effect). Then particles are stopped in what we call a 'calorimeter', depositing all its energy. This allows to measure the position and energy of neutral particles. A first layer of calorimeter measures the electromagnetic particles, using short radiation length material, then the hadrons are stopped in iron. Two types of particle escape from the calorimeters. Muons, which are identified by the fact that they emerge from the detector and are seen in dedicated large chambers since they are charged, and neutrinos, which are not detected at all, except by techniques for detecting 'missing energy': the initial momentum and energy are known, subtracting all the measured particles gives an estimate of the direction and energy of a possible neutrino. The luminosity (interaction probability) is measured by counting how many electrons have scattered elastically, a process whose properties are well known. Dedicated detectors are placed close to the beam line and as far as possible (4 meters) from the luminous region, as these electrons are emitted mainly at very low angle.

The detector is composed of a cylindrical part, with axis along the beam line and which contains the tracking system, and two end caps, which mainly consist of calorimeters.

1.2. Constraints

- Hermeticity: Particles produced in the interaction are emitted in all directions, and the detector should cover the whole solid angle. This is especially important for the missing energy technique. Of course the beam should circulate, so the coverage is limited by the diameter of the beam pipe, which gives rise to an unavoidable dead area of about 10 cm diameter. The rest of the volume should be sensitive. All passive material, such as electronics, cables, cooling, support structures, should be minimized, and arranged in such a way that the presence of a particle in this region should be detected, even if it can not be measured as accurately as elsewhere.
- Speed: The machine was designed for 4 bunches of electrons (and 4 of positrons) equally spaced around the ring. They travel (almost) at the speed of light, and thus there is a beam crossing every 22.4 µs. This is a very long time interval for current electronics, and every signal can be integrated, shaped, measured and a decision taken before the next beam crossing. However, some detectors have a very slow response, such as the Time Projection Chambers (TPC) described later, where the signal from a collision may arrive on the electronics after the next collision. However, the probability of collision is very low, only 10 to 100 of the 45 000 crossings every second are producing some activity in the detector and therefore the chance of events overlapping in the time resolution of even these slow detectors is negligible.
- Precision: One of the main goals of LEP was to perform precision measurements, in order to check the electroweak theory. This implies stable and precise detectors that are accurately aligned and well calibrated. The detectors were used to collect data for 12 years, and many analyses required 5 years of data to be combined. Dead channels had to be identified and repaired as soon as possible. But the accessibility was limited, opening the detectors to access the inner part could be done at most once a year, as this was a long operation which required the machine, and therefore the other experiments, to be stopped.

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2. The four detectors

As mentioned earlier, the global approach is the same. Very close to the interaction, a very precise detector. These devices are described in the contribution by Coyle and Schneider [1]. A tracking system, in a magnetic field, to measure direction and momentum. Particle identification is also performed. Then particles are stopped in calorimeters, first an electromagnetic one and then a hadronic one. Muons are finally measured as tracks emerging from the calorimeters. However, the four detectors are quite different, as different emphasis was put on measuring different properties: is it more important to measure momentum or particle type? Position or energy? Can we bet on new detection techniques, or play safe? The choices of the collaborations are clearly visible in the detector they have built.

2.1. ALEPH

The characteristics of the ALEPH detector (Fig. 1) [2] are: reasonably new technologies, homogeneous detector, granularity more than energy resolution. The heart of the detector is a large TPC and a high granularity (200 000 channels) electromagnetic calorimeter in a large superconducting magnet. The technologies are the same for barrel and end-cap detectors, giving only 5 types of detectors.

2.2. DELPHI

The DELPHI detector set-up (Fig. 2) [3] has many more detectors. Here, the choice was more on very new technologies, and a larger variety of techniques. The main components are a TPC, a Ring Imaging CHerenkov (RICH) to identify charged particles, and a very fine grained calorimeter. The superconducting solenoid is the largest ever built.

2.3. L3

The L3 detector (Fig. 3) [4] is quite different from the 3 others. The emphasis was put on measuring leptons (and photons) with high resolution. The tracking system is very small, and is surrounded by a very high resolution calorimeter with 10 700 BGO crystals. The muon system has many large chambers, and the whole detector is inside a huge warm magnet, having around 10 m internal aperture.

2.4. OPAL

OPAL (Fig. 4) was designed to use only proven and reliable technologies, to be sure at least one of these huge detectors would be ready in time. A classical magnet, 11 700 lead glass blocks and drift wire chambers for the tracking are the main components.

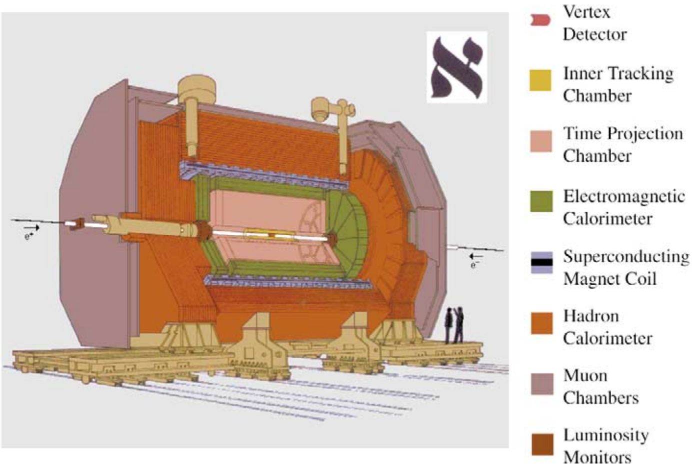

Figure 1. The ALEPH detector.

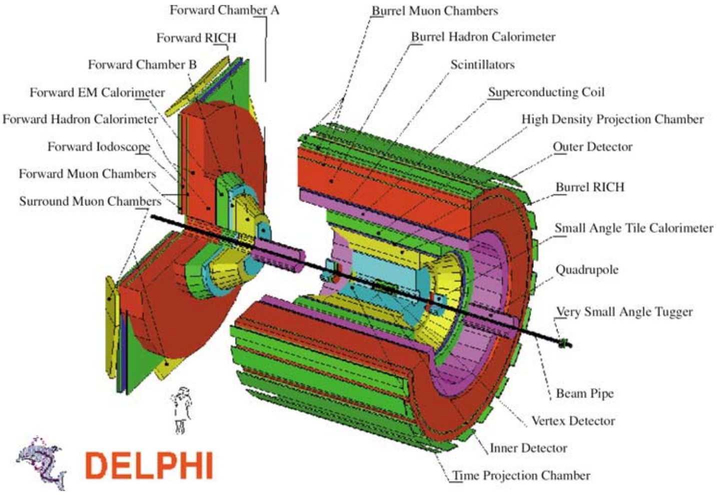

Figure 2. The DELPHI detector.

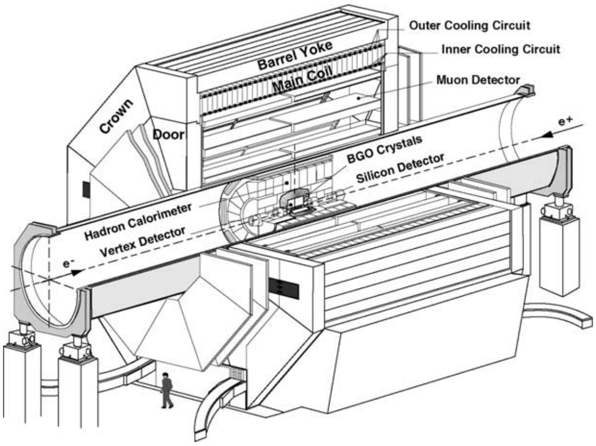

Figure 3. The L3 detector.

2.5. Standard techniques

There is not enough space here to describe all components. Detailed descriptions can be found in the references [2–4]. Three basic techniques in common are as follows:

- The basic technique to detect charged particles is the proportional wire chamber, where the primary ionisation deposited in an inert gas is amplified in the electric field close to a wire of low diameter, typically 50 micrometers. The huge field near the wire amplifies by avalanche the ionisation by 10^4, giving enough charge to be detected by an electronic device. One can use a simple threshold, indicating if a particle passed near the wire, or measure the amplitude, to measure also the amount of ionization, which gives an indication of the nature of the particle. A variant is to measure the time taken by the ionisation to reach the wire, which gives more precision on the particle's trajectory.
- A second technique is the use of plastic scintillators, in which molecules are excited by the passage of the particle, and then emit photons. A light sensitive detector, usually a photomultiplier, transforms the light into a charge pulse, which can be measured.
- The last basic technique is the Cherenkov effect, described in Section 5.1.

Some of the key sub-detectors at LEP use a more original technology, and are described in the following sections.

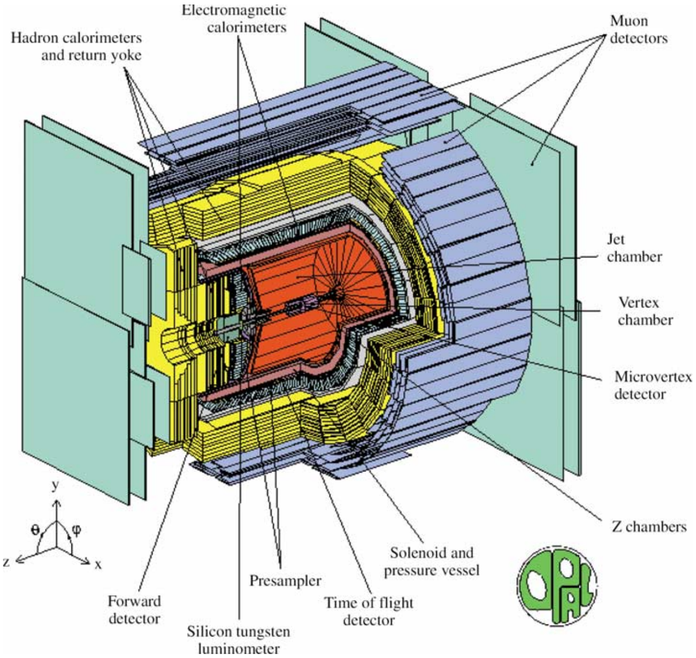

Figure 4. The OPAL detector.

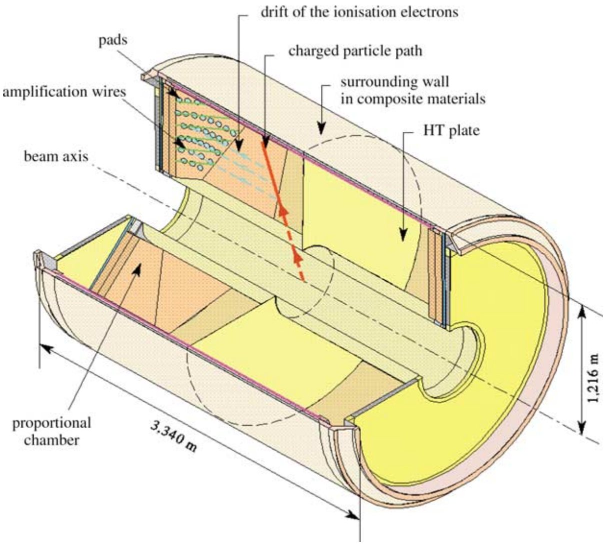

Figure 5. A Time Projection Chamber.

3. The Time Projection Chamber

3.1. Basic principle

While OPAL was using a conventional although large drift chamber as central detector, and L3 a very compact tracker (Time Expansion Chamber), ALEPH and DELPHI were equipped with large Time Projection Chambers (TPC). Unlike Multiwire Proportional Chambers (MWPC) or Drift Chambers (DC), TPCs measure directly points on the charged tracks trajectories in 3 dimensions.

The principle is very simple (Fig. 5): a large vessel contains an ionisable gas (mixture of Argon and methane) in which charged particles produce ionisation electrons. An electric field lets these electrons drift in the vessel towards a MWPC located at the end of the drift volume. This MWPC is equipped not only with readout electronics on its wires, but rows of pads designed on the cathode to allow a two-dimensional measurement of the avalanche position. An interpolation method between the pads hit by an avalanche give a precision of about 250 µm.

The third dimension (the distance between the track and the MWPC) is obtained by measuring the drift time of the electrons. A precision of the order of 0.5 mm can be obtained on each measured point for this third dimension. A track however is measured by a large number of pads and wires, which gives a very good accuracy on the track position.

Drifting electrons over long distances (1–2 m) however poses problems such as dispersion of the electrons due to their interaction with the gas. This effect is much reduced by the fact that the drifting vessel is contained in a magnetic field (used to measure particle momentum from the curvature of their trajectories). The magnetic field has a focussing effect on the electrons which tend to follow it rather than the electric field. It is thus very important that both fields are quite parallel, to better than 10^{-4}. Corrections have eventually to be applied on the measured positions to take these effects into account. The electric field is produced by two so-called field cages, consisting in an inner and an outer cylinder delimiting the drift volume. Circular copper strips sitting on these cages (3 mm wide, spaced by 1 mm) are connected by a resistor chain. The strip at the centre of the chamber is set to a negative high voltage while that close to the MWPC is connected to the ground. This creates a regularly increasing potential all along the drift path of the electrons that drift at a speed of the order of $7\ \mathrm{cm \cdot \mu s^{-1}}$.

3.2. How to reach final precision

Since the measurement of space points in a TPC are inferred from a time measurement after a long drift path, it is essential that the characteristics of the drift process are perfectly known.

3.2.1. *Drift velocity*

The first obvious parameter is the drift velocity of the electrons in the field. It has to be known to a precision of the order of 5×10^{-5} if one wants a contribution to the measurement error of 100 µm after a drift of 150 cm. Several calibration methods can be used, one of which uses laser beams shot inside the drift volume. One can shoot the laser a couple of times per minute and obtain a precision on the drift velocity not far from the figures quoted above.

Another method consists of using the tracks coming from the interactions themselves. They are measured with an extremely high precision (6 µm) by several layers of silicon microvertex detectors. Using their matching from the silicon detector to the TPC allows one to achieve a continuous monitoring of the drift velocity throughout data taking, without having to rely on external devices.

3.2.2. *Electrostatic corrections*

A good knowledge of the electrostatic configuration of the field cage is also essential. The drift of electrons can be affected by imperfections in the geometry of the field cages (e.g., bad alignment of the two cages), by the settings of voltages around the MWPC, where electrons have to traverse from a moderate electric field to an intense field.

Modifications in the electron drift occur as well when the magnetic and electric fields are not perfectly aligned: the electrons tend to follow the magnetic field rather than the electric field, which displaces the avalanche position in the MWPC with respect to what would be otherwise expected. Accidents may also occur (see below) which cause short circuits between two adjacent strips, inducing a local perturbation of the electric field.

Additional corrections have to be applied in order to take into account the imperfections in the geometry of the whole mechanical assembly (position and tilt of the MWPC). These corrections can be parametrised and fitted on the data themselves, using here again the silicon detector as a reference.

3.3. An example of a small mistake with painful consequences

In the ALEPH TPC, a bad soldering inside the field cage had to be fixed in 1991. The fix went well, and the last operation was to glue again a cover with some epoxy glue. A high-tech sponge was used to absorb the extra glue. It was discovered later that this sponge contained short carbon fibers, one centimeter long and a few ten microns diameter. Some of the fibers stayed inside the TPC. During some catastrophic beam losses near ALEPH, the ionization in the TPC was such that the fibers moved, and managed from time to time to short circuit two of the rings of the field cage, introducing distortions in the electric field which had to be understood (i.e., which two rings are connected) and corrected off line. Careful eye inspections allowed the fibers to be found in some cases, but this could be done only during winter shutdowns. In other cases, another large beam loss moved again the fiber, removing the short.

4. Calorimeters

The word ‘calorimeter’ may be misleading, as it does not measure heat dissipation. It converts all the energy of the particles by stopping them, in what is called a ‘shower’, where one particle is transformed by successive interactions into many particles of lower energy. The number of particles increases, until the ‘daughters’ starts to have low enough energy to stop. By measuring the number of particles, one can calculate the energy of the initial ‘parent’. Two choices are possible:

- One can use a homogeneous medium such as lead-glass or BGO, in which electrons produce Cherenkov light. A light sensitive detector sees a signal proportional to the total length of the electron tracks.
- One can also use a sampling technique: the calorimeter is a succession of alternate layers, dense material (lead, iron) to produce the interactions, and sensitive detectors to count the number of tracks. The number of such pairs of layers is between 20 for hadronic calorimeters and 50 for electromagnetic calorimeters.

Both approaches have pros and cons. The sampling technique is used for all hadronic calorimeters, while the two options are used for electromagnetic calorimeters. Comments on the experience gained working with these calorimeters can be found in [5].

4.1. High resolution: BGO

The L3 detector is designed to measure accurately electrons, muons and photons. Electrons and photons are measured by the electromagnetic calorimeter composed of a barrel and two end-caps of BGO crystals read by two photodiodes. Its energy resolution is below 1% for particles above 10 GeV.

The internal radius of the calorimeter is chosen in order to optimise its performance/cost ratio. It implies that the size of inner tracker is small. Therefore the muons are measured outside the calorimeter by large drift chambers located inside the magnetic volume of the 7800 t magnet providing a 0.5 T field. A momentum resolution of 2.5% at 45 GeV is reached.

In order to guarantee for more than 10 years the accuracy of the energy measurement several calibration methods and monitoring systems were developed. The light collection efficiency of the crystal and the gain of readout electronic is monitored by a Xenon lamp system. Regular crystal calibration were performed using a Radio-Frequency Quadrupole (RFQ) particle accelerator which produces photons of known energy.

4.2. High granularity: the ALEPH electromagnetic calorimeter

Another approach to calorimetry is the high granularity choice, adopted by ALEPH and DELPHI. The argument is that it is better to separate the various particles in a jet than to measure precisely the energy of isolated particles. The ALEPH electromagnetic calorimeter had about 70 000 towers, each divided into three compartments in depth. This gives access to the longitudinal profile of the energy deposition, which enhances the electron-hadron separation. Mechanically, it is made of 36 modules, 12 in the barrel and 12 in each end-cap. A barrel module is about 5 m long, 1 m wide and 50 cm thick, and contains 4000 towers, each of them pointing towards the interaction point.

The lead sheets, 2 mm thick in the first two sections and 4 mm in the last section, is interspread with proportional wire chambers with readout on cathode pads, about 3×3 cm^2. The 2 million pads are connected on the side of each detector module to form the 220 000 readout storeys. As each tower sustains the same solid angle, each layer has a slightly different pad size, to obtain pointing geometry. The 45 wire planes of each module are also readout, allowing one to get a precise longitudinal profile of the shower. Of course this is useful only when a single particle hits the module, but this was a very effective tool to understand the behavior of the detector.

The 220 000 electronics channels are readout by two 12 bit ADCs, with a gain ratio of 8, allowing an effective dynamic range of 15 bits. In fact, the analog signal is sampled and stored on the front-end electronics, then digitized sequentially, 256 towers are digitized with the same ADC chip. The card also performs zero suppression and automatic selection of the best gain, in such a way that one reads out only a few hundred towers per event, in less than 10 ms. With a few Hz of trigger rate, this results in an acceptable dead time.

The front end electronics were entirely replaced after a few years, since a manufacturing defect (bad curing of an isolating coating) was causing the failure of about one card every week. Not only the basic design was improved, taking into account the progress in custom integrated circuits, but also the quality control of the production was re-inforced, to avoid other bad surprises. There have been essentially no card failure in the last 5 years of operation.

5. RICH

When analyzing in particular exclusive decays (e.g., of B particles), it is very important to identify the nature of reconstructed particles. Electrons and muons are respectively identified by their electromagnetic shower in the calorimeter and the fact that they succeed in traversing a thick layer of matter (electromagnetic and hadronic calorimeter, equivalent to more than a meter of iron). Hadrons on the other hand are more difficult to identify, and the best way to differentiate pions from kaons and protons is to measure their velocity.

5.1. Basic principle

For a given momentum (measured by the curvature of the trajectory inside the magnetic field), particles of different masses have different velocities. Hence measuring this velocity provides a means to test the various mass hypotheses, allowing the different particle types to be disentangled.

The measurement is based on the Cherenkov effect, which is the equivalent of a sound shock wave for light. It occurs when a fast charged particle travels in a medium with a refractive index n, faster than the light it emits when interacting with the medium. The Cherenkov light is emitted along a cone aligned with the particle momentum and characterized by an angle θ which only depends on the particle velocity relative to the speed of light in the medium (c/n) and such that $\cos\theta = nv/c$.

5.2. Cherenkov counters

Cherenkov light has been known and used for long in the detection of high energy particles: it is the light observed in calorimeters made of BGO as described previously, or of lead glass. It has also been used in so-called threshold Cherenkov counters: one detects the presence or the absence of Cherenkov light, indicating whether the velocity is larger of smaller than $1/n$. A given type of particle produces light only if it is above the Cherenkov momentum threshold. The presence or absence of light allows a rough discrimination to be made.

The Ring Imaging Cherenkov technique selects and measures the actual angle of emission of the Cherenkov light. For this, the light produced in a radiator of well known refractive index is reflected by

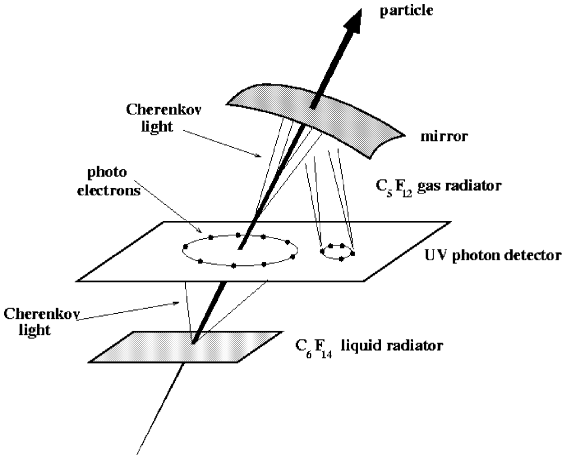

Figure 6. The DELPHI photon detector.

a spherical mirror onto a focal plane where it is detected. The optical property of the mirror is such that the light emitted along the trajectory of the particle forms an image in the focal point which is a ring. The diameter of the ring is directly related to the emission angle.

In DELPHI, which is the only LEP experiment to use this technique, two radiators are used with different refractive indices allowing complementary powers of separation between pions, kaons and protons. A liquid radiator of C_6F_{14} is thin enough to produce rings directly in the photon detector, which also acts as a separation with the gas radiator of C_5F_{12} where a spherical mirror is used. The photon detector used in DELPHI is a thin Time Projection Chamber where TMAE (a very photosensitive vapour) is added to the standard gas mixture (Fig. 6).

The electrons are thus produced at the bottom of the detection layer for the photons originating from the liquid and at the top for those from the gas. They drift as in a standard TPC towards small MWPCs where the position and drift time are recorded, allowing spatial reconstruction of the position of the photons. About 10 photons are produced for each particle, allowing rings to be reconstructed, given the particle trajectory. One then deduces the Cherenkov angle which, combined with the momentum measurement allows the mass of the particle to be deduced.

Another way to visualize the separation between different hadrons is shown here where the Cherenkov angle is shown in Fig. 7 as a function of momentum. Each particle type produces a band in this plot, showing that a good separation can be achieved when combining the information from the two radiators. The top plot shows the angle in the liquid radiator, the bottom plot is for the gas radiator. The bands correspond from right to left to protons, kaons and pions.

6. Triggering

The advantage of e^+e^- machines is that all inelastic collisions are interesting, but their rate is very low. At the highest luminosity, LEP produced less than one Z^0 per second, and at most a dozen other non-trivial interactions, for 44 000 beam crossings. A very simple detection of activity was enough. Asking for 5 GeV in the electromagnetic calorimeter was selecting over 95% of the interesting events! However, getting 99.9% efficiency requires triggering on more peculiar events, and a more sophisticated scheme was used. The relatively long separation between collisions allowed sufficient time to collect all the information, take the decision and reset properly if needed, before the next collision. The experiments therefore had a multi-level trigger:

- a first level synchronous, taking the decision between two crossing;
- a second level for some experiments with a slow detector (TPC) where 40 µs to 60 µs was needed to collect all the information on the tracks and confirm the first level;

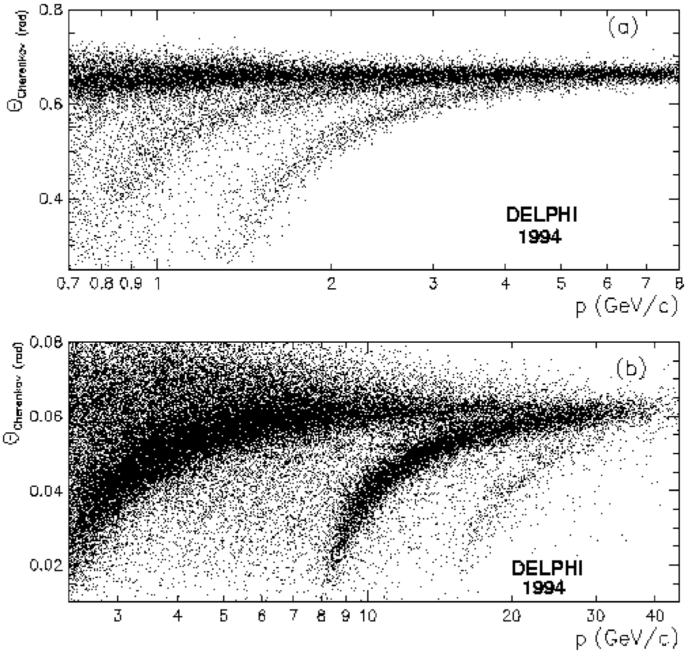

Figure 7. Cherenkov angle as a function of momentum.

- after that, the events were readout and passed to a software trigger, running on readout processors (DELPHI), on dedicated specialized processor farm (L3) or as filtering programs in the main computer system (ALEPH).

The typical rates were 10 Hz for the first level trigger, and a few Hz written to tape, with an average event size around 50 kbytes. This was a reasonably high number in 1989, when the experiments started, but is ridiculously low for current computers and link speeds.

7. Readout

The readout electronics were built on a similar architecture for all detectors. The digitizers are hosted in Fastbus crates, a standard used mainly in High Energy Physics. Crates are connected together with Segment Interconnects, so that a single master (the host computer interface) can read and write in any module of the tree-like system. But having the host computer reading directly each module would be very inefficient. Local readout processors, reading the digitizers and performing data reduction and formatting, are readout by event-builder modules, collecting the event fragments from several processors. After a few stages of event building, the complete event is assembled, and readout by the main computer, or by the high level trigger system.

This looks nice on paper. The experience showed that having almost all modules connected on a bus makes the debugging sometimes painful. If one module shorts a line, the only way to find the culprit is to split the system in pieces, e.g., removing half the modules, to see if the fault persists, and continue. Those who have been confronted with these problems are now strongly advocating point-to-point links instead of busses!

Over the years some of the systems were re-implemented with more modern processors, as challenging computer performance in 1985 became very feeble by the mid-nineties. For example, ALEPH replaced all the Fastbus processors and event building ‘tree’ by a VME based system, with a noticeable improvement in reliability. The gain was also to replace 4 types of modules, made in 4 laboratories with 4 operating systems by a single one, known and maintained by the team in charge of running the detector.

7.1. Performance

One of the challenges in these big systems is the optimization of the live time, i.e., the fraction of the delivered luminosity which is stored on tape and usable for physics analysis. After a teething period in the first year, this parameter was carefully monitored, reported and compared in weekly meetings. The source of inefficiencies were classified in three categories: 'Operational', when one part of the detector was not ready to take data, 'Acquisition' when the detector was ready, but the readout system not working, and 'dead time' when the detector was unable to collect an event, being busy reading out a previous event. Starting from a poor 80% in 1989, all experiments managed to collect more than 90%, sometimes up to 95%, of the delivered luminosity during the last years, despite the appearance of aging problems, after 12 years of data taking.

8. Conclusion

The LEP detectors were designed in the years 1980–1985, and have taken efficiently good quality data during 12 years of operation. Several improvements were made during that long period of activity, keeping the same main components to measure as accurately as possible all particles produced in the interaction. They have now been dismantled, some small parts have been re-used, but most of them scrapped. They were too big to be easily re-used, and too small for the next generation of detectors for the LHC. However, one has been kept, so that visitors of CERN could see one of those complex assemblies that collected the data used to produce the nice physics results which are described in the forthcoming contributions.

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