The Online Event Filter of the OPAL Experiment at LEP

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Abstract

The online event filter of the OPAL experiment at LEP is described. It acts as the second-level software trigger, following the first-level hardware trigger and is implemented on a workstation fully integrated into the data acquisition system. In addition to background rejection and event classification it provides detailed monitoring of the detector status and data quality, event visualisation and data compression. The partial event reconstruction and the selections based on physics quantities used for the event classification are described, and the performance of the system as used for data taking in 1991 is discussed.

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1 Introduction

The OPAL experiment, which has operated at the LEP e^+e^- collider since 1989, has a second-level software trigger fully integrated into its data acquisition system. This "filter" system performs the tasks of thorough monitoring and classification of events based on a partial event reconstruction, in which raw detector data are converted into physical quantities such as momenta or energies.

The general layout of the OPAL detector [1] is shown in Figure 1. Tracking of charged particles is performed by a solid state silicon microvertex detector and three drift chambers: a vertex detector, a large volume jet chamber, and chambers for measuring the z coordinates¹ of tracks as they leave the jet chamber, all placed in a 0.435 T axial magnetic field. The jet chamber is divided into twenty-four azimuthal sectors, with wires oriented parallel to the beam direction. Time-of-flight hodoscopes surround the magnet coil. The electromagnetic calorimeter is composed of 12 000 lead-glass blocks. It is divided into a central, cylindrical barrel region, and two endcaps, and is equipped with a presampler. The magnet return yoke is instrumented for use as a hadron calorimeter, and outside it muon chambers, again divided into barrel and endcap regions, detect penetrating particles. A calorimetric forward detector plugs the holes around the beam direction at each end, and is used for measuring luminosity.

At LEP design luminosity of $1.6 \times 10^{31} \text{ cm}^{-2}\text{s}^{-1}$ and at the peak of the Z^0 resonance (91 GeV), the visible Z^0 production rate is 0.55 Hz, with a ratio of 7:1 "multihadron" events to others (see Section 5 for a discussion of event types). In addition, about 1.5 Hz of small angle elastic scattering events enter the forward detectors and are used for the luminosity measurement.

The hardware trigger system [2] reduces the 45 kHz beam crossing rate to a trigger rate of a few Hz, using information from the tracking chambers, the time-of-flight system, calorimetry and muon detectors. There are up to 120 trigger signals, the "trigger pattern", which are of two types. Individual subdetectors generate "stand-alone" signals. Alternatively, signals are derived from a coarse segmentation in solid angle, possibly taking account of correlations between subdetectors. The central trigger performs a logical combination of these signals to derive the overall trigger decision. The trigger definition representing this logic consists of a logical OR of a set of trigger conditions, with each trigger condition corresponding to a single trigger signal or a coincidence of a few trigger signals. Typically 60 trigger conditions are active during data taking and the high degree of redundancy leads to close to 100 % efficiency for triggering on the visible decay modes of the Z^0 .

The filter is a multipurpose system. Its primary role is to act as a second-level trigger to reduce the backgrounds that are accepted through the first-level hardware trigger. These are predominantly interactions of off-momentum electrons with the beam pipe, cosmic rays, and detector noise. Events from the OPAL detector are well suited to fast online processing for the second-level trigger since the low noise and excellent stability of the major components of the detector allow simple criteria to be used for event classification and rejection. The filter further provides monitoring and data processing capabilities, and supports a graphical event display.

For the 1989 and 1990 LEP runs, the filter system was implemented [1] with single board computers on VMEbus. It carried out event classification and rejection of background and was used for "express-line" data selection. This system selected and displayed the first Z^0 event recorded at LEP, on 13 August 1989. Since 1991 the filter system has been implemented on a multiprocessor workstation with the capacity to perform data compression. The high degree of data compression achieved allows data to be recorded and passed for full event reconstruction using disk buffers.

This paper describes the design and implementation of the OPAL filter system and its performance during the 1991 LEP data taking. It will be used with only minor modifications in 1992. Section 2 outlines the structure of the OPAL data acquisition, and Section 3 discusses how the filter is implemented within that framework. The processing performed on events by the filter is summarised in Section 4. Physics aspects of the event classification provided by the filter are described in Section 5,

¹The coordinate system is defined with positive z along the outgoing e^- beam direction, θ and ϕ being the polar and azimuthal angles. The origin is taken to be the nominal interaction point.

emphasising how effective and reliable second-level triggering is achieved. Section 6 describes the data monitoring performed in the filter, using the results of the event classification. Finally the performance of the system is reviewed, and conclusions drawn.

2 The OPAL data acquisition system

The data acquisition system [3] is a modular and distributed system based on a heterogeneous selection of computers. The lowest level of data collection consists of VMEbus-based [4] subdetector systems called local system crates, LSC's. All single board computers in VME are based on a MC680x0 CPU and run the OS-9 operating system. Upon a trigger, digitisation is initiated and the separate components of the detector are read out in parallel by the LSC's. Data reduction, such as pedestal subtraction, zero-suppression and pulse shape analysis is performed. The LSC's are connected to the "event builder", also implemented in VME, with VICbuses [5]. The event builder synchronises and merges the event data from the subdetectors into a single event record. Memory buffers at various levels in the data acquisition provide event buffering for up to several seconds.

The filter system is implemented on an HP Apollo DN10000 [6] workstation and connected to the event builder via VICbus. The complete events are transmitted in sequence from the event builder and then processed in the filter. At this stage, a multihadron event typically occupies 210 kbyte of data storage and other events 60 kbyte. In the final stages of processing by the filter, events are compressed, reducing the data volume by an average factor of five, and are written to a buffer disk in files. This buffer, with a capacity corresponding to several hours data taking, is used to decouple the data acquisition from subsequent event reconstruction and data recording. For backup purposes, the event files are copied from the filter disk buffer to IBM compatible 3480 cartridge tapes.

A VAX cluster provides general services, such as the common data acquisition control. An Ethernet Local Area Network connects all computer systems and is used for all communications, apart from triggering and transport of the event data.

The event reconstruction system, based on a network of HP Apollo workstations, fetches the event files from the filter buffer disk over the Apollo Token Ring network, records them on optical disks for long term storage and performs the full event reconstruction as soon as up-to-date calibration data from the LSC's are available.

The event data are in ZEBRA [7] format data structures from the LSC level onwards. Each ZEBRA structure of a complete event includes a "header" with 64 words of basic event information, such as trigger pattern and filter event classification. It can be updated during event processing and is used for fast selection of events of a particular type.

The compressed data format was introduced to reduce data storage requirements. Event data are packed into this format before storage and unpacked into the original ZEBRA structure before reconstruction, using purpose-built procedures. This data compression performed by the filter increases the effective disk buffer and reduces requirements for data storage and network bandwidth to such a level that the Apollo Token Ring can be used for transmission of the event data.

Monitoring is performed at various levels in the data acquisition chain. The LSC's perform detailed monitoring of subdetectors. At the filter level, complete events are available, so correlations between the subdetectors can be made and the event classification can be used. The results are immediately available, so that problems can be spotted quickly. The event reconstruction system monitors the combined detector performance after full processing has been performed. These results are typically available an hour after data collection.

3 Implementation of the filter system

Several considerations influenced the choice of platform for the filter. The system needed a high-speed connection to the VMEbus-based event builder. CPU resources which could not be provided by a

single CPU system were needed. A hard disk was required for data recording. A machine with the same number representation and byte ordering as the MC680x0 was preferred in order to avoid the necessity of data conversion. Finally, a convenient program development environment was desirable.

A fully commercial and complete computer system met these requirements at moderate cost. An implementation based on workstations rather than a set of VMEbus single board computers, as used for the 1989 and 1990 filter system, has the advantage that it provides a complete computer system including hard disk, networking interfaces and full operating system with networking support and program development tools such as compilers, symbolic debuggers and performance analysis tools. The choice of a single multiprocessor workstation means that common resources such as hard disk and interfaces are shared and avoids the difficulty and cost of providing sufficiently high-speed connections between workstations.

An HP Apollo DN10000 workstation was chosen. It is a RISC-based symmetric multiprocessor. The filter workstation is configured with four CPU boards² and 64 Mbyte of main memory on the internal bus. The VMEbus used as a peripheral bus hosts two disk controllers supporting four 700 Mbyte disks used in sector striped mode, and interfaces to both Ethernet and Apollo Token Ring networks. The DN10000 runs the Domain/OS operating system, which provides full implementations of both the SysV.3 and BSD4.3 UNIX [8] environments as well as the Apollo Aegis system.

The filter has three hardware interfaces to the rest of the data acquisition system: VMEbus, Apollo Token Ring and Ethernet. The VMEbus is used for the transfer of the events from the event builder, and the Apollo Token Ring for transmission of compressed events to the event reconstruction system. All other communications use Ethernet with TCP/IP as network protocol.

The VMEbus of the filter and event builder are connected via VICbus modules [5]. On the filter, an Aegis device driver allows the mapping of VME addresses to virtual addresses and handles VME interrupts. The memories inside the VICbus modules are used to buffer the event data and use is made of the module's interrupting capabilities to implement a message exchange mechanism. Events can be transferred at around 3 Mbyte/s, depending on the DMA device in the event builder.

The symmetric multiprocessor architecture requires that the processing load is divided between several tasks operating in parallel. For the filter application this can be achieved by either multiple instances of the same task processing different events, or by splitting the different stages of event processing between tasks. A combination of the two strategies is implemented for the event processing by the filter. The MODEL Buffer Manager (MBM) [9], ported to UNIX, is used to coordinate the event handling, where events are stored in a shared memory area while being processed, and the flow of events is achieved by passing the byte offset of the event data to the tasks in turn, with signals employed to indicate the availability of events.

The underlying structure of the event data is always the ZEBRA memory format. Use is made of a special C implementation of the ZEBRA routines. It provides memory mapping of the FORTRAN COMMON blocks holding the ZEBRA data structures, so that the data need never be copied. The programs performing the monitoring use the HBOOK [10] package³ for filling and storing histograms.

The filter runs a number of tasks for local control and network communication with central services [3] for integrated operation. The filter is controlled during common data taking from the data acquisition control system, which contains a model for the filter as an abstract object which can be in a few states. State transitions can be induced by commands and completed transitions are reported back. Further services available include general error reporting and access to databases for status information and storage of bookkeeping information.

As programming languages, FORTRAN and C are used. All application code related to the event processing, such as the filter analysis, is in FORTRAN and can also run in the offline environment. C is used for most of the support software, which is online specific.

²One DN10000 CPU board is rated 22 MIPS/5 MFLOP.

³For the filter, HBOOK was slightly adapted to provide storage for all histograms in a single shared memory area, accessible to all tasks on any of the processors.

Portability is furthermore ensured by using UNIX for all shell programming and as the application programming interface to system primitives. The only exception is the device driver for the VMEbus interface which is necessarily Aegis specific.

4 Event processing

The filter processing performs a series of separate functions on each event received from the event builder. These functions are:

Validation: It is verified that the format of the data of each event conforms to a generic ZEBRA structure.

Analysis: A partial event reconstruction is performed and the events are subsequently classified. In particular background events are flagged for rejection. The procedure applied is described in Section 5. This processing step adds the filter analysis results to the event data structure and updates the event header.

Monitoring: Based on the results of the analysis step the data quality is checked. Results are accumulated in histograms. A copy of the event data is passed to the online event display if a request for that particular event type is pending. The monitoring is described in Section 6.

Data compression: For events which are to be retained, the data compression procedure is performed. Lists of the maximum possible ranges of all words defined in the data structure are used to store the compressed information in as few bits as possible, across word boundaries. In addition some noise hits and information used only for monitoring are removed, and all data values found out of range are truncated at the boundary values. A count is kept of all such occurrences. Since every data word is scrutinised during compression, this process has the valuable secondary function of checking the data integrity at the finest level.

Recording: The event data and associated information concerning the events are written onto disk. The compressed data are recorded in 20 Mbyte files, containing typically 2000 events. For the rejected events only the event headers are kept. Several other files are written in addition to the event file – one file contains copies of the event headers, another contains the byte offsets to the start of each event in the event file, and a further contains calibration bookkeeping information. Two Gbyte of disk space is available for buffering the event files.

The data structure validation contributes to the robustness of the system. Should one of the event processing tasks nevertheless crash due to corrupt or invalid input event data, the task is automatically restarted. Subsequent processing of the event is skipped but the event data are still recorded.

The event header is kept for each event, rejected or not, to allow the tracing of all triggers and the analysis of the filter performance. The file with copies of all event headers helps in book-keeping, as it can be used to cross check that no events have been lost in subsequent processing of event files. This assurance of data completeness is important for high precision physics analyses.

The bulk of the CPU requirements for the event processing come from the data compression procedure. This consumes roughly 200 ms of CPU time for low activity events, and 800 ms for multihadron events. The other processing adds another 100 ms per event to this.

5 Event classification

The properties of the events are analysed for two purposes. Firstly, rejection of background events reduces the data handling requirements of subsequent stages in the data processing chain, and secondly

recognition of different types of Z^0 decay can provide well-defined samples for the monitoring of detector performance.

The physics objectives of the first phase of operation of the LEP collider centre around production and decays of large numbers of Z^0 particles. The event signatures are as follows:

- Z^0 decays to quark-antiquark pairs produce final states with many hadrons. Such "multihadron" events are characterised by having a large number of charged tracks in the tracking chambers, and many energy clusters in the calorimetry. Particles in multihadron events typically have momenta ranging up to a few GeV. A typical multihadron event, as depicted by the online event display program (see Section 6.4) is shown in Figure 2.
- Final states with an e^+e^- pair arise from both Z^0 decays and t-channel scattering processes. When the final state particles propagate at a large angle to the beam direction, these events are characterised by two charged tracks with very high momenta, equal to that of the incoming particles, and two energy clusters in the calorimeter of the same magnitude. An e^+e^- event with the final state particles striking the endcap calorimeters is shown in Figure 3.
- Events where the e^+ and e^- scatter at small angles to the beam direction ("luminosity events") are little affected by the properties of the Z^0 , so are used to measure the luminosity of the beam collisions. These events are detected as two clusters with large energy, one in each end of the forward detector.
- The Z^0 decays to $\mu^+\mu^-$. These events have two very high momentum tracks, leave small energy deposits in the electromagnetic calorimeters, typically 0.5 GeV each, and give hits in the outer muon chambers.
- The Z^0 also decays to $\tau^+\tau^-$. Each τ lepton decays to between one and five charged particles, detected as high momentum tracks, and deposits energy in the calorimeters. The decay tracks of each τ are highly collimated, due to the large boost of the lepton.
- In addition to the above charged decay modes, the Z^0 can decay into a neutrino and antineutrino. Although these decay products are undetectable, in a small number of such events a photon is emitted from one of the colliding particles. This results in an event signature of a single photon with no other activity. Backgrounds are potentially large from radiative small-angle e^+e^- scattering, but are estimated to be manageable if the photon has an energy of more than 1 GeV.
- Two-photon scattering processes of the incoming electrons and positrons produce events with low momentum final-state particles in the detector, sometimes tagged by one of the e^+ or e^- scattering into one end of the forward detector.
- Unexpected physics processes, such as new particle production and decay, can result in various other physics signatures, detectable if they contain one or more energetic particles.

In addition to these desired physics processes, a special category of events is recorded containing a random sample of beam crossings interspersed between physics triggers. Since the large majority of beam crossings contain no interactions or background, this sample consists of mainly empty events. These are useful for analysing noise characteristics of the detector and trigger systems, and as such must be retained by the filter.

Background events to the signals listed above arise as follows:

- Off-momentum beam particles strike the wall of the beam pipe in the vicinity of the detector. These collisions occur at low angles of incidence with the beam pipe, and so showering occurs. The events are characterised by low momentum shower products spiralling in the inner part of

the tracking chambers, close to the beam pipe, or by low energy depositions in one endcap of the electromagnetic calorimeter. The typical spiralling tracks of beam-wall events can be seen in the example shown in Figure 4.

- Cosmic rays pass through the detector, giving typically hits in the muon detectors, 1 GeV or more in the calorimeters, but usually no tracks in the tracking chambers near to the interaction region. The rate is strongly suppressed by the 80 m of rock above the experimental cavern.
- High energy "halo" muons are produced by beam particles striking collimators upstream of the experiment. Such particles can give sizeable energy deposits as they can scrape along the calorimeters nearly parallel to the beam. The energy clusters they produce are easily recognised by their characteristic long thin profile.
- Interactions of the beam with residual gas molecules in the vacuum chamber occur infrequently.
- Random hits in gas chambers, and electronic noise in readout or trigger systems can cause the hardware trigger to fire without there being any significant signals in the detector. These noise events occur infrequently.

Of these background sources, beam-wall interactions are dominant, and lead to hardware trigger rates of a few Hz. Cosmic ray events contribute a constant rate of less than 0.5 Hz.

The primary physics goals of LEP require that the different decay modes of the Z^0 to charged particles are selected with high and precisely measurable efficiency. This necessity is met by the hardware trigger system, and must not be compromised by the filter. The requirement is satisfied by applying several loose, independent selection criteria based on different parts of the OPAL detector and keeping an event if it passes any of these. It is found that even with simple criteria a substantial number of background events can be removed.

5.1 Partial event reconstruction

The event classification requires partial event reconstruction. The detector components and algorithms used in the analysis are as follows:

The electromagnetic calorimeter: A fast cluster-finding algorithm is applied to the signals from both barrel and endcap lead-glass arrays. All blocks with energy above 100 MeV are found, and used in descending energy order to initiate clusters. Blocks above 50 MeV around the initiator blocks are added to the cluster, unless they have already been assigned to another cluster. A cluster is required to contain more than one block. This clustering algorithm is appropriate because fake electromagnetic trigger signals arise chiefly from two classes of electronics problems: from single noisy or drifting channels, or from coherent noise in the electronics which induces a signal of a few MeV in hundreds or thousands of channels. In addition, noisy or drifting channels are suppressed in the barrel part of the calorimeter if they have been found to fire frequently in recent random beam crossing events. Real electromagnetic showers of energies above a few hundred MeV are practically never confined to a single block.

The jet chamber: A track reconstruction algorithm is run on the jet chamber raw data [11] providing the track parameters (momentum, direction, closest approach to the interaction region). This data processing is carried out in the jet chamber LSC for all events except for the very largest ones, much less than 1% of the total, as their processing would introduce deadtime into the system. The tracks are used in the filter selections if they pass within 2 cm of the nominal beam axis. While the other tracking detectors are needed offline to improve the resolution of measured track parameters, the jet chamber alone is sufficient for the purpose of categorising events in the filter.

The forward detector: The signals observed in the forward detector calorimeter are converted to energy, and a fast cluster reconstruction algorithm run.

The muon chambers: Hits are used for event classification, and track segments reconstructed in the muon chambers by the filter are used for monitoring purposes.

The hardware trigger: The trigger pattern of the event is analysed and each of the trigger conditions used in the trigger definition is evaluated.

5.2 Event selections for filtering

Loose event selections are made in order to reject unambiguous background events. Events are retained if they satisfy any of these selections, which are intended to cover all visible decay modes of the Z^0 with at least two selections ("redundancy"). Independent electromagnetic calorimeter and charged track criteria are used. Various special criteria serve to pick up other event types. The criteria are listed in Table 1 (selections (1) to (13)).

First of all, events are kept if they satisfy a trigger condition which is classified as "non-rejectable". This provides a convenient and flexible mechanism for retaining special events such as random beam-crossing triggers. It is also used in cases where new trigger conditions are introduced in the course of a year's running, perhaps to look for some new physics channel not covered by the existing selections. It ensures that all events satisfying such a new trigger condition are kept. The trigger condition will typically become rejectable after a few months of running, if it is verified that its acceptance is covered by a filter selection. For example, throughout the 1991 data taking, a special trigger condition designed to pick up $e^+e^- \rightarrow \nu\bar{\nu}\gamma$ events where the photon converts in the tracking chambers or coil was non-rejectable.

Criteria (2) to (5) use the results of the electromagnetic cluster finding. The first two of these selections give full efficiency for multihadron and large angle e^+e^- final state events. The barrel energy deposit selection, (4), can be satisfied by either a cluster or a single block, so giving high efficiency for any minimum ionising particle traversing the barrel electromagnetic calorimeter, such as muons or some charged hadrons. Lists of noisy channels derived from random beam-crossing events are needed to ensure the stability of this selection. The endcap cluster criterion, (5), has a similarly high efficiency for events with a minimum ionising particle in both endcaps. Together, selections (4) and (5) give very high efficiency for Z^0 decays to $\mu^+\mu^-$ and $\tau^+\tau^-$. Selections (3) and (4) give a high efficiency for single photon final states, if the photon energy is above 1 GeV.

An independent check of the efficiency for detecting muons in the endcap regions is provided by selection (6).

The charged track criteria (7) to (10) are effectively fully efficient for all Z^0 charged decay modes that are within the detector acceptance. They also provide good acceptance for two-photon processes $e^+e^- \rightarrow e^+e^-X$, provided X contains charged tracks, in the kinematic region where there is a large hardware trigger acceptance.

Criteria (11) and (12) provide full acceptance for luminosity events. Criterion (11) requires energy clusters in both ends of the forward detector of at least 10 GeV. Luminosity trigger conditions (criterion (12)) require coincidences between the two ends of the forward detector, or else a deposit close to the beam energy in one end.

The special criterion (13) enhances the acceptance for tagged two-photon scattering events. A trigger is required from either end of the forward detector, together with a track with transverse momentum relative to the beam axis of 0.1 GeV/c or more.

Many of the criteria listed are sensitive to single energetic particles, and so would accept new physics processes with signatures such as unbalanced events.

5.3 Event selections for monitoring

In addition to these loose selections for event filtering, special tighter selections ((14) to (18) in Table 1) are made of multihadron events, luminosity events, and candidate lepton pair final states:

- "Gold-plated multihadron events" are selected by requiring a total electromagnetic cluster energy of 8 GeV or more, that there be six or more electromagnetic clusters, that there be 2 GeV or more of energy in the hemisphere opposite the largest cluster, and that there be more than three time-of-flight scintillators hit if there are at least two clusters in the barrel part of the electromagnetic calorimeter. A veto is applied to events identified as being due to halo muons. This selection is $97 \pm 1\%$ efficient, with less than 1% background.
- Luminosity events are selected by requiring that the average calorimeter energy seen in the two ends of the forward detector be at least 82% of the beam energy, that there be clusters at both ends with energy of at least 54% of the beam energy, and that the highest energy clusters at the two ends be roughly back-to-back. This selection has an acceptance of 50 nb^{-1} .
- Candidate lepton pair events are identified by requiring a small number of high-momentum tracks to be reconstructed. The efficiency for these events is usually above 90% of the equivalent final physics selection, and the backgrounds from non-leptonic final states are small.

These special selections are used both for monitoring the general detector performance, and for monitoring the first-level trigger, as described in Section 6.

5.4 Classification Performance

The fraction of events accepted by the first-level trigger which pass each of the filter selection criteria is shown in Table 1. In normal running conditions, roughly one third of events are rejected by the filter. These are predominantly beam-wall events (where, for example, the track trigger may have been fired by the spiralling shower products), electronic noise, and some cosmic rays.

The performance of the filter selections is assessed by comparison with physics analysis selections made using the results of full event reconstruction. Such selections can be made tighter than the filtering event selections because better calibration constants are available, and more time-consuming algorithms employed. Also these selections can be remade if it is discovered that errors were made. Use of fully reconstructed and calibrated quantities means that about half the events selected by the filter fail the first stage selection. The third of triggered events not retained by this physics preselection, but passing a filter selection, contain most of the cosmic rays, as well as beam-wall events with energetic wide angle products. Final physics analysis selections are made after detailed data analysis, weeks or months after data taking. Selected events provide well-defined samples of Z^0 decays, for example.

After major detector or code changes the filter algorithms are applied to flag events, but none are rejected. This allows the filter flagging to be checked against the physics selections without risk of loss of useful events. At the start of the 1991 data-taking period, a sample corresponding to 70 000 multihadron events was recorded in this way. Typically 1-2% of the events passing the physics preselection cuts were not selected by the filter; many were examined visually, and nearly all were determined to originate from the various background sources. The remaining small fraction of the preselected events rejected by the filter were two-photon events and lay very close to the nominal filter rejection cuts. Where the fully reconstructed tracks passed the filter cuts, but the online tracks did not, discrepancies of more than a few MeV/c in momentum resolution were always ascribable to different tracking behaviour for poorly measured tracks. None of the events flagged as rejectable by the filter passed any of the final physics selections.

In normal physics running rejection is activated. The redundancy of the filter cuts allows the efficiency of each loose selection to be monitored using independent detector components. No measurable inefficiency has been found for any charged Z^0 decay which would pass the final physics selections.

Given these extremely low inefficiencies, and the existence of redundant selections, there is nothing to be gained by keeping a fraction of the rejected events. Hence, all events flagged as rejectable are discarded.

6 Monitoring

One of the most important roles of the filter system is the continuous checking of the quality of the data. The immediate availability of complete events, and the large CPU capacity, provide an ideal monitoring environment. The checking is divided into two parts: an analysis of the performance of the hardware trigger system, and general data quality monitoring.

Monitoring results are filled into over five hundred histograms. Efficiency plots are derived by a special asynchronous task by dividing counter histograms at one minute intervals. This task also produces time evolution plots of various quantities. These histograms can be viewed from workstations at the experiment, or remotely. In addition, the histograms are saved onto disk as a permanent record at the end of each LEP fill.

Anomalies detected by the monitoring are reported by messages to the operator. Further monitoring in the form of an online event display provides a powerful tool for identifying problems quickly.

6.1 Monitoring of the hardware trigger

Three different kinds of trigger monitoring are performed. Firstly, the propagation of digital trigger signals from the various subdetectors are checked by comparing for each event the information stored by the subdetector LSC's with that from the central trigger LSC. Errors detected in signal propagation are reported immediately by messages to the operator, as well as being tallied in histograms. Secondly, efficiency curves are derived for the various trigger signals using unbiased samples of events. The different efficiency curves are accumulated into histograms. Thirdly, the efficiency of all trigger conditions for selected physics channels (multihadron, luminosity, and candidate lepton pair final states) are derived and recorded in histograms. Each of these well identified physics events is checked and clear-cut failures of triggers result in error messages sent to the operator.

6.2 General monitoring of the data quality

General monitoring of the data quality is carried out for several subdetectors, to supplement any such monitoring in the LSC's. All results are accumulated as histograms. For example, hit maps are filled for the electromagnetic calorimeters for random beam crossing events, and are used to derive lists of noisy channels.

The events flagged in specific physics channels are used to produce estimates of the machine luminosity and physics cross-sections over periods of a few minutes, allowing detector problems to be spotted quickly.

6.3 Histogram Display

A Macintosh II [12] computer⁴ is dedicated to displaying the filter histograms in the control room. A Macintosh style user interface [13] allows easy selection of histograms, and large, high resolution colour screens permit the display of many histograms simultaneously. Pages of critical monitoring plots are shown during data taking. Part of a typical display screen is shown in Figure 5. Gross trigger or detector problems can be seen at a glance. The histograms can also be viewed from remote workstations on the CERN-wide Ethernet using PAW [14], which accesses the histogram data over TCP/IP.

⁴The Macintosh II computers used for histogram presentation and event display communicate with the filter via VICbus.

6.4 Event Display

The event display is used for visual inspection of event properties and for immediate visual monitoring of the detector and trigger performance. Use is made of a second Macintosh II computer running the OPAL online event display program. This is written in Real-Time FORTRAN [15], using the MacSys operating environment [16]. Macintosh toolbox routines are called directly to give a fast event display rate. A 12 inch bitmap display device (1024×768 pixels with a 256 colour palette) is used for the graphical output. Typical images produced are shown in Figures 2 to 4. With a Macintosh IIfx, each event is drawn in a second or two, and events can be displayed every few seconds.

The display includes all trigger conditions and filter classifications satisfied for the event. An unbiased sample of events can be selected for display, or samples selected using trigger signals or filter classifications can be shown, including events rejected by the filter. This selection can be set interactively, and also the view and magnification changed.

7 Performance

During the seven month running period in 1991, about 4 million events were accumulated, including 352400 multihadron events.

The throughput of the filter system is limited by the CPU capacity of the DN10000 computer. Typically in 1991, the event rate was 5 Hz or less, with 0.3 Hz or less of multihadrons. This results in a mean loading of 40 to 50 %. At LEP design luminosity, the multihadron rate is 0.5 Hz, and the hardware trigger rate is expected to be less than 10 Hz. Such a rate would fully load the filter CPU capacity. As the originally anticipated upgrade path using DN10000 CPU boards running at double the clock speed is not realisable, alternatives based on other UNIX workstations are being considered.

The filter system is reliable. Errors occur infrequently and almost all of them are handled successfully by the automatic restart procedure, with no loss of live time. Non-recoverable errors are extremely rare, occurring at the rate of one every few months in 1991. These were typically related to interfacing with the rest of the data acquisition system. The overall live time of the filter system in 1991 data taking was above 99.9 %.

8 Conclusion

From the outset, an online event filter has been fully integrated into the data acquisition system of the OPAL experiment. The emphasis has moved from "express-line" event selection to background rejection and data compression. It has been found that a high-performance UNIX workstation can be used in a demanding online environment with excellent reliability, and with a limited development timescale. Typically one third of the events are rejected as background, and the data compressed by a factor five. This reduction in data volume allows the use of disk buffering and of low cost networks to transfer the event data.

The event classification applies independent selection criteria on physics quantities from different components of the detector. This allows monitoring of the filter event selection efficiency. No measurable inefficiency has been found for any charged Z^0 decay which would pass the final physics selections.

The extensive detector, hardware trigger and data quality monitoring performed by the filter allows problems to be spotted quickly and contributes to the high data-taking efficiency of OPAL.

The filter performance in 1991 was very satisfactory, and with only minor changes the system continues to be used for 1992 data taking. Anticipating higher LEP luminosity (associated with increasing the number of bunches), the present filter system has to be upgraded in CPU power. The use of cheaper and more performant UNIX workstations now available will be facilitated by the portable implementation of the filter software.

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Tables

	Selection	Fraction of Events
(1)	Non-rejectable trigger condition	35%
(2)	Energy in clusters $\Sigma E_{clus} > 2$ GeV	16%
(3)	Any cluster with $E_{clus} > 1$ GeV	16%
(4)	Barrel energy deposit above 0.2 GeV	26%
(5)	$E_{clus} > 0.2$ GeV cluster in both left and right endcaps	4%
(6)	Muon endcap hits consistent with muon produced at interaction point	3%
(7)	A track with $p_t > 0.4$ GeV/c	16%
(8)	Two tracks with $p_t > 0.25$ GeV/c	12%
(9)	Total $\Sigma p_t > 0.7$ GeV/c	14%
(10)	Tracking not done	0.03%
(11)	Forward detector clusters	14%
(12)	Luminosity trigger condition	16%
(13)	Tagged two-photon	1%
	Rejected	34%
(14)	Gold-plated multihadron	6%
(15)	Luminosity event	10%
(16)	e^+e^- candidate	0.8%
(17)	$\mu^+\mu^-$ candidate	0.3%
(18)	$\tau^+\tau^-$ candidate	0.3%

Table 1: List of filter selection criteria, discussed in the text, and fractions of events passing them. E_{clus} denotes energy in an electromagnetic calorimeter cluster, p_t the momentum component transverse to the beam axis of a reconstructed track. Note that the selections are not exclusive.

Figures

Figure 1: General layout of the OPAL detector.

Figure 2: Image of a multihadron event as depicted by the online event display (see Section 6.4). Hits on wires (for example in the tracking chambers) are shown as dots, calorimeter energy deposits are drawn as polygons with length proportional to energy, and hits in the muon chambers as short line segments. The view shown is a projection onto the $z = 0$ plane of the barrel detectors.

Figure 3: Side view of an $e^+e^- \rightarrow e^+e^-$ event as represented by the online event display. In this view the endcap calorimeters are shown.

Figure 4: Online event display image of a typical beam-wall background event, showing spiralling low-momentum tracks. This event was rejected by the filter.

Figure 5: Part of a typical page of monitoring histograms as displayed on the Macintosh II computer. Maps of hits in different detectors, time histories of quantities, and trigger efficiency plots are shown.

MUON CHAMBERS

TIME OF FLIGHT
AND PRESAMPLER

Z CHAMBERS

JET CHAMBER

VERTEX CHAMBER

OPAL-ENSEMBLE EN PERSPECTIVE
MARS 86 1989

ELECTROMAGNETIC
CALORIMETERS

HADRON
CALORIMETERS

FORWARD
DETECTOR

fig.1

Triggers
 TH1
 TH2
 TH3
 TH4
 TH5
 TH6
 TH7
 TH8
 TH9
 TH10
 TH11
 TH12
 TH13
 TH14
 TH15
 TH16
 TH17
 TH18
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 TH96
 TH97
 TH98
 TH99
 TH100

Run 3234 Evt 81320 Total E(cus): 32.93 GeV N(custers): 16 Nrk: 17 8.65 GeV/c
 CU CJ C2 TB PB EB PE EE E(cus) EB: 32.93 GeV N(cus) EB: 16 PTrk1: 8.65 GeV/c
 HT HS HP NB NE FD TR TT E(cus) EEL: 0.00 GeV N(cus) EEL: 0 PTrk2: 5.99 GeV/c
 SC F1 S1 F11: 1117 Ebeam: 45.625 GeV (from EUB) HoEB: 0
 Filter Flags: 0
 Sum E(cus) > 2
 Min Ion EB
 E(cus) > 1
 PTrk1 > 400
 PTrk2 > 250
 Sum Pt > 700
 NO spec. trig
 Loose RH
 Loose L+-
 GPH

fig.2

Stop Hold Print View Save Replay Grow Shrink

Waiting for event...

Triggers
 TT1
 TT2
 TT3
 UXH
 J1H
 J2H
 EELHI
 EERHI
 TPENL
 TPENR
 EELTPH
 EERTPH
 EELLO
 EERLO
 TPITL_1
 TPITR_1
 TPIT1
 TPIT2
 TP401
 TP402
 TPITL
 TPITR
 TP40R
 TPITCL

Run 3165 Evt 20016 Total Eclus): 81.49 GeV Ntrk: 2
 CU CJ CZ TB PB EB PE EE Eclus) EB: 8.00 GeV Nclus) EB: 36.06 GeV/c
 HT HS HP HB HE FD TR TT Eclus) EEL: 48.88 GeV Nclus) EEL: 15.38 GeV/c
 SC FI SI FILL: 1837 Ebeam: 45.625 GeV (from EUB) NoEB: 0

Filter Flaps
 Sum Eclus) > 2
 Eclus) > 1
 MinLowEE Lor
 PTrk1 > 400
 PTrk2 > 250
 Sum Pt > 700
 NO spec.trig
 Loose l+l-
 e+e-
 l+l-

Stop Hold Print View Save Replay Grow Shrink

fig.3

Waiting for event...

Triggers
 TH1
 TH2
 TH3
 UXH
 J2H
 J3H
 TP1TL_1
 TP1TR_1
 TP1TH
 TP1TB
 TP1T1
 TP1T2
 TP1H1
 TP1H2
 TP1TL
 TP1TH
 TP1HR
 TP1HCL

Run 3165 Evt.17665 Total E(c lus): 0.00 GeV N(c lus): 0 Nrk: 0 0.00 GeV/c
 CU CJ C2 TB PB EB PE EE E(c lus) EB: 0.00 GeV N(c lus) EEL: 0 PIRK1: 0.00 GeV/c
 HT HS HP MB ME FD TR TT E(c lus) EEL: 0.00 GeV N(c lus) EER: 0 PIRK2: 0.00 GeV/c
 SC F1 S1 Fill: 1837 Ebeam: 45.525 GeV (from EUB) NoteB: 0
 Filter Flags: 0
 NO spec. trig
 Global NO
 EUT REJECTED

Stop Hold Print View Save Replay Grow Shrink

Waiting for event...

fig.4

fig.5