Measurements of the W-pair production rate and the W mass using four-jet events at LEP
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Chapter 3

Tools

3.1 LEP

The Large Electron Positron (LEP) collider has been built to study the carriers of the electroweak force, the Z and W$^\pm$ bosons. For this purpose electrons are collided on positrons with energies sufficient to produce these particles. The collisions take place at four interaction points, where the LEP detectors ALEPH [61], DELPHI [62], L3 [63] and OPAL [64] are located.

In the first phase of the LEP program, a center-of-mass energy sufficient to produce a Z-boson at rest was used. The first physics data at this energy have been taken in 1989, while this phase has been finished in 1995. In the second phase, the LEP collider has been upgraded, so that the leptons can be accelerated to energies exceeding 100 GeV. In this phase the center-of-mass energy is such that the threshold for W$^+W^-$ production is exceeded, i.e. two W bosons can be produced. The integrated luminosity at different center-of-mass energies collected by the L3 detector in the years 1990–1998 is summarized in Table 3.1.

The LEP collider consists of an accelerator ring with a circumference of about 26.7 km, and is situated between 50 and 150 meters underground on the French-Swiss border near Geneva. A schematic view is shown in Figure 3.1. The electron and positron beams are provided by the LEP injector chain [65] using the previously existing Proton Synchrotron (PS) and Super Proton Synchrotron (SPS), see Figure 3.2. Positrons are created in a tungsten converter target by a 200 MeV electron beam from a high-intensity linear accelerator (LINAC). A second LINAC accelerates the electrons and positrons up to 600 MeV, to be accumulated in the Electron–Positron Accumulation Ring (EPA). The PS and SPS are subsequently used to accelerate the beams up to 3.5 GeV and 20 GeV respectively, after which they can be injected to LEP. Once in the LEP collider the leptons are accelerated to the desired energy by radiofrequency cavities. In the first phase of LEP copper cavities were used, for the second phase of LEP, dedicated to W-pair production, superconducting cavities were installed to achieve the required increase of center-of-mass energy. More details about the
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Table 3.1: The integrated luminosity $\mathcal{L}$ at different center-of-mass energies collected by the L3 detector during 1991–1998. For years where data was collected at several slightly different energies the average energy is given.

LEP accelerator and its energy upgrade can be found in References [66, 67].

### 3.1.1 LEP Beam Energy Determination

For the analysis of the W mass, as described in this thesis, a precise knowledge of the LEP beam energies is important. The LEP Energy Working Group has constructed a LEP Beam Energy Model that calculates the center-of-mass energies $\sqrt{s}$ in each of the 4 interaction points as a function of time, taking into account all RF and magnet configurations, as well as additional effects that influence the beam energy, such as tides, the water level in Lake Geneva, and parasitic currents due to electric trains. The LEP Beam Energy Model provides $\sqrt{s}$ in each of the 4 interaction points separately, since the beam energy is very much influenced by the different layout of RF accelerating voltage in the straight sections.

At LEP1, the LEP beam energy was accurately calibrated using the technique of resonant depolarization. In $e^+e^-$ synchrotrons, the beams obtain a natural transverse polarization due to the emission of synchrotron radiation. The polarization is destroyed by the application of a small RF field if the applied RF frequency matches the electron spin precession frequency, which is proportional to the beam energy. Since this frequency can be accurately measured, the beam energy is known to a precision of $\mathcal{O}(1)$ MeV.

Unfortunately, above beam energies of about 60 GeV, transverse polarization of the beams no longer builds up due to the presence of depolarizing resonances and the increased beam energy spread. Thus, the technique of resonant depolarization can no longer be applied. The LEP beam energy is proportional to the strength of the magnetic field in the dipoles, and a measurement of the dipole fields thus provides a handle on the beam energy. This is done in two ways: with sixteen Nuclear Magnetic Resonance (NMR) probes in the arcs of LEP, and with a flux loop system that sees 96.5% of the dipole field. The NMR probes are calibrated using resonant depolarization at beam energies between 40 and 60 GeV, and extrapolation...
into the high energy regime then provides the beam energy calibration at LEP2 energies. The accuracy achieved is 25 MeV at $\sqrt{s} = 183$ GeV, and 20 MeV at $\sqrt{s} = 189$ GeV; the better accuracy achieved at 189 GeV is due to the fact that more data was taken in a longer running period. The uncertainty is dominated by observed differences between the NMR’s and the flux loop system, by fluctuations in the NMR’s, by uncertainties in the field not measured by the flux loop, and by the RF model.

A number of alternative methods to calibrate the beam energies are under investigation, but have not yet yielded conclusive results. The LEP spectrometer project consists of the replacement in 1998 of a standard dipole by a steel dipole with accurately calibrated magnetic field plus two arms of high precision beam position monitors. The bending of the beams in the dipole is measured, which is inversely proportional to the beam energy. In order to reach 10 MeV precision on the beam energy, the beam positions must be measured to accuracies of $\mathcal{O}(1) \mu$m. It is not yet clear whether this can be achieved. Another approach consists of the measurement of the energy loss by the beams through the measurement of the synchrotron tune. An accuracy of 15 MeV may be achieved. Finally, experimental measurements of radiative return events, $e^+e^- \rightarrow Z\gamma \rightarrow f\bar{f}\gamma$, can be used to measure the beam energy; it is still uncertain what precision can be achieved.

### 3.2 The L3 Detector

The L3 detector is designed to study high energy $e^+e^-$ collisions up to center-of-mass energies of about 200 GeV, with emphasis on high resolution energy measurement of electrons and photons, as well as on high resolution muon spectroscopy. An extensive description of
the detector can be found in Reference [63], while shorter descriptions can for example be found in [68, 69].

An impression of the total detector is shown in Figure 3.3. The central part is shown in more detail in Figure 3.4. The L3 subdetectors are arranged in layers of increasing size surrounding the interaction point and are supported by a 32 m long and 4.5 m diameter steel tube. Starting from the interaction point radially outwards, the main detector components are:

- a Silicon Microvertex Detector (SMD), a central tracking detector (a Time Expansion Chamber, TEC), Forward Tracking Chambers (FTC), and z-chambers. This system measures the direction and momenta of charged particles;
- an electromagnetic calorimeter (ECAL), mainly measuring the energies and directions of electrons and photons;
- scintillation counters, providing timing information;
- a hadron calorimeter (HCAL), measuring the energies and directions of hadrons;
- muon chambers (MUCH), measuring the directions and momenta of muons.
- another layer of scintillation counters, exclusively used to study cosmic ray muons [70].

In addition, luminosity monitors are installed close to the beam pipe at a distance of 2.8 meters from the interaction point. These consist of BGO crystals (the LUMI) with a silicon strip detector in front (the SLUM).

The entire detector is surrounded by a solenoidal magnet (inside radius of the coil 5.9 m, length 11.9 m), providing a magnetic field of 0.5 T along the beam axis. Additional coils, installed on the magnet doors for LEP2 data taking, provide a 1.2 T toroidal field for muon momentum measurements in the endcaps. In the following sections the subdetectors are described in greater detail. The beam axis is chosen as the z-axis.

**L3 Tracking System**

The aim of the L3 tracking system is to reconstruct charged particle trajectories in the central region of L3, to measure particle charge and momentum, and to reconstruct secondary vertices from decays in flight. It includes a Silicon Microvertex Detector (SMD), a Time Expansion Chamber (TEC), z-chambers and Forward Tracking Chambers (FTC). A view of this part of the detector in the plane perpendicular to the beam axis is shown in Figure 3.5.

The SMD [71] consists of two layers of double-sided silicon ladders 35.5 cm long, situated at radial distances of 6 cm and 8 cm from the z-axis and covering the polar angles $22^\circ - 158^\circ$. The outer silicon surface of each ladder is read out with a 50 $\mu$m pitch for the
Figure 3.3: Perspective view of the L3 detector at LEP. A man is drawn near the magnet to give an idea of the scale. The inner detector is shown in more detail in Figure 3.4.
$r\phi$ coordinate measurements; the inner surface is read out with a 150 $\mu$m pitch (central region) or 200 $\mu$m pitch (forward regions) for the $z$ coordinate measurements. The single track resolution of the SMD is 6 $\mu$m in the $r\phi$ direction and 20–25 $\mu$m in the $z$ direction.

The TEC [72] is a drift chamber with an inner radius of 8.5 cm, an outer radius of 47 cm, and a length of 98 cm. Radial cathode wire planes divide the TEC into 12 inner and 24 outer sectors. The sectors are subdivided radially by a plane of mixed anode sense wires and additional cathode wires. Planes of closely spaced grid wires on either side of each anode plane provide a homogeneous low electric field in most of the sector (drift region), and a small high-field region near the anode plane (amplification region). Secondary particles, produced by ionization along a charged track, drift slowly in the low field region towards the high field region, where they produce further ionization particles in an avalanche that amplifies the original signal. The timing of the signal, measured at each anode, determines the distance to the track along a line perpendicular to the anode plane with an average resolution of about 50 $\mu$m.

The $z$ coordinate of a track is measured by two layers of proportional chambers surrounding the cylindrical outer surface of TEC and covering the polar angles $45^\circ < \theta < 135^\circ$. 

Figure 3.4: View of the inner part of the L3 detector, shown in the $yz$ plane.
Figure 3.5: View of the innermost part of the L3 detector in the plane perpendicular to the beam axis. Going outwards from the interaction point, the Silicon Microvertex Detector (SMD), Time Expansion Chamber (TEC) and the z-chambers are drawn, respectively.

Another two layers of proportional chambers with strips at an angle 70.1° with respect to the beam axis provide additional stereo information. The z-chambers provide a single track resolution of approximately 300 μm.

In Fig 3.6(a) an event is shown with four tracks in the TEC.

**Electromagnetic Calorimeter**

The electromagnetic calorimeter uses about 11000 bismuth germanium oxide (Bi$_4$Ge$_3$O$_{12}$, usually abbreviated as BGO) crystals as the showering medium for electrons and photons. Since BGO is a scintillator, part of the energy of the incoming particles is converted to light. The small radiation length of this material allows the construction of a compact calorimeter. Electrons and photons traversing the BGO calorimeter interact electromagnetically, producing secondary electrons and photons that also interact in a chain reaction leading to an electromagnetic shower. When the energy of an electron in a shower falls below 10 MeV, it loses its remaining energy primarily by ionization, creating excitations in the crystal lattice. The excitations decay producing photons, so that the total amount of scintillation light produced by the shower is proportional to the energy deposited. The light yield is measured using two photodiodes, glued to the rear of each crystal. Electrons and photons produce
practically indistinguishable electromagnetic showers, leaving most of their energy in the calorimeter. Hadrons in the BGO can lose energy through nuclear interactions, which then result in diffuse deposits with large fluctuations. Usually hadrons are not stopped by the BGO, and deposit most energy in the hadronic calorimeter, located behind the electromagnetic calorimeter. Muons do not interact strongly in the BGO and produce small signals that are almost independent of their energy (Minimum Ionizing Particles, or MIPs).

The BGO barrel calorimeter consists of two symmetrical half barrels which contain in total 7680 crystals and surround the central tracking system, covering a polar angle range of $42^\circ < \theta < 138^\circ$. Two BGO endcap calorimeters (1527 crystals each) cover a polar angle of $10^\circ < \theta < 37^\circ$ and $143^\circ < \theta < 170^\circ$, as can be seen in Figures 3.4. The barrel crystals are 24 cm long truncated pyramids about $2 \times 2 \text{ cm}^2$ at the inner and $3 \times 3 \text{ cm}^2$ at the outer end. In the theta direction the crystals are aligned with their long axis pointing to the interaction point. In the phi direction the crystals are tilted by about $0.6^\circ$ to minimize the chance that a particle escapes undetected through the inactive material between the crystals.

For electrons and photons of more than 5 GeV the energy resolution is better than 2% with an angular resolution better than 2 mrad. A more detailed description of the electromagnetic calorimeter can be found in Reference [69].

In 1996 the gap between the barrel and endcap parts of the calorimeter was filled with blocks of lead threaded with plastic scintillating fibres. This so called SPACAL detector improves the hermeticity of the L3 detector.

An example of an electromagnetic energy deposit is shown in Fig 3.6(b). A considerable amount of energy is not matched to a track, which indicates the presence of one or more photons, for example from $\pi^0$ decay.

**Scintillation Counters**

The purpose of the plastic scintillation counters, located between the electromagnetic and hadronic calorimeters, is to provide time-of-flight information to reject background from muons originating from cosmic rays. One of these passing near the interaction point can fake a muon pair event produced in $e^+e^-$ collisions. In this case the time difference between opposite scintillation counter hits is about 6 ns, while for signal events the time difference is zero. The timing information provided by the scintillators is accurate enough to distinguish between cosmic ray muons and muons produced in $e^+e^-$ interactions. In addition, the scintillator counters are used in the trigger.

**Hadron Calorimeter**

The hadron calorimeter surrounds the ECAL and is designed to measure the energy of hadrons, typically depositing only a fraction of their energy in the ECAL. Hadrons traversing the HCAL loose their energy through nuclear interactions in layers of depleted uranium initiating showers of low energy particles that are detected in proportional wire chambers.
interspersed with the absorber. The wires in successive layers of the wire chambers in the barrel area are rotated by 90° thus providing the coordinate measurements in both, \( \phi \) and \( z \) directions. In the endcaps, wires in successive chambers are rotated each by 22.5°.

The HCAL barrel is divided into 16 modules in \( \phi \) and 9 modules in \( z \), with an angular coverage between \( 35^\circ < \theta < 145^\circ \). The HCAL endcaps consist of three rings: an outer ring and two inner rings, covering the polar angle regions \( 5.5^\circ < \theta < 35^\circ \) and \( 145^\circ < \theta < 174.5^\circ \).

The hadron calorimeter acts as a filter as well as a calorimeter, allowing only non-showering particles to reach the precision muon detector. The thickness of the HCAL together with the electromagnetic calorimeter and support structures is about 6 nuclear interaction lengths in the barrel part and 6–7 nuclear interaction lengths in the endcaps.

A muon filter surrounds the barrel HCAL, and is mounted on the inside wall of the support tube. It consists of eight octants of brass absorber plates (thickness about 1 nuclear absorption length), interleaved with five layers of proportional chambers. The aim of the muon filter is to ensure that only muons and neutrinos pass through to the muon chambers.

In Fig 3.6(c), a significant amount of hadronic energy deposit is shown on one side, whereas the energy deposited in the top of the calorimeter is consistent with a minimum ionizing particle.

**Muon Chambers**

The barrel muon chambers consist of octants, each containing three layers of drift chambers: MI (inner), MM (middle) and MO (outer). Each layer consists of "P"-chambers, measuring the \( r\phi \) coordinates; in addition the MI and MO layers contain "Z"-chambers, measuring the \( z \) coordinate. The barrel muon chambers cover the angular range \( 43^\circ < \theta < 137^\circ \).

To improve hermeticity, forward-backward muon chambers have been installed before LEP2. These consist of three additional layers of drift chambers mounted on the magnet doors in either side of the interaction point, extending the angular coverage down to \( 22^\circ \) from the beam pipe.

The barrel muon chambers provide a momentum resolution for muons of 3%, at 45 GeV. The momentum resolution of the endcaps is between 3% and 30%, at low polar angles the resolution becomes worse, mostly due to multiple scattering in the magnet doors.

In Fig 3.6(d), a muon is shown in the barrel muon system, measured in three layers of drift chambers.

**L3 Luminosity Measurement**

The luminosity measurement at L3 is based on small-angle Bhabha scattering, \( e^+e^- \rightarrow e^+e^- \). The accepted cross section \( \sigma_{\text{accepted}} \) for this process is high and can, using only QED, be calculated with high precision. This means that the measured number of Bhabha events \( N_{\text{bhabha}} \) can be converted to a measurement of the luminosity \( \mathcal{L} \) using the relation \( N_{\text{bhabha}} = \sigma_{\text{accepted}} \mathcal{L} \).
As the Bhabha cross section peaks at low polar angles the original luminosity detector of L3 consisted of a BGO calorimeter (LUMI) at both sides of the interaction point with polar angle coverage 31–62 mrad, see Figure 3.4. Before the 1993 run this setup was upgraded with a silicon tracker (SLUM) in front of LUMI, providing better position measurement for electrons and positrons entering the calorimeter, and thus allowing a more accurate measurement of the experimental acceptance. Using these detectors the luminosity can typically be measured with a precision of the order of 0.1%.

Trigger and Data Acquisition

The aim of the trigger system is to decide after each beam crossing, whether an $e^+e^-$ interaction took place, in which case the detector signals are read out, digitized and written to tape (the event is triggered).

Triggering is done in three levels of increasing complexity. The level 1 trigger uses signals from subdetectors and either initiates digitization, or clears the front end electronics in time for the next beam crossing. After a positive decision the detector data are stored within 500 μs in multi-event buffers. As during that time all further data taking is stopped, it is important to keep the frequency of positive level 1 decisions low. The level 2 trigger combines the fast digitized trigger data from all subdetectors, whereas level 3 trigger uses already fully digitized signals from all subdetectors to make a final decision. The level 1 trigger rate varies between 5–20 Hz, the final event rate written to tape is about 1–5 Hz. At these rates, the detector dead time introduced by the readout of accepted events is kept to 3% or smaller. Various subtriggers that can lead to a positive level 1 decision are listed below.

- The energy trigger checks the total calorimetric energy, the energy in the ECAL alone, the ECAL and HCAL energies in the barrel part only, or searches for localized clusters of large energy deposits. If any of these quantities exceeds a preset threshold, the event is accepted.

- The TEC trigger uses 14 sense wires from outer TEC chambers to search for tracks. Events are triggered, if at least two tracks are found with transverse momentum exceeding 150 MeV and acolinearity less than 60°.

- The scintillator trigger selects high multiplicity events, where at least 5 out of 30 scintillation counters are hit within 30 ns of the beam crossing time and the hits are spread by more than 90° in azimuth.

- The luminosity trigger selects events with two back-to-back energy deposits of at least 15 GeV in LUMI calorimeters; at least 25 GeV in one of the calorimeters together with at least 5 GeV in the other calorimeter; or at least 30 GeV in one of the calorimeters (this last “single tag” trigger is prescaled by a factor 40).
• The muon trigger selects events with at least one particle penetrating the muon chambers.

Any of these five triggers suffices for level 1 selection. Almost all $W^+W^-$ events are triggered by more than one of the above criteria.

The level 2 trigger aims to reject background events selected by the level 1 trigger. Events with more than one first level subtrigger are automatically accepted, whereas part of the remaining events will be rejected on the basis of more detailed calorimetric and track analyses, and the matching (or lack thereof) between tracks, calorimeters and scintillators.

The level 3 trigger uses the complete data available for the event. The event energies are recalculated and more stringent criteria are applied for track quality and scintillator timings. As for the level 2 trigger, events triggered by more than one level 1 subtrigger are accepted automatically.

3.3 Monte Carlo Simulation

For most processes that are being studied, many particles are produced in the $e^+e^-$ collision. This holds especially if quarks are involved in the production process. The particles subsequently interact in the detector materials. It is important to understand these complex processes, for instance to determine the fraction of the events of a certain process that will pass all detection criteria. The most convenient way to do this is to produce and study a set of simulated events. For the production of simulated events, the first step is to generate particles with distributions as predicted by the theory. The programs used for that are called event generators. Next, the detector response is modeled by the detector simulation program, which is based on GEANT [73]. Finally, the simulated events are passed through the standard event reconstruction program, in the same way as the data events.

The event sample obtained in this way is called the Monte Carlo sample. Using it, most quantities of interest can be calculated with a statistical accuracy decreasing as $\frac{1}{\sqrt{N_{MC}}}$, when one increases the number of Monte Carlo events $N_{MC}$. Below the two steps important in the generation of Monte Carlo events are described in more detail.

3.3.1 Event Generators

Usually the generation of the particles produced in a simulated $e^+e^-$ collision happens in two steps. First the particles that are produced in the electroweak part of the physics process are generated by programs dedicated to this. An example of this would be the generation of four quarks for the process $e^+e^- \rightarrow W^+W^- \rightarrow q\bar{q}q\bar{q}$. The particles are then stored, and if necessary a second program is called for the fragmentation and hadronization. In the example just given this would be done to describe the production of hadrons from the four quark system.
Electroweak Event Generators

The following programs are commonly used in L3:

- **KORALW** [74, 75]. This is the L3 standard event generator for the generation of WW events. KORALW can generate events according to the CC03 diagrams for WW production, or alternatively it can generate more general $e^+e^- \rightarrow f\bar{f}f\bar{f}$ using the matrix elements of GRACE [76]. In L3 it is typically used in the CC03 mode. KORALW can generate multiple photons from initial and final state radiation using an $\mathcal{O}(\alpha)$ YFS exponentiated calculation. Radiation in higher orders of $\alpha$ are included in the leading log approximation. KORALW treats $\tau$ decays with an interface to the TAUOLA [77] program. The full CKM matrix is included, so that also CKM-suppressed W decays, such as $W^+ \rightarrow u\bar{s}$, are included. The Coulomb interaction between the two W's is included in approximation. The matrix elements are, for technical reasons, calculated assuming zero fermion masses. For the event kinematics, however, the proper masses are used.

- **YFSWW3** [34] implements the $\mathcal{O}(\alpha)$ radiative corrections, including the non-factorizable ones, in the double pole approximation, and will mainly be used to estimate uncertainties due to radiative corrections.

- **EXCALIBUR** [78]. This program has as main advantage that all 4-fermion diagrams and their interferences are calculated, using a Weyl-van Waarden spinor technique. However, the program is of limited use for final calculations due to the fact that only collinear initial state radiation is implemented, using structure functions, no final state radiation is implemented by the authors, massless matrix elements and phase space are used, only a diagonal CKM matrix is implemented, and no Coulomb interactions are taken into account.

- **PYTHIA** [41]. This program is a versatile multi-purpose event generator with many options. It is not meant to be a state-of-the-art WW event generator, but it is used for systematic studies of color reconnection and Bose-Einstein correlations in WW events, as well as for the simulation of the $e^+e^- \rightarrow q\bar{q}(\gamma)$ and $e^+e^- \rightarrow ZZ$ backgrounds.

Fragmentation and Hadronization

For the simulation of fragmentation and hadronization, the programs JETSET [41], ARIDANE [43], and HERWIG [42] are used, as explained in Section 2.5.2. Each of these programs contain a number of free parameters that must be tuned such as to make the predictions of these programs agree with the data. The statistics of the LEP2 data is not sufficient to do this precisely, therefore high statistics $Z$ data from LEP1 is used. The L3 tuning of these parameters is described in Reference [46]. A short summary is given here.
3.3. Monte Carlo Simulation

The HERWIG Monte Carlo event samples used in this thesis were generated with HERWIG version 5.9, the parameters $\Lambda_{\text{MLLA}}$, CLMAX and CLPOW were tuned [79]. Here $\Lambda_{\text{MLLA}}$ denotes the cut-off parameter used in the simulation of the perturbative QCD shower, calculated using the Modified Leading Log Approximation. The parameters CLMAX and CLPOW control whether a cluster will split before hadronisation. In JETSET 7.4 and ARIADNE 4.08 (linked to PYTHIA 5.7), the tuned parameters were $\Lambda_{\text{LLA}}$, $b$ and $\sigma_q$ [46]. Here $\Lambda_{\text{LLA}}$ is again the QCD cut-off parameter, where LLA indicates that JETSET uses the Leading Log Approximation. The parameter $b$ is part of the Lund fragmentation function, and $\sigma_q$ controls the smearing of the hadronic transverse momenta. The tuning was performed on corrected Z data distributions of four variables, which were chosen such as to minimize the correlations between them: $y_{34}$ in the JADE algorithm, the minor thrust evaluated in the hemisphere with the narrow jet, the fourth Fox-Wolfram moment, and the charged multiplicity distribution. The quality of the tuning was subsequently tested on 14 other variables, including the major event shape variables. A $\chi^2$ per degree of freedom, $\chi^2$/d.o.f., was calculated for each tuning, with the simplification of not taking into account the correlations between the variables:

- **JETSET**: For the four variables used in the tuning, $\chi^2$/d.o.f. = 30.3/53, and for all 18 variables $\chi^2$/d.o.f. = 237/226;
- **ARIADNE**: $\chi^2$/d.o.f. = 25.9/53 for the four tuning variables, and $\chi^2$/d.o.f. = 188/226 for all 18 variables;
- **HERWIG**: $\chi^2$/d.o.f. = 85.4/53 for the four tuning variables, and $\chi^2$/d.o.f. = 347/226 for all 18 variables.

It is clear that HERWIG does not describe the Z data as well as JETSET or ARIADNE, even after the tuning. This holds not just for one or two distributions, but for the majority of them. Further investigation of differences between JETSET and HERWIG revealed a number of problems with version 5.9 of HERWIG, which were corrected in a later version HERWIG 6.1. At the time of writing of this thesis, tuning of HERWIG 6.1 was still in progress, and no event samples were available yet.

The tuning of JETSET was performed with Bose-Einstein correlations switched on, using the BE$_0$ variant of the LUBOEI algorithm. A set of tuned variables also exists for JETSET without Bose-Einstein correlations [80]. It has been checked that the set with Bose-Einstein correlations switched on also describes the data well if the BE$_{32}$ variant is used [81].

The parameter tuning used in the Monte Carlo samples used in this thesis was performed on L3 data taken at $\sqrt{s} \approx m_Z$ in 1991. Recently, the parameters were retuned for PYTHIA 6.1, which incorporates JETSET, with a larger sample of Z data events [82]. Although no Monte Carlo event samples were available yet at the time of writing of this thesis, it is interesting to look at the new tuning results. The new tuned parameters differ from the old
Parameters by 0.3 to 1.3 (old) standard deviations, and have errors that are 2.0 to 2.5 times smaller.

### 3.3.2 Detector Simulation

The L3 detector simulation tries to mimic as best as possible the response of the L3 detector to particles created in the collision and entering the detector. It is based on the GEANT [73] package, which offers a modular framework to define the detector geometry, define particles and their properties, track particles through the detector including the effects of the magnetic field, deposit energy in sensitive detector elements, and simulate the response of the detector to such energy deposits.

During the tracking, particles may interact with the material they cross, leading to processes like ionization energy loss, bremsstrahlung, multiple scattering, pair production or nuclear interactions, or they may decay into other particles. GEANT contains a set of routines to simulate each of these processes, as well as general bookkeeping routines to ensure that the cross sections of the interactions and the particle lifetimes are correct. GEANT keeps tracking the particles until their decay or capture, or until their energy falls below a predefined cut-off, below which the detector is no longer sensitive to the particle.

Most particles that enter the ECAL or HCAL will start a shower of secondary and further particles, and will eventually be absorbed, depositing all their energy in the calorimeter. In the L3 detector simulation program, electromagnetic and hadronic showers are fully simulated, no use is made of any shower libraries or parametrizations. Electromagnetic showers are simulated by GEANT itself, whereas the hadronic shower simulation is based on the GHEISHA [83] program.

Detector parts can be declared “sensitive” if they correspond to a part of the real detector that actually contributes to a measurement of a property of the particle passing through it. Energy deposits in these detector parts form “hits”, which are used to simulate as accurately as possible the actual detector output in the form of “digitizations”.

Although the detector simulation tries to simulate the response of L3 as accurately as possible, it cannot simulate very well a number of time-dependent effects. These effects include inactive cells or wires in the TEC or muon chambers, inactive silicon sensors in the SMD, inactive BGO crystals in the ECAL, noise in the SMD, ECAL or HCAL, small variations in the drift gas in the TEC or muon chambers, and the time dependence of the BGO light output. For a good description of the data, simulation of these effects is required. This is performed in a dedicated step after the initial simulation. Samples of simulated events are mapped onto the data taking period for which they are simulated, proportional to the amount of luminosity gathered. Then, using a data base of time-dependent effects, corrections to the initial simulation are applied in this so-called “realistic detector simulation”. All Monte Carlo simulated events used in the analyses described in this thesis have been subjected to this procedure.
3.3. Monte Carlo Simulation

Figure 3.6: Various views of an $e^+e^- \rightarrow W^+W^- \rightarrow \mu^+\nu_\mu, \tau^+\nu_\tau$ event candidate. a): TEC view. b): view of the energy in the EM calorimeter (ECAL). c): HCAL view showing hadronic energy deposit and a minimum-ionization trail for the muon. d): View of the muon chambers (MUCH).