Measurement of the W boson mass and width with the L3 detector
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Chapter 2

Experimental setup

In this chapter the main experimental features will be described. First the LEP collider and the beam energy calibration will be discussed. Then the L3 detector’s main characteristics will be explained. Finally the event reconstruction and simulation will be described.

2.1 LEP accelerator

The Large Electron Positron (LEP) collider was located at CERN, the European Centre for Particle Physics, near Geneva on the Swiss border with France. At a depth ranging from 50 to 150 meters below the surface, lies the LEP ring with a circumference of 26.7 km. A view of LEP is shown in figure 2.1.

Operation of the LEP machine was started in 1989. In the first period until 1995 LEP operated near the centre-of-mass energy at about 91 GeV which is close to the Z mass. From 1996 to 2000 the second phase of LEP started. In this LEP2 phase the energy threshold of approximately 161 GeV of the W-pair production was crossed. Since then the centre-of-mass energy was continuously increased every year. Starting November 2000 the detectors and collider have been dismantled.

2.1.1 LEP injection scheme

In LEP electron and positrons were stored, accelerated and collided head-on. A schematic overview of the LEP injection scheme is shown in figure 2.2.

The LEP beam exists of four bunches, where the particles are grouped, which are several centimeters long and a few millimeters high and wide over most of the LEP ring.

The acceleration of the beam is done in different stages. First, the electrons are generated by an electron gun and accelerated to 200 MeV by the LEP Injector Lineac (LIL) and shot at a tungsten target where positrons are produced. A second linear accelerator gives the beam an energy of 600 MeV. The electron and positrons are stored in the Electron Positron Accumulator ring (EPA), after which the bunches are accelerated to 3.5 GeV in the Proton Synchrotron (PS). In the Super Proton Synchrotron (SPS) these bunches of electrons and positrons are further accelerated to 20 GeV and injected into the LEP ring, where they are finally accelerated to the required beam energies.
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Figure 2.1: Situation of the LEP collider and the four interaction points.

The electrons and positrons travel in opposite directions in the vacuum beam pipe. The orbit of these bunches are controlled by 3304 bending magnets. The particles are accelerated by (superconducting) radio frequency cavities (RF cavities). These cavities also compensate for the energy loss due to synchrotron radiation. A system of quadrupoles and sextupole magnets focus the beam. An in-depth description of the LEP accelerator can be found in [31–34].

2.1.2 LEP beam energy calibration

For the W mass measurement a precise knowledge of the LEP beam energy, \( E_b \), is important. The centre-of-mass energy in the collision point is used in the energy conservation constraint in the kinematic fit as shown in chapter 4. In particular the error on the beam energy \( \Delta E_b \) results in an error \( \Delta M_W \) on the W mass measurement,

\[
\frac{\Delta M_W}{M_W} \approx \frac{\Delta E_b}{E_b}. \tag{2.1}
\]

To calibrate the beam energy the LEP machine is described by a model containing the RF and magnet configurations as well as external influences like the tides, hydrological strains, geological movements, temperature and leakage currents from railway trains. Due to the different configurations at the different interaction points the beam energy is separately determined in every interaction point and provided to the LEP experiments.
The first method to determine the LEP beam energy is the resonant depolarisation method. In a $e^+e^-$ storage ring the synchrotron radiation leads to a build-up of transverse polarisation of the electron spin as described by Sokolov-Ternov [35]. Application of a small RF field will destroy the polarisation if the RF frequency matches the natural spin precession frequency. The
2.2. General description of the L3 detector

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Spin precession frequency \( \nu_s \) is proportional to the beam energy \( E_b \), \[ \nu_s = \frac{g_e - 2}{2} \cdot \frac{E_b}{M_e} = \frac{E_b}{440.6486(1) \text{ MeV}}, \] (2.2)

where \((g_e - 2)/2\) is the electron anomalous magnetic moment and \( M_e \) its mass. The determination of this frequency yields the beam energy and has an accuracy of 1 MeV.

However, this method is not appropriate for beam energies higher than about 60 GeV. Beyond this energy point the level of spin polarisation becomes too low due to depolarising resonances and the increased beam energy spread.

Two other methods are available for higher beam energies: The Nuclear Magnetic Resonance (NMR) probes and the flux loop measurement.

The beam energy is proportional to the magnetic bending field \( B \) along the ring,

\[ E_b \sim \int_B B ds. \] (2.3)

Sixteen NMR probes are placed to measure the field strength inside several main bending dipole magnets.

The flux loop system consists of induction coils in the bending magnets. The average magnetic field is measured by measuring the induced voltage. The flux loops cover in total 95.6% of the bending field.

The NMR probe and flux loop systems are calibrated in the energy region between 41 and 61 GeV where the resonant depolarisation method is available and very precise. To evaluate the beam energies at LEP2 physics conditions the result is extrapolated to higher energy regimes.

The estimated precision for the LEP beam energy determined this way is of the order of 20 MeV \[36,37\], which mainly comes from the difference between the NMR and flux loop measurement and the extrapolation procedure.

Another approach is a beam spectrometer which measures the bending angle, \( \theta \), of the beam passing through a magnetic dipole field, \( B \). These variables are related to the beam energy by

\[ E_b \sim \int \frac{B ds}{\theta}. \] (2.4)

The integrated field of the placed dipole magnets can be determined with a relative accuracy of about \(3 \times 10^{-5}\). With a position measurement of the beam with about 1 \( \mu \)m the estimated accuracy of the beam energy combined with the other approaches to determine the beam energy results in an uncertainty below 15 MeV \[36,37\]. Another method is based on measuring the energy loss per turn by synchrotron radiation, which increases with the fourth power of energy. Observables sensitive to the energy loss per turn can be used to determine the beam energy.

2.2 General description of the L3 detector

Charged particles can be reconstructed in a detector by their interaction with the detector material. These interactions can for example be electron-hole pair creation in a semiconductor, gas ionisation, electromagnetic interaction via bremsstrahlung or strong interactions with the nuclei.
of the detector material. Neutral particles might be detected by their charged decay products. Neutral hadrons can also be detected by strong interactions. Photons are observed by their electromagnetic interaction with the detector material. From every sub-detector or combination of sub-detectors, one can reconstruct the type of particle, the energy, the momentum and the charge of the particle for the analysis. The basic layout of a detector and the possible detection of particles is shown in figure 2.3.

Figure 2.3: The basic layout of a detector. Every particle leaves a certain signature in the sub-detectors from which one can infer the components of the event.

LEP has four interaction points, where the electron and positron beams collide. At one of these four interaction points the L3 detector is situated.

The L3 detector lies approximately 50 meters underground in a cavern. The sub-detectors are enclosed in a 16 m high and 14 m long octagonally shaped solenoid magnet with a homogeneous magnetic field of 0.5 T parallel to the beam line. The inner detectors are placed in a 32 m long and 4.45 m diameter steel tube within the solenoid.

The L3 detector consists of various sub-detectors. These sub-detectors are placed cylindrically symmetric along the beam pipe around the interaction point. Moving radially outwards from the interaction point of the L3 detector in figure 2.4 the main detectors are:
2.2. General description of the L3 detector

Experimental setup

Figure 2.4: A cross section of the L3 detector. The sub-detectors are enclosed in the L3 magnet.

- Silicon Micro-vertex Detector (SMD);
- Time Expansion Chamber (TEC);
- Electromagnetic Calorimeter (ECAL);
- Hadronic Calorimeter (HCAL);
- Muon Chambers (MUCH).

These main detectors are complemented by various other sub-detectors and electronics:

- The scintillation counters which are located between the electromagnetic and hadron calorimeters;
- The luminosity monitor (LUMI) in the very forward direction for the measurement of the LEP luminosity, by counting the Bhabha event rate at small polar angle. The cross section for this $e^+e^-\rightarrow e^+e^-(\gamma)$ process is known very accurately from the QED theory;
- The muon filter, to reduce the amount of punch-through, by adding an extra interaction length to the hadron calorimeter;
2.3 Central track detectors

The central track detectors consist of a Silicon Micro-vertex Detector (SMD) and a Time Expansion Chamber (TEC). The central track detectors are designed to detect charged particles.

2.3.1 Silicon microvertex detector

The SMD was installed in 1993 to improve the tracking system and the vertex reconstruction by taking advantage of the fact that the radius of the beam pipe of LEP at the interaction points was reduced from 80 mm to 55 mm [38].

The SMD is installed between the beam pipe and the TEC, as shown in figure 2.6. It consists
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### 2.3.1 Active lead rings

The inner layer of the active lead rings has a distance of 6.0 cm from the interaction point and the outer layer is at a radius of 7.7 cm from the interaction point. The detector exists of double sided silicon detector with an area of $70 \times 40 \text{ mm}^2$ and a thickness of 300 $\mu\text{m}$. Four detectors form a ladder. The inner and outer layers are constructed by a total of 24 of such ladders.

The basic unit of the SMD is a half ladder. Subsequent inner half-ladders have an overlap of about 4.5° to facilitate the alignment. The outer ladders have been positioned with a stereo angle of 2° with respect to the inner layer [39], see figure 2.7.

The strips are implanted parallel to the beam pipe on one side and orthogonally on the other side, thus giving on one side the $r\phi$ measurement and the other side the $rz$ measurement. These strips are referred to as $r\phi$ and $z$ strips. The measurement in the $r\phi$ direction has a resolution of 6 $\mu\text{m}$ and in the $z$ direction 20 $\mu\text{m}$. The SMD polar angular coverage with this configuration is $22^\circ < \theta < 158^\circ$.

### 2.3.2 Time expansion chamber

In the TEC detector the track of a charged particle is reconstructed. The TEC is a multi-wire proportional chamber. It consists of two parts, the inner and outer TEC. The inner TEC is at a distance of 11 cm to 15 cm from the beam line. The radial distance of the outer part to the interaction region is up to 43 cm.
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Figure 2.7: The left figure shows a perspective view of the SMD where one can see the four wafers and the half-ladders. At the right a transverse view of the two SMD layers is seen. The overlap of the subsequent inner layers is clearly shown.

The inner and outer TEC are divided into sectors by cathodes running parallel to the beam line. The wire configuration of a sector is shown on the right of figure 2.8. Each sector consists of anode wires. Two of these wires are read out on both ends to provide a $z$ measurement. The two wires in each sector are the so-called charge division wires. Between these anode wires there are focus cathodes. On each side of the anode wires is a plane of grid wires at ground potential, which separates the amplification region and drift region electrically, and ensures that the electric field in the drift region is homogeneous. This is depicted on the left of figure 2.8. A group of five grid wires on both sides are isolated from the rest of the grid and are read out to resolve the left right ambiguity.

The inner TEC consists of 12 sectors with 8 anode wires, spaced 4.8 mm apart. The grid wire plane is at a distance of 3 mm from the anodes. The outer TEC has 24 sectors and 54 wires in each sector.

To have a low drift velocity a gas mixture should be characterised by a high collision cross section for the drifting electrons with the gas molecules. This is achieved in the TEC by using a gas mixture of 80% carbon-dioxide ($\text{CO}_2$) and and 20% iso-butane ($\text{iC}_4\text{H}_{10}$) at a pressure of 1.2 atm and a temperature of 291 K. The average drift velocity in the amplification region is about 50 $\mu$m/ns. In the drift region the velocity is about 6 $\mu$m/ns [40].

A charged particle traversing the TEC will ionise the gas volume. In the electric field the electrons will drift to the anode while the positive charged ions drift to the cathode. After the electrons have passed the drift region they come in the amplification region where electrons are accelerated and create an avalanche of ionisations. From the drift time the positional information where the ionisation took place can be extracted with an average resolution of about 50 $\mu$m. This is obtained by calibrating the detector using low multiplicity $Z$ decays: $e^+e^- \rightarrow Z \rightarrow e^+e^-$ and $e^+e^- \rightarrow Z \rightarrow \mu^+\mu^-$. The momentum $p$ and transverse momentum $p_t$ are related to the magnetic field $B$ and the curvature $\rho$ of the trajectory which a charged particle describe in a plane perpendicular to the
2.3. Central track detectors

Experimental setup

Figure 2.8: Left: Principle of the TEC. The lines in the drift region are the electric field lines. A charged particle crossing the TEC gives rise to a track. Right: the TEC wire configuration.
magnetic field. This relation is:

\[ pt = p \sin \theta = \frac{qB}{\rho}. \]  

(2.5)

The charge \( q \) in units of \( e \) determines a clock-wise or counter clock-wise curve.

The most sensitive region is in the polar angular range of \( 44^\circ \leq \theta \leq 136^\circ \). In this region the charged particle will be measured by all 62 wires. Particles leaving the interaction point with an angle of \( \theta < 10^\circ \) or \( \theta > 170^\circ \) will completely miss detection by the TEC.

### 2.4 Calorimeter detectors

In the calorimeters the energies of the particles are measured. The L3 detector has two main calorimeters, the electromagnetic and hadron calorimeter.

Electrons and photons loose all their energy in the electromagnetic calorimeters.

Hadrons penetrate the electromagnetic calorimeter losing only part of their energy after which they are completely absorbed in the hadron calorimeter.

#### 2.4.1 Electromagnetic calorimeter

In the electromagnetic calorimeter (ECAL) the energy and the positions of the electrons and photons are measured. Above a certain energy the electrons and photons loose their energy mainly through electromagnetic interactions with the nuclei. Electrons or positrons will interact with the nuclei of the detector material through which high-energetic Bremsstrahlung photons will be emitted. After interacting with a nucleus a high energetic photon will decay into an electron positron pair. In this way, the cascade of Bremsstrahlung emission and electron-positron pair creation from an incoming energetic electron or photon will create a shower. Below a certain energy (critical energy) the energy loss due to ionisation starts to dominate over Bremsstrahlung and pair production, the shower dies out. At this point ionisation and excitation of the crystal becomes important. The excited atoms emit scintillating light, which can be detected by photodiodes at the end of the crystal.

The active material of the ECAL consists of about 11000 crystals of Bismuth Germanate (\( \text{Bi}_4\text{Ge}_3\text{O}_{12}, \text{BGO} \)). The threshold energy for the cascade processes is 10 MeV and its radiation length is \( X_0 = 1.12 \text{ cm} \).

These BGO crystals have a length of 24 cm and are in the form of a truncated pyramid with a front area of \( 2 \times 2 \text{ cm}^2 \) and the back face varying from \( 2.6 \times 2.6 \text{ cm}^2 \) to \( 2.9 \times 2.9 \text{ cm}^2 \). They are mounted with their axis to the interaction region. At the back of each crystal two photodiodes are glued to detect the BGO scintillating light.

The ECAL is divided into two parts: the barrel and the endcap, see figure 2.6. The barrel has 48 rings and 160 crystals in the \( \phi \)-direction, thus a total of 7680 crystal in the barrel. Each endcap counts a total of 1536 BGO crystals.

The polar angular coverage of the barrel is \( 42^\circ < \theta < 138^\circ \). The angular region is extended by the endcap where the coverage is \( 11^\circ < \theta < 38^\circ \) and \( 142^\circ < \theta < 169^\circ \).

The light of a Xenon lamp is sent through a system of optical fibres to each crystal to calibrate the collection efficiency of the crystals and the readout. An additional calibration is done by
2.4. Calorimeter detectors

Experimental setup

shooting $H^{-}$ ions on a Lithium target. A photon with well known energy is then used to calibrate the BGO crystals. Bhabha events are also used to determine the angular resolution.

For electron and photon energies greater than 1 GeV the energy resolution is better than 2% while a resolution of approximate 1% is reached at energies of 45 GeV. The angular resolution is about 0.5° [41].

The $4°$ gap between the barrel and endcap was filled in 1996 by a new detector, the SPACAL or EGAP, see figure 2.9. It consists of lead brick with scintillating fibres inside. With the extended angular coverage the azimuthal angle can be measured for a particle passing through the gap, minimising the chance that a particle escapes detection in this region. The energy resolution in this region is about 5% at 45 GeV [41].

2.4.2 Hadron calorimeter

The hadron calorimeter (HCAL) acts as calorimeter and as a filter, allowing only non-showering particles to reach the muon detector. The energy and direction of the hadrons emerging from the $e^+e^-$ collisions are measured. The HCAL consists of depleted uranium plates (5 - 10 mm) as an absorber, with a short nuclear interaction length of about 11 cm and multi-wire proportional chambers (5.6 mm) as sampling elements.

The HCAL barrel provides a coverage of the polar angle region of $35° < \theta < 145°$. The barrel is 4725 mm long with an outer radius of 1795 mm and an inner radius of 886 mm for the three inner rings and 979 mm for the outer rings, see figure 2.10. The endcaps cover $5.5° < \theta < 35°$ and $145° < \theta < 174.5°$. The endcap consists of three parts, an outer ring (HC1) and two inner
2.4. Calorimeter detectors

Figure 2.10: A perspective view of the hadron calorimeter. The 9 rings and 16 modules with the 2 inner rings are clearly shown.

rings (HC2 and HC3). The splitting into two rings in the longitudinal direction, provides access to the other central detector components. The barrel HCAL is made up of 144 identical modules grouped into 9 rings of 16 modules.

A module consists of approximately 60 layers of multi-wire proportional chambers. The gas used consists of 80% Ar and 20% CO₂. The wires in alternate planes are oriented at 90°, so that one set of wires is parallel to the beam and the other set perpendicular. The wires in each module are grouped into readout cells or towers. The wire grouping is such that there are 10 (8) towers in the radial direction and 9 layers in the \( \phi \) and \( z \) direction. The towers cover \( \Delta \phi = 2.5^\circ \), \( \Delta z = 6 \text{ cm} \) and \( \Delta r = 8 \text{ cm} \). The thickness in terms of the nuclear absorption lengths in the barrel is at least 6, including the electromagnetic calorimeter. For the endcaps it varies between 6 to 7 nuclear absorption lengths.

The resolution for a hadronic jet depends on the jet energy and direction of the jet. This improves with increasing energy and is better in the central part of the detector. Back-to-back events \( e^+e^- \rightarrow Z \rightarrow q\bar{q} \) are studied for the energy calibration. The relative energy resolution for a quark jet of 45 GeV in the centre of the barrel is about 14% while the angular resolutions are about 1.43° for \( \theta \) and about 1.52° for \( \phi \) [41].
2.5 Muon spectrometer

The muon spectrometer consists of a barrel and forward-backward component. The barrel muon detector is split along the beam direction into two Ferris wheels placed inside the solenoid magnet. Each wheel is made up of eight octants in three layers, the inner layer (MI) at a distance of 2530 mm from the beam line, the middle layer (MM) at a distance of 4010 mm from the beam line and the outer layer (MO) at a distance of 5425 mm from the beam line, see figure 2.11.

The chambers are drift chambers. Each octant has two chambers next to each other in the outer (MO) layer with 16 wires, two chambers in the middle (MM) layers with 24 wires and one chamber in the inner (MI) layer with 16 wires. The wires in these precision (P) chambers are parallel to the beam axis and measure the \( r - \phi \) coordinates of the muon. There is a solenoidal magnetic bending field in the central part of the detector. The gas mixture is 38.5% ethane and 61.5% Ar.

Both sides of the outer and inner chamber are covered by six drift chambers with the sense wires perpendicular to the beam axis, the Z chambers. The Z chambers consist of two layers of drift cells, which are offset by one half cell, to resolve the left-right ambiguity. With these detectors the \( z \) coordinate along the beam is measured. The gas mixture is 8.5% ethane and 91.5% Ar.

The forward-backward (FB) muon chambers consists also of three layers. One is installed inside the magnet door and two outside the magnet door. The gas mixture is 86% Ar, 10% CO\(_2\) and 4% isobutane. Coils provide a toroidal field of 1.2 T in each door.

The polar angle coverage of the barrel muon spectrometer solely is from \( 44^\circ < \theta < 136^\circ \). The angular region which is only covered by the forward-backward muon spectrometer is from
$22^\circ < \theta < 36^\circ$. Between $36^\circ$ and $44^\circ$ a muon is measured in the middle and inner chambers in the barrel and the inner chamber of the forward muon detector. In figure 2.12 a part of the different polar angular regions for muon detection are indicated.

Figure 2.12: The side view of the FB-muon detector. The inner (FI), middle (FM) and outer (FO) muon chambers are shown. The polar angular regions are indicated by S and T. In the region covered by S the muon is measured by both the barrel and forward chambers. In the angular region T the muon is only covered by the forward region.

When measured by the three layers in the barrel, a 45 GeV muon has an accuracy of about 3.7%. This resolution is found from di-muon, $e^+e^- \rightarrow Z \rightarrow \mu^+\mu^-$, event studies.

2.6 Scintillation counters

The scintillation counters are mounted between the ECAL and the HCAL, as is clearly shown in figure 2.6. These counters are used to measure the time of the particles passing through the detector with respect to the beam crossing time. They are designed to trigger hadronic events and to discriminate di-muon events from cosmic muons which pass near the interaction vertex. The
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time difference between the hit of two opposite scintillation counters is 5.8 ns for cosmic muons and nil for genuine muon pairs, \( e^+e^- \rightarrow \mu^+\mu^- \).

There are 30 barrel scintillation counters and 32 endcap counters extending the polar region coverage down to \( 25^\circ < \theta < 155^\circ \).

2.7 The L3 trigger

The beam crossing rate at L3 interaction point is 45 kHz. However, not all crossings result in real \( e^+e^- \) collisions. Furthermore, there are background processes which include cosmics, beam gas events, beam wall events, synchrotron radiation, and noise in electronics channels.

The aim of the trigger system is to decide if a genuine \( e^+e^- \) event took place and if affirmative whether the event should be recorded. This is done in three different stages to avoid dead time during data taking.

- The level-1 trigger analyses the trigger data. If a positive decision is taken the data is digitised and recorded in buffer memories otherwise the electronics is cleared. This has to be done within 22 \( \mu \)s, which is the time between two beam crossings. The level-1 trigger neglects correlations between different parts of the detector and is the logical OR of trigger conditions from different sources: calorimetric trigger, muon trigger, TEC trigger and scintillator trigger. The trigger rate is about 20 Hz.

- The level-2 trigger receives information, e.g. charge and drift time, which was not available in time to be processed by the level-1. It can correlate signals from different sub-detectors, improving the level-1 decision. Events that fulfill more than one level-1 trigger condition, are automatically accepted by the level-2 trigger. This trigger will mainly reject background events selected by the level-1 coming from electronic noise, beam gas, beam wall interaction and synchrotron radiation.

  The average rejection rate is about 30%-50% over all accepted level-1 triggers.

- The level-3 trigger uses the complete digitised data. The selection of good events is based on

  - the correlation of the energy deposited in the ECAL and the HCAL;
  - the reconstruction of the muon track;
  - the reconstruction of the vertex in the TEC chamber.

  The output rate of the level-3 trigger is in the order of 2-3 Hz.

  Finally if the event is accepted the information from all sub-detectors is collected and built into an event and written to tape.
2.8 Simulation and reconstruction

To make a comparison of the measurement with the theory and to study the effects of the detector response on the event reconstruction, Monte Carlo event generators are used to simulate the signal and background reactions. The KandY [12] event generator is used to simulate the signal of WW production and decay to the four fermion final state. This Monte Carlo combines the four fermion KORALW [42, 43] event generator, based on CC03 matrix elements with the YFSWW3 [10, 11] event generator, which implements the $O(\alpha)$ radiative correction, including the non-factorisable virtual corrections in the double pole approximation. A complete four fermion description is provided by EXCALIBUR [44, 45]. For hadronic background PYTHIA [46] and KK2F [47] are used. Hadronic and leptonic two-photon collision processes are generated with PHOJET [48, 49] and DIAG36 [50] respectively. KORALZ [51] simulates muon pairs and tau pairs.

A schematic overview of the analysis steps is given in figure 2.13. The real data and simulated data are compared.

The Monte Carlo events are passed through the SIL3 simulation program. SIL3 simulates the L3 detector by simulating the interaction of the generated particles with the L3 detector material using the GEANT [52] program. GEANT models the decay of unstable particles, the effect of energy loss, multiple scattering, creation of $e^+e^-$ pairs and showering in the detector material. Hadronic interaction processes are simulated by GHEISHA [53], which is embedded in GEANT. The output format is the same as produced and recorded on-line by real events in the detector.

The sample generated this way is called the ideal detector simulation. However, the detector does not have a full efficiency due to problems in the high voltage supplies, inactive crystals, inactive cells or wires, variations in drift gas, noise and so forth. During data taking these time dependent informations are recorded in a database. This database is then used to create a realistic detector simulation from the ideal detector simulation.

The raw data output of the simulation and the real data are transformed by the reconstruction program REL3 into physical quantities like tracks and energy clusters, which can be related to particles and are used in the analysis.

Some of the objects which are created by the reconstruction program are:

**Track:** The hits in the TEC and SMD are reconstructed to obtain a track using a pattern recognition and fitting algorithm.

**ASRC:** The set of contiguous hits in the ECAL/HCAL are grouped to form an energy cluster. The adjacent electromagnetic and/or hadronic clusters are combined into a single calorimetric cluster to form an ASRC (A Smallest Resolvable Cluster).

**AMUI:** A combination of muon chamber track with hits in the hadron, TEC tracks and electromagnetic calorimeter.

**ASJT:** An set of adjacent ASRCs is combined by the L3 reconstruction program to a ASJT (A Single JeT). The most energetic cluster is taken as the seed. All clusters within a 30° cone around the seed axis are grouped together. An energy weighted vector sum of these clusters induce a new seed axis and a new 30° cone is defined.
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Figure 2.13: A schematic view of the analysis steps. On one side data is collected from $e^+e^-$ collisions and the reconstruction program REL3 reconstructs higher level objects from this output. On the other side Monte Carlo events are generated. The SIL3 program simulates the L3 detector response on this Monte Carlo data set. After this the REL3 program reconstructs the objects in the same sense as the real data. The data analysis is performed and a comparison of real data and Monte Carlo is made and interpreted.
G-factors

Dead material, cables and gaps in the L3 detector deteriorate the energy measurements in the calorimeters. To improve the measurement an off-line energy calibration is performed.

The G-factors are also introduced to calibrate the ratio between electromagnetic and hadronic component of the shower. They are determined by optimising the jet energy resolution in calibration data and in Monte Carlo.

The real energy deposit in the calorimeters is obtained by scaling the energy deposition with G-factors.

2.9 Luminosity

The luminosity $L$, is the “brightness” of the beams: the number of possible collisions between $e^+$ and $e^-$ measured in cm$^{-2}$s$^{-1}$. During data taking the luminosity $L$ is in the order of $10^{31}$ cm$^{-2}$s$^{-1}$.

The integrated luminosity is defined by:

$$\mathcal{L} = \int L dt.$$  \hspace{1cm} (2.6)

It is determined by measuring the number of small angle Bhabha events, $N_{Bhabha}$. Since the cross section, $\sigma_{Bhabha}$, of this process is known very accurately from QED, the integrated luminosity can be determined from

$$N_{Bhabha} = \sigma_{Bhabha} \cdot \mathcal{L} \cdot \epsilon.$$  \hspace{1cm} (2.7)

The efficiency $\epsilon$, corrects for the acceptance and background.

The luminosity monitors are placed at a distance of approximately 3 m from the interaction point with a polar angular coverage of 1.7° to 3.4° and are made of BGO crystals. They are complemented with a tracker of single sided silicon wafers, SLUM, which optimises the accuracy of the electron and positron position measurement. The positioning of the LUMI and SLUM is shown in figure 2.6.

This thesis concerns the data of LEP2 taken in the period from 1998 until 2000. The integrated luminosity, $\mathcal{L}$, for each year and mean centre-of-mass energy, $\sqrt{s}$, is given in table 2.1. The total collected luminosity is 629.3 pb$^{-1}$.

The experimental systematic error on the luminosity arises from event selection criteria, detector geometry and Monte Carlo statistics and is in the order of 0.13%. The theoretical uncertainty from the BHLUMI generator is 0.12% [54]. The total uncertainty on the luminosity varies between 0.18% and 22% [55].
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Experimental setup

Table 2.1: Integrated luminosity $\mathcal{L}$ for LEP2 and the corresponding mean centre-of-mass energy $\sqrt{s}$. The uncertainty on the integrated luminosity is in the order of 0.18% to 0.22%.

<table>
<thead>
<tr>
<th>year</th>
<th>$\sqrt{s}$ (GeV)</th>
<th>$\mathcal{L}$ (pb$^{-1}$)</th>
<th>$\Delta\sqrt{s}$</th>
</tr>
</thead>
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<td>1998</td>
<td>188.6</td>
<td>176.8</td>
<td>10.8</td>
</tr>
<tr>
<td>1999</td>
<td>191.6</td>
<td>29.8</td>
<td>10.8</td>
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<td>84.1</td>
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