Direct measurement of the W boson mass in $e^+ e^-\$ collisions at LEP
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Chapter 3

Experimental set-up

3.1 The LEP collider

![Schematic view of the CERN site at the border between Switzerland and France, situated between the Jura mountains and the Geneva airport (shaded in grey).](image)

The Large Electron Positron (LEP) collider was built and operated by the European Organisation for Nuclear Research (CERN) in Geneva; its geographical location is shown in Figure 3.1. The electrons and positrons are produced and accelerated in a chain of accelerators before being injected into the LEP main ring, illustrated in Figure 3.2. First of all the LEP Injector Linacs (LIL) produce electrons and positrons and accelerate them to 600 MeV. The Electron Positron Accumulator collects the electrons and positrons in bunches which are accelerated to 3.5 GeV in the Proton Synchrotron (PS). Before injecting the bunches into the LEP main ring, the Super Proton Synchrotron (SPS) accelerates them to 22 GeV. The electrons and positrons are collected in four
Figure 3.2: Schematic drawing of the LEP $e^+e^-$ injection and accelerator set-up.

bunches inside LEP, increasing their number until the maximum beam current is reached. Then the LEP RF voltages are increased, accelerating the electrons and positrons to physics energies. When the beam reaches stable conditions at the correct energy, the superconducting quadrupole magnets a few metres away from the interaction points focus the beams in the interaction region. As soon as 'colliding beams' settings are declared, the collaborations ramp up the voltages of their detectors and start recording data of the physics processes that occur each time an $e^-$ and $e^+$ collide. A ‘fill’ of electrons and positrons can typically be kept inside LEP for several hours until the beam is dumped and the whole procedure is repeated from the beginning.

The LEP ring is located in an almost circular tunnel, on average 100 m below the surface. In eight regions the tunnel is straight over a distance of a few hundred metres. In four of these straight sections, large underground halls house the detectors that are operated by the 4 LEP collaborations: ALEPH, DELPHI, L3 and OPAL. The particles travel inside a vacuum pipe, surrounded by magnets to keep them in their orbit and radio frequency (RF) cavities to accelerate them. During the first years (LEP1) copper cavities were used, allowing centre-of-mass energies around the Z° peak, while during the LEP2 phase superconducting cavities were installed every year, reaching centre-of-mass energies up to 209 GeV in 2000 — the final year of LEP running. The RF cavities are needed not only for acceleration, but also to continuously replenish the energy that is lost ‘in orbit’ due to the synchrotron radiation emitted by the electrons and positrons moving through the LEP magnetic field. The radiated power for a relativistic particle is given by

$$P_{\text{radiated}} = \frac{q^2 c \gamma^4 \beta^4}{6 \pi \epsilon_0 \rho^2} \quad (3.1)$$

where $\gamma = E_{\text{beam}}/m_e$, $q$ denotes the charge of the particle and $\rho$ is the local bending radius.
The velocity of the electrons and positrons in the LEP beam is very close to the speed of light, $\beta \equiv v/c \approx 1$, and assuming that the local bending radius inside all magnets is constant the energy loss is equal to:

$$E_{\text{loss}} = 8.85 \times 10^{-5} \frac{E_{\text{beam}}^4}{\rho} \text{ MeV (per turn)}$$

(3.2)

where $E_{\text{beam}}$ is given in GeV and $\rho$ in km. This corresponds to $\approx 2$ GeV per turn at $\sqrt{s} = 200$ GeV. The accelerating RF cavities are located in the straight sections while the bending field is concentrated in the arc sections, so the energy of the particles is not constant along the circumference of LEP, but shows a saw-tooth like dependence with variations in energy of about $E_{\text{loss}}/4 \sim 600$ MeV. Such variations in energy can be monitored and have been accurately modelled. The results of a simulation are shown in Figure 3.3.

![Figure 3.3](image)

Figure 3.3: The energy ‘saw-tooth’ (see text) for a typical RF configuration at a centre-of-mass energy of 183 GeV. The variations in energy are shown separately for the electron beam (dotted line) and positron beam (solid line). $\Delta E = 0$ corresponds to the average LEP energy [46] for this fill.

**LEP beam energy model**

A precise knowledge of the LEP energy scale is of crucial importance for the W mass (and Z mass) measurements because the centre-of-mass energy is used in the analyses to set the mass scale. Hence the relative variations of energy along the circumference of LEP (or at least in the Interaction Points (IP) where the experiments are situated) and as a function of time have to be understood with an MeV-level precision, two or three orders of magnitude better than the
amplitude of the energy variation discussed above. Furthermore the absolute scale has to be calibrated with similar accuracy.

The LEP Beam Energy Model describes all relative variations in energy taking into account the precise RF and magnet configuration at all times. Additionally it includes small corrections in order to reach a systematic precision better than 2 MeV at the $Z^0$ peak [10]. An example of the kind of effects which need to be taken into account is the gravitational pull of the Moon and Sun distorting the Earth’s crust and thereby periodically changing the circumference of the LEP ring by approximately $\pm 0.5$ mm. In Figure 3.4 the measured effect on the LEP beam energy is compared to the prediction from a geological model.

![Graph](image)

Figure 3.4: The shift of the LEP beam energy during a full Moon tide. The measured energy is compared to the prediction from a geological model [47].

**Resonant Depolarisation**

The calibration of the absolute energy scale is based on the method of Resonant De-Polarisation (RDP). The emission of synchrotron radiation leads to the build-up of transverse beam polarisation in $e^+e^-$ storage rings. Application of a small RF magnetic field perpendicular to the LEP bending field will rotate the spins of the electrons in the beam, and destroy the polarisation, provided the applied RF frequency matches the natural spin precession frequency which is proportional to the beam energy:

$$\nu = \frac{g_0 - 2}{2} \frac{E_{\text{beam}}}{m_e c^2}$$  \hspace{1cm} (3.3)

where $(g_0 - 2)/2$ is the electron anomalous magnetic moment and $m_e$ is its mass. Using this method a precision better than 1 MeV has been achieved.
Energy calibration at LEP2

Unfortunately, for beam energies at LEP2 a direct calibration using the RDP technique is not possible, because at energies above 60 GeV transverse polarisation does not build up (due to the increased beam energy spread). Instead, one has to rely on magnetic extrapolation. In 1997 sixteen Nuclear Magnetic Resonance (NMR) probes were installed in the arc sections of LEP to continuously monitor the local magnetic bending fields. These probes were calibrated with RDP energy measurements in the region between 41 and 61 GeV, and were then used to determine the beam energy during physics conditions by means of a linear extrapolation. A similar magnetic extrapolation can be done using the flux loop system that is installed in the LEP dipole magnets, covering 96.5% of the total bending field. This measures the change of the bending field through magnetic induction during magnet cycling. A comparison of these two methods showed a difference of about 10-15 MeV for a beam energy of 94.5 GeV. This extrapolation uncertainty constitutes the largest contribution to the systematic error quoted by the LEP energy working group. Numerous other possible sources of systematics have been studied and are taken into account. For illustrative purposes the complete list of error contributions is shown in Table 3.1; a precise description can be found in [46].

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Table 3.1: List of contributions to uncertainty on the LEP beam energy calibration [46].
In order to reduce this significant systematic uncertainty, the LEP Energy Working Group has been working on alternative methods to cross-check the energy extrapolation:

- The LEP spectrometer project:
  In 1998 one of the LEP dipole magnets was replaced by a high quality steel dipole with a particularly well known magnetic field, with two arms of high precision beam position monitors as shown in Figure 3.5. By measuring very precisely the direction of the beam before and after the magnet, the beam energy $E_{\text{beam}}$ can be derived from the bending angle $\theta$ via the relation

$$\theta \propto \frac{\int B \, ds}{E_{\text{beam}}}$$

(3.4)

where $\int B \, ds$ is the integral over the magnetic field. When the ongoing study of systematic effects is finished, the aim is to achieve an uncertainty on the beam energy of 10-15 MeV at physics energies, which can be extrapolated back in time to improve the energy calibration during the whole LEP2 program.

![Figure 3.5: Layout of the LEP spectrometer set-up](image)

- Energy determination based on energy loss measurements:
  A complementary approach to high energy calibration is to use observables that are sensitive to the energy loss per turn. As this energy loss is proportional to $E_{\text{beam}}^4$, a suitable observable would be very sensitive to the physics energy scale. One of the most promising observables turns out to be the synchrotron tune $Q_s$, defined as the ratio between the synchrotron oscillation frequency $\Omega$ and the revolution frequency of particles in LEP:

$$Q_s \equiv \frac{\Omega}{\omega_{\text{rev}}}$$

(3.5)

The revolution frequency is fixed (11,249 kHz), while $\Omega$ depends on the settings of the accelerator. Among other parameters, $\Omega$ depends to first approximation on the amplitude of the effective total RF cavity voltage $V_{\text{RF}}$, with the following dependence:

$$Q_s^2 \propto \frac{1}{E_{\text{beam}}} \sqrt{e^2 V_{\text{RF}}^2 - E_{\text{loss}}^2}$$

(3.6)

By fitting the measured $Q_s$ as a function of $V_{\text{RF}}$ the beam energy scale can be extracted. Work in progress indicates that the systematics of this measurement (using a more refined model) can be controlled to the level of 1.5 MeV.
EXPERIMENTAL SET-UP

- Experimental determination:
  Experiments have used events containing a radiative return to the Z resonance ($e^+e^- \rightarrow Z\gamma \rightarrow ff\gamma$), where the ISR photon escaped undetected along the beam, to reconstruct the Z boson mass using the beam energy as constraint. Comparing the newly measured $m_Z$ with the precise measurement performed at LEP1, an extra cross-check on the extrapolation is obtained [48]. It is still uncertain whether measurements of this type will yield results of sufficient precision.

It is hoped that the ongoing evaluation of these independent cross-checks will reduce the final uncertainty on the extrapolation from the lower energy, where RDP calibration is possible, to LEP2 energy scales. The currently quoted error on the LEP beam energy is one of the major contributions to the systematic uncertainty on the W mass measurement, as will be discussed in more detail in chapter 7.

Energy Spread

The energy calibration described above determines the average energy of the beam. From event to event, however, the actual $e^+e^-$ centre-of-mass energy $\sqrt{s} = 2 \cdot E_{\text{beam}}$ shows a statistical random variation due to the natural energy spread $\sigma_E$ of electrons and positrons in the beam. This spread can be predicted for certain settings of the beam optics, energy and RF frequency shift, or derived from the longitudinal size of the interaction region $\sigma_{z}\text{IP}$ that can be measured by the experiments, via the relation

$$\frac{\sigma_E}{E_{\text{beam}}} \propto \omega_{\text{rev}} Q_e \sigma_{z}\text{IP} \quad (3.7)$$

This corresponds to a typical spread in $\sqrt{s}$ of the order of 200 MeV. More detailed numbers are given in section 7.2 where also the consequences for the W mass and width measurement are discussed. Due to its statistical nature the spread is not worrying for the mass measurement, but its potential bias on the width measurement has to be considered.

Luminosity

Another important collider parameter is the luminosity. The instantaneous luminosity is related to the number of particles that cross the collision region per unit of (transverse) area per second. The event rate $\dot{N}$ of a physical process with a cross-section $\sigma_{\text{proc}}$ is proportional to the luminosity $\mathcal{L}$:

$$\dot{N} = \mathcal{L} \cdot \sigma_{\text{proc}} \quad (3.8)$$

The number of events available for physics analysis is therefore determined by the luminosity, integrated over the period of data taking:

$$\int_{\Delta t} \mathcal{L} \, dt = \frac{N}{\sigma_{\text{proc}}} \quad (3.9)$$

As the cross-sections for typical processes studied at LEP are usually expressed in pb (where $10^{12} \text{ pb} = 1 \text{ b} \equiv 10^{-28} \text{ m}^2$), the integrated luminosity is often quoted in units of inverse cross-section such as pb$^{-1}$. A high integrated luminosity is desirable to obtain the best statistical precision on a measurement or increase the reach of a particle search. LEP has surpassed all expectations by delivering $\approx 800 \text{ pb}^{-1}$ of integrated luminosity to each of the LEP experiments during
the LEP2 program, where the original aim was 500 pb\(^{-1}\) per experiment. The most precise determination of the luminosity at LEP was obtained by measuring the rate of small angle Bhabha scattering (\(e^+e^- \rightarrow e^+e^-\)) events, for which the cross-section is high and accurately known, using a detector with well-defined geometrical acceptance (the STIC in the case of DELPHI, see page 42). The precise knowledge of the integrated luminosity does not play an essential role in the analysis presented in this thesis.

### 3.2 The DELPHI detector

The DELPHI (DEtector with Lepton, Photon and Hadron Identification) detector was designed as a general purpose detector with coverage of almost the full 4\(\pi\) solid angle. An overview of the detector and its sub-systems is shown in Figure 3.7. The detector consists of a cylindrical 'barrel' part and two end-caps covering 'forward' regions (only one of which is shown in Figure 3.7). Both the diameter and overall length of the detector are about 10 m, and the design is symmetrical in the \(z = 0\) plane, with the coordinate system as defined in Figure 3.6.

![Diagram of the DELPHI detector](image)

**Figure 3.6:** In the standard DELPHI coordinate system, the origin is the nominal interaction point, which coincides with the geometrical center of the detector. The \(z\) axis points along the flight direction of the beam electrons, the \(x\) axis in the horizontal plane towards the centre of LEP, and the \(y\) axis points upwards. Cylindrical coordinates \((R,\phi,\theta)\) are defined with respect to the Cartesian system in the usual way.

In the design of DELPHI special emphasis was put on charged particle identification. In particular the Ring Imaging CHERenkov (RICH) detectors provide particle identification capabilities unique among the 4 LEP experiments. Also the high precision silicon Vertex Detector provides excellent identification of b-quark jets through secondary vertex reconstruction. However, the analysis presented here did not exploit DELPHI's extended particle identification capabilities. In the fully hadronic channel, b-tagging is used in the event selection, but it does not play an essential role. The information from the RICH detectors is not used at all in this analysis.
Figure 3.7: Overview of the DELPHI detector.
The W mass measurement relies mainly on the reconstruction of jets and identification of occasional isolated (ISR) photons. In the $q\bar{q}\ell\nu$ channel also the measurement of isolated high-momentum leptons is needed. These functions all rely on tracking (for the detection of charged particles) and calorimetry (for the detection of both charged and neutral particles):

**Tracking:** The DELPHI tracking system in the barrel region consists of four detectors at different radii centered at the beam axis. They are surrounded by a superconducting solenoidal coil with an inner diameter of 5.2 m and a length of 7.5 m providing a homogeneous magnetic field of 1.23 Tesla aligned along the $z$ axis. The bending radius of charged particle tracks in the magnetic field as recorded by the DELPHI tracking detectors can thus be used to measure the momentum/charge ratio of the corresponding particle. The system consists of the Vertex Detector (VD), Inner Detector (ID), Time Projection Chamber (TPC) and the Outer Detector (OD). Out of these detectors the main tracking device is the TPC, which is able to reconstruct 3D tracks with good resolution over a large volume.

The inclusion of the RICH system inside the tracking volume limited the volume available for other tracking systems, in particular the TPC. Hence, in order to have precise tracking with adequate lever arm for the precise reconstruction of high momentum tracks, an additional layer of tracking (i.e. the Outer Detector) was included outside the RICH but still inside the solenoid magnetic field.

Also in the forward regions ($11^\circ \leq \theta \leq 33^\circ$ and $147^\circ \leq \theta \leq 169^\circ$) a tracking detector is placed before (Forward Chambers A, FCA) and just after (Forward Chambers B, FCB) the Forward RICH. The outer layer of DELPHI consists of the Barrel, Forward and Surround muon chambers (MUB, MUF and SMC).

**Calorimetry:** The DELPHI electromagnetic calorimeters are the High density Projection Chamber (HPC) located in the barrel on the inside of the solenoid, and the lead-glass Forward ElectroMagnetic Calorimeter (FEMC) in the end-caps. The Hadron Calorimeter (HAC) is an iron-gas sampling calorimeter integrated in the iron return yoke of the solenoid, covering the whole polar angle between $10^\circ$ and $170^\circ$. On both sides of the interaction region, about 2 m away, the Small angle Tile Calorimeter (STIC) encloses the beam-pipe, covering the polar angle regions between about $w^\circ$ and $10^\circ$. This electromagnetic calorimeter is also used for the luminosity measurements based on small angle Bhabha scattering.

More details about the DELPHI sub-detectors can be found in [49]. Here we concentrate on the aspects most relevant to the W mass measurement. After a brief overview of some further points concerning the DELPHI data processing in the next paragraph, section 3.4 concentrates on the reconstruction of muons, electrons and photons. A separate section 3.5 is dedicated to the reconstruction of jets and energyflow, which play a dominant role in the W mass measurement.
3.3 Trigger, data stream and simulation

The DELPHI trigger system consists of four levels. The first two levels are fully electronic and synchronised with the beam crossing (every 22 μs), making their trigger decision within 3.5 μs and 40 μs respectively. The third and fourth levels are slower (software based) and asynchronous with the beam. The trigger efficiency for semi-leptonic and fully hadronic WW events selected by the analysis is practically 100% with respect to the efficiency for the Bhabha events used to define the integrated luminosity.

**Online system** For all events passing the trigger, the DELPHI data acquisition system collects the raw digitized data from the event buffers from each of the sub-detector systems. The data is written to disk and then stored on magnetic tape for later analysis. Information about the status of the subdetectors and LEP, calibration constants relevant for data reconstruction, or other specific conditions at a given moment are kept in a database.

**Offline system** The DELPHI reconstruction program DELAN A [50] reconstructs particles by applying pattern recognition and track fitting to combine information from different subdetectors. It also uses the information stored in the database. Some particle identification is done already at this stage and a basic event classification is performed. The output from DELANA is stored on magnetic Data Summary Tapes (DST), from where it is available for physics analysis.

The analysis presented here relied on the standard DELPHI software packages PHDST [51] for reading data from the DST, SKELANA [52] providing a convenient analysis framework and WWAN A [53] for its routines aimed at the identification of isolated leptons in W pair events.

Alternatively, the working of the DELPHI detector can be simulated using the DELphi SIMulation program DELSIM [54]. Applied to simulated particles produced by a Monte Carlo generator this package simulates the detailed response of the DELPHI detector to the particles traversing the detector, taking granularity, resolution and efficiencies of the detector into account. The output of DELSIM is in raw data format, to be analysed further by DELANA in an identical manner to the real data.

3.4 Reconstruction of leptons and photons

In this section a short description is given of the standard tools used for the identification of leptons in the qqlν channel and of isolated (ISR) photons:

**electrons and photons** are identified and distinguished using the REMCLU (Reconstruction of ElectroMagnetic CLUsters) software package [55]: electrons are identified as a track in the central tracking chamber whose extrapolation points to a shower in the electromagnetic calorimeter, without associated activity in the hadron calorimeter. The ratio of the shower energy \( E \) and the measured track momentum \( p \) is expected to be close to 1 (compared to \( E/p < 0.05 \) for muons), and the REMCLU package makes an empirical combination of the two to obtain a best estimate of the electron energy, with a resolution between \( \approx 5\% \) and
\approx 15\%$, depending on the electron energy and the polar angle. Both the identification and the energy resolution are hampered by interactions that electrons can have before reaching the calorimeters, especially in the forward region.

Photons are also treated by REMCLU, being identified as electromagnetic clusters without an associated track. Complications arise from photon conversion into $e^+e^-$ pairs before the calorimeter. About 40\% of all photons convert before reaching the HPC, including about 7\% even before reaching the TPC, thus creating visible tracks.

**muons** can be identified with excellent efficiency by their minimum ionising signature in the calorimeters, complemented with at least one hit in the muon chambers. Their momentum can be measured with a good resolution of about 3\% in the momentum range of interest (20 - 70 GeV/c).

**taus** decay before reaching the detector, producing at least one additional neutrino. As the neutrino cannot be detected only the direction of the momentum can be determined with reasonable precision; not its magnitude. Therefore the contribution of the tau lepton to the reconstruction of the invariant mass of the $W$ bosons is negligible. However, for the selection of $q\bar{q}\tau\nu$ events the identification of the tau is essential. Besides that, especially for decay modes with more than one visible particle in the tau final state, it is crucial to distinguish and separate the decay products of the tau from the hadronic decay of the other $W$ boson. For the $q\bar{q}\ell\nu$ study the standard WWANA tau treatment was used, basically identifying the tau lepton as the lowest multiplicity jet in a 3-jet configuration.

### 3.5 Reconstruction of jets: energyflow

The reconstruction of jets plays a dominant role both in the $q\bar{q}q\bar{q}$ and the $q\bar{q}\ell\nu$ channel. As jets contain both neutral and charged particles, a combination of tracking and calorimetry is needed for the optimal measurement of the jet energy and direction. Typically the particles inside a jet are close to each other in the detector, which further complicates the reconstruction. The detector response for different types of particles can briefly be summarised as follows:

- Neutrinos escape without detection;

- Charged particles are generally measured with excellent efficiency and good momentum resolution. The momentum resolution can be estimated on a particle-by-particle basis from the track fit using the known resolution of the different sub-detectors involved;

- Neutral hadrons and photons are generally reconstructed on the basis of calorimetric information only. The resolution on the measured energy has to be estimated on a statistical basis, and is typically significantly worse than the resolution for charged particles. The vicinity of other (charged) particles inside jets further complicates the association of the measured showers to the corresponding particle.
EXPERIMENTAL SET-UP

Sources of energyflow mis-reconstruction

The ability of the detector to correctly reconstruct the energy and direction of jets will from now on be called 'energyflow' response.

The overall jet 4-momentum is determined simply as the sum of the 4-momenta of the particles. The errors on the momenta of individual particles are not taken into account, since preliminary studies using such an approach did not show a clear improvement. The underlying reason is that the effect of the measurement resolution of correctly measured particles is small compared to the uncertainty induced by particles that are mis-reconstructed or not reconstructed at all.

Instead a simple parameterisation of the jet energy resolution can be extracted from the data (see next paragraph) and used to estimate the average jet energy resolution as a function of the jet direction (see the left hand plot in Figure 3.8, and section 4.2).

DELPHI energyflow

The energyflow resolution and efficiency vary depending on the direction of the jet, because the detector is not perfectly homogeneous. Although the DELPHI detector hermetically covers more than 99% of the solid angle and about 98% with full tracking, some weak regions exist, especially in the electromagnetic calorimetry. These are:

- $\theta \simeq 90^\circ$
  In this region the midwall of the TPC causes a small loss in efficiency.

- $\theta \simeq 40^\circ$ and $\theta \simeq 140^\circ$
  The gap between the barrel and the end-caps contains a significant amount of dead material in the form of cables. The gap in polar angle between the HPC and the FEMC ranges from 35° to 42° (and from 138° to 145°, corresponding to $0.74 < |\cos \theta| < 0.82$).

- $\phi \simeq 7.5^\circ + (n-1) \cdot 15^\circ, n = 1 \ldots 24$
  Close to the $\phi$ cracks between the 24 HPC modules the electromagnetic showers are less well contained, and energy is also deposited in the hadron calorimeter. This makes a correct reconstruction of particle energies more complicated.

The plot in Figure 3.8 shows the reconstructed energy of jets as a function of $\cos(\theta)$ and as a function of $\phi$, for 2-jet $Z^0$ events from the calibration runs in 1998. For these events the jet energies are known to be equal to $E_{\text{beam}} \approx 45.6$ GeV, so the corresponding energyflow efficiency can be calculated directly as $E_{\text{measured}}/E_{\text{beam}}$. Some of the weak regions discussed above are visible as dips in the efficiency. Also a clear trend is seen towards lower efficiencies in the forward directions. This is due to the reduced redundancy of the forward tracking and, more importantly, the increased amount of material in front of the calorimeters. But even though the resolution and efficiency are poorer, the jets are not lost. Where tracking ceases in the very forward region, calorimetry takes over and it is still possible to design algorithms to recover the measurement of forward jets. This is important, because even though the forward region covers a small fraction of the solid angle, with 4 or 5 jets in a single event a non-negligible chance exists that this region will contain at least one jet.
Figure 3.8: Jet energy reconstruction efficiency as a function of the fitted polar (left) and azimuthal angles (right) of the jet. The black band indicates the average jet energy efficiency, while the shaded area corresponds to the energy resolution per jet. Resolution and average were extracted as the RMS spread and average value of the $a$ parameter defined as $a \equiv \ln(E_{\text{beam}}/E_{\text{jet}})$ in the spirit of the constrained fit parameterisation to be discussed in section 4.2. The weak region around $|\cos\theta| \approx 0.77$ (see text) is visible as a dip in the energyflow efficiency. The $\phi$ cracks are too narrow to be seen in the jet energyflow. The dashed line (left) indicates the ‘expected’ energyflow efficiency and the dotted lines the one standard deviation error band as a function of $\theta$ used as input for the constrained fit (the $a_0(\theta)$ and $\sigma_{a_0}(\theta)$ parameters in equation (4.14)).

**B-tagging**

For specific analyses involving the study of heavy-quark production, DELPHI has developed the combined b-tagging algorithm AABTAG [56]. It combines several pieces of information in order to separate b-quark jets from light-quark jets. It searches for signs of long-lived B mesons, using the impact parameters of each track and calculating the probability that all tracks originated from the primary vertex. Whenever a secondary vertex can be reconstructed, additional information like the invariant mass of the decay products is used. Although this b-tag did not play a crucial role in the analysis, it is used in the event selection (see page 90) and some of the systematic studies (appendix A).
3.6 Visualising the energyflow

In order to visualise the often complicated energyflow structure of hadronic multi-jet events, a new type of event display was introduced in DELPHI. This energyflow plot is used by the VINCENT [57] (Visual INterface to Constraine d fit and ENergyflow Tool) program and is also part of the standard DELPHI event display program DELGRA [58].

The VINCENT program is an interface to the Monte Carlo simulation in which the user can see on an event-by-event basis how the energyflow develops while having access to all relevant information at generator level. Figure 3.9 shows an example of the production of a simulated fully hadronic WW event at $\sqrt{s} = 189$ GeV in four successive stages:

- The first plot (top left) shows the 4 fermions (quarks and anti-quarks) generated by EXCALIBUR. The $q\bar{q}$ pair originating from one of the W bosons is encircled by the dashed line.

- The second plot (top right) shows the resulting partons generated by the Parton Shower (see section 2.5), including the radiation of hard gluons.

- The third plot (bottom left) displays all the stable particles that emerge from the hadronisation process. The sum of momenta and the energy are still conserved, and at generator level it is still possible to identify which particles should belong to which W boson (not shown). An ideal detector would measure all these particles with perfect resolution.

- The last plot displays the particles that are reconstructed after applying the full DELSIM detector simulation and the DELANA reconstruction program.

It is instructive to see that already at the perturbative stage of hard gluon radiation the final energyflow pattern of the event is determined. Already at that stage it would be difficult — without the dashed line — to see which decay products originated from which W boson. The hadronisation process and the detector response do not change the pattern significantly. Even though many of the low-momentum (especially neutral) particles are lost and some fake particles are reconstructed, in general the energyflow pattern is rather well reconstructed. Several of the jets have lost some energy, but a jet clustering algorithm (see next chapter) should recognise each of the jets.

This demonstrates that it is possible to reconstruct the energy flow pattern of hadronic events (though not with perfect resolution and efficiency), and that the hard gluon radiation poses a bigger challenge to the analysis of this event than the detector response. Quantitative analysis has shown that this is typically the case for hadronic WW events [59].

The basic tools that are used for the further treatment of the energyflow through jet clustering and constrained fits are discussed in the next chapter.
Figure 3.9: Simulation of a $\sqrt{s} = 189$ GeV $q\bar{q}q\bar{q}$ event in four stages (see text). The energyflow plots should be read in the following way: The surface of each dot is proportional to the particle energy, and the position of the dot marks the $(\theta, \phi)$ direction of its momentum. The angle $\theta$ is plotted on the horizontal axis (from 0 to $\pi$) and $\phi$ is plotted on the vertical axis, multiplied by $\sin \theta$. 

10 GeV

Theta

4 jets Run -11001 Evt 2

Plot - quarks+gluons (MC) Run -11001 Evt 2

Phi* sin(Theta)
— 45 deg
— 0 deg

Plot - before detector (MC) Run -11001 Evt 2

Theta

Plot - EW truth (MC) Run -11001 Evt 2

Phi* sin(Theta)
— 45 deg
— 0 deg

CHARGED
NEUTRAL BM
NEUTRAL HAD
ELECTRON
MOON
NEUTRINO