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

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Chapter 3

Event selection

In this thesis the signal events are W pairs decaying into $qqqq$ (the fully hadronic events) or $qq\ell\nu$ (the semi-leptonic events). W pairs can also decay into $\ell\nu\ell\nu$ (the fully leptonic events), but since the $\ell\nu\ell\nu$ channel has very little mass information due to the two undetected neutrinos, this channel is not considered for the W mass measurement in this thesis.

To select the desired events it is important to know their typical signature in the detector. The fully hadronic decay mode has a high multiplicity, while the semi-leptonic mode is characterised by moderate multiplicity, missing energy and an energetic lepton in case of the electron and the muon channel. Events from other sources that mimic these signatures are denoted as background events.

By putting a cut on the number of clusters, $N_{ASRC}$, the fully leptonic mode and the non-hadronic $\gamma\gamma$ events can be rejected from the data sample.

In case of the semi-leptonic channel, the lepton will be identified first by looking at the properties of the required lepton. After excluding the reconstructed lepton all other objects in the detector are clustered into two jets by the Durham algorithm described in appendix A.

The neutrino is reconstructed using momentum conservation:

$$\vec{p}_\nu = \vec{p}_{miss} = -(\vec{p}_l + \vec{p}_{j1} + \vec{p}_{j2}), \quad (3.1)$$

where $\vec{p}_\nu$ is the momentum of the neutrino, $\vec{p}_l$ the momentum of the lepton and $\vec{p}_{j1}$ and $\vec{p}_{j2}$ the momentum of the two jets in a WW event.

A cut-based analysis is used to discriminate signal and background. The main object is to maximise both the efficiency and the purity. On the other hand maximising one of the two usually means degrading the other. Therefore, an optimum for both the purity and efficiency is searched for. The optimisation of the event selection is done by maximising the product of efficiency and purity.

As the kinematics change with higher centre-of-mass energies, the selection requirements change too. For every $\sqrt{s}$ an optimisation for the cuts is applied to maximise the product of efficiency and purity.

The main features of the selection for the particular channels will be discussed in the following sections.
3.1 Selection of the $q\bar{q}e\nu$ Events

Electron Identification

The electron in the detector is identified by the shower profile of the deposited energy in the ECAL. The typical shower shapes of an electron and a hadron in the ECAL are shown in figure 3.1. The shower of an electron is very narrow in contrast to the hadronic shower shape which shows a wider spread over the BGO crystals. While a hadron shows a shower profile in both ECAL and HCAL, the energy of an electron is completely absorbed in the ECAL. Hence, an electron does not have a matched shower in the HCAL.

Figure 3.1: The energy distribution in the ECAL over the crystals is much narrower for an electron (left) than for a hadron (right).

The shower profiles of a photon and an electron are practically identical. To separate a photon from an electron, an associated TEC track matching the deposited energy in the ECAL is required.

The shower profile is studied in detail to obtain a maximum separation between a hadron and an electron. Two variables are important for the electromagnetic selection criteria. First, the variable $E_9/E_{25}$, which is the ratio of the energy deposit in 9 and 25 crystals surrounding the most energetic crystal. Secondly, the $\chi^2_{em}$ calculated by comparing the shower profile in a $3 \times 3$ array of crystals around the most energetic crystal with an electron shower profile obtained from test beam measurements.

The following electromagnetic selection criteria have been used:

- $E_9/E_{25} > 0.98$;
- $\chi^2_{em} \leq 35.0$.

The BGO bump is matched with a TEC track to dispose of possible photons. A matching track is defined as:
3.1. Selection of the \( qq\tau\nu \) events

- hits/span > 0.5; Span is the difference between the first and last wire hit expressed in the number of wires.
- DCA < 50 mm; The DCA is the distance of closest approach of the reconstructed track to the event vertex.
- \( p_T > 0.5 \) GeV, with \( p_T \) the transverse momentum;
- \( \Delta \phi \leq 20 \) mrad if \( |\cos \theta_e| \leq 0.90 \), else \( \Omega \leq 5.6 \) srad. The \( \Delta \phi \) cut is applied on the difference between the azimuthal angle between the track extrapolated to the ECAL and the BGO bump, where \( \theta_e \) is the polar angle of the electron. And \( \Omega \) is the solid angle subtended by the two jets and the electron.

After the identification of the electron, the ECAL bump and the associated TEC track are removed from the event. The remaining objects are clustered into two jets using the Durham algorithm explained in appendix A.

**Selection**

The main WW background comes from the \( qq\tau\nu \) channel, \( e^+e^- \rightarrow WW \rightarrow qq\tau\nu \) which, depending on the \( \tau \) charge, decays as \( q\bar{q}\tau^-\bar{\nu}_\tau \rightarrow q\bar{q}e^-\bar{\nu}_e\tau \) or \( q\bar{q}\tau^+\nu_\tau \rightarrow q\bar{q}e^+\nu_e\tau \). The \( \tau \)-lepton has a branching ratio of about 18% for the decay into a electron and two neutrinos. But the electron from the \( \tau \)-decay is less energetic and the mass of the reconstructed \( e\nu \)-system is much smaller than from the ordinary WW-decay into the \( qq\tau\nu \) channel. Hence, a cut is applied on the energy of the electron and the invariant mass \( M_\tau \), to reject the \( qq\tau\nu \) background.

A WW pair decaying into the muon channel can also fake \( qq\tau\nu \) events. An electron in a jet can have such a large angle with respect to the other objects in the jet that it is identified as an isolated electron. The electron will be removed and the muon will be clustered with the jet. To reduce this type of background, a cut on the transverse momentum of the muon with respect to the jets, \( p_T(\mu, jet) > \) is used. The \( p_T(\mu, jet) \) of a muon coming from a jet is much smaller than the transverse momentum coming from a \( qq\mu\nu \) event.

The most important non-WW background comes from the \( q\bar{q}(\gamma) \) events. An electron produced in the jets can be identified as an isolated electron. Most of the radiative photons escape undetected along the beam pipe and result in large missing momenta. The distribution of the missing momenta for these events is peaked at low polar angle \( \theta_\nu \). Consequently putting a cut on \( |\cos \theta_\nu| \) will reduce these events. For 1999 and 2000 data the variable \( \alpha_{ej} \cdot |\sin \theta_\nu| \), with \( \alpha_{ej} \) the angle between electron and nearest jet, is used to enhance the separation power. Since the electron in these background events are emanating from one of the jets, the distribution of the angle \( \alpha_{ej} \) is also peaked at low values for \( q\bar{q}(\gamma) \).

A photon from the \( q\bar{q}(\gamma) \) event can convert into an \( e^+e^- \) pair, which can also fake the signal event. To reject these events a cut is applied on the difference in electron energy measured in the ECAL and the momentum of the associated TEC track.

The selection efficiency ranges between 78.1% and 72.8% and the purity is about 90%. The number of expected signal and background events is listed in table 3.1.

The complete set of cut values can be found in [56].

A candidate \( qq\tau\nu \) event is shown in figure 3.2.
3.2 Selection of the $qq\mu\nu$ events

Muon identification

Two classes of muons have to be distinguished for the muon identification. The first type of muon, which is measured in at least two layers of muon chambers is called AMUI. The second type of muon is reconstructed by its signature of a minimum ionising particle, MIP, using information from the central tracking chamber and the electromagnetic and hadronic calorimeters. The MIP events are meant to recover events where the muon is not detected by the muon chambers.

Both muon types are reconstructed separately. A thorough description of the reconstruction of the muons can be found in [41]. The main features are given below.

- AMUI:
  - $N_{AMUI} \geq 1$, a muon reconstructed by the standard L3 routines;
  - $r_{DCA} < 100 \mu m$, $|z_{DCA}| < 500 \mu m$, where the $r_{DCA}$ and $z_{DCA}$ mean respectively the DCA in the $r\phi$-plane and in the $z$-direction. These requirements eliminate most cosmic muons.

Figure 3.2: An $xy$-view of a selected candidate $qq\mu\nu$ event at $\sqrt{s} = 196$ GeV. The main detectors, radially outward, are the TEC, ECAL, HCAL, muon filter and the inner layer of the muon chambers. The electron is represented by the large narrow bump. The clustered depositions in the HCAL represent the two jets.
3.2 Selection of the $qg\mu\nu$ events

- **MIP:**
  - $N_{\text{MIP}} \geq 1$, a MIP reconstructed by the standard L3 routines;
  - DCA $\leq 2$ mm.

**Selection**

In the selection of the $qg\mu\nu$ channel the AMUI and MIPs are handled separately. Although most of the selection variables are the same, the cut values differ for both types of classes.

To reduce $\ell\nu\nu$ background events with low multiplicity the cut $N_{\text{ASRC}} > 10$ is applied. The number of ASRC's in the $qg\mu\nu$ analysis is counted from all ECAL and HCAL clusters above 0.1 GeV. This cut removes all low multiplicity background.

By demanding $25 \text{ GeV} \leq M_{qq} \leq 125 \text{ GeV}$ and $M_{\mu\nu} \geq 53 \text{ GeV}$ for the AMUI and $50 \text{ GeV} \leq M_{qq} \leq 98 \text{ GeV}$ for the MIPs most of the hadronic $\gamma\gamma$ events are excluded.

Again $qg\tau\nu$ events form the most important background. Approximately 18% of the $\tau$'s decay into a muon plus two neutrinos. This type of events is removed by studying the muon momentum spectrum. Due to the W polarisation higher energetic muons exhibit an inclination to the forward region with respect to the W. The muons from the $\tau$-decay are less energetic. The variable $P^* = |p_\mu| - 10(\cos \theta^* + 1)(\text{GeV})$, with $\theta^*$ the decay angle of the muon in the W rest frame, is introduced to get a better separation. The applied cuts for the muons are: $P^* > 18.5 \text{ GeV}$ for the AMUI, and $P^* > 15 \text{ GeV}$ for the MIP. This does not only remove the $qg\tau\nu$ channel but also takes the $q\bar{q}(\gamma)$ background into account.

As in the case of the electron a similar variable regarding the angle of the missing momentum or neutrino, $\theta_\nu$, and the angle between the muon and the closest jet, $\alpha_{\mu j}$, can be defined as $\alpha_{\mu j} \cdot \sin \theta_\nu$ to expunge $q\bar{q}(\gamma)$ events. For the MIPs the cut is put to be greater than 20° and for the AMUI to be greater than 5.5°.

ZZ events can also mimic the signal by their decay to $q\bar{q}\mu^+\mu^-$. One of the muons may overlap with one of the jets or disappear in the beam pipe. By incorrect energy momentum measurement, a possible missing momentum is assigned.

The invariant mass of the two most energetic muons $M_{\mu\mu}$ shows a peak in the distribution of the invariant mass around the Z boson mass. A cut at $M_{\mu\mu} < 80 \text{ GeV}$ removes these events for the AMUI class of events.

There is no completely reconstructed muon for the MIP events. Therefore the velocity of the W,

$$\beta_W = \frac{|\vec{p}_{j_1} + \vec{p}_{j_2}|}{E_{j_1} + E_{j_2}} \quad (3.2)$$

determined from the energy and momenta of the jets, is used to separate the ZZ background and signal. Because of the mass difference between the W and the Z their velocity is different for a given centre-of-mass energy. The requirement varies from $\beta_W > 0.34$ to $\beta_W > 0.49$ depending on the $\sqrt{s}$ from 189 – 208 GeV.

Figure 3.3 shows an AMUI type event, while figure 3.4 is an illustration of a MIP type event. About 85% of the muons in the selected samples are in the AMUI class. The efficiency varies from 77.7% – 73.0% while the purity ranges from 91.5% – 90.0%.

The number of expected signal and background events is listed in table 3.1.

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3.3 Selection of the $qq\tau\nu$ events

Event selection

Figure 3.3: A $xy$-view of a candidate $qq\mu\nu$ AMUI event at $\sqrt{s} = 200$ GeV. The three layers of the muon chambers are shown. The muon is identified by the hits in the MI, MM and MO layers.

3.3 Selection of the $qq\tau\nu$ events

Tau identification

The $\tau$-lepton can decay leptonically or hadronically. There are at least two neutrinos in the $qq\tau\nu$ events. In the leptonic decay of the $\tau$ another neutrino is produced. This results into reduced visible energy and missing momentum.

The electron and muon definitions are the same as described in sections 3.1 and 3.2.

If no electron or muon is found the event is analysed to look for a $\tau$. The hadronically decaying $\tau$-jet is identified by a neural network analysis based on the input variables:

- $N_{\text{TRK}}$: the number of TEC tracks;
- $N_{\text{ASRC}}$: number of calorimetric clusters;
- $E_{\text{ECAL}}$: the energy in the ECAL;
- the half opening angle of the jet.

The jet with the highest output value of the neural network analysis is considered to be the $\tau$-jet. The probability of misidentification is about 20%.
3.3. Selection of the \( qq\nu \nu \) events

Pre-selection cuts dispose a part of the background events, especially \( qq(\gamma) \) and \( qqqq \). The missing momentum and visible energy are strong indicators whether an event should be accepted or not. The difference between the missing momentum and visible energy has to be less than 135 GeV and the sum of the missing momentum and mass must be larger than 110 GeV. The transverse energy imbalance must be larger than 10 GeV.

The \( qqqq \) background can be reduced by requiring that the solid angle between the two jets and the \( \tau \)-jet has to be below 6 sr. The polar angle between the two jets should be less than 2.5 rad.

The requirement \( | \cos \theta_{\nu} | < 0.91 \) further suppresses the \( q\bar{q}(\gamma) \) events in which the photon will mainly escape along the beam pipe.

The semi-leptonic WW channel \( q\bar{q}\nu e \), for which the electron is not identified, also needs to be rejected. A high energy deposit in the electromagnetic calorimeter and a small energy deposit in the hadronic calorimeter is an indication for these types of events. Therefore, the events where

Figure 3.4: A longitudinal view of a \( qq\mu\nu \) event containing a MIP (upper left) at \( \sqrt{s} = 196 \text{ GeV} \).
the $\tau$-jet has more than 35 GeV in the electromagnetic calorimeter and less than 2 GeV in the hadronic calorimeter are not accepted.

Events in which the muon is not identified in the muon chamber are excluded when the $\tau$-jet is compatible with a MIP.

A $\tau$ decaying into a lepton is shown in figure 3.5. A hadronically decaying $\tau$ is shown in figure 3.6.

![Diagram](image)

Figure 3.5: An $xy$-view of a candidate $qq\tau\nu$ event at $\sqrt{s} = 196$ GeV, where the $\tau$ decays leptonically (i.e. in this case a electron).

The selection efficiency ranges from 56.0% to 50.3%, while the purity is around 66%. The number of expected signal and background events is listed in table 3.1.

### 3.4 Selection of the $qqqq$ events

The $qqqq$ channel is characterised by four hadronic jets. These events show a very high multiplicity. Since four jets are expected to be seen, and no lepton neutrino pair the missing energy should in addition be small. The electrons or muons produced in the jets typically will not have large energies.

The clustering into four jets is done by the Durham algorithm, see appendix A.
Selection of the $qqq$ events

The selection of $qqq$ events is done in two stages.

In the first stage a cut-based analysis is used to reject leptonic events and events with missing energy:

- $N_{\text{ASRC}} \geq 20$ with $E \geq 0.3$ GeV to remove events with low multiplicity;
- $E_{\text{vis}} \geq 0.75\sqrt{s}$ requires that the missing energy is small;
- $E_{\parallel} \leq 0.3E_{\text{vis}}$ removes events where a large amount of energy is lost in the beam pipe;
- $E_{\gamma} \leq 25$ GeV;
- $E_{e} \leq 25$ GeV, $|P_{\mu}| \leq 25$ GeV helps in reducing the semi-leptonic WW events;
- $y_{34} \geq 0.0015$ rejects background events with 2 and 3 jets. The definition of $y_{34}$ is given in appendix A;
- $\frac{E_{\text{ECAL}}}{E_{\text{ECAL}+E_{\text{HCAL}}}} > 0.2$ discards events triggered due to noise in the HCAL.

The first two cuts ensure high energy and high multiplicity events, mainly disposing the $\gamma\gamma$ background. The third and fourth cuts reject $q\bar{q}(\gamma)$ events. If the photon is lost in the beam pipe there is a large longitudinal imbalance which is rejected by the third cut. If the photon is detected it is rejected by the fourth requirement.

In the second stage a neural network based analysis is used to reduce the rest of the background by training the neural network using proper input variables. The chosen variables are:
3.4. Selection of the $qqqq$ events

Event selection

- the spherocity [57];
- track multiplicity of the jets;
- sum of the cosines of the six angles between the four reconstructed jets;
- $y_{34}$;
- energy of the most energetic jet;
- energy of the least energetic jet;
- difference in the energies of the second and third most energetic jets;
- jet broadening [58] of the most energetic jet;
- jet broadening of the least energetic jet;
- probability of a 4C kinematic fit. (The kinematic fit will be explained in chapter 4).

These variables mainly examine whether the energy and broadening of the jets are evenly spread across jets. The large imbalance across jets in the background events arises from gluon radiation. The probability of the 4C kinematic fit is also lower due to the fake gluon jet. The signal and background neural network outputs are quite different as shown in figure 3.7, hence signal and background are rather well separated.

An event scan of a $qqqq$ candidate is shown in figure 3.8. Events are selected using a cut of 0.6 on the neural network output.

With increasing $\sqrt{s}$ the efficiency ranges from 88.1% – 83.4%, while the purity changes between 79.4% and 81.6%. The number of expected signal and background events is listed in table 3.1.
Figure 3.7: The neural network output for the trained network using variables as described in the text. The separation between signal and background is quite well. The selection cut is placed at the value 0.6.

Table 3.1: Number of expected signal, ‘exp’, and background, ‘bkg’, events according to Monte Carlo simulations at different centre-of-mass energies. The total number of selected events from data is given in the column under the heading ‘sel’.

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<th>(\sqrt{s}) [GeV]</th>
<th>(q\bar{q}e\nu)</th>
<th>(q\bar{q}\mu\nu)</th>
<th>(q\bar{q}\tau\nu)</th>
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Figure 3.8: A xy-view of a $qqqq$ event at $\sqrt{s} = 196$ GeV. In the picture the four jets can be observed.