

GLAS-PPE/1999–16
November 1999



UNIVERSITY
of
GLASGOW

Precision Measurements of Particle Masses using Jets at LEP2

J. Jason Ward

*Department of Physics and Astronomy
University of Glasgow
Glasgow, G12 8QQ
United Kingdom*

E-mail: Jason.Ward@cern.ch

Abstract

How massive elementary particles get their mass is one of the greatest open questions in physics. Two of the major goals of the current LEP2 physics program that help to address this question are (a) to measure as precisely as possible the W Boson mass m_W and (b) to exclude or discover the Higgs Boson within the available kinematic region. The reconstruction of invariant masses with jets from 4-jet channels (e.g. $WW \rightarrow q\bar{q}q\bar{q}$ and $HZ \rightarrow b\bar{b}q\bar{q}$) and missing energy channels (e.g. $WW \rightarrow e\bar{\nu}q\bar{q}$ and $e^+e^- \rightarrow H\nu\bar{\nu}$) is discussed. The emphasis is on the determination of m_W , from which the rôle of calorimetry in such a precision measurement is emphasised.

*Invited Talk at the VIII International Conference on Calorimetry in
High Energy Physics, Lisbon, Portugal, June 13-19, 1999.*

1 Introduction

How elementary particles obtain the property of mass is one of the greatest unanswered questions in physics. Measuring as precisely as possible the masses of elementary particles, particularly gauge bosons, will be vital data for the theoretical physicist wanting to tackle the mass mechanism problem. Then when a candidate theory exists, such as the Higgs mechanism, it has to be tested by experiment.

In the first phase of the LEP program (LEP1), the mass and width of the Z boson were measured to be $m_Z = 91.1867 \pm 0.0021$ GeV and $\Gamma_Z = 2.4939 \pm 0.0024$ GeV [1], via measurements of *cross-sections* around the Z-peak.

In the second phase of the LEP program (LEP2), pairs of W bosons are produced. The new experimental challenge is to measure m_W by *direct reconstruction* of the W decay products with a precision that matches that of the *indirect* measurements of m_W (~ 30 MeV). Significant disagreement between the direct and indirect determinations of m_W might indicate the breakdown of the Standard Model. As the e^+e^- centre-of-mass energy continues to increase, we also search for a Higgs boson signal.

2 W Mass by Direct Reconstruction at LEP2

2.1 W Pair Production

At LEP2, the three basic W-pair production diagrams contain $Z \rightarrow WW$, $\gamma \rightarrow WW$ and t-channel neutrino exchange (which dominates near the W-pair threshold). The issue of directly reconstructing the mass of a heavy boson naturally focusses on these events, since W-pairs have already been produced in their thousands in each of the four LEP detectors. Typical statistics of W pair events are shown in Table 1.

Table 1: Year, e^+e^- centre-of-mass energy, integrated luminosity per LEP experiment and approximate number of W-pair events per LEP experiment.

Year	\sqrt{s} (GeV)	$\mathcal{L}(\text{pb}^{-1})/\text{expt}$	N_{WW}/expt
1996	161	~ 10	~ 35
	172	~ 10	~ 120
1997	183	~ 57	~ 850
1998	189	~ 175	~ 2700

Given that $\text{BR}(W \rightarrow q\bar{q}) \simeq 68\%$ and that the remaining decays are leptonic, one sees that the W pair sample subdivides as follows: hadronic channel ($WW \rightarrow q\bar{q}q\bar{q}$) $\simeq 46\%$, semileptonic channels ($WW \rightarrow l\nu q\bar{q}$) $\simeq 44\%$ and the fully leptonic channels ($WW \rightarrow l\nu l\nu$) are $\simeq 10\%$, where l denotes e, μ or τ .

2.2 Selecting WW Events

The rôle of calorimetry in characterising WW events is implicitly assumed in this brief outline of selection. Hadronic WW events are characterised by four hadronic jets, and the total missing energy and momentum are small. Typical preselection of hadronic events would use information on missing energy, multiplicity, sparsity and thrust. A final selection would be based on kinematical variables or a multidimensional analysis (e.g. neural network). Selections are highly efficient ($\sim 85\%$) but notably not entirely pure (purity $\sim 80\%$) with the background mostly coming from $q\bar{q}(\gamma)$ events.

The semileptonic events are characterised by two hadronic jets, one isolated high momentum lepton and large missing momentum (using both direction and magnitude information). Choosing the lepton within the event uses lepton identification, in addition to the fact that, at LEP energies not too far above the W-pair threshold, the charged lepton is likely to be the track with the highest momentum component antiparallel to the missing momentum. $q\bar{q}(\gamma)$ events and 4-fermion events are most of the background, but the selection purity, typically 80-95%, is greater than in the hadronic channel.

Fully leptonic WW events have large missing energy and missing p_T and two acoplanar, acollinear leptons. Selection of these events uses lepton identification and event topology. Since there are two neutrinos, one from each W, extracting the W mass from these events relies on using the lepton energy spectra. This non-jet channel is not discussed, although there is a recent ALEPH result for m_W determined using the fully leptonic channel [2, 3].

2.3 Jets, Leptons and Kinematic Fitting

In a selected W-pair event with two or four jets, the reconstructed W mass is obtained from the di-jet mass. One sees, assuming the simple case of massless jets, that the di-jet mass $m_{J_1 J_2}$ depends on the jet *energies* and *angles*;

$$m_{J_1 J_2}^2 \simeq 2E_{J_1} E_{J_2} (1 - \cos \theta_{J_1 J_2}).$$

Jets are obtained by clustering detector objects with a chosen algorithm. The hadronic channel poses particular problems arising from mis-assignment of soft particles to the wrong W, interconnection effects between particles from different W's, such as Bose-Einstein correlations and colour-reconnection, and jet combinatorics (three ways to form two di-jets from four-jet events). In the semileptonic channels, calorimeter objects created near the charged lepton, by Final State Radiation or Bremsstrahlung, can evade association to the lepton and thus degrade the event mass estimator.

Table 2 compares jet and lepton resolutions for two LEP experiments, OPAL [4] and ALEPH [5]. One should note that the energy of an electron is measured much more precisely than a jet. The intrinsic energy resolution for an OPAL lead glass block is considerably better than the quoted resolution for 47 GeV electrons in OPAL implies, for a number of reasons [6]. Predominantly this is because there are $\sim 2X_0$ of material in front of the lead glass blocks, mostly the magnet coil and pressure vessel. Smaller effects

Table 2: Examples of jet and lepton resolutions from OPAL and ALEPH.

OPAL	ALEPH
<p>Combined tracking: $(\sigma_{p_T}/p_T)^2 = (0.020)^2 + (0.0015p_T)^2/\text{GeV}^2$</p> <p>Electromagnetic Calorimeter: 11704 lead glass blocks. For Barrel: $\sigma_E/E \simeq 0.2\% + 6.3\%/\sqrt{E(\text{GeV})}$ For $E_{elec} \simeq 47 \text{ GeV}$, $\Delta E/E \simeq 3\%$.</p> <p>Jet Energy Resolution (Z Peak): $\sigma_E/E \simeq 20\%$</p> <p>Jet Angular Resolution: 20-30 mrad (depending on E_{jet} and θ_{jet})</p>	<p>Combined tracking: $\sigma_{p_T}/p_T = 0.0006p_T + 0.005$</p> <p>Electromagnetic Calorimeter: Lead/wire plane sampling device $\sigma_E/E \simeq 0.9\% + 18\%/\sqrt{E(\text{GeV})}$ For $E_{elec} \simeq 47 \text{ GeV}$, $\Delta E/E \simeq 3.5\%$.</p> <p>Jet Energy Resolution (Z Peak): $\sigma_E/E \simeq 11\%$</p> <p>Jet Angular Resolution: 20-30 mrad (depending on E_{jet} and θ_{jet})</p>

come from the reduction of the gain of the photomultipliers at LEP2, which was done to increase their dynamic range to allow for 100 GeV electrons, and the fact that the calibration of the barrel region is more difficult with a smaller sample of central detector Bhabhas.

The next stage of analysis is the kinematic fit. The aim of such a fit is to evaluate a set of four 4-vectors (two for each W) for each event, consistent with (a) (E, p) conservation (the LEP beam energy is known to high precision, $\Delta E_{beam} \simeq 20 \text{ MeV}$ for $\sqrt{s} = 189 \text{ GeV}$ data); (b) Expected biases (determined from WW MC and detector simulation) e.g. average jet energy loss for a given (E_{jet}, θ_{jet}) ; (c) Measured energies and angles of the jets and leptons, within their resolutions.

Using (E, p) conservation in the hadronic channel imposes four constraints (4C) and results in two mass values per event (for a given di-jet combination). However, an additional requirement that these two masses are equal may be imposed, resulting in a total of five constraints (5C) and only one mass value per event. This is made possible by the fact that the mass resolution of the reconstruction, which is about 2-3 GeV, is very similar to the W width, Γ_W . In the semileptonic channels, three constraints are lost in reconstructing the neutrino, thus 4C and 5C reduce to 1C and 2C respectively.

Kinematic fitting results in the significant improvement of mass resolution. The choice of using the additional equal mass constraint varies between LEP experiments. One can appreciate at this stage that since a tight constraint on energy is being provided by the beam energy, the most important information from jets is their direction.

For small angle jets, detector simulation predicts that the reconstructed jet energy is 30-40% lower than the true jet energy. This is not surprising, since as the polar

angle decreases (towards the beamline) there are numerous subdetector boundaries and changes, and more emphasis on electromagnetic calorimetry for luminosity measurements. The expected energy loss is implemented in the kinematic fit, however one must ensure it correctly reproduces the effect in data. This is achieved by looking at $Z \rightarrow q\bar{q}$ events at the Z-pole, noting that in a two-jet event, the true jet energy should be the same value as the precisely known beam energy. Thus any discrepancy in energy loss between data and Monte Carlo can be accounted for, and for the LEP experiments it is typically 2-3% in the most forward regions. DELPHI additionally use 3-jet events [8]. ALEPH correct for the effect, using the error on the correction as a systematic error [9].

Three of the four LEP experiments use a Monte Carlo reweighting method [4, 9, 10]. A large sample of Monte Carlo events generated with a known m_W are reweighted to different m_W values using matrix element information, until the MC mass distributions best fit the data. If the MC correctly models the data, biases are implicitly accounted for. ISR is implemented in the MC up to $\mathcal{O}(\alpha^\epsilon \mathcal{L}^\epsilon)$ and a systematic error can be estimated to represent the omission of higher order terms. DELPHI employ a convolution method [8].

2.4 Example of Calorimeter Uncertainties (ALEPH)

A number of methods are used to calibrate the electromagnetic calorimeter (ECAL) of ALEPH [5]. The ECAL gain is directly monitored by looking at an Fe^{55} source (which ages [11]). The amplitude of the gain variation is $\sim 2 - 3\%$ over one year, which after correction is stable to better than 0.3%.

For a range of electron energies, the ratio of ECAL energies to electron track momenta can be measured from various processes at the Z-peak: $e^+e^- \rightarrow e^+e^-e^+e^-$ yields electrons in the 1-10 GeV range and $Z \rightarrow \tau^+\tau^-(\tau \rightarrow e\nu\bar{\nu})$ electrons in the 10-30 GeV range. Also the $Z \rightarrow e^+e^-$ and Bhabha processes produce electrons at the beam energy (45.6 GeV).

For high energy LEP runs, one can measure E_{ECAL}/E_{beam} for Bhabha events. With large data samples, the high energy runs can also be split into smaller runs to estimate the time dependence of ECAL variations.

The typical net ECAL energy calibration uncertainty is $\pm(0.7 - 0.9)\%$.

The hadronic calorimeter (HCAL) of ALEPH also uses physics processes for calibration [5]. The idea is to constrain the peak of the muon energy distribution in HCAL to its expected position (~ 3.7 GeV for muons crossing the calorimeter) which is measured in beam test. Then at the start of every data-taking period, $Z \rightarrow \mu^+\mu^-$ and $Z \rightarrow q\bar{q}$ events are used to calibrate. The use of hadronic Z decays provides a much more statistically powerful sample, which can be used because the ratio between the average energy released by hadronic Z decays and an isolated muon in an HCAL module is well known from data. This technique gives a ‘time 0’ uncertainty of $\pm 1\%$.

For high energy running it is possible to compare data and MC for $\gamma\gamma \rightarrow \mu^+\mu^-$ events, yielding muons in the energy range 2.5-10 GeV. The energy distributions agree at the 1.5% level.

The typical net uncertainty is thus $\pm 2\%$.

The effects of the calorimeter uncertainties on the m_W measurements are evaluated by changing, in Monte Carlo samples, the calibration of the subdetectors by the net uncertainties described above, and performing mass fits before and after such a change.

2.5 Using $Z\gamma$ Events

The emission of a hard ISR γ reduces the effective centre-of-mass energy of e^+e^- interactions, such that the effective interaction can be at the Z resonance. Kinematic reconstruction of these so-called “ $Z\gamma$ ” events, with $Z \rightarrow q\bar{q}$, can provide a cross-check to W mass measurements, by measuring either m_Z or E_{beam} , and comparing these values to independent measurements.

L3 measure m_Z from $q\bar{q}\gamma$ events [10] at $\sqrt{s} = 189$ GeV using ~ 10 K events. This is a check of detector calibration, jet reconstruction, fitting method etc., and uses a kinematic fit and a reweighting technique as in their W mass analysis. The fitted value from $Z\gamma$ events is $m_Z = 91.106 \pm 0.062$ GeV (prel.), in good agreement with m_Z extracted from their cross-section measurements at the Z -pole of $m_Z = 91.195 \pm 0.009$ GeV. This represents an important test of the complete mass analysis method.

Since the beam energy is used in the kinematic fits of WW events, the uncertainty on it propagates through to the W mass measurement. The error on the beam energy is very precise at LEP1, less than 1 MeV, as it is measured by resonant depolarisation. Polarisation has not been achieved above a beam energy of 60 GeV, so the same technique does not work at LEP2. Instead, beam energy measurements at lower beam energies are extrapolated to higher energies, resulting in a larger beam energy error (25 MeV at $\sqrt{s} = 183$ GeV [12]). As a cross-check of the LEP determination of E_{CM} , ALEPH use the $q\bar{q}\gamma$ events by providing the precise (m_Z, Γ_Z) information and using the jet angles to extract E_{CM} . The average LEP centre-of-mass energy at ALEPH for the $\sqrt{s} = 183$ GeV run of 1997 is measured to be $182.50 \pm 0.19(\text{stat}) \pm 0.08(\text{syst})$ GeV [13], which is consistent with the estimate from the LEP energy working group [12] of 182.652 ± 0.050 GeV.

2.6 m_W Results

Preliminary ALEPH results from the 189 GeV data are shown in Table 3. This example illustrates the size of calorimetric-based systematic errors (i.e. calibration uncertainties and jet corrections, shown in bold) relative to other systematic errors. One should remember that these systematic errors are evaluated with finite MC and data samples, and are therefore subject to some degree of statistical fluctuation. Combining these results with data from previous years, and with the measurement of m_W from the lepton energy spectrum at 183 GeV [2], ALEPH obtain the following preliminary result [14]:

$$m_W = 80.411 \pm 0.064(\text{stat.}) \pm 0.037(\text{syst.}) \pm 0.022(\text{theory}) \pm 0.018(\text{LEP}) \text{ GeV}$$

Table 3: Summary of the correlated and uncorrelated systematic errors on m_W . The results are ALEPH data (preliminary) from the 189 GeV run. ‡ denotes error taken from 183 GeV studies.

Error source	Δm_W (MeV)			
	4q	e	μ	τ
Statistical	116	180	164	332
<i>Correlated Systematics:</i>				
Fragmentation	35‡	25‡	25‡	30‡
Calorimeter calibrations	30	27	14	19
Tracking	-	7	3	3
Jet corrections	8	14	4	7
Initial state radiation	10‡	5‡	5‡	5‡
LEP energy	17	17	17	17
<i>Uncorrelated Systematics:</i>				
Reference MC Statistics	10	16	15	23
Background contamination	10‡	8	1	25
Colour reconnection	25‡	-	-	-
Bose-Einstein effects	50‡	-	-	-
Total Systematics	77	47	37	53

which has a total error of ~ 80 MeV. The LEP combined result for the measurement of m_W by direct reconstruction, based on preliminary results available at the time of the Spring 1999 conferences [3], was $m_W = 80.368 \pm 0.065$ GeV. When combined with the W mass derived from WW cross-section measurements at and above threshold, this becomes $m_W = 80.370 \pm 0.063$ GeV. The error is dominated by the systematic error.

3 Standard Model Higgs Boson

Production of the Standard Model Higgs boson at LEP2 would mainly proceed via the ‘Higgsstrahlung’ process ($Z^* \rightarrow HZ$). Additional small contributions would come from ZZ or WW fusion processes (resulting in He^+e^- and $H\nu\bar{\nu}$ final states respectively).

Using all of the available Electroweak measurements at the time of the Spring 1999 conferences, the Higgs mass was indirectly determined [15] to be $m_H = 71_{-42}^{+75} \pm 5$ GeV (central value and 68% C.L. errors) and $m_H < 220$ GeV at 95% C.L. For data collected at $\sqrt{s} \leq 183$ GeV, the combined LEP direct search lower mass limit is $m_H > 89.7$ GeV. The reconstructed m_H in candidate events, from all final states, is a variable entering the calculation of confidence levels. Figures 1 and 2 show MC Higgs mass distributions ($m_H = 70$ GeV) for various final states, taken from an ALEPH analysis [16].

The Hl^+l^- ($l = e$ or μ) final state represents 6.7% of the Higgsstrahlung cross-section. It is characterised by two oppositely charged isolated leptons, where the mass of the lepton

pair is close to the Z mass. The recoil mass can be calculated from the $ll(\gamma)$ system, where the γ refers to any final state radiation that is emitted. Due to the high resolution of charged leptons (see Table 2), the reconstructed Higgs mass also has high resolution.

The missing energy channel $H\nu\bar{\nu}$ represents 20% of the Higgsstrahlung cross-section. In the event of a signal, there would be large missing energy, a missing mass near the Z mass, acoplanar jets and the possibility of b-tagging these jets. The Higgs mass would have to be reconstructed from the di-jet mass, so it has larger width and a longer low-mass tail in the reconstructed mass distribution compared to that of the Hl^+l^- channel. This is clearly apparent in Figure 1. Forward calorimetry that is as hermetic as possible plays an important part in the event selection, contributing to the rejection of $Z\gamma$, $W e\nu$ and Zee events.

The four-jet channel, $HZ\rightarrow b\bar{b}q\bar{q}$, comprises 64.6% of the Higgsstrahlung cross-section. A signal in this final state would contain four isolated jets. A kinematic fit can be employed, after which the key trick is to plot $m_{12} + m_{34} - m_Z$. The subscripts refer to jet pairings options. In Figure 2 the subsequent low mass tail due to jet combinatorics can be seen, which exists even though only the combination for which m_{12} is closest to the nominal Z mass is shown.

4 Summary

This contribution has discussed in some detail the direct reconstruction of m_W at LEP. Even though detector performance is intricately linked to complex analytical procedures and varying features of different channels, it is clear that calorimetry plays a central rôle in the m_W measurement. A repeated feature is the use of precisely-known quantities (m_Z and LEP beam energy) to improve errors on mass measurements. As LEP data continues to accumulate, understanding systematic errors, including detector calibration uncertainties and possible jet angular biases, become even more important.

Acknowledgments

I would like to thank the organisers of the conference for arranging an excellent meeting. Prof. D. Saxon and the University of Glasgow are gratefully acknowledged for funding my participation. Many ALEPH colleagues have helped in the preparation of this contribution, particularly A. Blondel, R. Tenchini, F. Ligabue, P. Teixeira-Dias and E. Lançon. Thanks also to M. Thomson (OPAL) and S. Gentile (L3) for their fast response to questions.

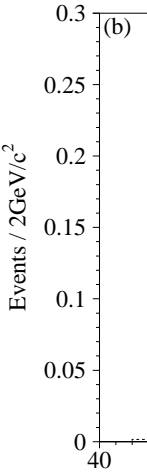
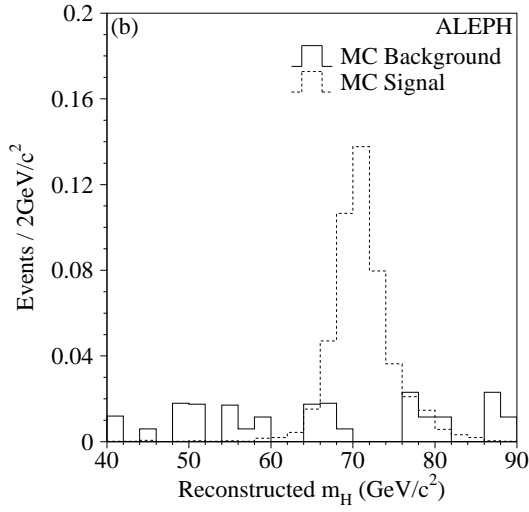


Figure 1: Left: distribution of the mass recoiling in the $H\mu^+\mu^-$ and $H\nu^+\nu^-$ channels after all selection criteria are applied. Right: The distribution of the reconstructed Higgs boson mass in the $H\nu\bar{\nu}$ channel. The solid histograms are background and the dashed histograms are signal.

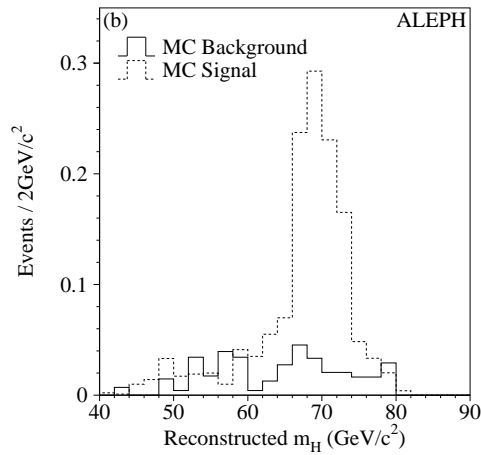


Figure 2: Distribution of the reconstructed Higgs boson mass in the channel $HZ \rightarrow b\bar{b}q\bar{q}$. The solid histogram is background and the dashed histogram is signal.

References

- [1] The LEP Collaborations ALEPH, DELPHI, L3, OPAL, the LEP Electroweak Working Group and the SLD Heavy Flavour and Electroweak Groups, *A Combination of Preliminary Electroweak Measurements and Constraints on the Standard Model*, CERN-EP/99-15.
- [2] ALEPH Coll., *Measurement of the W mass from the lepton energy spectrum at 183 GeV*, contributed paper to the 1999 Winter Conferences.
- [3] I. Riu, *W mass measurement at LEP*, talk presented at the XXXIVth Rencontres de Moriond, Les Arcs, France, 13-20 March, 1999.
- [4] OPAL Coll., *Measurement of the W Mass and Width in e^+e^- Collisions at 183 GeV*, CERN-EP/98-197, Phys. Lett. B 453 (1999) 138 .
- [5] ALEPH Coll., *Performance of the ALEPH detector at LEP*, Nucl. Inst. and Meth. A360 (1995) 481.
- [6] M. Thomson, Private Communication, June 1999.
- [7] OPAL Coll., *The OPAL detector at LEP*, Nucl. Inst. and Meth. A305 (1991) 275.
- [8] DELPHI Coll., *Measurement of the mass of the W boson using direct reconstruction at $\sqrt{s} = 183$ GeV*, CERN-EP/99-79, submitted to Phys. Lett. B.
- [9] ALEPH Coll., *Measurement of the W Mass in e^+e^- Collisions at 183 GeV*, CERN-EP/99-027, submitted to Phys. Lett. B.
- [10] L3 Coll., *Preliminary Results on the Measurement of Mass and Width of the W Boson at LEP*, L3 Note 2377, submitted to EPS-HEP 99, Tampere, 15-21 July 1999.
- [11] O. Callot, These proceedings.
- [12] LEP Energy Working Group, *Evaluation of the LEP Centre-of-Mass energy above the WW production threshold*, CERN-EP/98-191, submitted to Eur.Phys.J.C.
- [13] ALEPH Coll., *Determination of the LEP centre-of-mass energy from $Z\gamma$ events*, CERN-EP/99-092, submitted to Phys. Lett. B.
- [14] ALEPH Coll., *Measurement of the W Mass in e^+e^- Collisions from 161 to 189 GeV*, contributed paper to the 1999 Winter Conferences.
- [15] M. Felcini, *Searches for Higgs particles at LEP*, talk presented at the XXXIVth Rencontres de Moriond, Les Arcs, France, 13-20 March, 1999.
- [16] ALEPH Coll., *Search for the Standard Model Higgs boson in e^+e^- collisions at $\sqrt{s} = 161, 170$ and 172 GeV.*, Phys. Lett. B 412 (1997) 155 .