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Measurement of the mass of the W boson at LEP

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Abstract. The measurement of the W boson mass at LEP is discussed in detail and current preliminary results are presented. The results of the four LEP experiments using approximately $2.3\,\mathrm{fb}^{-1}$ of data are combined to give $m_\mathrm{W} = 80.412 \pm 0.029(\mathrm{stat.}) \pm 0.031(\mathrm{sys.})$ GeV. This result is consistent with other direct measurements and with the value obtained from global fits to electroweak data.

1 Introduction

During 1996−2000 the CERN LEP $\mathrm{e^+e^-}$ collider operated above the threshold for W pair production. The centre-of-mass energy, $\sqrt{s}$, was increased in several steps from 161 GeV to 209 GeV. At LEP $\mathrm{e^+e^-} \to \mathrm{W^+W^-}$ events produce clear experimental signatures. In approximately 45 % of cases both W bosons decay to quarks resulting in a fully hadronic final state ($\mathrm{q\overline{q}q\overline{q}}$). In 44 % of cases one W boson decays to two quarks and the other decays leptonically, producing a $\mathrm{q\overline{q}}\ell\overline{\nu}_\ell$ final state. In the remaining 11 % of decays both W bosons decay leptonically producing a $\ell^+\nu_\ell\ell^-\overline{\nu}_\ell$ final state. The relatively large production cross section, $16-17$ pb at the relevant LEP energies, and the clear $\mathrm{W^+W^-}$ decay topologies allow efficient and clean identification of $\mathrm{W^+W^-}$ events with typical event selection efficiencies and purities given in Table 1.

In the early stages of LEP2, the accelerator operated just above the $\mathrm{W^+W^-}$ pair production threshold where the $\mathrm{W^+W^-}$ cross section is sensitive to the W boson mass, m_W. Using approximately $10\,\mathrm{pb}^{-1}$ of data and assuming the Standard Model (SM) dependence of the $\mathrm{W^+W^-}$ cross section on m_W, the LEP experiments [1-4] obtained [5]:

$$m_\mathrm{W} = 80.40 \pm 0.20(\mathrm{stat.}) \pm 0.07(\mathrm{sys.})\,\mathrm{GeV}.$$

However, the majority of the LEP2 data were recorded at centre-of-mass energies significantly above the $\mathrm{W^+W^-}$ threshold, where the $\mathrm{e^+e^-} \to \mathrm{W^+W^-}$ cross section has little sensitivity to m_W. At these higher energies, the four LEP experiments recorded data corresponding to a combined total integrated luminosity of $\sim 2.5\,\mathrm{fb}^{-1}$, with each experiment accumulating a sample of approximately 10000 $\mathrm{W^+W^-}$ events. For these data m_W is measured by direct reconstruction of the W boson invariant mass from the observed jets and leptons. These precise measurements are the subject of this paper.

Table 1. Typical $\mathrm{W^+W^-}$ event selection efficiencies and purities at LEP

	Efficiency	Purity
$\ell^+\nu_\ell\ell^-\overline{\nu}_\ell$	70 %	90 %
$\mathrm{q\overline{q}}\ell\overline{\nu}_\ell$	80 %	85 %
$\mathrm{q\overline{q}q\overline{q}}$	80 %	80 %

2 m_W from direct reconstruction

The measurement of m_W at LEP from the direct reconstruction of the W boson invariant mass proceeds in two distinct stages:

- The invariant masses of the two W bosons are reconstructed on an event-by-event basis from the measured four-momenta of the four fermions from the decay of the $\mathrm{W^+W^-}$ system.
- The distribution of event-by-event masses is compared with the expectation from Monte Carlo (MC) simulation to extract a measured value of m_W.

Although the exact details differ, the four LEP experiments adopt similar procedures to reconstruct the event-by-event invariant mass in $\mathrm{W^+W^-}$ events. The general features are summarised below. Once events are selected, algorithms are applied to obtain measurements of the four-momenta of the fermions. For $\mathrm{q\overline{q}}\ell\overline{\nu}_\ell$ events, photons from final state radiation (FSR) may be recombined with the identified lepton. The tracks and clusters which are not associated with the lepton are forced into two jets using either the Durham [6] or the LUCLUS [7] algorithm. Similarly, the tracks and clusters in selected $\mathrm{W^+W^-} \to \mathrm{q\overline{q}q\overline{q}}$ events are forced into four jets (although both DELPHI and OPAL allow for the possibility of a fifth 'gluon' jet). For both $\mathrm{q\overline{q}}\ell\overline{\nu}_\ell$ and $\mathrm{q\overline{q}q\overline{q}}$ events the tracks and clusters assigned to a jet are used to obtain an estimate of the jet energy and jet momentum and hence an estimate of the invariant mass of the jet.

The measurement of m_{W} from direct reconstruction relies on accurate measurements of the fermion momenta. However, the jet energy resolution achieved by the four LEP experiments is rather poor, $\sigma_E/E \sim (60-90)\,\%/\sqrt{E}$. In addition, the neutrino from leptonic W decays is unobserved. Consequently the W boson mass resolution obtained using the measured quantities alone is much greater than the W boson width, Γ_{W}. However, significant improvements are obtained by employing kinematic fits.

2.1 Kinematic fitting

The kinematic fits employed by the LEP experiments impose the constraints of energy and momentum conservation, $(\mathrm{E},\mathbf{p}) = (\sqrt{s},\mathbf{0})$. In most cases the LEP experiments also employ, the additional constraint that the masses of the two W bosons are the same, *i.e.* neglecting Γ_{W}, resulting in a five-constraint (5C) fit. The result of the 5C kinematic fit is a single reconstructed mass for each event which approximates to the average of the two fermion-pair masses. In $\ell^+\nu_\ell\ell^-\overline{\nu}_\ell$ events there are six unknown quantities (the three-momenta of two neutrinos) and the problem is under-constrained. As a result there is rather limited sensitivity to m_{W} and only ALEPH [8] and OPAL [9] have published results from the $\ell^+\nu_\ell\ell^-\overline{\nu}_\ell$ channel.

The most important aspect of the kinematic fit is the constraint that the sum of the energies of the four fermions is equal to the centre-of-mass energy of the $\mathrm{e}^+\mathrm{e}^-$ collision, $\sqrt{s}$. However, in the presence of initial state radiation (ISR), this procedure introduces a bias in the reconstructed mass since the energies of the four fermions should be constrained to the centre-of-mass energy *after* photon radiation, $\sqrt{s'}$, rather than $\sqrt{s}$. Hence, the reconstructed invariant mass distribution depends strongly on the $\sqrt{s'}$ distribution and the peak of the reconstructed invariant mass distribution is several hundred MeV higher than m_{W} (the exact value depends on $\sqrt{s}$). This bias is removed by calibrating against Monte Carlo. Thus the measurement of m_{W} at LEP relies on a sophisticated Monte Carlo treatment of photon radiation in the $\mathrm{W}^+\mathrm{W}^-$ production process. The LEP collaborations use MC simulations based on YFSWW [10] which includes exact $\mathcal{O}(\alpha)$ YFS exponentiation [11] for the $\mathrm{W}^+\mathrm{W}^-$ production process, with $\mathcal{O}(\alpha)$ electroweak non-leading (NL) corrections combined with YFS exponentiated $\mathcal{O}(\alpha^3)$ leading logarithm (LL) ISR.

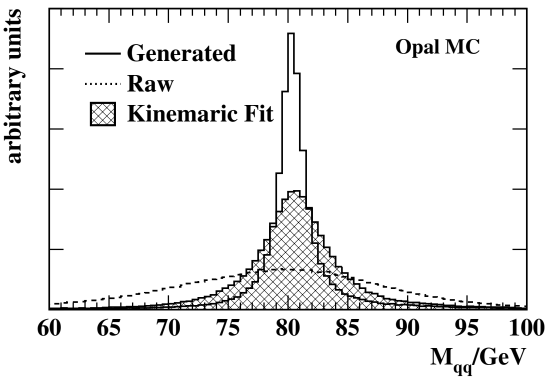

Fig. 1. A comparison of the reconstructed invariant mass distribution from the $\mathrm{q}\overline{\mathrm{q}}$ system in $\mathrm{W}^+\mathrm{W}^-\to\mathrm{q}\overline{\mathrm{q}}\ell\overline{\nu}_\ell$ events using the measured quantities (Raw) and the result of the kinematic fit. Also shown is the underlying generated distribution

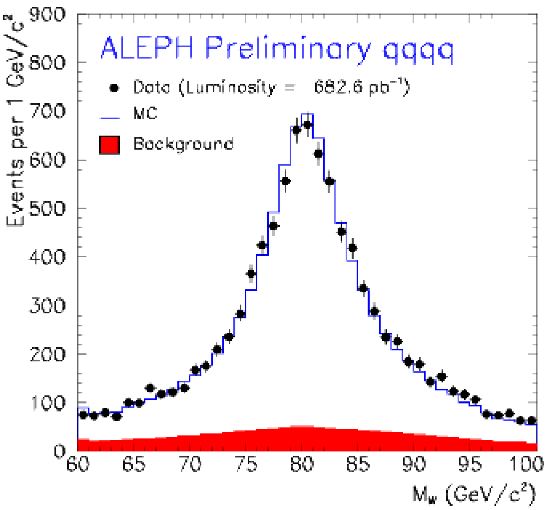

Fig. 2. The reconstructed mass distribution for the ALEPH $\mathrm{q}\overline{\mathrm{q}}\mathrm{q}\overline{\mathrm{q}}$ events [13]

2.2 Mass reconstruction in $\mathrm{W}^+\mathrm{W}^-\to\mathrm{q}\overline{\mathrm{q}}\ell\overline{\nu}_\ell$ events

In $\mathrm{W}^+\mathrm{W}^-\to\mathrm{q}\overline{\mathrm{q}}\ell\overline{\nu}_\ell$ events most of the mass information comes from the jet-jet system. The mass of the hadronically decaying W boson can be expressed as:

$$\mathrm{M}^2_{\mathrm{q}\overline{\mathrm{q}}} = \mathrm{M}_1^2 + \mathrm{M}_2^2 + 2\mathrm{E}_1\mathrm{E}_2(1-\beta_1\beta_2\cos\theta_{12}), \qquad (1)$$

where θ_{12} is the angle between the two jets, M_i, E_i and β_i are the invariant mass, energy and boost, $\beta = |p|/\mathrm{E}$, of the two jets. The resolution on the reconstructed invariant mass is dominated by the jet energy resolution as the jet direction is better measured than the energy. Consequently, the 5C kinematic fit, which imposes the constraint that $\mathrm{E}_1+\mathrm{E}_2 = \mathrm{E}_{\mathrm{beam}}$, results in a significant improvement in mass resolution as shown in Fig. 1. Typical mass resolutions after the kinematic fit are $3-4$ GeV compared to $8-10$ GeV obtained using the measured quantities alone[1]. There is an additional advantage of using the kinematic fit, namely it significantly reduces the sensitivity of the measurement to the jet energy scale. Finally, it should be noted that the reconstructed invariant mass depends on the reconstructed jet masses (M_1^2 and M_2^2 in 1). In the kinematic fit all LEP experiments scale the reconstructed jet masses such that the ratio of $|p|/\mathrm{E}$ is constant (fixed β), a treatment which is to some extent arbitrary.

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[1] These numbers are meant to be indicative of the performance of the kinematic fit, there are also non-Gaussian tails.

2.3 Mass reconstruction in $W^+W^- \to q\overline{q}q\overline{q}$ events

The event-by-event mass resolution in the $q\overline{q}q\overline{q}$ channel is typically 3 GeV, *i.e.* only slightly better than that obtained from the $q\overline{q}\ell\overline{\nu}_\ell$ channel. In principle, one might expect the $q\overline{q}q\overline{q}$ channel to be even more sensitive as all final state fermions are measured providing information on the masses of both W bosons. However, there are a number of additional considerations: due to the higher particle multiplicities there is greater ambiguity in the assignment of particles to jets; the non-W^+W^- backgrounds are larger, predominantly $e^+e^- \to q\overline{q}$ and $e^+e^- \to ZZ$, both of which can lead to four jet final states; and most importantly, for $q\overline{q}q\overline{q}$ events there are three possible pairings of jets to the two W bosons. The incorrect jet-pairings contain no W mass information and result in a combinatoric background. The four LEP collaborations have developed algorithms to identify the correct jet-pairing and thus reduce this combinatoric background. For example, for events where the correct jet-pairing gives a reasonable kinematic fit probability, the correct pairing corresponds to the highest probability fit in $80-85\,\%$ of cases. Both the L3 and OPAL collaborations select the highest and second highest probability fits in their determination of m_W. ALEPH selects the jet-pairing combination which is most consistent with the kinematics of W^+W^- decay. The DELPHI collaboration adopts a different approach, including information from all pairings in the m_W fit. Figure 2 shows an example of the reconstructed invariant mass distribution from the selected jet-pairings.

2.4 m_W extraction

The LEP collaborations have developed three distinct techniques to extract m_W from the reconstructed invariant mass distributions:

- Breit-Wigner Parametrisation (used by OPAL [12]): an empirical function based on a Breit-Wigner distribution is used to fit the mass distributions. The function is chosen such that it provides a good description of the reconstructed mass distribution obtained from MC. The peak of the function is used as an estimator of m_W. However, due to biases from experimental effects and from ISR, the peak does not correspond to m_W exactly. Consequently, Monte Carlo samples are used to determine a bias correction, typically of order 100 MeV, which is applied to the measured value.

- Monte Carlo Reweighting (used by ALEPH [13], L3 [14] and OPAL [15]): the reconstructed mass distribution is compared to Monte Carlo spectra corresponding to different values of m_W and $\chi^2(m_W)$ is determined. Rather than generating a large number of MC samples corresponding to different values of m_W, a large sample of MC events is generated at fixed $(m_W, \mathit{\Gamma}_W)$. This sample can then be reweighted to $(m_W{}', \mathit{\Gamma}_W{}')$ using the appropriate event weights. For a MC event with W boson masses (m_1, m_2) the weight is of the form:

$$w^i = \frac{\mathcal{BW}(m_1, m_2 : m_W{}', \mathit{\Gamma}_W{}')}{\mathcal{BW}(m_1, m_2 : m_W, \mathit{\Gamma}_W)},$$

  i.e. the ratio of two Breit-Wigner distributions. All biases (at least those correctly described by the Monte Carlo) are implicitly included and no additional bias correction is required.

- Convolution fit (used by DELPHI [16]): the results of the kinematic fit are interpreted as a probability density function (PDF). The convolution of this function with a Breit-Wigner distribution $\mathcal{BW}(m_W)$ is used to calculate the event likelihood as a function of m_W; $\mathcal{L}(m_W) = \mathrm{PDF}_i \otimes \mathcal{BW}(m_W)$. The measured value of m_W is determined from the maximum likelihood obtained by summing over all events. As is the case for the Breit-Wigner method, Monte Carlo is used to determine the bias correction.

All the above methods of extracting m_W essentially locate the peak of the reconstructed invariant mass distribution and use Monte Carlo to correct for biases, either implicitly or explicitly. The degree to which the Monte Carlo describes the data ultimately determines the systematic uncertainties.

Table 2. Breakdown of systematic and statistical error sources for the LEP measurement of m_W from direct reconstruction

Source	Systematic Error on m_W (MeV)		
	$q\overline{q}\ell\overline{\nu}_\ell$	$q\overline{q}q\overline{q}$	Comb.
Hadronisation	19	18	18
QED (ISR/FSR, etc)	8	8	8
Detector Systematics	14	10	14
LEP Beam Energy	17	17	17
Colour Reconnection	–	90	9
Bose-Einstein	–	35	3
Other	4	5	4
Total Systematic	31	101	31
Statistical	32	35	29
Total	44	107	43

3 Systematic uncertainties

The preliminary results from the LEP experiments have been combined by the LEP electroweak working group, taking correlated systematic uncertainties into account [5]. The resulting breakdown of the statistical and systematic errors for the $q\overline{q}\ell\overline{\nu}_\ell$ and $q\overline{q}q\overline{q}$ channels and for the two channels combined is given in Table 2. The $q\overline{q}\ell\overline{\nu}_\ell$ and $q\overline{q}q\overline{q}$ channels yield similar statistical errors (due to comparable mass resolution and almost equal branching fractions). However, in the LEP combination of the results from the two channels the q$\bar{\text{q}}$q$\bar{\text{q}}$ channel enters with a weight of only 10 %. This is a consequence of the large systematic uncertainties from final state interactions (FSI), *i.e.* colour reconnection (CR) and Bose-Einstein correlations (BEC), which dominate the uncertainties in m_{W} from the q$\bar{\text{q}}$q$\bar{\text{q}}$ channel. Where possible the estimates of the systematic uncertainties are obtained from data. The most important effects are discussed briefly below.

3.1 Detector effects

The calibration of the detector response to jets and leptons is determined from data, mainly using $\mathrm{e}^+\mathrm{e}^- \to \mathrm{Z}$ events recorded at $\sqrt{s} \sim M_{\mathrm{Z}}$ during each year of LEP2 operation (these samples, corresponding to approximately $13\,\mathrm{pb}^{-1}$, were taken specifically for the purposes of calibration). For the individual LEP experiments, the detector related systematic uncertainties lie in the range 20–30 MeV. However, since this source of uncertainty is uncorrelated between experiments, the effect on the LEP combined measurement is acceptable, 14 MeV.

3.2 QCD uncertainties – fragmentation/hadronisation

The process whereby the quarks from W→ q$\bar{\text{q}}$ produce the observed hadronic jets lies in the realm of non-perturbative QCD. Consequently, the related systematic uncertainties are estimated by comparing biases in m_{W} using different phenomenological models of the fragmentation and hadronisation process. The LEP experiments have compared the PYTHIA [17] string model, the HERWIG [18] cluster model and the ARIADNE [19] colour dipole model. All models are tuned using the large LEP1 data samples of $\mathrm{e}^+\mathrm{e}^- \to \mathrm{q}\bar{\mathrm{q}}$ events such that they provide a good description of event shapes, particle production rates, *etc.* Differences between the model predictions are used to assess the systematic uncertainty which is taken as 100 % correlated between experiments and channels. This is currently the largest single systematic error on the combined LEP measurement (18 MeV).

3.3 QED/electroweak uncertainties

Due to the kinematic fit, ISR produces a significant distortion of the reconstructed invariant mass distribution, producing biases of a few hundred MeV. However, YFSWW includes a sophisticated treatment of ISR and the related systematic uncertainty is estimated to be small, 1 MeV. A recent estimate suggests a *total* theoretical uncertainty due to QED/electroweak effects of 5 MeV [20]. However, this study neglected the effect of the kinematic fit [21]. The main consequence being that the m_{W} analysis is also sensitive to photon radiation from the W-bosons which, through interference with ISR, modifies the $\sqrt{s'}$ distribution. The OPAL Collaboration have used measurements of the $\mathrm{W}^+\mathrm{W}^-\gamma$ cross section at LEP2 to place constraints on the possible size of QED uncertainties due to real photon production away from the collinear region [22], indicating that the related m_{W} systematic uncertainty is no more than 6 MeV. It appears likely that QED/Electroweak uncertainties will not contribute significantly to the final LEP uncertainty on m_{W}.

3.4 LEP beam energy

The main effect of the kinematic fit is to scale the energies of the observed fermions to $\sqrt{s}$. Consequently, uncertainties in the LEP beam energy propagate to uncertainties on m_{W} as:

$$\sigma_{m_{\mathrm{W}}} = \frac{m_{\mathrm{W}}}{E_{\mathrm{beam}}}\sigma_{E_{\mathrm{beam}}}.$$

The current uncertainty on m_{W} due to the beam energy uncertainty is 18 MeV, although this is likely to be reduced when the final LEP beam energy analysis is completed.

3.5 Final state interactions

The MC programs used to simulate $\mathrm{W}^+\mathrm{W}^- \to \mathrm{q}\bar{\mathrm{q}}\mathrm{q}\bar{\mathrm{q}}$ events assume independent hadronisation of the quarks from the two W bosons. However, at LEP the two W decay vertices are typically separated by 0.1 fm, which is small compared to the hadronisation scale of 1.0 fm. Consequently, the hadronisation of quarks from two different W bosons occurs in the same region of space-time, opening up the possibility of non-independent hadronisation of the W bosons in $\mathrm{W}^+\mathrm{W}^- \to \mathrm{q}\bar{\mathrm{q}}\mathrm{q}\bar{\mathrm{q}}$ events. Such effects can distort the reconstructed mass spectra and lead to potentially large systematic errors. There are two sources of possible final state interactions, Bose-Einstein correlations (BEC) and Colour Reconnection (CR). Both of which are discussed in detail elsewhere in these proceeding [23,24]. In both cases systematic uncertainties are estimated by comparing Monte Carlo models with and without BEC/CR. Currently the systematic error in the q$\bar{\text{q}}$q$\bar{\text{q}}$ channel is dominated by CR as implemented in the SK1 model [25]. This model has a free parameter, κ, which allows the fraction of colour reconnection to be adjusted. For the systematic error estimate the largest value of κ consistent with data is used. It has been demonstrated that the four LEP experiments are equally sensitive to CR effects and a common energy-dependent correlated systematic uncertainty, ranging from 74 – 105 MeV (increasing with $\sqrt{s}$), is used [5].

4 Results

Figure 3 summarises the preliminary W mass results from the four LEP experiments using the method of direct reconstruction. The results differ from those in [12,13,14, 16] in that common CR and BEC systematic uncertainties have been used. Combining the results from the different experiments taking into account correlated sources of systematic error yields

$$m_{\mathrm{W}} = 80.412 \pm 0.029(\text{stat.}) \pm 0.031(\text{sys.})\ \text{GeV}.$$

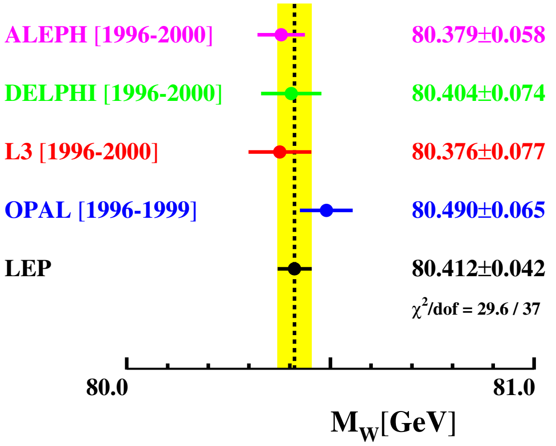

Fig. 3. Preliminary m_{W} results from the four LEP experiments. The results all use the common LEP estimates of FSI systematic uncertainties

The difference between the LEP combined m_{W} measurements from the $\mathrm{q\bar{q}q\bar{q}}$ and $\mathrm{q\bar{q}}\ell\overline{\nu}_\ell$ channels is [5]

$$\Delta m_{\mathrm{W}}(\mathrm{q\bar{q}q\bar{q}} - \mathrm{q\bar{q}}\ell\overline{\nu}_\ell) = +22 \pm 43\,\mathrm{MeV}.$$

A significant non-zero value would provide evidence for CR and/or BEC effects in the $\mathrm{q\bar{q}q\bar{q}}$ channel[2]. The method of direct reconstruction also yields a direct measurement of Γ_{W}, where the LEP combined measurement [5] gives

$$\Gamma_{\mathrm{W}} = 2.150 \pm 0.068(\mathrm{stat.}) \pm 0.060(\mathrm{sys.})\ \mathrm{GeV}.$$

The m_{W} measurement from LEP can be combined with that measured at the Tevatron, $m_{\mathrm{W}} = 80.454 \pm 0.059\,\mathrm{GeV}$ [26], to give a world average value of

$$m_{\mathrm{W}} = 80.426 \pm 0.034\,\mathrm{GeV}.$$

5 Conclusions and future outlook

In the absence of systematic uncertainties the LEP statistical precision on m_{W} is ±21 MeV. However, when systematic uncertainties are taken into account the total uncertainty increases to 43 MeV. The most important sources of systematic error are those from possible FSI in the $\mathrm{q\bar{q}q\bar{q}}$ channel. Consequently, the $\mathrm{q\bar{q}q\bar{q}}$ channel contributes little to the LEP combination; the total error from the $\mathrm{q\bar{q}}\ell\overline{\nu}_\ell$ channel alone is 44 MeV. As the LEP collaborations move towards final results, the importance of better understanding these effects cannot be overstated. There are a number of on-going efforts to reanalyse the $\mathrm{q\bar{q}q\bar{q}}$ data in a way that reduces the sensitivity to CR [23]. Other expected improvements include: a reduced beam energy uncertainty, the inclusion of $0.22\,\mathrm{fb}^{-1}$ of data above 204 GeV by OPAL, improved understanding of hadronisation/detector systematic errors. Taking this into account, the ultimate LEP m_{W} uncertainty is likely to lie in the range $32 - 40\,\mathrm{MeV}$, depending mainly on progress with understanding FSI.

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[2] In this combination CR and BEC systematic errors are set to zero as Δm_{W} is primarily of interest as a test of FSI.