

# Measurement of the W Mass from LEP2

D. Glenzinski

*Enrico Fermi Institute, University of Chicago*

(with the LEP Collaborations)

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In 1997 each LEP experiment collected approximately  $55 \text{ pb}^{-1}$  of data at a center-of-mass energy of 183 GeV. These data yield a sample of candidate  $e^+e^- \rightarrow W^+W^-$  events from which the mass of the W boson,  $M_W$ , is measured. The preliminary LEP combined result, including data taken at  $\sqrt{s} = 161$  and 172 GeV and assuming the Standard Model relation between the W decay width and mass, is  $M_W = 80.38 \pm 0.07(\text{exp}) \pm 0.03(\text{CR/BE}) \pm 0.02(\text{E}_{\text{bm}})$  GeV, where the uncertainties correspond to experimental, colour-reconnection/Bose-Einstein, and LEP beam energy respectively.

## I. INTRODUCTION

The success of the Standard Model (SM) over the last two decades should not obscure the importance of thoroughly investigating the weak interaction. It is interesting to consider that 15 years ago, when neutrino scattering experiments had measured  $\sin^2 \theta_W = 0.217 \pm 0.014$ , the following SM constraints were available [1]:

$$M_W(\text{indirect}) = 83.0 \pm 2.8 \text{ GeV} \quad (1)$$

$$M_{Z^0}(\text{indirect}) = 93.8 \pm 2.3 \text{ GeV} \quad (2)$$

*Tree level* deviations could be accommodated in those errors! Today we have measured [2]  $\sin^2 \theta_W$  to 0.0002,  $M_{Z^0}$  to 0.002 GeV, and  $M_W$  to 0.07 GeV — the success of the SM is so thorough that it can only be wrong at the quantum loop level, and even then, beyond leading order. Despite this rousing success, it is still necessary to test the SM by confronting experimental observations with theoretical predictions as any deviations might point to new physics. As a fundamental parameter of the SM, the mass of the W boson,  $M_W$ , is of particular importance.

Aside from being an important test of the SM in its own right, the direct measurement of  $M_W$  can be used to set constraints on the mass of the Higgs boson,  $M_H$ , by comparison with theoretical predictions involving radiative corrections sensitive to  $M_H$ . The constraints imposed using  $M_W$  are complimentary to the constraints imposed by the asymmetry ( $A_{\text{FB}}^b, A_{\text{FB}}^\ell, A_{\text{LR}}, \dots$ ) and width ( $R_\ell, R_b, R_c, \dots$ ) measurements. For example, the very precise asymmetry measurements presently yield the tightest constraints on  $M_H$ , but are very sensitive to the uncertainty in the hadronic contribution to the photon vacuum polarisation,  $\Pi_{\text{had}}^{\gamma\gamma}$ . In contrast, the constraint afforded by a direct measure of  $M_W$  is comparably tight but with a much smaller sensitivity to  $\Pi_{\text{had}}^{\gamma\gamma}$ , and is presently dominated by statistical uncertainties [3].

### A. WW Production at LEP

At LEP W bosons are predominantly produced in pairs through the reaction  $e^+e^- \rightarrow W^+W^-$ , with each W subsequently decaying either hadronically ( $q\bar{q}$ ), or leptonically ( $\ell\bar{\nu}$ ,  $\ell = e, \mu, \text{ or } \tau$ ). This yields three possible four-fermion final states, hadronic ( $W^+W^- \rightarrow q\bar{q}q\bar{q}$ ), semi-leptonic ( $W^+W^- \rightarrow q\bar{q}\ell\bar{\nu}$ ), and leptonic ( $W^+W^- \rightarrow \ell^-\bar{\nu}_\ell\ell'^+\nu_{\ell'}$ ), with branching fractions of 45%, 44%, and 11% respectively. The  $W^+W^-$  production cross-section varies from 3.6 pb at  $\sqrt{s} = 161$  GeV to 16.7 pb at  $\sqrt{s} = 189$  GeV. These can be contrasted with the production cross-sections for the dominant backgrounds  $\sigma(e^+e^- \rightarrow Z^*/\gamma^* \rightarrow q\bar{q}) \approx 100$  pb,  $\sigma(e^+e^- \rightarrow Z^0 e^+e^-) \approx 2.8$  pb,  $\sigma(e^+e^- \rightarrow (Z^*/\gamma^*)(Z^*/\gamma^*)) \approx 0.6$  pb, and  $\sigma(e^+e^- \rightarrow W e\bar{\nu}) \approx 0.6$  pb. Aside from the  $Z^*/\gamma^* \rightarrow q\bar{q}$  process, which falls from  $\approx 150$  pb at  $\sqrt{s} = 161$  GeV, these background cross-sections vary slowly for  $\sqrt{s} < 185$  GeV, when the  $e^+e^- \rightarrow ZZ$  process begins to turn-on.

TABLE I. The  $W^+W^-$  selection efficiency,  $\varepsilon$ , and purity,  $\mathcal{P}$ , for the  $q\bar{q}q\bar{q}$  and  $q\bar{q}\ell\bar{\nu}$  channels for each of the four LEP experiments. DELPHI employs no explicit  $q\bar{q}\tau\bar{\nu}$  selection.

channel		experiment			
		A	D	L	O
$q\bar{q}q\bar{q}$	$\varepsilon$ (%)	83	85	88	85
	$\mathcal{P}$ (%)	83	65	80	80
$q\bar{q}e\bar{\nu}(\mu\bar{\nu})$	$\varepsilon$ (%)	89	71	87	90
	$\mathcal{P}$ (%)	96	94	96	94
$q\bar{q}\tau\bar{\nu}$	$\varepsilon$ (%)	64	–	59	75
	$\mathcal{P}$ (%)	93	–	87	83

## B. LEP Measurement Techniques

There are two main methods available for measuring  $M_W$  at LEP2. The first exploits the fact that the  $W^+W^-$  production cross-section is particularly sensitive to  $M_W$  for  $\sqrt{s} \approx 2M_W$ . In this threshold (TH) region, assuming SM couplings and production mechanisms, a measure of the production cross-section yields a measure of  $M_W$ . In early 1996 the four LEP experiments collected roughly  $10 \text{ pb}^{-1}$  of data at  $\sqrt{s} = 161 \text{ GeV}$ , resulting in a combined determination of the W boson mass of  $M_W(\text{TH}) = 80.40 \pm 0.20(\text{exp}) \pm 0.03(\text{E}_{\text{bm}}) \text{ GeV}$ , where the uncertainties correspond to experimental and LEP beam energy respectively [2,4].

The second method uses the shape of the reconstructed invariant mass distribution to extract a measure of  $M_W$ . This method is particularly useful for  $\sqrt{s} \geq 170 \text{ GeV}$  where the  $W^+W^-$  production cross-section is larger and phase-space effects on the reconstructed mass distribution are smaller. Each experiment collected roughly  $10 \text{ pb}^{-1}$  at  $\sqrt{s} = 172 \text{ GeV}$  [5] in later 1996, and in 1997, roughly  $55 \text{ pb}^{-1}$  at  $\sqrt{s} = 183 \text{ GeV}$ . Since most of the LEP2 data has been collected at center-of-mass energies well above the  $W^+W^-$  threshold, the LEP2  $M_W$  determination is dominated by these direct reconstruction (DR) methods. For this reason, the rest of this article will concentrate on the details of this method.

## II. DIRECT RECONSTRUCTION OF $M_W$

To measure  $M_W$  using direct reconstruction techniques one must

1. Select  $W^+W^- \rightarrow f\bar{f}f\bar{f}$  events.
2. Obtain the reconstructed invariant mass,  $m_{\text{rec}}$ , for each event.
3. Extract a measure of  $M_W$  from the  $m_{\text{rec}}$  distribution.

Each of these steps are discussed in detail in the section below and in Reference [5]. It should be noted that none of the LEP experiments presently exploits the  $W^+W^- \rightarrow \ell^-\bar{\nu}_\ell \ell'^+\nu_{\ell'}$  final state in the DR methods<sup>1</sup>; it is therefore discussed no further.

### A. Event Selection

The expected statistical error on  $M_W$  varies as,  $\Delta M_W(\text{stat}) \sim \frac{1}{\sqrt{N_{\text{WW}}}} \cdot \frac{1}{\sqrt{\text{Purity}}}$ , so that high efficiency, high purity selections are important. The  $W^+W^-$  selection efficiencies and purities are given in Table I for each of the four LEP experiments.

<sup>1</sup>A measure of  $M_W$  can be obtained from the  $W^+W^- \rightarrow \ell^-\bar{\nu}_\ell \ell'^+\nu_{\ell'}$  channel by using the lepton energy spectrum. However, it is estimated to be a factor of 4-5 less sensitive than the measurements available from the other  $W^+W^-$  final states.

For the data taken at  $\sqrt{s} = 183$  GeV, these efficiencies and purities give approximately 700  $W^+W^-$  candidate events per experiment, about 100 of which are non- $W^+W^-$  background. The selection efficiencies have a total uncertainty of about 1% (absolute) and have a negligible effect ( $< 1$  MeV) on the  $M_W$  determination. The accepted background cross-sections have a total uncertainty of 10 – 20% (relative) and effect the  $M_W$  determination at the 10 – 15 MeV level (cf. Section IV).

## B. Invariant Mass Reconstruction

There are several methods available for reconstructing the invariant mass of a  $W^\pm$  candidate. The best resolution is obtained by using a kinematic fit which exploits the fact that the center-of-mass energy of the collision is known *a priori*<sup>2</sup>. There are two “flavours” of kinematic fit:

1. 4C-fit: Enforces  $\Sigma(\mathbf{P}, E) = (\mathbf{0}, \sqrt{s})$  constraints; yields *two* reconstructed masses per event,  $(m_{\text{rec}_1}, m_{\text{rec}_2})$ , one for each  $W^\pm$  in the final state.
2. 5C-fit: In addition to the four constraints above, ignores the finite width of the  $W^\pm$  and requires that  $m_{\text{rec}_1} = m_{\text{rec}_2}$ ; yields a *single* reconstructed mass per event.

The type of fit used depends on the final state. For instance, in the  $q\bar{q}e\bar{\nu}$  and  $q\bar{q}\mu\bar{\nu}$  channels, because the prompt neutrino from the leptonic  $W^\pm$  decay takes three degrees-of-freedom (*dof*),  $\mathbf{P}_\nu$ , the fits effectively become 1C and 2C fits respectively. For the  $q\bar{q}\tau\bar{\nu}$  channel, high energy neutrinos from the  $\tau$ -decay itself lose at least one additional *dof* and so require that all 5 constraints be used, thus yielding a 1C fit<sup>3</sup>.

In the  $q\bar{q}q\bar{q}$  channel, since there are (nominally) four jets, there exist three possible jet-jet pairings. This pairing ambiguity gives rise to a combinatoric background unique to the  $q\bar{q}q\bar{q}$  channel. Each LEP experiment employs a different technique for choosing the best combination(s). L3 uses the 5C-fit probabilities (the equal mass constraint yields a different fit  $\chi^2$  for each combination) to choose the *two* best combinations per event. At the cost of some additional combinatorics, this algorithm has the correct combination among those chosen about 90% of the time. OPAL, DELPHI and ALEPH employ a 4C-fit and exploit kinematic information to choose the best combination. The algorithms employed by ALEPH and OPAL choose a single combination per event; this combination corresponds to the correct combination approximately 85% of the time at no additional cost in combinatorics. DELPHI uses all combinations and weights each according to the likelihood that it corresponds to the correct combination.

## C. Extracting $M_W$

The ensemble of selected events yields a  $m_{\text{rec}}$  distribution from which a measure of  $M_W$  is extracted. There are several methods available for extracting  $M_W$ . ALEPH, L3, and OPAL all employ a traditional maximum likelihood comparison of data to Monte Carlo (MC) spectra corresponding to various  $M_W$ . In addition to its simplicity, this method has the advantage that all biases (ie. from resolution, ISR, selection, etc.) are implicitly included in the MC spectra. The disadvantage of this method is that it does not make optimal use of all available information. DELPHI employs a convolution technique, which makes use of all available information; in particular, events with large fit-errors are de-weighted relative to fits with small fit-errors. The convolution has the limitations that it

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<sup>2</sup>Strictly speaking, this is not true since any initial state radiation (ISR) reduces the collision energy to less than twice the beam energy. The kinematic fits assume no ISR. The effect of ISR uncertainties is incorporated in the total systematic error discussed in Section IV.

<sup>3</sup>Such a fit is possible only if one assumes that the  $\tau$ -lepton direction is given by the direction of the visible decay products associated with the  $\tau$ .

TABLE II. Results for data taken at  $\sqrt{s} = 183$  GeV. All quantities are given in units of GeV

q $\bar{q}\ell\bar{\nu}$ channel			
exp	$M_W \pm (\text{stat}) \pm (\text{syst})$		$\hat{\sigma}_{\text{stat}}$
A	$80.34 \pm 0.19 \pm 0.05$		0.20
D	$80.50 \pm 0.26 \pm 0.07$		0.25
L	$80.03 \pm 0.24 \pm 0.07$		0.21
O	$80.33 \pm 0.17 \pm 0.06$		0.19
LEP	$80.31 \pm 0.10 \pm 0.03$		$\chi^2 = 1.9/3$

TABLE III. Results for data taken at  $\sqrt{s} = 183$  GeV. All quantities are given in units of GeV.

q $\bar{q}q\bar{q}$ channel			
exp	$M_W \pm (\text{stat}) \pm (\text{syst}) \pm (\text{CR/BE})$		$\hat{\sigma}_{\text{stat}}$
A	$80.41 \pm 0.18 \pm 0.05 \pm 0.06$		0.18
D	$80.02 \pm 0.20 \pm 0.05 \pm 0.06$		0.20
L	$80.51 \pm 0.21 \pm 0.08 \pm 0.06$		0.19
O	$80.53 \pm 0.23 \pm 0.07 \pm 0.06$		0.19
LEP	$80.35 \pm 0.10 \pm 0.04 \pm 0.06$		$\chi^2 = 3.7/3$

requires various approximations (ie. the resolution is often assumed to be Gaussian) and often requires an *a posteriori* correction as the fit procedure does not account for all biases, notably from ISR and selection.

### III. RESULTS

The results from each LEP experiment, using data collected at  $\sqrt{s} = 183$  GeV, are given in Table II for q $\bar{q}\ell\bar{\nu}$  channel and in Table III for the q $\bar{q}q\bar{q}$  channel<sup>4</sup>. Also included is the mass obtained when combining all four measurements<sup>5</sup>. For the LEP combinations, the ISR, hadronization, LEP beam energy, and color-reconnection/Bose-Einstein (CR/BE) uncertainties are taken as completely correlated between the four experiments. The errors given correspond to the observed statistical and the total systematic (including that associated with the LEP beam energy) uncertainties respectively. For the q $\bar{q}q\bar{q}$  channel, the error associated with CR/BE uncertainties is given separately and is taken as a 60 MeV common error. Also shown in Tables II and III is the expected statistical error,  $\hat{\sigma}_{\text{stat}}$ , for each experiment. As an example, the OPAL fits are shown in Figure 1.

Using data taken at  $\sqrt{s} = 172$  and 183 GeV, the preliminary LEP combined  $M_W$  using DR methods for the q $\bar{q}\ell\bar{\nu}$  and q $\bar{q}q\bar{q}$  channels separately is:

$$M_W(\text{q}\bar{\text{q}}\ell\bar{\nu}) = 80.33 \pm 0.09(\text{stat}) \pm 0.03(\text{syst}) \text{ GeV} \quad (3)$$

$$M_W(\text{q}\bar{\text{q}}\text{q}\bar{\text{q}}) = 80.39 \pm 0.09(\text{stat}) \pm 0.04(\text{syst}) \pm 0.06(\text{CR}) \text{ GeV} \quad (4)$$

Note that these results are statistically consistent with each other.

### IV. SYSTEMATIC ERRORS

The systematic errors for a typical LEP experiment are given in Table IV. It should be noted that for all four LEP experiments the errors associated with ISR, hadronization, and four-fermion interference uncertainties are limited by

<sup>4</sup>From these results, only the OPAL numbers are final [6] while the rest are the latest available pre-liminary results.

<sup>5</sup>Note that since the OPAL numbers have changed since the last “official” LEP combination, the combinations given here are the author’s own.

TABLE IV. Table of systematic errors on  $M_W$  for a typical LEP experiment.

systematic source	$\Delta M_W$ (MeV)	$\Delta M_W$ (MeV)
	$q\bar{q}\ell\bar{\nu}$	$q\bar{q}q\bar{q}$
initial state radiation	15	15
hadronization	25	30
four fermion	20	20
detector effects	30	35
fit procedure	30	30
Sub-total	55	60
beam energy	22	22
CR/BE	–	60
Total	59	88

the statistics of the comparison. Uncertainties associated with the selection efficiencies and accepted backgrounds are included in the line labeled “fit procedure”. For the  $q\bar{q}\ell\bar{\nu}$  channel the largest single contribution to the systematic uncertainty is due to detector effects (eg. energy scales, resolutions, and modelling). These errors are expected to decrease as more data is collected. For the  $q\bar{q}q\bar{q}$  channel the dominant systematic uncertainty is due to CR/BE effects.

There has been recent progress in experimentally constraining the available CR models by comparing event shape and charged particle multiplicity distributions as predicted by various MC models (both including and excluding CR effects) with those observed in the data. On the basis of these studies, some of the models have been excluded as they fail to adequately describe the data [7]. In particular, the VNI [8] model is excluded, which predicted systematic shifts to the measured  $M_W(q\bar{q}q\bar{q})$  on the order of 100 MeV. The surviving models are used to estimate the systematic uncertainty associated with the modeling of CR effects and yield estimates in the range of 20 – 55 MeV. For a more complete discussion, see Reference [7]. Additional data should help to further constrain the remaining CR models and thus improve these errors.

## V. CONCLUSIONS

Using approximately  $10 \text{ pb}^{-1}$  of data collected at  $\sqrt{s} = 161$  and  $172 \text{ GeV}$  and  $55 \text{ pb}^{-1}$  at  $\sqrt{s} = 183 \text{ GeV}$  the LEP experiments have measured the mass of the W boson. The LEP combined result, assuming the Standard Model relation between the W decay width and mass, is  $M_W = 80.38 \pm 0.07(\text{exp}) \pm 0.03(\text{CR/BE}) \pm 0.02(E_{\text{bm}}) \text{ GeV}$ , where the errors correspond to experimental, colour-reconnection/Bose-Einstein, and LEP beam energy uncertainties respectively. This value ( $80.38 \pm 0.08 \text{ GeV}$ ) is consistent with the direct measurement from the TeVatron ( $80.41 \pm 0.09 \text{ GeV}$ ) [9], and the indirect determinations from NuTeV ( $80.26 \pm 0.11 \text{ GeV}$ ) [10] and SM fits to precision electroweak data ( $80.37 \pm 0.03$ ) [3].

During 1998 LEP delivered approximately  $180 \text{ pb}^{-1}$  per experiment at  $\sqrt{s} \approx 189 \text{ GeV}$ . This additional data increased the presently available statistics for the DR method by more than a factor of two. Incorporating this data should yield a statistical error for the LEP combined determination of  $M_W$  of 40 – 50 MeV and will allow for tighter experimental constraints on various color-reconnection and Bose-Einstein models in the  $q\bar{q}q\bar{q}$  final state.

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# OPAL, $\sqrt{s} = 183 \text{ GeV}$

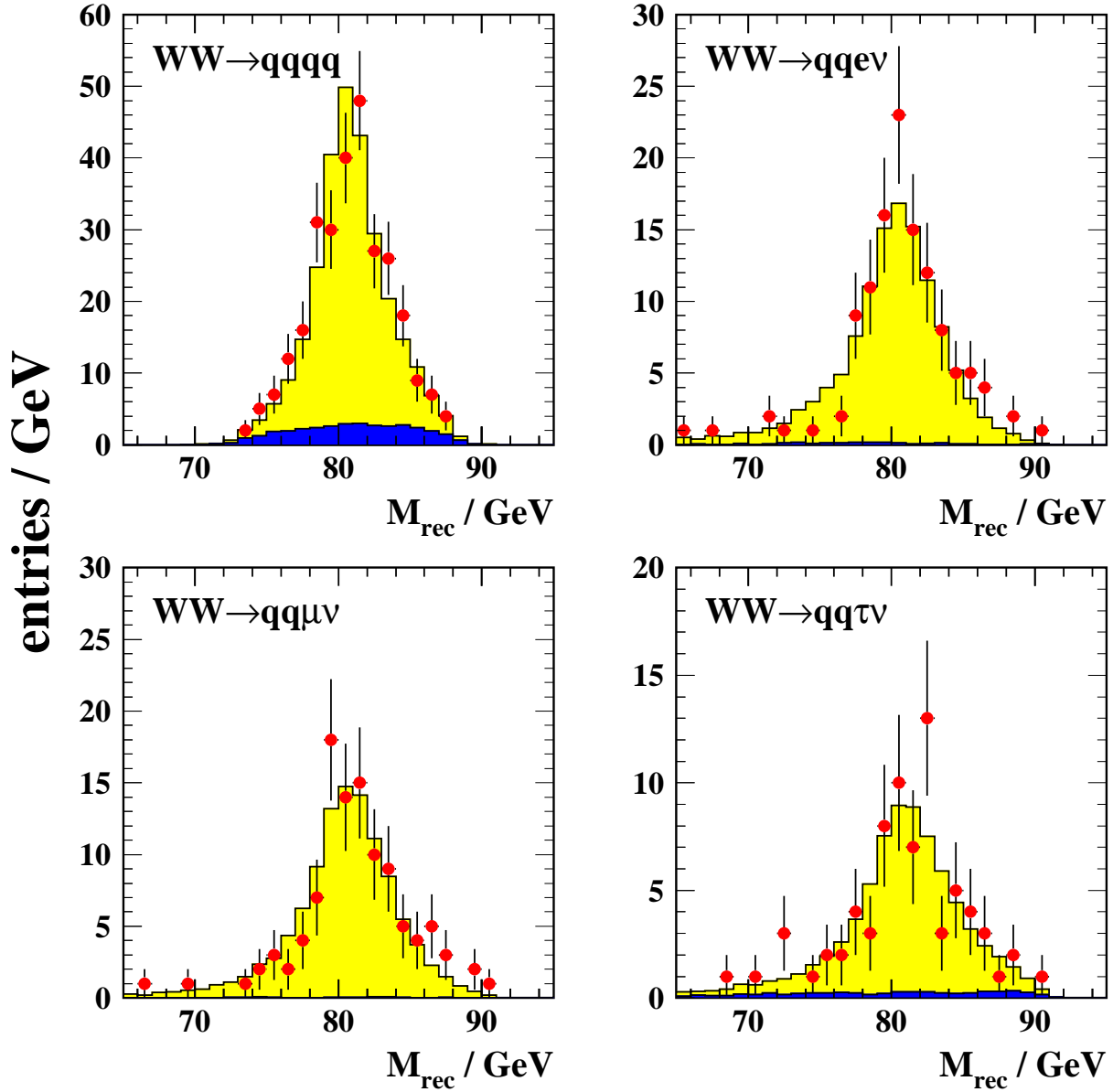


FIG. 1. Fit results for  $\sqrt{s} = 183 \text{ GeV}$  data. The points are OPAL data, the histogram is the fit result, and background contributions are shown as the dark shaded regions.