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Measurement of the mass and width of the W Boson in e^+e^- Collisions at $\sqrt{s} \simeq$ 192-209 GeV

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Abstract

Preliminary results are presented for a measurement of the W mass and W width from the data collected by the DELPHI experiment during 1999 and 2000. This data sample corresponds to an integrated luminosity of 436 pb^{-1} and was collected at centre-of-mass energies ranging from 192 to 209 GeV. Results were obtained by applying the method of direct reconstruction to both $\mathrm{W^+W^-} \rightarrow \ell\overline{\nu}_\ell \mathrm{q\bar{q}'}$ and $\mathrm{W^+W^-} \rightarrow \mathrm{q\bar{q}'\bar{q}q'}$ events. Combining these results with those previously published by the DELPHI Collaboration gives :

$$\mathrm{M_W} = 80.401 \pm 0.045(stat.) \pm 0.034(syst.) \pm 0.029(FSI) \pm 0.017(LEP)\ \mathrm{GeV/c^2}$$

and

$$\Gamma_\mathrm{W} = 2.109 \pm 0.099(stat.) \pm 0.057(syst.) \pm 0.042(FSI)\ \mathrm{GeV/c^2},$$

where FSI represents the uncertainty due to final state interaction effects in the $\mathrm{q\bar{q}'\bar{q}q'}$ channel.

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1 Introduction

The W mass and W width have been measured by the DELPHI collaboration using the data collected during 1999 and 2000. This direct measurement of m_W provides an important test of the Standard Model by comparison with the indirect measurement from precise electroweak results at lower energies [1] and helps to constrain the mass of the Higgs boson.

Section 2 of this paper describes the characteristics of the analysed data sample and of the event generators used in this analysis. The analysis was performed through the direct reconstruction of the mass of the W boson from its decay products in the $W^+W^- \to q\bar{q}'\bar{q}q'$ (fully-hadronic) and $W^+W^- \to \ell\overline{\nu}_\ell q\bar{q}'$ (semi-leptonic) decay channels. The applied analysis methods are briefly described in section 3. A more extensive description, which also includes the evaluation of systematic uncertainties, can be found in [2]. The results of this analysis are reported in section 4, where the combination is made with the previous DELPHI results at centre-of-mass energies of 161 GeV [3] and 172 GeV in 1996 [4], 183 GeV in 1997 [5] and 189 GeV in 1998 [2].

2 Apparatus and Simulation

A detailed description of the DELPHI apparatus and its performance can be found in [6]. In the data sample considered for analysis all the detectors essential for this measurement were required to be fully efficient; the operation of the central tracking detectors was important for all decay channels, in the $\ell\overline{\nu}_\ell q\bar{q}'$ analysis stricter requirements than in the $q\bar{q}'\bar{q}q'$ channel were placed on the electromagnetic calorimeters. The selected samples have an integrated luminosity of 221 pb^{-1} in 1999 and 215 pb^{-1} in 2000. In 1999 the data was collected at four centre-of-mass energies $\sqrt{s} \simeq$ 191.6, 195.5, 199.5 and 201.6 GeV. The data in 2000 was collected at a range of energies between 199.5 and 208.9 GeV, with over 90% of the data collected within 1.5 GeV of 206 GeV. The collected data in each year was split into sub-samples by centre-of-mass energy and simulation samples with an appropriate centre-of-mass energy were used in the analysis.

The response of the detector to various physical processes was modelled using the simulation program `DELSIM` [7], which incorporates the resolution, granularity and efficiency of the detector components. The W^+W^- events and all other four-fermion (4-f) processes were produced using the event generator `EXCALIBUR` [8], with initial-state radiation described using the `QEDPS` program [9]. The W mass and width notation used throughout this paper correspond to a W propagator with an s-dependent width. All background processes, including $e^+e^- \to q\bar{q}(\gamma)$, were produced with the `PYTHIA` 6.125 [10] event generator. The fragmentation of all 4-f events was performed using either `JETSET` 7.4 [11] or `PYTHIA` 6.125 tuned to the DELPHI LEP1 data.

2.1 TPC Problems

Unfortunately one twelfth of the Time Projection Chamber (TPC), which is the central DELPHI tracking detector, was not operational during the final two months of data taking in 2000. 25% of the collected luminosity in 2000 was taken in this configuration, where the tracking in the angular acceptance of this sector of the TPC relied on the silicon Vertex Detector, Inner and Outer detectors.

Simulation events were produced with a model of the detector that matched the status of DELPHI during this period. The modelling of the data was checked using both Z peak and high energy events, and no significant problems were found. The agreement between data and simulation for two-jet hadronic Z peak events with jets in the non-functional sector of the TPC are shown in Figure 1. Smearings and corrections to the jet energies and directions were calculated to improve the agreement between data and simulation. These corrections were compared with the standard DELPHI corrections and no adjustment to the quoted systematic uncertainty from this source was found to be necessary.

3 Analysis Method

3.1 Semi-Leptonic Decay Channel

The analysis presented here is based on that described in [2] for the $\mathrm{e}\overline{\nu}_{\mathrm{e}}\mathrm{q}\bar{\mathrm{q}}'$, $\mu\overline{\nu}_{\mu}\mathrm{q}\bar{\mathrm{q}}'$ and $\tau\overline{\nu}_{\tau}\mathrm{q}\bar{\mathrm{q}}'$ decay channels. Having removed this lepton candidate in $\mathrm{e}\overline{\nu}_{\mathrm{e}}\mathrm{q}\bar{\mathrm{q}}'$ and $\mu\overline{\nu}_{\mu}\mathrm{q}\bar{\mathrm{q}}'$ events, the LUCLUS [11] jet clustering algorithm (with a d_{join} of 7.5 GeV/c) was used to cluster the remaining particles. Events containing more than three jets were re-clustered, forcing them into a three-jet configuration. The $\tau\overline{\nu}_{\tau}\mathrm{q}\bar{\mathrm{q}}'$ events were clustered as the tau candidate and a two-jet system.

In the analysis of the 2000 data an improved selection of the candidate tau jet was applied which better separated the tracks from the hadronic system of the event and those resulting from the tau decay. The algorithm compared the invariant mass of the candidate tau jet with or without particular tracks and significantly reduced the bias in the analysis.

The events in all semi-leptonic decay channels were reconstructed using a constrained fit imposing conservation of four-momentum and equality of the two W masses.

The event selection in all semi-leptonic channels is based on a multi-layer perceptron neural-network [12], which was separately tuned for $\mathrm{e}\overline{\nu}_{\mathrm{e}}\mathrm{q}\bar{\mathrm{q}}'$, $\mu\overline{\nu}_{\mu}\mathrm{q}\bar{\mathrm{q}}'$, single charged particle $\tau\overline{\nu}_{\tau}\mathrm{q}\bar{\mathrm{q}}'$ candidates and other $\tau\overline{\nu}_{\tau}\mathrm{q}\bar{\mathrm{q}}'$ candidates to give the optimal selection efficiency and purity.

The selected fraction of semi-leptonic WW events in the data sample was estimated from simulation as a function of the event-by-event neural-network output, giving an event purity P_e. This feature is particularly useful for the tau analysis, where the proportion of background events is highest.

An event-by-event likelihood $\mathcal{L}_e(m_W)$ (or $\mathcal{L}_e(\Gamma_W)$ in the case of the W width measurement) was evaluated for all selected events [2] with a reconstructed mass in the range $67 - 95$ GeV/c^2. The probability density function is a weighted sum, according to the event purity, of signal and background terms. The signal term is a phase-space corrected Breit-Wigner distribution convoluted with a one dimensional Gaussian detector resolution function and a function describing the ISR spectrum in WW events.

3.2 Fully-Hadronic Decay Channel

This analysis is based on that applied in [2]. A sample of hadronic events was selected by requiring more than 13 charged particles and a total visible energy exceeding 1.15 E_{BEAM}. The $q\bar{q}(\gamma)$ events were suppressed by demanding an effective centre-of-mass energy [13], after ISR emission, of greater than 161 GeV. The DURHAM jet clustering algorithm [14] with y_{cut} of 0.002 was applied to the event. If one of the resulting jets had less than four particles or had an invariant mass smaller than 1 GeV/c^2, clustering was continued to a higher y_{cut} value. Events with less than four jets were then rejected, while events that contained six or more jets were re-clustered into five objects. The events were reconstructed using a constrained fit enforcing conservation of energy and momentum.

An event purity for the selection of 4-f events was estimated based upon the fitted jet energies and the inter-jet angles. Events with an estimated purity below 25 % were rejected. A soft anti-b-tag cut was then applied [15].

An event-by-event likelihood $\mathcal{L}_e(m_W)$ (or $\mathcal{L}_e(\Gamma_W)$ in the case of the W width measurement) was evaluated for all selected events [2]. The probability density function is a weighted sum, according to the effective event purity, of a phase-space corrected double resonant Breit-Wigner 4-f term and a uniform combined background term for $q\bar{q}(\gamma)$ events and wrong jet pairings. This theoretical p.d.f was convoluted with a two dimensional ideogram $p_e(m_x; m_y)$ (where m_x and m_y are the fitted masses of the two heavy objects), which reflects the reconstructed mass information from the kinematics of the event. For every event this probability density function was calculated for all possible jet pairings [1] and for three different jet clustering algorithms (`DURHAM` [14], `DICLUS` [16] and `CAMBRIDGE` [17]). All of these ideograms were summed to obtain the overall observed two-dimensional probability density function of the event. A treatment of unseen collinear ISR was also included in this ideogram construction.

3.3 Mass and Width Extraction

The distribution of the reconstructed invariant masses of the selected events are shown in Figures 2 and 3. These masses were obtained by applying a kinematic fit imposing four-momentum conservation and equality of the two W masses. These plots are provided for illustrative purposes only, the mass and width fitting procedure are described below.

The combined likelihood of the data was obtained from the product of the event likelihoods described above. The W mass and width were extracted with a maximum likelihood fit. Results for the W mass were obtained by keeping the W width fixed to its Standard Model value, while the width was extracted assuming a mass of 80.35 GeV/c^2.

For the W mass and width analyses, calibration curves at the diffferent centre-of-mass energies were constructed as described in [5] by the use of independent simulation samples generated at three W mass or width values or by using a re-weighting procedure. The re-weighting was performed using the extracted matrix elements of the `EXCALIBUR` generator, separately at each energy and for each of the decay channels ($\mathrm{q\bar{q}'\bar{q}q'}$,$\mathrm{e\bar{\nu}_e q\bar{q}'}$,$\mu\bar{\nu}_\mu \mathrm{q\bar{q}'}$,$\tau\bar{\nu}_\tau \mathrm{q\bar{q}'}$). The analyses were corrected with the calibration results obtained.

3.4 Results

The systematic error uncertainties are obtained from studies performed on Z peak data and simulation events at LEP2 energies (see Tables 1 and 2). These studies are reported in [2].

Generator level studies using the double-pole approximation Monte-Carlo calculations that have recently become available [18, 19] predict a shift of approximately 10 MeV/c^2 on

[1]Three combinations for events with a 4-jet topology and 10 for events with a 5-jet topology

the W mass relative to the calculation of generators such as `EXCALIBUR`. The correction has not been applied in the results presented here, and no additional systematic error is currently ascribed to this source. However, we note that the effect is at a similar or smaller level to the previously determined ISR systematic uncertainty.

The results obtained in each of the channels analysed are presented in Table 3 and 4.

For each of the decay channels the W mass results obtained at the range of centre-of-mass energies explored during the LEP2 programme are fully compatible, as can be seen in Figure 4.

4 Combined Results

The masses and widths measured in the semi-leptonic and hadronic analyses are in good agreement within statistics. Combining them yields for the 1999 data :

$$\begin{aligned} \mathrm{M_W} &= 80.397 \pm 0.073(stat.) \pm 0.034(syst.) \pm 0.033(FSI) \pm 0.017(LEP)\ \mathrm{GeV/c^2} \\ \Gamma_\mathrm{W} &= 1.965 \pm 0.157(stat.) \pm 0.061(syst.) \pm 0.040(FSI)\ \mathrm{GeV/c^2}. \end{aligned}$$

where FSI represents the uncertainty due to the imperfect knowledge of final state interference effects and where LEP denotes the uncertainty which comes from the experimental uncertainty on the beam energy [20].

The analysis of the year 2000 data gave :

$$\begin{aligned} \mathrm{M_W} &= 80.441 \pm 0.079(stat.) \pm 0.034(syst.) \pm 0.035(FSI) \pm 0.020(LEP)\ \mathrm{GeV/c^2} \\ \Gamma_\mathrm{W} &= 2.123 \pm 0.183(stat.) \pm 0.058(syst.) \pm 0.044(FSI)\ \mathrm{GeV/c^2}. \end{aligned}$$

Previous DELPHI measurements obtained from the data collected at centre-of-mass energies 172 GeV, 183 GeV and 189 GeV are fully compatible with these values, see Figure 4. Combining these measurements yields:

$$\begin{aligned} \mathrm{M_W} &= 80.399 \pm 0.045(stat.) \pm 0.035(syst.) \pm 0.030(FSI) \pm 0.017(LEP)\ \mathrm{GeV/c^2} \\ \Gamma_\mathrm{W} &= 2.109 \pm 0.099(stat.) \pm 0.057(syst.) \pm 0.042(FSI)\ \mathrm{GeV/c^2} \end{aligned}$$

with a $\chi^2/ndf = 0.60$ (probability of 80.0%) for the W mass and a $\chi^2/ndf = 1.50$ (probability of 16.2%) for the W width, where *ndf* denotes the number of degrees of freedom in the fit.

Independent fits of the W mass determined from the fully-hadronic and semi-leptonic decay channels yield:

$$\begin{aligned} \mathrm{M_{W_{q\bar{q}'\bar{q}q'}}} &= 80.383 \pm 0.053(stat.) \pm 0.028(syst.) \pm 0.056(FSI) \pm 0.017(LEP)\ \mathrm{GeV/c^2} \\ \mathrm{M_{W_{\ell\overline{\nu}_\ell q\bar{q}'}}} &= 80.414 \pm 0.074(stat.) \pm 0.045(syst.) \pm 0.017(LEP)\ \mathrm{GeV/c^2}. \end{aligned}$$

In addition the difference between the W mass estimated for $\mathrm{q\bar{q}'\bar{q}q'}$ events and $\ell\overline{\nu}_\ell \mathrm{q\bar{q}'}$ events has been determined from a two parameter fit to the results including the inter-channel correlations. A significant non-zero value for the mass difference could indicate that FSI effects are biasing the value of M_W from $q\bar{q}'\bar{q}q'$ events. Since the mass difference is primarily a check of FSI effects, the errors from colour reconnection and Bose-Einstein correlations are set to zero in this estimate. We do not observe a significant mass difference and obtain the result:

$$\Delta M_W(q\bar{q}'\bar{q}q' - \ell\overline{\nu}_\ell q\bar{q}') = -32 \pm 94 \text{ MeV/c}^2.$$

The mass results may also be combined with the determination obtained from the measurement of the W^+W^- cross-section close to the production threshold [21], giving

$$M_W = 80.401 \pm 0.045(stat.) \pm 0.034(syst.) \pm 0.029(FSI) \pm 0.017(LEP)\ \text{GeV/c}^2.$$

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Sources of systematic error (MeV/c^2)	$e\overline{\nu}_e q\bar{q}'$	$\mu\overline{\nu}_\mu q\bar{q}'$	$\tau\overline{\nu}_\tau q\bar{q}'$	$\ell\overline{\nu}_\ell q\bar{q}'$	$q\bar{q}'\bar{q}q'$	Combined
Statistical error on calibration						3
1999 data	15	12	17	8	7	
2000 data	18	14	19	10	5	
Lepton energy						6
1999 data	29	11	-	10	-	
2000 data	32	9	-	14	-	
Jet energy						26
1999 data	39	27	48	35	18	
2000 data	36	26	54	36	18	
Background	10	3	4	3	5	3
Aspect ratio	2	2	2	2	7	3
Fragmentation	20	20	20	20	12	15
I.S.R.	16	16	16	16	16	15
LEP energy						
1999 data	**17**	**17**	**17**	**17**	**17**	**17**
2000 data	**20**	**20**	**20**	**20**	**20**	**20**
Colour reconnection	-	-	-	-	46	24
Bose Einstein correlations	-	-	-	-	32	17

Table 1: Contributions to the systematic uncertainty on the mass measurement. The final column gives the contribution to the total error when performing the combination of all DELPHI mass results (1996-2000).

Sources of systematic error (MeV/c^2)	$\ell\overline{\nu}_\ell q\bar{q}'$	$q\bar{q}'\bar{q}q'$	Combined
Statistical error on calibration			8
1999 data	24	19	
2000 data	23	12	
Lepton energy			9
1999 data	28	-	
2000 data	35	-	
Jet energy			36
1999 data	63	26	
2000 data	59	26	
Background	19	40	29
Fragmentation	42	24	28
I.S.R.	16	16	16
Colour reconnection	-	54	37
Bose Einstein correlations	-	26	18

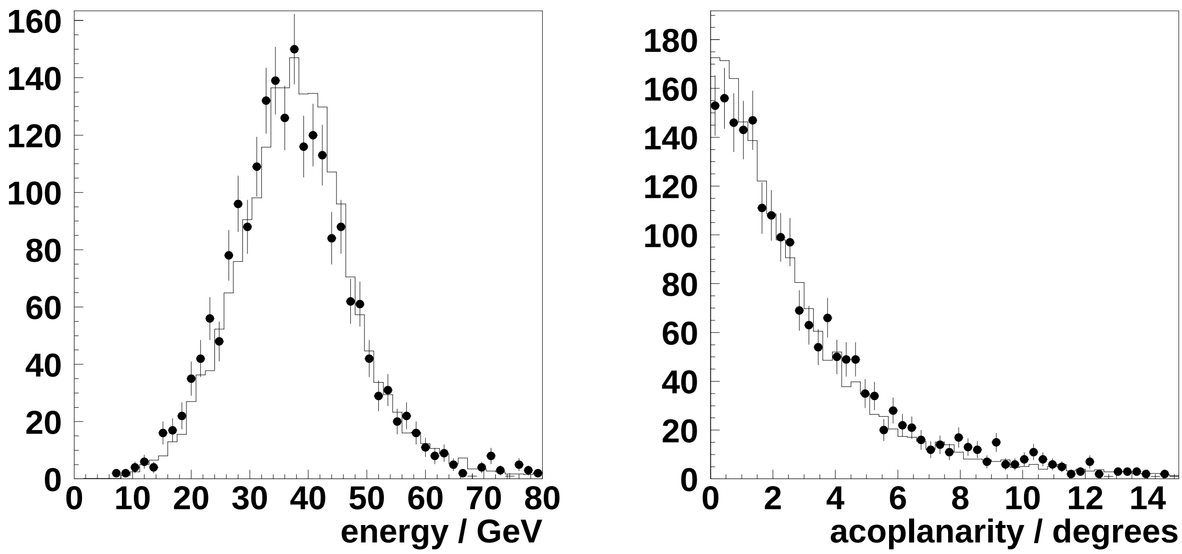
Table 2: Contributions to the systematic uncertainty on the width measurement. The final column gives the contribution to the total error when performing the combination of all DELPHI width results (1997-2000).

1999 and 2000 M_W results (GeV/c^2)						
Year	Channel	M_W	*stat.*	*syst.*	*LEP*	*FSI*
1999	$e\overline{\nu}_e q\bar{q}'$	80.359	±0.239	±0.058	±0.017	-
2000	$e\overline{\nu}_e q\bar{q}'$	80.813	±0.246	±0.058	±0.020	-
1999	$\mu\overline{\nu}_\mu q\bar{q}'$	80.361	±0.171	±0.041	±0.017	-
2000	$\mu\overline{\nu}_\mu q\bar{q}'$	80.149	±0.211	±0.040	±0.020	-
1999	$\tau\overline{\nu}_\tau q\bar{q}'$	80.649	±0.248	±0.057	±0.017	-
2000	$\tau\overline{\nu}_\tau q\bar{q}'$	80.687	±0.276	±0.063	±0.020	-
1999	$\ell\overline{\nu}_\ell q\bar{q}'$	80.429	±0.121	±0.045	±0.017	-
2000	$\ell\overline{\nu}_\ell q\bar{q}'$	80.495	±0.138	±0.048	±0.020	-
1999	$q\bar{q}'\bar{q}q'$	80.375	±0.091	±0.028	±0.017	±0.056
2000	$q\bar{q}'\bar{q}q'$	80.409	±0.095	±0.028	±0.020	±0.056

Table 3: M_W results from 1999 and 2000. The error is divided into its statistical component, indicated *stat*, the main systematic component *syst* and the systematic from the beam energy uncertainty *LEP*. In the $q\bar{q}'\bar{q}q'$ channel an error from final state interference effects *FSI* is also included. The $\ell\overline{\nu}_\ell q\bar{q}'$ results represents the combination of the results obtained in the three semi-leptonic channels.

1999 and 2000 Γ_W results (GeV/c^2)					
Year	Channel	Γ_W	*stat.*	*syst.*	*FSI*
1999	$\ell\overline{\nu}_\ell q\bar{q}'$	1.543	±0.275	±0.088	-
2000	$\ell\overline{\nu}_\ell q\bar{q}'$	2.542	±0.365	±0.087	-
1999	$q\bar{q}'\bar{q}q'$	2.180	±0.192	±0.059	±0.060
2000	$q\bar{q}'\bar{q}q'$	1.975	±0.211	±0.057	±0.060

Table 4: Γ_W results from 1999 and 2000. The error is divided into its statistical component, indicated *stat*, the main systematic component *syst* and the systematic from the beam energy uncertainty *LEP*. In the $q\bar{q}'\bar{q}q'$ channel an error from final state interference effects *FSI* is also included. The $\ell\overline{\nu}_\ell q\bar{q}'$ results represents the combination of the results obtained in the three semi-leptonic channels.



(a) (b)

Figure 1: Agreement between data and simulation for two-jet hadronic Z peak events with jets entering the non-operational sector of the DELPHI TPC. The total charged and neutral visible energy is shown in Figure (a) and the acoplanarity distribution in Figure (b).

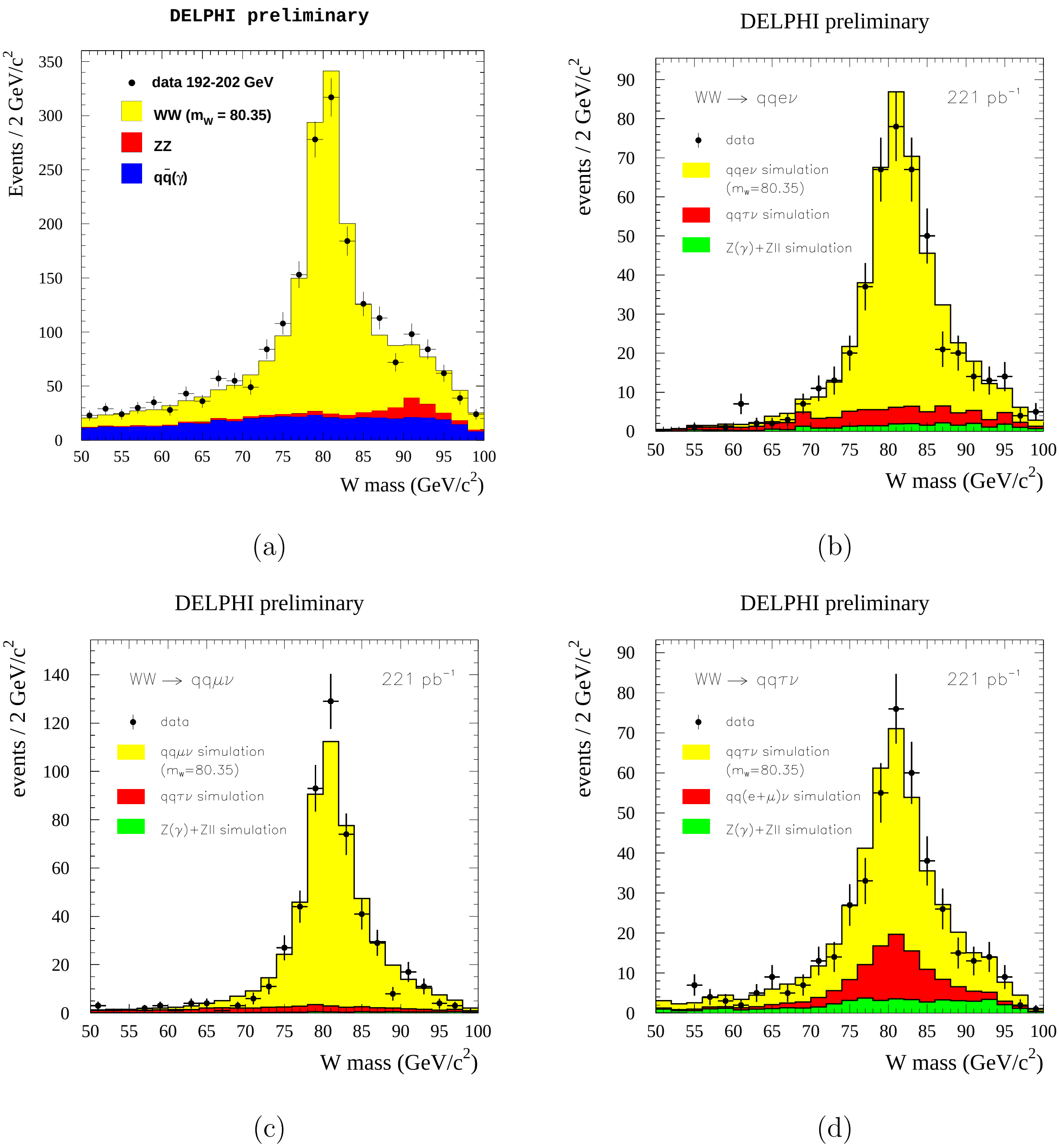
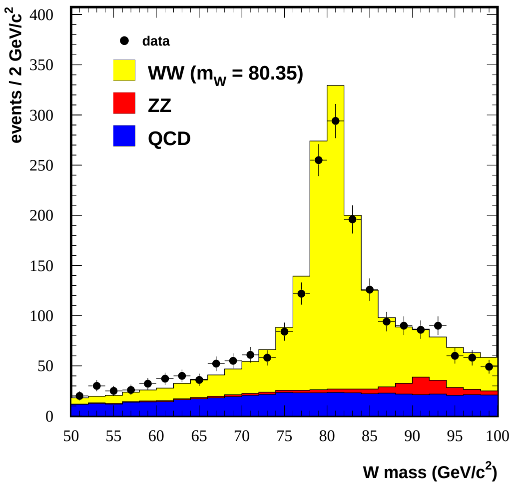
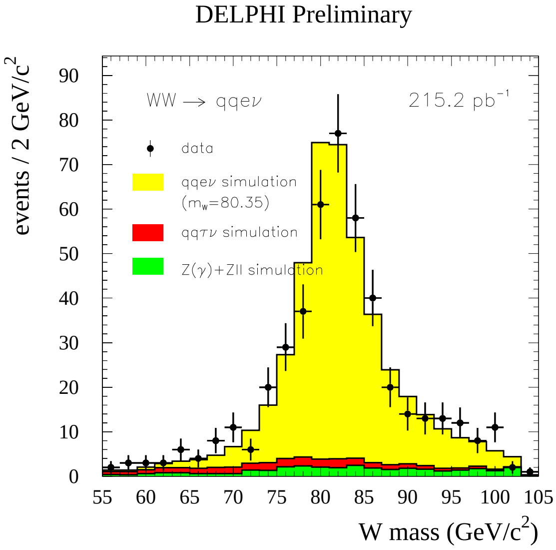


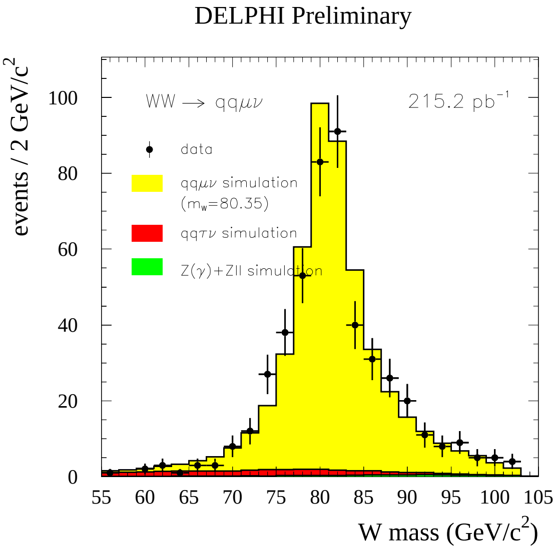
Figure 2: The distribution of the reconstructed W masses in the 1999 data from a kinematic fit with five constraints imposed in the (a) $q\bar{q}'\bar{q}q'$, (b) $e\overline{\nu}_e q\bar{q}'$, (c) $\mu\overline{\nu}_\mu q\bar{q}'$ and (d) $\tau\overline{\nu}_\tau q\bar{q}'$ analysis channels. In the $q\bar{q}'\bar{q}q'$ channel, only the jet pairing with the highest probability is included in this figure.



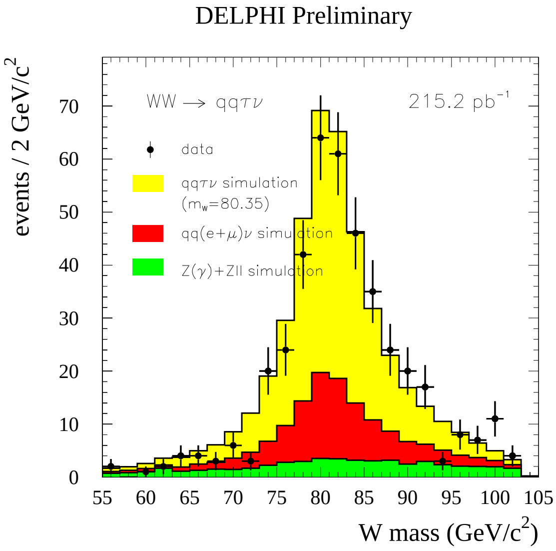
(a)



(b)

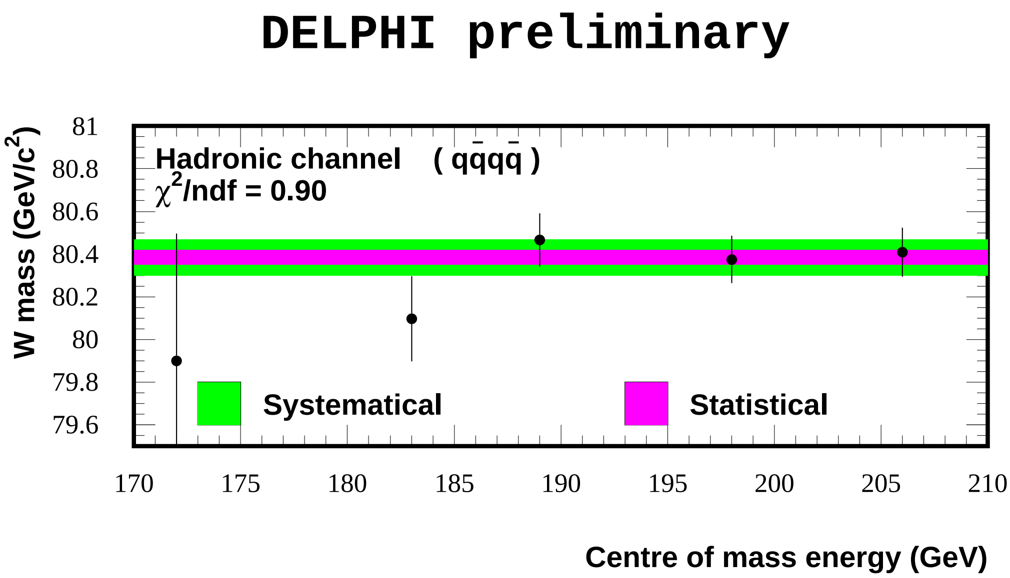


(c)

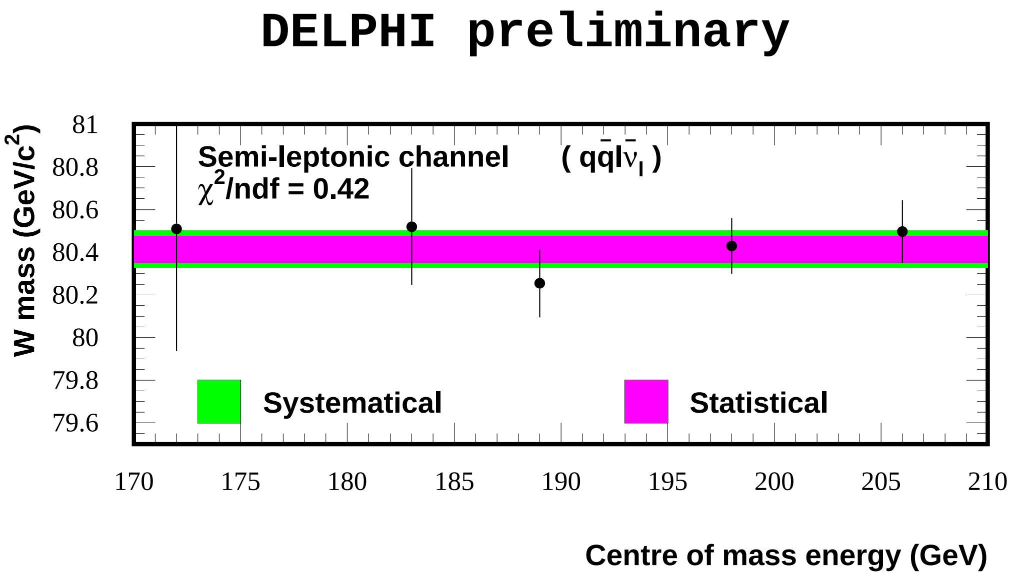


(d)

Figure 3: The distribution of the reconstructed W masses in the 2000 data from a kinematic fit with five constraints imposed in the (a) $q\bar{q}'\bar{q}q'$, (b) $e\overline{\nu}_e q\bar{q}'$, (c) $\mu\overline{\nu}_\mu q\bar{q}'$ and (d) $\tau\overline{\nu}_\tau q\bar{q}'$ analysis channels. In the $q\bar{q}'\bar{q}q'$ channel, only the jet pairing with the highest probability is included in this figure.



(a)



(b)

Figure 4: Fitted W mass as function of the centre-of-mass energy in the (a) $q\bar{q}'\bar{q}q'$ and (b) $\ell\overline{\nu}_\ell q\bar{q}'$ analysis channels are shown. The statistical and systematic components of the combined W mass uncertainty are shown, where the shaded areas are proportional to the ratio of the squares of the two component errors.