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Measurement of the mass and width of the W Boson in e^+e^- Collisions at $\sqrt{s} \simeq$ 192-202 GeV

D.Bloch[1], **R.Chierici**[2], **F.Cossutti**[2], **C.De Clercq**[3], **J.D'Hondt**[3], **D.Jeans**[4], **N.J.Kjaer**[2], **J.Montenegro**[5], **M.Mulders**[5], **A.Ouraou**[6], **J.Palacios**[4], **C.Parkes**[7], **P.Renton**[4], **I.Ripp-Baudot**[1], **L.Simard**[6], **J.Timmermans**[5], **S.Todorova**[2], **A.Tonazzo**[8], **M.L.Turluer**[6], **P.Zoller**[1]

Editor/Contact: Chris.Parkes@cern.ch

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. This data sample corresponds to an integrated luminosity of 228 pb^{-1} and was collected at centre-of-mass energies ranging from 192 to 202 GeV. Results were obtained by applying the method of direct reconstruction of 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 channels the following results were obtained :

$$\mathrm{M_W} = 80.397 \pm 0.073(stat.) \pm 0.034(syst.) \pm 0.033(FSI) \pm 0.017(LEP)\mathrm{GeV/c^2}$$

$$\Gamma_\mathrm{W} = 1.965 \pm 0.157(stat.) \pm 0.061(syst.) \pm 0.040(FSI)\mathrm{GeV/c^2}$$

where FSI represents the uncertainty due to final state interaction effects in the $\mathrm{q\bar{q}'\bar{q}q'}$ channel. Combining these results with those previously published by the DELPHI Collaboration gives

$$\mathrm{M_W} = 80.381 \pm 0.053(stat.) \pm 0.034(syst.) \pm 0.030(FSI) \pm 0.016(LEP)\mathrm{GeV/c^2}$$

$$\Gamma_\mathrm{W} = 2.096 \pm 0.118(stat.) \pm 0.058(syst.) \pm 0.044(FSI)\mathrm{GeV/c^2}$$

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[1]Inst. de Recherches Subatomiques, IN2P3-CNRS/ULP-BP20, FR-67037 Strasbourg Cedex 05, France
[2]CERN, CH-1211 Geneva 23, Switzerland
[3]IIHE (ULB-VUB), Pleinlaan 2, BE-1050 Brussels, Belgium
[4]Department of Physics, University of Oxford, Keble Road, Oxford OX1 3RH, UK
[5]NIKHEF, Postbus 41882, NL-1009 DB Amsterdam, The Netherlands
[6]DAPNIA/Service de Physique des Particules, CEA-Saclay, FR-91191 Gif-sur-Yvette Cedex, France
[7]Department of Physics, University of Liverpool,P.O.Box 147,Liverpool L69 3BX, UK
[8]Dipartimento di Fisica, Università di Milano and INFN-MILANO,Via Celoria 16, IT-20133 Milan, Italy

1 Introduction

The W mass and W width have been measured by the DELPHI collaboration using the data collected during 1999. 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 1999 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 $\mathrm{W^+W^-} \rightarrow \mathrm{q\bar{q}'\bar{q}q'}$ (fully-hadronic) and $\mathrm{W^+W^-} \rightarrow \ell\overline{\nu}_\ell \mathrm{q\bar{q}'}$ (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 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 $\ell\overline{\nu}_\ell \mathrm{q\bar{q}'}$ analysis stricter requirements than in the $\mathrm{q\bar{q}'\bar{q}q'}$ channel were placed on the electromagnetic calorimeters. The selected samples, corresponding to an integrated luminosity of 228 pb^{-1}, was collected at four centre-of-mass energies $\sqrt{s} \simeq$ 191.6, 195.5, 199.5 and 201.6 GeV.

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 $\mathrm{W^+W^-}$ events and all other four-fermion 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 $e^+e^- \rightarrow q\bar{q}(\gamma)$, 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. For these preliminary results, simulation samples of 4-f and $q\bar{q}(\gamma)$ events were generated at each of the four centre-of-mass energies.

3 Analysis Method

3.1 Semi-Leptonic Decay Channel

The analysis presented here is based on that described in [2] for the $\mathrm{e}\overline{\nu}_\mathrm{e}\mathrm{q\bar{q}'}$, $\mu\overline{\nu}_\mu\mathrm{q\bar{q}'}$ and $\tau\overline{\nu}_\tau\mathrm{q\bar{q}'}$ decay channels. Having removed this lepton candidate in $\mathrm{e}\overline{\nu}_\mathrm{e}\mathrm{q\bar{q}'}$ and $\mu\overline{\nu}_\mu\mathrm{q\bar{q}'}$ 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 $\tau\overline{\nu}_\tau\mathrm{q\bar{q}'}$ events were clustered as the tau candidate and a two-jet system. The events 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 $68 - 92$ 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.

A 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.

[1] 3 combinations for events with a 4-jet topology and 10 for events with a 5-jet topology

3.3 Mass and width extraction

The distribution of the reconstructed invariant masses of the selected events are shown in figure 1. 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 analyses, calibration curves at the four centre-of-mass energies were constructed as described in [5] by the use of independent simulation samples generated at three W mass values. For the calibration curves of the W width analyses a re-weighting procedure was used. The re-weighting was performed using the extracted matrix elements of the `EXCALIBUR` generator, separately at each energy and for each decay channels ($\mathrm{q\bar{q}'\bar{q}q'}$,$\mathrm{e\overline{\nu}_e q\bar{q}'}$,$\mu\overline{\nu}_\mu \mathrm{q\bar{q}'}$,$\tau\overline{\nu}_\tau \mathrm{q\bar{q}'}$). The analyses were corrected with the calibration results obtained.

3.4 Results

The systematic error uncertainties are mostly obtained from studies done on Z^0 data and simulation events at a centre-of-mass energy of 189 GeV (see tables 1 and 2) .

For each of the decay channels the obtained results at the four centre-of-mass energies are fully compatible, as can be seen in figure 2. The analysis on the semi-leptonic channels gave the following results :

$$m_W = 80.359 \pm 0.239(stat.) \pm 0.058(syst.) \pm 0.017(LEP) GeV/c^2$$
$$\Gamma_W = 3.009 \pm 0.646(stat.) \pm 0.113(syst.) GeV/c^2$$

for the electron events,

$$m_W = 80.361 \pm 0.171(stat.) \pm 0.041(syst.) \pm 0.017(LEP) GeV/c^2$$
$$\Gamma_W = 1.143 \pm 0.344(stat.) \pm 0.085(syst.) GeV/c^2$$

for the muon events and

$$m_W = 80.649 \pm 0.248(stat.) \pm 0.057(syst.) \pm 0.017(LEP) GeV/c^2$$
$$\Gamma_W = 1.491 \pm 0.643(stat.) \pm 0.146(syst.) GeV/c^2$$

for the tau events, where LEP denotes the uncertainty which comes from the experimental uncertainty on the beam energy [18]. Combining these results from the semi-leptonic decay channels one obtains :

$$m_W = 80.429 \pm 0.121(stat.) \pm 0.045(syst.) \pm 0.017(LEP) GeV/c^2$$
$$\Gamma_W = 1.543 \pm 0.275(stat.) \pm 0.088(syst.) GeV/c^2.$$

The analysis on the fully-hadronic channel gave the following result :

$$m_W = 80.375 \pm 0.091(stat.) \pm 0.028(syst.) \pm 0.056(FSI) \pm 0.017(LEP) GeV/c^2$$

$$\Gamma_W = 2.180 \pm 0.192(stat.) \pm 0.059(syst.) \pm 0.060(FSI) GeV/c^2$$

where FSI represents the uncertainty due to the imperfect knowledge of final state interaction effects.

4 Combined Results

The masses and widths measured in the semi-leptonic and hadronic analysis are in good agreement within statistics. Combining them yields

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

Previous DELPHI measurements obtained from the data collected at centre-of-mass energies of 161 GeV, 172 GeV, 183 GeV and 189 GeV are fully compatible with these values, see figure 2. Combining these measurements yields:

$$\begin{aligned} \mathrm{M_W} &= 80.381 \pm 0.053(stat.) \pm 0.034(syst.) \pm 0.030(FSI) \pm 0.016(LEP)\ \mathrm{GeV/c^2} \\ \Gamma_\mathrm{W} &= 2.096 \pm 0.118(stat.) \pm 0.058(syst.) \pm 0.044(FSI)\ \mathrm{GeV/c^2} \end{aligned}$$

with a $\chi^2/ndf = 0.59$ for the W mass and a $\chi^2/ndf = 1.73$ for the W width, where *ndf* denotes the number of degrees of freedom in the fit.

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. A significant non-zero value for the mass difference could indicate that FSI effects are biasing the value of $\mathrm{M_W}$ from $\mathrm{q\bar{q}'\bar{q}q'}$ 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:

$$\Delta\mathrm{M_W}(\mathrm{q\bar{q}'\bar{q}q'} - \ell\overline{\nu}_\ell\mathrm{q\bar{q}'}) = -11 \pm 112\ \mathrm{MeV}.$$

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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	15	12	17	8	7	5
Lepton energy	29	11	-	10	-	4
Jet energy	39	27	48	35	18	25
Background	10	3	4	3	5	3
Aspect ratio	2	2	2	2	7	5
Fragmentation	20	20	20	20	12	15
I.S.R.	16	16	16	16	16	16
LEP energy	**17**	**17**	**17**	**17**	**17**	**17**
Colour reconnection	-	-	-	-	46	27
Bose Einstein correlations	-	-	-	-	32	19

Table 1: Contributions to the systematic uncertainty on the mass measurement. The error sources have been separated into those uncorrelated and correlated between the different LEP experiments.

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	38	33	46	24	19	15
Lepton energy	41	46	-	28	-	11
Jet energy	82	43	102	63	26	40
Background	29	8	82	19	40	32
Fragmentation	42	42	42	42	24	31
I.S.R.	16	16	16	16	16	16
Colour reconnection	-	-	-	-	54	36
Bose Einstein correlations	-	-	-	-	26	17

Table 2: Contributions to the systematic uncertainty on the width measurement. The error sources have been separated into those uncorrelated and correlated between the different LEP experiments.

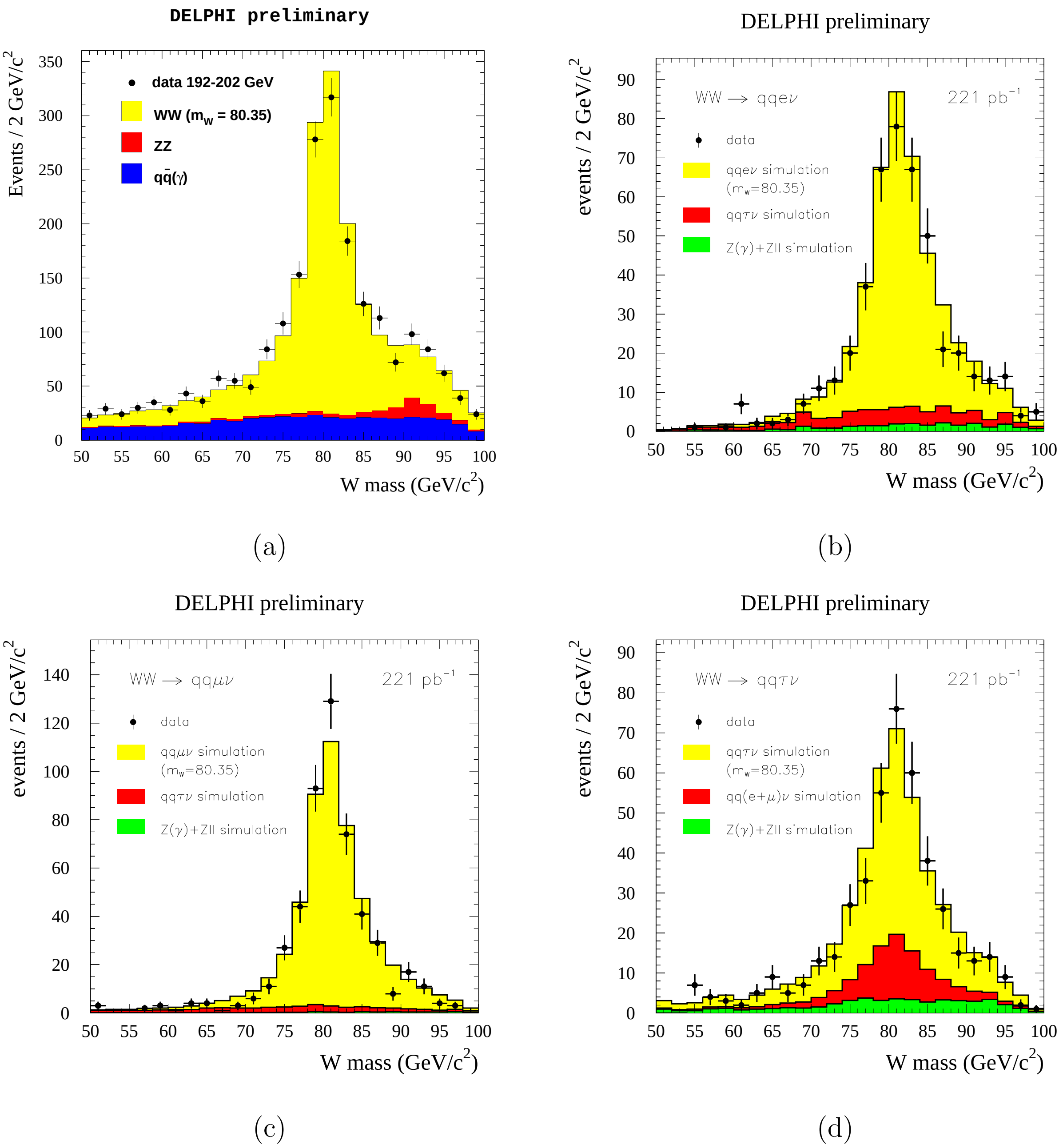

Figure 1: The distribution of the reconstructed W masses from a kinematic fit with five constraints imposed in the (a) $q\bar{q}'\bar{q}q'$, (b) $e\overline{\nu}_e q\bar{q}'$, (c) $\mu\overline{\nu}_\mu q\bar{q}'$ and (d) $\tau\overline{\nu}_\tau q\bar{q}'$ analysis channels. In the $q\bar{q}'\bar{q}q'$ channel, only the jet pairing with the highest probability is included in this figure.

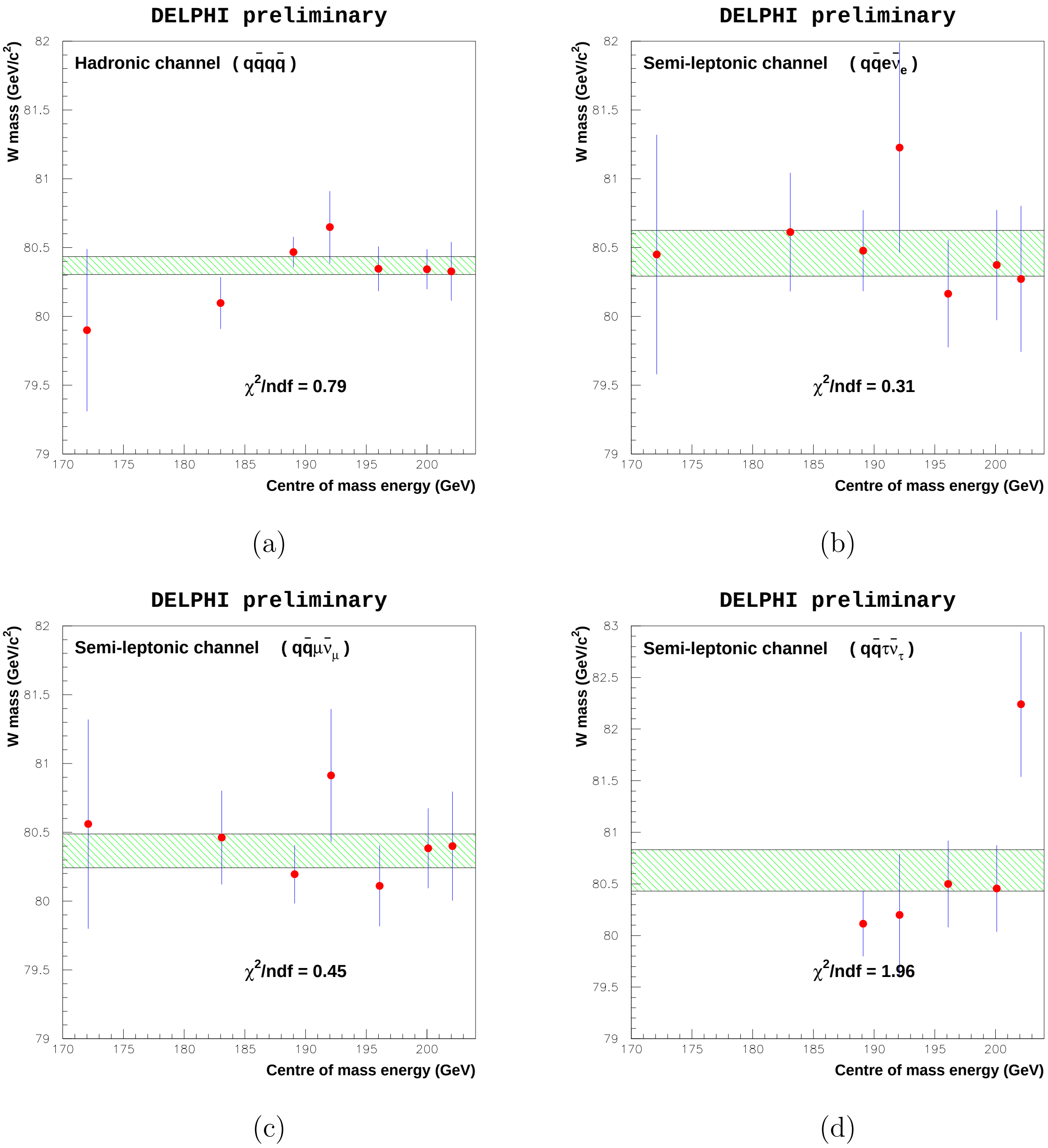

Figure 2: Fitted W mass as function of the centre-of-mass energy. The χ^2/ndf of an uncorrelated invariant W mass fit over the different data samples in the (a) $q\bar{q}'\bar{q}q'$, (b) $e\overline{\nu}_e q\bar{q}'$, (c) $\mu\overline{\nu}_\mu q\bar{q}'$ and (d) $\tau\overline{\nu}_\tau q\bar{q}'$ analysis channels are given. Only statistical uncertainties are taken into account. The 1σ band of the combined invariant W mass is given.