DELPHI Collaboration

DELPHI 2001-015 CONF 456
5 March, 2001

Update of the ZZ cross-section measurement in e^+e^- interactions using data collected in 2000

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Abstract

Preliminary measurements of the ZZ cross-section using data collected in 2000 with energies ranging between 201.5 and 208.5 GeV are presented. The values of the cross-section were derived based on the analysis of five main categories of ZZ final states: $q\bar{q}q\bar{q}$, $l^+l^-q\bar{q}$, $\nu\bar{\nu}q\bar{q}$, $l^+l^-l^+l^-$ and $\nu\bar{\nu}l^+l^-$, where $l = \mu, e, \tau$. These results complement those obtained with data collected at lower energies in 1997-1999 [1, 2]. The sub-channel $\tau^+\tau^-q\bar{q}$ was recently analysed and is included in the present combination.

Contributed Paper for Moriond 2001 Conference

1 Introduction

During the last year of LEP operation in 2000, the data were collected at energies ranging between 201.5 and 208.5 GeV, clustered mainly around two energy points. In total 83 pb^{-1} of integrated luminosity were accumulated around 205 GeV and 141 pb^{-1} around 207 GeV.

Preliminary results for the on-shell ZZ production were obtained at these two energy points from the analysis of five main categories of ZZ final states: $q\bar{q}q\bar{q}$, $\nu\bar{\nu}q\bar{q}$, $l^+l^-q\bar{q}$, $l^+l^-l^+l^-$ and $\nu\bar{\nu}l^+l^-$, where $l = \mu, e, \tau$. The selection procedures are in most part very similar to those described in Refs [1, 2]. A brief summary is given in Sec. 2, along with the main results for each channel. The analysis of the $\tau^+\tau^-q\bar{q}$ sub-channel, which was developed recently, is presented in more detail in Sec. 3.

One sector of the main tracking device TPC (1/12 of the whole detector) was inactive from the beginning of September 2000 which corresponds to one third of the whole data sample. The corresponding small change of analysis sensitivity from this period was taken into account in the extraction of the cross-sections.

2 Results

2.1 Four Jets

The probabilistic selection method used to analyse the four jet channel in previous years [1, 2] based on the invariant mass information, b-tag probability and topological information, was applied without changes. The combined P_{ZZ} distribution for the events from both energy bins is shown in Fig. 1. The numbers of events selected after a cut on P_{ZZ} to maximise the product of the efficiency and purity are listed in Table 1. The cross-section in the four jet channel was determined by means of a binned maximum likelihood fit to the P_{ZZ} distribution. Reasonable agreement between data and Monte-Carlo was found for the different variables used, and for the distribution of the P_{ZZ} probability.

2.2 Jets and a pair of isolated leptons

The analysis of the $\tau^+\tau^-q\bar{q}$ channel was developed recently. The corresponding selection method and results are described in Sec. 3. The $e^+e^-q\bar{q}$ and $\mu^+\mu^-q\bar{q}$ channels were analysed in the same way as in Ref. [1, 2]. Events were selected by sequential cuts, initially without explicit condition on the invariant mass of the lepton and quark system. The particle identification criteria were carefully tuned to maximise the efficiency of selecting leptons and signal to background ratio. Mass cuts were then applied to isolate the ZZ contribution. The distributions of the mass of one fermion pair (e^+e^-, $\mu^+\mu^-$ or $q\bar{q}$) when the mass of the second pair is within 15 GeV/c^2 of the nominal Z mass, and of the sum of masses of two fermion pairs, are shown in Fig. 2a,b,c, prior to the mass cuts used to select the ZZ component [1]. The observed distributions are in reasonable agreement with the predictions from simulation. The results obtained in the analysis of the $e^+e^- \to l^+l^-q\bar{q}$ ($l = e, \mu$) can be found in Table 1.

$E_{cms} = 205$ GeV				
Channel (Analysis)	Integrated luminosity [pb^{-1}]	Selection efficiency [%]	Predicted background	Selected events
$q\bar{q}q\bar{q}$	83.3	33.0	14.1	26
$e^+e^-q\bar{q}$	83.3	73.7	0.34	4
$\mu^+\mu^-q\bar{q}$	83.3	86.6	0.17	2
$\tau^+\tau^-q\bar{q}$	83.3	41.0	0.38	5
$\nu\bar{\nu}q\bar{q}$ (IDA)	82.1	49.3	21.3	28
$\nu\bar{\nu}q\bar{q}$ (PROB)	82.1	48.3	18.0	24
$l^+l^-l^+l^-$	83.3	33.1	0.08	0
$\nu\bar{\nu}l^+l^-$	83.3	27.3	0.52	1
$E_{cms} = 207$ GeV				
Channel (Analysis)	Integrated luminosity [pb^{-1}]	Selection efficiency [%]	Predicted background	Selected events
$q\bar{q}q\bar{q}$	141.8	34.0	27.1	49
$e^+e^-q\bar{q}$	141.8	69.9	0.55	4
$\mu^+\mu^-q\bar{q}$	141.8	84.4	0.30	5
$\tau^+\tau^-q\bar{q}$	141.8	40.0	0.82	4
$\nu\bar{\nu}q\bar{q}$ (IDA)	138.4	50.4	44.4	60
$\nu\bar{\nu}q\bar{q}$ (PROB)	135.3	45.4	29.6	48
$l^+l^-l^+l^-$	141.8	30.4	0.12	0
$\nu\bar{\nu}l^+l^-$	141.8	23.9	0.95	2

Table 1: Integrated luminosities, selection efficiencies, number of predicted background events and number of selected events for two energy points of 2000 data. For the two channels $q\bar{q}q\bar{q}$ and $\nu\bar{\nu}q\bar{q}$ (IDA and PROB methods), the numbers shown are those obtained after applying a cut on the corresponding discriminating variable (see Figs 1, 3 and 4) to maximise the product of the efficiency and purity. In the case of the $q\bar{q}q\bar{q}$ and $\nu\bar{\nu}q\bar{q}$ (IDA method) channels the cross-section was extracted by means of binned maximum likelihood fit to the corresponding distribution (see the text). IDA indicates the Iterative Discriminant Analysis and PROB stands for the probabilistic approach as described in Sec. 2.3.

2.3 Jets and missing energy

For the $\nu\bar{\nu}q\bar{q}$ final state, two independent analyses were used. The selection of the events was done in almost the same way as in Ref. [2], using in the first case the Iterative Discriminant Analysis program (IDA) [3] to combine the different variables, and in the second a probabilistic approach [4]. In each of the two analyses, track and neutral cluster selections, as well as the general preselection of events, were done in a similar way as in the Higgs search [5].

These two approaches proved to be equally efficient and their average was used in the combination of the cross-section, conservatively using for the statistical error the larger of the two. The distributions of the discriminant variables obtained in each method are shown in Figs 3 and 4. In the case of the IDA method, the cross-section was determined by means of a binned maximum likelihood fit to the corresponding distribution, while the probabilistic analysis used the numbers of observed and expected events, obtained after a cut on the discriminant variable chosen to maximise the product of the efficiency and purity. The numbers of events selected after such a cut are listed for both analyses in Table 1.

2.4 Four leptons final states

For the $l^+l^-l^+l^-$ and $\nu\bar{\nu}l^+l^-$ topologies the sequential cut analyses described in Ref [2] were applied without major changes to the data collected in 2000. Due to the small branching fraction for $Z \to l^+l^-$ only a few events are expected in the data. The $l^+l^-l^+l^-$ channel is very clean. For the $\nu\bar{\nu}l^+l^-$ channel large background coming from WW production results in a signal to background ratio near one. Three candidates were selected in the $\nu\bar{\nu}l^+l^-$ channel, one at 205 GeV and two at 207 GeV (see Table 1).

3 Selection of $\tau^+\tau^-q\bar{q}$ final states

3.1 Procedure

The search for the $\tau^+\tau^-q\bar{q}$ final state is based on the inclusive selection of isolated clusters of particles with low charged multiplicity and low invariant mass. Each pair of such clusters is considered as a possible $\tau^+\tau^-$ candidate, with all other particles assumed to originate from a $q\bar{q}$ system. Assuming this topology, a set of discriminating variables reflecting the isolation of the clusters and the likelihood of the $\tau^+\tau^-q\bar{q}$ hypothesis is defined. All these variables are combined into a single one using a likelihood method. Cutting on this combined variable enables to select $\tau^+\tau^-q\bar{q}$ final states consistent with ZZ production with high efficiency and low background contamination. Since the analysis of the $\tau^+\tau^-q\bar{q}$ channel is described for the first time, the results for all LEP-2 energies are presented.

3.2 Definition of τ-clusters

Each charged particle with momentum exceeding 1 GeV/c is considered as a τ-cluster candidate. One then tries to add to each one of these candidates, successively, every other charged particle (with energy exceeding 1 GeV), and photon (with energy exceeding

0.5 GeV). At each trial the incremental change in the cluster mass ΔM_{cl} is computed. All particles are sorted in increasing order of ΔM_{cl} and the particle producing the minimal ΔM_{cl} is included in the cluster if the following conditions are satisfied:

- the resulting number of charged particles in the cluster is less than 4;
- the resulting number of neutral particles in the cluster is less than 4;
- ΔM_{cl} is less than 1.5 GeV/c^2;
- for a cluster with one charged particle the resulting mass M_{cl} is less than 2.5 GeV/c^2;
- for a cluster with more than one charged particle the resulting mass M_{cl} is less than 1.9 GeV/c^2.

After adding each particle, the determination of ΔM_{cl} is repeated for all remaining particles with the modified cluster. The procedure is continued until all combinations have been tried. If the initial charged particle is identified as a lepton (electron or muon), only photons are admitted in the cluster.

Isolation criteria are then defined for each τ-cluster candidate, having first used the JADE algorithm [6] to cluster all particles into jets (using $d_{join} = 0.01$), by subtracting the four-momenta of its corresponding tracks from the jets to which they were assigned, and by determining the nearest jet with a remaining energy exceeding a minimum value E_{lim}. E_{lim} is set to 3 GeV for a cluster with one charged particle and to 1.5 GeV otherwise. Two variables characterising the isolation of the cluster are the angle θ_{cl} between the cluster and the nearest jet and the transverse momentum P_t of the most energetic particle in the cluster with respect to the nearest jet.

3.3 Preselection of $\tau^+\tau^- q\bar{q}$ events

The next step in the analysis is the preselection of $\tau^+\tau^- q\bar{q}$ events. Events are required to have at least 7 charged particles and a charged energy greater than 0.30 $\sqrt{s}$. To suppress radiative returns to the Z, events are rejected if a photon with an energy exceeding 55% of the beam energy is found. At least two isolated τ-clusters per event are required. The cluster is considered isolated if $|\cos\theta_{cl}| < 0.95$ for a cluster with one charged particle and $|\cos\theta_{cl}| < 0.92$ otherwise. The sum of charges of two clusters should satisfy the condition: $|Q_1 + Q_2| < 2$ and at least one of these clusters should contain only one charged particle.

To reject $l^+l^- q\bar{q}$ events ($l = e, \mu$), which have a similar topology, the large missing energy in the τ decays is exploited. To this end, all particles not used to define the two τ candidates are clustered in jets and a kinematic fit [7] with six constraints (6C) (consisting of four momentum conservation and $M_{\tau^+\tau^-} = M_{q\bar{q}} = M_Z$) is applied to the event. The missing energies of each τ-cluster D_E^1 and D_E^2 are then defined as the differences between each of their fitted and visible energies, and the following conditions are imposed:

- $\min(D_E^1, D_E^2) > -15$ GeV in all cases;
- if both τ clusters contain identified leptons of the same type, then $\min(D_E^1, D_E^2) > 10$ GeV;
- if a τ-cluster contains an identified lepton, then $D_E > 3$ GeV;
- if one or both τ-clusters contain an identified lepton, then $D_E^1 + D_E^2 > 10$ GeV.

The number of events passing all these preselection criteria is given in Table 2. There is a reasonable agreement between data and simulation, although slightly more events are selected in data at all energies.

Energy GeV	Data	MC tot.	$\tau^+\tau^-$ $q\bar{q}$	MC WW	MC $q\bar{q}$	l^+l^- $q\bar{q}$
183	36	35.7	0.8	24.1	9.5	1.3
189	107	102.5	3.4	72.8	22.0	4.3
192-202	170	159.7	6.8	123.1	22.0	7.8
204-209 (2000 data)	192	162.8	7.2	127.8	19.5	8.3
Total	505	460.7	18.2	347.8	73.0	21.7

Table 2: Number of preselected events for different c.m.s energies and the expected contribution from various processes

3.4 Probabilistic selection

In order to reduce the main backgrounds (in particular the W^+W^- component) a likelihood method is used to combine a set of discriminating variables, defined both at the level of the τ-clusters:

• the fitted energy of the τ-clusters after 6C fit;

• D_E^1, D_E^2, the missing energies of each τ-cluster;

• $\cos\theta_{cl}^1$, $\cos\theta_{cl}^2$, the cosine of each of the cluster isolation angles;

• P_t the transverse momentum of the most energetic particle in the cluster with respect to the nearest jet.

and at the level of the event as a whole:

• χ^2_{4C}, the χ^2 of a 4C fit applied to the event requiring only four momentum conservation;

• χ^2_{ZZ}, the χ^2 of the 6C fit applied requiring both four momentum conservation and $M_{\tau^+\tau^-} = M_{q\bar{q}} = M_Z$;

• χ^2_{WW}, the χ^2 of the 6C fit applied in the assumption of a $WW \to q\bar{q}q\bar{q}$, requiring both, four momentum conservation and that each of the two di-quark masses be equal to M_W (among the three possible jet pairings the one with smallest χ^2_{WW} was chosen)

The combined tagging variable is defined as:

$$Y = \prod Y_i; \quad Y_i = f_i^{WW}(x_i)/f_i^{ZZ}(x_i) \tag{1}$$

where f^{WW}, f^{ZZ} are the probability density functions of each variable, for the $WW \to q\bar{q}q\bar{q}$ component of the background and for the $ZZ \to \tau^+\tau^-q\bar{q}$ signal[1], respectively. The probability density functions were determined separately for τ-clusters with leptons, with one charged particle and with more than one charged particle.

In order to optimally select the signal, a cut chosen to maximise the product of the efficiency and purity was then applied on this combined variable: $-\log_{10} Y > 0.5$. The number of events remaining is given in Table 3. As can be seen, the background is reduced significantly. Although the reduction of $\tau^+\tau^-q\bar{q}$ is also large, it concerns mainly events outside the ZZ mass region. This is of course expected since the combined variables includes the variable χ^2_{ZZ}, which quantifies the compatibility with the $ZZ \to \tau^+\tau^-q\bar{q}$ hypothesis. To illustrate the separation power of the discriminant variable Fig. 5 shows the distribution of $-\log_{10} Y$ for the sample enriched with signal events by requiring $M_{\tau^+\tau^-}$

[1]Here, the $ZZ \to \tau^+\tau^-q\bar{q}$ signal is defined as the subset of $\tau^+\tau^-q\bar{q}$ events satisfying the kinematical conditions (applied at reconstruction level) described at the end of this section.

and $M_{q\bar{q}}$ to be compatible with the Z boson mass. The resulting mass[2] distributions for $\tau^+\tau^-$ and $q\bar{q}$ pairs in events passing this selection are shown in Fig. 6 for illustration. In both of Figs 5 and 6, the full data sample collected by DELPHI at LEP-2 in 1997-2000 is included.

In order to further improve the signal to background ratio, the reconstructed mass of the $\tau^+\tau^-$ and $q\bar{q}$ pairs is required to be compatible with ZZ production. The following set of cuts are used:

- $75 < M_{\tau^+\tau^-} < 110$ GeV/c^2;
- $75 < M_{q\bar{q}} < 110$ GeV/c^2;
- $170 < M_{\tau^+\tau^-} + M_{q\bar{q}} < 200$ GeV/c^2;

The number of selected events is shown in Table 4. The purities and efficiencies obtained were about 80% and 40%, respectively.

Energy (GeV)	Data	MC tot.	$\tau^+\tau^-$ $q\bar{q}$	MC WW	MC $q\bar{q}$	l^+l^- $q\bar{q}$
183	1	1.08	0.43	0.40	0.23	0.02
189	2	5.25	2.15	2.25	0.46	0.39
192	1	1.11	0.49	0.41	0.11	0.10
196	2	3.44	1.57	1.21	0.31	0.35
200	1	4.06	1.87	1.52	0.35	0.32
202	7	1.83	0.92	0.64	0.12	0.15
204-209 (2000 data)	11	9.68	5.10	3.16	0.62	0.80
Total	25	26.45	12.53	9.59	2.20	2.13

Table 3: Number of events selected after $-\log_{10} Y > 0.5$ cut for different c.m.s energies and the expected contribution from various processes

Energy (GeV)	Data	MC tot.	$\tau^+\tau^-$ $q\bar{q}$	MC WW	MC $q\bar{q}$	l^+l^- $q\bar{q}$
183	0	0.28	0.19	0.06	0.02	0.01
189	1	2.08	1.58	0.34	0.07	0.09
192	0	0.49	0.38	0.08	0.01	0.02
196	0	1.56	1.26	0.18	0.03	0.09
200	1	1.91	1.51	0.32	0.00	0.08
202	2	0.94	0.75	0.14	0.01	0.04
204-209 (2000 data)	9	5.17	4.20	0.68	0.03	0.26
Total	13	12.43	9.87	1.80	0.17	0.59

Table 4: Number of events selected after Z^0Z^0 mass selection for different c.m.s energies and the expected contribution from various processes

[2]Both $M_{\tau^+\tau^-}$ and $M_{q\bar{q}}$ were computed after applying the 4C kinematical fit assuming energy and momentum conservation in the event.

4 Combined NC02 cross-sections

To derive a combined value for the NC02 cross-section, a global likelihood was then constructed as in previous years by combining the likelihoods from the fits performed in $q\bar{q}q\bar{q}$ and $\nu\bar{\nu}q\bar{q}$ (IDA version) channels with the Poisson probabilities for observing the number of events seen in each of the cut based analyses, given the predicted numbers. This global likelihood was then maximised with respect to the value of the NC02 cross-section, assuming branching ratios of the Z fixed to those expected in the Standard Model.

The values for the NC02 cross-sections obtained (both in individual channels and in the combination) and expected, using the YFSZZ generator [8], are shown in Table 5. The errors shown are only statistical. Systematic uncertainties were not yet evaluated for these preliminary measurements.

E_{cms} GeV	$q\bar{q}q\bar{q}$	$l^+l^-q\bar{q}$ ($l = e, \mu$)	$\nu\bar{\nu}q\bar{q}$	All	Prediction
205	1.18 ± 0.36	0.91 ± 0.40	0.53 ± 0.47	1.05 ± 0.23	1.05
207	1.17 ± 0.27	0.83 ± 0.30	0.80 ± 0.38	0.98 ± 0.18	1.07

Table 5: The measured and expected values of the NC02 cross-sections for the data collected in 2000. All channels were used in the total combination. The individual numbers are only shown for three main final states: $q\bar{q}q\bar{q}$, $l^+l^-q\bar{q}$ ($l = e, \mu$) and $\nu\bar{\nu}q\bar{q}$.

The results of the combination are also presented in graphical form in Fig. 7, including also the values obtained at lower energies [1, 2]. As can be seen, there is good global agreement with the Standard Model. The predicted values shown in Fig. 7 were obtained using the YFSZZ generator [8]. The `ZZTO`[9] semi-analytical calculation was also used to evaluate the theoretical uncertainty associated to these expectations, resulting in values within ± 1 % of those obtained with YFSZZ.

Acknowledgements

We are greatly indebted to our technical collaborators, to the members of the CERN-SL Division for the excellent performance of the LEP collider, and to the funding agencies for their support in building and operating the DELPHI detector.

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PRELIMINARY

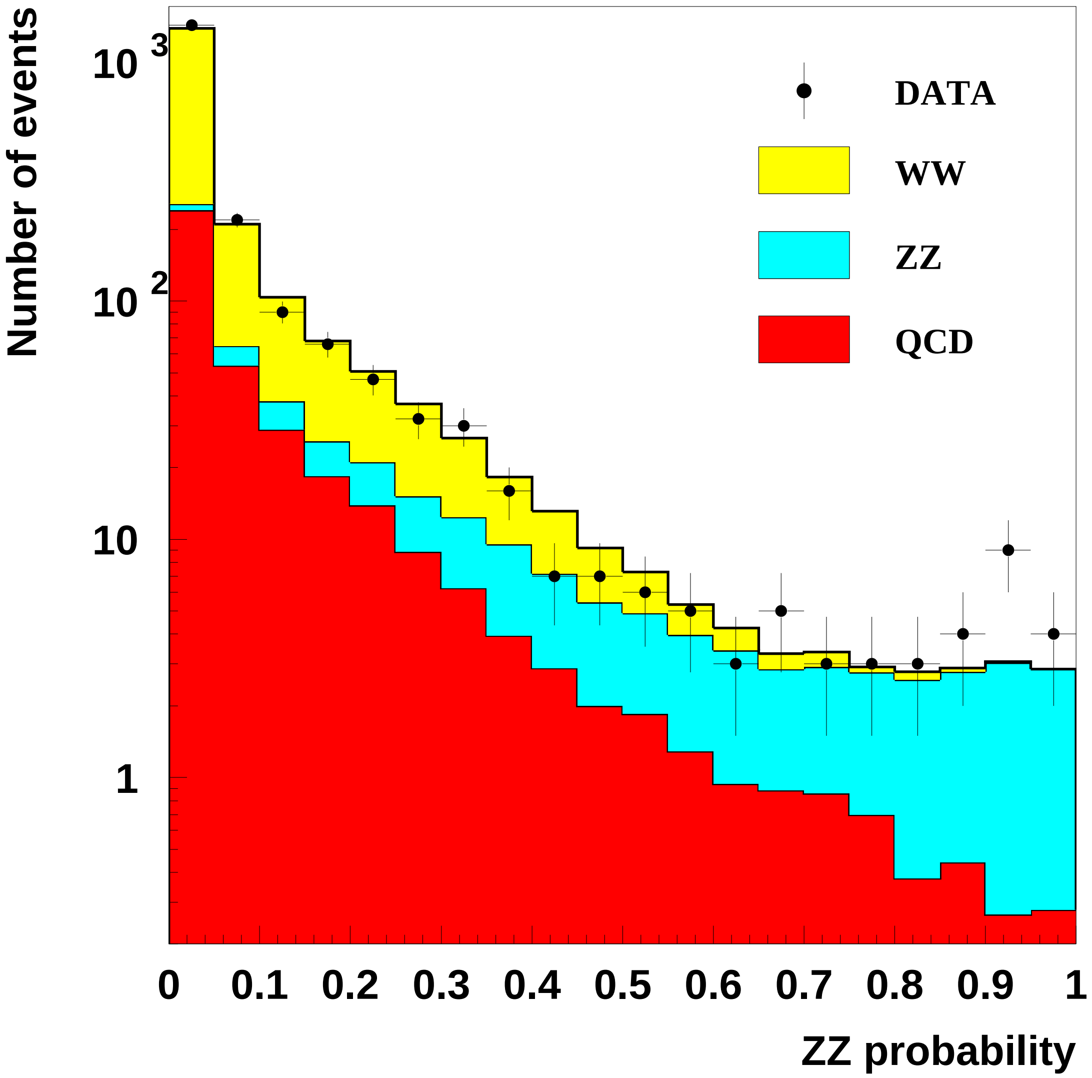

Figure 1: Distribution of the ZZ probability for all events collected in 2000, constructed by combining invariant mass, b-tag and topological information, as well as the predicted Standard Model cross-sections and branching ratios into the different quark configurations (see [1, 10]). It has been shown that this variable gives a good estimate of the actual probability to select ZZ events.

PRELIMINARY

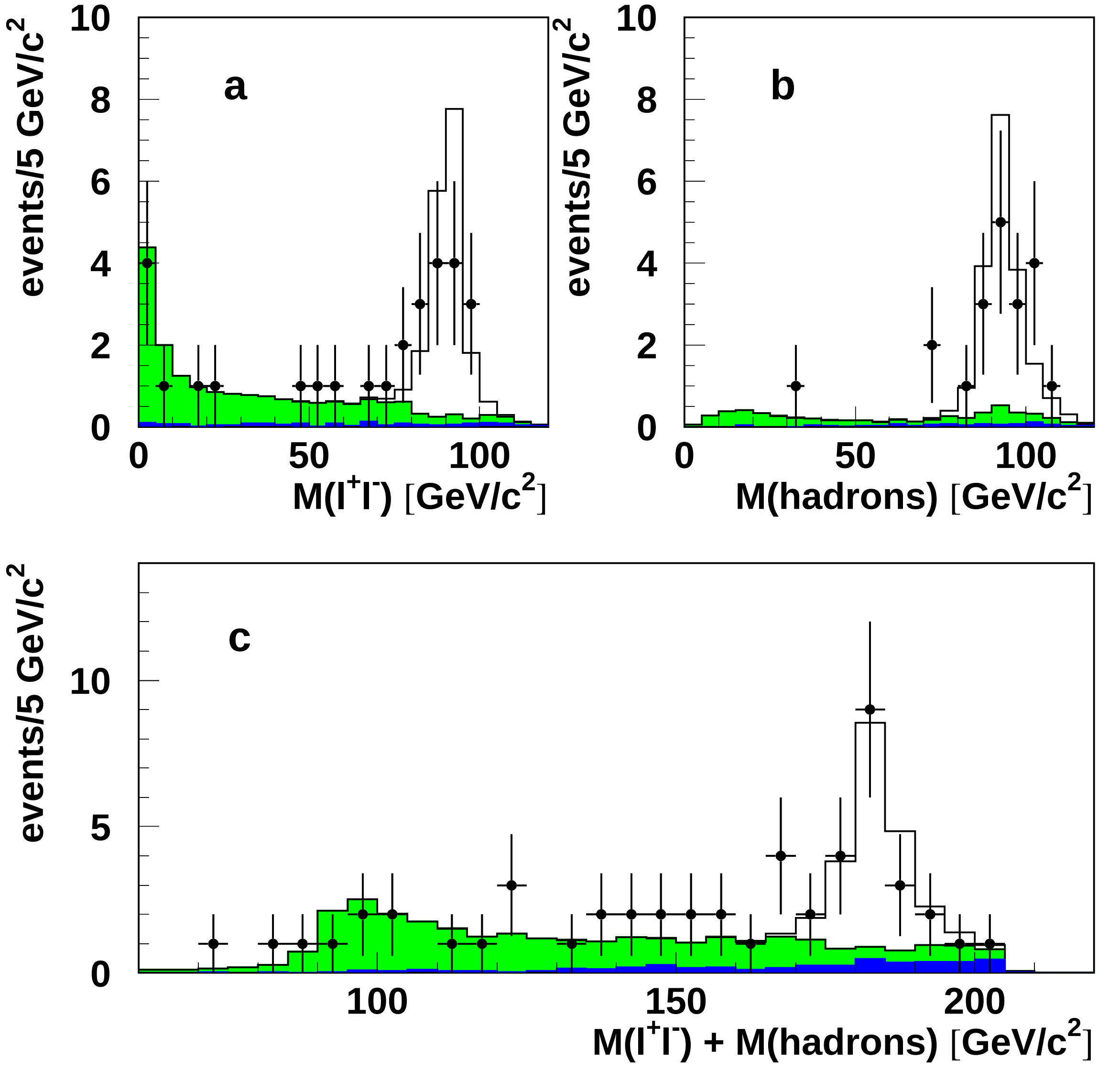

Figure 2: a) the distribution of the mass of the l^+l^- pair when the mass of the hadron system is within 15 GeV/c^2 of the nominal Z mass; b) the distribution of the mass of the hadron system when the mass of the l^+l^- pair is within 15 GeV/c^2 of the nominal Z mass; c) the distribution of the sum of the masses of the l^+l^- pair and of the hadron system. The points are the data collected in 2000 and the histogram is the simulation prediction. The contributions from the signal, as defined in [1], is indicated by the white histogram. The contributions from backgrounds, respectively arising and not arising from $l^+l^-q\bar{q}$ final states, are indicated each with light grey and dark filling.

PRELIMINARY

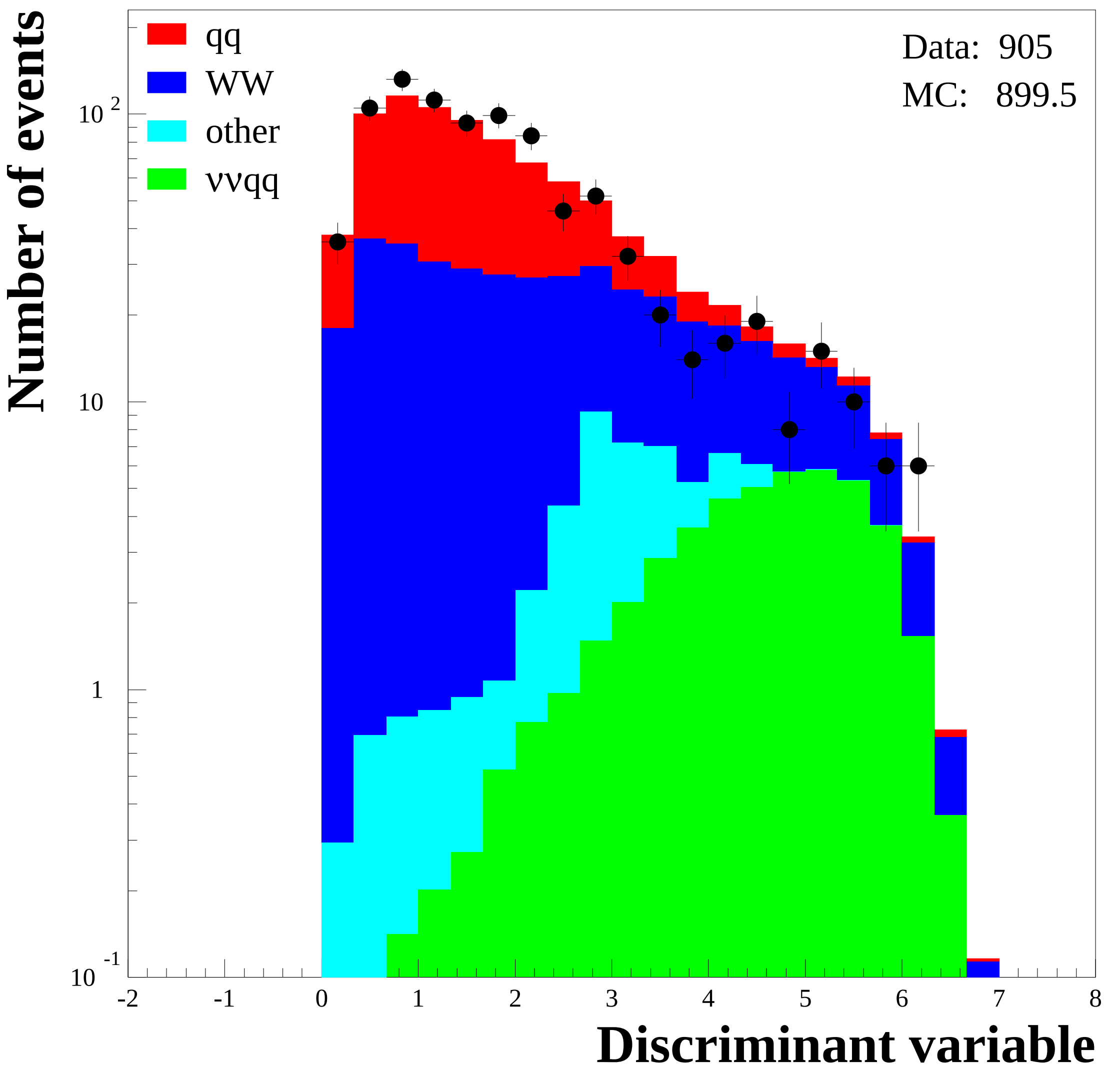

Figure 3: The distribution of the global discriminant variable for the $\nu\bar{\nu}q\bar{q}$ channel (IDA method), shown for the full 2000 data sample.

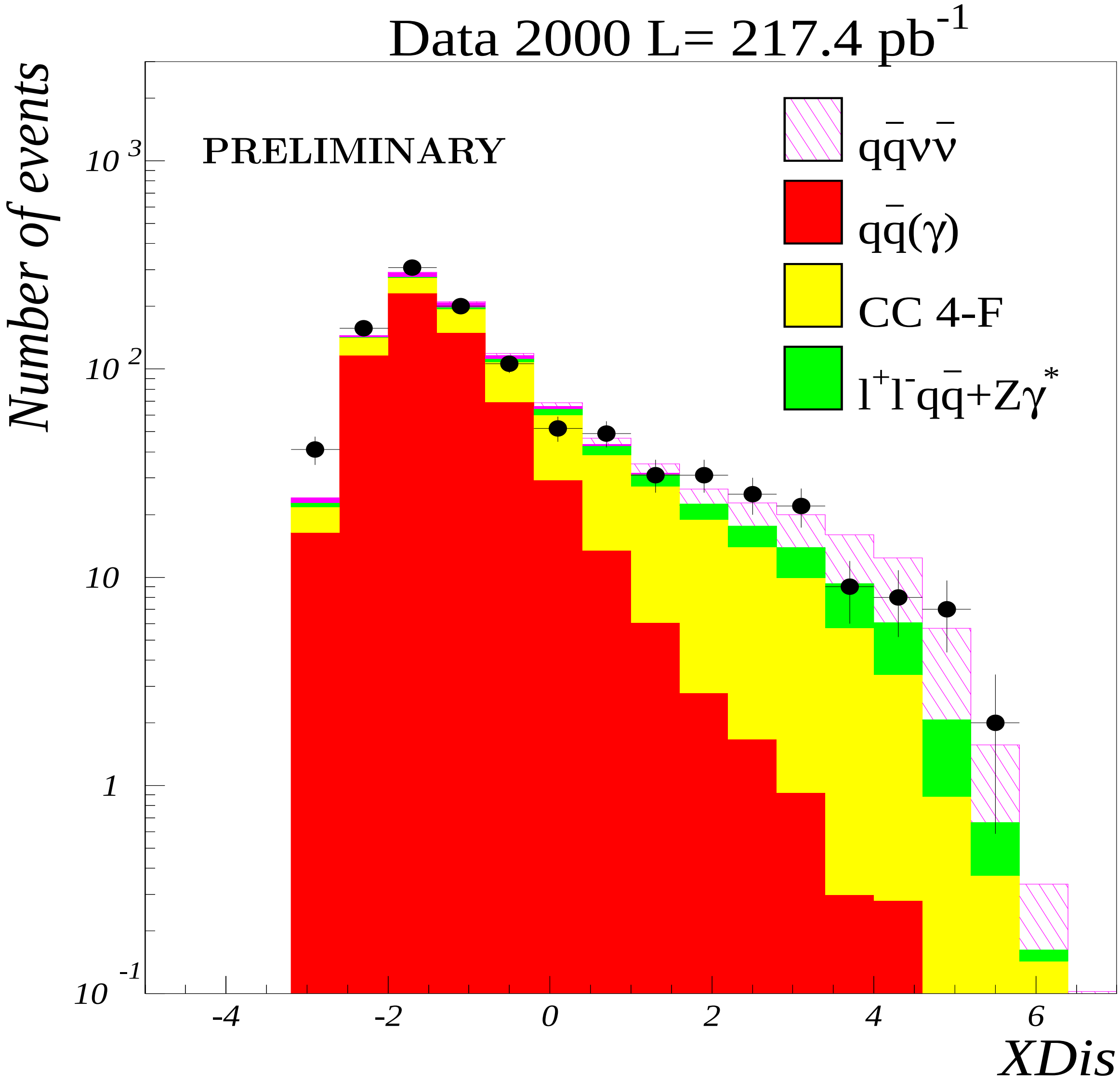

Figure 4: The distribution of the global discriminant variable for the $\nu\bar{\nu}q\bar{q}$ channel (probabilistic method), shown for the full 2000 data sample.

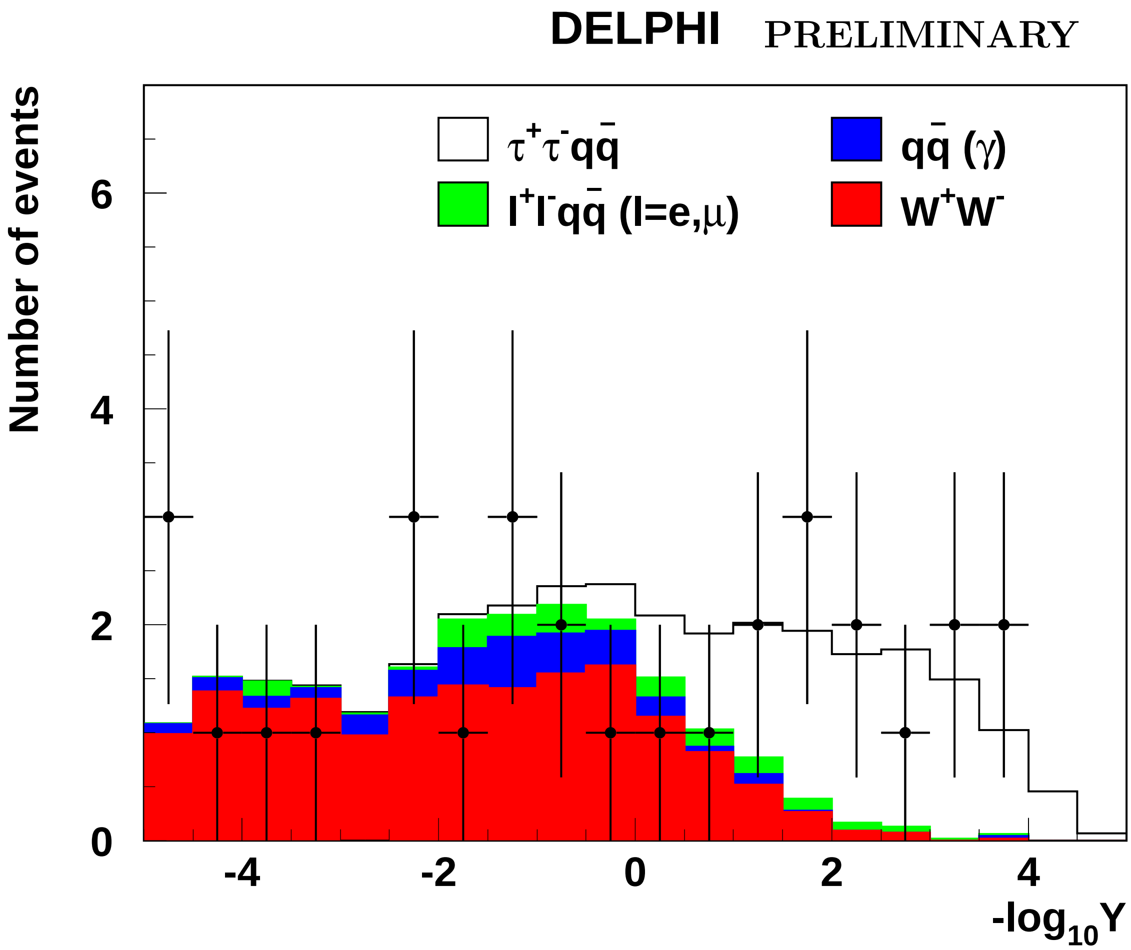

Figure 5: Illustration of the separation power of the combined tagging variable for the $\tau^+\tau^- q\bar{q}$ analysis. The distribution corresponds to the full LEP-2 data sample, and is obtained after enriching with signal events by requiring $M_{\tau^+\tau^-}$ and $M_{q\bar{q}}$ to be compatible with the Z boson mass. Points are the data and histograms the simulation.

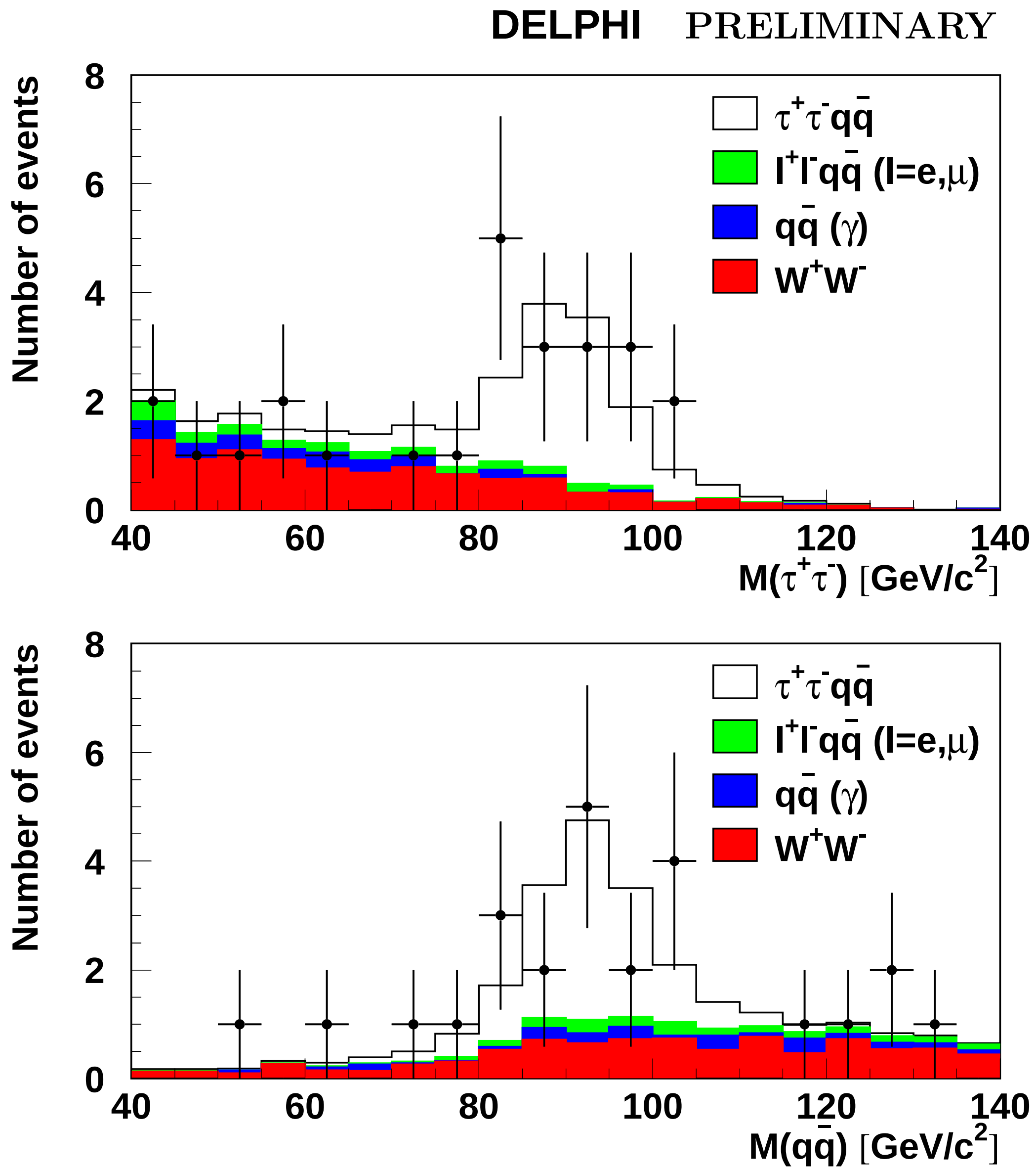

Figure 6: Distribution of $M_{\tau^+\tau^-}$ and $M_{q\bar{q}}$ for the events selected from all LEP-2 data. Points are the data and histograms the simulation.

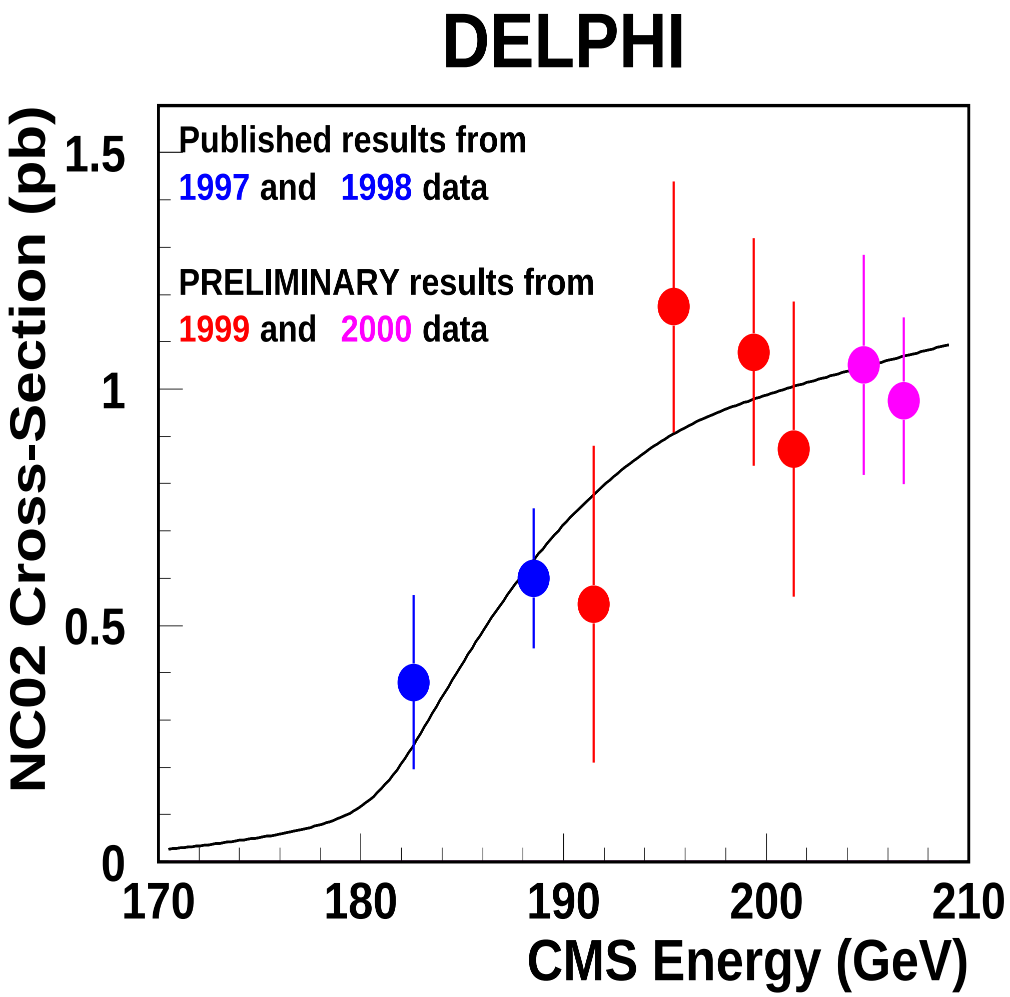

Figure 7: Combined NC02 cross-sections measured from data collected in 1997, 1998, 1999 and 2000. The results obtained with the data collected in 1999 and 2000 are preliminary, and the corresponding errors shown are statistical only. The solid curve is computed using the YFSZZ generator [8]. The corresponding values were checked using the `ZZTO`[9] semianalytical calculation, resulting in values within ± 1 % of those obtained with YFSZZ.