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Report of the LEP Working Group on four-jet production in e^+e^- collisions at centre-of-mass energies of 130 - 172 GeV

The LEP Working Group on Four Jets [1]

Abstract

The four-jet topology is studied, using data collected by ALEPH, DELPHI, L3 and OPAL at centre-of-mass energies of 130-136 GeV in 1995 and of 161 GeV and 172 GeV in 1996. ALEPH has reported an excess in the sum of the dijet masses around 105 GeV/c^2 . No excess is observed by the other three experiments which are consistent with Standard Model expectations. The analyses of the four experiments are compared; all four experiments select and reconstruct four jet events with similar efficiencies and mass resolutions. In the hypothesis of pair-production of a new particle the excess around 105 GeV/c^2 in the ALEPH data would correspond to an average cross section of 2.3 ± 0.6 pb. From the combined mass distribution of DELPHI, L3 and OPAL a 95% C.L. upper limit cross section of 0.6 pb is derived. Probabilities for different hypotheses are estimated. This study is based on preliminary results from the four LEP experiments.

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1 Introduction

In 1995 with data collected at LEP running at centre-of-mass energies around 133 GeV, ALEPH reported [1] an excess with respect to Standard Model predictions in the four-jet final state. The excess events clustered in the sum of dijet masses around 105 GeV/c^2. In this channel, the sum of dijet masses is particularly sensitive to pair production of new particles, since it is measured with very good mass resolution after jet energy rescaling.

The ALEPH analysis was originally designed to search for the process $e^+e^- \rightarrow$ hA; however, the large observed cross-section and the the non-observation of b-flavoured jets disfavour this hypothesis. From the two high energy runs of LEP in 1996 at 161 GeV and 172 GeV, ALEPH reported [2, 3] an additional excess in the same mass window around 105 GeV/c^2.

Similar searches were also performed by DELPHI [4], L3 [5] and OPAL [8, 6] with no significant excess reported. Their results are compatible with Standard Model expectations. In the framework of this working group L3 [7] and OPAL [9] have developed selection procedures which emulate the published ALEPH selection. Again, no excess has been found.

The luminosity collected by each experiment during the three high energy runs are given in Table 1.

$\sqrt{s}$ (GeV)	ALEPH	DELPHI	L3	OPAL
133	5.7	5.9	5.0	5.2
161	11.0	9.9	10.9	10.0
172	10.6	10.0	10.3	10.2

Table 1: Integrated luminosities in pb^{-1}, recorded by ALEPH, DELPHI, L3 and OPAL at the three centre-of-mass energies of LEP II running.

In this report the most recent results of the four experiments are summarized and the different analyses are compared in terms of selection efficiency, mass resolution and other properties. Various checks are presented, in particular a study, using the ALEPH events at 133 GeV as input for simulations with the other detectors. Finally, the results of the different experiments are combined and limits are derived.

2 The four-jet analysis of the LEP experiments.

In the following the selection criteria and the analysis procedures of the four experiments are summarised. In the case of DELPHI, L3 and OPAL the emulations of the ALEPH selection are described.

2.1 ALEPH analysis

The ALEPH selection criteria are explained in detail in Ref. [1] for the data sample at 133 GeV. For the high energy runs in 1996, these cuts remain basically unchanged, except for some cuts which scale with the centre-of-mass energy and for anti-WW cuts [10]. The selection cuts are:

1. Only events compatible with a hadronic final state are selected. It is required that at least eight charged particles be reconstructed within a polar angle of $|\cos\theta| < 0.95$ and the scalar sum of the charged particle momenta be larger than 10% of the centre-of-mass energy.

2. The radiative process $e^+e^- \rightarrow Z\gamma \rightarrow q\bar{q}\gamma$ ("radiative returns to the Z") is largely eliminated by requiring the missing momentum measured along the beam direction to be smaller than $C \times (m_{vis} - 90\ \mathrm{GeV}/c^2)$ (C=0.75 at 133 GeV and 1.5 at 161, 172 GeV), where m_{vis} is the invariant mass of all energy flow particles.

3. Events are clustered into four or more jets using the Durham algorithm with y_{cut} =0.008. For the sake of simplicity the additional selection using the JADE algorithm, as described in Ref. [1], has been abandoned with 10% relative loss in efficiency corresponding to the loss of one event in the peak.

4. After forcing the events into four jets by letting y_{cut} go to larger values, the energies of the jets are rescaled by imposing energy-momentum conservation with the assumption that the jet velocities are perfectly measured. In the ALEPH publication, events with more than four jets were treated differently; the two jets with the smallest mass where combined. The mass distributions happen to be very similar for both methods.

5. The maximum electromagnetic energy fraction of a jet is less than 80% and the minimum number of charged particles in a jet is two.

6. All four-jet masses, assuming charged particles to be pions and neutral particles to be massless, must exceed 1 GeV/c^2.

7. All combinations of dijet masses must exceed $0.192 \times E_{\mathrm{cms}}$ to reduce contributions from $e^+e^- \rightarrow q\bar{q}$.

8. The sum of the masses of the two lightest jets is required to be larger than 10 GeV/c^2 and the sum of their charged particle multiplicity be at least ten. This cut reduces the $e^+e^- \rightarrow Z\gamma^*$ contribution at 133 GeV.

9. At $E_{\mathrm{cms}} \geq 161$ GeV, W^+W^- production is partly rejected by the following cuts. The event is considered to be a WW candidate (and rejected) if the sum of dijet masses is close to twice the W mass and the mass difference is small enough. If the three possible dijet pairings are ordered according to their masses difference ($\Delta m_1 < \Delta m_2 < \Delta m_3$),

   $\Delta m_1 < 15\ \mathrm{GeV}/c^2$ and $|\Sigma m_1 - 160| < 10\ \mathrm{GeV}/c^2$, or

   $\Delta m_2 < 30\ \mathrm{GeV}/c^2$ and $|\Sigma m_2 - 160| < 10\ \mathrm{GeV}/c^2$, or

   $\Delta m_3 < 60\ \mathrm{GeV}/c^2$ and $|\Sigma m_3 - 160| < 5\ \mathrm{GeV}/c^2$ (at $\sqrt{s}$ =161 GeV only).

2.2 DELPHI analysis

Following the ALEPH analysis similar selection cuts are applied. The values of cuts 7 and 8 are relaxed by 10% to maintain the same overall efficiency for hA-like events:

1. Hadronic events are selected requiring at least 12 charged particles with $p > 100\ \mathrm{MeV}/c$ and a total energy exceeding $0.12 \times E_{\mathrm{cms}}$. A cut on the total electromagnetic energy of the event ($E_{\mathrm{em}} < 0.7 \times E_{\mathrm{cms}}$) and a cut on the total charged particle energy (above $0.3 \times E_{\mathrm{cms}}$) is imposed.

2. Radiative $q\bar{q}\gamma$ events with a visible photon seen in the STIC or in the EMF or an undetected photon aligned along the beam are rejected. In the latter, the missing photon energy was computed from energy and momentum conservation, after clustering the event into two jets and assuming a photon collinear to the beam axis. Events with a visible or reconstructed photon of more than 20 GeV at E_{cms} =133 GeV or 35 GeV at E_{cms} =161 GeV and 172 GeV, with an isolation angle of at least 15° are rejected.

3. Events are required to have at least four jets applying the Durham algorithm with $\mathrm{y_{cut}}$ =0.008 or with the JADE clustering using $\mathrm{y_{cut}}$ =0.022. Events with more than four jets are forced to a four-jet configuration by letting $\mathrm{y_{cut}}$ go to higher values.

4. Jet energies are rescaled, based on total energy and momentum conservation and fixed jet velocities.

5. Jets are required to be hadronic-like by demanding at least two charged particles per jet and that at most 80% of their energy is electromagnetic (i.e. measured in the HPC, EMF or STIC).

6. The minimum dijet mass: $\min(m_{ij}^{\mathrm{rec}}) > 0.17 \times E_{\mathrm{cms}}$.

7. The minimum of the sum of to jet masses: $\min(m_i^{\mathrm{rec}} + m_j^{\mathrm{rec}}) > 9 \ \mathrm{GeV}/c^2$.
   The minimum charged multiplicity of two jets: $\min(n_{\mathrm{CH}i} + n_{\mathrm{CH}j}) \geq 9$.

8. Finally, for $E_{\mathrm{cms}} = 161$ and $172\,\mathrm{GeV}$, the same anti-WW cut used in the ALEPH analysis is applied.

2.3 L3 analysis

One selection of L3 follows closely the published ALEPH analysis, which is described in detail in [7],[5] and is summarized in the following:

1. Hadronic events are preselected requiring at least 10 charged particles, at least 30 calorimetric deposits and a total energy deposition greater than 70% $\times\sqrt{s}$. The effective centre-of-mass energy is required to be larger than 80% $\times$ $\sqrt{s}$.

2. Events surviving the high multiplicity selection are reconstructed both with the Durham algorithm ($\mathrm{y_{cut}}$ =0.008) and with the JADE algorithm ($\mathrm{y_{cut}}$ =0.02). They are accepted if any of the two jet reconstructions gives at least four jets with electromagnetic energy less than 85% of the total jet energy.

3. After forcing the events into four jets, energies are rescaled in order to conserve the four momentum and with jets directions and velocities kept unchanged. The rescaled energies are required to be positive and the invariant masses of the single jets larger than 1 GeV/c^2 .

4. All the pairs of jets in the event are then required to have an invariant mass greater than $0.17 \times\sqrt{s}$, the sum of the jet masses greater than $0.07\sqrt{\mathrm{s}}$ and at least 9 tracks.

5. To reduce WW background at $\sqrt{\mathrm{s}} = 161$ GeV the events are rejected if the combination with the smallest dijet mass difference is greater than 150 GeV/c^2 , if the one with the second difference is greater than 152 GeV/c^2 or if the last is greater than 156 GeV/c^2 . At $\sqrt{\mathrm{s}} = 170 - 172$ GeV the WW rejection is looser: the event is rejected if the first combination is within 7 GeV/c^2 of the W mass or if the second combination has $\Delta m <$ 35 GeV and the sum of the masses is within 4 GeV/c^2 of $M_{\mathrm{W}^\pm}$.

2.4 OPAL analysis

The procedure for selection and reconstruction of four-jet hadronic events, following the ALEPH analysis, is described in detail in Ref.[9] and summarized in the following. For convenience, the item numbers correspond to the ones used in the description of the ALEPH selection.

1. Events are required to have at least five charged tracks and seven electromagnetic calorimeter clusters. The sum of the ECAL cluster energies should be at least 10% of the centre-of-mass energy, and the ECAL energy is required to be roughly balanced along the beam direction: $\sum E_i \cos\theta_i \leq 0.65 \sum E_i$, where the sums run over measured ECAL clusters.

2. The selection is identical to that used by ALEPH for the 133 and 161 GeV data. For the 172 GeV data, OPAL uses a coefficient C of 1.65, as originally proposed [3], rather than the value 1.5 now used by ALEPH.

3. Jets are formed with the Durham jet-finder via the same procedure as ALEPH.

4. Jets are combined in events which have more than 4 jets, following the procedure originally used by ALEPH [1]. The jet pair having the smallest invariant di-jet mass is combined into a single jet. No event was found to contain six jets, consistent with the expectation from simulation. After forcing the event into four jets, jet energy rescaling using energy-momentum conservation is performed by the same technique as employed in ALEPH.

5. The maximum electromagnetic energy fraction of a jet is less than 80%, as applied by ALEPH. No requirement that jets contain charged particle tracks is applied.

6. An identical selection is applied on individual jet masses as in ALEPH.

7. An identical selection is applied on dijet masses as in ALEPH.

8. All combinations of jet pairs must have a sum of the individual jet masses $m_i + m_j > 10$ GeV, which is the same requirement as ALEPH. For the charged track multiplicity, the OPAL analysis requires the minimum charged multiplicity of 10 for all combinations of two jets.

9. W-pair veto: A W-pair veto is applied to the 161 and 172 GeV data. For the 161 GeV data sample, a W-pair veto is applied following the original ALEPH prescription [2]. A requirement is placed on the dijet mass sum for each of the three possible pairings of jets: $m \leq 150$ GeV for the pairing with the smallest Δm, $m \leq 152$ GeV for the pairing with intermediate Δm, and $m \leq 156$ GeV for the pairing with the largest Δm. For the 172 GeV data, the same W-pair veto is applied as described for ALEPH in this note.

2.5 Results

The resulting distributions of the dijet mass sums from the selections as described above are shown in Figs. 1 - 6 for the four experiments at the three centre-of-mass energies. Distributions with looser selection cuts are shown for the L3 (Fig. 4) and OPAL (Fig. 6) data samples. The corresponding number of events observed in data together with the expectations from Standard Model processes ($Z/\gamma^* \to q\bar{q}$ and four-fermion final states), are given in Table 2. Event counts in mass windows around 105 GeV/c^2 of $\pm 4.0, \pm 5.6$ and $\pm$ 6.0 GeV/c^2 at the three centre-of-mass energies are shown as well. These mass windows were chosen to contain on average $\approx$ 60% of the signal.

Simulated events of the process $e^+e^- \to$ hA, with $m_{\mathrm{h}} = m_{\mathrm{A}} = 55$ GeV/c^2 have been used to estimate the selection efficiency and the mass resolution. The determination of the mass resolution by fitting a Gaussian is not possible unambiguously, since there are considerable non-Gaussian components (see Fig. 8). Instead of the width of a Gaussian, the mass interval which contains 50% of the hA signal, after cuts, is determined for a comparison of the resolution. These values are summarized in Table 3. The cross sections for the selected events from Standard Model processes are also given. All four experiments have very similar efficiencies and mass resolutions.

The distribution of the smallest dijet mass difference is shown in Fig. 7 for the four experiments, in good agreement with each other. The resolution in the mass difference is worse than the one in the dijet mass sum, about 6 GeV/c^2 at $\sqrt{s}$ =133 GeV and about 4 GeV/c^2 at $\sqrt{s}$ =172 GeV. This is a purely kinematical effect induced by the energy conservation constraint.

		ALEPH		DELPHI		L3		OPAL	
	$\sqrt{s}$ (GeV)	data	MC	data	MC	data	MC	data	MC
all $\sum m$	133	16	8.3	13	9.3	12	8.1	8	7.1
$105 \pm 4\,\mathrm{GeV}/c^2$	133	9	1.0	4	1.0	2	1.1	1	0.8
all $\sum m$	161	8	8.2	12	10.8	7	8.0	7	6.2
$105 \pm 5.6\,\mathrm{GeV}/c^2$	161	5	1.2	2	1.8	1	1.2	0	1.0
all $\sum m$	172	13	13.8	15	14.3	14	13.5	5	12.7
$105 \pm 6\,\mathrm{GeV}/c^2$	172	3	1.8	1	2.4	2	1.8	0	1.8

Table 2: Numbers of events for "ALEPH like" selection (all cuts) for data and Standard Model expectations in the full $\sum m$ spectrum and within a mass window around $105\,\mathrm{GeV}/c^2$ (These mass intervals are slightly larger than the ones originally chosen by ALEPH [1]).

	$\sqrt{s}$ (GeV)	ALEPH	DELPHI	L3	OPAL
efficiency / σ_{SM}	133	41% / 1.5pb	44% / 1.6pb	45% / 1.6pb	45% / 1.4pb
	161	30% / 0.7pb	31% / 1.1pb	32% / 0.7pb	28% / 0.6pb
	172	30% / 1.3pb	26% / 1.4pb	26% / 1.3pb	30% / 1.3pb
error on efficiency		±0.6%	±2.1%	±1.5%	±1.0%
width of mass interval in GeV/c^2 for 50% of signal	133	±3.6	± 2.5	±3.6	±3.1
	161	±2.9	± 3.3	±3.5	±2.9
	172	±3.0	± 3.4	±3.6	±2.9
error (GeV/c^2)		±0.2	±0.4	±0.3	±0.4
Mass shift(GeV/c^2)		-0.7	-0.4	-0.6	-0.3

Table 3: Overall four-jet selection efficiency and dijet mass resolution for all dijet masses for a hA signal with m_{h}=m_{A}=55 GeV/c^2 for the four LEP experiments. Together with the efficiencies the overall cross section of Standard Model processes for events passing the selection is given. In the lower half of the Table the resolution is estimated by the $\sum m$ mass window, containing 50% of the signal after cuts.

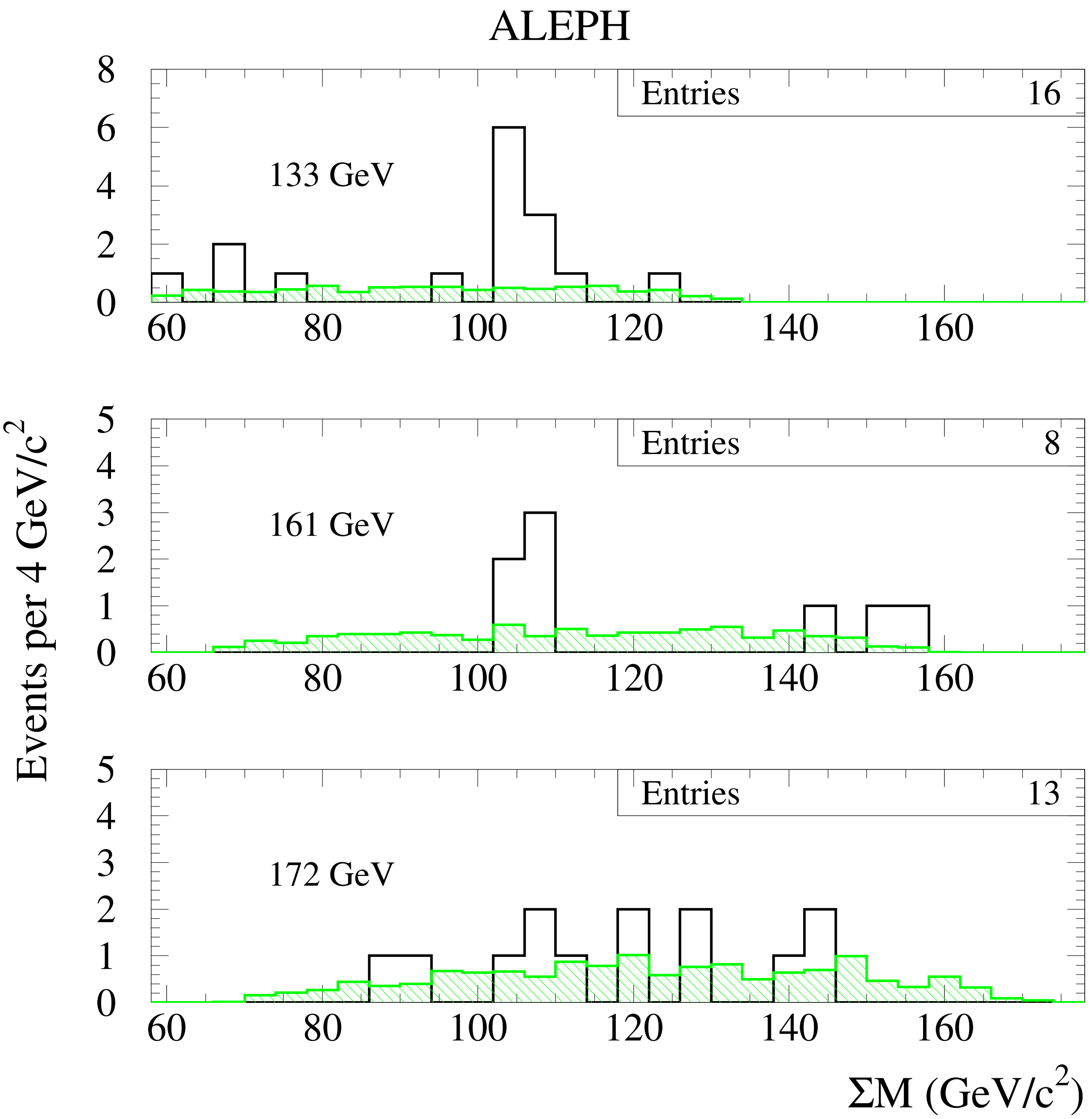

Figure 1: ALEPH 133/161/172 GeV: Distributions of the sum of the dijet masses for the pairing with the smallest mass difference after all selection cuts. a) $\sqrt{s}$ =133 GeV, b) $\sqrt{s}$ =161 GeV, c) $\sqrt{s}$ =172 GeV. The open histograms show data, the hatched ones show the expectation from Standard Model processes.

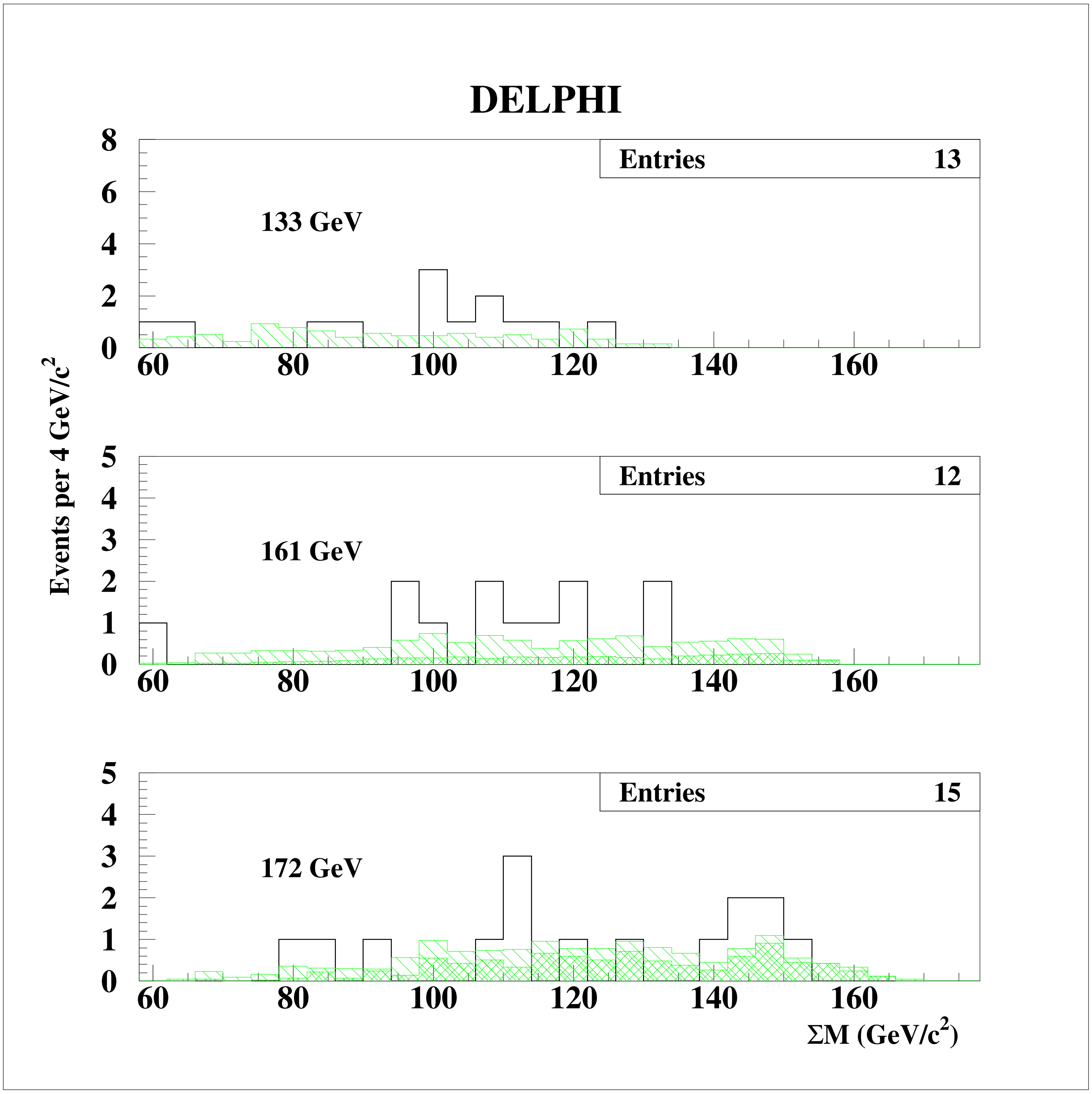

Figure 2: DELPHI 133/161/172 GeV: Distributions of the sum of the dijet masses for the pairing with the smallest mass difference after all selection cuts. a) $\sqrt{s}$ =133 GeV, b) $\sqrt{s}$ =161 GeV, c) $\sqrt{s}$ =172 GeV. The dark hatched histograms show the expectation from WW production, the light hatched histograms show the total expectation from Standard Model processes.

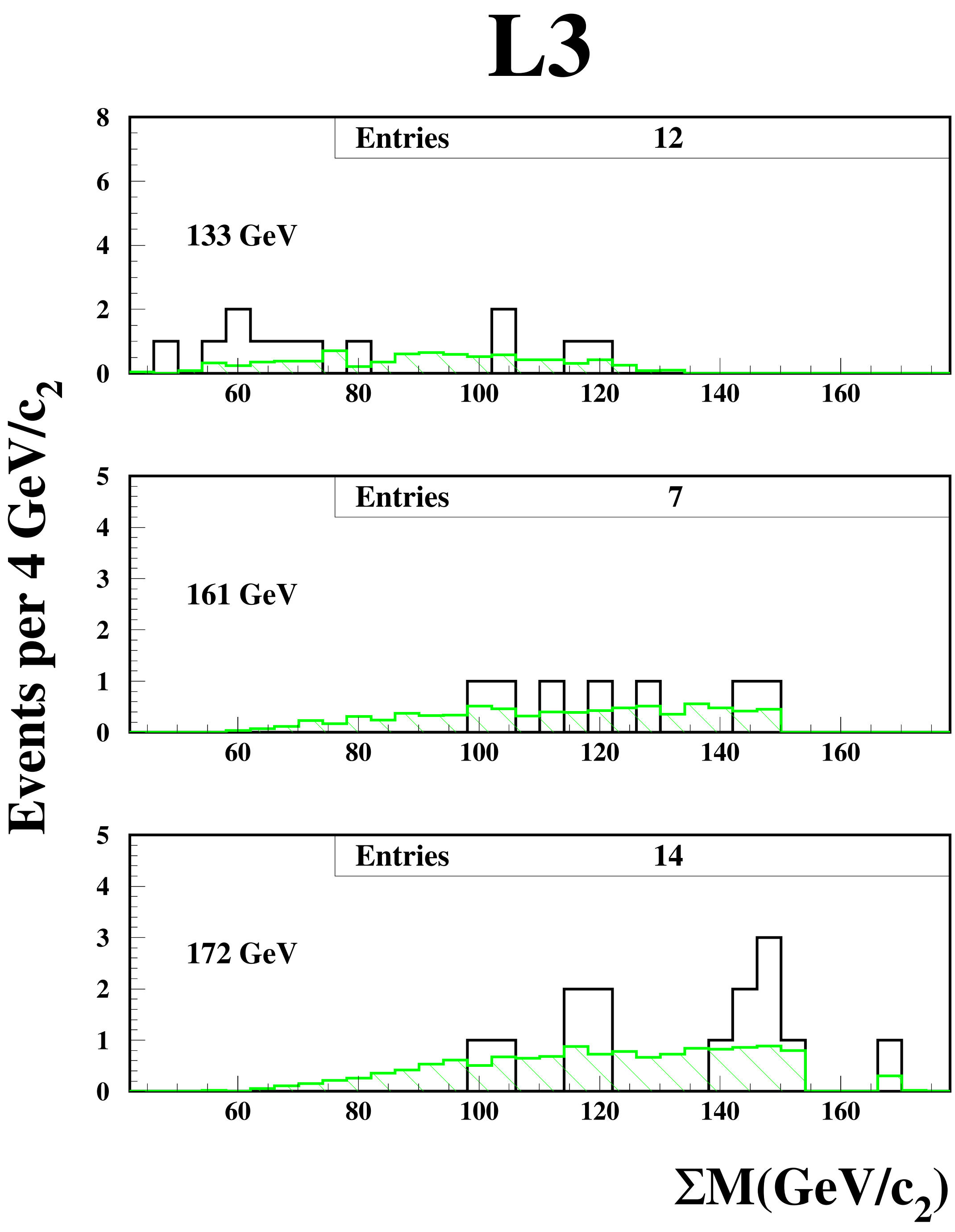

Figure 3: L3 133/161/172 GeV: Distributions of the sum of the masses for the smallest difference after all selection cuts. a) $\sqrt{s}$ =130 GeV, b) $\sqrt{s}$ =161 GeV, $\sqrt{s}$ =172 GeV. Histograms are the Standard Model expectations.

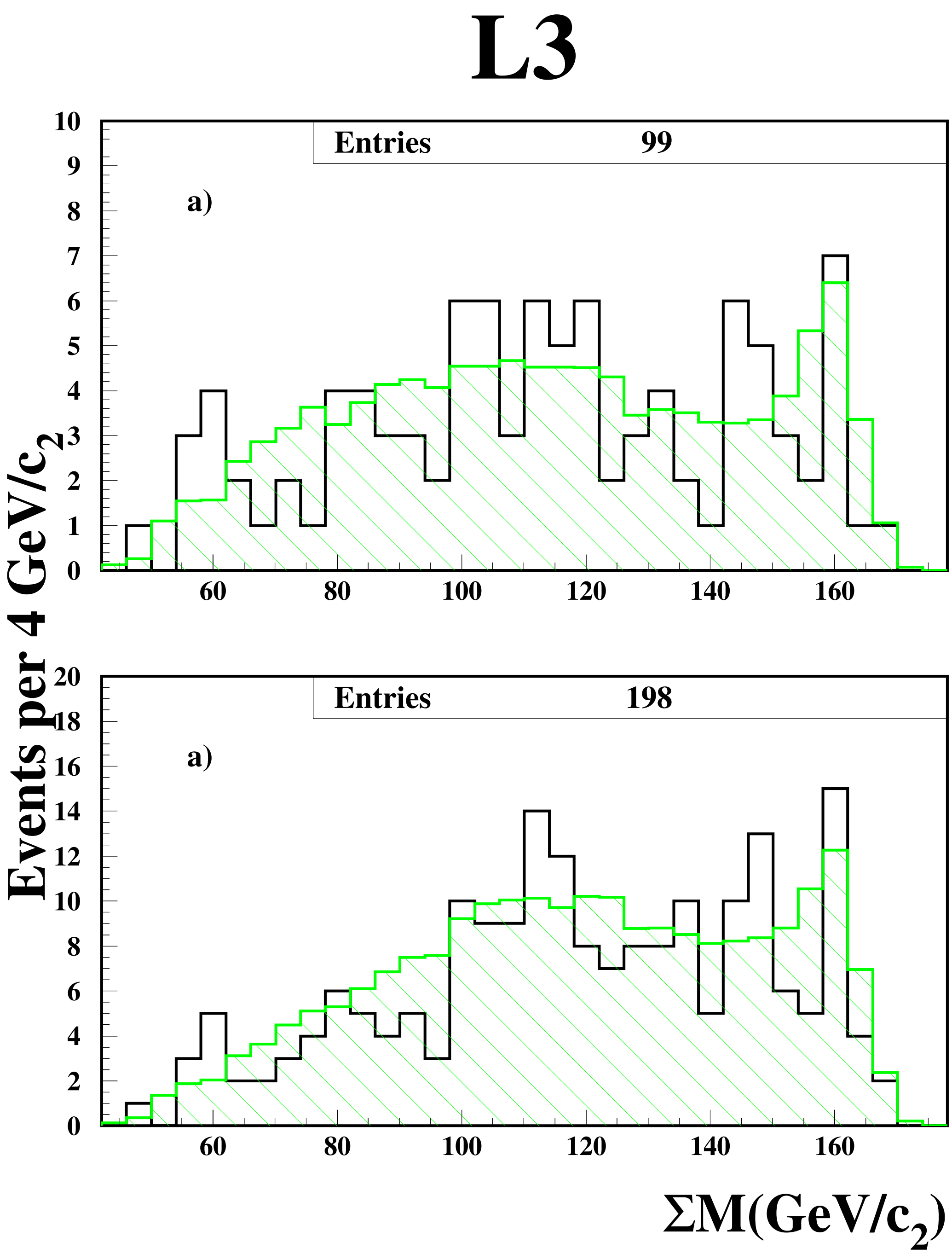

Figure 4: L3: Distributions of the sum of the masses at all three centre-of-mass energies before the cut on the sum of the jet masses, the cut on the sum of the tracks in the di-jet and the WW rejection. a) for the smallest mass difference. b) for the two smallest mass differences. Histograms are the Standard Model expectations.

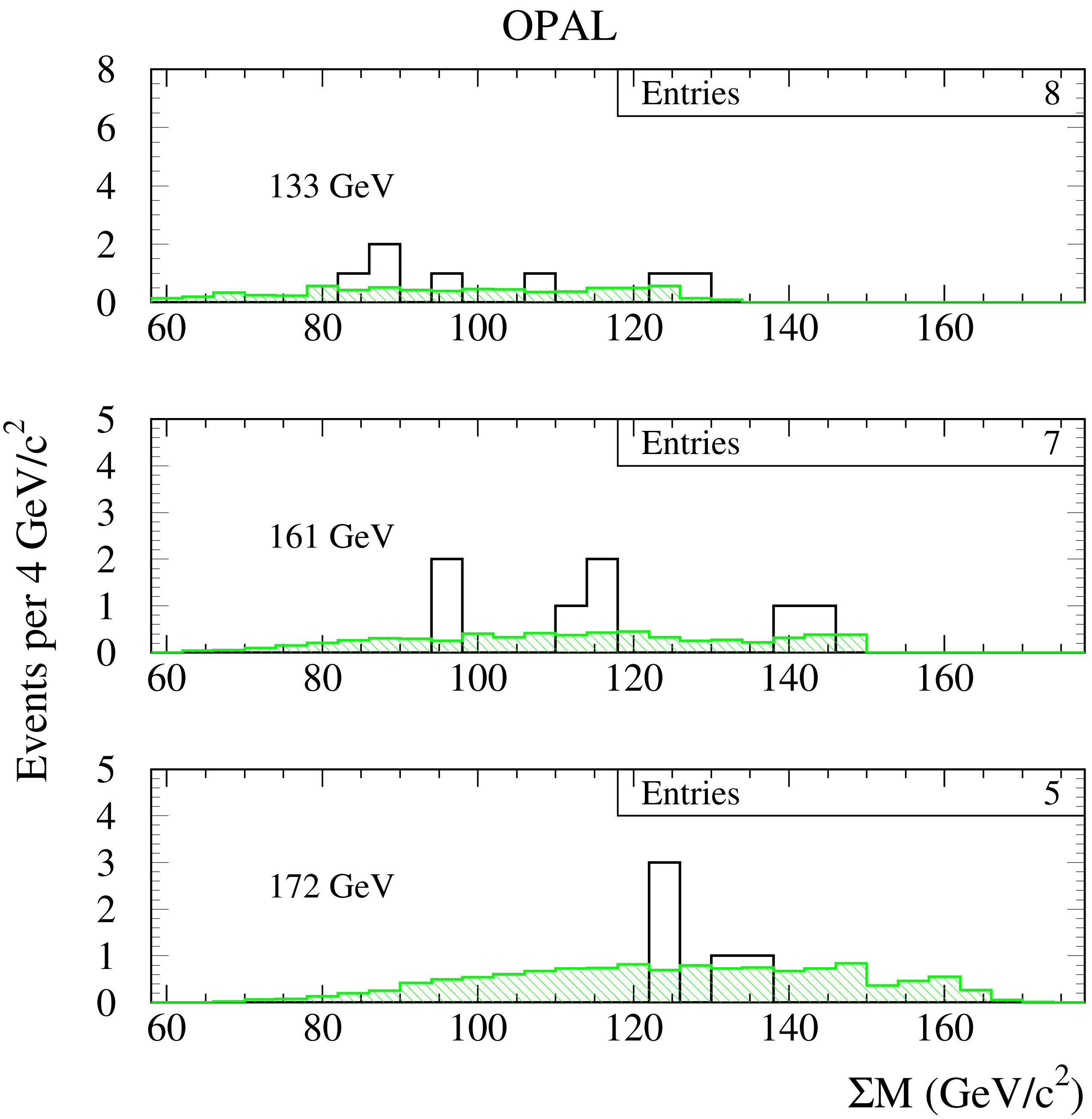

Figure 5: OPAL 133/161/172 GeV: Distributions of the sum of the dijet masses for the pairing with the smallest mass difference after all selection cuts. a) $\sqrt{s}$ =133 GeV, b) $\sqrt{s}$ =161 GeV, c) $\sqrt{s}$ =172 GeV. The open histograms show data, the hatched ones show the expectation from Standard Model processes.

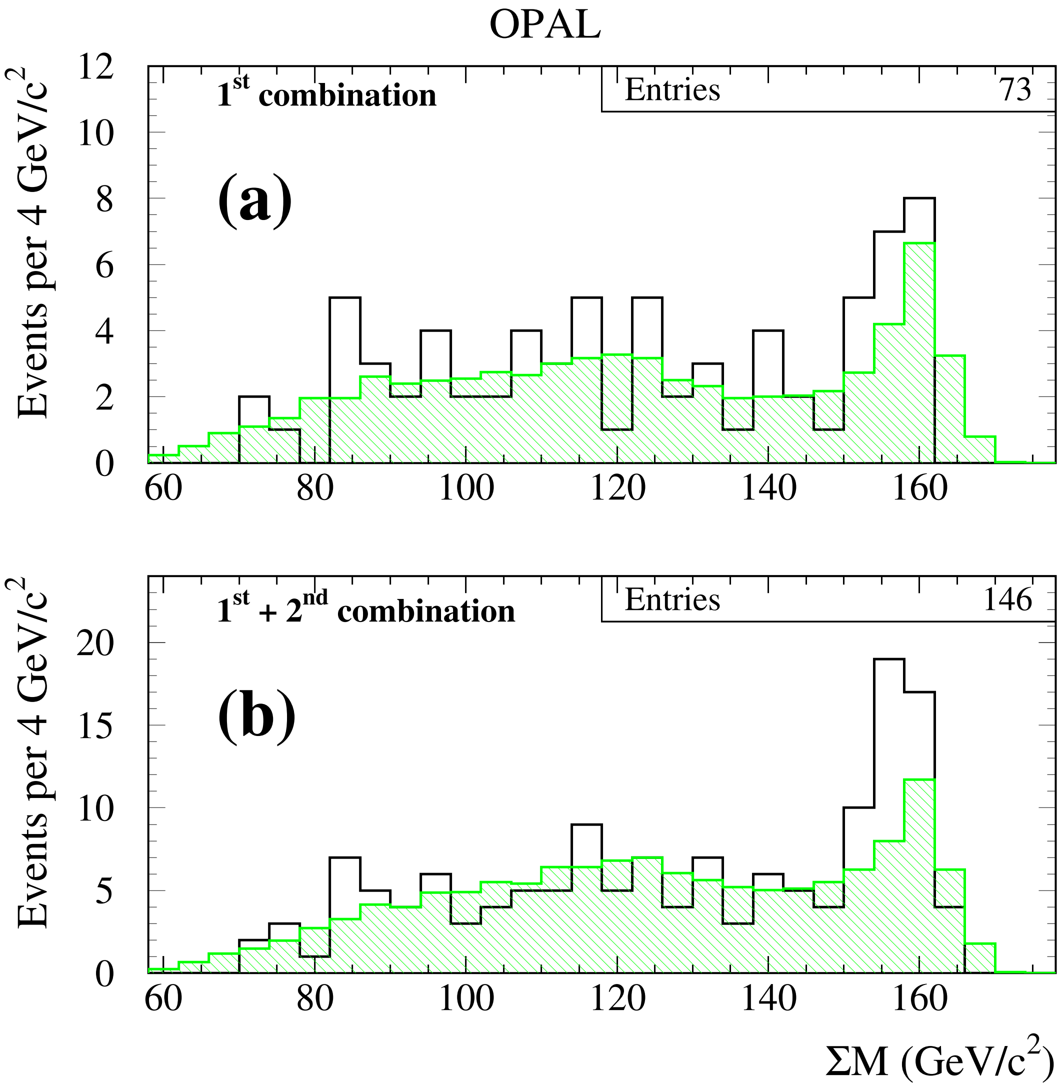

Figure 6: OPAL: Distributions of the sum of the masses at all three centre-of-mass energies before the cut on the sum of the jet masses, the cut on the sum of the tracks in the di-jet (cut 8) and the WW rejection (cut 9). a) for the smallest mass difference. b) for the two smallest mass differences. Histograms are the Standard Model expectations.

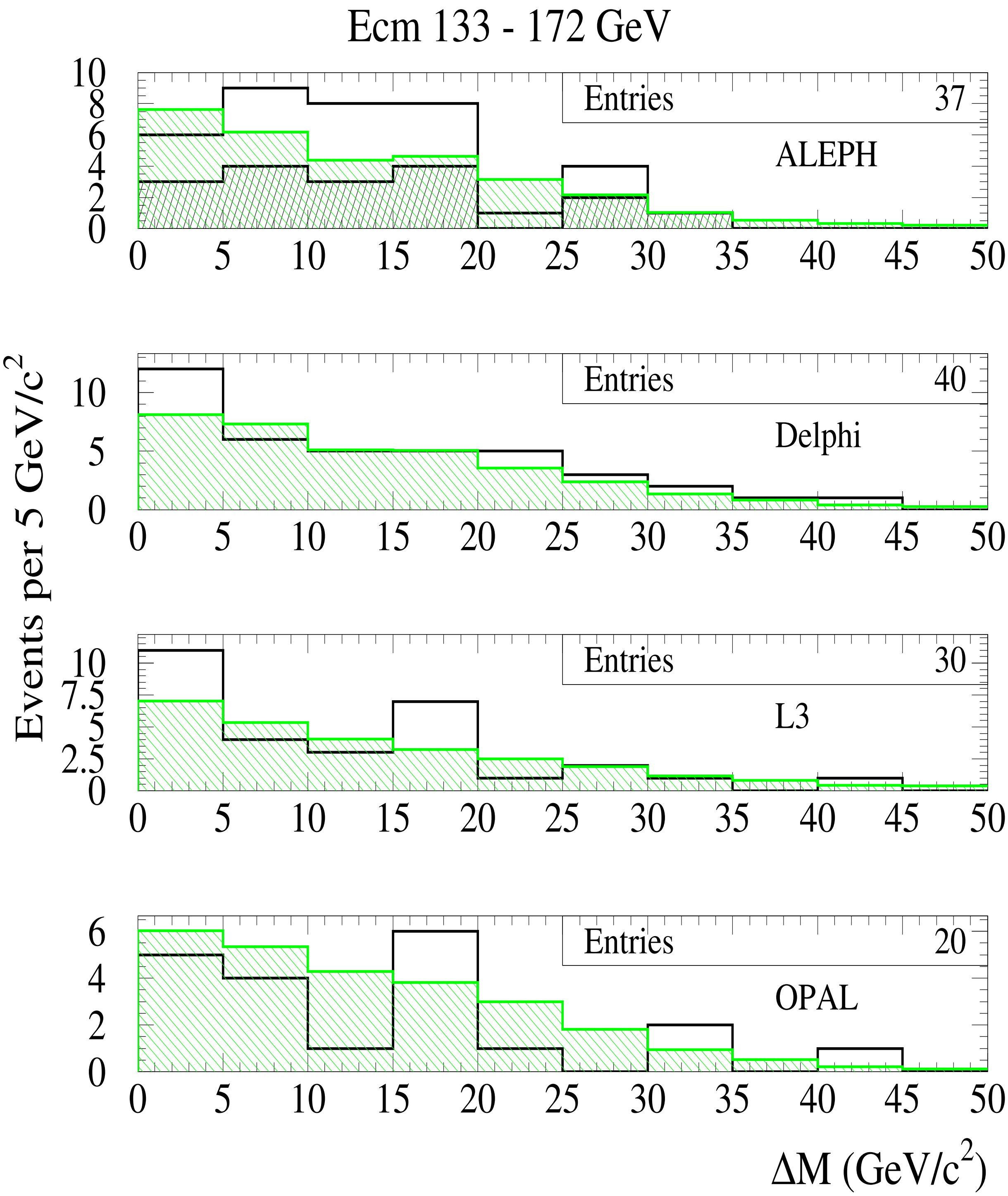

Figure 7: Distributions of the smallest mass difference for $\sqrt{s}$ =133 GeV - 172 GeV. The open histogram is for data, the hatched one for Monte Carlo. The doubly hatched histogram in the ALEPH distribution is for the peak events in the data.

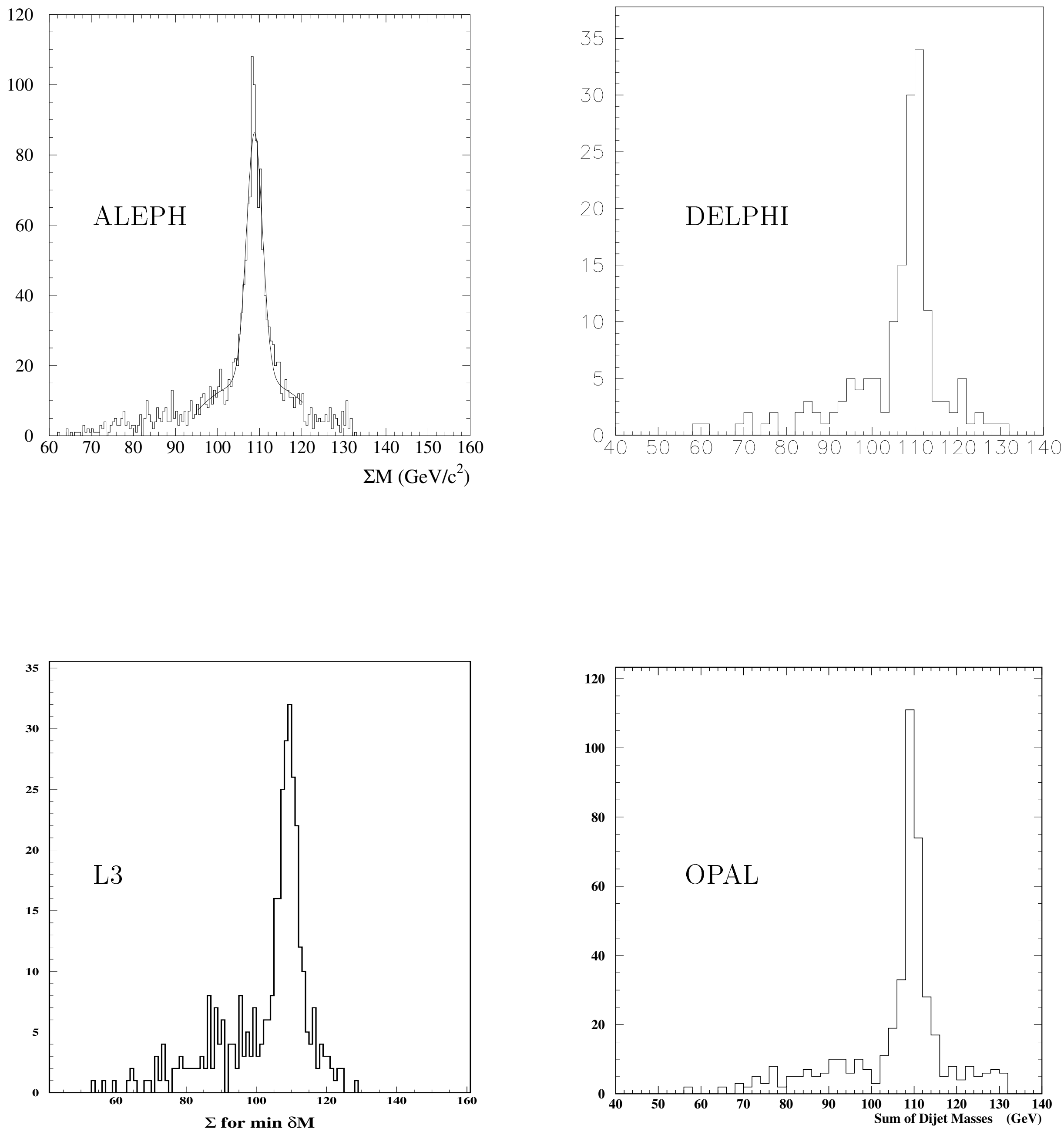

Figure 8: Dijet mass sum distributions for hA Monte Carlo events (m=55 GeV/c^2) at $\sqrt{s}$ =133 GeV for the four experiments.

3 Comparison of jet algorithms with ALEPH data

The standard ALEPH four-jets analysis has been repeated with the JADE jet algorithm (y_{cut} =0.02) using the same selection cuts with data at 130 GeV.

The two jet algorithms have a similar dijet mass sum resolution as determined with hA Monte Carlo events. A 4.5% increase in efficiency is observed on hA Monte Carlo when the JADE algorithm is used with this y_{cut} (see Table 4). However, the number of events expected from standard processes ($q\overline{q}$ events only) also increased from 8.3 to 9.6. In the data sample collected at $\sqrt{s}$ = 133 GeV, 16 events are selected with the Durham jet algorithm while 18 are selected with the JADE algorithm.

	Efficiency	Data	S.M. pred.	Data (peak)	S.M. (peak)
Durham, E scheme	41%	16	8.3	9	1.0
JADE, E scheme	45%	18	9.6	8	1.1

Table 4: Selection efficiency as measured with hA Monte Carlo events, number of selected events in data and number of expected events (from $q\overline{q}$ process) for the two jet algorithms. The "peak" interval is defined as 105 ± 4 GeV/c^2 .

In Fig. 9 the dijet mass sum distributions are shown for events selected with the two algorithms. Eleven events are common to the two selections. In the dijet mass sum interval 105 ± 4 GeV/c^2 , nine events are found with the Durham jet algorithm for 1.0 expected, and eight events are reconstructed with the JADE algorithm for 1.1 expected. In this interval, 6 events are in common for both selections.

Within statistics both jet finding algorithms give the same mass distribution with similar efficiency and resolution. Further studies on other jet finding algorithms are discussed in the appendix.

4 Checks using $Z\gamma$ events

The events from radiative returns to the Z, $q\bar{q}\gamma$, have been used to verify the Monte Carlo simulation of jet reconstruction. Events have been selected requiring an isolated photon or one jet with more than 80% of electromagnetic energy. The DELPHI selection requires in addition a photon energy above 15 GeV (resp. 25 GeV) at $\sqrt{s}$ =133 GeV (resp 161/172 GeV). In the L3 analysis a cut on the photon energy of ± 5 GeV around the one expected in radiative returns to the Z is applied.

Reconstruction of four jets is then enforced, using the Durham algorithm. Jets containing a single photon are accepted. The jet energies are rescaled by imposing energy-momentum conservation with the assumption that the jet velocities are perfectly measured. The distributions of hadronic mass calculated using rescaled jet energies and momenta are shown in Fig. 10 for the four experiments and compared to Monte Carlo simulations. The Z peak is fitted with a Gaussian and a background polynomial. Mean values and width are summarized in Table 5. The mass peak is reasonably well simulated in position and shape by all four experiments.

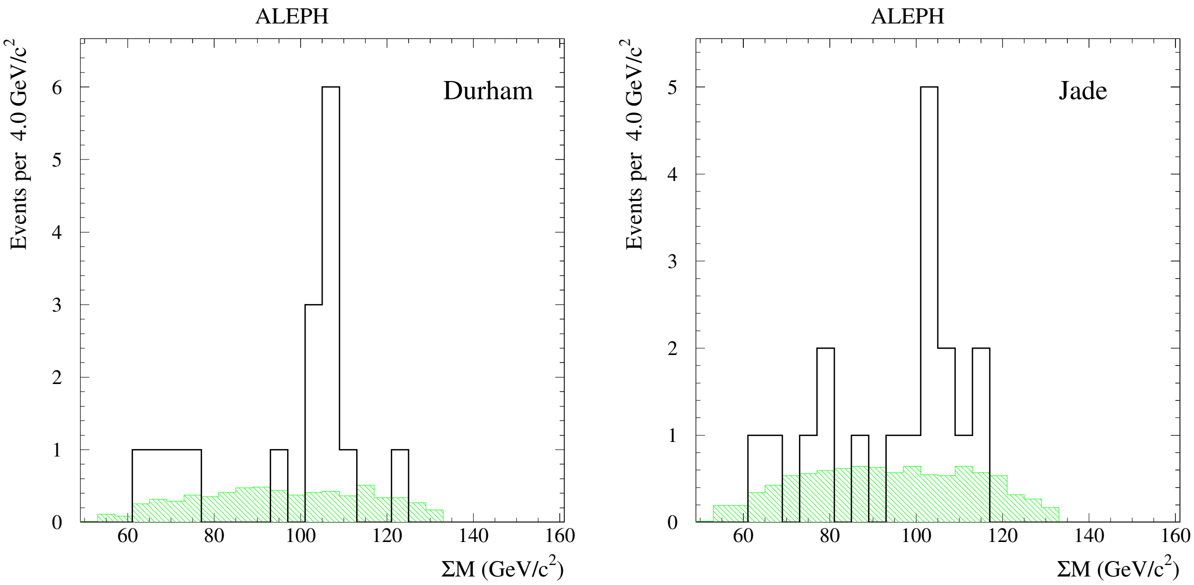

Figure 9: Distribution of the dijet mass sum after selection cuts for events reconstructed with the Durham (left) and JADE (right) jet algorithms at $\sqrt{s}$ =133 GeV. The open histogram shows data, the hatched one Monte Carlo.

	ALEPH	DELPHI	L3	OPAL
σ_m Data (GeV/c^2)	2.5 ± 0.2	2.8 ± 0.8	3.0 ± 0.2	2.1 ± 0.3
σ_m MC (GeV/c^2)	2.7 ± 0.02	3.6 ± 0.2	3.2 ± 0.06	2.6 ± 0.4
mass shift: data-MC (GeV/c^2)	-0.04 ± 0.16	0.3 ± 0.5	0.4 ± 0.5	-0.4 ± 0.5

Table 5: Comparison of mass resolutions for $q\bar{q}\gamma$ events (radiative returns to the Z) for data and Monte Carlo at 133-172 GeV for ALEPH, L3 and OPAL and at 133 GeV for DELPHI.

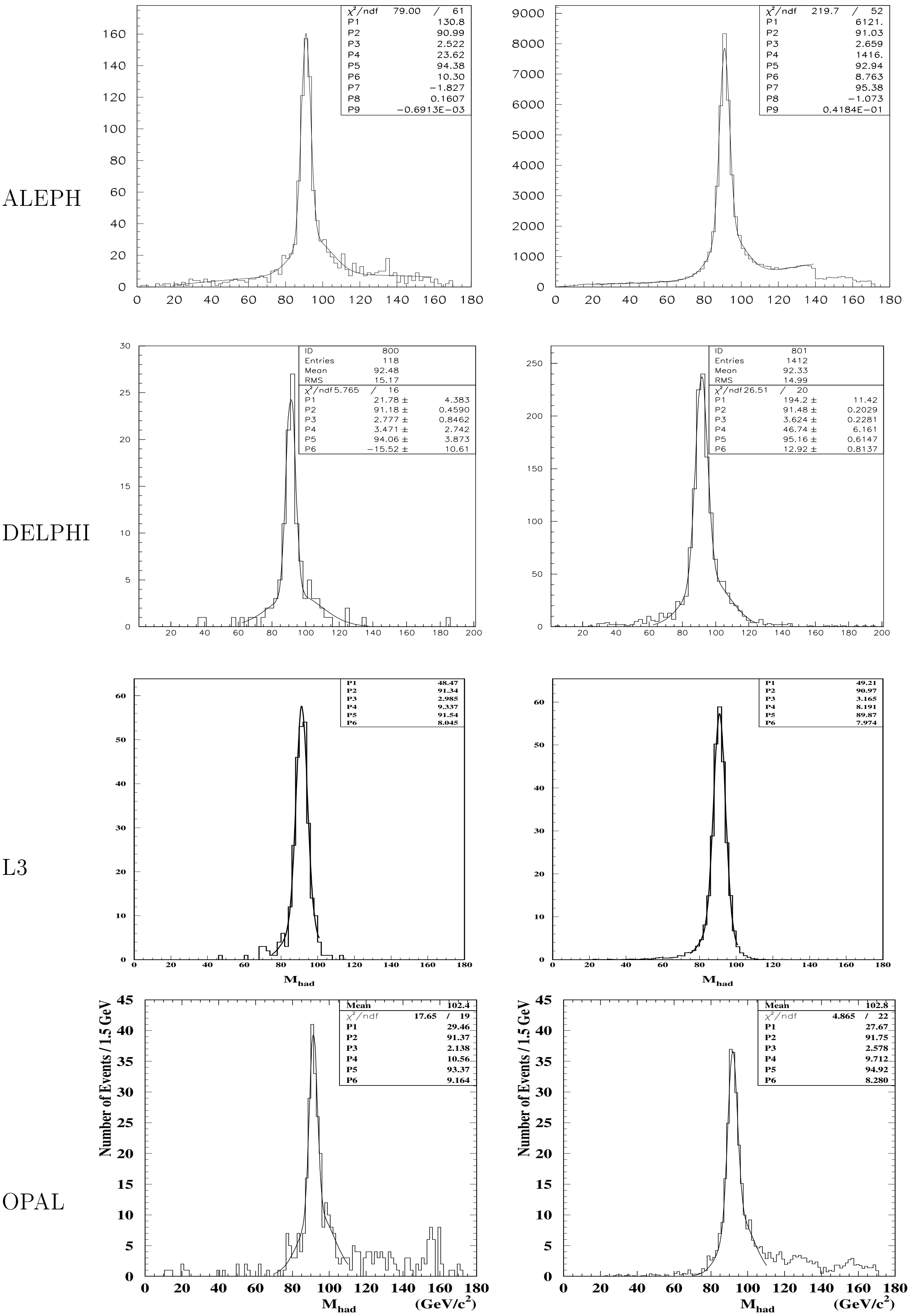

Figure 10: Calculated hadronic mass in $q\bar{q}\gamma$ events (left: data, right: Monte Carlo) from radiative returns to the Z.

5 Studies with ALEPH events at E_{cms} =133 GeV

The ALEPH collaboration has provided to the other collaborations four-vectors of 24 events at $\sqrt{s}$ =133 GeV, selected without applying the cut on the minimum sum of two jet masses and multiplicities (cut 8). The purpose was to study if these events would have been found with the other detectors and selections. These events were used as input to the detector simulation programs. The simulations have been repeated many times (10 to 100) and the selection procedure has been applied again.

As a result of this study, all four experiments find an excess of events around 105 GeV/c^2 as observed in the input data. However, since detector resolution effects are accounted twice, typically 30% to 40% of the events are lost in the selection. In many events the combinations with the smallest and second smallest dijet mass difference interchange. Therefore, in Fig. 11, the mass sums for the two smallest combinations are shown. In order to compare the mass resolutions of the experiments events are passed through the simulation and selection programs and the reconstructed jets are matched to the original jets found by ALEPH. This matching is done on the basis of the three-momentum difference between the reconstructed and original jets. In each event, the combination which had the smallest mass difference in the ALEPH analysis is then selected and the reconstructed dijet mass sum and difference of that combination, relative to that originally measured by ALEPH, are plotted. These distributions for the 12 ALEPH events in the peak are shown in Figs. 12 and 13 for the dijet mass sum and difference. To gain statistics the 9 events with the smallest Δm and 3 with the second smallest $\Delta m$are used.

All four experiments have similar resolutions of $\approx 2\,\mathrm{GeV}/c^2$ for the dijet mass sum. The observed resolution function for the mass difference is not always Gaussian, therefore the rms value (ignoring 5% of events in the tails) is more appropriate for a comparison. These results, summarized in Table 6, show similar sensitivity of the four experiments to the detection of such events. The resolution in the measurement of the mass difference (last line in Table 6 and Fig. 13) is slightly different. Therefore, it is important to check the dijet mass distributions not only for the combination with the smallest mass difference but also for the one with the second-smallest mass difference.

	ALEPH	DELPHI	L3	OPAL
<selected/all>	68%	65%	61%	68%
mass shift (GeV/c^2)	0.1	-0.9	0.6	-0.2
$< \sigma(\sum m) >$ (GeV/c^2)	2.2	2.5	2.2	2.0
<rms(Δm)> (GeV/c^2)	5.4	8.2	7.1	8.6

Table 6: Average fraction of events surviving the cuts described in Section 2, mass shift and resolutions for the simulated " experiments" using the 12 ALEPH peak events at 133 GeV. For the Δm, the truncated rms values (cutting 5% of the events in the tails) are given. The original ALEPH mass combination has been used as reference.

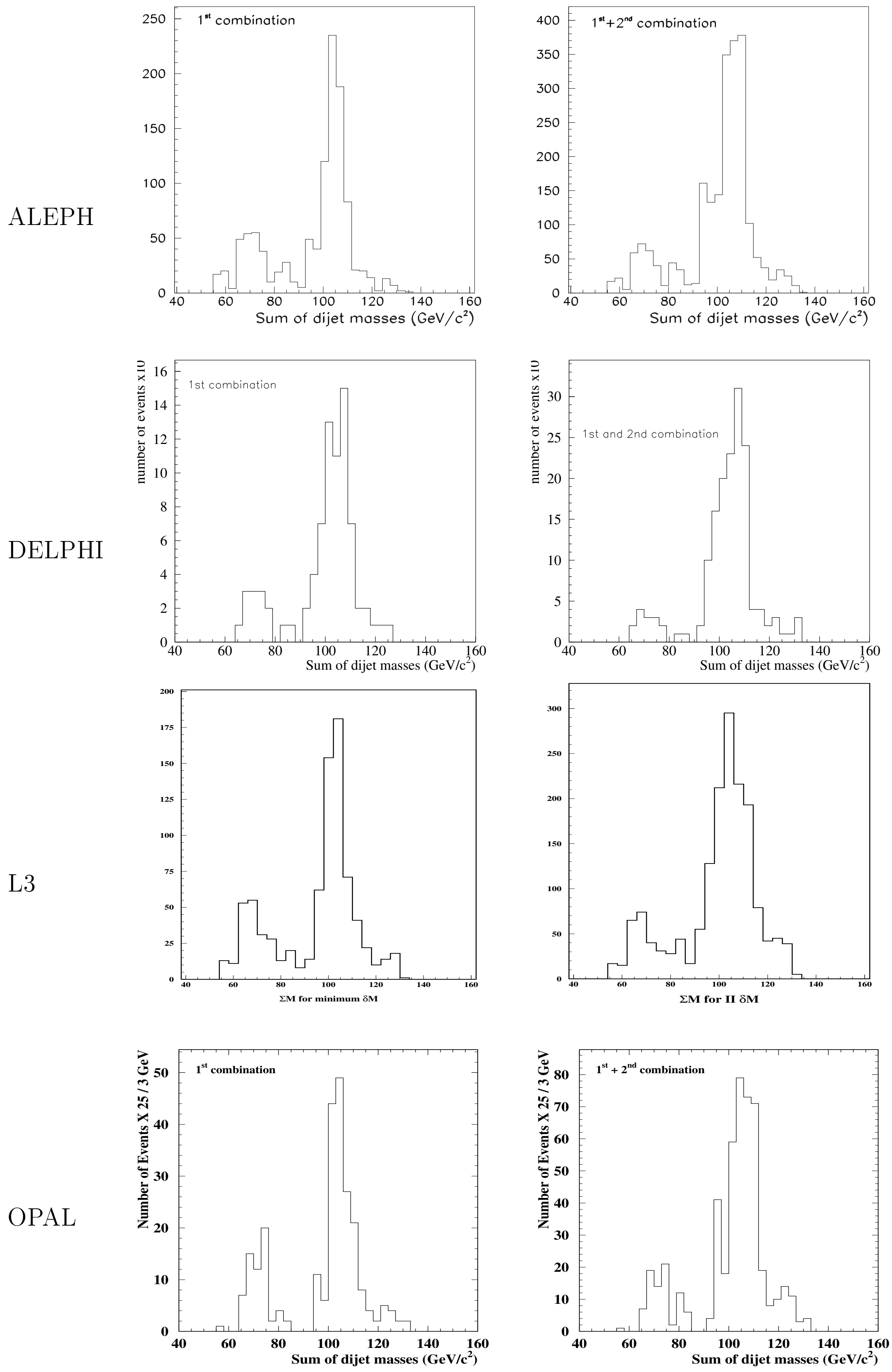

Figure 11: Sum of dijet masses from simulated experiments using 24 ALEPH events at 133 GeV and after the four-jet event selection. Left side for combination with smallest and right side for two smallest mass differences. (Note, the "peak" around $95\,\mathrm{GeV}/c^2$ in the OPAL study when considering the combination with the two smallest mass differences corresponds to a single event.)

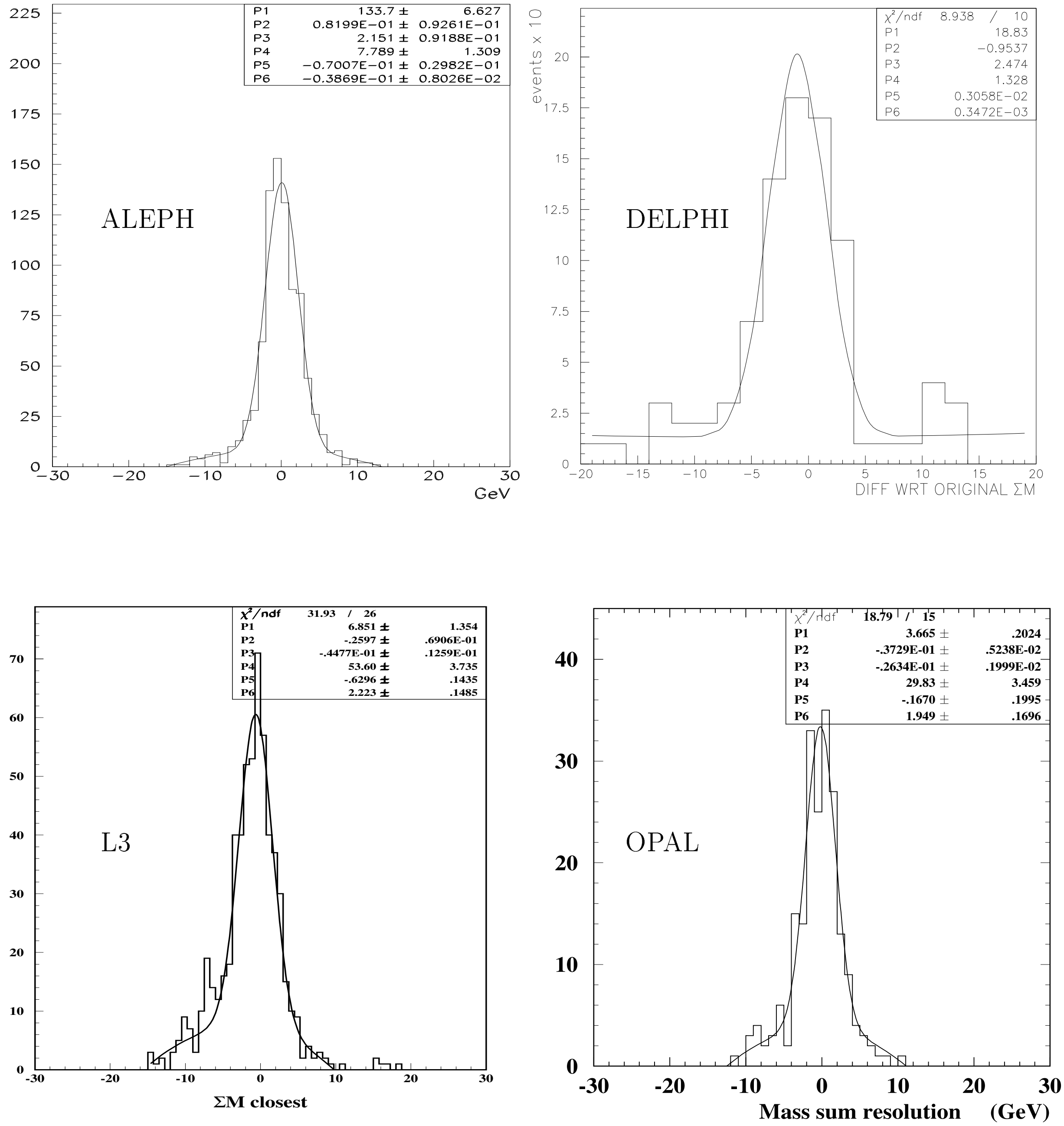

Figure 12: Reconstructed dijet mass sum relative to that originally measured by ALEPH. The 12 ALEPH events in the peak have been used in simulated experiments.

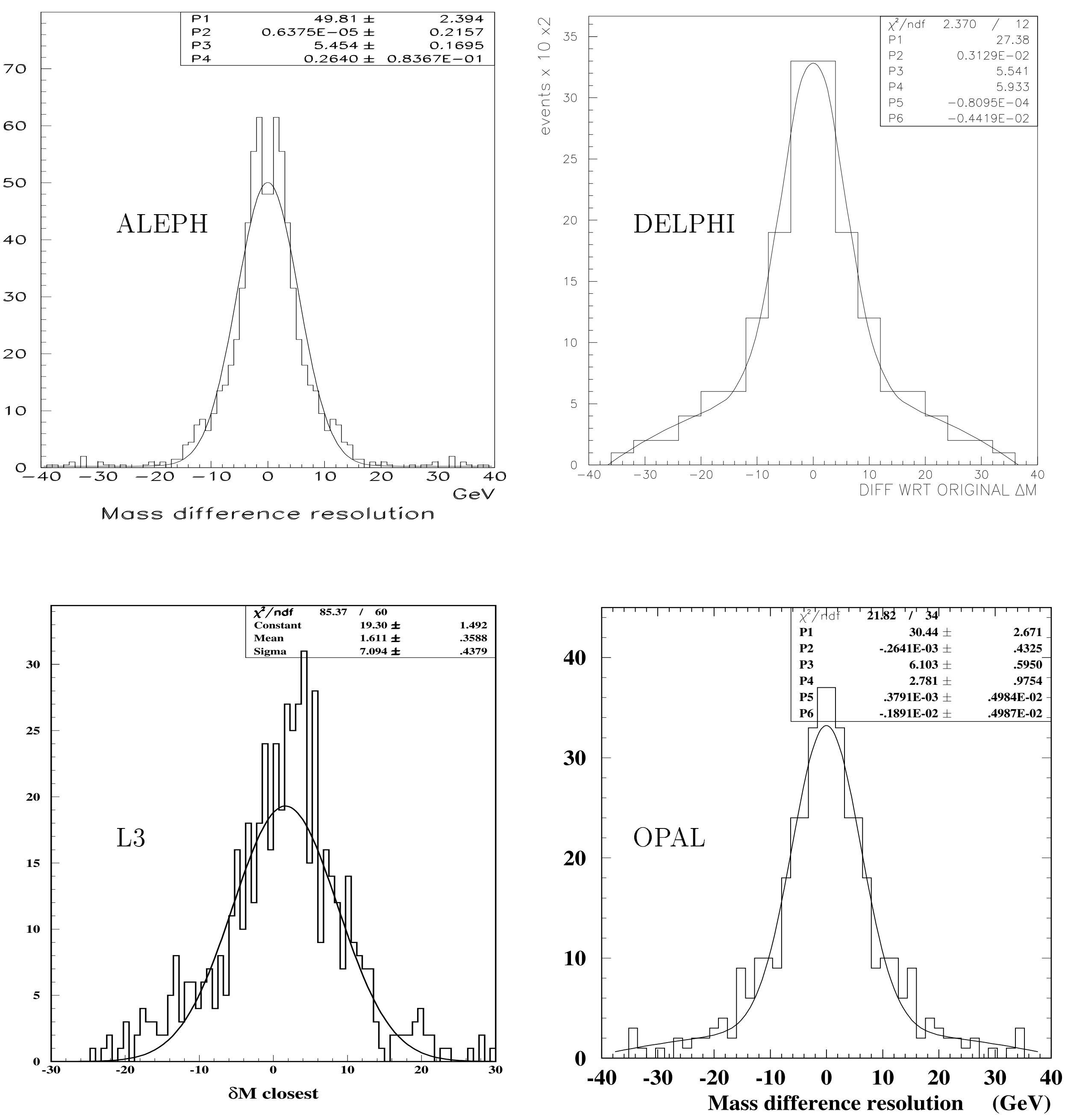

Figure 13: Reconstructed dijet mass difference relative to that originally measured by ALEPH. The 12 ALEPH events in the peak have been used in simulated experiments. The distributions of ALEPH, DELPHI and OPAL are symmetrized (two entries per event).

6 Combination of dijet mass sum spectra

The dijet mass distributions of DELPHI, L3 and OPAL are combined using the samples from all three centre-of-mass energies, the result is shown in Fig. 14a. Good agreement with Standard Model expectations is observed.

A 95% C.L. upper limit on the production cross-section of a possible signal coming from pair production of a new particle is computed starting from the number of events expected and observed in mass intervals containing approximately 60% of the hA signal (4.0, 5.6, 6.0 GeV/c^2 at the three energies). From Poisson statistics the maximum number of signal events (N_s) compatible with observations is extracted at 95% confidence level and the cross section limit (assuming no variation with energy) is computed as

$$\sigma_{lim} = \frac{N_s}{\sum_{i,j} \epsilon_{ij} L_{ij}} \tag{1}$$

where ϵ_{ij} is the signal efficiency in the mass interval for the experiment "i" and the run "j". L_{ij} is corresponding integrated luminosity collected.

In the hypothesis that the signal cross section decreases as $1/s$ with the centre-of-mass energy, ignoring phase space effects, the cross section limit at 133 GeV can be computed substituting Eqn. 1 with

$$\sigma^{133}_{lim} = \frac{N_s}{\sum_{i,j} \epsilon_{ij} L_{ij} \xi_j} \tag{2}$$

where $\xi_j = (\frac{133}{E^{CM}_j(\mathrm{GeV})})^2$.

The two 95% C.L. upper limits from DELPHI, L3 and OPAL are σ_{lim}=0.6 pb and σ^{133}_{lim}=0.8 pb.

Figure 14b shows the ALEPH mass distribution combined for all three centre-of-mass energies. If the excess around 105 GeV/c^2 were interpreted as arising from new physics, the cross section would be 2.3 ± 0.6 pb assuming no s dependence and 3.2 ± 0.8 pb at E_{cms} =133 GeV/c^2 with $1/s$ dependence.

Figure 15 shows the corresponding mass distribution for the combinations with the smallest and second smallest mass difference (two entries per event). The inclusion of the second combination does not alter the previous conclusions.

Assuming no systematic errors in the event reconstruction or in the expectation from Standard Model processes, the following probabilities have been estimated (details of the probability calculations are given in the appendix). For the ALEPH dijet mass sum distribution the probability that one obtains a fluctuation larger than the one observed, using mass intervals as defined above, is 1.8×10^{-4}. The probability for any one of the four experiments is then 7.2×10^{-4}.

For the combined distribution of DELPHI, L3 and OPAL the probability of obtaining a larger fluctuation than that observed in any mass bin is $\approx 50\%$.

The combined confidence level that the dijet mass sum distributions of ALEPH and DLO being simultaneously compatible with a signal at 105 GeV/c^2 is 6.7×10^{-4}. A similar estimate, using binomial probabilities, that one experiment will fluctuate as high as the ALEPH event count, again allowing for a signal, yields 5.7×10^{-4}.

These probabilities depend on the choice of mass interval. Since the resolutions cannot be parametrized by a single Gaussian (see section 2.5) these estimates have been repeated for fixed mass intervals; ± 4 GeV/c^2 as an optimistic guess of the resolution and ± 6 GeV/c^2 as a conservative guess (see Table 9). This has little effect on the probabilities where a signal is allowed while the probability of Standard Model processes fluctuating upwards decreases to 4×10^{-5}).

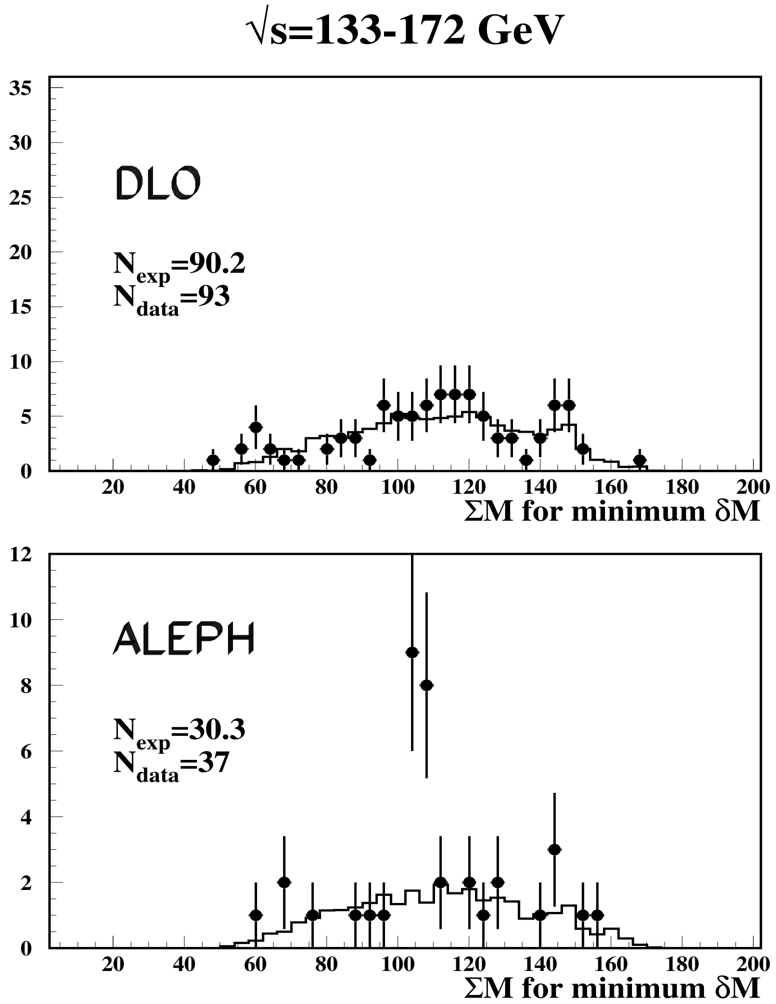

Figure 14: Distribution of the sum of the dijet masses for the smallest mass difference at 133 - 172 GeV. Top: combination of DELPHI + L3 + OPAL (=DLO), bottom: for ALEPH.

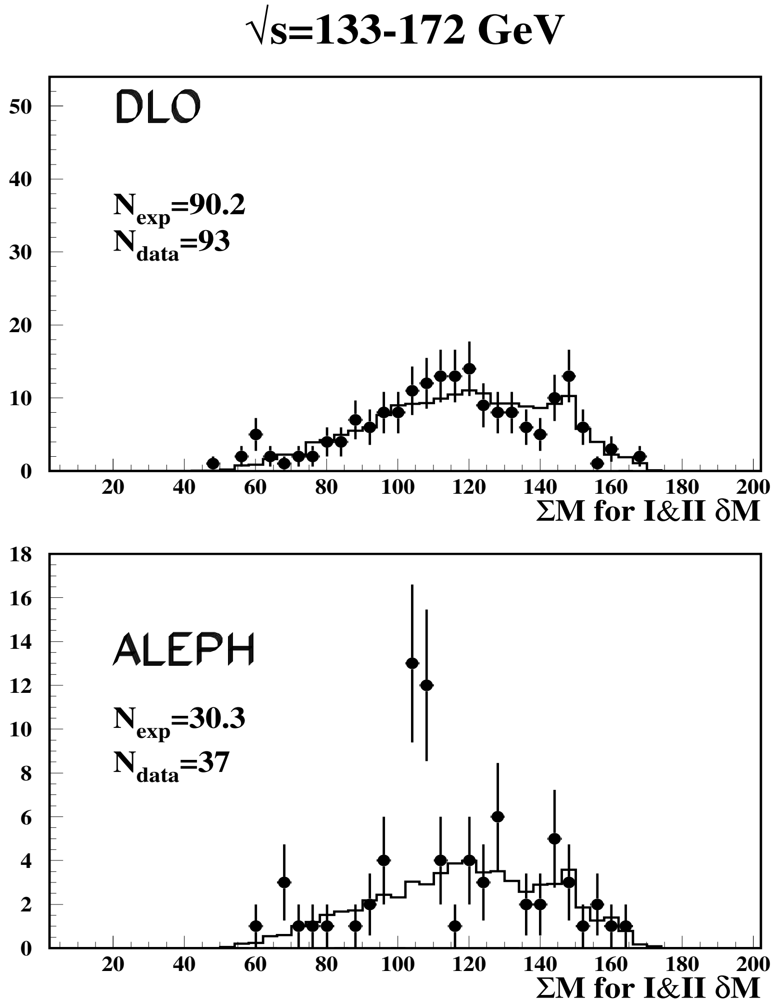

Figure 15: Distribution of the sum of the dijet masses for the first and second smallest mass difference at 133 - 172 GeV. a) Combination of DELPHI + L3 + OPAL (=DLO). b) ALEPH.

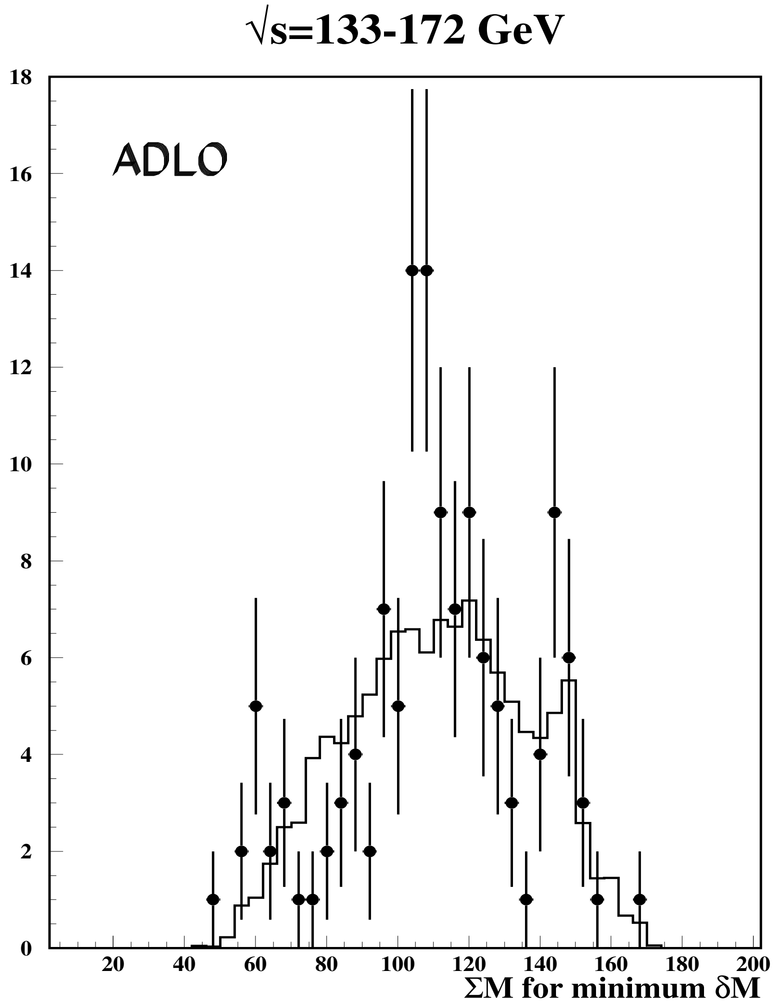

Figure 16: Combined distribution of the sum of the dijet masses for the smallest mass difference at 133 - 172 GeV for all four experiments.

7 Summary

Following the observation of anomalous four-jet production by ALEPH, the selection procedures and jet reconstruction have been compared among the four LEP experiments. Simulated events for hA production have been used to study signal efficiency and resolution for possible pair production. ALEPH data at 133 GeV were used as input to the detector simulation programs of all four experiments. Events with radiative returns to the Z have been used to compare data with the Monte Carlo simulation of jets. The results are summarized as follows:

- All four experiments are able to select and reconstruct four-jet events with similar efficiencies and mass resolutions.

- The combined distribution of the dijet mass sum from DELPHI, L3 and OPAL does not confirm the peak around 105 GeV/c^2 as observed by ALEPH. A 95% C.L. upper limit of 0.6 pb is derived as compared to a cross section of 2.3±0.6 pb for a possible pair production signal in the ALEPH data taking mass intervals of $\pm4, \pm5.6$ and ±6 GeV/c^2 for the three centre-of-mass energies.

- The probability that any one of the four experiments would observe a fluctuation as large as that observed in the ALEPH data is $\approx 7 \times 10^{-4}$ (statistical errors only). The probability to find a fluctuation as large as the biggest one in the combined DELPHI, L3 and OPAL data is about 50%.

  The maximum value of the probability of the dijet mass sum distributions of ALEPH and DLO being simultaneously compatible with a signal at 105 GeV/c^2 is $\approx 7 \times 10^{-4}$.

The origin of the discrepancy between ALEPH and the other three experiments has not been identified.

A Appendix

The ALEPH events at 133 GeV have been used to study two effects on the jet reconstruction. Firstly, the particular jet-finding scheme used to force the event into four jets has been varied, to see if this has any effect on reconstructed invariant masses. Secondly, the assignment of masses to the neutral elements has been varied upwards from zero, and the effect on the reconstructed invariant masses noted. The selection as applied by ALEPH has been used.

A.1 Mass stability with different jet finders

The difference in reconstructed mass, obtained when different jet finding algorithms have been used in the analysis, has been studied. Besides the Durham jet-finding algorithm, which was used in the original analysis, the Geneva and two variants of the Jade (E0 and E) algorithm have been used. The analysis has been applied to both ALEPH data and ALEPH hA Monte Carlo. (It should be noted that the hA sample used was generated at $\sqrt{s} = 161$ GeV).

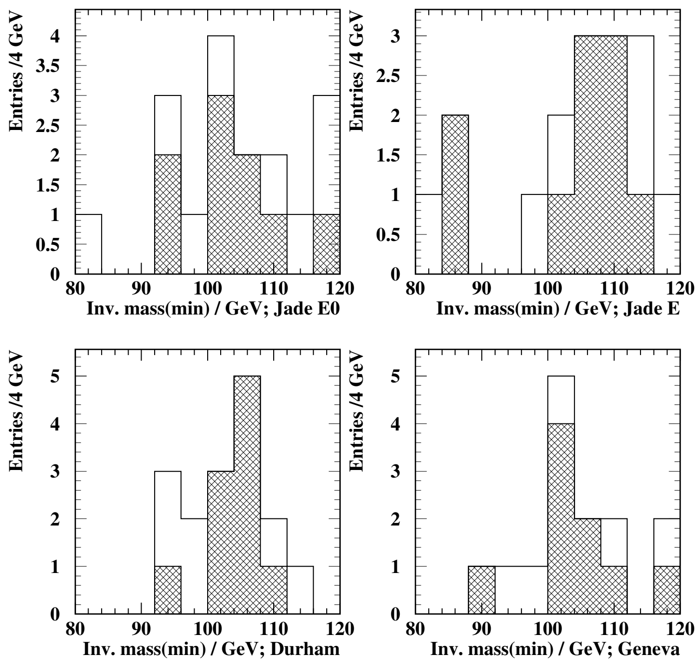

Figure 17: Summed invariant masses for the minimum mass difference jet-jet pair combinations, using four different jet finders. The shaded histograms are for peak events only.

The invariant mass sum for the jet-jet pair which have the smallest difference between invariant masses, Δm_{min}, is plotted (for all jet finders) for data in Fig. 17. It can be seen that an enhancement around 105 GeV/c^2 is visible, although the mass reconstruction of individual events has changed.

Fig. 18 show the difference in invariant mass obtained, for each event in the peak, when each jet finder output is compared to the Durham output. Both Δm_{min} and Δm_{mid}, the corresponding quantity for middle mass difference combination, are shown.

Two types of behaviour are apparent; firstly that solutions between the middle and minimum mass difference combinations can be swapped, and secondly that small variations of up to 10 GeV can occur.

The stability of the hA Monte Carlo was also studied. 30 subsamples of 24 events were run through the analysis chain, using all four jet-finders. The mean of the absolute difference

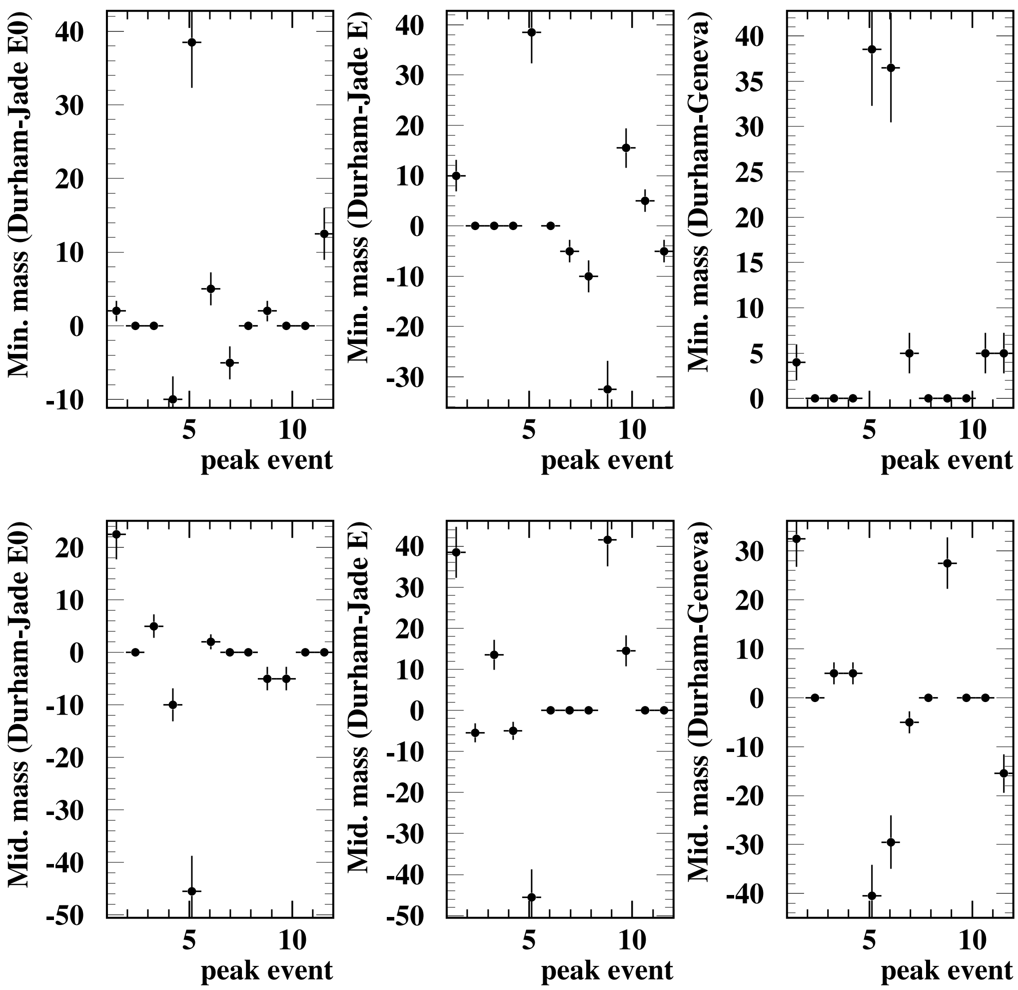

Figure 18: Invariant mass differences (per event) as the result of each jet finder is compared to the default Durham scheme. Only peak events are shown.

in Δm_{min} and Δm_{mid}, for results obtained using Jade or Geneva and compared to Durham, was noted for each subsample. In this way an expected variation can be found. The values for minimum and middle mass combinations, for each jet finder, are given in Table 7 below, together with the corresponding mean of the data. It can be seen that the instability in the data is consistent with that observed in hA Monte Carlo.

Deviation	M.C. mean (GeV)	M.C. rms (GeV)	Data mean
Minimum mass			
Jade E0-Durham	12.64	3.05	11.88
Jade E-Durham	12.37	2.52	12.53
Geneva-Durham	13.28	3.99	9.33
Middle mass			
Jade E0-Durham	12.47	3.00	11.78
Jade E-Durham	12.30	2.28	17.38
Geneva-Durham	13.26	2.88	12.86

Table 7: Mean and rms deviations in invariant mass, in hA Monte Carlo events, for invariant masses obtained using the jet-finders given in the Table. The mean difference observed in data is also shown.

A.2 Mass stability with different neutral mass assignments

The variation of the reconstructed mass with the neutral mass assignment was investigated. All charged tracks were assigned the pion mass, and the Durham jet finder was used to force each event into four jets. After energy rescaling the invariant masses were found.

Three values for the neutral mass were tested; $m_{neut} = 0$, m_{neut}= 0.14, and m_{neut}=0.3 GeV. The invariant masses obtained with the last two assignments were compared to those obtained with a neutral mass of zero. It should be noted that the neutral mass assignment is applied to all events, and is thus an overestimate of any effects caused by a subset of misassigned events. All differences are small, with the exception of one event where the minimum and middle mass solutions have swapped. Table 8 lists the means and rms values of these offsets, both with and without the outlier event. The neutral mass assignment does not appear to affect significantly the reconstructed masses.

Comparison	mean offset (GeV)	rms offset (GeV)
$m_{neut} = 0.14 - m_{neut} = 0.00$	1.857	7.676
$m_{neut} = 0.30 - m_{neut} = 0.00$	3.022	7.749
$m_{neut} = 0.14 - m_{neut} = 0.00$ (*)	0.30	0.22
$m_{neut} = 0.30 - m_{neut} = 0.00$ (*)	1.49	1.66

Table 8: Difference in summed invariant mass, for the closest mass jet-jet combination, for different neutral mass assignments. Combinations denoted (*) have removed the outlier where middle and minimum mass solutions swap.

A.3 Probability estimates

The following procedure to obtain an estimate of the statistical probability for a fluctuation of the expected distribution as large as the observed one has been applied. An estimator for the "unlikeliness" of a given distribution is defined as the Poisson probability to observe $\geq n_x$ events in any bin of given width when b_x events are expected:

$$\mathcal{E} = Inf\left(\sum_{i=n_x}^{\infty} \frac{b_x^i}{i!} \exp\left(-b_x\right)\right)$$

where Inf(x) is the smallest value of x in any bin. These estimators have been calculated for the ALEPH dijet mass sum distribution, ($\mathcal{E}_{\mathrm{ALEPH}}$) and the one from DELPHI, L3 and OPAL ($\mathcal{E}_{\mathrm{DLO}}$). A large number of simulated experiments have been performed according to the Monte Carlo expectation. The final probability is then the fraction of such simulated experiments that lead to smaller values of $\mathcal{E}_{\mathrm{ALEPH}}$ or $\mathcal{E}_{\mathrm{DLO}}$ respectively. For the choice of mass windows as given in Table 2 the result is

$$P_{\mathrm{ALEPH}} = 1.8 \times 10^{-4} \text{ and}$$
$$P_{\mathrm{DLO}} \approx 50\%.$$

The probability of the dijet mass sum distributions of ALEPH and DLO being simultaneously compatible with a signal at 105 GeV/c^2 has also been computed. Let S be the number of signal events for ALEPH in the mass intervals around 105 GeV/c^2 used in Table 2. Since the efficiencies are quite similar for the four experiments, the number of signal events predicted for DLO is $3S$. Using the observed event counts and background estimates from Table 2, ALEPH observes 17 events and expects $4.0 + S$, and DLO observes 13 events and expects $12.9 + 3S$.

Let p_1 be the Poisson probability to observe 17 events or more when $4.0+S$ are expected and let p_2 be the Poisson probability to observe 13 events or less, when $12.9+3S$ are expected. The probability of an experimental outcome with a joint probability of no more than p_1p_2 depends on S and has been calculated as a discrete sum over possible experimental outcomes [11]. The most likely value of S, the one that maximizes $P(S)$, is $S = 3.3$. ALEPH would then expect 7.3 events (17 observed, $p_1 = 1.5 \times 10^{-3}$) and DLO would expect 22.8 events (13 observed, $p_2 = 1.9 \times 10^{-2}$), corresponding to a maximum $P(S) = 1.7 \times 10^{-4}$. Any of the four experiments could have observed an excess and hence this probability must be multiplied by four to obtain

$$P(S) = 6.7 \times 10^{-4}.$$

Another way to quantify the consistency of the ALEPH and DLO observations is to ask what is the probability that the observed events in the region of interest would have partitioned themselves among the experiments, holding the total number of events fixed. The probability that one experiment observes a fluctuation at least as high as the observed ALEPH event count is given by the sum of binomial probabilities. If the fraction of total event count ALEPH expects to observe is calculated only from background expectations, one obtains $P_{\mathrm{binom}} = 4.2 \times 10^{-4}$, including the factor of four. If the fraction is calculated from the expected event counts using the best value of S from the above calculation, one obtains

$$P(S)_{\mathrm{binom}} = 5.7 \times 10^{-4}$$

comparable to the previous consistency probability.

These estimates have been recalculated for different choices of mass intervals. One with an optimistic assumption of $\pm 4\,\mathrm{GeV}/c^2$ for the mass resolution and a more conservative one of $\pm 6\,\mathrm{GeV}/c^2$. The results are summarized in Table 9.

bin width ($\pm$ in GeV/c^2)	4/5.6/6	4 fixed	6 fixed
P_{A} (10^{-4})	7.2	0.4	7.3
$P(S)$ (10^{-4})	6.7	9.5	8.1
P_{binom} (10^{-4})	4.2	7.0	4.1
$P(S)_{\mathrm{binom}}$ (10^{-4})	5.7	8.0	6.3

Table 9: Summary of probabilities (factor 4 included) for different hypotheses (see text) for three choices of mass intervals around 105 GeV/c^2.

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