4-JET EVENTS AT LEP

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Results of a special study made by the four LEP experiments on 4-jet events recorded at $\sqrt{s} = 130 - 136$, 161 and 172 GeV are related. This study concerns the ALEPH analysis which has shown an excess of 4-jet events in data recorded at $\sqrt{s} = 130 - 136$ GeV. No significant evidence has been found by the 3 other experiments. Results have been combined after several checks which did not show differences of performance between the four LEP experiments.

1 Introduction

The ALEPH experiment has reported [1] in 1995 an excess of 4-jet events in e^+e^- collisions registered at $\sqrt{s} = 130-136$ GeV, in an analysis dedicated to search two heavy objects decaying hadronically, such as $e^+e^- \to hA \to b\bar{b}b\bar{b}$. This excess is characterized by an accumulation of 9 events in the sum of the dijet masses around 105 GeV/c^2, while 0.8 events were expected from standard processes, and no b flavoured jets have been observed, which excludes hA production hypothesis.
In data collected at $\sqrt{s} = 161$ and 172 GeV in 1996, ALEPH has selected 8 more events around 105 GeV/c^2 (3 expected). Similar analysis have been performed by DELPHI, L3 and OPAL collaborations, using the three high energy runs whose recorded luminosities are recalled in Table 1. There is no confirmation of the ALEPH excess.
In section 2, the analysis is briefly described and individual results are shown. In section 3 several checks, which have been made in the framework of a LEP Working Group, concerning mass resolutions and efficiencies, as well as an estimate of the "efficiency" of each experiment to the ALEPH events, are presented. Combined results are finally given and limits on an hypothetical signal production are derived.

	ALEPH	DELPHI	L3	OPAL
130-136 GeV	5.7	5.9	5.0	5.2
161 GeV	11.0	9.9	10.9	10.0
172 GeV	10.6	10.0	10.3	10.2

Table 1: Integrated luminosities (in pb^{-1}) recorded by the 4 LEP experiments in 1995 and 1996.

2 4-jet events analyses in ALEPH, DELPHI, L3, and OPAL

The main backgrounds in multi-jet analyses with no expected missing energy, at LEP2 consists in $e^+e^- \to Z \to q\bar{q}gg$ and $e^+e^- \to Z/\gamma^* \to q\bar{q}q'\bar{q}'$. DELPHI [3], L3 [4] and OPAL [5] have followed the original ALEPH [2] analysis, whose main steps are summarized in the following.

- Simple 4-jet selection based on hA preselection:
  After having selected hadronic events and suppressed the "radiative returns to the Z" ($e^+e^- \to Z\gamma \to q\bar{q}\gamma$), are clustered into four or more jets by requiring that the DURHAM distance y_{cut} is higher than 0.008, where y_{cut} is the value at which events change from 4 to 3-jet topologies. After forcing events to the 4-jet by letting ycut to increase, the 4-vectors of each jet are rescaled, imposing energy-momentum conservation (the direction of the jets is assumed to be perfectly measured). This improves the resolution on the sum of the masses of the two dijets. Events containing γ-like jets corresponding to remaining "radiative returns" are rejected by requiring that less than 80% of the jet energy is electromagnetic, that at least two tracks are present per jet and that the masses of the jets are greater than 1 GeV/c^2. For the three possible pairings, dijet masses are computed (corresponding to minimal, intermediate and maximal dijet masses difference), and the one which minimizes the mass difference is considered as the right one, since two objects of equivalent masses are looked for.

- QCD and 4 fermions background suppression:
  All dijet masses must exceed 19.2 % $\sqrt{s}$ (this reduces the QCD background where soft gluons are radiated by quarks). The sum of the masses of the two lightest jets is required to be larger than 10 GeV and the sum of the charged multiplicity must exceed 10 tracks (reduction of the Z/γ^* background). It should be mentionned that DELPHI and L3 have relaxed by 10% the three last cuts, in order to maintain a similar efficiency on the hA signal as ALEPH (see section 3.1).

- anti WW cuts:
  At $\sqrt{s} >$ 160 GeV, it has been necessary to apply anti WW cuts based on the fact that the sum of the masses of the two W is expected to be close to 160 GeV. but as near the WW threshold, only 30% of the correct WW jet pairings are given by the one which minimizes the mass difference, it has been required that, for the three combinaisons, the sum of the masses is outside the interval 160 $\pm$ 10 GeV. More details can be found in [6] and [7].

Final distributions of the sum of the dijet masses for the combinaisons which minimizes the mass difference are shown in Figure 1, for the four LEP experiments at the three centre-of-mass energies. Numbers of observed and expected events, in the full mass range and in the mass windows centered on 105 GeV and of $\pm$ 4.0, $\pm$ 5.6 and $\pm$ 6.0 GeV extensions respectively, that reflects the $\sqrt{s}$ dependence of the mass resolution for a 4-jet signal like hA at a given Higgs mass, are summarized in Table 2.

		ALEPH		DELPHI		L3		OPAL	
	$\sqrt{s}$(GeV)	data	MC	data	MC	data	MC	data	MC
full range	133	16	8.3	13	9.3	12	8.1	8	7.1
105 ± 4 GeV/c^2		9	1.0	4	1.0	2	1.1	1	0.8
full range	161	8	8.2	12	10.8	7	8.0	7	6.2
105 ± 4.6 GeV/c^2		5	1.2	2	1.8	1	1.2	0	1.0
full range	172	13	13.8	15	14.3	14	13.5	5	12.7
105 ± 6 GeV/c^2		3	1.8	1	2.4	2	1.8	0	1.8

Table 2: Final numbers of events selected by the four LEP experiments at the three high energy runs.

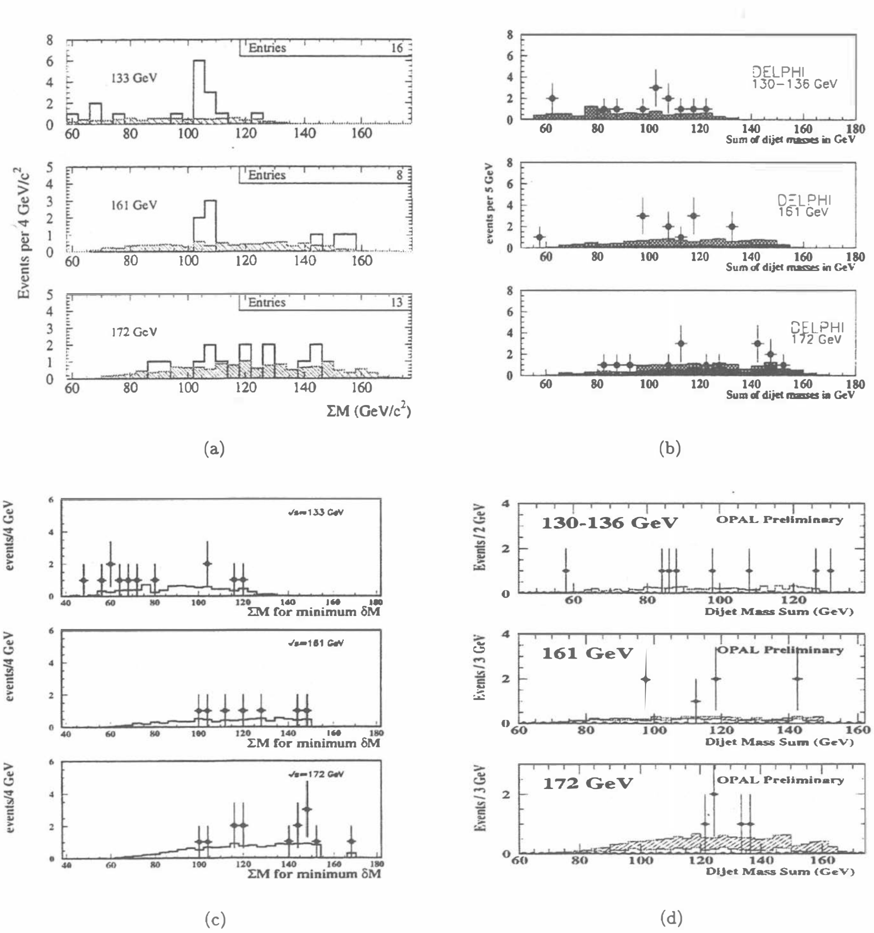


Figure 1: Final distributions of the sum of the dijet masses for the smallest mass difference combination measured in ALEPH (a) DELPHI (b) L3 (c) and OPAL (d) experiments in the three high energy runs. (Upper distributions correspond to 130-136 GeV data, medium to 161 GeV data and lower to 172 GeV).

3 Checks and comparisons

Before combining results from the four experiments, it has to be verified that all experiments would have been able to select events like ALEPH did, in terms of efficiency and mass resolution.

3.1 Comparisons on mass resolution and efficiency for the hA channel

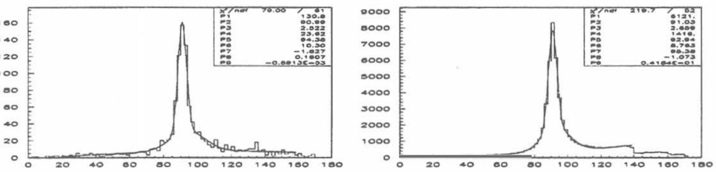
The resolutions on the sum of the dijet masses for the smallest mass difference pairing have been compared for a hA signal ($m_A = m_h = 55$ GeV). The resolution has been evaluated as the mass window which contains 50% of the signal (the mass peak cannot be properly fitted by a unique Gaussian function). Numbers are given in Table 3. No significant difference has been seen.

	$\sqrt{s}$	ALEPH	DELPHI	L3	OPAL
Mass resolution (GeV)	133 GeV	±3.6	±2.5	±3.6	±3.1
	161 GeV	±2.9	±3.3	±3.5	±2.9
	172 GeV	±3.0	±3.4	±3.6	±2.9
efficiency /σ_{SM}	133 GeV	41% / 1.5 pb	44% / 1.6 pb	45% / 1.6 pb	45% / 1.4 pb
	161 GeV	30% / 0.7 pb	31% / 1.1 pb	32% / 0.7 pb	28% / 0.6 pb
	172 GeV	30% / 1.3 pb	26% / 1.4 pb	26% / 1.3 pb	30% / 1.3 pb

Table 3: Expected resolution on the sum of dijet masses and efficiency for hA simulated events ($m_A = m_h = 55$ GeV). The overall expected cross-section of background events passing all cuts is also given.

3.2 Check of the detector resolution on Z(γ) events

In order to check the jet reconstruction and energy-momentum rescaling method on data and to compare with the MC simulation, radiative returns to the Z events have been used. They have been selected by requiring an isolated γ or a γ-like jet (jet whose electromagnetic energy fraction is higher than 80%). Figure 2 shows the recoiling mass distribution obtained by ALEPH. Equivalent results have been obtained by the other experiments and are summarized in table 4.



(a) (b)

Figure 2: Reconstructed hadronic mass distributions in "radiative returns to the Z" events selected in data (a) and MC (b) by ALEPH.

	ALEPH	DELPHI	L3	OPAL
σ_m DATA (GeV/c^2)	2.5	2.8	3.0	2.1
σ_m MC (GeV/c^2)	2.7	3.6	3.4	2.6
Mass shift data-MC (GeV/c^2)	-0.04	0.3	0.2	-0.4

Table 4: Measured width of the Z in "radiative returns" events for data and MC at 130-172 GeV for ALEPH and L3 and at 130-136 GeV for DELPHI and OPAL.

3.3 Studies on ALEPH events

In order to evaluate the "efficiency" of each experiment to the events selected by ALEPH, and to rule out any hypothetical problem of reconstruction, the ALEPH collaboration has provided, the 4-vectors of the particles measured in 24 events (including 12 events situated in the peak region when using the smallest and the intermediate mass difference combinations) recorded at $\sqrt{s} = 130 - 136$ GeV. These 4-vectors have been used as input to the detector simulation programs of the other experiments, and this procedure has been repeated several times for the same input events. The ALEPH like analysis selection has then been applied. The four experiments have similar performances: 30-40% of the events are lost, and some swapping between the pairings has been observed (bumps around 70 GeV in Figure 3). The mass resolution is evaluated by fitting the distribution of the difference between the sum of masses reconstructed in each detector simulation and the value given by ALEPH. Numbers are given in Table 5 and Figure 3 shows the spectra of the sum of dijet masses observed in each experiment.

	ALEPH	DELPHI	L3	OPAL
Efficiency	68%	65%	61%	68%
$\sigma(\Sigma\mathrm{m})$ (GeV/c^2)	2.2	2.5	2.2	2.0
Mass shift (GeV/c^2)	0.1	-0.1	-0.3	0.02

Table 5: Fraction of ALEPH peak events passing the ALEPH like analysis selection and corresponding mass resolution, after having used these events as input to simulation programs.

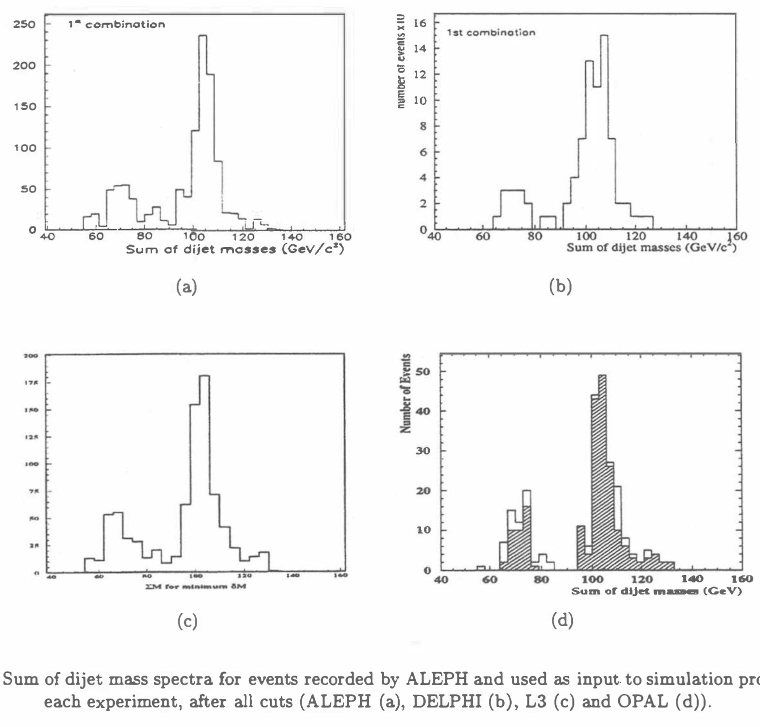


Figure 3: Sum of dijet mass spectra for events recorded by ALEPH and used as input to simulation programs in each experiment, after all cuts (ALEPH (a), DELPHI (b), L3 (c) and OPAL (d)).

4 Combined results:

As no significant difference between the performances of the four experiments has been found, results have been combined. The upper part of Figure 4 shows the combined mass spectrum for DELPHI, L3 and OPAL (DLO) exhibiting a good agreement with SM expectations. A 95% CL upper limit on the cross-section of an hypothical pair-produced signal cross-section has been derived using Poisson statistics.

$\sigma_{95\%} \leq 0.6$ pb assuming no $\sqrt{s}$ dependence of the cross-section.

$\sigma_{95\%} \leq 0.8$ pb assuming that the cross-section decreases as $\frac{1}{\sqrt{s}}$.

The lower part of Figure 4 presents the ALEPH mass spectrum showing clearly two excited bins. If one interprets this excess as a signal, it corresponds to a cross-section of 2.3 ±0.6 pb. Moreover no additional effect is observed when the intermediate mass difference dijet pairing is also included in the mass spectrum [6].

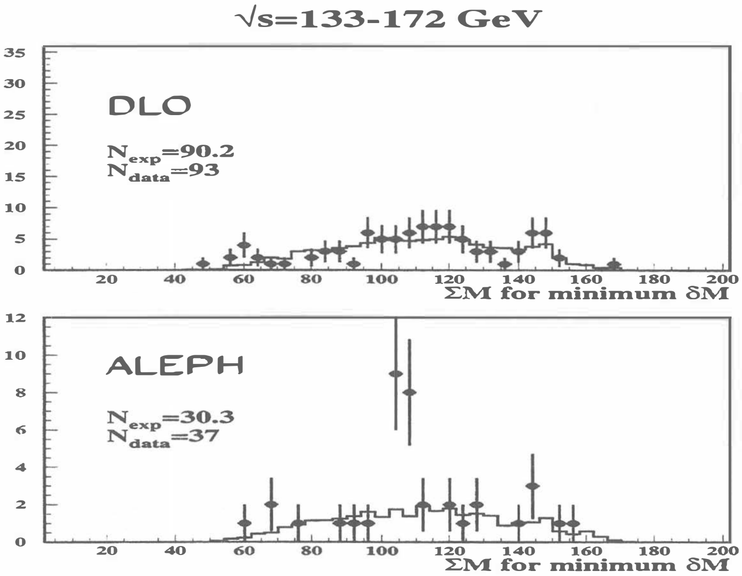


Figure 4: Combined results of the 3 high energy runs (on top DELPHI, L3 and OPAL, below ALEPH). The histograms correspond to the expected distributions from the simulation; the bin width is equal to 4 GeV.

5 Summary

A global excess of 10 events (40 observed, 30 expected) has been seen by the ALEPH Collaboration in an analysis dedicated to look for two heavy objects decaying hadronically, in e^+e^- collisions using data recorded at $\sqrt{s}$=130, 136 161 and 172 GeV. This excess is characterized by an accumulation in the sum of the dijet masses around 106 GeV (excess of 15 events in 106 ± 4 GeV). No confirmation has been obtained by DELPHI, L3 or OPAL. Several checks and comparisons between the performances have shown that the four LEP experiments would have been able to see such an accumulation. A 95% CL upper limit has been extracted from DELPHI, L3 and OPAL results of 0.6 pb, while the excess in ALEPH data would correspond to a cross-section of 2.3 ± 0.6 pb.

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