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Study of the four-jet anomaly observed at LEP centre-of-mass energies of 130 and 136 GeV

DELPHI Collaboration

Abstract

The four-jet events collected by DELPHI during the special LEP run at centre-of-mass energies of 130 and 136 GeV in 1997 with an integrated luminosity of $5.9\,\mathrm{pb}^{-1}$ are analysed. Their rate and the distributions of their di-jet masses, their smallest jet charges, and their di-jet charge separations all agree well with Standard Model predictions. Thus the hypothesis of pair production of a new particle with a sum of di-jet masses around $105\,\mathrm{GeV}/c^2$ is not supported. The combined result of the four LEP collaborations refuting this hypothesis at over 99% confidence level is also given.

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1 Introduction

A special run of LEP at centre-of-mass energies of 130 and 136 GeV was performed in October 1997 in order to confirm or refute the hypothesis of pair production of a new particle that had been suggested by an excess of four-jet events with a sum of di-jet masses around $105\,\mathrm{GeV}/c^2$ observed by the ALEPH collaboration in a previous run in 1995 at the same energies [1].

In those ALEPH data, corresponding to an integrated luminosity of $5.7\,\mathrm{pb}^{-1}$, 9 events were selected with a sum of di-jet masses in the range $105 \pm 4\,\mathrm{GeV}$ where only 0.7 events were expected from Standard Model processes, see Figure 1a). This sum of di-jet masses is particularly sensitive to pair production of new particles as it is measured with very good precision after jet energy rescaling based on total energy and momentum conservation. In addition, the selected events appeared to be characterized by unusual parton content, indicated by large values of the smallest jet charge and of the di-jet charge separation.

To check this, the other three LEP collaborations, DELPHI [2], L3 [3], and OPAL [4] (called "DLO" below) then performed similar "ALEPH-like" analyses. Together DLO saw 7 events in the same mass bin (including 4 from DELPHI) where they expected 3.9 (1.0 from DELPHI), see Figure 1b). This did not confirm the effect, but also did not clearly exclude it. Data taken at centre-of-mass energies of 161 and 172 GeV in 1996 showed a reduction of the effect in ALEPH [5–7], and a complete agreement with the expected background in the other detectors [3,4,6].

A LEP working group on four-jet events compared these analyses [6]. It concluded that similar efficiencies ($\simeq 40\%$) and mass resolutions ($\simeq 2\,\mathrm{GeV}$, but with large non-Gaussian tails) were expected in all four detectors. No explanation of the apparent discrepancy between the ALEPH and the DLO data shown in Figure 1 was found. The combined results of the four experiments corresponded to a total luminosity of 21.9 pb^{-1}.

To confirm or refute the hypothesis of pair production of a new particle, a dedicated run at 130-136 GeV was therefore proposed [5], and approved for a total luminosity per experiment of 12 pb^{-1}. The event selection and analysis procedures to be applied by the four collaborations were agreed in advance, under the auspices of the LEP working group, as was the criterion for possibly considering the hypothesis refuted after only 6 pb^{-1} per experiment had been taken and analysed. The run was performed in October 1997. This letter briefly presents the results obtained by DELPHI and also includes, for completeness, the combined result obtained by the four LEP collaborations.

2 Event selection and analysis

The event selection and analysis procedure used by DELPHI was identical to that published previously [2,6], with the sole exception that only the DURHAM jet algorithm was used. Additionally, these data benefit from the improvements of the DELPHI detector, upgraded for the LEP2 phase [8].

The integrated luminosities collected by DELPHI in this run were $3.03\,\mathrm{pb}^{-1}$ at a centre-of-mass energy of 130 GeV and $2.91\,\mathrm{pb}^{-1}$ at 136 GeV. Monte Carlo samples with at least six times the expected number of events have been used to estimate the Standard Model backgrounds (mainly QCD events, mostly $q\bar{q}gg$, generated with JETSET/PYTHIA [9]).

Table 1 shows the numbers of events found in the 1997 data and those expected from Standard Model processes, after the different selection criteria: at least four jets were found with the DURHAM clustering algorithm using a cut parameter $y_{cut} = 0.008$, with positive rescaling factors, and all jet pairs were requested to have a di-jet invariant mass

($M_{ij}^{\rm rec}$) of at least 22.5 GeV/c^2, a minimum sum of jet masses ($m_i^{\rm rec} + m_j^{\rm rec}$) of 9 GeV/$c^2$, and at least 9 charged particles ($\min(n_{CHi} + n_{CHj}) \geq 9$).

Good agreement is observed between the data and the expected backgrounds, and a high efficiency is obtained for the reference signal corresponding to the production of a pair of neutral Higgs bosons predicted by the Minimal Supersymmetric extension of the Standard Model (MSSM), h and A, with equal masses of 55 GeV/c^2 [2].

	observed events	expected events (QCD + ZZ + WW)	hA-signal efficiency
Four-jet events	19	16.4 ± 1.6	58%
$\min(M_{ij}^{\rm rec}) > 22.5\,{\rm GeV}/c^2$	15	11.6 ± 1.4	52%
$\min(m_i^{\rm rec} + m_j^{\rm rec}) > 9\,{\rm GeV}/c^2$	11	8.3 ± 1.2	44%
$\min(n_{{\rm CH}i} + n_{{\rm CH}j}) \geq 9$	11	8.0 ± 1.1	43%

Table 1: Effects of the ALEPH-like selection cuts.

3 Event properties

3.1 Di-jet masses

After ordering the three possible pairings of the four jets to form two di-jet systems by increasing mass difference ΔM between the two di-jets, any pair production of similar mass objects is expected to be seen in the distribution of the sum of the di-jet masses for the first pairing. Figure 2 shows the corresponding distribution: the data agree well with the expectations from Standard Model processes. No mass interval contains a significant excess of events. In particular, only one event is observed in the interval $105 \pm 4\,{\rm GeV}/c^2$ for 0.8 expected.

3.2 Jet charges

The jet charge $Q_{\rm jet}$ used here is defined [1] as

$$Q_{\rm jet} = \frac{\sum_{i=1}^{N} q_i \cdot y_i}{\sum_{i=1}^{N} y_i}, \tag{1}$$

where the sum extends over the N charged particles of the jet, q_i being the electric charge of particle i and y_i its rapidity with respect to the jet axis. In QCD four-jet events, the smallest of the absolute values of the four jet charges,

$$Q_{\rm min} = \min\left(|Q_1|, |Q_2|, |Q_3|, |Q_4|\right), \tag{2}$$

should often arise from a gluon jet, and thus reflect the zero electric charge of the gluon. Figure 3 plots $Q_{\rm min}$ against the sum of di-jet masses for the first combination in the event, including also the data from the 1995 run at 130-136 GeV. No anomaly is observed in the interesting mass region. In particular there is no clustering of events with $Q_{\rm min}$ above 0.1.

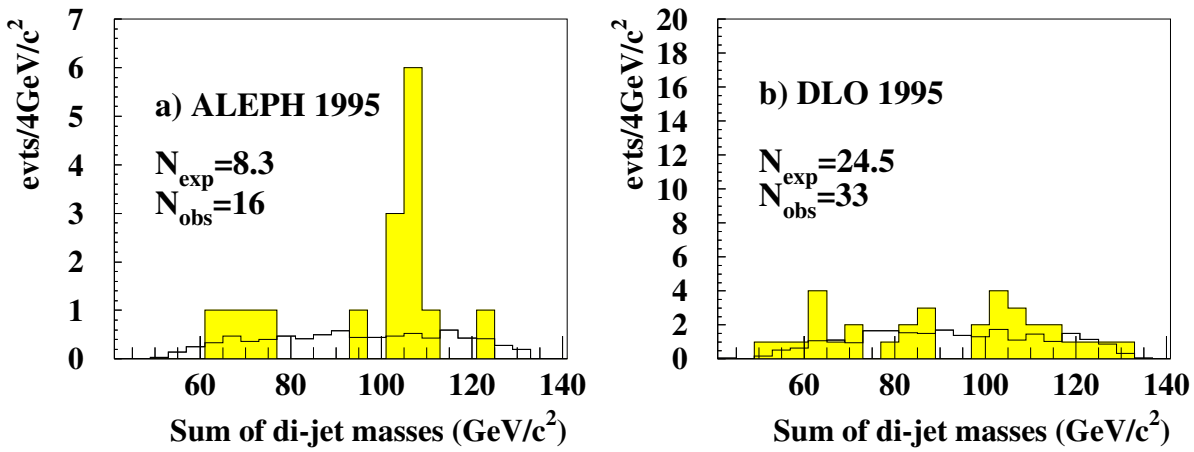

Figure 1: 1995 data: distributions of the sum of the di-jet masses for the pairing with the smallest di-jet mass difference after all selection cuts for ALEPH data (a) and for DELPHI, L3 and OPAL data combined (b), labelled DLO. The shaded histograms show the data, the open ones show the expectation from Standard Model processes.

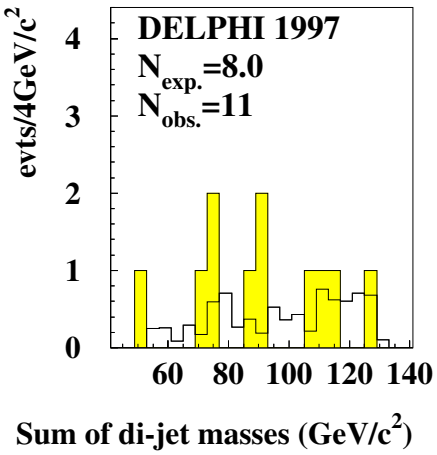

Figure 2: Distribution of the sum of the di-jet masses for the combination with the smallest di-jet mass difference. The shaded histogram shows the data taken in 1997 and the open one the distribution expected from simulation of the Standard Model processes.

The di-jet charge separation ΔQ used here is defined [1] as the absolute difference in summed jet charge between the first and second di-jet

$$\Delta Q = |(Q_1 + Q_2) - (Q_3 + Q_4)| \,. \tag{3}$$

Figure 4 plots this di-jet charge separation versus the sum of di-jet masses. Again no anomaly is observed in the mass region around $105\,\mathrm{GeV}/c^2$. In particular there is no deficit of events with ΔQ below 0.3 and no excess of events with ΔQ above 0.6 or 0.9.

4 Check at higher energies

The same analysis was repeated using the data collected during 1996 and 1997 at centre-of-mass energies from 161 GeV to 183 GeV, but including another ALEPH-like cut [7] to select against the copious WW background: an event was rejected if it had a di-jet combination with masses close to a WW configuration (i.e., if the di-jet mass difference was below $15\,\mathrm{GeV}/c^2$ for the first combination or below $30\,\mathrm{GeV}/c^2$ for the second one, and the corresponding sum of di-jet masses was within $10\,\mathrm{GeV}/c^2$ of $2M_\mathrm{W}$). Again no anomaly was found. Table 2 shows the numbers of events expected and found in total and in a mass window around $105\,\mathrm{GeV}/c^2$ of twice the estimated mass resolution (i.e., of $\pm 4\,\mathrm{GeV}/c^2$ at 161 GeV, $\pm 5.6\,\mathrm{GeV}/c^2$ at 172 GeV, and $\pm 6\,\mathrm{GeV}/c^2$ at 183 GeV).

centre-of-mass energy	integrated luminosity	data events	expected events
161 GeV	$9.9\,\mathrm{pb}^{-1}$	12 (2)	10.8 (1.8)
172 GeV	$10.0\,\mathrm{pb}^{-1}$	15 (1)	14.3 (2.4)
183 GeV	$54.0\,\mathrm{pb}^{-1}$	73 (5)	77.0 (8.2)

Table 2: Numbers of events selected at higher energies. The numbers of events in the interesting mass region ($105 \pm 2\sigma_M\,\mathrm{GeV}/c^2$) are given in parentheses.

5 Combined data of the four LEP collaborations

The results [7,10,11] of the short run in 1997 obtained by the four LEP collaborations, using the analysis procedures (essentially the same as in 1995) that had been agreed before the data were taken, are shown combined in Figure 5. The total integrated luminosity was $26\,\mathrm{pb}^{-1}$, equally shared between 130 and 136 GeV (as in 1995). The excess seen in the 1995 data is not reproduced: both the total number of events (35 observed for 37.2 expected) and the number of events in the mass interval $105 \pm 4\,\mathrm{GeV}/c^2$ (5 events observed for 4.1 expected) agree well with the Standard Model expectations.

It had been agreed to stop the run after an average of $6\,\mathrm{pb}^{-1}$ per experiment had been taken and analysed if by then a new physics signal corresponding to 12 events in that mass interval in the 1995 data (i.e., one standard deviation less than the number actually observed in 1995) had already been excluded at more than 99% confidence level, i.e., if 5 events or less had been observed in that mass interval. The run was therefore stopped.

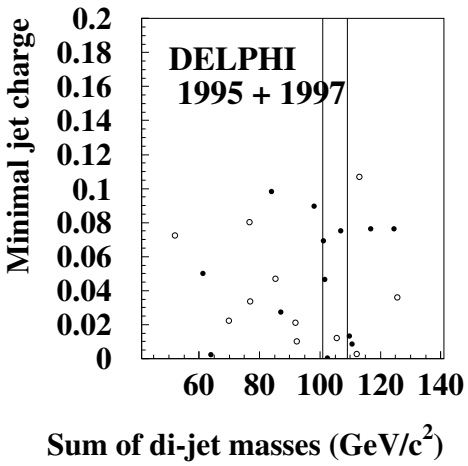

Figure 3: Smallest jet charge $Q_{\min}$ versus the sum of di-jet masses for 1995 (black dots) and 1997 (white dots) data. The mass region of interest is indicated by the vertical lines.

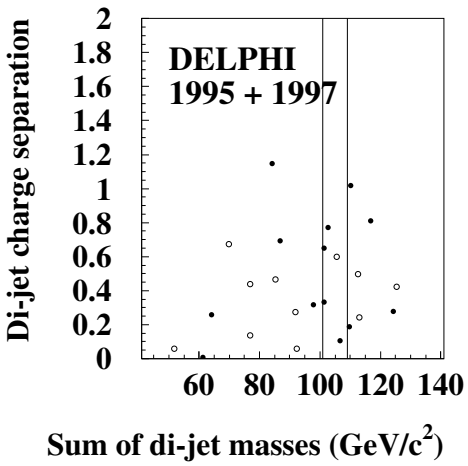

Figure 4: Di-jet charge separation ΔQ versus the sum of di-jet masses for 1995 (black dots) and 1997 (white dots) data. The mass region of interest is indicated by the vertical lines.

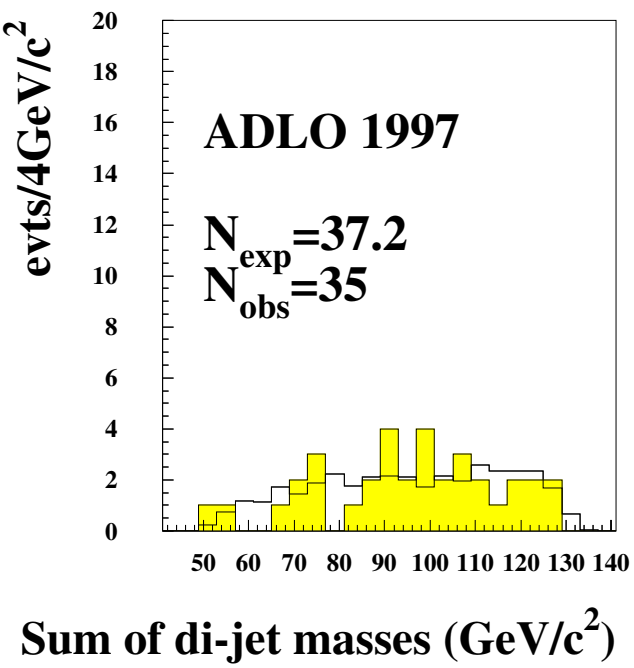

Figure 5: 1997 data: distributions of the sum of the di-jet masses for the pairing with the smallest mass difference after all selection cuts for ALEPH, DELPHI, L3 and OPAL combined. The shaded histogram shows the data, the open one shows the expectation from Standard Model processes.

6 Conclusions

The data collected by the DELPHI detector in October 1997 at centre-of-mass energies of 130 GeV and 136 GeV, corresponding to a total integrated luminosity of $5.94\,\mathrm{pb}^{-1}$, have been analysed to look for an anomaly in the production of four-jet events. Good agreement with the predictions of the Standard Model was found. The sum of di-jet invariant masses, the di-jet charge separations, and the smallest jet charges in the events were all fully compatible with expectations from Standard Model processes. In particular, no accumulation around $105\,\mathrm{GeV}/c^2$ in the sum of di-jet masses was found, with one event observed in the mass interval $105 \pm 4\,\mathrm{GeV}/c^2$ for 0.8 expected.

The results are compatible with the previous DELPHI results [2] and do not support the excess of four-jet events observed in 1995 by the ALEPH collaboration [1].

According to the criteria agreed before the data were taken, the combined LEP data from this 1997 run refuted the hypothesis that the excess was a sign of new physics at over 99% confidence level.

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