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Search for anomalous four-jet events in e^+e^- annihilation at $\sqrt{s} = 130 - 172$ GeV

L3 Collaboration

Abstract

A study of hadronic events with high jet-multiplicity is performed using the data sample collected by the L3 experiment at LEP at $\sqrt{s} = 130 - 172$ GeV. The observed event rates agree with the Standard Model predictions and upper limits are set on the production cross section of pairs of heavy particles that decay hadronically.

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1 Introduction

The increase in energy of the LEP accelerator opens new possibilities to investigate physics beyond the Standard Model. Several of these possibilities, like supersymmetric Higgs production and R-parity violation processes in Supersymmetry [1], are characterized by topologies with a high number of jets and no missing energy. The report from the ALEPH collaboration [2] of anomalous four-jet production has given additional motivation for the search in these channels.

In this paper we report on a search for anomalous four-jet events at $\sqrt{s} = 130-172$ GeV. The associated production of hadronically decaying particles (that is the process $\mathrm{e^+e^-} \rightarrow XY \rightarrow q\bar{q}\ q\bar{q}$) would show up as a resonance in the distribution of the invariant mass of the two pairs of jets. The choice among the three possible pairings of the jets depends on the signal searched for. In the hypothesis $M_X = M_Y$ the combination where the difference between the two reconstructed masses is the smallest is considered, while in case the two masses are allowed to be different the other combinations are also used.

2 Data Reconstruction and Monte Carlo samples

The data collected by the L3 experiment during the three runs of LEP at $\sqrt{s} = 130 - 140$ GeV (herein referred to as 133 GeV run) in 1995 , 161 GeV and $170 - 172$ GeV (herein referred to as 172 GeV run) in 1996 corresponding to an integrated luminosity of L=5.0 $\mathrm{pb^{-1}}$, 10.9 $\mathrm{pb^{-1}}$ and 10.3 $\mathrm{pb^{-1}}$ respectively are analysed.

A detailed description of the L3 detector and its performance is given in Reference [3]. Hadronic events are reconstructed using information from all subdetectors. In particular the energy of the event is obtained taking into account the energy deposition in the electromagnetic and hadronic calorimeters and the charged particles momenta measured by the central tracking chamber and the muon chambers.

In order to evaluate the expectations from Standard Model processes, Monte Carlo (MC) event samples of $q\bar{q}(\gamma)$, $e^+e^-q\bar{q}$, $Z/\gamma^*Z/\gamma^*$ were produced using PYTHIA [4] and W^+W^- using KORALW [5]. As a reference reaction to evaluate the efficiency on a possible signal, a sample of MC events $\mathrm{e^+e^-} \rightarrow \mathrm{hA} \rightarrow \bar{b}b\bar{b}b$ was generated with PYTHIA for several Higgs bosons h and A masses in the range from 30 to 130 GeV. All events were then fully simulated in the L3 detector using the GEANT library [6].

3 Analysis

3.1 Selection of four-jet events

The main sources of production of four-jet events in the Standard Model are hard gluon emission or jet misreconstruction in hadronic events and, at $\sqrt{s} \geq 161$ GeV, W and Z pair production. The separate contributions at the different energies are shown in table 1. The selection of four-jet events is divided in the following steps:

- High Multiplicity Requirement:
  Events are required to have at least 10 tracks and 30 calorimetric clusters. In addition the visible energy is required to be greater than 70% of the center-of-mass energy.

- Four-Jet Criteria:
  Events consistent with radiative return to the Z ($\mathrm{e^+e^-} \rightarrow \mathrm{Z}\gamma \rightarrow q\bar{q}\ \gamma$) are rejected by

process	$\sqrt{s} = 130$ GeV	$\sqrt{s} = 136$ GeV	$\sqrt{\mathrm{s}} = 161$ GeV	$\sqrt{\mathrm{s}} = 172$ GeV
$e^+e^- \to q\bar{q}$	336	280	149	124
$e^+e^- \to WW$	0.07	0.11	3.24	12.2
$\mathrm{e}^+\mathrm{e}^- \to Z/\gamma^* Z/\gamma^*$	0.50	0.47	0.46	0.43

Table 1: Cross sections (pb) of processes contributing to four-jet events production.

requiring the effective center-of-mass energy ($\sqrt{s'}$) to be greater than $0.87\sqrt{\mathrm{s}}$. If the radiative photon is not detected in the calorimeters $\sqrt{s'}$ is computed from the jet angles with the assumption that one photon has escaped in the beam pipe.

Jets are then reconstructed using the Durham [7] algorithm and events are rejected if they have less than four jets for the jet resolution parameter y_{cut} =0.008. In addition none of the jets must contain electromagnetic energy in excess of 85% of the jet energy. Events satisfying these requirements are reconstructed again but with a variable y_{cut} chosen in order to have exactly four jets.

A kinematic fit that requires four momentum conservation is applied to improve the energy and angular resolution. This constraint induces a negative correlation between the two jet pair masses such that the sum of the masses has a better resolution than the difference. Thus in the following the sum of the reconstructed masses of the two combinations with the smallest difference of masses (called respectively $\Sigma\mathrm{M}_1$ and $\Sigma\mathrm{M}_2$) are shown.

- Jet Quality Requirements:
  Events are rejected if any of the four jets has an energy smaller than $5\%\sqrt{s}$, has no tracks or is within an 8° cone around the beam pipe. After applying these criteria mainly QCD four-jet events and hadronic W decays are expected from Standard Model processes.

- Kinematic Requirements:
  QCD four-jet events predominantly consist of two nearly back to back energetic jets and two low energy jets. These events are therefore characterized by a high difference between the most and the least energetic jet ($\Delta_E = E_{max} - E_{min}$) and a maximum angle between jets (θ_{max}) close to 180°. The minimum invariant mass of jet pairs (M_{min}) is small.
  Events are therefore required to have $\Delta_E < 0.3\sqrt{s}$, $M_{min} > 0.18\sqrt{s}$ and, for the 161 GeV data, $\cos(\theta_{max}) > -0.95$.

- W Pair Rejection:
  W pair events are identified using a kinematic fit with the assumption that for one possible pairing of the four jets both di-jet invariant masses are equal to the W mass. Events are rejected if the χ^2 of this fit is small.

The number of events expected from Standard Model processes, the efficiency on the signal, for the mass points $M_h = M_A = 55$ or 60 GeV at 133 and $161 - 172$ GeV respectively, and the number of data events observed are shown in table 2. Agreement between data and MC is found at all the stages of the analysis as shown in figure 1. In order to search for signals where the two particles produced do not have the same masses both $\Sigma\mathrm{M}_1$ and $\Sigma\mathrm{M}_2$ are plotted in figure 2. No significant deviation from the Standard Model expectations is found in these distributions.

Set of cuts	N_{data}	N_{ex}	$\epsilon_s(\%)$
$\sqrt{s} = 130 - 140$ GeV			
High Multiplicity	1032	934±4	96.7±0.6
Four Jets	24	23.4±1.0	58.6±1.6
Jet Quality	19	19.3±0.9	57.6±1.6
Kinematics	14	9.6±0.6	48.6±1.7
$\sqrt{s} = 161$ GeV			
High Multiplicity	827	790±2	93.6±0.5
Four Jets	28	32.9±0.5	56.5±1.6
Jet Quality	24	29.2±0.4	55.1±1.5
Kinematics	7	10.0±0.3	35.5±1.5
WW rejection	6	7.9±0.2	33.8±1.5
$\sqrt{s} = 170 - 172$ GeV			
High Multiplicity	623	610 ±3	92.1 ±0.9
Four Jets	49	54.8±0.4	52.8 ±1.6
Jet Quality	48	49.8±0.4	50.7 ±1.6
Kinematics	33	36.4±0.2	40.8 ±1.6
WW rejection	14	14.0±0.2	31.1 ±1.4

Table 2: Number of data events observed (N_{data}), number of events expected from Standard Model processes (N_{ex}) and efficiency for an $e^+e^- \to hA$ signal at different stages of the analysis. The quoted errors are due to MC statistics only.

3.2 Experimental checks

Several studies using control data samples are carried out to verify the detector performance.

- Return to the Z events:
  A sample of radiative return to the Z events with an energetic, isolated photon in the electromagnetic calorimeter is selected. The measured photon energy is required to be within ±5 GeV of the expected one. These events are reconstructed imposing a three body constraint, assuming that the photon direction is known and leaving its energy free. The measured mass of the hadronic system peaks at the mass of the Z (figure 3a) and the width of the distribution in the data is 3.0 ± 0.2 GeV. There is agreement between data and MC and no shift is observed: the difference between the mean values is 0.2 ± 0.2 GeV. The consistency between data and MC confirms that the evaluation of the sensitivity to the signal using MC samples is correct.

- MC simulation of $e^+e^- \to hA$:
  In order to evaluate the mass resolution for a four-jet signal, the MC sample with $M_A = M_h = 55$ GeV at 133 GeV and $M_A = M_h = 60$ GeV at 161 and 172 GeV respectively were considered. The fit to the distribution of the sum of the masses ΣM_1 (figure 3b) gives a resolution of 2.2 ± 0.2 GeV at $\sqrt{s} = 133$ GeV, 2.5 ± 0.2 at $\sqrt{s} = 161$ GeV and 3.2 ± 0.2 GeV at $\sqrt{s} = 172$ GeV. The mean values of the fits are consistent with the generated mass values within 0.5 GeV.

- WW events at $\sqrt{s} = 172$ GeV:
  The distribution of the sum of the di-jet invariant masses ΣM_1 and ΣM_2 at $\sqrt{s} = 172$

GeV before the WW rejection (figure 4) shows a peak around 160 GeV due to W pair production. As a check of the analysis we extract the $e^+e^- \to W^+W^-$ cross section in a log-likelihood fit to this distribution assuming the Standard Model branching ratio of the W into hadrons. The result $\sigma_{WW} = (10.9 \pm 2.4(stat.))$pb is in agreement with the Standard Model prediction of 12.2 pb.

- Complementary analyses:
  In addition several analyses with different energy flows and kinematic rescalings have been performed yielding results similar to the one described in section 3.1.
  In particular an analysis close to the one published by the ALEPH collaboration [2] with similar efficiencies and resolutions was performed. The number of data events selected, the number of events expected from Standard Model processes and the efficiency on a possible signal are reported in table 3. The differences between this analysis and the one described in section 3.1 are in the jet reconstruction, in the di-jet quality requirements and in the WW rejection. For this analysis figure 5 shows the combined plot of ΣM_1 and ΣM_2 for the three running periods after all cuts. Also for this analysis we find good agreement between data and Standard Model expectations.

$\sqrt{s}$ (GeV)	N_{data}	N_{ex}	$\epsilon_s(\%)$
$130-140$	12	8.1±0.6	44.8±1.7
161	7	8.0±0.2	32.2±1.5
$170-172$	14	13.5±0.2	25.7±1.4

Table 3: Number of data events observed (N_{data}), number of events expected from the Standard Model (N_{ex}) and efficiency for the signal $e^+e^- \to$ hA (ϵ_s) using a selection that follows the one published by ALEPH. Errors are due to MC statistics only.

4 Results

Good agreement is found between our data and the expectations from the Standard Model both in the rate of four-jet events and in their mass spectrum. The DELPHI and OPAL collaborations reported on similar studies on $130-140$ GeV data [8].

Upper limits on the production cross section of possible new physics in this channel are derived using the events that satisfy the criteria described in section 3.1. The efficiencies calculated from the $e^+e^- \to$ hA$\to b\bar{b}b\bar{b}$ MC are assumed. The number of events predicted by the Standard Model is computed in ΣM_1 windows with a half width corresponding to approximately twice the resolution. The central ΣM_1 values of these windows are moved from 90 to 150 GeV in 1 GeV steps. In each window the maximum number of signal events compatible at 95% C.L. with our observation is calculated and converted into a cross section upper limit (σ_{lim}) at each center-of-mass energy (figure 6a-c). The combination of data at different center-of-mass energies is also made, assuming constant signal cross section.

Removing the constraint that the two hadronically decaying particles produced have equal masses, the same procedure is carried out for the sum of the masses selecting jet pairs with mass differences closest to 10 and 20 GeV. As shown in figure 6d the cross section upper limit σ_{lim} ranges between 0.7 and 1.6 pb for $\Sigma M_1 <$ 140 GeV.

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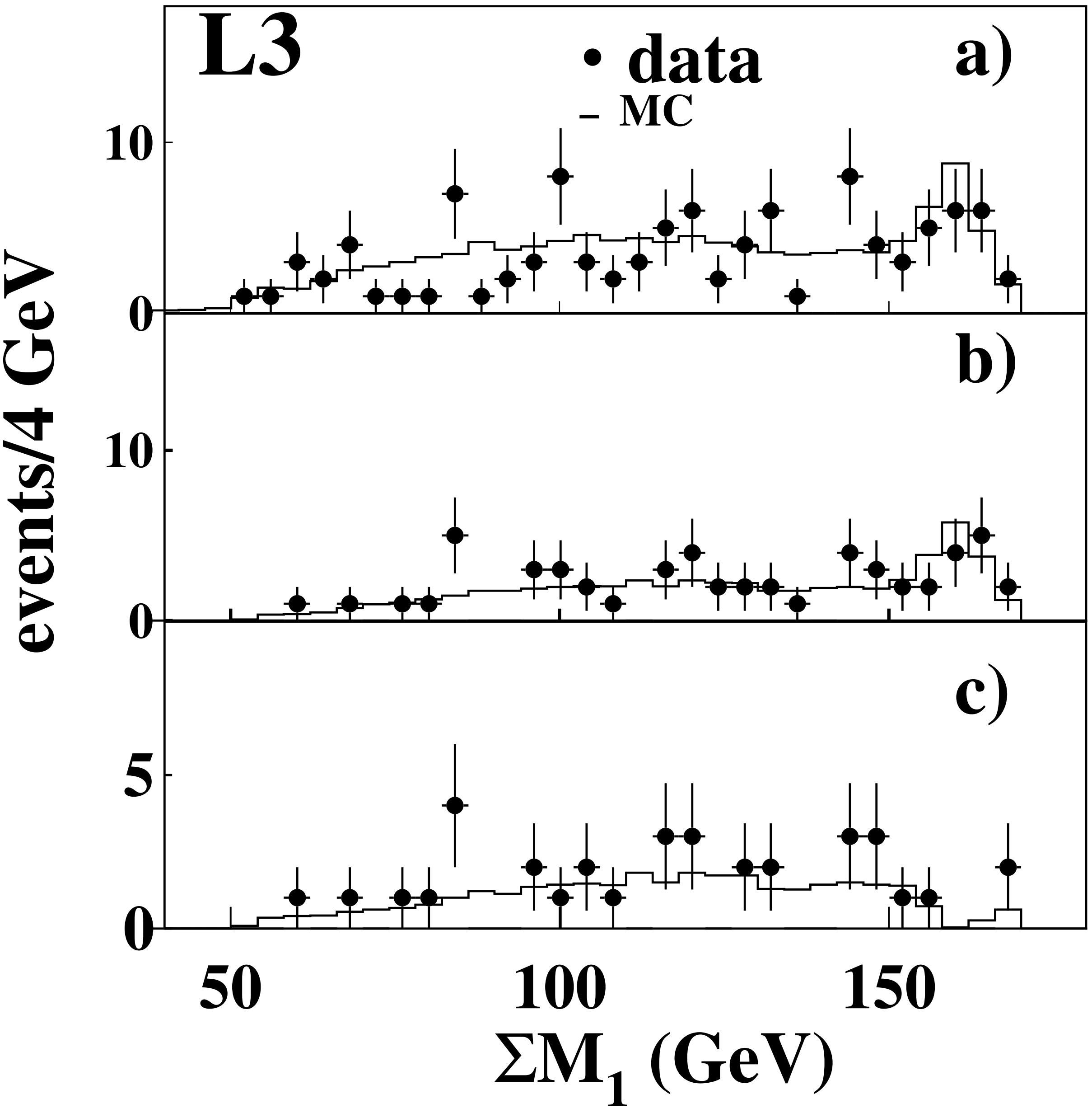

Figure 1: Distribution of the sum of the masses for the smallest difference (ΣM_1) at different stages of the analysis: (a) after the requirement of four jets, (b) after the requirements on kinematics and (c) after all cuts. Histograms are the expectations from the Standard Model while the dots are the data collected at $\sqrt{s} = 130 - 172$ GeV.

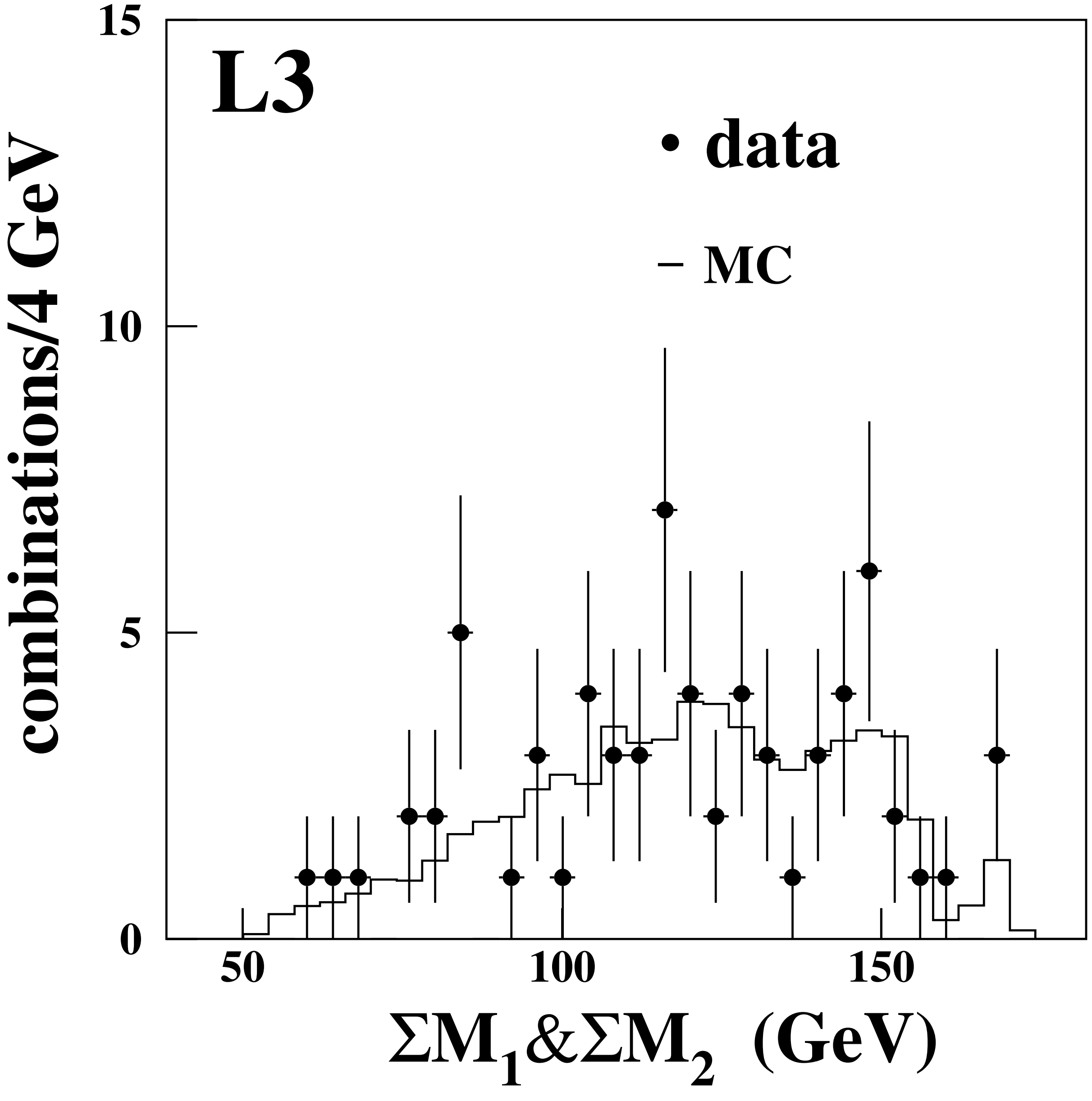

Figure 2: Distribution of the sum of the masses for the two smallest combinations (ΣM_1 and ΣM_2) together (two entries per event) after the selection. The whole data set collected at $\sqrt{s} = 130 - 172$ GeV is used.

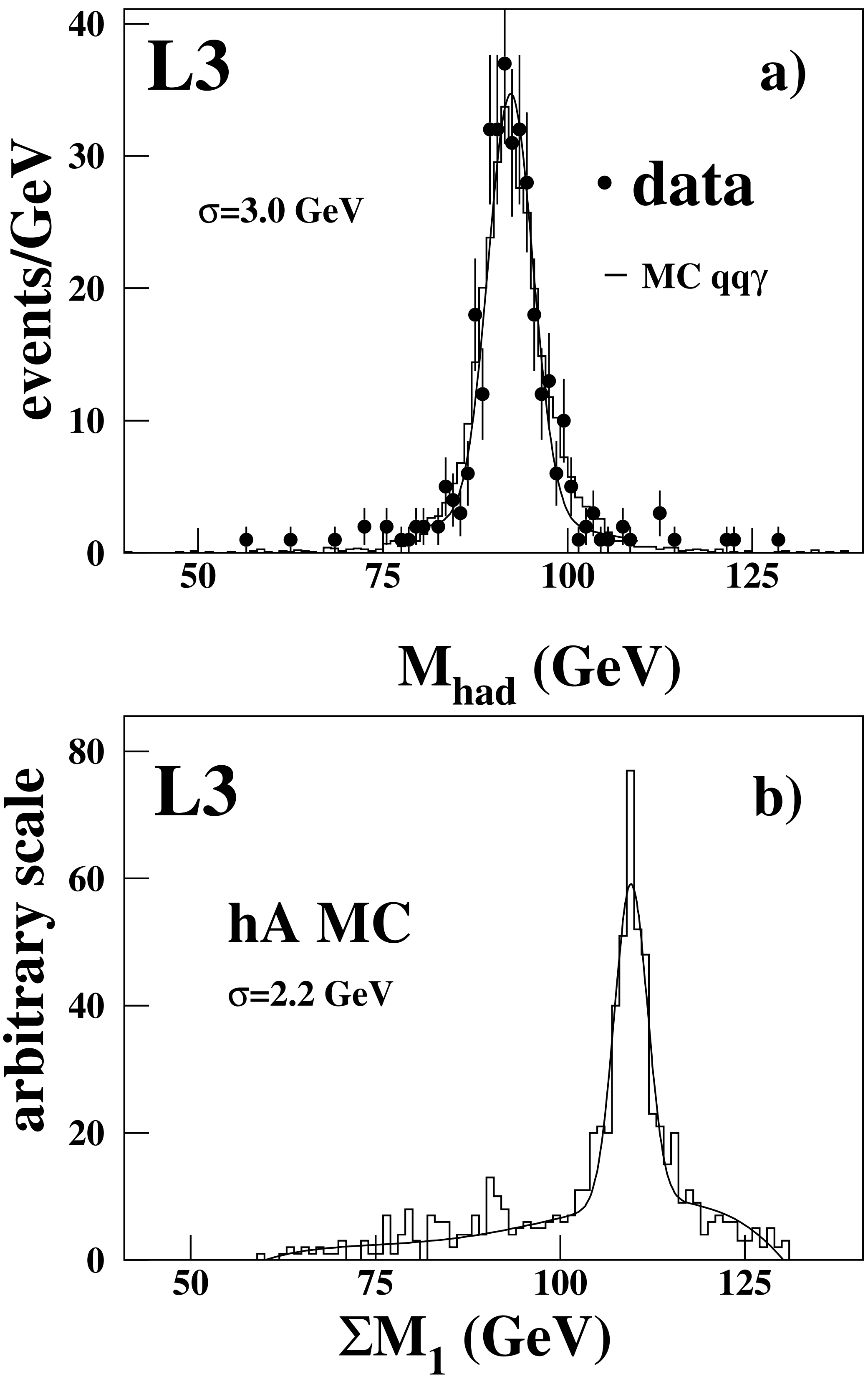

Figure 3: (a) Distribution of the reconstructed Z mass in $q\bar{q}\ \gamma$ events for data and MC at $130 < \sqrt{s} < 172$ GeV. (b) Spectrum of $\Sigma \mathrm{M}_1$ for an $\mathrm{e}^+\mathrm{e}^- \rightarrow$ hA MC sample with $M_A = M_h = 55$ GeV at $\sqrt{s} = 133$ GeV.

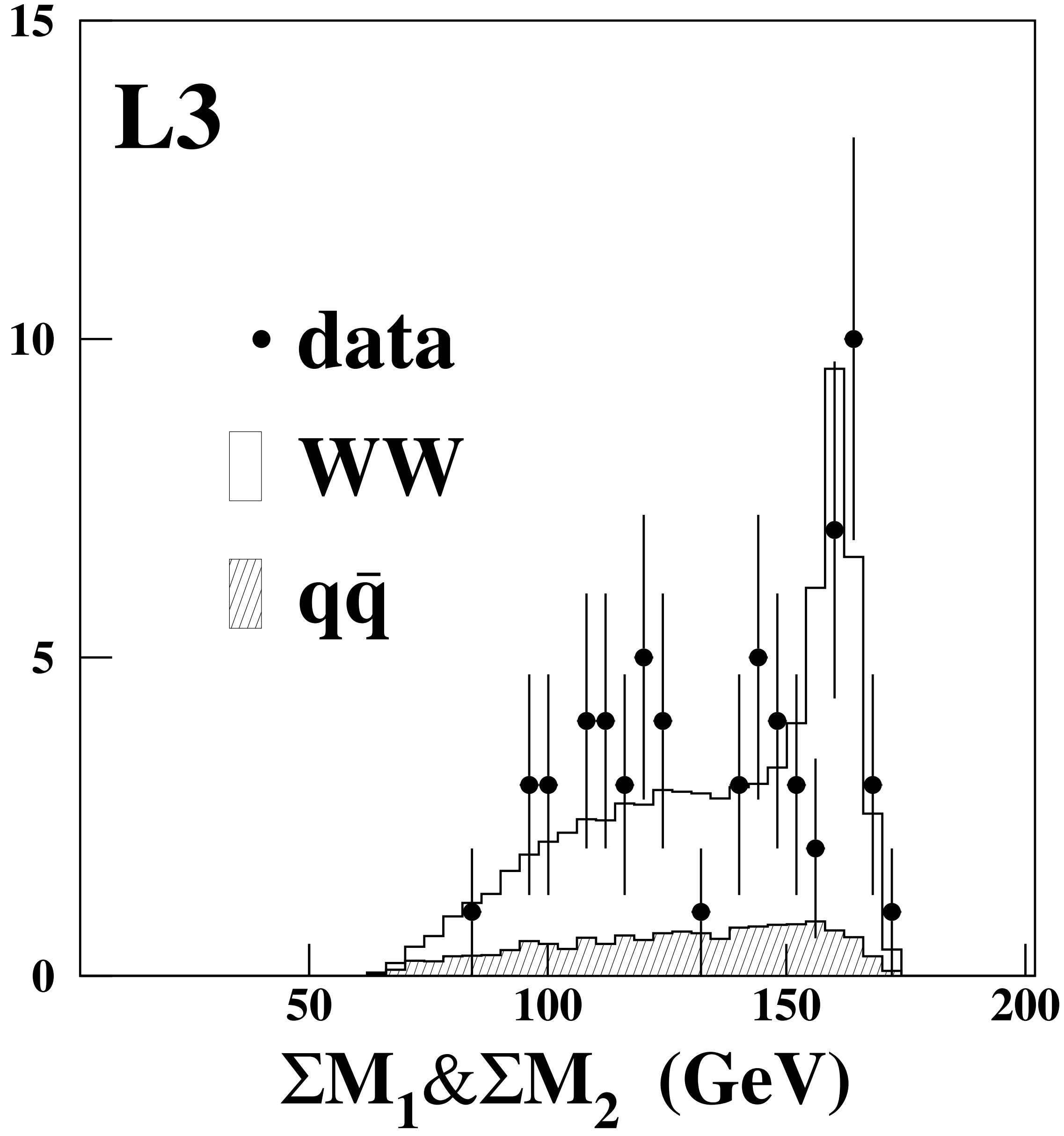

Figure 4: Distribution of $\Sigma\mathrm{M}_1$and $\Sigma\mathrm{M}_2$ at $\sqrt{s} = 172$ GeV before the WW rejection is applied.

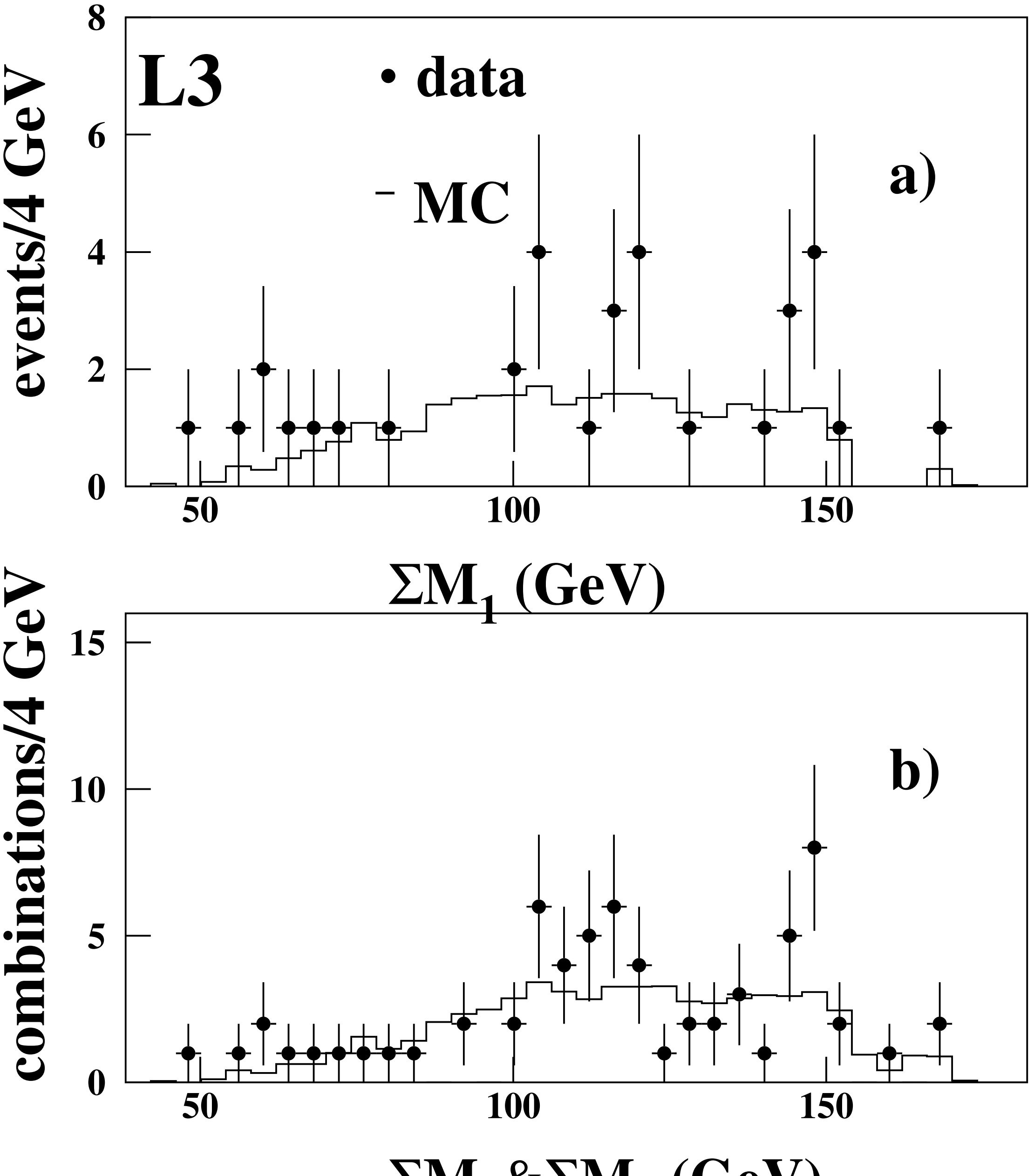

Figure 5: (a)Distribution of ΣM_1 and (b) of ΣM_1 and ΣM_2 with two entries per event obtained in the complementary analysis descibed in section 3.2. The data from $\sqrt{s}$ = 130 to 172 GeV are combined.

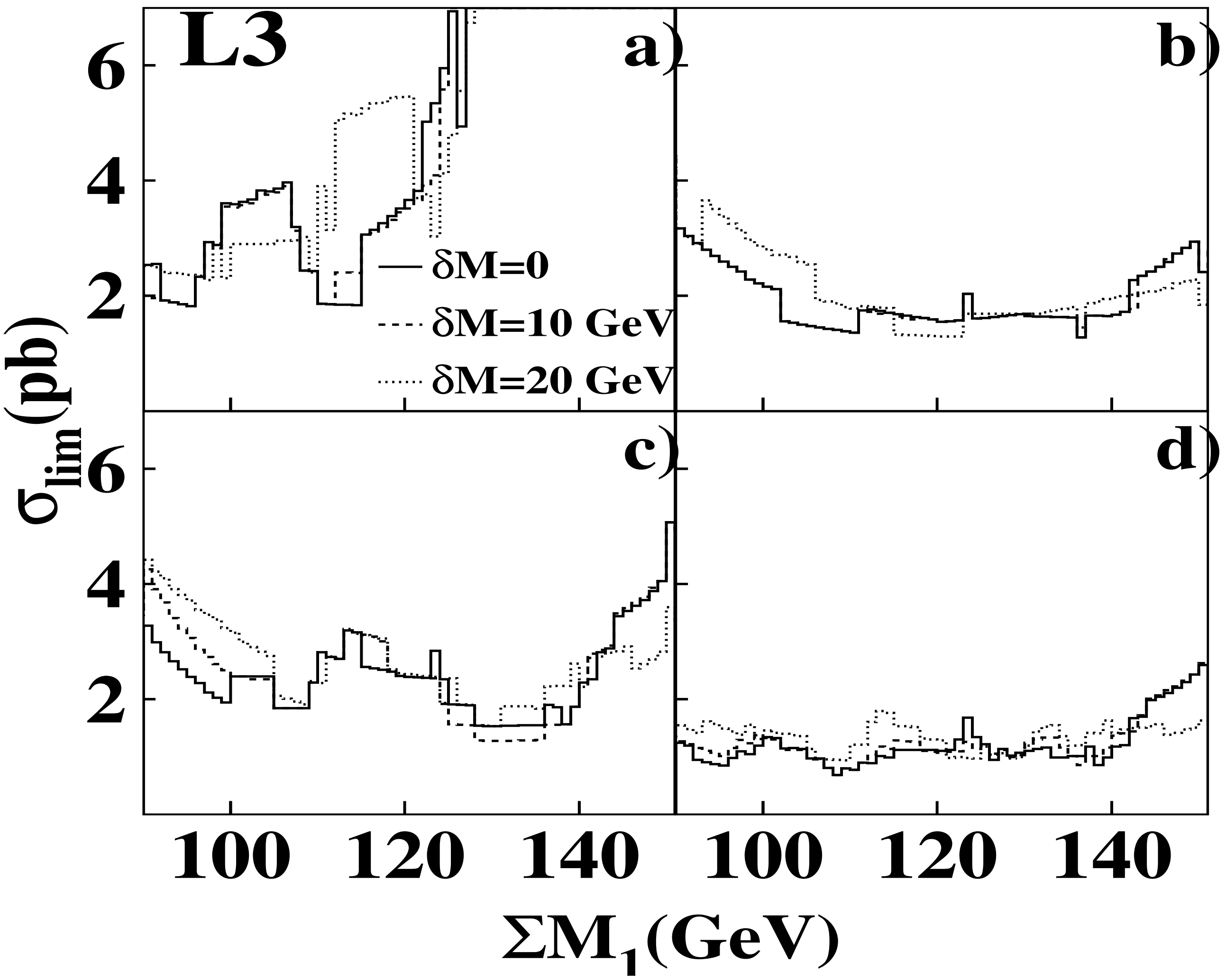

Figure 6: Maximum cross section (σ_{lim}) of a possible signal compatible with observations at 95% C.L. as a function of the sum of the masses ΣM_1: a) $\sqrt{s} = 133$ GeV, b) $\sqrt{s} = 161$ GeV, c) $\sqrt{s} = 172$ GeV and d) combination of the three center-of-mass energies assuming a cross section constant with energy. Three different hypothesis are considered: the difference between the masses of the two bosons produced being 0, 10 or 20 GeV.