AN ANALYSIS OF MULTIHADRONIC EVENTS PRODUCED WITH TWO ENERGETIC LEPTONS IN e^+e^- ANNIHILATION

CELLO Collaboration

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A search for multihadronic events produced with two energetic leptons has been performed at PETRA using 130 pb^{-1} accumulated by the CELLO detector at 35 GeV $\leqslant\sqrt{s}\leqslant$46.8 GeV. Three $\mu^+\mu^-$, eleven e^+e^- and three $e\mu$ events were observed. The measured yields and the event characteristics are in good agreement with the expectation from the α^4 QED processes $e^+e^-\to\ell^+\ell^-q\bar{q}$ and from semileptonic decays of pairs of heavy quarks.

1. Introduction

In 1984, the CELLO Collaboration observed an unusual multihadronic event produced in e^+e^- annihilation at $\sqrt{s}=43.45$ GeV [1]. This event, hereafter called "Event 1", contains two high energy muons produced together with two jets. All μ–μ, μ–jet and jet–jet invariant masses are large ($\geqslant 10$ GeV), a feature which made its explanation by conventional processes very unlikely, given the limited integrated luminosity accumulated at that time. Since then, CELLO has increased its statistics by almost a factor 10 at $\sqrt{s}>43$ GeV, and in addition large integrated luminosities have been accumulated at lower energies (table 1). Therefore, it was decided to search for events with a generally similar topology, and to compare their features with the expectation from simultaneous semileptonic decays of pairs of heavy quarks on the one hand, and from the α^4 QED processes $e^+e^-\to\ell^+\ell^-q\bar{q}$ on the other.

The CELLO detector is particularly well suited for lepton identification in a complex multiparticle environment. Its main characteristics can be found in ref. [2]; here we only mention the features most relevant for the present analysis. The central tracking device consists of interleaved cylindrical drift and proportional chambers, inside a 1.3 T axial magnetic field. The track detector provides charged particle momentum measurement over 92% of the solid angle with a resolution $\sigma_{P_T}=0.013\sqrt{1+P_T^2}\times P_T$ (P_T in GeV/c). Electromagnetic showers are measured in a lead–liquid argon calorimeter located outside the thin (0.5 X^0) superconducting solenoidal coil. The 20 X^0 thick calorimeter consists of a barrel part ($|\cos(\theta)|<0.86$) and of two end caps ($0.92<|\cos(\theta)|<0.99$). Its fine lateral and longitudinal segmentation provides efficient tools to distinguish electromagnetic and hadronic showers. The electromagnetic shower energy resolution is $\sigma(E)/E=0.05+0.10/\sqrt{E}$ (E in GeV). Finally, muons are identified over 92% of 4π in large planar drift chambers surrounding an 80 cm thick iron absorber.

Table 1
Energies and integrated luminosities of the data samples used in the present analysis; also shown, the energies at which the events in the $\mu^+\mu^-$, e^+e^- and $e\mu$ classes have been found.

$\sqrt{s}$(GeV)	$\mathscr{L}$(pb^{-1})	$N_{\mu^+\mu^-}$	$N_{e^+e^-}$	$N_{e\mu}$
35.00	86.0	2	8	2
38.28	8.9			
43.43	1.4	1		
43.60	17.0		3	1
44.20	9.2			
46.57	1.0			
43.4–46.8	7.2			

2. Lepton identification.

To qualify as an electron, a charged particle track had to be linked to an electromagnetic shower of energy above 1.5 GeV. The track momentum and the shower energy had to agree within 6σ, taking both momentum and energy resolutions into account. The longitudinal shower development was required to be compatible with that expected for an electromagnetic shower; typically, the energy fraction deposited in the

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first seven radiation lengths of the calorimeter had to exceed 0.4. In addition, in order to eliminate electrons originating from photons converted when passing through the beam pipe, it was required that no oppositely charged particle track be found within 1° of the direction of the candidate electron. For $|\cos(\theta)| < 0.85$, the efficiency of these criteria is 92% as determined using electrons from QED reactions, and the fraction of pions faking electrons is $\sim 0.5\%$, as measured with a sample of $\tau^+\tau^-$ events in which one of the τ's decays to three charged particles.

All charged particle tracks above 1.5 GeV/c were extrapolated to the muon detector. If the expected impact of the track was within 3σ from a hit, taking into account the track measurement errors and the multiple scattering, the particle was called a muon provided the absolute distance between the impact and the hit was less than 40 cm. With these criteria and for $|\cos(\theta)| < 0.85$, the muon identification efficiency rises from 50% at 1.5 GeV/c to 85% above 2.5 GeV/c. The fraction of pions faking muons is $< \sim 0.4\%$, again determined with τ decays to three charged particles.

3. Event selection

Two classes of events were selected: multihadronic events with two leptons; and four lepton events, the latter sample being kept for control purposes.

All charged particle tracks within $|\cos(\theta)| < 0.91$, except for the two highest energy leptons, and all neutral showers in the barrel and end cap calorimeters were taken into account to define the hadronic system. This hadronic system was boosted to its center of mass, and then divided into two halves with respect to a plane perpendicular to the sphericity axis. The ensemble of tracks and showers within a given hemisphere is called a jet.

The selection criteria for the multihadron sample were:

(i) at least 5 charged particles with $|\cos(\theta)| < 0.91$,

(ii) including at least 2 identified leptons with $|\cos(\theta)| < 0.85$,

(iii) one of these with a fractional energy XL1 > 0.2 (the second highest fractional lepton energy will be denoted XL2),

(iv) the lepton pair fractional invariant mass XLL > 0.2,

(v) the hadronic system fractional invariant mass XQQ > 0.115, and

(vi) the higher fractional mass of the two lepton–jet systems XLQ1 > 0.3, and the lower one XLQ2 > 0.05.

All fractional energies or masses are calculated with respect to the beam energy. Of the two possible lepton–jet pairings, the one with the smaller product XLQ1 × XLQ2 was taken. The selection criteria were chosen so that the α^4 QED processes were preferentially selected, but keeping away from the poles for vanishing XLL and XQQ. The purpose of the cuts on XLQ1 and XLQ2 is to depress the contribution from semileptonic decays of heavy quarks, in which the leptons tend to be emitted close to the jet directions. The cut values were optimized using the Monte Carlo simulations described below.

The 29 events surviving these criteria were visually inspected, and ten background events were rejected: interactions of a beam particle with the residual gas or with the beam pipe; radiative four lepton events with converted photons; events showing obvious errors in the charged track or shower pattern recognition, spoiling the energy measurements and/or the particle identification.

In addition, one e^+e^-–hadrons and one eμ–hadrons events were interpreted as resulting from the reaction $e^+e^- \to e^+e^-\tau^+\tau^-$, with one of the τ's decaying to three prongs, to be compared with a Monte Carlo expectation of 0.8 such events. Since the topological features of these events are clear enough, we prefer to remove them explicitly rather than statistically from the final sample. This finally contains

$3\mu^+\mu^-$ events, including "Event 1",

11 e^+e^- events,

3 eμ events,

at energies as indicated in table 1. Here, the event classes are labelled according to the nature of the lepton pair. No event with two like-sign muon or electron pair was observed. An event belonging to the $\mu^+\mu^-$ class (other than "Event 1" which was presented in ref. [1]), and an event belonging to the e^+e^- class are shown in fig. 1.

The selection criteria for the four lepton events were:

(i) exactly four charged particles with $|\cos(\theta)|$

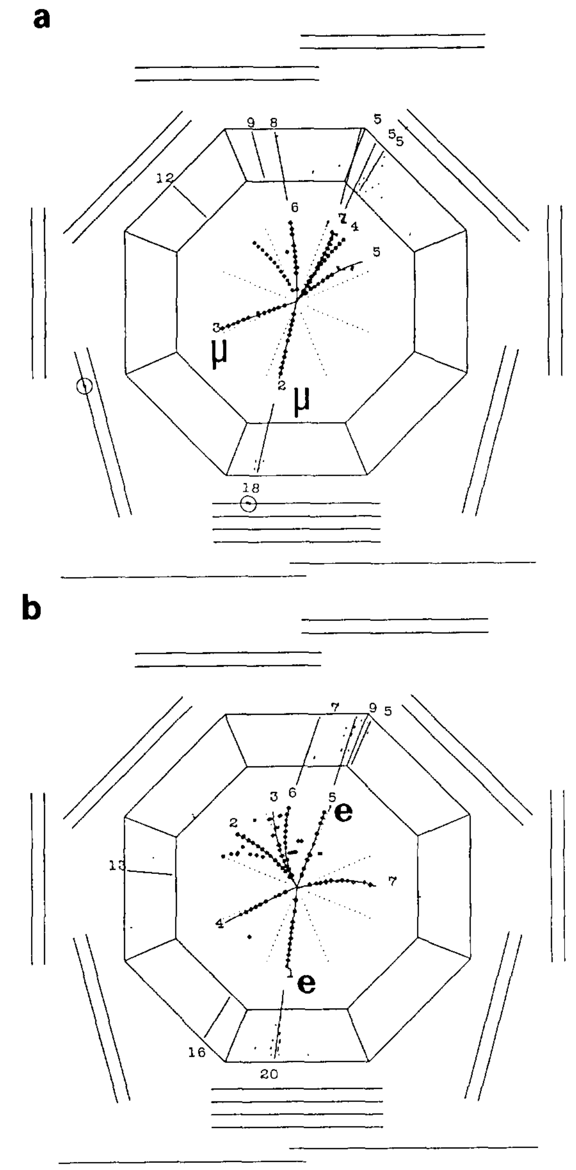

Fig. 1. Two examples of selected events: (a) In the $\mu^+\mu^-$ class. (b) In the e^+e^- class.

<0.91 and an arbitrary number of photonic showers,

(ii) at least three identified leptons with $|\cos(\theta)| < 0.85$, including at least one muon,

(iii)–(iv) as above, with the following conventions:
the two highest energy leptons are called "leptons" the remaining tracks and showers form the "hadronic" system.

These criteria led to five e^+e^- $\mu^+\mu^-(\gamma)$ events which all gave a good kinematical 3C-fit, allowing for an additional photon assumed to be emitted along the beam line.

4. Monte Carlo simulation

In order to compare the selected event yields and characteristics with the expectation from standard physics, the following reactions were simulated:
- the "QED" process $e^+e^- \to \ell^+\ell^-$ $q\bar{q}$, with $\ell = e$ or μ and $e^+e^- \to e^+e^-$ $\mu^+\mu^-$
- the "STG" process $e^+e^- \to (e)$ $eq\bar{q}$, followed by a semileptonic decay; (e) is undetected in the beam pipe; STG stands for "Single Tag",
- the "QCD" process $e^+e^- \to q\bar{q}$ (+gluons).

To generate "QED" and "STG" events, we used the generator of ref. [3]. Radiative corrections have been incorporated to leading order, using an equivalent radiator method based on the calculations of ref. [4]. The produced quarks were fragmented using the LUND 6.3 Monte Carlo program [5]. This program was also used to generate "QCD" events. In the case of the $e^+e^- \to \ell^+\ell$ $q\bar{q}$ reaction, the $\gamma q\bar{q}$ vertices occurring in the contributing diagrams shown in fig. 2 were modified so as to take into account the deviation of the measured cross section for $e^+e^- \to \gamma^* \to$ hadrons from the naive quark model expectation (in particular because of the occurrence of heavy quark resonances near threshold).

A simulation of the detector response and of the analysis procedure was applied to the generated events. In particular, geometrical acceptance, reconstruction inefficiencies, shower energy and track momentum resolutions, electron and muon identification efficiencies and the corresponding hadron contamination probabilities were taken into account.

The four lepton channel was used to check the simulation procedure of the α^4 QED reactions. From the Monte Carlo simulation, we expect 4.0 ± 0.1 e^+e^- $\mu^+\mu^-$ events, in agreement with our observation of five events.

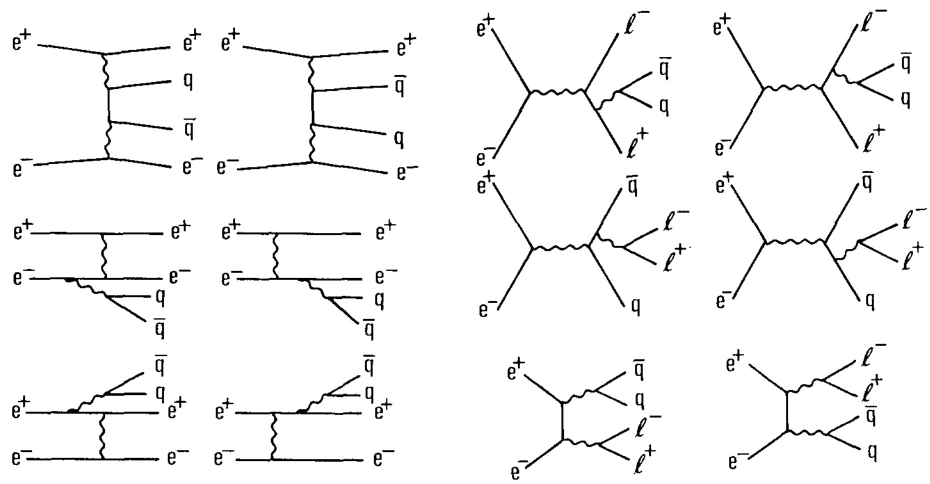

Fig. 2. Feynman diagrams contributing to the reaction $e^+e^- \to \ell^+\ell^- q\bar{q}$. If $\ell \neq e$, only the six diagrams to the right contribute.

5. Results

In table 2, the numbers of events observed in the various classes are compared with the expectations from the "QED", "STG" and "QCD" processes. Within the rather limited statistics, the overall agreement is good. In particular, the non-observation of like-sign ee or μμ events is a good indication that the lepton misidentification probabilities are not significantly underestimated.

Fig. 3 shows the distributions of the dynamical variables used in this analysis for the $\mu^+\mu^-$ and e^+e^- classes, both for the observed events and for the Monte Carlo expectations. The overall agreement is very satisfactory. In a more quantitative fashion, we have performed a likelihood test on the XLL, XQQ, XLQ1 and XLQ2 distributions simultaneously for our data on the one hand, and for a large number of Monte Carlo experiments, each with a number of events equal to the number of events observed, on the other. We found that 13%, 61% and 17% of the Monte Carlo experiments were less likely than our actual experiment for the $\mu^+\mu^-$, e^+e^- and eμ classes respectively, thus showing no evidence for disagreement between data and expectation.

It turns out therefore that the $\mu^+\mu^-$ class does not deviate particularly from expectation. If we let the fraction of "QED" events vary freely in this class, the maximum of likelihood is obtained when two events, among which "Event 1", are ascribed to the "QED" process, with the third event being "QCD" like. This sharing of events is well consistent with expectation, as can be inferred from table 2.

A detailed description of the analysis reported here

Table 2
Expected and observed numbers of events (see the text for the definitions of the "QED", "STG" and "QCD" processes). The errors on the numbers of events expected reflect the limited Monte Carlo statistics.

Class	Expected				Observed
	QED	STG	QCD	total	
$\mu^+\mu^-$	1.3 ± 0.1		1.2 ± 0.2	2.5 ± 0.2	3
e^+e^-	7.2 ± 0.2	0.5 ± 0.1	1.4 ± 0.3	9.1 ± 0.4	11
$\mu^\pm\mu^\pm$			0.3 ± 0.1	0.3 ± 0.1	0
$e^\pm e^\pm$		0.4 ± 0.1	0.5 ± 0.2	0.9 ± 0.2	0
eμ		0.8 ± 0.1	3.3 ± 0.4	4.2 ± 0.4	3

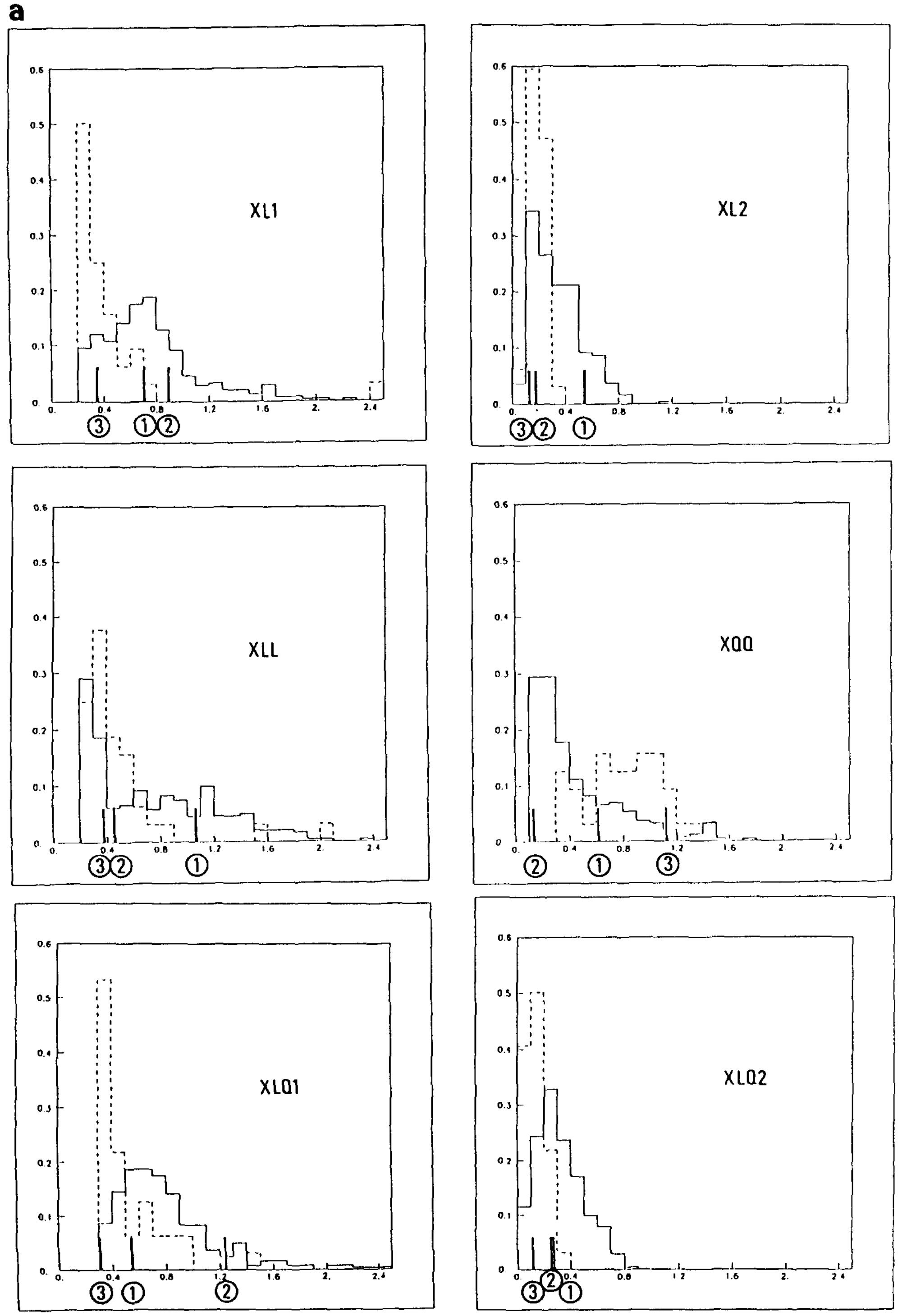

Fig. 3. Distributions of the dynamical variables XL1, XL2, XLL, XQQ, XLQ1, XLQ2 (see the text for their definitions): (a) For the $\mu^+\mu^-$ class. (b) For the e^+e^- class. Full histogram: QED Monte Carlo prediction. Dashed histogram: STG+QCD Monte Carlo prediction. The Monte Carlo predictions are normalized to the experimental luminosity (table 1). The position of each observed event is indicated by a vertical bar. In (a) the observed events are individually numbered.

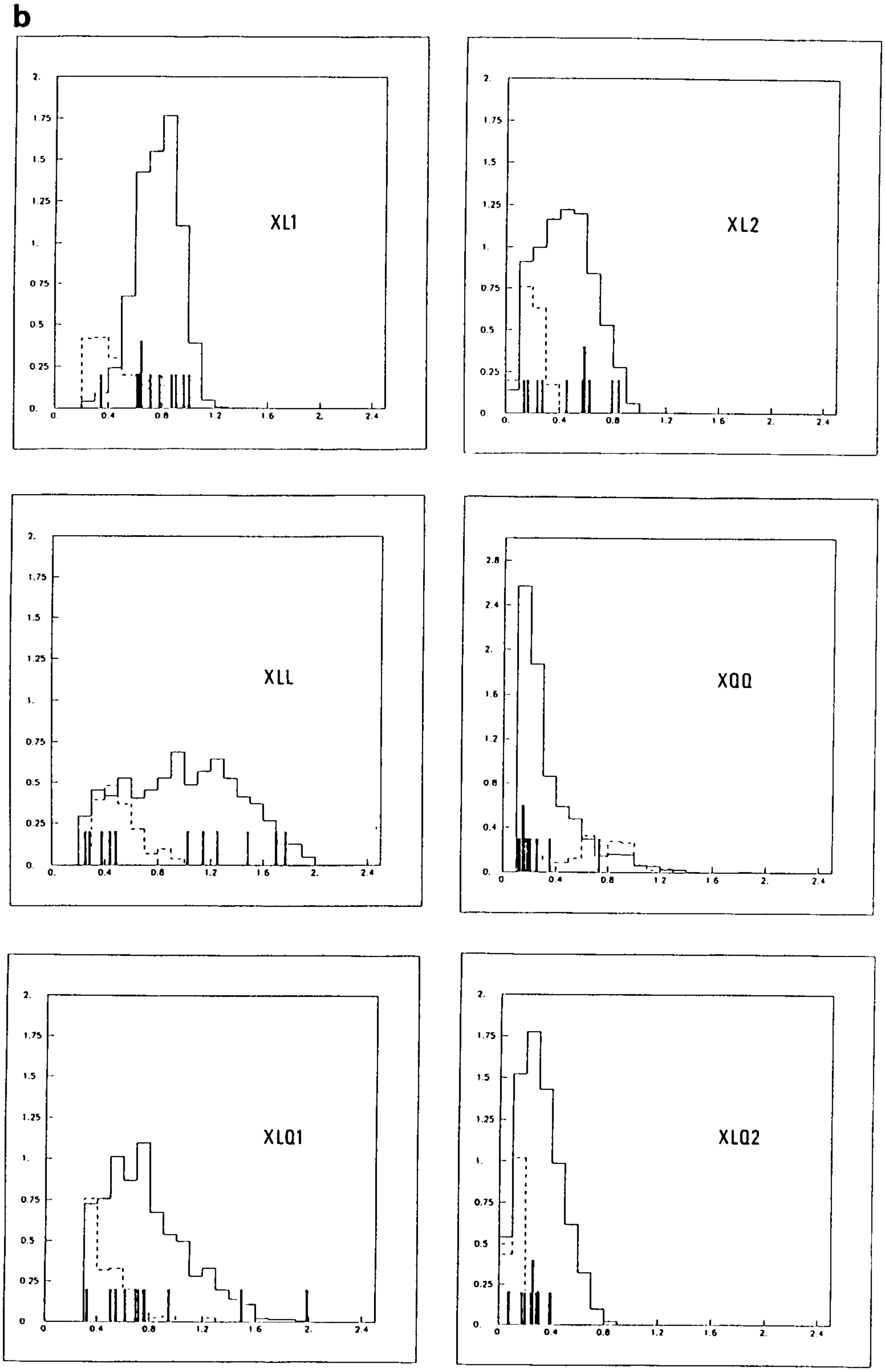

Fig. 3. continued.

can be found in ref. [6]. A less comprehensive study of the $\mu^+\mu^-$ class has been performed by the JADE Collaboration who also observe no disagreement with expectation [7].

6. Conclusion

In 130 pb^{-1} collected by the CELLO detector at $\sqrt{s} \geqslant 35$ GeV, we have searched for multihandronic events produced with two leptons and with large invariant masses for the lepton–lepton, lepton–jet and jet–jet pairs. Three such events with a $\mu^+\mu^-$ pair (including the previously reported event [1]) and eleven with an e^+e^- pair were observed. These numbers and the event characteristics are in good agreement with the expectation from α^4 QED and from semileptonic decays of heavy quarks.

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