OBSERVATION OF A MULTIPARTICLE EVENT WITH TWO ISOLATED ENERGETIC MUONS IN e^+e^- INTERACTIONS

CELLO Collaboration

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An event from e^+e^- annihilation at $\sqrt{s} = 43.450$ GeV containing two topologically isolated energetic muons and two hadronic jets has been observed. The masses of the $\mu-\mu$, jet–jet and μ–jet combinations are all large. The expected number of such events from known processes is about 10^{-3}.

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High-energy data between 43.2 and 45.2 GeV CM energy taken late in 1983 by the CELLO detector at PETRA have been analysed to search for multihadronic events with isolated muons. The data correspond to an integrated luminosity of 3.9 pb^{-1}. Such events might indicate the production of new particles. This search has led to the finding of an unusual event where most of CM energy is shared between the charged particles and two topologically isolated energetic muons.

The CELLO detector [1] has good multiparticle event detection and lepton identification. Interleaved cylindrical drift and proportional chambers measure charged particle momenta over 92% of the solid angle. The momentum resolution is $\sigma_{p_T} \simeq 0.013(1+p_T^2)^{1/2} p_T$ (p_T in GeV/c) using a constrained vertex.

Electromagnetic showers are measured in a lead–liquid-argon calorimeter over 86% of 4π sterad with an neergy resolution of $\sigma(E)/E \simeq 0.13/\sqrt{E}$.

The muon detector consists of large planar drift chambers mounted on a hadron absorber made of 80 cm thick iron. The muon identification is possible in 92% of 4π sterad with a spacial resolution of 0.6 cm.

Searching for isolated leptons we started by performing the muon search – for isolated electrons large backgrounds from inelastic e–γ scattering and Compton scattering are expected [2] – using the following criteria:

(1) At least five charged particles with $p_T \geqslant 120$ MeV/c.

(2) An isolated particle with momentum $\geqslant 4$ GeV/c in the central detector (angle between the track direction and the beam direction $30° < \theta < 150°$) and no other charged particles in its neighbourhood: $\cos\delta_{min} < 0.8$, where δ_{min} is the angle between the direction of the energetic track and the direction of the nearest charged particle with $p_T \geqslant 120$ MeV/c.

(3) An invariant mass of all charged particles $\geqslant 8$ GeV/c^2 in order to reject 2γ-mediated processes.

(4) Finally, the nature of the isolated particle was defined by requesting a reconstructed point in a muon chamber. This point had to match the extrapolation of the track through the hadron filter taking into account multiple scattering and the track covariance matrix. In addition, we demanded an energy deposition in the liquid-argon calorimeter associated to the isolated track which is compatible with a minimum ionizing particle. This selection procedure led to five candidates, among which is the event with two energetic muons presented here. The second muon in this event does not satisfy strictly our selection criteria due to a low energy track inside the isolation cone. No similar event is seen with two energetic electrons identified with high-energy showers in the central electromagnetic calorimeter.

A view of the event in the plane perpendicular to the beam axis is shown in fig. 1. The event has a low aplanarity of $A \simeq 0.003$ (A with respect to the two-muon plane is 0.063 and $\langle|p_T^{out}|\rangle \simeq 270$ MeV/c, where p_T^{out} is the momentum perpendicular to the two-muon plane) and has the structure of two subsystems each containing a high-momentum muon back to back to a jet of hadrons. This structure is evident also from the nearly equal masses found when the jet and the muon are paired in this way.

Sphericity and thrust values are respectively 0.36 and 0.86. Transverse momenta relative to the thrust axis are 7.2 GeV/c for the μ^+ and 4.2 GeV/c for the μ^-. The closest particle to the μ^+ is at $\cos\delta_{min} \simeq 0.47$ while the closest one to the μ^- is at $\cos\delta_{min} \simeq 0.97$. Values for muon and jet momenta and μ–μ and μ–jet invariant masses are given in tables 1, 2. Here we assumed that all particles in the jets are pions. There is almost no additional energy detected in the calorimeter. Since nearly all the visible energy is equal to the available center of mass energy, we performed kinematic fits. The 4-C and 3-C fits (where in the latter we allow for the emission of a radiative photon along the beam line) did not give acceptable fit probabilities. A 1-C fit accounting for the loss of a single light particle gave a satisfactory solution with the following momentum vector:

$$p_x = -2.4 \pm 0.8 \text{ GeV}/c\,.$$

$$p_y = -1.1 \pm 1.2 \text{ GeV}/c,$$

$$p_z = 2.3 \pm 0.5 \text{ GeV}/c\,.$$

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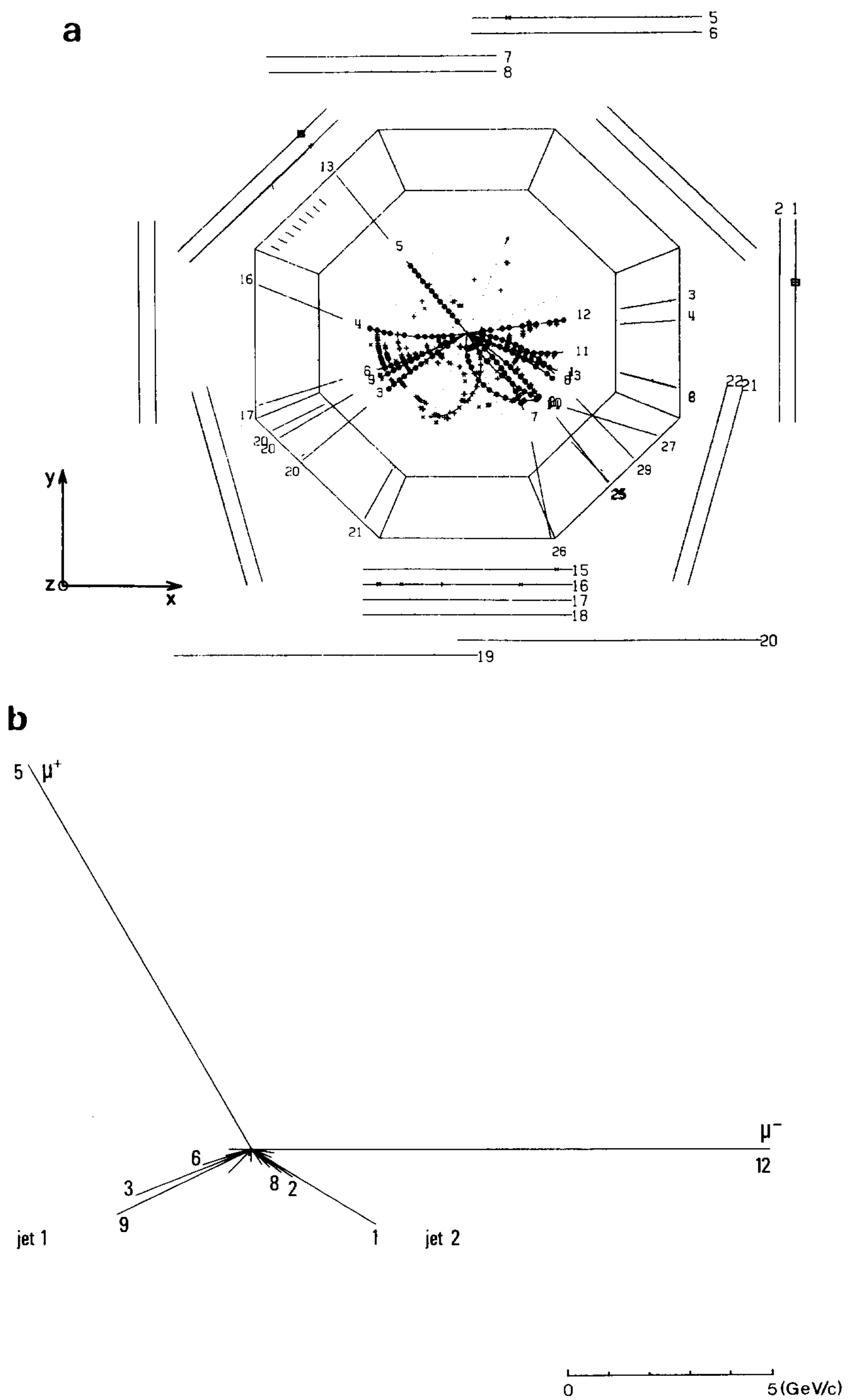

Fig. 1. (a) Event view in the plane perpendicular to the beam axis. The coordinate system is indicated. (b) Momentum diagram in the $\mu^+\mu^-$ plane, the track numbers are as specified for (a).

Table 1
Muon and jet four-vectors (GeV).

	E	p_x	p_y	p_z	M
μ^+	11.0	−7.0	8.5	0.5	0.105
μ^-	12.6	11.0	1.3	−6.1	0.105
jet 1	10.1	−7.4	−4.2	4.8	2.4
jet 2	9.1	6.7	−3.5	−2.0	4.7

Table 2
Invariant masses (GeV)

	μ^+	μ^-	jet 1
jet 2	19.4 ± 1.3	9.5 ± 0.5	17.3 ± 0.3
jet 1	14.1 ± 1.0	22.2 ± 1.6	
μ^-	20.4 ± 1.1		

Such a particle could well have escaped detection if it were a photon between two calorimeter modules, or a non-interacting K^0_L, or neutrinos provided their combined mass remains small. Because of the unusual topology of the event we have made fits for the production of a pair of particles with equal masses by grouping the muons and jets in pairs, where the pairs represent the decay of each primordial particle. For the three possibilities, namely $\mu^+\mu^-$–jet$_1$ jet$_2$, μ^+jet$_2$–μ^-jet$_1$, μ^+jet$_1$–μ^-jet$_2$, we deduce as primordial particle masses 19, 21 and 14 GeV/c^2, respectively. However, since the assignment of particles to the two jets is not unique, we cannot rule out other possible solutions. We note that the planar topology of the event favours the higher μ–jet-mass solution.

We now consider whether any conventional sources of events with muon pairs could account for this event. In multihadronic events from e^+e^- annihilation, muons have their origin in semileptonic decays of heavy quarks and meson decays in flight. In addition punch-through and background in the muon chambers give fake muon signals. To get an estimate for all these contributions, the LUND event generator [3] was used with the muonic branching ratios $BR(b \to \mu\nu_\mu + X) \sim 0.12$ and $BR(c \to \mu\nu_\mu + X) \sim 0.09$ and the Peterson fragmentation function [4] for heavy quarks. This generator was found to agree with data in a previous search for isolated muons at $\sqrt{s} = 34$ GeV. Multiplicities and prompt lepton momenta from B and D meson decays in their rest frame had been found to be in good agreement with data from DELCO and CLEO [5]. In our analysis of inclusive leptons [6] and in the TASSO analysis [7], both of which used the LUND event generator with the same fragmentation functions, the transverse momenta of leptons relative to the thrust axis of the events were correctly described by the Monte Carlo. We also checked that charged multiplicities and momentum spectra of hadrons in multihadronic events were well reproduced by the simulation. Table 3 shows in parentheses the number of expected events for different $\cos\delta_{min}$ values. We studied the $\cos\delta_{min}$ distribution for energetic hadrons at $\sqrt{s} = 34$ GeV ($p \geqslant 4$ GeV/c) and no discrepancies were found between data and Monte Carlo (fig. 2). In the present data 22 events with isolated hadrons ($p > 4$ GeV/c, $\cos\delta_{min} \leqslant 0.8$) have been found where 28 were expected from our simulation. Furthermore we have estimated the probability for energetic hadrons to fake prompt muons using our detector-simulation program. In this program, hadrons are propagated through the lead–liquid-argon calorimeter

Table 3
Expected number of events from $e^+e^- \to q\bar{q}(g)$. Numbers are given for the expected number of isolated hadrons faking 2 muons, and for the semileptonic decay of b and c quarks in brackets. $p > 6$ GeV/c.

	$\cos\delta_{min} < 0.98$	$\cos\delta_{min} < 0.9$	$\cos\delta_{min} < 0.8$	$\cos\delta_{min} < 0.5$
$\cos\delta_{min} < 0.98$	2.7×10^{-2} (2.0×10^{-2})			
$\cos\delta_{min} < 0.9$	1.6×10^{-2} (1.3×10^{-2})	6.1×10^{-3} (5.0×10^{-3})		
$\cos\delta_{min} < 0.8$	4.0×10^{-3} (2.5×10^{-3})	1.8×10^{-3} (1.6×10^{-3})	$<8.0 \times 10^{-4}$ $(<8.0 \times 10^{-4})$	
$\cos\delta_{min} < 0.5$	$<8.0 \times 10^{-4}$ $(<8.0 \times 10^{-4})$	$<8.0 \times 10^{-4}$ $(<8.0 \times 10^{-4})$	$<8.0 \times 10^{-4}$ $(<8.0 \times 10^{-4})$	$<8.0 \times 10^{-4}$ $(<8.0 \times 10^{-4})$

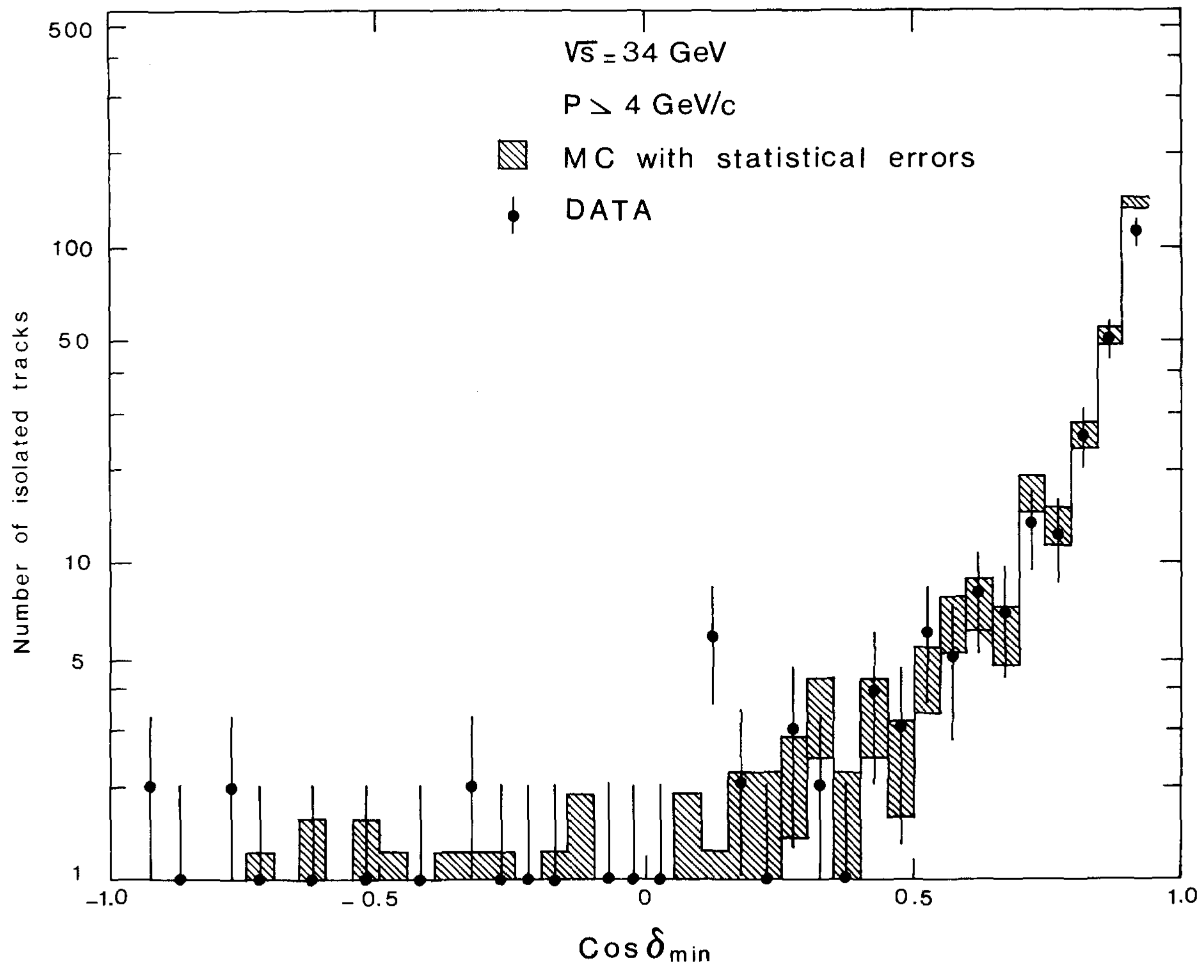

Fig. 2. A comparison of Monte Carlo and data for the distribution of $\cos\delta_{min}$ at 34 GeV CM energy for hadrons with $P > 4$ GeV/c (δ_{min} is the angle between the direction of the energetic track and the direction of the nearest charged particle).

and the hadron filter. The ability of the program to reproduce punch-through correctly was checked by comparing its results for different absorber thicknesses with measurements [8]. The overall punch-through probability in our detector is 0.03 ± 0.01 (systematic) for energetic hadrons ($p = 7$ GeV/c). From this complete simulation of multihadron production and detection in the detector, we find an expected number of 8×10^{-4} events in which two energetic muons ($p > 10$ GeV/c) are isolated from all other charged particles by a cone about their directions of 10 degrees. This is a conservative estimate since one of the muons in the event has the nearest charged particle at $\cos\delta_{min} = 0.47$. Table 3 also shows the number of events expected for different $\cos\delta_{min}$ values.

Electromagnetic processes with two virtual photons can also contribute to a $\mu^+\mu^-$ two-jet final state. For order α^4, several types of diagram can be considered, as shown in fig. 3, each of which corresponds to two distinct graphs.

From the observation that a good description of $e^+e^- \to \mu^+\mu^-\gamma$ can be found [9] for $M_{\mu\mu} \lesssim \frac{1}{2}\sqrt{s}$ with a cross section which factorizes into $e^+e^- \to \gamma\gamma^*$ and $\gamma^* \to \mu^+\mu^-$ (where γ^* stands for a virtual photon

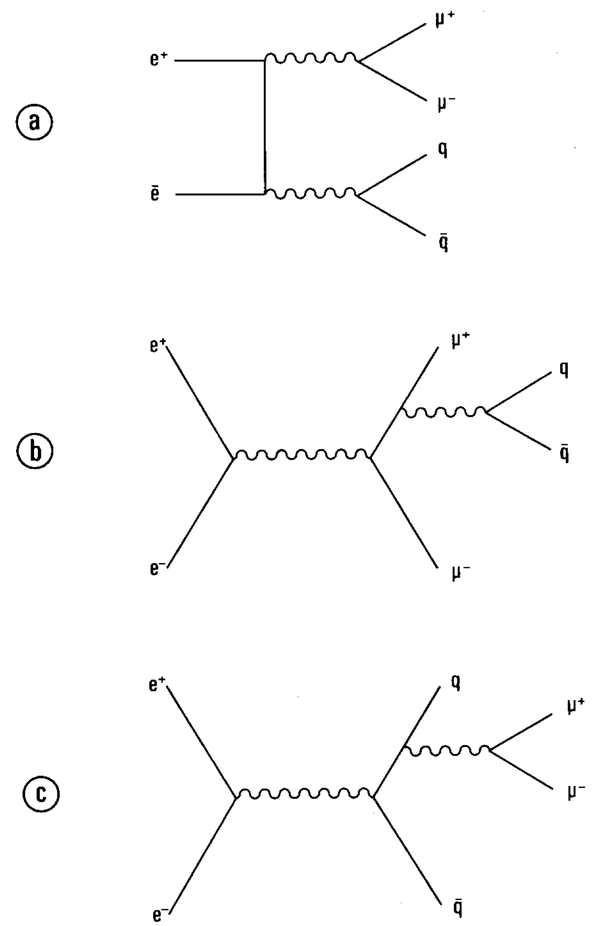

Fig. 3. Feynman graphs for $e^+e^- \to q\bar{q}\mu^+\mu^-$ for order α^4.

with a mass $M_{\mu\mu}$), we apply the same method to process a) and argue that it is the dominant graph when $M_{\mu\mu}$ and $M_{q\bar{q}}$ are both large. We therefore write

$$d^3\sigma/dM^2_{\mu\mu}\,dM^2_{q\bar{q}}\,d\cos\theta_{\gamma^*} \qquad (1)$$

$$= (\alpha/3\pi)^2(R(M^2_{q\bar{q}})/M^2_{\mu\mu}M^2_{q\bar{q}})\,d\sigma(M_{\mu\mu}, M_{q\bar{q}})/d\cos\theta_{\gamma^*}$$

where $d\sigma/d\cos\theta_{\gamma^*}$ is the differential cross section for $e^+e^- \to \gamma^*\gamma^*$ which takes into account the fact that the photons are off-mass shell, both for the amplitude and the phase-space factor. We have checked our off-mass shell procedure by comparison with the processes $e^+e^- \to Z^0Z^0$ and $e^+e^- \to Z^0\gamma$ [10]. $R(M^2_{q\bar{q}})$ is the ratio of $\sigma(ee \to \text{hadrons})$ to $\sigma(ee \to \mu\mu)$ at $s = M^2_{q\bar{q}}$.

As already mentioned, such a factorized expression describes well the process $e^+e^- \to \mu^+\mu^-\gamma$ for low $\mu\mu$ masses. In fact the factorization property can be shown to be exact in this limit [11]. It is interesting that the same description holds true to good approximation up to $M_{\mu\mu} \sim \frac{1}{2}\sqrt{s}$. We have checked this point in our present data. We expect 0.8 $\mu^+\mu^-\gamma$ events with $M_{\mu\mu} > 8$ GeV and $30 < \theta_\gamma < 150°$, and we find one event.

A further check is made by comparing the predicted yield of $\mu^+\mu^-\ell^+\ell^-$ to the result of a recent calculation by Kleiss [12]. At $\sqrt{s} = 30$ GeV, for $M_{\mu\mu}$, $M_{\ell\bar{\ell}} > 1$ GeV and $45° < \theta_\mu, \theta_\ell < 135°$, we calculate a cross section of $(6.8 \pm 0.3) \times 10^{-3}$ pb, whereas Kleiss obtains $(8.2 \pm 0.5) \times 10^{-3}$ pb using diagrams (a), (b) and (c) [‡1]. Thus while this comparison concerns mostly masses lower than the observed ones, we feel that neglecting diagrams (b) and (c) is still justified for the production of higher mass pairs.

Using expression (1) and a full MC simulation of $q\bar{q}$ jets [3] we have computed the expected number of events within our selection criteria for $\mu\mu$ and $q\bar{q}$ masses larger than 5 GeV/c^2. The results are given in fig. 4. We find the probability to observe one event of

[‡1] R. Kleiss has since evaluated the α^4 QED cross section for $e^+e^- \to \mu^+\mu^- q\bar{q}$ for our configuration using all six contributing graphs and finds good agreement with our results.

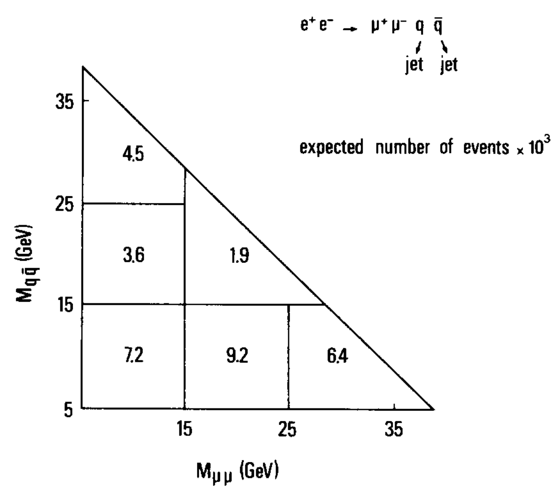

Fig. 4. Number of expected events ($\times 10^3$) for $e^+e^- \to q\bar{q}\mu^+\mu^-$ process within acceptance and selection criteria as a function of $\mu^+\mu^-$ and $q\bar{q}$ masses estimated from the diagrams in fig. 3.

this process with $\mu\mu$ and $q\bar{q}$ masses equal to or greater than the observed masses is less than $(3.2 \pm 1.0) \times 10^{-4}$.

We turn now to non-conventional dimuon sources namely the production of new heavy quarks, of Higgs particles, of charged spin-1/2 new heavy leptons or of heavy neutrinos.

The production of new heavy quarks could give rise to muons with a large p_T with respect to the event thrust axis. However, the non-observation of a narrow resonance below 43.450 GeV and the absence of a step ($\Delta R = 1.3$) in the measurement of the R ratio at PETRA rule out the production of a charge-2/3 t quark. An interpretation in terms of continuum production of new quarks $b'\bar{b}'$ cannot be ruled out for a b' charge of $-1/3$, though missing energy and momentum carried away by neutrinos would be expected to be substantially higher than observed.

Assuming production of Higgs-like charged particle H^+H^-, the Higgs coupling constants are proportional to the mass of the fermions into which they decay. Therefore $\nu_\tau\tau$, $c\bar{s}$ and $c\bar{b}$ decays are favoured. In order to obtain at least one isolated muon, the decay of one of the Higgs particles into $\nu_\tau\tau$ can be invoked, however substantial energy should be missing in that case. Furthermore the energy of all charged particles excluding one of the muons should be less than the beam energy. Since this last condition is not fulfilled, this possibility can be rejected.

The cross section for the production of spin-1/2 charged heavy leptons $L^\pm$ increases rapidly near threshold

$$\sigma(e^+e^- \to L^+L^-) = (2\pi\alpha^2/3s)\beta(3 - \beta^2) ,$$

$$\text{with } \beta = (1 - 4M_L^2/s)^{1/2} .$$

Therefore, a sequential charged heavy lepton with a mass of 21.6 GeV/c^2 would lead to three expected events for $BR(L^\pm \to \mu + \text{neutrinos}) \simeq 0.1$. Similar arguments as given in the previous paragraph rule out this possibility.

The pair production of a heavy muon close to threshold would explain the observed topology if the μ^* decays to μ + hadrons. However, about 30 such events for CM energies between 43.450 and 45.2 GeV and for a μ^* mass of 21.725 GeV/c^2 would be expected.

An alternative to the production of μ^* pairs is $e^+e^- \to \mu\mu^*$, for which one has to invoke an unconventional current of the form [13] $(e/\Lambda)\bar{\psi}_{\mu^*}\sigma^{\lambda\nu}F_{\lambda\nu} \times \psi_\mu$ (where Λ is a scale parameter with mass dimension and $F_{\lambda\nu} = \partial_\lambda A_\nu - \partial_\nu A_\lambda$). The cross section for this process can be written

$$\sigma = (16\pi\alpha^2/3\Lambda^2)(1 - M_{\mu^*}^2/s)^2(1 + 2M_{\mu^*}^2/s) .$$

A scale parameter of the order of 800 GeV would give one expected event for a μ^* mass around 29 GeV/c^2 from both μ^+ + hadrons or μ^- + hadrons. Using our data at lower energy ($\sqrt{s} = 34$ GeV), we would also expect one event. None were seen. Our data alone would not rule out the $\mu\mu^*$ interpretation, but other PETRA experiments with larger integrated luminosity should have seen such events.

Pair production of a heavy neutrino has a cross section rising linearly with s:

$$\sigma(e^+e^- \to \nu_H\bar{\nu}_H) = (G^2/96\pi)(sM_Z^4/(s - M_Z^2)^2)$$
$$\times \beta(3 + \beta^2)[1 - 4\sin^2\theta_W + 8\sin^4\theta_W]$$

with G the Fermi constant, M_Z the Z^0 mass and θ_W the Weinberg angle. For a 20 GeV/c^2 neutrino, the cross section is of the order of 0.3 pb (i.e. 1.2 events are expected).

The lifetime for a heavy neutrino can be expressed simply using the muon lifetime

$$\tau_H = \tau_\mu(M_\mu/M_H)^5 BR(W^+ \to e\nu)\left(\sum_\ell |U_{\ell H}|^2\right)^{-1} ,$$

where τ_μ is the μ lifetime, M_μ and M_H the μ and the ν_H masses, $BR(W^+ \to e\nu)$ the branching ratio of the virtual W to electron ($\simeq 0.1$), and $|U_{\ell H}|$ the elements of the lepton mixing matrix. Since the common vertex of charged particles is close to the interaction point, we can estimate the lifetime to be less than 10^{-10} s. A 20 GeV/c^2 neutrino would not severely constrain the mixing angles ($\Sigma_\ell |U_{\ell H}|^2 > 9 \times 10^{-9}$). But taking a V – A coupling, the mass recoiling against the muon should be peaked around $M_H/2$. The observed jet masses are substantially lower than this value.

We have also considered the possible production of a pair of spin 0 heavy muonic neutrinos as predicted by supersymmetric models. In this case, the rate would be small for a 20 GeV/c^2 neutrino, essentially because of the β^3 threshold behaviour (0.12 event expected). It is also not clear that the observed event would fit naturally in the phenomenological framework describing the decay of these objects [14].

In summary, we have found one multihadronic event with two isolated energetic muons in which both the hadronic and dimuon masses are large. We expect of the order of 10^{-3} events of this kind from conventional sources.

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