SEARCH FOR NEW HEAVY QUARKS IN e^+e^- COLLISIONS UP TO 46.78 GeV CM ENERGY

CELLO Collaboration

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Received 25 June 1984

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The total e^+e^- annihilation cross section into hadrons has been measured at CM energies between 33.00 and 36.72 GeV and between 38.66 and 46.78 GeV in steps of 20 and 30 MeV respectively. The average of the ratio $R = \sigma(e^+e^- \to \text{hadrons})/\sigma_{point}$ is $\langle R \rangle = 3.85 \pm 0.12$ and $\langle R \rangle = 4.04 \pm 0.10$ for the two energy ranges. The systematic error on $\langle R \rangle$ is 0.31. Both values are consistent with the expectation for the known coloured quarks u, d, s, c and b. No evidence was found for the production of new quarks. If the largest fluctuation in R is interpreted as a narrow resonance, it corresponds to a product of the electronic width and the hadronic branching ratio $\Gamma_{ee}B_{had} < 2.9$ keV at the 95% confidence level, well below the value expected for the toponium vector ground state with charge $\frac{2}{3}e$. The observed number of aplanar final states rules out the continuum production of a new heavy flavour with pointlike cross section up to a CM energy of 45.4 GeV for a quark charge of $\frac{1}{3}e$ and up to 46.6 GeV for $\frac{2}{3}e$ at the 95% confidence level.

This paper presents results of a measurement of the total e^+e^- annihilation cross section into multihadron final states up to a CM energy of 46.78 GeV, which is the highest energy reached in e^+e^- collisions so far. The experiment has been performed at the DESY storage ring PETRA using the magnetic detector CELLO.

Previous measurements [1–3] [‡1] have shown that the ratio $R = \sigma(e^+e^- \to \text{hadrons})/\sigma_{point}$ is consistent with the quantum flavour dynamics (QFC) expectation for coloured u, d, s, c, and b quarks taking second order QCD and electroweak corrections into account. The main objective of this measurement was to search for the theoretically expected t quark of charge $\frac{2}{3}e$ through the following signals:

(i) The existence of narrow resonances of $t\bar{t}$-bound states.

(ii) An increase of R by approximately 4/3 above the $t\bar{t}$-production threshold.

(iii) The occurrence of events of large sphericity and aplanarity expected from pair production and subsequent decays of heavy hadrons containing the t quark.

The data were taken at energies between 33.00 and 36.72 GeV in 1980 [3] and between 38.66 and 46.78 GeV in 1983 and 1984. The two data samples will be referred to as E1 and E2. Time integrated luminosities of 3.7 pb^{-1} (E1) and 12.1 pb^{-1} (E2) were collected during these periods. The center of mass energy $W = 2E_{beam}$ was normally varied in steps of 20 MeV (E1) and 30 MeV (E2). With a CM energy spread σ_W of about 25 MeV (E1) and 37 MeV (E2), a continuous coverage of the following energy ranges was obtained:

$$33.00 < W < 33.80 \text{ GeV},$$

$$34.00 < W < 35.26 \text{ GeV},$$

$$35.6 < W < 35.80 \text{ GeV},$$

$$36.08 < W < 36.72 \text{ GeV},$$

for E1

$$38.66 < W < 38.78 \text{ GeV},$$

$$39.79 < W < 46.78 \text{ GeV},$$

for E2.

CELLO is a general purpose magnetic detector equipped with a superconducting solenoid. It enables the detection of charged particles and photons over a solid angle of almost 4π. For a detailed description of the detector and its performance see ref. [4]. The analysis of multihadron production presented here is primarily based on the following two detector components:

(i) The central detector consisting of cylindrical proportional wire and drift chambers covering 91% of 4π.

(ii) The cylindrical lead liquid argon calorimeter consisting of 16 modules and covering 87% of 4π.

Forward spectrometers consisting of scintillation counters and lead glass shower counters are used for a relative point-to-point luminosity determination by measuring Bhabha scattering at angles between 25 and 50 mrad. The absolute normalization of the data is based on a measurement of Bhabha scattering [5] in the central part of the detector.

The trigger condition relevant for the detection of

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[‡1] A review of older data can be found e.g. in ref. [2].

multihadron final states is derived from a fast track search performed by a hardware processor [6] which is initiated at each e^+e^- bunch crossing (3.8 μs period with 2 bunches per beam). The track search is independently done in the bending plane ($r\phi$) and in the plane containing the beam axis (rz) using 7 anode wire layers in $r\phi$ and 5 layers of annular cathode strips in rz. In addition, the total shower energy of each of the 16 calorimeter modules is available to the fast trigger and in the data for fast preselection. The standard trigger required two or more tracks in $r\phi$ with a momentum perpendicular to the beam axis $p > 200$ MeV/c and at least 1 track in rz originating from a region of ± 10 cm around the interaction point. Typical trigger rates were 1–2 Hz. At the higher energies for the data sample E2, the trigger conditions had to be changed due to considerably higher backgrounds from beam–wall interactions and synchrotron radiation. Five or more tracks with $p > 600$ MeV/c in $r\phi$ and three or more tracks in rz were required. Events with less than five tracks in $r\phi$ were also accepted if they had at least two tracks with an opening angle above 135°. In addition, an independent shower energy trigger requiring two non-adjacent calorimeter modules with at least 2.5 GeV in each and a combined trigger requiring either one track in $r\phi$ and 2 GeV shower energy or two tracks and 1 GeV shower energy were used. This leads to a trigger rate of 2–4 Hz for E2. The trigger efficiency for multihadron events is 95% for E1 and 97% for E2 as determined by Monte Carlo simulation.

The selection of multihadron events was done as follows: For a preselection we required at least four tracks and approximate transverse and longitudinal momentum balance using the direction and momentum of each track found by the track finding logic. These criteria reduce the number of triggers by a factor of 100. For the E2 data sample the preselection was performed online and required in addition that the shower energy summed over all 16 stacks was at least 4 GeV.

The accepted events were than passed through our standard track- and shower-reconstruction programs. All tracks were required to have $p > 120$ MeV/c. At least one track had to have $p > 400$ MeV/c and to come from the interaction region. The following requirements were imposed to discriminate against hadron production in $\gamma\gamma$ collisions, beam–gas and beam–wall interactions, and a small contribution from $\tau^+\tau^-$ events:

– more than four reconstructed tracks;
– at least one track in the $+z$ and in the $-z$ hemisphere (for E1 only);
– "visible energy" of charged particles

$$\sum |p_i| > 0.24\ W \quad (\mathrm{E1}),$$

$$> 0.125\, W \quad (\mathrm{E2}),$$

– sum of the charges of all tracks less than seven;
–the visible energy of charged particles and reconstructed neutral showers

$$\sum |p_i| + E_n > 0.4\ W \qquad (\text{for E2 only}),$$

– in the $r\phi$ plane the angle between at least one pair of tracks has to be $>130°$ (for E2 only).

A small contamination from Bhabha events interacting in the beam–pipe and beam–gas (–wall) interactions was removed by visual inspection. The total number of multihadron events is 967 for the energy scan E1 and 1998 for E2.

The trigger efficiency, detector acceptance, losses due to the cuts described, and radiative corrections [7] – dominated by hard photon radiation in the initial state – were determined by a Monte Carlo (MC) simulation of the experiment. The high synchrotron radiation background in the E2 energy range was simulated by overlaying events from randomly selected bunch crossings with MC generated data. Multihadron events were generated using $q\bar{q}$ and $q\bar{q}g$ creation and fragmentation [8] (q = u, d, s, c, b). Allowing for a radiated photon energy up to 0.99 E_{beam}, the radiative correction including leptonic and hadronic vacuum polarization is 1.35 (1.38) and the overall detection efficiency is 0.72 (0.66) for E1 (E2).

The measured values of R as a function of W are shown in figs. 1a, 1b and 1c. Only statistical errors are shown. Systematic point-to-point variations are small compared to the statistical fluctuations. The data show neither a statistically significant narrow resonance nor an increase of R of the size expected for $t\bar{t}$ production. To search for resonances much narrower that σ_W, the data was fitted by a gaussian of width $\sigma_W = 2.2 \times 10^{-5}\ W^2$/GeV taking into account radiative smearing [9] and a constant background. The integral over W of the hadronic cross section, σ_υ, of a narrow $J^P = 1^-$ Breit–Wigner resonance of mass M_υ is given by:

$$\int \sigma_\upsilon(W)\mathrm{d}W = (6\pi^2/M_\upsilon^2)\Gamma_{ee}\Gamma_{had}/\Gamma_{tot}\,,$$

where Γ_{tot}, Γ_{ee}, and Γ_{had} are the total width and the partial decay widths into e^+e^- and hadrons respectively. The gaussian fit was found to be largest for $W = 42.94$ GeV giving an upper limit of

$$B_{had}\Gamma_{ee} = (\Gamma_{had}/\Gamma_{tot})\Gamma_{ee} < 2.9\ \mathrm{keV}$$

at the 95% confidence level. For a quark charge $\frac{2}{3}e$ Γ_{ee} is expected to be between 4 and 5 keV [10]. Assuming a hadronic branching fraction $\Gamma_{had}/\Gamma_{tot}$ of 0.8, our experimental upper limit on Γ_{ee} is well below a $t\bar{t}$ bound state in the covered mass range.

The average values of R for the energy scans E1 and E2 are

$R = 3.85 \pm 0.12$ (statistical) ± 0.31 (systematic) (E1),

$R = 4.04 \pm 0.10$ (statistical) ± 0.31 (systematic) (E2).

Our estimate of the overall normalization uncertainty is dominated by the systematic errors of the MC simulation and the luminosity measurement.

The measured values are consistent with $\langle R\rangle = 3.91$ (E1) and 4.01 (E2) expected for the five known quarks including second order QCD ($\alpha_s = 0.18$ [11] at $Q^2 = 1200$ GeV^2 in $\overline{\mathrm{MS}}$-scheme) and electroweak ($\sin^2\theta_W = 0.22$) corrections. Our $\langle R\rangle$ values agree with results previous measurements [1]. They strongly disfavour the existence of a t quark in or below our energy range, for which one expects $R = 5.4$ for the pointlike production of open top flavour.

Further evidence against the existence of a new heavy quark is obtained from an analysis of the aplanarity [‡2] distribution of multihadronic events. Fig. 2 shows the observed aplanarity A for the data from $W = 45.7$–46.78 GeV. The data are in good agreement with a Monte Carlo simulation involving the known five quarks and QCD corrections up to second order. Also shown in fig. 2 is the MC simulation, if one adds the pointlike production of a new quark with a mass of 21 GeV and charge e_q with a change in R of $3\,e_q^2$.

As can be seen, the data above 45.7 GeV clearly rules out both charge possibilities of $\frac{1}{3}e$ and $\frac{2}{3}e$. A limit on the threshold W_{th} for the continuum production of new flavours has been obtained by varying W_{th} up to the energy, where the MC prediction for the number of aplanar events ($A > 0.1$) for six quarks equals the 95% confidence level upper limit on the observed number of aplanar events above W_{th}.

Assuming a contribution to R above W_{th} of $3\,e_q^2$, we find that the continuum production of a new quark is ruled out at 95% confidence level below CM energies of 45.4 and 46.6 GeV for quark charges $\frac{1}{3}e$ and $\frac{2}{3}e$, respectively. Here we neglected the threshold factor de-

[‡2] The aplanarity $A = \frac{3}{2}Q_1$, where Q_1 is the smallest eigenvalue of the momentum tensor, proposed in ref. [12].

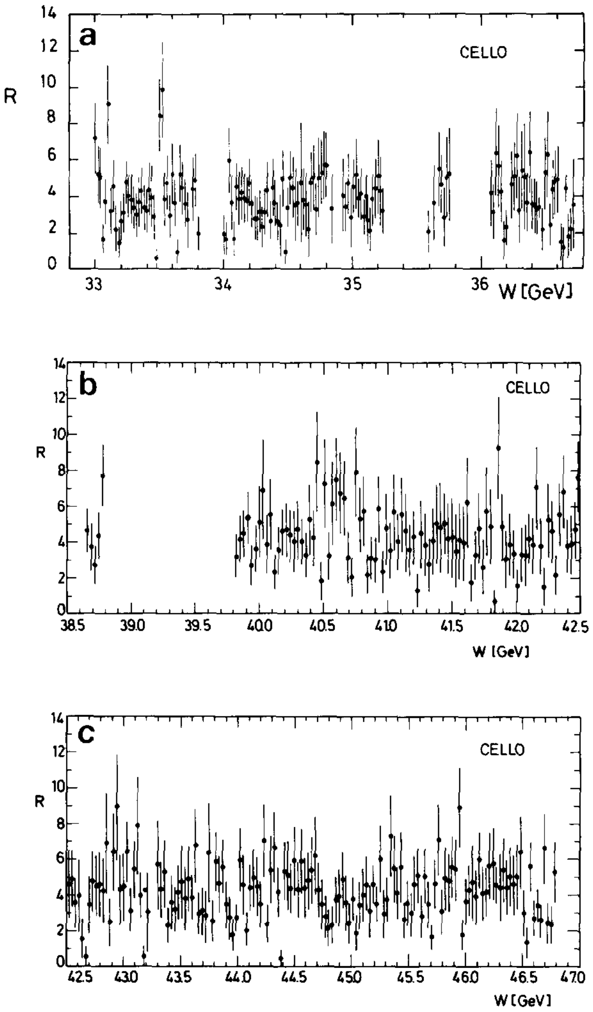

Fig. 1. $R = \sigma(e^+e^- \to \mathrm{hadrons})/\sigma_{point}$ versus CM energy W. Only statistical errors are shown. (a) for energy scan E1. (b) and (c) for energy scan E2.

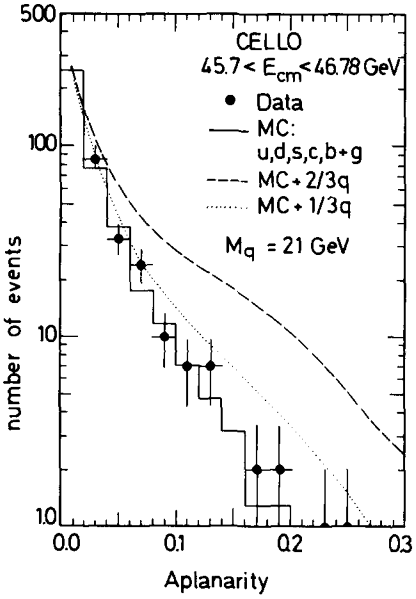

Fig. 2. Distribution of events in aplanarity for data above CM energies of 45.7 GeV. The solid line represents a MC simulation of $q\bar{q}$ and $q\bar{q}g$ production and fragmentation with q = u, d, s, c, b. The dashed–dotted line includes an additional quark with charge $\frac{2}{3}$ ($\frac{1}{3}$) e and a mass of 21 GeV.

pending on the velocity of the new quark, since just above W_{th} the cross section is usually enhanced by resonances.

In conclusion, the average value of R up to the highest CM energies obtained in e^+e^- annihilation – 46.78 GeV – is in good agreement with the QFC expectation for five coloured quarks.

The absence of narrow resonances in our data excludes the existence of a new quark with charge $\frac{2}{3}e$ in the scanned energy range. A new quark with charge $\frac{2}{3}e$ at lower masse is excluded by the average value of R. The sensitivity for new quarks can be enhanced by searching for aplanar final states. From the number of events with aplanarity >0.1, we rule out at the 95% confidence level the point-like continuum production of new flavours below 45.4 GeV/c for a quark charge of $\frac{1}{3}$ e and below 46.6 GeV/c for a quark charge of $\frac{2}{3}e$.

We gratefully acknowledge the outstanding efforts of the PETRA machine group which enabled these measurements. We are indebted to the DESY computer center for rheir excellent support during the experiment. We acknowledge the invaluable effort of all engineers and technicians of the collaborating institutions in the construction and maintenance of the apparatus, in particular the operation of the magnet system by M. Clausen and the cryogenics group. The visiting groups wish to thank the DESY directorate for the support and kind hospitality extended to them. This work was partly supported by the Bundesministerium für Forschung and Technology (Germany) and by the Science and Engineering Research Council (UK).

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