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SEARCH FOR NARROW QUARKONIUM STATES AND PAIR PRODUCTION OF HEAVY QUARKS AT C.M. ENERGIES FROM 33.0 TO 36.7 GeV

by

CELLO Collaboration

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Search for Narrow Quarkonium States and Pair Production of New Heavy Quarks at C.M. Energies from 33.0 to 36.7 GeV

CELLO-Collaboration

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Abstract

The total e^+e^- annihilation cross section into hadrons has been measured at c.m. energies between 33.00 and 36.72 GeV in steps of 20 MeV. The average ratio $R = \sigma(e^+e^- \to \text{hadrons})/\sigma_{\mu\mu} = 3.85 \pm 0.12$ (stat.)±0.31 (syst.) is consistent with the quark-parton model expectation for coloured u, d, s, c, and b quarks. For a narrow $J^P = 1^-$ quarkonium state of a hypothetical t quark of charge 2/3 e, we find an upper limit $\Gamma_{ee} \cdot \Gamma_{had}/\Gamma_{tot} < 2.2$ keV at 95% c.l.. The observed number of aplanar final states excludes a contribution to R of 4/3 from a new quark with a mass between 6 and 16.5 GeV, and a contribution of 1/3 for quark masses between 9 and 16.5 GeV.

This paper presents results of a measurement of the total e^+e^- annihilation cross section into multihadron final states at c.m. energies between 33.00 and 36.72 GeV. The experiment has been performed at the DESY storage ring PETRA using the magnetic detector CELLO.

Previous measurements[1] at energies below 31.6 GeV have shown that the ratio $R = \sigma(e^+e^- \rightarrow \text{hadrons})/\sigma(e^+e^- \rightarrow \mu^+\mu^-)$ is consistent with the quark-parton model expectation for coloured u, d, s, c, and b quarks taking lowest order QCD corrections into account. The main objective of this measurement was to search for the following signals for the hypothetical t quark of charge 2/3 e:

- the existence of narrow $t\bar{t}$ bound states,
- an increase of R by approximately 4/3 above the $t\bar{t}$ production threshold, and
- 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 between April and November 1980. A time integrated luminosity of 3.7 pb^{-1} was collected during that period. The center of mass energy $W = 2 \cdot E_{beam}$ was normally varied in steps of 20 MeV. With a c.m. energy spread σ_W of about 27 MeV, a continuous coverage of the following 3 energy ranges was assured:

$$33.00 < W < 33.80 \text{ GeV}$$
$$34.00 < W < 35.26 \text{ GeV}$$
$$36.08 < W < 36.72 \text{ GeV}.$$

Additional data points were taken at 7 energies around W = 35.7 GeV.

CELLO is a general purpose magnetic detector equipped with a superconducting solenoid[2]. It allows for 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. 3. The analysis of multihadron production presented here is primarily based on the detection

and momentum measurement of charged particles in the central detector consisting of cylindrical proportional wire and drift chambers. The track detector covers 91% of 4π.

Forward spectrometers consisting of scintillation counters, drift chambers 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[4] in the central part of the detector.

The trigger condition relevant for the detection of multihadron final states is derived from a very fast track search[5] 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. The standard trigger requires 2 or more tracks in $r\phi$ with a momentum perpendicular to the beam axis $p_\perp > 200$ MeV/c and at least 1 track in rz originating from a region of ± 10 cm around the interaction point. Typical trigger rates are 1-2 Hz. The trigger efficiency for multihadron events is 95% as determined by Monte Carlo simulation.

The offline selection of multihadron events was done in the following sequence. For a preselection we required at least 4 tracks and some crude 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. The accepted events were then passed through a track reconstruction program. All tracks were required to have $p_\perp > 120$ MeV/c. At least one track had to have $p_\perp > 400$ MeV/c and come from the interaction region. Finally, 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 4 reconstructed tracks
- at least one track in the +z and one track in the -z hemisphere
- "visible energy" of charged particles per event (Fig. 1)

$$\Sigma \mid \vec{p}_i \mid > 0.24 \cdot W$$

- net electric charge per event < 7.

The remaining events were all double scanned by physicists. A residual contamination, mostly Bhabha events interacting in the beam pipe (9%), and beam gas (wall) interactions (1.3%), was removed. The total number of multihadrons is 967. Small corrections for indistinguishable back-grounds from $\tau^+\tau^-$ production (3%) and 2-photon processes (0.6%) were applied.

The trigger efficiency, detector acceptance, losses due to the cuts described, and radiative corrections[6] - dominated by hard photon radiation in the initial state - were determined by a Monte Carlo (MC) simulation of the experiment. Multihadron events were generated using $q\bar{q}$ and $q\bar{q}g$ creation and fragmentation[7] (q = u, d, s, c, b). Allowing for a radiated photon energy up to $0.99 \cdot E_{beam}$, the radiative correction is 1.29 and the overall detection efficiency is 0.72. A further correction of 1.05 for leptonic and hadronic vacuum polarization was applied.

The measured values of R as a function of W are shown in Fig. 2. Only statistical errors are shown. Systematic point to point variations are small compared to the statistical fluctuations. The overall normalization uncertainty is $\Delta R = \pm 0.31$. The data show neither a statistically significant narrow resonance nor an increase of R of the size expected for $t\bar{t}$ production. In order to search for resonances much narrower than σ_W, we fitted the data to a Gaussian of width $\sigma_W = 2.2 \times 10^{-5}$ W^2/GeV and a constant background including radiative smearing[8]. The integrated hadronic cross section of a narrow $J^P = 1^-$ Breit Wigner resonance of mass M_V is given by:

$$\int \sigma_V(W)dW = \frac{6\pi^2}{M_V^2} \frac{\Gamma_{ee} \Gamma_{had}}{\Gamma_{tot}}$$

(Γ_{tot}, Γ_{ee}, and Γ_{had} are the total width and the partial decay widths into e^+e^- and hadrons respectively).

At M_V = 33.52 GeV we obtain the largest upper limit:

$$\int \sigma_V(W)dW < 45.0 \text{ nb} \cdot \text{MeV} \quad \text{(95\% confidence level)}$$

or

$$\frac{\Gamma_{had}}{\Gamma_{tot}} \Gamma_{ee} < 2.2 \text{ keV}.$$

For a quark of charge 2/3 e one expects Γ_{ee} to be between 4 and 5 keV[9]. Assuming a hadronic branching fraction $\Gamma_{had}/\Gamma_{tot}$ of 0.7, our experimental upper limit on Γ_{ee} excludes a $t\bar{t}$ bound state in the covered mass range by at least 3.2 standard deviations (s.d.).

The signal to background ratio for a narrow quarkonium state can be enhanced by selecting multihadron events of large sphericity S[10]. The background is dominated by two jet events of small S, whereas the decay of a narrow bound state would result in events of larger S. Taking only events with S > 0.25 failed to reveal any statistically significant resonance structure. In particular the S cut reduced the significance of the structure at W = 33.52 GeV considerably. This effect therefore has to be considered a statistical fluctuation in the number of low sphericity events. The absence of narrow $t\bar{t}$ resonances in our data is in agreement with the recently published null result of the JADE collaboration[11] in the same energy range.

The average value of R over the energy range studied is

$$R = 3.85 \pm 0.12 \text{ (statistical)} \pm 0.31 \text{ (systematic)}$$

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

The measured value of R is consistent with

$$R = 11/3\ (1 + \alpha_s/\pi) = 3.88$$

expected for u, d, s, c, and b quark contributions including first order QCD correction using $\alpha_s = 0.18$[12]. It also agrees with results of other PETRA experiments below W = 31.6 GeV[1] and the result of the JADE collaboration[11] in the energy range of this experiment. The measured value of R strongly disfavours the existence of a t quark, which far enough above threshold, would increase R to 5.29.

Further evidence against the existence of a new heavy quark is obtained from an analysis of the distribution of multihadron events in the plane of sphericity $S = 3/2\ (Q_1+Q_2)$ and aplanarity $A = 3/2\ Q_1$ (Fig. 3a). $Q_1 < Q_2 < Q_3$ are the normalized eigenvalues of the momentum tensor[10] $M_{\alpha\beta} = \sum_i p_{i\alpha} p_{i\beta}$ (α, β = x, y, z) computed from the charged particle momenta only[+].

+) A more complete analysis of distributions in momentum space including neutral energy as well, will be the subject of a forthcoming paper.

As expected, for light quark production and gluon bremsstrahlung, two jet events (small S and A) dominate and a long tail of planar events is observed (see MC simulation in Fig. 3b). For heavy quark pair production one expects a much more uniform population of the S-A-plane as seen in Fig. 3c. In the energy range covered by this experiment, the pair production of a quark of charge 2/3 e and a mass of 16 GeV should yield 96.3±4.2 multihadron events of $A > 0.15$ for the amount of data we have taken[7]. The observed number of 9 events is consistent with 5.2±1.4 events expected from $q\bar{q}$ and $q\bar{q}g$ production and excludes the existence of a t quark by 8.7 s.d.. A new heavy quark of charge 1/3 e which would yield 31.3±1.4 events is excluded by 4.3 s.d.. For quark masses less than 16 GeV, we expect fewer events with high aplanarity. Our data exclude the production of new quarks with charge 2/3 e down to a mass of 6 GeV and charge 1/3 e down to 9 GeV with 95% confidence. The above limits are based on a production cross section of $3e_Q^2\sigma_{\mu\mu}$ for a hypothetical heavy quark Q of charge e_Q.

In conclusion we can state that the absence of narrow resonances in our data, the average value of R, and the topology of hadronic final states exclude the existence of a new quark of charge 2/3 e with mass between 6 and 18.35 GeV. A continuum contribution of a new quark of charge 1/3 e with mass between 9 and 16.5 GeV is ruled out by the observed number of aplanar events.

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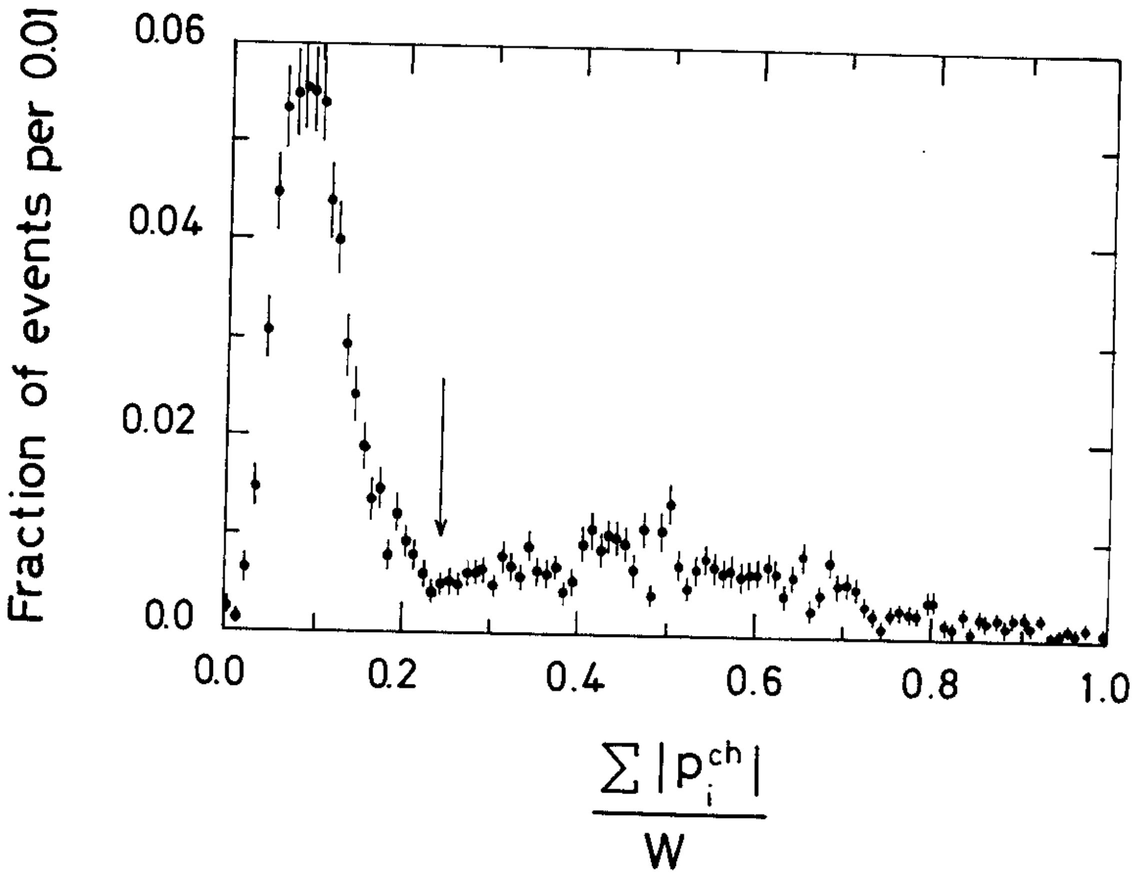
Figure captions

Fig. 1: Distribution of the sum of the momenta divided by the c.m. energy W for charged tracks in hadronic final states. The cut at 0.24 is used to separate two photon interactions having low momentum sums from single photon annihilations.

Fig. 2: $R = \sigma(e^+e^- \rightarrow \text{hadrons})/\sigma_{\mu\mu}$ vs c.m. energy W. Only statistical errors are shown.

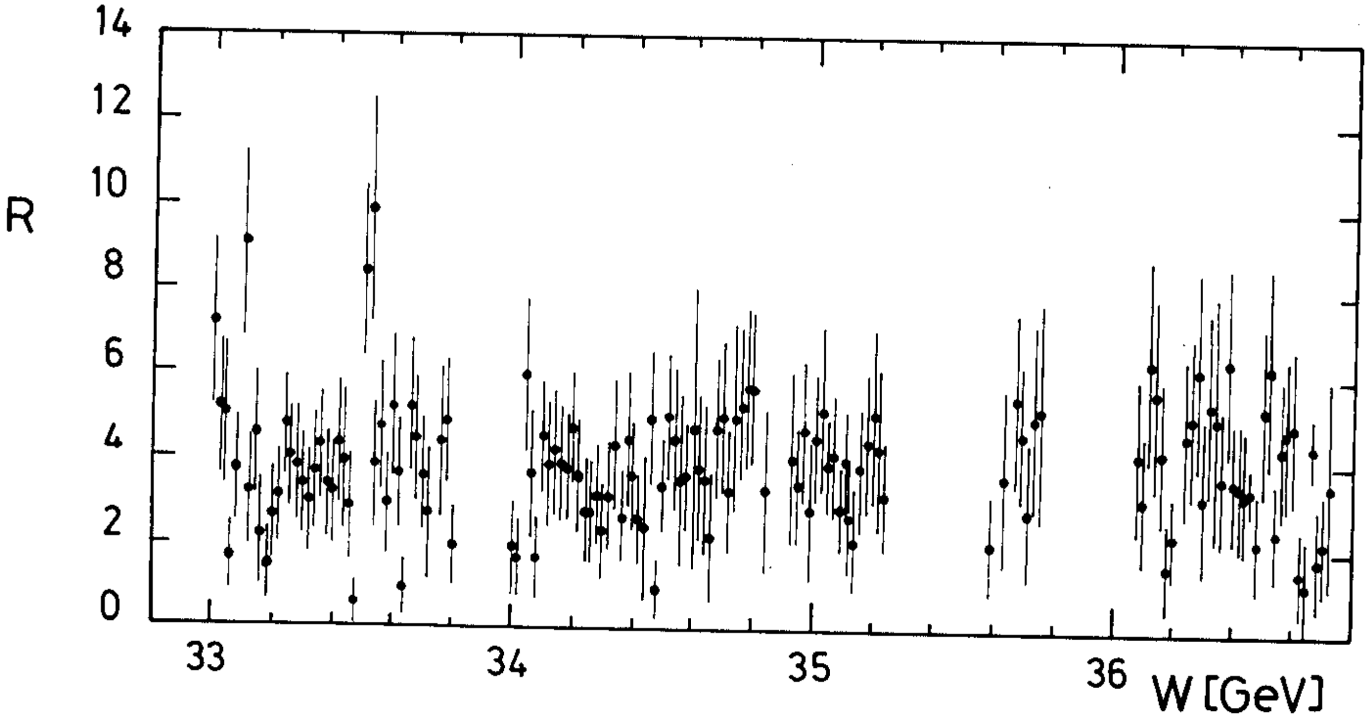
Fig. 3: Distribution of events in aplanarity and sphericity
a) all data, $33.00 \leq W \leq 36.72$ GeV
b) MC[7] simulation of $q\bar{q}$ and $q\bar{q}g$ production and fragmentation in the energy range covered by this experiment (q = u, d, s, c, and b)
c) MC[7] simulation of non-resonant $t\bar{t}$ production in the energy range covered by this experiment using $M_t = 16.00$ GeV.

The cut at A = 0.15 is used to isolate events of large A as expected from $t\bar{t}$ production.



Fraction of events per 0.01
0.06
0.04
0.02
0.0
0.0
0.2
0.4
0.6
0.8
1.0
$\frac{\sum |p_i^{ch}|}{W}$

Fig.1



R
14
12
10
8
6
4
2
0
33
34
35
36
W [GeV]

Fig. 2

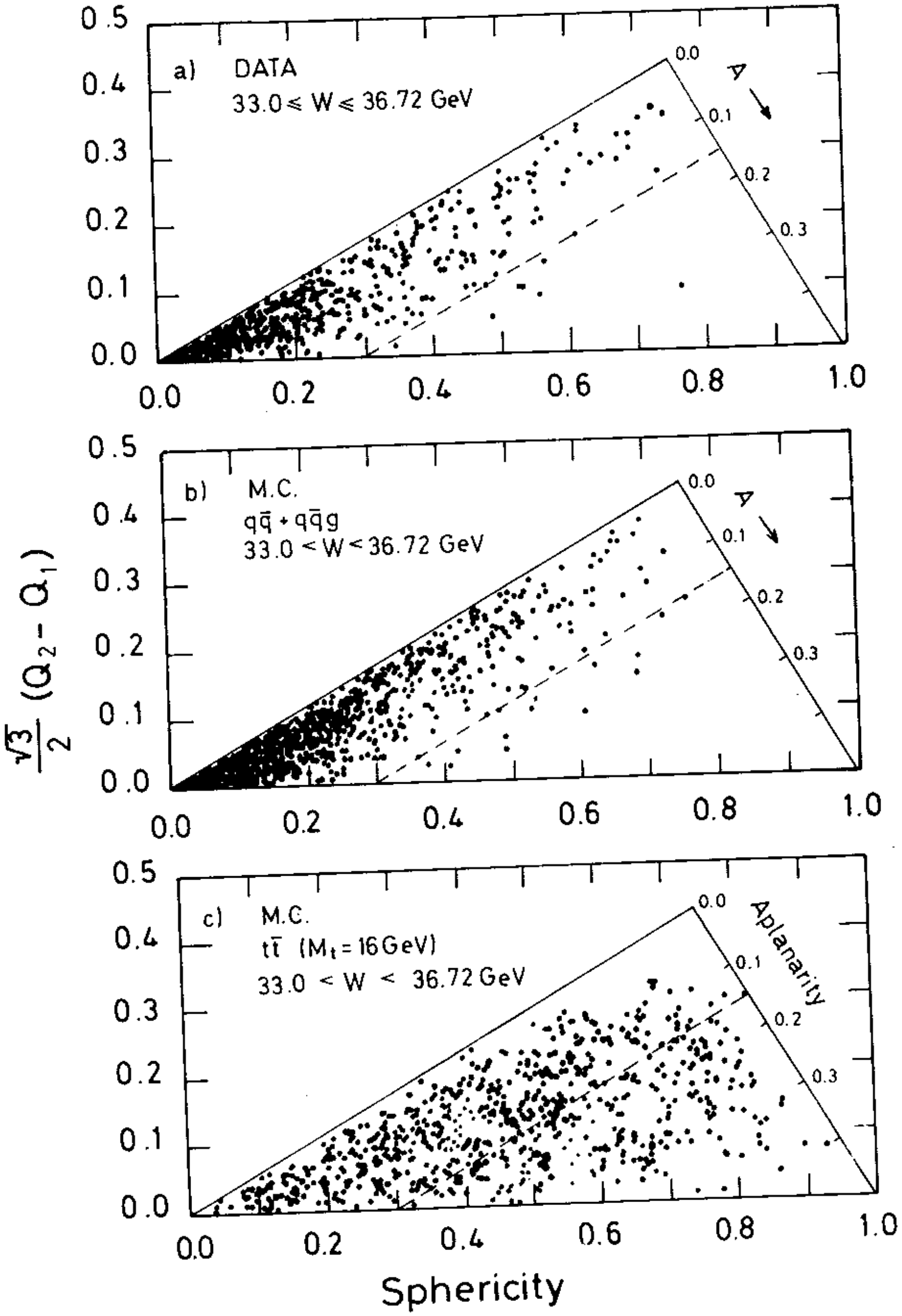

a) DATA
33.0 ≤ W ≤ 36.72 GeV
b) M.C.
qq̄ + qq̄g
33.0 < W < 36.72 GeV
c) M.C.
tt̄ (M_t = 16 GeV)
33.0 < W < 36.72 GeV
A
Aplanarity
√3/2 (Q_2 - Q_1)
Sphericity
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.8
1.0

Fig.3